HIGH POWER FREE-ELECTRON LASERS*

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Abstract

Though free-electron lasers have long had the potential for high average power, only recently has significant progress towards this goal been evident. This paper will summarize some of the issues that all high average power free-electron lasers must contend with and will show how researchers have addressed these problems as encountered in four different approaches.

Progress and problems in each of these programs will be summarized and the paths towards even higher power will be discussed.

1 INTRODUCTION

From the early days of free-electron lasers, it was generally believed that FELs were capable of high average power, if for no other reason than that high average power electron beams had been demonstrated. The Strategic Defense Initiative produced a huge effort aimed at producing high average power from a FEL but the initial efforts were predominantly aimed at developing the technologies involved in building a high power device rather than actually building one [1]. Recently several projects have been initiated using existing technologies to build a high average power free-electron laser (HAPFEL). This paper will discuss the problems such projects face and will describe four projects as examples of the approaches possible.

It is useful to start with the most basic ideas. The power from a free-electron laser is given by

$$P_{FEL} = E_{eb} I_{eb} \eta_{FEL} \eta_{opt} \qquad (1)$$

where E_{eb} is the electron beam energy, I_{eb} is the average electron beam current, η_{FEL} is the efficiency of conversion of electron beam energy to laser light, and η_{opt} is the output coupling efficiency of the optical cavity. The electron beam energy is bracketed by the resonance equation for FELs

$$\lambda = \frac{\lambda_W (1+K^2)}{(1+\beta)\beta\gamma^2} \qquad (2)$$

where λ_W is the wiggler wavelength, K is the wiggler parameter, β is the velocity of the electron divided by the speed of light and γ is the relativistic energy divided by the rest mass of the electron. The numerator can range from about 3 cm to 300 cm for an undulator capable of transporting a high-average-power electron beam. This brackets the energy for any given wavelength to a range of a factor of ten. One generally likes to operate at the highest energy one can afford in this range. The energy of a HAPFEL is therefore determined more by the desired cost and footprint rather than by any physics requirements.

The output coupling efficiency is normally rather close to unity. It is very unwise to design a high average power device with low efficiency since the power lost in the cavity will lead to problems with component failure. Since this efficiency is already high, the dominant knobs one has to increase the power are the average electron beam current and the FEL efficiency.

Increasing the electron beam current leads to many practical design problems such as providing the required acceleration and dumping the beam after the FEL. One approach to these problems is to recover as much of the energy of the electrons as possible. The higher the efficiency, the more difficult a task energy recovery becomes. When using energy recovery, the efficiency is limited to a few percent. If one can increase the efficiency by a large factor, the required beam current is reduced by the same factor for a given average power. The problem with this approach is that the requirement for electron beam brightness is much more stringent.

With all the previous comments in hand, two approaches to attaining high average power present themselves. The first is to produce a very high-average-current beam with moderate brightness, lase with moderate efficiency, and recover as much of the electron beam energy as possible. The second approach is to produce a very high brightness electron beam at moderate average current, extract as much power as possible, and dump the beam at full energy.

A third possible approach which has received a great deal of study is the use of a storage ring. Unfortunately the efficiency of storage ring FELs is limited by the so-called Renieri limit [2] which limits the laser power to a small fraction of the synchrotron light emission in the ring. Until this limit can be circumvented, storage ring FELs will not scale well to very high power.

Different energy ranges are more efficiently provided with different accelerator technologies. We therefore find that the mm-wave region is best served by DC or long pulse accelerating techniques such as Pelletrons, modulators, and Induction linacs. To reach the optical wavelength range it is more efficient to use RF acceleration. When energy recovery is used, the choice of superconducting RF is very attractive since the RF power required is dramatically reduced. The cost and complexity of SRF acceleration may not be as attractive for systems without energy recovery though it may still be appropriate due to the large aperture of the SRF cavities. The low shunt impedance of the SRF cavities reduces wake fields that cause emittance and energy spread growth.

