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HIGH-CURRENT BEAM DYNAMICS AND TRANSPORT, THEORY AND EXPERIMENT*

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Abstract

Recent progress in the understanding of beam physics and technology factors determining the current and brightness of ion and electron beams in linear accelerators will be reviewed. Topics to be discussed include phase-space density constraints of particle sources, low-energy beam transport including charge neutralization, emittance growth due to mismatch, energy exchange, instabilities, nonlinear effects, and longitudinal bunching.

Introduction

A general review on the transport of high intensity beams, including major results of ongoing work at that time, was presented at the 1985 Particle Accelerator Conference.[1] The problem is of continuing interest, and active research is in progress at various laboratories, such as the Los Alamos National Laboratory, the Lawrence Berkeley Laboratory, GSI Darmstadt, the University of Maryland, the University of Frankfurt, the FOM Institute in Amsterdam, and other places. There are several papers at this conference which will report the latest results of these studies. I will therefore limit any talk to a discussion of some general issues, to recent work that was done in connection with the University of Maryland experiment, and to calling attention to some results by others that should be of special interest. The main emphasis will be on ion beams, with the exception of the Maryland electron transport experiment and some comments on electron linacs. The Maryland experiment is designed to study the physics of space charge dominated transport through periodic focusing channels with many results applicable to both electron and ion beams (through appropriate scaling laws). It serves as an inexpensive facility to test analytical theories and simulation codes dealing with current limits, collective instabilities and nonlinear effects in beam transport.

The transport of high-current electron or ion beams in the kA or mega-ampere range produced by pulsed-power generators will not be included since these beams form a special category that is outside the scope of my talk. The major topics of discussion will be: 1) Low-energy transport of high-current, high-brightness beams, 2) transport in periodic focusing channels, and 3) transport of bunched beams in linear accelerators.

Low-Energy Transport of High-Current High-Brightness Beams

Intrinsic Phase-Space Density Limits of Particle Sources. It is well recognized that the fundamental limits for current and emittance of particle beams are determined by physics and technology constraints of the source. A considerable amount of theoretical work has been devoted over the years to the causes of emittance growth and loss of brightness in accelerators and transport systems. Substantial progress has been made both in understanding of the beam physics as well as in improvement of the intensity and emittance of accelerator beams.

Particle sources, in particular ion sources, have traditionally been considered as "empirical art," not suitable to theoretical analysis. Yet steady progress in development of new sources as well as in theoretical understanding of source physics and technological factors has been made. Not suprisingly, very significant contributions in this process have been made by researchers with a plasma physics background. The large variety of sources and particle species and the difference in operating conditions (e.g., pulsed versus dc) make it, of course very difficult, if not impossible, to derive general scaling laws for the performance limits. However, for specific types of sources, e.g., sources having a simple diode-like geometry and producing singly charged particles, an evaluation of current and brightness limits is possible. The best example is an electron gun with a thermionic cathode, Pierce geometry, and no grids. The normalized intrinsic emittance (defined as four times the RMS emittance) is determined by the cathode temperature T and radius r_s and is given by the formula[2]

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

Where m_oc^2 is the rest energy. The measured emittance of the electron beam emitted from the gun in the Maryland experiment was found to be only about 11% larger than this intrinsic value.[3] For many high-power applications the output current of an electron gun is limited by the current density J_c at the cathode rather than high-voltage breakdown (as in the case for ion sources). The desired electron beam current $I = J_c r_s^2 \pi$ thus determines the cathode radius r_s and the normalized emittance ε_N. Using $r_s = (I/J_c\pi)^{1/2}$ we can write Eq. (1) in the form

$$\varepsilon_N = 2(I/J_c\pi)^{1/2}(kT/m_oc^2)^{1/2} . \qquad (2)$$

Depending on the desired life time, average power, and other factors, current densities of 10-20 A/cm^2 are practical limits (though values up to ten times higher may be achievable in special cases, or advanced designs). Using $J_c = 10$ A/cm^2 = 10^5 A/m^2 and a cathode temperature of $kT \cong 0.1$ eV one obtains the relation

$$\varepsilon_N = 1.6 \times 10^{-6} I^{1/2} \text{ m-rad} , \qquad (3)$$

where the current is in amperes. The brightness, defined in terms of the unnormalized emittance $\varepsilon\pi = \varepsilon_N\pi/\beta\gamma$, is then given by

