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R. A. Jong
E. T. Scharlemann

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HIGH GAIN FREE ELECTRON LASER FOR HEATING AND
CURRENT DRIVE IN THE ALCATOR-C TOKAMAK*

R. A. Jong and E. T. Scharlemann

Lawrence Livermore National Laboratory
University of California
P. O. Box 808, L-626, Livermore, CA 94550

ABSTRACT

We have used the free electron laser particle simulation code, FRED, to examine the design of an FEL for amplifying radiation in the one to two millimeter wavelength range for use in electron heating and current drive in a tokamak device such as ALCATOR-C. We have used as a desired design goal a peak output power of 8 GW, with a minimum input power in the 1 to 100 watt range. We have examined the effects of electron beam current, energy and brightness, laser frequency and input power as well as wiggler wavelength and overall wiggler length on the performance of the FEL. We find that to obtain the desired power output, we require a 3 kA electron beam with a brightness of about 1×10^5 A/cm². For a 1 mm wavelength system, the beam energy must be at least 10 MeV, the laser input power must be at least 100 watts, and the wiggler wavelength is 8 cm, with an overall length of at least 6 m. For a 2 mm wavelength system, the output power goals can be met with a 7 MeV electron beam, with 10 watts of input laser power, and a wiggler with an 8 cm wavelength

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and total length of at least 6 m. The beam and laser requirements to meet the design criteria are less stringent for the 2 mm wavelength system. The magnet requirements to meet the design power level goal is more difficult to meet with a wiggler wavelength of 8 cm compared to a 9.8 cm wiggler wavelength. With the 10 MeV beam energy of the 1 mm system and the 7 MeV beam energy of the 2 mm system, the peak magnetic field changes from about .4 Tesla to .6 Tesla when the wiggler wavelength changes from 9.8 cm to 8 cm.

I. Introduction

The high gain free-electron laser (FEL) amplifier technology being developed at the Lawrence Livermore National Laboratory can be used to produce a high power microwave source [1]. Localized plasma heating at the electron cyclotron frequency, magnetic island stabilization [2], and current drive experiments [3] in tokamak devices are areas of magnetic fusion research that would benefit greatly by the existence of a high average power, high frequency, tunable microwave source. This type of microwave source can be produced by an FEL based high gain amplifier.

In this paper, we describe design calculations for a high gain FEL amplifier in the 1 to 2 mm wavelength range that will supply power for heating and current drive experiments in the ALCATOR-C tokamak. The FEL will be driven by an electron beam provided by an induction linac, and the low power microwave driver radiation (1 to 100 watts) will be provided by microwave tubes called extended interaction oscillators (EIOs). The electron beam and microwave radiation will be transported through the wiggler by a waveguide with a 2.8 cm square cross section, and a quasi-optical transmission line will transport the

high power microwave beam from the end of the wiggler to the entrance port of the tokamak. The details of the quasi-optical system and the physics of the plasma heating will not be discussed further in this paper. We will describe the calculations which will form a basis for the design of the FEL wiggler.

We have considered a range of driver frequencies from 280 GHz (1 mm system) to 140 GHz (2 mm system). The upper frequency range is determined by the desire to operate the ALCATOR experiment with plasma densities in the high 10^{14} to 10^{15} cm⁻³ range with magnetic fields up to about 9 Tesla. The lower frequency range is determined by the existence of radiation sources with power levels at the 1 to 200 watt level. The desired average power goal for the heating and current drive experiments is 2 MW. Since the induction linac has a design goal of a 50 nsec pulse length and a 5 kHz repetition rate (4000:1 duty factor), the peak pulse power goal becomes 8 GW. In addition, to make the heating and current drive experiments in the tokamak easier (to do and to explain), this power is desired to be in the lowest order waveguide mode, the TE₀₁ mode.

