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PROGRESS IN PHOTOINJECTORS FOR LINACS*

Richard L. Sheffield

Abstract

Several programs have started which are based on the photoinjector as the electron source. Some reasons for using a laser to produce an electron beam are improved beam brightness, high-charge single-bunch pulses (>50 nC), and several high-current pulses closely spaced in time.

This presentation will cover present and planned activities in photoinjector development. Topics will include materials, gun designs, and present experimental results.

Introduction

Free-electron lasers and collider machines require electron accelerators capable of delivering pulse trains of electron bunches of high charge density. A high electron density implies a high peak current (100 A to 2000 A) and a low transverse beam emittance (<40 π·mm·mrad). This paper describes the present on-going research in photoinjectors[1][2]. A photoinjector is a laser-switched photoemissive source located in an rf accelerator cell. By placing the photoemitter in a high-gradient rf cavity (Fig. 1), the space-charge effects due high-electron densities can be substantially reduced. A laser-switched electron source gives precise control over all aspects of the electron distribution: peak current, spatial profile, and temporal profiles. This type of source also has a large flexibility in interpulse spacing; the interpulse spacing can range from picosecond pulse separations to a single pulse. The number of

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photoinjectors which are either operating or planned for operation has increased dramatically over the last several years. Figure 2 shows the increase in the number of projects which are based on this type of source.

This paper is divided into three sections following the introduction. The first section covers presently operating photoinjectors; the second section covers planned systems; and the third section covers some of the physics and engineering considerations.

Present research programs using photoinjectors electron sources

Upgrade of Los Alamos FEL Accelerator

The Los Alamos FEL (High Brightness Accelerator Facility or HIBAF) has been upgraded to provide electron beams of the quality and intensity required by shorter wavelength (<3 microns) FELs[34]. The improved electron beam is primarily the result of adding a photoinjector to the accelerator. However, the entire device is being modified to demonstrate that the beam quality can be transported to the FEL without degradation. The facility has produced initial data at 17 MeV. The results are a 300 A peak current, 12 ps pulse width and an emittance of 40 π·mm·mrad (90%, normalized). The photocathode was CsK_2Sb.

The purpose of HIBAF is to provide a benchmark of the computational models used to design advanced FELs. The final design goals of HIBAF are 40 MeV of electron energy, peak currents of 300 A, and a normalized emittance less than 35 π·mm·mrad (90%). An experiment layout is given in Fig. 3.

Duke-Rocketdyne Experiment

The construction of the Mark III accelerator has been described in detail elsewhere[5]. The layout of the experiment is shown in Fig. 4. The machine parameters are as follows: macropulse length of 2-5 μs, micropulse length of 2.2 ps after obtaining an increase of 10 in peak current from the alpha magnet, and a gun energy of 1 MeV. The alpha magnet is a momentum filter and is able to limit the electron energy spread to less than 0.5%. The electron source is a LaB_6 cathode. Originally the cathode produced electrons by pure thermal emission. However, because the electrons are emitted at all phases of the rf, many of the electrons are accelerated at phases which enable the electrons to back-stream into the cathode. Since current emission from the cathode is limited by average-power heating, then by using the laser to limit the emission to the correct rf phase, higher peak currents can be obtained[6]. In this mode the LaB_6 was operated just below its normal emission temperature, and a laser was used to pulse the cathode. Operation with the laser resulted in an increase in peak current from 33 A to 75 A with no observable loss in beam emittance. The beam emittance was estimated to be 4-8 π·mm·mrad. During operation, the gun pressure was about 5×10^9. Not enough operation time has been available to study the cathode lifetime; but based on previous performance, the expected lifetime should be much greater than 1000 hours.

LEL-HF in Bruyeres-le-Chatel

This photoinjector design[78] has a cavity frequency of 144 MHz. The lower frequency was chosen to reduce the rf effects by using larger cavity apertures and by having the rf fields approximate DC conditions during the electron transit. The design parameters are a beam with 10 to 20 nC, a 1 to 1.5 MeV exit energy from the first cavity, bunch lengths of 50 to 100 ps, an accelerator gap of 7 cm, and a surface field at the cathode of 15-20 MV/m. A schematic of the experiment is shown in Fig. 5. They have measured emittances of 80 π·mm·mrad at 10 nC.

