INJECTION SYSTEMS FOR HIGH CURRENT ION ACCELERATORS*

T. Weis
Institut für Angewandte Physik, Johann Wolfgang Goethe-Universität
D-6000 Frankfurt am Main 1, Postfach 111 932, West Germany

Abstract

Creation, extraction and beam formation of high current beams (1-1000 mA) and their injection into rf accelerators is of increasing interest. Typical properties of high current ion sources will be discussed together with the space charge limits of rf accelerators (mainly RFQ). Especially in the heavy ion case problems arise with the proper adaption of ion sources, appropriate focusing systems, and possibly mass or charge separation and it is not clear if desired maximum beam transmission and minimum emittance growth can be obtained simultaneously. A comparison of magnetic and electric low energy beam transport systems is included, covering the influence of space charge compensation on the transverse emittance.

Fundamental aspects will be discussed and typical examples of existing and proposed injection lines including an overview on recent development of high current rf accelerators will be given.

Introduction

Among the main inventions, which revolutionized accelerator physics, the discovery of the strong alternating gradient (AG-) focusing principle is of particular significance. Henceforth cyclic as well as linear accelerators could be built with smaller apertures and the focusing was even strong enough to keep a space charge dominated beam within the limiting apertures.

Large dc-accelerators (mainly Cockroft-Walton) were necessary to close the gap between ion source extraction voltage and the input beam energy required for the successive accelerator and the maximum current was determined either by the current capability of the dc-system or by the current transport properties of the low energy beam transport (LEBT)-line.

The invention of the "spatially continuous strong focusing" principle [1] has originated a tremendous research on the so-called radio frequency quadrupole (RFQ)-accelerator, where a modulated radio frequency quadrupole arrangement is used to focus, bunch and accelerate high current ion beams at very low energies (typically 10-100 keV for protons, 1-10 keV/nucleon for medium and heavy ions).

For light and medium ions the RFQ is able to capture the ion beam right from the ion source, and overall beam transmissions of more than 90% have been achieved. For high current heavy ion beams the charge state is only one or two and therefore an additional dc-voltage is necessary to reach the input energy.

The development of high current and also high brightness ion sources ran parallel with the increasing current capacity of available accelerators, resulting in widely spread applications. High current accelerators of medium and high energy are nowadays of interest in particle and nuclear physics as well as in the heavy ion confinement fusion program. Low energy applications are for example neutral beam heating of plasmas in the plasma fusion program, and implantation of ions into semiconductors and metals.

The injection system of an accelerator system (here defined as ion source, extraction system, and LEBT-section (including perhaps a dc-column) has the task to provide an ion beam with the right current, emittance, mass and charge and time structure (macro- and/or micropulsed or cw) to be matched into the adjacent accelerator structure. Additional devices such as bunchers for longitudinal beam compression, electric and magnetic dipoles for mass and charge separation, choppers for preparing a special micro structure or kicker magnets may be included in the LEBT-section.

Transverse beam emittance and space charge forces tend to increase the beam dimensions, and the injection system has to provide enough focusing strength $\varkappa$ to keep the beam within the limiting aperture. The variation of the beam diameter R of a circular beam along the beam path z is given by the enveloppe equation [2]

$$\frac{d^2}{dz^2} R = \frac{\varepsilon^2}{R^3} + \frac{K}{R} - \varkappa(z) R \,. \qquad (1)$$

Here ε is the absolute transverse emittance and the generalized beam perveance K is given by

$$K = \frac{\zeta e}{A m_0} \cdot \frac{I}{2\pi \varepsilon_0 v^3} \,. \qquad (2)$$

with the ion charge $\zeta \cdot e$ and mass $A \cdot m_0$. The ion current and the beam velocity is denoted by I and v respectively. In fact equation (1) is valid for the second order moments (rms-values) of ε and R only.

At low energies the behaviour of high current beams is dominated by the beam perveance term K/R (space charge dominated), exceeding the emittance term by more than an order of magnitude.

The ion source and here mainly the extraction system sets the limit for maximum beam current and minimum emittance. The LEBT section as well as the accelerator have to provide enough current capability and acceptance for proper and loss free transport and acceleration.

The successive chapters are dedicated to the basic limits of ion beam properties set by the ion source, the transport line and the high current rf accelerator respectively. Data and operating experience of typical existing and proposed injection systems are given.

Limits Set by the Ion Source

The present chapter is primarily concerned with principal limits of extractable current and beam emittance of high current ion sources (> 1 mA) based on plasma generators. The amount of existing references is huge; a comprehensive survey has been given by R. Keller [3].

