Trends in the Development of Microwave Tubes

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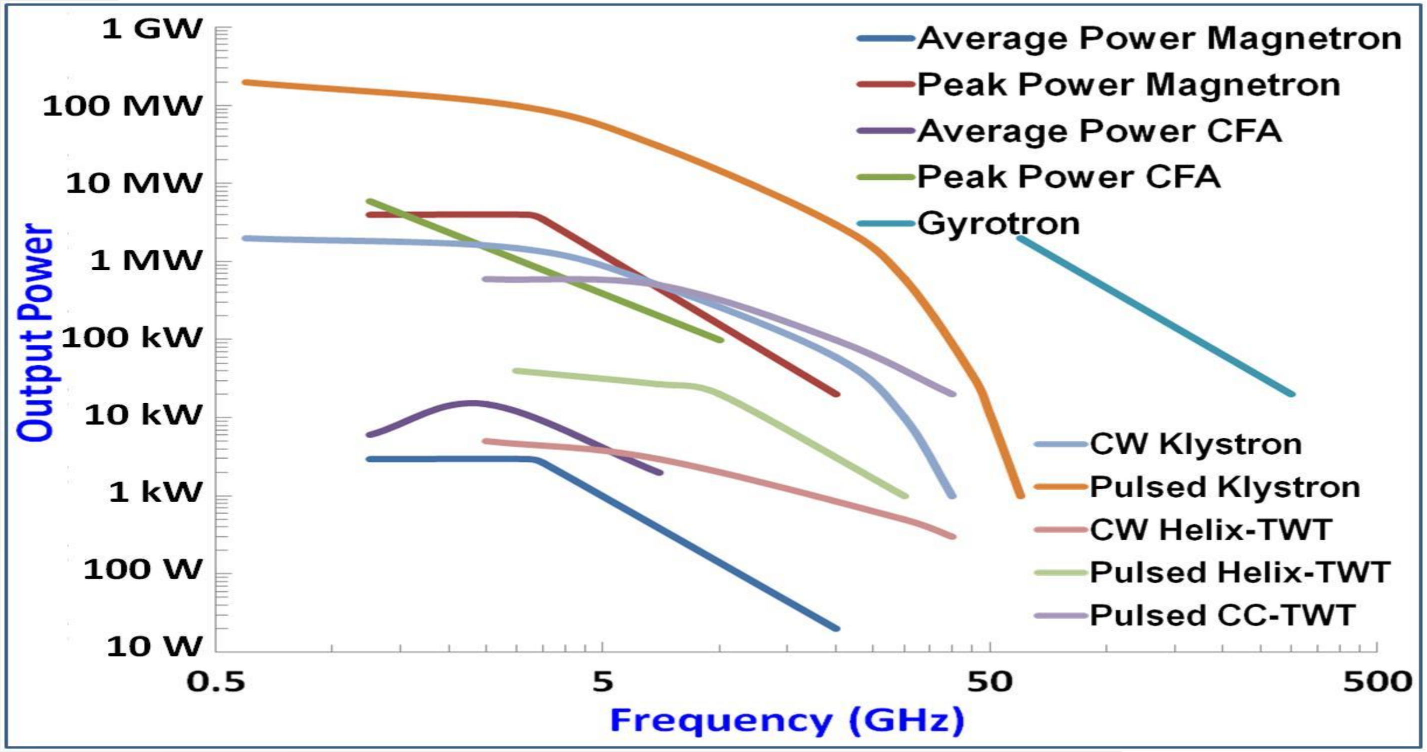
"Was there ever a more horrible blasphemy than the statement that all the knowledge of God is confined to this or that book? How dare men call God infinite, and yet try to compress Him within the covers of a little book!"

— Swami Vivekananda (Raja-Yoga)

<table>
<tr><th>Frequency ranges/bands (MHz/kHz/GHz)</th><th>Terminology</th></tr>
<tr><td>Radio waves: 3 kHz-3 GHz</td><td rowspan="5">ISM: Industrial, Scientific and Medical
ELF: Extremely low frequency
VLF: Very low frequency
LF: Low frequency
VHF: Very high frequency
UHF: Ultra high frequency
SHF: Super high frequency</td></tr>
<tr><td>Microwaves: 3-300 GHz</td></tr>
<tr><td>ISM band: 6.765-6.795 MHz; 13.553-13.567 MHz; 26.957-27.283 MHz; 40.66-40.7 MHz; 433.05-434.79 MHz; 902-928 MHz; 2.4-2.5 GHz; 5.725-5.875 GHz, 24-24.25 GHz</td></tr>
<tr><td>ELF: <3 kHz; VLF: 3-30 kHz; LF: 30-300 kHz; MF: 0.3-3 MHz; HF: 3-30 MHz (short radio wave); VHF: 30-300 MHz (FM radio, TV); UHF: 300-3000 MHz (TV, mobile phone, GPS); SHF: 3-30 GHz (radar); EHF: 30-300 GHz (millimetre-wave); Terahertz: 300-3000 GHz (sensing and imaging)</td></tr>
<tr><td>L: 1.12-1.70 GHz; S: 2.60-3.95 GHz; C: 3.95-5.85 GHz; X: 8.20-12.40 GHz; Ku: 12.40-18.00 GHz; K: 18.00-26.50 GHz; Ka: 26.50-40.00 GHz; V: 40.00-60.00 GHz; E: 60.00-90.00 GHz; F: 90.00-140.00 GHz; W: 75-110 GHz (satellite communications, targeting, tracking, active denial system)</td></tr>
</table>

Output power of typical microwave tubes in different frequency ranges



Power capabilities of typical travelling-wave tubes

TWT	Manufacturer	Band	Power (W)
Satellite communication (ground-station)	Thales	Ku	750
	CPI	Ku	1200 (Peak)/600 (CW)
	Teledyne	C/X/Ku	350/600/350
	NEC	Ka	350 (Peak)/250 (CW)
Satellite communication (space)	L-3	K	50 to 130
	Thales	Ku	100 to 150
	CPI	S	130 k, 8% duty cycle
Radar	e2V	X	20 k, 8% duty cycle
	Thales	Ka	1k, 12% duty cycle
	L-3	4.5-18GHz	110

……Power capabilities of typical travelling-wave tubes

EW	e2V	4.5-18GHz	100
	Thales	6-16GHz 4.5-18GHz	1500 200
mm-wave CW radar and EW	Hughes (now L-3)	59.7-60.3GHz	50
mm-wave CW communication (space-type)	Hughes (now L-3)	84-86GHz	200
mm-wave CW ground terminal	Hughes (now L-3)	91-96GHz	100

Power capabilities of typical high power microwave tubes

Device (manufacturer/ developer)	(GHz)	(MW)	(ms/μs/ns)	PRF (Hz/single-shot)
Klystron (CPI)	2.998	150	3μs	60
Klystron (multi-beam) (Thompson CSF)	1.3	10	1.5ms	10
RELTRON (Titan)	2.85	25	2μs	10
Magnetron (CPI VMS)	2.845	50	600ns	10
MILO (AFRL)	1.2	300	600ns	Single-shot

Power capabilities of typical gyrotrons

Type	Power	Frequency	Efficiency
Conventional Pulsed power gyrotron	340kW	Ka-Band	——
	1.1MW	100GHz	
	645kW	140GHz	
Conventional short-pulse (<10ms) gyrotron	2.1MW 1.2MW	100GHz	30%
	1.2MW	231GHz	20%
Conventional CW power gyrotron	200kW	28-60GHz	——
	100kW	140GHz	

……Power capabilities of typical gyrotrons

Type	Power	Frequency	Efficiency
Conventional Quasi-CW (long-pulse) gyrotron	1.05MW	8GHz	——
	0.37MW	110GHz	——
	10kW	503GHz	5.5%
Coaxial cavity ($TE_{20,13}$ mode) gyrotron	2.1MW	100GHz	——

……Power capabilities of typical gyrotrons

QOG (quasi-optical) gyrotron	1kW CW	34GHz (9% frequency tunability)	——
	600kW (pulse length: 0.013ms)	120GHz	9%
Relativistic (beam voltage: 3.3MV, beam current: 80kA)	1000MW	8.35-13	0.4%
Commercial	200kW	60GHz	——
	100kW	140GHz	——

Historical Timeline

1901-1920		
Fleming valve (vacuum tube diode)	John Ambrose Fleming	1904
First rudimentary radar	C. Hülsmeyer	1904
Audion or triode valve	Lee DeForest	1906
Physics of electric oscillation and radio telegraphy	G. Marconi and K. F. Braun (Nobel prize)	1909
Magnetron in early form	H. Gerdien	1910
Commercial electron tube	Radio Corporation of America (RCA)	1920

1921-1940		
Smooth-wall, split-anode magnetrons	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	Albert Hull and N. H. Williamsat General Electric and Bernard Tellegen at Phillips	1926
Beam diffraction oscillogram (beam and helix-wave interaction)	A. V. Haeff	1933
Travelling-wave tube	A. V. Haeff	1933

Multi-cavity magnetron	K. Posthumas, H.E. Hollmann	1935
Linear beam MWT theory	Oskar Heil	1935
Klystron	George F. *Metcalf* and William C. *Hahn*	1936
Klystron	Russel Varian and Siguard Varian	1937
Improved cavity magnetron for radar	J. T. Randall and H. A. H. Boot	1939
Travelling-wave tube	N. E. Lindenblad (US patent 2,300,052 filed on May 4, 1940 issued on October 27, 1942)	1940

1941-60		
Travelling-wave tube	Rudolf Kompfner	1942
Travelling-wave tube	Lester M. *Field* (U. S. Patent 2,575,383)	1946
Travelling-wave tube	J. R. Pierce (U. S. Patent 2,602,148)	1946
Generation of microwaves by rotational energy of helical electron beam	H. Kleinwachter	1950
Maser	James P. Gordon	1954
Electron cyclotron maser interaction theory	J. Schneider R. Twiss A. Gaponov	1957 1958 1959

1961-1980		
Gyrotrons (earliest version) in Russia (1965)	1965	1965
1981-1990		
Gyrotron in JET and ITER		
1990 onwards		
Modern gyrotron technology IAP, Russia; Gycom, Russia; FZK, Germany; JAERI, Japan; Toshiba, Japan; CPI, USA; TTE, France; CRPP, France, MURI, USA, CSIR-CEERI, India, and so on		

Who was the inventor of what?

"SUCCESS HAS MANY FATHERS, BUT FAILURE IS AN ORPHAN."

