Proceedings

Third Webinar

Expert Talk

(First Ever TWT Built in India) &

Young Researchers' Talk Series

(Large-Signal Analysis of Helix-TWT & Recent Trends in Millimeter/THz Wave Vacuum Electron Beam Devices)

7 November 2020, Saturday

Editors:

Vishal Kesari
Raj Singh
B N Basu

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Thinkers in Vacuum Electron Devices Group
India

From Editorial Desk

We thank the Convener Mr. Raj Singh for organizing our third webinar on 7th November 2020 with web-support to the Group from Dr. Uttam Goswami, Dr. Vishant Gahlaut, and their associates.

Professor LM Joshi was with us in the programme of the webinar and he proposed Vote of Thanks on his behalf and on behalf of our Group.

We thank Dr. Vishant Dwivedi for hosting the second session of the webinar. In this session, Dr. Richards Joe Stanislaus presented the glimpse of his 'Large-signal analysis of a helix-TWT'. It was also so nice of Dr. S Yuvraj in this session to enlighten us by his talk on 'Recent trends in millimetre-/THz-wave vacuum electron devices'. He elaborated on multi-frequency coaxial-cavity gyrotron as well.

Professor Lalit Kumar suggested that the benchmarking of the large-signal analysis of Dr. Richards, even in the small-signal regime, would add value to the analysis. On the same line, Professor LM Joshi suggested that the commercially available code such as MAGIC could also be tried out for the validation of the analysis. On the question addressed to Dr. Yuvraj by Mr. Shyam Gopal Yadav related to the beam velocity pitch factor and beam velocity spread, Dr. Anirban Bera from the Gyrotron lab of CEERI wished to elaborate the answer to Mr. Yadav and Dr. Yuvraj through email. (The Group immediately provided the email addresses of Mr. Yadav and Dr. Yuvral to Dr. Bera). At this juncture, Dr. SN Joshi strongly suggested that it would be so good if Dr. Yuvral and Dr. Bera join their hands together for the progress of gyrotron research in India.

We have no words to express our gratitude to Dr. SSS Agarwala for showering his blessings on our Group in this webinar. We thank Professor Lalit Kumar to encourage us by inviting Dr. Agarwala to present, before our Group, a glimpse of his experience in the area of vacuum electron devices. We thank Professor SN Joshi and Dr. Vishant Dwivedi for linking with Dr. Agarwala for making his appearance in this webinar a happening.

We also thank Professor Lalit Kumar for kindly introducing Dr. Agarwala to younger members of the Group. Professor Lalit Kumar was present throughout the programme providing his guidance to the Group despite his engagements in teaching and research besides his engagements as the Editor of IEEE Transactions on Electron Devices.

We cannot write anything more than say that we were mesmerised by the brilliant talk by Dr. SSS Agarwala.

We believe that Dr. Vishant Gahlaut has video-recorded the talk by Dr. Agarawala.

It was so nice of Professor Chandra Shekhar, the erstwhile Director of CEERI, for kindly chairing the first session of the webinar in which Professor SN Joshi presented his talk on the first ever travelling-wave tube (TWT) developed in India. We are fortunate that Professor Chandra Shekhar could spare his precious time to be present in our programme despite his engagements as the Chancellor of Academy of Scientific and Innovative Research of CSIR and in spite of his other engagements including teaching students and carrying out research at BITS, Pilani. The talk of Professor SN Joshi on the development of the first ever TWT in India was very exciting. It was a helix-TWT comprising a Pierce electron gun using an oxide-coated cathode, a non-depressed collector and a helix closely fitting in a glass tube with contra-wound helical couplers and contra-wound helical attenuator, the latter in a resistive medium, both the couplers and attenuator being arranged external to the tube. A solenoidal magnetic field was used for Brillouin confinement of the electron beam. Professor Joshi also presented the measured output parameters of the tube including the AM-to-PM conversion coefficient.

In connection with this glass tube, Dr. Agarwala in passing mentioned about the work of the legendary Dr. DT Swift-Hook. One of us (BN Basu) remembers that Dr. Swift-Hook felicitated him (BN Basu) in a programme in London for citing one of Dr. Swift-Hook's paper maximum numbers in journals. He (BN Basu) is profoundly thankful to Dr. Agarwala for sharing with him a hard copy of the said paper: D.T. Swift-Hook, "Dispersion curves for a helix in a glass tube", *Proc. IEE 105b* (1958) 747-755.

In passing, it was mentioned perhaps by Professor SN Joshi that Rudolf Kompfner invented the TWT. In fact, at one point of time, the TWT used to be known as the Kompfner tube. We draw the attention of the Group to Figure 10.1 on page 271 of the book: A.S. Gilmour, Jr., *Microwave Tubes* (Artech House, Washington, 1986). There we get that, on 12th November 1942, Kompfner sketched how an 'untuned' amplifier could be conceived in a device to be later known as the TWT. Apparently, Kompfner was unaware of the US Patent #2,300,052, filed much earlier on May 4, 1940 by N. E. Lindenblad on 'TWT amplification at 390 MHz over a 30 MHz band'. However, Andrei Haeff filed a patent on a primitive type of TWT as early as in 1933 much before Lindenblad had filed his patent. Unfortunately, the invention of TWT by Haeff 'has been largely ignored'. We sincerely thank Professor Chandra Shekhar for mentioning the work of Haeff in one of his remarks while referring to the hand-in-hand progress of both vacuum electron devices and solid state devices in 1940's.

Finally, we are sincerely grateful to our Group for extending their cooperation in bringing out Proceedings on Webinar#3 held on 7th November 2020.

Vishal Kesari

On behalf of the Editorial Board

Foreword

A forum that cross-links all the researchers in VED area across institutional boundaries for mutual strengthening and leveraging to meet vital national challenges is a great service to the discipline of VED.

I congratulate Dr. Basu and others involved in conceptualising and implementing this initiative.

It was also a great idea to bring the generations together to share the perspectives and evolving context.

Best wishes!

Professor Chandra Shekhar
Chairman Board of Governors and Chancellor
Academy of Scientific and Innovative Research (AcSIR) Council of Scientific and Industrial Research (CSIR)
Erstwhile Director of Central Electronics Engineering Research Institute, Pilani, India.

Programme of the Webinar

Date: 7 November 2020, Saturday

Time: 04:00 – 06:00 pm

Convener: Mr. Raj Singh

Introductory Talk:

Dr. Lalit Kumar to introduce Dr. S S S Agarwala to the younger generation of the group.

Duration	Topic of deliberation	Speaker
04:00 - 04:30 pm	Good Wishes to the Group	Dr. SSS Agarwala

Session 1 - Expert Talk

Chair: Professor Chandra Shekhar

Duration	Topic of deliberation	Speaker
04:30 - 04:35 pm	Opening Remark	Professor Chandra Shekhar
04:35 - 05:10 pm	First Ever TWT Built in India	Dr. SN Joshi

Session 2 – Young Researcher's Talk Series

Research contributions of younger researchers in VEDs

Host: Dr. Vishant Dwivedi

Duration	Topic of deliberation	Speaker
05:10 - 05:30 pm	Large-Signal Analysis of Helix-TWT	Dr. Richards Joe Stanislaus
05:30 - 05:50 pm	Recent Trends in Millimeter/THz Wave Vacuum Electron Beam Devices	Dr. S. Yuvaraj
05:50 - 06:00 pm	Vote of thanks	Dr. LM Joshi

Organizing Committee

Name	Designation	Affiliation	Role
Professor Chandra Shekhar	Chairman Board of Governors and Chancellor	Academy of Scientific and Innovative Research (AcSIR) Council of Scientific and Industrial Research (CSIR)	Chair
Raj Singh	Scientist H	Institute of Plasma Research, Gandhinagar	Convener
Prof. B N Basu	Adjunct Professor	Supreme Knowledge Foundation Group of Institutions	Advisor
Dr. LM Joshi	Ex-Scientist	Central Electronics Engineering Research Institute, Pilani	Vote of Thanks
Dr. Vishal Kesari	Scientist E	Microwave Tube Research and Development Centre, Bangalore	Editor Proceedings
Dr. Vishant Dwivedi	Senior Scientist	Central Electronics Engineering Research Institute, Pilani	Host
Dr. Vishant Gahlaut	Assistant Professor	Banasthali Vidyapith, Banasthali	Webinar Coordinator

Dr. Lalit Kumar

AICTE-INAE Distinguished Visiting Professor
Editor, IEEE Transactions on Electron Devices
Distinguished Research Advisor, SIT, Tumkur
Former Director, MTRDC, DRDO, Bangalore
Former Chairman, Centre for Personnel Talent Management (CEPTAM), DRDO, Delhi

Dr. Siddhi Sadhan Swarup Agrawala

- A Doyen of Indian Vacuum Electronic Device Fraternity

It is my privilege and honour to introduce Dr Siddhi Sadhan Swarup Agarwala to the audience of this 'VED Thinker's Webinar. I had the privilege to serve under him for over a decade during my early years as a Scientist at CSIR-CEERI, Pilani. He has been a mentor and a role model for me.

Dr Agarwala, a doyen of the Indian Vacuum Electronics Fraternity, needs no introduction to this audience. However, for the benefit of younger colleagues, I would like to say a few words about him.

Dr Agarwala, superannuated as 'Scientist G' in February 1990, a post he was promoted to in 1983, is popularly known among his peers and colleagues as 'SSS'.

He was born in Muzaffarnagar Uttar Pradesh on 21st February 1930. He obtained his B. Sc. and M. Sc. (Physics -Wireless) degrees both from the Allahabad University. He was a bright student throughout his academic years and was awarded 'The Ward Vidyanta Gold Medal' of Allahabad University for his highest rank in M. Sc in the year 1951. In the same year, he joined the CSIR-National Physical Laboratory

(NPL), New Delhi, and carried out research on nuclear magnetic resonance and electron paramagnetic resonance. He was awarded the prestigious Colombo Plan Scholarship and proceeded to England in 1956, to join the Imperial College of Science and Technology, London. He earned the Postgraduate Diploma of Membership of the Imperial College (DIC) in Electrical Engineering in the year 1958. In the same year, he was also awarded a Ph. D. (Microwaves) degree by the University of London on his thesis: "Investigation of a non-reciprocal slow-wave structure." Professor John Robinson Pierce visited the laboratory at Imperial College where Dr. Agarwala had developed his experimental setup for cold testing of slow-wave structure. Dr. Agarwala, who was, however, not present during this visit, was told by those who were present that Professor Pierce described the setup as "quite interesting".

On his return from England, he was posted to CEERI, Pilani on promotion in 1959. That was the beginning of his long illustrious career in vacuum electronics at CEERI. He served as the Head of Vacuum Tubes Division/ Coordinator of Microwave Tube Area of CEERI, for over three decades and spearheaded the R&D activities in VEDs. Under his stewardship, a full-fledged facility for development and batch production of microwave tubes was set up at CEERI.

He pioneered the indigenous development of the first helix TWT in India. A variety of VEDs: fixed-frequency and tuneable magnetrons, carcinotrons, TWTs, klystrons, power triodes, flash tubes, and induction heaters were developed under his leadership. He initiated and facilitated activities on analytical modelling and computer aided design of microwave tubes, high density dispenser cathodes, contra-wound couplers, thin-film attenuators, automated vacuum tube processing, and stock-piling of tube grade raw materials. He had strong linkages with all the scientific departments: ISRO, DRDO, DAE and Defence Services, and served on several national committees. He played a key role in organising the First Asia-Pacific Microwave Conference in Delhi and several national conferences at CEERI. He initiated collaborations with Lancaster University and Tubingen University and facilitated foreign visits of CEERI Scientists. He also hosted international Scientists: Dr. Steyskal (Chalmers), Dr. JRM Vaughan (Litton), Prof. OP Gandhi (Utah), Prof. Erwin Kasper (Tuebingen), Prof. RG Carter, (Lancaster), and Dr. W Schmidt (Valvo), to name a few.

He is well known for inculcating a stern discipline in the work culture, so essential for the unforgiving vacuum device technology. He is well known for his vast knowledge and deep insight on theoretical and experimental aspects of VEDs and being well versed in vacuum-tube technology. Dr. Agarwala truly symbolised his 'HEAD' ship by his qualities of Honesty, Earnestness, Administration and Discipline. He was like a father figure and a true mentor, and the lessons learned from him proved so useful in our careers.

For his outstanding contribution to the area of VED, Dr. Agarwala was felicitated with the 'Lifetime Achievement Award – 2008', by the Vacuum Electron Devices and Application (VEDA) Society, India. He is Life Fellow of IETE and VEDAS, Life Member of IEEE, and member of AIP, and so on. He is Fellow of VEDAS, Life Fellow of IETE, Life Member of IET (UK), IEEE (USA) and IVS (India), and past member of

AIP, AIP and AAAS.

Dr Agarwala is presently settled in his hometown: Muzaffarnagar and enjoys light reading and the juicy mangoes from his big orchards. His son: Ajay Agarwal—an engineer and daughter: Dr. Amita Gupta—a Scientist, are well settled in their lives. His wife and true companion Mrs. Sushma Agarwala, a noble and learned lady, departed to her heavenly a heavenly abode last year.

On behalf of myself and the VED Thinkers Group, I am thus privileged to offer my salutation to Dr SSS Agarwala and thank him from the bottom of my heart. I thank Prof Basu and colleagues for organising this webinar.

Dr. Siddhi Sadhan Swarup Agrawala

Retired Head, Vacuum Tube Division
CSIR - Central Electronics Engineering Research Institute
Pilani - 333 031 (Rajasthan), INDIA

Good Wishes to the Group

The speaker talked about his work and experiences at Imperial College (London University) as a Colombo Plan scholar, on leave from CSIR-NPL (New Delhi), from Jan.1956 to Oct.1958, which earned him DIC (Imperial College) and PhD (London University). Later, in Nov. 1959, he was transferred to CSIR-CEERI (Pilani) where he was attached to the Vacuum Tubes Division (later renamed 'Microwave Tubes Area). He also spoke about the country's first TWT indigenously designed and developed successfully there by a team of which he was a member.

Session 1
Expert Talk

Topic of Deliberation

First Ever TWT Built in India

Speaker

Dr. SN Joshi

Professor Chandra Shekhar

Chairman Board of Governors and Chancellor
Academy of Scientific and Innovative Research (AcSIR) Council of Scientific and Industrial Research (CSIR)
Erstwhile Director of Central Electronics Engineering Research Institute, Pilani, India.

Chairman's Desk

Dr. S.N. Joshi started by recounting the origins of Microwave Tube R&D in India – with the initiation of research on Magnetrons at IRPE, Kolkata and University of Delhi. These efforts were carried further by NPL and eventually CEERI - as the pioneering researcher of the area, Dr. Amarjit Singh, finally moved to CEERI, Pilani. Subsequently, CRMT, BHU, Varanasi and DRDO-MTRDC got added up among the prominent R&D centres of MWTs. TIFR initiated early R&D in Klystrons which was utilized by SAMEER, Mumbai in LINAC development. BEL, Bangalore and CEL, Sahibabad came up as PSU manufacturers. Dr. Joshi noted that today a strong base in the design and technologies of both slow-wave and fast-wave MWTs exists in the country across these institutions. IIT-Roorkee and NIT, Patna have also come up with important research groups in this area. Additionally, PETD Pvt. Ltd, Sangrur has come up as a producer of some of these devices in the private sector.

He summarized the global pioneering work on interaction phenomenon, theory and eventual practical demonstration of the TWT in 1947. He described in great detail the efforts to develop the first indigenous TWT by CEERI – covering its design, structural, technological and performance details. The TWT met all the targeted technical specifications and was tested and used in ISRO's ground station. Dr. Joshi who had led the effort under the overarching leadership and mentorship of Dr. S.S.S. Agarwala, recalled and thanked the contributions of all the team members.

Dr. Chandra Shekhar, who chaired the session, in his concluding remarks commented that this exposition by a pioneers of the TWTs in the country must have greatly motivated the young researchers of MWT area. Such authentic talks provide a real exposure to the participants and give them a perspective on the development of technologies in the country. He noticed the interesting coincidence that both the TWT (a vacuum electronic device) and the transistor (a semiconductor electronic device) were demonstrated in the same year, 1947 - the year of India's independence. He further commented that both these devices proved crucial for communication technologies. While TWTs moved to ever higher frequencies and ever higher power levels, transistors moved towards higher frequencies and lower power levels through miniaturization, thereby leading to large scale and very large scale integrated circuits crucial for miniaturization of computers. He thanked Dr. Joshi for his valuable presentation and the organizing team of the webinar for their enthusiasm and untiring efforts for making it possible on behalf of the MWT community.

Dr. S N Joshi

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Ex-Emeritus Scientist and National Coordinator-Gyrotron
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First Ever TWT Built in India

Vacuum electron devices (encompassing microwave tubes) got prominence around World War II, when magnetrons were used by British Forces in RADAR Systems. However, in India, it took relatively longer time to initiate research and development in this strategic area due to some obvious reasons. A few academic institutions such as Institute of Radio Physics and Electronics, Calcutta University and Department of Physics, Delhi University initiated some theoretical and experimental studies in this area in early days though they did not continue further.

National Physical Laboratory, New Delhi initiated R&D in pulsed magnetrons under the leadership of Dr. Amarjit Singh. As subsequently Dr. Singh was given the responsibility to lead CEERI, Pilani, the activities continued further there. Thus, CSIR-CEERI (earlier CEERI) has the privilege of further carrying out research and development in the area of microwave tubes right from its inception and has developed a variety of microwave tubes for different user agencies.

With time, other organisations like Centre of Research in Microwave Tubes, BHU, Varanasi (1979); DRDO-Microwave Tubes Research and Development Centre, Bangalore (1984) and Bharat Electronics, Bangalore (1969), the latter as production agency, came into existence. In addition to the above, TIFR initiated work on klystrons and established related technologies for the development of klystrons, which were later on utilised by SAMEER, Mumbai for the development of linear accelerators. Central Electronics Limited, Sahibabad also developed production facilities in 1977 for magnetrons in collaboration with CEERI and continued for about a decade.

As on today, all related agencies have developed a strong design and technological base for the design and development of these sophisticated devices both in their slow-wave and fast-wave categories. IIT, Roorkee has developed very strong linkages with foreign agencies particularly in the area of fast-wave devices. NIT, Patna has also been involved in the design of high power devices. Institute of Plasma Research, Gandhinagar has been involved with other organisations in the development of fast-wave devices. Pilani Electron Tubes and Devices Private Limited, Sangrur (Punjab) was established in 1992 and very recently has also initiated the development of CW magnetrons. Thus, with the involvement of different academic, R&D and production agencies, a strong base has been established in the country for the development of these devices.

As regard travelling-wave tubes (TWTs), the basic interaction phenomenon related to such devices was established by Haeff in1933 and TWT phenomenon was established by Kompfner in1942 and realised the first device in 1943. However, Pierce has the credit of developing the theory of TWT in 1946 and a practical TWT was realised by him in 1947. Even though quite late, CSIR- CEERI, Pilani has the credit of developing the first TWT in the Country, which met all the targeted specifications (2.0 to 4.0 GHz bandwidth, 2 W CW power output with 30 dB gain). The success of this initiative resulted in to the design and development of other sophisticated TWTs, both for ground and space sectors. The design and development of this TWT (Figure 1) was initiated at CSIR-CEERI from scratch following the design approach provided in the book of Pierce. After completing the design of electron gun, helical RF structure, collector, focussing structure, input and output couplers, attenuator, etc., the shapes of the different electrodes of the electron gun were finalised using the electrolytic tank, which was also developed at the Institute. The vacuum envelope of the TWT was made of Corning 7052 glass having two diameters, bigger one for housing the Electron Gun and the smaller one to house the helical RF structure. The electron gun was of the Pierce convergence type with an area convergence of 6, using an oxide-coated cathode of about 3.5 mm diameter and beam diameter was about 1.6 mm. The helical structure was plain helix having uniform pitch and was made using tungsten rhenium (3%) wire. The helix was directly inserted into the glass tube, corresponding to DLF (dielectric loading factor) of about 0.6. The magnetic focussing was provided by an external solenoid type. Though the calculated Brillouin magnetic field was about 200 Gauss, the tube was operated at 400 Gauss providing the laminarities in the electron beam. The coupled-helix attenuator was designed to incorporate a minimum loss of about 40 dB throughout the operating frequency band.

The helix of the attenuator was made of molybdenum or nichrome wire and it was wrapped around a lossy paper (TELEDELTOS). and inserted outside the glass envelope (around the mid-point of the length of the helix). The input and output couplers were designed to provide VSWR of better than 1.5 throughout the operating frequency band. They were made out of contrawound helix having coaxial to helix transition.

Figure 1: First indigenous TWT.

The collector was designed as undepressed type and a radiating fin was mounted on it for its cooling by forced air. Before assembling the TWT, all individual assemblies were characterised for their cold performance over the desired frequency band, and the electron gun was tested for their beam current, etc. at the rated voltages. All the subassemblies were then integrated to make the complete TWT. Within the electron Gun, a barium getter was also mounted to take care of the evolving gas loads during the operation. The integrated tube was then tested for leaks, before mounting it into the vacuum pump system for vacuum processing. During those days, UHV valves were not available, and so the complete vacuum processing had to be finished in one go, requiring about 36 to

48 hours of continuous pumping, until the TWT is sealed off from the vacuum system.

Once TWT is ready after vacuum processing, the input, output couplers, and attenuator were mounted at their respective appropriate places over the TWT glass envelope, after their cold characterisation. TWT along with its housing is then mounted in the solenoid focussing system.

The beam transmission is then checked and optimised by adjusting the position of the focussing structure with respect to the tube. Once the proper transmission is achieved, the RF power is fed to the input end and TWT is characterised for various parameters, namely, gain, bandwidth and, output power. In addition to above, noise figure and AM-to-PM conversion coefficient were also measured. The successive TWT prototypes developed gave almost similar performances and that marked the successful completion of the project. It was a indeed a credit to CEERI for developing the first ever TWT in the country with indigenous design.

The team (Dr. S.S.S Agarwala, Mr. C Dattatreyan, Ms. Deepti Das, Mr. KR Bendale, Mr. SL Bawalia, Mr. Srinivasan, Dr. RS Raju, Prof. BN Basu, and Dr. SN Joshi) would like to express their gratitude to Dr. Amarjit Singh, the then Director of CEERI for providing necessary help in executing the project. They also thank Dr. GS Sidhu, Dr. H Steyskal (UNESCO expert) for their expert suggestions. The team is also thankful to Mr. SS Gupta, Mr. (Late) Devinder Singh, Mr Inderjit Singh and all colleagues of the then VT Division (now Microwave Tubes Division) of CEERI for providing necessary help and cooperation.

I (SN Joshi) would like to put on record the overall guidance provided by Dr. SSS Agarwala, the then Head of VT Division of CEERI throughout the execution of the project. I would also express my special attributes to Dr. Uttam Goswami, who helped me during the Webinar# 3. I also express my sincere gratitude to Prof. BN Basu, for creating this Vibrant Platform "Thinkers in VED", which has provided us the opportunity to present this activity in this Group. My special thanks to Mr. Raj Singh and his entire team, for organising the event as well as to those, who could participate in this Webinar from different organisations.

Session 2

Young Researcher's Talk Series

Research contributions of younger researchers in VEDs

Topic of Deliberation 1

Large-Signal Analysis of Helix-TWT

Speaker 1

Dr. Richards Joe Stanislaus

Topic of Deliberation 2

Recent Trends in Millimeter/THz Wave Vacuum Electron Beam Devices

Speaker 2

Dr. S. Yuvaraj

Dr. Vishant Dwivedi

Senior Scientist
Microwave Devices Division
CSIR - Central Electronics Engineering Research Institute
Pilani - 333 031 (Rajasthan), INDIA

Host's words

Thinkers in VED group conducted its third webinar on 7th November 2020. I was tasked with the responsibility of hosting the second session of the webinar. The second session focussed upon "Research Contributions of Younger Researchers in VEDs". This session consisted of individual presentations by two young and bright speakers. The first speaker was Dr. Richards Joe Stanislaus, who presented his work on the topic "Large-Signal Analysis of Helix-TWT". The second talk was delivered by Dr. S. Yuvaraj, who spoke on the topic "Recent Trends in Millimeter/THz Wave Vacuum Electron Beam Devices". Although, Dr. Richards talk was related to TWTs, while Dr. Yuvaraj talk focused on Gyrotrons, the underlying common factor of both the talks was development of indigenous computation tools.

Computation tools are mandatory for the design of VEDs. The VED community heavily relies on commercial simulation tools like Computer Simulation Technology (CST), High-Frequency Structure Simulator (HFSS) etc. which are versatile and generic computation tools for design of VEDs. Apart from these generic tools, there has been considerable research in the field of development of device specific computation tools. Researchers like Dr. Vishnu Srivatsava and Dr. Lalit Kumar have contributed tremendously in the field of development of TWT design tools. On the other hand, Dr. A.K. Sinha and Dr. M. V. Kartikeyan have significantly advanced the understanding of Gyrotron device by development gyrotron specific computational models and codes. The work of Dr. Richards and Dr. Yuvaraj can be seen as the continuation of efforts in this direction. Their work is very important for the VEDs community as it enhances the understanding of the device physics and would lead to enhanced computer models/codes.

After the presentation, Dr. Lalit Kumar suggested that Dr. Richards should compare the results of his code with the results of the already existing indigenous TWT codes. Similarly, Professor B. N. Basu suggested Dr. Yuvaraj that he should have discussion with Dr. Anirban Bera (CSIR – CEERI) to explore the possibility of Gyrotron specific code and device development.

Each presentation witnessed multiple questions from the experts as well young researchers. The questions were answered to the satisfaction of the questioner by both the presenters. This session was followed by the Vote of thanks by a globally renowned scientist- Dr. L. M. Joshi.

Dr. Richards Joe Stanislaus
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Large-Signal Analysis of Helix-Traveling Wave Tube

Travelling wave tube (TWT) is a microwave vacuum electronic device predominantly used in satellites and defence RADARs for its stable operation at high power levels and much wider bandwidths. The TWT consists of an electron gun to generate a linear electron beam, an interaction region in which RF input signal to be amplified interacts with the electron beam, and a collector at which the spent electrons are collected. The interaction region consists of dielectric rods supported slow wave structure (SWS) which slows down the RF signal for the beam-wave interaction (BWI). The SWS considered here is a practically relevant anisotropically conducting tape helix wound along axial coordinate, in which the tape surface current density is in parallel to the tape winding ignoring its variation along the perpendicular direction. The electron beam in the interaction region is modelled using the Lagrangian approach in which, the electron arrival time within the beam is represented as a function of the electron entrance time, its axial and radial coordinate. In the large signal modelling of the interaction region, the novel approach incorporating this Lagrangian model of the electron beam together with the much accurate tape helix model is of high importance as the existing modelling techniques consider multiple approximations in their formulation. Using Green's function sequence, the field components in the SWS are designated as nonlinear functionals of electron arrival time. The electron arrival time in the beam region is formulated into a nonlinear operator in the Banach space mapping form by substituting the axial electric field component into the electron ballistic equation. The nonlinear beam-wave interaction is then obtained by determining the electron arrival time through extensive successive approximations, and thus exact electric and magnetic field components in the tape helix SWS are attained. The numerical computation of the proposed model yields definitive analytical results for the electron exit velocity, induced surface current density, power gain, conversion efficiency and optimum interaction length.

Reltron is a narrowband megawatt (MW) HPM source, which is compact and efficient. Reltron fulfils the vital requirements of a high-efficiency microwave source, such as, intense electron bunching, least energy spread and efficient RF extraction without breakdown. It is developed through the exploration of the cavity of the split-cavity oscillator (SCO), which is comparable to the klystron cavity in nature. Its operating principle is also similar to that of the conventional klystron where the RF power is coupled out through a series of output cavities from the intense electron bunches. However, it is primarily distinct in two ways: (i) the bunching process is different and (ii) the intense electron bunches are reaccelerated to the higher energy by applying an additional DC potential. The external DC magnetic field is not required in a reltron and the self-magnetic field developed in the RF interaction cavity is used to the focus the electrons in the longitudinal direction. Long pulses, upto microsecond duration can be generated, which enables it to radiate both high RF peak power and high RF energy per pulse. The other features of the tube include its frequency tunability and inherent energy storage capability and its compatibility with the external power conditioning elements and pulse forming networks.

Dr. S. Yuvaraj
Assistant Professor
National Institute of Technology
Andhra Pradesh, Tadepalligudem, INDIA

Recent Trends in Millimeter/THz Wave Vacuum Electron Beam Devices

Vacuum electronic devices are widely used for high power applications as they are capable of generating high power electromagnetic waves at higher frequencies over solid-state devices. Nowadays, vacuum electronic communities around the world are aiming towards the mastering of the device development at THz frequencies. Research activities are being conducted for the development of devices for both high power applications (in the range of MW) and medium power applications (in the range of few watts to few kilowatts). High power devices are being developed for applications such as plasma heating in thermonuclear fusion tokamaks, generation of ionized particles, and also in defence applications like active denial systems. Medium power THz wave devices are used in applications such as in medical spectroscopy, in THz imaging systems such as the detection of foreign bodies in food samples, nondestructive testing of the materials. In this talk recent advances in millimeter/ THz wave electron beam devices will be discussed. Focus will be given to the design of gyrotron at these frequency levels.

Topic of Deliberation

Vote of Thanks

Proposed by

Dr. LM Joshi

Dr. LM Joshi
Ex. Chief Scientist & Professor AcSIR
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Dr. SSS Agarwala, Dr Chandra Shekhar, Prof. Basu, Dr. Joshi, Dr. Lalit Kumar, Sri Raj Singh, Dr. Bhat, Dr. Raju, other senior and younger colleagues and friends, I hope all of you will agree with me that it has been a very special evening to have an opportunity to listen to two most eminent personalities who will always glitter as brightest stars on VED sky. It is my proud privilege to propose the vote of thanks.

At the outset, let me thank Dr. Lalit Kumar for introducing the 'pitamah' of VED in India, Dr. SSS Agarwal, particularly to younger participants.

I thank Dr. Agarwala for sharing his experience at Imperial College of London as PhD scholar and subsequently as mentor of most of us at CSIR-CEERI, Pilani. Thank you sir for sharing your experiences.

I take this opportunity to thank Dr. SN Joshi for his wonderful talk on very first TWT developed in India. It is creditable that such a technically complex tube was successfully developed way back in 70s based on fully indigenous design and technology without any CAD tools, one go vacuum processing and glass sealing. It would be a great source of inspiration to all the younger researchers involved in this field. We thank Dr. Chandra Shekhar for chairing the session and also for his valuable comments.

The second session was chaired by Dr. Vishant Dwivedi, a bright young scientist working at CEERI. Two young researchers presented their recent work during the session. The first talk was by Dr. Richard on large signal analysis of TWTs. He presented very interesting results.

Dr. Yuvraj talk on mm wave/THz VEDs. He gave a brilliant overview of various mm wave VEDs with specific emphasis on Gyrotrons. I thank both the young speakers and hope they will carry their good work to next stage.

I thank Sri Raj Singh, convener, Dr. Vishal Keshari and Dr. Vishant Gahalot for their untiring efforts to make the webinar a great success.

Last, but not the least, I thank all the participants to webinar.

Annexure I:

A Tribute to Dr. S S S Agarwala

By Professor B. N. Basu

TRIPLE M — 'MOTIVATING MICROWAVE MAESTRO'

IN

TRIPLE S — 'SIDDHI SADHAN SWARUP'

A Tribute

by

B. N. Basu

College of Engineering and Technology
IFTM Campus
Moradabad-244 001

Formerly at
Centre of Research in Microwave Tubes
Banaras Hindu University-221 005

I most humbly dedicate this presentation

to

Dr. GS Sidhu

Dear Dr. Basu, 17th April 2009

Thank you Dr. Basu for doing this honour to me. I wish I could attend the function but my handicap prevents me from doing so.

I would like to point out one omission in the text of your paper. Dr. Deb was the project leader of Magnetron project when this development work was being carried out at RPE in the Mid fifties.

Your paper gives an excellent overview of the field of Microwave Tubes in the country. It is very apt tribute to Dr. S.S.S Agarwala for the service he has done to this field.

Our Colleagues in the MWT Group will continue to benefit from tradition of discipline, dedicated work, honest and realistic approach which he has given to the group.

I am still benefiting from these in my present work.

Thanks and regards,

G. S. Sidhu

I worked at

- Defence Electronics Research Laboratory, Hyderabad
- Regional Institute of Technology, Jamshedpur
- Central Electronics Engineering Research Institute, Pilani
- Banaras Hindu University

I continued to receive the encouragement and support in terms of literature and research facilities from SSS even when I was no longer an employee of CEERI

- Distinguished Visiting Scientist Scheme of CSIR

- Adoption as the third partner in a programme under ALIS originally between CEERI and Lancaster University

- Honour of being offered the huge stock of IEEE journals from the personal library of SSS

“*Every so often, it still happens that someone tells me that there is an irreconcilable conflict between teaching and research, that dedicated teachers do not do research because it takes away time that they could be spending on their teaching, or that serious research physicists cannot afford to devote significant amounts of time and effort to teaching. As a generalization, this has always struck me as ludicrous.*”

— Robert H. Romer, Editor, American Journal of Physics, from “Teaching or research, research or teaching? - Thoughts about Edward M. Purcell,” Am. J. Phys. vol. 65, 689 (1997)

(cited by Edl Schamiloglu in New Mexico University Website)

SSS and the tradition that he established supported academia in carrying out research in the area of microwave tubes

- Centre of Research in Microwave Tubes, Banaras Hindu University
- Burdwan University
- IIT-Roorkee
- Devi Ahilya Vishwavidyalaya, Indore

M. Tech students of Burdwan University who have carried out their M. Tech thesis work at CEERI, Pilani in the areas of direct relevance to the ongoing sponsored projects on microwave tubes (The list is not complete)

1. Debojoity Chaudhary (1996)
2. Mrinal (1997)
3. Arindam Chakraborty (1998)
4. Sivendra Maurya (1999)
5. Gautam Sarkar (1999)
6. Ayan Banerjee (2000
7. Hasibur Rahaman (2000)
8. Anirban Bera (2001)
9. Shiv Chadan (2001)
10. Raudra Gatak (2001)
11. Amitavo Roy Chaudhary (2002)
12. Promod Kumar (2002)
13. Shalabh Gunjan (2002)
14. Maifuz Ali (2002)
15. Sarbani Basu (2002)
16. Shiv Kumar (2003)
17. Shubhamaya Bose (2003)
18. Intekhab (2004)
19. Indrajit Banerjee (2004)
20. Asim Biswas (2004)
21. Anal Hembram (2004)
22. Aritra Bhaumik (2004)
23. Pranab (2004)
24. Raju Manna (2005)
25. MitraBarun Sarkar(2005)
26. Naru Gopal Nayek (2005)
27. Narendranath Mukherjee (2005)
28. Pampa Debnath (2005)
29. Deblina basudhar (2005)
30 Debashish Pal(2005)
31. Tanuja (2005)
32. Santanu Mandal (2006)
33. Partha sarathi Nandi (2006)
34. Anirban Karmakar (2006)
35. Tanima Giri (2006)
36. Maria Rosi
37. Jyotirmoy Koner (2007)
38. Rezoul Karim (2007)
39. Joydeep Banerjee (2007)
40. Dipankar Mondal (2007)
41. Anujit Adhikari (2007)

…. ……….

A journey from the magnetron to the gyrotron

Where do we stand in the historical timeline of the development of microwave tubes?

1921-1940

Smooth-wall magnetron — A. W. Hull (1921)

Tube scanning system for television — Philo T. Farnsworth (1922)

Iconoscope or cathode-ray tube and kinescope — Vladimir K Zworykin (1923)

Tetrode valve — Hull and Williams (1926)

Beam diffraction oscillogram
(beam and helix-wave interaction) — Haeff (1933)

Cavity magnetron — Posthumas (1935), Randall and Boot (1939)

Linear beam microwave tube theory — Oskar and Heil (1935)

Magnetron: Institute of Radiophysics and Electronics, Calcutta University

Professors S. K. Sen, H. F. Steyskal, BN Das, NB Chakrabarty (late 1950’s).

CU Annual Report : 1956-57 published in 1958
“RPE
C. Electron Tubes

“Work on electron tubes has been intensified since Spt 156, when the UNESCO Expert, Dr. H. F. Steyskal joined the Institute. The aim of the work was to improve the research facilities of the existing electron tube laboratory and to develop various special processes involved in the electron tube making., especially with regard to all metal tubes, including microwave tubes, e.g., magnetron. The equipment in the lab has been enriched by the following items:

Two high vacuum pumping units with provision for measuring pressures of 10-7 mm Hg.
A Tubular Hydrogen Furnace for temperatures upto 1000 C.
A large chamber for heat treatment in protective atmosphere at temperatures upto 1200 C.
A strain viewer for glass ware.
A ball Mill for powdering chemicals.
An apparatus for spraying insulating coatings and emission pastes.
An Electrolytic trough for investigation of potential fields.
A 6 KW RG heating unit (Gift fro UNESCO).
A glass lathe (Gift from UNESCO).

Furthermore, the following practical processes have been developed:

Manufacture of graded glass seals and tubular seals between glass and metals like copper and Kovar; vacuum tight brazing of metals in protective atmospheres and in vacuum; fabrication of special brazing alloy, electroplating, precision machining of magnetron parts., and of plane and cylindrical oxide cathodes and their appropriate filaments. Finally the properties of self made oxide cathodes and the activation schedule of thoriated tungsten cathodes were investigated and satisfactory results obtained.

1958-59

(c) Electron Tubes

A programme of work on parametric amplifiers has been started. This includes both electron beam type and the semiconductor diode type of parametric devices.

Work on beam type largely centred round the design of a low voltage electron gun. The various electrode structures required have been worked out. With regard to semiconductor diode a cavity simultaneously resonant to the pump and the signal frequency for the degenerate mode of operation has been designed. Its electrical response characteristics are being measured.

1961-62

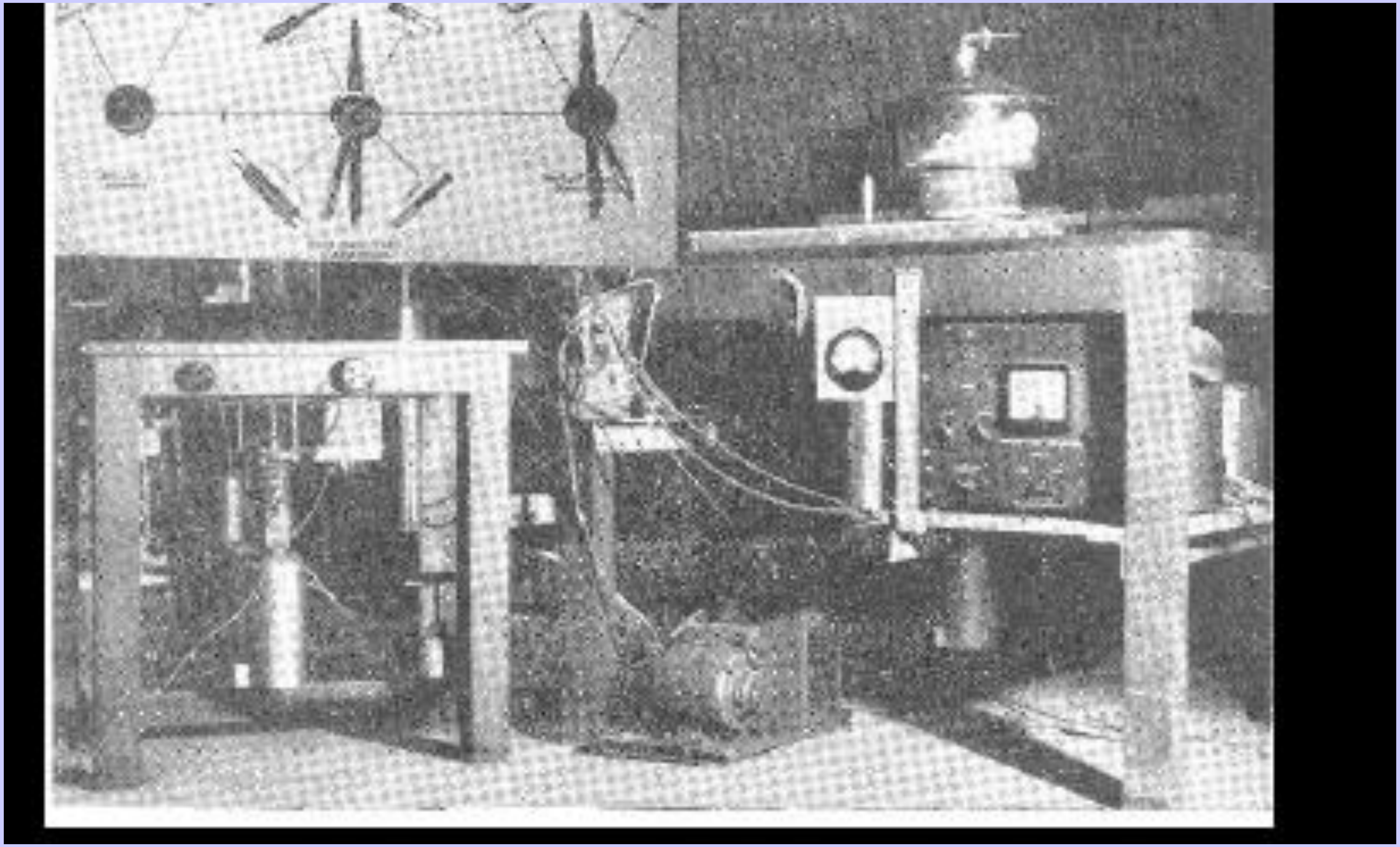
(e) Electron Tubes and Plasma Electronics

“ Work is also in progress towards better design and performance of 10 cm multicavity CW magnetron.”

N. B. Chakraborty, “Lower frequency pumping of electron beam parametric amplifiers,” *Int. J. Electron.*, vol. 8, no. 3, 161-165 (1960)

N. B. Chakraborty, “Analysis of fast-wave amplifiers for transverse field parametric amplifiers,” *Int. J. Electron.*, vol. 10, no. 2, 147-151 (1961)

Professor N. B. Chakraborty directed me to join CEERI where I received tutelage from ‘SSS’ whom I describe as ‘MMM’ — Motivating Microwave Maestro!



