Development of High Power Vacuum Tubes for Accelerators and Plasma Heating

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Abstract. High pulsed power magnetrons and klystrons for medical and industrial accelerators, and high CW power klystrons and gyrotrons for plasma heating in tokamak, are being developed at CEERI. S-band 2.0MW pulsed tunable magnetrons of centre frequency 2856MHz and 2998 MHz were developed, and S-band 2.6MW pulsed tunable magnetron is being developed for medical LINAC, and 3MW pulsed tunable magnetron is being developed for industrial accelerator. S-band (2856MHz), 5MW pulsed klystron was developed for particle accelerator, and S-band 6MW pulsed klystron is under development for 10MeV industrial accelerator. 350MHz, 100kW (CW) klystron is being developed for proton accelerator, and C-band 250kW (CW) klystron is being developed for plasma heating. 42GHz, 200kW (CW/Long pulse) gyrotron is under development for plasma heating. Plasma filled tubes are also being developed for switching. 25kV/1kA and 40kV/3kA thyratrons were developed for high voltage high current switching in pulse modulators for magnetrons and klystrons. 25kV/3kA Pseudospark switch of current rise time of 1kA/μ-sec and pulse repetition rate of 500Hz is being developed. Plasma assisted high power microwave device is also being investigated.

1. Introduction

High power vacuum tubes like magnetrons, klystrons, inductive output tubes (IOT) and gyrotrons are required both for the high energy particle accelerators, and for plasma heating in tokamaks [1-6]. High pulsed microwave power in MW range from 350MHz to over 10GHz is used for high energy linear accelerators. Lower frequencies, e.g., 350MHz and MW of power levels are used for proton accelerators. In an accelerator, propagating electron beam is energized by high microwave power that is injected into the RF propagating structure. Magnetron has the distinction of generating MW of pulsed microwave power in the frequency range varying from around 700MHz to well above 10GHz. It is the most compact, low cost, high efficient and the lowest operating voltage device but it has the disadvantage of phase and amplitude instabilities. Efforts are being made world over of improving magnetron coherency by injection locking techniques. Klystron has the distinction of producing pulsed power in MW range by amplifying low driving signal with high gain and low noise. Klystrons of MW of output power in the frequency range varying from around 350MHz to well above 10GHz are available. Single-beam klystrons of MW of output power are very large in size and have very high operating voltages compared to equivalent output power magnetrons. Multi-beam klystrons are new development for low voltage requirement and compact size. Klystrons of GW of pulsed output power are being investigated using sheet beam technology.

Microwave tubes of MW of CW power level are required for plasma heating in thermonuclear controlled fusion by generation of plasma and energizing ions suitable for energy production. In the operation principle of Electron Cyclotron Resonance (ECR) ion source, electrons confined by the magnetic field structure are heated to high energy by microwaves that have been injected into the plasma. These hot electrons then produce ions by successive electron impact ionization. Microwave frequency is decided by the electron cyclotron frequency. When electrons move in a magnetic field (B) they gyrate around the magnetic field lines due to the Lorentz force. The gyration frequency is called the cyclotron frequency ωc. If microwave radiation of the same frequency (ωrf) propagates into such a region, the electrons are resonantly accelerated or decelerated (depending on the phase of their transversal velocity component with respect to the electric field vector) when the following electron cyclotron resonance condition is fulfilled:

$$\omega rf = \omega c = (e/m) \times B$$

Here, e and m denote the charge and mass of the electron, respectively.

170GHz gyrotrons of MW of CW output power are used in European Tokamak. Optimum plasma heating requires high power vacuum tubes of generating low frequencies of 100's of MHz to 10's of GHz to 100'sGHz. Heavy ion particle like proton requires less frequency source around 350MHz. Tetrodes, klystrons and gyrotrons are therefore used in combination for plasma heating.

2. Development of high power vacuum tubes

CEERI, Pilani is engaged since long with the development of high pulsed power magnetrons and klystrons for medical, scientific and industrial accelerators, and with the development of CW klystrons and long pulse/CW gyrotrons for plasma heating. Plasma filled vacuum tubes like thyratrons and pseudospark switches are also being developed for high voltage/high current switching. The development of such high power microwave tubes are presented in this paper.

