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THE INJECTOR FOR THE CEBAF CW SUPERCONDUCTING LINAC*

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Abstract

The CEBAF cw superconducting linac contains two 0.5 GeV linacs connected by recirculator arcs. The electron beam from the injector must be sufficiently relativistic to match a 1 GeV recirculated beam in the first linac. An injector is described that produces a high quality electron beam with transverse emittance of ≤ π mm-mrad and longitudinal emittance of ≤ 15 π keV-degrees. A subharmonic chopper and three independently adjustable chopping slits are used to differentially load successive bunches. A room temperature linac is used to accelerate the electron beam from 100 keV to about 0.6 MeV. Eighteen five-cell superconducting cavities are used to increase the energy to approximately 45 MeV for matching with the rest of the linac.

Introduction

The quality of the beam produced by the injector is set by the requirements of the final beam from the linac. The specifications of the electron beam from the CEBAF linac are listed in Table I.

Table I. DESIGN BEAM PARAMETERS

Energy	$0.5 \le E_o \le 4.0$ GeV
Total average beam current	$1 \le I_{ave} \le 200$ μA
Number of simultaneous extracted beams	3
Minimum current in individual beam	≥ 1% of total
Beam emittance ($\pi\epsilon$) (at 1 GeV)	2×10^{-9} π m-rad
Beam energy spread (4σ)	$\Delta E/E \le 10^{-4}$

In order to achieve this beam quality the injector must provide a beam with a transverse emittance significantly better than the desired final value because effects such as rf steering,[1] synchrotron radiation and emittance dilution from misalignments[2] will degrade it. Therefore, the design emittance of the electron gun and the 100 keV beamline is 1 π mm-mad. This is less than 10 % of the final emittance requirement.

The ultimate energy resolution from an accelerator, if all other aspects are held perfect, is related to the bunch width Φ from the injector by

$$\Delta E/E \sim \Delta\Phi^2/8.$$

The required energy resolution can be achieved with a bunch width of 1.5°, but a bunch width of 1° or less is desirable to reduce the effects of rf steering[1] and to relax the tolerance on the rf drive line[3].

Figure 1 shows a schematic view of the CEBAF injector. A 100 keV line, described in the next section, is used to prepare a chopped and bunched beam that is then accelerated in the capture section. The electron beam is captured in a graded-beta, room temperature, standing wave structure and accelerated to about 0.6 MeV. It is then further accelerated up to about 5.5 MeV with two five-cell superconducting rf (SRF) cavities that act as a preaccelerator. After the preaccelerator, there is a region of about 6 m for beam diagnostics, tuneup and for placing differential pumping at the ends of both cryogenic accelerators. Two standard eight-cavity cryomodules are used to provide the necessary acceleration to increase the electron beam energy up to approximately 45 MeV for injection into the linac.

100 keV Line

The 100 keV line is modeled after the injectors for the microtrons at the National Bureau of Standards[4] (NBS) and the University of Illinois Nuclear Physics Laboratory (NPL)[5]. Figure 2 shows a schematic view of the 100 keV section of the injector. The electron beam is produced with a 100 keV electron gun and focused on the first of two emittance defining apertures, A-1 and A-2. Preliminary design of an electron gun has been completed, and the results checked with a gun design computer code by Herrmannsfeldt[6]. It uses a 1 mm diameter cathode in Pierce geometry and a control electrode to produce a beam of up to 10 mA with an emittance of less than 1 π mm-mrad at 5 mA. Apertures A-1 and A-2 are used to maintain an emittance of 1 π mm-mrad over the entire dynamic range of operation.

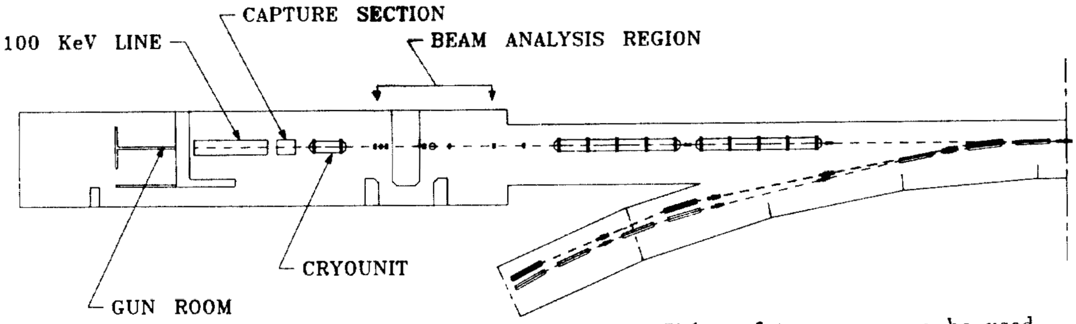

Figure 1. General layout of the CEBAF injector. Either of two guns can be used to provide a beam that is chopped and bunched in the 100 keV line and accelerated in the capture section and preaccelerator. A final beam energy of nearly 50 MeV is obtained from the two cryomodules.