Set up (1056) at Institute of Radiophysics and Electronics, Calcutta University

Magnetron activities at NPL and CEERI

Dr. Amarjit Singh

Dr. NC Vaidya

and others

Production: CEL, Sahibabad, BEL, Bangalore

Klystron — Metcalf and Hahn (1936)

Klystron — Russel and Siguard (Varian brothers) (1937)

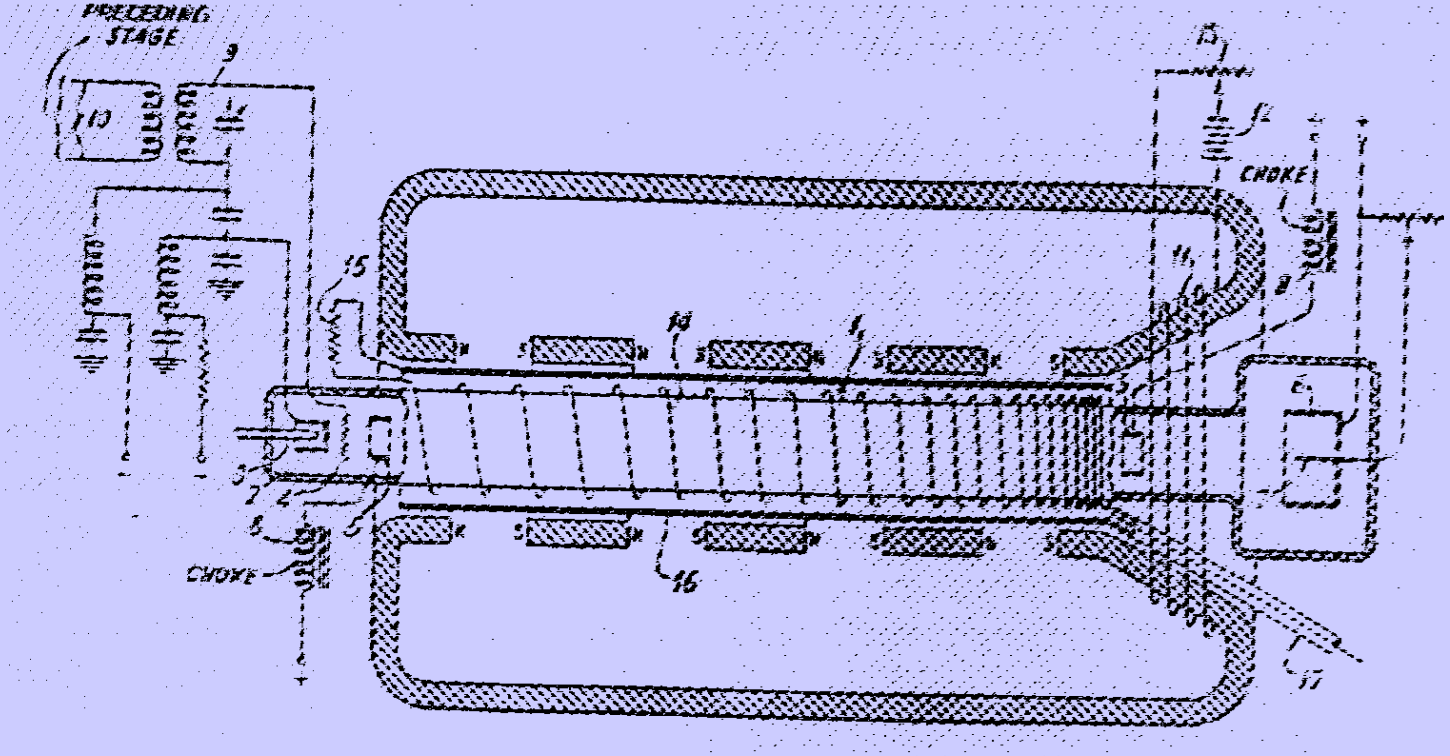
Cavity magnetron — Randall and Boot (1939)

Travelling-wave tube (TWT) — N. E. Lindenblad (1940)
(PM series focusing, helix pitch tapering)
(U. S. Patent 2,300,052, filed on **May 4, 1940** issued on October 27, 1942)

First ever TWT in India: 1977 at CEERI, Pilani (SSS Agarwala, SN Joshi)

1941-60

Travelling-wave tube — **Kompfner (1942)**
— Field (1946) (U. S. Patent 2,575,383)
— Pierce (1946) (U. S. Patent 2,602,148)
Maser — Gordon (1954)
ECM interaction theory — J. Schneider (1957)
— R. Twiss (1958)
— A. Gaponov (1959)



Lindenblad’s travelling-wave tube amplification at 390 MHz over a 30 MHz band (U. S. Patent 2,300,052, filed on May 4, 1940 issued on October 27, 1942)

Helix wound around the outside the glass envelope.

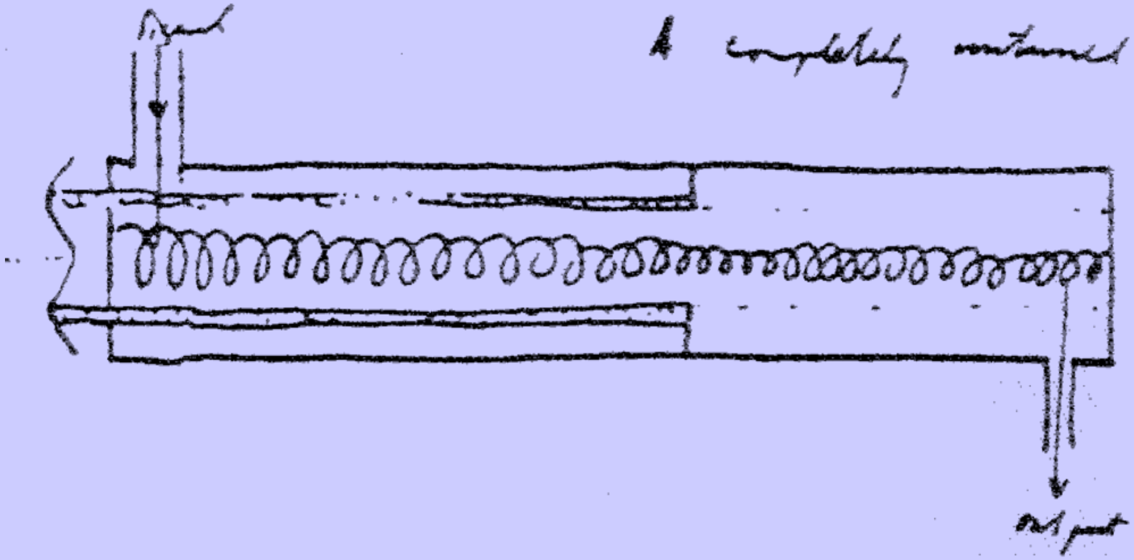
Signal applied to the grid of the electron gun (also applied to the helix in other experiments)

Series of permanent magnets (non-periodic)

Pitch tapered for velocity re-synchronization

12. 11. 42

A completely contained amplifier ?



Would it work? Are the electrons in the output region not moving <u>parallel</u> to the equipotential surfaces of the line? If so, then there can be no amplified shotnoise

Sketch of the travelling-wave tube from Kompfner’s note book

1961 onwards

Earliest version of gyrotrons in Russia (1965)

Proposals on JET and ITER (1980 onwards)

Modern gyrotron technology (1990 onwards):

IAP, Russia; FZK, Germany; JAERI, Japan; Toshiba, Japan; CPI, USA; TTE, France; CRPP, France, MURI, USA, and so on

Development of **magnetrons, klystrons and TWTs** at CEERI, Pilani (Dr. Amarjit Singh, Dr. O. P. Gandhi, Dr. S. S. S. Agarwala, Dr. R. P. Wadha, Dr. G. S. Sidhu, Mr. H. N. Bandopdadhya, Dr. S. N. Joshi, and others)

Establishment of a dedicated Centre at BHU (Professor N. C. Vaidya)

Participation of Burdwan University M. Tech students (Professor BN Biswas)

Establishment of MTRDC (DRDO) (Dr. Raj Narayan and Mr. K. U. Limaye, Dr. Lalit Kumar, and others)

Production of microwave tubes at BEL and the contribution of Mr. T. R. K. Janardan

Contribution of Professor K. P. Maheswari at Devi Ahilya Vishwavidyalaya, Indore in the area of relativistic tubes

Microwave tubes is a subject of applied electromagnetics — microwave engineering

Time-independent fields:

- Formation of an electron beam — electron guns
- Confinement of an electron beam — focusing structures

Time-dependent fields:

- Interaction structures
- Beam-wave interaction

‘SSS’ encouraged us to develop the understanding of microwave tubes from first principles using electromagnetic analysis

Classification of microwave tubes

(based on the mechanism of electron beam bunching and conversion of beam energy into electromagnetic energy)

- O- and M-types (O standing for TPO — tubes à propagation des ondes, and M for TPOM — tubes à propagation des ondes à champs magnetique)
- Kinetic energy and potential energy conversion types
- Longitudinal space-charge-wave, transverse space-charge-wave, and cyclotron-mode interaction types
- Distributed and localised interaction types
- Slow-wave and fast-wave types
- Non-relativistic and relativistic bunching types
- Cerenkov, transition, and bremsstrahlung radiation types
- CRM instability and Weibel instability types

Trends in microwave tubes

Improved performance tubes

Group 1

MPM and micro-fabricated tubes

Group 2

IREB-driven HPM tubes

Group 3

Fast-wave tubes

Group 4

Plasma-filled tubes

Group 5

Grouping of microwave tubes

Group 1	Improved performance conventional microwave tubes: TWT (ultra-wide bandwidths, high efficiency); Klystron (EIK — wider bandwidths, higher power, EIO — millimeter-wave, low-power, MBK (large beam current, low beam voltage, high power, compact); Magnetron (oven, millimeter wave radar, relativistic — high power, long pulse).
Group 2	MPM and microfabricated tubes: MPM: (ground and air-borne platforms, ECM and towed decoys, phased-array and power-combined EW, mobile and satellite communication, missile seeker and surveillance radar); Microfabricated tubes: Triode, Klystron, Klystrino, FW-TWT (folded waveguide TWT), etc.
Group 3	HPM Tube driven by IREB: VIRCATOR (no magnetic fields), BWO, Orotron (RDG), MWCG (multi-wave Cerenkov generator), MWDG (multi-wave diffraction generator), MILO (magnetically insulated line oscillator (no external magnetic field, magnetic insulation), Relativistic klystron, RELTRON, plasma-filled BWO/ PASOTRON, etc.
Group 4	Fast-wave tubes: Gyrotron (high-harmonic, low-magnetic field, large-orbit, vane-loaded, coaxial-cavity, quasi-optical, etc.); Gyro-TWT (dielectric-loaded, disc-loaded, frequency multiplying, etc.); Gyro-klystron; Gyro-twystrons, PHIGTRON (phase-coherent, harmonic multiplying, inverted gyro-twystron); Gyro-BWO; CARM; SWCA; Peniotron, etc.
Group 5	Plasma-filled tubes: Pasotron (BWO) (IREB-driven Group 3), Coupled-cavity TWT (Group 2), Gyrotron (Group 4) (Plasma filling for large beam transport, relaxation of magnetic field, larger structure cross section, etc.)

Recent microwave tube activities at CEERI include

Klystrons

TWTs

Plasma-Assisted Devices

Magnetrons

Gyrotrons

Electron guns

Cathodes

Interaction structures and RF couplers

Innovative interaction structures

Slow-wave structures for wideband TWTs: Dispersion-controlled helical structures

- Inhomogeneous loading — by shaping dielectric helix-supports
- Anisotropic loading — by using an angularly periodic metal envelope (vane/segment loading)

- Ring-and-bar structures for high power TWTs
- Structure losses (structure material and attenuator coating)
- Fast-wave structures
  - — Mode selective structures for gyrotrons: coaxial cavity, photonic band-gap cavity, etc.)
  - — Dielectric and disc loaded structures for wideband gyro-TWTs

Wideband multi-octave TWTs

Zero-to-slightly-negative-dispersion structure for wideband performance:

Negative dispersion ensures the constancy of Pirece's velocity synchronization parameter *b*

Anisotropically loaded helix:

Metal vane/ segment loaded envelope

Inhomogeneously loaded helix:

Helix with tapered geometry dielectric supports such as half-moon-shaped and T-shaped supports

Multi-dispersion, multi-section helix for wideband performance:

The value of N in the gain parameter CN depends on both the frequency and the interaction helix length.

One positive-dispersion helix section of length l_1 is synchronous only at lower frequencies and the other no-dispersion helix section of length l_2 is synchronous both at lower and higher frequencies.

Causes an increase in effective length to $l_1 + l_2$ at lower frequencies and a decrease in effective length to l_2 at higher frequencies

Reduction of length at higher frequencies prevents oscillation at higher frequencies

Dr. SSS Agarwala’s doctoral work at the University of London in 1958

SSS carried out research in the area of slow-wave structures (non-reciprocal structures) at the University of London

From the letter sent by Dr. Amarjit Singh to Dr. SN Joshi on 14th April 2009

………..“I had known him from the mid nineteen fifties, when we were colleagues in NPL. Sent from there, as a Visiting Scientist to UK, he had worked on Traveling Tubes, with non reciprocal attenuation, provided in the middle region of the helix, by use of ferrites. As such he was uniquely qualified to lead the R and D on TWT’s at CEERI. He did this with great distinction, so that CEERI continues to be a pioneer in this field in India, to this day. As Area Leader for Vacuum Devices at CEERI, he provided judicious guidance to colleagues working on various projects in the Area. The achievements of the Vacuum Tubes group over the years, are in no small measure due to his professional competence, clear vision, and personal qualities as a leader.”

………. “His meticulous approach towards everything that his touched, was truly remarkable.”

‘SSS’ motivated us to work in the area of helical slow-wave structure

Two Internal Reports at CEERI on electromagnetic analysis of helical slow-wave structures were brought out in quick succession in 1978 under the guidance of Dr. SSS Agarwala

One based on

- **field analysis** and the other on
- **equivalent circuit analysis**, both yielding the same dispersion relation

Issues involved: sheath-helix boundary conditions, number of boundary conditions to be handled at a time, interaction impedance, characteristic impedances, and dispersion relation

The manuscripts of the reports were thoroughly edited by ‘SSS’

Incidentally, who were the ‘authors’ of these reports?

One of the reports were handwritten by Dr. SN Joshi, subsequently later, typewritten by Professor PK Jain.

Extension of the theory that was developed at CEERI under the guidance of ‘SSS’

- Inhomogeneous and anisotropic helix-loading (AK Sinha, SK Ghosh)
- Asymmetry of dielectric helix supports (AK Sinha, SK Datta)
- Helix finite resistivity and attenuator coating (PK Jain, SK Datta)
- Unconventional dielectric helix supports (SK Ghosh)
- Tape-helix model (AK Sinha, SK Ghosh)

….. to mention a few

Sharing my experience with the following, which 'SSS' stood for:

- Extension of all technical support to genuine researchers
- No compromise on discipline
- Recognition of work

An anecdote:

Measurement of AM-to-PM conversion coefficient of the first ever TWT built in the country required by ISRO in connection with the funding of a project to CEERI

Today, we are honouring the entire microwave tube community by honouring

‘SSS’ synonymous with

‘MMM’ —‘Motivating Microwave Maestro’

who, however, always distanced himself from such honours!

I am grateful to CEERI and VEDA Society to give me this opportunity to pay my tribute to Dr. SSS Agarwala!

Thank you!

Annexure II:

Expert Talk Slides

Design & Development of the first TWT in India

SN Joshi

Ex. CSIR-Central Electronics Engineering Research Institute (CEERI),
Pilani, Rajasthan

snjoshi_15@yahoo.com, snjceeri@gmail.com

Outlines :

- Introduction
- Timelines in TWTs
- History of VEDs (MWTs) in India
- First Indigenous TWT
    - Specifications
    - Design and fabrication
    - Couplers and Attenuators
    - Results
    - Conclusion

Historical Timelines in TWT

Year	Events
1933	Interaction phenomenon by Haeff
1942	TWT phenomenon established by Kompfner
1943	First TWT by Kompfner
1946	Theory of Helix TWT by Pierce
1947	Practical TWT by Pierce
1950	L- Cathodes (Philips)
1953	B- Type Cathodes
1960	M-Type Cathodes
1969	Bharat Electronics, Bangalore established
70's onward	Had staff competition with Semiconductor Amplifiers
1976	First indigenous TWT in the country (CEERI)
1978	Resonant loss technology for wideband TWTs
1979	CRMT (IT-BHU) established
1984	MTRDC (DRDO) established at Bangalore
80's onward	This decade saw advancements in technologies, design tools, analytical concepts and advent of new materials
90's onward	Above continued, successful EW and communication TWTs developed by CEERI and MTRDC and productionised by BEL
1995	Realization of MPM
2000 onward	Advent of sophisticated 3D tools, MPMs, work started on Gyro-TWTs, THz TWT including EW and space TWTs, advanced dispenser cathodes

R&D Initiatives in India (-for VEDs)

- India is one among about 10 countries engaged in Microwave Tubes
- Pulse Magnetron activity in early 50’s in NPL, New Delhi
- Magnetron activity was shifted to CEERI, Pilani almost at its inception in 1957. CEERI has been a major player since then in this area
- Academic agencies like Institute of Radio Physics and Electronics, Kolkata and Delhi University, Delhi were involved
- S-band Klystron activities initiated at TIFR, Mumbai in 60’s (lot of related technologies established)
- Later on this technology was utilized for developing Linear Accelerators (LINACs)

- Centre for Research in Microwave Tubes (CRMT) at BHU was established in 1979 with the support of then DOE
- Microwave Tube Research and Development Centre (MTRDC), Bangalore was established by DRDO in 1984
- Bharat Electronics started production of Magnetrons in 1969. It had a major collaboration in 1985 with M/s Varian, USA
- It also has collaboration with EEV, Thales, Philips, MTRDC and CEERI
- Central Electronics Limited (CEL), Sahibabad established Microwave Production facilities in 1977 and continued for one decade
- Pilani Electron Tubes and Devices Private Limited (PET&DPL), Sangrur was established in early 1991, Production started in 1994

First Indigenous TWT

Team:

- Dr SSS Agarwala
- Mr C Dattatreyan
- Mr KC Chhabra
- Ms Dipti Das
- Mr K R Bendale
- Mr S L Bawalia
- Mr Srinivasan
- Dr R S Raju
- Dr B N Basu
- S N Joshi

Acknowledgement :

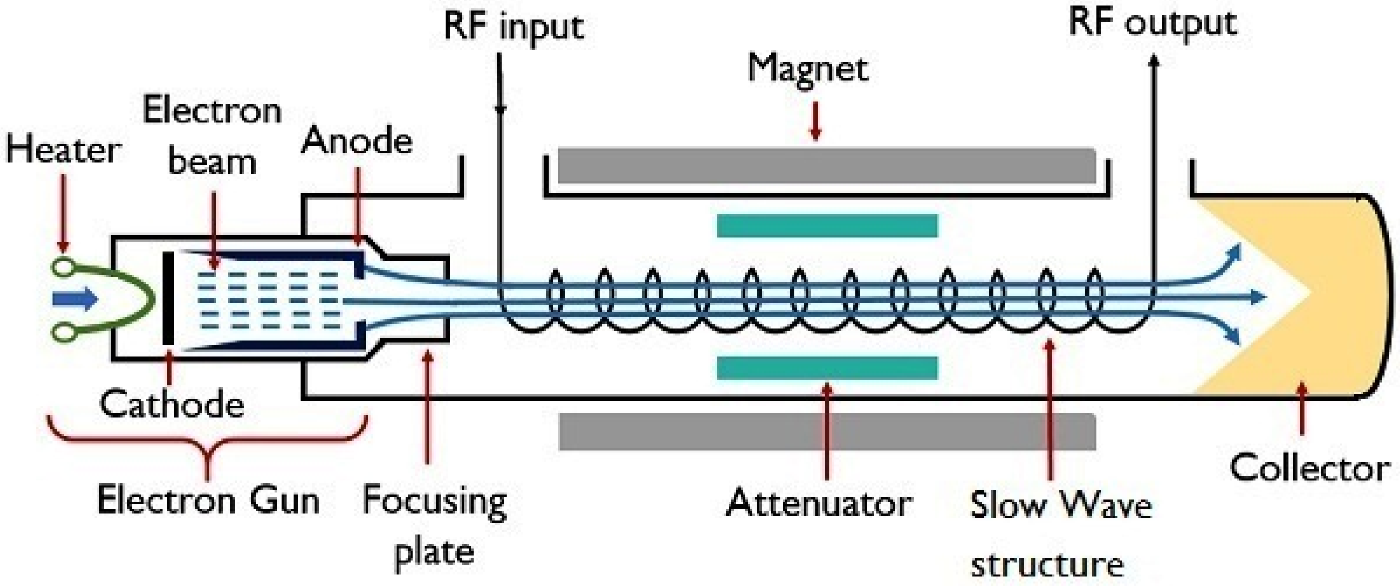
- Dr Amarjit Singh, Then Director
- Dr G S Sidhu
- Dr H Steyskal
- Mr S S Gupta
- Mr Devinder Singh
- Mr Inderjit Singh
- Colleagues of then VT Division and EME Division

Special Attribute:

- Dr Uttam Goswami

Schematic of Travelling-wave Tube

TWT
(Slow-wave Device)



Design specification of S-band TWT

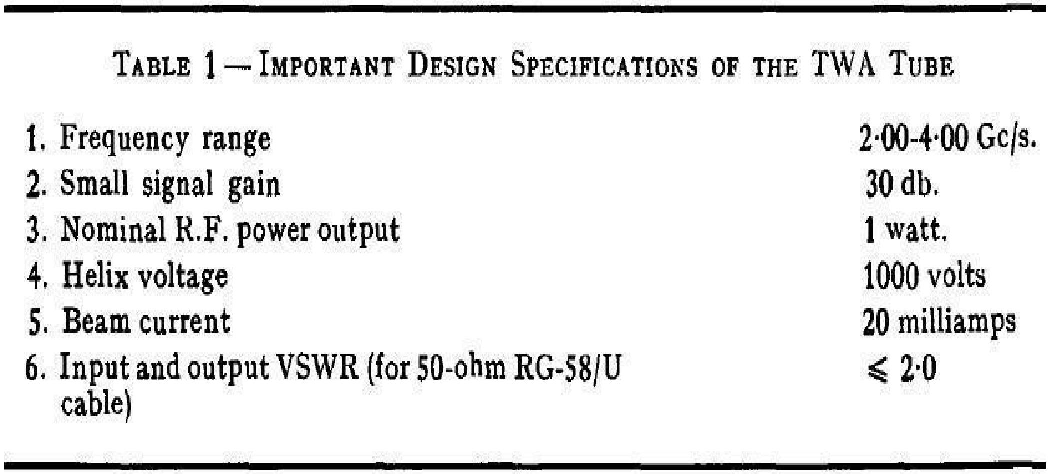


TABLE 1 — IMPORTANT DESIGN SPECIFICATIONS OF THE TWA TUBE

1. Frequency range	2·00-4·00 Gc/s.
2. Small signal gain	30 db.
3. Nominal R.F. power output	1 watt.
4. Helix voltage	1000 volts
5. Beam current	20 milliamps
6. Input and output VSWR (for 50-ohm RG-58/U cable)	$\leqslant 2{\cdot}0$

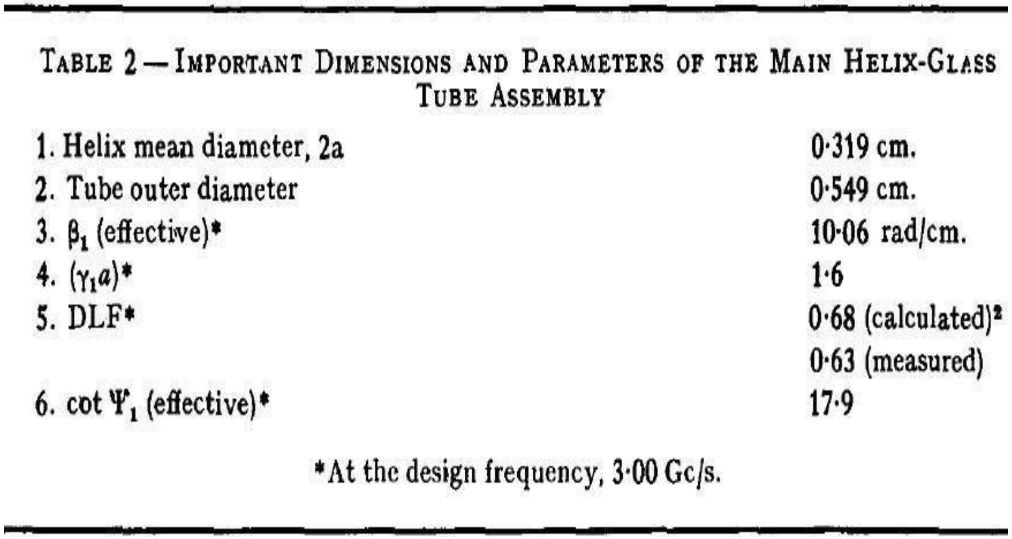


TABLE 2 — IMPORTANT DIMENSIONS AND PARAMETERS OF THE MAIN HELIX-GLASS TUBE ASSEMBLY

1. Helix mean diameter, 2a	0·319 cm.
2. Tube outer diameter	0·549 cm.
3. β_1 (effective)*	10·06 rad/cm.
4. $(\gamma_1 a)$*	1·6
5. DLF*	0·68 (calculated)[2] 0·63 (measured)
6. cot Ψ_1 (effective)*	17·9

*At the design frequency, 3·00 Gc/s.

Design and Fabrication of TWT:

- The design of complete TWT was done indigenously essentially following the approach given in Pierce Book.
- Electron gun was pierce type convergent gun having an area convergence of 6.
- The cathode was Oxide Cathode type with diameter of about 3.5 mm
- Shape of different electrodes were finalized with the help of Electrolytic Tank.
- Beam diameter was around 1.6 mm and beam filling factor was around 0.55
- The beam current was 20-25 mA and Helix Voltage was 1200 V
- The helix was made of Tungsten Rehinium (3 %) wire and had same pitch around its length
- The housing was of Corning 7052 glass for electron gun and helix
- The Dielectric Loading Factor was about 0.6
- The magnetic focusing was provided by a Solenoid.
- TWT was operated at 400 Gauss (the calculated Brillouin field was 200 Gauss)
- Attenuator was made of a countra-wound helix using moly as well as nichrome wire
- A lossy paper (Teledeltos) was wrapped around the helix and then this assembly was inserted somewhere at the middle of the helix. It provided attenuation of 35-45 dB.
- Collector was undepressed type and a cooling fin was mounted over it during testing for its cooling.

Electron Gun:

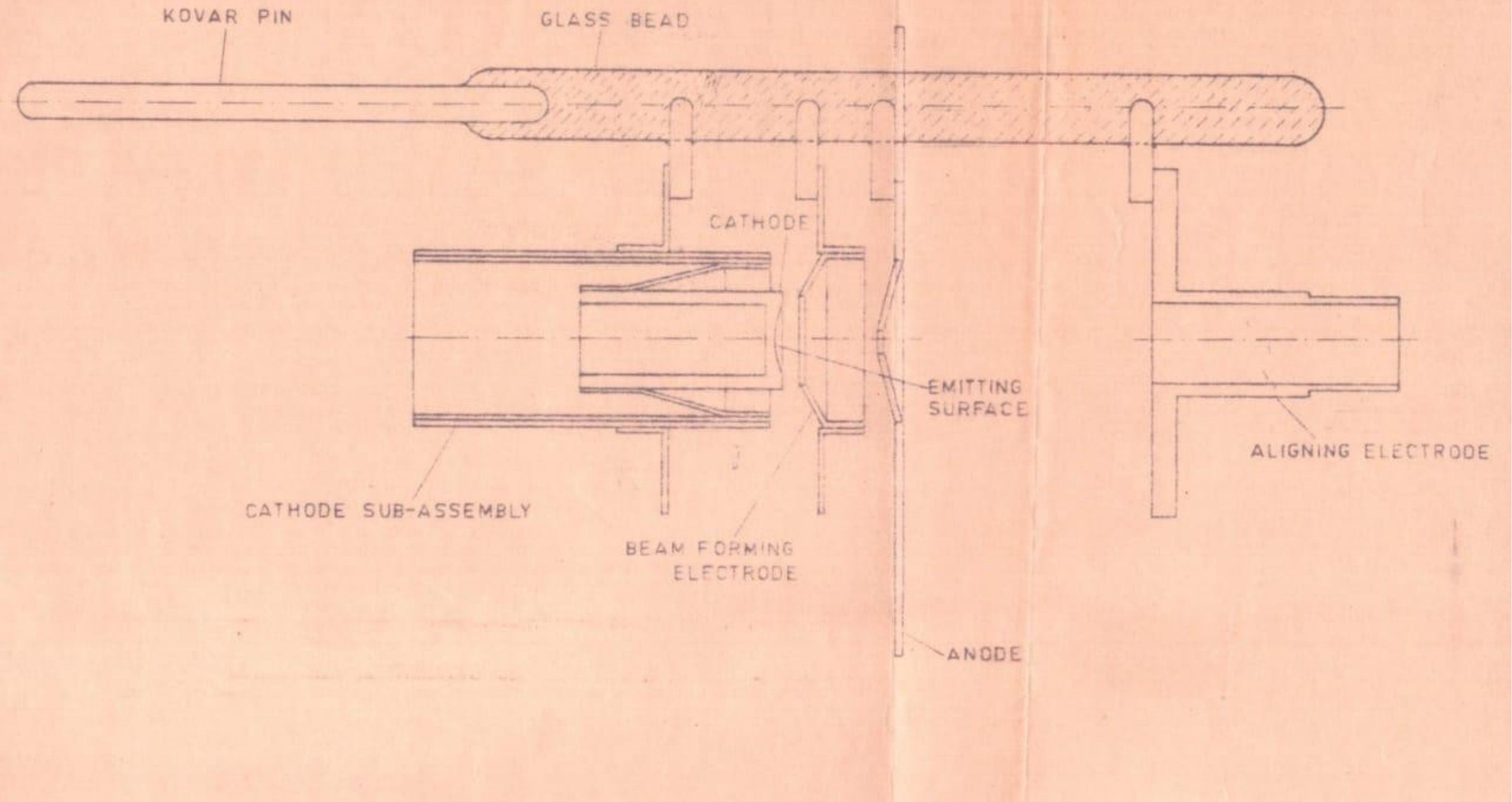


FIG.1 ELECTRON-GUN ASSEMBLY

Helical Coupler:

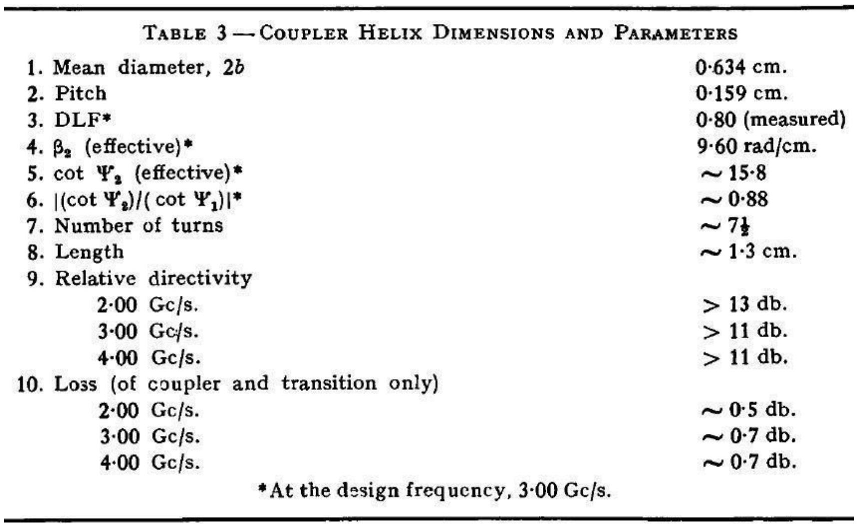


TABLE 3 — COUPLER HELIX DIMENSIONS AND PARAMETERS

1. Mean diameter, $2b$	0·634 cm.
2. Pitch	0·159 cm.
3. DLF*	0·80 (measured)
4. β_2 (effective)*	9·60 rad/cm.
5. cot Ψ_2 (effective)*	~ 15·8
6. $\|(\cot \Psi_2)/(\cot \Psi_1)\|$*	~ 0·88
7. Number of turns	~ 7½
8. Length	~ 1·3 cm.
9. Relative directivity	
2·00 Gc/s.	> 13 db.
3·00 Gc/s.	> 11 db.
4·00 Gc/s.	> 11 db.
10. Loss (of coupler and transition only)	
2·00 Gc/s.	~ 0·5 db.
3·00 Gc/s.	~ 0·7 db.
4·00 Gc/s.	~ 0·7 db.

*At the design frequency, 3·00 Gc/s.

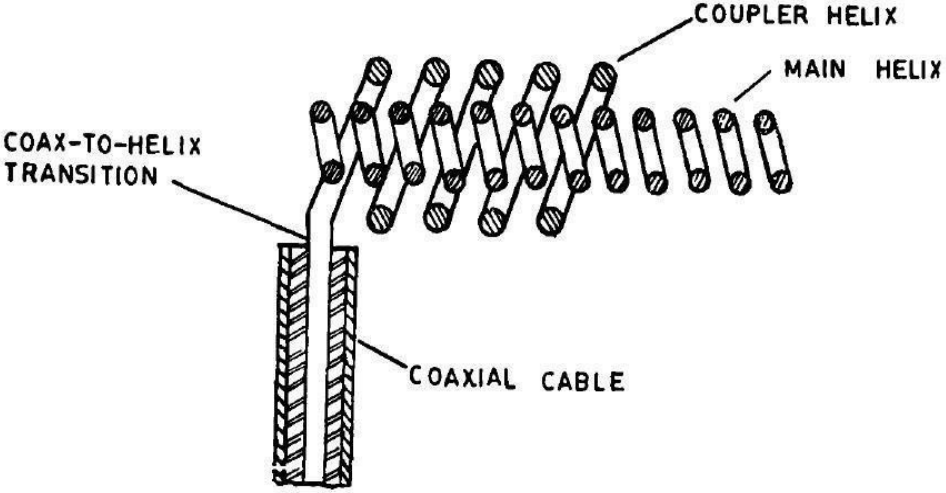


Fig. 1 — Basic form of a helical coupler

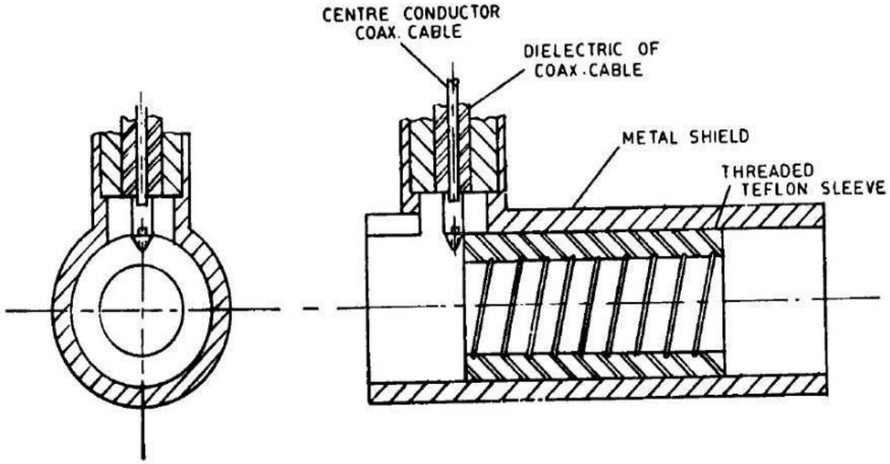


Fig. 2 — Coupler housing, with coax-to-helix transition

The coupled-helix Attenuator :

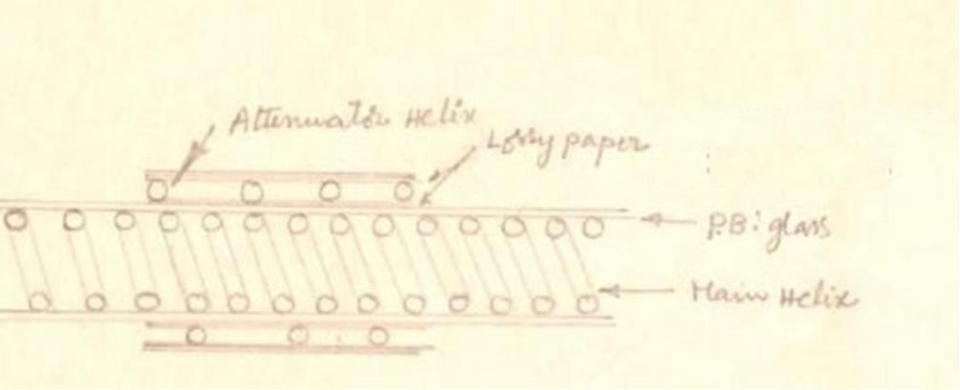
Two methods :

First

Molybdenum and nichrome wire coupler helices were threaded in a lossy-medium sleeve.

Second

Made by moulding with araldite resin impregnated with aquadag (5 to 50 %) and several helix pitches



Results :

(The paper had a DC surface resistivity 10,000 ohms/square)

- Single moly-wire helices over a resistive paper sheath were promising
- An attenuator helix pitch of 0.171 cm gave 6 dB/cm loss through out the band
- With 30 turns of helix (length = 5.13 cm) and 5.5 cm long resistive paper sheath, attenuation achieved 35 dB in 2-4 Gc/s

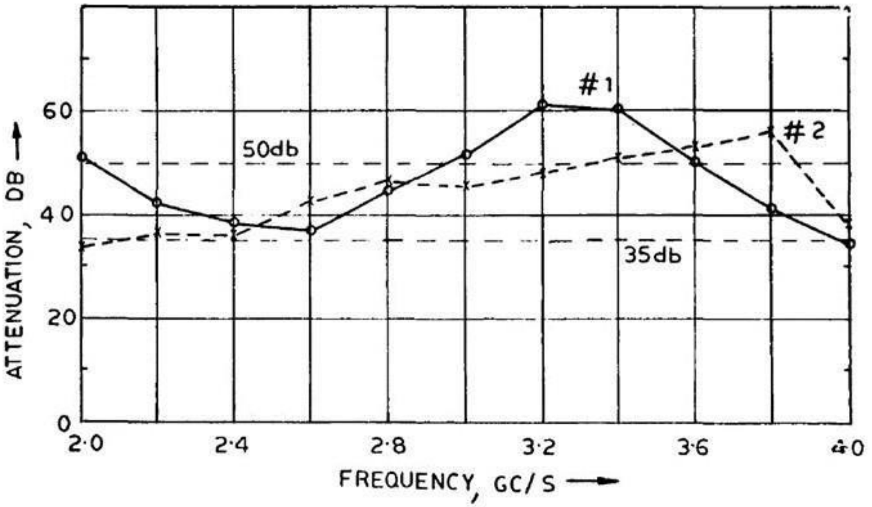
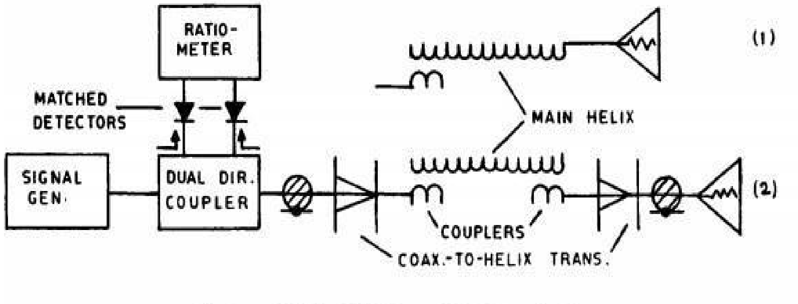
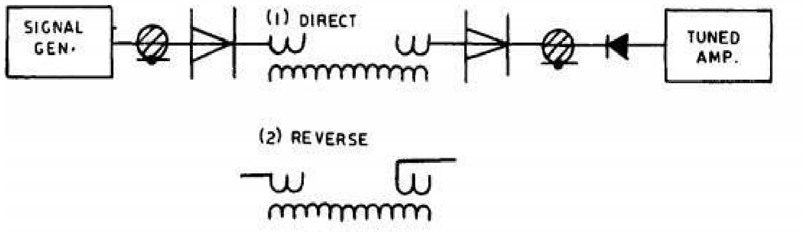


Fig. 5 — Measured characteristics of coupled-helix attenuators

Measurement set-up for coupler characteristics:



(a) REFLECTION COEFFICIENT



(b) DIRECTIVITY

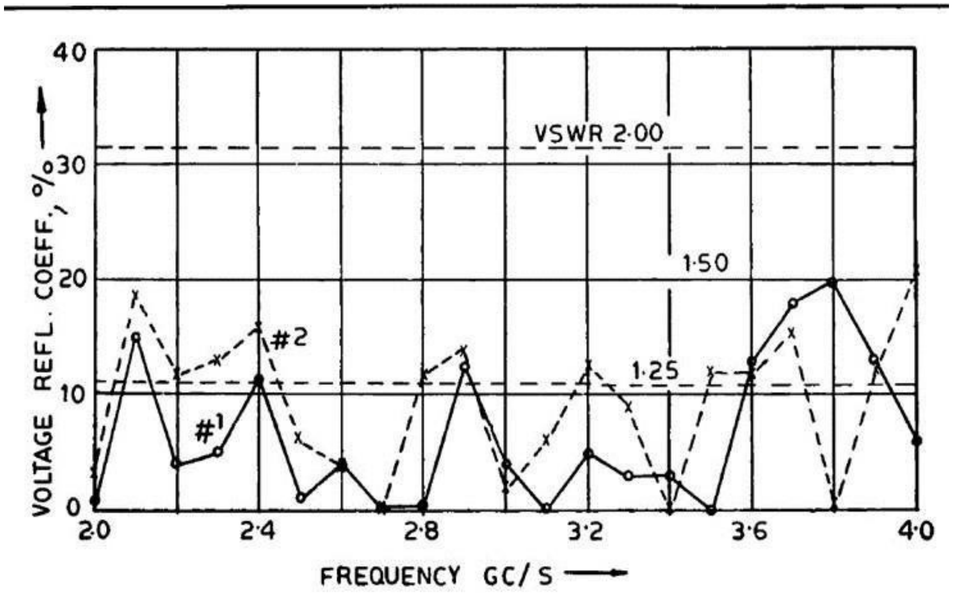
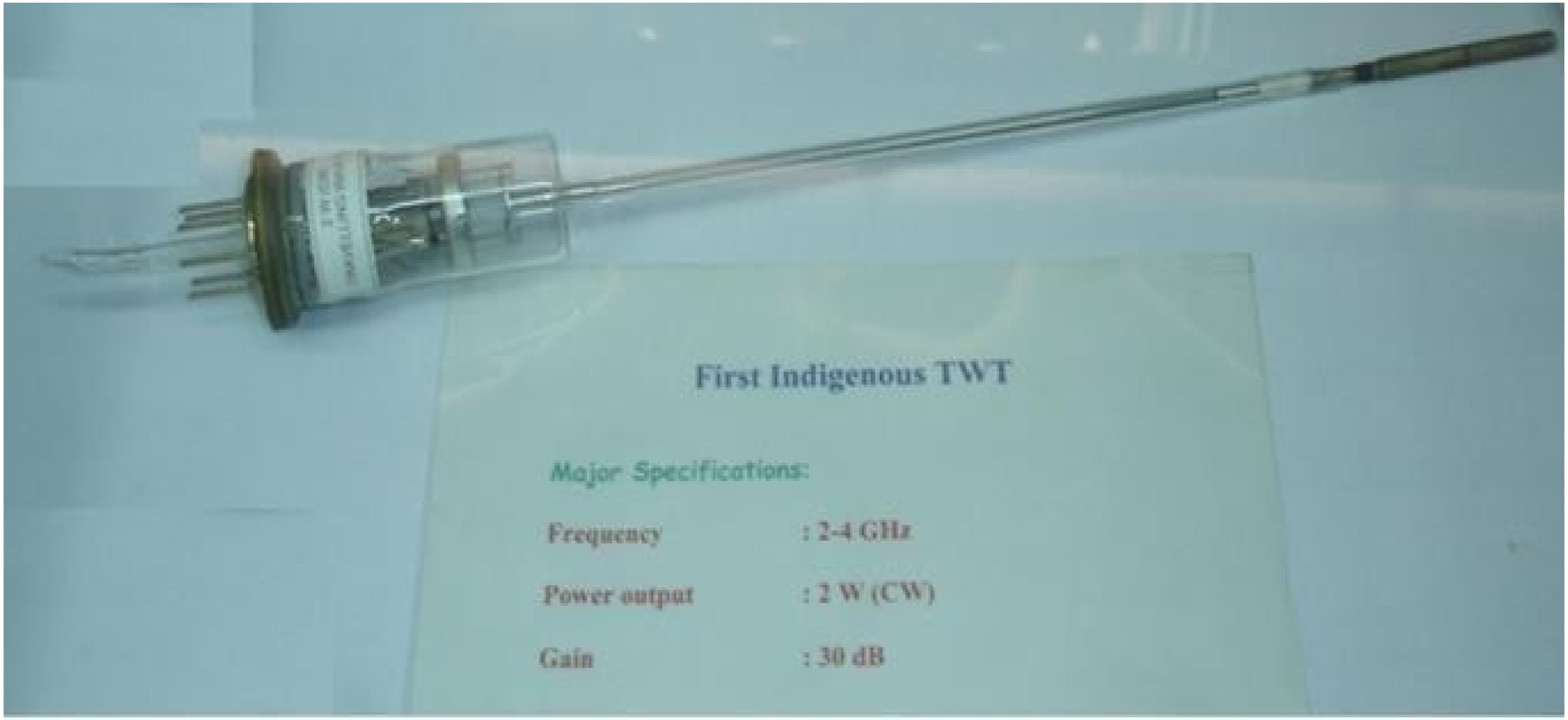


Fig. 3 — Measured matching characteristics of couplers (including coaxial cable and connector adapters)

First Indigenous TWT



First Indigenous TWT

Major Specifications:

Frequency : 2-4 GHz

Power output : 2 W (CW)

Gain : 30 dB

Results & Discussion:

- All the components as well as complete design of TWT was carried out.
- Based on the design, components were fabricated.
- Individual sub-assemblies were made and tested for various aspects.
- Cold RF tests conducted on helices, Couplers and Attenuators.
- Tubes integrated maintaining proper alignment etc
- Continuous vacuum processing, as UHV Valves were not available at that time
- Detailed RF tests were conducted for various aspects throughout the frequency band 2 to 4 GHz.

