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Design of a Tunable 4-MW Free Electron Maser for Heating Fusion Plasmas*

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ABSTRACT

There is an ongoing program at the FOM institute, The Netherlands, to develop a 1-MW, long-pulse, 200-GHz Free Electron Maser (FEM) using a DC accelerator system with depressed collector. We present an extrapolation of this design to more than 4 MW of output microwave power in order to reduce the cost per kW and increase the power per module in a plasma heating system.

Introduction

The FOM Institute for Plasma Physics, The Netherlands, is now constructing a Free Electron Maser (FEM) to be used as a high-frequency tunable microwave source for heating fusion plasmas.[1] This source has been designed to ultimately operate CW at the 1-MW power level over an adjustable tuning range of 150–250 GHz. The design philosophy is to use a high-voltage, DC beam system with depressed collector in order to make the overall wall plug efficiency 40–50%. The high-voltage, 1.75-MV power supply provides only loss current (~ 30 mA) while the 12-A beam current is supplied by the 100–200 kV collector supplies.

A compatible microwave interaction circuit, coupling system and wiggler magnet is shown in Figure 1. The rectangular corrugated circuit operating in HE_{11} mode is very low loss capable of handling multi-megawatts of power CW. The stepped waveguide system allows feedback and output coupling in highly overmoded guide while maintaining mode purity. The two-stage stepped undulator allows for increased electronic efficiency while maintaining high-quality focusing.

There is an interest in extrapolating this design to higher powers in order to reduce the cost/kW and develop a more compact microwave system. The most straight forward extrapolation is to increase the current beyond 12 A to as high as 30 A, keeping as much of the system the same while ensuring the integrity of the beam-focusing system and CW power-handling capability. The cost savings occur because the high-voltage supply costs scale slowly with current.

High-Current Design

It is important to note that the 1.75-MeV beam radius is determined by emittance in the 10 to 30-A range. As the beam current increases, the emittance is also allowed to increase in order to keep the electron charge density from increasing excessively, causing problems due to ionization of background gas. The increase in emittance does not degrade microwave interaction efficiency.

The original focusing system for the low-current design can be used even though the beam radius increases by 40%, the charge density increases by 20%, and the emittance increases by a factor 2. The low-loss corrugated waveguide system can handle up to 5 MW with acceptable wall loading (< 1 kW/cm^2). Further stepping of the waveguide would be required to separate the power into 4 output ports each having corrugated distributed cooled windows capable of handling ~ 1 MW CW power.[2] Table 1 gives the modified 30-A design from the original FOM design. It is still assumed that the depressed collector can recover 90% of the power and dissipate up to 5 MW.

Computer Simulations

The FEM performance was modelled using a fully self-consistent 3D multimode non-wiggle averaged computer code including both AC and DC space charge effects.[3] The beam is modelled as several hundred particles which represent a specified emittance and charge density profile.

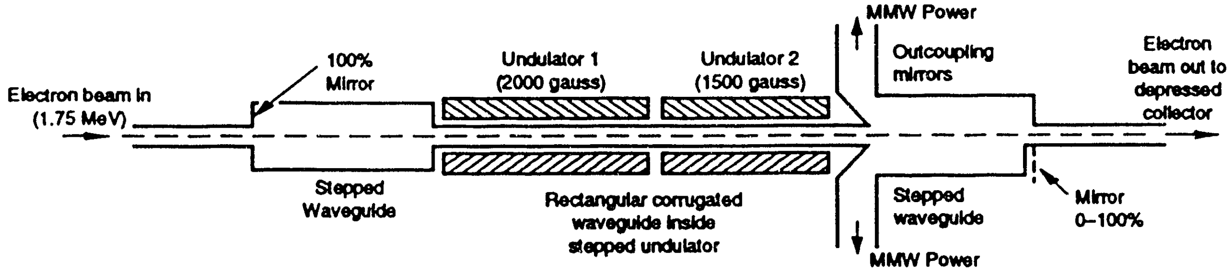

Fig 1. Schematic of MMW cavity of FEM showing step undulator, waveguide, and reflection/outcoupling system.

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FEM Parameters	FOM Design	Extrapolation of FOM Design to High Power
Net Microwave Output	1.3 Megawatts	4.7 Megawatts
Beam Current	12 amperes	30 amperes
Beam Voltage	1.75 MeV	same
Reflection Coefficient	29%	20%
Beam emittance	50 π mm m rad	90 π mm m rad
Beam radius	0.92 mm	1.28 mm
Overall total length	158 cm	138 cm
No. full periods Section 1	20	17
No full periods Section 2	14	13
Peak wiggler field Section 1	2.0 kG	same
Peak wiggler field Section 2	1.6 kG	1.5 kG
Inter wiggler gap	6.0 cm	6.4 cm
Wiggler period	4 cm	same
Waveguide mode	HE_{11} rectangular	same
Waveguide height	2 cm	same
Waveguide width	1.5 cm	same
Frequency	200 GHz	same
High voltage loss current	< 40 milliamps	<100 milliamps
Depressed collector efficiency	90%	same
Wall plug efficiency	40%	50%