Transmission and Reception of Radio Waves:

G. Marconi?

A. S. Popov?

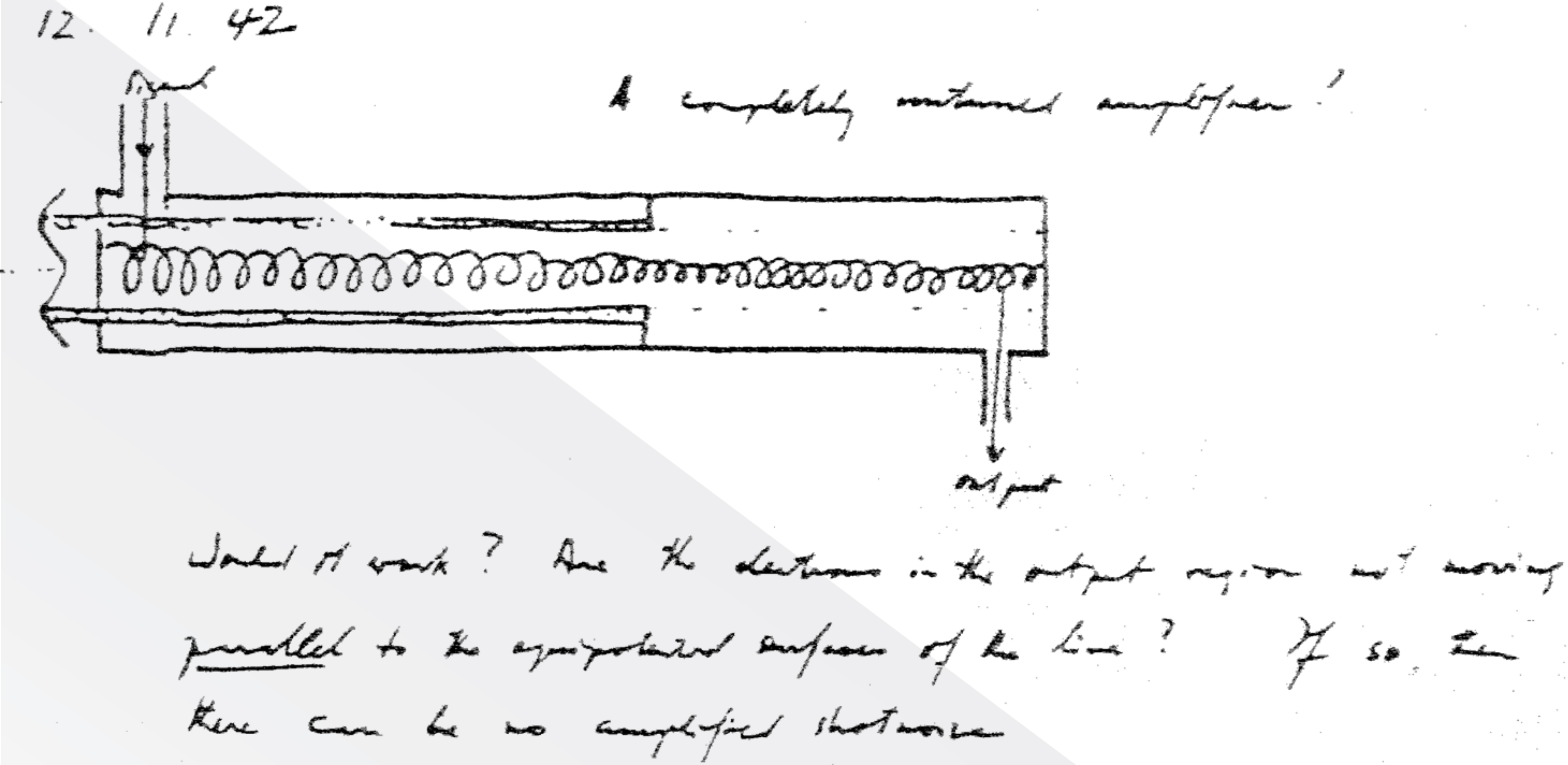
J. C. Bose?

Travelling-Wave Tube:

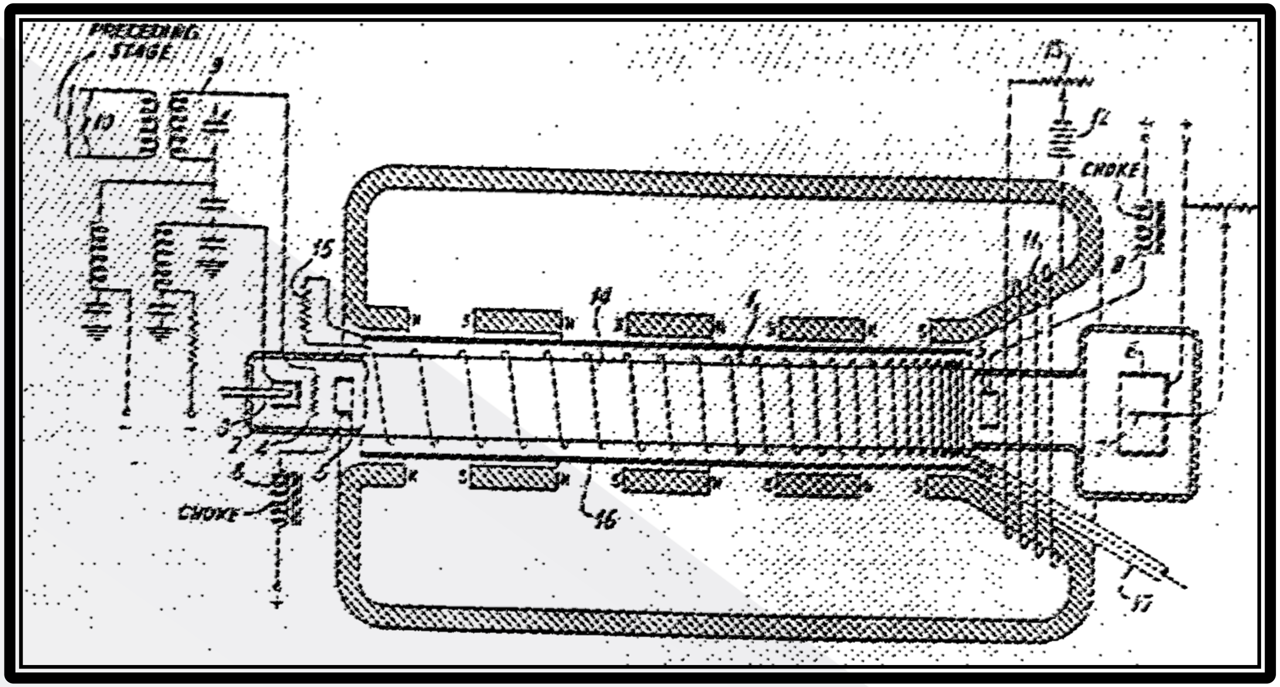
R. Kompfner?

N. E. Lindenblad?

A. Haeff?

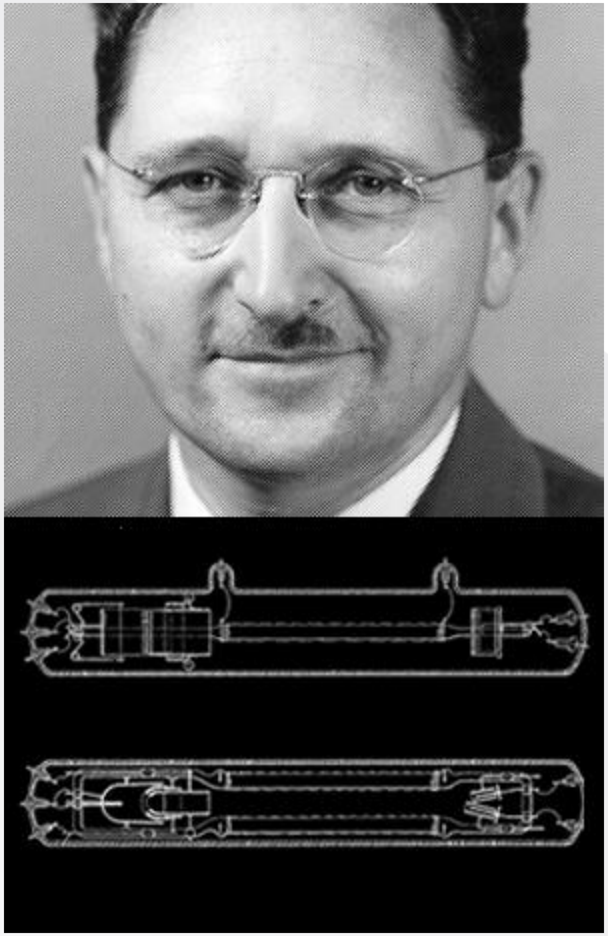


Sketch of the travelling-wave tube from R. Kompfner's note book



N. E. 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



The patent Andrei Haeff filed in 1933 for a primitive type of traveling-wave tube has been largely ignored.

J. C. Bose

All Indians should be inspired by the momentous work of J.C. Bose. He is the first ever scientist in the world to demonstrate the wireless transmission of electromagnetic waves. Hertz in 1888 generated and detected electromagnetic waves typically at 30 and 450 MHz; on the contrary, J. C. Bose of India demonstrated these phenomena in the millimetre-wave frequency range. (Edited by Subhradeep)

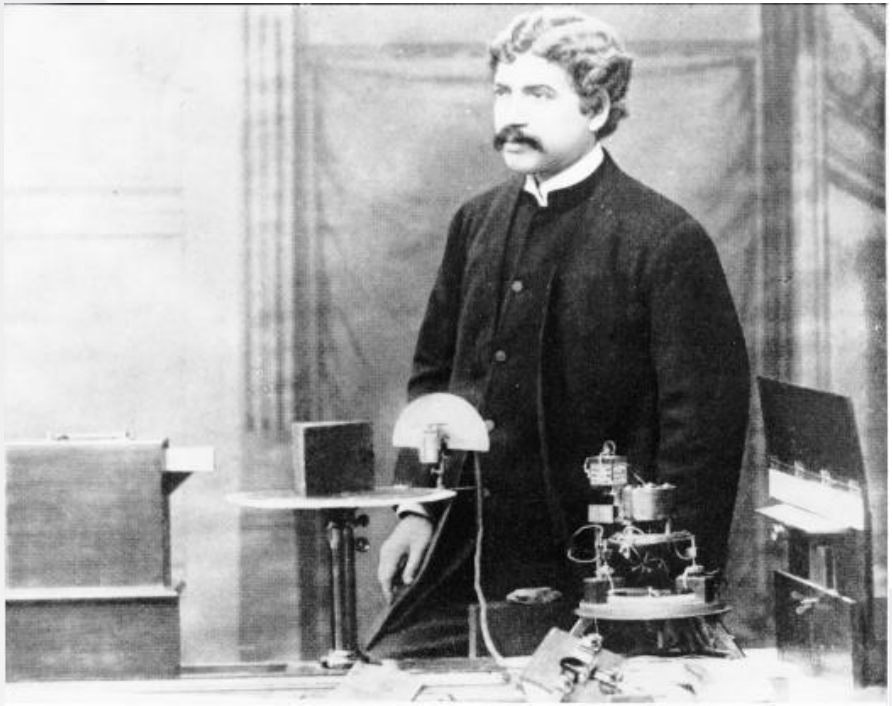
J.C. Bose (1858-1937) at the Royal Institution, London, 1897

জগদীশ চন্দ্র বসু

Jagadish Chandra Basu

Jagadis Chunder Bose

J.C. Bose



J.C. Bose (1858-1937) at the Royal Institution, London, 1897

In 1895 Bose gave his first public demonstration of electromagnetic waves, using them to ring a bell remotely and to explode some gunpowder. In 1896 the Daily Chronicle of England reported: ***"The inventor (J.C. Bose) has transmitted signals to a distance of nearly a mile and herein lies the first and obvious and exceedingly valuable application of this new theoretical marvel."***

"Popov in Russia was doing similar experiments, but had written in December 1895 that he was still entertaining the hope of remote signaling with radio waves."

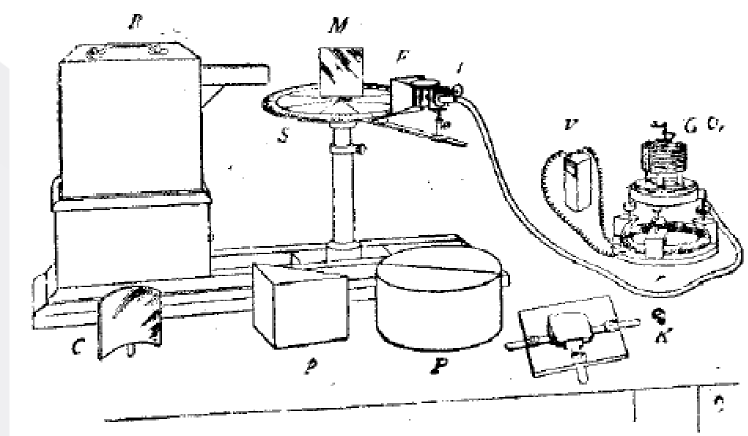
"The first successful wireless signaling experiment by Marconi on Salisbury Plain in England was not until May 1897."