  It gave 30 dB gain throughout the band.
- Set up developed for measuring Noise Figure (< 30dB) as well as AM to PM Conversion Coefficient (3 degree/dB at Small Signal Level).
- Number of tubes were developed and similar performance was observed.

Conclusion :

This was a very first successful initiative by CEERI, Pilani in the Country for indigenous design and development of this TWT. It was a great success as it gave required performance in all respect. This was very well appreciated at that point of time and CEERI got recognition by different agencies and they supported for further advancements in the area of TWTs.

Acknowledgement :

- We would like to express our special gratitude to Dr SSS Agarwala, Head of then VT division for his overall guidance and sustained support in all aspects for executing this project.
- We are thankful to Prof BN Basu for creating a very special group "**Thinkers in VED**", which is providing a platform for discussing various issues related to these devices.
- I also express my gratitude to the organisers of this group (Sh Raj Singh and his team) for giving me an opportunity to present this work.
- My sincere thanks to all the members from different organizations, who have made it possible to attend this webinar.

Thanks

Annexure III:

Young Researcher's Talk-1 Slides

Large Signal Field Analysis of Traveling Wave Tube Amplifier for Helix Slow Wave Structure

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Presentation is based on:10.1080/09205071.2017.1394916 & http://hdl.handle.net/10603/220790

Outline

- Introduction to TWTA and literature survey
- Interaction region modelling
- Problem Formulation of the TWTA
- Solution procedure
- Numerical computation and results
- Conclusion
- Publications

Traveling wave tube – Cross sections

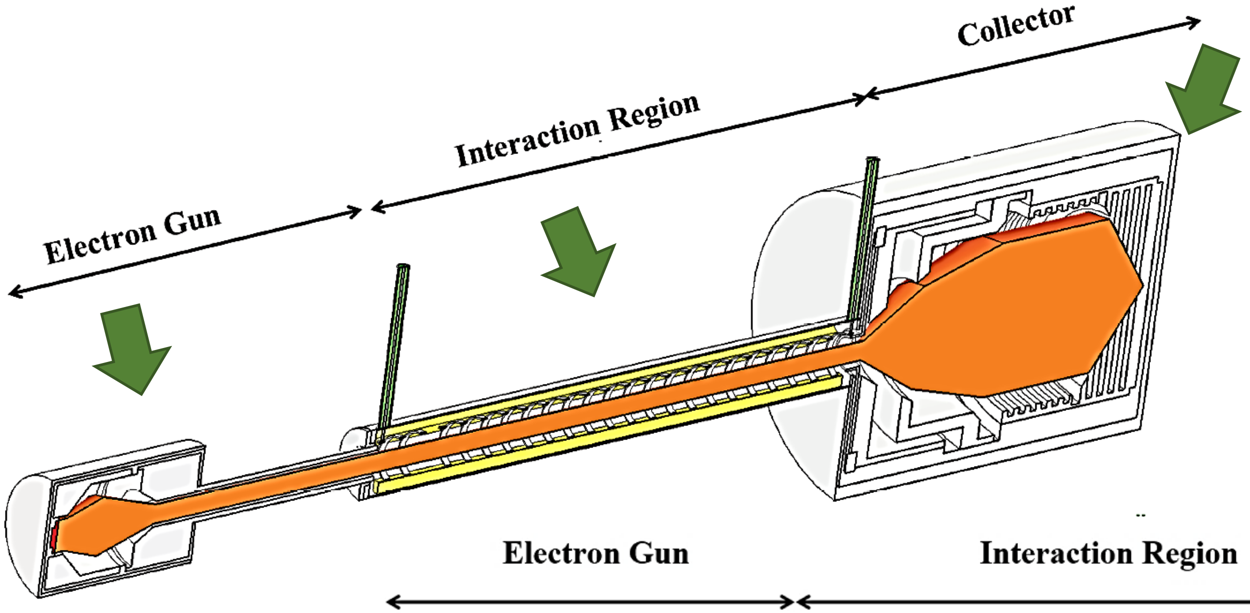


Fig. 4a. Cross sectional view of Travelling wave tube amplifier without the periodic permanent magnets

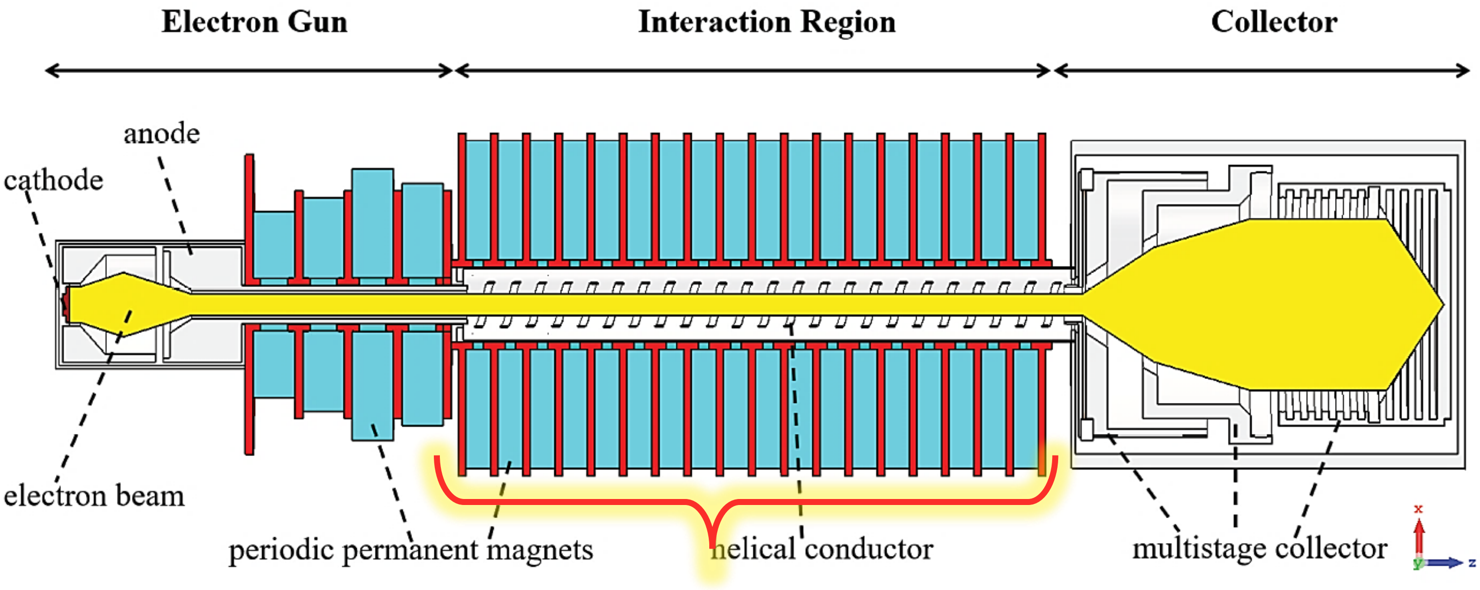


Fig. 4b. Cross sectional view of 3 major parts of the TWTA:

1. **Electron gun**,
2. **Interaction region** and
3. **Collector**

3. Interaction region

Large Signal Field Analysis of Linear Beam **Traveling Wave Tube** Amplifier for Anisotropically Conducting **Tape Helix Slow Wave Structure Supported by Dielectric Rods**

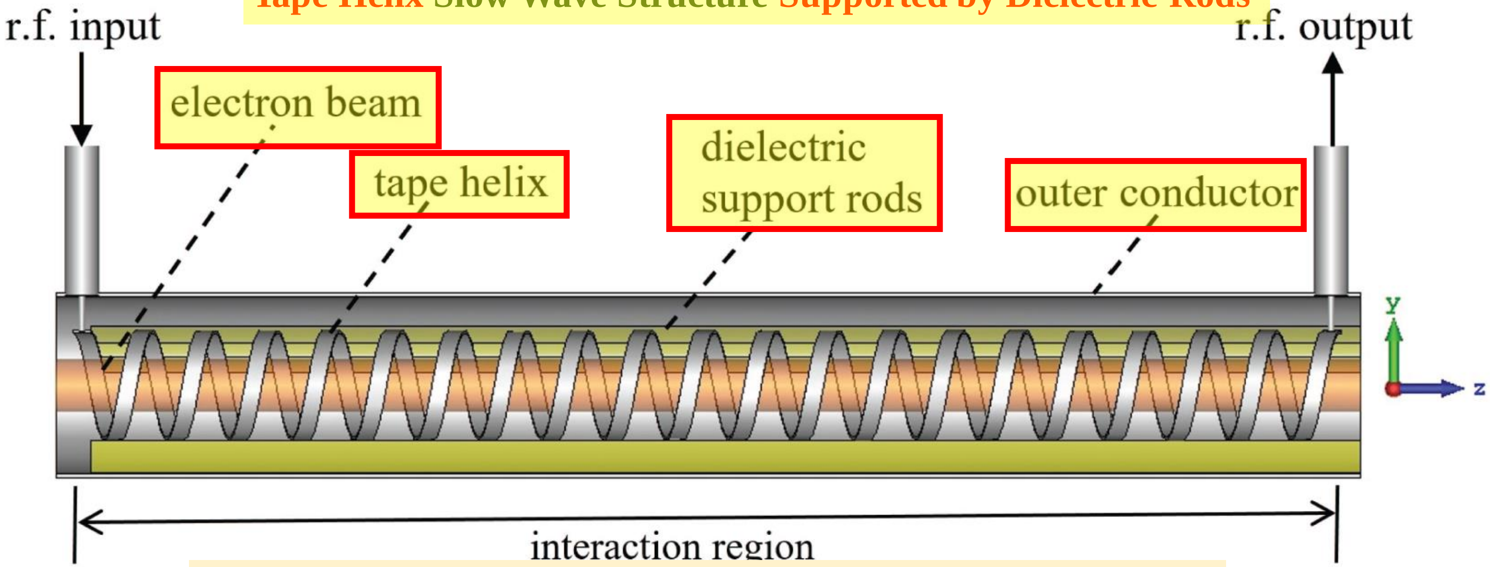


Fig. 7. Cross sectional view of interaction region

- **Electron beam** – For beam wave interaction
- **Slow wave structure (SWS)** – Tape helix conductor slows down the RF signal
- **Dielectric support rods** – support the SWS
- **Outer conductor** – encapsulating the vacuum tube
- **Periodic permanent magnets** – Prevent electron divergence

Beam wave interaction in SWS

- ☐ The helical slow wave structure (**SWS**) helps in the interaction of the electric fields and the electron beam in the interaction region, by **slowing down** the velocity of the RF fields.
- ☐ DC **beam velocity** of the beam is maintained slightly **greater** than that of the axial field.

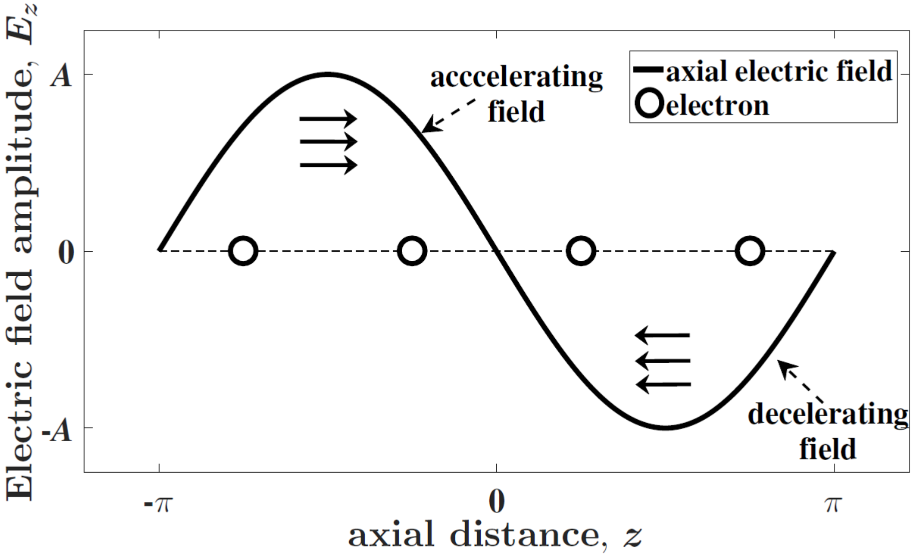


Fig. 8. Forces acting on electrons due to one RF cycle of the axial electric field. [21] The direction of periodic forces on the electrons is indicated by the horizontal arrows.

Beam wave interaction in SWS

Large Signal Field Analysis of Linear Beam **Traveling Wave Tube Amplifier** for Anisotropically Conducting Tape Helix Slow Wave Structure Supported by Dielectric Rods

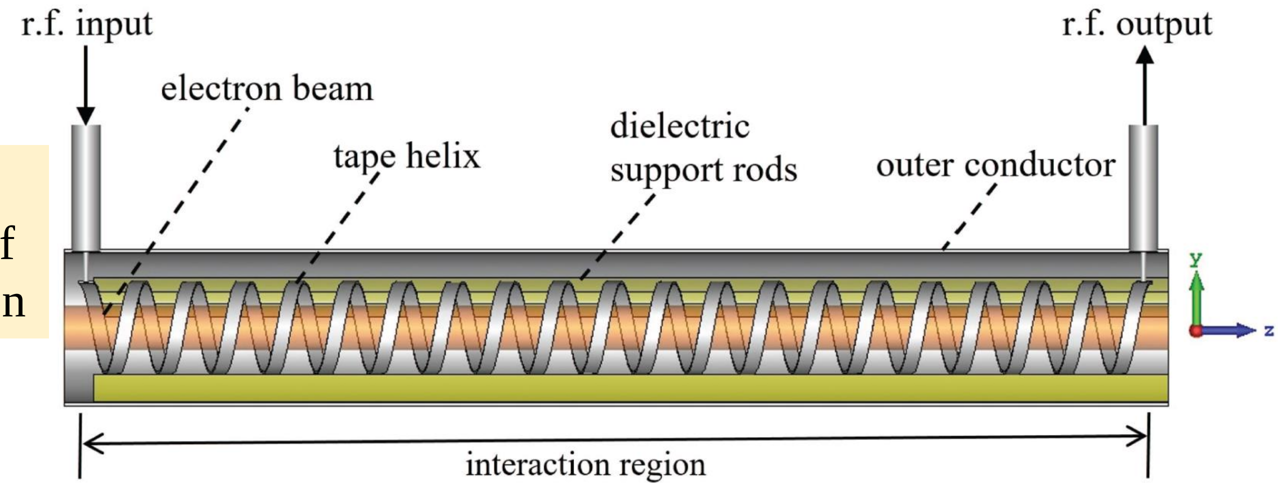


Fig. 9. Cross sectional view of interaction region

RF input given in Helix

Generation of Electron beam

Interaction of RF Signal with electron beam

Electron Bunches <=>Amplification of RF Signal

Amplified RF Signal received at output terminal

Tape helix model: Anisotropically conducting tape helix

Large Signal Field Analysis of Linear Beam Traveling Wave Tube Amplifier for Anisotropically Conducting Tape Helix Slow Wave Structure Supported by Dielectric Rods

Anisotropically conducting tape helix model has **surface current density only along the direction** **parallel** to the tape winding direction. ($J_{\|}$) [41,42]

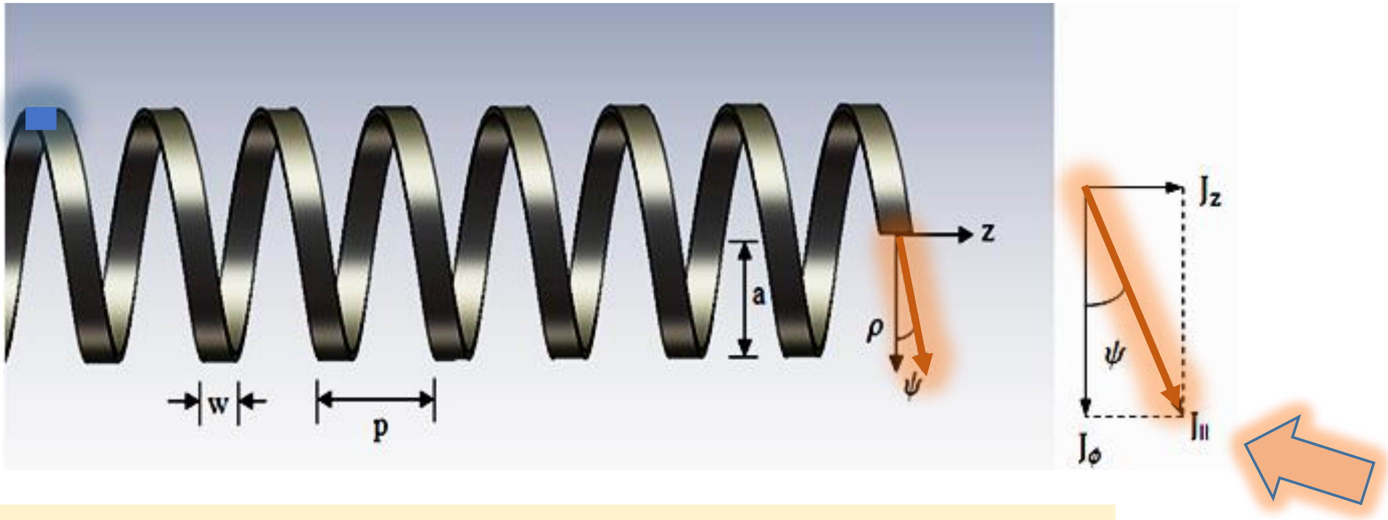


Fig. 18a. Anisotropically conducting tape helix structure

Published:

1. G. Naveen Babu, Richards Joe Stanislaus and S. Joshi, "Wave propagation characteristics in anisotropically conducting dielectric loaded tape helix slow wave structures," ***IEEE IVEC-2014***.
2. G. Naveen Babu, Richards Joe Stanislaus, "Fast wave propagation characteristics of dielectric loaded anisotropically conducting tape helix structures placed around and within a cylindrical conducting core", ***IEEE ICMETE-2016***.
3. G. Naveen Babu, Richards Joe Stanislaus, "Full wave propagation characteristics of a tape helix structure placed around and within a cylindrical core", ***ICMARS 2017***.

Tape helix model: Perfectly conducting tape helix

Perfectly conducting tape helix model has **surface current density variation along the both the directions parallel and perpendicular** to the tape winding direction. ($J_{\parallel}$ and $J_{\perp}$). [43,44]

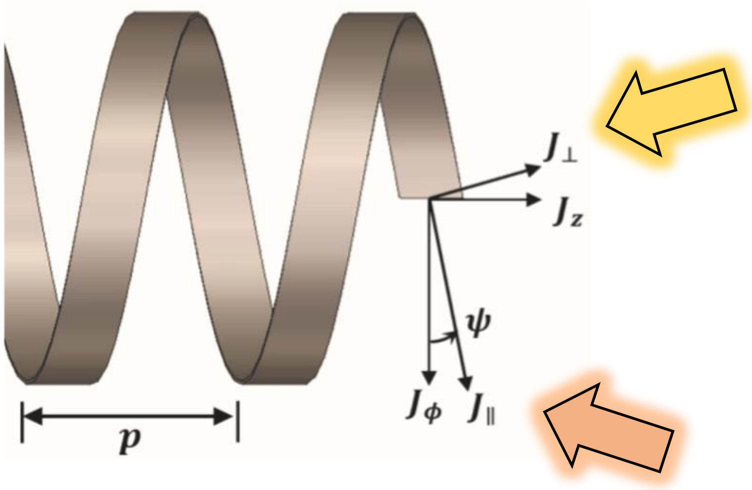


Fig. 18b. Perfectly conducting tape helix structure

Published:

1. G. Naveen Babu and Richards Joe Stanislaus, "Propagation of electromagnetic waves guided by perfectly conducting model of a tape helix supported by dielectric rods," in ***IET Microwaves, Antennas & Propagation***, vol. 10, no. 6,

Practical case of dielectric support rods

The practical TWTs consists of either rectangular, circular, specially tapered cross section or wedge shaped cross section.

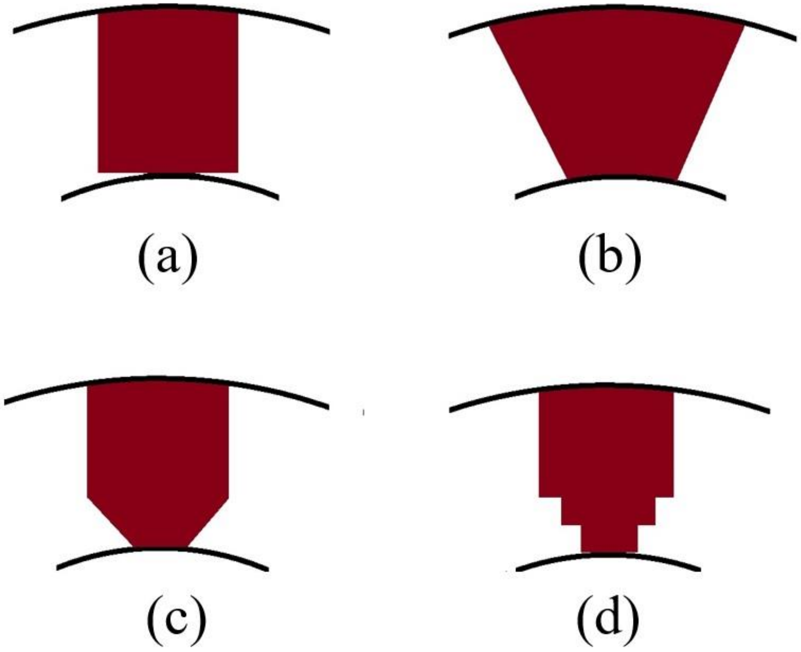

(a) (b) (c) (d)

Fig. 19. Cross section of dielectric support rods: (a) Rectangular, (b) wedge and (c, d) specially tapered

Azimuthally averaging the region between tape helix and outer conductor

Large Signal Field Analysis of Linear Beam Traveling Wave Tube Amplifier for Anisotropically Conducting Tape Helix Slow Wave Structure **Supported by Dielectric Rods**

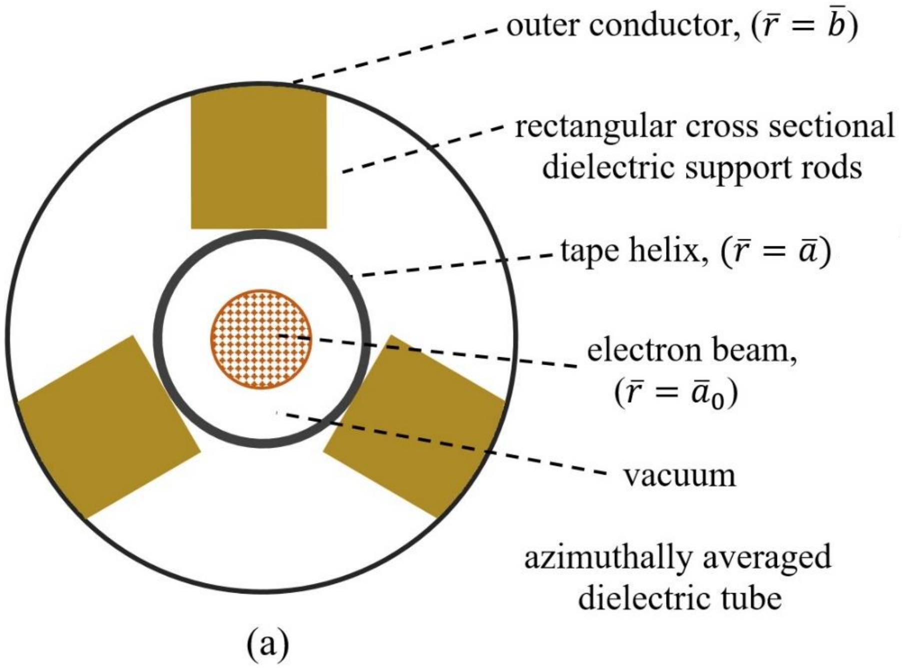
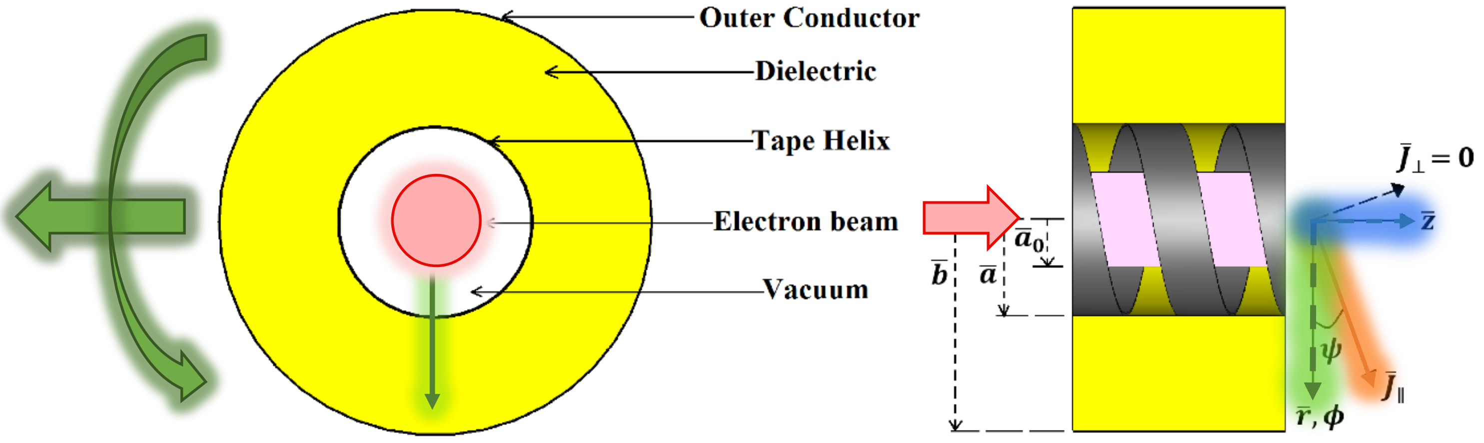


Fig. 20. **Azimuthally averaged concentric dielectric tubes** as in [16] in the region $\bar{a} < \bar{r} < \bar{b}$

Dispersion:

A circuit in which the **wave velocity varies with frequency** is said to have **dispersion**. The dielectric's effective permittivity affects the dispersion of the SWS.

Assumptions



(a) (b)

Fig. 21. Cross sectional views of anisotropically conducting tape helix supported by azimuthally averaged dielectric rod

1. Dielectric loaded **Anisotropically conducting** Tape Helix model for the slow-wave circuit.
2. Axially symmetric mode of operation
3. **Axially confined electron beam** partially filling the tube.
4. Negligible effect of transverse electric field **on the electron motion**
5. **Zero transverse speed of electrons** when electron enters the interaction region.

Assumptions contd..

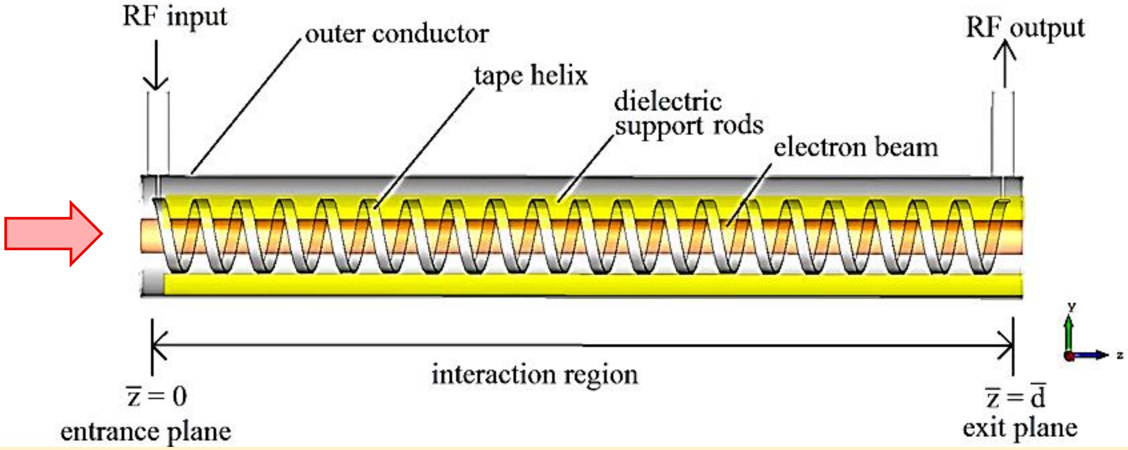


Fig. 22. Cross sectional view of dielectric rods supported tape helix SWS

6. **Nonrelativistic operation** justifying the dropping of r.f. magnetic force terms from the electron ballistic equation.
7. The **axial speed v_0 and the charge density** ρ_0 of the entering electron stream remain constant with respect to the transverse co-ordinates and the time.
8. The electron entrance speed $v_0 \cong v_p$, the cold-wave phase speed at the input signal frequency $\frac{\omega_0}{2*pi}$
9. Thermal effects are not included in this analysis.

Workflow

1. Parameter $\boldsymbol{\alpha}$ is obtained from **coldwave power flow** and the **dc power** required to generate the desired electron beam velocity.
2. $\boldsymbol{A_0}$, the amplitude of the r.f. input signal is determined based on $\boldsymbol{\alpha}$**.**
3. The electromagnetic fields, current density are solved through **Maxwell's equations**, **electron ballistic equation** and **boundary conditions**. A **Green's function sequence** is derived for the axial component of the electric field.
4. **Axial Electric field** and other field components are obtained as a function of electron arrival time.
5. **Tape surface current density** is computed from the field components.
6. **Power gain** due to signal amplification is derived. The **conversion efficiency**, the ratio of power gained in the interaction region and the dc power is determined.

Gain and conversion efficiency

The parameter $\boxed{\alpha \triangleq 10\log_{10}\frac{P_{in}}{P_{dc}},}$

where P_{in} is the **actual input signal power** (forward propagating cold wave at input signal frequency) $\boxed{P_{in} = \pi\bar{a}^2 A_0^2 Y_0\, P_{11}}$

where, Amplitude of axial E.F. at $\bar{z} = 0\ and\ \bar{r} = \bar{a}$, $\boxed{A_0 \triangleq \sup_t|\bar{E}_1(0,\bar{a},\bar{t})|}$

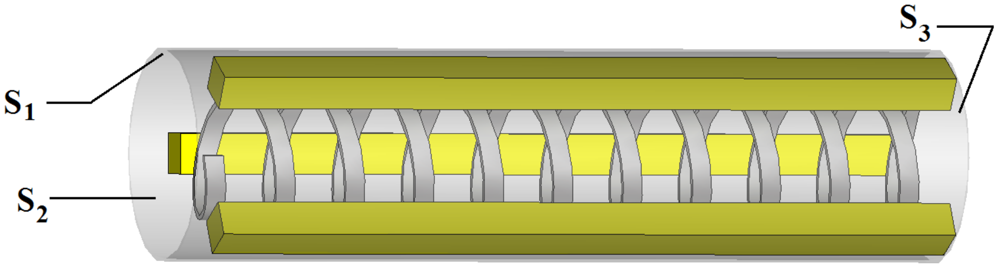
and the intrinsic admittance of the free space is $Y_0 = 1/Z_0$

Gain(total) $\boxed{g_{tot} \triangleq P_{out}/P_{in}}$

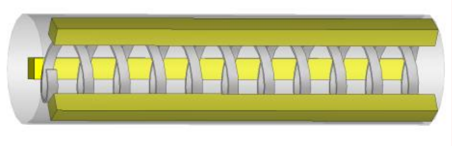
Total conversion efficiency, $\eta_{tot} \triangleq \frac{P_{out}-P_{in}}{P_{dc}}$

The numerator term indicates the **power gained in the volume** enclosed by the surfaces $S_1, S_2\ and\ S_3$.

Fig. 23. Cold wave structure



Cold wave fields [41,42]



$$E_\rho = \begin{cases} \sum_{n\in\mathbb{Z}} \left[-j\beta_n P_n A_n S_n'(P_n\rho) + \frac{n\omega\mu_0}{\rho} B_n S_n(P_n\rho) \right] e^{j(n\phi-\beta_n z)}, & 0 \le \rho \le a \\ \sum_{n\in\mathbb{Z}} \left[\begin{matrix} -j\beta_n P_n^+ C_n[S_n'(P_n^+\rho) - \sigma_{bn} T_n'(P_n^+\rho)] \\ + \frac{\omega\mu_0 n}{\rho} D_n[S_n(P_n^+\rho) - \sigma_{bn}' T_n(P_n^+\rho)] \end{matrix} \right] e^{j(n\phi-\beta_n z)}, & \\ a < \rho \le b & \end{cases}$$

$\boldsymbol{A_n, B_n, C_n, D_n}$: Arbitrary constants that depend on boundary conditions

$\boldsymbol{\beta_n}$: Axial propagation constant

$\boldsymbol{p_n}$: Transverse propagation constant in vacuum

$\boldsymbol{p_n^+}$: Transverse propagation constant in dielectric medium

$\boldsymbol{S_n}$, $\boldsymbol{T_n}$: Bessel functions and Modified Bessel functions

$\boldsymbol{S_n'}$, $\boldsymbol{T_n'}$: Their derivatives

0 to a: within helix (vacuum)

a to b: in between helix and outer conductor (effective dielectric medium)

Cold wave power flow

According to Sensiper, the total **average flow of power** **in z direction** along the interaction length is defined as

$$P_z = Re\left[\int \bar{S}_A \, dA\right]$$

$$= Re\left[\frac{1}{2}\int \bar{a}_z.(\bar{E} \times \bar{H}^*) \, dA\right]$$

$$= \ Re\left[\frac{1}{2}\int_0^{2\pi}\int_0^{b} \bar{a}_z.(\bar{E} \times \bar{H}^*) \, r \, dr \, d\theta\right]$$

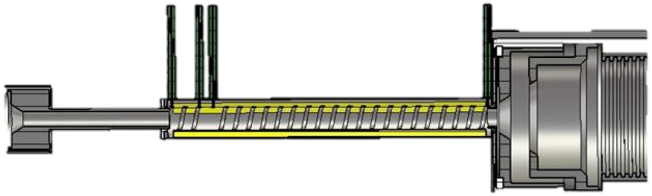


Fig. 24. Absence of electron beam in the TWT for cold wave analysis

Since field expressions for $r < a$ and $a < r < b$ are different, the integral must be performed in two steps(internal and external to tape)

$$P_z^{i,e} = \ Re\left[\frac{1}{2}\int_0^{2\pi}\int_{0,a}^{a,b} \bar{a}_z.(\bar{E} \times \bar{H}^*) \, r \, dr \, d\theta\right]$$

DC Power

The **DC power of the beam**,

$$P_{dc} = V_0 I_0$$

From the dispersion analysis of the cold wave structure(without the electron beam), the **phase velocity**, v_p is calculated from

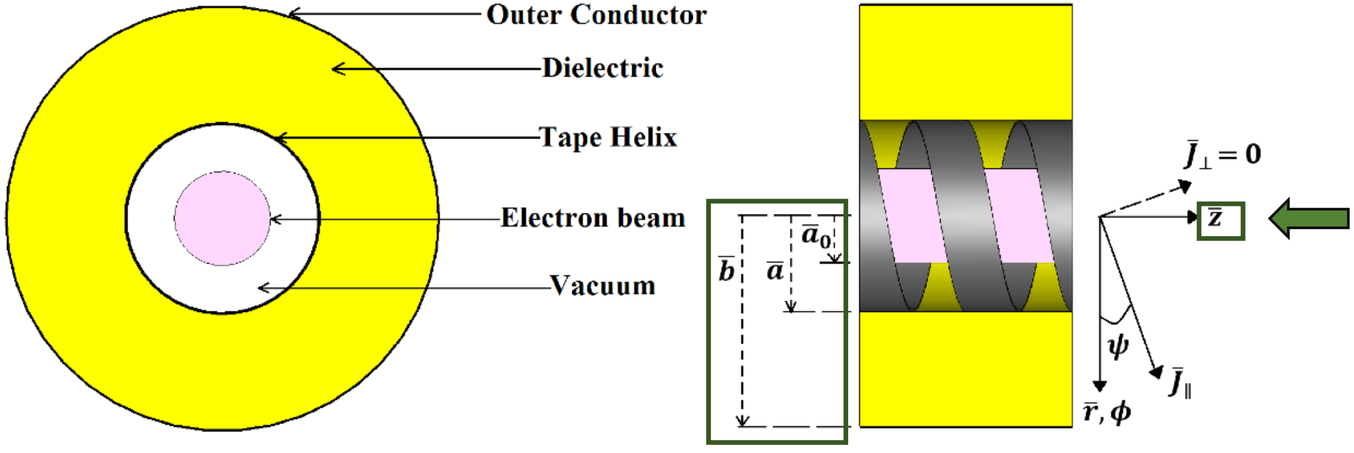
$$\frac{\boldsymbol{v_p}}{\boldsymbol{c}} = \frac{\boldsymbol{k_{0a}}}{\boldsymbol{\beta_{0a}}} \qquad \text{(constant } v_p \text{ for the respective bandwidth)}$$

For perfect synchronism to occur between the electron beam and the travelling EM wave at the input plane, the **electron beam's velocity, $\boldsymbol{v_0}$**, should be set to the **phase velocity $\boldsymbol{v_p}$** of the travelling EM wave. Hence the **applied potential** across the anode and the cathode is found using

$$\frac{1}{2} m v_0^2 = e\mathrm{V}_0$$

Hence, $\mathrm{V}_0 = \frac{1}{2}\frac{m v_0^2}{e}$ ($\mathrm{V}_0 = 4.6668$ kV for electron velocity $v_0 = 0.1351\, c$, where c is the velocity of light.)

Variables rendered dimensionless



(a) (b)

Fig. 25. Transverse and longitudinal cross sectional views of anisotropically conducting tape helix supported by azimuthally averaged dielectric tube

Electron beam radius, $a = \dfrac{\bar{a}_0}{\bar{a}}$

Tape helix radius, $1 = \dfrac{\bar{a}}{\bar{a}}$

Outer conductor radius, $b = \dfrac{\bar{b}}{\bar{a}}$

Interaction length, $d = \dfrac{\omega_0 \bar{d}}{v_0}$

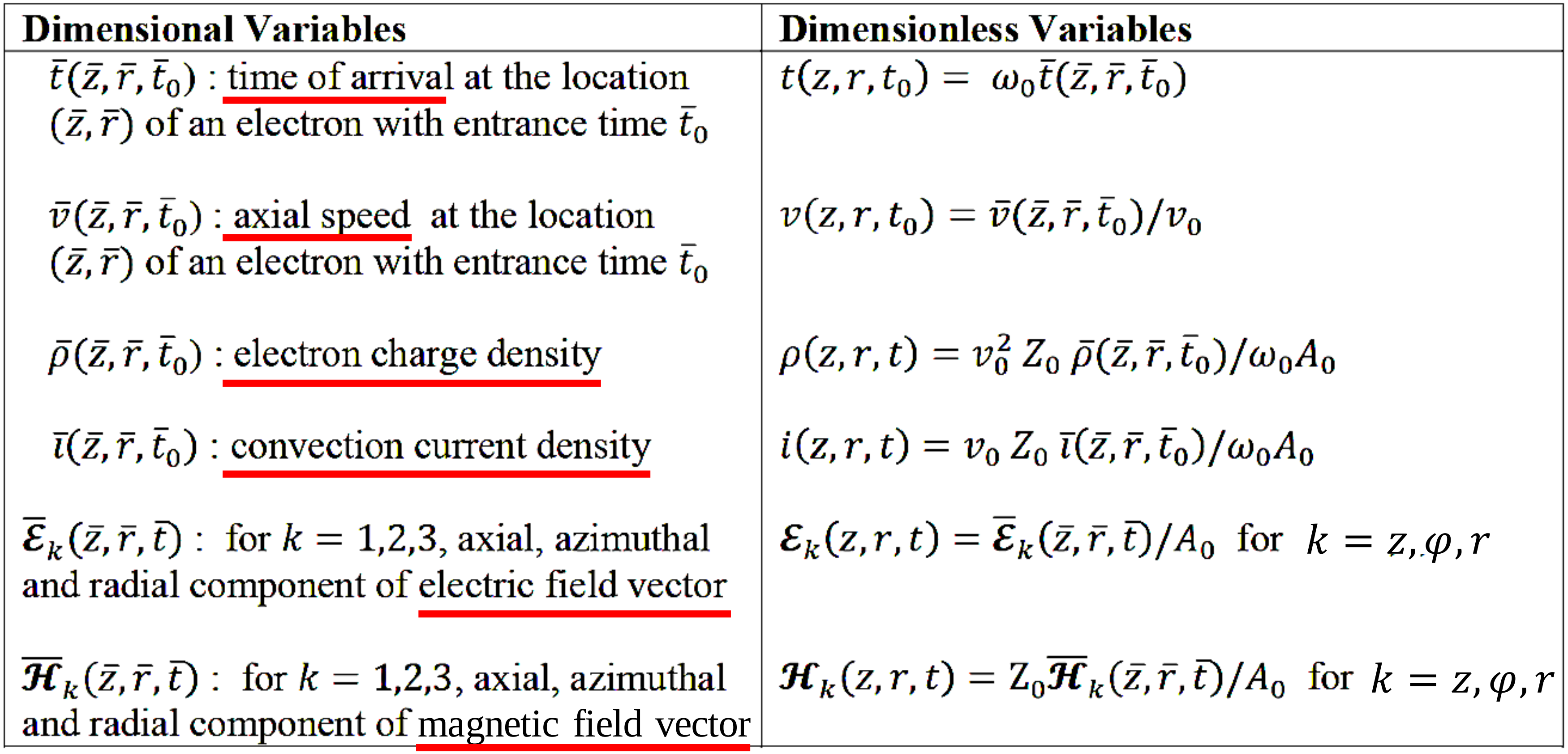
Axial electron speed, $v_0(z,r,t) = 1/t_z(z,r,t_0)$ (1)

Dimensional Variables	Dimensionless Variables
$\bar{z}$ axial co-ordinate	$z = \omega_0 \bar{z}/v_0$
$\bar{r}$ radial co-ordinate	$r = \bar{r}/\bar{a}$
$\bar{t}$ time	$t = \omega_0 \bar{t}$
$\bar{t}_0$ electron entrance time	$t_0 = \omega_0 \bar{t}_0$

Pitch angle, $\psi = 10°$

$k_d = \dfrac{2*\pi}{d}$

Variables rendered dimensionless contd..



