FIRST SUCCESSFUL OPERATION OF THE FUSION FEM

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Abstract

The "Fusion-Free-Electron-Maser" is the prototype of a high power, rapid-tuneable mm-wave source, operating in the range 130-260 GHz. The device is driven by a 2 MeV, 12 A DC electron beam from an electrostatic accelerator. Output power and frequency spectra have been measured at various settings of the beam energy and the reflection coefficient of the mm-wave cavity. Up to 730 kW of mm-wave power at 200 GHz (with a 7.2 A, 1.77 MeV electron beam) has been generated. As the energy and beam recovery system has not yet been installed, the pulse duration is limited to 12 μs. Nevertheless the experiments confirm the theoretical predictions on start-up time, output power and the tendency to operate at a single frequency.

1 INTRODUCTION

In a Free Electron Maser (FEM) radiation is generated by a relativistic electron beam which is given a small transverse oscillation in an undulator. The remaining longitudinal velocity Doppler- shifts the radiation from undulating micro bunches of electrons into the mm-wave range. Micro bunching develops in the ponderomotive wave formed by the sinusoidal component of the electron motion and the mm-wave radiation.

A promising approach to realize long pulse operation is the use of electrostatic beam acceleration and deceleration. In this scheme the electron beam is accelerated to the interaction region, and afterwards decelerated and collected in a multistage depressed collector. In this scheme, the main beam power is supplied at the collector side, i.e., at a low voltage, while the accelerator voltage generator has to supply only the beam loss current. Consequently, to reach long-pulse operation, the loss current has to be extremely low, in our case of the order of 0.2%. The straight electron beam line is chosen to ease full recovery of the electron beam. Free Electron MASERS of this type, with the undulator at high voltage level, have been build in Sante Barbara, (full beam recovery in 1998) [1] and in Tel-Aviv (first lasing in 1997) [2]. The Fusion FEM, which is described in ref. [3], has two orders of magnitude higher output power. It is intended as a long pulse to quasi CW mm-wave source for application on plasma physics research devices. For such applications power sources of at least 1 MW in the frequency range from 140 to 200 GHz at a system efficiency of 50% are required. Fast tunability over a small range and a Gaussian output beam would be an advantage.

In october 1996 almost complete electron beam transport through a rectangular tube in the undulator was demonstrated [4]. The mm-wave system was installed and in october 1997 the first mm-waves were generated. Currently, the fusion-FEM is being rebuild towards the final set-up which amounts to the installation of a decelerator and a depressed collector behind the mm-wave cavity, for energy recovery of the unspent electron beam [5], [6].

2 LAYOUT OF THE FEM

The system basically consists of an 80 kV triode electron gun, a DC accelerator, a mm-wave cavity with the undulator and a beam (and energy) recovery system consisting of a DC decelerator and a depressed collector. In the experiments described here the beam recovery system was not installed. Consequently, the beam current is fed from the capacitance of the HV-terminal (1 nF), and thus the beam energy droops by 1 kV/μs per ampère of beam current.

The undulator is step tapered to compensate for the energy loss of the electrons at high power level. Therefore it is build from two sections in series with an adjustable drift gap in between [7]. This gap determines the phase in which the microbunches formed in the first undulator enter the second undulator. The influence of the gap on the measured output power is about sinusoidal and has been set for maximum power output for the results presented.

The mm-wave cavity consists of the "undulator waveguide" - a rectangular corrugated waveguide with a cross section of 15 x 20 mm^2 - and two stepped waveguides at either side, as shown in fig. 1. The stepped waveguides act as mirrors which allow the electron beam to pass [8]. The bandwidth of these "mirrors" is about 5% and therefore have to be tuned mechanically to cover the whole range. The upstream "mirror" has 100% reflection, the downstream "mirror" has an adjustable reflection coefficient. The principle of the stepped waveguide is the separation of the beam into two off-axis beams which are again reconstructed and hence also the output emerges as two beams which have to be combined. The outside world is reached via a quasi-optical mirror line, which covers a frequency band from 130 - 250 GHz, and a Brewster-angle window [9].

