Generation of High Power 140 GHz Microwaves with an FEL for the MTX Experiment*

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ABSTRACT

We have used the improved ETA-II linear induction accelerator (ETA-III) and the IMP steady-state wiggler to generate high power (1-2 GW) microwaves at 140 GHz. The FEL was used in an amplifier configuration with a gyrotron driver. Improved control of energy sweep and computerized magnetic alignment in ETA-III resulted in small beam corkscrew motion (< 1.5 mm) at 6 Mev, 2.5 kA. Reduction of wiggler errors (< 0.2%), improved electron beam matching, and tapered wiggler operation resulted in peak microwave power (single-pulse) of up to 2 GW. These pulses were transported to the MTX tokamak for microwave absorption experiments. In addition, the FEL was run in a burst mode, generating 50-pulse bursts of microwaves; these results are discussed elsewhere [1].

I. INTRODUCTION

Generation of high power microwaves with an FEL is advantageous for fusion experiments for several reasons: 1) the output is a simple TE_{01} mode which couples directly to the plasma, 2) there is no output window which could fail at high power, and 3) frequency sweeping is possible by varying a low power source. The FEL for the MTX experiment is made up of four major parts: the ETA-II linear induction accelerator, the electron beamline, the IMP wiggler, and a quasi-optical microwave transport system connected to the MTX tokamak. FEL performance in 1989 was limited to short (5-10 ns) 0.2 GW pulses at 140 GHz because of a substantial corkscrew motion (~1 cm) of the beam and the nonreproducibility of the electron beam pulse (making empirical wiggler tapering difficult). The corkscrew motion is caused by the energy sweep of the beam during the pulse, coupled with misalignments of the solenoidal transport system of the accelerator [2].

The 2-D FEL simulation code FRED [3] was used to estimate the beam parameters required for high-power FEL operation. At a beam energy of 7.35 Mev, 2 kA of beam current, and 50 W of drive power, calculated output power is approximately 5 GW [4]. This estimate requires a ±0.1 cm beam displacement, a ±1% energy sweep, and a 0.1% error in the wiggler magnetic fields. The sensitivity of the output power to these quantities is shown in Table 1, along with achieved parameters.

Table 1
FRED Predictions of FEL Output Power

Parameter	Variation	% Out	Achieved
Beam Energy	7.5 to 6 Mev	50	6.3 Mev
Beam Current	2.5 to 2 kA	60	2.5 kA
	2.0 to 2 kA	17	
Brightness	1 to 0.2×10^8 A m^{-2} r^{-2}	60	$>10^8$
Beam Motion			±1 mm (40ns)
Energy Sweep	±1% to ±2%	80	±1%(35 ns)
Wiggler Error			0.2% RMS

Several hardware and operational improvements were first tested on a 20-cell version of the whole (60 cell) ETA-III system, resulting in reduction of the corkscrew motion and improved energy regulation [2,5-6]. These improvements were then implemented on a 60-cell version called ETA-III, and a steady-state wiggler was installed. Note from Table 1 that the required electron beam parameters have been achieved. Tapered FEL operation resulted in the generation of single pulse microwaves up to 2 GW which were transported to the MTX tokamak with a quasi-optical microwave transport system. Further optimization of the output power was not performed because of extremely limited experimental time. Electron Cyclotron Resonance Heating (ECRH) experiments on MTX with the FEL demonstrated nonlinear absorption of the high power microwaves, in agreement with theory [7]. Extrapolation of this theory shows good absorption for reactor conditions, indicating that FELs are useful for future fusion machines.

II. DESCRIPTION OF THE FEL

A. *The ETA-II 60-Cell Accelerator*

The ETA-II accelerator consists of an electron beam injector and 60 accelerator cells. The injector consists of a thermionic, osmium-coated (12.7-cm-diameter) dispenser cathode operated in a diode configuration to generate about 2500 A at 1 Mev in the space-charge limited regime. Several

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improvements tested on the 20-call prototype were implemented on the 60-cell version of ETA-II for these experiments: 1) a multicable pulse distribution system[8], 2) arc and overvoltage protection, 3) feedback control of pulse timing, 4) an improved cell design to minimize arcing and the Beam Break-Up Instability, 5) in-situ magnetic alignment[9], and 6) a computerized tuning algorithm to minimize corkscrew directly[10]. The computer processing was substantially improved compared to the 20 cell case so that the whole accelerator could be tuned in about 1 day. Improvements (1) and (3) resulted in much better energy regulation, as shown in Table 1, $\Delta T/T$ of $\pm 1\%$ for 35 ns was achieved. The feedback system enabled pulse-to-pulse corrections in the timing of each magnetic compressor (MAG-1D) to be maintained within ~1-2 ns; daily variations of over 20 ns were continuously corrected. Energy flatness was also improved by optimization of the operating point of the MAG-1D; a slightly rising waveform was used on the first 20 cells to compensate for a falling waveform from the injector. The corkscrew amplitude was found to depend weakly on the operating point (± 10 kV from 90 kV per cell gap).