Dimensional Variables	Dimensionless Variables
$\bar{t}(\bar{z},\bar{r},\bar{t}_0)$: time of arrival at the location $(\bar{z},\bar{r})$ of an electron with entrance time $\bar{t}_0$	$t(z,r,t_0) = \omega_0\bar{t}(\bar{z},\bar{r},\bar{t}_0)$
$\bar{v}(\bar{z},\bar{r},\bar{t}_0)$: axial speed at the location $(\bar{z},\bar{r})$ of an electron with entrance time $\bar{t}_0$	$v(z,r,t_0) = \bar{v}(\bar{z},\bar{r},\bar{t}_0)/v_0$
$\bar{\rho}(\bar{z},\bar{r},\bar{t}_0)$: electron charge density	$\rho(z,r,t) = v_0^2\, Z_0\, \bar{\rho}(\bar{z},\bar{r},\bar{t}_0)/\omega_0 A_0$
$\bar{\imath}(\bar{z},\bar{r},\bar{t}_0)$: convection current density	$i(z,r,t) = v_0\, Z_0\, \bar{\imath}(\bar{z},\bar{r},\bar{t}_0)/\omega_0 A_0$
$\bar{\mathcal{E}}_k(\bar{z},\bar{r},\bar{t})$: for $k = 1,2,3$, axial, azimuthal and radial component of electric field vector	$\mathcal{E}_k(z,r,t) = \bar{\mathcal{E}}_k(\bar{z},\bar{r},\bar{t})/A_0$ for $k = z,\varphi,r$
$\bar{\mathcal{H}}_k(\bar{z},\bar{r},\bar{t})$: for $k = 1,2,3$, axial, azimuthal and radial component of magnetic field vector	$\mathcal{H}_k(z,r,t) = Z_0\bar{\mathcal{H}}_k(\bar{z},\bar{r},\bar{t})/A_0$ for $k = z,\varphi,r$

Z_0 - free space intrinsic impedance

A_0 - axial electric field amplitude on the tape helix at the entrance plane

Fourier series expansion of **current density** and **charge density**

- $q_0(= v_0^2\rho_0 Z_0/\omega_0 A_0)$ corresponds to both the dimensionless **convection current density** and the **charge density** at the entrance plane, $z = 0$.
- t_{0l} corresponds to the entrance time of the l^{th} electron which contributes to the time of arrival at (z, r) location at time t.
- The **current density** and the **charge density** terms are then expanded in **Fourier series**

$$i(z,r,t) = \sum_l q_0 \left| t_{t_0}\left(z,r,t_{0l}(z,r,t)\right) \right|^{-1} \qquad (2a)$$

$$\rho(z,r,t) = \sum_l q_0 \frac{t_z\left(z,r,t_{0l}(z,r,t)\right)}{\left| t_{t_0}\left(z,r,t_{0l}(z,r,t)\right) \right|} \qquad (2b)$$

$$i(z,r,t) = q_0 I_{[0,a]}(r) + \sum_{m=1}^{\infty} \left(i_m(z,r) \exp jmt + c.c. \right) \qquad (2c)$$

$$\rho(z,r,t) = q_0 I_{[0,a]}(r) + \sum_{m=1}^{\infty} \left(\rho_m(z,r) \exp jmt + c.c. \right) \qquad (2d)$$

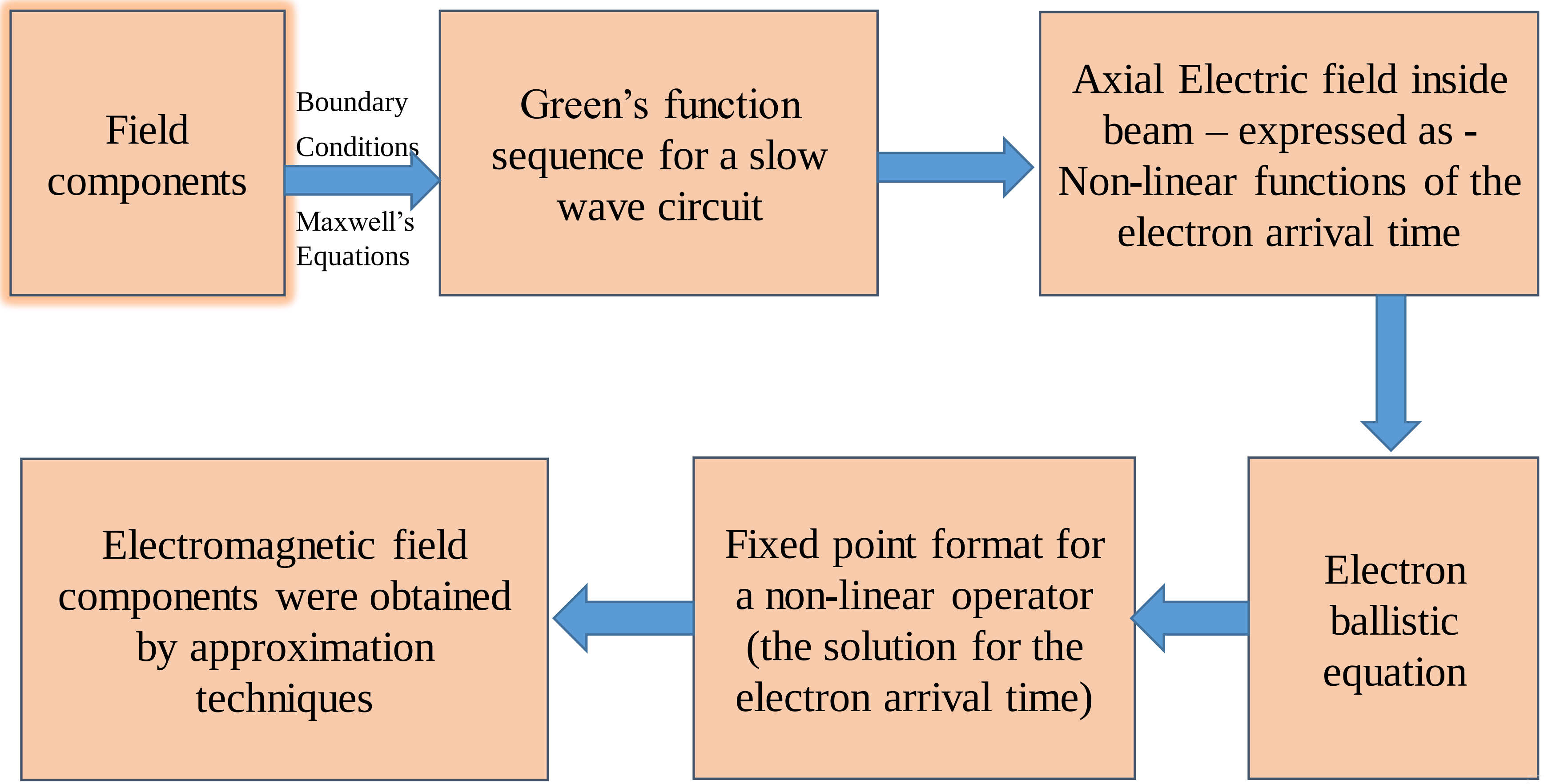
Fourier series expansion of current density and charge density, contd..

Fourier coefficients are expanded in terms of the contribution of every electron's arrival time

$$
\begin{aligned}
&i_m(z,r)\\
&= \left(\frac{q_0}{2\pi}\right)\int_{-\pi}^{\pi}\left\{\sum_l \left|t_{t_0}(z,r,t_{0l}(z,r,t))\right|^{-1}\right\}\exp(-jmt)\,dt && \text{(3a)}\\
&= (q_0/2\pi)\int_{-\pi}^{\pi}\exp(-jm\underbrace{t(z,r,t_0)}\,dt_0 && (3b)
\end{aligned}
$$

$$
\begin{aligned}
&\rho_m(z,r)\\
&= (q_0/2\pi)\int_{-\pi}^{\pi}\left\{\sum_l \frac{t_z(z,r,t_{0l}(z,r,t))}{\left|t_{t_0}(z,r,t_{0l}(z,r,t))\right|}\right\}\exp(-jmt)\,dt && \text{(4a)}\\
&= (q_0/2\pi)\int_{-\pi}^{\pi}\underbrace{\mathrm{t_z(z,r,t_0)}}\exp(-jm\underbrace{t(z,r,t_0)}\,dt_0 && (4b)
\end{aligned}
$$

Approach



Field components

Boundary Conditions

Maxwell’s Equations

Green’s function sequence for a slow wave circuit

Axial Electric field inside beam – expressed as - Non-linear functions of the electron arrival time

Electron ballistic equation

Fixed point format for a non-linear operator (the solution for the electron arrival time)

Electromagnetic field components were obtained by approximation techniques

Maxwell’s equations and Electron Ballistic equation - simplified

The **Maxwell’s equations** are

$$a_1\kappa(r)\mathcal{E}_{z_t} - a_2(\mathcal{H}_{\varphi_r} + \mathcal{H}_{\varphi}/r) = -i(z,r,t) \tag{5a}$$

$$a_1\kappa(r)\mathcal{E}_{\varphi_t} - \mathcal{H}_{r_z} + a_2\mathcal{H}_{z_r} = 0 \tag{5b}$$

$$a_1\kappa(r)\mathcal{E}_{r_t} + \mathcal{H}_{\varphi_z} = 0 \tag{5c}$$

$$a_1\mathcal{H}_{z_t} + a_2(\mathcal{E}_{\varphi_r} + \mathcal{E}_{\varphi}/r) = 0 \tag{5d}$$

$$a_1\mathcal{H}_{\varphi_t} + \mathcal{E}_{r_z} - a_2\mathcal{E}_{z_r} = 0 \tag{5e}$$

$$a_1\mathcal{H}_{r_t} - \mathcal{E}_{\varphi_z} = 0 \tag{5f}$$

$$\mathcal{E}_{z_z} + a_2(\mathcal{E}_{r_r} + \mathcal{E}_r/r) = \rho(z,r,t)/a_1 \tag{6a}$$

$$\mathcal{H}_{z_z} + a_2(\mathcal{H}_{r_r} + \mathcal{H}_r/r) = 0 \tag{6b}$$

Electron ballistic equation

$$t_{zz}(z,r,t_0) = \varepsilon\big(t_z(z,r,t_0)\big)^3\mathcal{E}_z\big(z,r,t(z,r,t_0)\big) \tag{7}$$

$$a_1 = v_0/c, a_2 = (v_0/\omega_0\bar{a}), \varepsilon = A_0 e/m_e\omega_0 v_0$$

$$\kappa(r) = \begin{cases} 1, & 0 < r < 1 \\ \varepsilon_{eff}, & 1 < r < b \end{cases}$$

with e being the electron charge and m_e is the rest mass of the electron.

Recap of the variables (Boundaries)

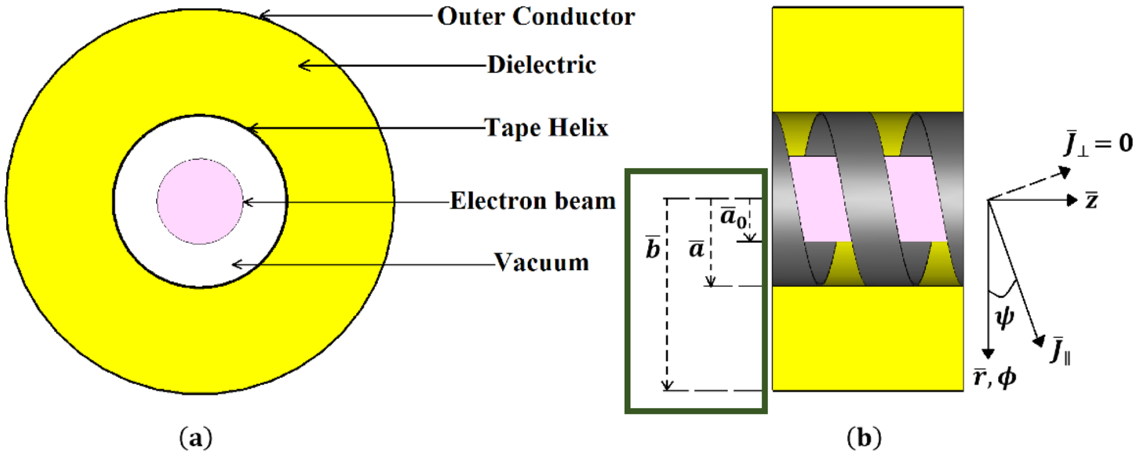


Fig. 26. Transverse and longitudinal cross sectional views of anisotropically conducting tape helix supported by azimuthally averaged dielectric tube

Electron beam radius, $a = \dfrac{\bar{a}_0}{\bar{a}}$

Tape helix radius, $1 = \dfrac{\bar{a}}{\bar{a}}$

Outer conductor radius, $b = \dfrac{\bar{b}}{\bar{a}}$

Interaction length, $d = \dfrac{\omega_0 \bar{d}}{v_0}$

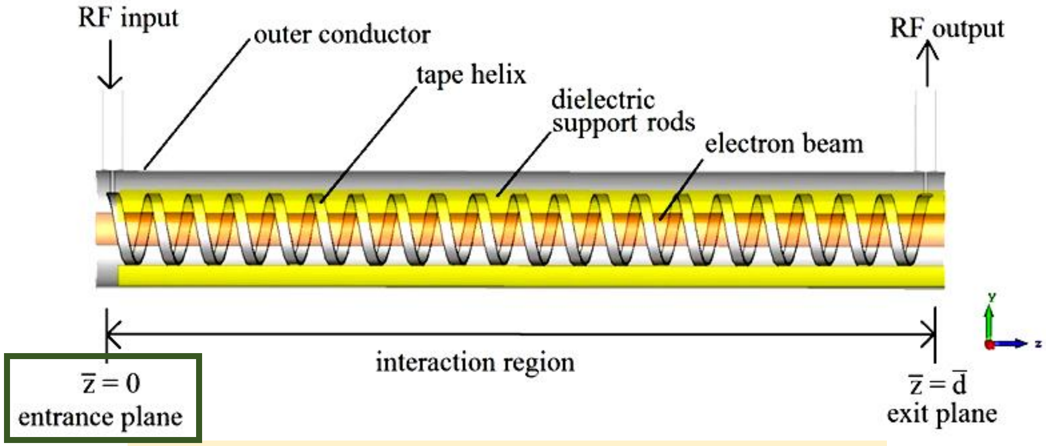


Fig. 27. Cross section of interaction region

Boundary conditions

In the **entrance plane** of the interaction region, $z = 0$,

$$t(0, r, t_0) = t_0 \qquad (8a)$$

$$t_z(0, r, t_0) = 1 \qquad (8b)$$

The **monochromatic signaling conditions** at the tape helix in the entrance plane, with the phase factor, $A(\triangleq \exp(j\theta))$, in the entrance plane is

$$\mathcal{E}_z(0, 1, t) = (A/2)exp(jt) + c.c. \qquad (8c)$$

$$\mathcal{E}_{z_z}(0, 1, t) = -j\beta_1(A/2)exp(jt) + c.c. \qquad (8d)$$

Along the boundary of the **electron beam radius, $r = a$**, the continuity of the electric and magnetic field components are

$$\mathcal{E}_k(z, a-, t) - \mathcal{E}_k(z, a+, t) = 0 \qquad (9a)$$

$$\mathcal{H}_k(z, a-, t) - \mathcal{H}_k(z, a+, t) = 0 \qquad (9b)$$

$$\text{for} \quad k = z, \varphi, r$$

Boundary conditions contd.

At the **tape helix radius**, the axial and azimuthal components of the electric fields are continuous in (10a-b). Equations (10c-d) states the discontinuity in the magnetic field amounting to **the surface current density of the parallel component**. In (10e), the null electric field exists only in the tape helix region.

$$\boldsymbol{\mathcal{E}}_z(z,1-,t)-\boldsymbol{\mathcal{E}}_z(z,1+,t)=0 \tag{10a}$$

$$\boldsymbol{\mathcal{E}}_\varphi(z,1-,t)-\boldsymbol{\mathcal{E}}_\varphi(z,1+,t)=0 \tag{10b}$$

$$\begin{aligned}&[\boldsymbol{\mathcal{H}}_z(z,1-,t)-\boldsymbol{\mathcal{H}}_z(z,1+,t)]\sin\psi\\ &\qquad+\left[\boldsymbol{\mathcal{H}}_\varphi(z,1-,t)-\boldsymbol{\mathcal{H}}_\varphi(z,1+,t)\right]\cos\psi=0\end{aligned} \tag{10c}$$

$$\begin{aligned}&[\boldsymbol{\mathcal{H}}_z(z,1-,t)-\boldsymbol{\mathcal{H}}_z(z,1+,t)]\cos\psi\\ &\qquad-\left[\boldsymbol{\mathcal{H}}_\varphi(z,1-,t)-\boldsymbol{\mathcal{H}}_\varphi(z,1+,t)\right]\sin\psi=\boldsymbol{J}_\parallel(z,1,t)\end{aligned} \tag{10d}$$

$$\left[\boldsymbol{\mathcal{E}}_z(z,1,t)-\boldsymbol{\mathcal{E}}_\varphi(z,1,t)\right]g(\varphi,z)=0 \tag{10e}$$

where $\boldsymbol{g}(\boldsymbol{\phi},\boldsymbol{z})$ is the indicator function from [13, 15, 17], which limits the current to the tape helix surface only.

The boundary condition at the outer conductor, $r=b-$, is

$$\mathcal{E}_k(z,b-,t)=0,\quad for\ k=z,\varphi$$

Field components – expanded in Fourier series

A Green's function sequence (G_m) will be developed for the slow wave circuit for $m \geq 1$, with the mth harmonic of the input signal frequency,$m\omega_0$, corresponding to the mth Green's function.

The **field components** are expressed in **Fourier series**,

$$\mathcal{E}_k(z,r,t) = \sum_{m=1}^{\infty}[E_{km}(z,r)\exp(jmt) + c.c] \quad for\ k = z, \varphi, r$$

$$\mathcal{H}_k(z,r,t) = \sum_{m=1}^{\infty}[H_{km}(z,r)\exp(jmt) + c.c], \qquad (12)$$

Boundary and Signalling conditions are expressed with Fourier coefficients

By substituting the Fourier expansions of the fields (12), current density and charge density in the **signaling conditions** and **boundary conditions**,

Entrance plane,

$$E_{zm}(0,1) = (A/2)\delta_{1m}$$
$$E_{zm_z}(0,1) = -j\beta_1(A/2)\delta_{1m} \qquad (13)$$

Tape helix,

$$\begin{aligned}
&E_{zm}(z,1-) - E_{zm}(z,1+) = 0\\
&E_{\varphi m}(z,1-) - E_{\varphi m}(z,1+) = 0\\
&[H_{zm}(z,1-) - H_{zm}(z,1+)]sin\psi\\
&\qquad + [H_{\varphi m}(z,1-) - H_{\varphi m}(z,1+)]cos\psi = 0\\
&[H_{zm}(z,1-) - H_{zm}(z,1+)]cos\psi\\
&\qquad - [H_{\varphi m}(z,1-) - H_{\varphi m}(z,1+)]sin\psi = i_{\|}\\
&[E_{zm}(z,1) + E_{\varphi m}(z,1)cot\psi]g(\varphi,z) = 0
\end{aligned} \qquad (14)$$

Electron beam,

$$E_{km}(z,a-) - E_{km}(z,a+) = 0$$
$$H_{km}(z,a-) - H_{km}(z,a+) = 0 \qquad (15)$$

Outer conductor

$$E_{km}(z,b-) = 0 \quad for \quad k = z,\varphi \qquad (16)$$

$$\delta_{1m} = \begin{cases} 1, & if\ m = 1 \\ 0, & otherwise \end{cases}$$

Fourier coefficients of field components : DC component

$$E_{z0} = H_{z0} = E_{\varphi 0} = H_{r0} = 0$$

$$H_{\varphi 0} = a_1 E_{r0} = \frac{q_0}{2a_2}\left[rI_{[0,a]}(r) + a^2 I_{(a,b)}(r)/r\right] \qquad (17)$$

where

$$I_{[x,y]}(r) = \begin{cases} 1, & x \le r \le y \\ 0, & otherwise \end{cases}.$$

As in [23, 24], the substitution of Fourier coefficients of the fields into the **Maxwell's equations** (5-6) are also carried out.

Fourier coefficients – Truncation at axial coordinate

$$i_m(z,r) = (q_0/2\pi)\int_{-\pi}^{\pi} \exp(-jmt(z,r,t_0))dt_0$$

Then the **non-homogeneous term** $i_m(z,r)$ is represented as a function of the axial **Fourier** components bounded by the interval [0,d]

$$i_m(z,r) = \sum_{n=-\infty}^{\infty} i_{mn}(r)\exp(-jnk_d z) \quad for \quad 0 \le z \le d \quad (18)$$

$$i_{m(-n)}(r) = i_{mn}(r)$$

$$i_{mn}(r) = \left(\frac{1}{d}\right)\int_0^d i_m(z,r)\cos nk_d z \ dz \qquad (19)$$

m^{th} harmonic of Field components – Homogeneous and Particular solutions

m^{th} harmonic of field component

Homogeneous solution

Particular solution(non homogeneous) due to axial truncation

$$\begin{aligned} E_{km}(z,r) &= \overbrace{E_{km}^{(h)}(z,r)} + \overbrace{E_{km}^{(p)}(z,r)} \\ H_{km}(z,r) &= \underbrace{H_{km}^{(h)}(z,r)} + \underbrace{H_{km}^{(p)}(z,r)} \end{aligned} \qquad (20)$$

Non-homogeneous solution of field components are re-expanded in Fourier series as,

➡ $$E_{zm}^{(p)}(z,r) = \sum_{n\in\mathbb{Z}} E_{zmn}(r)\exp(-jnk_d z)$$

Homogeneous solutions

Homogeneous solutions are obtained as,

$$
\begin{aligned}
E_{zm}^{(h)}(r) = {} & \delta_{1m}\frac{A}{2}W_m(r)\mathrm{exp}(-j\beta_m z) \\
& - \frac{j}{ma_1 d}W_m(r)\mathrm{cos}\beta_m z\int_0^d\int_0^a U_m(x,y)i_m(x,y)ydydx
\end{aligned}
$$

$$
\begin{aligned}
H_{zm}^{(h)}(r) = {} & \delta_{1m}\frac{-ja_2\mathrm{tan}\psi}{ma_1}\frac{A}{2}V_m(r)\mathrm{exp}(-j\beta_m z) \\
& - \frac{a_2\mathrm{tan}\psi}{m^2a_1^2 d}V_m(r)\mathrm{cos}\beta_m z\int_0^d\int_0^a U_m(x,y)i_m(x,y)ydydx
\end{aligned}
$$

$$E_{\varphi m}^{(h)}(z,r) = \frac{-jma_1}{a_2\tau_m^2(r)}H_{zm_r}^{(h)}(z,r)$$

$$H_{\varphi m}^{(h)}(z,r) = \frac{jma_1\kappa(r)}{a_2\tau_m^2(r)}E_{zm_r}^{(h)}(z,r)$$

$$E_{rm}^{(h)}(z,r) = \frac{j}{ma_1^2\kappa(r)}H_{\varphi m_z}^{(h)}(z,r)$$

$$H_{rm}^{(h)}(z,r) = \frac{-j}{ma_1}E_{\varphi m_z}^{(h)}(z,r) \qquad \text{for} \quad 0\le r<b, \quad 0\le z\le d$$

Axial electric field – Particular solution

The **particular solution** of the **axial electric field** is given as,

$$E_{zm}^{(p)}(z,r) = \sum_{n\in\mathbb{Z}} E_{zmn}(r)\exp(-jnk_d z)$$

$$E_{zmn}(r) = \begin{cases} (j/(ma_1 d))\int_0^d\int_0^a G_{mn}(r,y)i_m(x,y)(\cos(nk_d x)ydydx & \text{if} \quad \tau_{mn}^2(r)\neq 0 \\ 0 & \text{if} \quad \tau_{mn}^2(r)=0 \end{cases} \tag{26}$$

$$G_{mn}(r,y) = \begin{cases} \frac{\tau_{mn}^2}{p_{mn}}C_0(p_{mn}r)\{[(\chi_a^- I_{[0,a]}(r) + (\frac{\chi_{a1}-\chi_a^-}{W_{a\bar{a}}})[(\Delta_g - \frac{D_1(p_{mn})}{C_1(p_{mn})}\frac{1-\Delta_{D1000}}{1-\Delta_{C1000}})I_{[0,1](r)} + \bar{W}_0(r)])\times & \\ (\chi_0-\chi_{(-1)}) - \chi_r^-(I_{[0,a]}(r)\chi_0 + I_{[0,r\wedge a]}(r)\chi_{(-1)})]\frac{\chi_{y1}C_1(p_{mn}y)}{y\chi_y^2 C_0^2(p_{mn}y)} + & \\ \frac{(\Delta_g - \frac{D_1(p_{mn})}{C_1(p_{mn})}\frac{1-\Delta_{D1000}}{1-\Delta_{C1000}})I_{[0,1](r)}+\bar{W}_0(r)}{a\chi_a^- C_0(p_{mn}a)C_1(p_{mn}a)W_{a\bar{a}}}\chi_{(-1)}\chi_y C_0(p_{mn}y)\} & \text{for} \quad 0\leq r<1 \\ \frac{\tau_{mn}^2}{p_{mn}}\frac{\Lambda_{mn00}(r)}{\Delta_{mn00}}[(\Delta_g - \frac{D_1(p_{mn})}{C_1(p_{mn})}\frac{1-\Delta_{D1000}}{1-\Delta_{C1000}})C_0(p_{mn}) + D_0(p_{mn})]\times & \\ [\frac{1}{W_{a\bar{a}}}]\{(\chi_0-\chi_{(-1)})(\chi_{a1}-\chi_a^-)(\frac{\chi_{y1}C_1(p_{mn}y)}{y\chi_y^2C_0^2(p_{mn}y)}) + \frac{\chi_{(-1)}\chi_y C_0(p_{mn}y)}{a\chi_a^- C_0(p_{mn}a)C_1(p_{mn}a)}\} & \text{for} \quad 1<r<b \end{cases} \tag{27}$$

$$V_{mn}(r) = \begin{cases} \tau_{mn}^2 C_0(p_{mn}r)/p_{mn}C_1(p_{mn}r) & \text{for} \quad 0\leq r<1 \\ \tau_{mn}^{+2}\Lambda_{mn01}(r)/p_{mn}^{+}\Delta_{mn11} & \text{for} \quad 1<r<b \end{cases} \tag{28}$$

Particular solutions

The Fourier coefficients with respect to the axial co-ordinate yields the terms in respective **particular solutions** as

$$E_{zmn}(r) = \begin{cases} (j/(ma_1 d)) \int_0^d \int_0^a G_{mn}(r,y) i_m(x,y)(\cos(nk_d x) y dy dx & \text{if} \quad \tau_{mn}^2(r) \neq 0 \\ 0 & \text{if} \quad \tau_{mn}^2(r) = 0 \end{cases}$$

$$H_{zmn}(r) = \begin{cases} a_2 tan(\psi)/(m^2 a_1^2 d)\Omega_g \int_0^d \int_0^a V_{mn}(r) C_0(p_{mn} y) i_m(x,y) \cos(nk_d x) y dy dx & \tau_{mn}^2(r) \neq 0 \\ 0 & \tau_{mn}^2(r) = 0 \end{cases}$$

$$E_{\varphi mn}(r) = (-jma_1/a_2 \tau_{mn}^2(r)) H_{zmn_r} \quad \text{for} \quad 0 \leq r < b$$

$$H_{\varphi mn}(r) = \begin{cases} (jma_1 \kappa(r)/(a_2 \tau_{mn}^2(r))) E_{zmn_r}(r) & \text{if} \quad \tau_{mn}^2(r) \neq 0 \\ (1/a_2 dr) \int_0^d \int_0^{r \wedge a} i_m(x,y) cos(nk_d z) y dy dx & \text{if} \quad \tau_{mn}^2 = 0 \\ 0 & \text{if} \quad \tau_{mn}^{+2} = 0 \end{cases} \qquad \text{for} \quad 0 \leq r < b$$

$$H_{rmn}(r) = (-nk_d/ma_1) * E_{\varphi mn}(r) \quad \text{for} \quad 0 \leq r < b$$

$$E_{rmn}(r) = \begin{cases} (nk_d/ma_1 \kappa(r)) H_{\varphi mn}(r) & \text{if} \quad \tau_{mn}^2 \neq 0 \\ (nk_d/ma_1) H_{\varphi mn}(r) & \text{if} \quad \tau_{mn}^2 = 0 \end{cases} \qquad \text{for} \quad 0 \leq r < b$$

Terms in the axial electric field

$$\Delta_g = \frac{\mathrm{D}_0(p_{mn}) * g(\phi, z)}{C_0(p_{mn}) + \Delta C_1(p_{mn})} * \left[\frac{C_0(p_{mn}) D_1(p_{mn})(1 - \Delta_{D1000})}{D_0(p_{mn}) C_1(p_{mn})(1 - \Delta_{C1000})} - 1\right] (29a)$$

$$\Delta = \left(\frac{m a_1 \cot\psi}{a_2}\right)^2 \frac{\Delta_{mn11}}{\tau_{mn} \tau_{mn}^{+} \Delta_{mn01}} \qquad (29b)$$

$$W_{a\bar{a}} = \frac{D_0(p_{mn} a)}{C_0(p_{mn} a)} - \frac{D_1(p_{mn} a)}{C_1(p_{mn} a)} \qquad (29c)$$

$$\Delta_{C1000} = \frac{p_{mn} C_0(p_{mn}) \Delta_{mn10}}{p_{mn}^{+} C_1(p_{mn}) \Delta_{mn00}} \qquad (30a)$$

$$\Delta_{D1000} = \frac{p_{mn} D_0(p_{mn}) \Delta_{mn10}}{p_{mn}^{+} D_1(p_{mn}) \Delta_{mn00}} \qquad (30b)$$

$$\Delta_{mn00} = C_0(p_{mn}^{+}) D_0(p_{mn}^{+} b) - C_0(p_{mn}^{+} b) D_0(p_{mn}^{+}) \qquad (31a)$$

$$\Delta_{mn01} = C_0(p_{mn}^{+}) D_1(p_{mn}^{+} b) - C_1(p_{mn}^{+} b) D_0(p_{mn}^{+}) \qquad (31b)$$

$$\Delta_{mn10} = C_1(p_{mn}^{+}) D_0(p_{mn}^{+} b) - C_0(p_{mn}^{+} b) D_1(p_{mn}^{+}) \qquad (31c)$$

$$\Delta_{mn11} = C_1(p_{mn}^{+}) D_1(p_{mn}^{+} b) - C_1(p_{mn}^{+} b) D_1(p_{mn}^{+}) \qquad (31d)$$

$$\Lambda_{mn00}(r) = C_0(p_{mn}^{+} r) D_0(p_{mn}^{+} b) - C_0(p_{mn}^{+} b) D_0(p_{mn}^{+} r) \quad (32)$$

Terms in the axial electric field contd..

$$\Delta_{m00} = C_0(p_m^+)D_0(p_m^+b) - C_0(p_m^+b)D_0(p_m^+) \qquad (33)$$

$$\Lambda_{m00}(r) = C_0(p_m^+r)D_0(p_m^+b) - C_0(p_m^+b)D_0(p_m^+r) \qquad (34)$$

$$\overline{W_0}(r) = \frac{D_0(p_{mn}a)}{C_0(p_{mn}a)} I_{[0,a)}(r) + \frac{D_0(p_{mn}r)}{C_0(p_{mn}r)} I_{[a,1]}(r) \qquad (35)$$

where, C_x and D_x are common symbols for the Bessel's functions and modified Bessel's functions for first kind and second kind

$$C_x(p_{mn}r) = \begin{cases} I_{m+x}(p_{mn}r) & \text{if} \quad \tau_{mn}^2 > 0 \\ J_{m+x}(p_{mn}r) & \text{if} \quad \tau_{mn}^2 < 0 \end{cases} \qquad (36a)$$

$$D_x(p_{mn}r) = \begin{cases} K_{m+x}(p_{mn}r) & \text{if} \quad \tau_{mn}^2 > 0 \\ (-1)^{m+x+1}(\pi/2)Y_{m+x}(p_{mn}r) & \text{if} \quad \tau_{mn}^2 < 0 \end{cases} \qquad (36b)$$

Variable	$\tau_{mn}^2 > 0$	$\tau_{mn}^2 < 0$	Variable	$\tau_{mn}^2 > 0$	$\tau_{mn}^2 < 0$
χ_r^-	-1	$\frac{D_0(p_{mn}r)}{C_0(p_{mn}r)}$	χ_0	1	0
χ_r	1	$\frac{D_0(p_{mn}r)}{C_0(p_{mn}r)}$	$\chi_{(-1)}$	1	-1
χ_{r1}	1	$\frac{D_1(p_{mn}r)}{C_1(p_{mn}r)}$			

Transverse mode number τ_m

$$p_{mn}^2 = |\tau_{mn}^2| \text{ and } p_{mn}^{+^2} = \left|\tau_{mn}^{+^2}\right| \qquad (37a)$$

$$p_m^2 = |\tau_m^2| \text{ and } p_m^{+^2} = \left|\tau_m^{+^2}\right| \qquad (37b)$$

$$\tau_{mn}^2(r) = [n^2k_d^2 - m^2a_1^2\kappa(r)]/a_2^2 = \begin{cases}\tau_{mn}^2, & 0 \le r < 1\\ \tau_{mn}^{+^2}, & 1 < r < b\end{cases} \qquad (38)$$

$$\tau_m^2(r) = [\beta_m^2 - \kappa(r)m^2a_1^2]/a_2^2 = \begin{cases}\tau_m^2, & 0 \le r < 1\\ \tau_m^{+^2}, & 1 < r < b\end{cases} \qquad (39)$$

where $\boldsymbol{\beta_m}(> 0)$ is the **phase shift constants** for the harmonic radian frequencies $m\omega_0$ derived from the cold wave analysis of dielectric supported anisotropically conducting tape helix structure [41,42].

Axial Electric field: complete solution (in terms of electron arrival time)

$$\mathcal{E}_z(z,r,t) = \sum_{m=1}^{\infty} E_{zm}(z,r)\exp(jmt) + c.c. \quad (40)$$

$$= \delta_{1m} W_1(r)\left[\frac{A}{2}\exp\big(j(t-\beta_1 z)\big) + c.c.\right] \quad (41)$$

$$+ \frac{jq_0}{2\pi a_1 d}\sum_{m=1}^{\infty}\frac{1}{m}e^{jmt}\int_0^d dx\int_0^a G_m(z,r;x,y)y\,dy\int_{-\pi}^{\pi}e^{-jmt(x,y,\tau)}d\tau + c.c.$$

where the **partial Green's function sequence G_m** is given as

$$\boxed{G_m(z,r;x,y) = \sum_{n\in\mathbb{Z}}[G_{mn}(r,y)\exp(-jnk_d z)\cos nk_d x] - W_m(r)\cos\beta_m z U_m(x,y)} \quad (42)$$

Electron Arrival time and Transit time

On re-arranging and integrating the electron ballistic expression (7), the electron arrival time $t(z,r,t_0)$ at any (z,r) co-ordinate in the interaction region is obtained as (43)

$$\begin{aligned} &\boxed{\underline{t(z,r,t_0)} = t_0 + \int_0^z \frac{ds}{\{1-2\varepsilon \int_0^s \boldsymbol{\mathcal{E}}_z(x,r,\underline{t(x,r,t_0)})dx\}^{1/2}}} \\ &\triangleq t_0 + \theta(z,r,t_0) \qquad \text{for} \quad 0 \le r \le a \quad \text{and} \quad 0 \le z \le d \end{aligned} \tag{43}$$

The electron transit time $\theta(z,r,t_0)$ is the time taken for an electron to reach (z,r) when it has originated the entrance plane with an entrance time, t_0.

$$\boxed{\theta(z,r,t_0) = t(z,r,t_0) - t_0} \tag{44}$$

Numerical computation

The Fourier series expansions of the axial electric field in (40) is truncated to **third temporal harmonic** $(1 \leq m \leq M = 5)$ and **64th spacial harmonic**$(|n| \leq N = 64)$.

Independent Parameter	Notation	Numeric Value
Operating Frequency	$f_0 = \omega_0/2\pi$	6GHz
Input-signal phase factor	$A = e^{j\theta}$	1
Tape-helix pitch angle	ψ	10°
Tape-helix radius	$\bar{a}$	0.01 m
Outer-conductor radius	$\bar{b}$	0.0224 m
Effective dielectric constant of support rods	ε_{eff}	2.25
Electron Beam current	$\bar{I}_0$	$60mA$
Electron beam radius	$\bar{a}_0$	0.005 m
Interaction region length	d	120
Parameter, α	α	-20dB

Numerical computation contd..

- The electron beam velocity required to generate the respective anode potential is maintained slightly above the cold-wave velocity v_p, obtained from the dispersion characteristics plot[14, 15].
- With $\boldsymbol{v_p = 0.13579 * c}$ where c is the velocity of light, the electron beam velocity at the entrance plane is chosen slightly greater than v_p as $\boldsymbol{v_0 = 0.1358 * c}$.
- The **normalized propagation phase constants** from the dispersion plot of anisotropically conducting tape-helix supported by dielectric rods [13, 14] are $\beta_1 = 1$, $\beta_2 = 1.6127$, $\beta_3 = 2.2257, \beta_4 = 2.8383$ and $\beta_5 = 3.451$.
- On solving the electron arrival time (43) by **successive approximation technique,** the electron arrival time at the end of interaction length (d) is plotted.

Electron transit time demonstration

The media below displays an example of **electrons entering** at entrance plane $z = 0$ with **different entrance times**, take **different transit times** to reach the exit plane $z = d$.

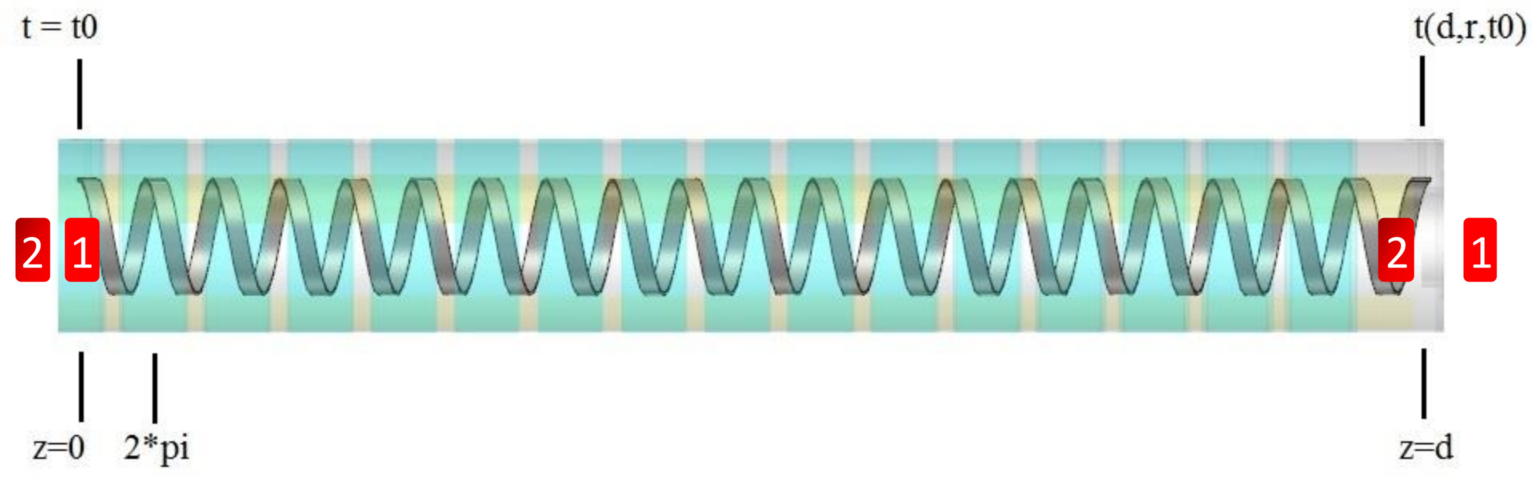


Fig. 28. The electrons arriving at different entrance times, travel at different velocities to reach the exit plane at different arrival times

Results: 1.1 Electron arrival time

Electron arrival time $\boldsymbol{t(d, r, t_0)}$, $\boldsymbol{\alpha = -20\mathrm{dB}}$ (d=120)

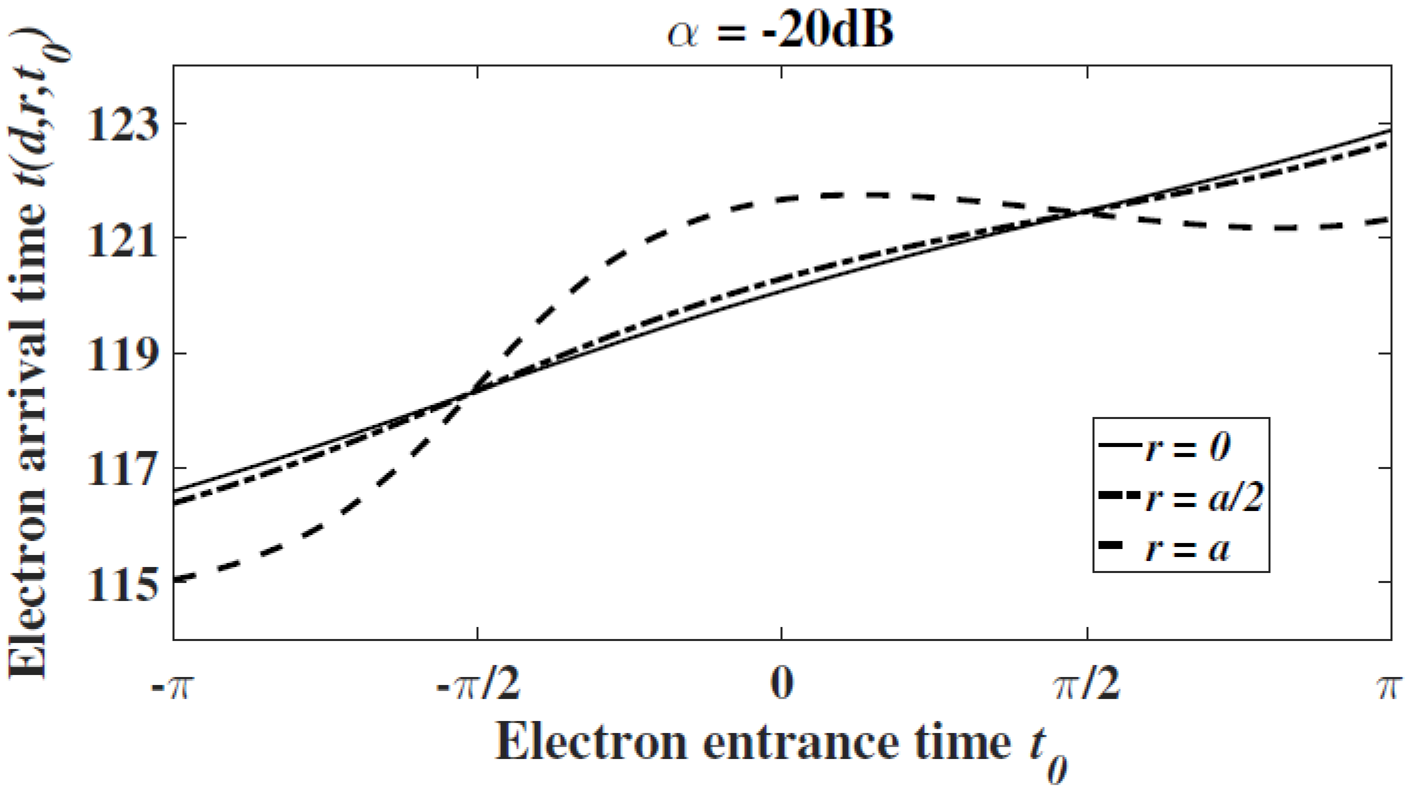


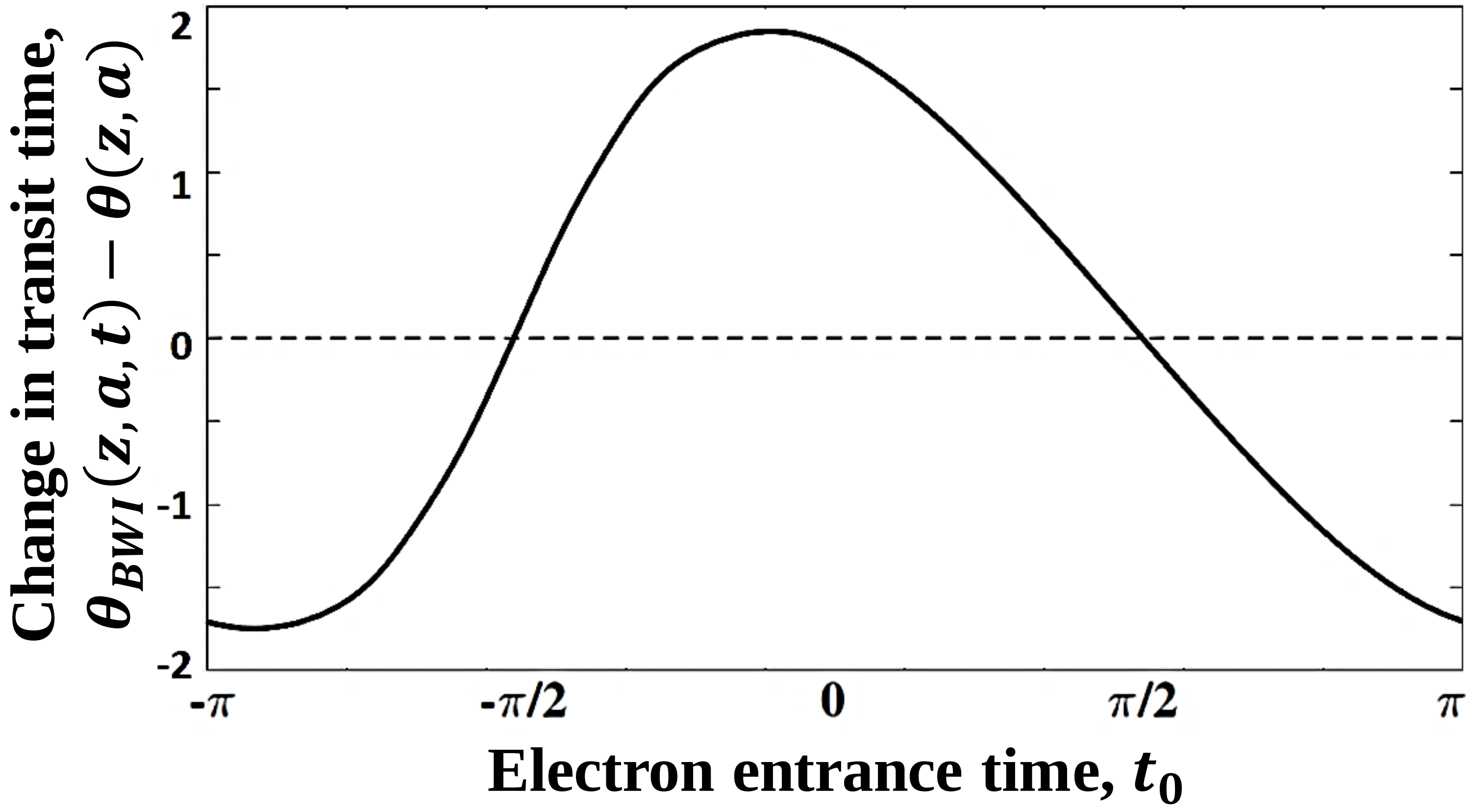
Fig. 29 Electron arrival time at the exit plane, plotted against electron entrance time for the electrons at **beam center** $(r = 0)$, **half way point**, $(r = a/2)$ and at the **edge of the electron beam** $(r = a)$ for $\alpha = -20\mathrm{dB}$

Results: 1.2 Electron arrival time contd..

