DOUBLE-BEND ACHROMAT BEAMLINE FOR INJECTION INTO A HIGH-POWER SUPERCONDUCTING ELECTRON LINAC

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Abstract

To take advantage of the high duty cycle operation of superconducting electron linacs, commercial systems use thermionic cathode electron guns that fill every radiofrequency (RF) bucket with an electron bunch. For continuous operation, the exit energy of these guns is limited when compared to pulsed systems. The bunch length and energy spreads at the exit of the gun are incompatible with low losses required for the superconducting cavity. To mitigate this issue, an achromatic bend system is used to transport and filter the beam from the gun to the superconducting RF cavities. This achromatic system efficiently exploits symmetries using a minimal combination of two solenoids and two dipoles to map an incident round beam profile into a round beam at the exit. Edge angle focusing of the dipoles is exploited to balance the focusing effects in the two transverse planes. This design also allows beam filtering at the symmetry plane (axial midpoint) where the dispersion is maximal. Additionally, the bend angle positions the electron gun off of the high energy beam axis, allowing multipass operation of the superconducting booster. This study details the optical design of the double-bend achromat along with the design of the magnets and beam chambers. Operational experience with the system is reviewed.

SRF ACCELERATORS FOR RADIOISOTOPE PRODUCTION

National laboratories around the world have developed superconducting radiofrequency (SRF) particle accelerators for both high energy and high average power accelerator systems for a broad variety of research applications. SRF accelerators offer a low-cost pathway to high average power electron beams for a variety of commercial and research applications. These systems are robust and flexible in terms of the beam energy and pulse structure, with duty cycles up to and including continuous (CW) operation.

Niowave designs use ~20 MeV, >10 kW electron beams to produce high-energy X-rays and neutrons for commercial applications. Medically and industrially relevant radioisotopes are made by fissioning of uranium or by knocking out protons or neutrons to transmute targets [1, 2]. A two-pass machine with a three-cell SRF cavity is shown in Fig. 1. These machines exploit an efficient solenoid double-bend achromat (DBA) to transport the beam from the gun to a multi-cell SRF cavity and recirculate the beam through the cavities a second time. Here we describe in detail the low-energy DBA, but the concepts involved in the design of the recirculating arc are analogous.

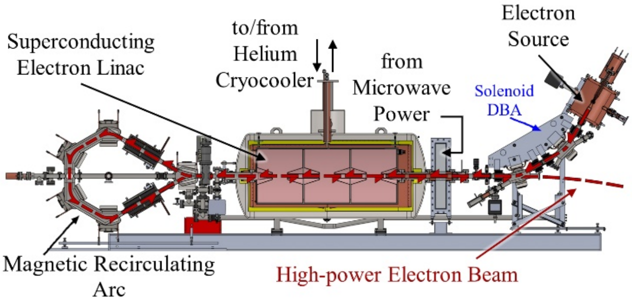

Figure 1: Annotated CAD model of a two-pass linac.

THERMIONIC-CATHODE RF ELECTRON GUN

The electron source for Niowave linacs is a normal conducting RF electron gun with a thermionic cathode. These cathodes are robust, with lifetimes upwards of 10,000 hours at the current densities required. With stable emission densities of 20 A/cm^2, small cathodes (~1 mm in diameter) provide the needed tens of mA to inject into the cryomodule for acceleration. These guns can operate CW, but the beam energy at the gun exit is low (~100 keV). The beam is only weakly relativistic until it reaches the first gap of the SRF booster cavity.

The requirement on the quality of the electron bunches (beam brightness) produced by the gun is simply that they are accelerated in a superconducting structure with low losses. The principal issue is the long bunch length. The bunch length at the gun exit is controlled by a combination of a DC reverse bias and two RF frequencies at the cathode surface. These same fields also mitigate back-bombardment of the cathode by preventing electron emission at phases that would not pass the accelerating gap of the gun. The gating design does not intercept any part of the electron beam. This design allows long cathode lifetime at high current with high beam brightness.

