A SHORT-PERIOD WIGGLER MILLIMETER-WAVE FREE ELECTRON LASER FOR PLASMA HEATING AND SPACE-BORNE RADAR

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ABSTRACT

We will report on the status of a new mm-wave FEL research program based on short-period electromagnet wigglers and a low voltage (500 kV) sheet electron beam. Recent results of measurements and theoretical modeling will be discussed. Potential applications of this device include space-based radar and electron cyclotron heating of the magnetic fusion plasmas.

INTRODUCTION

High power, tunable, radiation sources operating at wavelengths near one millimeter are of interest for Electron Cyclotron Resonance Heating (ECRH) of the plasma in advanced magnetic confinement experiments, for space-borne radar, and as drivers for accelerator-based Free Electron Lasers (FELs). ECRH Source candidates require CW operation combined with high efficiency and moderate voltage in order to meet budgetary constraints. Space-borne radar operating at wavelengths near one millimeter would achieve superior imaging at greater distances, when compared with longer wavelength radar, provided a compact, lightweight, and highly efficient system could be developed. For oscillator drivers of accelerator-based FELs, a premium is placed on tunability and simplicity.

At the University of Maryland's Laboratory for Plasma and Fusion Energy Studies (LPF), research is underway to assess the feasibility of a new FEL configuration which aims to produce millimeter-wave radiation with modest beam voltages ($\phi_{beam} \lesssim 500$ keV) while keeping output power large and achieving a high system efficiency. The concept is based upon the utilization of short-period wigglers ($5\text{mm} < \ell_w < 10\text{mm}$) and sheet electron beams [1,2]. In addition, to increase overall FEL efficiency, we consider the use of multistage depressed collectors to recover energy in the spent electron beam.

While short-period wigglers reduce the required FEL beam energy, they introduce a potential problem since a strong FEL interaction requires that all the electrons must be a small distance from the wiggler magnet compared with the wiggler period. For a planar, bilateral wiggler, this implies a small gap between magnet halves and necessitates the use of sheet or ribbon electron beams to keep beam current and rf power large. Typical designs call for a wiggler period-to-gap ratio of approximately two (i.e. $0.25 \text{ mm} < \delta < 0.5$ mm, where δ is the gap spacing), a sheet electron beam thickness of 0.5 to 1.0 mm, and an electron beam width of several centimeters.

FEL DESIGN AND FEASIBILITY ASSESSMENT

Design of the proposed FEL system requires evaluation of five issues: (1) short-period wiggler fabrication, (2) sheet beam generation and propagation in narrow channels, (3) rf structure design, (4) efficiency and gain of the FEL interaction, and (5) spent beam energy recovery. It was the result of success with the first issue--development of an inexpensive, versatile, electromagnet wiggler [1,2] design--that motivated the present research project. Most recently, efforts to reduce leakage flux in these magnets [2] have resulted in achievment of peak magnetic fields approaching 3 kG for 1.0 cm period wigglers with narrow gap spacings (3-4 mm) [3]. Improved magnet fabrication techniques are being studied with a goal of improving field uniformity. The remainder of this paper will describe the status of our investigations into issues (2)-(4). Issue (5), critical for improving total system efficiency, is discussed in Ref. [3].

The reduction in electron beam voltage to values below 500 kV allows one to consider the use of a conventional, thermionic cathode, Pierce electron gun. Such a device would be capable of producing a low emittance beam using conventional modulators and/or dc power supplies, rather than electron accelerators. FEL tunability could be achieved without loss of beam quality by reducing the beam voltage at constant perveance. In addition, preliminary gun design calculations have verified that standard, two-electrode (cathode, anode) Pierce gun diode designs can meet state-of-the-art dc breakdown holdoff criteria at voltages approaching 500 KV [4]. For voltages greater than or equal to 500 kV, dc operation is feasible by utilizing a modified, multiple-electrode-anode design [4].

In planar, bi-lateral wigglers, magnetic fields are purely transverse on-axis $[\underline{B}\ (y = 0) \approx B_{yo} \sin(k_w y)\ e_y]$ but include strong axial components ($\underline{B} \approx B_y e_y + B_z e_z$) near the magnet surfaces [1,2]. These axial components lead to strong wiggler focusing of the type first discussed by Sturrock [5] and later verified by Dryden [6]. To avoid beam scrape-off in short-period wiggler FELs, this focusing force must be sufficient to confine both the betratron oscillation amplitudes of individual electrons as well as the collective beam expansion due to space-charge repulsion. Using the fields derived in [1,2] one can quantify these two beam confinement criteria in terms of maximum limits on beam angular divergence, $\Delta\theta$,

