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HIGH-CURRENT NEGATIVE-ION BEAM TRANSPORT*

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ABSTRACT

The requirements for transporting high-current, negative-ion beams are presented with particular emphasis on applications involving negative-hydrogen-ion beams. In addition to the usual matching and steering problems, particular attention must be paid to beam emittance growth in the transport system. Depending on the application, a number of approaches have been developed using both magnetic and electric lenses. I discuss the design considerations for transporting and matching these beams to radio-frequency quadrupole accelerators, and present a survey of the various types of beamlines now used for negative-ion beams.

INTRODUCTION

Negative-ion beams for accelerator applications were first proposed by Alvarez.¹ Negative-hydrogen-ion beams were first used in tandem Van de Graaff accelerators to obtain beam energies twice the terminal potential. The Novosibirsk group² showed that these beams could be used for charge-exchange injection and thus preclude the limitations of Liouville's theorem for proton beam injection. This technique is commonly used for most synchrotron accelerators. Negative-ion beams were introduced for linear accelerator applications because of the possibility of phase-space tailoring and of splitting beams with low losses at high-beam energies. Negative-ion beam use also affords us the flexibility of simultaneously running both positive and negative beams in the same accelerator. Recently, neutral-particle beams produced from negative ions have been developed for plasma heating in fusion applications and for strategic defense missions. Work in these programs resulted in developing ion sources with higher current and higher brightness, which required the subsequent development of better beam-transport systems.

The main requirement for any low-energy, beam-transport (LEBT) system is to achieve proper matching and centroid control from the ion source to the accelerator. Most ion sources produce divergent beams, particularly as the beam brightness increases. The acceptance requirements depend on the accelerator, but rarely is the acceptance such that the ion beam can be directly injected into the accelerator without some external focusing. Modern accelerators, such as the radio frequency quadrupole (RFQ) accelerators, require a small, highly convergent beam at the match point. Thus, the LEBT system must provide strong focusing lenses to transport a divergent beam from the ion source to a well focused, convergent beam at this accelerator. Steering elements are usually needed to compensate for the inevitable errors in the ion source and beam transport alignment. Often, the effluent gas from the ion source must be pumped out in the transport line before reaching the main accelerator. Beam induced instabilities in the background gas often lead to emittance growth of H⁻ beams. Good beam quiescence is required to limit emittance growth of high perveance beams in low energy transport lines. All these factors must be considered in designing H⁻ beam transport lines.

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LOW-ENERGY BEAM-TRANSPORT ISSUES

In the early 1980s, Soviet scientists Gabovitch et al. reported on the spatial development of ion-ion instabilities in the propagation of low-energy H^- ion beams and on the stabilizing effect of adding heavy gases such as argon into the beamline.³⁻⁵ Subsequently, particle-in-cell simulations gave good agreement with their experimental results.⁶ These simulations showed the onset of low-frequency oscillations (~ 1 MHz) in the beam, a net negative-beam potential for argon pressures less than 2×10^{-5} torr, and a positive-beam potential with damped oscillations at argon pressures greater than 3×10^{-5} torr. Simulations with higher currents and higher energies gave a stability diagram (Fig. 1) showing the perveance limits for stable operation of a 1-m long LEBT operated with 3×10^{-5} torr of argon and 1×10^{-5} torr of hydrogen gas. This case was studied for the design of the 35-keV LEBT employed in the Ground Test Accelerator (GTA) at Los Alamos. Although the intermediate region between stable and unstable operation has not been explored, the GTA operating point is within the "stable" region. Transport of sufficiently high perveance beams entails instabilities from space-charge decompensation that lead to emittance growth. We must determine the stability limits of a given design to ensure operation within the stable region.

Fig. 1 Perveance stability diagram for the GTA LEBT.

Emittance growth is always a key issue for designing low energy beamlines for high brightness, high perveance beams. Several factors can cause emittance growth: aperture and chromatic aberrations, nonlinear space-charge effects, beam-plasma instabilities, and explicit time dependence in the beam parameters. Chromatic aberrations are especially a problem for electric lenses, whereas both magnetic and electric lenses have aperture aberrations. Limiting the beam size in these lenses is sufficient to prevent serious aperture aberration problems. Explicit time dependence of the beam parameters will result in a smearing of the output beam phase space distribution and effective emittance growth. Variations in beam current can also result in dynamic decompensation of the neutralization with subsequent emittance growth. Also, if beam neutralization is not established early in the transport line, the evolution of the phase space distribution can result in emittance growth as space charge energy becomes converted to beam kinetic energy.⁷

