TRANSPORT OF HIGH-INTENSITY BEAMS*

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Abstract

The transport of high-intensity, high-brightness beams is reviewed. Recent results of theoretical studies and experiments are presented.

Introduction

The generation, transport, and acceleration of high-intensity, high-brightness beams is of great current interest for heavy ion inertial fusion (HIF), spallation neutron sources, injector linacs for future high-energy physics machines, free-electron lasers (FEL), and other applications. The behavior of such beams is dominated by space charge, rather than emittance, i.e. one operates near the space-charge limit where the forces due to the internal fields are comparable to the external focusing forces. Space-charge effects are most pronounced at low energy, and the only machines capable of accelerating low-energy beams of high intensity are rf linacs or induction linacs.

Beam transport entails the transverse and longitudinal focusing of the particles from the source through the accelerator to the target. In a typical low-energy transport section for an rf linac, the beam has to be pre-accelerated, bunched, focused, and matched into the linac. Today, for ion beams, the Radio-Frequency-Quadrupole Linac (RFQ) with its superior performance characteristics is being used for this task.

In the linac, acceleration, transverse, and longitudinal focusing actions occur at periodic time intervals. Thus, in the frame moving with the particles, the linac is a periodic beam transport system. At the high-energy end, the beam has to be transported to the target with magnetic quadrupole lenses, since solenoids and electric lenses are not effective at high particle velocities. In an HIF system, this transport has to be provided over a very large distance, and a periodic FODO channel is required to accomplish this task. The major bottleneck in an HIF accelerator though is at the low-energy end. Since the currents produced by ion sources are several orders of magnitude below the levels required for pellet ignition, various schemes of current multiplication have to be employed such as longitudinal pulse compression, multiple-beam arrays in the induction linac, or funneling in the rf linac system for HIF.

Historically, we can distinguish two periods in the study of high-brightness beams. The first period occurred in the late sixties and early seventies in connection with the design and operation of the high-energy injector linacs at CERN, Brookhaven, and Fermilab and the LAMPF accelerator at Los Alamos. Particularly noteworthy for this period is the development and use of computer simulation codes,[1] to study the beam transport through an rf linac. In addition, considerable progress was made in developing analytical methods to describe the effects of space charge on the beam dynamics, such as the concept of rms emittance and equivalent beams by Lapostolle and Sacherer.[2]

The main results of both computer simulations as well as measurements from that period can perhaps best be summarized by the following empirical relation between normalized output and input emittance for an rf linac:

$$\varepsilon_{N,out} = (\varepsilon^2_{N,in} + kI^n)^{1/2} , \qquad (1)$$

Here, I is the current in the bunch, n a number in the range $0.6 < n < 1.0$ and k a constant. This formula, attributed to Promé,[3] implies that there is a fundamental limit to the emittance and brightness of a linac beam which depends on the beam current. As the input emittance is decreased, the output emittance approaches a lower limit which depends on the current and is given by $(kI^n)^{1/2}$. This is illustrated in Fig. 1 which is from a paper by R. Stephens[4] of Los Alamos showing theoretical emittance curves according to Eq. (1) and measurements at LAMPF for different currents in schematic form.

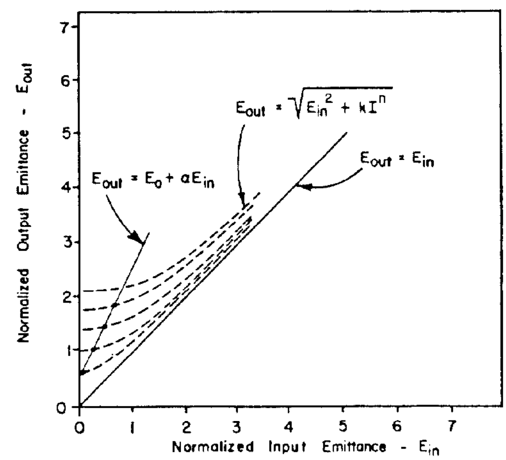

FIG. 1. Characterization of rf linac output emittance as a function of input emittance for different currents. Dashed curves represent relation (1), circles indicated experimental data points (from R. Stephens, Ref. 4).