$$\Delta\theta < \frac{\Omega_w}{2\gamma\beta_z c} \frac{b_{rf}}{2}, \qquad (1)$$

and beam plasma frequency, ω_p,

$$\omega_p << \left(\frac{\gamma}{2} \Omega_w^2 \right)^{1/2} \qquad (2)$$

where b_{rf} is the small transverse waveguide dimension, β_z is the normalized axial velocity, c is the speed of light, $\Omega_w = qB_o/m$, and γ is the relativistic energy parameter. Typical limits include electron density $n \lesssim 2.2 \times 10^{11} cm^{-3}$ and $\Delta\theta \lesssim 3$ degrees for $B_o \approx 2$ kG, $\gamma \approx 2$, and $b_{rf} \approx 0.22$ cm. Pulse-line accelerator experiments are currently underway to verify these focusing relations. Preliminary results appear promising.

Several significant reqirements have been placed on the design of an rf structure for our proposed FEL oscillator. For example, to maximize the efficiency of the FEL interaction, a high value of circulating cavity power--and thus a high "Q" cavity--is desireable. It is important to ensure, however, that a large cavity Q for the desired FEL mode (TE_{01} mode) does not also result in large growth rates for the unwanted transverse modes ($TE/TM_{m,1}$ modes, $m \geq 1$). Presently, we are investigating the design of mode and frequency selective oscillator cavities using a two-dimensional electromagnetics code [7]. In addition to enhancing the FEL interaction, large cavity powers will result in high thermal loads in the walls of the rf structure. Based on state-of-the-art cooling techniques for gyrotron cavities, our current oscillator designs assume a maximum 2.0 kW/cm^2 rf power ohmic losses in the walls. The requirements on wiggler-to-beam proximity, however, leave questions on the feasibility of dissipating this heat load in the interaction region. Efforts are now in progress to analyze this problem with a three-dimensional heat transport code [8].

All FEL conceptual designs are verified to satisfy start oscillation conditions using a linear dispersion relation derived for a thin sheet beam in a planar wiggler [9]. Nonlinear calculations of FEL efficiency are then considered using a one-dimensional pendulum equation formalism which assumes that the FEL is operating in a low gain regime [10], that there is a single electromagnetic mode, and that space charge effects may be neglected. For example, with $B_w = 2$ kG, $\ell_w = 0.54$ cm, $f_r = 296$ GHz (resonant operating frequency), and an untapered wiggler, we find electronic efficiency can reach a saturated value of $\eta_E = 5.0\%$, where we define $\eta_E \equiv \langle(\gamma_{in} - \gamma_{out})/(\gamma_{in} - 1)\rangle$. Alternatively, by tapering the wiggler period we can increase the electronic efficiency by a factor of three to $\eta_E \approx 16\%$. Typically, these values of efficiency can be maintained over a range of axial energies, $\Delta\gamma_z/(\gamma_z - 1) \approx \pm 2\%$. In addition, these values of saturated efficiency can be maintained over frequency ranges as large as 30-40%, for both tapered and untapered wigglers.

In Table I we have summarized conceptual design parameters for three oscillator designs, all operating at 296 GHz. Two designs--one tapered, one untapered--each produce in excess of 1 MW rf output power. These power levels are attractive for space-based radar and ECRH sources. For an ECRH source, however, CW operation will require successful dissipation of the 2 kW/cm^2 of ohmic wall losses. It should also be noted that the factor of three increase in η_E was obtained at a cost of increasing the magnet and resonator lengths from 13 to 65 periods. Propagation of the sheet beam through such a long channel remains to be studied. The third set of parameters correspond to a much more modest output power of 20 kW. The wall loading in this case is less than 100 W/cm^2. Such a device might be an attractive driver for accelerator-based FEL amplifiers.

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Table 1
Short-Period Wiggler FEL Oscillator Designs

Pout (kW)	1200	1250	20
Taper	No	Yes	No
Wiggler Period (cm)	0.54	0.54	0.54
Waveguide Gap (cm)	0.22	0.22	0.22
Thermal Wall Load (w/cm^2)	2000	2000	< 100
Peak Wiggler Field (kG)	2.0	2.0	2.0
Cavity Power (MW)	28	28	0.5
Beam Voltage (kV)	500	500	500
Beam Current (A)	50	20	<2.4
FEL Efficiency (%)	5	16	2.0
No. of Periods	13	65	16
Total Wall Losses (kW)	70	350	< 3.5
Output Transmissivity (%)	4.2	4.5	4.0
Waveguide Width (cm)	5.0	5.0	2.0
Frequency (GHz)	296	296	296