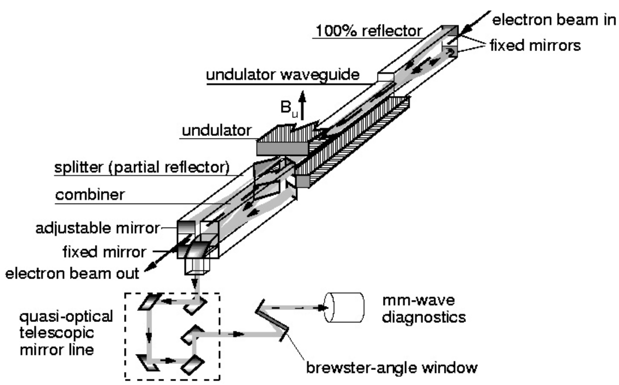

Figure 1: Layout of the mm-wave cavity. Mirrors of the stepped waveguide type are mechanically adjustable for "coarse" tuning. At the downstream side also the reflection coefficient is adjustable.

3 MM-WAVE MEASUREMENTS

The temporal behavior of the power in the mm-wave beam is measured with a semi conductor detector. The evolution of the frequency spectrum is obtained by means of a heterodyne mixer, a fast oscilloscope as storage medium and a computer to perform the FFT. The mm-wave beam is dumped in a calorimeter to calibrate the detector. The mm-wave beam profile (antenna pattern) is measured by insertion of a dissipative sheet in the beam and looking at the resulting temperature profile with an infrared camera.

Fig. 2 shows the highest output power during the pulse that we have measured at a beam energy of 1.77 MeV and a beam current of 7.2 A. As mentioned before, no beam recovery is installed yet. Consequently, the beam energy droops and thus the gain curve shifts across the frequency band of the cavity. This changes the characteristics of the interaction and results in variation of the output power during the pulse. In fig. 3 we see that the corresponding evolution of the spectrum tends to remain at a single mode. This behavior is typical for a setting of the cavity resonance frequency slightly below the peak of the gain curve. With the resonance peak of the cavity on the other side of the gain curve the start-up mode does not reach saturation before a mode with a lower frequency takes over. We see this behavior demonstrated in fig. 4 and 5 for a 10 keV lower beam energy and the same cavity setting as before.

The FEM was also operated at 161 GHz for an electron beam energy around 1.65 MeV by adjusting the stepped waveguides. The mm-wave output power was half the value at 1.77 MeV. This could be explained by a substantially higher loss of the undulator waveguide at 161 GHz.

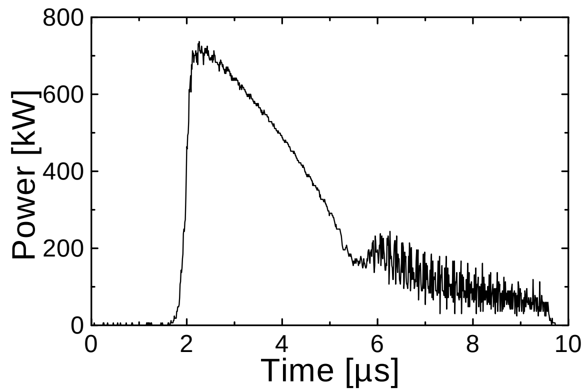

Figure 2: Measured mm-wave output power, for a 1.77 MeV, 7.2 A electron beam The electron beam starts at t = 0. The (initial) beam energy is above the resonance peak of the cavity

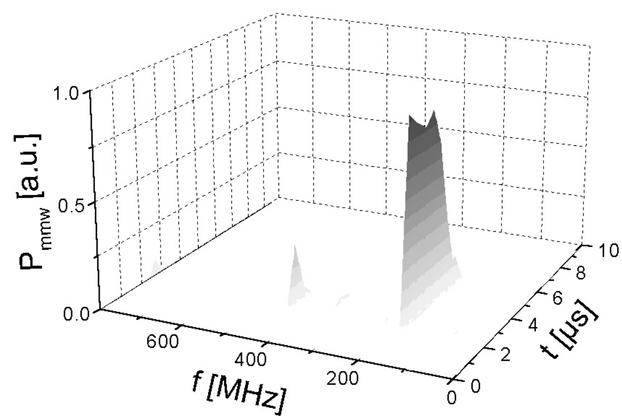

Figure 3: Frequency spectrum from the mixer corresponding to fig 2. The frequency of the local oscillator is 205.7 GHz.