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$$I/(\varepsilon\pi)^2 = 3.96 \times 10^{10}(\beta\gamma)^2 \ A/(m\text{-}rad)^2 , \quad (4)$$

which in the relativistic limit ($\beta \sim 1$) is seen to increase as γ^2, independent of the current.

For plasma-type ion sources with simple extraction optics, on the other hand, the phase space density is limited by Child's law and voltage breakdown rather than current density, as was pointed out in my previous paper. The scaling law for the achievable brightness then depends on whether the emittance is determined by nonlinearities in the beam optic, as assumed by R. Keller in his recent paper,[4] or by the plasma ion temperature. Holmes[5] and others believe that sources can be designed such that nonlinearities have only a negligible effect on the emittance and that hence the ion temperature represents the intrinsic limit. We will adopt their viewpoint, but use Keller's empirical relations for the space-charge limit and voltage breakdown in the following analysis.

The space-charge limited maximum current that can be extracted from a source producing a single ion species with a charge Ze and mass number A is according to Child's law

$$I_{[A]} = 1.73\pi \times 10^{-3} \ V_{[kV]}^{3/2} \left(\frac{r_s}{d}\right)^2 \left(\frac{Z}{A}\right)^{1/2} , \quad (5)$$

where V is the extraction voltage and d the effective gap width between the plasma exit aperture and the extraction electrode. Keller points out that beam optics requirements limit the aspect ratio $S = r_s/d$, and he uses a value of S = 1 for his scaling laws.[5] He then gives a practical current limit (based on experience with ion sources) of[4]

$$I_{[A]} = 0.7 \times 10^{-3} \ V_{[kV]}^{3/2} \left(\frac{Z}{A}\right)^{1/2} , \quad (6)$$

which is almost a factor eight times lower than the theoretical limit of Eq. (5). The voltage V is limited by electrical breakdown. For dc ion sources Keller examined the data from many experiments and proposes as the best fit the relation[4]

$$d_{[cm]} = 1.4 \times 10^{-3} \ V_{[kV]}^{3/2} . \quad (7)$$

The intrinsic normalized emittance ε_N due to the ion temperature, as given by Eq. (1), can be expressed in the form

$$\varepsilon_{N[cm \cdot mrad]} = 6.5 \times 10^{-5} \ r_{s[cm]} \left[\frac{(kT_i)_{[eV]}}{A}\right]^{1/2} . \quad (8)$$

If we assume that the source aperture radius r_s is equal to the gap width d, we can substitute Eq. (7) into Eq. (8) and obtain

$$\varepsilon_{N[cm \cdot mrad]} = 9.1 \times 10^{-8} \ V_{[kV]}^{3/2} \left[\frac{(kT_i)_{[eV]}}{A}\right]^{1/2} . \quad (9)$$

Using the ratio of current I and normalized emittance ε_N as a figure of merit to measure the intrinsic phase-space density limit of an ion beam, we obtain for singly charged ions (Z = 1) such as protons, H^-, etc. from Eqs. (6) and (9) the relation

$$\frac{I}{\varepsilon_N} = \frac{7.7}{\left[(kT_i)_{[eV]}\right]^{1/2}} \ \frac{A}{cm \cdot mrad} . \quad (10)$$

Interestingly, this limit is independent of the ion mass since both I and ε_N vary as $A^{-1/2}$. Typical ion temperatures are in the range of 1 eV, hence $I/\varepsilon_N \approx 8$ A/cm · mrad.

Kapchinsky[6] reviewed the phase-space density values achieved within the laboratory with unbunched proton beams for linear accelerators and pointed out that they increased by almost a factor 10 from 0.2 A/cm · mrad in 1966 to 2 A/cm · mrad in 1981. If one compares this with Eq. (10) and assumes that lower ion temperatures in the range of 0.1 eV could be achieved, one concludes that another factor of 10 increase might be possible in the future.

