

SOURCE AND INJECTOR DESIGN FOR INTENSE LIGHT ION BEAMS INCLUDING SPACE CHARGE NEUTRALISATION

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Abstract

One of the major challenge in the design of the Low Energy Beam Transport (LEBT) section of the high intensity proton, H^- and deuteron beam accelerators is to transport the beam from the ion source to the RFQ with minimizing the emittance growth.

New PIC ray-tracing methods allows to design and simulate the transport of high intensity beam in the LEBT systems of future accelerators like FAIR Proton Linac or IFMIF-EVEDA linacs. These techniques enable a precise prediction of the effect of residual gas ionisation and the consequent neutralisation of the large beam space charge on the beam emittances. The amount of space charge compensation along a high intensity LEBT section is crucial for the achievable beam quality at the exit of the section. An algorithm for adequate modelling of the compensation is presented. It includes the dynamic behaviour of the compensation as well as its dependence on the longitudinal and radial position along the beam line. The impact of this dependence on the beam quality and the source and LEBT design is presented.

INTRODUCTION

Over the last decade, the interest of the international scientific community for high power light ion accelerators in the mega watt range increased significantly. Several machines have been built and are now in commissioning or operational phase and a notable number of projects have been launched all over the world. The application fields of such accelerators are the spallation neutron sources dedicated to condensed matter physics (like SNS [1], J-PARC [2], ISIS [3], ESS [4] and CSNS [5]), the muons factories (SPL [6], ISIS, J-PARC), the radioactive ion beam production (SPIRAL 2 [7], FAIR [8]) or accelerator driven sub-critical system. Another example is the International Fusion Materials Irradiation Facility (IFMIF) [10] which aims at producing a high flux of 14 MeV neutron dedicated to the characterization of candidate materials for future fusion reactors. The accelerator driver consist of two high power Linacs each delivering a 40 MeV – 125 mA cw deuteron beam to a common lithium target.

Some of the above mentioned machines accelerate protons (H^+) or deuterons (D^+) if the final beam impacts a target; in the case of short pulses facilities negative ions beam (H^-) are necessary for polarity-changing by stripping process before the injection in an accumulator ring. The high

power accelerators require an ion source to produce a continuous or pulsed beam with an intensity from several tens up to a hundred of mA and with an energy that usually ranges from 30 to 100 keV. Then, a Low Energy Beam Transport (LEBT) line has to transport and match the beam to the subsequent accelerating structure, generally a Radio Frequency Quadrupole (RFQ). Typically, the beam emittance required at the RFQ entrance is around 0.20-0.30 π mm.mrad, so, the transport in the LEBT has to be done with the idea of limiting the beam halo formation and the subsequent emittance growth. The ion source and LEBT apparatus is communally called injector.

HIGH INTENSITY BEAMS AT LOW ENERGY ISSUES

Emittance Growth

The possible sources of beam halo and emittance growth in a high intensity injector are:

- aberrations due to the ion source extraction optics.
- optical aberrations of the focalizing elements of the LEBT.
- beam fluctuations due to ion source instability or power regulation.
- non-linearity of the electric field created by the beam space charge.

For high intensity beams at low energy, the space charge is particularly strong. The electric field created by the space charge tends to defocus the beam and is strongly non-linear as it is induced by the non-uniform distribution of the charge particles of the beam. The defocusing effect of the space charge can be compensated by transporting the low energy beam in a space charge compensation (SCC) regime.

Space Charge Compensation

The space charge compensation (or neutralization) occurs when a beam is propagating through the residual gas of the beam line and subsequently, induce ionization of the molecules of this gas. The secondary particles produced by ionization (i.e. electrons or ions), which have an opposite polarity of the particle of the beam, are trapped by it until a steady state is reached. Thus, the low energy beam can be considered as a plasma that creates a focusing effect which counteracts the space charge effect.

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In this section, basic expressions of the space charge compensation degree and time are given to obtain some orders of magnitude for design and experimental considerations. More elaborated descriptions of the SCC evolution can be found in detailed analytical [11, 12] and numerical [12, 13] works.