Transit time with $\alpha = -20dB$

$\boldsymbol{\theta_{BWI}(z,a,t)}$: Transit time in BWI $\boldsymbol{\theta(z,a)}$**:** Transit time of linear beam

Numerically computed normalized transit time ($\boldsymbol{z = 0}$ to $\boldsymbol{d}$)



Results: 1.3 Electron arrival time contd..

Electron bunching with $\alpha = -20dB$

- Electron bunching along the interaction length is plotted below, for $\alpha = -20dB$.
- **Numerically computed electron arrival times**

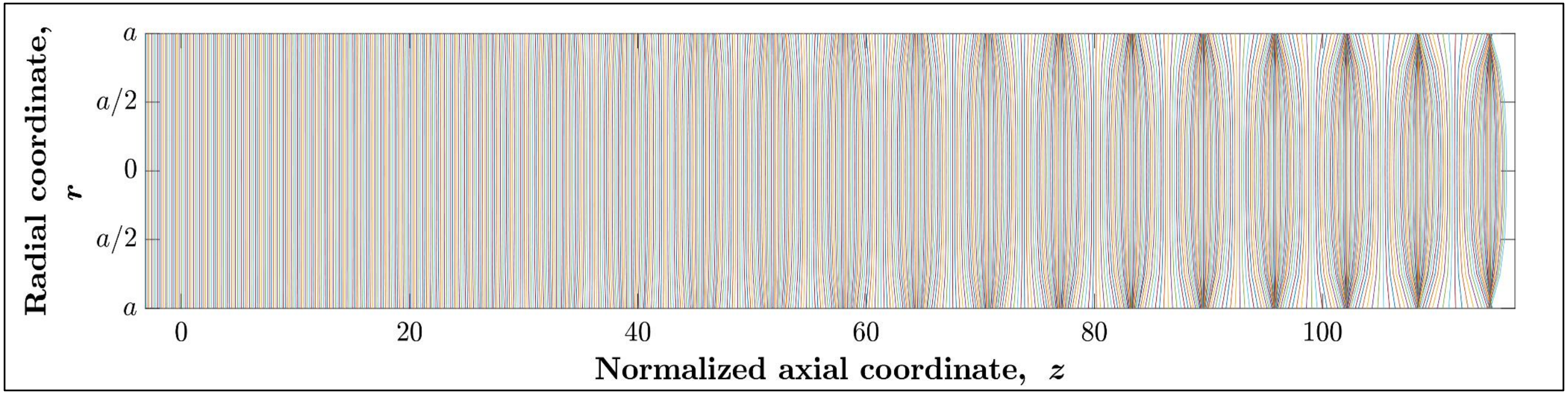


Fig. 30 Numerically computed Electron arrival time along z at various radial locations are plotted

Results: 1.4 Electron arrival time contd..

Electron arrival time $\mathbf{t(\boldsymbol{d},\boldsymbol{r},\boldsymbol{t_0})}$, $\boldsymbol{\alpha} = \mathbf{-25dB}$ (d=120)

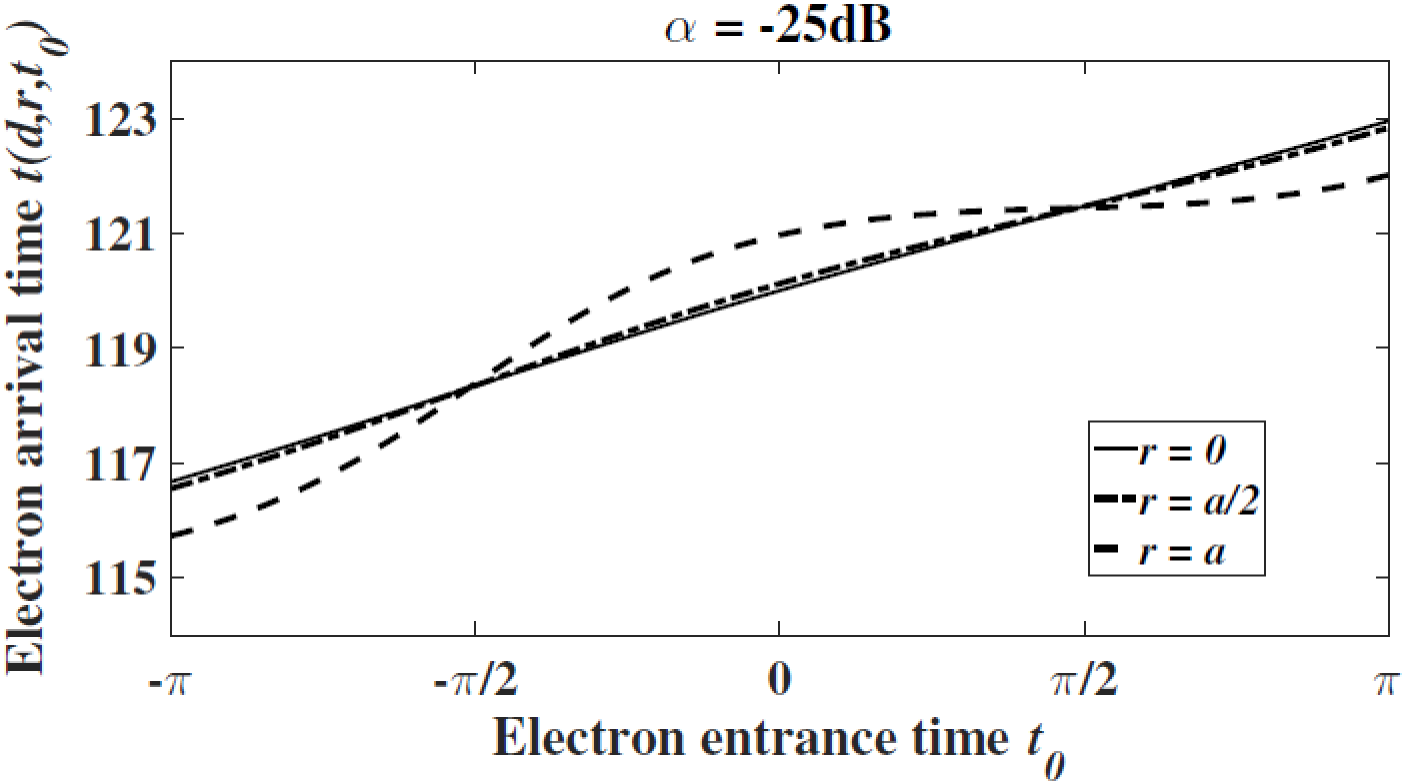


Fig. 31 Electron arrival time at the exit plane, plotted against electron entrance time for the electrons at the **beam center**$(r = 0)$, **half way point**, $(r = a/2)$ and at the **edge of the electron beam**$(r = a)$ for $\alpha = -25\text{dB}$

Results: 1.5 Electron arrival time contd..

Electron arrival time $\boldsymbol{t(d, a, t_0)}$: **vary $\boldsymbol{\alpha}$** $(d = 120)$

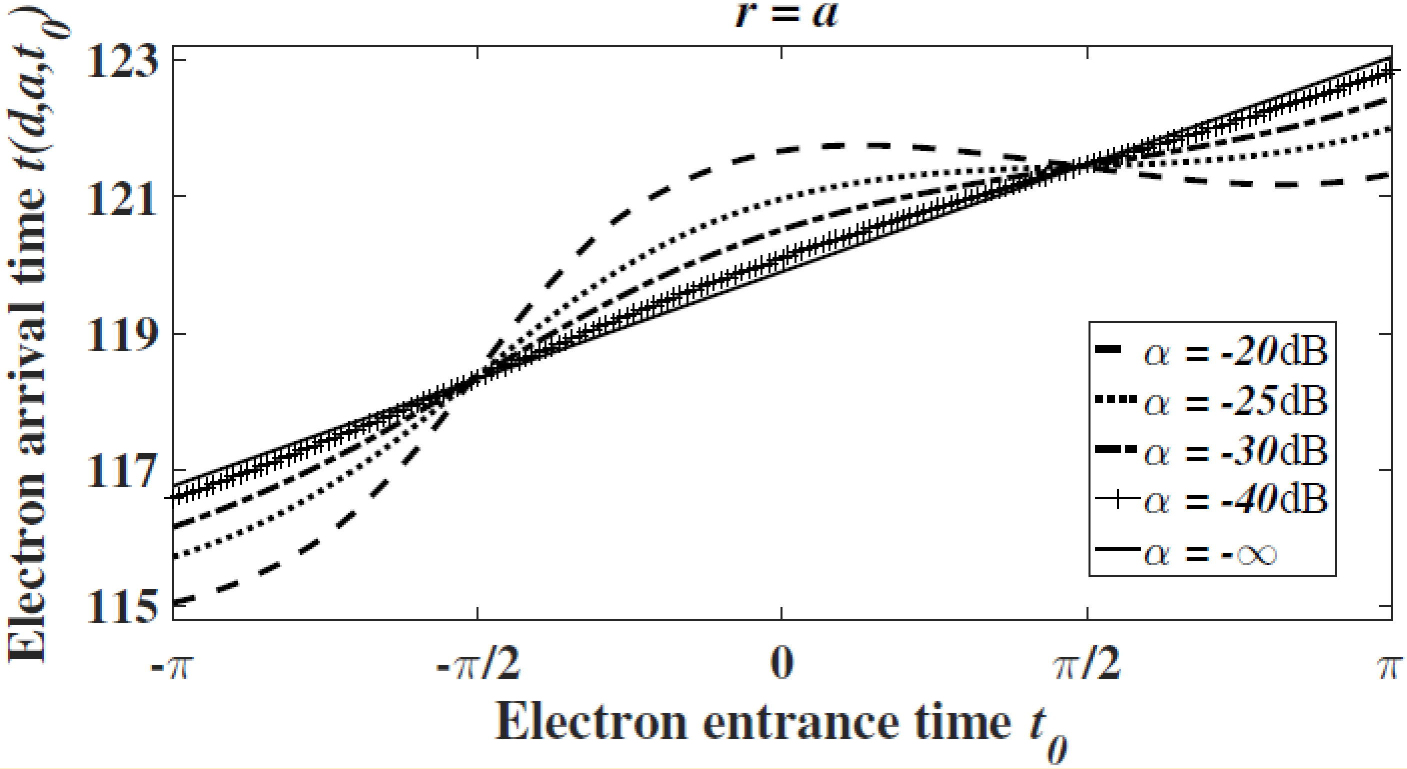


Fig. 32 Electron arrival time at the **outer edge of the electron beam $\boldsymbol{r = a}$**, at the exit plane, plotted against electron entrance time for the **different input powers** with $\alpha = -20dB,\ -25dB, -30dB,\ -40dB,\ -\infty$

Results: 2 Electron exit speed at $z = d$

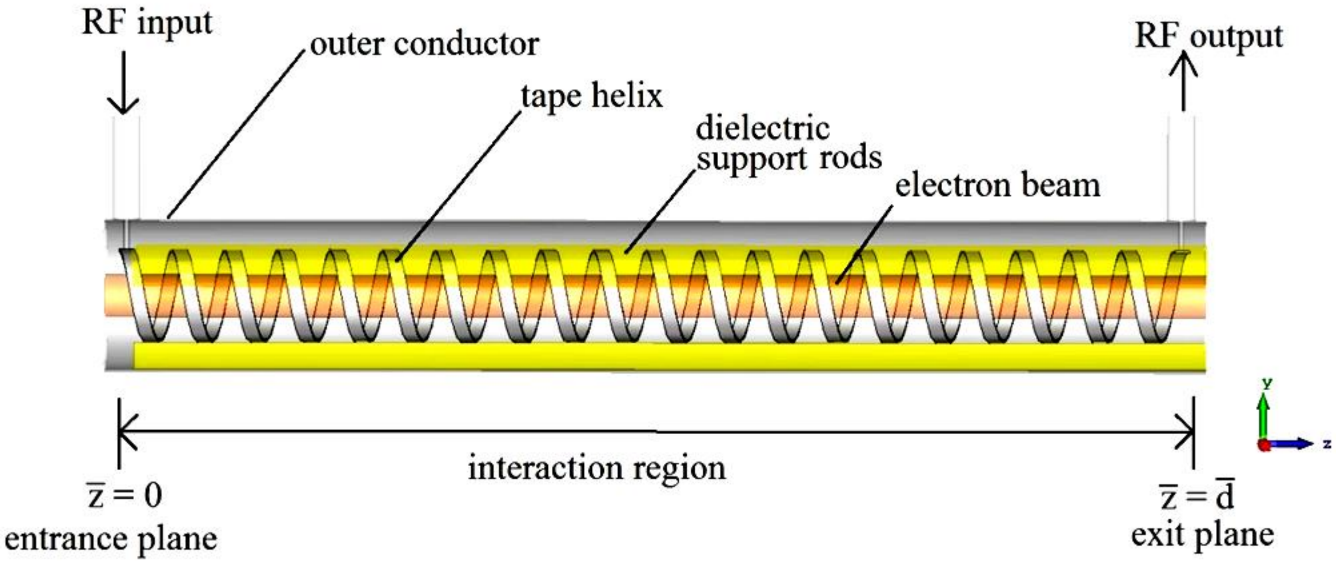


Fig. 33 Cross sectional view of the interaction region

$$v(d, r, t_0) = 1/t_z(d, r, t_0) = \{1 - 2\varepsilon \int_0^d \mathcal{E}_z(s, r, t(s, r, t_0))ds\}^{1/2}$$

Results: 2.1 Electron exit velocity

Electron exit speed $\boldsymbol{v_d(d, r, t_0)}$, $\boldsymbol{\alpha = -20\mathrm{dB}}$ **(d=120)**

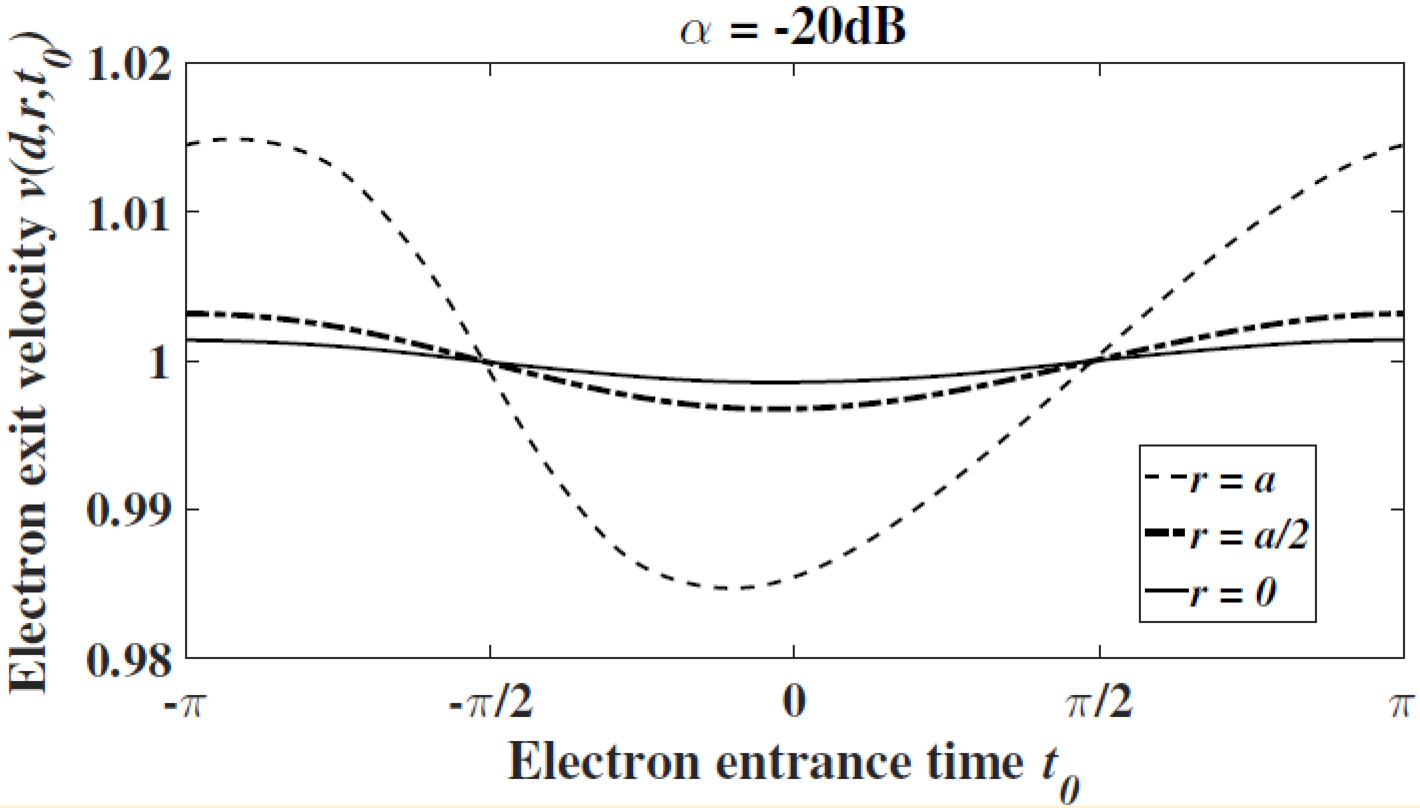


Fig. 34 Electron exit speed at the exit plane, plotted against electron entrance time for the electrons at the **beam center**$(r = 0)$, **half way point**, $(r = a/2)$ and at the **edge of the electron beam**$(r = a)$ for $\alpha = -20\mathrm{dB}$

Results: 2.3 Electron exit speed contd..

Electron exit speed $\mathbf{v_d}(d, a, t_0)$: **vary α** (d=120)

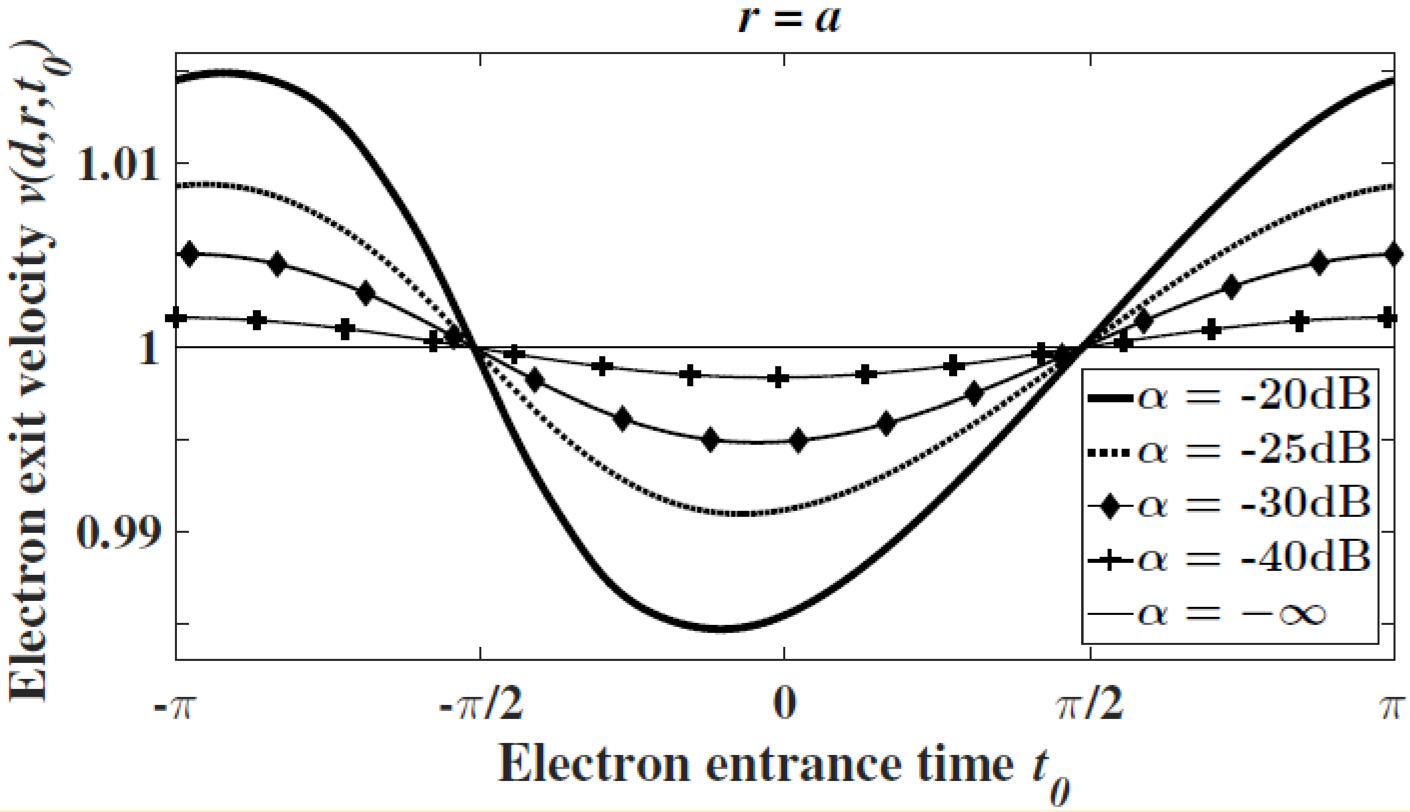


Fig. 36 Electron exit speed at **the outer edge of the electron beam** $r = a$, at the **exit plane**, plotted against electron entrance time for the **different input powers** with $\alpha = -20dB,\ -25dB, -30dB, -40dB, -\infty$

Results: 3.2 Axial electric field contd..

Electric field $E_z(z, r, t_0)$ at $r = 0$

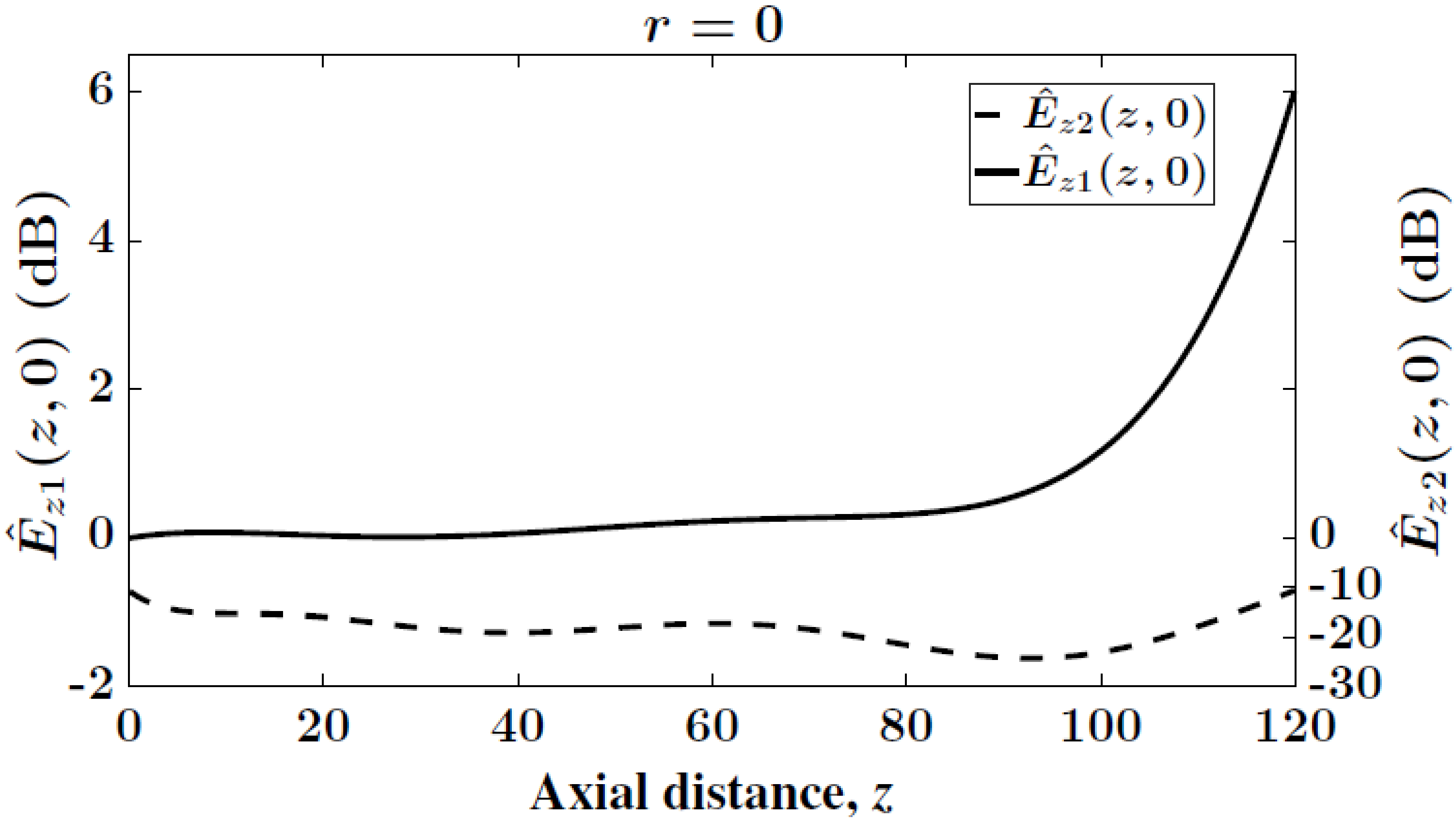


Fig. 38 The fundamental and the second harmonic of the axial electric fields computed at the **center of the electron beam** ($r = 0$) are plotted against the axial distance for $\alpha = -20dB$

Results: 3.3 Axial electric field contd..

Electric field $\mathbf{E_z}(z, r, t_0)$ at $r = 1$ (tape helix)

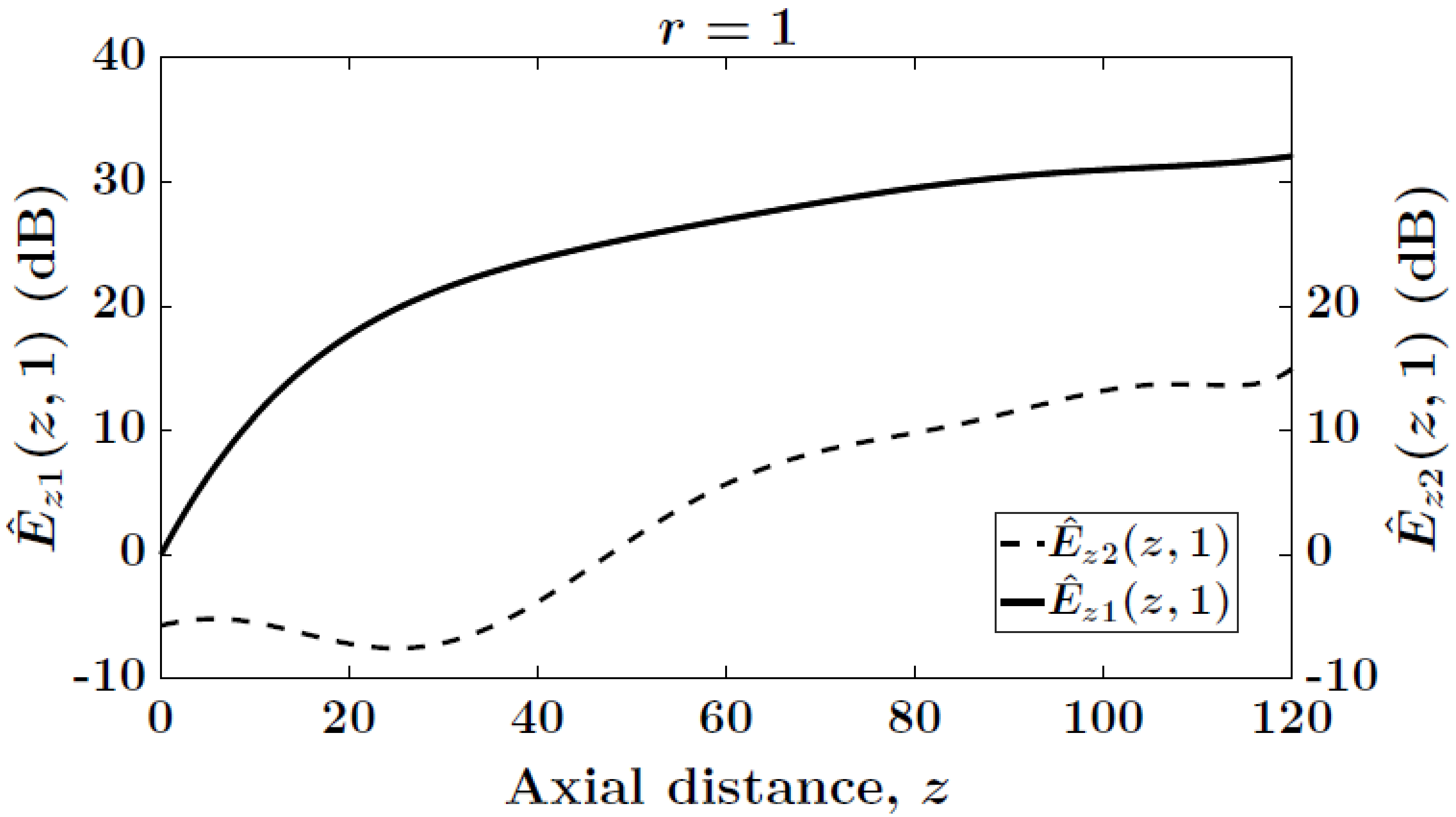


Fig. 39 The fundamental and the second harmonic of the axial electric fields computed at the **tape helix radius** $(r = 1)$ are plotted against the axial distance for $\alpha = -20dB$

Parallel component of the current density

From **the boundary conditions of the anisotropically conducting tape helix**, the discontinuity in the tangential magnetic field equals the surface current density on the tape surface:

$$J_{\phi}(z) = H_z(z, 1-) - H_z(z, 1+)$$

$$-J_z(z) = H_{\phi}(z, 1-) - H_{\phi}(z, 1+)$$

Hence the **normalized parallel component of the current density** is given as

$$J_{\parallel}(z) = \frac{[H_z(z,1-) - H_z(z,1+)]\cos\psi - \left[H_{\varphi}(z,1-) - H_{\varphi}(z,1+)\right]\sin\psi}{[H_z(0,1-) - H_z(0,1+)]\cos\psi - \left[H_{\varphi}(0,1-) - H_{\varphi}(0,1+)\right]\sin\psi}$$

Result: 4. Parallel component of the current density

Tape surface current density $J_{s1}(z, 1)$ at $r = 1$ (tape helix)

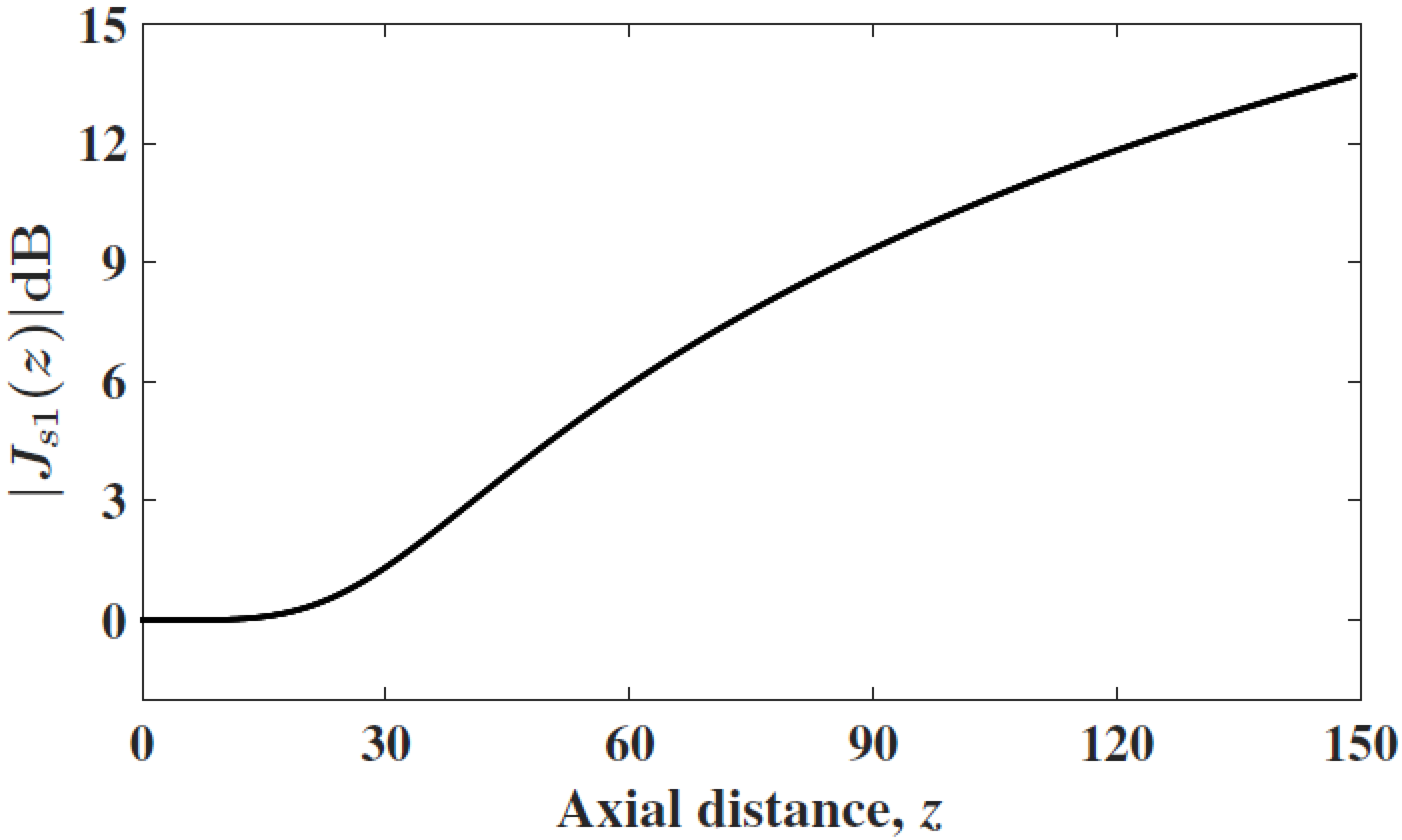


Fig. 40 The fundamental harmonic of the tape surface current density computed at the tape helix radius $(r = 1)$ is plotted against the axial distance for $\alpha = -20dB$

Result: 4. Parallel component of the current density

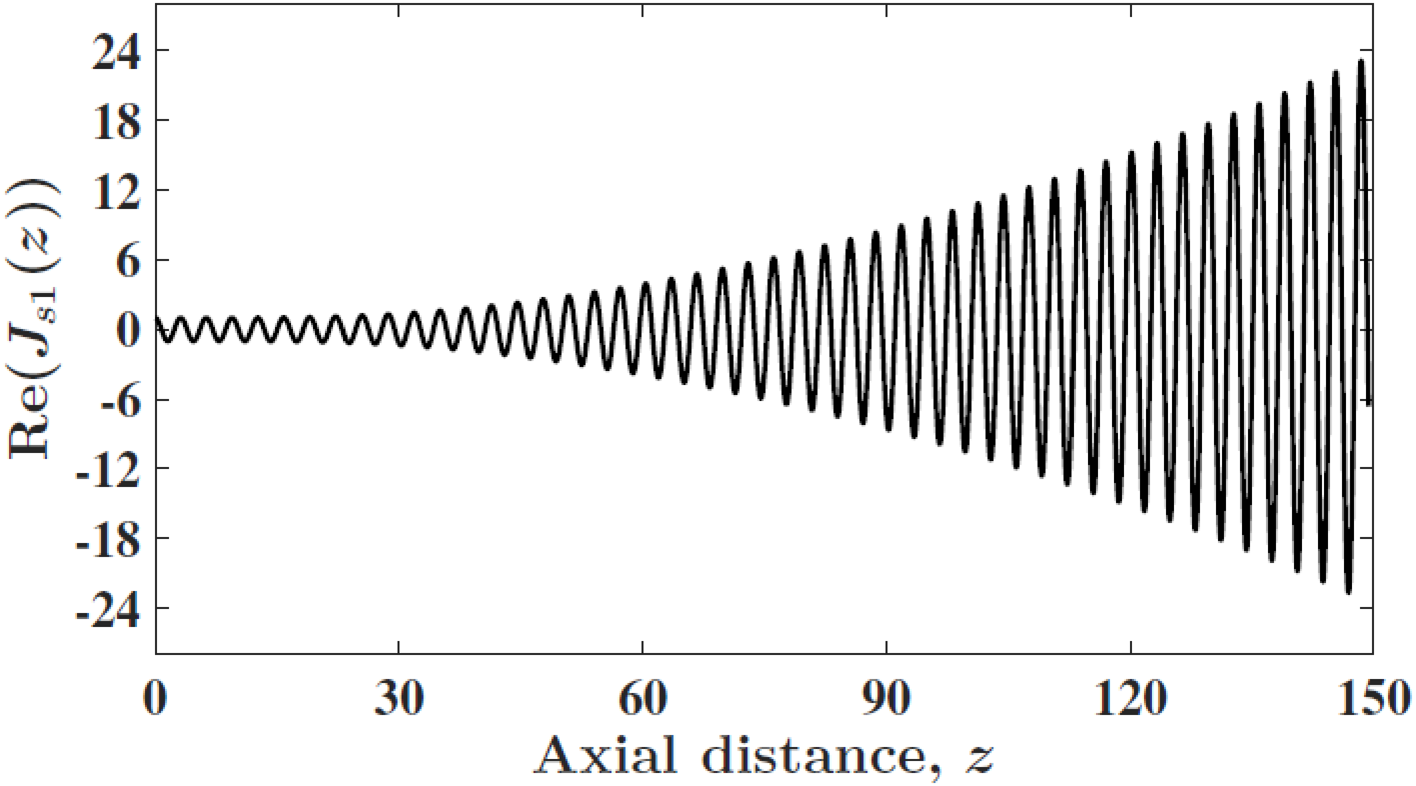


Fig. 41 Real part of the tape surface current density

Power gain

Normalized power of the frequency component of axial mode m

$$P_m = -Re \int^{d}\int^{a} E_{zm}(z,r) i_m^*(z,r)\, r dr\, dz$$

$$\begin{aligned} P_m = {} & -\delta_{1m}\frac{q_0}{2\pi d}\frac{A}{2}\frac{1}{\beta_1 - nk_d}\sum_{n=0}^{\infty}(2-\delta_{n0})\{\lambda_{cmn}\sin\beta_1 d + \lambda_{smn}(1-\cos\beta_1 d)\} \\ & - \left(\frac{q_0}{2\pi d}\right)^2 \frac{\beta_m \sin\beta_m d}{m a_1}\left[\sum_{n=0}^{\infty}(2-\delta_{n0})\mu_{smn}(1)\sum_{n=0}^{\infty}(2-\delta_{n0})\lambda_{cmn}/(\beta_m^2 - n^2k_d^2)\right. \\ & \left. + \sum_{n=0}^{\infty}(2-\delta_{n0})\mu_{cmn}(1)\sum_{n=0}^{\infty}(2-\delta_{n0})\lambda_{smn}/(\beta_m^2 - n^2k_d^2)\right] \end{aligned}$$

$$\lambda_{imn} = \int_0^a W_m(r) f_{imn}(r) r dr \quad \text{for} \quad i = s, c$$

$$\mu_{imn}(1) = \int_0^a G_{mn}(1,y) f_{imn}(y) y dy \quad \text{for} \quad i = s, c$$

Gain in the fundamental component

$$g_1 = \frac{P_{out}}{P_{in}} = \frac{4\pi\bar{a}^2 A_0^2 Y_0 P_m + P_{in}}{P_{in}} = \frac{4\pi\bar{a}^2 A_0^2 Y_0 P_m}{P_{in}} + 1 = \frac{4P_1}{P_{11}} + 1$$

Result: 5.1 Gain, g_1(dB)

Power gain G_1 plotted against axial distance d ($\alpha = -20dB$)

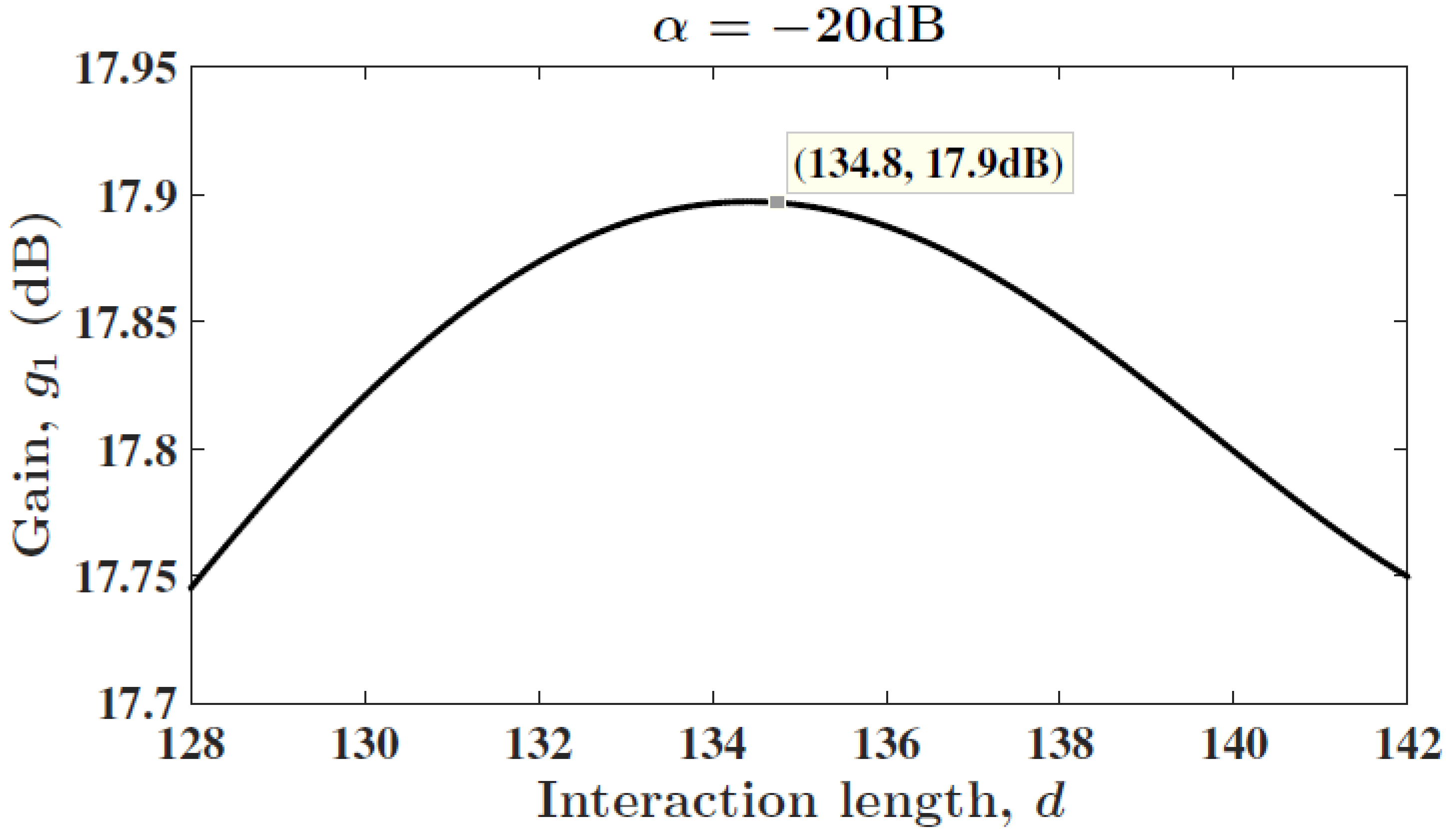


Fig. 42 The power gained with respect to the power at the entrance plane, plotted against the interaction length, d for $\boldsymbol{\alpha = -20dB}$ (Input power 20dB below the dc power)

Result: 5.3 Gain, g_1(dB) contd..