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With the previous comments as a guiding principle, I have organized this paper as follows: In section 2 I discuss some of the design issues in common with all. I then cover, in section 3, a pair of examples of low energy electron accelerators driving mm-wave FELs both with and without energy recovery. Finally, in section 4, I discuss two high-energy RF accelerators driving infrared FELs again with and without energy recovery.

2. GENERAL DESIGN ISSUES

Many of the challenges in building a high power FEL are common to all approaches. This section discusses some of these challenges.

The biggest design challenge facing those building high power FELs is to build an electron source with a combination of high average current and high brightness. Either feature is easy to produce but they are rarely available simultaneously. For high-energy RF accelerators this pushes one towards photocathode sources. DC and long pulse sources are well served by state-of-the-art thermionic guns.

Even with a high-extraction-efficiency FEL, the average current in a HAPFEL is quite high. Since the peak current is also high, the possibility of non-linear effects leading to halo formation arises. Halo created in the injector is often present as well. The beam loss in the transport system must be held as low as possible. It is important to remember that the electron beam in such a device will have on the order of 1 MW of power. A loss of even 0.1% can lead to serious problems unless the loss point is designed to handle the power. Energy recovery can exacerbate this problem since the energy spread after the FEL can be quite large and the energy aperture must be larger than this energy spread.

Even if losses are low in most of the system, the final beam dump is usually a tremendous design challenge. If the beam is dumped at high energy, activation of the dump and production of radionuclides is a problem that must be dealt with. At low energy, the current density must be sufficiently low to keep the power density on the dump below 1 kW/cm^2. Since the total power at the dump might be as large as 1 MW, the resulting size of the dump can be quite large.

FELs have very good optical mode quality and a very small mode volume. This means that the power density in the optical cavity can be enormous in a HAPFEL. The optical cavity must be designed so that the mode diffracts out to a reasonable power density before hitting any surface. This can lead to a large increase in the device footprint, especially at short wavelengths where the mode divergence is small.

Finally, it should be noted that the overall system cost for a given average power increases as the net efficiency of the FEL falls [3]. Thus, the net efficiency must be made reasonably high to keep the capital cost down.

3. LOW ENERGY MACHINES

FELs operating in the mm-wave region required electron beam energies in the range of 2–20 MeV. Electron beam brightness in the range can be quite high using DC acceleration as in a Pelletron or in a pulsed modulator or an induction linac. The very high peak current in the induction linac provides one with the option of high efficiency. The first approach discussed here is an induction linac used to drive a high-extraction-efficiency FEL. The example used is that of the ETA III induction linac driving a 2.1 mm FEL used for plasma heating experiments in the Alcator C tokamak [4]. The ETA III produced high current pulses with a 35 nsec, 2.5 kA, flattop at an energy of 6.3 MeV. The typical repetition rate was 1 Hz but the machine could be operated in a burst mode with up to 50 pulses being emitted at 2 kHz. In low repetition rate operation the laser put out up to 2 GW in a 15 nsec pulse. The peak efficiency was therefore over 12%. In burst mode, the efficiency dropped but approximately 6 kW in a 12 ms burst was achieved.

Though the peak power and efficiency in the ETA III device is quite impressive, it is important to note that the efficiency averaged over the 50 nsec FWHM pulse is not quite as impressive and the efficiency in burst mode was quite modest. Any attempt to scale this system to high average power will have to deal with the problem of the wasted beam during the turn-on and turn-off transients. Since this beam may not be well transported, it may lead to transport problems as well. In general, high average power lasers have been CW or long-pulse devices. Pulsed systems, though useful in their own right, do not scale well to high average power.

A second approach to achieving high-average-power mm-wave radiation is being used at the FOM Plasma Physics Institute in Rinhuizen, the Netherlands. The application, as with the ETA III FEL, is for plasma heating. It uses a DC accelerator with an energy up to 2 MV to accelerate a continuous electron beam along a straight beam path through the FEL and then decelerate the beam back to a depressed collector [5]. The design current is up to 12 Amperes. The power supply for the accelerator is only capable of providing 20 mA of current so the energy recovery must be greater than 99.8% for this device to operate with CW beam.