The characteristic features of high current ion sources are determined by the properties of the plasma generator and the extraction system (accelerator column), and in principle a cold, quiet, and homogeneous plasma is necessary to obtain high currents and high brightness beams. Under the assumption that the beam extraction is not limited by the current density available from the plasma, the Child-Langmuir law [4] can be used to obtain the maximum extractable ion current I_{max} under space charge limited conditions

$$I_{max} = P \cdot \sqrt{\zeta / A} \cdot U^{3/2} \qquad (3)$$

where U is the extraction voltage, ζ and A the charge and mass number of the ion. The perveance P depends only on the aspect ratio S = a/d (with a the aperture radius for a circular extraction hole and d the effective extraction gap width) and optical properties. Therefore the total extractable current I_{max} does not depend on the actual size of the extraction system. Naturally the extraction system has to provide a beam with minimum emittance and with a main fraction of current within a reasonable divergence angle to be captured by the successive transport system. As we are interested for practical reasons in reasonable and transportable ion beams we stick to a model proposed by R. Keller [5], where the maximum transportable current I_{tr} for a single round aperture is given by

$$I_{tr} = 2.2 \cdot 10^{-8} \, A/V^{3/2} \cdot \sqrt{\zeta / A} \cdot U^{3/2} \qquad (4)$$

(see fig. 1) using 20 mrad for the beam divergence half angle α

---

*Work supported by BMFT under contract no. 06 OF 1861

and an aspect ratio $S = a/d = 1$ for a two-gap extraction system.

The emittance of the beam however depends on the actual size of the extraction system and on the plasma ion temperature [5,6,7]. For ion beams containing a substantial fraction of the space charge limited current the aberrations caused by the not ideal optics of the extraction system determine the minimum absolute beam emittance ε via the acceptance of the extraction channel. For $S = 1$ the absolute emittance is given by

$$\varepsilon = \alpha * r = \alpha * a/2 = \alpha * d/2, \qquad (5)$$

with r denoting the minimum beam radius in the extraction system. Experiments and numerical simulations have shown that r is roughly about half of the outlet aperture radius a [5].

Minimum emittance therefore calls for minimum extraction width d. Based on the Kilpatrick criteria [8], relating minimum gap widths to applied voltage, $d = 4.47 * 10^{-10}\,\mathrm{m} * U^{3/2}$ seems to be a conservative limit [5] giving an absolute emittance (see fig. 1) of ($\alpha = 20$ mrad)

$$\varepsilon = 4.47 * 10^{-6}\,\pi * \mathrm{mm} * \mathrm{mrad}/V^{3/2} * U^{3/2}. \qquad (6)$$

The normalized emittance ε_n depends on the ion velocity and therefore on the ion species giving $\varepsilon_n \sim \sqrt{\zeta/A} * U^2$. High extraction voltage results in high extracted currents at the expense of increasing emittance. The beam brightness, whether based on absolute or normalized emittance is decreasing with U, thus leading to different design goals (brightness or current optimized) for high current sources.

So far the given current and emittance limits are valid for a single round aperture. Using a high ratio of extracting voltage and beam energy (accel/decel-system) the current can be significantly increased [6,9] resulting in increasing beam divergence. Slit apertures allow higher currents to be extracted from the plasma, but demand a homogenious plasma with an appropriate spatial extent. The latter is also valid if a multi aperture system of round or slit apertures is used, increasing the total current by a factor given by the number N of apertures at the expense of increased emittance.

Limits Set by the High Current Accelerator

In many injection systems dc-columns are covering the gap between ion source and medium energy accelerator. Cockroft-Walton type dc accelerators have been built e.g. for 30 mA, cw operation at 900 kV at the Paul Scherrer Institut,Villigen [10] and some hundreds of mA at very low duty cycle [11]. Emittance increase at high currents due to large beam diameters caused by the weak focusing and lower available currents at high duty factors set a severe limit for high current applications especially at higher energies. A solution for the first case may be the "constant current variable voltage" design, investigated at Lawrence Berkeley Laboratory LBL [12], where strong electrostatic focusing is applied in a dc-column.

Induction linear accelerators are mainly investigated at Lawrence Livermore Laboratory and LBL [13] for very high intensities in the ampere range at very short pulse lengths. The special time structure of such linacs e.g. does not allow an operation as preaccelerator for common used high energy rf accelerators.

Radiofrequency linear accelerators for low ion energies have been built in a variety of different types [14]. Magnetic as well as electric AG-focusing have been applied. For very low ion energy electrostatic quadrupoles are favorable. A system designed for multi beam acceleration is the MEQALAC-system proposed by Maschke [15], where standard rf acceleration is combined with an array of electrostatic quadrupoles. The transverse focusing is spatially inhomogenious, causing increasing fringe field effects for short quads at low energies thus giving the lower limit of electrostatic quadrupole applications.

