Long-Pulse Operation at Constant Output Power and Single-Frequency Mode of a High-Power Electrostatic Free-Electron Maser with Depressed Collector

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The Fusion Free-Electron Maser (FFF) is the prototype of a high-power, tunable source of mm-wave radiation, for use on fusion plasma devices. In previous experiments a net output power of 730 kW at 206 GHz was generated in short pulses. The present experiment has been equipped with a system to recover the charge and energy of the spent electron beam. We present experimental results which show output of mm-wave radiation at constant power level during the full pulse length, as well as single-frequency operation; even though the cavity is highly overmoded; the latter is reached by effective suppression of spurious modes by the feedback system.

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High-power mm-wave radiation is an important tool for heating, control, and diagnostics of plasma in thermonuclear fusion devices [1]. Thanks to the spatial dependence of the magnetic field in a toroidal fusion device, e.g., a tokamak, precisely localized deposition of power can be achieved by tuning the radiation to the electron cyclotron resonance frequency. For local plasma heating in large devices, a mm-wave source with narrow spectral bandwidth, frequency range up to 170 GHz or higher, output power in the MW range, at pulse lengths of seconds, is required. For plasma control, tunability is an added requirement. Present generation gyrotrons, generating mm-wave output at the MW level at pulse lengths of seconds at frequencies up to 140 GHz, largely meet the first requirement, while high-power step-tunable gyrotrons (steps of several GHz) are in development [2,3]. A promising alternative is provided by the electrostatic Free-Electron Maser (FEM), featuring fast and continuous tunability as well as the possibility to reach higher frequencies (hundreds of GHz) as its main advantages [4]. At FOM such a device, the FOM Fusion FEM (FFF), has been developed with the aim to demonstrate single-mode operation and tunability at high-power, long pulse operation. In the FFF, a relativistic electron beam is accelerated to the interaction region, where the electron beam follows a wiggle motion in the undulator field and power is transferred to the mm-wave beam (see Fig. 1). The radiation frequency is determined by the magnetic field strength and periodicity of the undulator field, and the electron beam energy. Similar devices have demonstrated the feasibility of this approach, although at a lower output power level of several kW's [5,6]. In order to reach high output power, apart from a high-power electron gun, in the FFF a step-tapered undulator is used for higher efficiency; the magnetic field (20 cells of 0.2 T followed by 14 cells of 0.16 T) follows the dropping electron energy upon passing through the undulator while it transfers energy to the mm-wave beam [7]. The interaction region is inside a rectangular corrugated waveguide of 15 by 20 mm which carry an HE_{11} mode. This mode is peaked at the center and gives optimum coupling to the electron beam, and minimum power losses on the waveguide walls. The

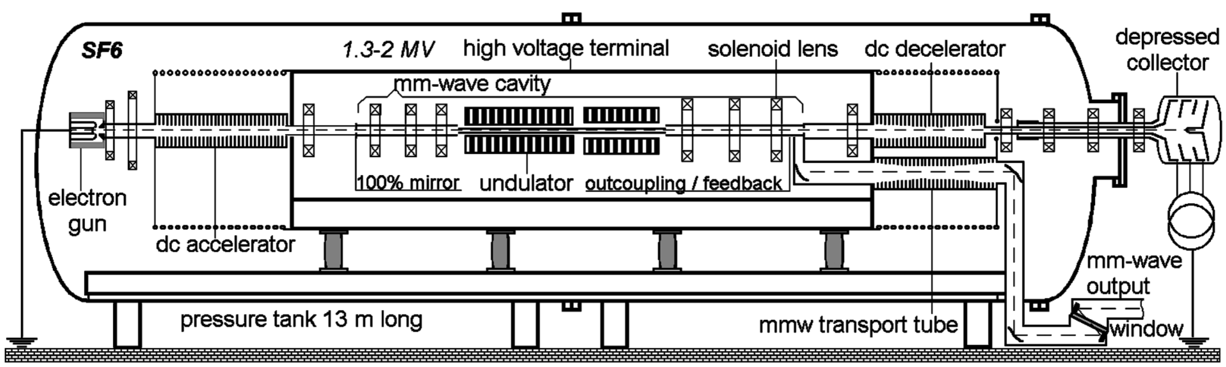

FIG. 1. Layout of the FOM Fusion FEM, including the energy recovery system.

latter is essential for high-power, long pulse devices. Feedback and outcoupling of the mm-wave power are provided by so-called stepped waveguides at both ends of the undulator waveguide. In these stepped waveguides, which have a larger cross section than the undulator waveguide, the mm-wave beam is split into two identical off-axis beams. At the position of full separation, mirrors are placed for feedback and outcoupling [8,9].

