Appendix

Trends in the Development of Microwave Tubes

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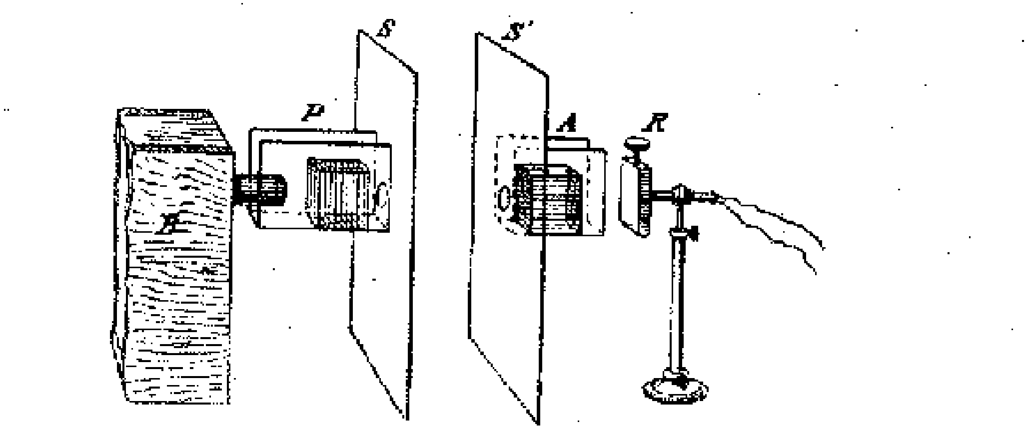
"Bose's experiment is believed to be the first ever microwave experiment in artificial materials (on twisted structures) for electromagnetic applications which exhibit the chiral characteristics!"

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



Polarisation apparatus. B, the radiating box; P, the polariser; A, the analyser; S, S', the screens; R, the receiver.

"On the rotation of plane of polarisation of electric waves by a twisted structure," Proc. R. Soc. Lond a 63 (1898), 146-152 by Jagadish Chunder Bose, M. A., D. Sc., Professor of Physical Science, Presidency College, Calcutta. Communicated by Lord Raleigh, F. R. S. Received February 14, read March 10, 1898.

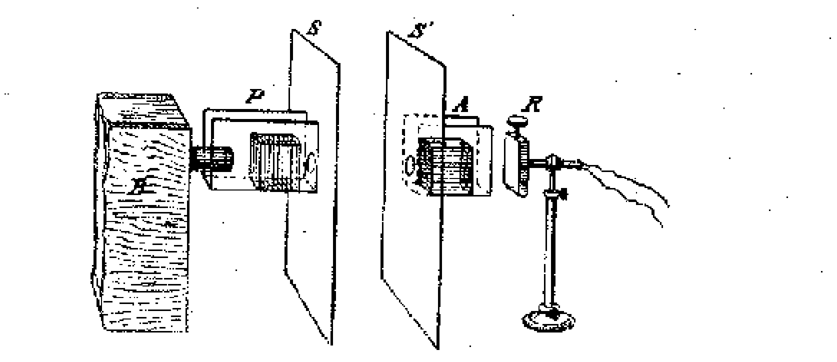
Polariser/ Anlyser:
- Wire gratings
- Parallel slits cut out of two square pieces of thick copper
- An ordinary book with its pages as absorbers (later improvised with alternate leaves of paper and tinfoil)

Bradshaw's
Railway Timetable

Leaves compressed to form a block, enclosed in a brass cell with circular openings on opposite sides for the passage of radiation. Typically, 6×6 cm of 4.5cm thick; opening/aperture diameter 4 cm. The brass cell is placed on a shelf attached to a screen of thick brass plate 35×35 cm, with a circular opening 4cm diameter for radiation to pass through.

Polarizer has vertical leaves. Analyzer has horizontal leaves.
When two such cells are crossed, the field is completely extinguished

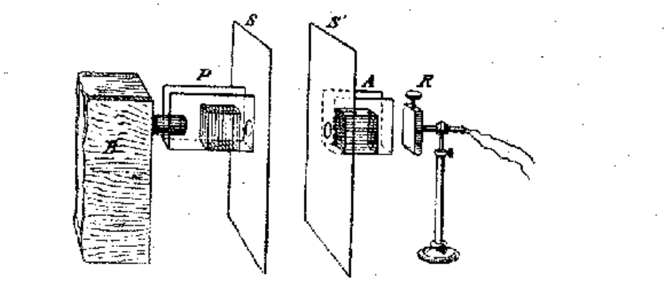
The field is partially restored when one’s fingers are placed at 45^0 between the crossed polarizer and analyzer



Polarisation apparatus. B, the radiating box ; P, the polariser ; A, the analyser ;
S, S′, the screens ; R, the receiver.

Electro-optic analogues of two varieties of sugar solutions, typically, dextrose and levulose

Bundles of elements (‘molecules’) of jute fibres (each element, typically, 10 cm length, 4.5 cm diameter) placed end to end



Polarisation apparatus. B, the radiating box; P, the polariser; A, the analyser; S, S', the screens; R, the receiver.

A: Untwisted

B: Twisted to the right (positive)

C: Twisted to the left (negative)

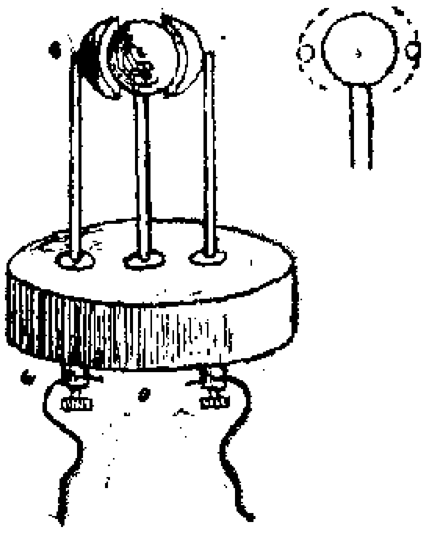
No fields recorded by the receiver when the bundles were not interposed between the crossed polariser and analyser

Restoration of field by the receiver when the bundles of variety B were interposed

Restoration of field by the receiver when the bundles of variety C were interposed

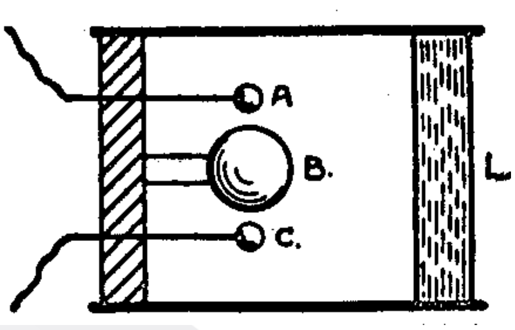
No restoration of fields when the bundles of variety A were interposed

No restoration of fields when the bundles of varieties B and C, in equal proportions, were interposed

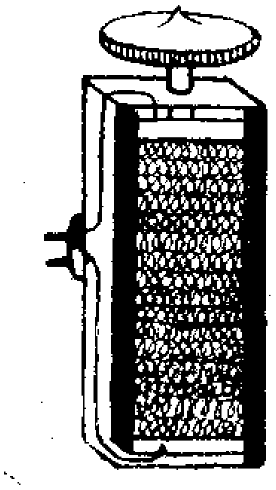


The Radiator.

(a)



(b)



The Spiral-spring Receiver.

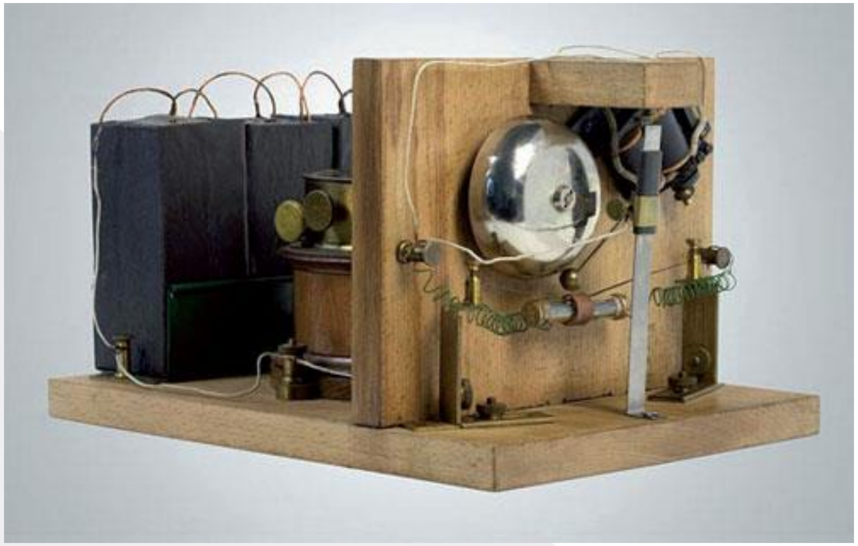
(c)

Oscillation is produced by sparking between 2 hollow hemispheres and the interposed sphere. There is a bead of platinum on the inside surface of each hemisphere (a). For some experiments, a lens of glass or of sulphur was used to collimate the radiation — the first waveguide-lens antenna (b). The lens was designed according to the refractive index measured by Bose at the wavelength in use.

Spiral-spring receiver used for 5-mm radiation (c)

"space-irradiated multi-contact semiconductor (using the natural oxide of the springs)."

Source: D. T. Emerson



Popov’s radio receiver

“The primary tool for detecting radio waves at the time was the *coherer*. Invented by Lodge based on the observation by Edouard Branley that powdered metal could conduct electricity after being exposed to electromagnetic waves, the coherer was a simple tube filled with iron filings between two electrodes. Initially, the resistance across the electrodes was relatively high thanks to the loosely packed powder and oxide coatings on each grain. A passing radio wave would cause the grains to almost weld together — sometimes sparks were reported coming from the coherer tube — which lowered the resistance enough to conduct electricity. Lodge had used his coherer to detect “Hertzian waves” in 1894, shortly after the death of their namesake.”

“A coherer is a one-shot device: once it detects a signal, it needs to be mechanically restored to the high resistance state by tapping to release the adhered metal granules. Popov’s decoherer was cleverly coupled to the bell used to signal a detected wave; once the clapper had struck the bell it would spring back to rest after tapping the coherer tube to jostle its contents.”

Microwave and Communication

Wireless communication depending on microwaves:

- Direct broadcast satellite (DBS)
- Personal communication system (PCS)
- Wireless local area networks (WLANS)
- Worldwide interoperability for microwave access (WIMAX)
- Cellular video (CV)
- Global positioning satellite (GPS)

High power Microwave sources and amplifiers constitute the backbones of

- Point-to point communication with more channel capacity
- Satellite-to-home communication (TVBS)
- Radar
- Electronic warfare
- Missile tracking and guidance
- Remote sensing
- Material processing
- Imaging

Exploration of millimeter-wave regime includes:

- Extension of radio range
- High information density communication
- Deep-space and specialized satellite communication
- High resolution radar

Magnetron was the key element in RADAR that significantly controlled World War II.

Synthetic Aperture Radar (SAR) has made it possible to simulate electronically an extremely large antenna or aperture that provides

- High-resolution remote sensing imagery at night or during inclement weather
- Reconnaissance and targeting information to military operations
- Reconnaissance terrain structural information to geologists for mineral exploration
- Oil spill boundaries on water to environmentalists
- Sea state and ice hazard maps to navigators

Civilian radars are used for

- Weather detection
- Highway collision avoidance
- Air-traffic control
- Burglar alarm
- Garage door opener
- Speed detectors (law enforcement)
- Air-traffic control
- Mapping of ground terrain
- Ground probing (for the detection of underground materials like gun emplacements, bunkers, mines, geological strata, pipes, voids, etc.)
- Remote sensing
- Imaging in atmospheric and planetary science
- Space debris phased-array mapping, analysis of cloud (as a sensor in environmental research), etc.
- Microwave life detection for sensing heart beats and breathing, for instance, under earth-quake rubbles

Industrial heating applications:

Industries: paper, leather, textile, plastic, wood, forest, food, printing, pharmacy, chemical, photographic, measurement, etc.

- Drying of leather, rubber, pharmaceuticals, tea, coffee, tobacco, textiles, film, etc.
- Food: precooking, cooking, pasteurizing, sterilizing, dough proofing, thawing, tempering, pasta drying, roasting of food grains/beans
- Plastic: sealing/ bonding, bulk heating, molding plastic foam, plastic laminate production, drying
- Forest: hardwood drying, plywood-veneer drying, pulp/wood-chip drying, destruction of fungi, and insects in wood
- Rubber: vulcanization, curing sponge rubber tubing, curing and foaming polyurethane bulk heating
- Chemical: drying paint and varnish, refractory processes, polymerizing

Courtesy: SN Joshi (CEERI)

◦ Photographic: film processing requiring selective coating: polyesters and acetates of low dielectric loss and emulsions of high dielectric loss (photographic)

◦ Measurement: thickness monitoring of metal/dielectric sheets in rolling mills

◦ Medical: medical diagnosis and treatment using the phenomenon of dielectric heating

  - ◊ Orthopedics: arthritis, sciatica, rheumatism
  - ◊ Internal medicine: asthma, bronchitis, urology
  - ◊ Dermatology: boils, carbuncles, sores, chilblains.
  - ◊ Oto-rhyno-laryngology: abscesses, laryngitis, etc.
  - ◊ Dental care and ophthalmology

Courtesy: SN Joshi (CEERI)

◊ Hyperthermia implemented by using phased-array antenna that locally heats the tumor cells selectively and raptures their membrane leading to the destruction of cancerous cells, without harming healthy ones, thus enabling such heated tissues to receive more nutrients and antibodies thereby speeding up the healing process

◊ Ablation that dries up or desiccates the tumor with localized application of heat for the removal unwanted tissues, for example, liver and lunge tumors of patients with poor surgical condition

Typical antenna applicator at 2.45 GHz (ISM band) can provide powers from100 mW/cm^2 to ~1 W/cm^2 for 15 to 30 minutes.

Other peaceful applications:

- Industrial heating
- Material processing
- Waste remediation
- Civil, mining and public health engineering—including breaking of rock, breaking of concrete, tunnel boring and soil treatment
- Plasma heating for a controlled thermonuclear reactor (electron cyclotron resonance heating of fusion plasmas) involving heating of hydrogen isotopes typically at ignition temperature of 108 K at 200 GHz
- Scientific applications including RF linear accelerators, plasma diagnostics and chemistry, nonlinear spectroscopy, etc.

- Material processing providing volumetric and selective heating millimeter-wave frequencies using gyrotrons

  → ceramic sintering and joining

  → production of new composite ceramics—stronger and less brittle—that can retain their high strength under high temperature and corrosive conditions

Consequently, this has made it possible to develop lightweight ceramic engines for aircraft and automobiles as well as strong, long-lived ceramic walls for thermonuclear power reactors.

Terahertz-regime applications:

- Imaging
- Security inspection
- Enhanced sensitivity spectroscopy
- Dynamic nuclear polarization enhanced nuclear magnetic resonance

Other unconventional applications:

- Satellite power station
- Artificially created ionized layers for the extension of radio range
- City lighting
- Nitrogen fertilizer raining on the earth
- Environmental control by both ozone generation and atmospheric purification of admixtures that destroy ozone layer

SSD versus VED/ Microwave Tube

Issue	**SSD**	**VED/ Microwave tube**
Collisional heat produced by electron stream	Throughout volume	At the collector
Operating temperature	Lower temperature operation for a longer life (lower mobility — a greater drag or inertial forces due to collision) Degradation at a higher temperature due to dopant migrating excessively, lattice becoming imperfect, mobility getting reduced impairing high frequency performance Wide-band-gap semiconductors like SiC and GaN to be used for high temperature operation	Higher temperature operation

SSD versus VED/ Microwave Tube (*in continuation*)

Issue	SSD	VED/ Microwave tube
Breakdown limit on maximum electric field inside the device	Lower	Higher
Base plate size Determined by cooling efficiency increasing with (i) the temperature difference between the hot surface and the cool environment and (ii) the surface area of the hot surface	Larger	Smaller (higher collector temperature)
Peak pulsed power	Lower Calls for power combining by multiple transistors and proportionate increase in package size	Higher Beam may be pulsed in the region separated from the interaction region
Ultra-bandwidth performance (Three-plus-octaves)	Possible below 1 GHz Corresponding to longer wavelengths ensuring negligible phase difference, for instance, in the voltage between the emitter and base	Usually not possible Controlling the structure dispersion is a challenging problem

MBK — multi-beam klystron

A parallel arrangement of low-perveance beamlets within a common RF structure for

- Large beam current and RF output power
- Low beam voltage and compactness due to reduced plasma wavelength (= beam velocity/ plasma frequency)
- PPM-stacked device

Each beam propagates in its own channel and then interacts with the field of a common interaction structure.

The space-charge effects and correspondingly the efficiency are the same as that of a single-beam tube but the beam current, beam perveance and power increase with the number of beamlets.

Typical SLAC MBK

- 10 individual 500 kV, 500 A (1.5 microperv) beams
- Output: 1 GW, 1 μs, 1.5 GHz, 36 dB gain, 40% efficiency

Typical L-3 Communications Electron Devices MBK

- 10 individual 115 kV, 13 A (1.6 microperv) beams
- Output: 10 MW, 1.5 μs, 1.3 GHz, 47 dB gain, 70% efficiency

Advantages of MBKs over conventional klystrons

The space-charge effects and correspondingly the efficiency are the same as that of a single-beam tube but the beam current, beam perveance and power increase with the number of beamlets.

- Reduced cathode voltage (40 to 50% less)
- Possible increase in pulse length
- Increased reliability of the HV power supply
- Fewer risks of gun arcing
- Smaller size at a given power level
- Easier protection against X-rays
- Higher efficiency
- Wider bandwidth

Devices accruing the advantages of solid-state devices and technology

Microwave power module (MPM)

Vacuum microelectronic tubes

- MPM Capitalizes relative strengths of both the solid-state and vacuum-electronic technologies
- Utilizes miniature, high-efficiency electronic power conditioner (EPC) technology to build a compact power amplifier

- Vacuum-microelectronic (microfabricated) tube fundamental advantages: (i) electron velocity in vacuum about a thousand times grater than that in semiconductor solids, and higher signal processing speeds, (ii) less collisions of moving electrons with atoms and less associated energy loss as heat, (iii) precision dimensioning of parts/ electromagnetic structures in the millimeter-wave and terahertz regimes, (iv) cold field-emission arrays cathodes (such as carbon nanotubes), batch production, etc.

Wideband multi-octave TWTs for EW applications

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

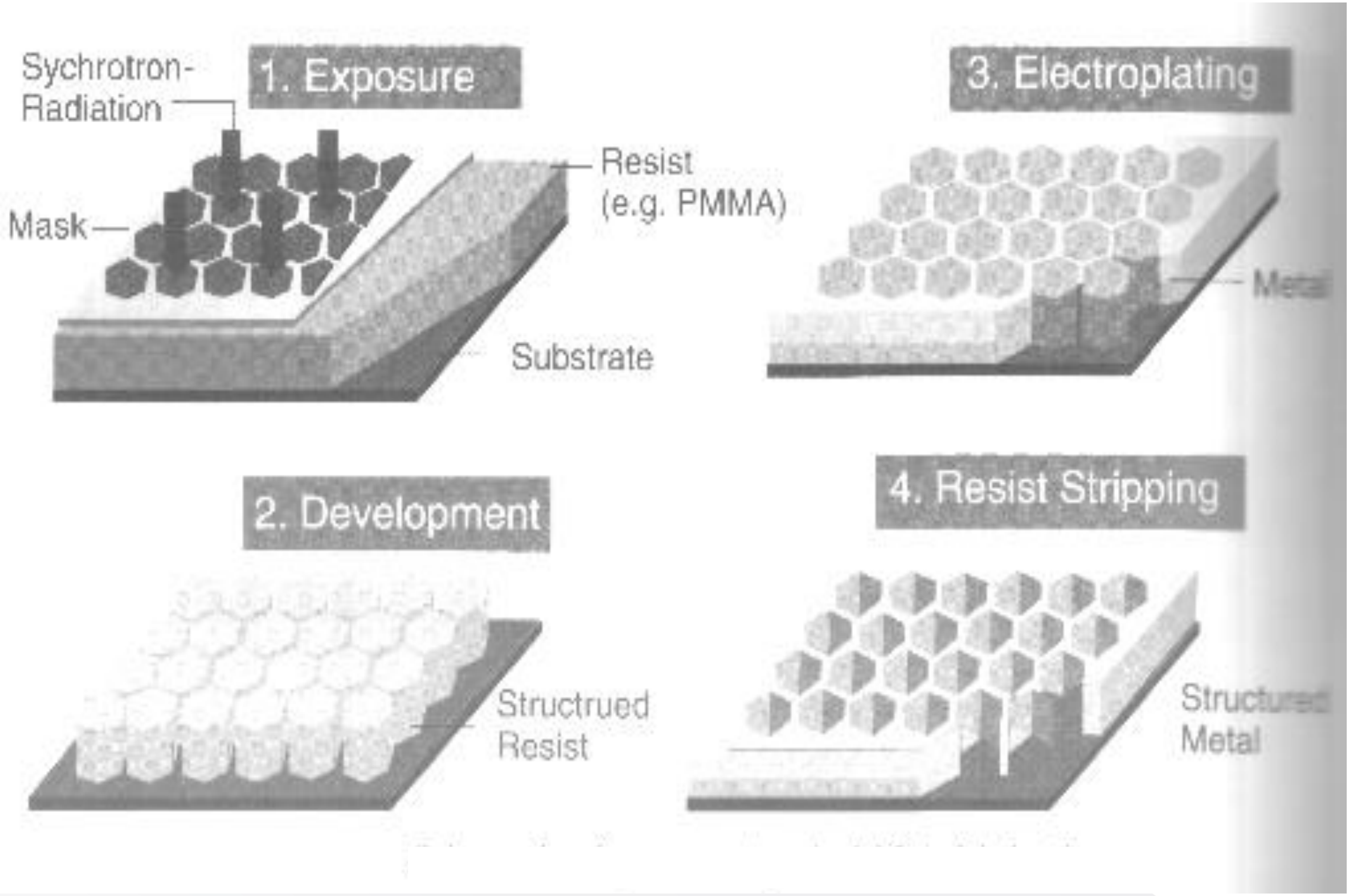
Vacuum microelectronic tubes in terahertz regime

- **Micro-fabricated TWTs**

- **Folded waveguide slow-wave structure using microfabrication techniques like**

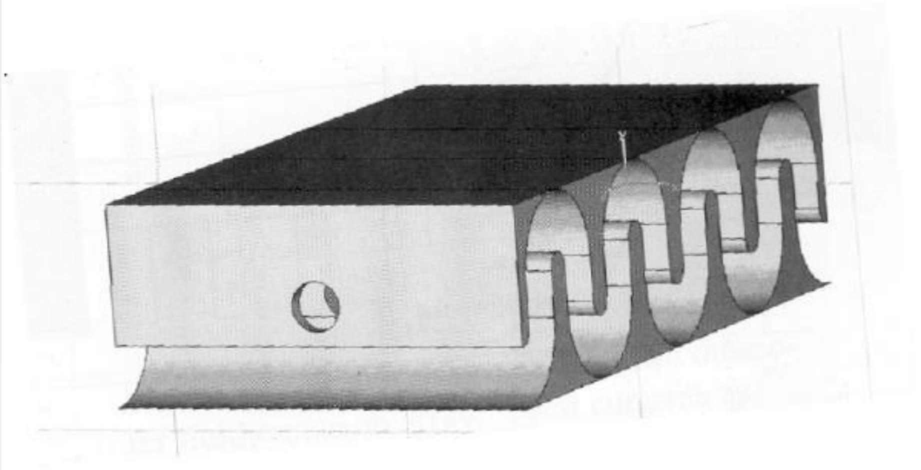
  EDM — electric discharge machining
  DRIE — deep reactive ion etching
  LIGA — lithographie, galvanoformung, abformung

Example: A folded (serpentine) trench is etched in silicon with a DRIE tool, and then gold-plated. Two such trenches bonded together form a folded waveguide
Field emission array cathode

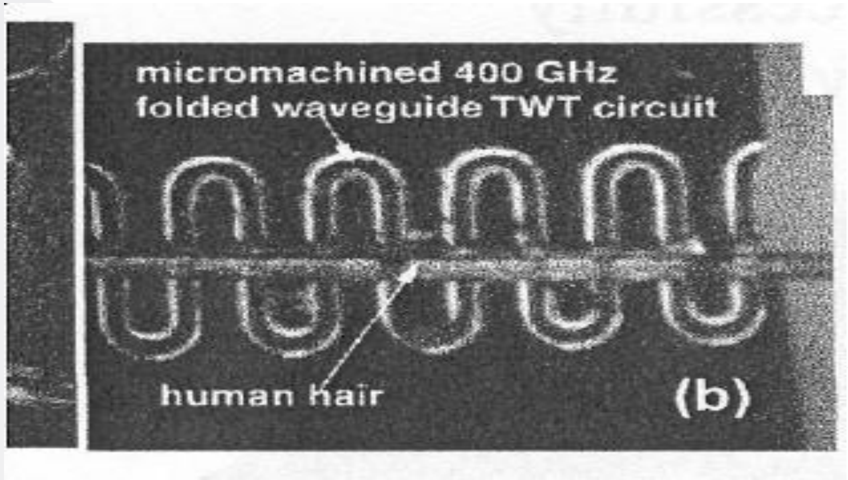


Schematic of process steps in LIGA fabrication

Gold-plated chrome mask
Polymethyl metahacrylate resist
Aluminum substrate (low atomic number to reduce back scattering)



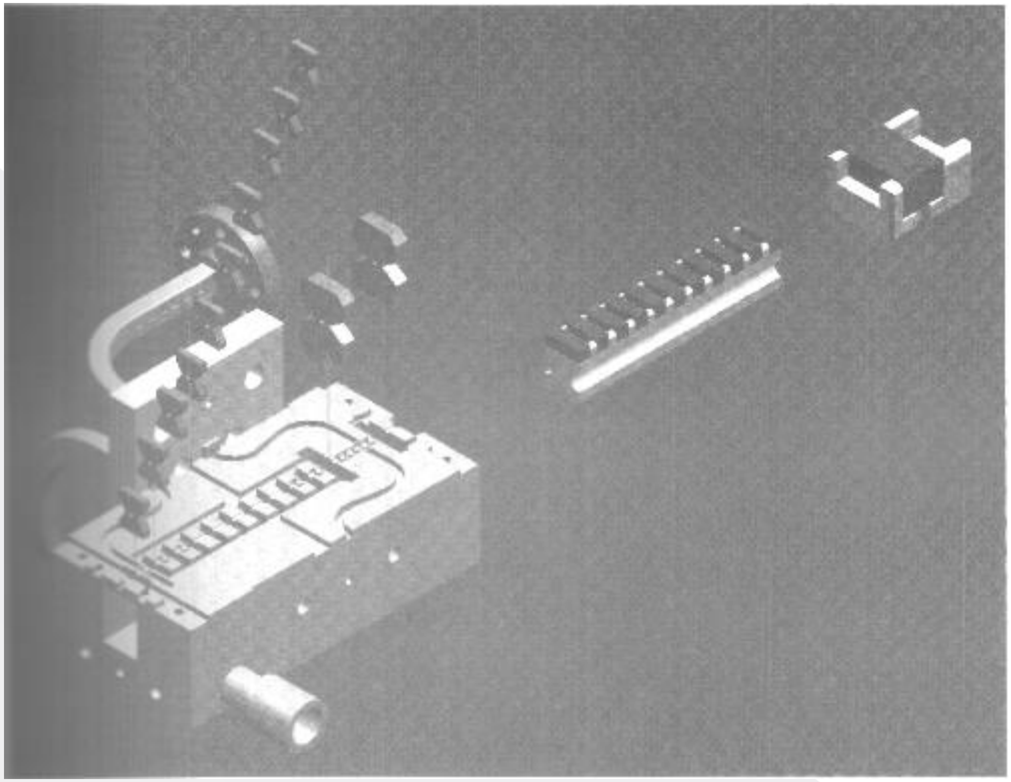
Folded waveguide for a TWT



Vacuum microelectronic klystrino

W band (~3 mm wavelength) Klystrinos in a klystron module
Dimensioning of conventional klystrons difficult in the millimeter-wave band
Lightweight PPM focusing possible in a klystrino
LIGA microfabrication technique for W-band klystrino cavity features with 2-3 μm tolerances and excellent surface finish

A typical klystron module, with 6 klystrinos in parallel, has separate electron guns 0.6 microperv each, cavities and PPM stacks, but a common vacuum and beam dump
Typical W-band klystrino parameters: 120 kV, 15 A; 0.5 MW peak, and 5 kW average; 6 inch dia, 12 inch length, < 20 lbs weight.



