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PROGRESS IN THE DESIGN OF A DC FEL POWER SOURCE USING A PELLETRON DRIVER

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Abstract

We discuss progress in the design of a DC Free Electron Laser power source using a Pelletron electrostatic accelerator as a driver. Such a power source should deliver up to 200 kW DC power in wavelengths ranging from a few microns to a few centimeters. The advantages of this system for use as a power source for future acceleration techniques are its efficiency, tunability and high average power. In order to achieve DC operation of the system extremely high electron recovery efficiencies are required. It is also likely that FEL operation will result in a large spread of electron energies. These design constraints require the development of a highly efficient electron beam collector as well as beam optics capable of recirculating beams with a large energy spread. We present collector and beamline designs and include electron optics studies for the full range of operating conditions.

Introduction

Assembling the next generation of linear particle accelerators requires progress in three areas. 1) Sources must be developed to provide the coherent electromagnetic radiation used to power the device. 2) Physical structures must be designed that efficiently transfer the power to the high energy beam. 3) Cooling techniques must be developed to enhance beam transport and to provide sufficient luminosity. The conventional approach to assembling electron positron colliders is to put power into the beams with electromagnetic radiation produced in klystrons. These devices are presently operated at voltage gradients of 17 MeV/m. The stored energy and the power needed to overcome resistive losses rise as the square of the gradient of a given R-F source. At constant gradient the stored energy varies as the inverse square of the frequency. It is plausible therefore to consider utilizing accelerating devices having a higher frequency of coherent electromagnetic radiation in order to minimize the cost of the next generation linear collider. One potential power source operating at frequencies above the 3 Gigahertz level of conventional klystrons is the Free Electron Laser (FEL).

One of the most promising types of new accelerators – the Plasma Beatwave Accelerator – uses two laser beams in a plasma with a frequency difference equal to the plasma frequency[1]. The resulting plasma oscillation that is excited in the plasma has the possibility of accelerating an electron beam with a very high gradient (in excess of 1 GeV per meter). Recent experiments at UCLA[2] and Canada[3] have demonstrated the first operational evidence for this concept. Major sources of uncertainty in the beatwave accelerator are the generation of the laser beam and the overall efficiency of the system. We believe that a two frequency FEL will provide the highest laser efficiency possible for such a device.

There are other important applications for the development of a DC FEL as well, including its application as a research tool over a continuous range of electromagnetic frequencies. Electron cyclotron resonant heating of magnetically confined fusion plasmas also requires a high power source of electromagnetic radiation in the millimeter wavelength range.

Researchers from the University of Wisconsin – Madison and the National Electrostatics Corporation (NEC) are now testing a 3 MeV, ampere intensity DC electron beam system using a NEC Pelletron accelerator with an interest in its eventual use as an intermediate energy electron cooler [4,5]. Elias has demonstrated lasing with a similar pulsed electrostatic accelerator[6]. A schematic of the electrostatic Pelletron accelerator is shown in Figure 1. The potential advantages to be obtained by using this system as an FEL are its high beam quality, high average power, and its high efficiency. By building up energy in an optical cavity and using Q switching techniques the peak power can be made to be sufficient for powering linear colliders. The maximum energy transfer from an electron to the electromagnetic field is given by Pellegrini[7]

$$\Delta \gamma_{max} = \frac{1}{2N} \gamma_{resonant} \tag{1}$$

With $\gamma_{resonant} = 7$ (the value for a 3 MeV Pelletron) and N = 34(where N is the number of wiggler periods) the electrons will be able to lose up to 50 KeV to the radiation field in the FEL interaction. The average energy loss of the beam should be about one half the maximum value given above, and assuming an eight ampere electron beam the DC power of the device will be 200 kW. With a Q value for the cavity of 10^4 the possible energy stored in the cavity is $(50kV)(4A)(10^4)(10^{-8}s)$ or 20 Joules. (The length of the cavity is 5 feet leading to a time length of 10^{-8} seconds.) By Q switching this radiation out, a peak power of 2 Gigawatts is attained.

In order to operate as a high energy collider any new acceleration technique must have the ability to be staged – the beam must



Figure 1 -Schematic of the recirculation test set up: (1) High pressure vessel; (2) High voltage terminal; (10) Electron gun assembly; (14) Electron beam collector; (18) Solenoids; (26) Dipole magnet.



Figure 2 - EGUN study of beam evolution with full acceleration into the Pelletron. (All units in mm.)

undergo acceleration by repeatedly passing through accelerating regions. An extremely important advantage of using a Pelletron driven FEL as a power source is its ability to synchronize the radiation of all the cavities by operating all the FEL's in a single cavity. This phase locking of high frequency radiation from one accelerating region to the next will allow a coherent acceleration of the high energy beam. Many existing schemes for future acceleration techniques do not have the capacity as of yet to synchronize successive accelerating regions.