For negative-ion beams, the onset of beam-plasma instabilities results in longitudinal potential oscillations in the beam with subsequent beam loss and large emittance growth. Many of these decompensation processes are driven by "noise" on the beam and good beam quiescence is essential for the transport of high-current, high-brightness beams. For ion sources with relatively low extracted-current densities ($\sim 50 \text{ mA/cm}^2$), such as converter sources or volume sources, these effects are usually not important. Optical aberrations in the beamline and extraction system are the most important causes of emittance growth. For Penning sources such as the Dudnikov source, with extracted current densities of the order of 1 A/cm^2 , plasma oscillations near 1 MHz are usually present and may lead to large emittance growth in the LEBT. Penning surface-plasma sources⁸ have been used at Los Alamos in the GTA as shown in Fig 2. Beam emittance measurements at two stations (Figs. 3 and 4) show the effect of beam "noise" in high-perveance beam transport. The first scan shown was taken at a point 12 cm from the ion source extractor on an off-line test stand used to characterize the ion source performance. The second scan was taken at emittance scanner 1, which is located at the midpoint of the LEBT about X cm from the source; the third scan was taken at emittance scanner 2, which is located at the end of the LEBT, 73 cm from the source. For beams with low noise ($< \pm 2\%$), minimal emittance growth is observed. As the beam-noise amplitude is allowed to grow ($> \pm 4\%$), large, third-order aberrations are observed in the emittance distributions at the end of the LEBT line. This growth occurs even though the LEBT is in the stable region and equilibrium has been reached in the beamline.

Fig. 2 Layout of the GTA LEBT.

COMPARISON OF MAGNETIC AND ELECTROSTATIC LEBES

Conventional electrostatic focusing systems, such as einzel lenses, have proved successful for low current beams. Typically, the einzel lens is operated in the defocusing mode and produces significant aberrations, but beam currents up to 30 nA have been transported with these lenses. For linear accelerators such as the Alvarez

drift tube linac (DTL), strong-focusing quadrupole channels are typically used to provide the required matching to the accelerator. With the advent of RFQ accelerators, solenoid lenses are generally employed, although in some applications einzel lenses may be used.

As the required beam currents increase, it becomes more difficult to use einzel lenses, particularly if there is significant electron contamination. Electrostatic quadrupole channels have been employed for beam currents up to 100 keV for neutral beam injectors.⁹ Magnetic-focusing channels have also been employed for high-current beams and will permit plasma buildup in the channel to provide space-charge neutralization of the beams.¹⁰ This mode of operation reduces the focusing strength required to obtain given match conditions, but entails neutralization times of 10 to 50 μ s. Accelerator match parameters are, therefore, time dependent and create a time-dependent beam mismatch in short pulse applications.

The injectors for synchrotron accelerators have historically used magnetic beam-transport systems because of the high-injection energy (typically 750 keV) required for the Alvarez DTL and have generally used strong-focusing quadrupole channels. The original LEBT at Brookhaven and the beamlines now in use at the Los Alamos Meson Physics Facility (LAMPF) and FermiLab employ such channels. A simplified layout of the LAMPF high-intensity H^- beamline is shown in Fig. 5.

Fig. 5 Layout of the high intensity H^- beamline at LAMPF.

Much lower injection energies (~ 100 keV) are required for an RFQ accelerator, and most RFQ beamlines employ magnetic solenoid lenses to facilitate matching. The low energy beamlines at Brookhaven, LAMPF, and DESY employ this LEBT concept. Recently, some consideration has been given to using an electrostatic LEBT employing einzel lenses. The CERN calibrator for the L3 detector uses a simple, defocusing einzel lens to match beams to a 200 MHz RFQ, and an electrostatic LEBT

is now being considered for the injection beamline at the Superconducting Super Collider (SSC).¹¹ A novel lens design employing a continuously focusing, helical-quadrupole structure (HESQ) is also being developed at SSC for H^- beams, and at KEK this lens is being used for the transport of heavy negative-ion beams.¹² The continuous helical structure permits the use of relatively low voltages to obtain the required focal strength.

Magnetic lenses do not change the ion energy and, therefore, have smaller chromatic aberrations than electric lenses. Both electric and magnetic lenses have aperture aberrations, requiring small beam size to limit emittance growth, particularly in the solenoid and einzel lenses. In magnetic transport lines, the beam transport is usually done with sufficient background gas pressure to ensure beam neutralization.¹³ This mode of operation reduces required focusing strength because of reduced beam space-charge effects. For short beam pulse lengths, transient effects must be considered. In some applications, transient effects are eliminated by using beam choppers. For high-current beams, ion-ion instabilities and nonlinear space-charge focusing in overcompensated beams are present. These beam-induced plasma effects are not present in electric lenses, and in principle, these lenses should be more tolerant of beam fluctuations, because stronger lenses are required for unneutralized beams. For RFQ accelerators, the preferred choices are circularly symmetric einzel lenses or ring lenses for the electrostatic case or solenoid lenses for the magnetic case because of the ease in matching to the accelerator.