It should be emphasized that there are to date no theoretical models that explain the linac beam physics responsible for the above relation and that predict the exact values for the parameters k and n.

The proposals by Maschke and Martin to use heavy ion accelerators for inertial fusion triggered new interest in the transport of intense beams and launched the present period of research activity in this field that began in the late seventies. In the meantime, of course, other applications of high-brightness beams have broadened the scope of this work considerably. A major part of the work so far has been devoted to the beam transport in a long periodic channel where theoretical studies predicted instabilities due to resonant interaction between beam

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modes and the periodic structure.

Looking back at the past few years, one can say that the concentration on transverse focusing of long beams proved to be very fruitful. The absence of longitudinal effects led to the successful diagnosis of various phenomena that otherwise tend to be obscured by the complicated three-dimensional beam dynamics in an rf linac. An excellent example is the problem of emittance growth in nonuniform beam distributions (via conversion of field energy into transverse kinetic energy) discussed in the invited paper by Wangler.[5] The emittance growth formula in this case is very similar to Eq. (1), and one can expect that this effect plays also an important role in bunched beams.

The following review of beam physics issues and ongoing experiments is limited for the most part to transverse focusing (transport) of long beams. Although the emphasis of recent work has been on periodic focusing, we will take a broader view here and include other aspects such as the particle source, transport through individual lenses, and charge neutralization effects. On the other hand, the very intense relativistic electron beams and ion beams produced in pulsed-power generators will be excluded since they form a special class of beams that are outside of the scope of this review.

Beam Physics Issues and Answers

Brightness Limitations of Charged Particle Sources

The central issue for the design of a high-intensity, high-brightness accelerator is that a beam with a desired current and emittance be delivered to a target without appreciable loss of particles and without excessive emittance growth during the transport and acceleration process. This task begins with the particle source which will be discussed first.

The typical source of electrons is a thermionic cathode while ions are usually extracted from the plasma of a gas discharge. When the cathode or the plasma are in thermal equilibrium at a temperature T, the velocity distribution of the particles is Maxwellian, i.e. $f(v) = \exp(-mv^2/kT)$. The source temperature represents an intrinsic lower limit for the normalized emittance, ε_N. If r_s denotes the radius of the cathode in an electron gun or of the emitting plasma surface of an ion source, and m_oc^2 the rest energy of the particles, the intrinsic normalized emittance is given by the relation[6]

$$\varepsilon_N = \beta\gamma\varepsilon = 2\, r_s(kT/m_oc^2)^{1/2} , \qquad (2)$$

where $\beta = v/c$, $\gamma = (1-\beta^2)^{-1/2}$. In electron guns, kT is typically about 0.1 eV; for plasma ion sources, kT may be several times larger than that.

The current density of the particle beam extracted from a source is limited intrinsically by the Child-Langmuir Law (in MKS units):

$$J = 1.67 \times 10^{-3}(q/m_oc^2)^{1/2}V_o^{\ 3/2}/d^2 . \qquad (3)$$

V_o is the extraction voltage and d the spacing between the emitter surface and the extraction electrode. This implies a fundamental current limit of

$$I = 0.52 \times 10^{-2}(q/m_oc^2)^{1/2}(r_s/d)^2\, V_o^{3/2} . \qquad (4)$$

From Eqs. (2) and (4), one obtains an upper bound, for the normalized brightness $B_N = I/\varepsilon_N^2$ of a charged particle beam.

In practice, one cannot achieve the high currents predicted by the Child-Langmuir law. Current densities for cathodes used in electron guns, for instance, are limited to about 10 A/cm^2. On the other hand, electrical breakdown, limits the voltage V_o (in kV) and gap spacing d (in cm) in any source such that $V_o < 100\sqrt{d}$. Furthermore, to avoid nonlinearities, and hence emittance deterioration, in the ion optics of the source,[7] the aspect ratio between the emitter radius and the cathode-anode spacing, r_s/d, must stay within limits which are typically between 0.5 and 1.0.

