SPACE-CHARGE COMPENSATION IN THE TRANSITION AREA BETWEEN LEBT AND RFQ*

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Abstract

The transition from a space-charge compensated beam in the LEBT to an uncompensated beam in the RFQ will influence the beam parameters. In order to investigate the impact of the electric fields on the space charge compensation, an insulated cone is used as a repeller electrode in front of the RFQ. Depending on the time dependent potential of the RFQ rods respectively to the beam potential, the compensation electrons may be prevented from moving into the RF field which oozes out of the RFQ entrance. The simulation studies are performed with the particle-in-cell code bender [1]. The simulations may substantiate measurements at the CW-operated RFQ in Frankfurt University [2] as well as at the foreseen MYRRHA LEBT-RFQ interface. [3]. In this contribution, a study on a LEBT-RFQ interface is shown.

INTRODUCTION

A particle accelerator consists of several different sections which are designed independently. In order to ensure the best performance for beam transport, transfer points are defined between these sections. Transfer points are typically set at the transfer from the ion source into the Low Energy Beam Transport (LEBT), from the LEBT into the Radio Frequency Quadrupole (RFQ), from the RFQ into the Drift Tube Linac (DTL), at the injection from the DTL into the Synchrotron and from the extraction to the experimental setups. If the machine is even more complex, several additional transfer points are present.

This work will focus on the transfer point between LEBT and RFQ of the FRANZ accelerator at Frankfurt University [2], shown in Fig. 1 on the left, and the MYRRHA accelerator [3], which also has a combined chopper-cone RFQ interface. Focus has been set on the insulated conical tube ("cone"), shown in Fig. 1 on the right, to study various beam effects at the RFQ injection region.

In order to fulfill an optimisation process of the injection, three approaches are applied. The first is a theoretical view at the impact of the injection parameters on the layout of the upstream LEBT section. Second, the redistribution of the particles due to decompensation is investigated. Third, numerical simulations of the effect of an injection cone have been performed and interpreted.

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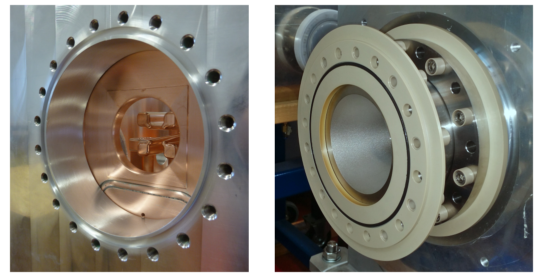

Figure 1: **Left**: injection region of an RFQ, **right**: injection cone mounted at the RFQ entrance.

INJECTION PARAMETERS

Due to the diversity of the requirements in each different section, usually a dedicated code model and different approximations are applied independently. It is crucial for correct physical description, that the whole information content about the beam and secondary particles is exchanged at the transfer point (e.g. the backflow of the compensation electrons). In most cases, an optimisation was made to fit a best matching scenario per section. Still, the overall performance globally might be better than the two independently calculated best matches at each machine section.

In general, the calculations or simulations end at a defined transfer plane. Any influence of a downstream machine into the upstream section is not taken into account. For synchrotrons and experiments, this sounds very reasonable, as there are several meters to tens of meters in between. In the case of the LEBT-RFQ-transfer, the distance is only a few ten to hundred milimeters. Anyhow, the optimisation of the LEBT does not include any influence of the RF-field from the RFQ on the beam before the transfer plane. Especially in case of space-charge compensation, when electrons are able to travel very fast within the beam potential, the RF-field can have a huge influence on the beam upstream the RFQ.

GEOMETRICAL LIMITS

At the injection plane a certain transversal momentum is specified. With paraxial approximation, the opening angle α can be computed. The other limitating factors are the radius, which is maximal allowed for proper beam transport in the last focusing element, r_{Sol} and the given radius r_{in} at the injection plane. In case of a linear propagation without any space-charge forces of the beam, the maximum distance $d = \frac{r_{\mathrm{Sol}}-r_{\mathrm{in}}}{\tan(\alpha)}$ from the mid-plane of the last focusing element upstream the RFQ to the injection plane can be calculated, which is the geometrical limit for injection.