INJECTORS FOR RFQ ACCELERATORS

A number of injectors have been built recently to provide H^- beams for RFQ accelerators. The injectors at DESY and at the Brookhaven National Laboratory employ magnetron ion sources and use magnetic solenoid lenses at low-beam energy (18 keV and 35 keV, respectively) to supply beams to relatively low-frequency RFQ accelerators. Normalized beam emittances of the order of $0.1 \pi\text{cm-mrad}$ for 90% of the beam are typically obtained. An H^- injector is used at CERN to provide neutral particle (H^0) beams to calibrate the scintillation crystals in the L3 detector that operates in a strong magnetic field. These H^0 beams are obtained from a 20-mA H^- injector using a volume ion source. The injector operates at 30 keV and uses a single einzel lens to match the beam to the RFQ. The GFA injector at Los Alamos provides 50-mA beams at 35 keV to a high frequency (425-MHz) RFQ. This injector employs a two-solenoid lens system and is equipped with a complete set of beam diagnostics. Beam emittances from 0.025 to $0.050 \pi\text{cm-mrad}$ are obtained for 90% of the beam. These applications entail relatively low duty-factor operation, so the primary consideration is getting sufficiently high transmission to obtain the desired output beam current. Thus, questions of steering and matching become primary issues to be addressed.

For a two solenoid lens system, matching is achieved by changing the excitation of the two lenses to produce the desired ellipse matching parameters (alpha and beta Twiss parameters) at the RFQ match point. The layout of a typical, two solenoid LEBT is shown in Fig. 2. Solenoid strengths are about 0.5 Tesla and the beamline is about 1 m in length. Because circularly symmetric beams are used, two independent excitations on the two lenses are sufficient to match a wide range of input beams to the RFQ accelerator. This tuning process is shown on an alpha-beta tuning diagram in which the output ellipse parameters (Twiss parameters) at the RFQ match point are plotted as the abscissa and ordinate for various excitation strengths of these lenses (Fig. 6). Each contour plotted in this alpha-beta space is the locus of points for constant excitation of the first lens while the second lens is varied over an appropriate

range near the match condition. The virtue of this two-lens system is that a large, two-dimensional region can be reached in the output tuning space, ensuring that the specified match point can be reached for a wide range of input beam parameters and for variable LEBT neutralization.

Fig. 6 Calculated tuning diagram at the RFQ match point for a two-solenoid lens system.

Steering corrections for a LEBT design are achieved by dipole steering pairs (typically two pairs) located between the solenoids. Automated steering algorithms have been developed that permit computer control of the compensation for ion source and alignment errors.¹⁴ Using two steering pairs permits independent variation of the four centroid parameters at the RFQ match point so all centroid parameters can be independently set.

Although magnetic LEBTs have provided required beams to RFQ accelerators in a number of applications, they exhibit time dependence during the first 200 μ s of the beam pulse. This time dependence has resulted in transients in the beam transmission through the RFQ used on the GFA (Fig. 7). The output beam current from the RFQ exhibits a long (100 μ s) rise time not seen in the input beam current. Similar transients have been observed in the operation of the H⁻ injector at DESY as shown in Fig. 8. The observed phase-space distributions at the RFQ match point show a continuous orientation variation from 30 to 120 μ s.

Fig. 7 Beam current waveform at the input and output of the GTA RFQ accelerator.

Fig. 8 Time dependence of the input beam for the DESY RFQ.

Concern over LEBT time dependence has led the SSC group to consider an electrostatic LEBT. A two-lens, circularly symmetric einzel-lens system is now being developed for their magnetron source, and a novel "ring" lens design has been proposed for use with an rf driven volume source.¹⁴ These axisymmetric lenses afford the same possibility for a wide tuning range as the solenoid lens LEBT. The ring lens system and the output alpha beta tuning diagram are shown in Fig. 9. In this case, each contour in this tuning space is the locus of points for which the first electrode has a specified voltage while the voltage of the second, or ring electrode, is varied. Again, there is a large, two dimensional tuning range accessible with this "two knob" system, and proper matching to the RFQ should be possible for a range of input beams. The steering in this design can probably most easily be affected by mechanical motion of the two intermediate lenses.

Fig. 9 Layout and tuning diagram of the proposed SSC electrostatic LEBT.

Some applications have used quadrupole-focusing channels to provide beams to RFQ accelerators. The Accelerator Test Stand facility at Los Alamos, which was a prototype to the GTA accelerator, employed permanent-magnet quadrupole lenses mounted on adjustable linear mounts to provide tuning capability.¹⁵ Various electrostatic quadrupole-lens systems have been investigated at Lawrence Berkeley Laboratory¹⁶ and are being investigated for SSC.¹⁷ The use of strong focusing lenses eases the requirements on lens strength, but the matching to a circularly symmetric RFQ admittance with a quadrupole channel is very sensitive to errors, and the tuning range is much more limited than for the circularly symmetric lenses.

CONCLUSIONS

Negative-ion beam transport can be effected by either magnetic and electrostatic beam transport systems. For high-perveance beams, beam-plasma effects often lead to significant emittance growth and time dependent effects if gas neutralization is employed. Electrostatic lenses will presumably prevent plasma buildup, but these lenses have not provided the required focusing strength for high-current beams. Matching and steering considerations are more critical for RFQ accelerators, and more precise tuning is required to prepare beams for these accelerators. Emittance growth control in transporting negative ion beam is still not completely understood; however, a variety of approaches for transporting negative ion beams are now being pursued.

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