The above relations define the intrinsic limits imposed by the source on the emittance, the current, and the brightness of a particle beam. They can serve as a benchmark for computer simulations or experimental data. In electron linacs, for instance, one finds[8] that the normalized emittance of the accelerated beams may be as much as 30 times larger than the intrinsic limit given by Eq. (2).

Maximum Transportable Current In Various Systems

Many high-intensity ion sources are capable of producing higher beam currents than can be handled in a beam transport system or by the low-energy end of the linear accelerator. Thus, it is important to know the theoretical current limits of various focusing systems such as a short lens followed by a drift tube, a long solenoid, a periodic focusing channel, and neutralization of the space charge. The current-handling capability of each focusing system can best be evaluated by using the uniform K-V beam model with linear space charge and external forces. The equation for the envelope radius R of such a beam has the well-known form

$$R'' + \kappa R - \frac{K}{R} - \frac{\varepsilon^2}{R^3} = 0 , \qquad (5)$$

where κ denotes the focusing strength, ε the unnormalized emittance, and K the generalized perveance defined as

$$K = (I/I_o)(2/\beta^3\gamma^3) . \qquad (6)$$

The characteristic current I_o is 1.7×10^4 amperes for electrons and 3.1×10^7 (A/Z) amperes for ions of mass number A and charge Ze.

In high-brightness beams without charge neutralization, the effect of the emittance on the beam radius is negligible, i.e. one can assume that $\varepsilon^2/R^3 \ll K/R$. The generalized perveance K takes on the role of a scaling parameter in this case. Let us now consider a transport channel with aperture radius a and length S. What is the maximum beam current that can be transported through such a channel if all forces are linear and if one allows the beam to fill the available aperture, (i.e. R = a)? The answer to this question for the focusing systems mentioned above is given below.

Single Lens and Drift Tube (radius a, length S): If f denotes the focal length of the lens, then the maximum current is passed through the tube when f = S/3.974. The corresponding value of the generalized perveance is[9]

$$K_{max} = 2.33\ (a/S)^2 , \qquad (7)$$

which shows that the maximum transportable current is proportional to the geometry factor $(a/S)^2$) and to $\beta^3\gamma^3$.

Uniform Focusing Channel (long solenoid): In this case one obtains from Eq. (5) with $R'' = 0$, R = a, and $\varepsilon = 0$ the result

$$K = \kappa a^2 = (qBa/2m_oc\beta\gamma)^2 , \qquad (8)$$

where B is the solenoidal magnetic field. The theory shows that there is an upper limit for K given by $K_{max} = 0.384$.

Periodic Focusing Channel (lens period S): This problem has received considerable attention in connection with the final transport of the beam in heavy ion fusion. From the smooth approximation theory[10] one obtains the result

$$K_{max} = \sigma_o \alpha/S = \sigma_o^2 (a/S)^2 G \tag{9}$$

where σ_o is the phase advance per lens period of the particle oscillation without space charge, α the channel acceptance, $G = (\bar{a}/a)^2$ the ripple factor, and $\bar{a}$ the average beam radius. Recent theoretical and experimental studies have shown that σ_o should not be greater than 90^0. If one takes this value ($\sigma_o = \pi/2$) and considers a quadrupole FODO channel, then one obtains $G \approx 0.4$ and hence

$$K_{max} = 0.987\ (a/S)^2 \ . \tag{10}$$

Note that the aspect ratio a/S cannot be made arbitrarily large. If one assumes $a/S = 0.2$ as an upper limit, one obtains $K_{max} = 0.294$. Thus, by comparison with the previous two cases, the transportable current is lowest in the periodic channel.

