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A High-Power Free-Electron Maser for RF Acceleration

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1. Introduction

Free-Electron Lasers (FELs) [1] are coherent sources of high-power electromagnetic radiation. In the microwave part of the spectrum, high efficiencies can be achieved at power levels in the multi-megawatt range. FELs can be operated as amplifiers or as phase-locked oscillators, which makes them suitable candidates for the next generation of drivers for high-frequency RF acceleration [2]. In this paper, results of the design and operation of a single-mode 28 GHz Free-Electron Maser (FEM) oscillator and a 35 GHz high-gain FEM amplifier are presented and discussed. The experiment is driven by a 700 kV, 900 Ω HV modulator, and operates with a pulse length of 1 μs at power levels in the 1-3 MW range. To obtain the 100-500 MW, 10 ns pulses required for RF acceleration at high frequencies (Ka-band), frequency chirping and subsequent pulse compression of the amplified RF signal may be used. For this type of application, phase stability is critical, and a detailed study comparing FEMs and Cyclotron Autoresonance Masers (CARMs) is currently underway at MIT [3]. Higher peak powers and shorter pulse lengths can also be obtained by driving the electron beam with a lower impedance accelerator, such as an induction linac.

2. Amplifier Experiments

The overall experimental setup is shown in Fig. 3. The electron beam used in both experiments is produced by a thermionic electron gun which was successfully operated up to 580 kV and 120 A, with a measured perveance of 0.27μperv in excellent agreement with the design value. Beam compression to a radius of 3 mm was achieved with minimal scalloping, in good agreement with adiabatic theory. The design value for the axial energy spread is $\Delta\gamma_{\parallel}/\gamma_{\parallel} < 0.2$ %. The spread inferred from experimental data is $\Delta\gamma_{\parallel}/\gamma_{\parallel} < 0.5$ %. The beam is then transported through the interaction region by a 2.35 kG axial guide magnetic field generated by a set of 7 water-cooled coils. A permanent magnet helical wiggler with 30 mm period and 500 G amplitude is used to provide the perpendicular momentum of the interacting electrons. To ensure stable high-quality group I helical orbits in the interaction region, the wiggler has a 10-period long linearly tapered introduction.

The very low energy spread and high currents obtained allow operation of both experiments in the Raman regime, as confirmed by our experimental data. At low gain (< 5 dB), and low power ($\simeq$ 100 mW), voltage tuning was obtained between 18 GHz and 40 GHz, and absorption tuning of the fast space-charge wave was observed from 18 GHz to 60 GHz. These results are in excellent agreement with what theory predicts for the coupling of the TE_{11} waveguide mode to the slow space-charge wave through the Raman free-electron laser interaction. The experimental FEM voltage tuning curve is shown in Fig. 1. In addition, we achieved very wide instantaneous bandwidth close to grazing interaction : 18 GHz to 30 GHz.

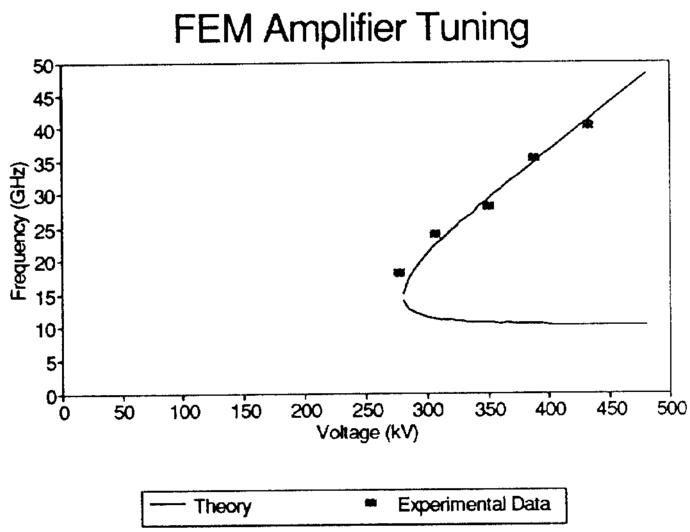

Figure 1: FEM Amplifier Voltage Tuning

In the high gain amplifier experiments, the input power will be provided by a 40 kW, 35 GHz, 400 ns magnetron and coupled into the system via an SF_6 pressurized waveguide and a linear TE_{11} mode launcher. For diagnostic purposes, the power is coupled out at the end of the interaction region by a dual 50 dB directional coupler with outputs at 90°. Feedback supression is obtained by inserting a 30 dB attenuator after the output coupler. Both the coupler and the load have VSWRs< 1.05 at 35 GHz. Computer simulations show that for a cold electron beam interacting with a TE_{11} electromagnetic mode with an input power of 5 kW at 35 GHz, the FEM saturates at z_{sat} = 80 cm, at a power level of 3 MW, yielding an untapered efficiency of 12 %. For an axial energy spread of $\Delta\gamma_{\parallel}/\gamma_{\parallel}$ = 2 % in the wiggler interaction region, the saturated power is predicted to be 2 MW.