Power gain G_1 plotted for various α, ($d_{optimum} = 134.8$)

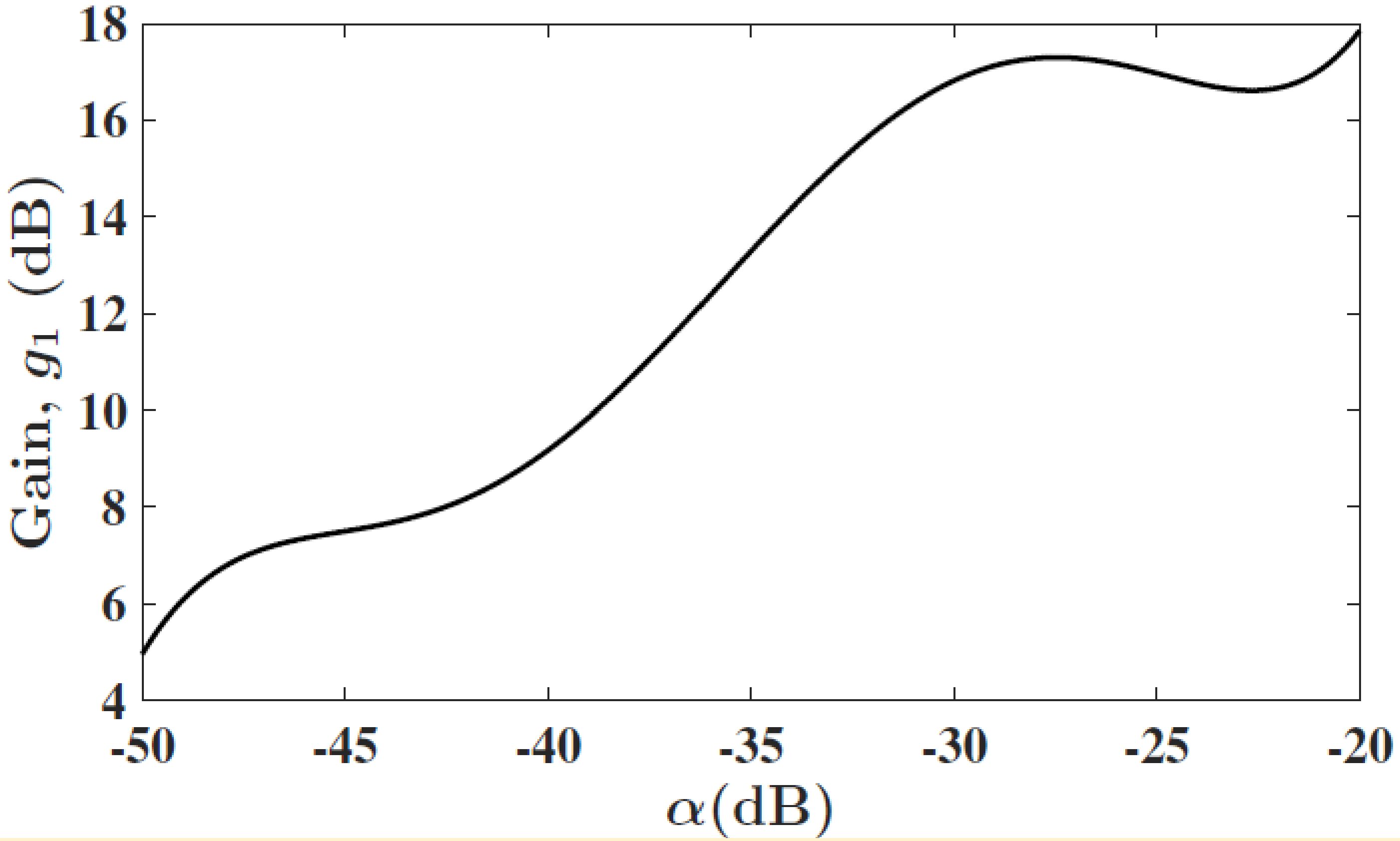


Fig. 44 The power gained with respect to the power at the entrance plane, plotted at $\boldsymbol{d = 134.8}$ for **different $\boldsymbol{\alpha}$ values**, for an input power level corresponding to $\alpha = -20dB$

Result: 5.3 Gain, g_1(dB) contd..

Power gain G_1 plotted for various f, ($d_{optimum} = 134.8$)

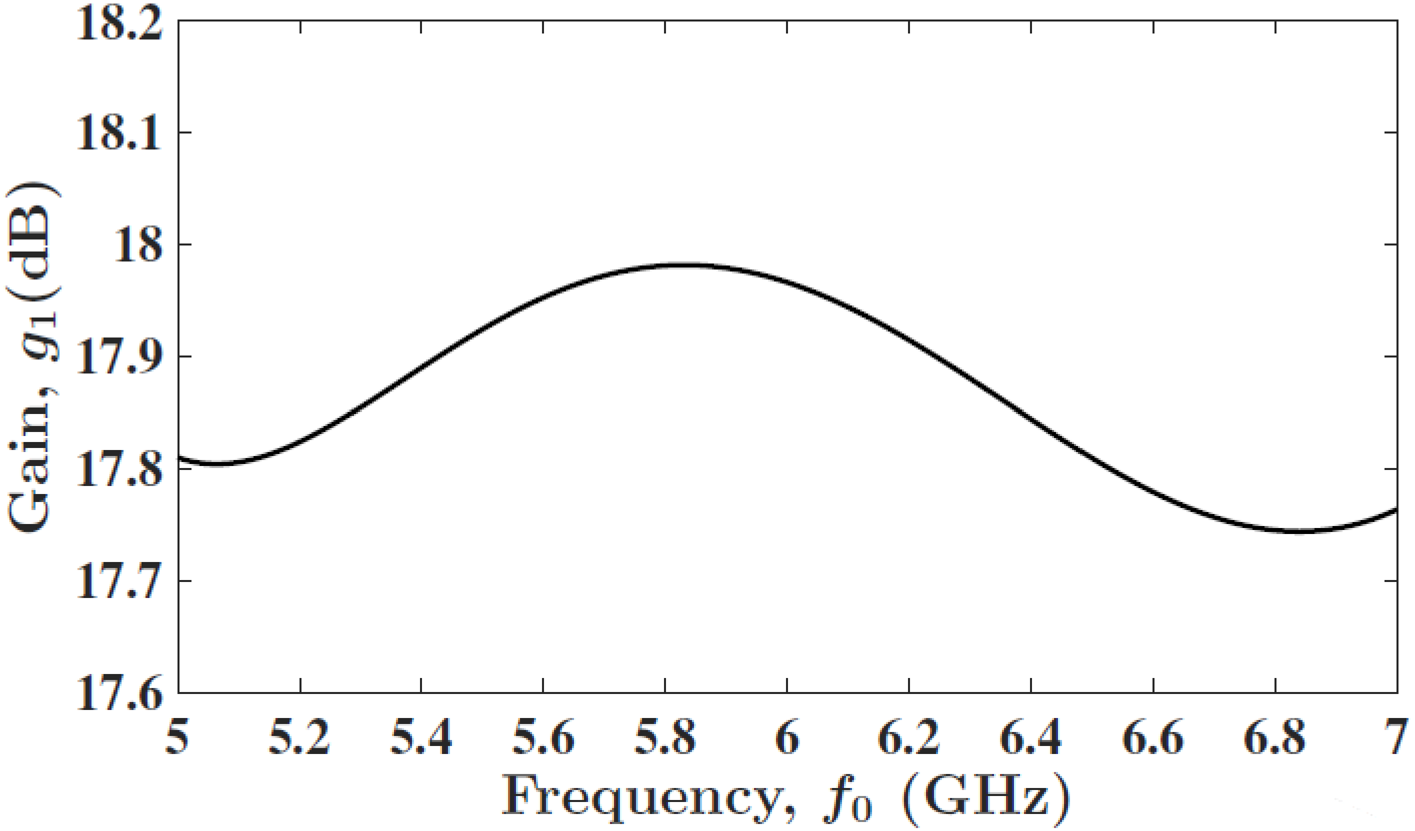


Fig. 45 The power gained with respect to the power at the entrance plane, plotted at $\boldsymbol{d = 134.8}$ for **different f values**, for an input power level corresponding to $\alpha = -20dB$

Result: 6.1 efficiency, $\eta_1(\%)$

Efficiency η_1 plotted against axial distance d ($\alpha = -20dB$)

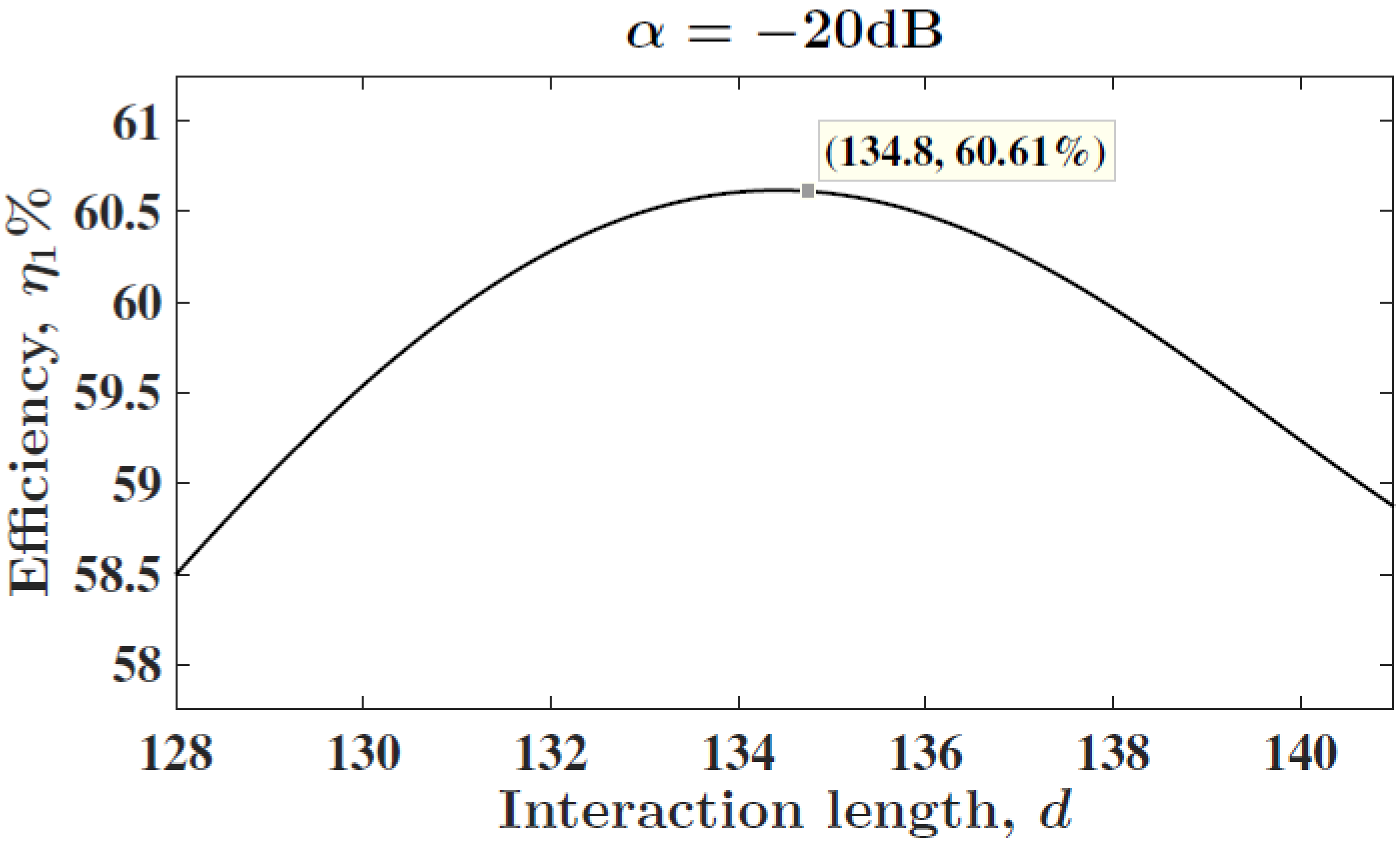


Fig. 46 Efficiency plotted against the interaction length, d for $\boldsymbol{\alpha = -20dB}$ (Input power 20dB below the dc power)

Result: 6.3 efficiency, $\eta_1(\%)$

Efficiency η_1 plotted for various α, ($d_{optimum} = 134.8$)

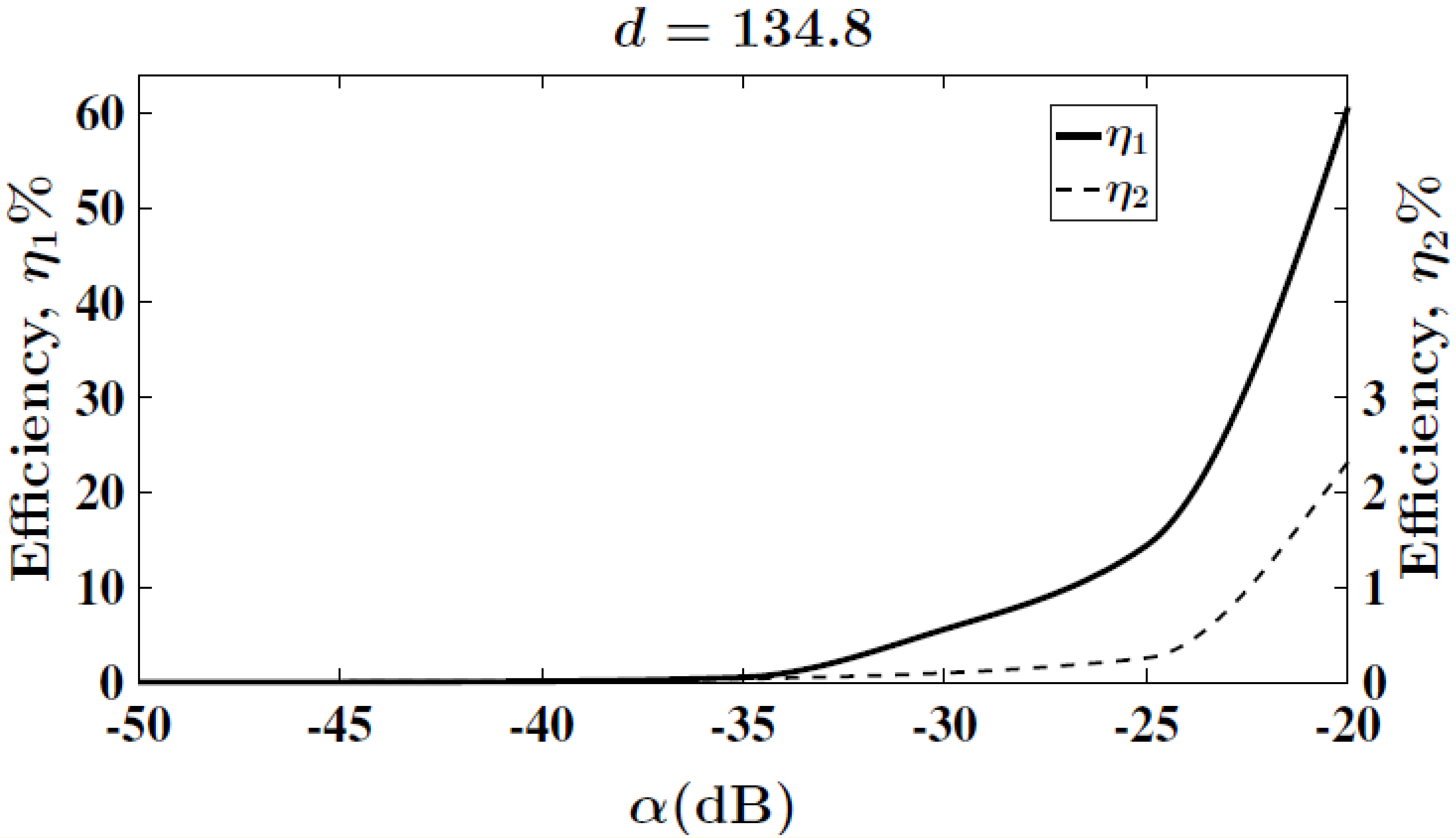


Fig. 44 The power gained with respect to the power at the entrance plane, plotted at $\boldsymbol{d = 134.8}$ for **different α values**, for an input power level corresponding to $\alpha = -20dB$

Conclusion

- The **saturation power gain** and the **conversion efficiency** from the presented large signal field analysis of tape helix SWS are admissible with the **other field theoretical models** [6, 75, 85, 90].

- The numerically computed results authenticate the **existence of an optimum interaction length** that depends on the linear beam TWT amplifier parameters and the input signal level as in the existing models [75, 85], and as observed in the **klystron amplifier** [20]. **Severe frequency distortions** due to the amplification of the **higher-order harmonics** are substantially **reduced on** operating the TWTA with **optimum interaction** length and maximum gain.

- The **fundamental harmonic** is large enough to evade any **significant performance** deterioration, though the space charge effect of the higher-order harmonics in the electron beam-wave interaction is observed to be slightly higher than the existing models. The model computed in this paper incorporated **additional temporal harmonics** for much accurate analysis when compared to the existing analyses [75,85]

- The computed gain vs frequency plot proposes the frequency response of the helix TWT operating at fixed input power level. The **optimum interaction length** (actual) is essentially opted for the **center frequency** f_c to be $\bar{d} = \frac{v_0 d_{opt}}{2\pi f_c}$ The broadband nature of the helix TWT is evidently seen from the frequency response plot computed for the SWS at the optimum interaction length

Future Work

❑ A much accurate, but numerically intense formulation may be performed with accurate **boundary conditions** at the exact surface of the rectangular cross sectional **dielectric support rods**.

❑ Future theoretical approaches may include the effects of **finite value of the focussing magnetic field** on the electron ballistics, the **thermal effects** on the dielectric support rods, and the theoretical modelling of the electron gun and the collector.

❑ 3D modeling of the **rectangular cross-sectional SWS** with sheet beam for Terahertz applications.

Publications (related to presentation)

Journals

1. Richards Joe Stanislaus and Gnanamoorthi Naveen Babu, "Large signal field analysis of linear beam traveling wave tube amplifier for anisotropically conducting tape helix slow wave structure supported by dielectric rods," ***Journal of Electromagnetic Waves and Applications****.* vol. 32, no. 4, pp. 439-470, 2018 (Published online: 31 Oct 2017). doi: 10.1080/09205071.2017.1394916.
2. G. Naveen Babu and Richards Joe Stanislaus, "Propagation of electromagnetic waves guided by perfectly conducting model of a tape helix supported by dielectric rods," in ***IET Microwaves, Antennas & Propagation***, vol. 10, no. 6, pp. 676-685, 4-24-2016. doi: 10.1049/iet-map.2015.0516 (Impact Factor: 1.187).
3. Richards Joe Stanislaus and Gnanamoorthi Naveen Babu, "Electron Transit-Time and Exit Velocity in Linear Beam Travelling Wave Amplifier for a Dielectric Rod Supported Tape-helix Slow Wave Structure," in ***e-FERMAT Communications 2*, ** vol. 21, May-Jun 2017. http://www.e-fermat.org/communication/stanislaus-comm-inae2016-2017-vol21-may-jun-002/ (ISSN: 2470-4202).

International Conferences

1. G. Naveen Babu, Richards Joe Stanislaus, "Full wave propagation characteristics of a tape helix structure placed around and within a cylindrical core", *12th International Conference on Microwaves, Antennas, Propagation and Remote Sensing(**ICMARS-2017**),* Jodhpur, February 2017. (**Best Presented Paper award**)
2. G. Naveen Babu, Richards Joe Stanislaus, "Fast wave propagation characteristics of dielectric loaded anisotropically conducting tape helix structures placed around and within a cylindrical conducting core", ***IEEE International Conference on Micro-Electronics and Telecommunication Engineering***, Ghaziabad, 22-23 September 2016.
3. G. Naveen Babu, Richards Joe Stanislaus and S. Joshi, "Wave propagation characteristics in anisotropically conducting dielectric loaded tape helix slow wave structures," ***Vacuum Electronics Conference, IEEE International***, Monterey, CA, US, pp.327,328, 22-24 April 2014 doi: 10.1109/IVEC.2014.6857622

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Prof BN Basu

Convener of Webinar 3

Members of VED community

Annexure IV:

Young Researcher's Talk-2 Slides

Recent Trends in Millimeter/THz Wave Vacuum Electron Beam Devices

Ph.D work carried out
at
Indian Institute of Technology (IIT) Roorkee
under the guidance of

Prof. M.V. Kartikeyan

by

Dr. S. Yuvaraj,
Assistant Professor,
Department of Electronics and Communication Engineering,
National Institute of Technology (NIT) Andhra Pradesh.

November 07, 2020

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- Traveling Wave Tube Amplifier
- Klystron Amplifier
- Backward Wave Oscillator
- Gyrotron Oscillator
- Motivation

2 Design studies of a 2 MW multi-frequency (220/251.5/283 GHz) coaxial cavity gyrotron

- Mode Selection & Interaction cavity design
- Feasibility Analysis
- Input System Design
- Output Coupling System Design
- Coaxial Insert Misalignment Studies

3 Conclusion and Future Scopes

Introduction

Introduction

Background

(A) Microwave tubes (Vacuum Electron Devices) dominate over solid state devices especially at high power applications.

(B) These tubes are widely used for RF heating in linear accelarators to nuclear fusion tokamaks.

(C) At millimeter and THz wave regime, they are competitive in offering power with greater reliability.

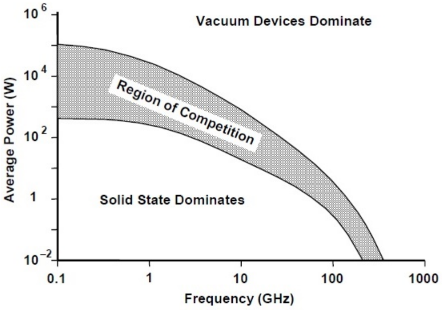

Figure: Comparison between Vacuum electron devices and solid state sources.

Traveling Wave Tube Amplifier

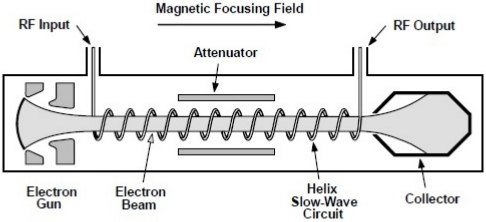

Figure: Schematic of TWT Amplifier.

State of the Art

- Satellite Communication
  - ❑ Q band TWT (37.5-42.5 GHz) developed offers 40 W with 3 GHz bandwidth.
- Commercial Communication (5G) - Wireless backhaul
  - ❑ 95 GHz TWT with 40 W power developed for 10 $\mathrm{Gbps/km^2}$.
  - ❑ D-band TWT (141-148.5 GHz) with 15 W power and G-band TWT (275 – 305 GHz) with 2 W power are developed for 100 $\mathrm{Gbps/km^2}$.

Because of the high robustness, larger band width, TWT continue to dominate in satellite applications.

Klystron Amplifier

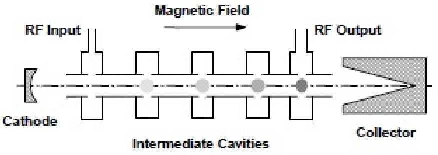

Figure: Schematic of a Klystron Amplifier.

State of the Art

- Sheet beam klystron
  - ❑ 95 GHz, 2 kW output power with 50% efficiency, CW for RADAR systems.
- Extended Interaction Klystron
  - ❑ Compact, 220 GHz, 9 W CW Klystron for imagining systems.

Because of their high gain, widely used as RF amplifiers in linear accelerators.

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* Figures taken from:
A. Gilmour, Microwave Tubes, Artech House, 1986.

Backward Wave Oscillator

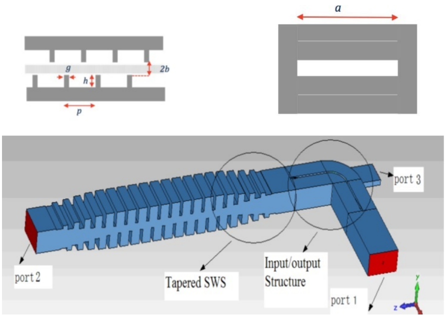

Figure: Backward wave oscillator operating at 346 GHz.

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* Figure taken from:
B. Popovic *et al.*, "Design and fabrication of a sheet beam BWO at 346 GHz," *2015 IEEE International Vacuum Electronics Conference (IVEC)*, Beijing, 2015, pp. 1-2. doi: 10.1109/IVEC.2015.7223816

Applications

- Local oscillators in fast-tuning receivers for remote sensing applications.
- BWOs are widely used for THz imaging and spectroscopy.
- BWOs operating at mm wave frequencies are also used in plasma diagnostic systems.

Gyrotron Oscillator

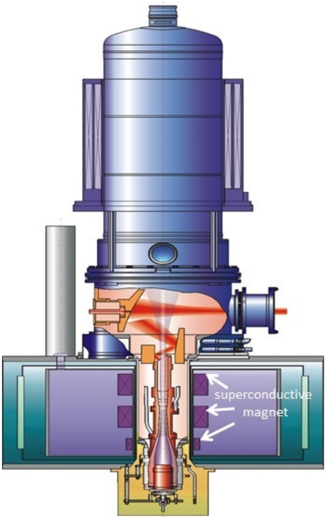


Figure: MW Class Gyrotron Oscillator for plasma heating application.

*Figure taken from:
M. K. Thumm, “State-of-the-art of high power gyro-devices and free electron masers. Update 2017,” *KIT, Karlsruhe, Germany*, Sci. Rep. 7750, 2018.

Gyrotron Oscillator

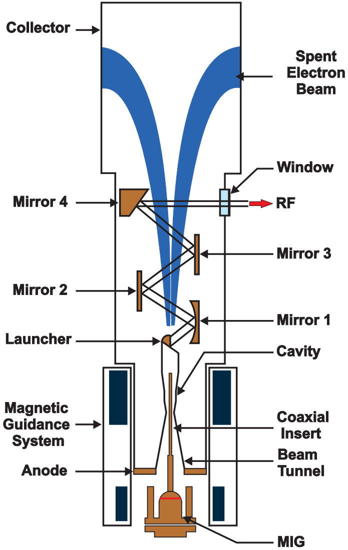


Figure: Schematic of a Gyrotron Oscillator.

Applications

(A) Prominently used for plasma heating (28-240 GHz with power of > 100 kW).

(B) Generation of highly ionized particles (30-80 GHz, around 100 kW power level).

(C) Material Processing (20-80 GHz, around 10-50 kW power level).

(D) Medical Spectroscopy (250-500 GHz with 20 W power)

Fusion Tokamak

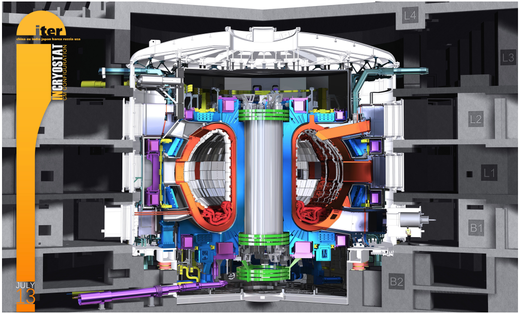


Figure: Schematic of International Thermonuclear Experimental Reactor (ITER) Tokamak

*Figure taken from www.iter.org

Gyrotron Requirements

- **(A)** Aditya /SST-1(Indian Tokamak) uses 42 GHz Gyrotron with 0.5 MW power.
- **(B)** ITER Tokamak proposes to use 24 gyrotrons each operating at 170 GHz delivering 1 MW power.
- **(C)** ASDEX-U (German Tokamak) uses 140 GHz 1 MW gyrotron.

Demonstration Power Plant (Commercial fusion prototype)

- 50 MW RF power with frequencies greater than 200 GHz.
- Multifrequency operation of gyrotron is preferred.

Fusion Tokamak

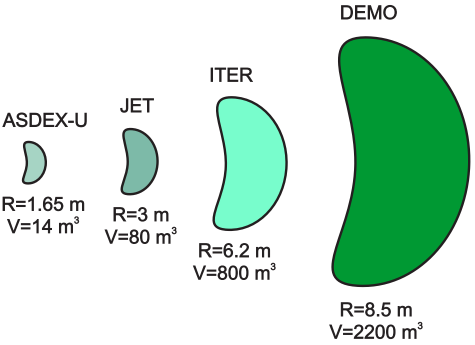
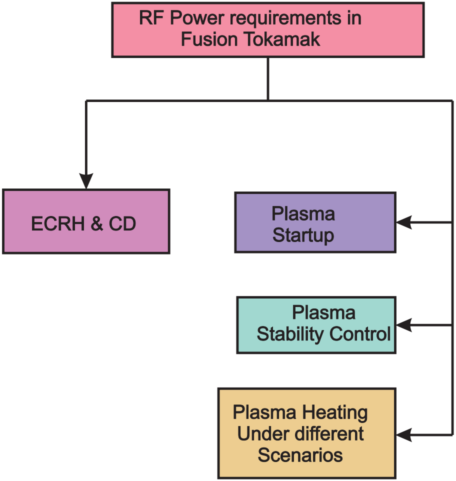


Figure: Core size of different experimental tokamaks. R is the major axis radius, V is the volume of the core.

- Increase in size of core, increases the number of fusion reactions occur in the tokamak and hence increase in overall machine gain.
- Next generation machines require high power sub-millimeter wave gyrotrons for their ECRH systems.

RF power requirements in Fusion Tokamak



RF Power requirements in Fusion Tokamak

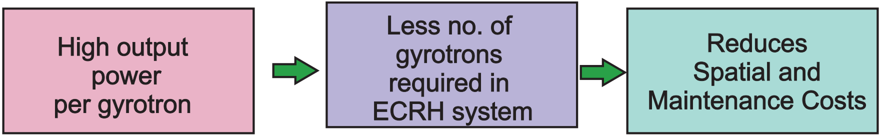
ECRH & CD

Plasma Startup

Plasma Stability Control

Plasma Heating Under different Scenarios

RF power requirements in Fusion Tokamak

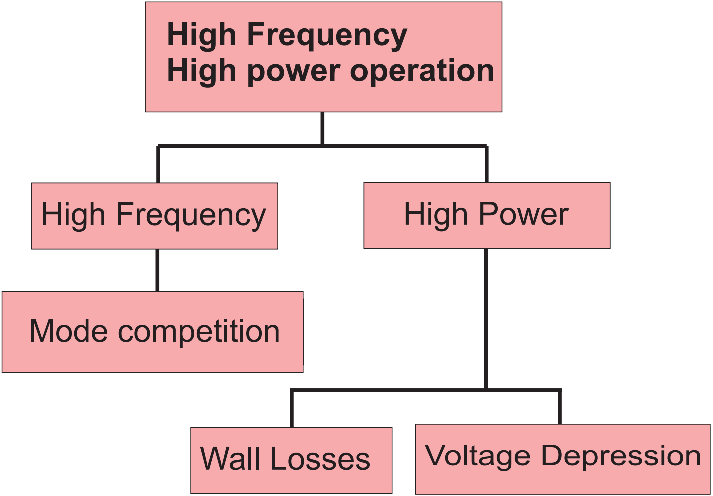


High output power per gyrotron → Less no. of gyrotrons required in ECRH system → Reduces Spatial and Maintenance Costs

⇒Thus, the **output power of coaxial cavity gyrotron can also be targeted above 2 MW.**

Design studies of a 2 MW multi-frequency (220/251.5/283 GHz) coaxial cavity gyrotron

General Problems in Megawatt Class Operation



High Frequency
High power operation

High Frequency

High Power

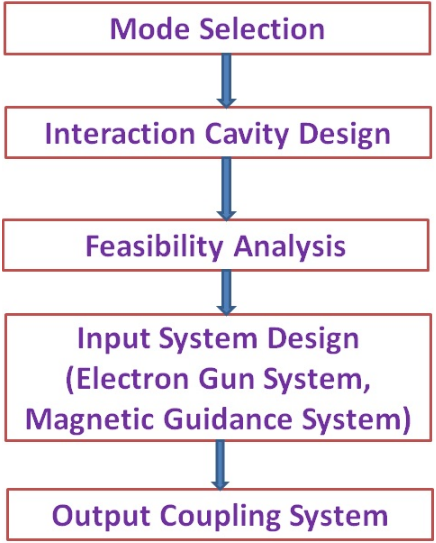
Mode competition

Wall Losses

Voltage Depression

Figure: High power High frequency operation.

Design studies of a 2 MW multi-frequency (220/251.5/283 GHz) coaxial cavity gyrotron



Mode Selection

Interaction Cavity Design

Feasibility Analysis

Input System Design
(Electron Gun System,
Magnetic Guidance System)

Output Coupling System

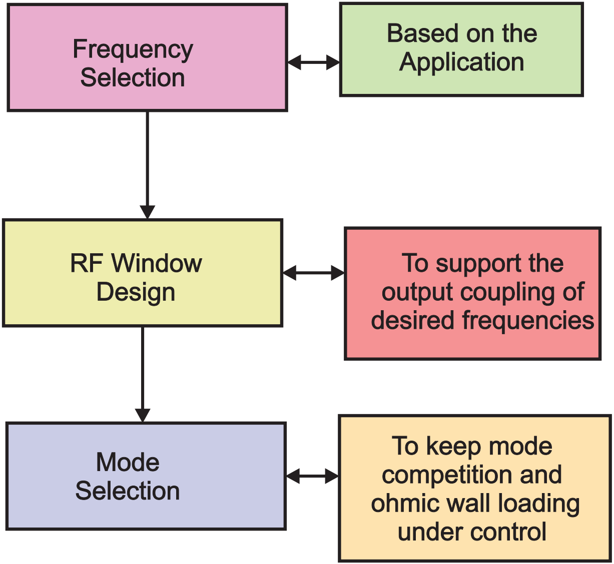
Design Goals and Technical Constraints

Table: Design goals and constraints for multifrequency operation.

Frequencies	220/251.5/283 GHz
Output RF Power	2.0 MW, CW
Diffractive quality factor	1200-2800
Beam Voltage	80-90 kV
Beam Current	65-70 A
Magnetic Field at Interaction Cavity	$\approx$ 8.80-8.90 T for 220 GHz $\approx$ 10.0-10.10 T for 251.5 GHz $\approx$ 11.0-11.5 T for 283 GHz
Electron Velocity Ratio	$\approx$ 1.30 - 1.34
Total Output Efficiency	> 34%
Estimated Wall Loading	$< 2\ \mathrm{kW/cm^2}$
Total Internal Losses	< 8%

* Frequencies are chosen such that designed gyrotron can be used for plasma heating application in future commercial tokamaks.

General Design Procedure- RF behavior Studies



Frequency Selection

Based on the Application

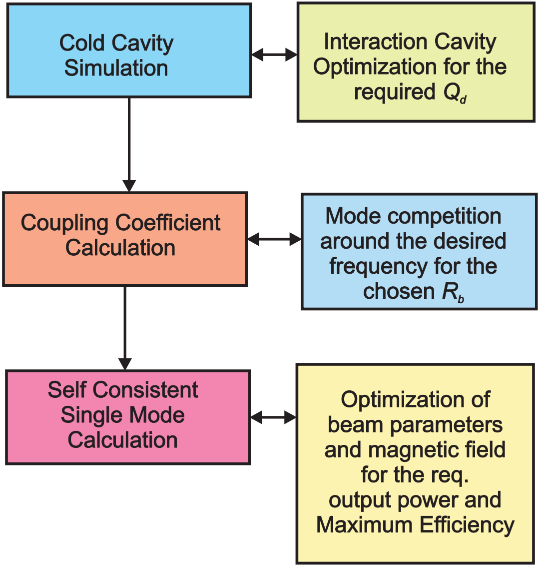
RF Window Design

To support the output coupling of desired frequencies

Mode Selection

To keep mode competition and ohmic wall loading under control

General Design Procedure- RF behavior Studies



Cold Cavity Simulation

Interaction Cavity Optimization for the required Q_d

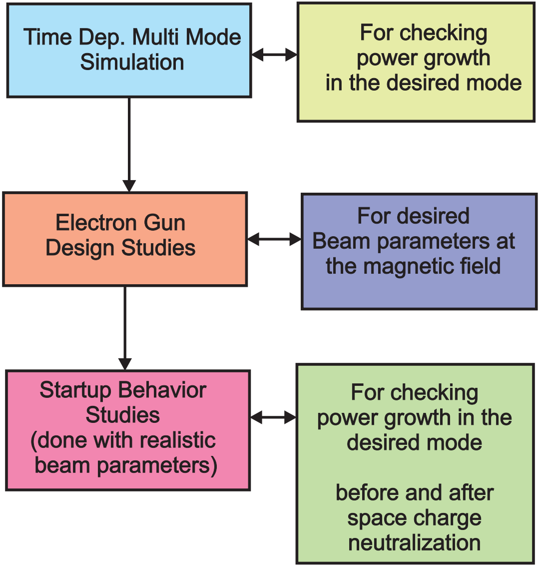
Coupling Coefficient Calculation

Mode competition around the desired frequency for the chosen R_b

Self Consistent Single Mode Calculation

Optimization of beam parameters and magnetic field for the req. output power and Maximum Efficiency

General Design Procedure- RF behavior Studies



Time Dep. Multi Mode Simulation

For checking power growth in the desired mode

Electron Gun Design Studies

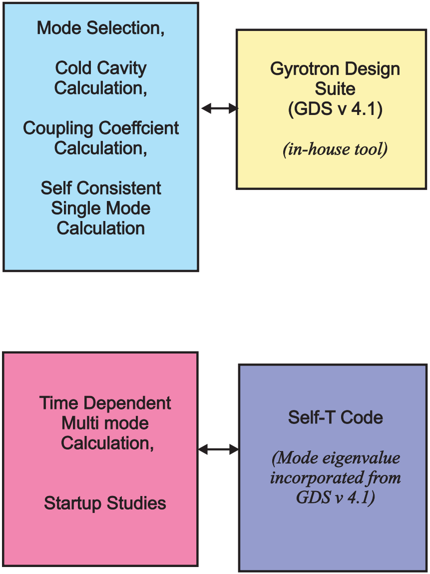
For desired Beam parameters at the magnetic field

Startup Behavior Studies (done with realistic beam parameters)

For checking power growth in the desired mode

before and after space charge neutralization

Design Tools - RF behavior Studies



Mode Selection,

Cold Cavity Calculation,

Coupling Coeffcient Calculation,

Self Consistent Single Mode Calculation

Gyrotron Design Suite (GDS v 4.1)

(in-house tool)

Time Dependent Multi mode Calculation,

Startup Studies

Self-T Code

(Mode eigenvalue incorporated from GDS v 4.1)

Gyrotron Design Suite 2018

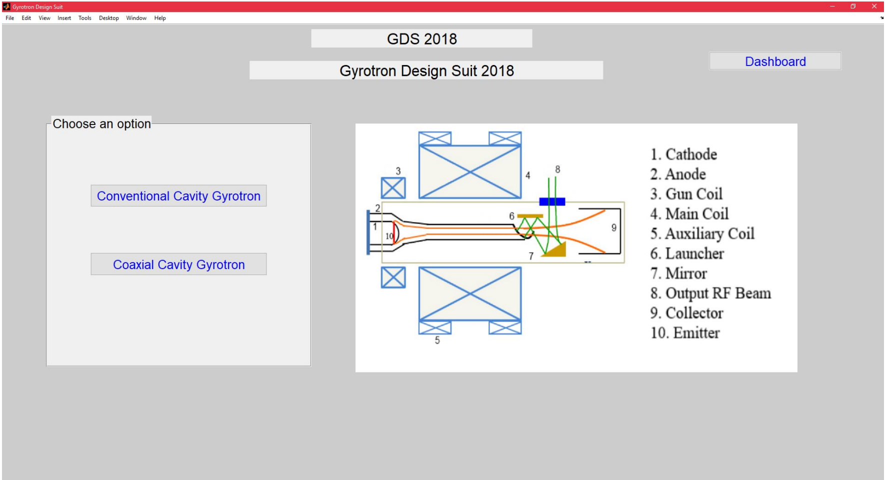


Figure: Basic layout of main window of GDS 2018 with option of choosing conventional or coaxial cavity gyrotron design studies.