Space charge compensation degree The potential well (i.e. potential on the beam axis) created by a uniform beam, without SCC, is given by [14]:

$$\phi_0 = \frac{I_B}{4\pi\epsilon_0\beta_B c} \left(1 + 2 \ln \left(\frac{r_P}{r_B} \right) \right) \quad (1)$$

where I_B , r_B and β_B are respectively the intensity, radius and reduced speed of the beam; r_P is the radius of the beam pipe, which is supposed to be grounded. During the SCC process, the neutralizing particles are trapped by this potential well. The equation 1 shows that the potential well (i.e. the space charge force) increase if the radius of the beam decrease. So, achieving a beam waist in a LEBT could be critical for the quality of the beam.

If we define by ϕ_c the potential well of the compensate beam, the SCC degree is then given by:

$$\eta = 1 - \frac{\phi_c}{\phi_0} \quad (2)$$

The beam potential well of the compensated beam can be experimentally measured. The values founded for the 75 keV – 130 mA proton beam of the LEDA range from 95 to 99% [15]. Along the LEBT, the SCC degree is not constant as the neutralizing particle trajectories can be modified by external fields of focusing element, for example.

Space charge compensation time The characteristic SCC transient time, τ , can be determined by considering the time it takes for a particle of the beam to produce a neutralizing particle on the residual gas. Then, it comes:

$$\tau = \frac{1}{\sigma_{ionis} n_g \beta_B c} \quad (3)$$

where σ_{ionis} is the ionization cross section of the incoming particles on the residual gas and n_g the gas density in the beam line. As an example, the SCC transient time for a 100 keV deuteron beam propagating in H_2 gas of pressure 5×10^{-5} hPa is 12 μs .

BEAM FORMATION AND HANDLING

Beam Formation

Comprehensive review papers have been recently written on the subject of high intensity H^- [16], H^+ and D^+ [17] ion sources. In this paper, only general characteristics will be briefly exposed.

The vast majority of the high-current light particle sources operating on Linacs uses a plasma to produce the

wanted ion. This plasma can be sustain by a filament or by rf power and is confined by a magnetic field.

The generation of H^- can be achieved by surface or volume ion sources. Theses sources are able to produce H^- beam intensity up to 80 mA in pulses length of the order of the millisecond. On can note that an increase of the pulse length leads to a beam current decrease. The typical rms emittances of the extracted beam range from 0.2 to 0.4 π mm.mrad. As an example, the J-PARC source [18] performances is: up to 38 mA of H^- beam current (of 500 μs length pulses) at 40 keV with an emittance of 0.22 π mm.mrad; a lifetime of 525 hours has been reached.

High current of H^+ and D^+ beam are generally provided by 2.45 GHz Electron Cyclotron Resonance (ECR) sources which can operate in cw or pulsed mode and have many advantages in terms of reliability and low maintenance. Continuous light ion beam currents above 100 mA can be typically extracted from ECR sources within a rms emittance around 0.1-0.2 π mm.mrad. Even if the desired ions are H^+ or D^+ , molecular ions like H_2^+ , H_3^+ or D_2^+ , D_3^+ are also produced in an ECR plasma. An optimization of the proton (or deuteron) fraction is done to reach up to 90% of the total extracted current, but the unwanted molecular species have to be removed from the main beam in the LEBT. The ECR sources can be operated in pulsed mode with the same beam intensity simply by pulsing the rf power. But a transient time of around 1 ms is necessary to reach the maximum current, for plasma stabilization reasons. So if a sharp pulse is needed, a beam chopper as to be inserted in the LEBT. For example, the LEDA source [19] produced a 117 mA continuous proton beam at 75 keV, with an emittance of 0.2 π mm.mrad (measured at the end of the LEBT).

The beam is formed and extracted from the ion source by applying an electric potential difference between the outlet electrode (called plasma electrode) and the extraction electrode (grounded). This applied electric field tends to penetrate through the plasma electrode aperture and is screened by the plasma. A dynamic equilibrium is reached between the extraction field and the plasma sheath to form a so-called meniscus, which forms a equipotential surface (at the potential of the plasma electrode) of an approximately spherical shape from which the ions are emitted [20]. If the meniscus presents a non-uniform curvature and/or the geometry of the extraction system induced a non-linear electric field, beam emittance growth will occur. Advanced design of plasma and extraction electrodes can limit this kind of optical aberrations. It's also possible to insert a polarized intermediate electrode (see Fig. 1) to adjust finely the plasma meniscus formation.

