SCHEME FOR A LOW ENERGY BEAM TRANSPORT WITH A NON-NEUTRALIZED SECTION*

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Abstract

A Low Energy Beam Transport (LEBT) line is the part of a modern ion accelerator between an ion source (IS) and a Radio-Frequency Quadrupole (RFQ). Its typical design includes 1-3 solenoidal lenses for focusing and relies on transport with nearly complete beam space charge neutralization over the entire length of the LEBT. In this paper, we discuss the possibility and rationality of imposing an un-neutralized transport in a portion of the LEBT adjacent to the RFQ. For estimations, we will use the parameters from PXIE [1], a test accelerator presently being constructed at Fermilab.

REASONING FOR A LEBT WITH AN UN-NEUTRALIZED SECTION

Often, a LEBT either operates with a pulsed ion source or is capable of creating pulses from an initially DC beam. Because the ionization process is not instantaneous, the front of the beam pulse is not neutralized as it propagates through the LEBT. Thus for long-pulse operation, when the accelerator optics is tuned for neutralized transport in the LEBT, the space charge at the beginning of the pulse may result in increased losses in the following beam line. In the case of PXIE, several microseconds pulses envisioned for tuning would not provide a representative envelope for CW operation.

Remedies include working at relatively high pressure to speed up the neutralization process, which, in turn shortens the time for the beam parameters to reach a steady state, and moving the chopping system as close as possible to the RFQ in order to decrease the distance that beam travels with full space charge and low energy. In both cases, reliability of the RFQ may suffer because of higher pressure and/or increased irradiation of the RFQ vanes during chopping.

Here we consider an alternative scheme, where the ion source works in the DC mode and the beam propagates through the first, 'high pressure' part of the LEBT being neutralized, but neutralization is stopped right upstream of an electrostatic chopper. Hence, in the ideal case with zero density for the neutralizing ions in the downstream part of the LEBT, the beam envelope is time-independent.

Applicability of such scheme depends on several factors, most importantly, the beam perveance $P_b = I_b / U_{IS}^{3/2}$, where I_b is the beam current and U_{IS} is the ion source bias voltage. If the perveance exceeds a certain limit, an un-neutralized beam simply cannot be transported in a LEBT with lumped focusing even in the linear approximation. In addition, even for a lower perveance, non-linear space charge effects can dramatically increase the beam emittance, making it not suitable for an accelerator.

LINEAR SPACE CHARGE EFFECT

To estimate the maximum perveance theoretically allowing lumped focusing, let's consider the space-charge dominated transport of a non-relativistic, round, completely un-neutralized H$^-$ beam with uniform transverse distribution of the charge density, i.e. neglecting the beam emittance and potential drop across the beam. The maximum length that the beam can propagate between two thin focusing elements while remaining within radius r_b can be expressed (using, for example, formulae from Ref. [2]) as

$$\frac{L_m}{r_b} = \sqrt{2.33 \frac{\sqrt{2e/M_i}}{P_b}} = \sqrt{\frac{3.59 \, \mu A / V^{3/2}}{P_b}} , \qquad (1)$$

where e is the electrical charge and M_i the ion mass. In real-life, for a typical solenoid, the magnetic lens inner radius is at least twice the beam radius and its length is roughly equal to its inner diameter. One can argue that the maximum allowable perveance corresponds to the case when the minimum possible physical distance between lenses exceeds their length by only a factor of 2-3 (with a factor of '1' meaning that the lenses would be touching). Taking a factor of 3 for the lenses' distance-to-length ratio implies $L_{m\_sc}/r_b \approx 12$ and a value of the maximum allowable perveance of

$$P_{bm} \approx \left(\frac{L_{m\_sc}}{r_b} \right)^{-2} \cdot 3.59 \, \mu A / V^{3/2} \approx 0.025 \, \mu A / V^{3/2} . \quad (2)$$

In the case of PXIE's LEBT, the perveance of the 10mA, 30 kV H$^-$ beam is $1.9 \cdot 10^{-3}$ μA/V$^{3/2}$, significantly lower than the estimation from Eq. (2). Therefore, for these parameters, un-neutralized transport is not excluded in this simplest model.

NONLINEAR SPACE CHARGE EFFECT

A significantly more important limitation is an emittance growth due to space charge. For a beam with a Gaussian current density distribution, the space charge force is highly non-linear outside of the beam core. The tail particles experience a lower radial kick, which distorts the beam phase portrait and increases the beam emittance.

An obvious solution to avoid emittance dilution due to space charge is to create a beam with constant radial

* Operated by Fermi Research Alliance, LLC, under Contract DE-AC02-07CH11359 with the United States Department of Energy
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current density distribution in the ion source, so that the space charge force is linear. However, for any realistic beam, the thermal radial velocities affect the particles' distribution as it propagates down the beam line. It is easier to comprehend for the case where space charge is negligible and the beam initially parallel: when the thermal velocities significantly increase the beam size as it propagates, a particle's transverse position is determined mainly by its initial radial velocity rather than its initial position. In turn, whatever the initial radial density distribution may be, it eventually becomes Gaussian, thus reflecting the thermal equilibrium in the ion source plasma.