The Pelletron driven two frequency FEL could be rapidly pulsed, enabling operation with larger numbers of bunches and smaller numbers of particles per bunch. This may help to avoid the problem of wake fields disturbing the quality of the accelerating field. (The speed of the pulsing depends on the Q-switching technology employed.)

The work of Pellegrini[7] states that any FEL (operating with a 'traditional' wiggler magnet design) will leave an electron beam with a range of electron energies. For this reason a collector capable of recovering an electron beam with a range of electron energies must be designed as a first step in obtaining an efficient FEL power source.

An investigation of the process of electrons interacting with a wiggler magnet and two frequencies of laser light [8] concluded that for the case of two frequency free electron laser generation electron motion was stable, and that a spread of electron energies would result that is nearly identical to that given by the single frequency free electron laser. This verifies the use of the single frequency FEL parameters that are presented above, i.e., an energy spread of 50 keV is expected to result from two frequency FEL generation.

Electron Beam Optical Design Study

Demonstration of electron beam recovery over a wide range of electron beam energies would show that the electron beam system described above is capable of performing as a DC two frequency free electron laser. In this section we describe our proposal for conducting such a test.

In order to test electron beam recovery over a wide range of electron beam energies, a method must be found to vary the cathode to collector potential. The simplest scheme is to vary the accelerating gradient in the initial portion of the electrostatic accelerating section, by using a variable power supply to provide the potential difference. In the extreme limit of shorting out the initial accelerating section, this process creates a region of non-accelerating drift for the electron beam. The computer code EGUN was used to calculate electron trajectories in the gun and initial accelerating region of the Pelletron for the case of full acceleration and for the case where the first 45 kV of acceleration in the Pelletron was shorted out. (These two calculations represent the extreme operating conditions. Intermediate cases show a smooth transition between these two extremes.)

Figure 2 presents the results of the EGUN study for the case of full acceleration of the electron beam. The electron gun design used in the study is the same as that used in the intermediate energy electron cooling effort. This electron gun was originally designed by Herrmannsfeldt to be an optical match to the Pelletron acceleration tube.

Figure 3 presents the results of the EGUN study for the case where the initial 45 kV of the Pelletron acceleration tube has been shorted out. The EGUN study indicates that the the beam is larger, and converging more rapidly in this situation than for the full acceleration case.

The output of the EGUN study is next used as input for the PELLET electron optics computer code. (PELLET is used to calcu-



Figure 3 - EGUN study of beam evolution with the first 45 kV of the Pelletron acceleration tube shorted out. (All units in mm.)



Figure 4 – Electron optics design for the full acceleration case. (Beam radius as a function of distance along the system. System schematic is presented in Figure 1.)

late beam envelope evolution in electrostatic accelerators [9].) The results of the PELLET studies are presented in Figures 4 and 5. The Figures show the evolution of the beam envelope as a function of position along the beamline. The beamline design is the same as that shown in Figure 1, and the positions of the acceleration tube, deceleration tube, and dipoles are indicated on the top of Figures 4 and 5. The study concludes that successful beam transmission will be achieved throughout the range of electron beam energies we wish to study (without changing the parameters of the beamline elements). (The figures show only the extreme cases, studies done on intermediate cases indicated successful transmission as well.)

An Efficient Single Stage Electron Beam Collector

The design of a single stage electron beam collector combines the successful technology employed in the Fermilab electron cooling experiment[10] with the traditional electron beam collection technique used in high power klystron tubes. The electron beam is slowed to an energy range of between 50 and 100 keV by the Pelletron deceleration tube prior to entering the collector. The collector uses a decelerating Pierce electrode geometry to slow the beam to between 2 and 52 keV without space charge blowup. The decelerated beam next passes into a solenoidal field region. Ions trapped in this region negate space charge blowup of the beam. The beam is then accelerated by 1 keV into the collector cup. The final accelerating voltage suppresses secondary electron emission. The copper collector cup is designed to be large enough so that space charge expansion of the beam will cause the energy deposition per unit area to be small enough to allow water cooling of the device. Figure 6 is a schematic of the proposed single stage electron beam collector.



Figure 6 – Single stage electron beam collector schematic. (Diagram not to scale.) 1) Pelletron deceleration tube; 2) Collector Pierce geometry; 3) Solenoidal drift; 4) Electron trajectories; 5) Collector cup.



Figure 5 – Electron optics design for the case where the initial 45 kV of the Pelletron acceleration tube has been shorted out. (Beam radius as a function of distance along the system. System schematic is presented in Figure 1.)

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