The use of an electrostatic acceleration and deceleration system offers the advantage of a continuous electron beam, needed for cw operation. A further advantage is the relatively straightforward frequency tunability by variation of the electron beam energy, i.e., the accelerating voltage. In addition, beam recovery can be simple; after interaction with the mm waves, the electron beam is electrostatically decelerated and enters a depressed collector at an average energy of less than 100 keV [10]. The charge and energy recovery result in a high system efficiency.

In our previous experiments [4] the electron beam recovery system was not yet installed. Consequently, the electron beam energy dropped sharply during the pulse, which had strong effects on the interaction mechanism; the amplification band shifted across the cavity resonance band and the mm-wave output power varied strongly [11]. The pulse duration was limited to a few μs. Nevertheless, these experiments already demonstrated high output power, frequency tunability, and the possibility of single-mode operation at 206 GHz.

In this Letter, we report the results of experiments with the electron beam recovery system installed (depressed collector). This results in a near-stable electron beam energy, which is a major difference as compared to former experiments.

An important issue to be investigated is whether single-mode or chaotic multimode output is generated.

Since FFF is a tunable oscillator, the mm-wave cavity needs to have a finite bandwidth. Consequently, a large number of longitudinal modes (frequencies) can in principle be excited, when they fall under the amplification band. The bandwidth of the latter is narrower than that of the cavity, and is determined by the electron beam energy and the undulator parameters [7]. However, even though many longitudinal modes fit in the cavity and amplification band, multimode oscillation does not necessarily take place. The general theory of the mode competition was developed in [12–14]. In [15,16], mode competition in an electrostatic FEL was studied and an explanation was given for mode instability, observed in the Stanford experiment. The method of description of the mode competition in a dispersive-feedback cavity of a special type used in the FFF was developed in the Letter [11]. Since the experimental results of the FFF in short pulse setup have been accurately predicted by Savilov *et al.* [4,17], we proceed following these theoretical models. In an oscillator, such as FEM, the issue of possible multimode operation is related to the parameter of excess over threshold, L. This is a dimensionless parameter which is proportional to the length of the interaction region, because in the simplest model it is defined as the product of this length and the cubic root of the electron beam current. If L exceeds its starting value and is less than some threshold, the single-mode operation is stable. If L exceeds the threshold of single-mode operation, complex multimode operation can take place, with fast fluctuations in output power due to beating of the excited modes [17].

In the experiments presented here, FFF is operated at $L \approx 3$. For this value multimode generation is possible but does not necessarily take place. As simulations have shown, even though the full width at half maximum of the feedback system is ≈ 10 GHz and the mode spacing between the eigenmodes of the cavity is only 40 MHz, the dispersive properties of the feedback system do have a significant influence on the process of mode competition. This is illustrated in Fig. 2, which shows that once a number of modes have been excited during the startup phase, some modes gain more in power than others, depending on their position in the amplification band and the dispersive properties of the cavity feedback system. If the center of the amplification band is at a higher frequency than the center of the feedback dispersion curve, the main mode experiences a higher gain than the most important parasitic mode, and single-mode operation will result. The stronger the difference in gain between the two modes, the shorter the time needed for the main mode to suppress the spurious mode. When the amplification band is at a lower frequency, the parasitic mode experiences the higher gain and multimode operation occurs; the output power will be chaotic and strongly fluctuating.

The process of power buildup depending on the electron beam energy has been demonstrated experimentally in the FFF. In order to analyze the mm-wave output beam, both the spectrum and the output power are measured with high resolution in time, frequency, and power. By means of a small open wave-guide antenna, attached to a fast mm-wave detector, the power of a fraction of the output beam is measured with a time resolution of 0.1 μs. The same signal is fed into a mixer for downshifting the frequency, after which the spectrum is analyzed with a resolution of 5 MHz, adequate for the spacing between the eigenmodes of the cavity, 40 MHz. The local oscillator is always adjusted below the main frequency; this is checked by step shifting this down and observing the upshifting of the main peak on the i.f. The total output energy during the pulse is measured with a calorimeter. This device integrates the energy during the pulse, and is used to calibrate the power signal as measured by the open waveguide antenna. During the experiments the electron beam current was 6.8 or 5.7 A. The beam energy and the cavity feedback were varied. By variation of the beam energy, single-mode operation regimes have been found. By variation of the cavity feedback, the output