This waveguide will be replaced. The qualitative behavior of the oscillation with respect to (initial) beam energy turned out to be very similar to that at 206 GHz.

The spatial power distribution (profile) of the output beam at 206 GHz is shown in fig. 6. At 161 GHz the beam profile is slightly worse. Nevertheless in both cases the profile is Gaussian within 99%.

4 DISCUSSION AND CONCLUSION

The experiments with drooping beam energy show that the Fusion-FEM remains oscillating at a single frequency during the pulse when the initial beam energy is above the resonance energy of the mm-wave cavity. This proves that the oscillation is characterized by mode suppression. The distance between the longitudinal modes in the cavity is 35 MHz while the bandwidth is several GHz. The mode with he highest gain suppresses the other modes. We do not see this behavior when the initial energy is below the resonance energy. This can be explained from the shorter interaction

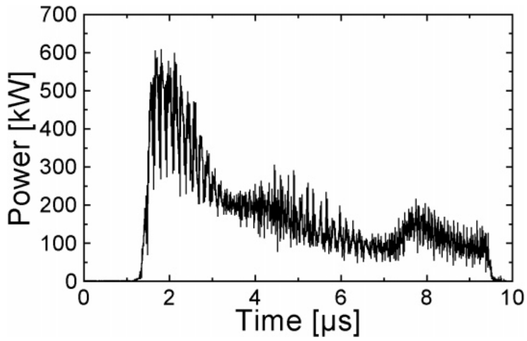

Figure 4: Output power when the (initial) beam energy is below the resonance peak (1.76 MeV)

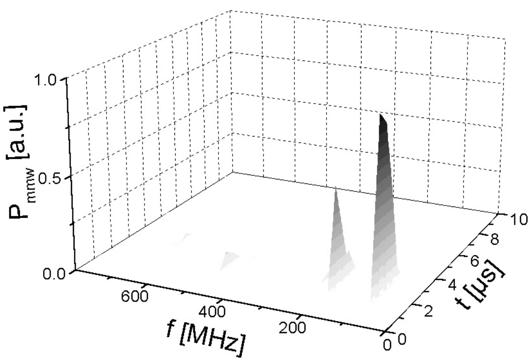

Figure 5: Spectrum corresponding to fig 4.

time in this case when the peak of the gain curve inmediately moves away from the frequency of the starting mode. We have seen this behavior at two different settings of the mm-wave cavity.

In view of the experimental results, we may be confident that, when the electron beam energy remains constant, which will be the case when the energy and beam recovery system are installed, the ”fusion-FEM” will always generate single-frequency output beams [10]. We may also expect more than 1 MW output power at 12 A beam current with 730 kW measured at 7.2 A. The start up time of the mm-wave beam agrees well with simulations. The electronic efficiency is 5.7%, which is slightly higher than expected. These results were obtained for a setting with low cavity losses, in our case around 200 GHz. The output beam profile is Gaussian.

5 ACKNOWLEDGMENT

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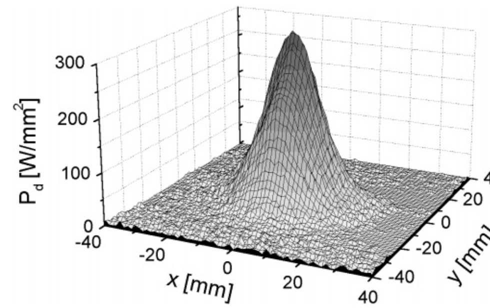

Figure 6: Beam profile at 206 GHz, as measured with an heat-absorbing foil and an IR-camera.

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