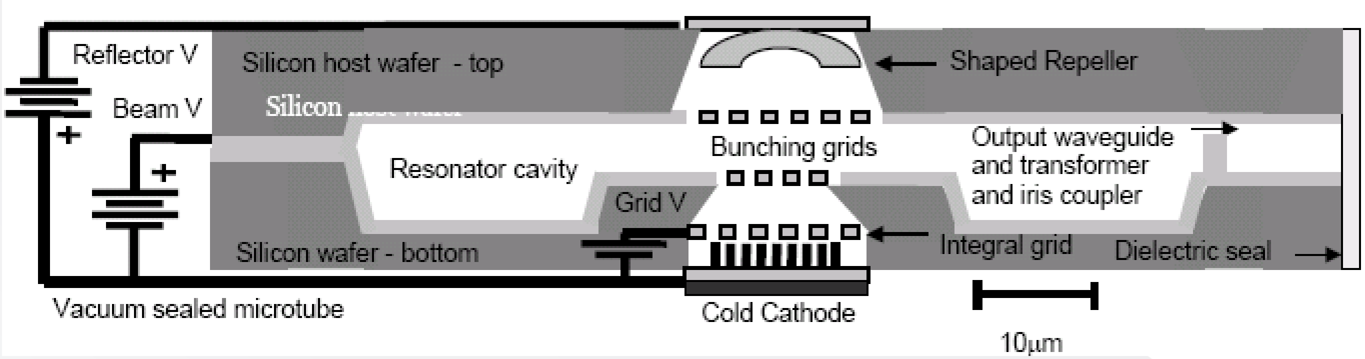
Explored model of klystrino circuit assembly with PPM pole pieces and magnet

Nanoklystron: a monolithic terahertz reflex klystron

Carbon nanotube field emitter

The structure is formed monolithically from two thermo-compression bonded silicon wafers processed using deep reactive ion etching (DRIE) technique and using carbon nanotube field emitter

~mW power at 1.2 THz



PH Siegel, and others: 12th Int. Conf. Space THz Technology, San Diego, Feb 14-16, 2001

HPM (1-100GHz)

Refers to:

i) long pulse duration, high-prf, or CW
ii) high-peak power, short-pulse duration, low-prf or single-shot

Both military and civilian applications:

Military — ∘ Conventional electronic warfare (EW) in the high power level

∘ Directed energy weaponry (DEW) of both the hard-kill type (physical destruction of targets), and the soft-kill type (making enemy's mission critical components either inoperative or faulty)

Civilian — **Satellite power stations (SPS), Artificially ionised layer (AIL):** Remote radio and TV communication, remote spectroscopy of atmosphere, city lighting and nitrogen fertiliser generation, Environmental control: repair of ozone hole, atmospheric purification of admixtures that destroy the ozone layer, etc.

… HPM–DEW

Hard-kill type:

Physical destruction of targets, burnout of or lethal damage to enemy electronic systems

Soft-kill type:

Making enemy’s mission-critical components either inoperative or faulty

10^{-7} Jcm^{-2} is good enough to cause bit error in computers and computer-aided equipment!), deception or spoofing of enemy systems into mission failure, temporary upset or disruption of enemy electronic systems, jamming of enemy microwave or RF receivers or radar sets to disrupt detection, communication and control systems

… HPM–DEW

- Non-lethal weaponry
    - provides 'friendly' troops with the ability to remotely neutralise the communication systems of 'aggressive' forces without loss of life on either side
- Energy, instead of matter, to be directed on targets
- Attacks at high speed
- Ammunition
    - Relies on power supply rather than on magazines of explosives
    - Spreading of microwaves by diffraction
- Accommodates lack of tracking precision requiring no pinpointing of a target, as in laser warfare
- Coarse pointing of targets
- Large image zone
- All-weather performance
- Exploits the vulnerability of small-size electronic components
- Effective even if the enemy system is switched off

… HPM-DEW

Typical parameters of HPM tubes:

Frequency: 10 MHz – 100 GHz

Power: 100 MW – 100 GW

Pulse width: Up to 1 msec

Duty factor: Single shot to 0.002

Intense electromagnetic pulse (EMP) of peak powers ~10’s of TW of very short duration ~100’s of ns (shock-wave) can be used for a directed energy weapon (DEW may be generated typically by ‘Electromagnetic Bomb’ made out of an HPM tube and a flux compression generator

Coupling Mechanisms:

- Front door : through transmitting /receiving antennas
- Back door : Power connector cables, grills/holes in enclosures,
  display screens of computers, etc.

Effect of HPM on systems

Dielectric heating

High voltage transients

High voltage breakdown

Deception or spoofing of target to mission failure

Jamming of radar, communication or control systems

Temporary upset or disruption of electronic systems

Burn-out of electronic devices

Breakdown voltage ratings of electronic devices

Silicon high frequency bipolar transistor: 15 V – 65 V
Gallium arsenide FET: ~ 10V
Dynamic random access memories (DRAM) ~ 7 V
CMOS logic: 7 V – 15 V
Microprocessor: ~ 5 V

Upset levels for electronic devices

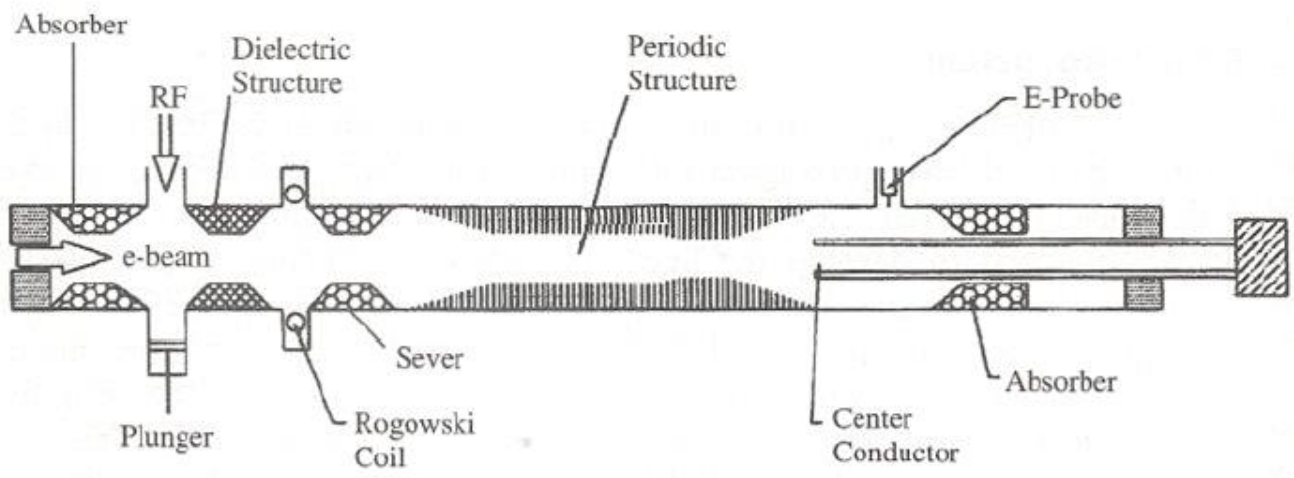
Type	**Power** (W)	**Energy** (J) @ 1msec
Operational amplifier	0.0009	9 X 10^{-10}
TTL device	0.008	8 X 10^{-9}
CMOS device	0.001	10^{-9}
Voltage regulators	0.09	9 x 10^{-8}
Comparator (output switches)	0.008	8 x 10^{-9}
VHSIC (pulsed exposure)	0.1	10^{-7}

Courtesy: SUM Reddy/S Kamath

Electronic device burnout thresholds

Component	**Energy** (J)
GaAs MESFET	10^{-7} – 10^{-6}
MMIC	7 x 10^{-7} –5 x 10^{-6}
Microwave diodes	2 x 10^{-6} –5 x 10^{-4}
VLSI	2 x 10^{-6} –2 x 10^{-5}
Bipolar transistor	10^{-5} –10^{-4}
CMOS RAM	7 x 10^{-5} – 10^{-4}
MSI	10^{-4} –6 x 10^{-4}
SSI	6 x 10^{-4} –10^{-3}
Operational amplifiers	2 x 10^{-3} –6 x 10^{-3}

Courtesy: SUM Reddy/S Kamath



Relativistic TWT

- Capable of delivering large RF power due to high beam voltage/ high beam power

- Larger dimensions due to high beam voltage

Synchronization is maintained even if significant reduction in beam kinetic energy takes place

VIRCATOR

- Virtual Cathode oscillator (vircator): Simple, no magnetic field required, single-shot device, low cost, tunable by controlling the space-charge density

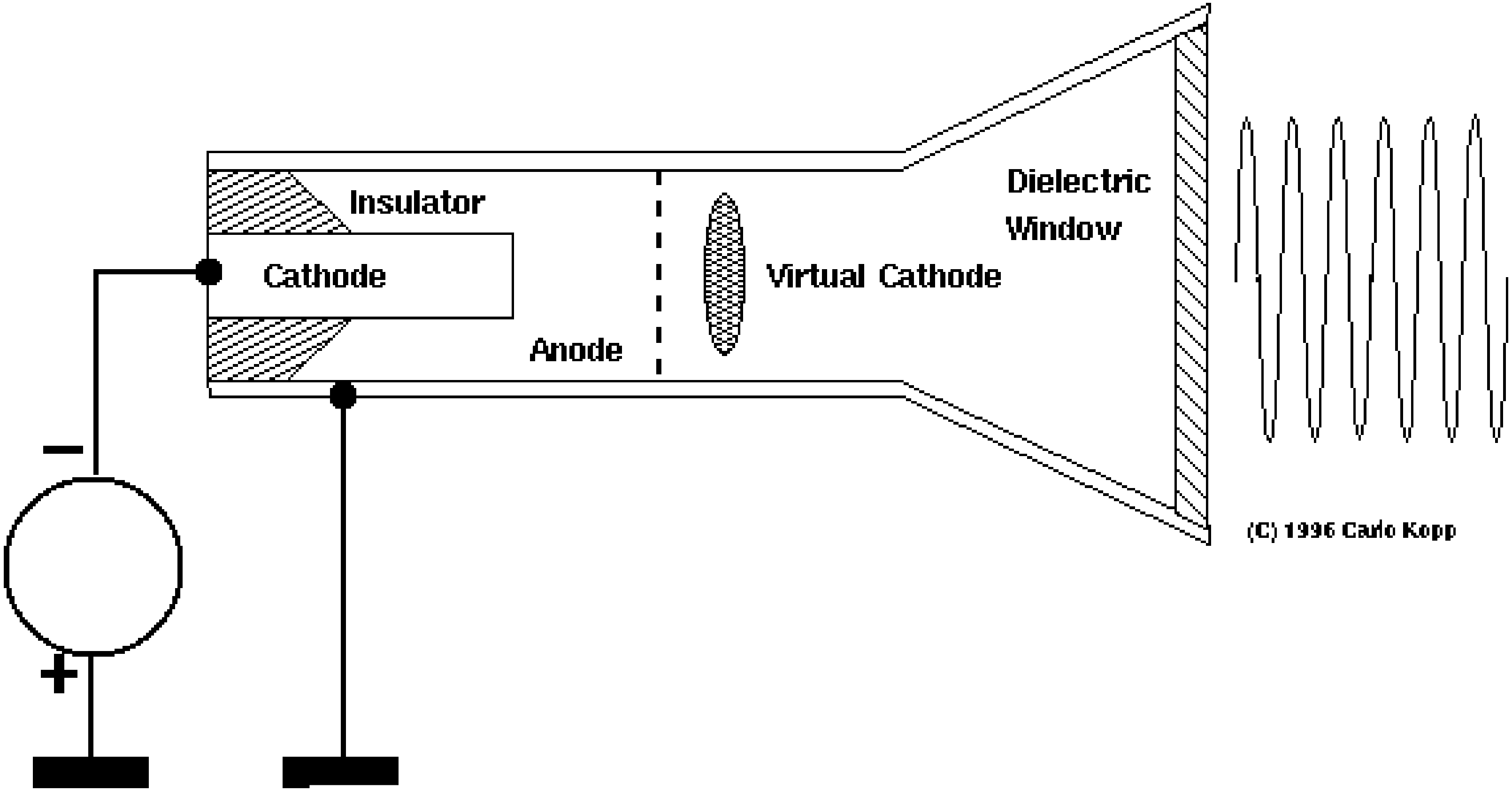
- Bremsstrahlung device in an electrostatic field realized in a waveguide resonator

- Virtual cathode forms beyond the anode at a distance equal to the anode-cathode spacing

Beam current > Space-charge limiting current

Space-charge limiting current in a metal drift tube:

Radial space-charge electric field (potential gradient) gives a radial electron velocity at the expense of longitudinally directed electron velocity. At the space-charge limiting current, the electrostatic potential energy corresponding to the potential difference between the beam and the drift tube equals the electron kinetic energy, and the beam electrons cannot propagate forward
Analogous to an *LC* oscillator generating microwaves, the virtual cathode acting as a capacitor *C* in storing the beam kinetic energy, and the beam current itself being like a time- varying current through an inductor *L*



Virtual cathode oscillator (VIRCATOR)

VIRCATOR

Types:

- Axial extraction (TM mode)
- Transverse extraction (TE mode)
- Coaxial structure
- Reditron (with the anode foil replaced by a thick metal anode with large holes)

Typical output parameters:

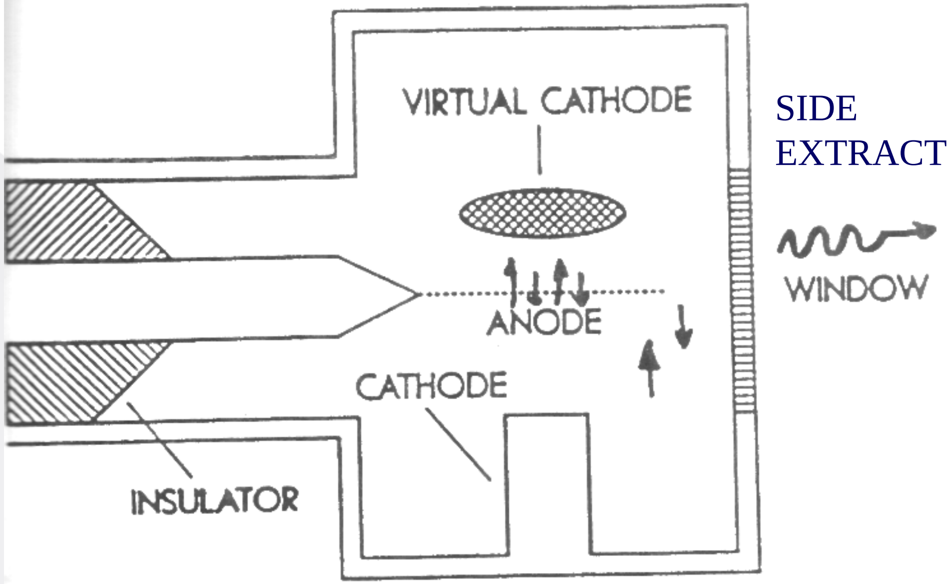
1 GW, 400-800 MHz, 75-125 ns, 100 J, single shot (220 lb)
400 MW, 435-544 MHz, ≤140 ns, 56 J, single shot (500 lb)
1GW, 2-4 GHz, 30 ns, 50 J, single shot (220 lb)

Typical beam voltage and current:

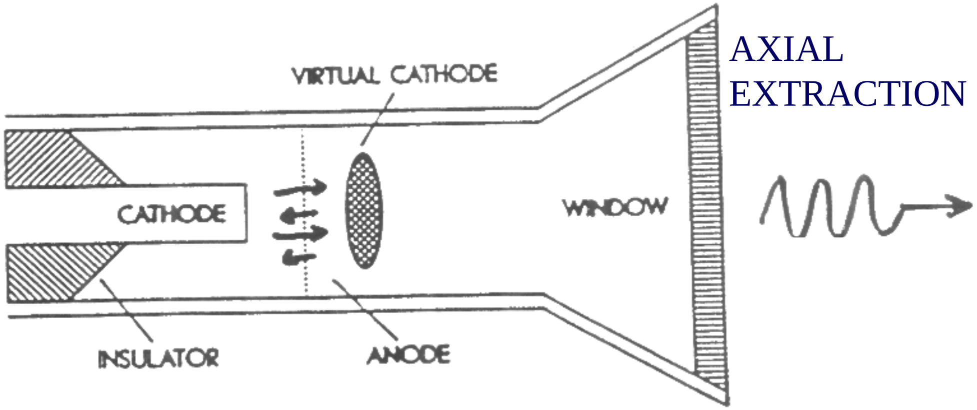
200 kV-6.5 kV; 10-100 kA (25 ns-1.7 μs)

Other typical reported specifications:

20 GW below 1 GHz; 7.5 GW at 1.7 GHz; 4 GW in C-band;
1 GW in X-band; 0.5 GW at 17 GHz

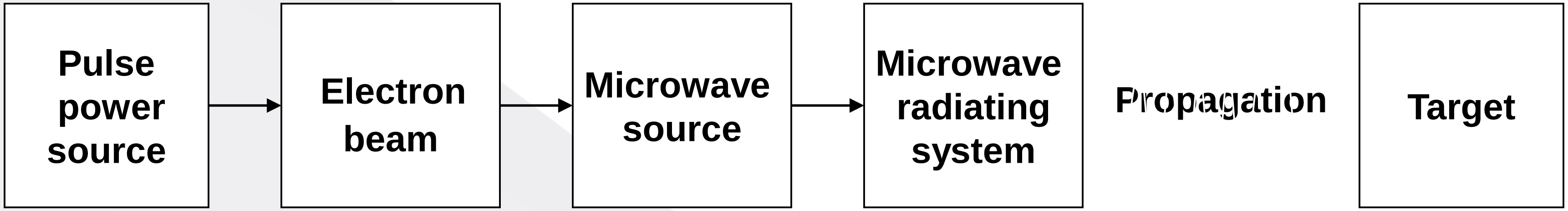


SIDE
EXTRACTION



AXIAL
EXTRACTION

HPM system configuration



Pulse power source

Electron beam

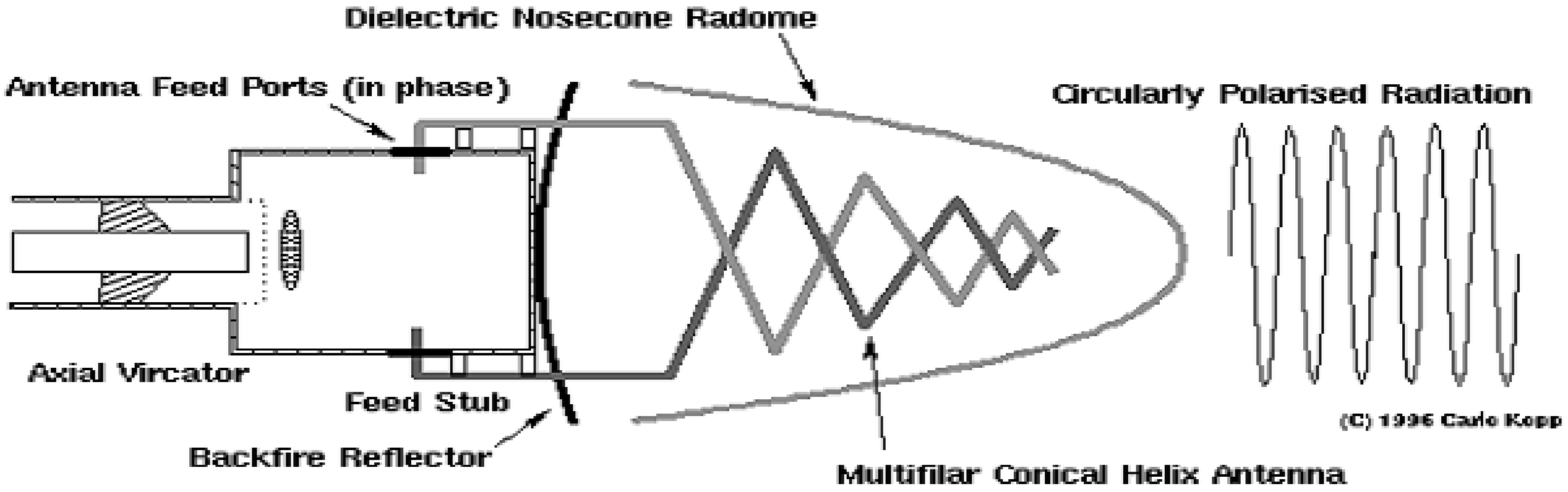
Microwave source

Microwave radiating system

Propagation

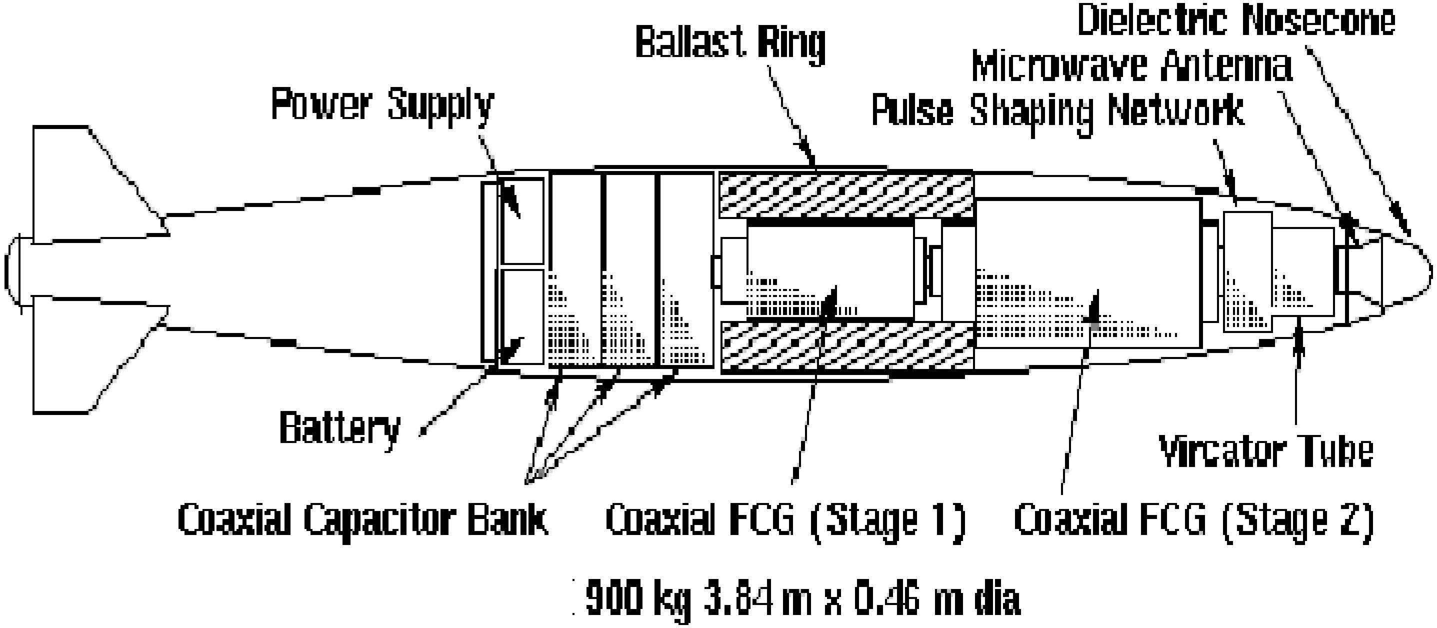
Target

Typical vircator-antenna assembly

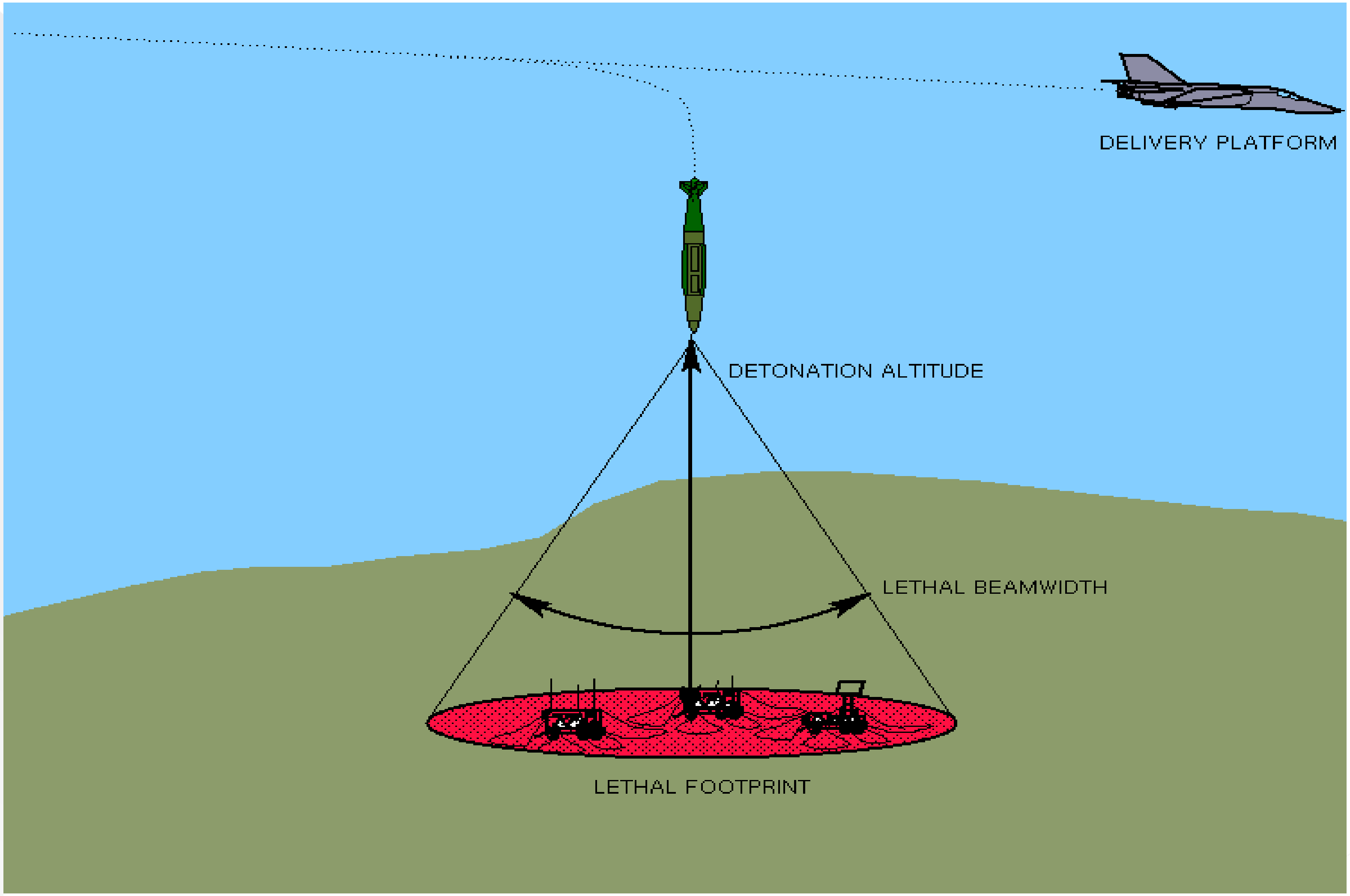


(C) 1996 Carlo Kopp

HPM E-bomb warhead

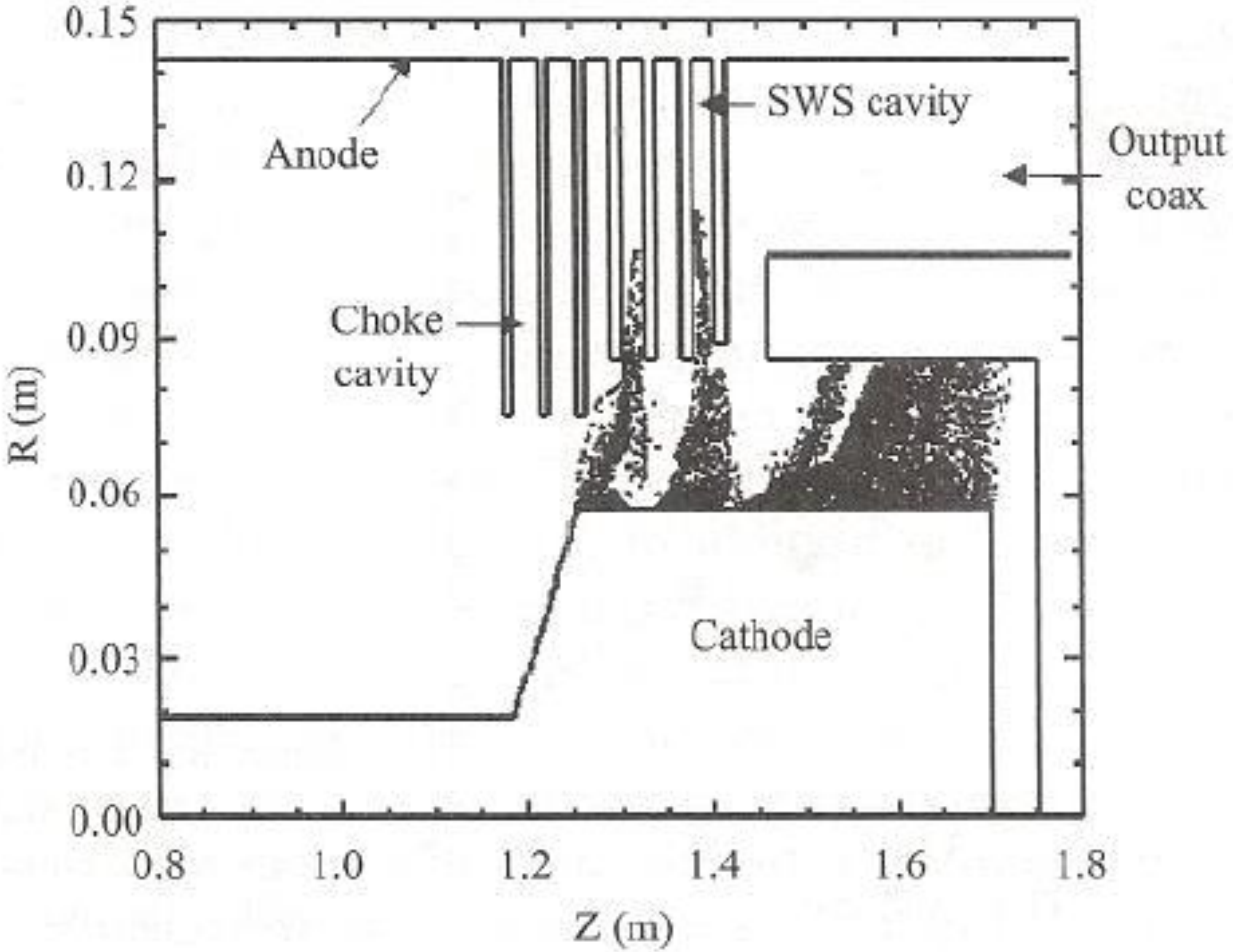


E-Bomb



Lethal footprint of an E-bomb in relation to altitude

MILO


0.15
0.12
0.09
0.06
0.03
0.00
R (m)
0.8
1.0
1.2
1.4
1.6
1.8
Z (m)
Anode
SWS cavity
Output
coax
Choke
cavity
Cathode

…MILO

Magnetically insulated line oscillator — MILO

- A crossed-field device but requires no external magnetic field
  - unlike a magnetron
- Self-generated magnetic field

  Intrinsic electron current generates azimuthal magnetic field.

