FORMATION AND TRANSPORT OF HIGH-BRIGHTNESS H^- BEAMS*

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ABSTRACT

For a specified normalized emittance, the H^- beam current, or brightness, that can be obtained is limited by physics and technological constraints of the ion source and the beam transport system. A review of these constraints and of the resulting sealing laws will be presented. The relative merits and limitations of three beam transport methods – gas focusing, gas focusing supplemented by magnetic lenses, and electrostatic focusing that avoids charge neutralization of the beam – will be discussed.

1. INTRODUCTION AND GENERAL CONSIDERATIONS

High brightness H^- beams are used for various applications such as high energy physics (H^- injector linacs), magnetic fusion (plasma heating with H° beams) and SDI (neutral particle beams in space for ICBM defense). Future H^- generators for plasma heating must produce high currents (20-40 A) at voltages of 1-2 MV in multiple-beam configurations for which Radio-Frequency-Quadrupole (RFQ) accelerators are being considered as an option.[1] Emittance requirements are not as stringent as in the other applications mentioned. H^- injectors for high energy physics[2] operate at low duty factor with desired average currents in the macropulse of 50 to 100 mA and a normalized emittance of $\epsilon_n\pi \approx 1\pi$ mm-mrad. Neutral hydrogen beams for space defense[3] require H^- currents in the range of $I \geq 100$ mA and a normalized emittance of $\epsilon_n = 0.1$ to 1.0 mm-mrad. The corresponding normalized brightness, defined as $B_n = 2I/\pi^2\epsilon_n^2$, thus ranges from 1×10^{10} A/(m-rad)^2 for high energy physics injectors to 2×10^{12} A/(m-rad)^2 for SDI applications. Such high-brightness beams have to be produced at relatively low voltage (< 50 kV) from H^- sources and transported to an RFQ accelerator in a "low energy beam transport" (LEBT) line. In most existing systems and experiments focusing in the LEBT line is provided by charge neutralization in a suitable background gas, e.g. Xenon, supplemented by magnetic lenses such as solenoids or quadrupoles. Major problems in such systems are particle loss due to stripping ($H^- \rightarrow H^\circ + e$ or $H^- \rightarrow H^+ + 2e$) or inadequate focusing, especially at the early part of the macropulse, and emittance growth due to nonlinear beam physics effects and beam-plasma instabilities.

The effective radius $R = 2R_{rms}$ of a charged particle beam in a transport system without acceleration is defined by the K-V envelope equation

$$R'' + k_0^2 R - \frac{K}{R} - \frac{\epsilon^2}{R^3} = 0, \qquad (1)$$

where $k_0^2 R$ represents the focusing force due to external lenses or charge neutralization, K/R the space-charge repulsive force, and ϵ^2/R^3 the beam divergence due to the emittance. The parameter K is the generalized perveance of the beam defined as $K = (I/I_0)(2/\beta^3\gamma^3)$, where $I_0 = 3.1 \times 10^7 A/Z$ amperes for ions with mass number A and charge number Z. For H^- beams at low voltage V_b we have the nonrelativistic relation

$$K = 6.5 \times 10^5 \times \frac{I_{[A]}}{V_{b[V]}^{3/2}} = 2.056 \times 10^{-2} \frac{I_{[mA]}}{V_{b[kV]}^{3/2}}. \qquad (2)$$

As an example, for I = 100 mA, V_b = 30kV, one finds $K = 1.25 \times 10^{-2}$. The effective unnormalized emittance in Eq. (1) is defined as $\epsilon = 4\epsilon_{rms}$ (following Lapostolle[4]) and related to the effective normalized emittance ϵ_n by $\epsilon = \epsilon_n/\beta\gamma$. For H^- beams of voltage V_b one has

$$\epsilon = 6.853 \times 10^2 \frac{\epsilon_n}{\sqrt{V_{b[kV]}}}. \qquad (3)$$

For high-brightness beams of the type discussed here, the beam radius in a transport line without charge neutralization is almost entirely determined by the perveance K, i.e., the emittance plays no significant role. (This is not the case when the beam is neutralized, as will be discussed in Section 3.)