Table 1. Extrapolation of FOM Design to High Power

Figure 2 shows the prediction for steady state microwave power generated as the beam traverses the wiggler. The step-tapered wiggler enhances the power by almost 2.5 times to 4.7 MW. Figure 3 shows the beam cross section upon entering and exiting the wiggler. The beam increases by a factor of 2 in size, but is still well confined and centered in the original waveguide structure. Figure 4 shows the electron energy spread in the beam after the interaction to be about 300 kV.

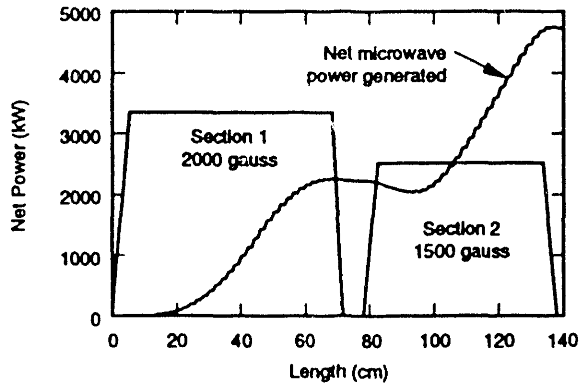
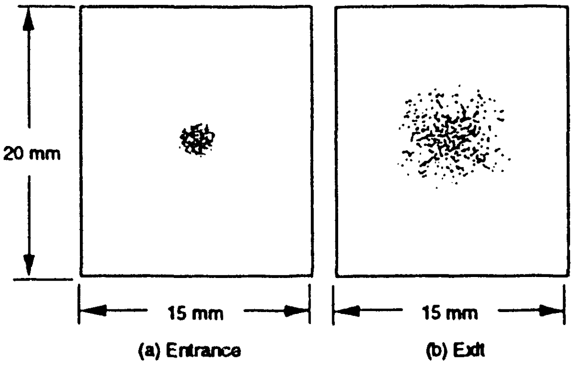


Fig 2. Net microwave power generated vs length for extrapolated high power design of Table I.



(a) Entrance

(b) Exit

Fig 3. Transverse beam cross-section in rectangular waveguide at (a) entrance to undulator 1 and (b) exit side of undulator 2 after traversing step wiggler interaction region

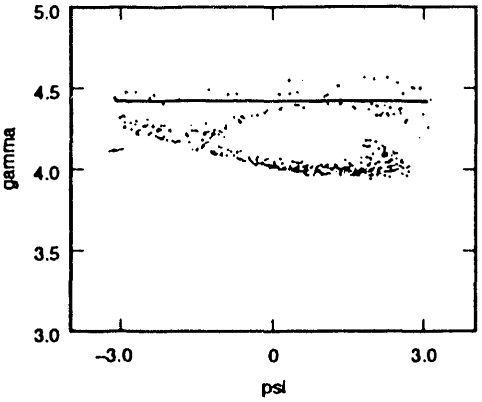


Fig 4. Energy of spent beam electrons vs phase angle at undulator exit.

A number of simulations were performed at various currents between 12 and 30 amperes with each case being optimized. The results are shown in Figure 5, which shows how the output power scales with beam current assuming a roughly fixed charge density. The dependency goes faster than linear (~ $I^{1.4}$) because the FEM efficiency increases with current.

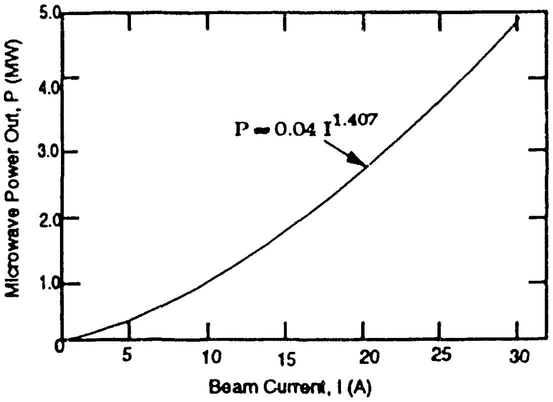


Fig. 5. The dependence of microwave output power on beam current for the configuration of Fig. 1.

Conclusion

The 1-MW FEM now being built at FOM could be upgraded to as much as 4.7 MW by increasing the current from 12 to 30 amperes, still keeping many of the key design parameters constant (voltage, wiggler configuration, microwave waveguide system).

The upgraded design can greatly reduce the cost/kW since power supply costs at fixed voltage increase slowly with current (much less than linear) while output power increases faster than linear with increasing current.

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