Source: D. T. Emerson, "The work of Jagadis Chunder Bose: 100 years of mm-wave research," *IEEE Trans. Microwave Th. Tech.* December 1997, 45, No. 12 (2267-2273)

J C Bose

IEEE Milestone Plaque for Sir JC Bose

By 1895, Sir. J. C. Bose made the first public demonstration of radio waves in the Kolkata town hall. Details of the apparatus used are vague, but at a distance of 75 feet, he remotely rang an electric bell and ignited a small charge of gunpowder. He called it *Adrisya Alok,* or “Invisible Light”. The frequency of operation is nearly 60 GHz. He termed horn antenna as collecting funnel.



R, radiator ; S, spectrometer-circle ; M, plane mirror ; C, cylindrical mirror ; p, totally reflecting prism ; P, semi-cylinders ; K, crystal-holder ; F, collecting funnel attached to the spiral spring receiver ; t, tangent screw, by which the receiver is rotated ; V, voltaic cell ; r, circular rheostat ; G, galvanometer.

Courtesy: Subhradeep (CEERI)

IEEE Milestone Plaque

IEEE MILESTONE IN ELECTRICAL ENGINEERING AND COMPUTING
First Millimeter-Wave Communication Equipment by JC Bose, 1894-1896

Sir Jagadish Chadra Bose, in 1895, first demonstrated at Presidency College, Calcutta, India, transmission and reception of electromagnetic waves at 60 GHz over a distance of 23 meters, through two intercepting walls by remotely ringing a bell and detonating gunpowder. For this communication system, Bose developed entire millimetre-wave components such as: a spark transmitter, coherer, dielectric lens, polarizer, horn antenna and cylindrical diffraction grating.

September 2012

IEEE Monogram

Courtesy: Subhradeep (CEERI)

J.C. Bose published his paper on ‘polarisation of electric rays by double-refracting crystals’ in the Asiatic Society Journal in May1895. He delivered a demonstration lecture at the Town Hall of Calcutta in November 1895 in the presence of the then Governor Sir William Mackenzie.

In this experiment, he sent a signal longer than the infrared and the invisible ray penetrated blocks of wood, human body, two walls and rang a bell and fired a cannon ball 23 meters. Earlier he did similar experiments at Presidency College, Calcutta, as detailed in IEEE Milestone Plaque.

Courtesy: Subhradeep (CEERI)

“Bose’s experiment is believed to be the first ever microwave experiment in artificial materials (on twisted structures) for electromagnetic applications which exhibit the chiral characteristics!”

(Nader Engheta and R. W. Ziolkowski (Ed.): Metamaterials — Physics and engineering exploration)

Initiation of Indian Efforts

Institute of Radiophysics and Electronics, Calcutta University, Kolkata:

Professor S Deb, Professor SK Sen, Dr. HF Steyskal (UNESCO expert), Professor NB Chakraborty, and others;

CSIR-National Physical Laboratory, New Delhi:

Dr. Amarjit Singh, Dr. NC Vaidya, and others

CSIR-Central Electronics Engineering Research Institute (CEERI), Pilani:

Dr. Amarjit Singh, Dr. NC Vaidya, Dr. SSS Agarwala, Dr. OP Gandhi, Dr. RP Wadhwa, and others

Centre of Research in Microwave Tubes (CRMT), Electronics Engineering Department, Banaras Hindu University, Varanasi:

Professor NC Vaidya, and others

Microwave Tube Research and Development Centre (MTRDC), Bangalore:

Dr. MD Raj Narayan, and others

IIT-Roorkee:

MV Kartikeyan, and others

Devi Ahalya Vishwa Vidyalaya (DAVV), Indore:

Professor KP Maheshwari, and others

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 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 up to 1000 C.

A large chamber for heat treatment in protective atmosphere at temperatures up to 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 from 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 around 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.

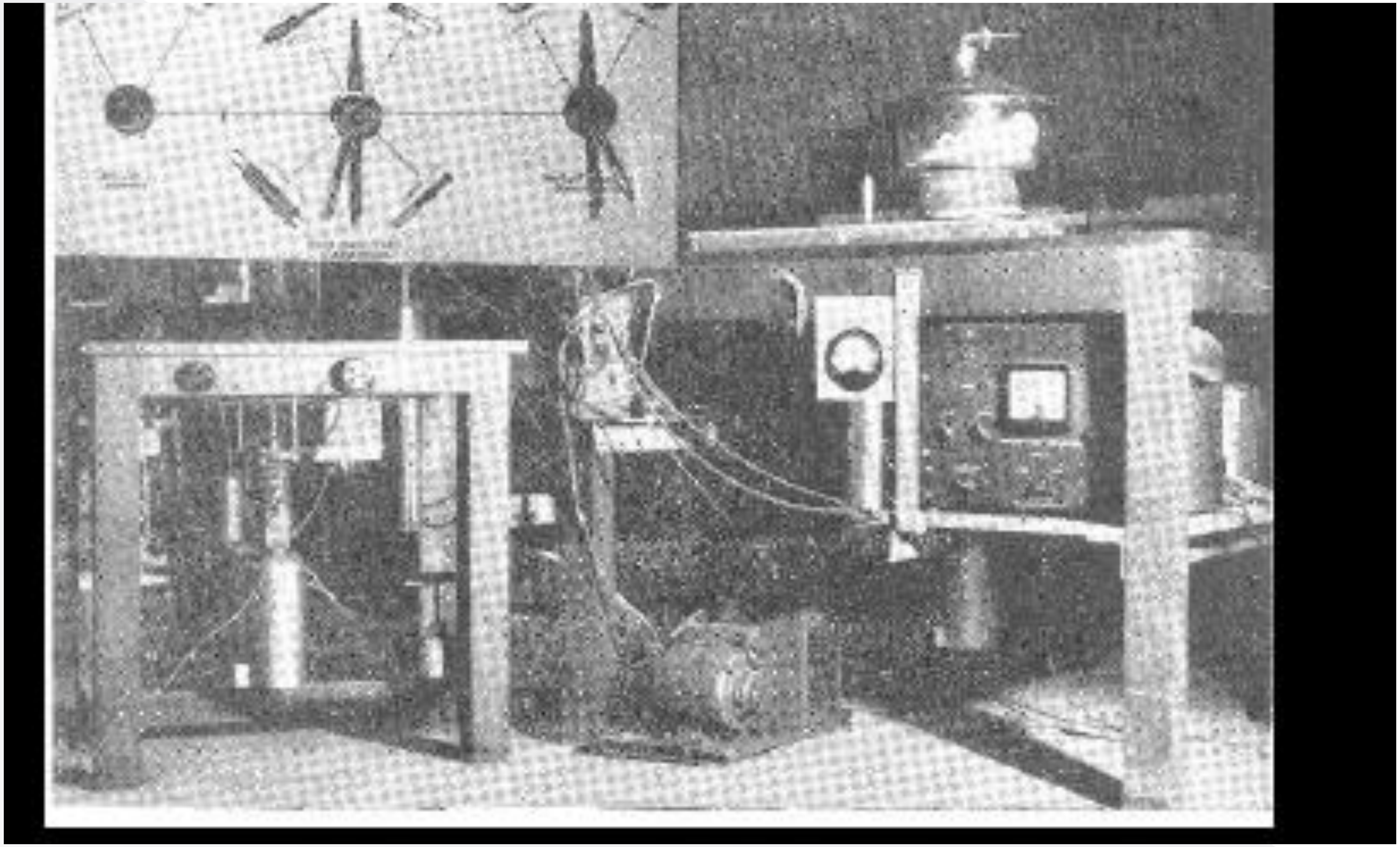
1961-62

(e) Electron Tubes and Plasma Electronics

Work is also in progress towards better design and performance of 10 cm multi-cavity 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).



Setup (1956) at Institute of Radiophysics and Electronics, Calcutta University

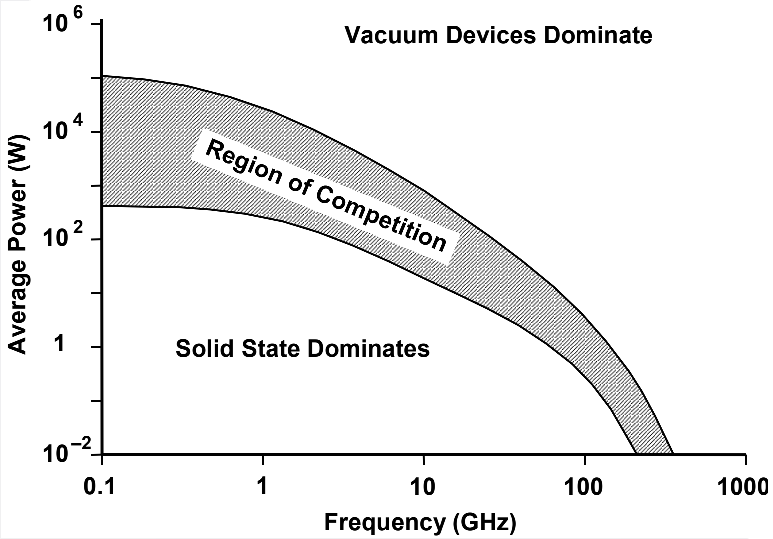
Microwave tubes enjoy superiority over their solid state counterparts with respect to having

- Lesser heat generated due to collision in the bulk of the device
- Higher breakdown limit on maximum electric field inside the device
- Smaller base-plate size (determined by the cooling efficiency)
- Higher peak pulsed-power operability
- Ultra-bandwidth (three-plus octave) performance above a gigahertz
- Inherently hardened against radiation and fairly resistant to temperature and mechanical extremes (being fabricated out of metals and ceramics)

In fact, attempts were made to replace space-TWTs with SSDs however with limited success in view the required $5X10^6$ hr MTBF (mean time before failure) in satellite qualified devices.

Thus, although SSDs were tried out in satellite communication system during the last decade of the twentieth century, for instance, replacing ~50% TWTs with SSDs in 1995, such replacements declined beyond 1998 to only ~10% making space TWTs more relevant than their SSD counterparts.

Thus, microwave tubes continue to be important despite competitive incursion from solid state devices (SSDs).



Solid state and vacuum device average power capabilities

Why use a thousand mice when one horse can do the job? (From Rodney Vaughan, Litton [Courtesy: A. S. Gilmour]

◊ **Both wideband helix-TWTs and coupled-cavity TWTs (CC-TWTs) are used in** radars.

◊ **Wideband helix-TWTs are used for**

∘ electronic warfare (EW)

→ Electronic countermeasure (ECM), for both brutal jamming and deceptive jamming of radars in order to reduce the effectiveness of radars

→ electronic counter countermeasure (ECCM) to protect radars from ECM

→ electronic support measure (ESM) by detecting, intercepting, identifying, locating, recording, and analyzing sources of radiated electromagnetic energy for the purposes of immediate threat recognition and thus providing a source of information required for decisions involving electronic protection (EP), electronic attack (EA), avoidance, targeting, and other tactical employment of forces.

◊ **Narrow-band helix TWTs are used for** missile tracking that has revolutionized the armored corps by enabling tanks and fighter jets to hit a target at a greater distance.

◊ **Klystrons are used for**

- radars
- satellite communication
- TV transmitters
- particle accelerators (considered the *sine qua non* of such accelerators)

◊ **Gyrotrons are used** in the millimeter-wave regime for long-distance radar, high resolution radar imaging and precision tracking. They have applications in material processing and fusion plasma heating, too.

◊ **High power microwave (HPM) tubes (using intensive relativistic electron beam) are used** in information warfare (IW) involving directed energy weapon (DEW) such as electromagnetic bomb.