The laser has been operated in “inverted mode” to date. In this mode, the gun is placed in the high voltage dome and the beam is accelerated down to ground. It is then passed through the FEL and dumped. The current in this case is coming from the stored energy in the accelerator and the pulse length is limited to around 20 μs before the voltage has drooped too much. In this mode the laser has operated with power levels as high as 730 kW at 1.46–1.52 mm with an electron beam energy of 1.75–1.83 MeV. The laser lases for around 10 microseconds before the electron beam moves out of resonance with the cavity mode. The efficiency of the FEL is approximately 5%, which is equal to the design value for full power operation.

The project is now installing the depressed collector and the mm-wave transport so that the machine can operate in energy recovery mode. Even when operated pulsed with ms pulses, the laser should be capable of kilojoule pulses. The FEL has a novel optical cavity that allows variable cavity output coupling and low losses while allowing the electron beam to pass through in a straight line. The power density on the mirrors in this cavity is extremely high and remains one of the largest risks of this project. The power may ultimately be limited by optical cavity distortion.

Note that there are many other efforts at producing high average power in the mm-wave range. The University of California at Santa Barbara [6], the University of Central Florida [7], Tel Aviv University [8], and KAERI in Korea [9] have programs producing machines similar to the FOM machine but with average power in the kilowatt range. The Naval Research Laboratory produced a pulsed modulator based device that produced up to 36 W of average power as well [10].

4 HIGH ENERGY MACHINES

4.1 Room temperature Linacs

An interesting approach using a room temperature linac with high-extraction-efficiency is the regenerative amplifier arrangement (RAFEL) [11]. The idea of this device is to use the simplest accelerator possible to produce a very high brightness electron beam. This is then sent through a high gain wiggler with two plane focussing. The first part of the wiggler is untapered to produce high gain. The second part is tapered to enhance the extraction efficiency. The outer edge of the output of this laser is scraped off using an annular mirror and recirculated back through the wiggler using another annular mirror. Since the gain is very high, the output is only weakly dependent on the recycled light. Since the exit mirror only sees the edge of the output distribution, it is not exposed to the high intensities in the center of the cavity. The output coupling efficiency is extremely high since only 8% of the light is actually picked off to be sent back into the optical cavity. The electron beam is separated from the optical mode using a magnet after the annular mirror and dumped.

Results to date from this device are impressive. With 4.5 nC, 16 ps long electron pulses at 16.7 MeV with a normalized emittance of 7 π mm-mrad and an energy spread of 0.5% FWHM, the laser output is 1.9 mJ per micropulse [10]. The macropulse energy for a 16 μsec macropulse is 2.1 J at 1 Hz. When the macropulse repetition rate is increased, the average power increases to 13 W at 10 Hz. For 1 Hz operation, the efficiency is 2.5%. The design efficiency is 5% for 6 nC bunches.

The biggest challenge facing the designer of RAFEL type lasers is increasing the duty cycle while maintaining the electron beam brightness. The present device is limited to around 30 μA of average beam current. A high power device will need average current exceeding 1 mA. The drive laser is the main limitation in the present system. A high power system may have to use a photocathode with a good efficiency in the visible. When the electron beam is raised above 20 MeV the issue of the beam dump must be addressed. Dumping a high power electron beam at high energy produces massive quantities of radionuclides. This is a major design challenge. In a very high power device the beam may have to be decelerated just to reduce the radiation.

There have been many proposals to use a high efficiency FEL to attain high average power but the Los Alamos device is the first to make much progress in showing that such devices may be practical. Design studies show that such a device may be scalable to the 100 kW power level.