The radiofrequency quadrupole (RFQ) however uses "spatially homogenious focusing" of a long rf powered quadrupole arrangement. The absence of transverse focusing fringe fields allows shorter cell lengths for a given frequency. The acceleration is introduced by longitudinal modulation of the conductors forming the quadrupole. A comprehensive overview on RFQ related development and references is given in [16,17].

Lowest input energy combined with the most efficient rf driven electric AG focusing and the possibility to vary rf stable phase, acceleration gradient together with focusing strength favor the RFQ over all existing high current rf accelerators.

Therefore the highest limits for current capability and channel acceptance are set by the RFQ structure. Compared to the model for ion sources described above it is quite complicated to derive similar relations for the RFQ. Though the choice of rf structure, frequency, power consumption, particle dynamics design philosophy and the voltage hold-off problems are linked to one another in a tight way, the RFQ-builder still has room for a specific layout.

Nevertheless for a pure non modulated transport RFQ structure simple scaling laws can be derived, which still hold for real RFQs by comparison with experimental and proposed data. Maschke [15] showed that in a zero order approximation the transverse current limit of a single transport or accelerating channel is independent of the channel size.

Following Reiser [18] the transverse current limit of a single channel is given by

$$I = \frac{I_0\ A}{2\ \zeta}\ \beta^3 \frac{\sigma_0}{L}\ \alpha\,(\,1 - \sigma^2/\sigma_0^2), \qquad (7)$$

where β is the ion velocity v divided by the light velocity c, L is the cell length of the structure, α the zero current acceptance, σ and σ_0 the phase advance (betatron tune) with and without current respectively. I_0 is given by $4\pi\varepsilon_0 m_0 c^3/e$ with e the electron charge, ε_0 the vacuum dielectric constant and m_0 the proton mass. For the sake of convenience we express β as a function of T, the voltage a singly charged ion has gained, and the cell length L via the rf frequency $f = v/L$. Assuming that the channel radius R is limited to values smaller than L/2 (length of the bunch exceeds transverse diameter) the transverse current limit can be written as

$$I = \varepsilon_0 \pi \sigma_0^2 \sqrt{2e\zeta/Am_0} * (\,1 - \sigma^2/\sigma_0^2\,) * T^{3/2}. \qquad (8)$$

Although there are reports on stable transport of high currents with σ_0 up to 90^0 or even more [19], phase advances per cell σ_0 smaller than 60^0 are strongly recommended due to enveloppe instabilities [20] and the tune depression $\sigma/\sigma_0 = \varepsilon/\alpha$ should remain above 0.4. Since the RFQ is an electrical system an RFQ related perveance P_{RFQ} can be obtained by using the numbers mentioned above giving

$$I = P_{RFQ} * \sqrt{\zeta/A} * T^{3/2} = 3.56 * 10^{-7} A/V^{3/2} * \sqrt{\zeta/A} * T^{3/2}. \qquad (9)$$

This is the theoretical transverse current limit of a transport RFQ without modulation and channel diameter equal cell length. No assumptions have been made yet concerning dimensions or frequency. The current is independent of the channel size and can be increased only by using multibeam techniques (Maschke's original intension [15]). Compared to the perveance limit of the extraction system given above ($2.2 * 10^{-8} A/V^{3/2}$), P_{RFQ} has a fairly high value. Existing and proposed current limits (normalized to proton values) of RFQs have been plotted in fig. 1 together with the limit for the extraction system, indicating that the tendency of the equation (9) is quite right, the "practical" limit of P_{RFQ} chosen by inspection but still arbitrary to be $5.5 * 10^{-8} A/V^{3/2}$.

The dimension of the RFQ is given either by practical reasons like availability of rf transmitters and rf structures, limits of voltage hold-off and the need for sufficient acceptance compared to the injected emittance of the beam or by the necessity to allow only for small emittance degradation during acceleration. Transverse emittance growth is mainly caused by charge density redistribution towards a constant value and by equipartitioning of emittance between transverse and longitudinal planes, the major emittance increase due to nonlinear longitudinal acceleration fields [21]. Both facts favor smallest channel dimensions at highest frequency and transverse focusing, leading e.g. to the Los Alamos design of proton and H^- RFQs operating at more than 400 MHz and typical channel radii of 2 mm. Injection energies of about 100 keV allow accelerated currents of more than 100 mA with low emittance increase.

The fact that the RFQ current limit is of the order or even exceeds the limit given by the ion source extraction system is quite nice but still leaves the problem to provide sufficient acceptance of the RFQ.

By again assuming an unmodulated transport RFQ a first order approxiamation for the zero current unnormalized acceptance is given by [16]

$$\alpha = \sigma_0 R^2/L\ , \quad \sigma_0 = \frac{e\,\zeta}{m_0 A\sqrt{8}\,\pi} * \frac{U_{el}}{R^2 f^2}\ , \quad L = \beta c/f \qquad (10)$$

where U_{el} is the interelectrode voltage. α therefore is proportional to U_{el} and 1/f, favouring low frequencies and large apertures. For lower frequencies larger and more complicated accelerator structures have to be used (if there are any) and the resulting power consumption may increase.