Classification of microwave tubes from various angles

Angle of view	Classification	Typical examples
Role of dc magnetic field in beam flow	TPO or O-type: dc magnetic field along beam flow M-type: beam flow perpendicular to crossed dc electric and magnetic fields	TWT, klystron, etc. (O-type) Magnetron, CFA (M-type)
Mechanism of the bunching of electrons	Relativistic and non-relativistic bunching	Gyrotron, gyro-TWT, etc. (relativistic bunching) TWT, klystron, magnetron, SWCA, etc. (non-relativistic bunching)
	Axial and azimuthal bunching	TWT, klystron, SWCA, etc. (axial bunching) Gyrotron, gyro-TWT, gyro-klystron, etc. (azimuthal bunching)

…….Classification of microwave tubes from various angles

Interaction structure	Propagating waveguide (slow or fast) and cavity resonator types	TWT, gyro-TWT, etc. (propagating waveguide type) Klystron, gyrotron, gyro-klystron, etc. (cavity resonator type)
Nature of wave supported by the beam	Space-charge and cyclotron-wave interaction	TWT, klystron, magnetron, etc. (space-charge wave interaction) Gyrotron, gyro-TWT, etc. (cyclotron-wave interaction)
Nature of interaction	Localized and distributed interaction	TWT, gyro-TWT, etc. (distributed interaction) Klystron (localized interaction)

…….Classification of microwave tubes from various angles

Mechanism of energy transfer from the beam to electromagnetic waves	Kinetic energy and potential energy conversion types	TWT, klystron, gyrotron, gyro-TWT, gyro-klystron (kinetic energy conversion), etc. Magnetron, CFA (potential energy conversion), etc.
Wave phase velocity of electromagnetic waves in the interaction structure	Slow-wave type: phase velocity $< c$ Fast-wave type: phase velocity $> c$	TWT, magnetron, CFA, etc. (slow-wave type) Gyrotron, gyro-TWT, gyro-klystron (fast-wave type)
Instability	CRM and Weibel instability types	Gyrotron (CRM instability), SWCA (Weibel instability) CARM (combined CRM and Weibel instabilities)

$> v_{ph}$

…….Classification of microwave tubes from various angles

Nature of radiation	Electrons moving in the interaction structure with a DC velocity : Cerenkov radiation type	TWT (Cherenkov radiation)
	Electron beam passing through the boundary between two media with different refractive indexes or through perturbation in a medium such as conducting grids, or gaps between conducting surfaces	Klystron, monotron (transition radiation type)
	Electron beam accelerated in electric and/or magnetic field: bremsstrahlung radiation	Gyrotron (bremsstrahlung in magnetic field) VIRCATOR (bremsstrahlung in electric field)
O stands for TPO—tubes à propagation des ondes, and M stands for TPOM—tubes à propagation des ondes à champs magnetique. CFA : crossed-field amplifier; SWCA: slow-wave cyclotron amplifier; CRM: cyclotron resonance maser; CARM: cyclotron auto-resonance maser; VIRCATOR: virtual cathode oscillator		

Microwave tubes vis-à-vis applications: a re-look

Microwave tube	System of application
Wideband helix-TWT	ECM, ECCM, ESM
Narrow-band helix-TWT	Radar; satellite and ground-based communication; telemetry and tele-command; missile seeker; astronomy/telescope
CC-TWT (narrow-band)	Radar
Klystron	Radar, particle accelerator; TV transmitter; satellite communication; microwave relay; astronomy/telescope
Magnetron	Radar; broadcasting; microwave heating

.....Microwave tubes vis-à-vis applications: a re-look

Microwave tube	System of application
CFA (crossed-field amplifier)	Buffer/driver for an amplifying tube such as klystron or CC-TWT
MILO	HPM/DEW
Relativistic tubes: magnetron, BWO, klystron	HPM/DEW
VIRCATOR/reflex triode	HPM/DEW
Gyrotron	Millimeter-wave radar; long-range radar; high resolution radar; high information density communication; plasma heating; material processing; low intensity conflict; active denial system (ADS)
Gyro-TWT	Millimeter-wave radar
Gyro-klystron	Millimeter-wave radar

Trends in Microwave Tubes

- Improved performance conventional tubes — **Group 1**
- MPM and micro-fabricated tubes — **Group 2**
- IREB-driven HPM tubes — **Group 3**
- Fast-wave gyro-tubes — **Group 4**
- Plasma-filled tubes — **Group 5**
- Metamaterial-assisted tubes — **Group 6**

Trend-Wise Grouping of Microwave Tubes

Group 1	Improved performance conventional tubes: TWT (ultra-wide bandwidths, high efficiency); Klystron (high-power klystron, EIK— wider bandwidths, higher power, EIO — millimeter-wave, low-power, MBK (large beam current, low effective beam perveance, low beam voltage, tube compactness at higher RF powers)
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	IREB-driven HPM tubes: 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, relativistic BWO, etc.
	(phase-coherent, harmonic multiplying, inverted gyro-twystron); Gyro-BWO; CARM; SWCA; Peniotron, etc.

Group 4	Fast-wave gyro-tubes: Gyrotron (High-harmonic, low magnetic fields, 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), Helix TWT, Gyrotron (Group 4) (Plasma filling for large beam transport, relaxation of magnetic field, larger structure cross section, etc.
Group 6	Metamaterial-assisted tubes: TWT, BWO, backward-wave amplifier, klystron, MBK, resistive-wall amplifier, etc.

Features of Trend-Wise-Grouped Microwave Tubes

Group	Tubes	Features
Group 1: Improved performance conventional tubes	Wideband electronic warfare TWTs, high efficiency, long-life, light-weight space-TWTs, high power compact multi-beam klystrons,etc.	Innovative tube-envelope/tapered dielectric helix-support/pitch profiling/depressed collection Multi-beam electron gun
Group 2: MPM and microfabricated tubes	Micro-fabricated tubes: folded-waveguide TWT, reflex klystron, etc. Microwave power module (MPM)	Tubes accruing the advantages of both vacuum and solid-state devices/electronics Terahertz generation/ batch production

Trend	Tubes	Some Features/Comments
Group 3: IREB-driven HPM tubes	VIRCATOR, MILO, relativistic backward-wave oscillator, relativistic klystron (RELTRON), OROTRON, etc.	Bremsstrahlung of electrons in electrostatic field (VIRCATOR) E-bomb using a magnetic flux compression generator (FCG) in conjunction with a VIRCATOR Self focussing (MILO) HPM/DEW/ Information warfare applications

Group 4: Fast-wave gyro-tubes	Gyrotron, gyro-TWT, gyro-klystron, etc.	Filling up of mm-wave technology gap in high power domain Bremsstrahlung of electrons in magnetic field, Periodic beam Coaxial structure, PBG structure for mode selection/rarefaction
Group 5: Plasma-filled tubes	Plasma-assisted TWT, pasotron, gyrotron, etc.	Space-charge neutralization for enhanced beam current transport/relaxed focussing Development of PCE gun
Group 6: Metamaterial-assisted tubes	TWT, BWO, backward-wave amplifier, klystron, MBK, resistive-wall amplifier, etc.	Typically, a left-handed/double-negative metamaterial exhibits negative refractive index, reversed Doppler effect, and reversed Cherenkov radiation

Organizations and their roles in the progress of microwave tubes area

Organization	Activity areas and status
Institute of Radiophysics and Electronics (Calcutta University), Kolkata	Establishment of the facilities for the development of magnetrons in late 1950's (since discontinued) Significant contribution to understanding the non-linear theory of electron beam parametric amplifiers by N. B. Chakrabarti Subsequently motivated study on nonlinear effects in multi-beam and beam-plasma devices and in TWTs, elsewhere in the country
National Physical laboratory (NPL), New Delhi (CSIR)	Development of magnetrons initiated at National Physical laboratory (NPL), New Delhi (CSIR) by Amarjit Singh and N. C. Vaidya Subsequent shifting of activities to Central Electronics and Engineering Research Institute (CEERI), Pilani (CSIR)

Central Electronics and Engineering Research Institute (CEERI), Pilani (CSIR)	Magnetron, Carcinotron, TWT (wide bandwidth, high efficiency), klystron, multi-beam technology, high emission density cathode, gyrotron, plasma-assisted tubes, HPM tubes (initiated)
Centre of Research in Microwave Tubes (CRMT), Banaras Hindu University (BHU), Varanasi	Established at the Banaras Hindu University (BHU) in 1979 by N. C. Vaidya Analysis of helical structures, broadbanding of TWTs, nonlinear Eulerian dynamics for harmonic and inter-modulation effects in TWTs, analyses of gyro-TWTs and gyrotrons, broadbanding of gyro-TWTs
Microwave Tube Research and Development Centre (MTRDC), Bangalore (DRDO)	Established in 1984 Helix and coupled-cavity TWTs, high emission density cathodes, gyro-TWTs, HPM tubes

Electronics and Radar Development Organisation (LRDE), Bangalore (DRDO)	Vulnerability of electronic systems to HPM generated, for instance, by the VIRCATOR in collaboration with MTRDC and BARC
Bhaba Atomic Research Centre, Mumbai (DAE)	Vulnerability of electronic systems to HPM generated, for instance, by the VIRCATOR in collaboration with MTRDC and LRDE

Bharat Electronics (BE) Limited, Bangalore	Manufacturer of microwave tubes such as magnetrons, klystrons and TWTs
Pilani Electron Tubes, Sangrur	Established by G. S. Sidhu Manufacturer of high power transmitting tubes having potential for manufacturing magnetrons
Indian Institute of Technology (IIT), Roorkee	Gyrotron theory due to M. V. Kartikeyan (with support from Karlsruhe Institute of Technology) Participation in a multi-institutional project for the development of the first ever gyrotron with CEERI, Pilani as the nodal centre
Devi Ahalya Vishwa Vidyalaya (DAVV), Indore	Initiated by K. P. Maheshwari and Y Choyal in the development of relativistic microwave tubes (TWTs and oscillators)

Effect of plasma filing a typical gyrotron

Parameters	Without plasma	With plasma
Power	100-200 MW	~1 GW
Beam Current	1-3 kA	~10 kA
Frequency	35 GHz	35 GHz
Beam Voltage	0.60-1.35 MV	0.60-1.35 MV
Plasma Density	——	$>10^{13}$ cm^{-3}

Courtesy: Udit (CEERI)

R&D Initiatives in India in the areas of microwave tubes

- India is one among ~ 10 countries engaged in microwave tubes development
- Pulsed magnetron activity in early 50's at NPL, CSIR, New Delhi
- Magnetron activity was shifted to CEERI, CSIR, Pilani in 1957
- Theoretical and experimental activities in 50's at Institute of Radio Physics and Electronics, Kolkata in the area of electron tubes including magnetrons
- S-band klystron activities initiated at TIFR, Mumbai in 60's (related technologies established)

  Later on this technology utilized for developing linear accelerators
- Centre of Research in Microwave Tubes (CRMT) at Banaras Hindu University (BHU) was established in 1979 with the support of the erstwhile DOE
- Microwave Tube Research and Development Centre (MTRDC), Bangalore was established by DRDO in 1985

Courtesy: SN Joshi (CEERI)

Global list of typical companies manufacturing microwave tubes

USA: Litton, CPI

Germany: Siemens, AEG, Philips

Russia: ISTOK, ALMAZ

France: Thales (Formerly Thompson CSF)

Italy : Electronica

Japan: Toshiba, NEC

China: BVEDRI

India: Bharat Electronics

Courtesy: SN Joshi (CEERI)

Major users of microwave tubes in India

- RR-CAT, Indore
- IPR, Gandhinagar
- BRAC, Mumbai
- ISRO
- DLRL
- DRDL
- RCI
- LRDE
- P&T
- Doordarshan
- Defence

Courtesy: SN Joshi (CEERI)

User	System	Microwave tube type
ISRO	INSAT/ GSLV	Space TWT
Defence and DRDO	Radar, EW	TWT, klystron magnetron, MPM
RR-CAT (DAE), SAMEER	Particle accelerator, pulsed system	Magnetron, klystron, GDT switches (thyratron)
IPR	Plasma heating (ECRH)	Gyrotron, long-pulsed klystron
IPR, BARC, LRDE, MTRDC	HPM	Vircator