  Azimuthal magnetic field inhibits electron flow from reaching the anode prior to oscillation (provides self insulation).
- Self-insulating property inhibits electrical breakdown of the anode-to-cathode gap
  - Can handle 10-100’s of GW at a voltage of 100’s of kV.
- Typical MILO experimental parameters:
  - 50 MW, 75 ns; 300 MW, 10 ns
- Tapered MILO for better efficiency and output power
  - First group (4-5) uniform cavities define the oscillation frequency
  - Second group of tapered cavities increase the group velocity, amplifies microwave signal and transforms into a travelling-wave mode in the output line.
  - Placement of the diode within the slow-wave region allows for energy recovery from the diode circuit.

Plasma-assisted tubes

o Neutralization of the space-charge by the plasma (denser the beam) allowing higher electron current transport (50-1000 A cm^{-2})

o Beam transport is provided by ions produced by the impact of the electron beam on neutral gas molecules

o Ions causing the partial compensation of beam space-charge forces, causing the beam to pinch (ion channeling) resulting in self focusing known as the Bennett effect

o Higher frequencies for a given tube size since the phase velocity of electromagnetic waves in a plasma is higher than in vacuum [size~ λ; $v_{ph} = f\lambda$)]

o Performance improvement with respect to

- Bandwidth (~30%)
- Efficiency (>70%)
- Long-pulse operation (~120 μs)
- High-prf operation

….

….

- o Larger interaction area as the beam could be placed far from the metal envelope
- o No or less externally required magnetic field
- o Passage of the electron beam → production of neutralizing ions → prevention of space charge blowup
- o Axial electron beam current → azimuthal magnetic field → radially inward force on the beam (magnetic confining force)
- o Allowance for misalignment of the magnetic field if any applied externally

….

Plasma-filled TWTs

Robert W. Schumacher et al. 1990: U.S. Pat. No. 4,912,367 (assigned to Hughes Aircraft Company)

A plasma-cathode electron gun coupled to a gas-filled, slow-wave structure (SWS) in the form of a rippled-wall waveguide

Space-charge waves on the beam resonantly coupled to rippled waveguide modes→ transfer of energy from the electron beam to RF waves → coupling to space through an output horn antenna

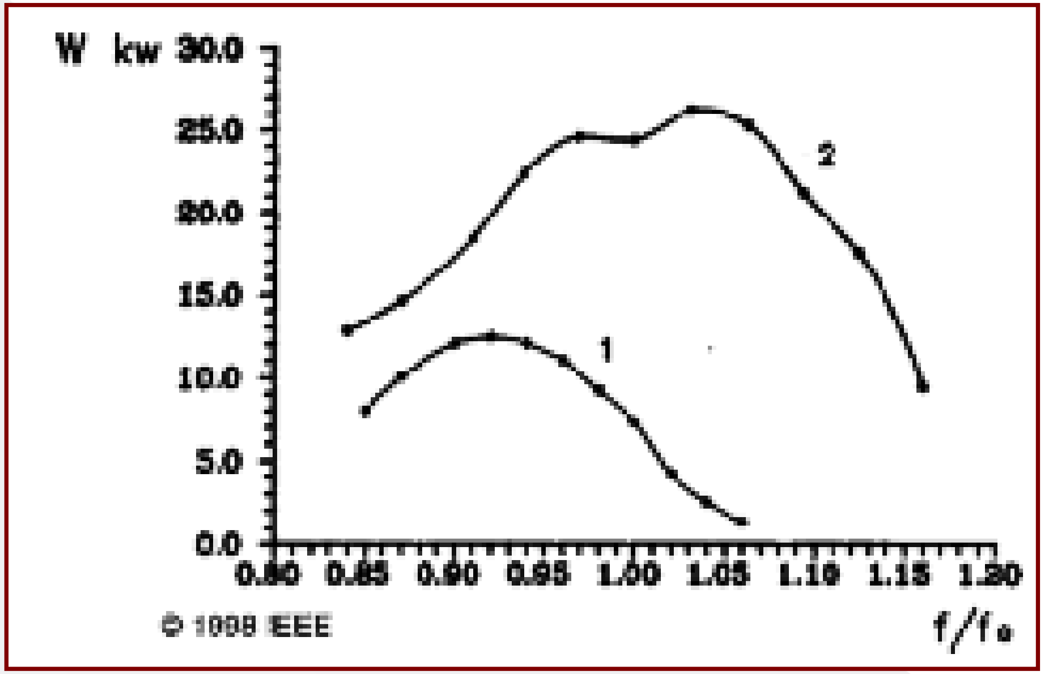
Zero cutoff frequency of the helix → reduction of the tube diameter → reduction of the tube size and weigh and tighter coupling with the beam

Helix-waveguide coupling structure that facilitates a flow of cooling liquid through the helix to remove heat generated during high-power operation

TEM mode of operation of the helix and its surrounding housing → conversion into the TE_{10} mode in input and output waveguides by the helix-waveguide coupling structure

S. K. Datta, Lalit Kumar, and B. N. Basu, "Pierce-type one-dimensional Eulerian hydrodynamic analysis of a plasma-filled helix TWT," *IEEE Trans. Plasma Science,* March, 882-890 (2011).

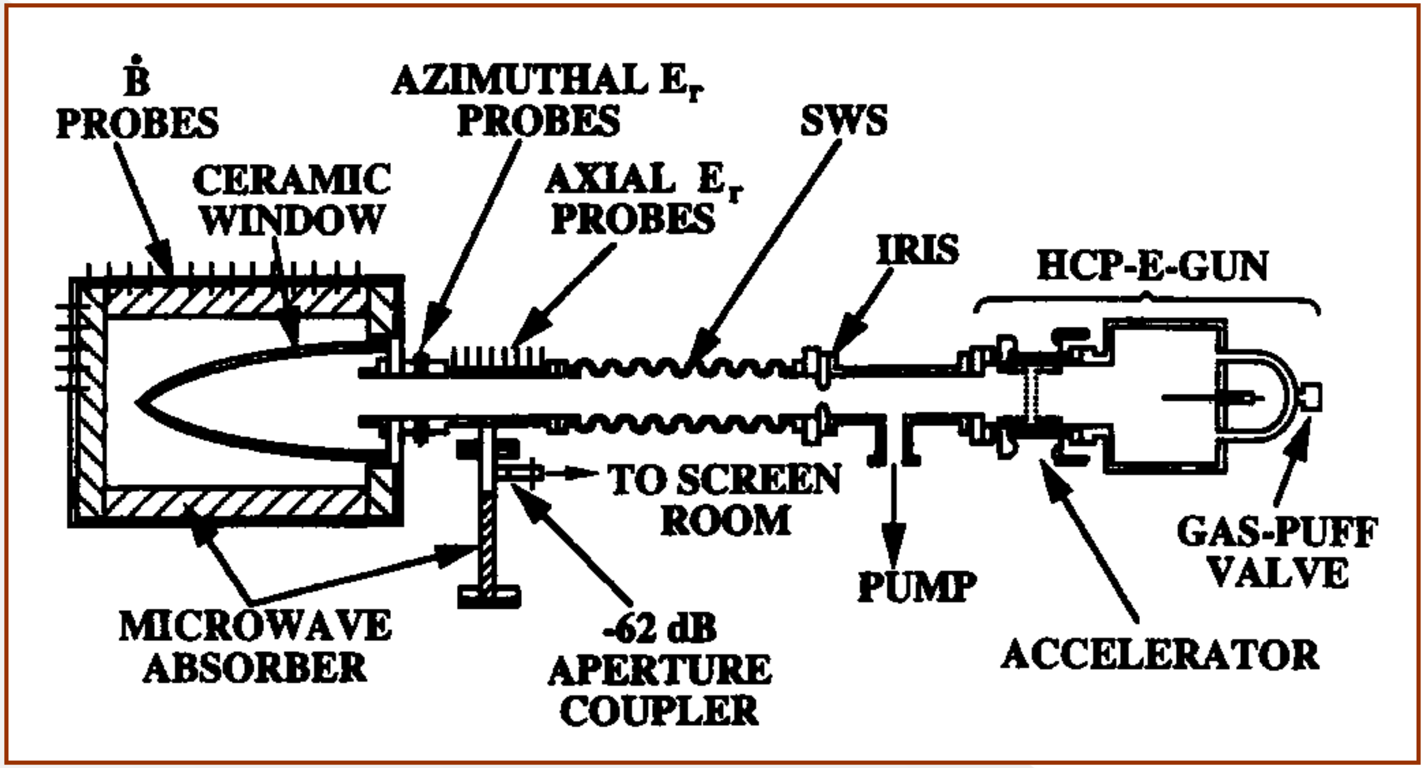
Effect of plasma filing in CC-TWT



Output power vs frequency characteristics of a typical vacuum (1) and plasma-filled (2) coupled cavity TWT showing increased power and bandwidth with plasma filling

Nusonovich et al.: *IEEE-PS* 26 628-644 (1998)

Rippled-walled pasotron (plasma-assisted slow-wave oscillator)



Pasotron schematic (Hughes make: JM Butler, RL Eisenhart, and AJ Schneider, *IEEE MTTT-S Digest*, 511-513 (1992)

Pasotron: a plasma-filled BWO

- Plasma aids electron beam transport through the interaction region
- Plasma contributes to the improvement of coupling of the beam to the structure yielding higher efficiency
- Capable of repetitively fired operation and exceptionally reproducible shot-to-shot characteristics
- Plasma-cathode electron gun to create a plasma-fill through impact ionization of the background gas, typically, 5-50 mTorr helium or hydrogen for high-current density (50-1000 A/cm^2) and long-pulse operation (>100 μsec)
- No magnetic field required: beam confined by its own magnetic field
- Compact, lightweight
- Slow-wave structure: typically, 3.25 cm average radius, 0.715 cm ripple-depth, and 2.4 cm periodicity
- A reflective iris positioned upstream for forward-wave RF extraction

Output: A typical L-band 200 kV PASOTRON produced 20 MW peak power (1 kJ per pulse)

CSIR Institutes/Labs

CBRI - Central Building Research Institute, Roorkee CCMB - Centre for Cellular & Molecular Biology, Hyderabad CDRI - Central Drug Research Institute, Lucknow CECRI - Central Electrochemical Research Institute, Karaikudi CEERI - Central Electronics Engineering Research Institute, Pilani CFRI - Central Fuel Research Institute, DhanbadCFTRI - Central Food Technological Research Institute, Mysore CGCRI - Central Glass & Ceramic research Institute, CalcuttaCIMAP - Central Institute of Medicinal & Aromatic Plants, LucknowCLRI - Central Leather Research Institute, Chennai CMERI - Central Mechanical Engineering Research Institute, Durgapur C-MMACS - CSIR Centre for Mathematical Modelling and Computer Simulation, Bangalore CMRI - Central Mining Research Institute, Dhanbad CRRI - Central Road Research Institute, New Delhi CSIO - Central Scientific Intruments Organisation, Chandigarh CSMCRI - Central Salt & Marine Chemicals Research Institute, Bhavnagar IICB - Indian Institute of Chemical Biology, Calcutta IICT - Indian Institute of Chemical Technology, Hyderabad IIP - Indian Institute of Petroleum, Dehradun IGIB - (Institute of genomics and Integrative Biology) formerly Centre for Biochemical Technology (CBT)IHBT - Institute of Himalayan Bioresource Technology, PalampurIMT - Institute of Microbial Technology, ChandigarhITRC - Industrial Toxicology Research Centre, Lucknow NAL - National Aerospace Laboratories, Bangalore NBRI - National Botanical Research Institute, Lucknow NCL - National Chemical Laboratory, PuneNEERI - National Environmental Engineering Research Institute, Nagpur NGRI - National Geophysical Research Institute, Hyderabad NIO - National Institute of Oceanography, GoaNISCAIR - National Institute of Science Communication and Information Resources, New DelhiNISTADS - National Institute of Science, Technology & Development Studies, New Delhi NML - National Mettalurgical Laboratory, Jamshedpur NPL - National Physical Laboratory, New DelhiRRL,BHO- Regional Research Laboratory, Bhopal RRL, BHU - Regional Research Laboratory, Bhubaneshwar RRL, JM - Regional Research Laboratory, Jammu RRL, JT - Regional Research Laboratory, Jorhat RRL, TVM - Regional Research Laboratory, Thiruvananthapuram SERC, M - Structural Engineering Research Centre, Madras

Information to be updated

Information to be updated

Research laboratories under CSIR

AMPRI - Advanced Materials and Processes Research Institute, Bhopal
C-MMACS - CSIR Centre for Mathematical Modelling and Computer Simulation, Bangalore
CBRI - CSIR-Central Building Research Institute, Roorkee
CCMB- Centre for Cellular and Molecular Biology, Hyderabad
CDRI - Central Drug Research Institute, Lucknow
CECRI- Central Electro Chemical Research Institute, Karaikudi
CEERI - Central Electronics Engineering Research Institute, Pilani
CFTRI - Central Food Technological Research Institute, Mysore
CGCRI - Central Glass and Ceramic Research Institute, Kolkata
CIMAP - Central Institute of Medicinal and Aromatic Plants, Lucknow
CIMFR - Central Institute of Mining and Fuel Research, Dhanbad
CLRI - Central Leather Research Institute, Chennai
CMERI - Central mechanical engineering research institute, Durgapur
CRRI - Central Road Research Institute, New Delhi
CSIO - Central Scientific Instruments Organisation, Chandigarh

Information to be updated

CSMCRI - Central Salt and Marine Chemicals Research Institute, Bhavnagar
IGIB - Institute of Genomics and Integrative Biology, Delhi
IHBT - Institute of Himalayan Bioresource Technology, Palampur
IICB - Indian Institute of Chemical Biology, Kolkata
IICT - Indian Institute of Chemical Technology, Hyderabad
IIIM, Jammu - Indian Institute of Integrative Medicine, Jammu
IIP - Indian Institute of Petroleum, Dehradun
IMMT - Institute of Minerals and Materials Technology, Bhubaneswar
IMTECH - Institute of Microbial Technology, Chandigarh
IITR - Indian Institute of Toxicology Research, Lucknow **(formerly known as** Industrial Toxicology Research Centre**)**
NAL - National Aerospace Laboratories, Bangalore
NBRI - National Botanical Research Institute, Lucknow
NCL - National Chemical Laboratory, Pune
NEERI - National Environmental Engineering Research Institute, Nagpur
NEIST (RRL), Jorhat - North East Institute of Science and Technology, Jorhat , Jorhat

Information to be updated

NGRI - National Geophysical Research Institute, Hyderabad
NIIST - National Institute for Interdisciplinary Science and Technology - Thiruvananthapuram
NIO - National Institute of Oceanography, Goa
NISCAIR - National Institute of Science Communication and Information Resources, New Delhi
NISTADS - National Institute of Science, Technology and Development Studies, New Delhi
NML - National Metallurgical Laboratory, Jamshedpur
NPL - National Physical Laboratory, New Delhi
OSDD - Open Source Drug Discovery
SERC - Structural Engineering Research Centre, Chennai
URDIP Unit for Research and Development of Information Products, Pune

DRDO operates through a network of around 47 laboratories and establishments located nationwide and manned by over 34,000 personnel, including about 16,000 scientific technical persons

Information to be updated

47 DRDO laboratories

1. AERIAL DELIVERY RESEARCH AND DEVELOPMENT ESTT. (AIRDEL) Station Road, Post Box No.51, Agra Cantt. 28,.1 001

2. VEHICLE RESEARCH &;DEVELOPMENT ESTABLISHMENT (VAHANVIKAS), Ahmednagar 414 001

3. DEFENCE AGRICULTURAL. RESEARCH LABORATORY
Almora 263 601

4. COMBAT VEHICLES RESEARCH AND DEVELOPMENT ESTT. (VEHICLEDEV) Avadi, Madras 600 054

5. PROOF AND EXPERIMENTAL ESTT. (PROOF)
PO Chandipore, Balasore 756 025

6. AERONAUTICAL DEVELOPMENT ESTT. (LABAIR)
Suranjan Dass Road, Jiwan Bima Nagar PO, Bangalore 560 075

7. GAS TURBINE RESEARCH ESTT. (TURBINE)
Suranjan Das Road, CV Raman Nagar PO, Bangalore 560 093

8. ELECTRONICS & RADAR DEVELOPMENT ESTT. (DEVELECTRONICS)
DRDO Complex, Byrasandra Village, Jivan Bima Nagar, Bangalore 560 075

9. DEFENCE BIO-ENGINEERING AND ELECTRO-MEDICAL LABORATORY (DEBEL)
High Grounds, Bangalore 560 001

10. CENTRE FOR AERONAUTICAL SYSTEM STUDIES AND ANALYSIS
(CASSA)Suranjan Das Road, Jivan Bima Nagar, Bangalore 560 075

11. MICROWAVE TUBE R & D CENTRE (MTRDC)
Ministry of Defence, BEL Complex, PO Jalahaiii, Bangalore 560 013

12. CENTRE FOR ARTIFICIAL INTELLIGENCE
LRDE Campus, Jivan Bima Nagar, Bangalore 560 075

13. NAVAL CHEMICAL &;METALLURICAL LABORATORY (NAVYLAB)
Naval Dockyard, Bombay 400 023

14. DEFENCE RESEARCH AND DEVELOPMENT UNIT (DEFUNIT)
S-212, Commissariat Road, Hastings, Calcutta 700 022

15. TERMINAL BALLISTICS RESEARCH LABORATORY (BALLISTICS)
Sector 30, Chandigarh

16. NAVAL PHYSICAL & OCEANOGRAPHIC LABORATORY (INPHYLAB)
Naval Base, Cochin 682 004

17. DEFENCE SCIENCE CENTRE (DEFSCCENT)
Metcalfe House, Delhi 110 054

18. SOLIDSTATE PHYSICS LABORATORY (SOLIDSTATE)
Lucknow Road, Delhi 110 007

19. INSTITUTE OF NUCLEAR MEDICINE AND ALLIED
SCIENCE (DEFSCIENCE) Lucknow Road, Delhi 110 007 NMAS

20. DEFENCE INSTITUTE OF PHYSIOLOGY AND ALLIED SCIENCES
(DEFSCIENCE/DIPAS) Delhi Cantt. I 10 010

21. INSTITUTE OF SYSTEMS STUDIES &;ANALYSIS
Metcalfe House, Delhi 110 054

22. DEFENCE INSTITUTE OF FIRE RESEARCH
(FIRERESCH) Probyn Road, Delhi 110 007

23. DEFENCE SCIENTIFIC INFORMATION AND DOCUMENTATIONS CENTRE
(DESIDOC) Metcalfe House, Delhi 110 054

24. DEFENCE TERRAIN RESEARCH LABORATORY (DEFSCIENCE/DTRL)
Metcalfe House, Delhi 110 054

25. SCIENTIFIC ANALYSIS GROUP (DEFSCIENCE/SAG) Metcalfe House, Delhi
110 054

26. DEFENCE INSTITUTE OF PSYCHOLOGICAL RESEARCH (DEF SCIENCE/DIPR)
West Block No. 8, Wing No. 1, R.K. Puram, New Delhi 110 066

27. INSTRUMENTS RESEARCH AND DEVELOPMENT ESTABLISHMENT (IRDE)
Rajpur Road, Dehradun 248 008

28. DEFENCE ELECTRONICS APPLICATION LAB (RAKESHELECTRONIK)
Rajpur Road, Dehradun 248 008

29. DEFENCE RESEARCH &;DEVELOPMENT ESTT. (DEFRES)
Tansen Road, Gwalior 474 002

30. DEFENCE RESEARCH &;DEVELOPMENT LAB (MISLAB)
Kanchanbagh PO, Hyderabad 500 258

31. DEFENCE METALLURGICAL RESEARCH LAB (DEFMETLAB)
Kanchanbagh PO DMRL, Hyderabad 500 258

32. DEFENCE ELECTRONICS RESEARCH LAB (DEFELECTRONICS)
Chandrayanguntta Lines, Hyderabad 500 005

33. DEFENCE LABORABTORY (DEFLAB)
Ramada Palace, Jodhpur 342 001

34. DEFENCE MATERIALS AND STORES RESEARCH AND DEVELOPMENT ESTT. (LABDEV)
DMSRDE Post Office, G.T. Road, Kanpur 208 013

35. DEFENCE INSTITUTE OF WORK STUDY (WORKSTUDY)
Landour Cantt., Mussoorie 240 179

36. DEFENCE FOOD RESEARCH LAB (RAKSHAKHADYA)
Jyotinagar, Mysore 570 011

37. ARMAMENT RESEARCH & DEVELOPMENT ESTABLISHMENT (AYODH &;ARMAMENTS)
Armament Post Pashan, Pune 411 021

38. EXPLOSIVE RESEARCH AND DEVELOPMENT LABORATORY (MEXDEV PASHAN)
Pashan Pune 411 021

39. RESEARCH AND DEVELOPMENT ESTT. {ENGRS} (ENGIVIKAS)
Pioneer Lines, Dighi, Pune 411 021

40. INSTITUTE OF ARMAMENT TECHNOLOGY (ARMINST {E})
Simhagad Road, Girinagar, Pune 411 025

41. DEFENCE RESEARCH LABORATORY (TEZLAB)
Post Bag No. 2, Tezpur, Assam 784 001

42. NAVAL SCIENCE &;TECHNOLOGICAL LABORATORY (ENESTIEL)
Vigyan Nagar, Visakhapatnam 530 006

43. SNOW AVALANCHE STUDY ESTT (MANALIEX CHANGE)
C/o 56 APO

44. FIELD RESEARCH LABORATORY
C/o 56 APO

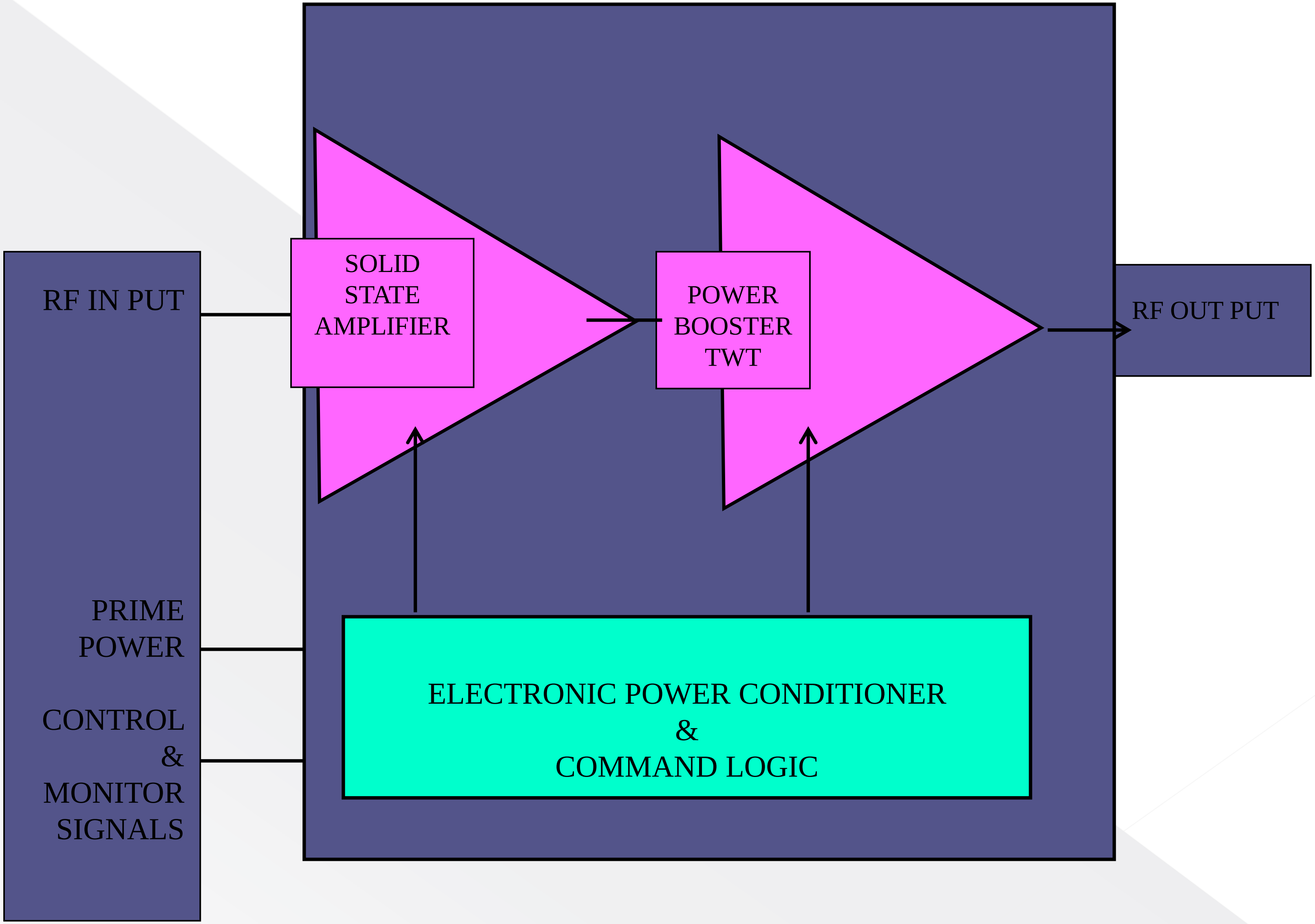
45. RANGE CENTRE &;INTERIM TEST RANGE
Balasore

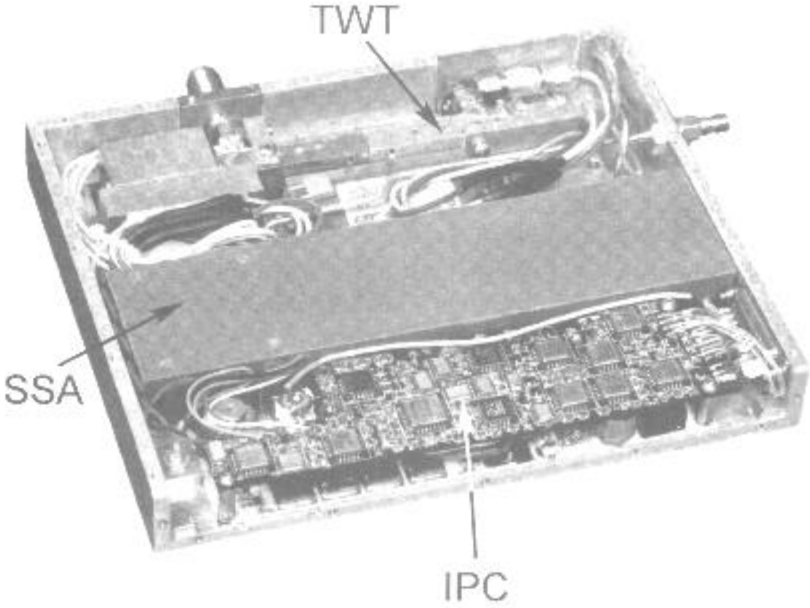
46. ADVANCE SYSTEMS INTEGRATION EVALUATION ORGANISATION (ASIEO)
Bangalore

47. DRDO COMPUTER CENTRE
Metcalfe House, Delhi 110 054

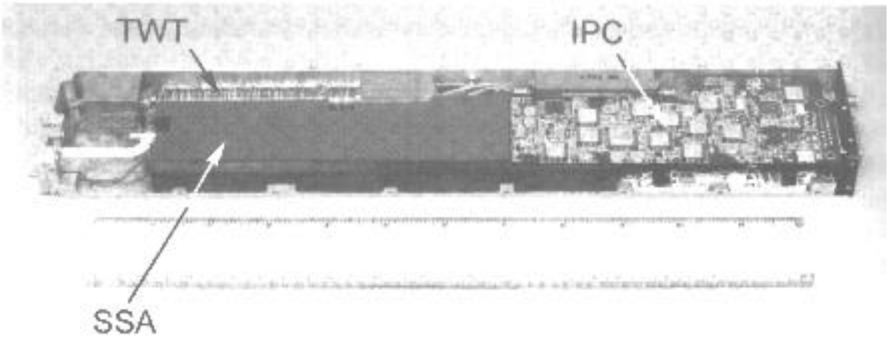
Information to be updated

Microwave Power Module (MPM)