II. Description of FRED

The calculations were all done using the Lawrence Livermore National Laboratory, free-electron laser simulation code, FRED [4]. This is a particle simulation code that follows a group of electrons in energy and phase angle in a single ponderomotive well of spatial extent approximately equal to the wavelength of the laser radiation. In a waveguide geometry, the code solves for the electric fields in two dimensions (x and z). However, with an assumed cosine dependence in the other transverse direction (y), we have the three dimensional dependence of the electric fields. This assumption restricts the

waveguide modes to be TE_{m1} , with m even. Alternatively, the code can solve for the (y,z) dependence of the fields and thus determine the TE_{0n} modes, where n is odd.

The electron motion is determined fully three dimensionally. This includes the particle betatron motion resulting from the beam emittance effects as well as initial beam offset. The code can simulate either linear or helical wigglers for free space propagation, and linear wigglers for waveguide propagation. For more details on the FRED code, see Ref. [4].

III. 1 mm (280 GHz) FEL System

To determine the best operating point for the 1 mm system, we surveyed a parameter space with variations in electron beam current, energy and brightness, laser input power and wiggler length and wavelength. The beam current for the calculations reported here was 3 kA, with an energy ranging from 7 to 15 MeV. Three brightness values of 10^4 , 10^5 , and 10^6 A/(rad-cm)² were scanned, with 10^5 A/(rad-cm)² found to be the optimum. The master oscillator input power was scanned from 10 watts up to 10^5 watts, with 100 watts being the standard value used for the majority of the calculations. The wiggler length was scanned from 5 meters up to 15 meters, and two wiggler wavelengths of 8 and 9.8 centimeters were considered. Most of the 1 mm calculations were done using the 9.8 cm wiggler wavelength. An increase in output power of about 30% could be achieved with a wiggler wavelength of 8 cm., although this increase in output power was accompanied by an increase in the required peak wiggler magnetic field.

In Fig. 1, is shown the total power output from a 5 m long untapered wiggler with a 7 MeV electron beam, plotted against the wiggler magnetic field

expressed as a fraction of the resonant (or synchronous) magnetic field. This detuning curve indicates that the optimum beam brightness is about $10^5 \text{ A}/(\text{rad-cm})^2$. Smaller values produce less power because the beam must fill a larger volume in phase space, while larger brightness values produce less power because deleterious longitudinal space charge effects reduce the gain.

Figure 2 displays the power output from a 5 m tapered wiggler as a function of the input laser power for both 7 and 10 MeV electron beams. Clearly, for 7 MeV electrons, the desired 8 GW power output cannot be achieved with input powers ranging from 10 watts up to 100 kilowatts. For input powers from 10 watts up to 1 kW, the output power ranges from 15 kW to 15 MW, corresponding to negligible power extraction from the beam. At input laser powers of 10 to 100 kW, the output power is in the 3 to 4 GW range, with extraction efficiencies of 15% to 20%. The output power achieved with a 10 MeV electron beam is less sensitive to the input laser power, but still cannot achieve the desired power levels in a 5 m wiggler with low input powers. It would take input powers in excess of 1 kW to achieve the design output power level in a 5 m long wiggler. The corresponding extraction efficiencies for the 10 MeV beam cases, range from 15% with 10 watts of input power to about 40% at 100 kW of input power.

The generally poor performance of the 280 GHz FEL based on a 7 MeV electron beam in a 5 m long wiggler is indicated in the plot of total output power as a function of length shown in Fig. 3. The exponential gain region takes up the whole 5 m length, and the gain is a low 6.5 dB/m. Even with longer wiggler lengths, as shown in Fig. 4, the desired output power cannot be attained with a 7 MeV electron beam. The extracted power is seen to level off at a value between 3 and 4 GW for wiggler lengths longer than 10 m. The ultimate value of the extracted power is dependent upon the value of the

parameter ψ_{ir0} , the phase of the resonant particle in the wiggler taper, since ψ_{ir0} affects the bucket depth as well as the tapering rate of the wiggler magnetic field.