4.2 SRF Linacs

The IR Demo FEL at Jefferson Lab was constructed in the period from July 1996 through July 1998 [12]. The accelerator is shown in figure 1. The beam is produced in a DC photocathode gun at a nominal voltage of 350 kV. It is then bunched in a room temperature buncher cavity and accelerated up to 9.5 MeV in two high performance superconducting cavities. The beam is then sent into a 38 MeV cryomodule using an achromatic chicane and accelerated up to the operating energy. For most of the results reported here the final kinetic energy was 38 MeV. The beam is then bent around the output coupler of the laser cavity and matched into a 40 period wiggler with a period of 2.7 cm and a wiggler parameter K of 0.98. The exhaust beam is then bent around the high reflector and transport back to the entrance of the cryomodule in two Bates style achromatic bends [13]. These bends have a design acceptance of greater than 6%.

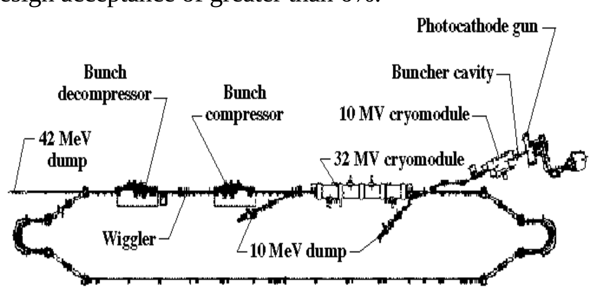

Figure 1. Schematic of IR Demo: the dimensions of the recirculation loop are roughly 49m x 6m.

When operated in a “straight-ahead” mode so that the beam is dumped at full energy, the average current is limited to 1.1 mA by the available RF power. In this configuration the laser emitted up to 311 W [11]. When the beam is recirculated very little RF power is required and the current is limited to 5 mA by the injector. The recirculator has been operated at current up to 4 mA with no lasing and 3.8 mA while lasing. When optimized, the laser emitted 710 W with a current of 3.6 mA on March 11, 1999. This is the highest average power yet recorded from a FEL.

Several features of this laser should be noted. First, the power required in the full cryomodule is essentially independent of the current up to 3.5 mA as shown in figure 2 [14]. This is a verification that recirculation is effective in reducing the required RF power. The loaded cavity Q was chosen to minimized the RF power for a level of microphonics much higher than actually seen so the required power might be lowered below that required now.

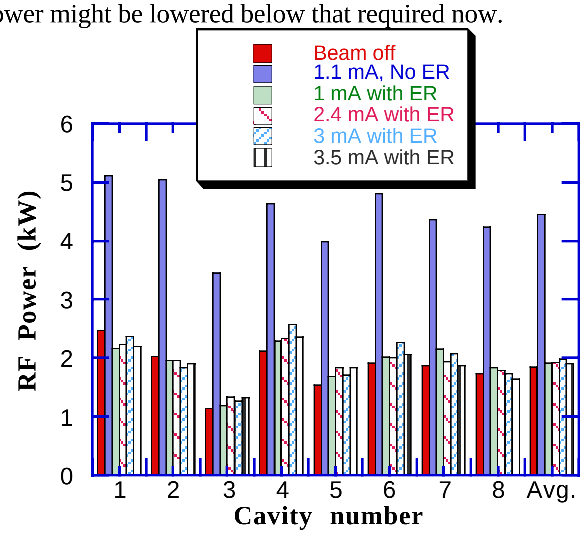

Figure 2. Required RF power for each of the 8 cavities of the full cryomodule and their average as a function of the current. The 1.1 mA values are without energy recovery. All values are with lasing.

The losses in the transport at full energy are quite low. This is very evident in radiation surveys taken after running at high current. When running in "straight-ahead" mode at 1.1 mA the radiation near the dump is over 100 mrem/hr even several hours after the beam is shut off. After running for hours with over 3 mA, the highest radiation level in the vault shortly after shutting off the beam was only 0.5 mrem/hr. This level was near an insertable dump used for tuning up the beam. The only loss point that could be found from these surveys is in the center of the cryomodule where the dose was 0.2 mrem/hr 30 cm from the module. Losses at the entrance of the wiggler with full current in the machine are less than 1 nA.