To describe this transition analytically, one can start with particle distribution in the form

$$f_0\left(x_0, x_0', y_0, y_0'\right) = \frac{1}{2\pi\sigma_{x'}^2}\frac{1}{\pi R_0^2}\cdot \exp\left(-\frac{\left(x_0'-kx_0\right)^2+\left(y_0'-ky_0\right)^2}{2\sigma_{x'}^2}\right)\cdot\begin{cases}1, & \sqrt{x_0^2+y_0^2}\le R_0\\ 0, & \sqrt{x_0^2+y_0^2}> R_0\end{cases} \quad (3)$$

where R_0 is the initial beam radius, $\sigma_{x'}$ is the local rms angular spread, and k characterizes the initial beam divergence. After the beam travels over the distance L, the current density j_1 at the location $\left(x_1, y_1\right)$ is determined by integration of all trajectories satisfying $x_1 = x_0 + x_0'L;\ y_1 = y_0 + y_0'L$:

$$j_1\left(x_1, y_1\right) = I_b\int dx_0'\int dy_0' f_0\left(x_0, x_0', y_0, y_0'\right), \quad (4)$$

The resulting radial dependence expressed in normalized variables (see details in [3]) is determined by a single parameter $\sigma_T = \frac{\sigma_{x'}L}{R_0\left(1+kL\right)}$ as follows

$$j_n\left(r_n\right) = \frac{1}{\sqrt{2\pi}\sigma_T}\int_{-1}^{1} dt\exp\left(-\frac{\left(t-r_n\right)^2}{2\sigma_T^2}\right)erf\left(\sqrt{\frac{1-t^2}{2\sigma_T^2}}\right)$$
$$j_n = \frac{j_1}{I_b}\pi R_0^2\left(1+kL\right)^2;\ r_n = \frac{r_1}{R_0\left(1+kL\right)}; \quad (5)$$

The radial distribution is close to uniform at small σ_T and becomes close to Gaussian at large σ_T (Fig. 1).

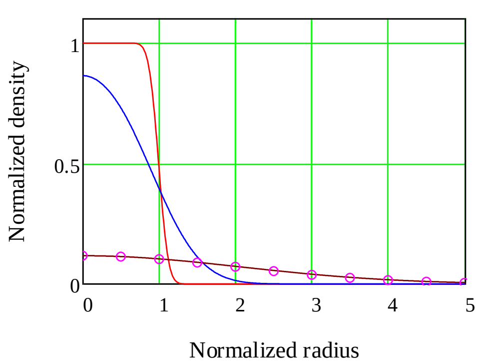

Figure 1. Normalized radial current density distributions calculated with Eq.(5). The value of σ_T for the solid lines is 0.1 (red), 0.5 (blue), and 2 (brown). The magenta circles show, for illustration, a Gaussian distribution.

Correspondingly, the rms beam width contains two components, related to the Gaussian and uniform distributions:

$$\sigma_{x_1}^2 = \left[\frac{R_0}{2}\left(1+kL\right)\right]^2 + \left(L\sigma_{x'}\right)^2 = \left[\frac{R_0}{2}\left(1+kL\right)\right]^2\left(1+4\sigma_T^2\right). \quad (6)$$

These components are equal at

$$\sigma_T = 0.5, \quad (7)$$

which can be defined as a characteristic value for the transition from uniform to Gaussian shape.

One can consider this result from the point of view of the Courant-Snyder formalism. The phase advance for particles propagating in free space is

$$\Delta\Psi = \int_0^L \frac{ds}{\beta_0 - 2\alpha_0 s + \gamma_0 s^2} = \operatorname{atan}\frac{L}{\beta_0 - \alpha_0 L}, \quad (8)$$

where $\alpha_0, \beta_0, \gamma_0$ are the initial Twiss parameters. Substituting in Eq. (8) $\beta_0 = \frac{R_0^2}{4\varepsilon}$, $\alpha_0 = -k\frac{R_0^2}{4\varepsilon}$, $\varepsilon = \frac{R_0}{2}\sigma_{x'}$ leads to a simple relationship between the two descriptions as $\tan\left(\Delta\Psi\right) = 2\sigma_T$. Hence, Eq. (7) defines that the transition between the two shapes occurs at

$$\Delta\Psi = \pi/4,\ L_{m\_eg} = \frac{R_0^2}{\varepsilon\left(1+2\alpha_0\right)} \quad (9)$$

While the previous consideration was about propagation in free space, in most of real LEBTs the beam is focused by axially symmetrical solenoidal lenses. In the case of completely neutralized beam transport with linear optics, the lens would replicate the initial (i.e. at the ion source exit) current density distribution in the image plane (at $\Delta\Psi = \pi$). Consequently, one can re-create a beam with a uniform current density distribution but magnified with respect to the one generated at the ion source.

In turn, the distance, over which the uniform-density profile is nearly preserved and, consequently, aberrations from space charge are mostly suppressed, increases in accordance with Eq. (9) as R_0^2.