Charge Neutralization Versus Vacuum Transport. The main task for a low-energy transport system is to focus the beam extracted from the source and match it into the RFQ accelerator (in the case of ions) or into a buncher/linac system (in the case of electrons). We will restrict our discussion in this section to ion beams. When particles with different charge-to-mass ratio are emitted by the source, the desired ion species has to be separated from the other particles (usually by a dipole magnet and slits).

Focusing lenses used for low energy ion transport are solenoids, magnetic quadrupoles, electrostatic einzel lenses or electric quadrupoles. All of them are limited with regard to the beam perveance $I/V^{3/2}$ that they can handle, i.e., for a given current I there is a minimum beam voltage V required. Electrostatic quadrupoles would appear to give the strongest focusing. As a general rule, the higher the voltage, the higher the current that can be transported. This rule is at odds with the ion source scaling (discussed in the previous section) which favors small gap spacing and low voltage (to avoid breakdown) for the generation of high-current, high-brightness beams. To bridge this gap between source output and focusing capability, charge neutralization and rapid increase of the ion energy in an accelerating column is being used. The difficulty with neutralization is that it leaves the particle energy unchanged while the accelerating column may not provide adequate focusing. The advantage of neutralization is the fact that it eliminates most of the space charge repulsion and thus prevents the rapid spreading of the beam or even provides a net focusing effect (as in the case of H^- ions). Neutralization is almost indispensable when charge separation is required. Without neutralization, the highly nonlinear space charge forces acting on the particles in the weak focusing dipole magnet could lead to unacceptable beam loss and phase-space deterioration.

Charge neutralization via beam particle collisions with the background gas molecules occurs naturally when the beam pulse length τ_p is comparable or larger than the neutralization time τ_N:

$$\tau_p < \tau_N \approx \frac{1}{n_g \sigma v} , \quad (11)$$

where n_g is the gas density, σ the ionization cross section,[8] and V the beam particle velocity. As an example, for 50–100 keV protons in hydrogen gas at 10^{-5} torr, the neutralization time is in the range of 50–100 μs. The pressure near the source is easily in that range or even higher so that neutralization takes place unless the beam pulses are shorter than 50-100 μs or electrostatic fields from special "clearing electrodes," electric lenses, or accelerating columns are present.

Neutralization is not yet fully understood, and opinions vary depending on experience in specific experiments. There may be instabilities, but they can be avoided[7] by the adddition of Xe gas. C. D. Curtis, et al. report improved H^- beam transport with neutralization.[8] On the other hand, considerable emittance growth was measured in transport of a neutralized Ar^+ beam through a magnetic quadrupole channel at GSI.[9] Also, the degree of neutralization was found to increase from zero at the front of the pulse to a maximum at the rear, which makes matching difficult. Clearly, more research, both experimental and theoretical, is needed in this area. There are obviously cases, such as sources emitting a spectrum of different particles, in which neutralization is necessary. On the other hand, for singly charged ion beams, an effective vacuum transport system with electrostatic quadrupoles would appear to be the better choice in my opinion. The successful C_s^+ beam experiment at Berkeley[10] supports this viewpoint.

Nonlinear Effects. Theoretical and experimental studies during the past few years have greatly improved our understanding of nonlinear effects, and new results are being reported at this meeting. For the purpose of this discussion it will be convenient to distinguish the effects due to nonlinear external focusing forces (e.g., lens aberrations) from those arising due to nonuniform space charge distributions. The former have been studied in great detail, and are well understood, for the cases when the space-charge forces are negligible. However, the effects on nonlinear focusing forces in space-charge dominated beams are drastically different from the behavior without space charge.

In the following we will discuss first the behavior of a uniform beam in a linear focusing system (e.g., a lens or a transport channel), and then a nonuniform beam in a linear focusing system. In both cases we will assume that the beam is space-charge dominated, i.e. the effect of emittance on the beam radius is negligible. Most of the physics can then be understood by considering the beam to be laminar, at least initially.