Courtesy: SN Joshi (CEERI)

Organizations involved in microwave tube research, development and production in India

Industries

- Bharat Electronics (BE) Limited (a public-sector organisation earmarked for defence production)
- Pilani Electron Tubes and Devices Pvt. Limited , Sangrur (a private industry)
- Central Electronics Limited, Sahibabad (a public sector organisation, which once use to manufacture magnetrons for defence application)

Laboratories

- Central Electronics Engineering Research Institute (CEERI), Pilani (CSIR)
- Microwave Tube Research and Development Centre (MTRDC), Bangalore (DRDO)
- Society for Applied Microwave Electronics Engineering and Research (SAMEER), Mumbai
- Electronics Radar Development Establishment, Bangalore (LRDE) (DRDO)
- Bhaba Atomic Research Centre (BARC), Mumbai
- Institute for Plasma Research (IPR), Gandhinagar
- Raja Ramanna Centre for Advanced Technology (RRCAT), Indore

Universities

- Banaras Hindu University, Centre of Research in Microwave Tubes (CRMT), Burdwan University, IIT-Roorkee, Devi Ahilya Vishwa Vidyalaya (DAVV), Indore

- **Bharat Electronics (BE), Bangalore** started producing magnetrons in 1969. It had a major collaboration in 1985 with M/s Varian, USA (TWT production). It also has collaboration with EEV, Thales, Philips, MTRDC and CEERI

- **Central Electronics Limited (CEL), Sahibabad** established magnetron production facilities in 1977 and continued for a decade

- **Pilani Electron Tubes and Devices Private Limited, Sangrur** was established in early 90s with capabilities of manufacturing electron tubes

Courtesy: SN Joshi (CEERI)

Centre of Research in Microwave Tubes (CRMT), Department of Electronics Engineering, Banaras Hindu University (BHU), Varanasi

Slow-wave tubes

- Field and equivalent circuit analyses of helical slow-wave structures for travelling-wave tubes
- Modelling of helix thickness, discrete dielectric helix-support rods, and metal envelope of helical slow-wave structures of TWTs
- Anisotropic helix loading (metal vane/segment loading) for widening the bandwidth of a TWT
- Inhomogeneous helix loading (using tapered-geometry dielectric helix-support rods) for widening the bandwidth of a TWT
- Nonlinear hydrodynamic analysis of helix TWTs for the estimation of harmonic content and intermodulation distortion
- Synthesis of Pierce electron guns

Fast-wave tubes

- Cold and hot (small-signal) analysis of a vane-loaded gyrotron for mode selectivity
- Analysis of a tapered-cross section, corrugated coaxial-cavity gyrotron for rarefaction
- Cold and hot (small-signal) analysis of a dielectric-loaded gyro-TWT for wide bandwidths
- Analysis of a tapered cross-section gyro-TWT for wide bandwidths
- Analysis of a disc-loaded gyro-TWT for wide bandwidths
- Simulation of gyrotron cavities
- Large-signal analysis and simulation of gyrotrons, gyro-TWTs, and gyro-klystrons, gyro-twystrons, relativistic BWO and MILO

Recent work at CRMT, IIT-BHU

MILO

Gyrotron

Gyro-Twystron

Gyro-TWT

Relativistic BWO

Non-conventional microwave tubes R&D in the country

HPM devices like the virtual cathode oscillator

BARC, Mumbai

MTRDC (DRDO), Bangalore

LRDE (DRDO), Bangalore

DAVV, Indore

Gyro-devices like the gyro-TWT and the gyrotron

Basic research in the area of gyro-TWTs initiated at CRMT, BHU (evidenced by publications of papers, theses and reports by B. Tech, M. Tech and Ph. D students)

A multi-institutional project funded by DST to develop a 42-GHz, 200-kW gyrotron forthe IPR Tokomak (with CEERI, IPR, SAMEER, BHU, and IIT-Roorkee as the participants), which is further important in view of India participating in the programme ITER (International Thermonuclear Experimental Reactor) aiming at demonstrating the scientific and technical feasibility of fusion power (the other participants being the European Union, USA, Japan, China, and South Korea)

The first ever TWT built in India (1977) at CEERI, Pilani 2 W (CW) S-band helix TWT

The first TWT developed by MTRDC (1993): 200 W X-Ku-band helix TWT

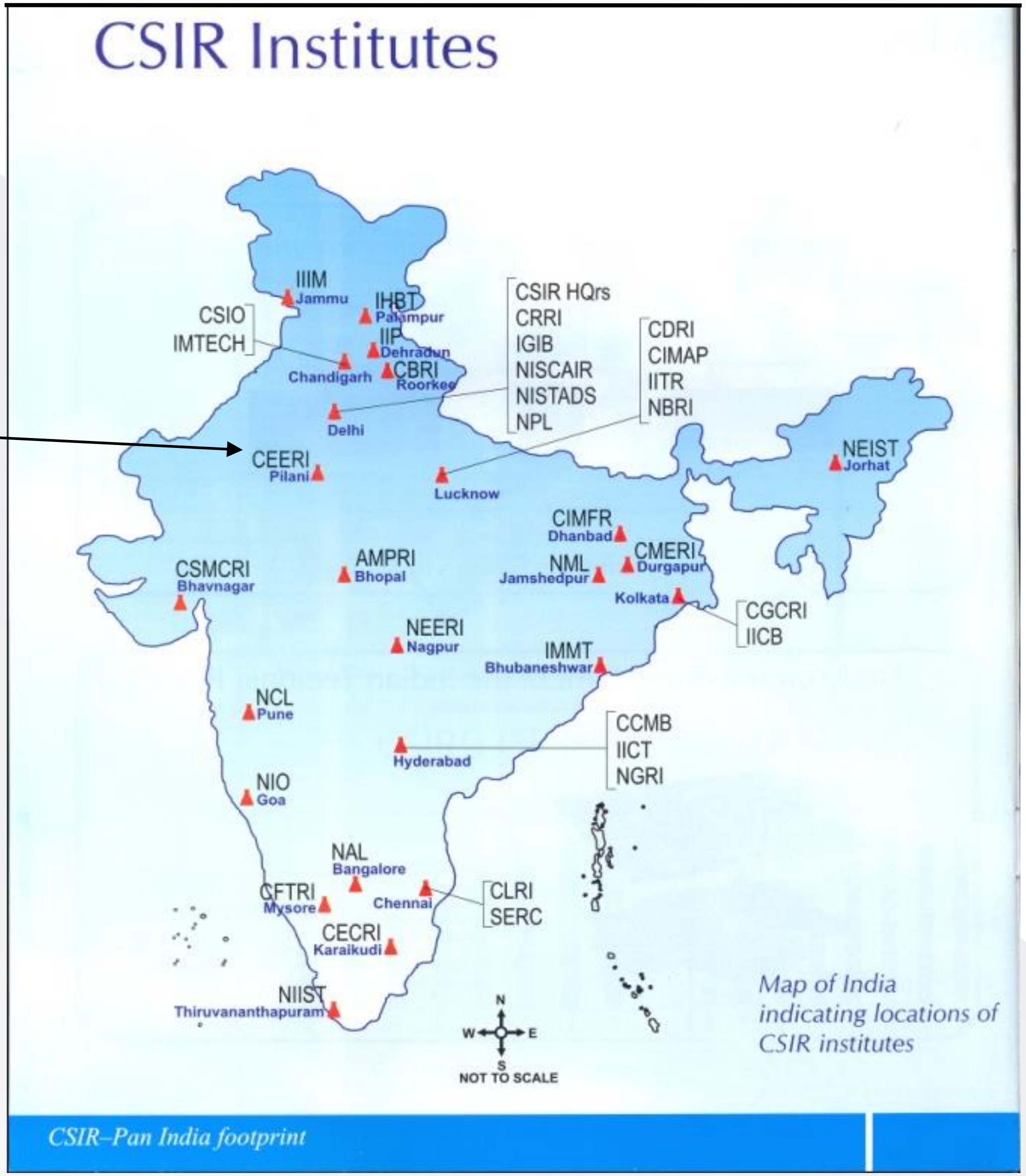
Subsequently, other helix TWTs developed in India such as

- C-band 20 W (CW) TWT (CEERI) for satellite communication
- S-band 30 W (pulsed) TWT (CEERI) 3D radar of Air force
- X-Ku-band 40 W (CW) Mini-TWT (CEERI) for EW
- X-Ku band 2 kW (Pulsed) TWT (MTRDC-BEL) for EW
- X-Ku band 300 W (CW) TWT (MTRDC-BEL) for EW
- C band 60 W (CW) TWT (CEERI-BEL) for space communication

Some other helix TWTs under development such as

- Ku-band 140 W (CW) TWT (CEERI-BEL) for communication
- K-Ka band 40 W (CW) TWT (MTRDC) for EW
- C-X-Ku band 100 W (CW) TWT (MTRDC) for EW
- C-X-Ku band 200 W (CW) TWT (MTRDC) for EW
- C-X-Ku band 1.5 kW (CW) TWT (MTRDC) for EW

CEERI



CSIR Institutes/Labs

Information to be updated

Courtesy: Uttam (CEERI)

Contribution of CEERI

- Started with pulse magnetrons: batch produced them and supplied to Indian Navy
- Developed various specifications of magnetrons, klystrons, TWTs, BWOs, and thyratrons
- Carried out limited production of S-band, 2 MW magnetron and supplied them to RRCAT and BARC
- Developed in India the first ever space-qualified TWT in collaboration with BE, Bangalore and handed over the flight models to ISRO
- Has created a design and technology base

Courtesy: SN Joshi (CEERI)

- Has established required infrastructure with the support of CSIR and other funding agencies
- Has collaboration with various national and international organisations
- Has taken up various R&D programmes with support from CSIR and other sponsors like DRDO, ISRO, DAE and DST
- Has been involved in developing various critical technologies for multi-beam electron gun, high power RF window, very high power (~ 250 KW CW) and high frequency (120 – 170 GHz) devices, multi-stage collectors, large geometry dispenser cathodes, THz and plasma devices
- Has adopted a multi-institutional approach for three major programmes with the support of CSIR, DST, and ISRO.

Courtesy: SN Joshi (CEERI)

Crossed-field (M-type) tube development at CEERI:

- 500 kW (S-band) magnetron
- 1.0 MW (S band) magnetron
- 800 kW (tunable S band) magnetron
- 2 MW/3 MW (S band) magnetron
- 10 kW CW magnetron
- Limited production of S-band, 2 MW magnetron (completed in 2005)
- Technology development for 170 GHz, 1 MW, long-pulse RF windows (completed in 2017)
- Development of glass sealed RF window for 4 MW S-band tunable pulse magnetron
- 200 W and 400 W (S band), BWO (Carcinotron)

Courtesy: Maurya (CEERI)

The major earlier work on the development of magnetrons was in S-band for pulsed operation using the hole-and-slot-type cavities and either the echelon or ring-type strapping.

Some experimental work was also carried out during 1980-1990 in coaxial magnetrons at 9.5 GHz (using the rising-sun structure).