A rough estimate of the unnormalized acceptance of three different RFQ designs are given in fig. 2 using the Kilpatrick limit for U_{el}. In fact more than twice as much have been applied in practice [22]. The evaluation of α still applies due to the fact that higher interelectrode voltages are required in a modulated RFQ to achieve the same acceptance compared to a pure transport device.

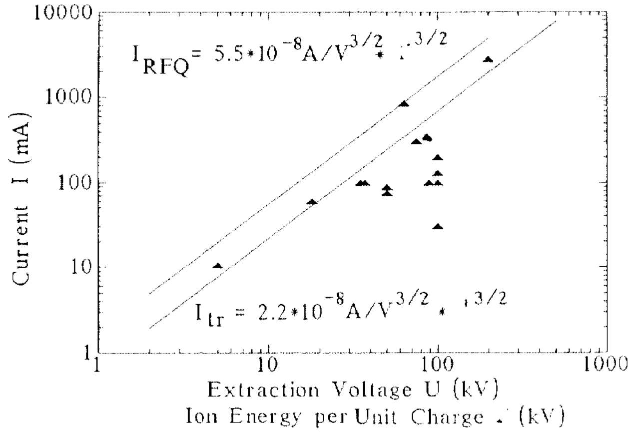

Fig. 1 Reasonable transported proton normalized ion currents I_{tr} from a single round aperture extraction system [5] versus ion extraction voltage and limits of proton normalized currents I_{RFQ} for RFQs versus ion energy per unit charge (see text)

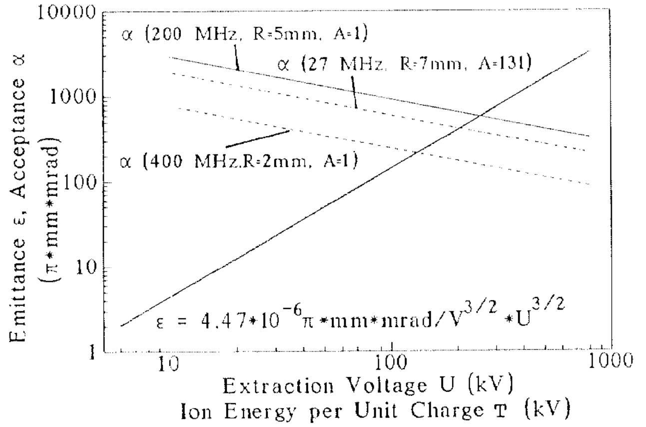

Fig. 2 Minimum unnormalized emittance of an ion beam extracted from a single round aperture versus extraction voltage [5] and unnormalized zero current acceptances for different types of RFQs (see text)

From fig.1 and 2 we can state the following: A high frequency RFQ (400 MHz) with small apertures has comparably low acceptance and is able to accelerate more than 100 mA of protons at 100 keV injection energy. The structure is highly effective to control emittance increase, but allows only a small margin between beam emittance and acceptance. This is exactly the Los Alamos design philosophy. Even 1.2 mm aperture radius have been used [23], which seems to be the limit due to mechanical and rf tuning tolerances.

Proton or H^--RFQs operating at 200 MHz have been built at different places with input energies from 18 to 100 keV [17], the current limit still ranging from some tens to more than 100 mA using larger aperture values. The margin between source emittance and acceptance is much higher, allowing e.g. substantial emittance growth in the LEBT section.

High source currents at extraction voltages up to 100 kV for protons and light ions and sufficient channel acceptance allow for the injection into the RFQ without additional dc-columns.

For heavy ions the situation looks quite different and will be explained using design data for the GSI High Current Injector [24,25] for the SIS heavy ion synchrotron. Up to 25 mA at a charge to mass ratio of 1/131 (Xe^+) have to be accelerated from 2.4 to 216 keV/nucleon to be injected into the existing Wideroe rf sections of the UNILAC. The injection energy per unit charge of more than 300 keV will provide enough current capability of the RFQ (fig. 1), the choice of 27 MHz with R approximately 7 mm leads to an α of about 500 π*mm*mrad. But an ion extraction with the high voltage of 300 kV, even it were possible would be disadvantageous; the beam emittance would exceed the RFQ acceptance. The ion extraction at lower voltages (here appr. 50 kV) and the use of a multiaperture system (N=7) allows low emittance and required current simultaneously. A successive dc-column of course has to rise the ion energy to the value needed for injection into the RFQ, at first approximation leaving the normalized emittance unchanged.

