# Electron Beam Optics of the 130-250 GHz, 1 MW, FOM-Fusion-FEM

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# Abstract

Layout and simulations of the 12 A, 2 MeV dc electron beam line of the 1 MW, 130-250 GHz, FOM Free-Electron Mascr for Fusion are presented. Beam profile measurements of the electron gun are given, which show a low halo current and a uniform beam current density, as required for low loss beam transport without emittance increase.

# 1. INTRODUCTION

The FOM-Fusion-Free Electron Maser (FEM) is the pilot experiment to develop a tuneable mm-wave source for plasma heating and control in future fusion research experiments such as ITER. In such fusion reactors plasma is confined by magnetic fields of the order of 6 T, which sets the frequency range for electron cyclotron resonance heating to 130-250 GHz. Unit power level should be at least 1 MW at a system efficiency (grid to mm-wave power) of over 35%. Fast frequency tuning over several percent is required to follow and suppress plasma instabilities. Most of these parameters can not be met by present day gyrotrons.

The aim of the FOM-FEM project is to generate 1 MW of output power, in the frequency range mentioned, in 100 ms pulses, with a tuneablity on ms-scale of +/-5% and a system efficiency of over 50%.

# 2. LAYOUT OF THE ELECTRON BEAM LINE

A schematic lay-out of the FEM is given in fig. 1. The ebeam line comprises a 12 A, 80 kV thermionic electron gun, a dc accelerator tube, the undulator, a dc decelerator tube and a depressed collector. One of the advantages of dc acceleration as compared to rf acceleration is the fast and simple tuning of the mm-wave frequency via the dc accelerator voltage [1,2]. For the undulator parameters chosen the mm-wave frequency can be varied from 130 to 250 GHz by varying the accelerator voltage from 1.35 to 2 MV. The dc accelerating voltage is delivered by an Insulated Core Transformer. The maximum current is only 20 mA, which means that the loss current in the e-beam line has to be less than 20 mA, i.e., 99.8% of the beam current has to be recovered. Because of this extremely low loss current, the beam line is completely straight. Especially behind the undulator, where the beam has some 10% energy spread, bends in the beam line are a complicating factor.

The low loss current sets strict requirements to the beam emittance and the halo current in relation to the acceptance of the e-beam line. The most critical item of the e-beam line is the mm-wave system, which is illustrated in fig. 2.

The central part of the mm-wave system is a rectangular corrugated waveguide inside the undulator. The transverse cross section measures  $15 \times 20 \text{ mm}^2$  internally, where the 20 mm direction is in the wiggle direction. At both ends of the waveguide, mirrors are mounted to form a cavity. These mirrors must be off-axis since the e-beam line is straight. This is accomplished as follows. Outside the undulator the waveguide cross section goes stepwise from  $15 \times 20 \text{ mm}^2$  to  $60 \times 20$ mm<sup>2</sup>. As a result, the mm-wave beam splits into two off-axis beams [2,3]. At the position of full separation sets of mirrors reflect the mm-wave beams. The e-beam passes through the space between the mirrors. The mirror set at the downstream side reflect some 30% of the power back towards the upstream mirror set. This is the feedback power. The remaining 70% is coupled out. The mirror set at the upstream side reflects 100% of the feedback power back into the waveguide.

The dimensions of the waveguides and the focusing scheme of the undulator determine the acceptance of the e-beam line. The hybrid undulator has side arrays of magnets to obtain



Fig. 1. Schematic lay-out of the FOM Free-Electron Maser. The system measures 11 m in length and 2.6 m in diameter.

focusing in both transverse directions [4,5]. The acceptance of the waveguide inside the undulator is  $350 \pi$  mm mrad [6].

Based on these figures and based on simulations of the interaction between the e-beam and the mm-wave beam, it is determined that 99% of the e-beam should have a normalised rms emittance of 50-70  $\pi$  mm mrad [2], and that less than 20 mA is allowed to fall outside an emittance of 150  $\pi$  mm mrad.

Because of the rotational symmetry of the gun and the accelerator, and the near-equal transverse focusing scheme of the undulator, round solenoid lenses are used for focusing in the entire e-beam line.



Fig. 2. Schematic lay-out of the mm-wave cavity.

# 3. ELECTRON GUN

The basic requirement for the electron gun are a beam current of 12 A, and the requirements with respect to the emittance as mentioned in section 2. Further, to prevent emittance growth, it is required that the beam has an homogeneous current density, or "top-hat profile".

The extraction voltage has been subject of discussion for some time. Because of technological constraints, the originally proposed 500 keV electron gun [1] has been replaced by a more conventional gun with an extraction voltage of 80 kV.

A triode-type thermionic gun has been produced by Varian. In between the spherical-surfaced cathode at ground potential and the anode at 80 kV dc, a modulation electrode is located to switch the beam on and off within 200 ns by a voltage sweep between +10 kV and -12 kV. Much attention has been paid to halo current and beam homogeneity. Fig. 3 shows an almost "top-hat" profile of the current density as obtained from beam analyser measurements on a prototype gun [7].

