COLLIMATION OF HIGH INTENSITY ION BEAMS*

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Abstract

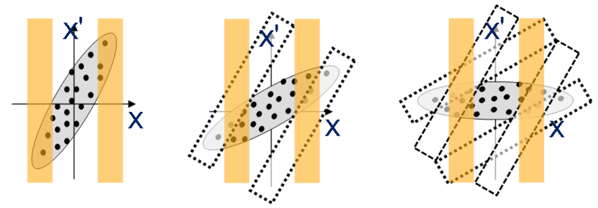
Intense ion beams with small phase space occupation (high brilliance) are mandatory to keep beam losses low in high current injector accelerators like those planned for the Facility for Antiproton and Ion Research (FAIR). The low energy beam transport from the ion source towards the linac has to keep the emittance growth low and has to support the optimization of the ion source tune. The Frankfurt Neutron Source at Stern-Gerlach-Zentrum (FRANZ) is currently under construction and might be a possible test stand for a collimation channel. An intense beam of protons (2 MeV, up to 150 mA) will be used for neutron production using the $Li^7(p,n)Be^7$ reaction for studies of the astrophysical s-process. A collimation channel, which can be adjusted to allow the transport of beams with a certain beam emittance, is an ideal tool to optimize the ion source tune in terms of beam brightness. Therefore a collimation channel in the Low Energy Beam Transport section (LEBT) will be used. Through defined apertures and transversal phase space rotation using focusing solenoids the outer part of the beam will be cut. Simulations and design done so far will be presented.

COLLIMATION PRINCIPLE

The brilliance of an ion beam is defined as $B = \frac{I}{\varepsilon_{xx'} \cdot \varepsilon_{yy'}}$ with I being the ion beam current and ε being the emittance in the xx' and yy' sub phase spaces. A collimation channel is an ideal tool to increase brilliance in the LEBT.
The Collimation Channel comprises two main functionalities:

- An online diagnostic for the ion source brilliance tuning
- To dump particles outside the acceptance of the accelerator in a controlled way before entering the cavities

The ion beam is extracted from the source and in an ideal case matched to the collimation channel. The channel is built upon three identical cells consisting of an aperture plate, a drift, a focussing element, another drift and ends with the aperture plate at the beginning of the following cell.
A collimation channel needs to be designed according to the parameters of the ion source (maximum beam radius and angle, the particle distribution and the maximum ion beam current) as well as the acceptance of the accelerator behind the channel. Figure 1 shows the principle of phase space rotation and cutting of the particle distribution in the 2-dimensional sub phase space.



(a) 1^{st} aperture (b) 2^{nd} aperture (c) 3^{rd} aperture

Figure 1: Phase space rotation and cutting. The beam particles are within the emittance ellipse (grey). (a) outer particles are cut, then phase space rotation, (b) beginning of second cell: cutting and rotation. (c) exit of channel, last aperture with cut. Scheme includes only two cells with 30° rotation per cell.

The idea is to cut the outer part of the beam in coordinate space (round aperture plates), which is equal to a vertical cut in phase space. This is shown in Fig. 1 (a). The transmitted particles are drifting towards the solenoid and experiencing a transverse phase advance through the magnetic field (and the drift behind it). At the end of the cell another cutting takes place by the aperture at the beginning of the proceeding cell. Since a total phase advance of 90 degrees is required, a phase advance of approximately 30° per cell is needed in a 3 cell setup.
The more cells are used, the more precise phase space manipulation can be done.
By setting calculated values for magnetic fields as well as apertures, only particles in a defined phase space volume (emittance) are transmitted through the entire channel. All other particles are stoped at the apertures within the channel. If the beam current is measured by using a Faraday cup downstream the channel, it is possible to increase the brilliance of the beam by just tuning the source to the maximum cup current without changing the phase advance or the aperture diameters.

Such a channel has been built up at National Superconducting Cyclotron Laboratory in East Lansing, MI, USA. First experimental studies of the collimation principle have been completed [1]. Since a collimation channel is a powerful tool for ion source tuning, GSI is aiming for this principle with respect to the new FAIR facility.

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* Work supported by HIC for FAIR within the LOEWE initiative of the state of Hesse, Germany

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SIMULATIONS FOR THE FRANZ LEBT

The idea for a collimation channel demonstrator was the integration of such a device into the FRANZ facility at IAP in Frankfurt. FRANZ is the Frankfurt Neutron Source at Stern-Gerlach-Zentrum which is under construction. FRANZ is a neutron-production facility for astrophysical experiments [2]. The ion source produces a 150 mA proton beam which is accelerated to about 2 MeV and will bombarde a Li-target in order to produce $5 \times 10^{10}\ n/s$. A schematic of the LEBT of the facility is shown in Figure 2. FRANZ would be an ideal test stand for the collimation channel, because one would not only have to deal with the function of the channel itself, but also the collimation of such a high-current beam and the problems of dumping a lot of power on the surface of the apertures. The simulations were initially done using COSY Infinity [3], but it had to be changed to Lintra [4], since space-charge effects have to be taken into account for this high current proton beam.