Limits set by the Low Energy Beam Transport Line

Stable transport of ion beams with beam perveances given above are hardly to obtain, especially if dipoles e.g. are included in the LEBT section. Commonly used magnetic transfer lines therefore use the effect of space charge neutralization to lower the acting space charge forces significantly. Although electrostatic focusing provides higher focusing strength at low energies, the current capability is smaller due to the fact that space charge compensation is not possible.

The emittance requirements for the accelerator input depend on the type of accelerator. For RFQs the focusing field is time dependent ideally requiring also a time dependent beam emittance pattern. A sophisticated radial matcher [26,27] can overcome this constraint, but needs a highly convergent (several degrees) and round beam with the beam waist inside the RFQ, thus favoring axisymmetric optical lenses. For electrostatically or magnetically AG focusing maschines the input emittance pattern is static but naturally a more or less elliptical beam is required, which favors quadrupole focusing in the LEBT section also.

Magnetic einzellenses (solenoids) have second order axisymmetric focusing and rather large aberrations and are applicable for light ions. For heavier elements AG-quadrupole focusing is necessary, which destroys the cylindrical symmetry, which is unfavourable for injection into RFQ systems.

Emittance degradation and particle losses in the LEBT line is a crucial point. To keep the rms emittance growth low, all kinds of nonlinearities of related fields have to be minimized. This holds as well for the external fields as for the internal electric self field of the beam. Careful design of LEBT elements and probably the use of only a fraction of the aperture is requested. Nonlinear space charge fields are correlated to not constant density profiles. It has been shown [28,29], that the increase of emittance is caused by the rearrangment of the density distribution towards a constant profile thus minimizing the internal field energy of the particles in their own space charge field. For constant or periodic focusing and assuming a round beam, the change of transverse rms emittance ε_{rms} along the beam path z is given by [30]

$$\frac{d}{dz}\varepsilon^2_{rms} = -2K < r^2 > \frac{d}{dz}\frac{W-W_u}{w_0} \qquad (11)$$

where K is the generalized beam perveance, $<r^2>$ the square of the rms beam size. $(W-W_u)/w_0$ is a normalized dimensionless parameter, which relates the nonlinear field energy $W-W_u$ to different beam profiles. The redistribution is an adiabatic process, which transforms nonlinear field energy into kinetic transverse energy. The increase of the emittance is clearly related to the perveance, but also to the beam size. The process is very fast, the adiabatic redistribution finished after at least one quarter of a plasma period. Minimum emittance degradation can therefore be obtained by the use of the strongest available focusing, which keeps the beam size small.

Magnetic Transfer Lines

Magnetic focusing elements like quadrupoles or higher order poles, solenoids and magnetic beam manipulating devices such as dipoles, kickers and steering elements are commonly used in conventional transport systems.

In the absence of electric fields and at normal operating residual gas pressures ranging from 10^{-4} to 10^{-7} mbar plasma build-up occurs, developed by ionizing collisions of beam ions with the background gas. Assuming positive ions, the produced slow electrons accumulate in the space charge potential of the positive ion beam and neutralize the positive space charge. The residual gas ions are expelled from the beam. The lower limit of the buildup time τ necessary to neutralize the space charge depends on the ionization cross section σ_i (in the order of 10^{-16}-10^{-15}cm^2), the beam velocity v and the density of the residual gas n and is given by $\tau = 1/(v\sigma_i n)$ and for keV beams in the order of µsec to msec.

Due to electron losses the neutralization rise time can in fact be much longer and a full compensation cannot be achieved. The final degree of neutralization is given by the dynamic equilibrium of electron production and losses, the latter due to the fact, that only electrons created with kinetic energies below the value of the actual space charge potential can contribute to the process. Other loss channels are longitudinal losses due to not ideal boundary conditions and electron heating via the thermalization of the electron velocity distribution caused by the ion beam and plasma or source instabilities [31,32,33].

A comprehensive overview on neutralization related phenomena including estimations of achievable degrees of compensation has been given by Holmes [34] and Gabovich [35].

Due to the fact, that the necessary focusing strength in a high current LEBT is governed rather by the beam perveance K than by the emittance, the neutralization process is quite helpful. For dc beams at extraction energy, compensation rates in the order of 90% up to 99% have been achieved, thus reducing the effective beam perveance drastically. On the other hand the change of residual gas pressure, mixture and beam radii along the line, and the effect of external fields cause substantial variation of the degree of neutralization. Theoretical and numerical predictions of the beam transport properties are therefore difficult to obtain.

Plasma build-up in a LEBT line for beams with pulsed time structure can be quite uncomfortable. Ion injectors for high energy synchrotrons e.g. have pulse lengths of some tens to some hundreds of µsec, leaving the front end of the pulse unneutralized, which gives rise to variing perveance and emittance along the pulse. Beam matching to successive elements in the line cannot be done simultaneously for all parts of the pulse.