were measured with current return monitors and processed into a corkscrew amplitude A by the MAESTRO system. The MAESTRO system also controls the 60 pairs of power supplies for the sin and cos correction coils in each cell block used to minimize A. The computer system has been optimized so that A is calculated and the currents are changed between pulses at 1 Hz. MAESTRO can automatically process all 60 cells in a few hours.

B. The IMP Wiggler and Microwave System

Shown in Fig. 1 is the FEL system; a series of magnetic lenses are used to transport and match the electron beam into the input of the wiggler. The 140 GHz gyrotron is the master oscillator (MO); a mirror in the sidecoupler focuses the microwave beam into the wiggler; a 4-cm diameter central hole is provided to pass the electron beam. The IMP wiggler[11] is a tuneable 5.5 m hybrid (both permanent and electromagnets) steady-state wiggler with a 10 cm period. The field is adjustable from 2.7-5.5 kG in the first half, and 0.6-4.1 kG in the second half of the wiggler. After careful

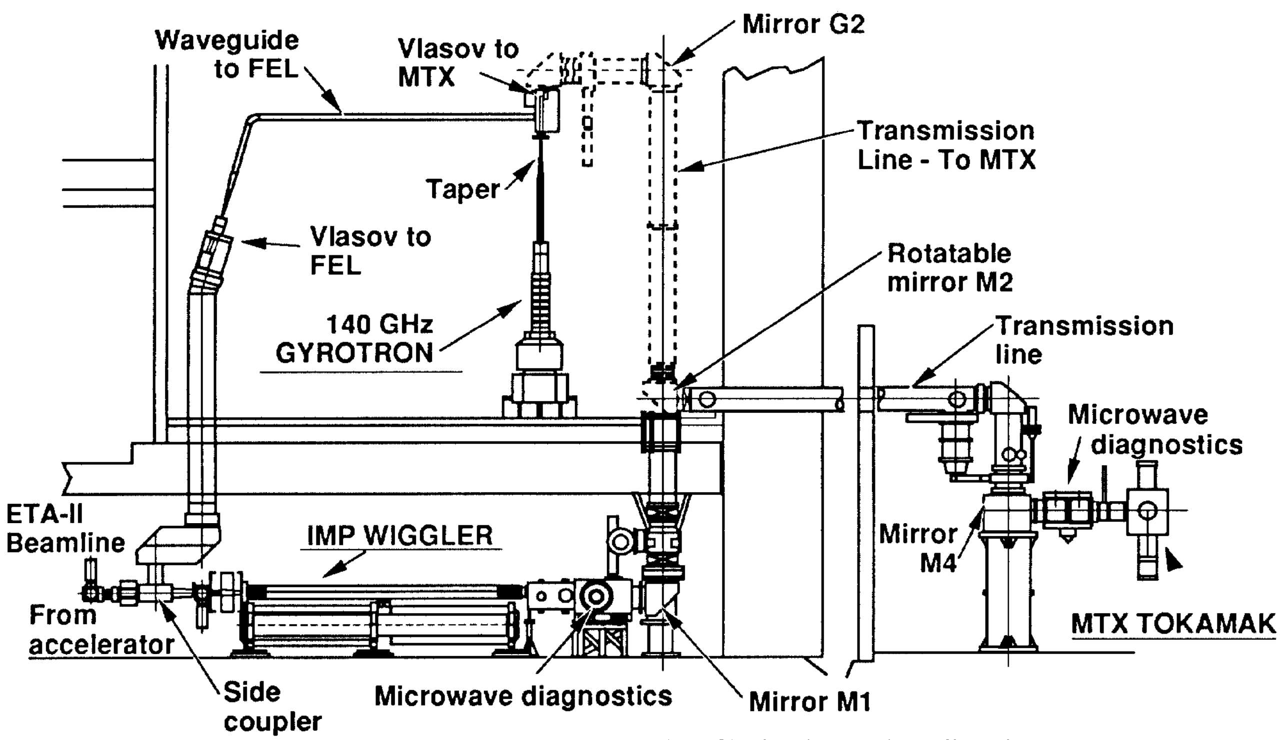

Fig. 1 The FEL is composed of the ETA-II accelerator (at left), the electron beamline, the master oscillator (gyrotron), and the quasi-optical microwave transport system to MTX.