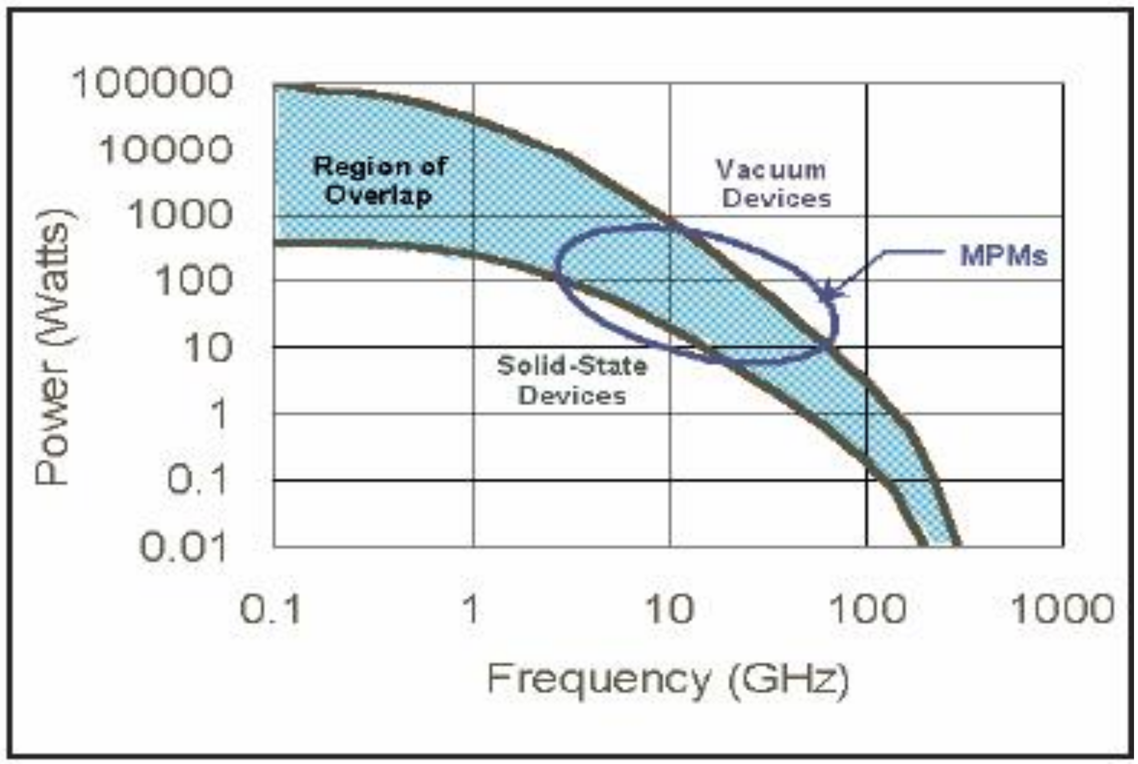


An 80-W, 6- to 8-GHz wideband MPM



Ka-band MPM

MPM in power versus frequency domain

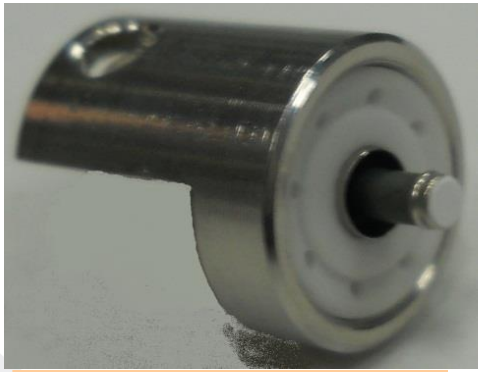


Cathode Activity at CSIR-CEERI

Ranan Barik (CSIR-CEERI)

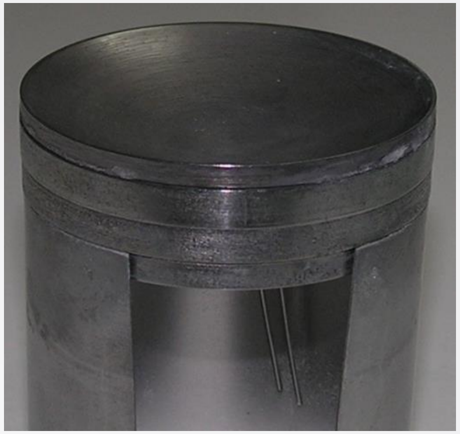
Cathode parts developed at CSIR-CEERI


Small Φ3.1 mm for TWT, Klystron, J> 50A/cm^2


Nanoparticle-based cathode, J>100A/cm^2


CPD cathode, J>50A/cm^2


MBK Cathode


S-Band Klystron cathode
Φ 50 mm diameter

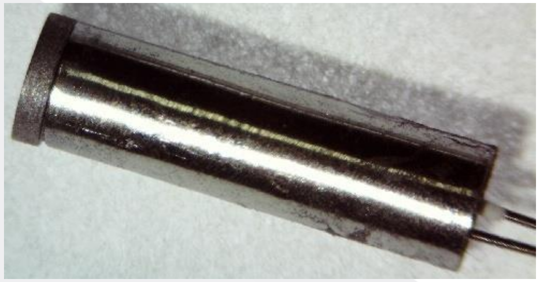

Gyrotron cathode


Gyrotron cathode under hot condition


Space Qualified Cathode

Future Plan

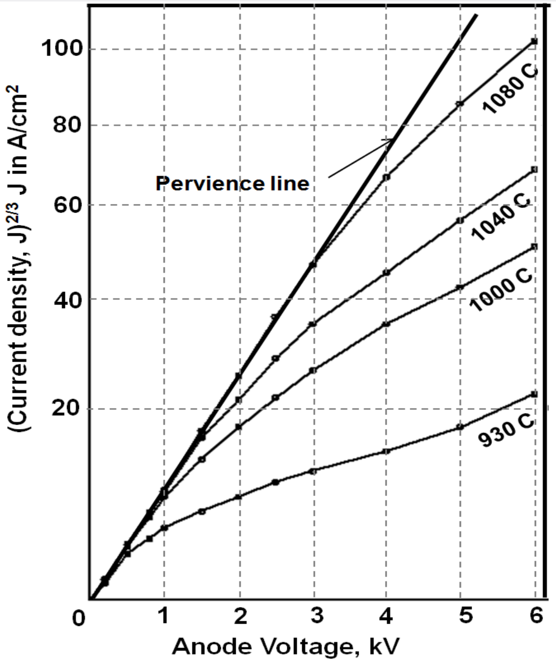
Ongoing Project: Development of high current density cathodes



Optical photograph of Cathode

User Specifications:

- Device Dimension: Φ 0.8 mm
- Current Density @1050 C > 100 A/cm^2
- Heater Power @ 1050 C= 6.5 W
- Cathode life = 1000 hours



I-V characterization in diode mode

Application Potential:

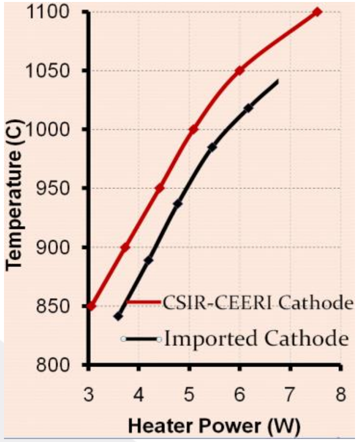
- THz Vacuum Electron Devices

Sponsoring Agency:
ER & IPR, DRDO, New Delhi

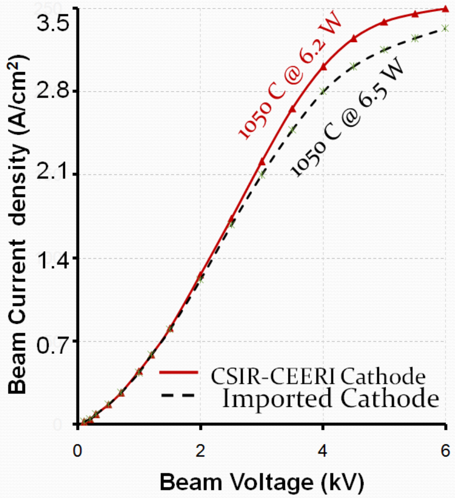
Sponsoring Agency:
Microwave Tube Research and Development Centre – DRDO, Bangalore

Ongoing Project: Technology development for small-size cathodes

Cathode mounted inside electron gun



I-V characterization inside electron gun



Thermal characterization inside electron gun

User Specifications:

- **Device Dimension: Φ 3mm**
- **Current Density @1050 C > 10 A/cm^2**
- **Heater Power @ 1050 C= 6.5 W**
- **Cathode life = 10000 hours**

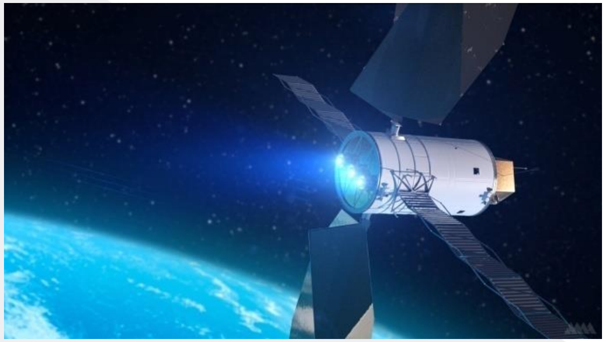
Application:

- **Microwave & mm wave Vacuum tubes**

Sponsoring Agency: CSIR

User Agency: Bharat Electronics Limited, Bangalore

Ongoing Project: Development of thermionic emitters for electric propulsion system



Electric propulsion system for satellite

User Specifications:

- **Dimension: Φ 5 mm, Length-15 mm**
- **Current Density > 12 A/cm^2 @1200 ^{0}C**
- **Cathode life = 1000 hours @1100 ^{0}C**

Optical image of thruster pellet

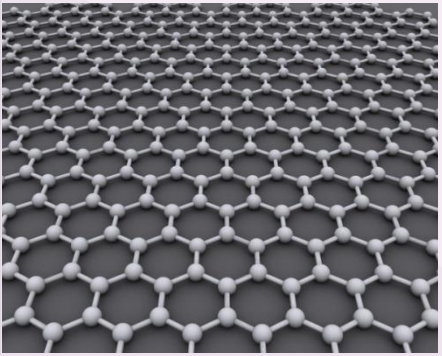
Application Potential:

- **Electric propulsion system for satellite**

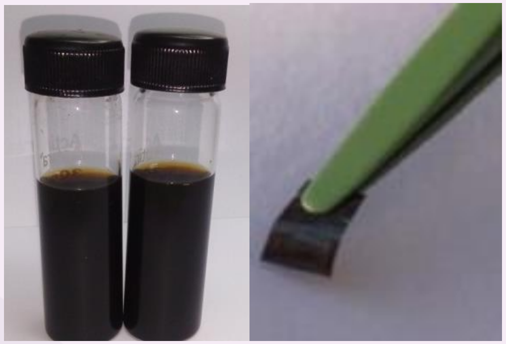
Sponsoring Agency: VSSC, ISRO

Advance Research Activities in Cathodes

Graphene based Field Emitter



Graphene
lattice structure

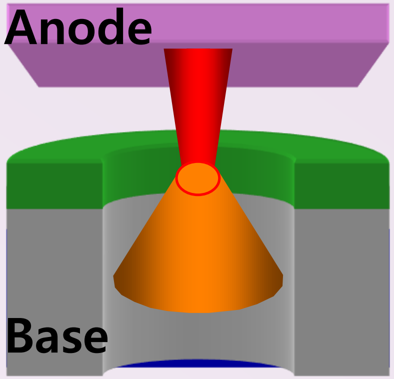


Synthesis of Graphene Oxide
using Modified Hummers
Method

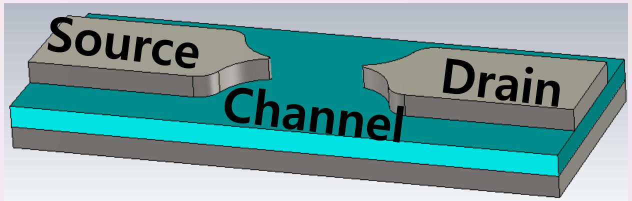
Promise:

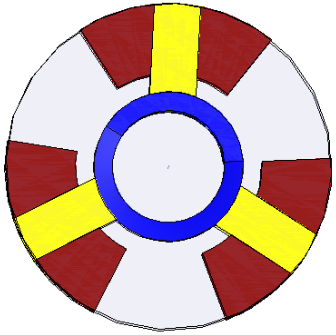
- ✓ Very High Current Density
- ✓ Micro-fabrication possible
- ✓ No warm up time required

Field Emitter based vacuum transistor

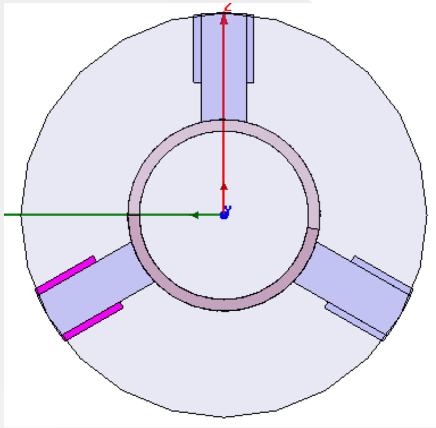


- Low voltage operation
- Increased life time.
- Device can be scaled to nm dim.
- Future transistor for electronic warfare



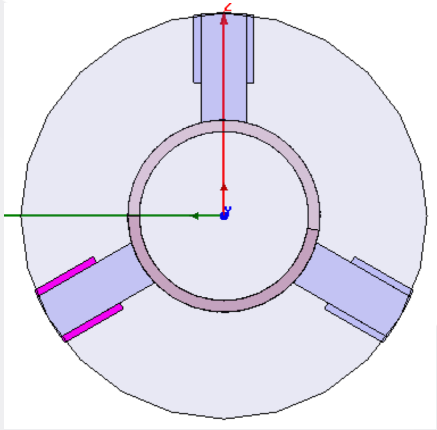


Embedded rod



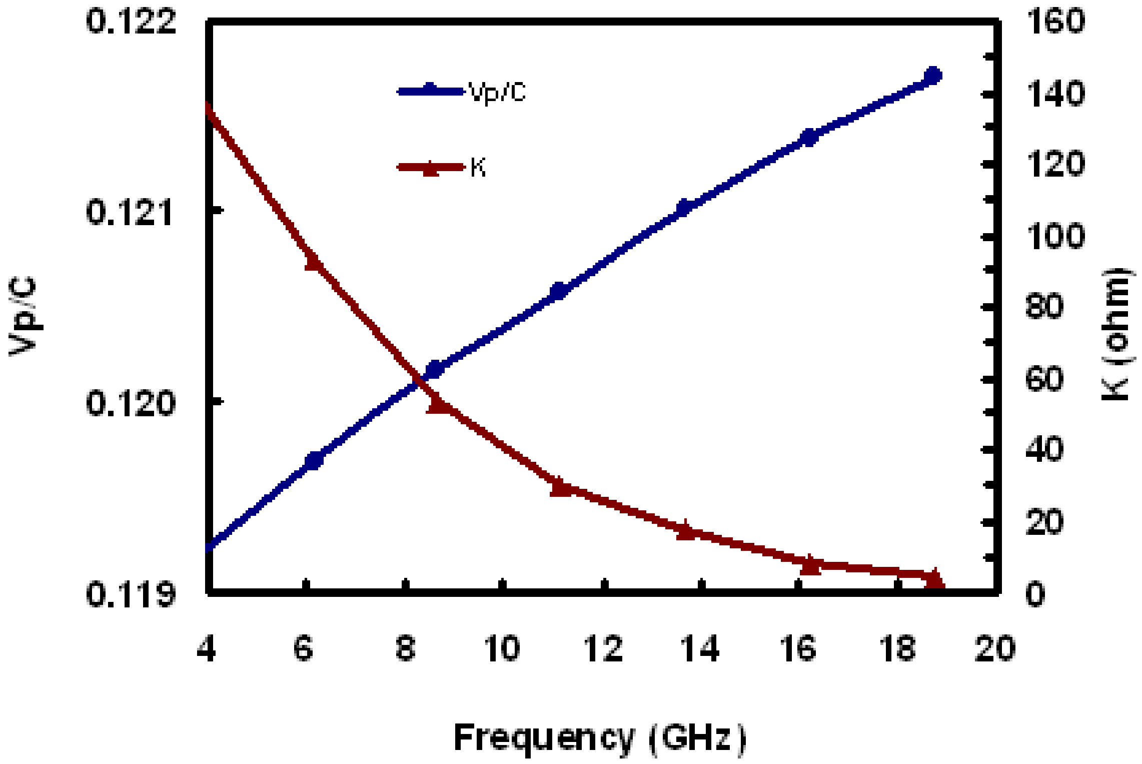
Metal-coated support rods

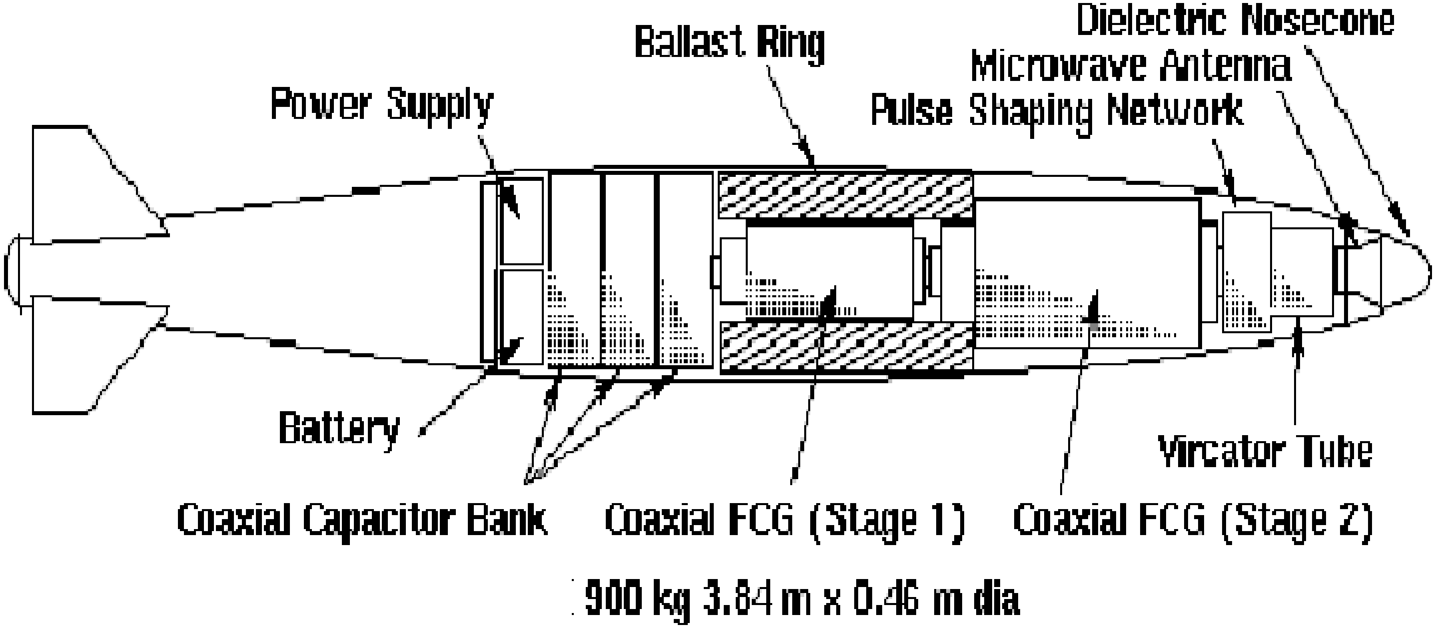
Source: MTRDC (DRDO)



Provides negative dispersion with quite high interaction impedance compared to other segment variants

Source: MTRDC (DRDO)





E-bomb warhead using vircator and two-stage FCG

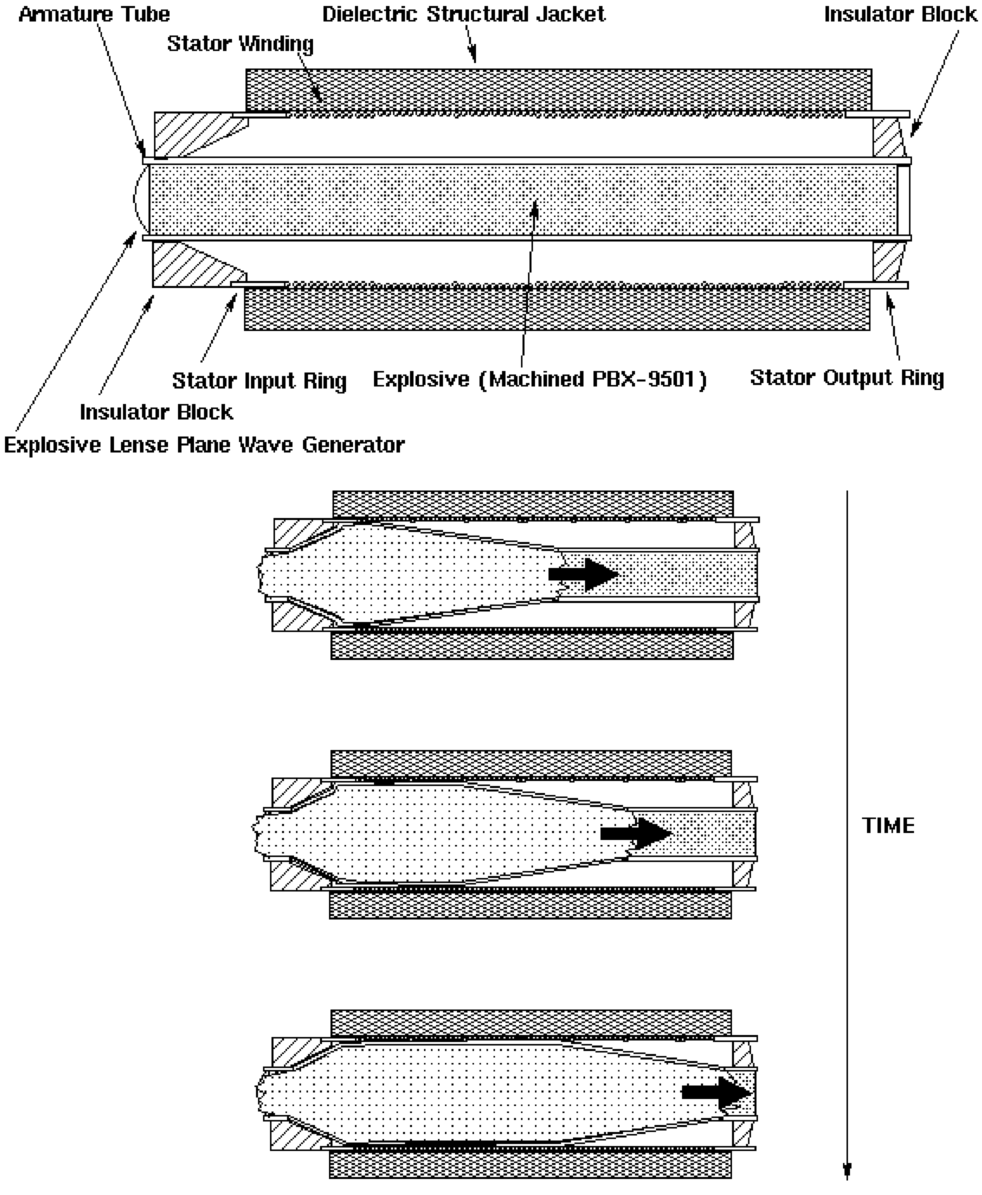
Flux compression generator (FCG)

FCG is a single-shot device delivering ~ 10’s of MJ of energy, TW – 10’s of TW of peak power in 100’s of μs of time

Used as a single device
  as a pulse power supply for HPM tubes
  in cascade — a smaller FCG priming a larger FCG for smallest possible start current source in application where space and weight are at a premium
Operation is based on transfer of energy from the explosive to the magnetic field
A copper tube (armature), filled in typically by PBX-9501 explosive, is surrounded typically by a helical winding coil of heavy wire typically of copper (stator), the armature tube and the stator coil being separated by an insulator block
Initial magnetic field prior to explosion is produced by a start current in helical coil supplied by an external source like Marx generator — an assembly of capacitors that are charged in parallel and then quickly switched into a series circuit (discharged in series), allowing the original charging voltage to be multiplied by the number of capacitor stages
Explosion breaks the insulation and shorts the turn, the short moving with time

Coaxial FCG

(Explosively pumped)



(C) 1996 Carlo Kopp

…….Flux compression generator (FCG)

Explosive is initiated when the start current peaks
Accomplished with an explosive lens plane wave generator producing a uniform plane wave detonation front in the explosive

Armature tube distorts and expands into conical shape to the full diameter of the stator coil winding thereby causing a short circuit between the coil ends isolating the start current source and trapping the current within the device

The propagating short results in magnetic flux compression and reduction in the inductance of the helical winding, and hence a ramping current (current multiplication ~60, typically) that peaks before the final disintegration of the device

10’s of MA’s peak current in 10’s-100’s μs and 10’s of MJ (typical)

LANL and AFWL demonstrated the viability of FCG

Ramping current pulse

$$H = ni$$

With the propagation of the detonation wave, the short propagates

$$B = \mu_0 H = \mu_0 ni$$

Number of turns *N* decreases

$$\phi_B = NAB = NA\mu_0 ni$$

Length of the coil *l* also decreases in the same proportion

$$L = \frac{\phi_B}{i} = \frac{NA\mu_0 ni}{i}$$

$$= \mu_0 AnN$$

Number of turns per unit length $n = N / l$ remains constant

Area of the coil *A* remains constant

Energy of the coil

$$= 1/2Li^2$$

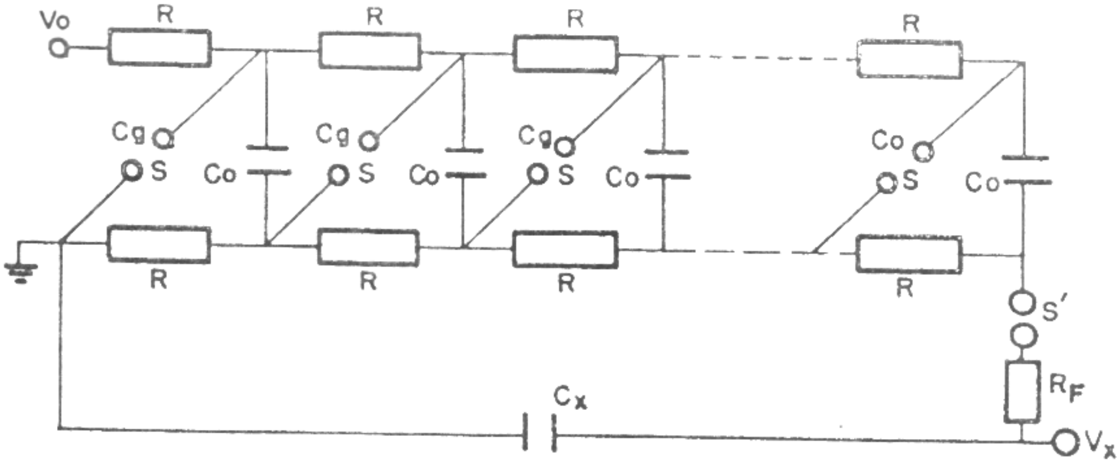
Inductance of the coil *L* decreases

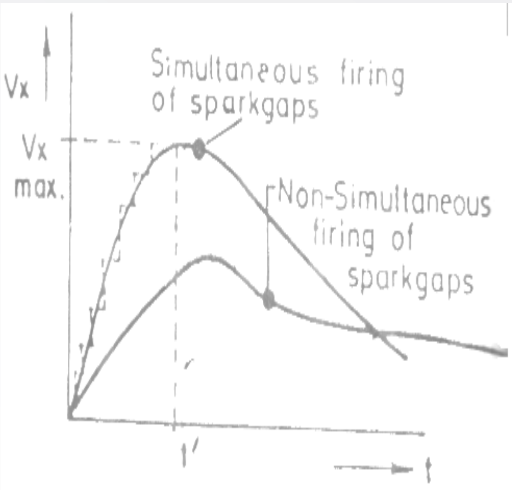
Energy of the coil $1/2Li^2$ remains constant

Current *i* increases (spikes) (ramping current)

Marx generator

— an assembly of capacitors that are charged in parallel and then quickly switched into a series circuit (discharged in series), allowing the original charging voltage to be multiplied by the number of capacitors





Capacitors C_0 are charged in parallel and discharged through spark gaps S initiated by triggering the first one or more spark gaps by an external triggering source, as a consequence of which the remaining gaps get overloaded thus causing their self-breakdown

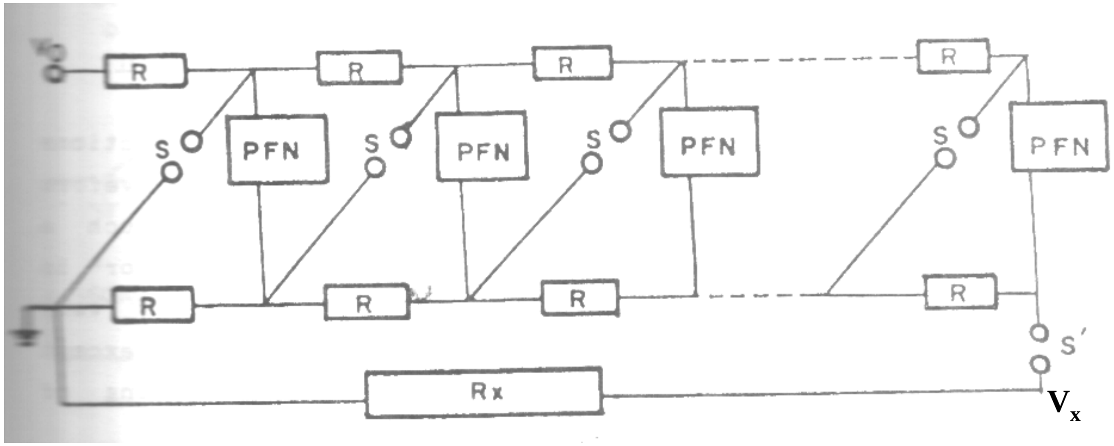
Reduction and distortion of output voltage for non-simultaneous triggering

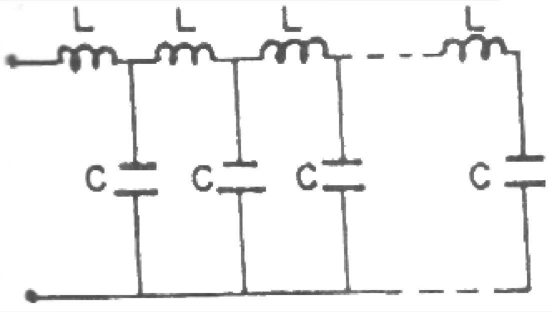
Spark gap S' is used to reduce the charging current though the external load, for instance $C_{x.}$

Maximum pulse voltage is $NV_{0.}$

Front resistor R_F, tail resistor R and number of stages used adjust the pulse duration

Improvised Marx generator with pulse forming network (PFN)