Space charge neutralization can drastically reduce the perveance of the beam, thus emittance degradation via density redistribution is limited by the beam perveance K in equation (11). In the case of a partly neutralized beam redistribution means rearrangement of both ions and electrons to give a linear space charge field. Unfortunately the electrons are not cold enough to follow exactly the ion movement, instead they have a thermal velocity distribution, which allows them to stay also outside the ion beam. This has been shown experimentally using an electron beam probe at Frankfurt [36]. Rearrangement of the space charge density profile therefore does not necessarily mean, that the ions have homogenious density. Moreover the redistribution is not adiabatic, because the creation and loss of electrons is a dynamic process correlated with the exchange of energy with the outer system and the beam. Variing compensation rates or even decompensation, which may be induced by electric elements, seem to be a never ending source of emittance increase. Measurements with a partially compensated Ar$^+$-beam at GSI have confirmed this [37].

In Frankfurt a magnetic LEBT line with solenoids has been set up to investigate the emittance increase due to different degrees of compensation [38]. It could be shown that the emittance degradation is proportionally to the effective perveance. The results also indicate, that a total decompensation of the beam inside a solenoid is not possible. From measurements of the radial potential depth of the ion beam for different beam radii, it could also be shown that the degree of compensation strongly depends on the beam size. At beam waist position (Ø = 2 mm) the space charge was almost unneutralized.

The decompensation of the beam in front of an accelerator system always leads to an emittance increase and a difficult matching behaviour.

Space charge neutralization also occurs in the case of negative ion beams caused by the trapping of positive residual gas ions. Even an overcompensated beam could be obtained. The beam is self focusing due to the net positive space charge, caused by the low mobility of the neutralizing ions [39]. The emittance related points mentioned apply also in this case.

Electric transfer lines

Electric elements prevent plasma build-up, if no electric field free regions exist. The focusing strength therefore has to be high enough to overcome the full unneutralized space charge forces. Voltage hold-off is the major problem leading to miniaturized transport channels for high current beams. Since the beam is unneutralized the time structure of the beam plays a less significant role. Beam behaviour and particle dynamics can be described very accurately by numerical simulations. Apart from the emittance increase right after the extraction system, the growth of emittance is governed by aberrations of the system and can be kept small by sophisticated design methods.

Since electrostatic einzellenses suffer from large aberrations, electric quadrupoles are especially suited in front of accelerators with AG-focusing. The use of quads for beam injection into RFQs requires special attention to the design of the last quad in order to allow for large beam diameters necessary to achieve the highly convergent beam [40]. Investigations with axisymmetric electrostatic lenses directly in front of the RFQ have been undertaken showing encouraging results [41].

Performance of Typical Injection Systems

A typical example for an injection system with magnetic LEBT section is the AGS preinjector at Brookhaven National Laboratory (BNL). In the end of 1988 the Cockroft-Walton has been replaced by an RFQ, accelerating the H$^-$ beam from 35 keV to 750 keV. From a magnetron type surface-plasma source typically 65 mA can be extracted at 5 Hz and 700 µsec pulse length. The LEBT line (1.9 m) contains two solenoids and from transport calculations a degree of compensation of at least 90% at 10^{-6} mbar has been reported. The neutralization rise time is about 50 µsec, leaving the front end of the macro pulse unneutralized. Emittance growth in the line could not be investigated. The normalized transverse 90% emittance is 1.2π*mm*mrad. Transmission has been approximately 85% with up to 50 mA at the exit of the RFQ. Excellent reliability and simpler maintenance have been gained at the same current level compared with the previous dc operation, and there is still the option to increase the beam current in the future [42].

The Tevatron at the Fermi National Accelerator Laboratory (FNAL) is equipped with two 750 kV dc-columns. The magnetron type H$^-$ sources both provide beam currents of 50-60 mA at 15 Hz and 30-60 µsec pulse length. The injecton into the accelerator column is done with double-focusing magnetic dipoles only. Magnetic quadrupole focusing is used in the 750 keV transport line. The 90% transverse emittance is reported to increase by a factor of 1.8. The operating pressure is about $2*10^{-6}$ mbar and space charge compensation is reported to be of no significance. The operation at 10^{-5} mbar causes 2 MHz plasma oszillations in the longer line (10m) at a slightly decreased emittance growth. The oscillation is believed to be due to a two-stream plasma instability. A change from the present dc injector to an RFQ based system has been considered, the RFQ accelerating the beam from about 30 keV to probably 2 or 3 MeV, followed by the injection into a new Alvarez tank, which is believed to cause much less emittance growth than the present one [43,44]. Beam transport and beam matching to the RFQ are considered to be performed by solenoids, Gabor plasma- and electrostatic lenses. Short pulse lengths require unneutralized transport with electrostatic focusing or preservation of the degree of compensation via the trapped electrons of a plasma lens. The operation of a plasma lens for negative ion beams however is doubtful [45].