Recent work on magnetron has focused on:

- Design and development of high power pulsed magnetron with hole-and-slot type cavities and echelon type strapping with higher powers (S band, ~5-7.5 MW peak)

- Design and development of CW magnetron (S-band,15 kW) using the vane-type, double-ring, strapped structure for magnetron in S-band (the first version having been already developed)

- Design and development of S-band 10-kW CW magnetron

- Theoretical work on spatial-harmonic magnetron with cold cathode in other such as planer configurations for higher frequencies

- Design and development of coaxial magnetrons from C-to-Ku-to Ka band as per requirements of users

Klystron development at CEERI:

- 1 kW CW (D/E band) klystron
- 5 MW (peak), 5 kW (average) (S band) klystron
- 6 MW peak, 24 kW average power klystron (for cargo scanning application)
- 300 W CW (KU/J-band) klystron for missile seekers
- 100 kW CW, 350 MHz klystron (prototype developed)
- 250 kW CW, 5 GHz klystron (for ITER lower hybrid current drive) (parts fabricated as per indigenous design)

Dr. LM Joshi <lmj1953@gmail.com>

Dr. Ayan Kumar Bandyopadhyay <ayan.bandyopadhyay@gmail.com>

Specifications of a typical klystron developed at CEERI

Peak output power	6	MW
Average power	24	kW
Pulse width	10	μS
Frequency	2856	MHz
PRF	400	Max
Gain	45	dB
Efficiency	45	%
-1 dB bandwidth	±4	MHz
Beam voltage	130	kV
Beam current	95	A
Focussing	Electromagnet	

Courtesy: Dr. LM Joshi, Dr. SN Joshi

In addition, the klystron group of CEERI has carried out related activities such as:

- Foundation of the development of multi-beam klystron (MBK) encompassing the design of a 19-beam gun and other parts and fabrication of piece parts of MBK

- Low-power air-cooled RF coupler (for low energy high-intensity proton accelerator)

- High power water-cooled coaxial RF coupler (for low-energy high-intensity proton accelerator)

- High-power water cooled iris coupled RF coupler (for low-energy high-intensity proton accelerator)

- Eight channel rectangular RF window (for IPR-Aditya TOKAMAK, lower hybrid current drive)

TWT development at CEERI:

- 2 W CW (S-band) helix TWT
  (first ever indigenous TWT in India in 1977)

- 20 W (C band) helix TWT (for ISRO)

- 30 W (S band) helix TWT

- 40 W CW (X-Ku band) mini-TWT (for DRDO)

- 60 W (CW) (C-band) space-TWT for ISRO) (jointly with BEL, Bangalore)
  (first ever indigenous space-TWT in India)

140W (Ku-Band/10.9 -11.7) GHz short length space-TWT (for ISRO)

Dr. Sanjay Kumar Ghosh <ghoshskdr@gmail.com>

- 60 W (CW) (C-band) space-TWT for ISRO) (jointly with BEL, Bangalore) — the country's first ever indigenous space-TWT

- 70kW pulsed (C-band) CC-TWT (for DRDO)

- 140 W (CW) (Ku-band) state-of-the-art space-TWTs for on-board satellite application (under development for ISRO-SAC)

- 100 W (CW) (Ka-band) state-of-the-art space-TWTs for on-board satellite application (under development for ISRO-SAC)

- Development of lab prototype of W-band (94 GHz) folded-waveguide TWT (underway)

Activities in the development of cathodes at CEERI:

- 20 A/cm2, >8 yr (extrapolated) B-type dispenser cathode
- > 100 A/cm2, >12 yr (extrapolated) alloy-coated dispenser cathode
- Technology development for reliable long-life dispenser cathodes
- Surface analytical studies on dispenser cathode using
- Development of large-area dispenser cathodes for high-power microwave tubes: M-type cathode, ~3.1 mm cathode diameter, >20 A per square cm current density, 1000 C operating temperature
- Development contract for triple-alloy coating

Ranjan Barik <ranjan.ceeri@gmail.com>

- Development of graphene-based field emitters
- Design and development of high current density (> 100 A/cm^2) thermionic cathode for terahertz devices application
- Design and development of the work function measurement setup at elevated temperatures of thermionic cathode
- Design and development of thermionic emitter for ISRO electric propulsion (ion-thruster) system
- Design and development of multi-beam cathode for multi beam klystron
- Design of sheet beam electron gun for THz vacuum electron devices
- Numerical design of vacuum micro-electronics devices using AI algorithm

Gyrotron development at CEERI:

- Design and development of 42 GHz, 220 kW CW gyrotron (for fusion plasma heating) (carried out under a DST-sponsored multi-institutional project)
- Design and development of 170 GHz, 1MW (short pulse) gyrotron
- EM simulator for gyrotron

Dr. ashok sinha <aksinha.ceeri@gmail.com>
Dr. Anirban Bera <bera.anirban@gmail.com>

Development of plasma based/ion source based devices and systems at CEERI:

- VUV/UV excimer sources based on DBD

Dr. Udit Pal <paludit@gmail.com>

Biomedical applications
Surface treatment
Water purification (jointly with CSIR-NEERI)

- High power plasma switches
- Thyratron (25 kV/1 kA and 40 kV/3 kA) (for RRCAT, Indore) and pseudospark switches (40 kV/5 kA and 20 kV/20 kA)
- Plasma cathode electron guns
- Electron and ion sources (40 kV/200 A, ~200 A/cm^2)
- Plasma assisted microwave sources
- PASOTRON (X-band, 0.5 MW) and THz sources
- Penning discharge devices
- Ion beam sources and VUV spectroscopy

Information to be updated

Microwave Tube Research and Development Centre (MTRDC) (DRDO)

MTRDC is a constituent R&D laboratory of Defence Research & Development Organisation (DRDO), Ministry of Defence. It was established in 1984, with an aim to develop advanced types of microwave tubes to meet the present and futuristic needs of the country and establish self-reliance in this strategic area.

MTRDC initially started in CASSA, Bangalore and moved to a small accommodation in the Bharat Electronics Complex, Bangalore. It was housed in its own building in 1992 near the Microwave Tube Division of Bharat Electronics in order to facilitate continuous interaction between the R&D and production teams. MTRDC has built a residential complex in HMT Township just 4 km away from the laboratory.

MTRDC, Bangalore (DRDO)

Achievement of MTRDC (typical)

200W (CW) X-Ku band helix TWT (for airborne jammer)

2 kW (pulsed) X-Ku band helix TWT (for airborne ECM, TEMPEST)

10 kW (pulsed), Ku-band CC-TWT (for AKASH missile seeker/DRDL, DRDO)

6.5 kW (pulsed), X-band CC-TWT (for LCA radar/ADA, DRDO)

Ongoing activities of MTRDC (typical)

130 kW (pulsed), S-band CC-TWT (for AWACS system, DRDO)

300 W (CW) X-Ku band helix TWT (for EW SANYUKTA / DLRL, DRDO)

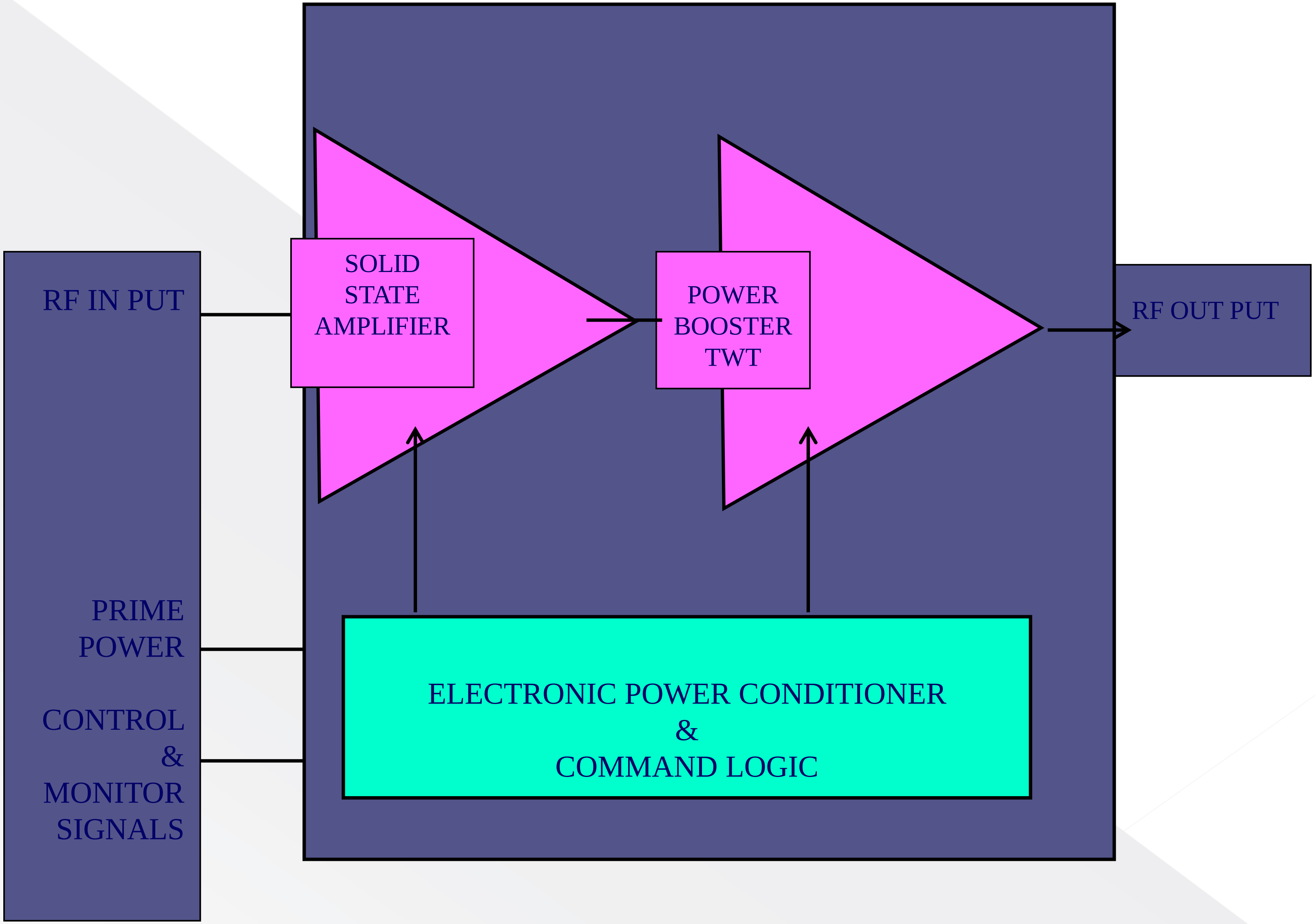
40 W (CW) mm-wave helix TWT (for EW SANGRAHA/ DLRL, DRDO)

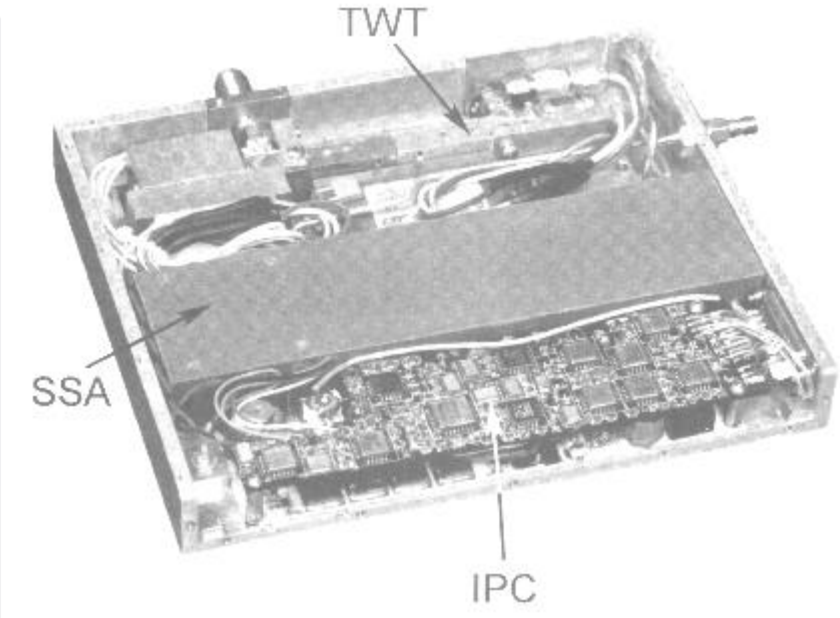
100 W, X-Ku band microwave power module (MPM) (for EW) SANYUKTA / DLRL, DRDO) (~4 kg; <85 ns EPC throughput delay)