From Eq. (1), we see that the relative effect of space charge versus emittance on the beam radius is defined by the parameter

$$h = \frac{KR^2}{\epsilon^2}, \qquad (4)$$

which measures the ratio of the space charge term to the emittance term. As an example, for a 100 mA, 30 kV H^- beam with effective normalized emittance of $\epsilon_n = 0.5$mm – mrad and a radius of 5 mm one obtains h = 79.85. Thus $K/R \gg \epsilon^2/R^3$ in the envelope equation, as stated.

If the beam is transported through a uniform or periodic focusing channel, the parameter h is related to the tune depression $k/k_0 = \omega/\omega_0$ of the betatron frequencies with and without space charge by

$$h = \frac{KR^2}{\epsilon^2} = \left(\frac{\omega_0}{\omega}\right)^2 - 1 = \left(\frac{k_0}{k}\right)^2 - 1. \qquad (5)$$

For the above example, one has $k/k_0 = 0.11$, which illustrates that such beams are characterized by tune depressions of a factor of 10 or even more.

In space charge dominated high-brightness beams (where $h \gg 1$), one of the potentially most harmful effects is emittance growth due to nonuniform charge distribution. This effect was first identified by the author in numerical simulation studies at GSI.[5] A theoretical model proposed in this work by the author and J. Struckmeier, based on conversion of nonlinear field energy into transverse kinetic energy, yielded relatively good agreement with the simulation results.[5] Subsequent theoretical and simulations studies by Wangler et al.[6], O. Anderson[7], and others confirmed the model and led to a more rigorous theoretical description of the effect. According to the theory, the equilibrium state of a space-charge dominated beam is associated with a uniform density profile. If the beam density profile is nonuniform, there is an excess amount of nonlinear field energy $\Delta W = U$ which is converted into transverse kinetic energy, and hence emittance growth, as the beam becomes uniform. This process of charge homogenization and emittance growth occurs in a distance of a quarter of the beam plasma period[6,7] given by

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$$z_p = \frac{\lambda_p}{4} = \frac{\pi v}{2\omega_p} = \frac{\pi R}{2\sqrt{2K}}. \quad (6)$$

The ratio of final emittance ϵ_f to initial emittance ϵ_i is given by the formula (Reiser, Struckmeier in Ref. 5, Wangler in Ref. 6)

$$\frac{\epsilon_f}{\epsilon_i} = \left[1 + \frac{KR^2}{2\epsilon_i^2}\frac{U}{w_0}\right]^{1/2} = \left[1 + \frac{1}{2}\left(\frac{k_0^2}{k_i^2} - 1\right)\frac{U}{w_0}\right]^{1/2}, \quad (7)$$

where relation (5) has been used and where U/w_0 represents a dimensionless parameters that depends only on the shape of the beam profile. Using our previous example of a 100 mA, 30 kV H^- beam one obtains for a Gaussian profile, where $U/w_0 = 0.154$, an emittance growth of $\epsilon_f/\epsilon_i = 2.67$. To avoid or minimize this effect one should, in view of Eq. (7), have a beam with as uniform a density profile as possible and a small beam radius. In this regard, using charge neutralization for beam transport is not very desirable since the beam profile in the gas-plasma channel tends to become nonuniform. As the beam becomes unneutralized, e.g. when passing through an acceleration column or entering and RFQ, emittance growth due to the nonlinear field energy may offset the advantages of gas focusing in cases where high brightness is very important. How much emittance growth can be tolerated in the LEBT line depends on the phase-space history of the beam through the subsequent accelerator sections (RFQ, drift-tube linac) and the final emittance requirements. (See the paper by Wangler in these proceedings[8].) For some applications emittance growth in a gas focusing channel may be tolerable. However, when the amount of emittance growth is not acceptable, one must use electrostatic transport with either einzel lenses or quadrupole lenses in which plasma buildup, and hence charge neutralization, is avoided. In either case, whether one uses gas focusing or electrostatic transport, additional lenses are required to match the beam from the LEBT line into the RFQ. Most existing systems use gas focusing, and matching is accomplished with either solenoids or permanent quadrupole magnets.

