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A High-Average Power Tapered FEL Amplifier at Submillimeter Frequencies Using Sheet Electron Beams and Short-Period Wigglers

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ABSTRACT

A high-average-power FEL amplifier operating at submillimeter frequencies is under development at the University of Maryland. Program goals are to produce a CW, ~ 1 MW, FEL amplifier source at frequencies between 280 GHz and 560 GHz. To this end, a high-gain, high-efficiency, tapered FEL amplifier using a sheet electron beam and a short-period (superconducting) wiggler has been chosen. Development of this amplifier is progressing in three stages: (1) beam propagation through a long length (~ 1 m) of short period (λ_w = 1 cm) wiggler, (2) demonstration of a proof-of-principle amplifier experiment at 98 GHz, and (3) designs of a superconducting tapered FEL amplifier meeting the ultimate design goal specifications.

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I. Introduction

The University of Maryland is developing a FEL amplifier operating at submillimeter frequencies. The specific program goals are to develop a CW, $\sim$ 1 MW, tapered FEL amplifier producing frequencies between 280 GHz and 560 GHz. The FEL will employ a sheet electron beam and a short-period wiggler magnet (likely superconducting). Use of a sheet electron beam[1,2] and a short-period wiggler[3,4] provides several advantages over other configurations, and a discussion of these advantages can be found in the referenced works. The FEL amplifier under development is intended for electron cyclotron resonance heating (ECRH) of experimental magnetic fusion reactors such as the Compact Ignition Tokamak (CIT). The general specifications for this heating source include an output power $\sim$ 1 MW, pulse durations of several seconds to CW, and operation with high reliability and efficiency.[5] Development of this amplifier is proceeding in three stages and this paper presents a short discussion of each stage. In the first stage, we are experimenting with sheet beam propagation through a long length of a short-period wiggler magnet. As the eventual amplifier will have an interaction length of 2 - 3 m, stable, confined propagation of the electron beam through this length is a critical issue. This experimental effort will be discussed in Section IV. Following successful demonstration of beam propagation, we will begin operation of a proof-of-principle (PoP) amplifier experiment. This device will be pulsed ($\approx$ 100 ns) and is intended to demonstrate linear regime amplification at 98 GHz. Following successful amplification, tapering of the PoP amplifier will be used to demonstrate operation at a high intrinsic efficiency. This experimental effort will be discussed in Section III. The final and third stage of development is the design and construction of the tapered amplifier at 280 GHz (560 GHz). A discussion of the eventual design goals follows.

II. Superconducting Tapered FEL Amplifier Designs

Previously, our effort concentrated on development of a CW oscillator to meet the specifications for the ECRH source.[6,7] However within the past year we have decided to alter our effort to the development of a tapered amplifier operated in the high-gain, Compton regime.[8] The primary motivation for this decision was the increased efficiency of the tapered amplifier and recent advances in superconducting wigglers demonstrating magnetic fields up to 7 kG using short period wigglers ($\lambda_w \sim 1$ cm).[9] Operation at such high fields will permit access to the high-gain (strong pump) regime and will make wiggler tapering for increased efficiency an attractive option.

A schematic for the envisioned amplifier is shown in Fig. 1. As shown, the amplifier will consist of four major components: (1) a thermionic, high voltage sheet beam gun, (2) an input signal source and injection scheme, (3) an interaction region consisting of a tapered, superconducting, planar wiggler, and (4) a spent beam energy recovery system including two power supplies.

Design parameters for the tapered amplifier can be found in Table 1. These designs are based upon a universal (dimensionless) analysis of the one-dimensional FEL particle and wave envelope equations.[10] Four designs are listed, two at 280 GHz, and two at 560 GHz. These frequencies correspond to the fundamental and first harmonic of electron cyclotron resonance in the CIT device. Operation at 560 GHz is preferable as this would allow power injection from the more accessible outer radius of the tokamak. The sheet beam gun will to operate at typically ~ 1 MV and deliver 10 A of current. We have done a preliminary design of this gun and have verified its feasibility.[11] As designed, this gun will be Pierce-type with a multianode structure which electrostatically focuses the beam into a 0.1 cm × 2.0 cm sheet. Critical electric field values are not exceeded anywhere in the gun or focusing structure and beam velocity spread is within specifications at the gun exit.

