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ABSTRACT

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A 1 MW (cw), millimeter wave FEL ($\lambda, \approx 0.5$ mm) is currently under development with an application for heating fusion plasmas. Two salient features of the FEL are the use of a short-period wiggler ($\ell_w \leq 10$ mm) electromagnet and a mildly relativistic ($E_{beam} \leq 1$ MeV) sheet electron beam. The FEL has been designed to operate in the high-gain regime and uses a tapered wiggler. The wiggler provides beam focusing as well as the magnetostatic pump wave. The effectiveness of wiggler focusing is being investigated. Planned experiments will address the critical issues of beam interception and stable single-mode operation.

1. INTRODUCTION

A high average power millimeter wave source is being developed to heat fusion plasmas by electron-cyclotron resonance (ECRH). Some specific requirements on the ECRH source for the Compact Ignition Tokamak (CIT) are 1 MW cw radiation in a single mode at 280 GHz with eventual operation at 560 GHz, corresponding to the fundamental and second-harmonic for ECRH. Source requirements also place an emphasis on overall device efficiency, cost, and reliability.¹

Our group has designed a high-gain FEL amplifier which meets the ECRH source criteria. The designs are based on using a short-period wiggler and a modest energy sheet electron beam.² As previously described, the proposed FEL is characterized by an electron energy of $\lesssim 1$ MV, wiggler period $\ell_w \lesssim 1$ cm, and use of depressed collectors to recover the spent beam energy.^{3,4} Our designs are compatible with cw operation and the low electron energy may make this approach very attractive. In this paper, we will describe our design procedures and discuss some critical issues which theory and experiments must address. The designs are presented in Section 2 then feasibility issues and near-term experiments are described in Section 3.

2. DESIGN OF HIGH-GAIN FEL AMPLIFIERS

FEL operation in the high-gain regime is attractive because the intrinsic efficiency may be greatly enhanced by selective changes in the wiggler, or tapering. Tapering provides a large efficiency enhancement by preserving synchronism between electron bunches and the ponderomotive beat-wave.

Table 1 contains a summary of the design parameters for a tapered amplifier.⁵ These designs are based on an analysis of one-dimensional particle and wave envelope equations.⁶ To access the high-gain regime and have a reasonably large electronic efficiency, the short-period wiggler magnet must provide both a large magnetic flux density (B_w) and be compatible with a tapering scheme, selective changes in ℓ_w , B_w , or both. Recent experimental results have demonstrated large dc magnetic fields using superconducting short-period wiggler electromagnets which would be compatible with our designs.⁷

Taking advantage of tapering requires that the wiggler parameter ($a_w \propto B_w \ell_w$) be initially as large as possible since the efficiency of the taper scales as the energy extracted by the tapered region, or

$$\eta_{taper} \sim \delta\gamma = \bar{\gamma}_z \left[\sqrt{1 + \frac{1}{2}a_{w,0}^2} - \sqrt{1 + \frac{1}{2}a_{w,L}^2} \right], \quad (1)$$

where $\bar{\gamma}_z$ is the period-averaged value of $\gamma_z = (1 - v_z^2/c^2)^{-1/2}$, $a_{w,0}$ and $a_{w,L}$ correspond to the value of the wiggler parameter at the taper entrance and exit respectively.

The use of energy recovery in these designs requires the use of at least two power supplies. Although this adds

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to system complexity, it eliminates the need for a single high-voltage, high-current, dc power supply. A low-voltage, low-current supply will bias the electron gun, while a lower voltage, high-current supply is used to power the depressed collectors and provide the bulk of the beam current. Although research has indicated that large a $\eta_r \geq 90\%$ is possible for a streaming electron beams,⁸ the FEL has been designed to permit an $\eta_r \sim 70 - 80\%$. Even with these values, the overall system efficiency remains respectable (see Table 1).

3. CRITICAL ISSUES AND NEAR-TERM EXPERIMENTS

One of the critical issues regarding this concept is the use of the wiggler to provide beam focusing. A considerable research effort has been performed and reported by our group regarding this issue.^{3,9} These experiments have used a pulse-line accelerator to drive a cold-cathode planar diode. A sheet electron beam was formed by using an aperture. The wiggler was placed adjacent to the aperture.