In the following we will propose theoretical scaling relations for the beam that can be expected from an H^- source (Section 2) and for an idealized gas focusing system (Section 3). Finally, in Section 4 we will discuss design considerations for a LEBT system using electrostatic quadrupole lenses.

2. SOURCE SCALING

The physics and technology of an H^- source is quite complicated and a discussion is beyond the scope of this paper. For our purpose of characterizing the output beam, we will assume a sufficient supply of ions from the source plasma so that one can operate at the space charge limit. In this case a few simple scaling laws can be established that define the current and emittance, and hence the brightness of the beam.

The first relation is the perveance of a space-charge limited H^- beam (Child's Law). If one examines the performance of various sources, one finds that

$$I_{[mA]} = C_1 V_{[kV]}^{3/2}, \quad (8)$$

where C_1 is an empirical constant which varies between about 0.2 and 1.8.

Beam optics, in particular the avoidance of nonlinear effects in the extraction gap, requires that the radius r_s of the source aperture is comparable to the effective gap spacing, i.e.,

$$r_s = C_2 d, \quad (9)$$

where the constant C_2 ranges from about 0.2 to 1.0 in various source designs.

The gap spacing d, on the other hand, must be large enough to avoid voltage breakdown. Empirical breakdown relations found in the literature can be put into the form $d \sim V^\alpha$, where the exponent α ranges from 1 to 2. We will adopt the breakdown relationship proposed by Keller[9] with $\alpha = 1.5$ that fits best with the experimental data from many ion sources. This relation says that to avoid voltage breakdown, the effective gap width d must satisfy the inequality

$$d_{[mm]} > C_3 V_{[kV]}^{3/2}, \quad (10)$$

where $C_3 = 1.4 \times 10^{-2}$.

Finally, we know that the normalized emittance is determined by the effective temperature, kT_i, of the H^- distribution and the aperture radius, r_s, by

$$\epsilon_n = 2r_s(kT_i/m_0c^2)^{1/2}. \quad (11)$$

The quantity kT_i represents the average transverse kinetic ion energy due to the plasma temperature as well as due to any nonlinear effects in the ion extraction process. For H^- ions with rest energy $m_0c^2 = 939.28$ MeV, one has

$$\epsilon_{n[mm-mrad]} = 0.065 r_{s[mm]}(kT_{i[eV]})^{1/2} \quad (12)$$

The above equations define the constraints on achievable beam current and emittance imposed by perveance, extraction optics, voltage breakdown and beam temperature. If the desired emittance is given, the beam current is uniquely determined as follows: From (11) or (12) one has for ϵ_n = const the scaling

$$r_s \sim \epsilon_n/\sqrt{kT_i} \quad (13)$$

Substituting into (9) and (10) one finds the scaling

$$V \sim \epsilon_n/(kT_i)^{1/3}, \quad (14)$$

and, from (8) and (14), the current then scales as

$$I \sim \epsilon_n/(kT_i)^{1/2}. \quad (15)$$

For a given emittance, the current that can be obtained thus increases with decreasing temperature. The reason is that a lower beam temperature allows one to build a source with larger output aperture, hence larger gap width and higher extraction voltage. The following example illustrates this scaling. Let us assume that the empirical constants have the values $C_1 = 1$, $C_2 = 0.5$, and $C_3 = 3 \times 10^{-2}$. (The latter is more than twice the value of Keller's relation to provide a safety margin.) Note that $C_1 = 1$ implies a generalized perceance of $K = 2.056 \times 10^{-2}$ from Eq. (1). If we require that the emittance is $\epsilon_n = 0.2$mm$-$mrad and compare a source having a high temperature of $kT_i = 6$ eV with a source having a low temperature of $kT_i = 1$ eV, we obtain the results for source aperture, extraction voltage, beam current, and normalized brightness $B_n = 2I/\pi^2\epsilon_n^2$ shown in Table 1.