As mentioned, one advantage of a tapered amplifier is its higher intrinsic efficiency compared to an oscillator. Previous oscillator designs indicated efficiencies of $\sim 3\%$ at 280 GHz and $\sim 1\%$ at 560 GHz.[7] This low efficiency has two implications. Firstly, to extract the desired 1 MW of radiative power, the oscillator requires very large beam powers ($\sim$ 30 MW).) Secondly, to meet overal system efficiencies of 30% - 40%, the oscillator places heavy demands upon highly efficient ($\eta_r \geq 90\%$) spent beam energy recovery. The designs shown in Table 1 indicate that with tapering an amplifier can be operated with intrinsic efficiencies of between 15% - 20%. This higher efficiency permits a reduction in electron beam power (through a reduction in beam current) to $\sim$ 10 MW. Such a reduction in beam power lessens the demand upon the high voltage power supply and decreases the ever present risk of beam-wall interception. Furthermore, the higher intrinsic efficiency of the tapered amplifier reduces the dependance upon the spent beam energy recovery system. Although research indicates recovery efficiencies $\geq 95\%$[12] are feasible for streaming electron beams, the tapered amplifier will permit recovery schemes with 70% - 80% efficiency. Less stringent demands upon the spent beam energy recovery system is in accordance with overall program goals of using reliable, proven technology wherever possible. As Table 1 indicates, spent beam energy efficiencies $\eta_r = 70\%$ - 80% result in attractive overall system efficiencies of 30% - 50%.

To achieve a high intrinsic efficiency by tapering requires that the wiggler parameter a_w be as large as possible. This is evidenced by the efficiency expression for a linear taper:

$$\eta_{taper} \approx \frac{\Delta\gamma}{\gamma_0 - 1}\frac{\overline{\beta}_z}{\beta_0} f_t$$

where $\Delta\gamma$ is the change in γ over the tapered region

$$\Delta\gamma = \overline{\gamma}_z\left[\sqrt{1+\tfrac{1}{2}a_{w,0}^2} - \sqrt{1+\tfrac{1}{2}a_{w,L}^2}\right],$$

γ is the relativistic energy parameter, β is the normalized velocity, f_t is the trapped beam fraction, and $a_{w,0}$ and $a_{w,L}$ correspond to the wiggler parameter at taper entrance and exit respectively. These designs assume a trapped beam fraction $f_t = 70\%$ which has been experimentally observed elsewhere.[13] The magnetic field values listed in Table 1 presuppose a superconducting magnetic field $B_{w,0} = 10$ kG within the uniform wiggler section with tapering to $B_{w,min} = 2$ kG at the wiggler exit. Maintaining beam trapping is the primary concern when choosing the minimum field at the wiggler exit. The intrinsic efficiency values found in Table 1 assume a linear taper model and are calculated from the preceding formula.

In addition to attractive overall system efficiencies, spent beam energy recovery permits the use of two power supplies and eliminates the need for a single ~ 1 MV, 10 A dc supply. One supply is a bias to the gun; it will be high voltage ~ 1 MV and low current ~ 100 mA. The other supply will bias the depressed collectors and provide the bulk of the beam current ~ 10 A. The characteristics of the lower voltage supply will depend to a large extent on the intrinsic and recovery efficiencies:

$$\phi_{LV} \approx \left[1 - \left(\eta_r - \eta_{taper}\right)\right]\phi_{HV}$$

Applying this to the designs of Table 1 suggests that the lower voltage supply will rate at 300 kV - 400 kV. Both the high and lower voltage power supplies are commercially available. A discussion of the proof-of-principle amplifier follows.

III. Proof-of-Principle FEL Amplifier at 98 GHz

As a stepping-stone to development of the eventual ECRH source, we are designing and constructing an experimental amplifier which has parameters of relevance to those of the eventual device. The fifth column of Table 1 lists the design parameters for the proof-of-principle (PoP) experiment.

Whereas the eventual source will operate CW, the PoP experiment will be a pulsed device. The electron beam will be generated from a cold (field emission) cathode which is connected to a pulse-line accelerator. The pulse-line accelerator operates from 200 to 800 kV with a nominal 100 ns pulse duration. A 3% voltage ripple is achievable during about 75 ns of this pulse and it is during this flat top that amplification is expected. Waveguide mode/beam resonance (TE_{01} mode) is achieved at 650 keV and in addition to resonance at 98.0 GHz, there is a lower waveguide mode/beam intersection at 29.9 GHz. Both are forward propagating waves. As a pulsed amplifier, no effort will be attempted at suppression of this lower frequency intersection or higher order interacting modes. For the eventual CW device, suppression of the lower intersection as well as any higher order modes is critical. Suggestions such as open sidewalls to allow higher order modes to diffract out of the interaction region have been proposed.[14]