SCHEME OF LEBT WITH PARTIAL NEUTRALIZATION

Based on the above considerations, the LEBT scheme with an un-neutralized section is proposed as follows:

- The ion source is optimized to generate a uniform spatial density distribution at the nominal beam current.
- Beam transport immediately following the ion source is as close as possible to being completely neutralized.
- The beam size near the image plane of the first solenoid is increased to the limit imposed by aperture limitations of critical elements downstream (e.g. chopping system).
- Near that image plane (phase advance ~ π), neutralization is interrupted: the flow of neutralizing ions from the upstream section with relatively high pressure is stopped by applying a positive voltage on an axially symmetrical electrode located near the image plane, and ions created downstream of this electrode are

removed by a transverse electric field applied, for example, to the chopper's kicker electrodes.

- The phase advance over the remaining length of the LEBT is minimized, and vacuum is kept as low as possible.

In this scheme, a low space charge-related emittance growth is achieved by the combination of neutralized transport in the upstream, high-pressure portion of the LEBT and the fact that space charge forces are mostly linear in the downstream part.

Such a scheme was simulated by VACO [3] keeping in mind its practical realization at PXIE. It employs three solenoids: one to optimize the beam propagation through a space allocated for the future installation of a bend and the following two to match the beam at the RFQ entrance. A chopping system, installed between the second and third solenoids, determines the allowable beam size in this region.

To simplify the simulations, we assume that the phase advance from the ion source emitting surface to the position where neutralization is complete is small and can be neglected. Consequently, the simulation begins in the location with full ion energy, complete neutralization, and uniform current density. While in a real beam line the assumption might be incorrect, the additional phase advance would result only in a shift of the optimum position of the image plane, not affecting the main conclusions.

Results of numerical simulations are presented in Fig. 2 for two cases, which differ by the initial current density distribution: uniform in one and Gaussian in another.

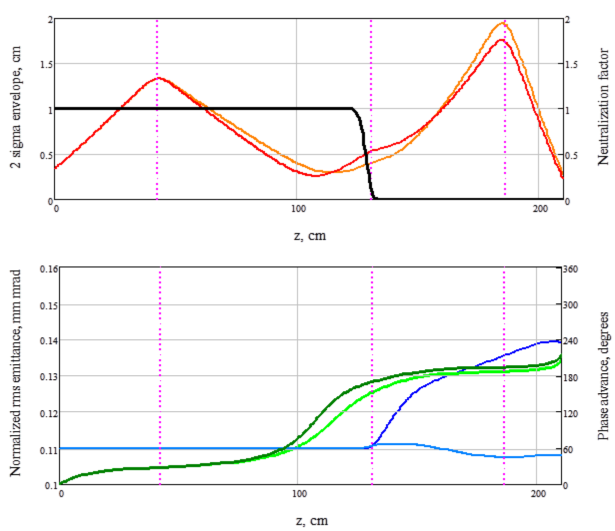

Figure 2. Top: Beam envelopes calculated with VACO (50000 macro-particles) starting with a beam distribution with uniform current density (red) and a Gaussian current density distribution (orange). The thick black line indicates the neutralization factor. Bottom: Corresponding emittance evolution (light blue for uniform current density, navy blue for Gaussian current density) and total phase advance (dark green for uniform current density, bright green for Gaussian current density). The pink dotted lines indicate the location of the solenoids (centers).

For both cases, the velocities distribution is Gaussian. Focusing is adjusted to have nearly identical Twiss parameters at the end of the beam line.

Fig. 2 shows that when the initial current density was chosen to be uniform, there is no emittance growth above the numerical noise, while the emittance grew by ~25% when the initial current density distribution was chosen to be Gaussian.

The phase advance over the non-neutralized portion of the line is ~0.8 rad, i.e. $\tan(\Delta\Psi) \approx 1$. Thus, according to the reasoning based on propagation in free space, the deviation from a uniform density distribution is significant. Nevertheless, the emittance did not grow. Likely, using the condition $\Delta\Psi << \pi/4$ as an indicator of the emittance growth threshold is too restrictive because it takes time for particles travelling in a non-linear field to accumulate non-linear perturbations that eventually lead to an increase of the emittance.

DISCUSSION

The proposed scheme accommodates a natural pressure distribution in a LEBT line: the high pressure near the ion source, unavoidable due to the gas flow from the source, helps neutralizing the upstream portion of the LEBT, while a low pressure, preferential for a reliable operation of the RFQ, is compatible with limiting the amount of neutralizing ions generated in the RFQ vicinity.

Also, in the case where an LEBT chopping system is necessary to tailor the beam pulse shape and frequency, this scheme allows locating the chopping system somewhat far from the RFQ decreasing possible detrimental effects of absorber outgassing.

This concept is the base of the PXIE LEBT that is presently being commissioned at Fermilab [5].

ACKNOWLEDGEMENTS

Authors acknowledge stimulating discussions with J.-F. Ostiguy and J. Staples and are thankful to V. Lebedev for writing VACO.

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