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Section A

A free-electron maser for thermonuclear fusion

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An update is given on the design effort for an electrostatic free-electron maser (FEM) producing a 1 MW cw output in the 150-250 GHz range.

1. Introduction

High-power FELs in the mm wave range (FEM) are being developed at several sites around the world, for application in electron-cyclotron heating and current drive of fusion plasmas. The common objective is to produce units generating at least 1 MW of average power at frequencies in the range of 150-300 (or even 600) GHz. The most advanced project is the induction-linac FEM at Lawrence Livermore National Laboratory, which already launched single pulses of hundreds of MW at 140 GHz into a tokamak. At the 1990 FEL conference, three more projects were reported in various stages of development. At Naka [1], a system similar to that at Livermore has undergone first testing. The group at University of Maryland has already performed a series of pilot experiments on key elements of an FEM [2]. At Rijnhuizen an FEM-project, based on an electrostatic accelerator, is in the design stage [3]. The present paper describes the progress in the design effort on the latter project. The aim of the project is to demonstrate an FEM having the following specifications: frequency adjustable in the 150-250 GHz range, tuneable over ±5%, with a cw output power of 1 MW in a near Gaussian mode, at an overall efficiency > 35%.

2. Design philosophy and basic parameters

The basic design philosophy was described earlier [3]. We are designing a medium-gain oscillator, having an undulator at high voltage and efficient recovery of the unspent electron beam charge and energy. The present concept of the layout is shown in fig. 1. The initial choice of beam parameters was 1 MeV and 20 A, which would require a 20 mm undulator period to generate the required frequencies. Further study has now led us to include 2 MeV and 10 A as what will probably be the preferred parameter set. The main reason for this change is that at 1 MeV the free space available in the undulator gap will only be about 15 mm. This is uncomfortably small from the point of view of beam scrape-off, power loading of the waveguide, and access for beam diagnostics. All these problems are alleviated when going to a higher beam energy.

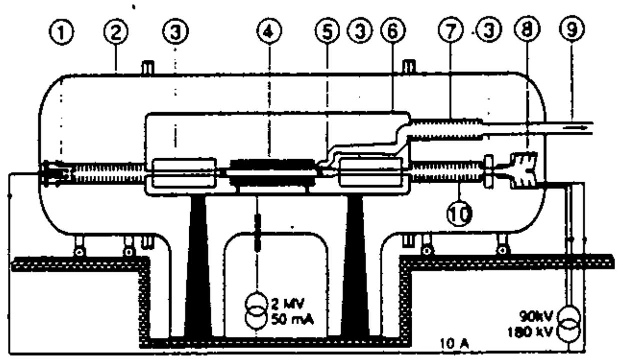

Fig. 1. Schematic of the 1 MW cw FEM: (1) electron gun and accelerator, (2) pressure vessel, (3) beam focusing, alignment and diagnostics, (4) undulator and wave guide, (5) EM outcoupling, (6) high-voltage terminal, (7) EM transport tube (quasi-optical), (8) depressed collector, (9) EM output wave guide, (10) decelerator tube.

3. Gain and efficiency

Given the basic design choice of operating the FEM as an oscillator with efficient energy recovery, the only a priori requirement is that the small-signal gain exceed the cavity losses. However, in practice, there are other limiting factors. Firstly, the power inside the cavity should not be much larger than the outcoupled 1 MW for reasons of power loading and rf breakdown. Secondly, the intrinsic efficiency should be such that the electron beam power remains within manageable bounds. From these considerations we derived the following targets: a saturated gain > 10% and an intrinsic efficiency of ~ 5%. We have performed various types of simulations in order to establish which main machine parameters, i.e., which undulator length for given beam energy and current, are consistent with the above requirements. Small-signal gain calculations were performed using two different, linear, 3-D codes, which both take beam emittance and energy spread into account. The Gover–Sprangle code [4] ignores the effect of the finite electron beam cross section on the plasma oscillation frequency, and therefore only gives bounds on the gain for the extreme values $r = 0$ and $r = 1$ of the so-called space-charge reduction factor. The G3DH-code treats this effect properly [5,6]. Both calculations derive the efficiency from the simple equation $\eta_o = \Delta\gamma_o/(\gamma_o - 1)$, i.e. the maximum extraction which is possible in principle. For both codes simulations have been done for a 20 A, 1 MeV electron beam with a normalized emittance of 10π mm mrad and an energy spread of 0.1%. The undulator period is 20 mm. Results from the G3DH-code are shown in fig. 2, for the TE_{01} mode of a 200 GHz EM beam in a 1×1 cm^2 waveguide. The minimum gains obtained with the Gover–Sprangle code, i.e. using a space-charge reduction factor of unity, are somewhat higher than those of the G3DH-code, e.g. 42 at 50 periods as compared to 28. The predicted efficiencies, on the other hand, are