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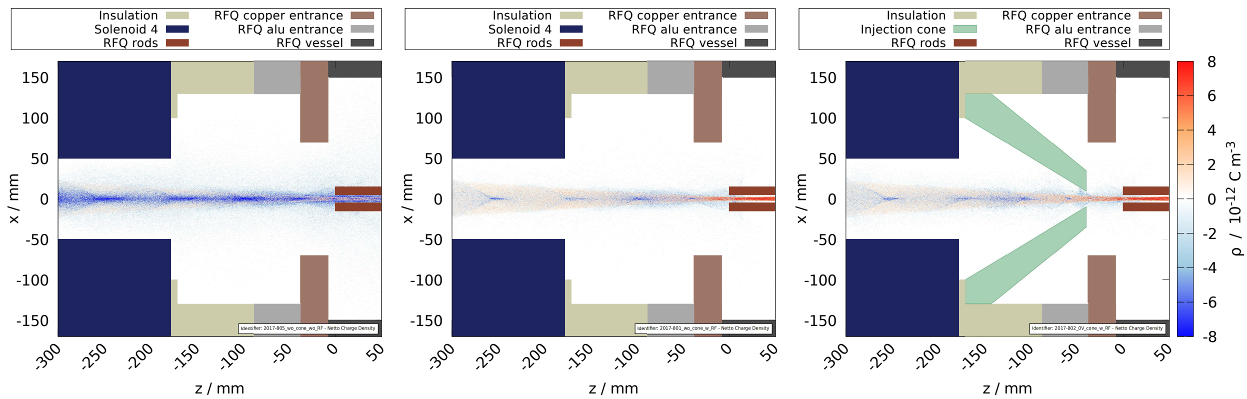

Figure 2: Netto charge densities for three injection cases. $z = 0$ mm is set to the injection plane of the RFQ. **Left**: without cone and without RF. **Center**: without cone but with RF. **Right**: with cone, $\Phi_{cone} = 0$ V

If the beam is not fully compensated, space-charge forces occur. This will decrease the possible choice of distance settings. If the limit is underrun, the beam dynamics gain more flexibility, as the beam radius has a broader range of possible combinations in radius and transversal momentum. In the design of the FRANZ beamline the geometrical limit is $d_{\mathrm{geo}} = 414$ mm and the setup distance is set to $d_{\mathrm{setup}} = 296$ mm which is 118 mm less than the geometrical limit for injection without space-charge to gain flexibility in beam current and solenoidal settings.

THERMALISATION DISTANCE

At the injection region, the collective effects of a non-homogeneous distribution have to be considered, as they can lead to an emittance growth [4]. If a space-charge compensated ion beam is decompensated by external eletrical fields the remaining ions will redistribute if the beam distribution is not homogeneous. In order to estimate the time in which this redistribution will happen roughly, the plasma frequency of the ion beam can be used, which is shown in Eq. (1).

$$\Omega_B = \sqrt{\frac{e I_{\mathrm{B}}}{\epsilon_0 \pi \mathrm{v_B} m_{\mathrm{B}} r_{\mathrm{B}}^2}}. \tag{1}$$

To obtain the distance, which the beam travels during this redistribution, we calculate $d_{\mathrm{therm}} = \frac{\mathrm{v_B}}{\Omega_{\mathrm{B}}}$. Hence, the thermalisation distance can be formulated as in Eq. (2).

$$d_{\mathrm{therm}} = \sqrt{(2\,U_{\mathrm{B}})^{3/2} \frac{\epsilon_0 \pi r_{\mathrm{B}}^2}{I_{\mathrm{B}}} \sqrt{\frac{\mathrm{e}}{m_{\mathrm{p}}}}}. \tag{2}$$

For a 120 kV, 50 mA, 3 mm Proton beam as is proposed at FRANZ we get $\Omega_{\mathrm{FRANZ}} \approx 63$ MHz and $d_{\mathrm{therm,FRANZ}} \approx 76$ mm. For the MYRRHA project with 30 kV, 5 mA and 3 mm we have a lower plasma frequency $\Omega_{\mathrm{MYRRHA}} \approx 28$ MHz but as the beam is also slower the thermalisation distance is in the same range: $d_{\mathrm{therm,MYRRHA}} \approx 84$ mm. In order to minimize the emittance growth caused by this thermalisation, the distance between the decompensation of the ion beam and the beginning of the RFQ rods has to been made as short as possible, in best case less than some tens of millimetres.

CONE

The transfer point of the FRANZ accelerator has been equipped with an insulated conical tube ("cone") to study various beam effects at the RFQ injection region. The water-cooled cone adds a mechanical acceptance of $r = 10$ mm right in front of the RFQ electrodes. The cone absorbs the geometrical mismatched particles, like the undesired hydrogen fractions H_2^+ and H_3^+ and therefore minimizes the losses within the RFQ [5]. The cone used in the MYRRHA LEBT has an aperture of 9mm right before the RFQ injection, is water-cooled and its purpose is also to add a mechanical acceptance such that the unmached fractions will be lost controlled on this device. Additional, in the MYRRHA LEBT the chopper will deflect the unwanted part of the beam onto the cone, and helps to imprint a required time structure on the beam. As a side effect, the cones' loss current can be used to optimise the beam injection by minimizing the losses on the cone.