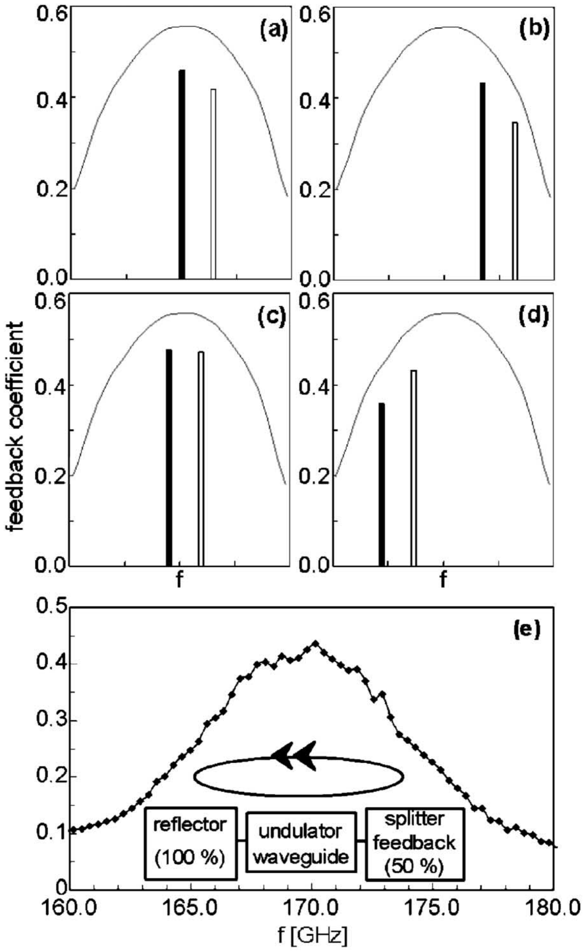

FIG. 2. Illustration of the interaction between the main mode (solid bar) and a spurious mode (open bar) in the cases of maximum gain of the main mode (a), strong suppression of the spurious mode (b), very weak suppression of the spurious mode (c), and chaotic output (d). The feedback curve, as measured with the cavity adjusted to 50%, is not smooth and shows some local maxima (e). This makes it more complicated to find regions with stable, single-frequency mm-wave generation.

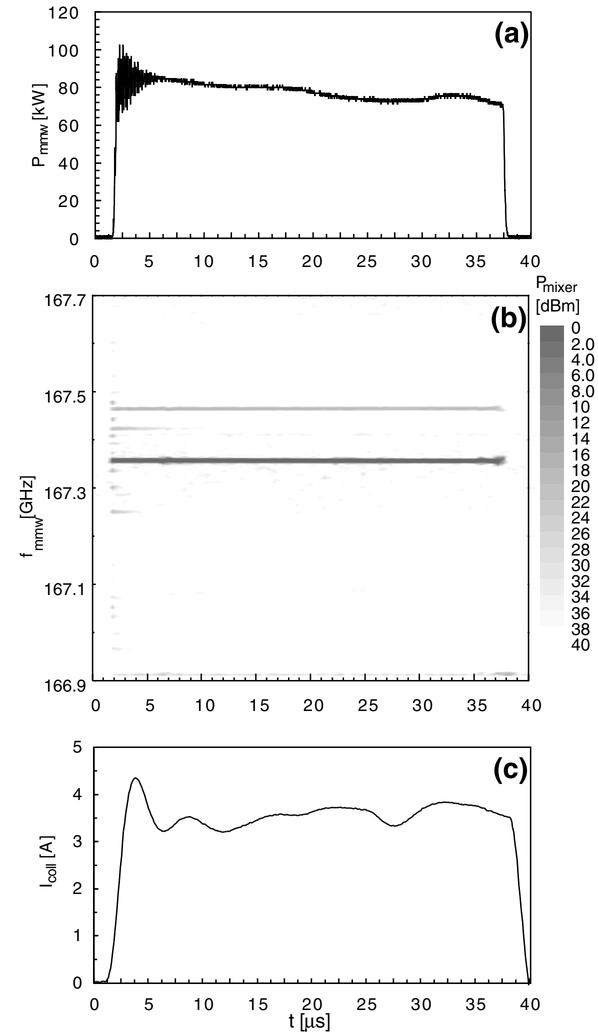

FIG. 3. Measured output power, P_{mmw}, (a) and frequency spectrum measured with local oscillator at 166.9 GHz (b) as a function of time. In this case the main mode has a much higher amplification than the spurious mode(s), and after only 3 μs single-mode operation is reached. The current measured on the second plate (170 kV) of the depressed collector is shown in Fig. 3(c). The peak in the first μs of the current is an overshoot of the measuring system. The electron beam current and energy were 6.8 A and 1.546 MeV, respectively, and the cavity feedback was 60%.