To summarize the main results, it was found that for a given B_w , no beam interception was observed when the injected electron beam divergence was sufficiently small and the current density did not exceed the Brillouin limit. These investigations were performed using wigglers which were more suitable for low-gain oscillators than high-gain amplifiers however. For this reason, experiments are currently underway to study the effectiveness of sheet electron beam focusing by a wiggler compatible with the new high-gain FEL designs. These wigglers have a greater number of total periods, initially larger B_w , and are tapered.

The 1 cm period wiggler fabricated for this investigation is very similar to our previous short-period electromagnet designs,² but each pole-piece consists of a double-layer of copper. The layers are connected in series such that the magnet current enters and exits in close proximity, providing both self-shielding and the possibility for easy addition of wiggler periods, thus increasing the wigglers overall length. The wiggler has been designed in 20 period modules, and the first experiments will investigate focusing through 3 such modules. Preliminary results have indicated that the beam is focused in the midplane of the waveguide, however some deflection in the wiggle-plane occurs. The sources of this are under investigation, however it appears to be related to the entrance condition. Over a large number of periods, it may be necessary to provide a focusing force in the wiggle-plane. The type of force most compatible with this type of wiggler can be provided by simply offsetting alternate iron regions.¹⁰ This effectively creates a side fringing field which can provide a net deflection force to restore electrons to the uniform field section of the wiggler. Preliminary experimental investigations have indicated that this is a very powerful method of steering the beam.

Following the conclusion of the beam focusing work, a proof-of-principle FEL amplifier experiment is planned. The design parameters are shown in the last column of Table 1. The experiment will be performed on a 100 ns pulse-line accelerator. Amplification of a low-power (20 W) 98 GHz signal from an extended interaction oscillator (EIO) is expected during the flat-top of this pulse. An input coupler is currently under design to couple the EIO signal into the highly-overmoded FEL interaction region with minimal mode conversion. Since the initial signal power is quite low, the launching loss must be kept a minimum. A wire-mesh reflector will be used to reflect the input signal yet still allow the electron beam to propagate.¹¹ This scheme is only compatible with pulsed operation. The screen is expected to have minimal effects on beam temperature at relevant energies.

The wiggler period length for this experiment is slightly larger than for the propagation work, since a very large a_w is required. Since the magnetic field increases nearly exponentially as the period is increased, a sufficiently large a_w can be generated at short periods without the necessity of superconductors. In fact, a wiggler based on our conventional electromagnet has been designed and a pulsed capacitor bank will be used to provide a large electric current.

Resonance between the electron beam and the desired waveguide mode (TE_{01}) mode occurs at about 650 keV. Since this interaction is taking place in a waveguide, there is a second possible interaction, at a much lower frequency. In these first experiments, no suppression will be attempted, however we are investigating techniques for suppression of both the low-frequency interaction and undesired spurious resonances or harmonics.¹² The first efforts will address stable operation without any tapering. Growth rates of 0.6 dB/cm are expected in the linear regime. Later experiments will address the efficiency enhancement possible with tapering.

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TABLE 1

frequency (GHz)	280	280	560	560	98
V_{beam} (MV)	1.0	1.0	1.0	1.5	0.65
I_{beam} (A)	10	10	10	10	8.6
A_{beam} (cm ²)	0.1×2.0	0.1×2.0	0.1×2.0	0.1×2.0	0.1×2.0
$B_{w,0}$ (kG)	7.0	10.0	10.0	10.0	7.0
$B_{w,min}$ (kG)	2.0	2.0	2.0	2.0	2.0
ℓ_w (mm)	12.1	10.5	6.8	10.0	14.3
$a_{w,0}$	0.79	0.98	0.63	0.93	0.93
A_{wg} (cm ²)	0.60×3.0	0.52×3.0	0.37×3.0	0.50×3.0	0.57×3.0
P_{sat} (MW)	0.13	0.14	0.09	0.14	0.13
z_{sat}^* (m)	0.8	0.6	0.6	0.9	1.0
η_{taper} (%) ($f_t = 0.7$)	12	17	9	15	18
L_{taper} (m)	1.2	1.3	1.0	2.3	0.7
P_{out} (MW)	1.2	1.7	0.9	2.1	1.0
η_{tot} (%) ($\eta_r = 0.7$)	31	41	24	36	—
η_{tot} (%) ($\eta_r = 0.8$)	41	51	32	46	—

* 1 kW input power at 280 GHz and 560 GHz. 1 W input power at 98 GHz.

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