The extraction electric field is attractive for the charge space neutralizing particles created by the beam and consequently, tends to decompensate it. In order to reduce as much as possible the non-compensated zone in the extraction region, a repelling electrode (also called trapping electrode) is inserted upstream of the final extraction electrode.

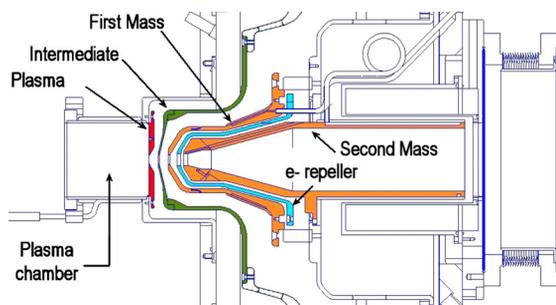


Figure 1: Five electrode beam extraction system of the SILHI source.

This electrode creates a potential barrier to keep the neutralizing particles within the beam by preventing them to be attracted toward the ion source.

The SILHI source has an intermediate and a repelling electrode, forming together with the plasma and grounded electrodes, a pentode extraction system (see Fig. 1) [21].

Beam Transport

Once the beam is created, it has to be transported and matched by the LEBT to the first accelerating structure like a RFQ. The focus can be done with electrostatic or magnetic elements. After the ion source, because of the geometry of the extraction system, the beam usually presents a cylindrical symmetry. In order to preserve this symmetry and to simplify the beam tuning, magnetic solenoid lenses or electrostatic Einzel lenses are more commonly used than quadrupoles.

Electrostatic LEBT In an electrostatic LEBT, the beam is propagating without any space charge compensation because the neutralizing particles are attracted (or repulsed) by the electric field induced by the focusing elements. This kind of beam line is compatible with beam chopping as there is no transient time for the SCC. Furthermore, the design of electrostatic LEBTs are simplified by the fact that no repelling electrode for the neutralizing particle trapping are needed. So, the beam lines are very compact, which tends to minimize the beam losses by charge exchange. As an example, the Fig. 2 shows SNS ion source with the 12 cm long LEBT equipped with two Einzel lenses.

On the down side, the electrostatic LEBTs are vulnerable to beam losses that can lead to high voltage breakdowns and beam trips. Besides, the Einzel lenses intrinsically induce optical aberrations that creates beam halo and emittance growth. To limit this effect, the beam radius should not exceed 2/3 of the lens aperture radius. Finally, the design of the electrostatic LEBTs are intensity limited. As the beam is not compensated, its divergence and size will increase rapidly with its intensity (especially for current of several tens of mA). So, its seems difficult to operate the LEBT with a higher current than the design current without expecting beam losses or dramatic emittance growth.

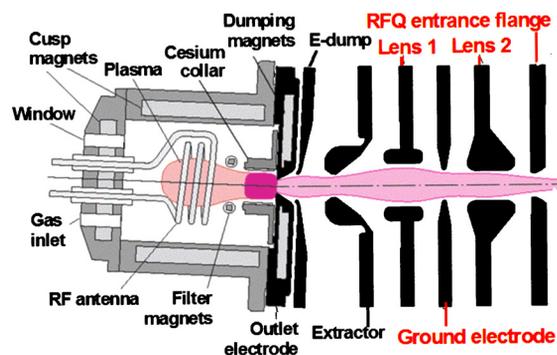


Figure 2: The SNS ion source and electrostatic LEBT.