From beam profile measurements at a number of longitudinal positions from the cathode, the normalised beam



Fig. 3. 3-D raster scan across the electron beam, logarithmic plot, of the beam current density,  $J_e$ .

emittance is calculated to be 50  $\pi$  mm mrad for 99% of the beam current and less than 150  $\pi$  mm mrad for 99.8% of the beam current [8]. Since the emittance is close to the required emittance *inside* the undulator, the emittance growth during transport and acceleration must be kept to a minimum.

### 4. BEAM LINE DESIGN

#### 4.1. Beam optics simulations

Transport of the 12 A beam is dominated by space charge in the low-energy part of the beam line, between the gun and the accelerator, and by emittance in the high energy part. Beam waists have to be formed at the upstream mirror set of the mm-wave cavity, see fig. 2, and at the undulator entrance.

The design is based on accurate calculations of the evolution of the beam envelop and emittance in the proposed set-up. Two methods are used. The first method makes use of the KV-equations for paraxial rays. The radial variation of the space charge force is taken into account by dividing the beam into many concentric cylinders [9]. Each cylinder has its specific current content and divergence. As a starting point the detailed gun measurements of fig. 3 are used. This method allows detailed study of the halo current behaviour.

The second method used the particle tracking code GPS [10], in which a dc e-beam is represented by a large number of pencil beams. The off-axis fields in the solenoids as well as in the accelerator are calculated from the axial fields and its derivatives to a much higher order as in the first method, which makes GPS most suitable to study aberations and emittance growth.

#### 4.2. Beam transport from gun to accelerator exit

To obtain a beam diameter of less than 10 mm at the exit of the accelerator, which is needed to have small-size beam transport into the waveguide, the beam diameter at the accelerator entrance must be larger than 50 mm, see fig. 4. The accelerator consists of 55 electrodes at 1-inch interval. Simulations are shown for final energies of 1.35 and 2 MeV. For a beam energy of 1.35 MeV it is necessary to apply the maximum accelerating field of 35 kV per inch, as for 2 MeV, to the first 36 electrodes and to shorten the remaining 19 electrodes.

Although the accelerator has focusing properties, a focusing solenoid, lens-1, is required to match the expanding beam from the gun to the accelerator entrance condition. Great care has been given to minimise the effects of lens aberations upon emittance growth in this 80 kV beam, with a maximum diameter of about 70 mm. A relatively straightforward way to minimise emittance growth is to give the lens a sufficiently large diameter. At an inner diameter of 500 mm for lens-1 the emittance growth is limited to less than 10  $\pi$  mm mrad. However, a consequence of this large lens diameter is that the field extends to the cathode of the gun. By placing a bucking coil at the right position the tail of the main lens field and its first derivative are compensated, such that in the entire region between cathode and anode the magnetic field is less than 1 gauss. Fig. 5 shows the beam envelope from the gun to the exit of the accelerator for different settings of lens-1. The final beam energy is 1.35 MeV. Clearly visible is the focusing effect of the accelerator but also the emittance growth at beam diameters too large at the entrance.



Fig. 4. FEM beam line and beam envelops of a 12 A beam, as it emerges from the gun, for acceleration to 2 MeV and 1.35 MeV, as indicated. The normalised rms emittance is  $50 \pi$  mm mrad. Also given are the on-axis fields of the solenoid lenses

(dotted line) and the beam pipe wall (thick line).





#### 4.3. Beam transport from accelerator to undulator

As shown in fig. 4., downstream of the accelerator lens-2 is placed to focus the beam into the waveguide system. Four more lenses are required to transport the beam through the waveguide system and into the undulator. The maximum beam diameter in the waveguide is 6 mm for 2 MeV and 7 mm for 1.35 MeV. The dimensions of the reflector are such that lenses-3, 4 and 5 have an inner diameter of 160 mm. The beam diameter as compared to the size of the lens is small enough in order to keep the emittance growth due to aberations negligible.

The lenses 2 through 5 have an identical design, known as Glaser lens. It makes use of an iron yoke to optimise the focusing strength with respect to the number of ampere-turns. The maximum field is 0.18 T, requiring 20000 ampere-turns. The power dissipation is 1 kW.

Lens-6 forms a beam waist of 1.2 mm radius at the entrance of the undulator. The stray field of this lens at the undulator entrance has to be sufficiently small because the axial field component in combination with the wiggle motion of the beam causes beam drift in the direction of the undulator field. Therefore, lens-6 is a smaller version of lens-2, with an inner diameter of only 35 mm. The maximum field is 0.35 T at 10000 ampere-turns. The power dissipation is 600 W.

# **5. CONCLUSIONS**

A low-loss, low emittance-growth beam line for accelerating and transporting a 12 A electron beam has been designed. Measurements on the gun show an extremely small halo current while, due to the uniform current distribution and proper lens designs, emittance growth is kept to less than 15%.

The system is now under construction. The undulator and accelerator tubes have been delivered and the gun will be delivered in fall 1994. The system will be operational early 1995.

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