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INDUCTION-LINAC BASED FREE-ELECTRON LASER AMPLIFIERS FOR PLASMA HEATING *

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ABSTRACT

We describe an induction-linac based free-electron laser amplifier that is presently under construction at the Lawrence Livermore National Laboratory. It is designed to produce up to 2 MW of average power at a frequency of 250 GHz for plasma heating experiments in the Microwave Tokamak Experiment. In addition, we shall describe a FEL amplifier design for plasma heating of advanced tokamak fusion devices. This system is designed to produce average power levels of about 10 MW at frequencies ranging from 280 to 560 GHz.

INTRODUCTION

Induction-linac driven free-electron laser (IFEL) amplifier experiments in the Electron Laser Facility (ELF) at the Lawrence Livermore National Laboratory (LLNL), have demonstrated high gain and efficiency at microwave frequencies ranging from 34.6 to 140 GHz[1,2]. At 34.6 GHz, exponential gains of 34 dB/m were observed, and overall gains of 43 dB were achieved [1]. Peak power levels of 1 GW were achieved with an overall extraction efficiency of 34%. At 140 GHz, exponential gains of 22 dB/m were demonstrated, along with peak powers exceeding 50 MW and overall gains of 65 dB [2]. These successes have encouraged the development of an IFEL amplifier named the Intense Microwave Prototype (IMP) that will provide high-average-power (about 2 MW) microwaves at 250 GHz for electron cyclotron resonance heating (ECRH) of the plasma in the Microwave Tokamak Experiment (MTX). In addition, we have examined some of the physics and technology issues necessary to extend the IMP design to higher average power levels of up to 10 MW per unit.

We first briefly summarize the physics design of IMP and its expected performance. Next we shall describe the experiment. Then we will discuss the design of an IFEL system for ECRH in advanced tokamak fusion devices such as the Compact Ignition Tokamak or the International Thermonuclear Experimental Reactor. This design will consider two operating frequencies, 280 GHz, suitable for fundamental heating at a 10 T magnetic field, and 560 GHz, suitable for second harmonic heating at 10 T. A summary concludes the report.

FEL PHYSICS DESIGN AND PERFORMANCE FOR IMP

The design calculations for IMP are detailed in Ref. 3. We used the two-dimensional version of the LLNL free-electron laser simulation code, FRED [4], the simulation code for sideband calculations, GINGER, and the methodology of the wiggler optimization [3] developed for the design of FEL systems, where moderate space-charge effects are important.

Engineering and physics constraints place limits on the waveguide dimensions, the optimum wiggler period, the peak wiggler magnetic flux density, and the maximum electron beam energy that can be used in the FEL system. The engineering constraints are the rf wall loading and the beam linear fill factor (defined as the ratio of the beam linear dimension to the waveguide linear dimension in the same plane). To satisfy these constraints we require a rectangular (or elliptical) waveguide with dimensions 3.5 by 3.0 cm, a wiggler with a 4-cm gap spacing and a 10-cm period, and a maximum peak magnetic field of about 5 kG. With these limits on the wiggler, the physics constraints (i.e. FEL synchronism) set the maximum beam energy at about 11 MeV. Our choice of a 10 MeV beam energy as the operating energy means that we choose to operate with a peak magnetic flux density of about 4.5 kG.

The calculations assumed an electron beam current of 3 kA, a beam energy of 10 MeV, a beam brightness of 10^8 $A/(m-rad)^2$, and an input laser power of 500 W at 250 GHz. We predict that the peak TE_{01} power will be 12.9 GW (out of a total of 13.2 GW), giving a modal purity of 98% and an energy extraction efficiency of about 44%. The overall gain is about 74 dB with an incremental gain of about 31 dB/m in the exponential gain region. Approximately 70% of the beam particles are trapped in the ponderomotive well.

The FEL performance described above assumes that the FEL parameters are all at their optimum values, with no alignment or wiggler errors, no beam displacements, no energy sweep, and the full rated beam current and input laser power. Such a situation is highly unlikely in the experiment. Calculations were performed to determine the acceptable ranges in the errors when they were applied individually and then when they were combined, i.e., when all the errors are applied simultaneously.