Magnetostatic LEBT In this case, the beam is fully neutralized by the ionization on the residual gas as explained in the previous section. The gas in the LEBT comes mainly from the ion source, but it has been shown experimentally that the beam emittance can be improved with a higher pressure in the beam line [23]. Besides, the nature of the injected gas has an influence on this emittance improvement. An emittance reduction of a factor of two has been reported with by replacing the H_2 gas by the same partial pressure of Kr [24]. Nevertheless, the gas injection in the beam line has to be done carefully: the higher the pressure, the higher beam losses by charge exchange. For example, with a Kr partial pressure of 4×10^{-5} hPa in a 2 m LEBT leads to a H^+ (100 keV) loss rate due to electron capture of around 2.4%. For positive ion beam, an other source of neutralizing particles can be mentioned, even if it is less significant: secondary electrons are produced when a beam hits the beam pipes. At the end of the LEBT, the the electric field of the RFQ tends to penetrate through the injection hole and have a significative effect on the SCC by attracting the neutralizing particles. Moreover, this region is critical from the space charge point of view, because a beam waist is perform to match the beam for its injection into the RFQ. So, like in the ion source extraction system, a polarized electrode is placed as close as possible to the RFQ entrance to repel the neutralizing particles in the LEBT and to minimize the uncompensated zone.

In a magnetic LEBT the rise time of the pulsed beams is dominated by the SCC transient time (i.e several tens of μs). A fast chopping system have to be inserted to reach a rise time in the order of the hundreds of ns. In the case of the H^- ion beams, a phenomena of overcompensation occurs during the SCC transient time [25]. When the beam is fully compensate, neutralizing particles (in that case H^+) are still created but, as they are significantly slower than the electrons, the SCC degree can be superior to 1 during the time it takes for the exceeding H^+ to be expelled from the beam. During that time, the beam is overfocused and instabilities can be observed.

One of the advantages of the magnetic LEBT is the possibility to purify the beams that contain different species. It has been showed in a previous section that molecular

ions are produced in an ECR source simultaneously as the wanted protons or deuterons. The molecular ions are extracted from the source with the same energy as the proton or deuterons, but their mass is two or three times higher. Therefore, they have a different magnetic rigidity and have a different trajectory after the solenoids lenses focusing. They will be stopped by the beam line, downstream the solenoids. For that reason, a cone is often placed after the last focusing element, just before the RFQ. The aperture angle of this cone is slightly higher than the optimum injection angle in the RFQ. Thus, the cone intercepts all the particles which have not the correct trajectory to be injected, in order to prevent undesirable losses in the RFQ.

Like the Einzel lenses, the magnetic solenoids lenses present geometrical aberrations that lead to emittance growth. To limit this effect, the beam diameter should stay under the half aperture of the solenoids.

BEAM DYNAMICS SIMULATIONS FOR INJECTOR DESIGN

Code Used to Simulate Source Extraction and LEBT Transport

Classical examples of numerical codes that are used for the simulation of the ion source extraction are: PBGUNS [26], AXCEL-INP [27] and SIMION [28]. With these codes, one can shape the electrodes, compute the generated electric field and track the particle in the defined domain. Over the last years, elaborated optimizations of the geometry of the extraction system have been performed to increase the extracted beams intensity while minimizing the optical aberration and the beam divergence.

In order to achieve realistic beam transport simulations of high intensity light ion beam at low energy (≤ 100 keV), it is necessary to take into account the space charge compensation of the beam on the residual gas. For that, it is necessary to use particle-in-cell (PIC) codes, like WARP [29] or SOLMAXP [30]. For example, SOLMAXP, has been recently developed at CEA/Saclay and is now used to design and simulate high intensity injectors. The basics of this code are described in reference [32].

Simulation for the IFMIF/EVEDA and FAIR Injectors

Simulation method First the modeling of the extraction system of the ECR source has been done with a AXCEL-INP. The electric field map of the source extraction system is included in the LEBT simulations to get relevant boundary conditions.

Then, a calculation is made with SOLMAXP, until the steady-state of the SCC is reached. The code inputs are the particle distributions calculated with the extraction system model and the applied external fields. The outputs are the particle distributions (ions, electrons, neutral) all along the beam line and the electric field map derived from the

potential created by the space charge along the beam line. A space charge potential map calculated by SOLMAXP in the case of the FAIR LEBT is represented in Fig. 4.

Finally the TraceWin [33] code is used to optimize the beam injection in the RFQ. TraceWin tracks the particles in the LEBT with this space charge electric field map superimposed to those of the beam line elements (solenoids, extraction system). So, the RFQ injection optimization is performed with SCC through the LEBT. During that TraceWin optimization process, the optics parameters are modified and consequently, the SCC should vary, because of the new particle distributions. Thus, another simulation has to be done with SOLMAXP. After a few steps of this back and forth process between the two codes, the convergence toward the optimized solution is reached.