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A subharmonic rectangular chopping cavity with an rf drive at 748.5 MHz (1/2 f_o) in one plane and 499 MHz (1/3 f_o) in the other plane is used to scan the electron beam on aperture A-3 with the scanning pattern shown in Fig. 3. The rectangular boxes represent regions where the beam is transmitted. These can be individually adjusted to produce three succeeding bunches with different charge per bunch and then recombined at the second chopper. At the extraction region these are separated with rf separators into three different electron beams that can be delivered to the three end stations. The current in each of the three electron beams can be controlled over a dynamic range of greater than 100 by this technique. The choppers and aperture A-3 will typically produce a 60° bunch for the maximum beam current. If the full 200 μA is in one beam at 1/3 f_o, then the required current from the electron gun is 3.6 mA. Since most applications will not require electron currents this high, the gun will be optimized for lower current. The chopped beam is further bunched to about 7° by a single cavity buncher. After a 1 m drift, the beam enters a graded-beta capture section.

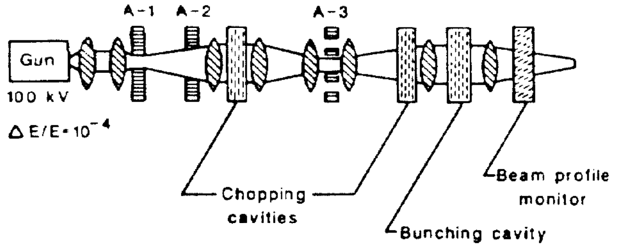

Figure 2. Schematic view of the 100 keV beamline. This section produces a chopped and bunched electron beam for further bunching and acceleration in the rest of the injector.

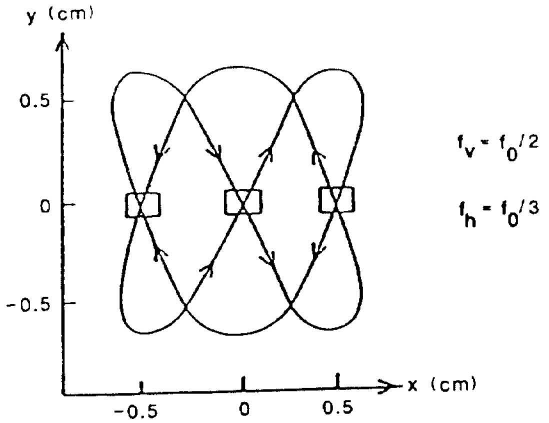

Figure 3. The electron beam pattern produced by the first chopper at the aperture A-3.

Capture Section

A standard CEBAF-Cornell SRF cavity has an aperture that is 7 cm diameter. Figure 4 shows the axial electric field for one-half of a five-cell cavity calculated by Superfish[7]. The upper half of the figure shows the geometry of the cavity, with the same length scale as the axial field plot. The dashed vertical line indicates the end of the cavity. Because of the large aperture, the electric field extends well beyond the entrance of the first cell. It is difficult to capture into this field with a 100 keV electron beam, a point that is discussed further in the section on PARMELA[8] calculations. In order to capture the 100 kev electron beam and increase its energy, several options were considered: a higher energy electron gun; a modified superconducting capture section; and a room temperature standing wave capture section. Higher electron gun energies were not attractive because a laser driven GaAs polarized electron source will be added, and operational problems for this type of source become more severe at higher gun energy. A superconducting capture section, modified to reduce the fringing field, would require development whereas a room temperature capture section could be largely copied from the microtron[4,5] designs. In order to use the same (nominal 5 kW) klystrons used for the superconducting cavities, a short, five-cell capture section that is graded in beta to match the increasing electron velocity, will be used. It will be powered by two 5 kW klystrons in parallel, operating at a nominal 8 kW of rf power. This produces an energy gain of 440 keV in the capture section, producing a 0.54 MeV electron beam at the exit. PARMELA calculations have been used to determine the optimum cell lengths to capture and continue bunching the low energy electron beam. The capture section must then be operated at the design gradient to obtain the desired electron beam properties. Investigations are under way to determine the effects of small changes in the rf amplitude and phase of the capture section on these properties.

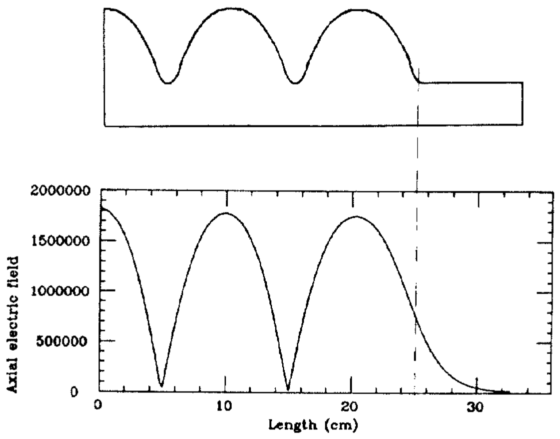

Figure 4. The axial electric field, calculated by Superfish, for half a five-cell superconducting cavity. The cavity geometry is shown to the same length scale, to show the extent of the fringing field.