2.1 High Power Pulsed Magnetrons for Accelerators:
S-band 3 MW (pulsed) magnetron (as shown in Fig.1) of given specifications, was developed for particle accelerators.

Fig. 1. S-band 3MW (pulsed) Magnetron of following specifications:

Frequency	2998MHz,
Tunable:	2992-3002MHz,
Pulse duration:	4μs,
Duty cycle	0.001
Beam voltage:	50kV
Beam current:	120A

Two versions of S-band pulsed magnetrons of peak output power of 2.0MW with centre frequency 2998 MHz (for version-1), and 2856MHz (for version-2), tuning range 10MHz, pulse width 4.0μsec and duty cycle 0.001, were developed for industrial LINACS and MICROTRONS. S-band pulsed magnetron of peak output power of 2.6MW, centre frequency 2998 MHz, tuning range 10MHz, pulse width 4.5μsec and duty cycle 0.001, is presently being developed for medical LINAC. S-band tunable pulsed magnetron of 3MW pulsed power at centre frequency 2856 MHz, tuning range 10MHz, pulse width 5.0µsec and duty cycle 0.001, and beam voltage/current 50kV/120A is being developed for industrial accelerator. CEERI is working with Lancaster University, U.K., for injection locked, high efficiency, high power 704 MHz magnetron of CW output power of 800kW for proton accelerator.

2.2 High Power Klystrons for Accelerators and Plasma heating:
S-band, 5MW (pulsed) klystron, as shown in Fig.2, was developed for linear accelerator. Electromagnet is used for the electron beam focusing, and it is liquid cooled.

Fig. 2. S-band 5MW (pulsed) Klystron of following specifications:

Frequency:	2856MHz
Tuning:	10 MHz
Gain:	50dB
Efficiency:	40%
Pulse duration:	5ms
Beam voltage:	120kV
Beam current:	90A

Development of S-band pulsed klystron with rating of 6 MW (peak), 24 kW (average) and operating beam voltage 130kV, beam current 95A, pulse width 10µsec, PRF 400 is in progress. This klystron is used in 10MeV Industrial accelerator to accelerate an electron beam at high energy, to obtain an intense X-radiation. This radiation is used for many industrial applications related to food sterilization, decontamination, non destructive control, etc. 350MHz, 100kW (CW) klystron of operating beam voltage 30kV, and beam current 7A is being developed for proton accelerator. C-band 250kW (CW) klystron of beam voltage 60kV and beam current 10A is being developed for plasma heating.

2.3 High Power Long Pulse / CW Gyrotrons for Plasma heating:
42GHz, 200kW (CW/Long pulse) gyrotron, as shown in Fig.3, is under development for plasma heating. This is a multi-institutional project at CEERI, Pilani with the collaboration of IIT-Roorkee, BHU-Varanasi, IPR-Gandhinagar and SAMEER-Mumbai for the use of Indian TOKAMAK at IPR-Gandhinagar. Magnetron Injection Gun (MIG) of this gyrotron has been fabricated for operating beam voltage of 65kV and beam current 10A, and magnetic field 1.61 Tesla. The cavity for symmetric TE03 mode has been fabricated and tested. Other critical components like nonlinear taper, collector, and high power window have been fabricated. Full tube will be assembled within few months.

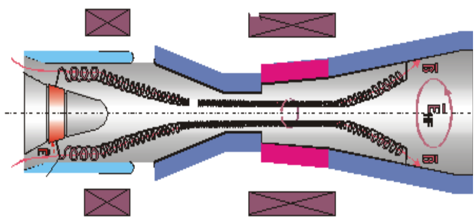

Fig. 3. Schematic diagram of 42GHz Gyrotron of output power 200kW

under development at CEERI-Pilani jointly with IIT-Roorkee, BHU-Varanasi, IPR-Gandhinagar & SAMEER.

120GHz, 1MW output power gyrotron is also being developed for plasma heating. The group is also working for design and development of gyrotrons at other frequencies.