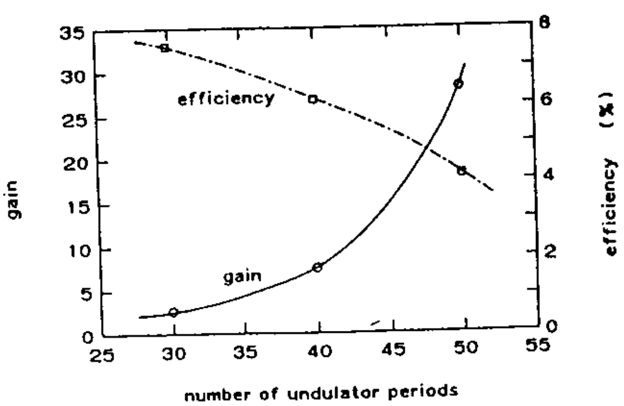

Fig. 2. Small-signal gain and efficiency versus the number of undulator periods, as calculated with the G3DH-code [5,6]. See text for details.

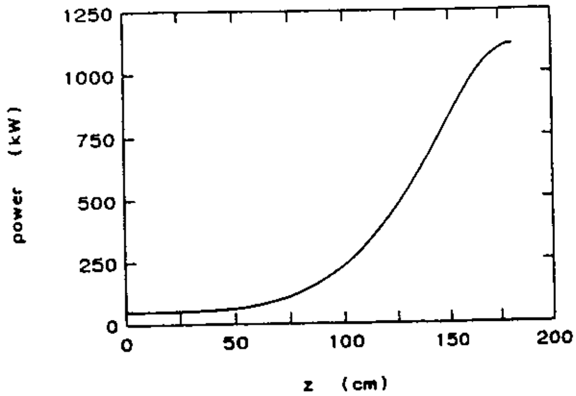

Fig. 3. EM power versus undulator length as calculated with a particle-pusher code. See text for details.

lower by about a factor of two. The differences are connected in the sense that the two codes yield different widths of the gain profiles. Our preliminary conclusion is that for ~ 45 undulator periods, the small-signal gain is well above the level required at saturation, while for the efficiency one of the two codes appears to favour a shorter undulator, obviously at the expense of some gain.

In parallel with the linear, 3-D simulations, we have used a 1-D, nonlinear particle-pushing code developed at TRW. With this code, results are obtained for the EM power along the undulator, given a specified input power in a specified resonator mode. The results shown in fig. 3 is for a 2 MeV, 12 A beam, 50 kW EM input at 150 GHz, and with the HE_{11} mode propagating in a 4 cm diameter circular corrugated waveguide. The required output of 1 MW is reached at an undulator length of 2.0 m, i.e. for 30 periods of 65 mm. The HE_{11} mode has a near Gaussian profile and very low attenuation. It is strongly dominant, since higher-order HE_{1n} modes are far from resonance. The corrugated waveguide has a bandwidth of about one octave for the HE_{11} mode.

Further work needs to be performed on several points. One is a comparison of the small-signal gain of the 3-D and 1-D codes for the same set of parameters. A second point concerns the maximum power allowable at the input of the undulator. The nonlinear 1-D code shows a drop of the saturation level beyond a certain input level. This phenomenon will further narrow the parameter window in which the FEM can be expected to operate. A final point concerns the transverse modes excited by the beam. When using a rectangular waveguide, the dominant modes to be considered are TE_{01}, TE_{21}, and TM_{21}. The gain profiles of the TE_{21} and TM_{21} peak at the same frequency and therefore these modes couple while the peak for the TE_{01} lies at a considerably higher frequency. The frequency separation is sufficient to allow easy selection by introducing some dispersion in the cavity. A coupled-mode calculation for the gain of the TE_{21}, TM_{21} modes is in progress at Tel Aviv University.

4. Electron beam optics

4.1. The electron gun and accelerator

The beam optics are operated such that through the entire system, except inside the undulator, the beam radius is kept large (10–15 mm). This way, space-charge induced beam blow up is kept small and only a small number of focusing elements, part of which are at high voltage level, is needed. This is a major change compared to the system presented previously [3], which used quadrupole focusing through the entire accelerator.

Behind the accelerator exit, solenoid lenses are used to focus the beam to the matched diameter in the undulator, which is several millimetres. Behind the undulator the beam will blow up strongly due to space charge forces. At this position a second set of solenoid lenses is used to focus the beam into the decelerator tube.

The main requirements of the electron gun are low beam emittance, cw mode of operation and fast (μs) modulation of the beam. The latter requirements are met by using a gun with a modulation electrode. Fast modulation of the beam is required for the start up of the FEM and to be able to use diagnostic devices as current transformers and button monitors.

