A 1 MW Free Electron Maser For Fusion Applications

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Abstract

The basic design is given for our electrostatic free-electron maser, FEM, producing a 1 MW cw output in the 140-250 GHz range. FEM simulations, the electron beam line, the undulator and the millimetre wave system are discussed.

1. INTRODUCTION

High-power, millimetre wave (mmw) FEM's, i.e., Free Electron Lasers operating in the mm-regime, are being developed for, amongst others, applications in electron-cyclotron heating, current drive and plasma density profile control in future generation tokamaks [1-3]. For these applications megawatts of mmw power at frequencies ranging from 140-300 GHz are needed. Further important requirements are that the mmw frequency be rapidly tunable, and that the overall efficiency (grid to mmw power) exceed 35%.

This paper describes the design of the FEM at Rijnhuizen having the following specifications: a frequency adjustable in the 140-250 GHz range and fast-tuneable over +/- 5% in 1 ms, an output power of 1 MW during a 0.1 s pulse and an overall efficiency greater than 35%. In a later stage the FEM will be operated in truly cw mode.

2. BASIC LAYOUT

The FEM will be a medium-gain oscillator, comprising a thermionic electron gun, a 2 MeV dc accelerator, an undulator and mmw system at high voltage, a dc decelerator and a depressed collector, see fig. 1. The depressed collector recovers the charge and energy of the unspent electron beam, i.e., the electron beam after passing the undulator, which results in a high overall efficiency.

DC acceleration is preferred for three reasons. Firstly, it offers a simple way of fast-tuning the mmw frequency via a variation of the electron energy, i.e., via a variation of the high voltage. Secondly, charge and energy recovery of the unspent electron beam is less complicated in a dc system as compared to an rf accelerating and decelerating system. Thirdly, operating rf accelerators in a cw mode is complicated while this is a standard way of operating dc accelerators.

Long pulse and cw operation of the FEM is possible only if the electron loss current is less than the current delivered by the 2 MV, dc power supply. Therefore, we have opted for a simple, straight electron beam line. Further, the extraction efficiency is kept relatively small, 5%, to avoid large energy spread in the unspent electron beam. A large energy spread makes efficient energy recovery virtually impossible.

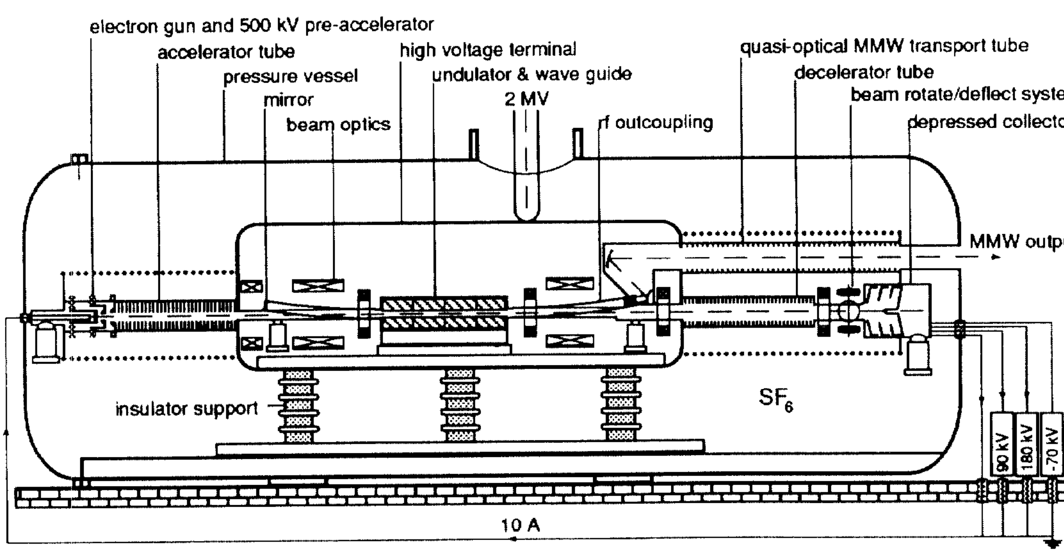

Fig. 1. Schematic layout of the Free Electron Maser. The system measures 10 m in length and 3 m in diameter.

3. Simulations on Gain and Efficiency

The interaction between the electron beam and the mmw beam is simulated using the CRMFEL code, a general purpose particle-pusher code for simulating electron beam-mmw beam interactions. This fully 3-D amplifier code treats non-linear effects, simulates a large number of transverse mmw modes simultaneously and takes transverse and longitudinal (AC) space charge into account. A non-linear code is essential for calculating the saturated power level of the mmw beam, such that the undulator length, the mmw feedback power and the gain at saturation can be optimized.