3. Oscillator Results

The 28 GHz FEM oscillator experiment will use a step-rippled

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Bragg resonator cavity optimized with power reflectivities $R_1 = 0.95$ and $R_2 = 0.25$ and an effective length $L^* = 25$ cm, for TE_{11} operation. The system was initially operated as an oscillator without the Bragg cavity and was found to operate in a single axial mode at 30 GHz, with a line width $\Delta f < 10$ MHz, at power levels of 1-2 MW and efficiencies above 10 %. Multimode operation was also observed, with a mode spacing of 55 MHz corresponding to the cavity length. In these experiments, the oscillator spectrum is measured by mixing the RF output with the signal of a local oscillator (LO). The resulting low-frequency beat wave ($|\omega_s - \omega_{LO}|/2\pi < 1.0$ GHz) is then gated for 100 ns and dispersed through a Surface Acoustic Wave (SAW) device. The delay is proportional to the frequency of the beat wave; the dispersion of the SAW device is 100 MHz/μs. For the data shown in Fig. 2, $\omega_{LO} = 29.5$ GHz,

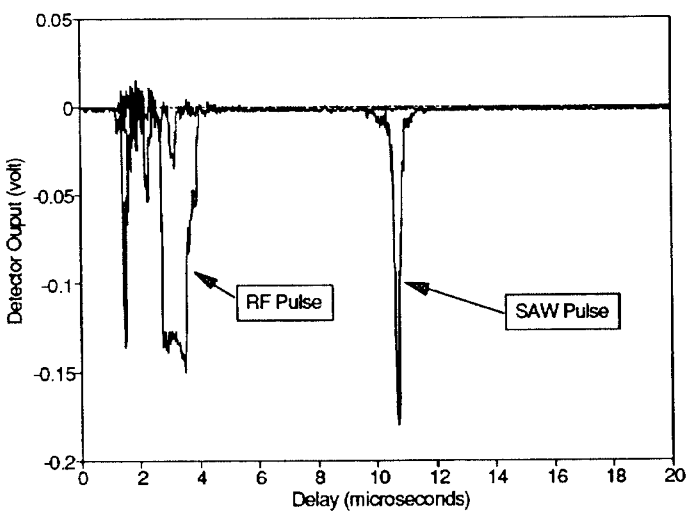

Figure 2: Single-mode Masing at 30 GHz

and we observe a single line at 30 GHz with a linewidth $\Delta\omega_s/2\pi < 10$ MHz. The oscillator can be then be phase-locked to a local oscillator, yielding the required phase control of the RF. However, for the oscillator, the cavity filling time may be relatively long, and the saturated power levels too low to achieve the parameters required for RF acceleration with the electron beam used here. Therefore, the amplifier approach, coupled to a pulse compression scheme, seems more suitable to this type of application.

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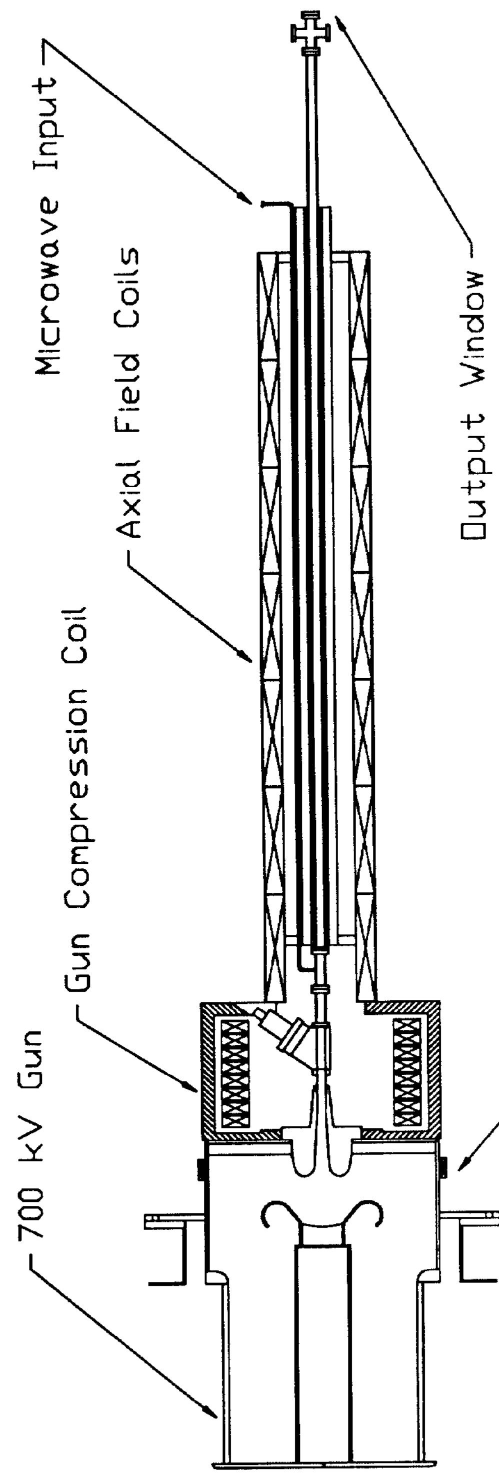

Figure 3: Overall Experimental Setup