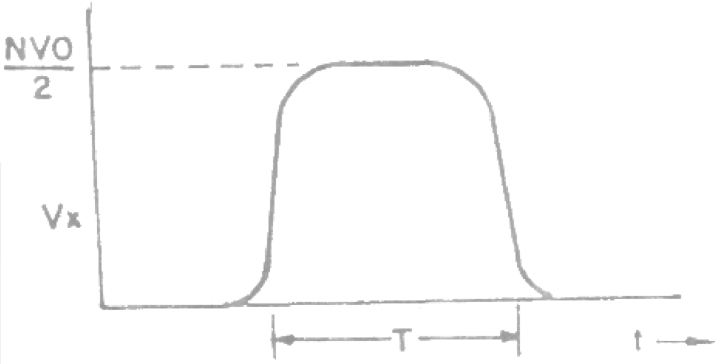
PFN

Characteristic impedance $R' = \sqrt{L/C}$

Load resistance $= NR'$

Output voltage $V_x = NV_0 / 2$

Pulse duration $= n\sqrt{LC}$



Flat-top pulse

Some MTRDC-developed tubes


S-band CCTWT


X-band CCTWT


Ku-band CCTWT


X-Ku-band 2 kW Helix TWT

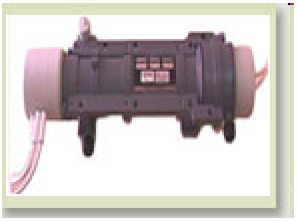

X-Ku-band 300W Helix TWT


100W (CW) C-X-Ku band MPM

Courtesy: SK Datta, MTRDC

2 kW pulsed X-Ku band helix TWT for airborne ECM system

10 kW pulsed Ku band coupled-cavity TWT for airborne radar



6.5 kW pulsed X-band coupled-cavity TWT for airborne radar

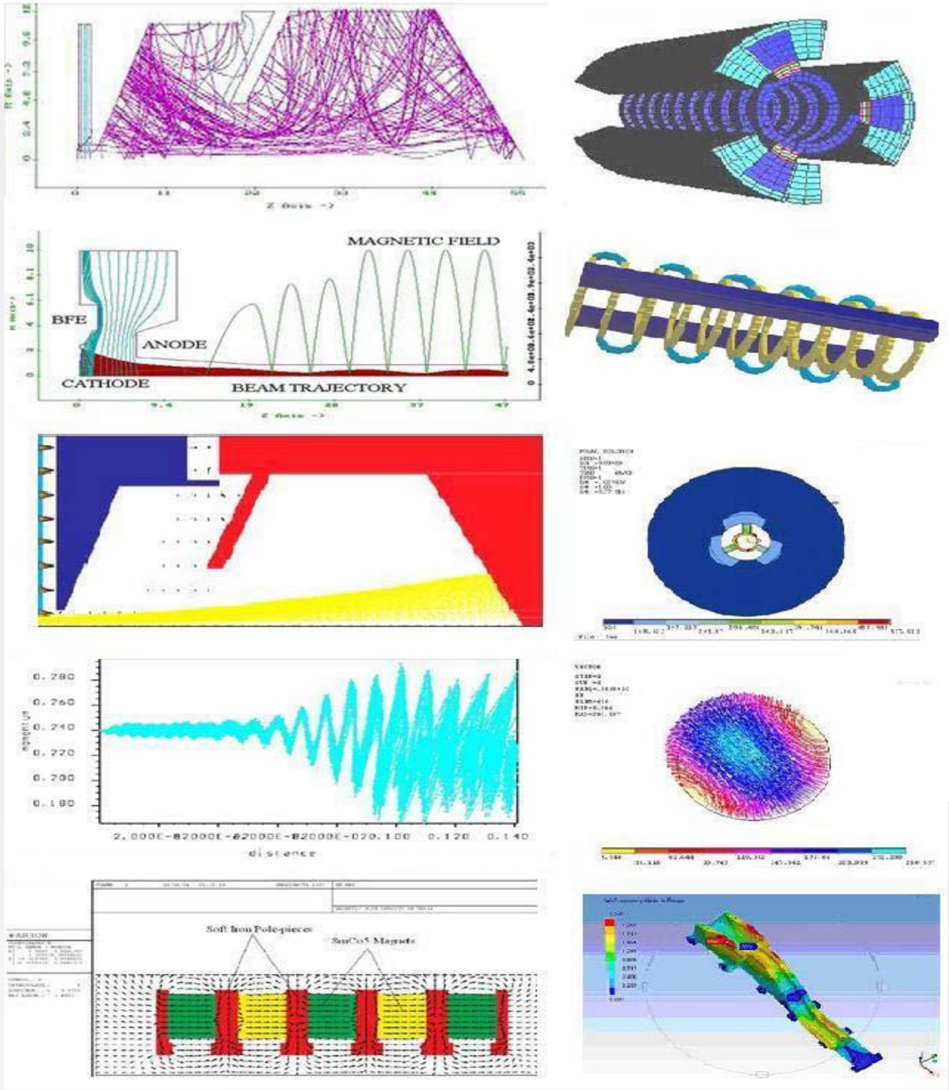
S-band 130 kW (pulsed) coupled -cavity TWT

M-type cathode

Microwave power module

Microwave tube components developed at MTRDC

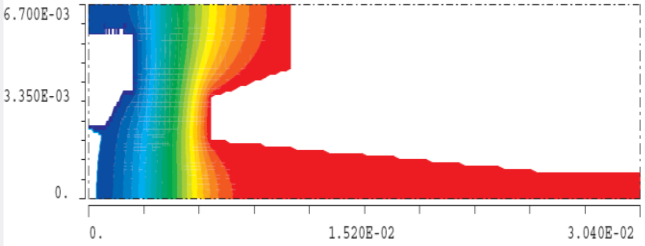
MTRDC: Courtesy: SK Datta

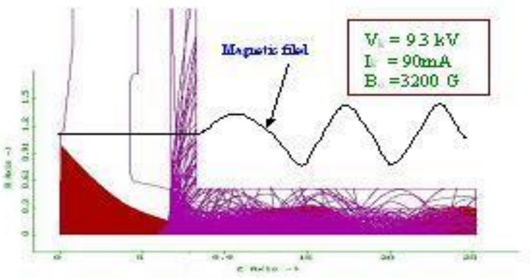


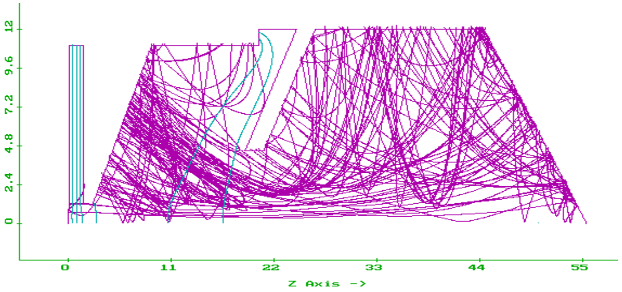
← **Typical CAD models of MTRDC**

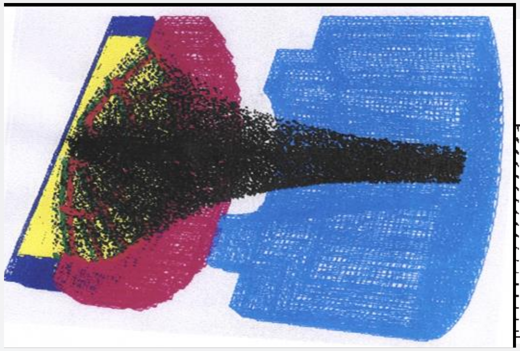
Courtesy: SK Datta

Electron-optic & Electromagnetic Simulation

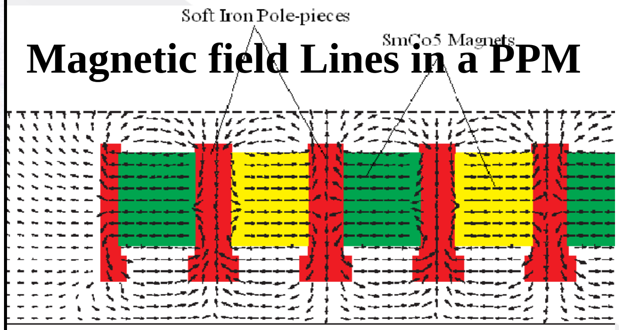


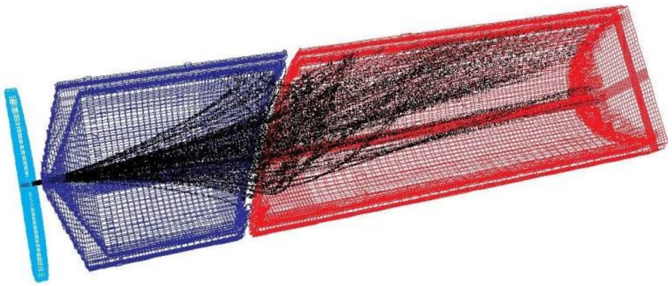


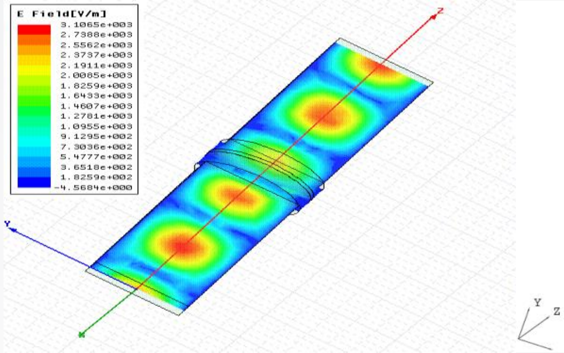


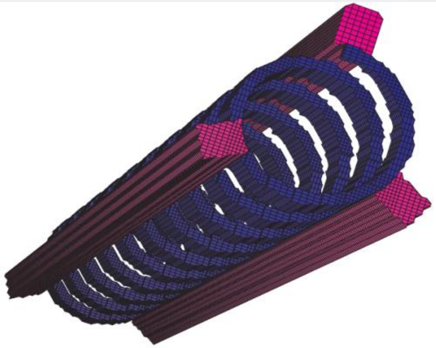


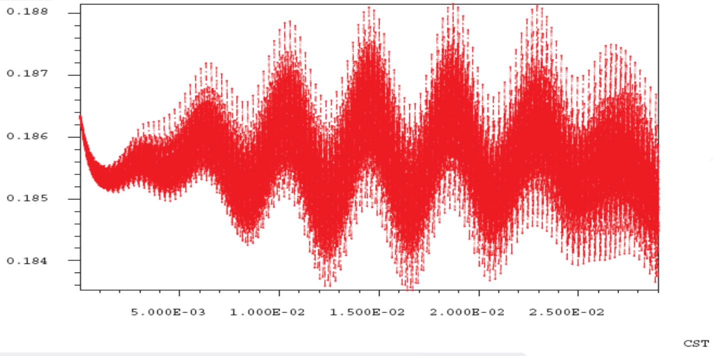
Magnetic field Lines in a PPM





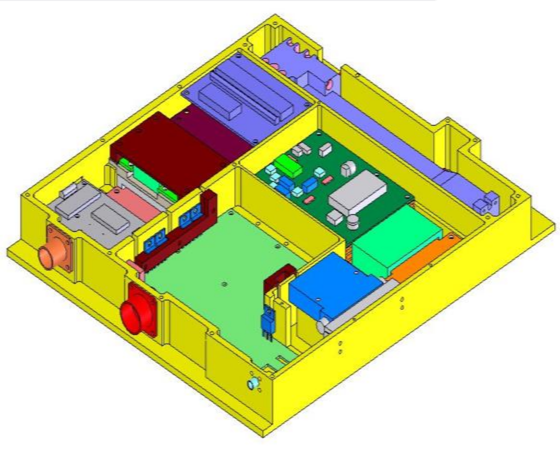


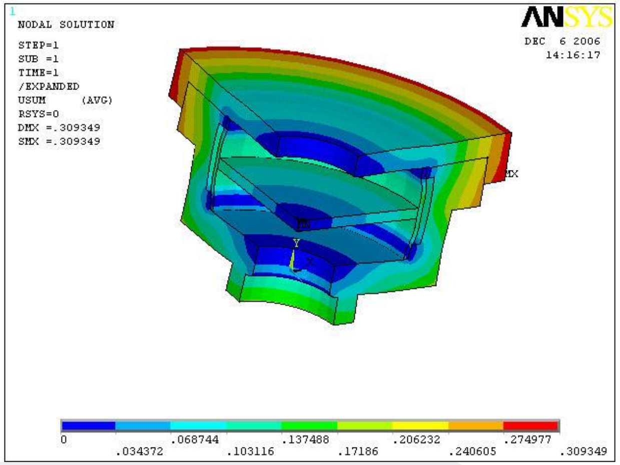




Helix Slow-wave Structure

Thermal Analysis of sub-systems of TWT & EPC

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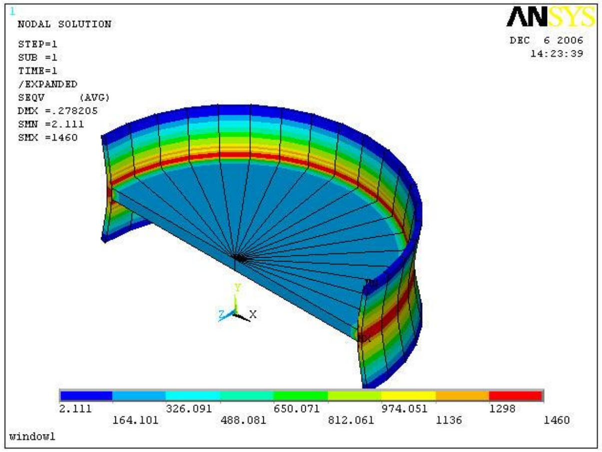
SUB =1
TIME=1
/EXPANDED
USUM (AVG)
RSYS=0
DMX =.309349
SMX =.309349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/EXPANDED
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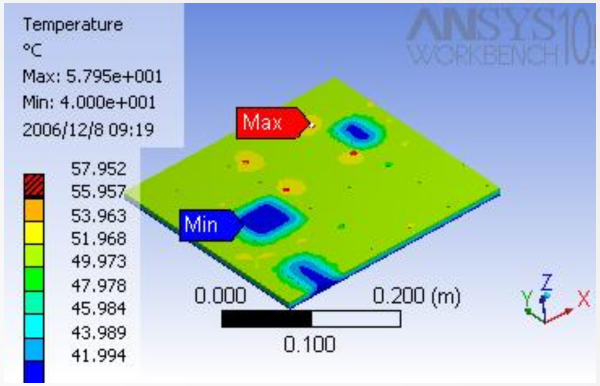
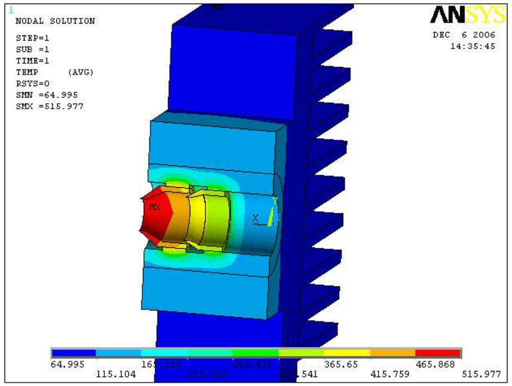
SMN =2.111
SMX =1460


Temperature
°C
Max: 5.795e+001
Min: 4.000e+001
2006/12/8 09:19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TIME=1
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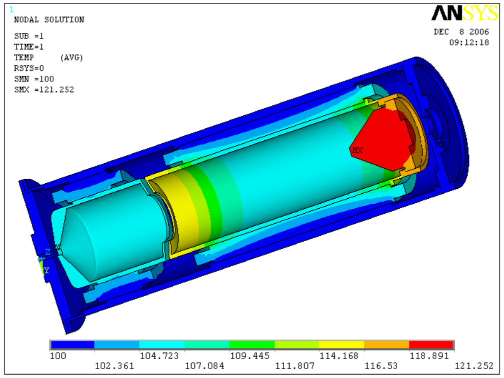
NODAL SOLUTION
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TIME=1
TEMP (AVG)
RSYS=0
SMN =100
SMX =121.252

Pulsed magnetrons developed at CEERI

400 W Ka-band

500 kW S-band

800 kW S-band

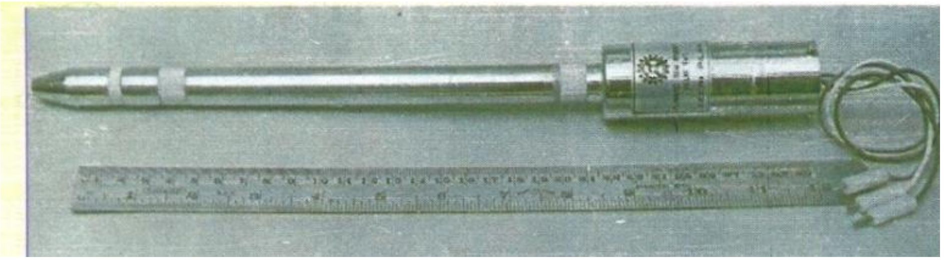
1 MW S-band

2 MW S-band

3 MW S-band

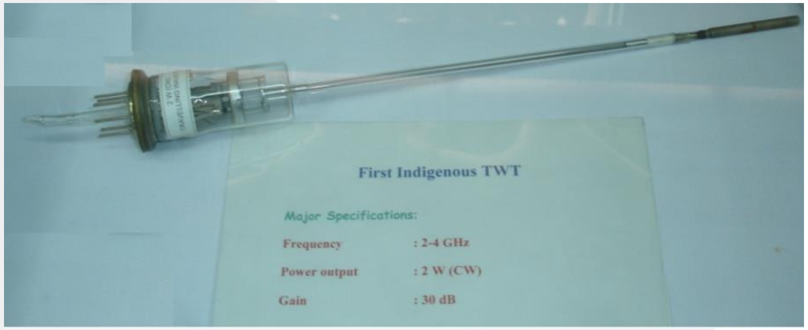
Courtesy: Dr. SN Joshi

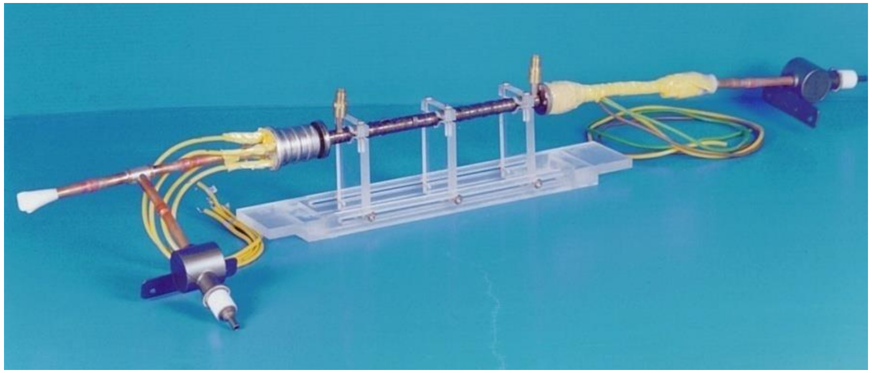
Ground-based TWTs developed by CEERI for communication and EW Systems

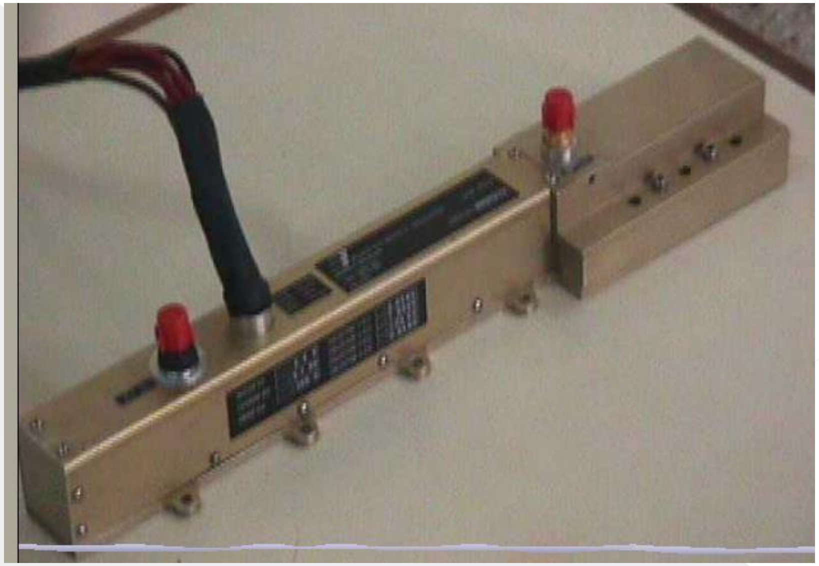


Courtesy: Dr. SN Joshi

Space TWTs for communication systems developed by CEERI

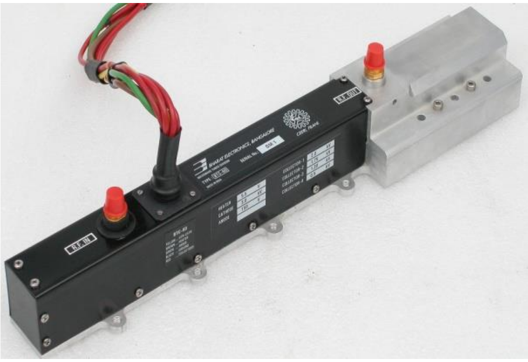






Courtesy: Dr. SN Joshi

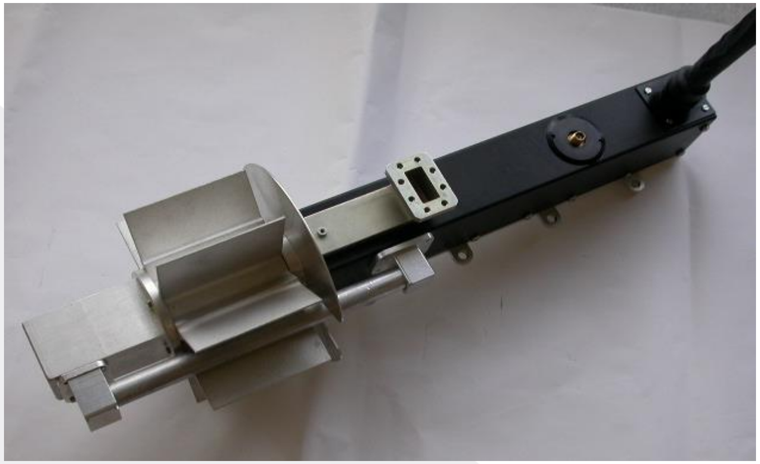
C-band 60W CEERI space-TWT
(developed jointly with Bharat Electronics)



C-Band 60W conduction cooled
Frequency: 3.6-4.2 GHz
Power: 60 W (CW)
Gain: 50 dB
Efficiency: >55%
AM/PM: < 5^0/dB
IMP: <-10 dBc @ 3 dB BO
Noise figure: 30 dB
Gain flatness: 1.0 dB p-p over 200 MHz
Group delay: <1 nS in any 40 MHz BW
2nd harmonics: < -16 dBc
Spurious: < -60 dBc

Courtesy: Dr. S. Ghosh and Dr. RK Sharma

Ku-band 140W CEERI space-TWT (developed jointly with Bharat Electronics)



Ku-band 140W radiation cooled
Frequency: 10.9-11.7 GHz
Power: 140 W (CW)
Gain: 50 dB
Efficiency: >55%
AM/PM: < 5^0/dB
IMP: <-10 dBc @ saturation
Noise figure: 30 dB
Gain flatness: 1.0 dB p-p over 200 MHz
Group delay: <1 nS in any 40 MHz BW
2nd harmonics: < -16 dBc
Spurious: < -60 dBc

Courtesy: Dr. S. Ghosh and Dr. RK Sharma

Ka band 100W CEERI helix TWT (Under CSIR Network Project)

Beam stick on pump station
Frequency: 20.6-21.2 GHz
Power: 100 W (CW)
Gain: 50 dB
Efficiency: 55%

Courtesy: Dr. S. Ghosh and Dr. RK Sharma

CEERI klystrons

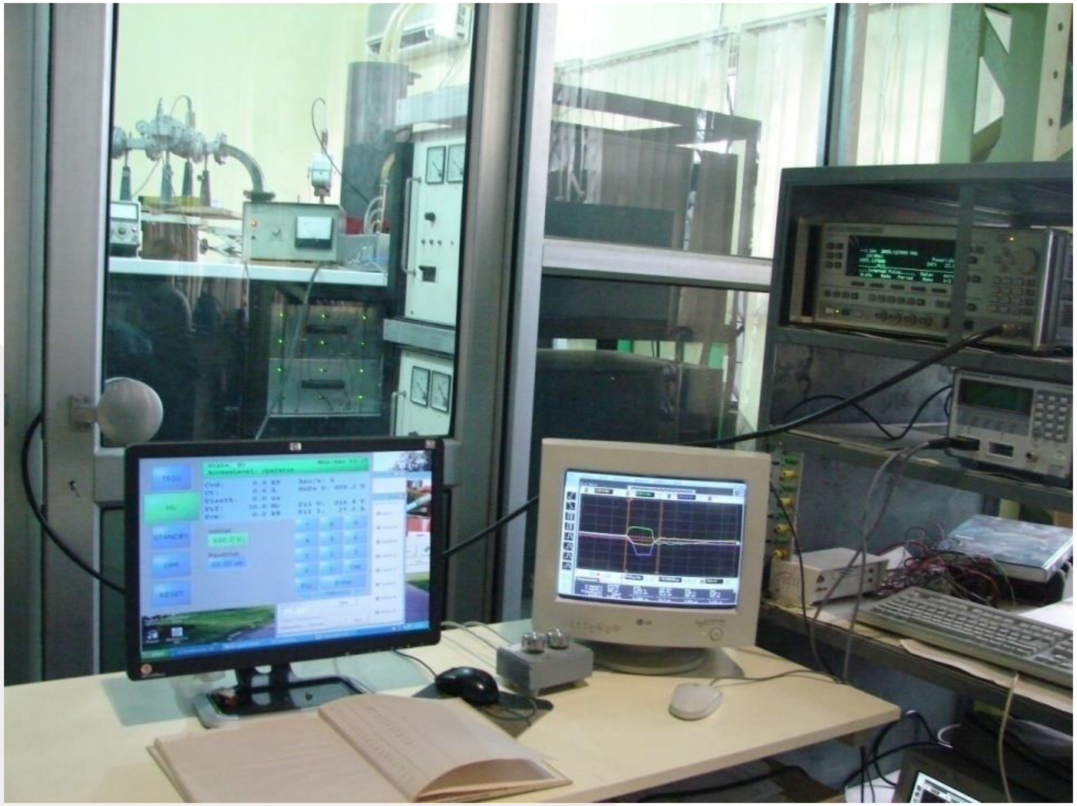
1 kW CW L/S-band Klystron

5 MW (P) 5 kW (Avg)
S-band Klystron

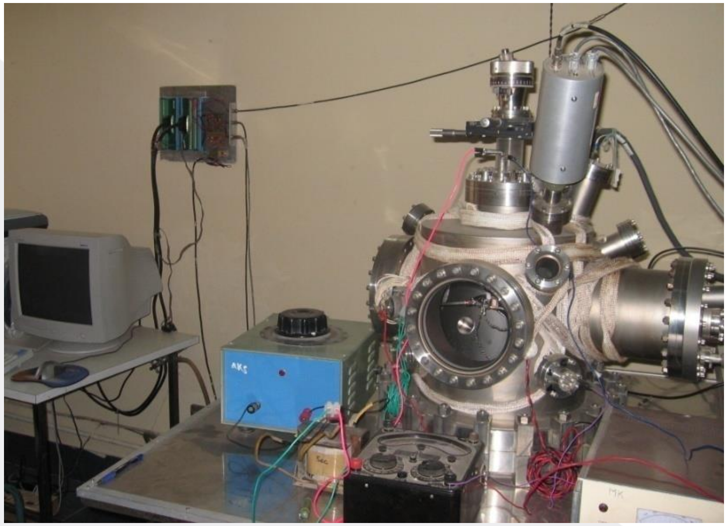
Courtesy: Dr. SN Joshi, Dr. LM Joshi

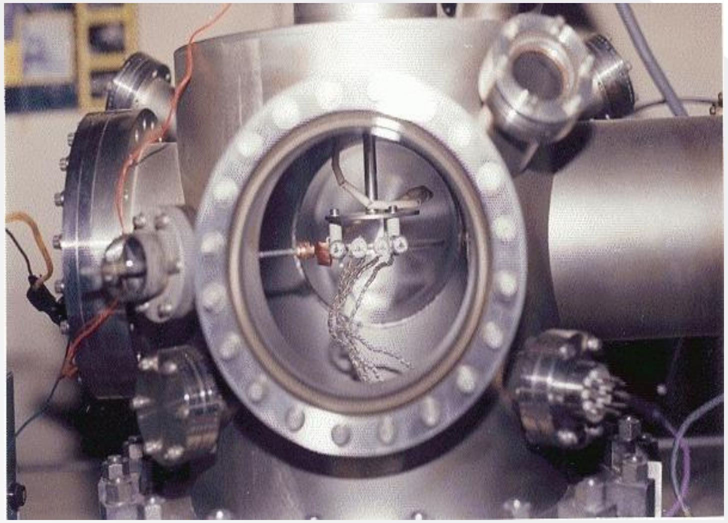
Klystron vacuum processing

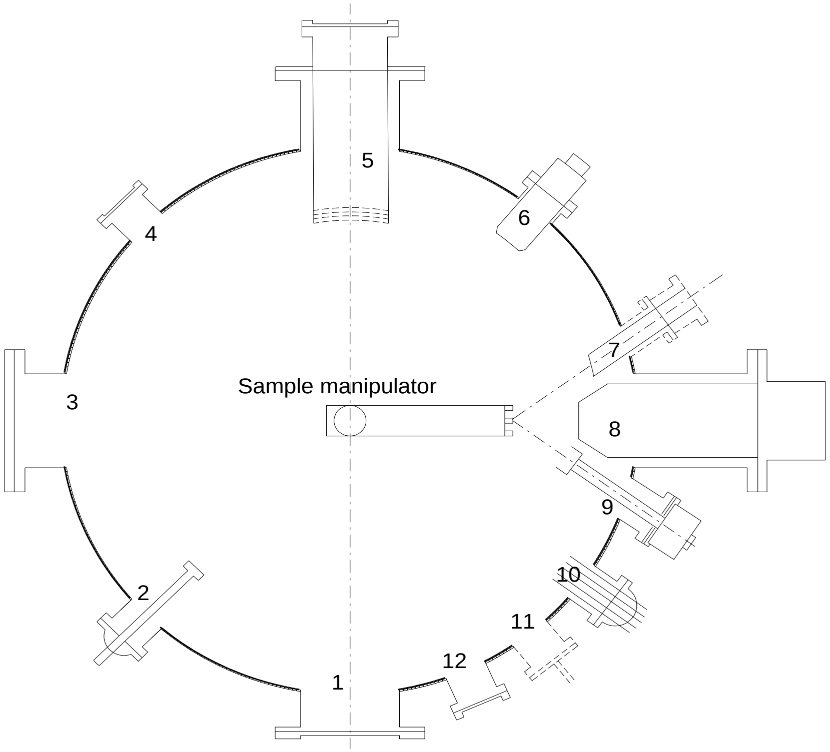
Klystron hot testing



Courtesy: Dr. SN Joshi, Dr. LM Joshi







Chamber of Analytical System

1. Viewing window
2. Anode
3. Access flange
4. Viewing window
5. ErLeed
6. Mass spectrameter
7. Ion Gun
8. CMA
9. Sec. El detector
10. El. feed through
11. Leak valve
12. Viewing window

Cathode assembly in UHV chamber

Courtesy: Dr. RS Raju

CEERI thyratron

25 kV, 1kA, Hydrogen thyratron

Pulse duration: 500 nsec
Rate of current rise: 20kA/µsec
Jitter: 5 nsec
PRR: 8kHz
- **Copper vapour laser system (tested at RRCAT, Indore).**

- **40 kV, 3kA, Deuterium thyratron**

Pulse duration: 3-5 µsec
Rate of current rise: 5kA/µsec
Jitter: 2 nsec
PRR: 300 kHz
- **BARC happy with the performance and want to test at their setup.**

Courtesy: Dr. Udit N Pal

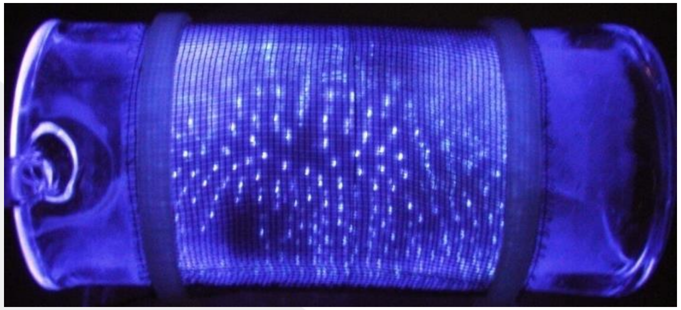
CEERI pseudospark high power plasma switch

40 kV/5kA pseudospark
Pulse duration: 3-5 μsec
Rate of current rise: 5kA/μsec
Jitter: 5 nsec
PRR: 300 kHz

Courtesy: Dr. Udit N Pal

CEERI VUV/UV excimer dielectric barrier discharge source

Wave length: 120-270 nm (Germicidal range)
Energy conversion efficiency: 30-40 %
Input power: up to 100 watt



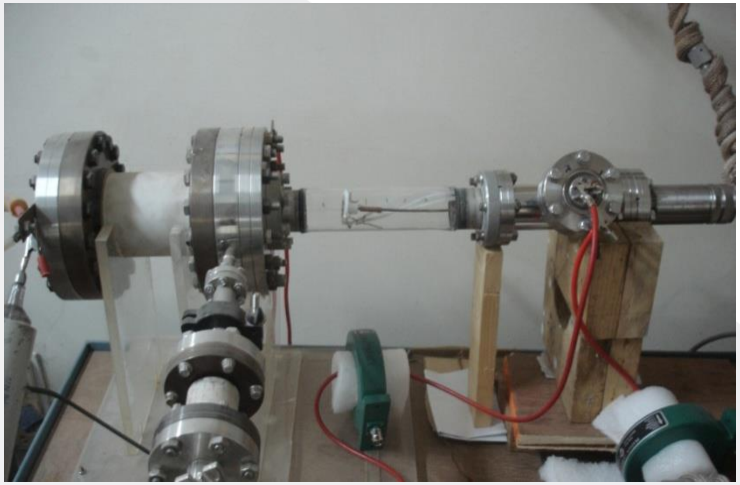
Different types of environment friendly, efficient VUV/UV source (Xenon, Ar, and N_2) have been developed.