Since it is clear that the design power cannot be achieved with a 7 MeV electron beam, we next examine the improvements possible using higher energy electron beams in a wiggler with fixed length. Figure 5 shows the total and TE_{01} output power achieved with a 5 m long wiggler as a function of the electron beam energy. In order to meet the design goal of 8 GW output in a 5 m long wiggler, a beam energy of at least 12 MeV would be required.

The dependence of the output power on the beam energy and wiggler length suggests that there may be an optimum energy and length combination that will permit us to reach the design goal. The plots shown in Fig. 6 show the power output and extraction percentage for the 280 GHz FEL as a function of wiggler length for the three different beam energies of 8, 9 and 10 MeV. Various taper designs are shown on this plot (different values of ψ_{ir0}), but it is clear that for an 8 MeV beam, the output power level peaks around 4 GW, and for a beam energy of 9 MeV, the power peaks around 7 GW. At a beam energy of 10 MeV, the output power levels off between 9 and 11 GW. Therefore, to achieve the 8 GW design goal, a beam energy of about 10 MeV is required, and the wiggler length must be at least 6 m. The corresponding energy extraction levels as seen from Fig. 6 for the 8 MeV, 9 MeV, and 10 MeV beams, are about 25%, 33%, and 40% respectively.

The poor FEL performance with a 7 MeV beam seen in Fig. 3 can now be contrasted with the FEL performance at 10 MeV shown in Fig. 7. The plot of output power as a function of wiggler length shows a strong exponential gain region in the first 4 m of wiggler, with a gain of about 22 dB/m (compared to 6.5 dB/m for a 7 MeV beam). Weak synchrotron oscillations are evident in the

last meter of the wiggler after saturation, but both the total and TE_{01} output powers that can be achieved are in excess of 10 GW.

IV. 2 mm (140 GHz) System

For the 2 mm (140 GHz) FEL calculations, we scanned a more limited parameter range than was used for the calculations of the 1 mm system. We settled on a beam current of 3 kA and a beam brightness of 10^5 A/(rad-cm)², as used in the calculations for the 1 mm system above. The beam energy was varied from 7 to 10 MeV, although only the 7 MeV beam results are described here. The input laser power ranged from 1 to 100 watts. The wiggler length varied from 5 to 7 meters and the wavelength was fixed at 8 cm.

The power output achievable with the 2 mm FEL system was larger than could be achieved with the 1 mm system, for the same electron beam, wiggler and input laser parameters. Recall from Fig. 2, for the 280 GHz FEL, that, for a 7 MeV electron beam energy with a 5 m wiggler, the output power did not exceed 1 GW until the input laser power was in the 1kW to 10 kW range. In contrast, at input power levels in the 1 to 100 watt range, the 140 GHz FEL can produce output powers in the 5 to 9 GW range for electron beam energies of 7 MeV in the 5 m long wiggler, as shown in Fig. 8. This figure indicates that there is only a weak dependence of the output power upon the input laser power, and that with proper optimization of the wiggler taper (by varying $\psi_{\text{in}0}$), output powers in the desired 8 GW range can be attained with a 7 MeV electron beam FEL system operating at 140 GHz. The corresponding power extraction efficiencies for the 140 GHz system are in the 40% to 45% range, again much higher than the comparable values at 280 GHz, which did not exceed 20% extraction, even at much higher input power levels.

In Figs. 9 and 10, the results of a sample calculation for the 2 mm FEL system using a 7 MeV electron beam in a 6 m long wiggler are shown. The input laser power was 10 watts, resulting in an output power in the TE_{01} mode of about 9 GW, corresponding to a total extraction efficiency of about 43%. The axial variation of the peak magnetic field is shown in Fig. 9, indicating the magnetic field taper from a peak value of 6.1 kGauss down to 2.2 kGauss. In Fig. 10, we see the strong exponential gain region in the first 2.5 m of wiggler, with a gain of about 40 dB/m. Following saturation, there are the usual synchrotron oscillations, but the 9 GW output power meets the design goal.