2.4 High Power TWTs:

Traveling-wave tubes (TWTs) are also being explored for new generation ion sources because of their wide tuning range, lower operating voltage, and stable tube operation. TWTs are now available in wide frequency range from 1 to 100GHz of output power up to hundreds of kW (CW) and tens of MW (pulsed). High pulsed power C-band 75kW coupled-cavity TWT (Fig.4), was developed for a radar system. Bandwidth of this tube is 5.4 to 5.9GHz, and operating voltage and current are 34kV and 10Amps, respectively. This tube has gridded gun with both control grid and shadow grid, and coupled-cavity structure has cylindrical cavities coupled through double slots in their common wall.

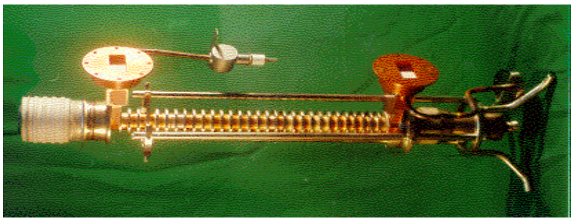

Fig. 4. C-band Coupled-cavity TWT of following specifications:

Pulsed output power: 75kW
Frequency range: 5.4 to 5.9GHz
Beam voltage/current: 34kV/10Amps

High efficiency C-band 60W (CW) TWT, Ku-band 140W (CW) TWT, and Ka-band 40W (CW) TWT are also being developed for their applications in satellite communication. THz TWT of frequency 94-100GHz and output power of 5-10W is also being developed for numerous applications.

2.5 Plasma filled tubes for switching:

25 kV/1kA and 40kV/3kA thyratrons (Fig.5) were developed and tested for high voltage high current switching in pulse modulators as required for magnetrons and klystrons.

Fig. 5(a). 25kV Thyratron

Peak Anode Voltage	25 kV
Peak Anode Current	1.0 kA
Avg. Anode Current	1.0 A
Time Jitter	3.0 nsec
PRF	60 kHZ
Di/dt	5000 A/µ sec
Hydrogen filled	

Fig. 5(b). 40kV Thyratron

Peak Anode Voltage	40 kV
Peak Anode Current	3.0 kA
Avg.Anode Current	3.0 A
Di/dt	5000 A/µsec
Anode delay	0.1 µsec
Time Jitter	1.0 nsec
Deuterium filled	

Plasma based 25 kV/5kA Pseudospark Switch and 40 kV/5kA Pseudospark Switch of current rise time of 1kA/µ-sec and pulse repetition rate of 500 Hz are being developed. Plasma based high power microwave devices like Pasotron are also being investigated using plasma based high current density electron gun.

4. Conclusion

In-house design and fabrication capabilities are developed at CEERI, Pilani, for the successful indigenous development of different types of high power microwave tubes and plasma filled high power devices for their applications in various accelerators and tokamaks. All efforts are being carried out for making these high power vacuum devices of low cost, compact and of high efficiency. Because of the many advantages of magnetrons over klystrons, CEERI is working with Lancaster University for injection locked 704MHz, 800kW magnetron for proton accelerators. Multi-beam and sheet beam technologies are also being developed for compact high power klystrons and for high power, very high frequency TWTs. Both multi-beam and sheet beam technologies have numerous advantages over single cylindrical beam because of significant reduction of space charge forces. CEERI is developing plasma filled devices for switching as well as for high microwave power generation. A plasma-assisted high power oscillator (*Pasotron*) is being investigated using plasma assisted electron gun.

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References:

[1] Caryotakis G, High-Power Microwave Tubes, IEEE Trans. Plasma Sci. 22(5) 683-91, 1994
[2] Barker R J and Schamiloglu E, High Power Microwave Sources and Technologies (III series, Inc., New York: IEEE press) 2001
[3] Schamiloglu E, High Power Microwave Sources and Applications, IEEE MTTS, Fort Worth, Texas, 2004
[4] Shrivastava P., et.al., Research, Design and Development Activities on High Power Pulsed RF/Microwave Systems and Test Facilities for Particle Accelerators, IEEE-IVEC-2011, 53-54.
[5] Dexter, A.C., et.al., First demonstration and performance of an injection locked continuous wave magnetron to phase control a superconducting cavity, PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 14, 032001-11, 2011.
[6] Choi, EM, et.al., Megawatt Power Level 120 GHz Gyrotrons for ITER Start-Up, Journal of Physics: Conference Series 25 (2005) 1–7.