Courtesy: Dr. Udit N Pal

Plasma cathode electron (PCE) gun for plasma-filled devices like the pasotron

Specifications

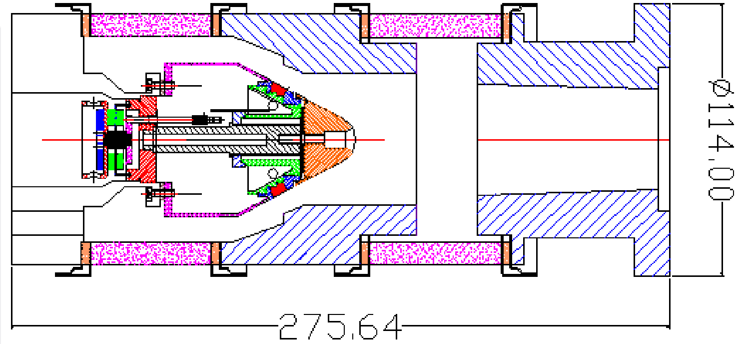
Beam current ≥ 30 A
Beam density ≥20 A/cm^2
Duration of beam current pulses ≥ 10 microsecond
Beam voltage: 50 kV ± 50%
Pulse repetition frequency: 0.1-10 Hz



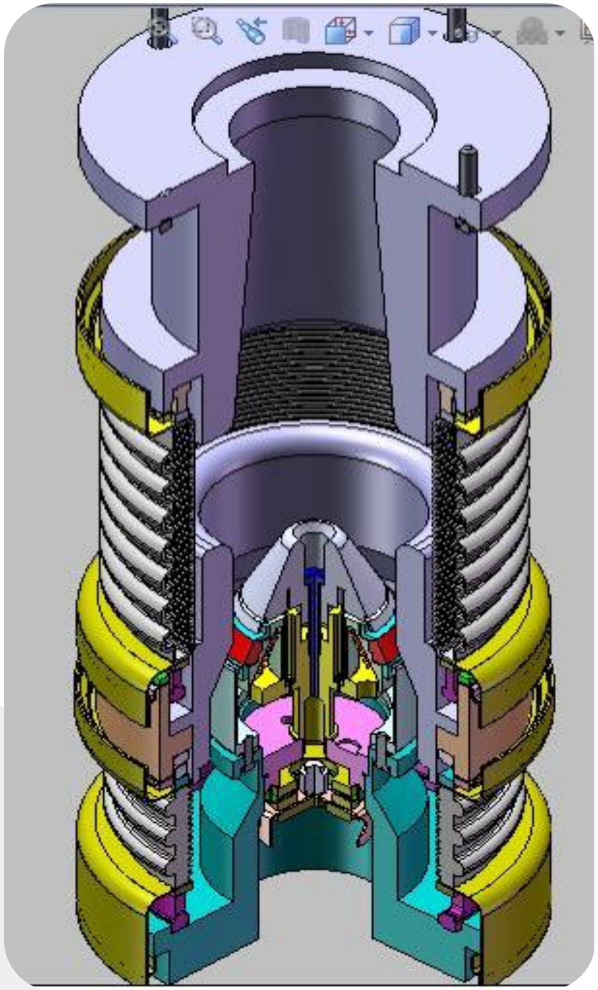
PCE gun preliminarily developed (20 kV/ 200 A at 0.5 mbar Argon)

Courtesy: Dr. Udit N Pal

Magnetron injection gun (MIG)



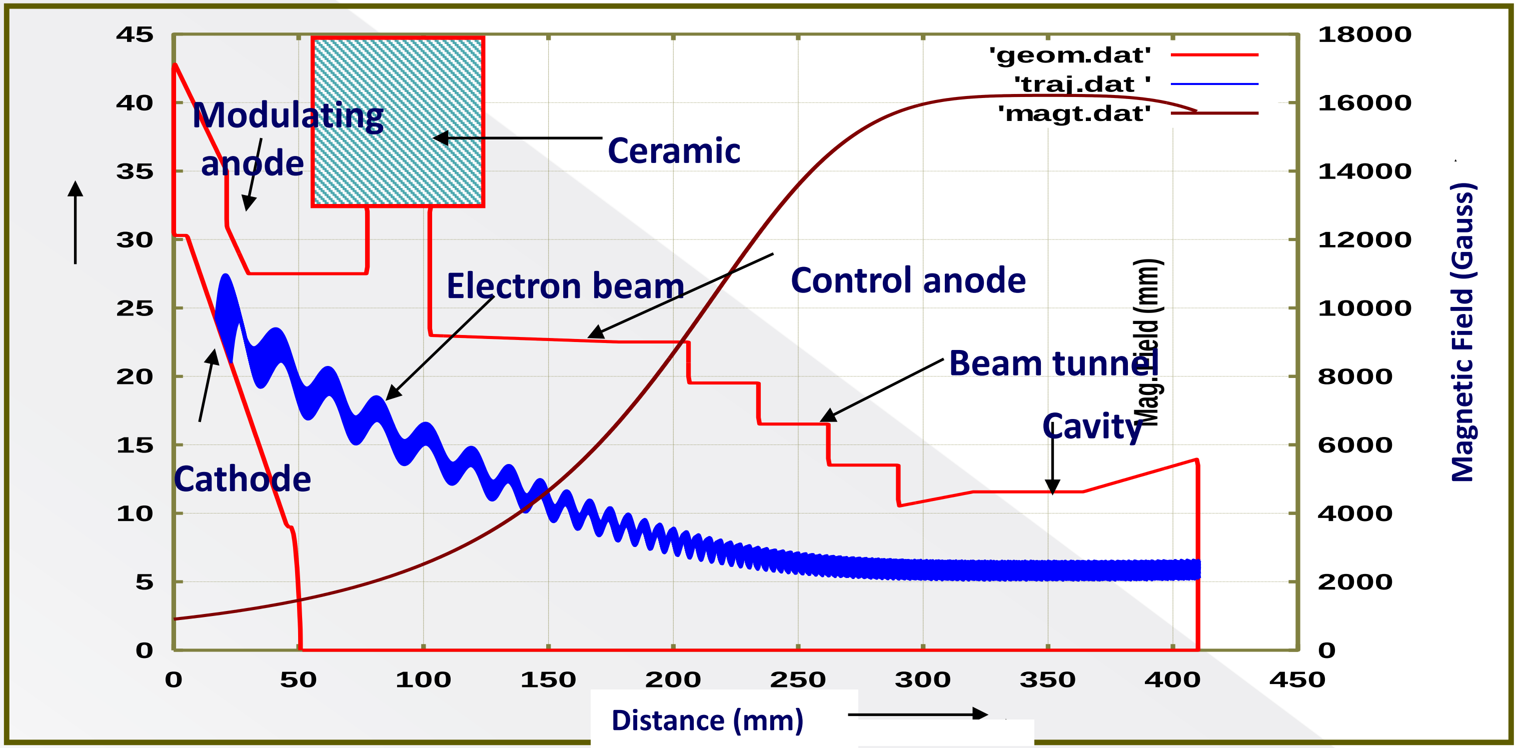
Parameters	Design values	Tolerance
Cathode radius	22.55 mm	± 0.05 mm
Cathode angle	28^{0}	± 1^{0}
Slant length	7 mm	± 0.1 mm
Modulating anode voltage	29 kV	± 0.5 kV
Beam voltage	65 kV	± 1 kV
Alpha (α)	1.26	± 5%
Magnetic field at interaction	1.61 Tesla	± 1%
Cathode anode distance	9 mm	±0.1mm
Beam current	10.3 A	±0.01 A
Larmor radius	0.42 mm	±0.02 mm
Avg. velocity spread	2.65%	±0.15%
Distance from cavity centre	330 mm	±0.05 mm
Cavity radius	11.57 mm	±0.03 mm



Courtesy: Dr. AK Sinha

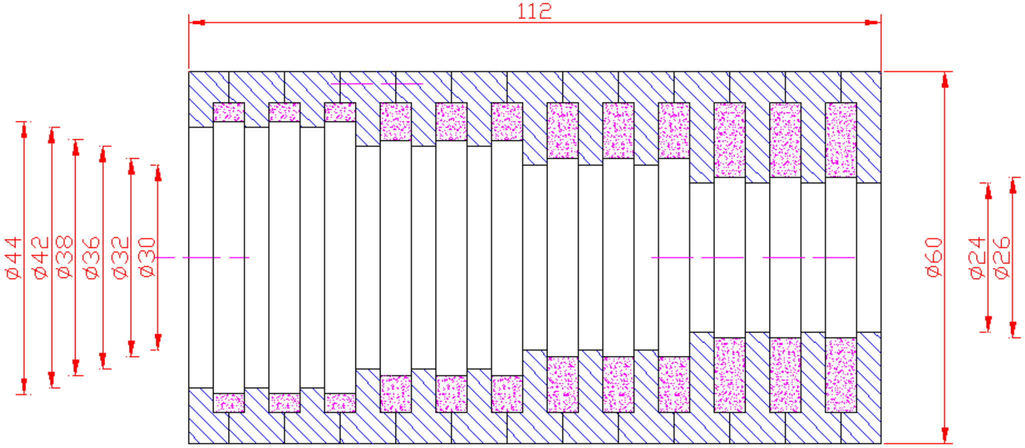
MIG with the electron beam and the magnetic firld profiles

Magnetic field at cathode centre	0.11 Tesla
Magnetic field at interaction region	1.65/ 1.61 Tesla
Variation of B field around Zcav+/-20mm	20 Gauss

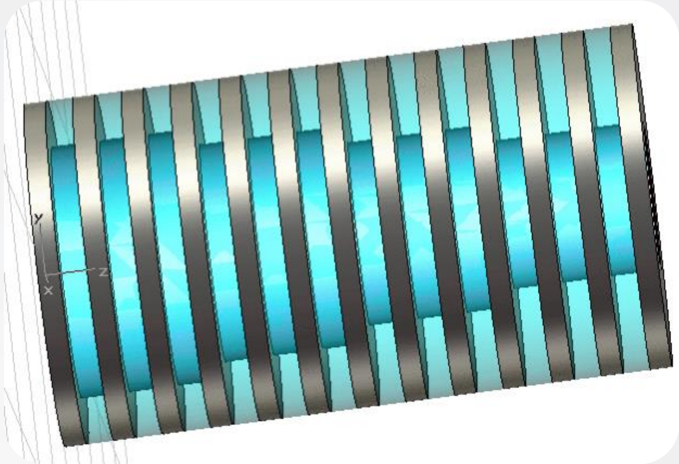


Courtesy: Dr. AK Sinha

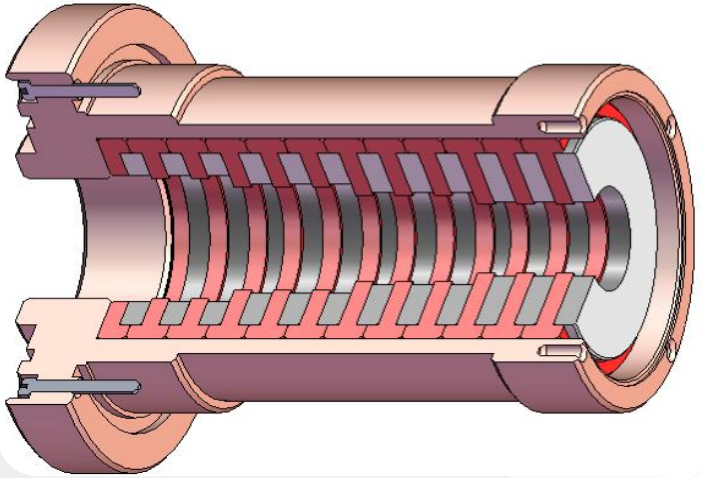
Gyrotron beam tunnel



(Diameter in mm)



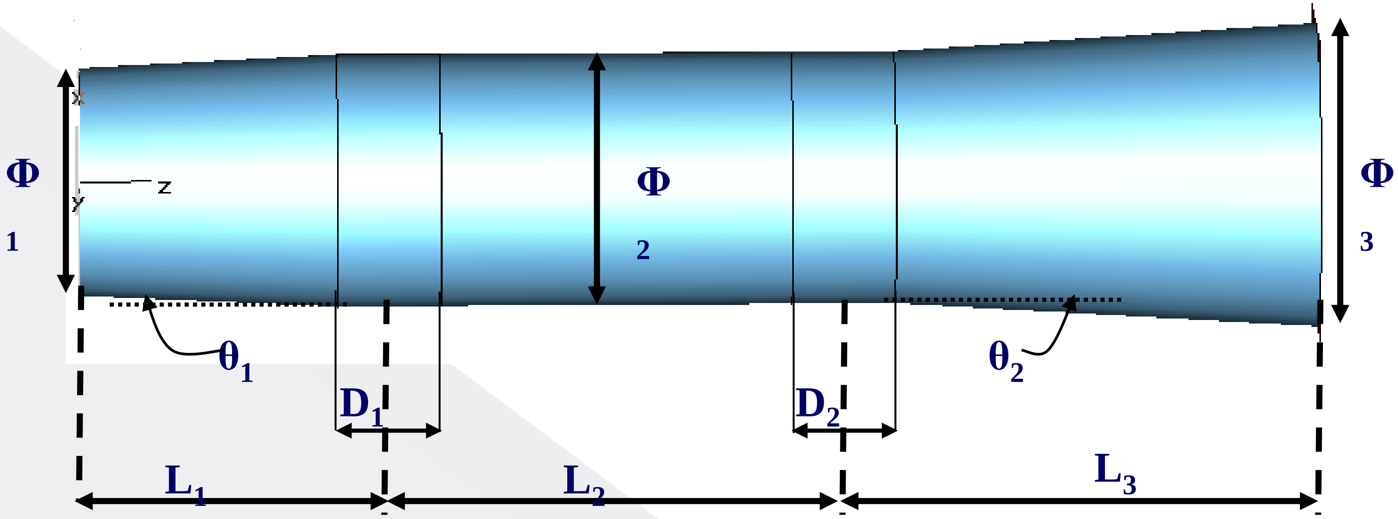
CST model



3D view

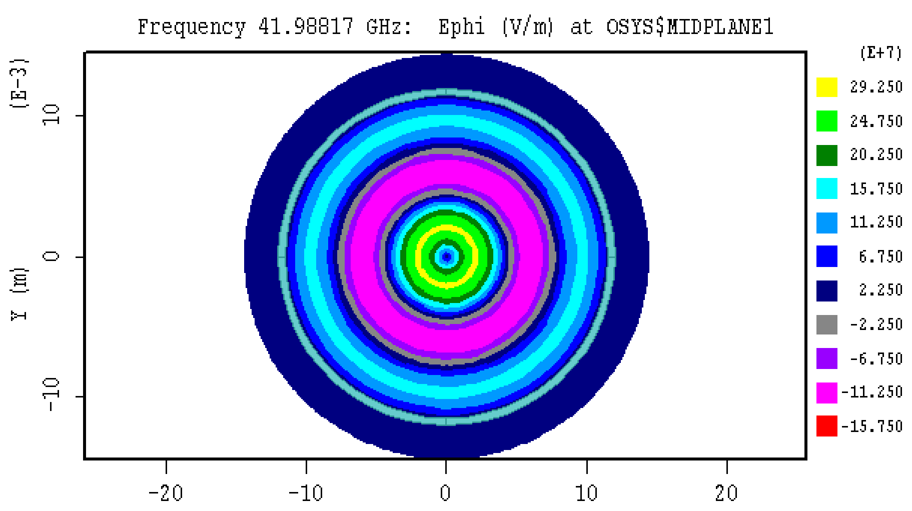
Courtesy: Dr. AK Sinha

Gyrotron interaction cavity

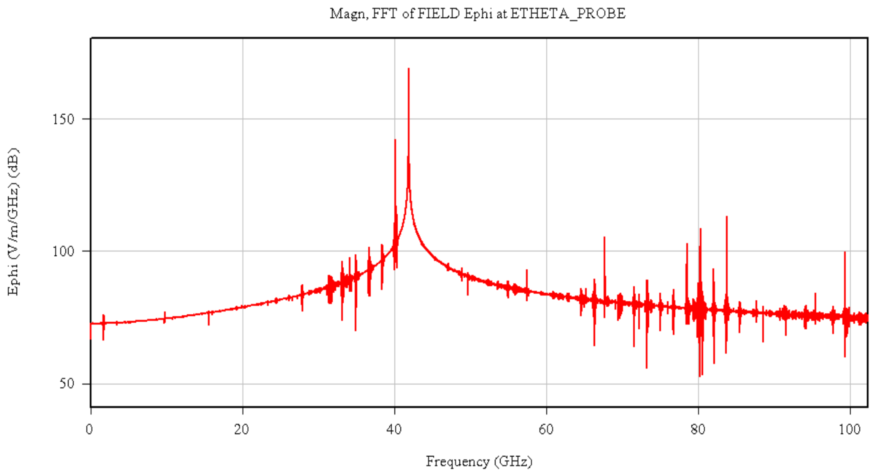


Dimensions	
Length $L_1/L_2/L_3$ (mm)	30/44/46
Taper angle $\theta_1/\theta_2/\theta_3$ (degree)	2°/0°/3°
Parabolic smoothing D_1/D_2 (mm)	10/10
Cavity diameter $\Phi_1/\ \Phi_2\ /\Phi_3$ (mm)	21.14/23.14/28

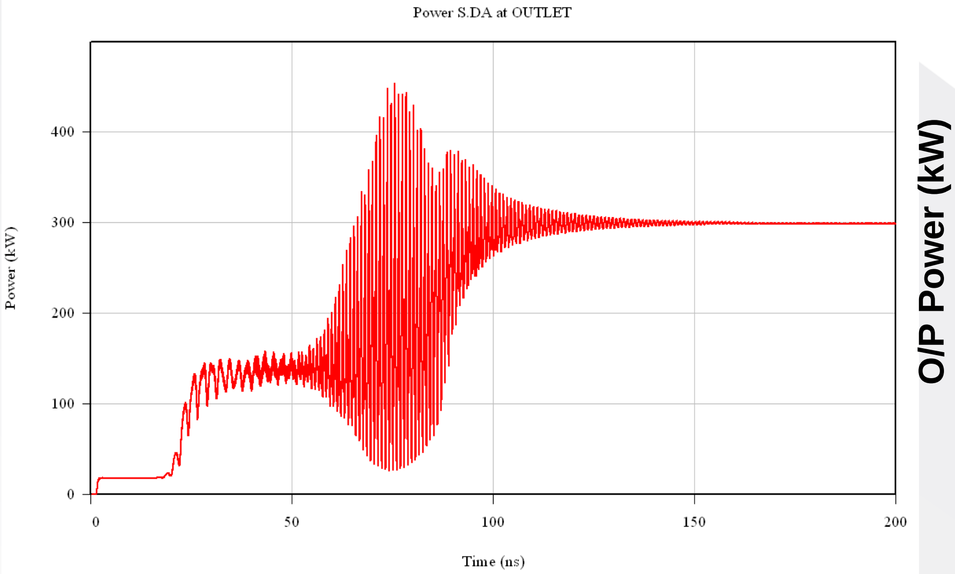
Courtesy: Dr. AK Sinha



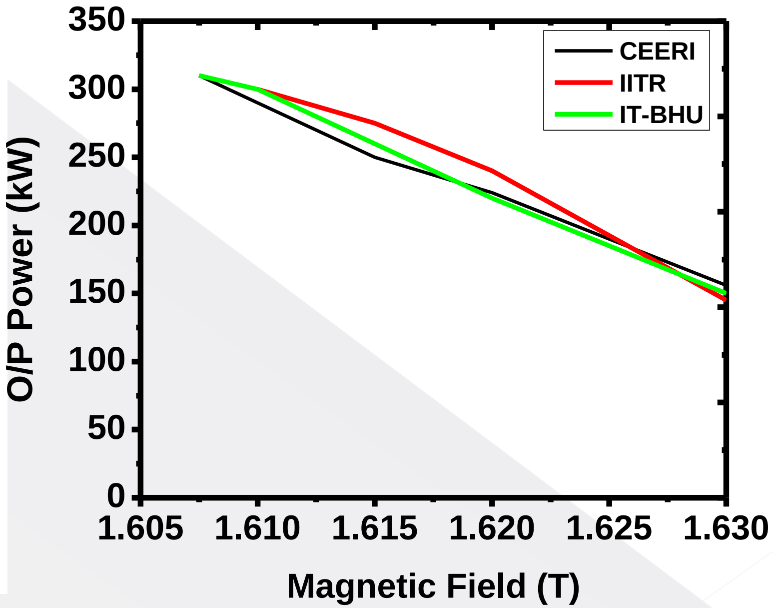
Field contour



Field versus frequency



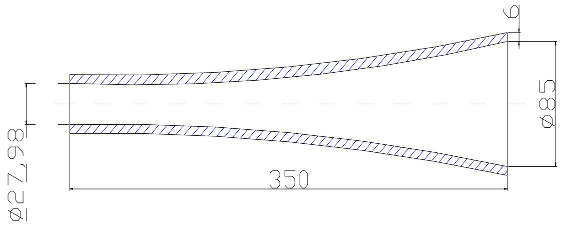
Output versus time



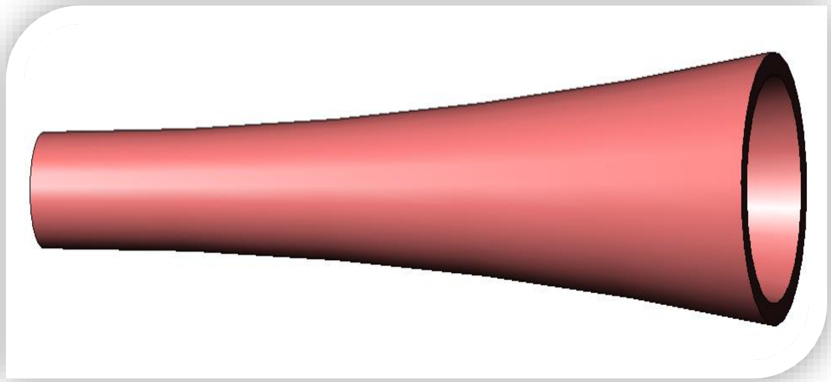
Output power versus time

Courtesy: Dr. AK Sinha

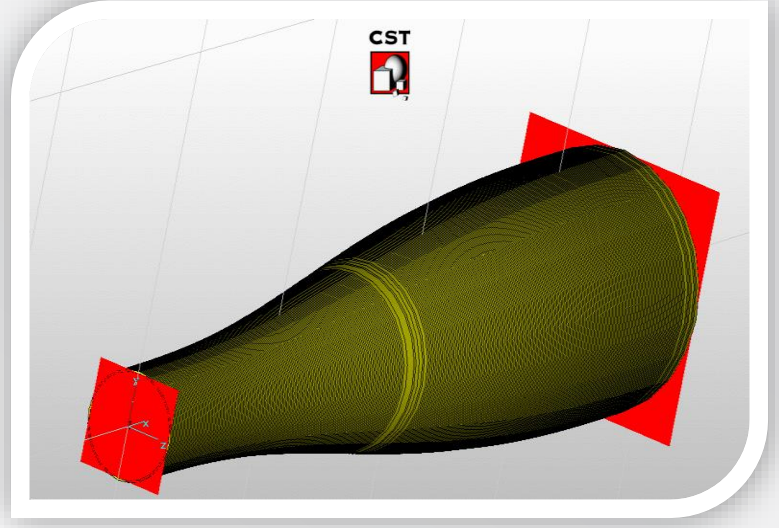
Gyrotron nonlinear taper



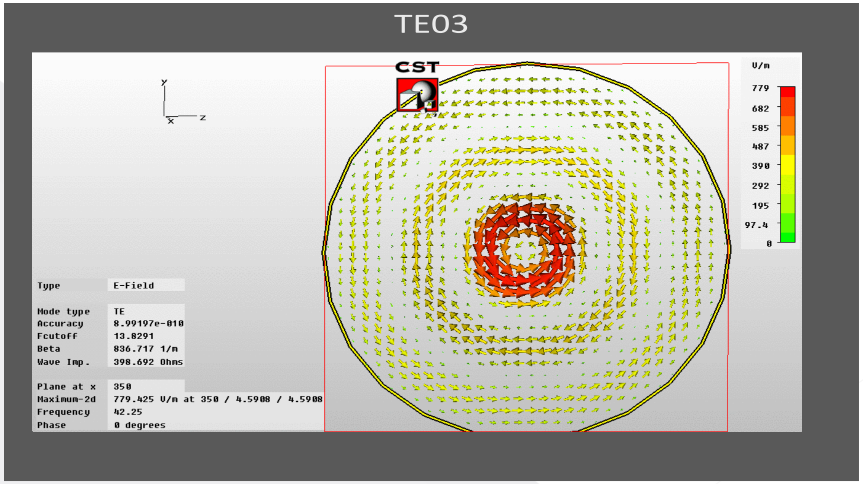
2D view



3D view of Non linear taper



Simulated model

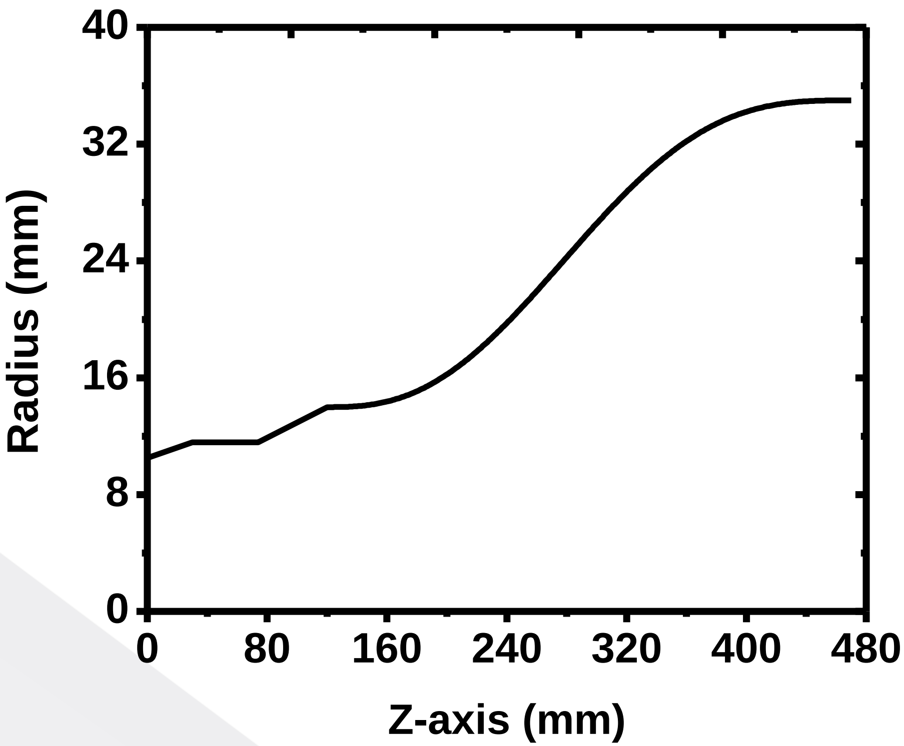


```
Type          E-Field

Mode type     TE
Accuracy      8.99197e-010
Fcutoff       13.8291
Beta          836.717 1/m
Wave Imp.     398.692 Ohms

Plane at x    350
Maximum-2d    779.425 V/m at 350 / 4.5908 / 4.5908
Frequency     42.25
Phase         0 degrees
```