Accelerator Test Facility at Brookhaven National Laboratory

The Accelerator Test Facility at Brookhaven National Laboratory (BNL) is being developed into a research facility for laser acceleration and FELs. The design goal for the accelerator is a final energy of 50 MeV and an emittance of 15 π·mm·mrad at 1 nC. They are building a 2.856-GHz photoinjector to drive the linac[9]. The S-band, standing wave, disk-loaded structure will operate in the short rf pulse regime (6 μs). The schematic of the photoinjector is shown in Fig. 6. The photocathode is made of yttrium metal. They have operated the photoinjector at the design gradients which corresponds to a peak cathode field of 102 MV/m and peak surface fields of 120 MV/m.[10]

Planned research facilities using photoinjectors sources

A number of experiments are planned for operation in the next few years (Fig. 7). The following text briefly describes differences in the planned experiments. Experiments which are similar to the BNL design of an S-band accelerator and metallic photocathodes are UCLA and CERN[11] (also investigating multialkali photocathodes). Experiments which are similar to the HIBAF design at 1300 MHz and multialkali photocathodes are the AFEL at Los Alamos National Laboratory and the FEL project at the University of Twente[12]. The Laboratoire de l'Accelerateur Lineaire in Orsay[13] is building a S-band two cavity gun with independent rf control for the two cavities and a laser-driven dispenser cathode. The ELFA FEL project[14] in Milan will use two 352 MHz cavities and a multialkali photocathode. The Frascati ARES project[15] and the Bergische Universitat-Gesamthoschule Wuppertal[16] project will use two superconducting 500 MHz cavities and multialkali photocathodes. Argonne National Laboratory's wakefield accelerator facility[17] will use two 1300 MHz cavities and a metal photocathode. Boeing[18] will use a two cavity 433 MHz injector with a 25% duty factor and a multialkali photocathode.

AFEL

At Los Alamos the design of a new 20 MeV compact linac based on the photoinjector has been completed. The linac will be approximately 1.2 m long and will be operated with a 10 μs macropulse at up to 10 Hz with a 0.5 A average during the macropulse. The final electron beam characteristics, from PARMELA simulations, are a beam emittance of less than 12 π·mm·mrad, an energy spread of 0.2%, and peak currents in excess of 350 A. At these performance parameters and the use of a microwiggler with a period of 3 mm operating on the third harmonic, the calculated gain at 400 nm is greater than 50 % at 20 MeV.

Physics and engineering considerations

By definition, a photoinjector relies on a light source to turn on and off the photoemitter. In almost every instance the light source is a laser. As a consequence, this type of electron source falls out of the typical experience of a source designer and could be viewed as a serious complication. However, laser development is also being driven by the development of photoinjectors and laser systems which match the requirements of some of the photoinjector designs can be bought from laser vendors.

The type of laser system depends on the choice of photocathode material. Photocathodes, such as GaAs and multialkali, can be manufactured to have a high quantum efficiency in the visible wavelength band. The laser for these types of cathodes can be built by existing laser vendors. The drawback of this type of photocathode is that it requires an UHV environment. Some photocathodes, such as LaB_6 and yttrium, have a response in the ultraviolet ($<$350 nm) but have much less stringent vacuum requirements. However, the laser system required to drive this type of cathode is more difficult to build and not readily supplied by vendors. Another consideration is the uniformity of the laser illumination and of the cathode quantum efficiency.

A possible problem in the higher quantum efficiency, high-gradient guns is field emission. The reduction in the work function at the cathode surface due to the presence of high fields can produce a measurable dark current. Dark currents have been observed at the HIBAF experiment. The dark current levels in that experiment did not adversely impact the operation of the accelerator but did produce a background signal on the beam diagnostics.

The remaining issue of the high quantum efficiency photocathodes is lifetime. Up to now, high quantum efficiency cathodes do not survive beyond a few days of operation in a rf cavity. However, the same cathodes have comparably long lifetimes when just rf is present or just the laser is present. Also, hundreds of coulombs have been extracted in DC gun experiments. The only observable difference when running a photoinjector is the presence of the a large pressure rise in the cavity when an electron beam is present. Ed Garwin of SLAC suggested that the lifetime problem might be similar to the problem experienced in storage rings. In storage rings, beam lifetime is limited by electron stimulated desorption (ESD) of gases from the walls of the ring. We know that some of the same gases produce by ESD can contaminate a cathode when present in small amounts (for instance, CO_2 or H_2O). ESD releases the gases trapped in the grain boundaries of the wall of the cavity. These gases are bound with several tens of eV energy. Therefore, a standard bake at 250 to 350 C would not drive out these gases. One way to clean up a system is to run beam. Figure 8 is photodesorption during beam conditioning for aluminum at the NSLS VUV storage ring[19]. For a low duty cycle experiment, this type of conditioning would take years and is therefore not practical. Another approach is to use glow discharge cleaning of the walls. Figures 9 and 10 demonstrate the effect on the rings at Brookhaven[20] and CERN[21], respectively. This type of cleaning will be tried at HIBAF and the results known by the end of the calendar year.

Conclusions

The production of high-current high-brightness electron beams has enjoyed considerable progress over the last several years, mainly because of changes in the requirements imposed by free electron lasers. The photoinjector has demonstrated the ability to produce very bright electron beams. Several groups around the world are designing bright beams based on this technology and continued improvement in photoinjector design and engineering is expected. The real limit of electron brightness using a photoinjector is still to be determined.

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