IFMIF/EVEDA injector simulation results The IFMIF injector has to deliver a 140 mA cw D^+ beam of 0.25π mm.mrad emittance. It is composed by a 2.45 GHz ECR source based on the SILHI design and a LEBT with a dual solenoid lenses focusing system [31].

Preliminary simulations [32] have been done to investigate the influence of the nature of the gas for the SCC. Assuming that the D_2 gas contribution to the total pressure in the beam line is 10^{-5} hPa (coming from the ion source), two simulations were done by adding a partial pressure (4×10^{-5} hPa) of either D_2 or krypton, all the other parameters remaining constant. An emittance improvement of around 25 % has been found in the case of the krypton injection. Dividing the Kr gas pressure by a factor of 2 leads also to an emittance growth [35]. This simulation results reproduce, at least qualitatively, phenomena that have been observed experimentally [23, 24].

The SOLMAXP simulations make possible to determine the SCC transient time. The simulation starts at the time $t=0$ with no beam in the line but only a fixed gas pressure. When the emittance is stabilized at the end of the LEBT, it is assumed that the SCC steady-state is reached. Thus, the founded SCC transient time is around 15 μ s.

The SCC degree has also been calculated along the IFMIF/EVEDA LEBT. The potential on the uncompensated beam axis ϕ_0 is calculated with the equation 1 and the SOLMAXP simulations give the potential on the compensated beam axis (see Fig 4 for $y=0$). The result is showed in Fig. 3. In this plot, the abscissa $z=0$ represents the position of the repelling electrode of the source extraction system, while $z=2.05$ m is the RFQ entrance. It can be observed that in the ion source extraction region and after the repelling electrode at the RFQ injection, the SCC is poor because the electrons are attracted out of the beam. In the central part of the LEBT, where the solenoids and a drift are located the SCC degree reach around 95%, which is compatible with the experimentally measured values [15, 23].

Finally, beam dynamics simulations showed that the IFMIF/EVEDA deuteron beam can be transported and injected into the RFQ with optimized emittance and Twiss parameters. Under these conditions, the RFQ transmis-

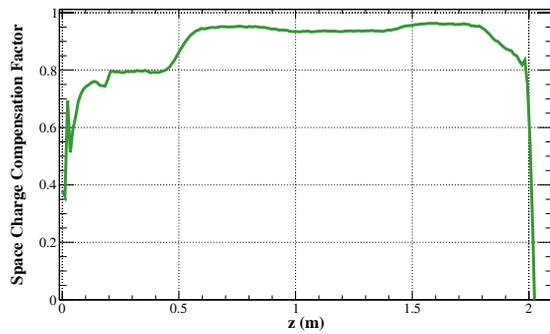


Figure 3: Space charge compensation degree along the IFMIF/EVEDA LEBT.

sion is above 95 %.

FAIR injector simulation results The FAIR injector has to deliver a 100 mA pulsed proton beam of 0.30π mm.mrad emittance. A SILHI-like source will be used, as it has already demonstrated performances [34] that fits with the FAIR injector requirements. The LEBT will be similar to the IFMIF one, but a fast beam chopper will be included between the second solenoid and the RFQ injection cone.

The space charge potential map through the FAIR LEBT is presented Fig. 4.

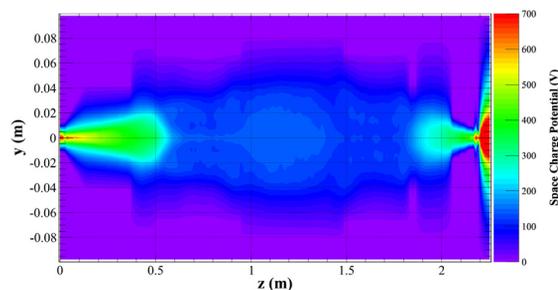


Figure 4: Two dimensions cut in the ($z0y$) plane of a space charge potential map in the FAIR LEBT.

The preliminary calculations of the FAIR injector shows that the beam can be transported and focused to reach the required conditions at the FAIR RFQ entrance.