Field pattern at the taper output port

Courtesy: Dr. AK Sinha

Radius (mm)	Nonlinear taper length (mm)	Transmission coefficient S_{21}
35.0	300.0	99.8299 %
35.0	350.0	99.7418 %
35.0	400.0	99.8376 %
40.0	300.0	98.9202 %
40.0	350.0	99.4713 %
40.0	400.0	99.8643 %
45.0	300.0	96.5986 %
45.0	350.0	98.9727 %
45.0	400.0	98.4444 %

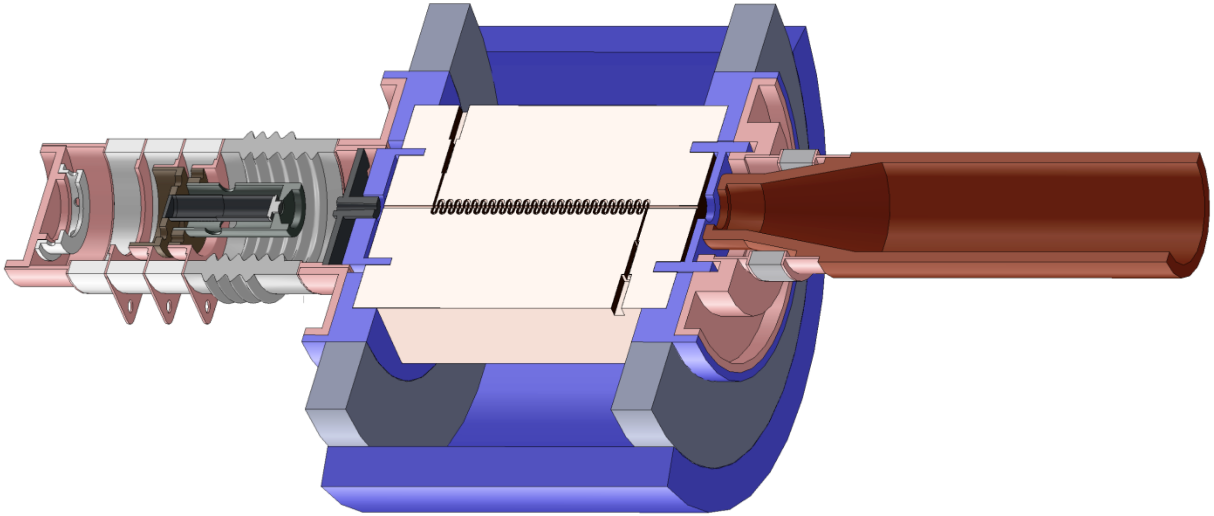


Mode purity at the end of the taper	**Better than 92%**

Courtesy: Dr. AK Sinha

CEERI folded-waveguide TWT in collaboration with TUB,Germany

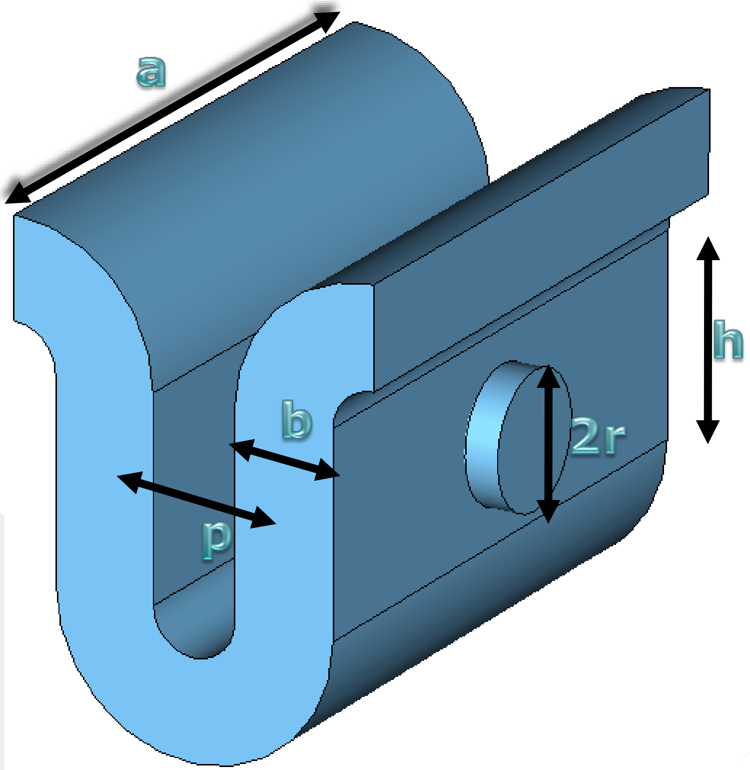
3D modeling



Courtesy: Ms. Isha Rathi, Dr. RK Sharma

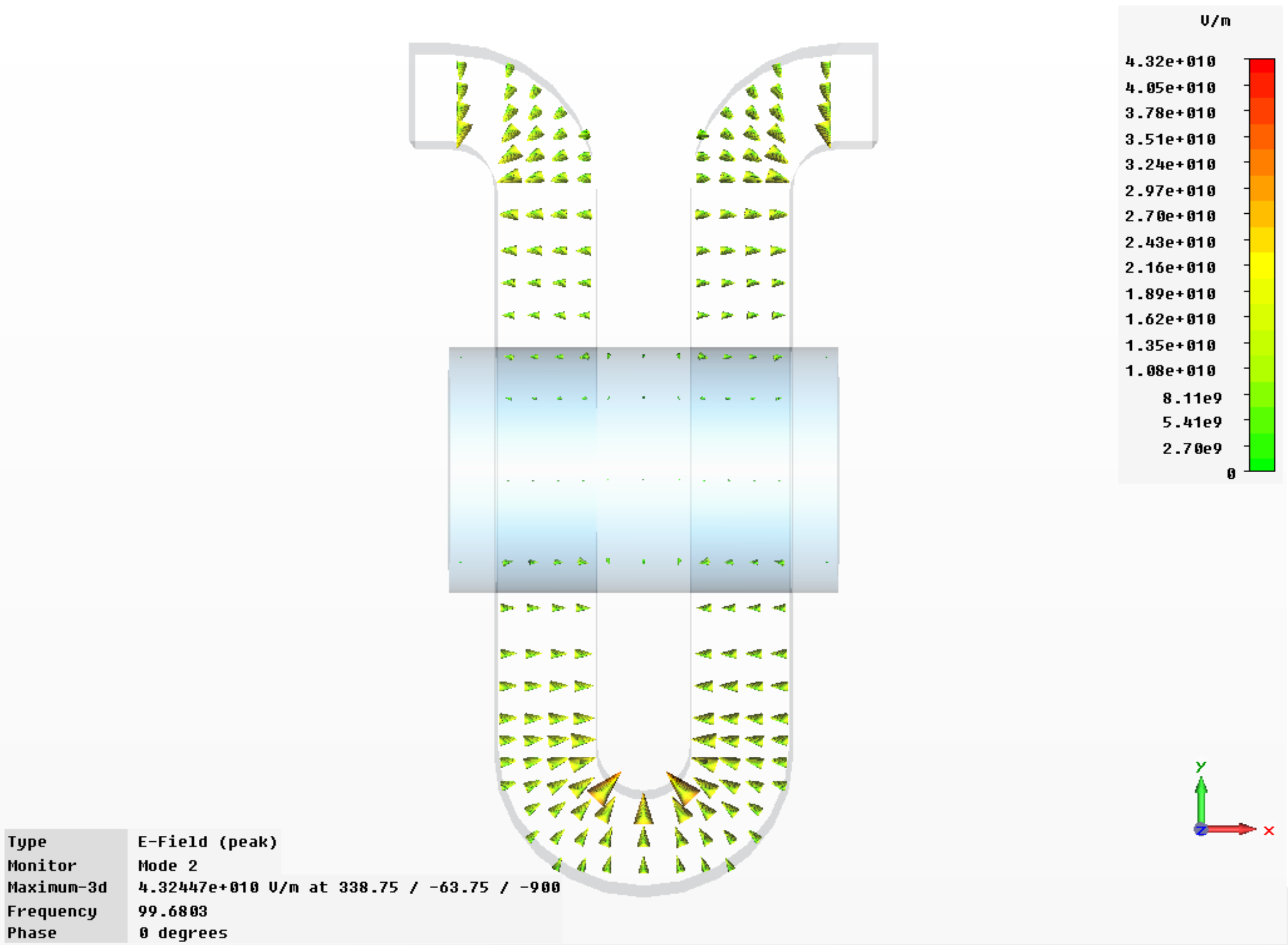
Optimized dimensions

Parameter	Dimension (µm)
Depth ‘a’	1800
Gap Width ‘b’	300
Pitch ‘p’	550
Straight Height ‘h’	600
Tunnel Radius ‘r’	200



Courtesy: Ms. Isha Rathi, Dr. RK Sharma

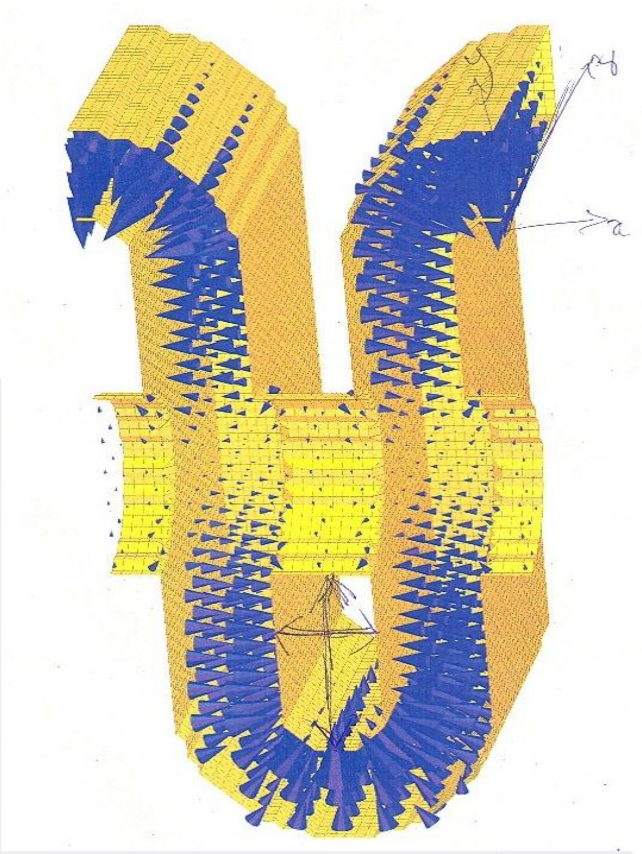
Electric field pattern
(CST)



Type	E-Field (peak)
Monitor	Mode 2
Maximum-3d	4.32447e+010 V/m at 338.75 / -63.75 / -900
Frequency	99.6803
Phase	0 degrees

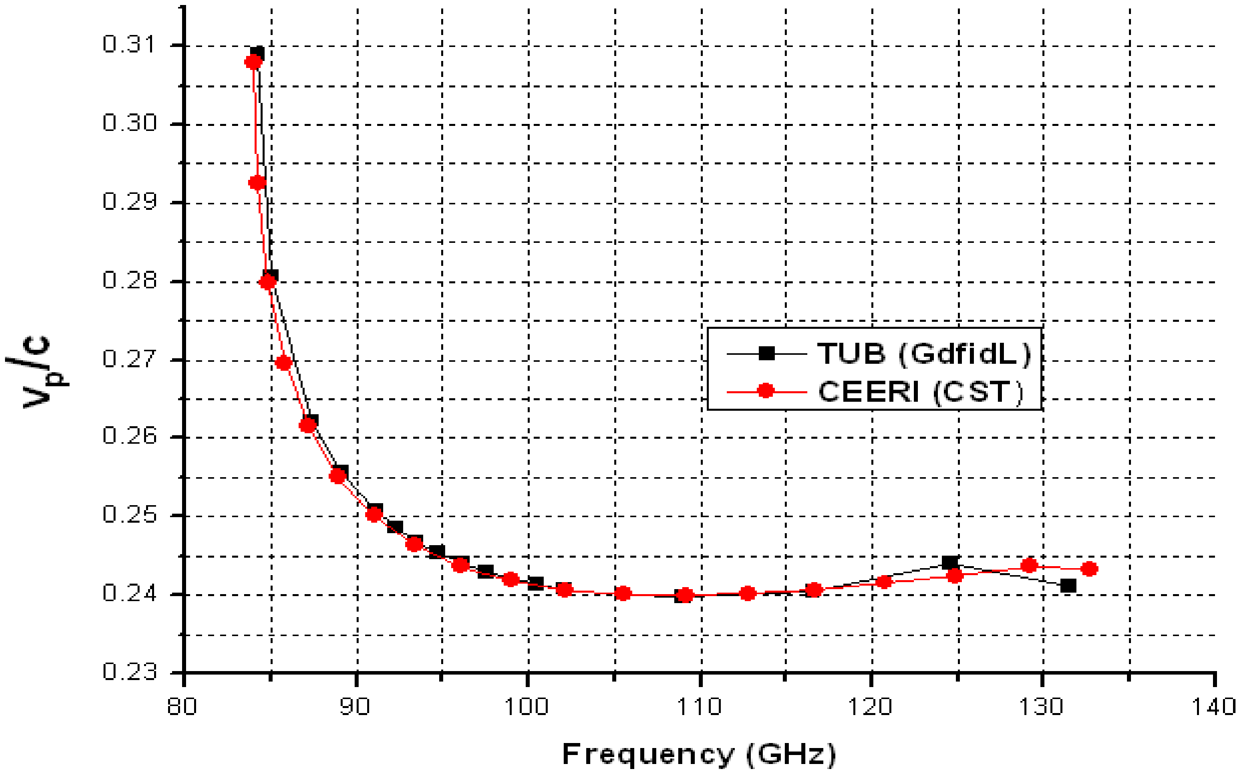
Courtesy: Ms. Isha Rathi, Dr. RK Sharma

Electric field pattern (using GdfidL at TUB)



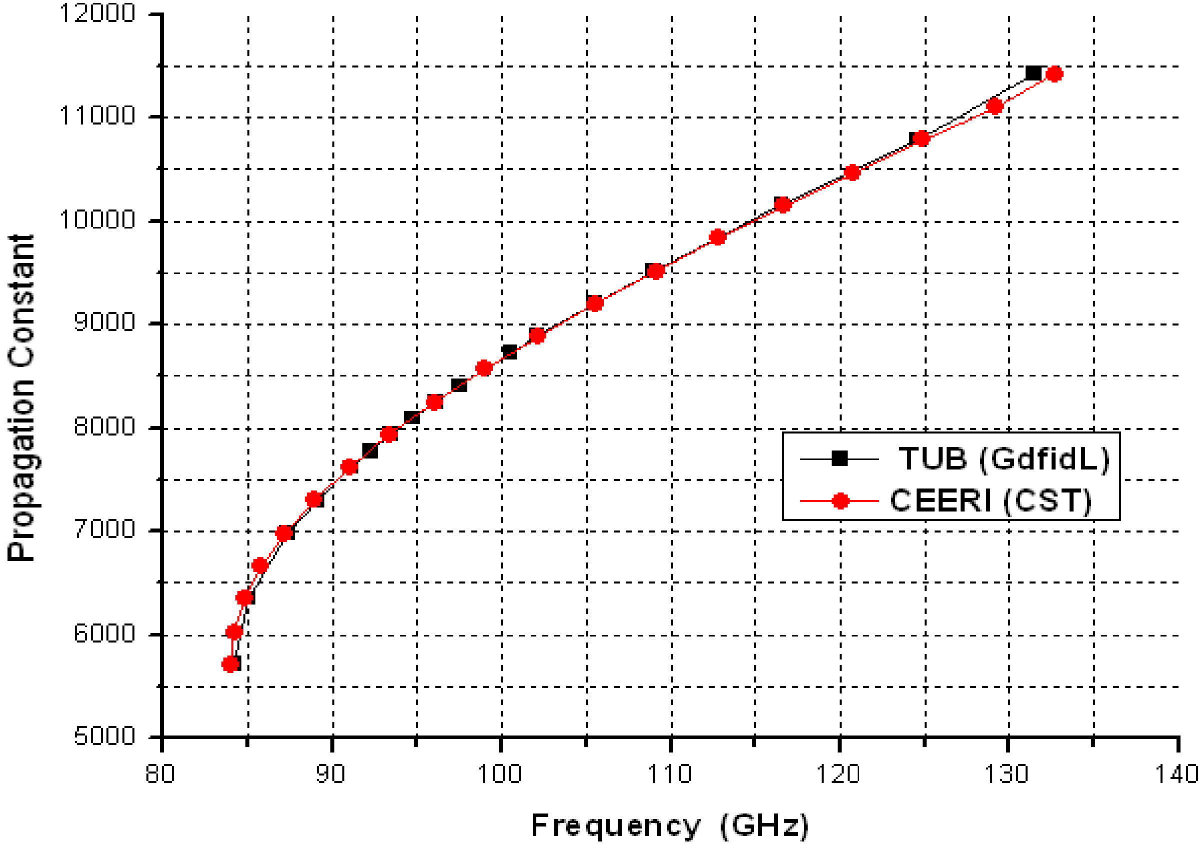
Courtesy: Dr. A. Grede, Prof. Dr. H. Henke (TUB)