The power and extraction efficiency seem to be in good agreement with simple theoretical estimates as shown in figure 3 [15]. The errors in the theory (about ±20%) are actually much larger than the differences between the theory and the experiment. The efficiency for a continuous beam should be approximately $1/4N$ where N is the number of wiggler periods. For a pulsed device the theoretical normalized efficiency is 70% of this value. This is close to what we see. The efficiency is also not dependent on the current. We have found that higher efficiency can be achieved by operating at a longer cavity length but that the efficiency is then dependent on the current. We do not understand this at this time. The IR Demo has had few problems arise in its commissioning. The most serious problem has been the availability of the gun, which is now around 35%. High voltage arcs during operation cause sufficient damage that several weeks are required to repair the gun after an arc. Recently the quantum efficiency of the photocathode has been poor as well. This has limited the photocathode to the 4 mA run to date. Finally, the pressure in the 10 MeV dump region grows rapidly for average current higher than 3 mA.

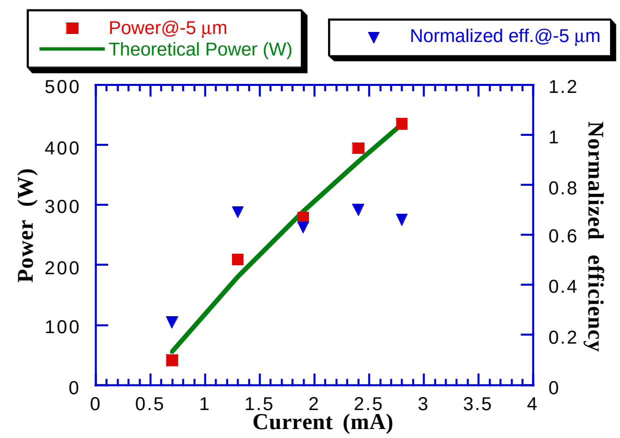

Figure 3. Power at a cavity detuning of –5 µm from the synchronous length and the efficiency divided by $4N$. The theoretical model assumes constant bunch length and emittance and energy spread proportional to the square root of the charge per bunch.

Many potential problems did not arise. No RF instabilities have been seen in the system. Calculations showed that this should be the case but the model could not use the exact physical model of the FEL gain medium. The laser has been very easy to start and diagnostics have allowed good optimization before lasing is attempted. The quality of the magnets has been excellent and the energy acceptance of the Bates bends has exceeded its specification.

Recent work has centered on lasing at 3 µm using a beam energy of 47 MeV. With only a few days operation we have succeeded in recirculating up to 3 mA of beam with no lasing. When high-power 3 µm mirrors are installed, lasing at over one kilowatt should be straightforward.

Several other groups have proposed or are building HAPFELs with energy recovery. Some do not use SRF cavities. A group from the INP in Novosibirsk has proposed a recirculating microtron with 100 mA of beam current and has built the injector for this device [16]. A group at JAERI has operated a device with SRF cavities but without energy recovery and achieved pulsed operation at 100 W [17]. Future plans include energy recovery to increase the average power. A group at Lawrence Berkeley Lab has proposed using PEP B Factory cavities to operate at very high average power in the near IR for power beaming [18]. All these devices have moderate efficiency and, at least in the future, energy recovery.

5 CONCLUSIONS

Clearly FELs are capable of high average power. The most promising devices to date use energy recovery to enhance the overall efficiency of the device. Since even a low peak current device can achieve reasonably high efficiency in the mm-wave region, there seems to be no clear benefit to using pulsed devices in that wavelength range. The FELs using DC accelerators seem to be extremely promising sources of very high mm-wave power. The high brightness available from pulsed photocathode RF guns make them attractive as sources for high average power FELs in the optical range with large extraction efficiency but the duty cycle must be increased by several orders of magnitude with no degradation of the beam quality. This is a major challenge. The lack of energy recovery is also a problem due to radiation hazards. The concept of recirculation and energy recovery has been proven at Jefferson Lab. The main challenge in that type of device is scaling up the energy and current to reach even higher power levels.

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