Reduction of magnetic errors with (5) and (6) resulted in transverse beam motion nearly comparable to that obtained for the 20-cell experiment[5], i.e., ± 1 mm for 40 ns. A Stretched Wire Alignment Technique (SWAT) was used for alignment before operation. During electron beam operation, the MAESTRO[10] computerized control system minimized the corkscrew directly. The x and y components of the beam motion (referenced either to the beam or apparatus centroid)

construction, hall probe measurements indicated that the RMS wiggler errors were reduced to 0.1% for electromagnets alone, and 0.2% for the whole wiggler. We have verified the electron beam matching in the wiggler with a moveable optical target; no strong evidence of beam steering or abnormal growth in beam size was observed.

III. Experimental Results

A. FEL Output Power at 140 GHz

The FEL system was operated at 1 Hz, and scans of the wiggler magnetic field were used to determine the IMP operating point. The wiggler was then tapered to optimize the output power, again using the MAESTRO system for control. We started with a theoretically-derived taper, and then empirically optimized the output power. The output power waveform was measured with both a calibrated diode and a receiver. A more precise calibration of the time-integral of this signal was provided by a precision calorimeter. An example of a pulse is shown in Fig. 2; we measured peak powers up to about 2 GW.

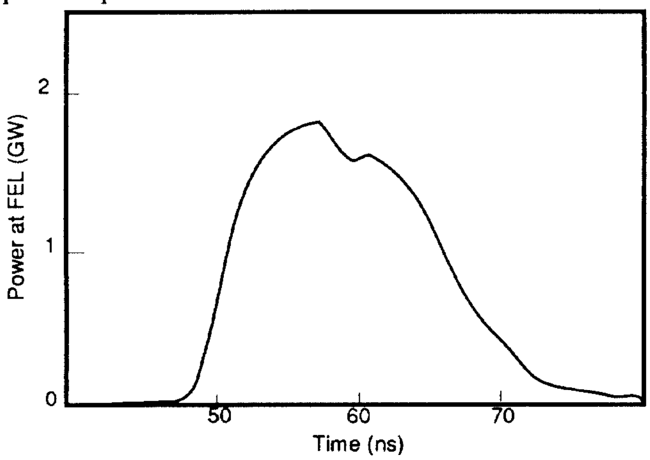

Fig. 2 A sample trace showing the output power versus time measured at the output of the FEL.

At this point, even though the theoretical models indicated that powers of 2-3 times greater were possible, we concentrated on MTX plasma experiments rather than FEL optimization. (In addition, one IMP coil was damaged, limiting the tuning range and therefore the usable tapers). The FEL output power was transmitted to the MTX tokamak with a quasi-optical transmission system consisting of several mirrors. This system is very efficient, transmitting nearly 90% of the power. FEL operation in the single-pulse mode was fairly reproducible; routine operation for several days with only minor tuning was achieved. An example of the peak power measured at MTX for one experimental day is shown in Fig. 3 (the FEL runs at 1 Hz, MTX shots are 5 minutes apart.)

IV. Discussion

Improved energy regulation and reduced corkscrew motion of the electron beam from the ETA-III accelerator have made possible high power FEL operation. Peak powers of ~2 GW at 140 GHz has been generated in single pulses. Further optimization of the FEL power was not possible due to limited experimental time. These high-power pulses were used in microwave transmission experiments in the MTX tokamak; nonlinear ECRH behavior was observed, in semi-quantitative agreement with theory. Burst mode operation of the FEL was also demonstrated, and is described in Ref. 1.

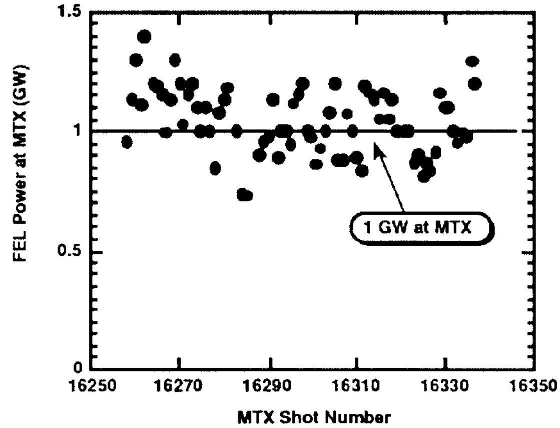

Fig. 3. The peak microwave power (measured at MTX) varies from 0.75-1.4 GW during a day of experiments

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