The volume-type ion source of FRANZ is fed with gaseous hydrogen. The extracted ion species are H^+, H_2^+ and H_3^+. A p^+ beam current of about 150 mA will be achieved, but there will be also the heavier beam fractions like H_2^+ and H_3^+ which might have a total beam current up to 30-40 mA. All simulations were carried out with an extraction radius at the source of 6 mm and a maximum divergence angle of 55 mrad, which is a reasonable assumption. The main fraction of the heavier particles should be dumped before entering the chopper system (see Fig. 2).

Since the beam dynamics for the FRANZ LEBT are nailed down almost completely, there are only three positions, where collimation apertures could be integrated into the beam line and therefore only 2 cells would be possible as it is shown in Fig. 2.

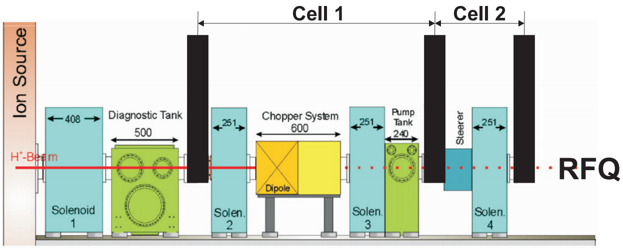

Figure 2: Possible collimation channel layout at FRANZ (black bars represent possible positions for collimation apertures).

Another critical point is the aperture of the chopper system (see Fig. 2 and 3), which is very narrow with a smallest aperture radius of 18 mm. Therefore variability of the matching solenoid 1 as well as solenoid 2 were checked in order to verify the possibility of collimation at the planned positions.

The magnetic fields were varied in steps of 5 mT. Out of 945 combinations of solenoid 1 and 2 only ten combinations show a transmission of more than 98% and six combinations of more than 99% of protons through the chopper system.

There is only one single combination where 100% protons are transmitted through the chopper (before looking to collimation at all). This is achieved with maximum field in solenoid 1 of 275 mT and 415 mT in solenoid 2. The envelopes of the beams are shown in Fig. 3. The boundary limits of variation of the solenoid strength is therefore restricted to a very narrow interval.

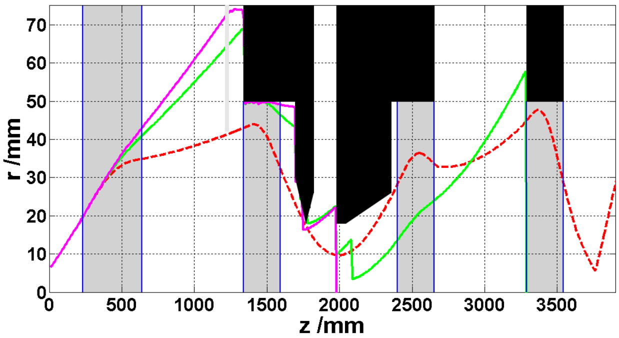

Figure 3: Envelopes of p$^+$ (dotted red, 150 mA), H_2^+ (green, 20 mA) and H_3^+ (magenta, 20 mA). In the nominal case 100% of p$^+$ are transmitted through the LEBT. All other/unwanted fractions are stopped as early as possible.

Most of the heavy H_2^+ and H_3^+ particles are lost in front of and inside the first short solenoid. Introduction of a cooled aperture plate at position z≈1200 mm could be used in order to dump the power of these beam fractions in a controlled way. The remaining 0.6% of H_2^+ and H_3^+ are dumped between the entrance of the choppper (z=1600 mm) and the last solenoid (z=3300 mm). Protons are transported without losses towards the radio-frequency quadrupole accelerator (RFQ).

The loss plot shows, that with this ideal setting it is possible to get 100% of the p$^+$ to the RFQ and also get rid of all H_2^+ and H_3^+ particles (see Fig. 4) far before being injected into the cavity.

As Fig. 2 shows, apertures can only be introduced into the beamline at three distinct positions in front of solenoid 2, inbetween solenoid 3 and 4 as well as right behind solenoid 4, because the RFQ will be at the focal point of the proton beam which is at an approximate z-position of 3700 mm (see Fig. 3).

Calculations have shown, that in the nominal case for the FRANZ LEBT the phase advance in the first cell would be approximately 255 degrees and 117 degrees in the second cell which corresponds to xy-space rotations of 133° and 84°.

