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April 1, 1995

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This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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Abstract

A Free Electron Maser (FEM) is now under construction at the FOM Institute (Rijnhuizen) Netherlands with the goal of producing 1 MW long pulse to CW microwave output in the range 130 GHz to 250 GHz with wall plug efficiencies of 50% (Verhoeven, et al EC-9 Conference). An extrapolated version of this device is proposed, which by scaling up the beam current, would produce microwave power levels of up to 5 MW CW in order to reduce the cost per watt and increase the power per module, thus providing the fusion community with a practical ECRH source.

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 one-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 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 has very low ohmic loss and is 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 is required to achieve the required electronic efficiency over the wide tuning range while maintaining mode purity and high quality focusing. There is great interest in exploring the possibilities to extrapolate the 1 MW design to higher powers in order to reduce the cost per kilowatt and develop a more compact microwave heating system. The extrapolated design will be based on the performance characteristics of the 1 MW FOM-FEM experiment to be done in the later part of 1995.

Predicted performance of the 1 MW FOM-FEM

The successful operation of the 1 MW FOM-FEM is highly dependent on maintaining low body interception current (< 30 ma). This is achieved by first utilizing an electron gun specifically designed to suppress the halo current caused by cathode edge effects [2]. The gun has been extensively characterized experimentally in a beam analyzer to determine the total beam emittance (80π mm mrad) and verify beam uniformity with the absence of halo current as illustrated in Figure 2. Secondly, a robust in line beam focusing system using solenoidal magnets, which conserve emittance has been developed. Finally,

the wiggler utilizes periodic side array focusing, which can be adjusted to eliminate field errors maintaining accurate focusing. Figure 3 illustrates the entire transport of the beam (3D simulation) from the electron gun to within the wiggler. The initial conditions for the simulation (beam size, expansion velocity, emittance) were determined from the beam analyzer data. The prediction is that the beam will be focused with a wide safety margin ensuring low body interception current. A stationary 3D beam interaction code [3] [4] was used to initially predict the linear gain, nonlinear gain and output power as illustrated in Figure 4. The predicted output power was 1.3 MW. Further investigation with a non-stationary code (multi-frequency) indicated that mode competition could be avoided by optimizing the feedback reflection coefficient and the gap between wiggler sections [5]. Figure 5 predicts that the FEM oscillator will evolve from noise into single mode operation above the 1 MW level.

Extrapolation to 5 MW design

An extrapolation of the 1 MW FOM-FEM is desirable since the capital cost of the high voltage system increases slowly compared to the increase in microwave output. The cost per kilowatt can be reduced by factors of 2-3 for a 5 MW system. A multi-megawatt source also reduces the cost and complexity of the microwave transmission system to the plasma. All key design features of the 1 MW system are applicable to much higher powers and in addition the interaction physics improves with higher power. The most straight forward extrapolation is to increase the beam current from 12 amperes to 30 amperes with minor changes in other parameters. This is possible since the beam is still emittance dominated resulting in a small change in radius for the same focusing fields. The design concepts and procedures incorporated in the multi-megawatt designs are taken from the FOM group and their collaborators which are:

- conventional 2 MeV DC accelerator system with depressed collector (FOM Institute),

- low emittance electron gun with halo current suppression to minimize body current. (Varian Associates, LLNL),

- step corrugated waveguide and/or open elliptic guide for CW power handling, feedback and beam-RF separation (IAP Institute, Russia),

- step tapered wiggler interaction circuit design (LLNL),

- periodic magnet side array focusing for the wiggler (Kurchatov Institute, Russia),

- low current loss and low emittance growth beam line system using solenoid focusing (FOM Institute),

- distributed cooled megawatt CW microwave windows (General Atomics, LLNL).

Figure 6 indicates how the microwave output power scales with current assuming a roughly fixed charge density (beam size) [6]. A proposed 5 MW design would require 30 amperes and at least double the allowed body interception current. Table I summarizes the key features of the extrapolated 5 MW design. Multi-frequency simulations show that with optimization, single mode output at 5 MW output level is achievable. (Figure 7)

Depressed Collector and Window

Practical CW operation is dependent both on a highly efficient depressed collector and an output microwave window capable of handling multi-megawatt CW output. The system efficiency E_s of the FEM is given by:

$$E_s = \frac{E_e}{1 - E_c(1 - E_e)} \equiv E_e \frac{V_b}{V_c}$$

where:

E_e = electronic efficiency

E_c = collector efficiency

V_b = beam voltage

V_c = effective collector supply voltage ($\geq$ effective energy spread)

Overall system efficiency of 50% requires a collector efficiency of 90% when the electronic efficiency is 9.5% (5 MW output). Figure 8 shows the energy spread in the spent beam for 5 MW output power. The maximum energy spread is of the order 250 keV which implies that a 90% collector efficiency is achievable. A new concept for windows which has distributed cooling throughout the window is now being developed for a 1 MW CW gyrotron. Figure 9 illustrates microwaves matched through such a structure, which under proper conditions behaves like a single disk window. This concept could be extended to handle 5 MW CW.

Conclusion

Experimental results from the FOM-FEM will be closely followed in the coming year to verify all design concepts and code predictions, thus providing a credible base for a 5 MW FEM development program in the future.

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Table I

Extrapolation of FOM design to higher power

<u>FEM parameters</u>	<u>FOM design</u>	<u>Extrapolated 5 MW design</u>
Output Power	1.2 MW	5 MW
Beam Voltage	1.75 MeV (200 GHz)	same
Beam Current	12 amperes	30 amperes
Allowed Body Current	< 30 milliamps	< 80 milliamps
Beam emittance	80π mm mrad	120π mm mrad
Beam radius	1.2 mm	1.5 mm
Wiggler period	4 cm	same
Wiggler Field Section 1	2.0 kG	same
Wiggler Field Section 2	1.6 kG	1.5 kG
Interaction length	158 cm	138 cm
Waveguide height	2.0 cm	same
Waveguide width	1.5 cm	same
Feedback reflection	24%	20%

Figure 1. Schematic for the FOM-FEM 1 Megawatt beam interaction circuit showing step undulator, corrugated waveguide and reflection/out coupling system.

Figure 2. Experimental results from Electron beam analyzer.
 (a) normalized emittance versus fraction of enclosed beam current for various focus electrode-cathode voltages.
 (b) measured current density profile 3 inches from 80 kV anode indicating absence of halo current.

Figure 3. Predicted beam transport of FOM-FEM design from gun through wiggler. Initial conditions taken from beam analyzer data (Figure 2)

Figure 4. Predicted microwave performance of FOM-FEM using stationary code.
 (a) net power generated versus distance through wiggler indicating 1.3 megawatts output.
 (b) linear and non-linear gain versus frequency for voltage of 1.75 MeV.

Figure 5. Predicted microwave performance of optimized FOM-FEM design using time-dependent code showing single mode operation evolving from noise. Net output power is 1.1 MW.

Figure 6. Predicted microwave power versus beam current for a multi-megawatt version of the FOM-FEM. Results using stationary code.

Figure 7. Predicted microwave output using the time-dependent code for an FEM operating a 1.75 MeV, 30 amperes.
 (a) time evolution of unoptimized design showing mode competition
 (b) optimized design with single mode operation. Net output power is 5 Megawatts.

Figure 8. Depressed collector concept.
 (a) schematic of multi-stage 90% efficient depressed collector
 (b) energy spread versus phase angle in the spent beam of a 5 MW FEM.

Figure 9. Electromagnetic simulation of matched microwave power propagating through a 1 MW CW distributed cooled window. Waves propagate from left to right.