The focusing of an initially uniform electron beam by a solenoid lens and the effects of the nonlinear lens forces have been studied both experimentally and computationally by P. Loschialpo, et al.[11,12] at the University of Maryland. In an axisymmetric beam with uniform particle density, i.e. $n(r) = n_o = \text{const.}$, the electric field E_r and hence the space-charge repulsive force F_s vary linearly with radius r:

$$F_s = eE_r = \frac{e^2 n_o}{2\varepsilon_o} r \ (\text{for } r < a = \text{beam radius}) \ . \qquad (12)$$

The nonlinear focusing force F_e, on the other hand, may be written in the form

$$F_e = - a_1 r - a_3 r^3 \qquad (13)$$

if terms involving the slope r' of the trajectories $(r'r^2, r'^2 r)$ and those higher than third order are neglected. For a solenoid lens with finite width, the coefficients a_1 and a_3 are functions of the axial coordinate z and the magnetic field of the lens. When the third-order term in Eq. (13) is absent, the solenoid behaves like a perfect lens. In this case, the beam is focused to a well-defined waist and then diverges again. The flow remains laminar, i.e. no particle trajectories cross each other or the axis, and the density profile remains uniform.

When the third-order term is present, the outer particles in the beam are focused more strongly than the inner ones and the minimum radius (waist) occurs at different axial positions. The internal (space-charge) force tries to balance the external focusing force, and the beam profile becomes hollow. As the focusing strength of the lens is increased, particles within a radial shell ($r_c < r < a$) near the edge of the beam gain enough transverse kinetic energy to overcome the space charge repulsion of the beam core. They cross the axis and form a separate nonlaminar group that gives rise to strange patterns and a "halo" formation in the beam profiles downstream from the lens.

In a continuous or periodic solenoidal focusing channel with nonlinear forces of the form in Eq. (13), the coefficients a_1 and a_3 are constant or vary periodically with z.[1] The beam becomes hollow and the beam radius is smaller than for the linear case ($a_3 = 0$). This behavior was seen in the Maryland solenoid transport channel and excellent agreement was found between theory and experiment.[1,11]

Next, we will consider the case of an initially nonuniform beam in a linear focusing system. As an example, let us assume a parabolic density variation of the form $n(r) = n_1(1 - r^2/R_1^2)$ for $r < R_1$. Then one finds from Gauss' law for the space-charge force F_s the relation

$$F_s = \frac{e^2 n_1}{2\varepsilon_o} \left(r - \frac{1}{2}\frac{r^3}{R_1^2}\right) \ , \qquad (14)$$

which includes a nonlinear term of third order in the radius r. Comparing this beam with a uniform beam having the same current and RMS radius one finds $n = (4/3)n_o$ and $R_1 = (1.5)^{1/2}$ a. Since the external force is linear, i.e. $F_e = - a_1 r$, there is an imbalance between the space-charge and the focusing forces. At small radii $F_s > F_e$, and at large radii $F_s < F_e$. The net result is that the beam wants to become uniform such that there is exact force balance at every radius. This behavior of a nonuniform beam was discovered in simulation studies of different particle distributions in a magnetic quadrupole channel with a linear, periodic focusing force.[13] More importantly and suprisingly, we found that this redistribution of particles towards a uniform profile occurs very rapidly (in one lens period) and is accompanied by a significant emittance growth. The author attributed this emittance growth to conversion of field energy to kinetic energy. We found that the nonuniform particle distributions have indeed more electrostatic field energy per unit length than the equivalent uniform beam with the same current I, RMS radius, and RMS emittance. Using energy conservation, we derived a formula for the emittance growth which yielded good agreement with the simulation results.[13] If ε_i denotes the initial emittance of the nonuniform beam and ε_f the final emittance (after the beam has become uniform), then the emittance growth formula can be written in the form[1]

$$\varepsilon_f = (\varepsilon_i^2 + kI^2)^{1/2} \ . \qquad (15)$$

The constant k is proportional to the relative difference in field energy between the nonuniform and the equivalent uniform beam and also depends on the strength of the focusing force and the kinetic energy of the particles.[1] As the initial emittance is decreased and the beam becomes laminar ($\varepsilon_i = 0$), a lower limit of $\varepsilon_f = \sqrt{k}\, I$ is reached for the final emittance.