Gyrotron Design Suite 2018

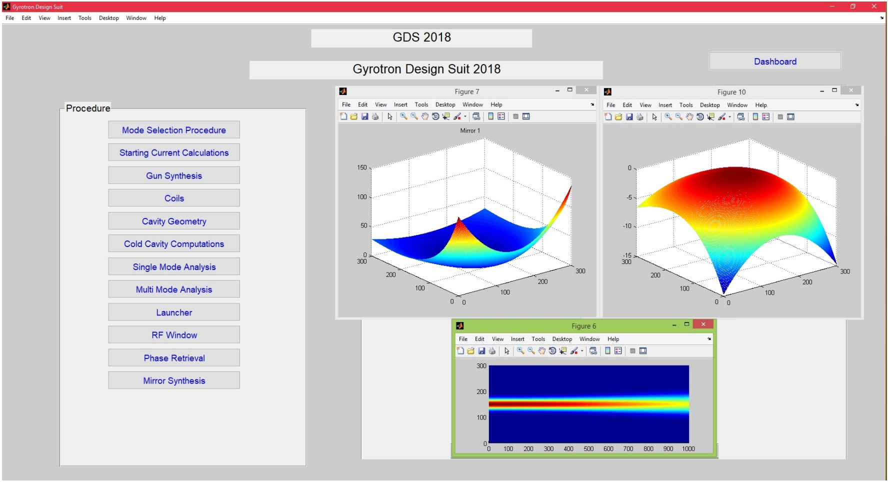


Figure: Complete design options available in GDS 2018.

Gyrotron Design Suite 2018

For axisymmetrical systems like waveguides, wave equation is obtained from the Maxwell's equation

$$(\nabla_t^2 + k_z^2)h = 0$$

where h is the axillary function which satisfies the field expression of the TE/TM modes in the waveguide. For TE modes, transverse component of electric field can be written as

$$\boldsymbol{E_t} = \sum_{mp} V_{mp}(z)\boldsymbol{e_{mp}}(r,\theta)$$

$$\frac{d^2 V_{mq}}{dz^2} + \left(\frac{\omega^2}{c^2} - k_{mq}^2\right) V_{mq} \simeq +j\omega J_{mq} \tag{1}$$

$$J_{mq} = \int d\theta \int_0^R r\boldsymbol{e_{mq}^*}.\boldsymbol{J}\, dr \tag{2}$$

Where J is the current density of the electron beam.

Gyrotron Design Suite 2018

The equation of motion for charge particles in the electric and magnetic fields is given by,

$$\frac{d\boldsymbol{p}}{dt} = -e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \tag{1a}$$

$$\frac{d\varepsilon}{dt} = -e\boldsymbol{E}.\boldsymbol{v} \tag{1b}$$

where $\boldsymbol{p} = \gamma m_e \boldsymbol{v}$, $\varepsilon = \gamma m_e c^2$, and $\gamma = 1/\sqrt{1 - v^2/c^2}$.

$$\begin{aligned} \frac{dP}{dz} + \frac{j\omega}{c\beta_{zo}} \left(\frac{\gamma}{\gamma_o} - \frac{\Omega_o}{\omega\gamma_o} \right) P = \frac{j\tilde{\eta}}{2} \frac{\gamma}{u_{zo}} C_{mp} k_{mp} V_{max} \left(\frac{\hat{f}_{mp}(z)}{(s-1)!} \right) \\ \times J_{m-s} \left(k_{mp} R_e \right) \left(\frac{c k_{mp} P^*}{2\Omega_o} \right)^{s-1} \end{aligned} \tag{2}$$

where P is related to transverse component of electron velocity.

Gyrotron Design Suite 2018

The equation of motion in presence of superposition of several modes is given by

$$\frac{dP}{dz}+\frac{j\omega_a}{c\beta_{zo}}\left(\frac{\gamma}{\gamma_o}-\frac{\Omega_o}{\omega_a\gamma_o}\right)P=-j\frac{\gamma\omega_a}{cu_{zo}}\sum_{mp}F_{mp}\hat{f}_{mp}(z)e^{[j\psi_{mp}]}\left(\frac{jck_{mp}P^*}{2\Omega_o}\right)^{s_{mp}-1} \tag{1}$$

$$\frac{d^2F_{mp}\hat{f}_{mp}}{dz^2}+\left(\frac{\omega_{mp}^2}{c^2}-k_{mp}^2\right)F_{mp}\hat{f}_{mp}-\frac{j2\omega_{mp}^2}{c^2}\frac{\partial}{\partial t}\left(F_{mp}\hat{f}_{mp}\right) = -Z_oI_o\left[\frac{C_{mp}k_{mp}G_{mp}}{(s_{mp}-1)!}\right]\left(\frac{\omega_{mp}}{cu_{zo}}\right)\left(\frac{-jck_{mp}}{2\Omega_o}\right)^{s_{mp}-1}\left\langle P^s exp[-j(\psi_{mp}-\psi_1)]\right\rangle \tag{2}$$

Mode Selection

Table: Mode selection for multi-frequency gyrotron.

f_r (GHz)	m	p	χ_{mp}	R_o (mm)	R_b (mm)	V_d* (kV)	m/χ_{mp}
220.000	46	29	150.7898	32.726	10.395	2.07	0.305
250.841	52	33	171.9283	32.726	10.282	1.97	0.302
281.817	58	37	193.0657	32.726	10.192	1.89	0.300
220.000	47	29	152.1125	33.013	10.616	2.18	0.309
252.487	54	33	174.5750	33.013	10.600	2.17	0.309
285.114	61	37	197.0375	33.013	10.580	2.16	0.310
220.000	**48**	**30**	**156.7365**	**34.016**	**10.838**	**2.10**	**0.306**
251.530	**55**	**34**	**179.1992**	**34.016**	**10.834**	**2.10**	**0.307**
283.208	**62**	**38**	**201.6619**	**34.016**	**10.829**	**2.09**	**0.307**
220.000	50	30	159.3778	34.590	11.281	2.31	0.314
251.006	57	34	181.8403	34.590	11.244	2.28	0.314
282.149	64	38	204.3028	34.590	11.214	2.25	0.313
220.000	51	29	157.3780	34.156	11.502	2.58	0.324
251.403	58	33	179.8422	34.156	11.420	2.52	0.323
282.942	65	37	202.3059	34.156	11.354	2.47	0.321

(* For the calculation of V_d, electron beam voltage, beam current, radii ratio and velocity ratio are 85 kV, 68 A, 3.8 and 1.27, respectively)

Interaction Cavity Design Studies

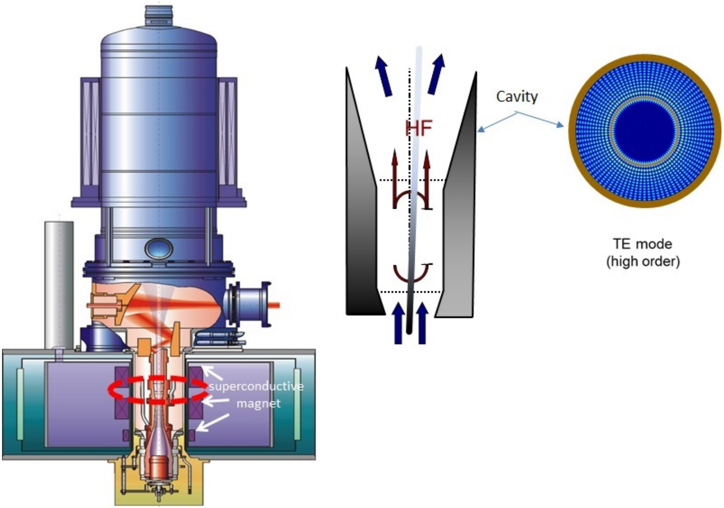


Figure: Interaction Region of Gyrotron.

Triangular Corrugated Insert

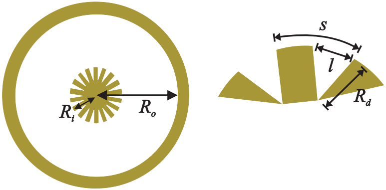


Figure: Cross section of a triangular corrugated coaxial cavity*.

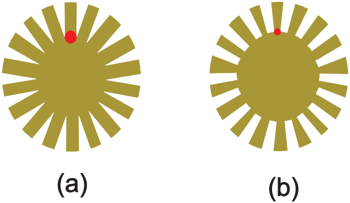
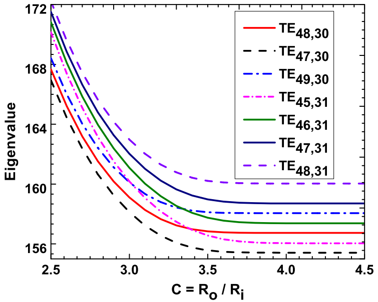


Figure: Corrugated Coaxial Insert with (a) triangular corrugations (b) rectangular corrugations

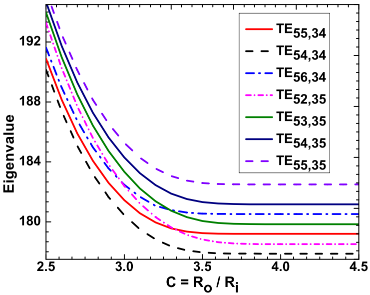
*Reference

Sukwinder Singh and M.V. Kartikeyan, “Analysis of a Triangular Corrugated Coaxial Cavity for Megawatt-Class Gyrotron,”*IEEE Trans. Electron Devices, vol. 62, no. 7, pp. 2333-2338, July 2015.*

Eigenvalue Analysis



(a)



(b)

Figure: Eigenvalue curves for the desired mode (a) $\mathrm{TE}_{48,30}$ at 220 GHz (b) $\mathrm{TE}_{55,34}$ at 251.5 GHz, along with the competing modes (R_o=34.00 mm, R_d=0.5 mm, l/s=0.7, N=130).

Eigenvalue Analysis

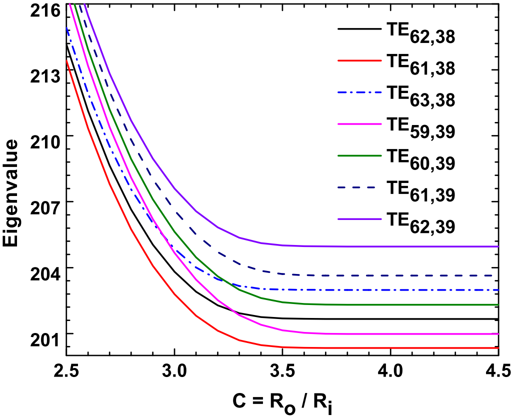


Figure: Eigenvalue curves for the desired mode $\mathrm{TE}_{62,38}$ at 283 GHz along with the competing modes (R_o=34.00 mm, R_d=0.5 mm, l/s=0.7, N=130).

Interaction Circuit Geometry

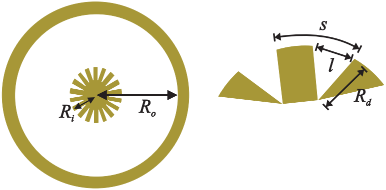


Figure: Cross section of a triangular corrugated coaxial cavity.

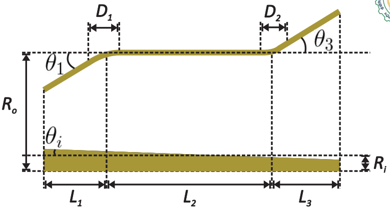


Figure: Geometry of the Interaction Region

Geometrical Parameters

Parameters	**Values**
$L_1/L_2/L_3(mm)$	16 / 12.5 / 16
$\theta_1/\theta_2/\theta_3(^\circ)$	3.5 / 0 / 3.0
$D_1/D_2(mm)$	4.0 / 4.0
$R_o/R_i(mm)$	34.00 / 8.95
N_s	130
$l/R_d(mm)$	0.3/0.5
$\theta_i(^\circ)$	-1

Interaction Circuit Calculations Cont...

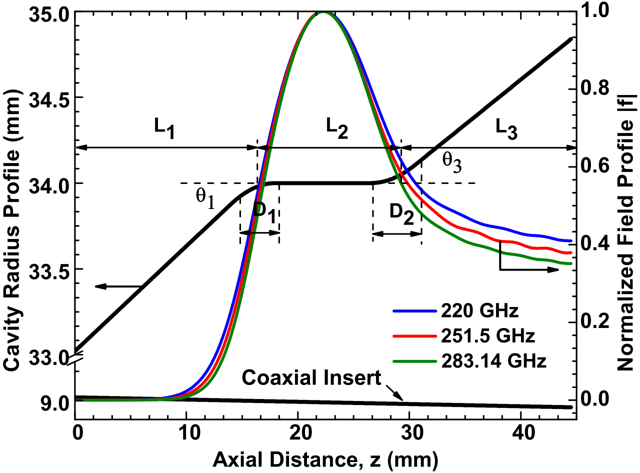
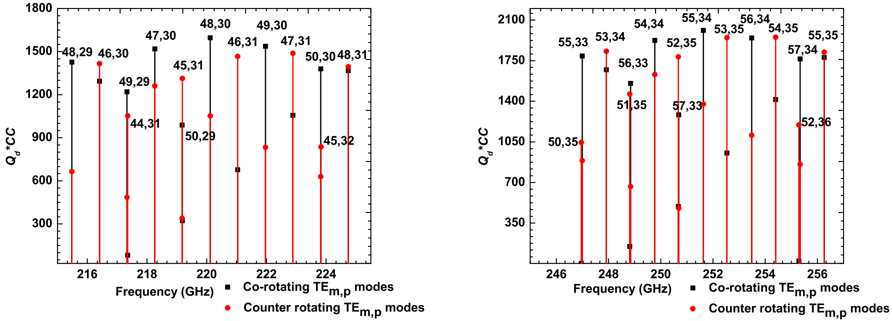


Figure: Normalized field amplitude along the cavity geometry. For the cavity modes $\mathrm{TE}_{48,30}/\mathrm{TE}_{55,34}/\mathrm{TE}_{62,38}$, calculated Q_D are 1596.8/2011.89/2518.63 at the resonant frequencies of 220.12/251.63/283 GHz

Mode Competition Studies



(a) 220 GHz operation

(b) 251.5 GHz operation

Figure: Mode spectrum of Q_d times coupling coefficient in the coaxial cavity for the desired mode of (a) $TE_{48,30}$ with R_b = 10.838 mm (b) $TE_{55,34}$ with R_b = 10.834 mm.

Mode Competition Studies

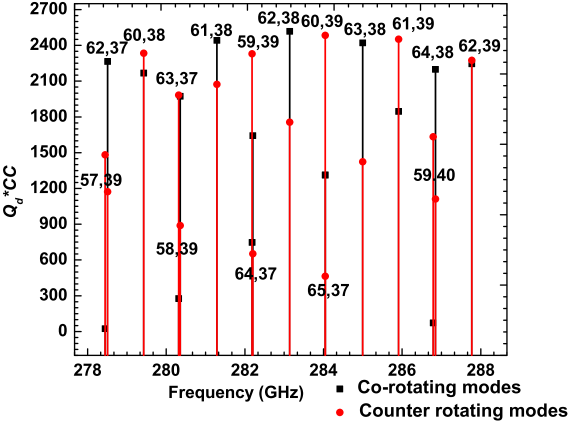


Figure: Mode spectrum of Q_d times coupling coefficient.

Feasibility Analysis- Single Mode calculations

Table: Single mode calculation results.

Parameters	220 GHz	251.5 GHz	283 GHz
$f_r(\ GHz)$	220.1175	251.6298	283.142
Q_D	1596.80	2011.89	2518.63
$R_b(mm)$	10.838	10.834	10.824
$V_b(kV)$	87	85	89
$I_b(A)$	70	68	68
α	1.27	1.27	1.23
$B_o(T)$	8.872	10.100	11.466
$''_{\mathrm{electronic}}(\%)$ incl. ohmic losses	35.51	34.78	34.35
$P_{out}(MW)$	2.163	2.01	2.09
$\rho_o(kW/cm^2)$	1.75	1.91	2.30
$\rho_i(kW/cm^2)$	0.13	0.04	0.02
Total Power Loss (kW)	43.9	45.4	52.36
Q_{Ohmic}	107208	116076	123411
$V_d(kV)$	2.26	2.21	2.12
$I_L(A)$	430.80	418.09	469.43

Feasibility Analysis- Multi-mode calculations (220 GHz)

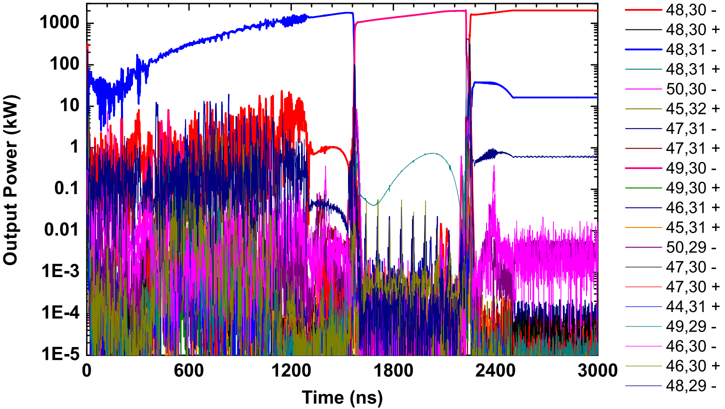


Figure: Time dependent Multi-mode calculations for the $\mathrm{TE}_{48,30-}$ mode along with the competing modes with $V_b = 50\text{-}87$ kV, $B_o = 8.867$ T, $\alpha = 1.27$ and $I_b = 70$ A. Logarithmic scale is used for the illustration of the output power, P_{out} (kW).

Feasibility Analysis- Multi-mode calculations (251.5 GHz) Cont.

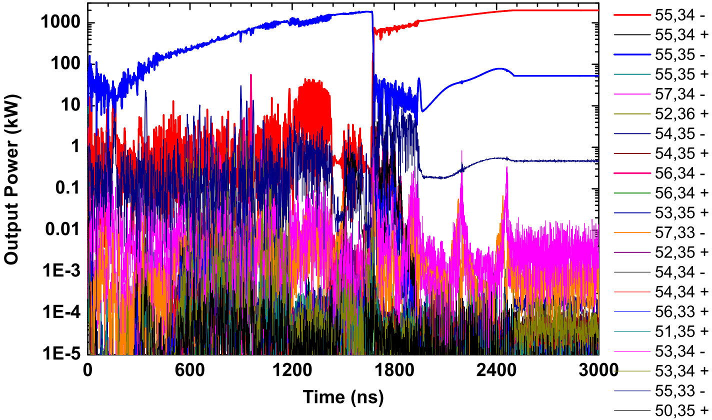


Figure: Time dependent Multi-mode calculations for the $\mathrm{TE}_{62,38-}$ mode along with the competing modes with $V_b = 50\text{-}85$ kV, $B_o = 10.105$ T, $\alpha = 1.27$ and $I_b = 68$ A. Logarithmic scale is used for the illustration of the output power, P_{out} (kW).

Feasibility Analysis- Multi-mode calculations (283 GHz) Cont...

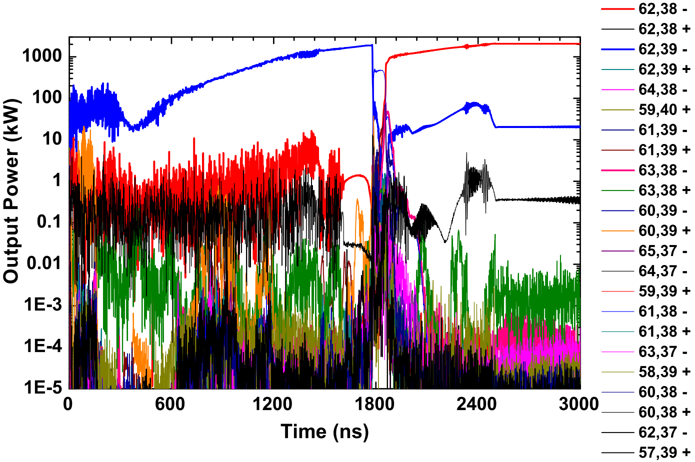


Figure: Time dependent Multi-mode calculations for the $\mathrm{TE}_{62,38-}$ mode along with the competing modes with $V_b = 50\text{-}89\,\mathrm{kV}$, $B_o = 11.430\,\mathrm{T}$, $\alpha = 1.23$ and $I_b = 68\,\mathrm{A}$. Logarithmic scale is used for the illustration of the output power, P_{out} (kW).

Input System Design (Magnetic System, Electron Gun)

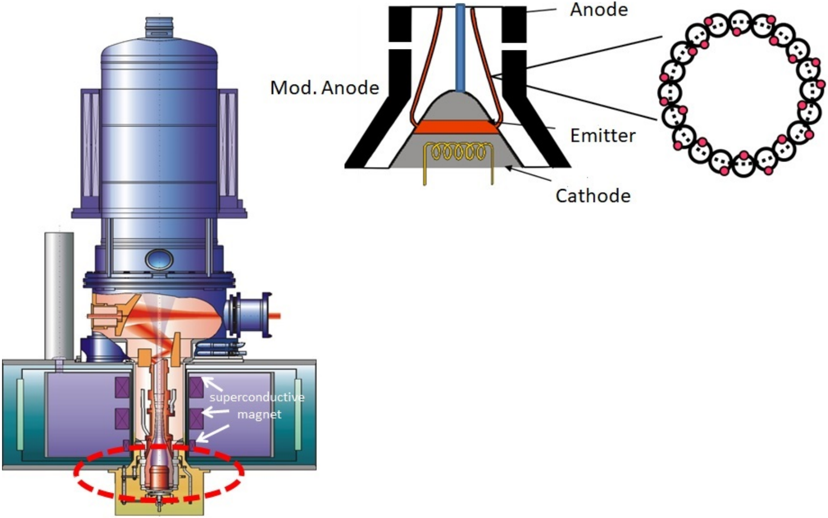


Figure: Input System of a Gyrotron.

Input System Design Cont...

Table: Optimized Coil Data.

Coils	Length ΔZ (mm)	Breadth ΔR (mm)	Coil radius (mm)	No. of turns N_C	Current 220 GHz (A)	Current 251.5 GHz (A)	Current 283 GHz (A)
Main Coil –1	440.00	30.00	120.00	24990	119.87	136.59	154.45
Main Coil –2	440.00	15.00	142.50	4930	119.87	136.59	154.45
Compensating Coil	70.00	45.0	147.50	2880	-63.5	-71.0	-82.5
Gun Coil – 1	65.00	25.0	137.50	645	7.5	5.45	8.43
Gun Coil –2	20.00	25.00	137.50	610	3.0	3.5	6.16

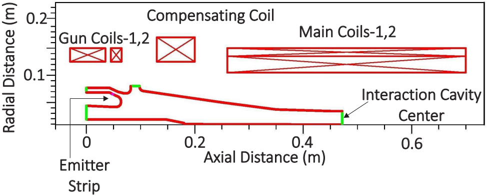


Figure: Position of the magnetic coils along the Electron Gun geometry.

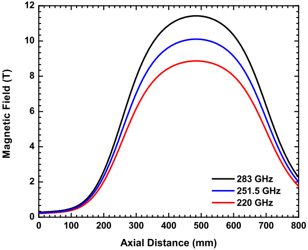


Figure: Magnetic field profile along the axial length of the gyrotron.

Optimized Electron Gun

Table: Geometrical Parameters.

Parameters	**Values**
Cathode radius	64.60 mm
Cathode angle	25°
Axial width of the emitter	4.4 mm
Cathode-mod. anode spacing	8.45 mm
Mod. anode angle	25°
Anode radius	71 mm

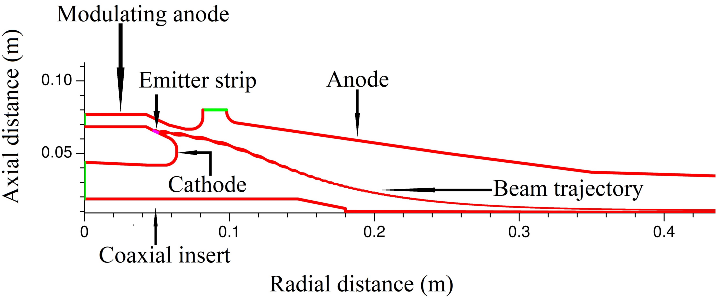


Figure: Electron beam trajectory in the designed Electron Gun.

Electron Gun Simulation Results

Table: Simulation Results of the Triode Type Coaxial MIG

Input Parameters			
Frequency	220 GHz	251.5 GHz	283 GHz
Beam current	70 A	68 A	68 A
Accelerating voltage	87 kV	85 kV	89 kV
Mod. anode voltage	40 kV	31.0 kV	26.6 kV
Emitter current density	3.8 $\mathrm{A/cm^2}$	3.8 $\mathrm{A/cm^2}$	3.8 $\mathrm{A/cm^2}$
Results			
Magnetic field at the emitter	0.21433 T	0.2405 T	0.333 T
Compression ratio	41.3708	42.0166	34.31
Electric field at cathode	5.9 kV/mm	6.29 kV/mm	6.8 kV/mm
Velocity ratio	1.28	1.27	1.23
Velocity spread (%)	2.5	3.8	1.7
Beam radius (interaction)	10.838 mm	10.834 mm	10.824 mm

Output Coupling System Design

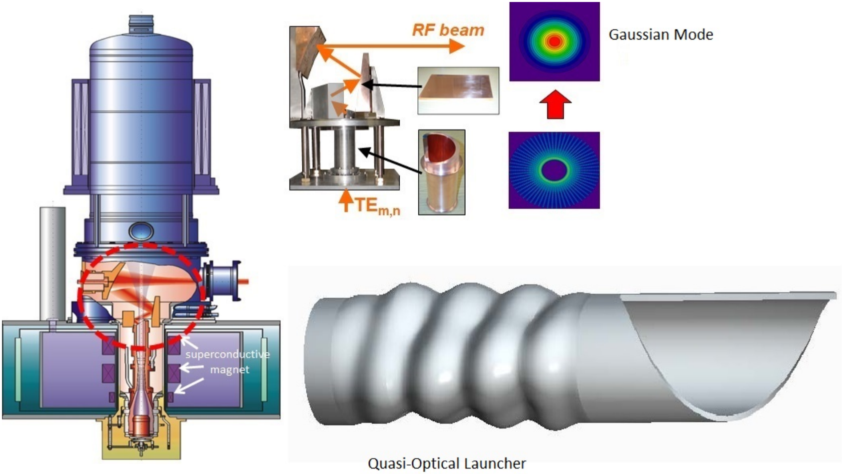


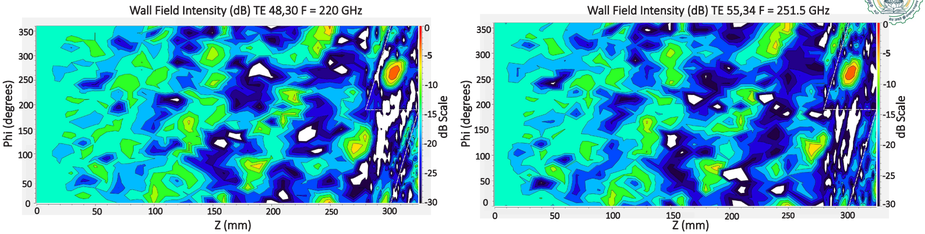
Figure: Output Coupling System of a Gyrotron.

Quasi-Optical Launcher Design

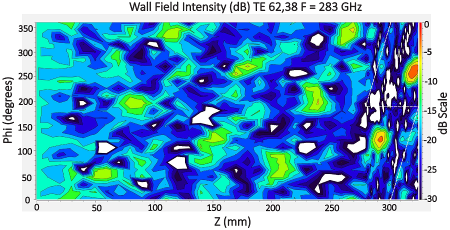
Table: Launcher design and LOT simulation results

Launcher length (mm)	325.0
Helical cut length (mm)	45.0
Waveguide radius (mm)	36.38
Taper angle (Rad.)	0.002
Gaussian content factor (GCF)	95.86% (for 220 GHz) 96.31 % (for 251.5 GHz) 95.33% (for 283 GHz)

QOL- Wall Field Intensity



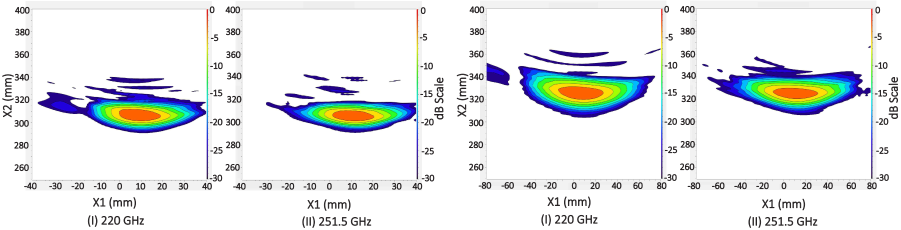
(a) $\mathrm{TE}_{48,30}$ mode at 220 GHz **(b)** $\mathrm{TE}_{55,34}$ mode at 251.5 GHz



(c) $\mathrm{TE}_{62,38}$ mode at 283 GHz

Figure: Field intensity on the unrolled launcher wall.

QOL- Field Intensity Patterns (a)



(a) **(b)**

Figure: Field intensity in the plane of the (a) launcher cut, (b) possible location of the first mirror.

QOL- Field Intensity Patterns (b)

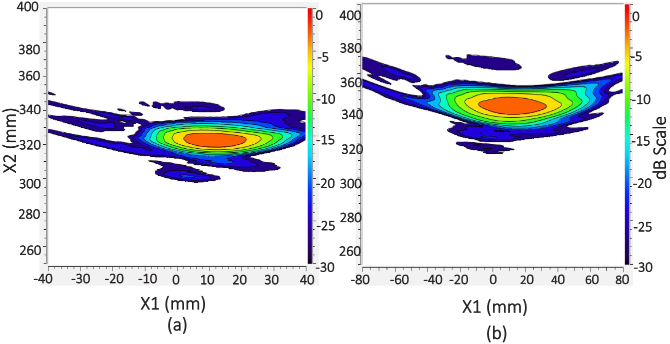


Figure: Field intensity in the plane of the (a) launcher cut, (b) possible location of the first mirror (283 GHz operation).

Misalignment Analysis

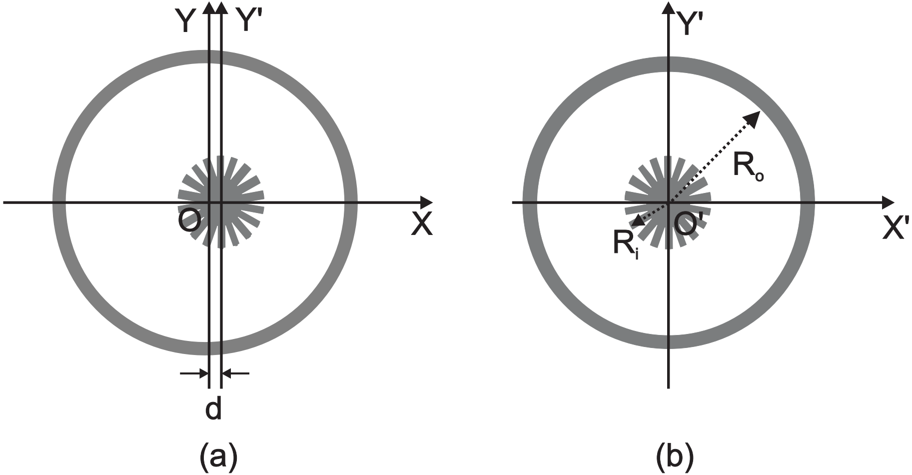


Figure: Cross section of a triangular corrugated coaxial cavity, (a) misaligned structure (system A), (b) perfect cavity (system B).

Fields in an ideal system

- The fields inside the triangular slots are given by

$$E_{r'_{slot}}(r^{'}, z) = 0$$

$$E_{\phi'_{slot}}(r^{'}, z) = k_{\perp} A_{01} J_0^{'}(k_{\perp} r^{'}) V_{mn} \hat{f}_z$$

$$H_{z_{slot}}(r^{'}, z) = -j \frac{k_{\perp}^2}{k_0 Z_0} A_{01} J_0(k_{\perp} r^{'}) V_{mn} \hat{f}_z$$

- Axial magnetic field in the coaxial region of the cavity is given by

$$H_{z_{coax}}(R^{'}, \phi^{'}, z) = \sum_m -j \frac{k_{\perp}^2}{k_0 Z_0} A_{mn} Z_m(k_{\perp} R^{'}) V_{mn} exp(-jm\phi^{'}) \hat{f}_z$$

  where

$$Z_m(k_{\perp} R^{'}) = J_m(k_{\perp} R^{'}) Y_m^{'}(\chi) - J_m^{'}(\chi) Y_m(k_{\perp} R^{'})$$

- In an ideal system, $(R^{'}, \phi^{'}, z)$ is the coordinate system.

Dispersion Relation

- By equating the impedances, dispersion relation for the coaxial cavity with triangular corrugated insert is given by

$$J_m^{'}(\chi)\left(Y_m^{'}(\chi/C)+\omega Y_m(\chi/C)\right)-Y_m^{'}(\chi)\left(J_m^{'}(\chi/C)+\omega J_m(\chi/C)\right)=0$$

- where ω is the normalized impedance at the insert surface and is given by

$$\omega=\frac{l}{s}\frac{J_1(\chi/C_d)}{J_0(\chi/C_d)}$$

and $C_d = R_o/R_d$.

Fields in a coaxial cavity with misaligned insert

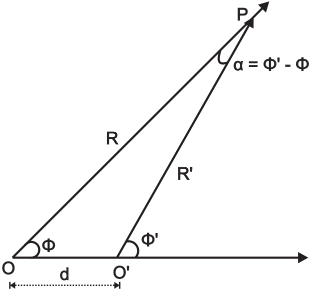


Figure: Coordinate system used for the analysis of the coaxial cavity with misaligned inner rod.

- By using the coordinate transformation, radial component of the fields in system A is related to that of system B by

$$\overrightarrow{R} = \overrightarrow{R'} + \overrightarrow{d}$$

- Graff addition theorem is used for the transformation of the fields in system B to system A.

$$J_m(k_\perp R').exp(-jm(\phi' - \phi)) = \sum_{p=-\infty}^{\infty} J_p(k_\perp d) J_{m+p}(k_\perp R).exp(-jp\phi)$$

$$Y_m(k_\perp R').exp(-jm(\phi' - \phi)) = \sum_{p=-\infty}^{\infty} J_p(k_\perp d) Y_{m+p}(k_\perp R).exp(-jp\phi)$$

Dispersion Relation in Misaligned System

- For the transverse electric modes, axial magnetic field in the coaxial region of system B is given as follows

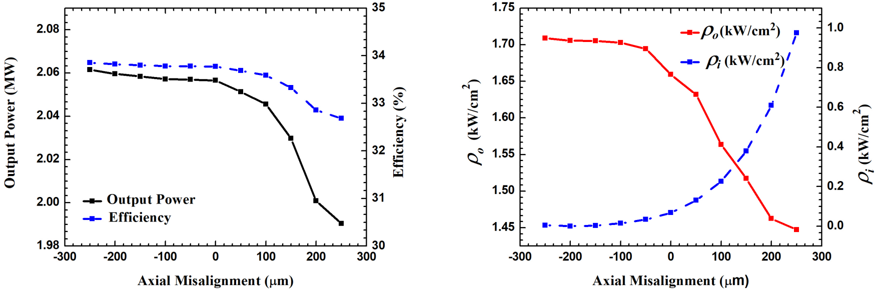
$$H_{z_{coax}}(R,\phi,z)=\sum_m\sum_{p=-\infty}^{\infty}-j\frac{k_\perp^2}{k_0 Z_0}A_{mn}J_p(k_\perp d)Z_{m+p}(k_\perp R)V_{mn}.exp(-j(m+p)\phi)\hat{f}_z$$

- Dispersion relation for misaligned system is given by

$$\sum_m J_{i-m}(\chi d/R_o)\Big[J_i^{'}(\chi)\Big(Y_m^{'}(\chi/C)+\omega Y_m(\chi/C)\Big) - Y_i^{'}(\chi)\Big(J_m^{'}(\chi/C)+\omega J_m(\chi/C)\Big)\Big]=0$$

$$i=0,\pm1,\pm2,\pm3...$$

Effect of Misalignment on 220 GHz operation



(a) (b)

Figure: Variation in the (a) output RF power and efficiency of the desired mode (b) Ohmic wall loading of the cavity and that of insert with the axial misalignment of the insert along with the additional tilt in the insert axis of 0.5° (220 GHz Operation and $TE_{48,30}$).

Conclusion and Future Scopes

Conclusion

Contribution of this Thesis

- To summarize, this research work contributes towards the design studies of the major components of coaxial cavity gyrotron supporting dual/multi-frequency operation.
- These gyrotrons can be used for ECRH application in the future experimental tokamaks.

Conclusion

- Next generation looks beyond 60GHz !
- Millimeter/THz Waves offer a potential applications in Modern 5G amenable communication systems; besides a variegated range of ISM applications including Energy, Medical Spectroscopy, Detection and Imaging.
- Vacuum electron sources will be competitive alternative for solid state devices in the region of mm/THz for both commercial low power applications and high power applications

Gyrotrons for Medical Spectroscopy Applications

Figure: Gyrotron operating at 527 GHz for DNP-NMR experiments.

* Figure taken from:
S. Jawla *et al.*, "Second Harmonic 527 GHz Gyrotron for DNP-NMR," *2019 IEEE International Vacuum Electronics Conference (IVEC)*, Busan, Korea (South), 2019, pp. 1-2. doi: 10.1109/IVEC.2019.8744878

State of the Art

- 10 W, 527 GHz gyrotron developed for DNP-NMR Experiments.

ACKNOWLEDGEMENTS

Thanks to VED Thinkers Fraternity !
Thanks for the invitation !!

Thank you

Annexure V:

Typical WhatsApp Chats with Thinkers in VED

03/10/2020, 07:42 - Dr. Vishal Kesari: FREE Virtual IEEE Authorship Workshop

Thursday, 15 October 2020

4:30-6:00 PM IST

Greetings from the IEEE,

As a valued IEEE member, we thought you might be interested in attending a free virtual IEEE authorship workshop on 15 October 2020 titled, "How to Publish a Quality Technical Paper with IEEE". Join distinguished lecturer and IEEE Fellow, Gaurav Sharma and IEEE Client Services Manager Dhanu Pattanashetti, for a virtual webinar offering advice on everything from the IEEE publishing process, to basic writing tips and how to submit a manuscript.

The goal of the workshop is to enable engineers, faculty, researchers, and authors to advance technology and their careers by enhancing their ability to get published and share their research with the scholarly community. The event is free to technology professionals with an interest in learning how to publish with IEEE.

Topics include:

- Basics of publishing
- Understanding different types of publications
- How to choose between a journal or a conference
- Benefits of getting published with IEEE
- Ethics and misconduct
- Importance of publishing for your career
- Free authorship tools available from IEEE
- IEEE Xplore Digital Library - Gateway to highly-cited, cutting-edge articles for your projects and assignments

Event Details:

Title: How to Publish a Quality Technical Paper with IEEE

Date: Thursday, 15 October 2020

Time: 4:30 to 6:00 PM IST

Speakers:

Gaurav Sharma, Professor in the Departments of Electrical and Computer Engineering, Computer Science, and Biostatistics and Computational Biology at the University of Rochester in New York.

Dhanu Pattanashetti, IEEE Client Services and University Partnership Program Manager for customers in southern and western regions in India and Sri Lanka.

We look forward to virtually meeting with you soon!

Sincerely,

IEEE Author Relations

03/10/2020, 08:01 - SNJoshi CEERI: Good morning Vishal and thanks for sharing this information about IEEE virtual Workshop.

With best wishes,

03/10/2020, 10:06 - Dr. Vishal Kesari: https://forms1.ieee.org/India-Authorship-Workshops.html?LT=FB_SCL_9.24.20_LM_IEEE_Authorship_Workshop_India

05/10/2020, 16:49 - BNBasu Prof: Professor Raj Singh informed me that he was going to announce the programme of Webinar#3 tentatively to be held on 7th November 2020. Professor Chnadra Shekhar is going to chair the first of the two sessions of this webinar in which Professor S. N Joshi will deliver his talk on the first ever TWT built in India. The second session of the webinar will be hosted by Dr. Vishant Dwivedi in which Dr. Richards Joe Stanislaus will deliver his talk on large-signal analysis of helix-TWTs and Dr. S. Yuvaraj on multi-frequency coaxial gyrotron.

Webinar#4, to be chaired by Professor P. K. Jain, is going to be held tentatively in January 2021. In this webinar, Professor Claudio Paoloni, Head of Engineering Department and Cockcroft Chair of Lancaster University, is going to deliver his talk on high frequency vacuum electron devices. Mrs. Rupa Basu of Lancaster University will let us know later the title of his talk.

Professor Raj Singh also informed me that Proceedings of Webinar#2 would come out soon.

05/10/2020, 21:21 - Raj Singh IPR: Dear All, in the series of our webinars/meetings, we are glad to announce the tentative program of 3rd webinar.

We hope you are all enjoying the series of webinars and meetings which are full of information and knowledge.

We are really thankful to all the speakers, who in the past have enriched our knowledge with their content rich talks.

Thanks to you, all participants whose enthusiasm and involvement makes these meetings and webinars relevant and justifies the energy and efforts put up by the speakers and other involved persons.

05/10/2020, 21:22 - Raj Singh IPR: Webinar #3

Tentative Programme

7th November 2020

From 4.00 PM to 5:30 PM

Session 1: Expert Talk

Duration: 40 minutes

Chair: Professor Chandra Shekhar

Speaker: Dr. S. N. Joshi

Duration: 40 minutes

Topic: First Ever TWT Built in India

Session 2:

Research Contributions of Younger Researchers in VEDs

Duration: 40 minutes

Host: Dr. Vishant Dwivedi

Speakers:

1. Richards Joe Stanislaus: Large-Signal Analysis of Helix-TWT
2. Dr. S. Yuvaraj: Investigation into Multi-Frequency Coaxial Gyrotron

05/10/2020, 21:52 - Dr. Vishal Kesari: Thanks for announcement of webinar#3. Most of us are waiting since long for the talk on First Ever TWT built in India.

Regards.

06/10/2020, 19:07 - Dr. Vishal Kesari: Please find the attached proceedings of webinar#2 held on 5 September 2020.

06/10/2020, 19:15 - BKShukla IPR Gandhinagar: Good work, thanks Vishal for your efforts

06/10/2020, 21:54 - SNJoshi CEERI: Thanks Vishal and your team for efforts in bringing the proceedings of Webinar 2.

07/10/2020, 09:25 - BNBasu Prof: Will a vacuum electron device work in ideally perfect vacuum? If yes, why? If no, why? I eagerly look forward to knowing its answer.