V. Conclusions

The design goal of at least 6 GW of output power in the TE_{01} mode could be achieved at both the frequencies considered, and by implication, at any intermediate driver frequency. With an electron beam brightness of $10^5 \text{ A}/(\text{rad-cm})^2$, and input laser powers of 10 to 100 watts, the minimum wiggler length is about 6 m for both frequencies. A beam energy of at least 10 MeV is required for the 1 mm (280 GHz) system, while for the 2 mm (140 GHz) system, the beam energy requirements are easier to meet, with a 7 MeV beam being adequate. The magnet requirements to meet the design energy goals are more difficult to meet with a wiggler wavelength of 8 cm compared to a 9.8 cm wiggler wavelength. With the 10 MeV beam energy of the 280 GHz system and the 7 MeV beam energy of the 140 GHz system, the peak magnetic field changes from about .4 Tesla to about .6 Tesla when the wiggler wavelength changes from 9.8 cm to 8 cm.

VI. References

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Figure Captions

- Fig. 1. Total power out in GW plotted as a function of the fraction of the resonant magnetic field for a 280 GHz FEL operating with a constant magnetic field, 5 m long wiggler and a 7 MeV electron beam with brightness values of 10^4 , 10^5 , and 10^6 A/(rad-cm)².
- Fig. 2. Power out in GW plotted as a function of input laser power for a 280 GHz FEL with a 5 m tapered wiggler, with electron beam energies of 7 and 10 MeV.
- Fig. 3. Total field power as a function of wiggler length for a 280 GHz FEL with a 7 MeV electron beam.
- Fig. 4. TE_{01} power in GW plotted as a function of wiggler length for a 280 GHz FEL system with a 7 MeV electron beam for various values of ψ_{ir0} (and hence various wiggler tapers).
- Fig. 5. Total and TE_{01} power out as a function of electron beam energy for a 280 GHz FEL with a 7 MeV electron beam and a 5 m wiggler.
- Fig. 6. TE_{01} power and extraction efficiency for a 280 GHz FEL plotted as a function of wiggler length for electron beam energies of 8, 9, and 10 MeV.
- Fig. 7. Total output power for a 280 GHz FEL with a 10 MeV electron beam as a function of wiggler length.
- Fig. 8. Output power in GW plotted as a function of input power for a 140 GHz FEL with a 5 m long tapered wiggler and a 7 MeV electron beam.
- Fig. 9. Axial profile of the wiggler magnetic field and various parameters for a sample calculation for a 140 GHz FEL system with a 6 m long wiggler and a 7 MeV electron beam.
- Fig. 10. TE_{01} output power for the 140 GHz FEL system sample calculation of Fig. 9, plotted as a function of the wiggler length.

Total power out in Gw in 5 m wiggler

260 GHz FEL constant wiggler at 7 MeV

Power out in Gw vs input laser power

Total field power at $E_b = 7$ MeV

TE01 power out in Gw vs wiggler length

Power out in Gw vs beam energy

TE₀₁ power out in Gw vs wiggler length

Total field power at $E_b = 10$ MeV

Power in Gw vs input power in W

Wiggler field

Run quantities

$P_{\text{laser}} = 10$ watts

$a_{w0\text{init}} = 3.2$

$B_{w0\text{init}} = 6.1$

$P_{\text{beam in}} = 2.1 \times 10^{10}$ watts

$E_{\text{beam}} = 7$ MeV

PSIRO = 0.06

$P_{\text{out}} = 9.0 \times 10^9$ watts

$a_{w0\text{final}} = 1.2$ rms

$B_{w0\text{final}} = 2.2$ kilogauss peak

Extraction % = 43.6

Wiggler length = 6 m

TE01 field power at 140 GHz