Subsequent studies for nonuniform distributions in a linear, continuous focusing channel by Wangler, et al.[14] led to the derivation of a differential equation for the emittance growth effect by Wangler. It was found that Eq. (15) represents a very good solution of this differential equation and that it was in excellent agreement with the numerical simulation results. Interestingly, Lapostolle[15] had already derived a similar differential equation in 1971; but at that time the importance of this effect was not fully recognized and Lapostolle's pioneering work had been forgotten, as is so often the case.

Now the emittance growth in nonuniform beams due to conversion of field energy into kinetic energy has become a subject of intense systematic studies, and new results are reported at this meeting by I. Hofmann,[16] T. Wangler, et al.[17] and O. Anderson. Hofmann and Wangler have investigated the combined effects of emittance growth of a nonuniform beam and equipartitioning (when the emittances in both transverse directions are different). They have also begun to study these effects for bunched beams relevant to linear accelerators. Anderson has studied the time evolution of the emittance growth in a nonuniform beam: the characteristic time is $\tau_p/4$ where $\tau_p = 2\pi/\omega_p$ is the period of a plasma oscillation.

Transport in Periodic Channels, the Maryland Experiment

The interest in periodic focusing systems was originally triggered by the need in Heavy Ion Fusion (HIF) to transport high-current beams over long distances from the accelerator to the reactor chamber. Experiments at the University of Maryland, at Berkeley, and at GSI were started to investigate whether laboratory beams are affected by the instabilities predicted for a K-V distribution.[19] These instabilities impose thresholds on the phase advance σ_o of the particle oscillations per channel period without space charge and on the depressed tune (or phase advance) due to space charge, σ. As a result, the beam current that can be transported through a periodic channel is limited. This current limit can be expressed by the the smooth-approximation formula[20]

$$I = \frac{I_o}{2}\, \beta^3\gamma^3\left(\frac{a}{S}\right)^2 \sigma_o^2 G\left[1 - (\sigma/\sigma_o)^2\right] , \qquad (16)$$

where a is the maximum beam radius (channel aperture), S the length of one period $I_o = 3.1 \times 10^7$ A/Z amperes (A = mass number, Z = charge state), and G is the ripple factor which for quadrupole channels of the FODO type is given to good approximation by

$$G = 1 - \frac{1.2}{\pi}\sigma_o . \qquad (17)$$

The two cases considered to be most dangerous for beam transport are the envelope instabilities predicted to occur for $\sigma_o > 90^0$ and the third-order instabilities for $\sigma_o > 60^0$. Below $\sigma_o = 60^0$, fourth-order modes were initially thought to pose a lower limit for the depressed tune of $\sigma = 24^0$. More recent theoretical and experimental studies[13,3,10] have shown that transport below $\sigma_o = 90^0$ and at very low tune depression of $\sigma/\sigma_o \approx 0.1$ is possible. At $\sigma_o = 90^0$, the stop band for the third-order mode of a K-V beam in a quadrupole channel is in the range $40^0 < \sigma < 55^0$. Thus, as long as σ stays below 40^0, one would not expect any problems with this mode even at $\sigma_o = 90^0$. In a solenoid channel, like the one at the University of Maryland, the third-order instability is considerably weaker than in a quadrupole system. At $\sigma_o = 90^0$, the main stop band is very narrow ($44^0 < \sigma < 48^0$) and the maximum growth rate is less than 1/3 of that in the quadrupole case. Thus, one would not expect any problems for labortory beams in a solenoid channel below $\sigma_o = 90^0$. Above $\sigma_o = 90^0$, the envelope instabilities occur both in quadrupole and in solenoid channels in addition to the third-order modes which become more pronounced in this region. The actual threshold for practical beam transport is being explored in the Maryland experiment.