07/10/2020, 09:37 - Meenu Kaushik: I think, yes it will work in perfect vacuum. As we do not want any hinderance in the path of electrons traversing to anode for avoiding wastage of electrons energy to any other particle and to avoid cathode stripping. However, perfect vacuum is difficult to achieve which is one of the reasons for limited lifetime of these tubes.

07/10/2020, 10:17 - BNBasu Prof: Meenu, Thanks for your quick response. However, I will be happy receiving the answers from others, too, before saying if I am satisfied with your answer. Let's benfit from such debate on this forum.

07/10/2020, 10:39 - +91 93143 96993: 1. It is the interaction of moving electrons with the input RF which amplifies the signal. Electrons moving linearly and evenly with constant speed does not radiate. Also, the electromagnetic field, which exists around particle, moves together with particle at the same speed, and its properties remain invariable. But if the trajectory of electrons non-linear or the electron begins to move unevenly (turns to be accelerated or slowed down), the state of its own electromagnetic field also changes. As a result, there arises a free electromagnetic field, i.e., electromagnetic radiation (EMR).

07/10/2020, 10:43 - BNBasu Prof: The answer doesn't really sound addressing my question.

07/10/2020, 10:44 - +91 93143 96993: 2. The high vacuum is required in a microwave device to prevent the collisions of electrons with gas atoms so that they don't loose their kinetic energy before crossing or passing through the anode of the tube. Also, the vacuum prevents ionization inside the tube caused by electrons colliding with atoms that produces positive ions, which can strike and poison the cathode and damage it. A high order of vacuum also prevents high power tubes from high voltage breakdown and arcing.

07/10/2020, 10:50 - BNBasu Prof: Please see my question. If the answer is yes, please say yes. Then please explain. If the answer is no, please say no. Then please explain. I am so grateful that you are helping me to develop my understanding.

07/10/2020, 10:54 - BNBasu Prof: Will a vacuum electron device work in ideally perfect vacuum? If yes, why? If no, why? I eagerly look forward to knowing its answer.

BNBasu Prof: Two possible answers: yes and no. Then explanatory support.

07/10/2020, 11:00 - +91 81074 33661: In my view, answer is no. Vacuum electron device requires some or large extent of plasma formation inside the tube. It depends on type of device. For creation of plasma, there is requirement of gas.

07/10/2020, 11:00 - SNJoshi CEERI: Basu Saheb is not satisfied with the answers. However, I appreciate you all for making sincere efforts.

07/10/2020, 11:23 - Dr. Lalit Kumar: Let us first understand what is "Perfect Vacuum"

07/10/2020, 11:31 - +91 93143 96993: perfect vacuum is one where there are no particle of mass. However, even in outer space, and even if we could remove every particle of mass, there would still be electromagnetic waves, because free space has a finite electric permittivity and magnetic permeability, the constituents of a wave thus being able to travel anywhere in space. That means that space is not really empty. Also there is the world of virtual particles that pop in and out of existence whenever a wave passes through.

07/10/2020, 11:52 - +91 80588 34146: If outer space is assumed as perfect vacuum, it indicates that the outer space should have no mass particle. This is indeed not the case. All the planets and heavenly bodies are made up of coagulated mass particle under high temperature and pressure. So conclusively outer space is not perfect vacuum, its just a higher level of vacuum as compared to what we attain in VEDs.

07/10/2020, 11:56 - +91 80588 34146: As per my reading and experience initially in electromagnetic theory scientist coined the term 'ether' to indicate medium which consists of some gas or air medium in trace amount. Vacuum or free space was a term coined later in theory. The point i want to make is perfect vacuum appears to be an ideal theoretical term having no real existance

07/10/2020, 11:58 - Vikram IIT BHU: Sir, Yes it can work. But still electron plasma is there in VED so we can not say complete vacuum. So as per my view theoretically yes, but practically pure vacuum is absent there in VED.

07/10/2020, 12:02 - +91 80588 34146: Answer is No,.........So conclusively, whenever electrons enters the VEDs, (which lets assume is in ideal vacuum), being a mass particle will disturb the definition of ideal vacuum and hence now the VED is in non ideal vacuum state during working. In addition, even while testing of any VED its found that the vacuum controller indicate a rise in pressure whenever electrons are ejected into the VEDs. This proves that the vacuum level is disturbed on electron (or mass particle) entry

07/10/2020, 12:21 - Dr. Lalit Kumar: The rise in vacuum is not because the electrons have appeared. due to heating either caused by the hot emitter or the degassing caused by the electrons wherever they impinge

"Also there is the world of virtual particles that pop in and out of existence whenever a wave passes through."

Could you please elaborate what you mean by "virtual particles pop up'

07/10/2020, 12:21 - Dr. Lalit Kumar: Dr. Meenu could you further elaborate as to what happens to' the perfect vacuum', when either the electrons or photons (microwave) enter tht space.

07/10/2020, 12:23 - Dr. Lalit Kumar: Dear Dr Neeraj you have said "In my view, answer is no. Vacuum electron device requires some or large extent of plasma formation inside the tube. It depends on type of device. For creation of plasma, there is requirement of gas." Could you elaborate what kind of plasma are you talking about: electron plasma or neutral plasma? Which one is essential and which one requires gas to be present?

07/10/2020, 12:31 - +91 92696 26411: I think the perfect vacuum is P=o. Now question is What is absolute zero pressure and when we can achieve. If I look in the ideal gas equation PV=RT. So for perfect vacuum you need T=0K. Which is not possible by the third law of thermodynamics. So we will never achieve the perfect vacuum.

07/10/2020, 12:33 - +91 92696 26411: We cannot achieve P=o theoretically at this temperature the existence of matter is not possible.

07/10/2020, 12:39 - +91 92696 26411: My answer is no. I heard that little bit of degradation of the vacuum helps to stop ions to reach towards the cathode (gun). So in my opinion the vacuum tube does not require a perfect vacuum. It will not operate in a perfect vacuum.

07/10/2020, 12:53 - Meenu Kaushik: Sir,

In my view, when lets say, spontaneous emission takes place in vacuum, if the vacuum is receptive (means if vacuum is enclosed in a metal enclosure enough bigger so that one or more wavelength can fit in it), in such conditions, an excited atom will emit radiation in the vacuum. As we have placed an anode there, the emitted electrons gets attracted further to the positive anode and the vacuum ensures no collision of these electrons with any other particles on their way to anode.

07/10/2020, 13:11 - Ansu Saran Singh VNS: I can recall that sir answered this question in veda 2018 at iit Guwahati.

07/10/2020, 13:16 - Dr. Lalit Kumar: At T= 0 deg K you have the Bose-Einstein Condensate state of matter.

07/10/2020, 13:21 - Dr. Lalit Kumar: May i suggest that you may just remain confined to the question and do not bring new scenarios.

07/10/2020, 13:22 - +91 92696 26411: Sir it is near to 0k not at 0k. Because 0k is not possible by nernst theorem thermodynamics third law.

07/10/2020, 13:24 - +91 81074 33661: Sir, I am talking about naturally occurring electron plasma. However neutral plasma is also essential for non-magnetic field tubes like pasotron where we insert the gas intentionally to eliminate the requirements of external magnetic field up-to some extent. For Pasotron like tube, plasma is required to focus the electron beam.

07/10/2020, 13:58 - Vikram IIT BHU: Good to know sir, impinge is the reason of Degassing. So there is rise of pressure in vacuum.

07/10/2020, 14:05 - Dr. Lalit Kumar: You are right. Absolute zero and the third law of thermodynamics may be the topic for another debate. All new physics is discovered only by challenging the existing Laws. Incidentally, achieving negative temperatures below 9 deg Kelvin experimentally reported (not sure if it has been independently confirmed by the peers)

07/10/2020, 14:06 - Dr. Lalit Kumar:
https://www.sciencedaily.com/releases/2013/01/130104143516.htm

07/10/2020, 14:18 - Sharad Prasad CEERI: Yes, a vaccum electron device will work in so called perfect vacuum as for as electron interaction is concerned but one has to ensure proper thermal dissipation. In perfect vaccum, there is no need of vacuum envelope of the vacuum electron device and it will further enhance the capability i.e. power as there is no limitations on physical dimensions. As regard magnetron, electron emission by back bombardment of cathode will not be required as primary emission will itself more than sufficient in perfect vacuum.

07/10/2020, 15:24 - KSBhat MTRDC: Practically speaking, better the vacuum better will be the performance of VEDs. But, at the same time it is not possible to create an 'ideally perfect vacuum' environment in the lab.

I believe, an environment of perfect vacuum is like a blackhole in which all types of matter and energy will sink into nothingness i.e., into absolute vacuum. No useful energy exchange can take place in such an environment. So, I feel the answer is NO.

07/10/2020, 15:35 - Datta S K MTRDC: We were taught that electronic transport is not possible in "ideal vacuum".

07/10/2020, 15:38 - Dr. Lalit Kumar: below 0 deg K (That's right)

07/10/2020, 18:38 - BNBasu Prof: (i) Anshu S Singh was probably hinting at a tutorial lecture at VEDA-Guwahati where it was mentioned in a ppt presentation:

"The motion of the electrons in a vacuum tube is possible due to the presence of the positive ions that are always practically present in the tube and that neutralize the negative charges of the electrons."

"If the neutralizing positive ions were absent, the negative space-charge of the electrons would have caused a depression in the potential in the region of the traversal of electrons thereby causing the electrons to slow down, stop and even return."

(2) I was checking the answer of Niraj to my question after reading the reaction of Dr. Lalit Kumar raising an issue which Niraj also addressed. Niraj also emphasizes some sort of "plasma formation" as the requirement for the working of a vacuum electron device. If he still remains as naughty as he was as a student in my class, I sense bringing 'plasma' in his answer as a sort of his poster for the 'Plasma Group of CEERI' which he serves as the project leader of a number of projects. Joke apart, perhaps he is forcing me to ask my next question:

What is the role of plasma in enhancing the space-charge limiting current of a vacuum electron device?

07/10/2020, 19:02 - Karmakar MTRDC: Sir, it is really enlightening to go through the debate initiated by your question. In my opinion, the answer is No. Reason: an electron beam can travel only in the space-charge neutralized background medium. So, few positive ions are necessary in the medium. In fact, for high power Gyrotrons, space charge depression caused due to high beam current is one of the major problem. If the potential-well caused due to space charge depression becomes deep enough, it may prevent the beam from propagating

07/10/2020, 19:14 - LMJoshi CEERI: Its indeed very interesting discussion. I am wondering whether the presence of electrons in an enclosure itself does not violate the state of perfect vacuum?

08/10/2020, 13:12 - BNBasu Prof: What is the role of plasma in enhancing the beam current transport in a vacuum electron device?

08/10/2020, 15:29 - Dr. Lalit Kumar: In my opinion this argument alone settles the debate.

08/10/2020, 18:34 - KSBhat MTRDC: I think this corroborates my earlier argument that in absolute vacuum no matter or energy can exist and everything will annihilate into nothingness.

08/10/2020, 19:23 - Raj Singh IPR: Dear Santanu, I have some queries. How do we get positive ions in normal case for space charge neutralisation? Neutralising space charge may require good number of postive ion or positive charge or few will be enough? Is this condition essential in every type of tube or r u talking about plasma filled microwave tubes. I feel an electron beam can travel in absolute vacuum. In academic terms once the electron beam travel or occupy the vacuumed space the absolute vacuum vanishes.

08/10/2020, 19:37 - Dr. Lalit Kumar: I think you are possibly assuming that there is a pump with infinite pumping speed connected to the space which is maintaining a perfect vacuum in the volume and pumps everything to maintain a perfect vacuum.

However, the concept of perfect vacuum is an 'ideal' concept.

When any particle enters the space having an ideal perfect vacuum. It cannot be called to have a 'perfect vacuum.'

It's just a concept.

Like when one marries and another person enters in life one ceases to be a bachelor!

08/10/2020, 20:36 - Karmakar MTRDC: Dear Dr Raj, I was referring normal vacuum tubes, not plasma assisted devices. To my understanding, the amount of residual ions present in an ultra-high vacuum enclosure is good enough to neutralize a normal electron beam. However, I'll brush-up my understanding once more and get back

08/10/2020, 21:59 - Dr. Lalit Kumar: https://www.mwrf.com/markets/defense/article/21141105/army-explores-directedenergy-weapons?utm_source=RF+Defense+Electronics+Update&utm_medium=email&utm_campaign=CPS201001054&o_eid=4933J5527389E0I&rdx.ident%5Bpull%5D=omeda%7C4933J5527389E0I&oly_enc_id=4933J5527389E0I

08/10/2020, 23:15 - BNBasu Prof: The girls (electrons) 'quarrel' and fail to make progress. This calls for a society (vacuum electron device) in which both boys (ions) and girls (electrons) coexist for the progress (electron beam transport) of the girls (electrons) in the society (vacuum electron device). Joke apart, an electron emitted from an emitter will exert repulsive Coulomb force preventing another electron from being emitted from the emitter in the absence of the neutralizing background of ions, which cannot be created in a perfect or ideal vacuum.

09/10/2020, 05:57 - BNBasu Prof: Meenu, all girls (electrons) don't quarrel. In a society (device) like peniotron, say, gyro-peniotron, all electrons are good. Both initially accelerated and initially decelerated electrons deliver their kinetic energy to RF waves.

09/10/2020, 08:02 - Dr. Lalit Kumar: I think the explanation is a bit flawed. A predecessor electron can at best scatter the successor electron but need not create enough negative potential to prevent the emission of a successor electron.

09/10/2020, 08:15 - Sanjay Malhotra BARC: In much cooler environs, (sister society of supercondutivity) the girls (electrons), tango in "cooper pairs" to provide zero resistance transmission of current !!!

09/10/2020, 10:01 - +91 93143 96993: I wonder if Coulomb force is enough powerful than field force between cathode and anode to prevent the electron from movement/ emission. In my view if cathode anode field is large enough and collector has capability to collect electrons, the emission and movement of electrons will take place smoothly.

09/10/2020, 10:29 - BNBasu Prof: Please go through Vacuum Tubes by Spangenberg.

09/10/2020, 11:10 - +91 92696 26411: Sir thank you for a nice explanation.

It is similar to current flow from a wire. The wire remains neutral during the current flow because of the same amount of electron and a positive ion. If electrons pile of anywhere in the wire it start to charge the conductor and make a disturbance in the flow of electron.

Now I am able to understand theoretically for similar thing happening for vacuum electron device for perfect vacuum case.

But sir I am still not able to get a mathematical condition (equation of motion) to stop the motion of an electron in a perfect vacuum.

In particle in cell (PIC) simulation a region defined as a vacuum by defining relative permeability and permittivity 1. In the simulation, we never define any positive ion around the electron beam. But beam propagates through the defined vacuum. I make a sketch diagram of pic simulation. In this, we have to define a boundary condition Et=0 at cathode and collector as shown in fig. If we will not define Et=0 then the emission of electron stop due to charging of cathode.

09/10/2020, 14:16 - Dr. Lalit Kumar: I wish to further add that that while discussing VED Physics it is essential to define the physical domain: 1. inside cathode boundary, 2. between cathode boundary and space charge created potential minimum i.e. 'virtual cathode' 3.the electron gun region . 4. Interaction region 5. Collector region.

For diode, triode and magnetron like devices 3 , 4 and 5 above do not apply and region 3 is between the potential minima or virtual cathode and anode.

The' device" physics that we commonly discuss begins beyond the emitter which mostly coincides with the physical surface of the emitter except in the space charge limited condition when it is at the virtual cathode position.

So if one is concerned about what happens up to region 2 we are discussing "cathode physics" and not "device" physics (earlier statement does not apply to space charge limited cathode physics, as it is meant for what happens in the VED region 3 onwards

(In most practical VEDs the virtual cathode may be less than a few micron away from the physical cathode surface and hence ignored.)

Furthermore, In high current beam analysis the Coulomb scattering among the electrons, (though present) is ignored.

09/10/2020, 21:49 - Dr. Lalit Kumar: 1. What is usually defined as vacuum in electromagnetics is ' free space' as you have described above.

2. The VED' are practical device functioning under real life conditions of vacuum and there is nothing 'ideal' about it.

3. The cathode in majority of VEDs is a thermionic- cathode operating under space charge limited emission condition except for gyrotron devices where it is mostly operated under temperature limited condition. The space charge limited cathode's emitting surface which faces the anode/grid is the 'virtual

cathode" next to it but very close. The electric field at this surface is zero. Most simulations use a variant of Child's Law to determine space charge limited thermionic emission under the applied field at the cathode. For implementation of Child's Law in numerical simulation you need to define a 'fictitious/virtual surface a few mesh width away from the physical cathode. (This surface is not to be confused with 'virtual cathode' mentioned above).

4. The boundary Et =0 simply means metallic boundary or the Dirichlet boundary. A positive value of Et would mean a Neumann Boundary (electrode gap or dielectric)

Hope that clarifies. Feel free to call me for any further clarification.

09/10/2020, 21:49 - BNBasu Prof: Dr. Mercy Latha has significantly contributed to the area of multi-stage depressed collectors for the efficiency enhancement of helix-TWTs.

09/10/2020, 21:51 - SNJoshi CEERI: Welcome Dr Mercy Latha to this vibrant group. The recent discussions on the problem raised by Prof. Basu is an example of its vibrancy.

I also take an opportunity to express my greetings to all who were part of this debate. My special gratitude to Prof.Basu for being great Guru.

With best wishes to you all in your future endeavors.

10/10/2020, 05:10 - BNBasu Prof: "Maxwell's equations have had a greater impact on human history than any ten presidents" ~Carl Sagan

IEEE APS SB Chapter of GEC Barton Hill and IEEE MTT-S KERALA SECTION is elated to invite you to the IEEE APS Distinguished Lecturer Program by Prof Levent Sevgi (Istanbul OKAN University, Turkey) on the topic From Engineering Electromagnetics to Electromagnetic Engineering-Teaching and Training Next Generation

Join with us and Experience the Technical edge of Electromagnetic Engineering!!

Date: 12th October, 2020

Time: 6 PM (IST)   8:30 PM(TRT)

Registration link: bit.ly/3l9rUHU

All Active participants will get an E-Certificate of Participation.

10/10/2020, 07:21 - Shyam BhU: https://ieeexplore.ieee.org/document/9217562?fbclid=IwAR3kb0Cc817R5UzS1JQddjUXcSEqgQV9hSZTS7--YpftKt_vD_73qSV79Ak

11/10/2020, 11:44 - BNBasu Prof: In the series of “First Ever Vacuum Electron Devices and Applications Thereof,’ Dr. S. N. Joshi is going to deliver his talk on ‘First ever TWT built in India’ in a session (Expert Talk) to be chaired by Professor Chandra Shekhar, at Webinar#3 to be held on 7th November 2020 during 4.00--5-30 pm (IST). In the second session ‘Research Contributions of Younger Researchers in VEDs’ of the same webinar to be hosted by Dr. Vishant Dwivedi, we have Dr. Richards Joe Stanislaus presenting his talk on ‘Large-signal analysis of helix-TWTs’ and Dr. S. Yuvaraj presenting his talk on 'Investigation into multi-frequency coaxial gyrotron'.

I request all speakers to kindly submit the Abstracts of their talks to Professor Raj Singh, the Convener of the programme.

I eagerly await hearing from Dr. Joshi about the glass tube envelope, RF input/output couplers, attenuator, and magnetic field for beam confinement; material selection; and hot-testing of the device encompassing the measurement of RF output power, harmonic generation, AM-to-PM conversion coefficient, etc., in the first ever TWT built in India.

With suspense, I would like to know from the talk of Richards if he assumes a form of tape surface current density distribution over the tape width, as is conventionally done in Sensiper's tape-helix model. To the best of my knowledge, for the first time in the world, his group, composed of Professor N Kalyansundaram, Professor Navin Babu and others, has not made such an assumption of tape surface current density distribution.

Similarly, I eagerly look forward to the presentation of Yuvaraj to know about the coaxial cavity gyrotron including such aspects as mode rarefaction implemented by tapering the dimensions of the inner conductor as well as by grooving the central conductor. The thermal management of the device is supposed to be a concern of relevance including the cooling of the central conductor in such a device.

12/10/2020, 18:31 - Chandra Shekhar CEERI: Shall I hazard an answer!

No, because electrons are required for interaction, and the moment they are there, there is no perfect vacuum (it is electron gas filled vacuum; a Fermion gas rather than a Boson gas)

12/10/2020, 18:59 - BNBasu Prof: Wonderful! My understanding was that an electron emitted will repel another electron to come out from the emitter. The square root of 4 are both +1 and -1. I am tempted to believe that both the answers are correct. You are the best judge. I value it so much.

The question is hypothetical and ideally the medium is perfect vacuum.

14/10/2020, 12:01 - BNBasu Prof: I am happy to inform that Professor K P Maheshwari has given his consent to deliver a lecture on this platform. I hope he would share his experience of developing the first ever relativistic backward-wave oscillator in India. I am sure Professor Raj Singh will kindly arrange it sometime in 2021.

15/10/2020, 12:28 - BNBasu Prof: Is there any highly efficient gyro-device in which 'all' electrons are 'good' in delivering their kinetic energy to RF waves?

15/10/2020, 12:35 - Meenu Kaushik: I wonder if you have already answered this question in this above comment while explaining good and bad electrons! You told us that Gyro-peniotron is such a device for having all good electrons.

17/10/2020, 18:51 - BNBasu Prof: There are gyro-devices with gyrating electrons, such as gyrotron, gyro-klystron and gyro-twystron, which belong to the family of fast-wave devices. Is there any gyro-device which belongs to the family of slow-wave devices?

17/10/2020, 23:04 - +91 95289 12230: synchrotron continuous wave accelerator or simply _Synchrotron_

18/10/2020, 11:51 - BNBasu Prof: I didn't get the answer to my satisfaction.

18/10/2020, 12:14 - Ansari BHU: I am guessing Sir...

Is it FEL ? FEL also refered as Synchrotron

18/10/2020, 12:17 - BNBasu Prof: Far from the answer to my satisfaction.

18/10/2020, 12:30 - Ansu Saran Singh VNS: It may a helical beam device with weibel instability.

SWCA seems fit in the requirement.

18/10/2020, 12:32 - Ansu Saran Singh VNS: Slow-wave cyclotron amplifier

18/10/2020, 13:34 - Shyam BhU: It is slow wave cyclotron amplifier (SWCA) based on bremsstrahlung radiation or deceleration radiation and weible instability. Here the decelerating particles loses their kinetic energy to the wave. SWCA is used in broadband application by introducing some severe/dielectric loading.

19/10/2020, 08:16 - BNBasu Prof: Thank you all for taking interest in answering my question. The answer that Anshu gave and Shyam corroborated is:

SLOW-WAVE CYCLOTRON AMPLIFIER (SWCA).

The answer excited my memory and I recall (from the book authored by Vishal titled "High power microwave tubes: basics and trends" (Volume 2) with me as his co-author) that SWCA is a gyro-device based on Weibel instability in which the axial, non-relativistic bunching takes place; the axial kinetic energy of the electron beam is converted into electromagnetic energy; and a slow waveguide-mode is destabilized in the waveguide (unlike in a conventional gyro-device, such as the gyro-TWT, which is based on cyclotron resonance maser instability, in which the azimuthal, relativistic bunching takes place; the azimuthal kinetic energy of the electron beam is converted into electromagnetic energy; and a fast waveguide-mode is destabilized in the waveguide).

Further, the slow-wave mode is realized in SWCA by dielectric lining the waveguide wall such that the waveguide-mode dispersion plot is depressed below the beam-mode dispersion line of the device. Also, the SWCA provides wideband coalescence between the beam-mode line and waveguide-mode dispersion plot that makes SWCA a wideband device. However, SWCA operates at relatively lower frequencies. It also operates at relatively lower beam voltages or beam powers, and hence it delivers lesser RF output powers as well. However, the presence of a dielectric in the waveguide to slow down the RF waves makes the device prone to heating by the charging of the dielectric if it is lossy. Thus, the device needs to be provided with a good beam alignment in the device to avoid the dielectric charging. A thin layer of metal coating on the dielectric surface has also been suggested to drain out the charge developed, if any, on the surface. Further, SWCA is a Doppler-shift device, operating at a large value of the axial phase propagation constant, thereby making SWCA prone to inhomogeneous broadening of the cyclotron band due to beam velocity spread.

19/10/2020, 19:32 - Dr. Vishal Kesari: Join online tomorrow, 20 October 2020, at 3:00p.m. IST for an interactive web workshop on 'Modeling Optic and Photonic devices using COMSOL Multiphysics ®'.

To register, please visit: http://comsol.co.in/c/b3i0

During this web workshop, you will:

- Explore the capabilities of COMSOL ® for modeling optic and photonic devices including lenses, polarizers, prisms, and beam splitters

- Learn how to solve Maxwell's equations to simulate optical wave propagation, reflection, absorption, scattering and diffraction

- Couple multiple physics to perform STOP analysis, as well as model thermally induced optical deformation and optoelectronics

I hope to see you there! Feel free to invite your colleagues too.

20/10/2020, 11:46 - BNBasu Prof: For some more details, one can see Lecture 24 in the 'Download' section of my website <www.bnbasu.com> uploaded by Debashis Mondal.

21/10/2020, 12:08 - BNBasu Prof:

Dear Professor Basu, Dear Vishal,

Thank you very much for informing me about the seminar and sending me the Proceedings of the 2nd Webinar in the VED Thinkers Group.

Congratulations! It has been an excellent idea to organize this virtual seminar and to keep the VED community in India well informed and assembled together in these strange and horrible times of Corona Pandemic!

I would be very thankful to you, if you would keep me up to date on the Webinars and would send me also the Proceedings of the other Seminars ....

Friendly yours

Manfred Thumm

23/10/2020, 14:37 - Student BNB Mankundu: 'At, this time I am reaching out to you on behalf of Prof. G. Rangarajan, Director, Indian Institute of Science (IISc), Bangalore. IISc is India's top ranked university, as per the MHRD NIRF Rankings in India and several international rankings. The Government of India has accorded to IISc the status of an "Institution of Eminence". (www.iisc.ac.in)

The Institute is looking for exceptionally bright and motivated individuals with an established record of high-quality research, and a strong commitment to teaching, for faculty positions in its various academic departments and centres spanning various branches of science and engineering. The Institute invites applications from citizens of India as well as other nationalities. IISc strongly encourages diversity among its faculty.

The Institute is delighted to hold an online interactive session with prospective faculty candidates keen on knowing more about faculty opportunities at IISc in all areas of science and engineering. This is scheduled on 19th and 20th November.

More details are available at : https://yrm.iisc.ac.in/

24/10/2020, 12:40 - Dr. Lalit Kumar: I think 2023 IVEC would be in Asia. It is India's turn but there seems to be no interest so far. Prof Kartijeyan could update on the matter.

25/10/2020, 11:41 - Dr. Lalit Kumar: I think Dr Kartikeyan, Member IEEE EDS VETC, Director MTRDC and President VEDAS are rightly placed to take the lead to organise the IVEC 2023. They would definitely get the whole hearted support of all the organizations involved in VED activities: MTRDC CEERI IPR SAC BARC SAMEER IITs, NIT/P VEDA society etc. and all of us.

If we do, it would become a tradition; IVEC 2011-2023 -2035 and so on: another 'KUMBH' of VED Gyan Ganga in India.

I request all colleagues to come forward with their views and support to make IVEC 2023 -INDIA a reality.

26/10/2020, 11:02 - Raj Singh IPR: Dear All,

We have announced the tentative programme of 3rd webinar to be held on 7th November 2020.

We are also planning our 4th, 5th, 6th and 7th webinar programmes to be held in 2021 as follows.

In the 4th webinar, Professor Cludio Paoloni of Lancaster University will deliver his talk, tentatively in January 2021. Ms. Rupa Basu at Lancaster University is coordinating with Professor Paoloni to let us know the date and title of his talk.

In the 5th webinar, to be held tentatively in March 2021, Dr. R S Raju will deliver a talk on Cathodes Encompassing - The First Ever Cathode Developed in the Country.

In the 6th webinar to be held tentatively in May 2021, Professor K P Maheshwari will share his experience on the first ever Relativistic Backward-Wave Oscillator developed in the country. Dr. Niraj Kumar is coordinating with Professor Maheshwari to let us know the date and title of his talk.

In the 7th webinar, Professor L M Joshi will deliver a talk on Klystrons Encompassing - The First Ever Klystron Delivered in the Country. Professor BN Basu is coordinating with Professor Joshi to let us know the date and title of his talk.

With the group members' cooperation, we may adjust the dates of the webinar programmes by reducing the time between consecutive programmes, if necessary. Members may also suggest the name of the speakers to whom they want to listen.

26/10/2020, 12:04 - BNBasu Prof: Thanks to the Convener of the webinars making the planning. I look forward to lectures of young researchers with due permission from their guides and/or concerned authorities. We have so far attended the lectures of Mumtaz Ali and Manpuran. On 7th November 2020, we're going to attend the lectures of Richards and Yuvraj. So the other potential speakers may please let us know the topics of their lectures.

26/10/2020, 18:30 - Dr. Lalit Kumar: https://youtu.be/8Cw35-_Bb0M

26/10/2020, 18:30 - Dr. Lalit Kumar: Talk by Prof. Annapurni Subramaniam (IIA, Bengaluru) titled "Astronomy & Astrophysics: Physics, Chemistry and Mathematics of the Universe" on 31st October at 5 pm.

27/10/2020, 17:38 - BNBasu Prof: Webinar#3; 7th November 2020:

Dr. S. Yuvaraj has revised the topic for his presentation replacing the previously announced topic

Investigation into Multi-Frequency Coaxial Gyrotron

with

Recent Trends in Millimeter/THz Wave Vacuum Electron Beam Devices.

I thank Dr. Vishal Kesari for bringing this point to my notice. Professor Raj Singh has assured me that he would kindly incorporate this modification in the final announcement of the programme. The host Dr. Vishant Dwivedi has also been informed of this change.

29/10/2020, 10:45 - BNBasu Prof: Webinar #4 to be held in January 2021 (following Webinar #3 to be held on 7th November 2020):

We have tentatively fixed the lecture by Professor Claudio Paoloni of University of Lancaster on 9th January 2021, Saturday, at IST 3:30 pm on Google Meet platform. Ms Rupa Shaw (Basu) and Dr. Uttam Goswami are coordinating the programme. Professor Raj Singh will kindly convene the programme and announce later the exact topic of the lecture. Professor PK Jain has kindly given his consent to chair the session and accordingly adjusted his calendar. Dr. P Raja Ramana Rao will kindly propose Vote of Thanks.

29/10/2020, 10:59 - Raj Singh IPR: Webinar #3

Tentative Programme

7th November 2020

From 4.00 PM to 5:30 PM

Session 1: Expert Talk

Duration: 40 minutes

Chair: Professor Chandra Shekhar

Speaker: Dr. S. N. Joshi: Topic: First Ever TWT Built in India

Session 2:

Research Contributions of Younger Researchers in VEDs

Duration: 40 minutes

Host: Dr. Vishant Dwivedi

Speakers:

1. Richards Joe Stanislaus: Topic: Large-Signal Analysis of Helix-TWT

2. Dr. S. Yuvaraj: Topic: Recent Trends in Millimeter/THz Wave Vacuum Electron Beam Devices

Convener: Raj Singh

30/10/2020, 18:22 - KSBhat MTRDC: https://spectrum.ieee.org/tech-history/space-age/the-11-greatest-vacuum-tubes-youve-never-heard-of

31/10/2020, 09:20 - KSBhat MTRDC: In fact I am looking for some info on compact, repetitive, pulse power systems based on explosive power (FCG) technology. If anyone can throw some light on this it would be nice.

31/10/2020, 11:33 - BNBasu Prof: My question pertains to a gyrotron with its interaction cavity excited in TE03 mode, as it is in the first ever gyrotron developed in India. As can be seen from the accompanying figure, for TE03 mode, in the azimuthal electric field pattern, there are two positive maxima and one negative maximum, the latter located in the radial position between two positive maxima. The beam is located at the positive maximum that is nearest to the wall and farthest from the cavity axis. Interestingly, at this beam location, the magnitude of maximum azimuthal electric field is the least of the magnitudes of maximum/minimum azimuthal electric field in the field pattern. My question is why the electron beam is positioned at such radial location to experience the least magnitude of maximum/minimum electric field to interact with. I am awaiting the answer for which I thank you in anticipation.

31/10/2020, 11:46 - Shyam BhU: As I think, electron beam positioned as to achieved maximum beam wave coupling as well minimum electron beam collision with tube wall.

31/10/2020, 11:46 - Dr. Lalit Kumar: One of the solutions could be to put multiple-stage FCGs somewhat similar to multiple stage rocket engines on a missile.

31/10/2020, 11:59 - KSBhat MTRDC: Yes sir. Even I was thinking in the same direction. In a rocket we may have two or three stages but here we need to have hundred of stages (FCGs) to be fired one after another. If we can do this we will have ultra compact repetitive pulse power systems ready to use in airborne platforms!

31/10/2020, 12:01 - Dr. Lalit Kumar: it may be easier to put a turbine engine to produce electricity on board.

31/10/2020, 12:02 - KSBhat MTRDC: But what about compactness we are looking for?

31/10/2020, 14:12 - Karmakar MTRDC: Sir, I think, the reason for keeping the hollow beam at the second field maxima, instead of first (even though the field strength is higher at the first field maxima) is as follows: If we keep the hollow beam at the first field maxima, the beam dia will significantly reduce. This will lead to very high space charge depression. So, in order to arrive at a trade-off, its better to keep the beam at 2nd maxima (though there will be lesser field available for interaction and higher possibility of body interception of beam)

31/10/2020, 15:29 - Ansu Saran Singh VNS: Radial wall location is the highest for TE03, therefore highest power handling capabilities can be achieved.

As well as, to minimize the space charge effect it is preferable to operate away from the radial half, towards wall.

31/10/2020, 15:32 - Ansari BHU: Sir

The space charge limiting current for annular electron beam increases with the increase in beam radius keeping cavity radius constant. Now, as the beam current increases and approach the space charge limiting current, the space charge factor start increasing exponentially which will cause voltage compression by the same factor.

Gyrotron is off to my research topic but I know in general that beam should be close to the interaction space with appropriate gap in between to reduce the voltage compression effect that can degrade the device efficiency. and higher order mode will help to improve the power handling capability of the device in addition to space charge limiting capability for the annular beam of the device in comparison to the fundamental mode.

31/10/2020, 15:37 - Ansu Saran Singh VNS: Voltage depression is decreasing and limiting current is incrasing with waveguide radius.

Apart from that it is mentioned in TE03 is well separated mode from parasitic modes.

01/11/2020, 12:35 - BNBasu Prof: Santanu: Your to-the-point answer followed by reasoning and explanation was very helpful. If, in your answer, by "second field maxima instead of first" you mean "second positive field maximum instead of first positive field maximum", according to my question, I understood your answer bringing the space-charge depression in your reasoning. I thank you very much for helping me understand the problem.

Further, now I remember that the expression for the space-charge limiting current imposed by space-charge depression, which supports your answer, has been deduced from first principle in Section 3.6 of the book: Vishal Kesari and B. N. Basu, High Power Microwave Tubes: Basics and Trends, Volume 1, Morgan and Claypool Publishers, San Rafael (California)/Bristol: IOP Publishing (2018). This also helps.

01/11/2020, 12:42 - BNBasu Prof: Santanu: See also page 430 of the attached paper of Temkin et al.

01/11/2020, 15:34 - Dr. Lalit Kumar: In gyrotron resonator operating in TE031 mode there are 3 power maxima. The positive/negative fields are only temporal. Temkins and others used the second power maxima and not the third (as appears to be hinted in this discussion) as that is very feeble and too close to the wall.

01/11/2020, 17:19 - BNBasu Prof: Thanks to Dr. Lalit Kumar for concluding the discussion giving us the clear-cut say about where to locate the beam. In the first gyrotron developed in India, this beam location for the TE03 waveguide mode was chosen for the interaction cavity.

01/11/2020, 19:01 - Dr. SSS Agarwala Ex-CEERI: I became a 'passive' member of this group, thanks to Prof Basu, and after seeing the learned and highly informative exchanges, I am glad I did. My very best wishes to all.

01/11/2020, 19:43 - Dr. Lalit Kumar: I request Respected Dr Agarwala - a role model and mentor to many of us to kindly share his experiences in Imperial college and highlights of his days in CEERI. We would all be delighted and inspired to hear him.

Request Prof Basu to make it possible.

02/11/2020, 20:17 - Raj Singh IPR: Dear All, there is small but important addition to the 3rd Webinar going to be held on 7th November 2020.

Dr. S S S Agarwala, Scientist, superannuated from CSIR-CEERI, Pilani, would share with the group his experience at CEERI and about his research at Imperial College of Science and Technology, London leading to his Ph. D. degree of London University.

Thus, we have the following tentative programme:

Webinar #3

Tentative Programme

7th November 2020

From 4.00 PM to 6:00 PM

Introductory Talk: Good Wishes to the Group

Speaker: Dr. S S S Agarwala

Though Dr. S S S Agarwala does not need any introduction yet Dr. Lalit Kumar will introduce Dr. S S S Agarwala to the younger generation of the group.

Session 1: Expert Talk

Chair: Professor Chandra Shekhar

Speaker: Dr. S. N. Joshi: Topic: First Ever TWT Built in India

Session 2: Research Contributions of Younger Researchers in VEDs

Host: Dr. Vishant Dwivedi

Speakers:

1. Dr. Richards Joe Stanislaus: Topic: Large-Signal Analysis of Helix-TWT

2. Dr. S. Yuvaraj: Topic: Recent Trends in Millimeter/THz Wave Vacuum Electron Beam Devices

Vote of Thanks: Dr. L M Joshi

Convener: Raj Singh

02/11/2020, 22:10 - Dr. Lalit Kumar:
https://www.mwrf.com/markets/defense/article/21143743/army-signs-verus-research-for-ew-and-directedenergy-

simulation?utm_source=RF+Defense+Electronics+Update&utm_medium=email&utm_campaign=CPS201028065&o_eid=4933J5527389E0I&rdx.ident%5Bpull%5D=omeda%7C4933J5527389E0I&oly_enc_id=4933J5527389E0I

03/11/2020, 19:57 - Ansari BHU: https://www.mwrf.com/markets/defense/article/21143743/army-signs-verus-research-for-ew-and-directedenergy-simulation?utm_source=RF+Defense+Electronics+Update&utm_medium=email&utm_campaign=CPS201028065&o_eid=4933J5527389E0I&rdx.ident%5Bpull%5D=omeda%7C4933J5527389E0I&oly_enc_id=4933J5527389E0I

05/11/2020, 09:40 - BNBasu Prof: Dear All, there is small but important addition to the 3rd Webinar going to be held on 7th November 2020.

Dr. S S S Agarwala, Scientist, superannuated from CSIR-CEERI, Pilani, would share with the group his experience at CEERI and about his research at Imperial College of Science and Technology, London leading to his Ph. D. degree of London University.

Thus, we have the following tentative programme:

Webinar #3

Tentative Programme

7th November 2020

From 4.00 PM to 6:00 PM

Introductory Talk: Good Wishes to the Group

Speaker: Dr. S S S Agarwala

Duration of talk: 30 minutes

Though Dr. S S S Agarwala does not need any introduction yet Dr. Lalit Kumar will introduce Dr. S S S Agarwala to the younger generation of the group.

Session 1: Expert Talk

Duration of session: 40 minutes

Chair: Professor Chandra Shekhar

Speaker: Dr. S. N. Joshi

Topic: First Ever TWT Built in India

Duration of talk: 40 minutes

Session 2: Research Contributions of Younger Researchers in VEDs

Duration of session: 40 minutes

Host: Dr. Vishant Dwivedi

Speakers:

1. Dr. Richards Joe Stanislaus: Topic: Large-Signal Analysis of Helix-TWT

2. Dr. S. Yuvaraj: Topic: Recent Trends in Millimeter/THz Wave Vacuum Electron Beam Devices

Vote of Thanks: Dr. L M Joshi

Convener: Raj Singh

05/11/2020, 21:23 - BNBasu Prof: Dr. Gahlaut, Please confirm if the link:

https://meet.google.com/htn-ckxd-ueg

is finalized to attend Webinar#3 to be held on 7th November. Please share the link with the members and interested non-members of the Group in the country and abroad.

06/11/2020, 07:36 - Raj Singh IPR: Webinar #3 Program

7th November 2020

From 4.00 PM to 6:00 PM

Introductory Talk: Good Wishes to the Group

Speaker: Dr. S S S Agarwala

Introduction of Dr. S S S Agarwala by Dr. Lalit Kumar

Session 1: Expert Talk

Chair: Professor Chandra Shekhar

Speaker: Dr. S. N. Joshi

Topic: First Ever TWT Built in India

Session 2: Research Contributions of Younger Researchers in VEDs

Host: Dr. Vishant Dwivedi

Speakers:

1. Dr. Richards Joe Stanislaus; Topic: Large-Signal Analysis of Helix-TWT
2. Dr. S. Yuvaraj; Topic: Recent Trends in Millimeter/THz Wave Vacuum Electron Beam Devices

Vote of Thanks: Dr. L M Joshi

Convener: Raj Singh

06/11/2020, 07:38 - Vishant Gahlaut Bansthali: Dear All

I request all the eminent members of VED thinkers to join the 3rd meeting via Google meet well before 4 PM in order to commence the webinar at scheduled time on 7th November 2020.

The web link is as follows;

https://meet.google.com/htn-ckxd-ueg

Thanks

07/11/2020, 21:43 - Dr. Vishal Kesari: Dear Dr. Richards Joe Stanislaus and Dr. S. Yuvaraj,

Please share your slides of today's talk to be included in the proceedings of webinar#3.

Thanks

Vishal Kesari

08/11/2020, 08:37 - Sheel Aditya Prof: It was a pleasure to hear the stalwarts, young researchers, as well as the expert comments. Congratulations to the organizers. Special thanks to Professor Basu for motivating and bringing the VED community together.

08/11/2020, 08:47 - KSBhat MTRDC: It was a great opportunity to hear Dr SSS Agarwala on his journey in vacuum tubes arena. Equally motivating was the talk by Dr SN Joshi on the very first tube designed and developed in the country. Presentations by the young researchers were are also impressive. Thanks to Prof Basu for creating the platform.

08/11/2020, 10:42 - Dr. SSS Agarwala Ex-CEERI: It was a great experience for me to participate in the Webinar yesterday evening. I warmly thank all who organised it, and Prof BN Basu, in particular, for getting me included in this group. My greetings and best wishes to all - SSSA

08/11/2020, 12:30 - SNJoshi CEERI: It was a very well organized Webinar under the domain of "Thinkers in VED". I very much appreciate the efforts of the organisers under the umbrella of Prof. BN Basu.

It was a great opportunity for all of us to hear the experiences of my mentor Dr SSS Agarwala, with whom I had a privilege to remain associated in CSIR-CEERI for about 24 years. He enriched the knowledge of all of us particularly those of our younger generations working in this critical area having vital significance.

This platform also provided an opportunity to me to share about the first TWT designed and developed by CEERI under the steward leadership of Dr. SSS Agarwala.

It was also nice to hear our two young and dynamic researchers working in this area. I express my best wishes to them in their endeavours.

With best wishes and greetings,

SN Joshi

08/11/2020, 14:42 - Chandra Shekhar CEERI: A forum that cross-links all the researchers in VED area across institutional boundaries for mutual strengthening and leveraging to meet vital national challenges is a great service to the discipline of VED.

I congratulate Dr. Basu and others involved in conceptualising and implementing this initiative.

Best wishes!

08/11/2020, 14:47 - Chandra Shekhar CEERI: It was also a great idea to bring the generations of researchers together to share the perspectives and evolving context.