CONCLUSION

Until now, the beam dynamics simulations of LEBTs have been done with particle tracking codes by imposing a constant SCC degree along the beam line (or slightly dependant of z , based on some empirical considerations). It has been demonstrated that a PIC code like SOLMAXP which simulates the SCC phenomena, can be used for injectors design. It allowed to optimize injector parameters, like the position of electron repeller electrode in the injection cone of the IFMIF/EVEDA LEBT, for instance.

The SOLMAXP code is in qualitatively good agreement with experimental results but some quantitative experimen-

tal confrontations will be done with future measurements of the beams of the IFMIF/EVEDA and FAIR injectors.

REFERENCES

- [1] S.Henderson et al., Proc. of PAC'07, Albuquerque, USA, MOXKI03, (2007).
- [2] High-intensity Proton Accelerator Project Team, JAERI-Tech 99-056, KEK Report 99-4, and JHF- 99-3 (1999).
- [3] D.Findlay, Proc. of PAC'07, Albuquerque, USA, TUYKI01, (2007).
- [4] A. Eshraqi et al, Proc. of IPAC'10, Kyoto, Japan, MOPD053 (2010).
- [5] J. Wei et al, Proc. of APAC'07, Indore, India, WEZMA02 (2007).
- [6] F. Gerigk et al, Report CERN-2006-006 (2006).
- [7] T. Junquera, Proc. of LINAC'08, Victoria, Canada.
- [8] O. Boine-Frankenheim, Proc. of IPAC'10, Kyoto, Japan, (2010).
- [9] J-L. Biarrotte et al, NIM A **562**, 565 (2006).
- [10] A. Mosnier et al, Proc. of PAC'09, Vancouver, Canada, FR201 (2008).
- [11] I.A. Soloshenko, IEEE Trans. Plasma Sci. **27**, 1097 (1999).
- [12] A. Ben Ismail, PhD Thesis, Univ. Paris XI-Orsay, France (2005).
- [13] J. -L. Vay et al, Nucl. Instr. and Meth. A **464**, 293 (2001).
- [14] M. Reiser, *Theory and Design of Charged Particle Beams*, Wiley-VCH (1994).
- [15] R. Ferdinand et al, Proc. of PAC'97, Vancouver, Canada, (1997).
- [16] R. Keller, Rev. Sci. Instrum. **81**, 02B311 (2010).
- [17] S. Gammino et al, Rev. Sci. Instrum. **81**, 02B313 (2010).
- [18] H. Oguri et al, Rev. Sci. Instrum. **79**, 02A506 (2008).
- [19] J. Sherman et al, Rev. Sci. Instrum. **69**, 1003 (1998).
- [20] Ian G. Brown, *The physics and technology of ion sources*, Wiley-VCH (2004).
- [21] O. Delferriere et al, Rev. Sci. Instrum. **75**, 1659 (2004).
- [22] M. Stockli et al, Rev. Sci. Instrum. **81**, 02A729 (2010).
- [23] R. Gobin et al, Rev. Sci. Instrum. **70**, 2652 (1999).
- [24] P-Y. Beauvais et al, Rev. Sci. Instrum. **71**, 1413 (2000).
- [25] R. Baartman and D. Yuan, Proc. of EPAC'88, Rome, Italy, (1988).
- [26] <http://www.far-tech.com/pbguns/>
- [27] INP, P. Spädke, Junkernst. 99, 65205 Wiesbaden, Germany.
- [28] <http://simion.com/>
- [29] D.P. Grote et al, AIP Conf. Proc. **749**, 55 (2005).
- [30] R. Duperrier, HIPPI 2008 Annual Meeting, CERN (2008).
- [31] R. Gobin et al., Rev. Sci. Instrum., **81**, 02B301 (2010).
- [32] N. Chauvin et al, Proc. of LINAC'08, Victoria, Canada, MOPO72 (2008).
- [33] <http://irfu.cea.fr/Sacm/logiciels/index.php>.
- [34] R. Gobin et al, Rev. Sci. Instrum. **73**, 922 (2002).
- [35] N. Chauvin et al, Proc. of PAC'09, Vancouver, Canada, TH5FPF004 (2009).