This example illustrates the importance of low temperature for applications where high currents and high brightness are desired.

Table 1. Comparison of H^- beams with same emittance (ϵ_n = 0.2 mm-mrad) but two different temperatures

kT_i[eV]	r_s[mm]	V[kV]	I[mA]	$B_n[A/(mm-mrad)^2]$
6	1.25	19.1	83	0.42
1	3.06	34.6	204	1.03

3. GAS FOCUSING

In the first section we discussed the relative merits of gas focusing and electrostatic focusing systems. As was pointed out, gas focusing is a natural effect that can be used or cultivated when emittance or brightness requirements are not very stringent (for instance, in plasma heating applications). Below, we will present some interesting scaling relations that have been derived using the results of our theoretical fluid model[10] for the steady state of a gas focusing system for an H^- beam.

When an H^- beam propagates through a background gas (for instance, Xenon) of sufficient density, its space charge can become over-neutralized, i.e., the ratio of positive ion density, n_i, to beam ion density, n_b, is greater than unity, or

$$f_e = \frac{n_i}{n_b} > 1. \tag{16}$$

According to the theory[10], a steady state exists in which the number of electrons and positive ions created by collisions between beam ions and background gas/plasma is balanced by the number of electrons and ions escaping from the system. The positive ions are accelerated out of the beam region by the positive potential gradient. Electrons are created in the collisions with a Maxwellian energy distribution. According to Rudd[11], the electron temperature, kT_e, is related to the beam voltage, V_b, and the ionization energy, eV_i, of the background gas by

$$kT_e = \frac{2}{3}\left(\frac{V_b V_i}{m_i/m_e}\right)^{1/2}, \tag{17}$$

where m_i/m_e is the ratio of beam ion mass to electron mass. For an H^- beam, one has $m_i/m_e = 1838$, and if the background gas is Xenon, the ionization energy to create Xe^+ is eV_i = 12.1eV. Then Eq. (17) may be written in the form

$$kT_{e[eV]} = 1.71(V_{b[kV]})^{1/2}. \tag{18}$$

The theory[10] says that the positive potential difference, $\Delta\phi$, between the center of the beam and the wall of the vacuum drift tube is proportional to the electron temperature, i.e.

$$\Delta\phi = \phi_0 - \phi_b = \phi_0 = \delta kT_e. \tag{19}$$

The proportionally constant δ is defined by the ratio of the electron density n_0 at $r = 0$ and n_b at the wall ($r = b$) by $\delta = \ell n(n_0/n_b)$. This ratio in turn depends on the gas density, the beam profile and the ratio of the effective beam radius $a = 2R_{rms}$ to wall radius b. From theory and fluid-code studies[12] one finds that δ has a typical range of $0.3 < \delta < 3$.

The potential across the beam must also satisfy Poisson's equation. If we model the beam profile by the equivalent uniform density distribution having the same effective radius, a, and current, I, and assume an over-neutralization factor, $f_e > 1$, we obtain for the potential difference ϕ_0 the relation

$$\phi_0 = \frac{30I(f_e-1)}{\beta}\left(1 + 2\ell n\frac{b}{a}\right), \tag{20}$$

For a nonrelativistic H^- beam with voltage V_b, the relativistic velocity factor, $\beta = v/c$, is given by

$$\beta = 1.46 \times 10^{-3}\sqrt{V_{b[kV]}}. \tag{21}$$

Consequently, Eq. (20) may be written as

$$\phi_{0[V]} = 20.56\frac{I_{[mA]}(f_e-1)}{\sqrt{V_{b[kV]}}}(1 + 2\ell nb/a). \tag{22}$$