The preinjector system for the proton storage ring HERA is the first system, which has been build primarily with an RFQ for a new high energy accelerator. A Fermilab type magnetron H$^-$ source is followed by a LEBT section consisting of dipole and two solenoids [46]. The nominal beam current at 1 Hz and about 100-150 μsec pulse length is 20 mA. The RFQ, built in Frankfurt [47], has been successfully tested and accelerates the beam from 18 to 750 keV. A maximum current of more than 50 mA has been achieved yet.

At the Paul-Scherrer-Institute (PSI), Villigen, the injector for the successive cyclotrons consists of a multi-cusp type ion source (routinely 10-20 mA, protons at 60 keV) followed by a dipole for mass selection and two solenoids. The percentage of space charge neutralization is in the high 90's [48]. The installed Cockroft-Walton is able to deliver 30 mA up to 900 kV at cw operation [10]. The high energy beam transport line uses magnetic quadrupole focusing. Measurements by the author [49] have shown that the degree of compensation at 10^{-5} mbar operating pressure is still about 50% at 870 keV and problems arise with the theoretical understanding of the measured beam behaviour [50]. Since dc operation and low energy spread are required, no considerations concerning an RFQ have been made.

The heavy ion synchrotron SIS at GSI, Darmstadt operating since beginning of this year, requires a new high current injector to be built in order to fill the synchrotron to the space charge limit [24]. Problems concerning the RFQ habe been mentioned previously in this paper. The current capability of the high voltage platform is limited to about 40 mA. To obtain e.g. 25 mA of Xe$^+$, charge and mass separation has to be done at ion source extraction energy. The use of a multiaperture extraction system as well as the high beam current at low energies allow the required high mass and charge resolution in a dipole only if the space charge is highly compensated. For a Kr beam of approximately 8 mA extracted from 7 apertures at 25 kV the resolution could indeed be obtained. Degrees of compensation of more than 98% could be measured [51].

At the FOM-Institute, Amsterdam a prototype of a MEQALAC-system has been successfully tested. The system combines standard rf acceleration with an array of electrostatic quadrupoles used for the LEBT-line and inside the rf-accelerator drift tubes [52]. Low transverse emittance growth by a factor of 1.2 have been reported in the LEBT-line at a nearly 100% transmission of 7 mA per beamlet (4 beamlets total) using He$^+$ at 40 keV [53]. The section consists of 34 quadrupoles with 6 mm aperture diameter. Successful transport of four nitrogen beams at 40 keV has been done, obtaining a beam transmission of more than 85% at 5.1 mA. Emittance growth by a factor of 1.5 has been observed [54].

An injection system for a 100 keV H$^-$ beam with 45 mA has been proposed by Anderson et al. [41] using electrostatic quads for beam transport. An additional electrostatic ring lens has been included in the system for proper beam matching into the RFQ. The system has been successfully tested. Full transmission has been obtained. The normalized emittance of 1.6π•mm•mrad showed negligable increase. The system prevents space charge compensation and therefore even short pulses in the order of only μsec or less can be transported stably. From computer simulations even higher transportable currents seem to be possible.

Conclusion

Estimations of current and emittance limits of high current ion sources as well as for RFQ accelerators have been given, showing that the maximum current of light and medium ions obtained from the source at a given extraction energy can in principle be injected into and accelerated by RFQ systems. For heavy ions however there is still need for an additional dc column. Stable transport of these high perveance beams are hardly to fulfill with the LEBT-line. Therefore the compensation of the ion beam space charge in magnetic lines is often used to ease transverse focusing. Enhanced emittance increase occur in partly compensated beams due to continues charge density redistribution and the transport of pulses short compared to the neutralization rise time is difficult or even impossible. From the point of view of emittance increase and stable transport of very short pulses electrostatic LEBT lines are favorable. Although encouraging results have been obtained with electrostatic focusing of high current beams, it is still an open question if these systems can replace the common used magnetic lines. Especially in the case, where additional magnetic devices are needed (dipoles e.g.) a mixed line composed of magnetic and electrostatic transport should be avoided to prevent additional emittance increase.

Acknowledgements

The author expresses his great appreciation to all colleagues, who provided information and help in preparing this paper. Special thanks are dedicated to H. Klein, H. Deitinghoff, A. Schempp and the "Frankfurt neutralization group".