power has been optimized. For an electron beam energy of 1.546 MeV, single-mode operation is reached. Figure 3 shows the output power of a 38 μs pulse and the corresponding frequency spectrum. The beam current as measured on the second electrode of the depressed collector is shown in Fig. 3(c). During the pulse the output power shows some fluctuation; due to small electron beam losses, the accelerating voltage drops slightly and the amplification band shifts with respect to the cavity resonance curve. Note (Fig. 3(b)) that the oscillation frequency locks to a specific value, when the electron beam energy drops. This phenomenon has also been observed in experiments without beam recovery where the electron energy dropped much faster [4]. Also in the case with a relatively slow and small drop in energy, the mm-wave frequency does not follow the electron beam energy but locks to a specific value. As long as the gain for this specific frequency is higher than for other modes, mm-wave power at this particular frequency will be generated. When this criterion is no longer satisfied, the existing mode dies out completely, and another mode is generated at the corresponding electron energy. The fact that the mode with the highest gain determines the output frequency is also illustrated in the case shown in Fig. 4. In this situation the electron beam energy was slightly lower (1.547 MeV) and initially multimode generation is observed. Apparently, in this case the gain for the various modes differ only slightly and the process of mode competition takes a relatively long time mainly due to the lower beam current. After some 8 μs the strongest mode has suppressed the other modes and from then on again a

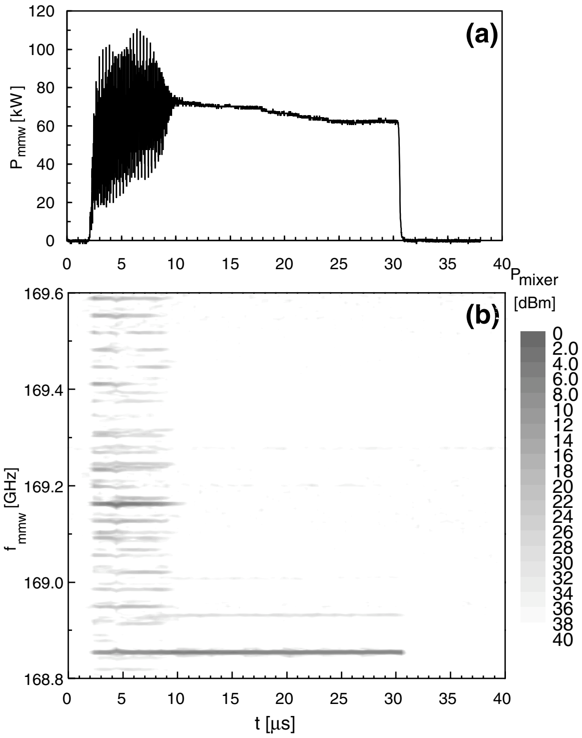

FIG. 4. Output power, P_{mmw}, (a) and frequency spectrum measured with local oscillator at 168.7 GHz (b) as a function of time. In this case the gain for the various modes differs only slightly, and it takes 8 μs to reach single-mode operation. The electron beam current and energy were 5.7 A and 1.547 MeV, respectively, and the cavity feedback was 60%

single-frequency signal is generated. Note that locking of FFF to a specific frequency imposes some limitations to tunability. Tuning by just changing the electron beam energy while the electron beam is on, will work in a rather crude way, as described above. The output power will decrease and the nearest mode excited, either lower or higher in frequency will be some 5 GHz away. In order to tune in smaller steps, the electron beam has to be interrupted for a short time, such that the existing mode dies out and a new mode starts up. Since FFF has a low-quality cavity, the ringdown time is less than a μs, and an interruption of the electron beam by 1–2 μs is sufficient. In this way, frequency tuning is in principle possible in steps as small as the mode spacing of the cavity, i.e., 40 MHz.

In conclusion, the FFF generates stable, single-frequency pulses of mm-wave power of several tens of μs. For technological reasons, higher output power and longer pulses were not reached because electron beam transport was not yet fully optimized inside the waveguides. Nevertheless, it is demonstrated that for stable electron beam current and energy, the output mm-wave beam is also stable, in both power and frequency. As predicted by theory, single-frequency operation is reached when the center of the amplification band is slightly higher than the center of the cavity resonance band. In our case single-frequency operation can be reached in just a few μs. This behavior has been accurately predicted by theoretical simulations.

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