The effective radius, R, of the overneutralized H^- beam must obey the envelope equation (1) where in our case the external focusing force is zero, i.e. $k_0^2 = 0$, and the generalized perveance K is replaced by $-K(f_e - 1)$ so that the space-charge term is positive. The equilibrium state is then characterized by R = a = const., R' = 0, R" = 0, hence

$$\frac{K(f_e-1)}{a} - \frac{\epsilon^2}{a^3} = 0, \tag{23}$$

or

$$a = \frac{\epsilon}{\sqrt{K(f_e-1)}} = \frac{\epsilon_n}{\beta\gamma\sqrt{K(f_e-1)}}. \tag{24}$$

Using relations (2) for the perveance K and (21) for β($\gamma = 1$ in our case), we find

$$a_{[mm]} = 4.776\frac{\epsilon_{n[mm-mrad]}V_{b[kV]}^{1/4}}{\sqrt{I_{[mA]}(f_e-1)}}. \tag{25}$$

Now, in view of Eq. (22), the product $I(f_e - 1)$ in the denominator of (25) is proportional to the potential difference, ϕ_0. However, according to Eq. (19), ϕ_0 is proportional to the electron temperature, kT_e, which, in turn, from (18), is a function of the beam voltage, V_b. Substituting these relationships into Eq. (25) we obtain for the effective beam radius in the steady state the result

$$a_{[mm]} = 16.56\frac{\epsilon_{n[mm-mrad]}[1 + 2\ell nb/a]^{1/2}}{\delta^{1/2}V_{b[kV]}^{1/4}}. \tag{26}$$

Thus one obtains the interesting result that the equilibrium beam radius in the ideal gas focusing system is independent of the current, depends only weakly on the beam voltage and is directly proportional to the normalized emittance, ϵ_n. If ϵ_n, V_b, δ, and the ratio b/a are given, one can solve Eq. (26) analytically. As an example, if we assume b/a = 10, δ = 1, and ϵ_n = 0.2 mm-mrad, we find for V_b = 19.1 kV (case 1 of Table 1), the result a = 3.75 mm, and for V_b = 34.6 kV (case 2 of Table 1), a = 3.23 mm.

In practice, both b/a and δ are not known a priori. As mentioned, the constant δ depends on the gas pressure and the radial distribution of the beam.[10] Its value is small when the beam profile is Gaussian with the tail extending to the wall and large when the beam is well confined with an effective radius that is small compared to the wall radius. The factor $[(1 + 2\ell nb/a)/\delta)]^{1/2}$ in Eq. (26) has only a weak dependence on the ratio b/a. In the above example (b/a = 10, δ = 1), its value is 2.37. If one takes b/a = 2, δ = 0.3 near the low end of the range, one obtains 2.82, while towards the upper end, say b/a =20, δ = 3.0, one gets a value of 1.53. Thus using an average value of $[(1 + 2\ell nb/a)\delta]^{1/2} = 2.25$, should yield a reasonably good approximation for the beam radius from Eq. (26), with an estimated error bar of about ± 30-50%. The most significant result of our analysis, however, is the fact that the radius scales as $a \sim \epsilon_n / V_b^{1/4}$ and is independent of the current. In practice, the beam may not be well matched and hence perform oscillations about the equilibrium radius or the equilibrium may not be stable.

It should be pointed out that the scaling relations proposed here are based on an idealized theoretical model. Thus the electron temperature is attributed to the kinetic energy with which the electrons are created in the ionizing collisions, neglecting the heating effect from the interaction with the beam as proposed in other models.[13,14] This assumption as well as the relations (19) and (20) are subject to question and may need further refinement. Furthermore, the theory must be checked with experiments such as the work reported by the Los Alamos group[15] at this conference.