An electron gun which meets our demands, and which has proven to operate reliably, is the 80 keV, 10 A gun used in a previous FEM experiment at TRW [7]. An EGUN simulation for this gun, mounted on a 500 kV pre-accelerator, is shown in fig. 4. The gun is operated in a space-charge limited mode in order to obtain a uniform beam. This way the halo current is small, which is required to obtain low current losses, while good uniformity is also needed to prevent emittance growth during transport and acceleration.

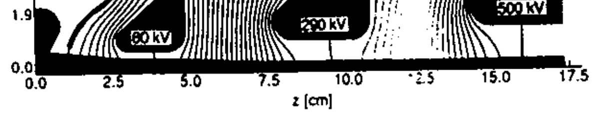

Fig. 4. EGUN simulations for the 10 A, 80 kV electron gun and the 500 keV pre-accelerator, showing from left to right the cathode (0 V), the modulation electrode (10 kV), the anode and two acceleration electrodes. Equipotential lines are drawn at 10 kV intervals.

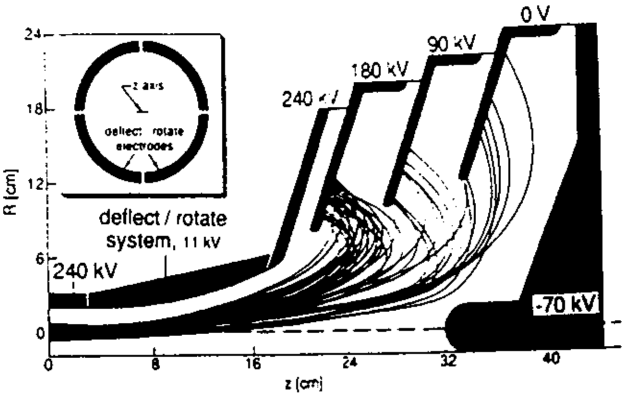

Fig. 5. EGUN simulation for the depressed collector. At $z = 0$ the beam is convergent and has a diameter of 14 mm. The inserted figure shows a cross section of the deflect-and-rotate electrodes. The rest of the system is rotationally symmetric with respect to the dashed line ($R = 0$).

At values for the modulation voltage down to 8 kV the beam quality is still acceptable. Hence, the current can be varied by 2 A, which is sufficient to operate button monitors, by fast pulsing of this voltage from 10 kV, which is the normal operating value, to 8 kV.

Acceleration of the electron beam will take place in two stages. First, a two-electrode pre-accelerator accelerates the beam within a 175 mm distance to 500 keV. Because of this short distance, space charge does not blow up the beam dramatically, as is shown in fig. 4. Behind the 500 keV pre-accelerator, the beam is accelerated to 2 MeV in a conventional accelerator tube, consisting of several tens of disc-shaped electrodes. Such a tube does not focus the beam. However, because of the small space charge forces, the beam blow up stays within acceptable limits.

4.2. The depressed collector

In the design of the collector we followed earlier designs for multi-stage depressed collectors as developed at the University of California at Santa Barbara. In this setup the electrons are decelerated to zero axial velocity and simultaneously deflected off-axis. The electrons then are (unavoidably) accelerated slightly backwards and are collected. This is illustrated in fig. 5. The advantage of this setup is that secondary electrons are forced back to the collector plates and cannot escape. A small disadvantage is that electrons do not land at zero energy. However, due to the continuous energy spectrum of the unspent beam, the average electron energy up on collection cannot be zero anyway. The energy of the unspent beam has been estimated with the 1-D particle-pusher code mentioned before, and ranges from −160 to 80 keV relative to the initial energy of 2 MeV. The decelerator first decelerates the beam by 1.76 MeV. The beam energy upon entering the collector ranges from 80 to 320 keV.

In order to collect a 10 A, cw electron beam without damaging the electrodes, a large collecting area has to be used. This can be achieved by deflecting the beam sideways before it enters the collector and rotating the deflected beam around the z-axis by a system of four deflection electrodes which carry an rf voltage. A further increase of the collecting area could be obtained when the amplitude of the deflection voltage is modulated.

5. RF cavity

In the undulator, the e.m. beam is transported through an oversized waveguide. In order to operate the FEM as an oscillator, a feedback system is required. Two systems are being investigated, a ring-type cavity with a rectangular waveguide, as proposed earlier [3], and a straight resonator with Bragg reflectors.

The Bragg-resonator cavity is under study at Stuttgart University. Calculations for a rectangular waveguide show that a Bragg reflector composed of periodic corrugations can provide a reflectivity from 0 up to 100% through the principle of periodic coherent coupling [8]. Using a special distribution of the slot depth, e.g. a Hamming window distribution, high mode purity and a ripple-free filter characteristic (40 GHz bandwidth) can be obtained. By using Bragg reflectors with reflection coefficients of 100% and 10% at the entrance and exit of the cavity, respectively, 90% of the internal microwave power is coupled out. This scheme can easily be combined with a directional coupler to separate the electron beam and the EM beam.

Acknowledgements

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