Charge Neutralization: For long beam pulses (say $\tau > 100\ \mu s$) propagating in moderate vacuum ($p \sim 10^{-6}$ Torr), charge neutralization via ionizing collisions with the background gas becomes important. Such neutralization may be desirable for high current transport, but it may also have undesirable effects, e.g. if the degree of neutralization f varies within the pulse or if emittance growth occurs. To illustrate the neutralization effect on beam transport, let us assume that the beam is fully neutralized, i.e. f = 1. The generalized perveance K in Eq. (5) is then zero, and the radius of the beam is entirely determined by the emittance. From Eq. (5) one finds with $R'' = 0$ and $K = 0$, the solution

$$R = a_o = (\varepsilon/\sqrt{\kappa})^{1/2} \ . \tag{11}$$

This radius can be considerably smaller than for the unneutralized beam, i.e. $a_o << a$. Thus, if I_u denotes the current of the unneutralized beam that can be transported through a drift tube or focusing channel with radius a and I_n the current of the neutralized beam, then

$$I_n \approx I_u (a/a_o)^2 \ . \tag{12}$$

This assumes of course, that more current is available from the source and that the emittance of the neutralized beam remains small enough for the particular application. Charge neutralization is a rather complex issue which is not fully understood yet, and the general attitude has been to avoid it when possible. However, the new interest in high-intensity beams may also lead to more research and better understanding of this problem.

Emittance Growth

The intensity limits of various focusing channels discussed in the previous section apply for ideal systems, i.e. matched beam, linear forces, and low emittance ($\varepsilon << R\sqrt{K}$). However, in practice, many effects may cause emittance growth and losses. Major sources of emittance growth are instabilities in periodic focusing channels, nonlinear forces due to external fields or the self fields, exchange between field energy and transverse kinetic energy in nonuniform beams, off-centered beams, lens misalignments and effects of image forces, and energy exchange between two directions (equipartioning). We will now briefly summarize the major results and the present status of studies devoted to these issues.

The main effort during the past few years has been concerned with beam transport in a long periodic focusing channel which is of crucial importance for heavy ion fusion. Analytical work and computer simulation using the ideal K-V distribution had indicated[11] that there is a window for safe transport defined by $\sigma_o < 60^0$ and $\sigma > 24^0$, where σ and σ_o are the phase advance with and without space charge, respectively. More recent work, both computer simulation[12] with non-K-V distributions as well as experiments, demonstrated that these instabilities do not affect laboratory beams as much as had been feared. Only the envelope-type instability poses an upper limit for σ_o leading to a more relaxed condition of $\sigma_o < 90^0$ with no lower limit on σ. As a result, the transportable current can be almost a factor two higher than had been assumed at first. However, other effects may impose additional constraints, as will be discussed below.

One such effect is spherical aberration which in axixsymmetric lenses, for instance, adds a cubic term to the radial force, i.e. the change of slope of a trajectory in the lens is given by

$$r'' = -a_1 r - a_3 r^3 \ . \tag{13}$$

For solenoids, the two coefficients a_1 and a_3 are positive; both terms are therefore focusing, and the ratio of the two force terms is $F_3/F_1 = (a_3/a_1)r^2$. Numerical simulation studies for K-V and thermal distributions in a periodic solenoid channel with a nonlinear lens force described by Eq. (13) have shown the following results:[13] at $\sigma_o = 60^0$, there is no emittance growth; at $\sigma_o = 90^0$, on the other hand, significant emittance growth may occur. This is shown in Fig. 2 where $\varepsilon_{out}/\varepsilon_{in}$ is plotted vs. F_3/F_1. Details can be found in our conference paper on this topic. These nonlinear effects thus may prohibit operation near $\sigma = 90^0$ or reduce the useful aperture radius (and hence acceptance) of the periodic transport channel. We have no experimental confirmation yet of these findings. A systematic study at the University of Maryland of the nonlinear effects in a single solenoid lens has been published recently.[14] It was shown that the beam becomes hollow and that a halo forms when the focusing strength is increased.

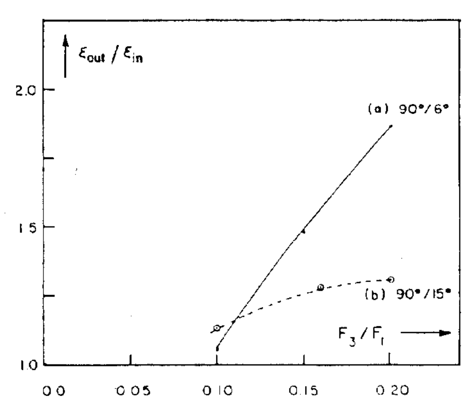

FIG. 2. Emittance growth versus F_3/F_1 after 50 periods, for thermal distribution in periodic solenoid channel at $\sigma_o = 90^0$, $\sigma = 15^0$, and $\sigma = 90^0$, $\sigma = 6^0$.