References

[1] I.M. Kapchinskii and V.A. Teplyakov, Prib. Tekh. Eksp., No.4 (1970) 17
[2] F.J. Sacherer, IEEE Trans. Nucl. Sci., 18 (1971) 1105
[3] R. Keller, "High Current Gaseous Ion Sources", published in I.G Brown, "The Physics and Techn. of Ion Sources", J. Wiley.NY (1989)
[4] C.D. Child, Phys. Rev (Ser.I) 32 (1911) 492
[5] R. Keller, "Ion Extraction", published in see [3]
[6] A.J.T. Holmes, Proc. of Europ. Part. Acc. Conf. 1988, World Scientific, ISBN 9971-50-642-4 (1989) 93
[7] P. Allison et al., Report LA-8808-MS. Los Alamos Nat. Lab. (1981)
[8] W.D. Kilpatrick, Rev. Sci. Instr. 28 (1957) 824
[9] K. Langbein, published in see [6] p. 1228
[10] M. Olivo, 1984 Lin. Acc. Conf., GSI-Report GSI-84-11 (1984) 380
[11] C. Schmidt, Fermi Nat. Acc. Lab. private communication
[12] O.A. Anderson, 1989 Part. Acc. Conf., IEEE 89CH2669-0 (1989) 1117
[13] D. Keefe, HIIF 1986 AIP Proc. 152 (1986) 63
[14] A. Schempp, published in see [6] p. 78
[15] A. W. Maschke, Brookh. Nat. Lab. Report BNL-51209 (1979)
[16] H. Klein, IEEE Trans. Nucl. Sci. NS-30 (1983) 3313
[17] A. Schempp, 1988 Lin. Acc. Conf., Cebaf-Report 89-001 (1989) 460
[18] M. Reiser, Part. Accelerators 8 (1978) 167
[19] A. Fallens et al., 1984 Lin. Acc. Conf., GSI-Report 84-11 (1984) 312
[20] I. Hofmann, Adv. Electr. and Electron Phys., Suppl. 13C (1983) 49
[21] T.P. Wangler, 1988 Lin. Acc. Conf., Cebaf-Report 89-001 (1989) 211
[22] A. Gerhard et al., published in see [6] p. 1108
[23] P. O'Shea et al., 1989 Part. Acc. Conf. IEEE 89CH2669-0 (1989)
[24] J. Klabunde, 1988 Lin. Acc. Conf., Cebaf-Report 89-001 (1989) 242
[25] A. Schempp, 1989 Part. Acc. Conf. IEEE 89CH2669-0 (1989) 1093
[26] R. Becker et al., 1984 Lin. Acc. Conf. GSI-Report 84-11 (1984) 342
[27] P. Junior et al. this conference
[28] J. Struckmeier et al., Part. Accel. 15 (1984) 47
[29] T.P. Wangler et al., IEEE Trans. Nucl. Sci. NS-32 (1985) 2196
[30] I. Hofmann et al., Part. Acc. 21 (1987) 69
[31] M.V. Nezlin, Plasma Phys. 10 (1968) 337
[32] I. Hofmann, GSI Annual Report 87-1 (1987) 381
[33] T. Weis et al., Nucl. Instr. Meth. A278 (1989) 224
[34] A.J.T. Holmes, Phys. Rev. A19 (1979) 389
[35] M.D. Gabovich, Ukr. Fiz. Zh. 24 (1979) 257
[36] P. Gross et al., this conference
[37] J. Klabunde et al. 1986 Lin. Acc. Conf. SLAC-Report 303 (1986)
[38] T. Weis et al., this conference
[39] J. Sherman et al., 1988 Lin. Acc. Conf., Cebaf-Report 89-001 (1989) 155
[40] M. Reiser, 1988 Lin. Acc. Conf., Cebaf-Report 89-001 (1989) 451
[41] O.A. Anderson et al., Proc. 5th Int. Symp. on the Prod. and Neutr. of Negative Ions and Beams, Upton, NY (1989) and this conference
[42] J. G. Alessi et al., 1989 Part. Acc. Conf. IEEE 89CH2669-0 (1989) 999 and private communication
[43] C. Schmidt et al., 1988 Lin. Acc. Conf., published in see [39] p. 188 and private communication
[44] C.D. Curtis et al., 1986 Lin. Acc. Conf., published in see [37] p. 138
[45] J.A. Palkovich et al., published in see [42] p. 305
[46] S.H. Wang, DESY Internal Report 84-92 (1984)
[47] A. Schempp, published in see [40] p. 73
[48] M. Olivo, private communication
[49] T. Weis et al., Inst. für Angewandte Physik, Univ. Frankfurt, Internal report 90-10 (1990)
[50] W. Joho, PSI, Villigen, private communication
[51] A. Schönlein et al., GSI Annual Report 88-1 (1988) 361
[52] W.H. Urbanus et al., published in see [6] p. 427
[53] F. Siebenlist et al., Nucl. Instr. Meth., A256 (1987) 219
[54] J.G. Bannenberg et al., Vacuum 39 (1989) 1031