SOLENOID-BASED DOUBLE-BEND ACHROMAT

In order to use the SRF cavity twice as shown in Fig. 1, the electron source must be moved away from the high-energy beam path. The beam is bent onto the SRF cavity axis with a DBA bend. The bend section also provides beam dispersion (transverse separation of different energy electrons) which makes it possible to further filter the energy spread and the accompanying bunch length by using a scraping aperture in the axial midplane (point of maximal dispersion). Classic Chasman-Green type DBAs were first developed for storage rings using quadrupole focusing elements between two bending elements to redirect different energy electrons back onto the reference trajectory upon passing through the second bend [3]. In the Niowave system, an achromat is implemented with reversed polarity solenoids as shown in Fig. 2. The low energy of the Niowave electron gun allows solenoids to be used efficiently for focusing. The DBA is symmetric about the axial midpoint. Dipoles are adjusted for 30° bend. The paired solenoids immediately upstream and downstream of the midpoint have reverse polarity (coils connected), which counters the rotation of the beam, restoring the dispersion to bend plane only.

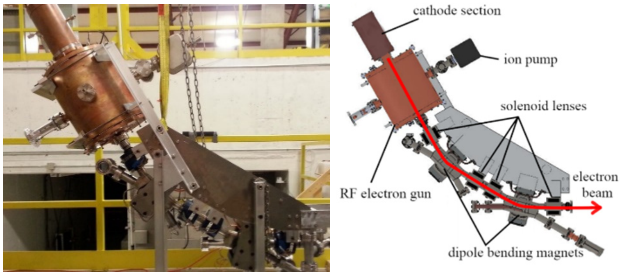

Figure 2: Niowave electron source and DBA (photo, left) and schematic diagram (right).

Figure 3 shows a MAD-X [4] hard-edge equivalent calculation of the *x*- (dipole bend plane) and *y*-plane beta functions $\beta_{x,y}$ and dispersion functions $D_{x,y}$ inside the DBA, with no coupling. Element symbols above the plot show the locations of solenoid and dipole optics. The calculation points out several relevant design features. A matching solenoid (letter a in the figure) focuses a beam waist (β_x minimum) at the symmetry midplane (between c and d) where the selection aperture is placed. The first dipole bend (b) creates dispersion D_x in the bend plane but generates no dispersion in *y*.

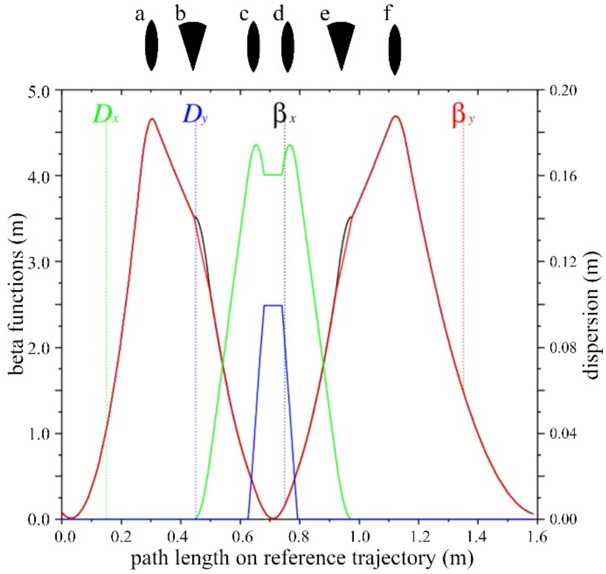

Figure 3: MAD-X calculation of beta functions and dispersion in the solenoid double-bend achromat.

As seen in the figure (note small difference in black and red curves), the beta functions β_x and β_y are only different from one another inside the two dipoles. Symmetry between the beta functions in the transverse planes is preserved by the choice of entrance (+) and exit (-) edge focusing angles in the dipole magnets.