Preaccelerator

The 0.54 MeV electron beam is accelerated by two superconducting cavities in a short cryostat dedicated to the injector. This is the only nonstandard cryostat in the linac, although the cavities are the same. The energy gain of the SFR cavities is the nominal 5 MeV/m that is expected in the rest of the linac. However, the first 0.5 m cavity is still bunching the beam and the energy gain is only 2.10 MeV, with a final energy of 5.15 MeV at the exit. There is a region of about 6 m after the preaccelerator that will contain a small bending magnet for beam diagnostics and a beam tune-up area, and a 5-foot-thick shielding wall. The electron beam is then injected into two standard eight-cavity cryomodules^9, increasing the energy up to about 50 MeV for injection into the first linac.

PARMELA Calculations

The optics of the entire injector have been studied with the PARMELA^8 code, a 2-dimensional particle simulation code that includes the effects of space charge for nonrelativistic electron beams. It also includes the correct radial and axial rf fields for the Los Alamos standing wave accelerator cells. These are used in the capture sections for the NBS and NPL microtrons, and will also be scaled to 1497 MHz for the CEBAF capture section. PARMELA has been modified at CEBAF to add the five-cell superconducting cavity, including the large axial fringing field, as is shown in Fig. 4. PARMELA calculates both the transverse and longitudinal optics of the electron beam during the acceleration process from the electron gun until the beam is fully relativistic.

PARMELA was used to model the capture process directly from an electron gun (plus chopper and buncher) into a five-cell superconducting cavity, over a wide range of input energies, phase and phase spread. Figure 5 shows some of the results of PARMELA calculations for the capture process, including the baseline design of 540 keV being captured. Electron beams of 200 μA average current and the energies shown were chopped and bunched to about 1.5° to 2° and injected into a five-cell SRF cavity over a range of input phase as shown on the abscissa. For energies below 300 keV, the energy gain was much less than the 2.5 MeV that could potentially be gained in the SRF cavity. The optimal spectral quality of the electron beam at the exit of the SRF cavity was also reduced for input energies below about 200 keV. The upper curve is the case of a 540 keV electron beam from the five-cell capture section into the SRF cavity. The arrow shows the phase that was used in the reference calculations for the rest of the injector.

Status

A baseline design for the injector of the CEBAF accelerator is nearly complete. It uses a 100 keV beamline to chop and bunch the electron beam and a room temperature capture section to increase its energy to 540 keV. These components are modeled on the proven injector designs of the NBS^4 and NPL^5 microtrons. The beam is further bunched and accelerated in two five-cell SRF cavities. After a tuneup area, the beam is accelerated to approximately 45 MeV before injection into the recirculating linac system. PARMELA calculations have shown that an electron beam with $\lesssim 1°$ and $\lesssim 20$ keV at 5 MeV can be obtained with this design. Modelling is continuing to determine the sensitivities of the electron beam to small changes in injector parameters such as gun voltage and the phase and amplitude of the rf elements. Procurement is underway for some of the hardware of the 100 keV beamline.

Acknowledgement

The author expresses his thanks for the contribution of G. Krafft, who did the coding to add the SRF cavity to the PARMELA code.

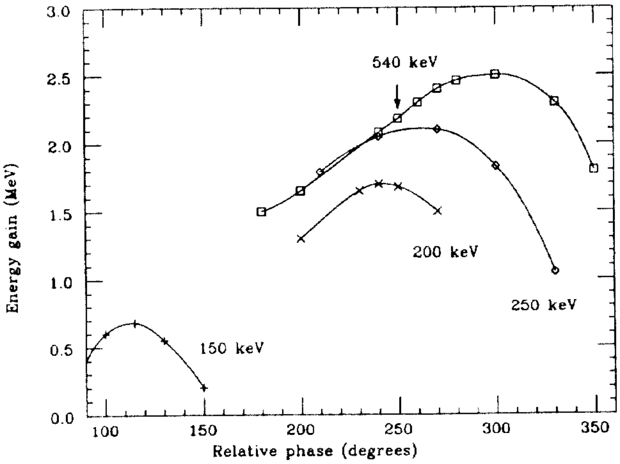

Figure 5. The energy gain, ΔE, in a 0.5 m, five-cell SRF cavity at an accelerating gradient of 5 MeV/m, as a function of the input phase Φ for electron beams with the input energy listed. The upper curve at 540 keV is the beam from the room temperature capture section.

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