Simulations have been performed for a planar undulator with 39 periods of 40 mm. The undulator is step-tapered; in the first 26 periods the pole gap is 25 mm and the undulator strength, K, is 0.55 and in the last 16 periods K=0.47. The electron beam current is 12 A, the normalized emittance is 20 π mm mrad and the energy is 1.75 MeV, which generates 200 GHz mm-waves. An electron energy of 2 MeV will be used to generate 250 GHz mm-waves.

Step-tapering is needed for the following reason. A high linear gain is needed for fast start-up of the FEM and for fast frequency pulling, i.e., varying the mmw frequency via the electron energy. A high linear gain is obtained in an untapered undulator; the gain increases exponentially with the length of the undulator, see fig. 2. However, when the entire undulator is untapered 1 MW mmw power is not reached with the electron beam parameters mentioned before. In order to increase the extraction efficiency and maintain sufficient linear gain part of the undulator is tapered. Because of a constructional reasons step-tapering is preferred instead of continues tapering.

The transverse mode structure of the mmw beam is a so-called hybrid TE mode; the electrical field has a gaussian distribution in x-direction (parallel to the undulator magnets), and a cosine distribution in y-direction. This mode is strongly peaked at the centre and has a strong interaction with the electron beam. The type of waveguide for this mode is discussed in section 5.

Results of the simulations are shown in fig. 2. The output power is 1.1 MW for a drive power, i.e., a reflected power, of 0.4 MW. The maximum intra-cavity power is 1.5 MW.

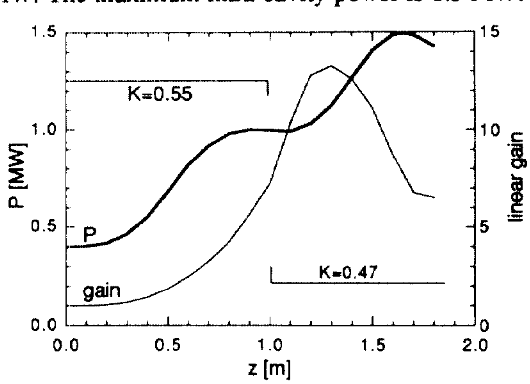

Fig. 2. The total intra-cavity power, P, and the linear gain as a function of the axial distance, z. The undulator strength K is indicated. The mmw frequency is 200 GHz.

4. Electron Beam Line

Since an extremely low loss current is allowed, of the order of 20 mA of the total beam current of 12 A, the electron gun has to meet several stringent specifications. The halo current has to be small, and should contain less than 20 mA, and the emittance has to be as small as possible. Further requirements are that the gun be suitable for cw operation and that the beam current can be modulated on µs-scale. The latter two requirements are met by using a gun with a modulation electrode, see fig. 3. Fast modulation of the beam is required for the start up of the FEM and to be able to use diagnostic devices such as current transformers and button monitors. As the basis for our gun design we have taken a 80 keV, 10 A gun used in a previous FEM experiment at TRW. EGUN simulations indicate that the normalized emittance of the electron beam is less than 10 π mm mrad for a beam current ranging from 8 to 12 A. The latter insures good beam transport when modulating the beam current by a few Amperes for operating the diagnostic devices.

Acceleration of the electron beam takes place in two stages. First, a two-electrode pre-accelerator accelerates the beam within 250 mm distance to 500 keV. Because of this short distance space charge does not blow up the beam dramatically. The beam is further accelerated to 2 MeV in a conventional dc accelerator tube.

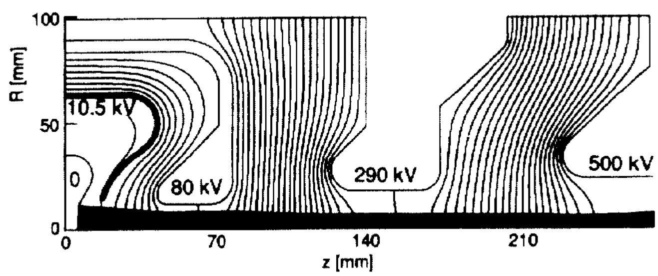

Fig. 3. Simulation of the 12 A, 80 keV electron gun integrated in the 500 keV pre-accelerator, showing the cathode, modulation electrode, anode and two accelerating electrodes. Equipotential curves are drawn at 10-kV intervals.

Next we discuss the undulator. Since the electron beam parameters are quite weak for 1 MW mmw output power a strong undulator is needed. Further, because of the required low electron loss current a large pole gap, 25 mm, is required. Note that the undulator period is 40 mm, i.e., the gap-over-period ratio is quite large. These contradictory requirements can be met by using an undulator geometry which has been developed at the I.V. Kurchatov Institute for Atomic Energy. This undulator consists of two hybrid magnet units with flat pole faces and two magnetic side arrays, see fig. 4. The effects of these side arrays are an enhanced undulator field in the central region as compared to conventional undulators, either pure magnet or hybrid types, and transverse focussing in two planes via field-shaping of the undulator field. The pole gap is fixed since tuning of the mmw frequency is done via a variation of the electron beam energy.