In recent studies of beam transport in a periodic channel the attention has shifted from the instabilities to nonlinear effects, beam off-centering, and image forces. The latest results of both experimental as well as numerical simulation studies for the solenoidal transport system at the University of Maryland have demonstrated a strong sensitivity of transport efficiency and emittance growth to alignment error, lens aberrations, and channel length. In previous work[3] with a short 12-lens section we had found a window of 100% transmission for $40^0 < \sigma_o < 110^0$ and very little emittance growth (by a factor of about 1.3). The latest results[21] in the full 36-lens channel with 1-2 mm beam off-centering due to misalignments showed that the 100% transmission window had narrowed to $60^0 < \sigma_o < 80^0$ and the measured emittance growth was 2.3 at $\sigma_o \approx 70^0$. There were three unexplained dips in the transport efficiency curve between 80^0 and 110^0 and then rapid catastrophic beam loss for $\sigma_o > 120^0$ which is consistent with third-order and envelope instabilities in this region. Simulation results for an off-centered beam ($\Delta r = 1.5$ mm) show the general trend observed in the experiments. They confirm the importance of accurate alignment and the fact that the beam radius must be smaller than a critical value (we call it the "linear aperture radius") to avoid emittance growth and beam loss. Further studies at the University of Maryland are aimed at improving the alignment of the electron gun and the solenoid lenses and at determining the linear aperture and the thresholds for σ_o.

Transport of Bunched Beams

With the steady progress achieved in our understanding of transverse focusing of long beams near the space charge limit, the time has come to consider transport of bunched beams and to reexamine the well-known problem of beam loss and emittance growth in rf linacs. As was mentioned above, all high current rf linacs exhibit emittance growth and brightness limitations which depend on the beam current. There is, in fact, an empirical relation between the output and input emittance of a linac very similar to Eq. (15), namely

$$\varepsilon_f = (\varepsilon_i^2 + kI^n)^{1/2} , \qquad (18)$$

where I is the current in the bunch, k is a constant, and n is a number in the range $0.6 < n < 1.0$. This emittance growth occurs predominantly in the bunching and low-energy section of the linac. There is also a fundamental difference between ion linacs and electron linacs which favors the former. On the one hand, we see from Eq. (1) that the intrinsic emittance of an ion beam scales as $\varepsilon_N \propto m_o^{-1/2}$, i.e. for the same source radius and temperature, the intrinsic emittance of a proton beam is a factor of $\sqrt{1836} \approx 43$ smaller than that of an electron beam. On the other hand, the use of an RFQ significantly reduces the beam loss and emittance growth for ions in the bunching process. Unfortunately, the RFQ is not suitable for electron beams. Thus, emittance growth is more severe in electron linacs than in ion linacs.

As mentioned above, Wangler and Hofmann have started to study emittance growth due to energy conversion of a nonlinear distribution and energy equipartitioning in bunched ion beams. Equipartitioning is an important effect in ion linacs where the kinetic energy spread (or the emittance) in the longitudinal direction usually differs from that in the transverse directon. As a result, when the current is above a certain threshold, relatively rapid energy transfer can take place associated with emittance growth in the direction where the initial emittance was smaller. Future work on bunched beams will follow the same path as in the case of long beams, i.e. one needs to study the effects of nonlinear external fields, of beam off-centering and misalignments, etc. Eventually, one should be able to quantify the various effects that can contribute to emittance growth or beam loss and develop guidelines for the optimum design of a linear accelerator. The ultimate goal would be to obtain a theoretical understanding of the empirical relation [Eq. (18)] for emittance growth in a linac and to reduce the magnitude of the constant k in Eq. (18) to an acceptable minimum value. For a given current I, this minimum emittance growth condition can be stated in the form

$$kI^n < \varepsilon^2_{thermal} = 4r_s^2 \frac{kT}{m_oc^2} , \qquad (19)$$

i.e., the emittance increase due to space-charge and other effects would be less than the intrinsic thermal emittance of the source.

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