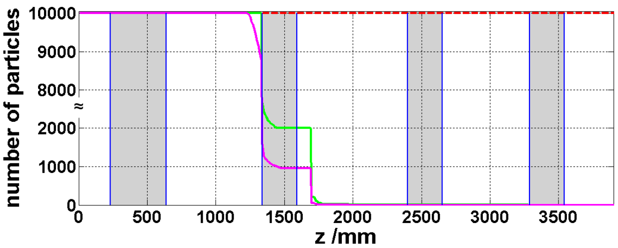

Figure 4: Losses of the two undesired fractions of the beamin the LEBT. In grey there are the matching as well as the three focussing solenoids. 80% of H_2^+ (green) are taken away in front of solenoid 2 as well as 90% of H_3^+ (magenta). The remaining particles of the heavy fractions are dumped in the electro-static part of the chopper system. 100% p$^+$ are transported through the LEBT.

FURTHER GENERAL SIMULATIONS

Apart from the simulations of the FRANZ LEBT some systematic studies with a tailored system have been carried out.
A homogenous distribution of 10000 particles within a phase space occupation of 200 π mm mrad was traced through a channel consisting of three symmetric cells of 520 mm total length each. Solenoids have an effective length of 251 mm. The beam is matched to the first aperture ($\alpha = 0$, $\beta = 0.5$, $\varepsilon = 200\,\pi$ mm mrad, A/Q = 4, E$_{kin}$ = 10 keV, I = 2 mA). With a maximum magnetic field of 120 mT particles experience a phase advance of 43° per cell ($\sigma = \frac{B}{2B\varrho} \cdot \sqrt{S \cdot L} \cdot \frac{180}{\pi}$; S = length of cell, L = length of solenoid). Particle distributions for this calculation in front of and behind each aperture are shown in Fig. 5.

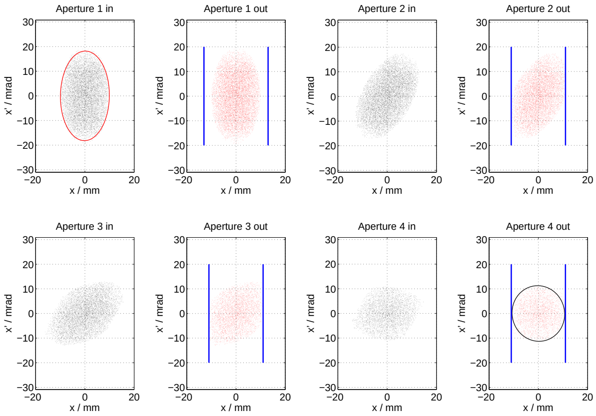

Figure 5: Particle distributions of start-to-end simulation with cutting at the apertures. Apertures in the xx' phase space are shown as blue lines (#1: r=13 mm; #2,3,4: r=11 mm).

By varying the aperture size of all apertures simultaneously with the same matched beam, the acceptance of the channel was calculated. The results are shown in Fig. 6.

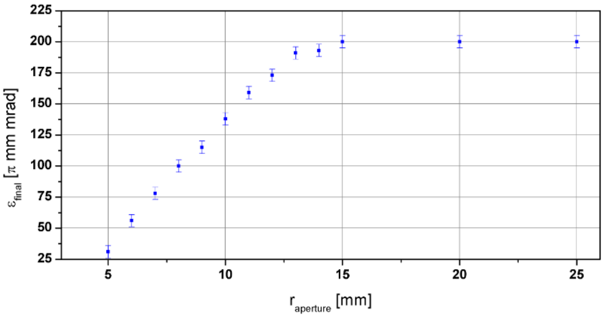

Figure 6: Emittance transported through the channel by varying the radius of the four apertures simultaneously with static phase advance.

If the beam is not matched to the channel ($\alpha \neq 0$), it is possible to use the first cell for matching and then only having the possibility to do phase space cutting and manipulation within two cells of the channel instead of three. If a non-matched beam is sent through the collimation channel, a significant drop in transmission as well as acceptance can be observed by just small variation of α. A factor of more than 2 in transmission loss can be seen by varying α between -1 and 1. In this case no corrections/matching within the first cell have been applied to the beam. This is subject to further studies.

RESULTS AND OUTLOOK

All results achieved so far demand a static collimator for the FRANZ facility as shown in Fig. 3 in front of the second solenoid in order to cut the heavier beam fractions of H_2^+ and H_3^+. A collimation channel would be ideally used for beams extracted from ECR ion sources, which might be tested at the EIS test stand at GSI. It would be possible to investigate the extracted beam from ECR sources with its extraordinary phase space distributions. GSI is also working on a correction scheme for beams extracted from ECR sources which could be experimentally proven together with a powerful tool like the collimation channel.
The next steps will include simulations of the EIS test stand geometry together with the use of electro-static lenses for creation of the phase advance of particles and with implementation of quadrupole duplets, triplets or quadruplets in order to fit optimum parameters.

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