Solenoids c and d are identical with opposite polarity. The two adjacent coils are wired in series to simplify adjustment. The first half (c) rotates the beam, transferring part of the *x*-plane dispersion (D_x) into the *y*-plane dispersion (D_y), while focusing the beam. This solenoid focusing affects the beta functions (symmetric $\beta_x = \beta_y$) relatively little because they are small, but is set sufficient to reduce the derivative of dispersion to zero at the axial midplane as required for achromatic symmetry. Solenoid (d) rotates the beam in the opposite direction, putting all the dispersion back into the bend plane, D_x and ensures by symmetry that $dD_y/dz = D_y = 0$ on exiting solenoid (d). The bending action of the second symmetric dipole (e) then removes the dispersion so that $dD_x/dz = D_x = 0$ on exiting the dipole.

The final solenoid (f) is adjusted to focus the round, dispersion-free beam to match into the superconducting booster cavity, whose first gap is located at ~1.6 m from the gun exit.

This solenoid DBA system can also be efficiently analysed using rotating "Larmor" frame. Here, lab frame explanations are used consistent with MAD-X which correctly models solenoid dispersion consistently in both planes.

MECHANICAL DESIGN

Priorities for the mechanical design of the DBA is that it handle much larger currents than presently needed (now ~2-5 mA) and that it be relatively compact, inexpensive to manufacture, and straightforward to assemble and align. The power handling of the DBA is limited by the water-cooling of the selection aperture. To shorten the beam bunch length, up to 80% (or more) of the beam emitted by the thermionic cathode is filtered at this aperture. These low-energy particles would not be properly accelerated by the SRF and would lead to cryogenic losses, limiting the attainable average beam power for the machine.

The selection aperture incorporates an optical imaging diagnostic to tune this filter. Figure 4 shows an image from this diagnostic produced with the beam completely striking the filter. The selection aperture is at a beta function minimum and a dispersion function maximum, allowing the beam to be efficiently filtered by momentum. The aperture itself is round so that it is not necessary to know prior to beam tuning what the rotation in the first half of the solenoid will be. By comparing the beam fraction passing through the aperture for different dipole settings, the beam energy spread can be measured and compared to Parmela simulations to guide tuning [5].

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Figure 4: Image of the beam at the selection aperture where the dispersion is maximal.

To simplify manufacture and alignment, the DBA chamber is mounted to an aluminium strongback as shown in Fig. 2. The solenoid elements are aligned mechanically on the strongback before welding. The reference trajectory along the axes of the solenoids is used to align the dipole magnet chambers. The design also includes mounting locations for seven combined vertical and horizontal window-frame type corrector magnets (pairs of dipoles) to allow centroid steering to compensate for any remaining misalignments and bending from Earth's magnetic field.

CONCLUSIONS AND NEXT STEPS

The double-bend achromat used in the low-energy section of Niowave superconducting electron linacs is a solenoid-based version of the classic Chasman-Green lattice originally designed for electron storage rings. By using a split solenoid with the two opposing halves having opposite polarity, the azimuthal rotation of the beam induced by the solenoid is compensated. Dipole edge angles are introduced to balance focusing between the two transverse planes while simultaneously tuning for dispersion symmetry. This design maps a round input beam to a round output beam for injection into the superconducting booster cavity with maximal aperture clearances. Furthermore, the introduction of an aperture at the symmetry plane (maximum dispersion and a beta function waist) allows the accelerator operators to filter the low-energy tail of the beam by positioning on a scraping aperture, reducing the bunch length for efficient acceleration in the booster.

Next steps along the Niowave accelerator development path are to increase the gun exit energy to >150 keV and beam current to >20 mA. The design of the selection aperture will be updated to increase the water-cooling capacity of the system. Along with improvements to the RF gating at the cathode in the higher energy gun, this DBA will then meet the requirements for higher average beam power needed for Niowave's radioisotope production program.

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