Of great importance for high-brightness beams is the emittance growth observed when a nonuniform beam is transported through a linear focusing system. This is the effect discovered in Ref. 12 and reviewed in the invited paper by T. Wangler.[5] The results of our studies can be summarized as follows: Near the space-charge limit ($\sigma/\sigma_o \to 0$), a matched beam in a linear focusing system must have a uniform density profile. If the beam is not uniform, it has an excess amount of field energy, $\Delta W/w_o$, which is converted into transverse kinetic energy and thus emittance growth. The theory yields the formula

$$\varepsilon_{out} = (\varepsilon_{in}^2 + kI^2)^{1/2} , \tag{14}$$

where

$$k = \frac{\Delta W}{w_o} \frac{2}{\kappa} \left(\frac{1}{I_o \beta^3 \gamma^3}\right)^2 . \tag{15}$$

Note that the effect occurs in a single lens and does not require a periodic force.

Equation (14) is similar to the empirical relation of Eq. (1) found for bunched beams in a linac, and one expects therefore that the above effect may help to explain the emittance growth in linear accelerators.

The problem just described raises a fundamental question for the theoretician, namely how to find equilibrium distributions in a periodic focusing channel. Until recently, the only known distribution was that of Kapchinskij-Vladimirskij (K-V beam). However, Struckmeier has shown that a generalized waterbag distribution also represents a matched beam in a periodic channel.[15] The associated density profile is nonuniform at large values of σ, but becomes uniform as $\sigma \to 0$.

A well-known source of particle loss encountered in experiments is beam off-centering and/or misalignment of lenses. This problem is currently being studied both at Berkeley and the University of Maryland. An off-centered beam performs coherent oscillations with an effective phase advance given by

$$\sigma_{coh} = (\sigma_o^2 - \sigma_{im}^2)^{1/2}, \tag{16}$$

where σ_{im}^2 is due to the image force seen at the center of the beam, and hence proportional to the beam current. In the electrostatic quadrupole channel at Berkeley, the image force due to a displaced beam contains a sextupole component ($\cos 3\theta$). It was found in simulation studies[16] that this force interacts resonantly with a sextupole beam mode which results in emittance growth. Similarly, a dodecapole component ($\cos 6\theta$) in the external focusing force (when acting without the image term) was found to result in emittance growth for an off-centered beam. Fortunately, due to opposite signs in the two forces, one can achieve complete cancellation and suppression of emittance growth by proper choice of the quadrupole geometry.

Experiments

The theoretical predictions of instabilities and current limits in long periodic focusing channels were based on the idealized K-V distribution. Several experiments were launched to check the validity of the theory. Over the past two years these experiments have produced first results, and there are a number of papers at this conference which describe the present status of these activities. Thus, I will limit myself to presenting a few highlights of ongoing experiments at the University of Maryland, Berkeley, and GSI.

At the University of Maryland[17,18] an electron beam (5 keV, 50 to 250 mA) is being transported through a periodic solenoid channel. The first stage of the channel consisted of 2 matching lenses and 12 periodically spaced lenses. We demonstrated 100% transmission of the injected current over a window of $40^0 < \sigma < 110^0$, with a tune depression of $\sigma/\sigma \approx 0.1$. The measured beam emittance was only about 40% higher than the intrinsic value of Eq. (2). Of particular interest has been the effect of nonlinear lens forces on the beam envelope. This is shown in Fig. 3 for the $\sigma_o = 60^0$ case where the measured beam radius is approximately 10% smaller than the theoretical result based on linear beam optics (top). P. Loschialpo developed a computer program that includes nonlinear effects in the external focusing forces up to third order as well as the nonuniform space charge. The results of his calculations[19] are in excellent agreement with the experimental data (bottom of Fig. 3).