We found that a 10% decrease in the current produces a 20% drop in the output TE_{01} power. The dependence of the output TE_{01} power on the input laser power is quite weak. Input powers ranging from 200 W to 1 kW are acceptable. The allowed combined error limits for the other listed parameters are ±1% beam energy sweep, 1 mm beam offset, and 0.1% rms wiggler error. With these combined errors, using a 3 kA beam with 500 W input power, the output TE_{01} power decreases from the "no error" value of 12.9 GW to about 11.5 GW. The extraction efficiency drops from 44% to 39%. Variations in beam current of about ±4% during the pulse may be required to achieve the desired energy regulation. A 4% average sag in the current during a pulse would reduce the output power to about 10 GW (36% extraction efficiency). The beam linear fill factor grows from the no-error value of 50% to about 60% with the combined errors.

DESCRIPTION OF THE EXPERIMENT

The overall experiment consists of several major segments that are complete experiments in their own right. The Electron Test Accelerator-II (ETA-II) [5] was designed as a high-average-power induction accelerator, expected to produce an electron beam with a current of 3 kA at an energy of up to 10 MeV and a brightness of over 10^8 $A/(m-rad)^2$. In addition, it was designed to produce 50-ns-wide pulses at a repetition rate (PRF) of 5 kHz for up to 30 s. It is currently being tested at an energy, current, brightness, and PRF of 5.5 MeV, 1 kA, 6×10^8 $A/(m-rad)^2$, and 1 Hz. In this paper, we assume that the accelerator will successfully provide the 3-kA current at an energy of 10 MeV and a brightness of 10^8 $A/(m-rad)^2$.

The IMP FEL itself consists of several major subsystems. There is a beam transport system with emittance filter and achromatic jog to transport the beam from the end of the accelerator to the wiggler, a rf coupling and beam matching section to bring the electron beam and input signal together at the entrance to the wiggler, the wiggler itself, and a microwave transport system that transmits the output power to the tokamak. We shall now briefly describe each subsystem.

Electron Beam Transport System

The electron beam transport system transports, diagnoses, and conditions the high-average-power electron beam prior to injecting it into the wiggler. It uses a series of solenoid and quadrupole magnets to transport the beam from the exit of the accelerator to the wiggler entrance. Diagnostics are provided in the beamline to measure beam current, energy, position, spatial shape, energy, and brightness. An emittance filter consisting of a series of range-thin graphite apertures in the beamline is used to scatter any low-density halo electrons to the wall over a distributed

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area. At the exit of the wiggler, an Enge magnet is used to magnetically "reimage" the beam from the FEL into a simple graphite beam absorber.

RF Coupling and Beam Matching Section

Two pairs of quadrupole doublets located immediately in front of the wiggler form the beam matching section, which properly focuses the electron beam into the wiggler to minimize any betatron motion that would otherwise degrade the FEL performance.

The rf coupling section, located near the beam matching section, injects the input microwave signal collinearly with the electron beam. For operation at high average power, a method of coupling the input microwave signal that does not intercept the electron beam is required. The baseline design uses an achromatic jog to offset the axis of the accelerator from that of the wiggler, thereby allowing the microwave signal to be injected straight through the beam matching section into the wiggler. An alternative method that does not require an achromatic jog is desired to minimize costs, and several methods are being studied. In general, these methods involve an apertured reflector that is located within the beamline and injects the microwave signal into the waveguide at an oblique angle.

Wiggler Design

The wiggler being designed for IMP will have a 3.8-m long high-field section tunable from 4.7 to approximately 2.5 kG, and a second, lower field section tunable from approximately 3.5 to 0.5 kG. It will have a 10- cm period and a gap of about 3.7 cm. In addition, to meet the random wiggler error tolerances determined in the simulations, the pole-to-pole random errors ($\Delta B/B$) must be less than 0.1% rms. We are designing a permanent-magnet laced electromagnetic wiggler for this application [6].

In the laced wiggler concept, permanent magnets are employed to suppress magnetic saturation in the poles of a dc iron-core electromagnetic wiggler; the laced geometry features permanent magnet blocks located between poles (just as in a permanent-magnet hybrid wiggler) actually interspersed in the coils. This configuration allows a higher maximum field to be attained, although the tuning range (within which the random field errors are acceptably small) is somewhat reduced.