Initial work/enabling technologies for gyro-TWTs, Vacuum microelectronic devices (with SSPL as a partner), Transmitters using MPMs, VIRCATOR, Relativistic devices (magnetrons and BWO) (with LRDE, BARC, and DAVV as partners)

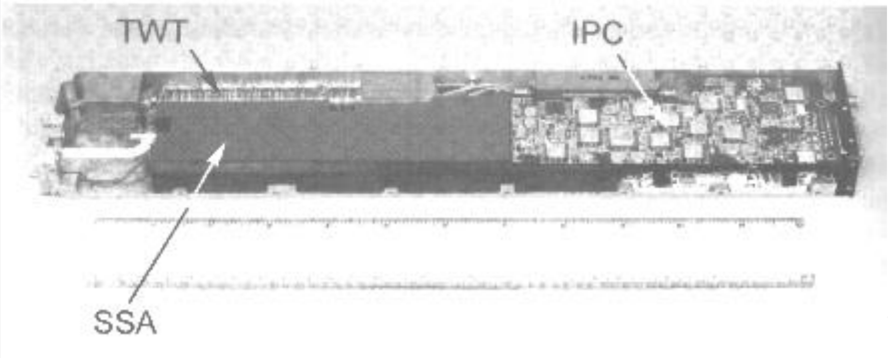
Information to be updated

Microwave Power Module (MPM)



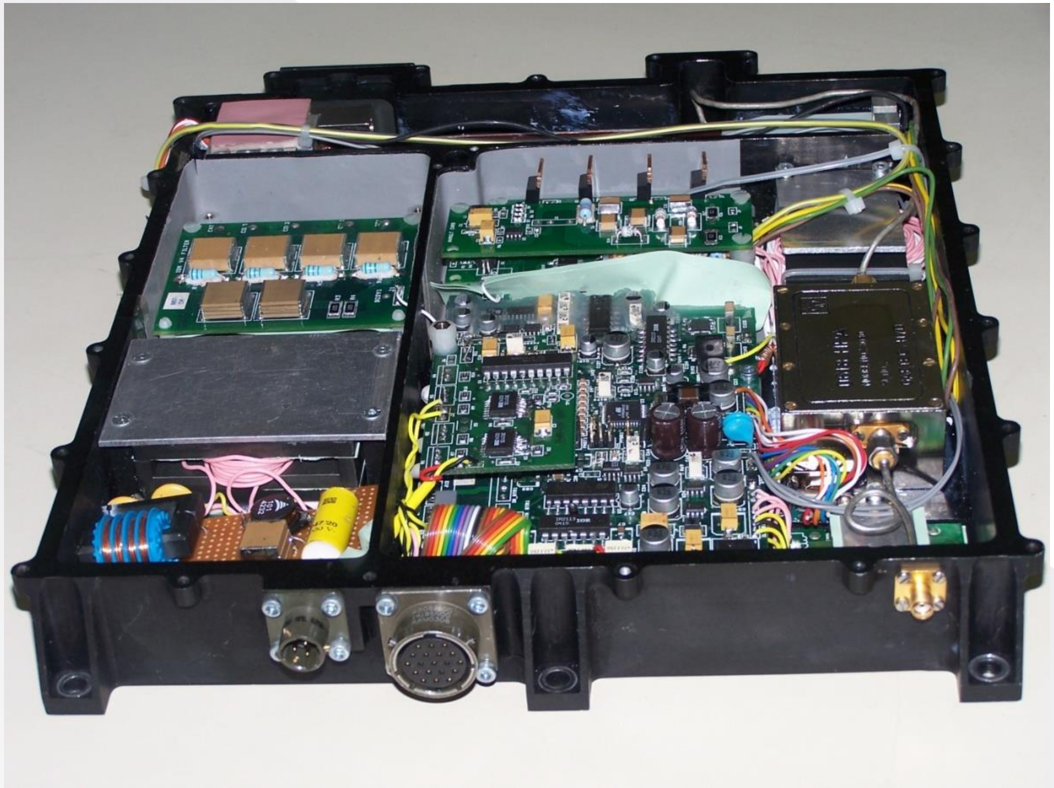


An 80-W, 6- to 8-GHz wideband MPM



Ka-band MPM

Microwave Power Module (MPM)



Ship/Air borne EW

Data-Link

Command & Guidance

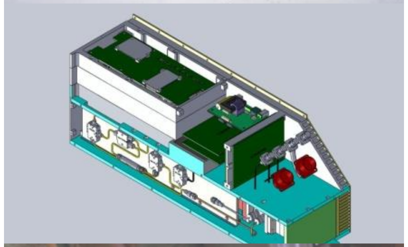
Towed Decoy

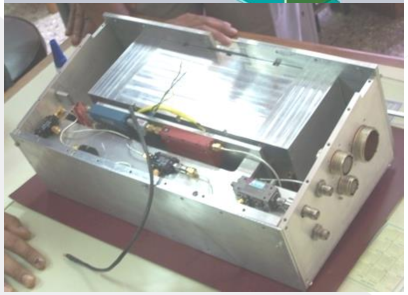
Seekers

SAR

Information to be updated

MPM/ Transmitters for EW & communication





Microwave Power Modules (MPM)

- 100 W (CW) Ku-band for SATCOM Data-link (ADE/DEAL)
- 100 W X-band for FLR for AKASH (LRDE/DRDL)
- MPM based Tx. For EWSFA (DARE)
- 100W (CW) C-Ku band
- 200 W (CW) C-Ku band
- 1500 W (P) C-Ku band

Power Booster TWTs for MPMs Developed by MTRDC

Information to be updated

	MCH-3550	MCH-3553	MPH-4052	MPH-5055
Band	C-Ku	C-Ku	X	Ku
Bandwidth (GHz)	12	12	1	2
Duty	CW/Pulsed	CW/Pulsed	Pulsed	Pulsed
Peak power (W)	100	200	180	375
Focussing	PPM	PPM	PPM	PPM
Cooling	Cold plate	Cold plate	Cold plate	Cold plate
Weight (gm)	540	800	500	500

In 1993, MTRDC developed its first TWT: 200W X-Ku-band helix TWT

Some other helix TWTs developed in India:

- C-band 20 W (CW) TWT (CEERI) for satellite communication
- S-band 30 W (pulsed) TWT (CEERI) 3D radar of Air force
- X-Ku-band 40 W (CW) Mini-TWT (CEERI) for EW
- X-Ku band 2 kW (Pulsed) TWT (MTRDC-BEL) for EW
- X-Ku band 300 W (CW) TWT (MTRDC-BEL) for EW
- C band 60 W (CW) TWT (CEERI-BEL) for space communication

Some other helix TWTs under development:

- Ku-band 140 W (CW) TWT (CEERI-BEL) for communication
- K-Ka band 40 W (CW) TWT (MTRDC) for EW
- C-X-Ku band 100 W (CW) TWT (MTRDC) for EW
- C-X-Ku band 200 W (CW) TWT (MTRDC) for EW
- C-X-Ku band 1.5 kW (CW) TWT (MTRDC) for EW

Dispenser cathodes at MTRDC:

> 50 A/cm^2 Os-coated; 30 A/cm^2, >20,000 hr Lithium oxide MM; > 50 A/cm^2, >45,000 hr W-Ir MM; > 40 A/sq cm, >40,000 hr W-Re MM; 35,000 hr Scandate cathode; >360 A/cm^2 PZT based ferroelectric

Information to be updated

CC-TWT development at MTRDC

CC-TWT development taken up in1993: S, X and Ku bands at MTRDC; C-band subcontracted to CEERI

New relevant technologies developed and critical areas addressed:
▪ Fabrication of shadow-gridded electron gun
▪ Distributed-loss and resonant-loss loading of cavities
▪ Development of samarium cobalt magnets with good homogeneity
▪ Thermal management were some of the key areas addressed under this project
▪ Collaboration with ISTOK, Russia on joint development of X- and Ku-band CC-TWTs
Qualified tubes delivered for multimode radar of LCA to HAL/ADA
• Technology for production of the X-band and S-band CC-TWTs transferred to BE resulting in limited series production

Design of miniaturized MBKs is also one of the key areas at MTRDC

Multi-Beam Klystrons Developed at MTRDC

150 W, Ku band

400 W, 60 MHz, Ku band

250 W, 90 MHz, Ku band

Information to be updated

The KALI series (KALI 80, KALI 200, KALI 1000, KALI 5000 and KALI 10000) of accelerators are described as "Single Shot Pulsed Gigawatt Electron Accelerators"

Under consideration of DRDO:

Single shot devices, using water filled capacitors to build the charge energy (0.4-40 GW; pulse time~60 ns)

KALI-5000:

3-5 GHz radiation range, pulsed accelerator of 1 MeV electron energy, 50-100 ns pulse time, 40 kA current and 40 GW power level; bulky 10 tons: power hungry, requiring a cooling tank of 12,000 liters of oil; too long recharging time to make it a viable weapon in its present form

X-rays emitted are used in Ballistics research as an illuminator for ultrahigh speed photography by the Defence Ballistics Research Institute (DBRL), Chandigarh

Microwave emissions for EM research

KALI microwave version used by DRDO for testing the vulnerability of the electronic systems such as those of LCA

Helped in designing electrostatic shields to "harden" the LCA and missiles from microwave attack by the enemy as well as protecting satellites against deadly Electromagnetic Impulses (EMI) generated by nuclear weapons and other cosmic disturbances, which "fry" and destroy electronic circuits

(Electronic components currently used in missiles can withstand fields of approx. 300 V/cm, while the fields in case of EMI attack reach thousands of V/cm)

Axial VIRCATOR

- LRDE/BARC: 5 MW, 1-4 GHz
- BARC/MTRDC/LRDE 100 MW KALI-200
- BARC/MTRDC: >500 MW, 2-4 GHz, KALI-5000

Cavity VIRCATOR

- MTRDC/LRDE/BARC 2 MW, KALI-1000
- MTRDC/LRDE 0.2 MW, KALI-200

BWO

- BARC/LRDE: 2 MW, 11 GHz
- BARC/DAVV: 1 MW, KALI-200, X-band

Plasma-filled REB device

- BARC/LRDE: 10-20 MW, 7-10 GHz

Information to be updated

Bharat Electronics Limited (BEL) **(public-sector organization)** was established at Bangalore, India, by the Government of India under the Ministry of Defence in 1954 to meet the specialized electronic needs of the Indian defence services. Over the years, it has grown into a multi-product, multi-technology, multi-unit company serving the needs of customers in diverse fields in India and abroad.

"Good service is when the customers come back and the goods don't."

Bharat Electronics (BE), Bangalore

- Conventional and coaxial magnetrons (L-, C-, K- and Ku-band), power levels from 400 W to 1.0 MW (pulsed)
- TWT (helix type: L-, S-, C-, X- and Ku-band), power levels from 1.0 W to 400 W (CW); 1 kW to 6 kW (pulsed) and coupled cavity type: X-, S band)
- Power triodes and tetrodes
- Klystrons (L-, S-, and C- band)

Technology know-how, when necessary, taken from CEERI, Pilani, MTRDC, Bangalore, Philips, EEV, UK, VARIAN (now CPI), USA, Thomson-CSF (now Thales), France, ISTOK, Russia, etc.