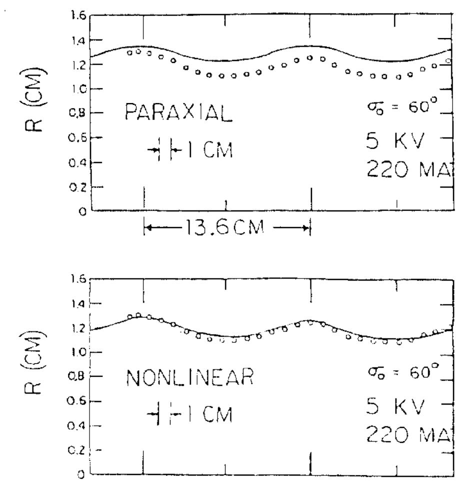

FIG. 3. Effect of nonlinear lens forces (spherical aberrations) on the beam envelope in the Maryland experiment (from Ref. 19).

Last year we added a second stage of 24 additional lenses to the channel. Transport studies with a different electron gun having a smaller cathode radius (0.5 cm vs. 1.25 cm of our large gun) yielded 100% beam transmission through the full channel for $40^0 < \sigma_o\ 100^0$ with rapid beam loss on either side of this window. In subsequent studies with our large gun we found that the beam was off-centered and we obtained 100% transmission only in a narrow range of σ_o values near $\sigma_o = 70^0$. Details of these studies are reported in our contributed paper.[18] Further investigation of the effects of off-centering and image forces are planned for the future.

The beam transport experiment at Berkeley[20] consists of a Cs^+ source (120-160 keV, 0.7-23 mA), a matching section of 5 electrostatic quadrupoles and a periodic focusing channel with 82 electrostatic quadrupoles (41 periods). Grids are used to cover a wide range in σ_o, σ parameter space. Beam transport was found to be stable below $\sigma_o = 90^0$ and down to accessible values of σ as low as 8^0. Unstable regimes of beam transport above $\sigma_o = 90^0$ were found to be in agreement with theoretical expectations.

In recent months the first stage of a multiple-beam experiment with 4 C_s^+ parallel beams, called MBE-4, was put into operation. It is designed to study beam physics issues relevant to heavy ion fusion.[21]

At the GSI laboratory, a short periodic channel consisting of 12 magnetic quadrupole lenses in a FODO configuration (6 periods) is being used to study the transport of high-brightness Ar^+ beams (190 keV, several mA). A major issue at Darmstadt is charge neutralization. The ion pulse length is > 1 ms and partial neutralization occurs which varies along the beam pulse. Another issue is the fact that the ion beam has a nonuniform profile which may lead to the rapid emittance growth described above. When the beam is partially neutralized, the nonlinear space-charge force responsible for the emittance growth is reduced by a factor $1 - f$, where f is the degree of neutralization. This is indeed observed in the experiments.[22] Figure 4 shows the variation of the energy of residual-gas ions [which indicates the beam potential, $V_o(1 - f)$, on the axis] and of the emittance along the beam pulse at the channel entrance. Note that in the early part of the pulse, where neutralization is negligible, the emittance is almost a factor two larger than in the remainder of the pulse.

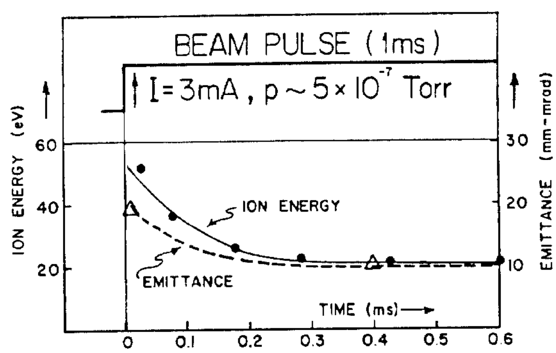

FIG. 4. Variation of the energy of residual-gas ions and of the beam emittance along the beam pulse at the channel entrance of the GSI experiment (From Ref. 22).

Finally, I want to mention that at the FOM Institute in Amsterdam, a MEQALAC system with 4 parallel He^+ beams is being studied. The MEQALAC is an rf linac with electrostatic quads focusing the beams between the acceleration gaps. The latest development at FOM are being reported in a contributed paper at this conference.[23]

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