Dispersion plot



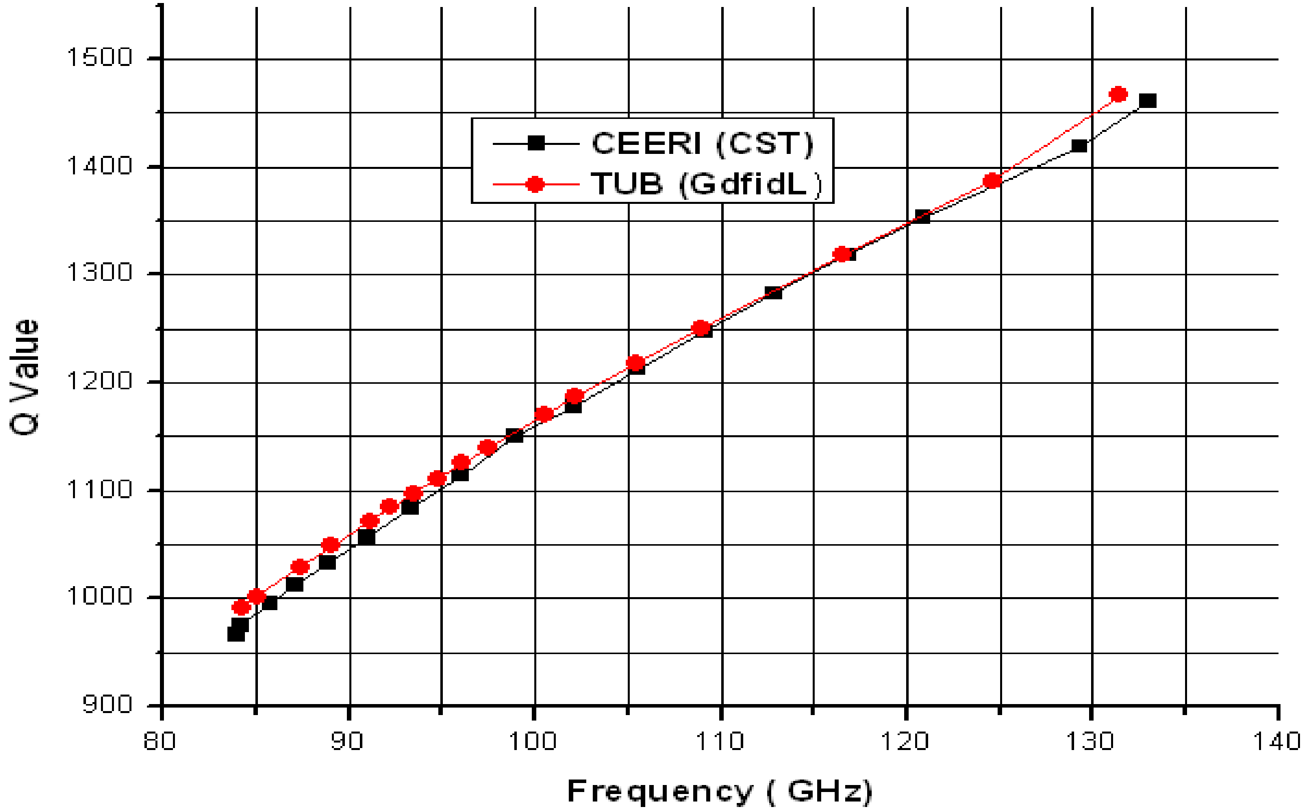
Courtesy: Ms. Isha Rathi, Dr. RK Sharma

Dispersion plot



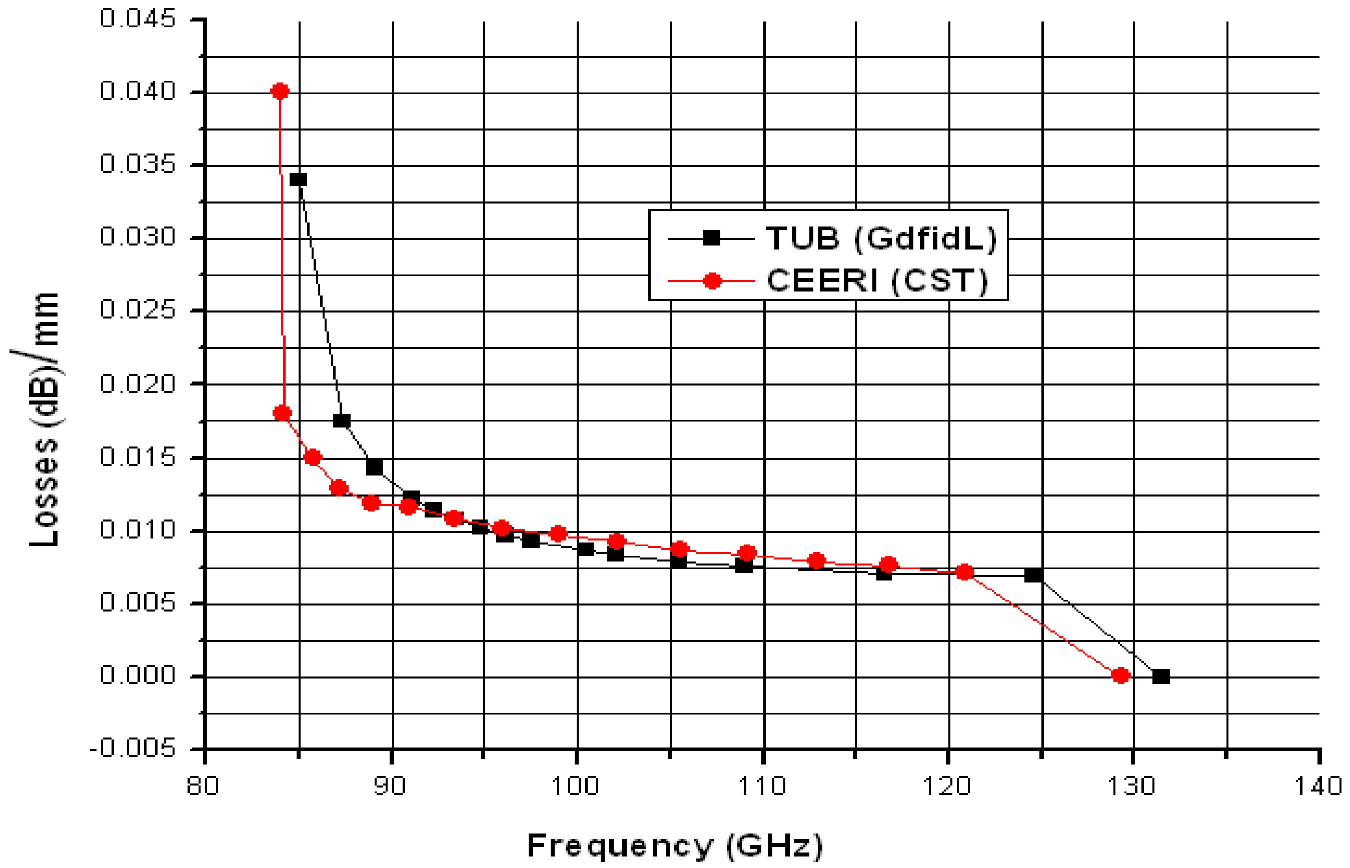
Courtesy: Ms. Isha Rathi, Dr. RK Sharma

Quality factor



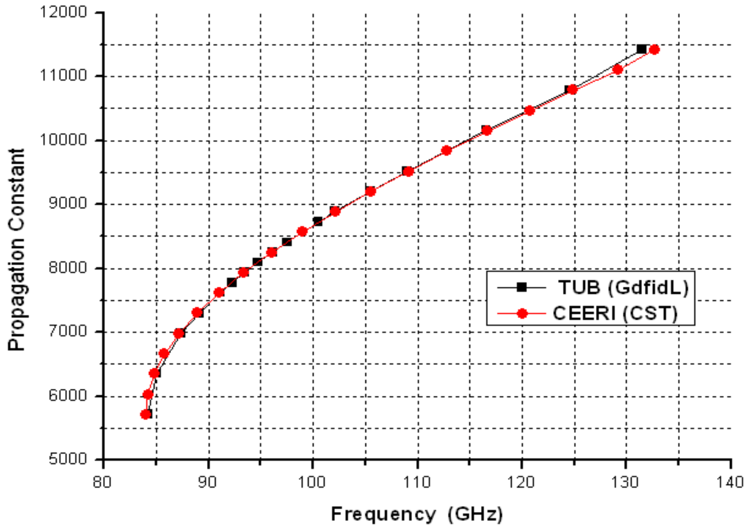
Courtesy: Ms. Isha Rathi, Dr. RK Sharma

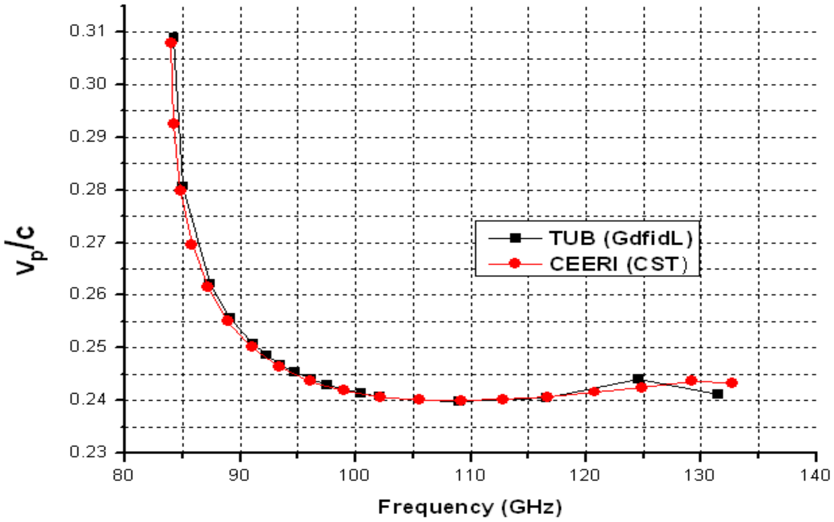
Loss characteristics



Courtesy: Ms. Isha Rathi, Dr. RK Sharma

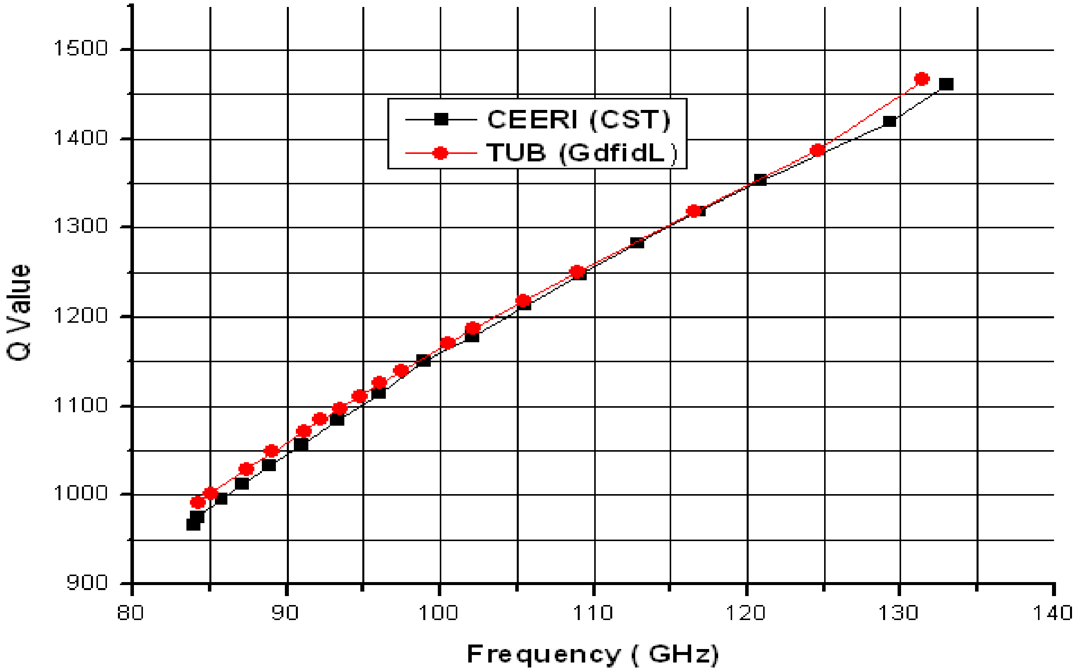
Dispersion plot





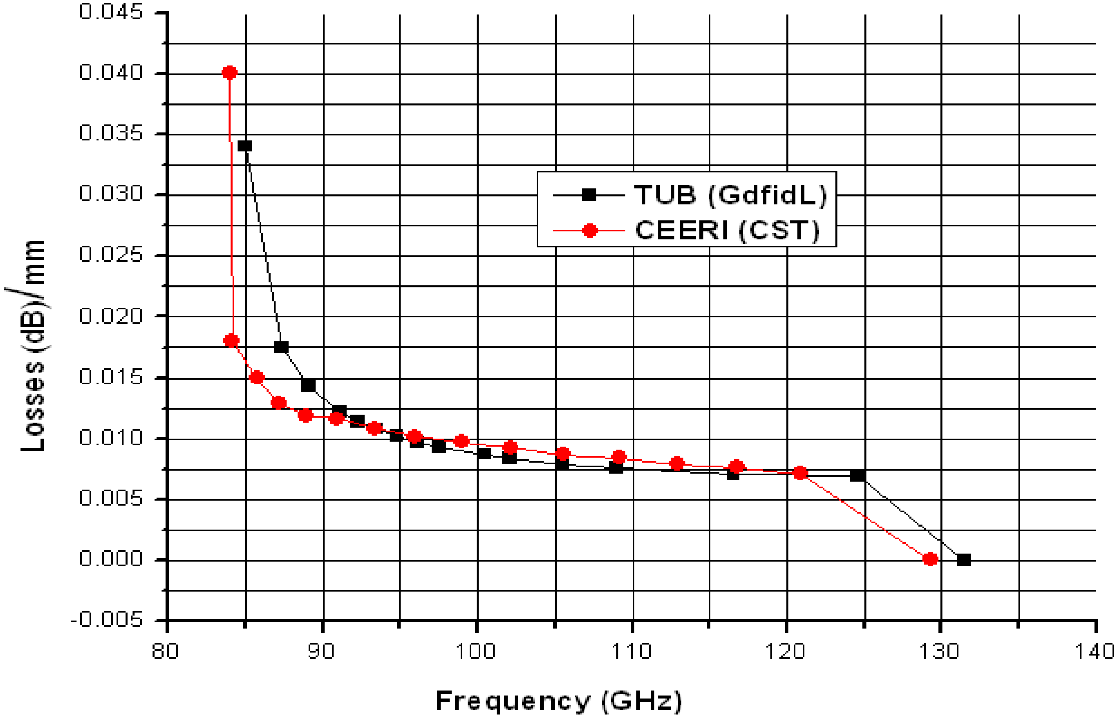
Courtesy: Ms. Isha Rathi, Dr. RK Sharma

Quality factor



Courtesy: Ms. Isha Rathi, Dr. RK Sharma

Circuit loss



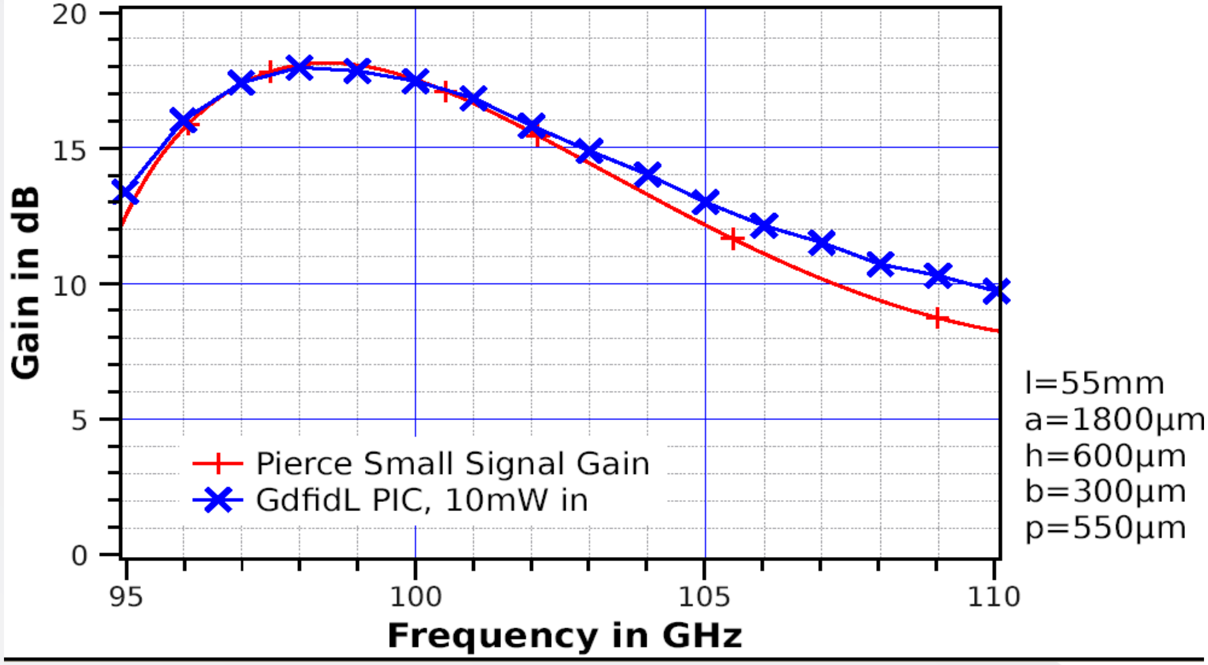
Courtesy: Ms. Isha Rathi, Dr. RK Sharma

Small signal gain using SUNRAY-1D for circuit length 55mm

Frequency in GHz	Gain in dB
85.02	-0.24
87.36	0.16
89.07	-1.87
91.11	-6.03
92.25	-5.93
93.46	2.19
94.74	11.14
96.10	15.85
97.50	17.79
100.52	17.06
102.11	15.43
105.45	11.63
108.98	8.73
116.54	7.55

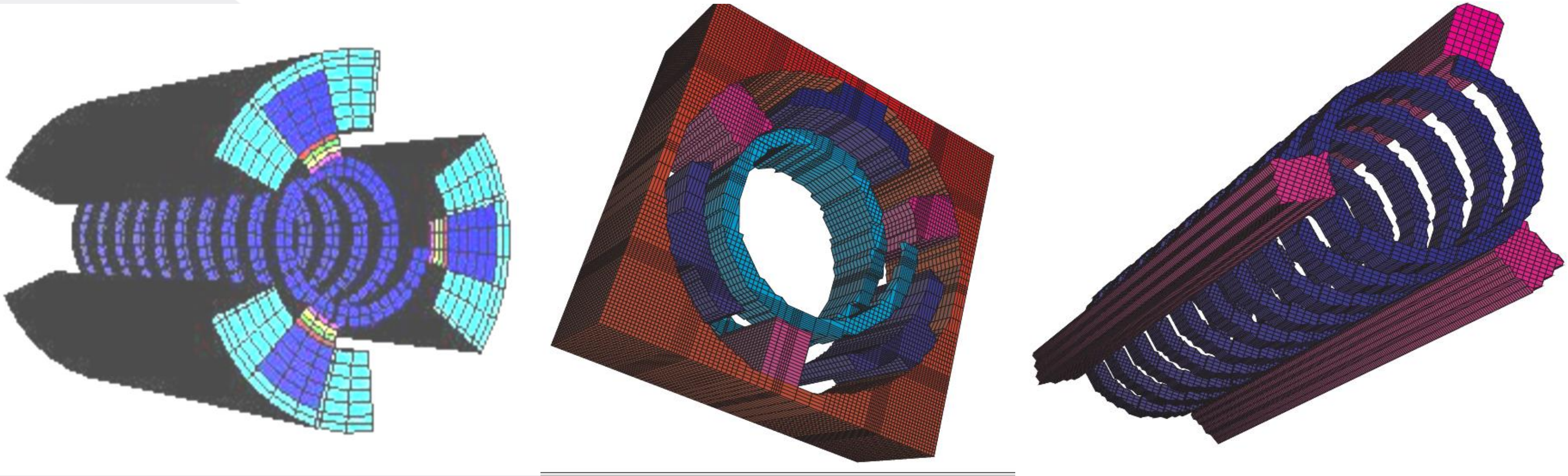
Courtesy: Ms. Isha Rathi, Dr. RK Sharma

PIC-simulation using Gdfid (TUB)

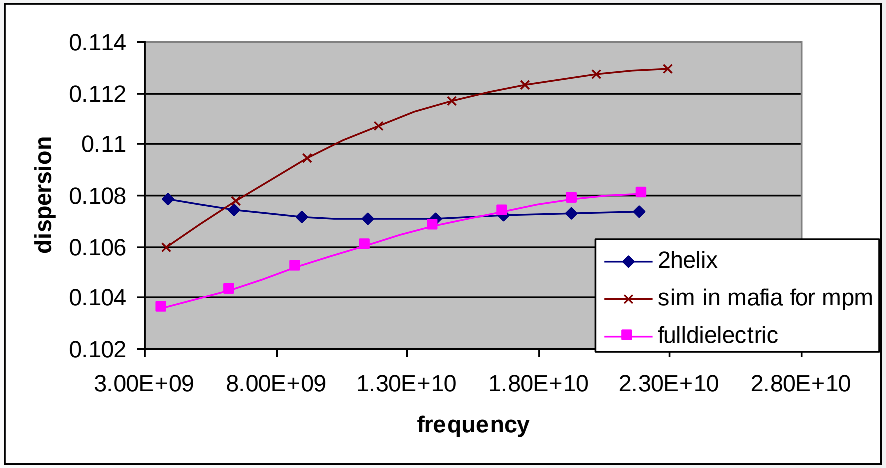


***Courtesy: A. Grede, H. Henke* (TUB)**

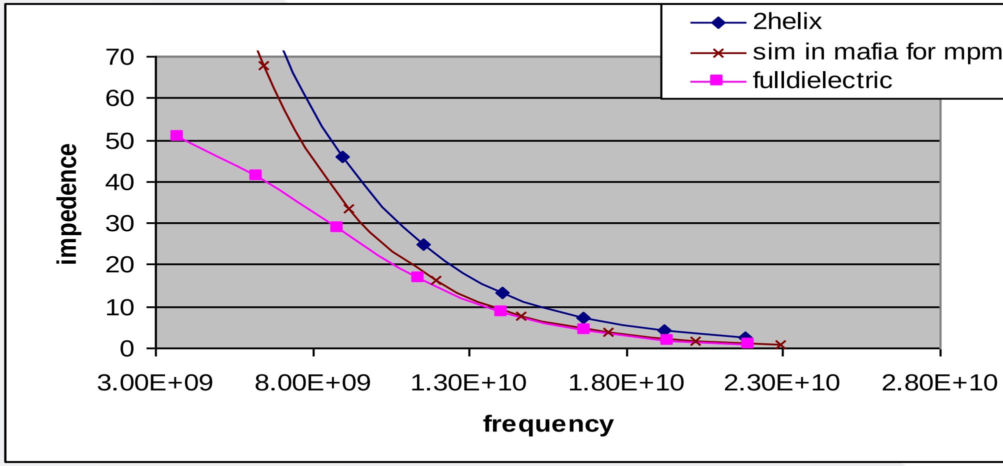
Helix Slow-wave Structure – 3D Simulation



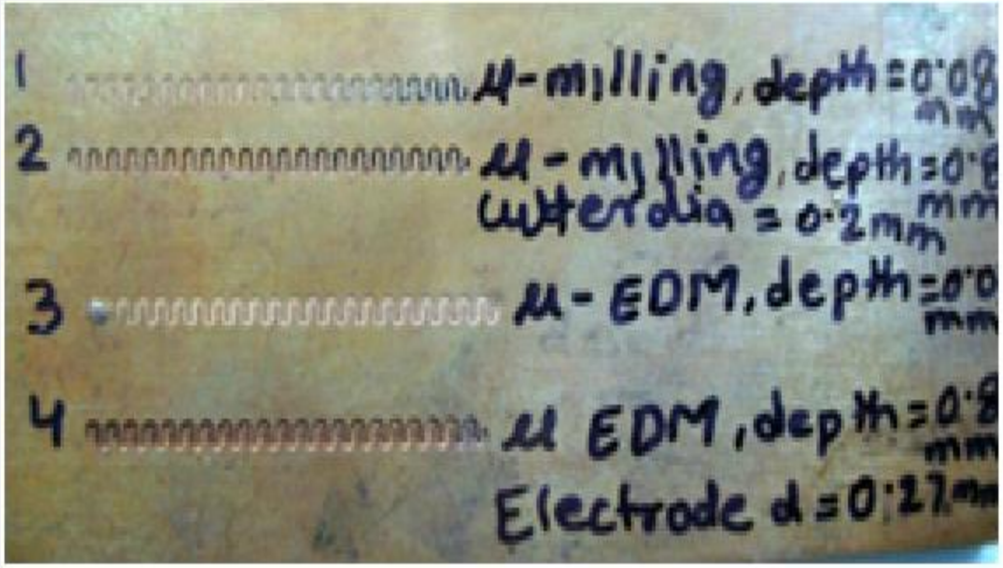
Dispersion Characteristics



Impedance Characteristics



Trial fabrication at CMRI in liaison with CEERI



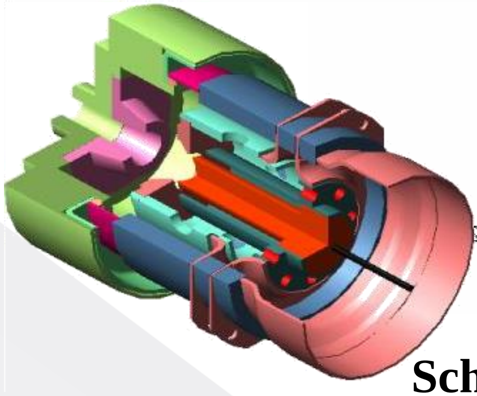
Trial using laser technology

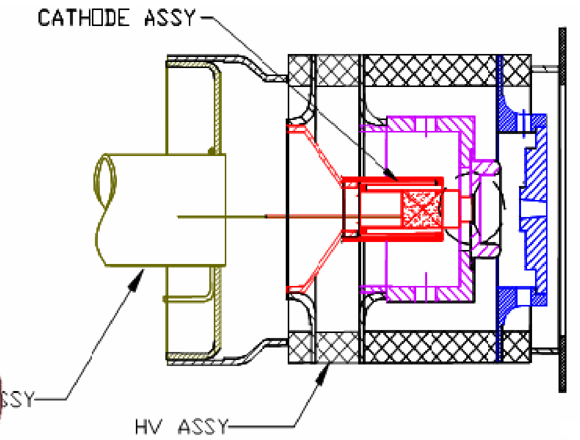
Courtesy: Ms. Isha Rathi, Dr. RK Sharma

Electron Gun for mm-wave TWT

Electron Gun for mm-wave TWT

- **Ion barrier Anode**
- **Beam diameter : 350µm**
- **Beam current : 100mA**
- **Highly thermal beam**

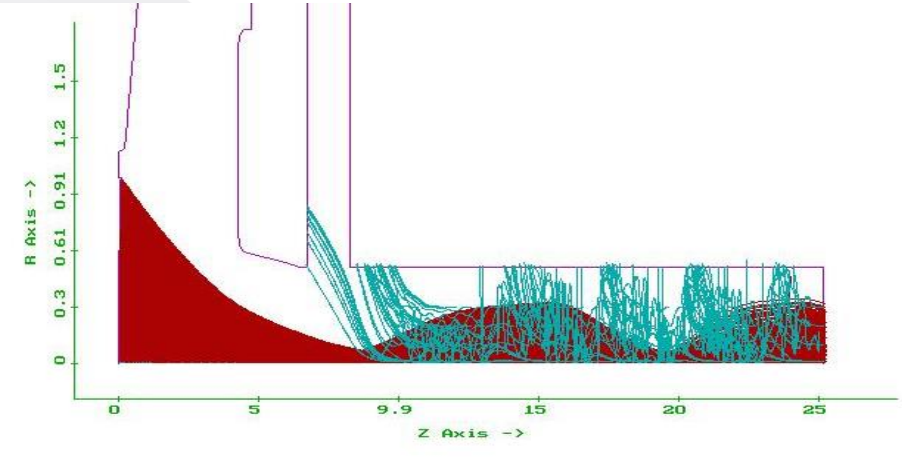




Schematic of electron gun

Ion effects in mm-wave gun

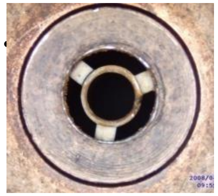
- **Ion generation major problem in mm wave guns**
- **Causes neutralization of electron beam**
- **Causes problems in beam focusing**
- **Cathode poisoning**

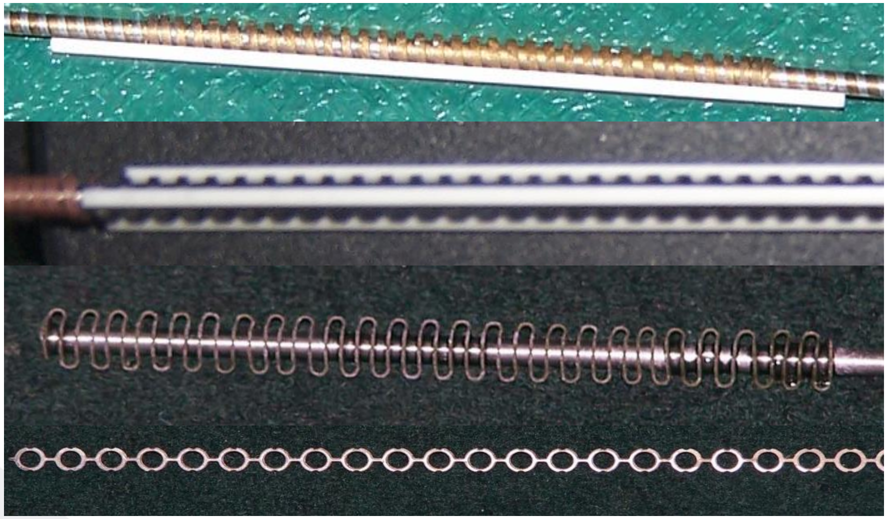


Ion anode barrier restricting ions to go to cathode

Advanced Technology for TWTs

- Brazed helix SWS.





- Ring-loop SWS

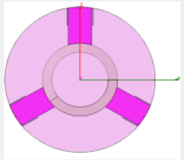
- Folded-waveguide

Ka-band FWS

- Resonant loss (meander line) for BWO suppression

Meander Line

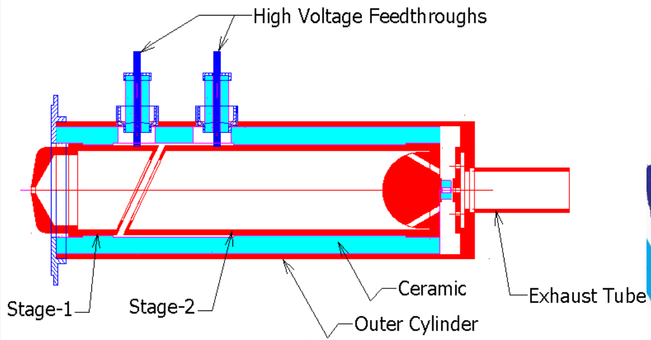
- Coated Vane SWS



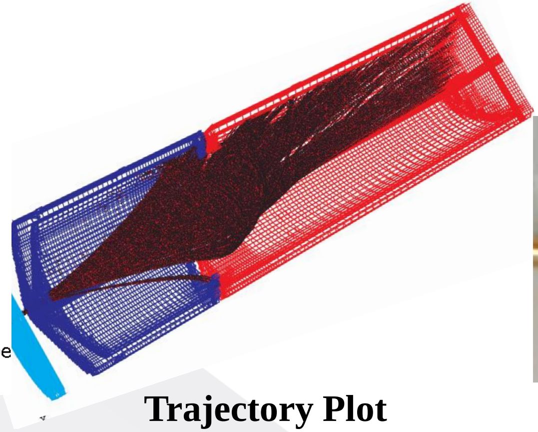
Depressed Collectors

Tilted Electric Field (TEF) Collector for mm-wave helix TWT

- **Higher efficiency collector (Typical Collector Efficiency ~ 70-80%**
- **Better Thermal Handling**



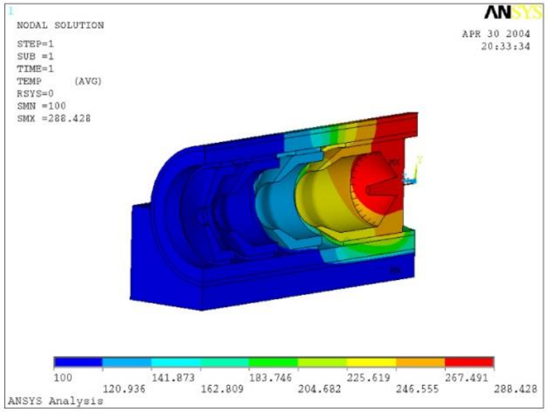
Cross Section



Trajectory Plot

Final Collector

Collector Piece Parts



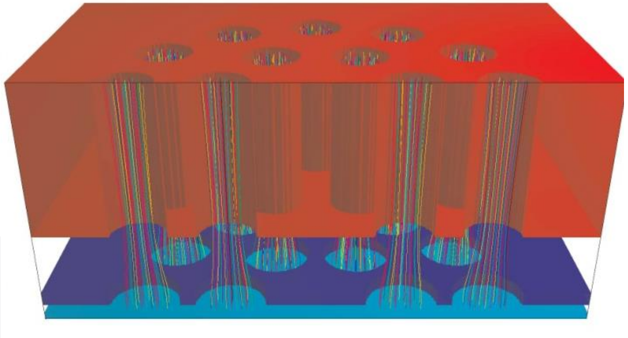
Thermal Analysis

Multiple Beam Klystrons (MBK)

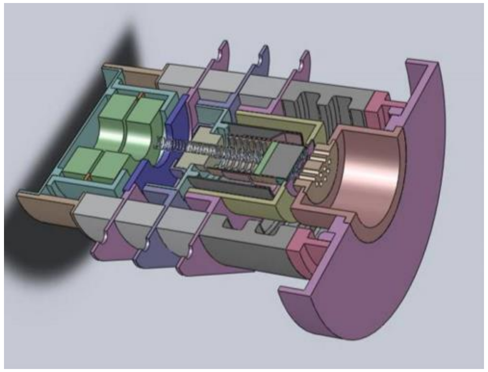
Specifications:

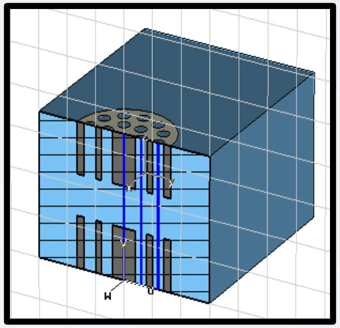
- **Frequency : Ku-Band**
- **Power Output : 400W (Min)**
- **Gain : 39 dB (min)**

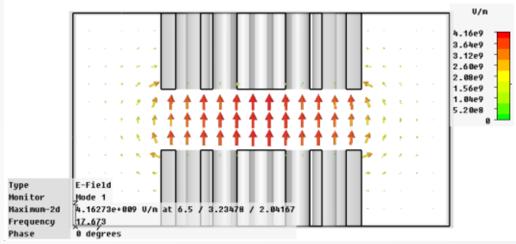
Electron Gun Simulation



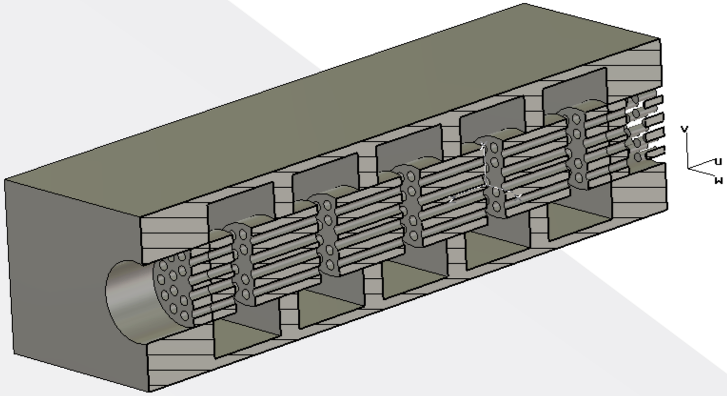
Solid model of Gun





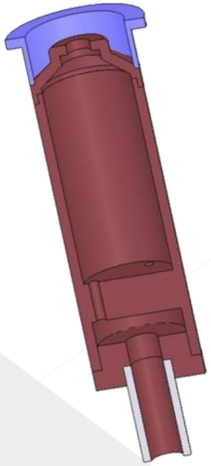


Type	E-Field
Monitor	Mode 1
Maximum-2d	4.16273e+009 V/m at 6.5 / 3.23478 / 2.04167
Frequency	17.673
Phase	0 degrees

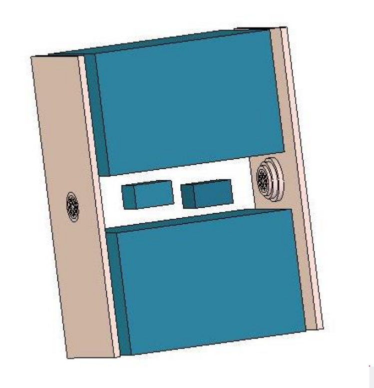


Cavity Simulation

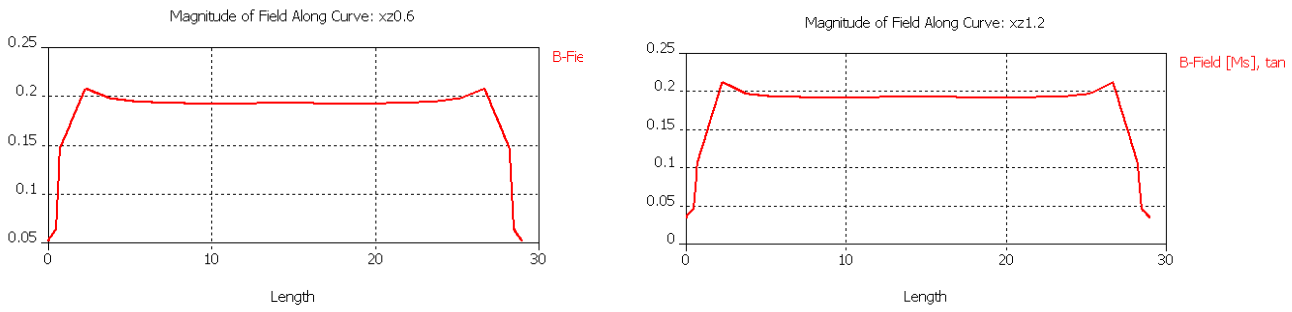
Solid Model of Collector



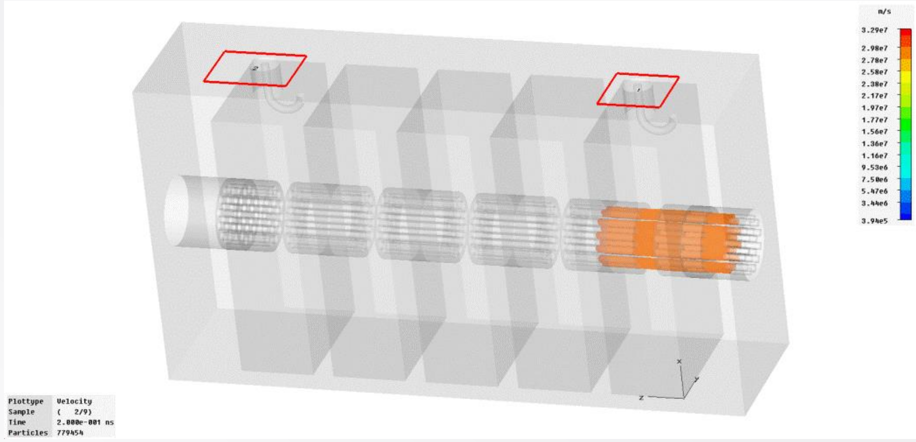
Multiple Beam Klystrons (MBK)



Magnetic Field Simulation

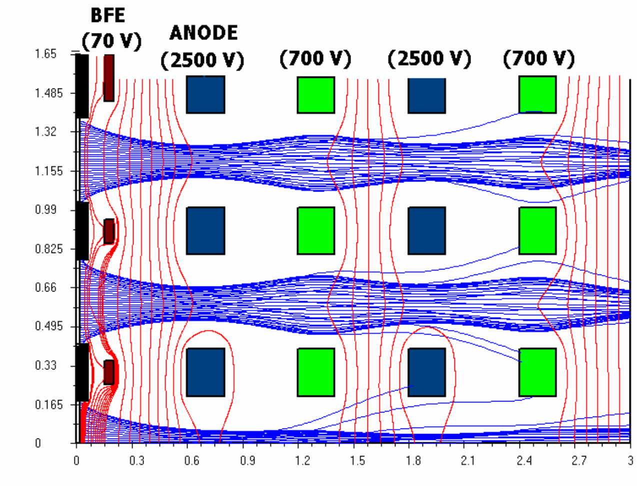


Off-axis magnetic fields



Plottype Velocity
Sample (2/9)
Time 2.000e-001 ns
Particles 779454

Magnetostatic Focusing



Electrostatic Focusing


Thank You!