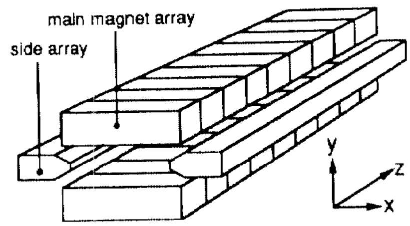

Fig. 4. Schematic layout of the undulator showing the main magnet arrays at the top and bottom and the field-shaping side arrays.

After passing the undulator the electron beam is decelerated in a decelerator tube before it enters the depressed collector. In the design of the multi-stage depressed collector we followed earlier designs for so-called parabolic shadow-side collectors [4]. In this set-up the electrons are decelerated to zero axial velocity and simultaneously deflected off-axis. The electrons then are accelerated slightly backwards and are collected. The advantage of this set-up is that secondary electrons are forced back to the collecting electrodes and cannot escape back into the decelerator tube.

To collect a 12 A, long pulse electron beam without damaging the electrodes, the collecting area has to be large. This can be achieved by rotating the deflected beam around the z-axis by a system of deflection electrodes, see fig. 5.

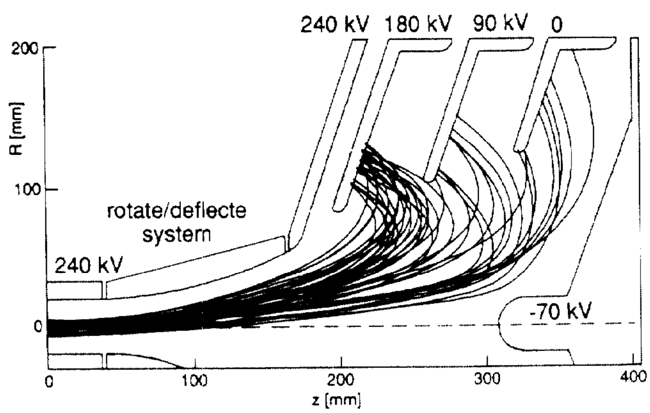

Fig. 5. Simulation of a 12 A electron beam in the depressed collector. The electron energy upon entering the collector ranges from 80 - 320 keV. The collector is rotational symmetric around the z-axis (dashed line).

5. MMW System

The essential design criteria for the mmw system are the capability of handling a circulating power of over 1 MW, to pass the electron beam without even intercepting a small part and to outcouple 1 MW of mmw power at a centre frequency of 200 GHz tunable over +/- 5%.

An oversized waveguide is mounted inside the undulator, with a height of 15 mm. Two possible waveguides are under investigation: an open elliptical waveguide, which consist of two elliptical surfaces and open sides, and a rectangular corrugated waveguide. The latter waveguide is corrugated at the vertical surfaces only. Both waveguides give the transverse mode structure of the mmw beam as mentioned in section 3.

Since the FEM will be operated as an oscillator a feedback system is needed. Further, an outcoupling system and separation of the electron beam and the mmw beam are required. For these purposes so-called open elliptical waveguides are mounted at both ends of the primary waveguide, i.e., the waveguide inside the undulator, see fig. 6. Separation of the mmw beam and the electron beam is performed by curving the elliptical waveguides sideways, in the horizontal plane, to bend the mmw beam out of the electron beam. Note that in fig. 1 the elliptical waveguides are schematically drawn curved in the vertical plane, which is in fact not the reality.

At the elliptical waveguide at the upstream side (gun side) of the undulator a mirror is mounted, which reflects 100% of the feedback mmw power. At the elliptical waveguide at the downstream side of the undulator a mechanically adjustable Bragg reflector is mounted, which reflects 0-40% of the mmw power and couples out the remaining 60-100% of the power. This Bragg reflector has corrugations at the top and bottom surfaces only. By changing the position or shape of these surfaces the reflection can be adjusted. In this way the saturated mmw power level can be optimized.

Transport of the mmw beam from the high voltage terminal to earth potential will be done quasi-optically via two mirrors and a mmw-transport tube. This transport tube is in fact a standard accelerator tube, which serves as a vacuum tube between the high voltage terminal and earth potential.

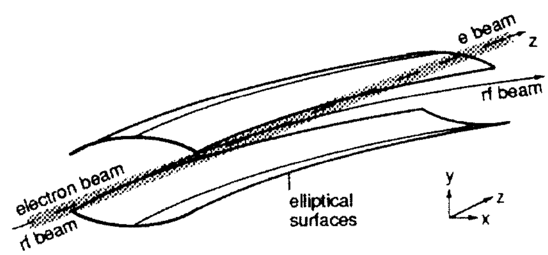

Fig. 6. Schematic layout of the open elliptical waveguide used to separate the mmw beam from the electron beam.

6. Acknowledgements

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