It is anticipated that in the linear gain regime the signal should experience a growth rate of 0.6 dB/cm. This value, calculated from the universal formalism, is in good agreement with the value calculated from the growth rate expressions of others.[15] As a driver, the PoP will use a commercial extended interaction oscillator (EIO) rated at 20 W of output power. It is desired to inject this power into the TE_{01} mode of the PoP waveguide. This waveguide, with dimensions of 0.57 cm by 3.0 cm, is highly overmoded at 98 GHz. To inject this signal, a taper is under construction which will connect from the EIO to the top of the PoP waveguide at a position prior to the wiggler magnet. A wire mesh placed within the waveguide will reflect the input signal, enabling copropagation of the signal and electron beam down the waveguide. Since the electron beam must pass through the wire mesh reflector, this scheme, while used successfully in pulsed experiments,[16] is inappropriate for the CW device. For the eventual device, we are considering other schemes such as injecting the input signal on axis, down the waveguide, from the position of the gun anode. The PoP design parameters given in Table 1 assume that 1 W of power is successfully injected into the desired TE_{01} mode.

At 98 GHz the PoP operates significantly below the desired frequencies of the eventual device. However, Table 1 shows the other PoP parameters to be relevant to those of the CW device. With a 7 kG peak pulsed magnetic field and a wiggler period $\lambda = 1.4$ cm, the PoP is characterized by a wiggler parameter of 0.93. This moderately high value of wiggler parameter will allow for tapering. Once signal saturation is achieved at 130 kW (after about 99 cm of uniform period wiggler), the tapered sections will be added boosting the power and efficiency. An intrinsic efficiency of 18% and output power of 1.0 MW is in agreement with the desired values for the eventual device.

IV. Short Period Wiggler Sheet Beam Propagation

An experimental effort is underway to study sheet electron beam transport through amplifier relevant lengths. Previous work has successfully demonstrated sheet electron beam propagation through planar electromagnet wigglers of modest length.[17] In particular, propagation through 10 cm (10 periods with $\lambda_w = 1$ cm) has shown the wiggler magnet to sufficiently focus a sheet beam ($\sim$ 500 keV, 7.2 A, 65 A/cm^2), in the narrow transverse dimension and to provide virtually 100% transport efficiency. No beam instabilities were observed in these approximately 35 ns pulsed experiments. In contrast to this work, the eventual and PoP devices call for interaction lengths of 2 - 3 m. While it is probable that, in the narrow transverse dimension, wiggler focusing will prove adequate over this length, caution demands demonstration of stable, confined propagation before proceeding with signal amplification. It is important to note that, as in previous propagation experiments, no axial magnetic field is used in transporting the sheet beam. Unfortunately, solenoidal magnetic fields are incompatible with sheet beam transport as $\mathbf{E} \times \mathbf{B}$ drift instabilities result from the beam's self transverse electric field $\mathbf{E}$ and the imposed magnetic field $\mathbf{B}$.

Similar to our previous magnet designs, the present wiggler consists of copper meander path windings with laminated iron pole pieces.[3] As a means of increasing the overall interaction length, the wiggler is designed in a modular fashion with 20 periods, $\lambda_w = 1.0$ cm, per module. Modules will be added to increase overall length as successful propagation is demonstrated. Preliminary measurements indicate a 3.4 kG peak, pulsed, magnetic field on-axis. Generation of the sheet electron beam is from a cold (field emission) cathode connected to a pulse-line accelerator. A machined slit within the anode serves to aperture the beam forming a sheet. Typically, the slit dimensions are 0.1 cm × 2.0 cm. A one-half magnitude step is used in the first wiggler period to help match the sheet beam into the wiggler region.

In the past, at overall interaction lengths of 10 cm, no effort was made to provide for side or wiggle plane focusing. However, for these propagation experiments, which will approach 1 m in total length, side focusing can not be ignored. The proposed mechanism of side focusing is an offset lamination technique. The laminated iron poles, on both the top and bottom wiggler halves, will be offset in the wide transverse dimension. It is hoped that the resulting net vertical dc fields at the sides will focus straying electrons back into the central region. A complete report on sheet beam propagation through amplifier relevant lengths will be given in the near future.

VI. Acknowledgement

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Table Caption

TABLE 1 Tapered FEL amplifier designs. First four columns show parameters of a superconducting wiggler amplifier at 280 GHz and 560 GHz using a spent beam energy recovery system. Fifth column is design of a PoP tapered amplifier at 98 GHz.