4. ELECTROSTATIC QUADRUPOLE FOCUSING

The most attractive alternative to gas focusing is electrostatic quadrupole (ESQ) focusing. In an ESQ system the focusing forces are of first order and hence stronger than the second-order forces of an axisymmetric system with electrostatic einzel lenses. Furthermore, the useful "linear" aperture for the beam is usually larger in ESQ lenses than in einzel lenses where nonlinear effects, especially spherical aberrations, are more troublesome than in ESQ lenses. On the other hand, matching the round beam from the source into the elliptical beam of an ESQ channel and then again matching from the ESQ channel into the RFQ (which requires a round beam at its entrance) is a cumbersome task. For modest intensity and brightness requirements, einzel lenses might therefore be more desireable from a practical point of view. At the upper limits of intensity and brightness requirements, however, ESQ focusing appears to be more appropriate.

The focusing or defocusing action of an ESQ lens of length ℓ, voltage V_q and aperture radius a_q is given by the strength parameter

$$\theta = \left(\frac{V_q}{V_b}\right)^{1/2} \frac{\ell}{a_q}. \qquad (27)$$

As discussed in Reference 10, a design must satisfy the voltage breakdown constraint (10), where d represents the spacing between nearest electrodes at different potentials. In addition, the ratio of beam radius, a, to quad radius, a_q, and to electrode length, ℓ, must not be too large in order to avoid excessive chromatic aberrations and nonlinear effects. For a periodic ESQ channel of the FODO type, one can use the smooth-approximation theory[16] to solve the envelope equation (1). The focusing constant k_0 is then replaced by σ_0/S, where σ_0 is the phase advance per period without space charge and $S = 2(\ell + L)$ is the length of one period with L denoting the drift space between the electrodes. From Eq. (1), one then obtains for the average matched envelope radius with $R = a =$ const, $R'' = 0$ the result

$$\frac{\sigma_0^2}{S^2} a - \frac{K}{a} - \frac{\epsilon^2}{a^3} = 0, \qquad (28)$$

or, neglecting the emittance term,

$$a \approx \frac{S\sqrt{K}}{\sigma_0}. \qquad (29)$$

The relationship between the phase advance σ_0 and the focusing strength θ is given in Reference 16. To avoid envelope instabilities one wants to have $\sigma_0 < 90°$. Choosing $\sigma_0 = 80° = 1.396$ rad, and $L/\ell = 0.5$, one finds $\theta = 1.1$. For the examples discussed in Table 1, Section 2, the generalized perveance is approximately $K \approx 2 \times 10^{-2}$, hence from Eq. (29) $a \simeq 0.1S$. Thus if one wants a beam radius of a = 3 mm, the length of one focusing cell consisting of two ESQ lenses should be S = 3 cm, with $\ell = 1.0$ cm and L = 0.5 cm. At first sight these dimensions seem to be rather small and one would be concerned about voltage breakdown. However, an ongoing study in our group at the University of Maryland shows that such an ESQ focusing channel can be designed without exceeding the breakdown limits. A specific design example of a 120 mA H^- beam is discussed in Reference 10. We achieved adequate FODO channel design parameters for beam voltages of 30 kV and 120 kV. However, we found in this study that it is difficult to match the low-voltage (30 kV, 120 mA) into the RFQ. At the RFQ entrance, the beam must be round and have a rather large convergence angle. To achieve this convergence, the beam must be allowed to expand radially, and then it is focused by a strong lens or system of lenses. For the low-voltage, high-perveance beam we could not find a design satisfying all our constraints of voltage breakdown, chromatic and spherical aberrations. However, acceleration from 30 kV to 120 kV solved this problem, and the maximum beam radius in the matching system did not exceed 5 mm. Further work will be concerned with nonlinear forces, emittance growth, and optimization of such an ESQ focusing system.

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