Pilani Electron Tubes and Devices Pvt. Ltd., Sangrur **(private industry)**

Power triodes up to 80 kW (typical)

CEL, Sahibabad **(public-sector)**

Magnetrons for Defence (since suspended)

Information to be updated

TWT (BE):

BEL6242: 2 GHz, 200 W (CW), 35 dB (3.9 kV, 525 mA)

BEL6252: 2-4 GHz, 200 W (CW), 37 dB (4.2 kV, 430 mA)

BTC401: 5.5-6.5 GHz, 400 W (CW), 50 dB (9.6 kV, 350 mA)

BTC6262: 4-8 GHz, 200 W (CW), 37 dB (9.0 kV, 300 mA)

BTU5191: 8-18 GHz, 1 kW (pulsed; 4% duty), 50 dB (11.5 kV, 1.8 A)

BEL mini-TWT: 7.5-18 GHz, 80 W (CW), 50 dB (4.2 kV, 175 mA)

BEL CC-TWT (BCCT 2000X): 9.2-9.5 GHz, 120 kW (pulsed; 0.5% duty), 50 dB (45 kV, 14 A)

BTC60 (Space-TWT): 3.6-4.2 GHz, 60 W (CW), 50 dB (3.2 kV, 80 mA)

BTU140: 10.9-11.7 GHz, 140 W (CW), 50 dB (6.2 kV, 120 mA)

Information to be updated

Klystron (BE):

BEL 4K3SL3: 1.7-2.4 GHz, 1 kW (CW) (7 kV, 650 mA)

BEL 4K3SL3: 1.7-2.4 GHz, 12 kW (CW) (20 kV, 3 A)

BEL 888E: BEL 888E: 4.4-5.0 GHz, 1.4 kW (CW) (8.5 kV, 600 mA)

Magnetrons (BE):

5J26: 1.22-1.35 GHz, 600 kW (pulsed, 0.25%) (34 kV, 55 A)

BEL 200 MX: 8.54-8.94GHz, 200 kW (pulsed, 0.11%) (23 kV, 12 A)

BEL 512 cm: 9-9.6 GHz, 200 kW (pulsed, 0.11%) (23 kV, 30 A)

Information to be updated

Requirement of microwave tubes in the country for the coming ten years

Requirement of microwave tubes has been estimated by CEERI, Pilani (CSIR) based on the deliberation at the Technical Meet of all concerned R&D, academia, production, and user organisations held on **April 10, 2006** at CSIR Vigyan Kendra, New Delhi to generate 'Position Paper on the 'Requirement of Microwave Tubes and their Development for the **coming ten years**'.

Consolidated requirement of <u>travelling-wave tubes</u> in coming ten years (number of tubes required is shown in parenthesis)

ISRO: CW space TWTs: Ka-band, 100 W (60); X-band, 40 W (15); L-band, 200 W (20); S-band, 230 W (40); C-band, 60 W (120); Ku-band, 140 W (150) Pulsed space TWTs: Ku-band, 150 W (12); X-band, 200 W (25)

RCI: Pulsed miniature TWTs: Ku-band, 300 W (300); X-band, 50-100 W (300); Ka-/ W-band; 50-100 W (300-500)

LRDE: Pulsed TWTs: X-band, 8/4 kW (20); X-band, 1 kW (20); C-band, 75 kW (20); S-band, 120 kW (20)

DLRL: CW TWTs: S-band, 500 W (09); S-C-band, 600 W (09); C-X-Ku-band, 350 W (15); K-Ka-band, 100 W (10); CW miniature TWTs: C-X-Ku-band, 100 W (80)

MTRDC: CW TWTs: K-Ka band, 40 W (04); X-Ku band, 300 W (04)

DEAL: CW TWTs X-band, 100 W (300)

ADA: CC-TWTs: X-band (100)

Consolidated requirement of <u>klystrons</u> in coming ten years (number of tubes required is shown in parenthesis)

RCI: CW miniature MBKs: Ku-band, 400 W (250)

RRCAT: Pulsed klystrons: S-band, 5 MW (05); CW MBKs: S-band, 64 kW (10); CW klystrons: 350 MHz and 700 MHz, 250 kW (07)

RRCAT/BARC: Pulsed klystrons: S-band (14)

IPR: CW klystrons: 3-10 GHz, 500 kW (22)

SAMEER: Pulsed klystrons: S-band, 5 MW (05)

BEL: Pulsed klystrons: S-band, 1.5 MW (15); for military communication: (150); for missiles: (150); for laboratory LINACS: (20)

Consolidated requirement of <u>magnetrons</u> in coming ten years (number of tubes required is shown in parenthesis)

BARC: CW magnetrons: 2.45 GHZ, 3 kW (10)

SAMEER: Pulsed magnetrons: S-band, 2.6 MW (20)

BEL: Pulsed magnetrons: X-band, 25 kW (200)

Pulsed magnetrons (coaxial): Ka-band, 80 kW (1000)

Consolidated requirement of gyrotrons in coming ten years (number of tubes required is shown in parenthesis)

BARC: CW gyrotrons: 24 GHz, 5 kW (02)

IPR: CW gyrotrons: 140 GHz, 500 kW (01); 170 GHz, 500 kW (01); 210 GHz, 500 kW (01); multi-frequency, 500 kW; 42 GHz, 200 kW (02)

BEL: ITER gyrotrons: (50)

Consolidated requirement of 'electron tubes other than microwave tubes' in coming ten years (number required is shown in parenthesis)

IPR: CW triodes/ tetrodes: 20-100 MHz, 20 kW (10); 20-100 MHz, 200 kW (10); 20-100 MHz, 1.5 MW (10)

BEL: Thyratrons: 20-25 kV, 100 A (peak) (100)

Consortium for the development of the first ever gyrotrons in the country for the IPR tokamak executed in a multi-institutional DST-sponsored project

42 GHz, 200 kW (CW or long pulse); 1.6-1.62 Tesla; 65-70 kV, 10-15 A; TE_{03} mode

Participating organizations:

1. CEERI, Pilani — Electron gun and beam tunnel, Collector, Fabrication of all parts, Assembly/Integration of parts, Processing, Testing, and Coordination with the other participants of the project working as the Nodal Centre

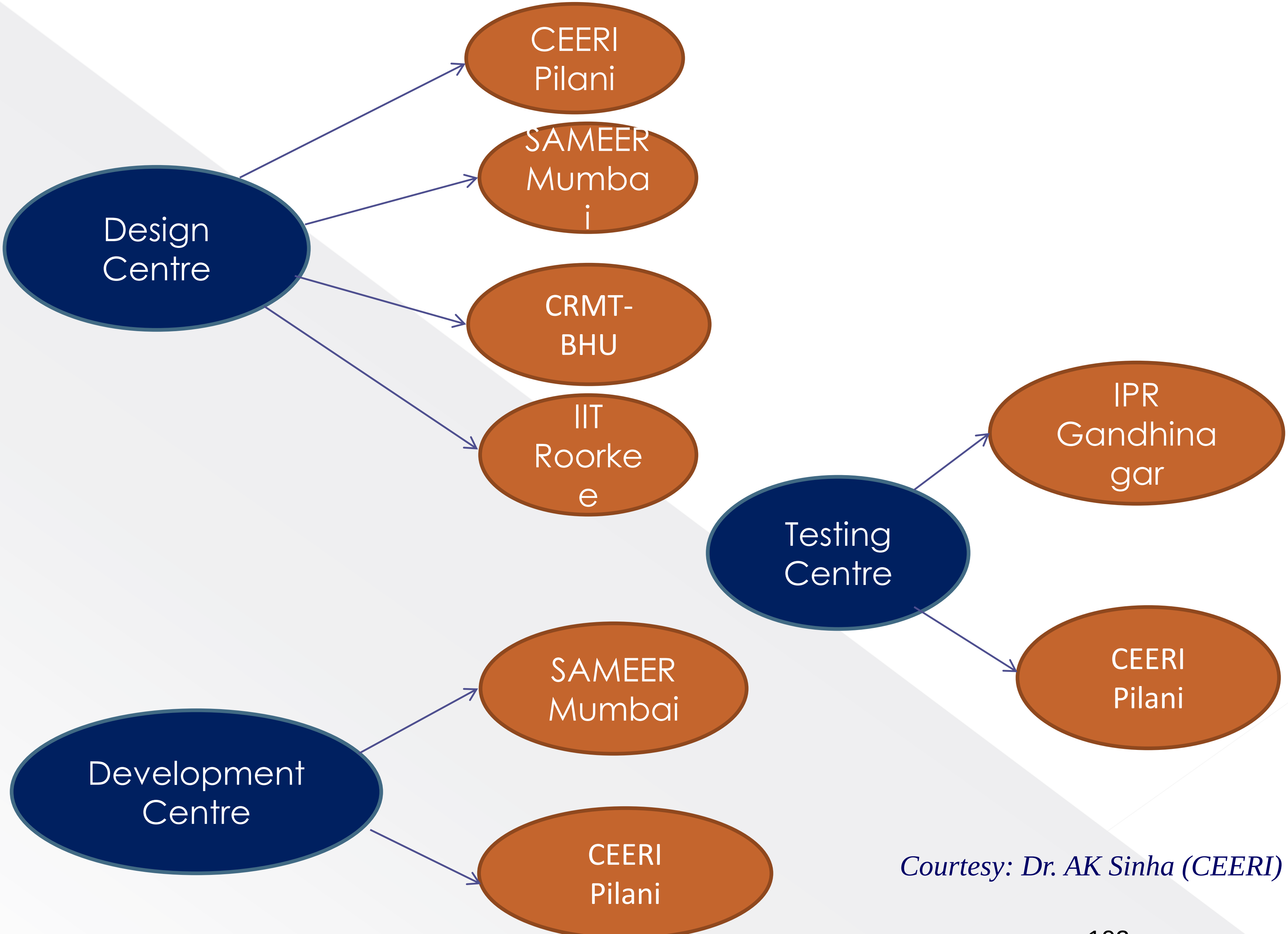
2. SAMEER, Mumbai — Window

3. IPR, Gandhinagar — Magnetic focusing structures, Thermal management, Power supply and Plumbing line

4. BHU — Cavity and Nonlinear taper

5. IIT-Roorkee — Providing assistance to the other participants in the design of the device and its parts

Bharat Electronics is one the members of the steering committee of the project with the understanding that the production of the gyrotron would be eventually taken up once it is designed and developed



Courtesy: Dr. AK Sinha (CEERI)

Vacuum Electron Devices and Applications (VEDA) Society

Organises either a workshop or a symposium usually every alternate year in the country

VEDA 2004 Symposium: MTRDC, Bangalore (30 & 31 October 2004)
VEDA 2005 Workshop: CRMT-BHU, Varanasi (18 & 19 January 2006)
VEDA 2006 Symposium: CEERI, Pilani (CSIR) (11-13 October 2006)
VEDA 2007 Workshop: SAMEER, Mumbai (22 & 23 November 2007)
VEDA 2008 Workshop: MTRDC, Bangalore (DRDO) (8-10 January 2009)
VEDA 2009 Symposium: CRMT-BHU, Varanasi (30 & 31 October 2009)
VEDA 2010 Workshop: CET, Moradabad (18 & 19 November 2010)
VEDA 2011 Workshop: RKGIT, Ghaziabad (18 & 19 November 2011)
IEEE-EDS IVEC-2011: Organized in Bangalore jointly with VEDA Society
VEDA 2012 Symposium: CEERI, Pilani (CSIR) (21-24 September 2012)
VEDA 2013 Workshop: IIT-R, Roorkee (18-20 October 2013)
VEDA 2014 Workshop: DAVV, Indore (20 & 21 March 2015)
VEDA 2015 Conference: MTRDC-DRDO, Bangalore (3-5 December 2015)
VEDA 2016 Conference: IPR-DAE, Gandhinagar (16-18 March 2017)
VEDA 2017 Symposium: IIT-R, Roorkee (17-19 November 2017)
VEDA 2018 Symposium: IIT-G, Guwahati (22-24 November 2018)
VEDA 2019 Workshop/ Symposium: NIT-Patna (21-23 November 2019)

List of M. Tech students of Burdwan University who have completed their thesis work at CEERI, Pilani in the areas of microwave tubes

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)

Incomplete list to be updated


Thank You!