Microwave Transport System

A quasi-optical microwave transmission system has been designed to transport the high power microwave radiation generated within the FEL from the wiggler to the tokamak, a distance of over 30 m. The system uses four copper mirrors, each about 17 by 23 in. in diameter, and whose surface is an elliptic paraboloid. The system has been designed to preserve horizontal polarization, to keep the microwave power density well below mirror surface-heating damage thresholds, and to maintain acceptable transmission losses. Microwave transport codes predict that the total transmission loss from the wiggler through the 4- by 30- cm MTX port is less than 8%, with only half of that occurring after the first mirror. The dominant losses at the first optic arise from loss of power in the side lobes in the far-field radiation pattern of the waveguide aperture. The transmission system is windowless, with the vacuum maintained by two turbopumps and the differential pumping between the FEL and tokamak systems that occurs naturally because of the long vacuum path.

IFEL DESIGN FOR CIT AND ITER APPLICATIONS

While wall loading was not a problem with the 2- MW average power and the short pulse length of 0.5 s in IMP, the higher average power levels and longer pulse lengths (5 to 10 s) required for the 10-MW designs would make the expected life of a smooth-walled copper waveguide much too short to be considered practical. By considering the low dissipation of the HE_{11} mode and propagation in a circular, corrugated waveguide, we calculate a temperature rise that is lower by two orders of magnitude (compared to the smooth-walled case), and consequently, the fatigue life of the waveguide is no longer an issue. However, the beam linear fill factor in the waveguide is still important and it determines the required waveguide size and the wiggler gap spacing. We require waveguides with an inner diameter of about 3.5 cm and thus need wiggler parameters that are identical to those of IMP, namely a 4 cm gap, a 10 cm wiggler period, and a limit of 5 kG on the flux density. Moreover, FEL synchronism considerations again put an upper limit on the usable electron beam energy of about 11.5 MeV at 280 GHz and 16 MeV at 560 GHz.

The FEL optimization and error considerations are similar to those for the IMP design. We again have a 3 kA beam with a brightness of 10^8 A/(m $-$ rad)^2. The master oscillator input power to the wiggler is 500 W. A summary of typical parameters is given in Table 1.

To examine the physics and technology advances needed to produce an economical IFEL system for heating CIT or ITER, we have undertaken a systems study [7] to examine the effects of higher magnetic fields and beam energies, changes in the PRF and pulse width, advances in the pulse power drivers, and improvements in ferrite material and cooling. The studies show that costs can be decreased if we do not have to multiplex two pulse power chains in each cell. The most efficient method of obtaining increased peak power in the FEL is to increase the initial electron beam energy. This increase will cause the accelerator costs to go up; however, if the gain increases sufficiently, only one pulsed power chain per cell is required and the costs would decrease. The cost and risk factors are folded into our design strategy to produce a system with minimum cost and reduced risks. For the basic configuration for the 280-GHz, 10-MW FEL, the accelerator has four pulse power chains, no multiplexing, a pulse width of 70 ns, and a PRF of 10 kHz.

SUMMARY

We have described the IMP FEL presently being built at LLNL for plasma heating experiments in MTX. We expect to produce 2 MW of average power at 250 GHz for periods up to 0.5 s using a 3-kA beam at an energy of 10 MeV and a brightness of 10^8 A/(m $-$ rad)^2. Even with realistic limits on the electron beam offset, beam energy sweep, and random wiggler errors, the calculations indicate that the desired power levels can be achieved.

We have also shown that IFEL technology can be used for plasma heating in an advanced tokamak fusion device, providing average power levels in the 10- MW range at frequencies of 280 and 560 GHz with basically the same machine. The design uses a corrugated waveguide to propagate the HE_{11} mode and appears to alleviate possible microwave loading problems on the waveguide walls. At 280 GHz, we have chosen as our baseline a 10-kHz design that minimizes the total system costs, since only one pulsed power chain is required per cell. We achieve the required duty factor by using a 70-ns pulse width and by increasing the electron beam energy to 13 MeV, thereby improving the extraction efficiency. We must use vanadium-permendur as the wiggler pole material to achieve the higher magnetic fields required at this higher beam energy.

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Table 1.

CIT/ITER FEL design summary. Values in parentheses show performance with combined standard errors.

Parameter	560 GHz	280 GHz
Beam energy (MeV)	14	10
Wiggler length (m)	4.0	3.0
Constant magnetic field (kG)	4.0	4.1
Minimum magnetic field (kG)	1.6	1.4
HE_{11} output power (GW)	15 (13)	12 (10)
Extraction efficiency (%)	37 (32)	43 (34)
Trapping efficiency (%)	69 (65)	74 (55)
Linear beam fill factor (%)	50 (60)	50 (60)