Figure Caption

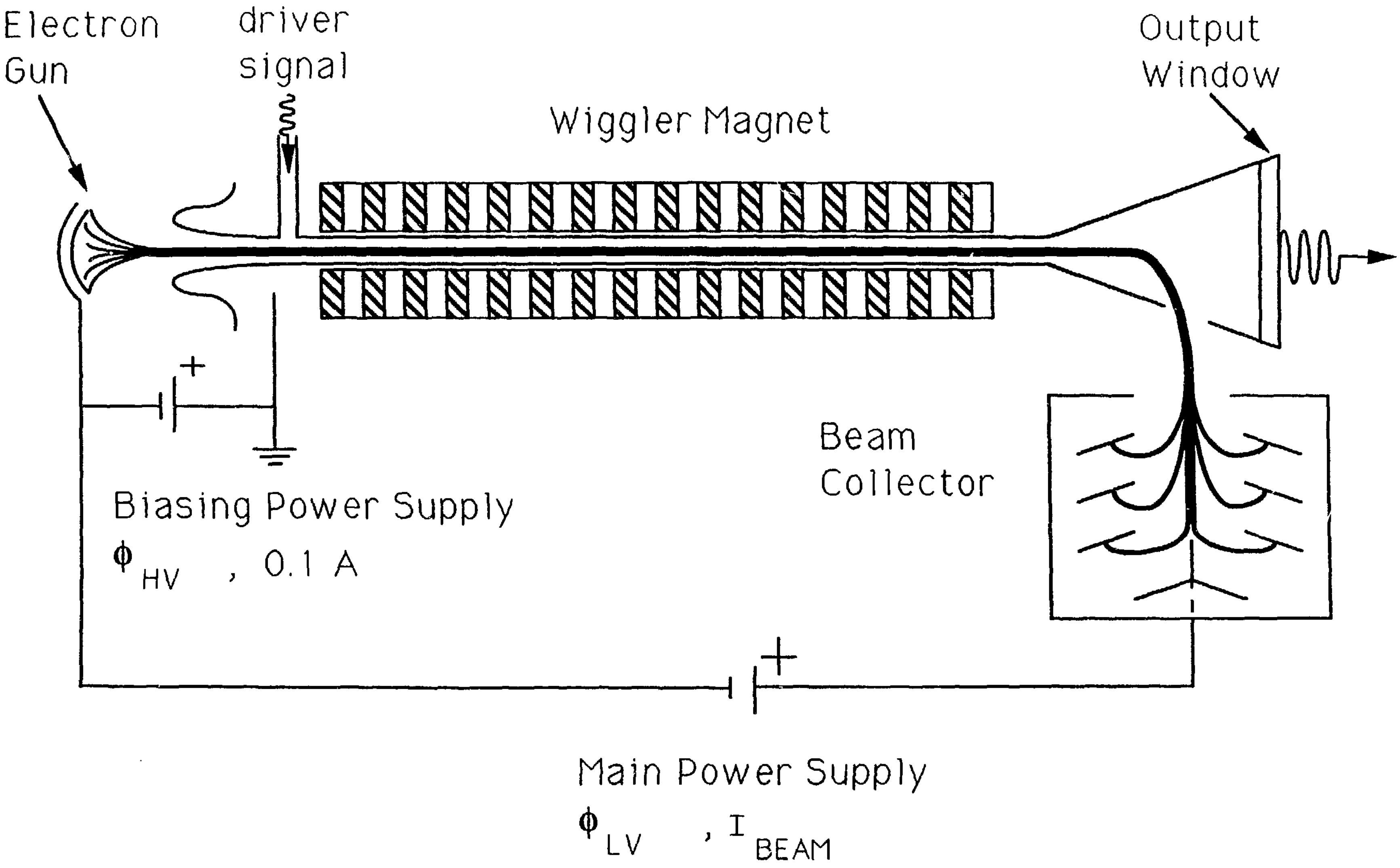
FIG. 1 Schematic of tapered, superconducting FEL amplifier including spent beam energy recovery and high and low voltage power supplies.

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
S_{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
λ_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
S_{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.

Figure 1


Electron Gun
driver signal
Wiggler Magnet
Output Window
+
Beam Collector
Biasing Power Supply
Φ_{HV} , 0.1 A
+
Main Power Supply
Φ_{LV} , I_{BEAM}