In case of a high voltage setting, it can control the space-charge compensation of the beam in the injection region. A possible emittance growth at the injection region might be caused from the decompensation of the beam by the high-gradient fields of the RFQ which pulls the electrons out of the beam potential. In order to investigate this effect numerically, simulations with the particle-in-cell code bender [1] have been performed. As a setup, the transfer point from the LEBT into the RFQ of the FRANZ beamline was chosen. As the accelerator test stand is designed to transport a beam of up to 200mA, the first step case of a 50mA beam was studied. A special interest is set on the behaviour of the compensation electrons which move through the beam potential while filling it and reduces the space-charge forces. In the transfer region the electrons are affected by the high voltage radio frequency field so they will be lost. The change in compensation of a beam will cause a focus shift [6], hence it is important to control and know the compensation at each point of the injection region, to make the simulations as accurate as possible.

Out of the numerous different possible combinations, four cases were selected to focus on. These are a beam transport into the RFQ without cone, beam transport with a cone on

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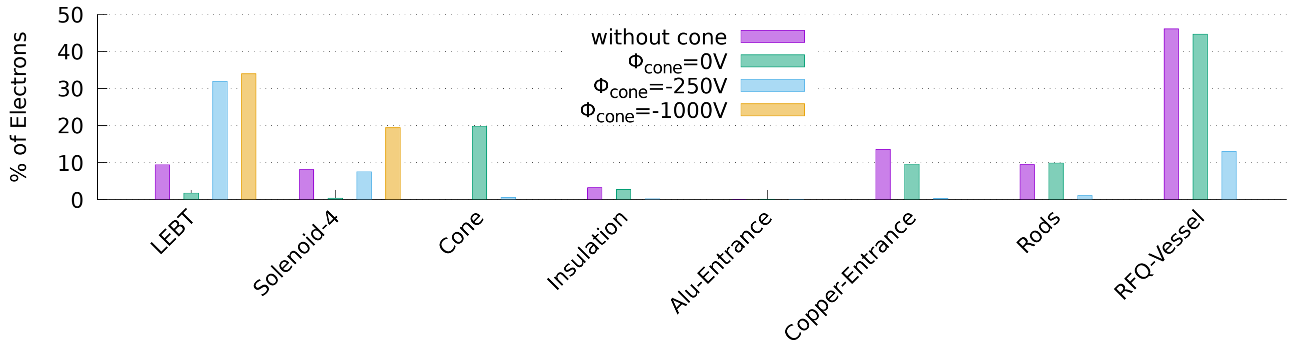

Figure 3: Losses at different objects in the injection region for the four different cases studied. The electrons labeled with "LEBT" stay captured in the beam potential within the LEBT. The electrons which are lost on the RFQ rods and in the RFQ vessel may facilitate sparks in the RFQ.

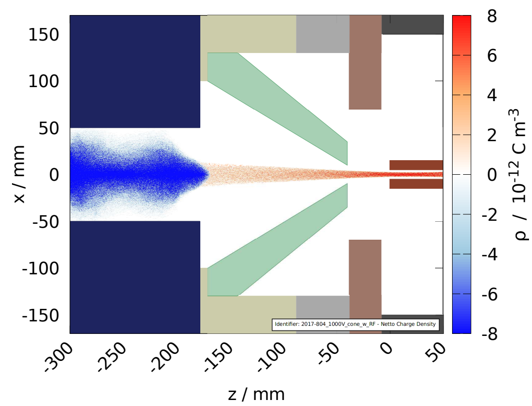

Figure 4: Netto charge densities for the injection with cone. $\Phi_{\text{Cone}} = -1000\,\text{V}$. Key see Fig. 2

ground potential and two cases with the impact of the cone as a repeller electrode on negative voltage, $\Phi_{\text{Cone}} = -250\,\text{V}$ and $\Phi_{\text{Cone}} = -1000\,\text{V}$. For the purpose of comparison, a simulation without cone and without RF has been performed.

All simulations have been run for a total time of 1000 ns. As the compensation rise time is usally several µs [7], a assumption for the production rate of electrons at the beam entrance was set to $6 \cdot 10^{-4}$ C/s such that the compensation can fill the beam over the simulation time. The initial energy of the electrons was chosen to 1 eV. The beam was prepared to fit into the RFQ by drift only and the solenoidal field is swiched off. Both, the proton and the electron particle distribution was chosen with a KV-distribution. In all figures, the netto charge density is indicated by a color bar in same scale.

In Fig. 2 left it is visible, that the whole beam is compensated by electrons if no RF-field is present. This changes dramatically, if RF is swiched on, see Fig. 2 center. By installation of a cone on ground potential, the situation stays similar. In Fig. 3, the losses of electrons at different objects in the injection region are shown. The installation of the cone shields the electrons repelled by the RFQ back into the LEBT as they are lost on the back side of the cone instead of staying in the LEBT or been lost on Solenoid 4. The losses on the copper entrance plate and on the rods stay almost the same.

If the cone is set on a potential of $\Phi_{\text{Cone}} = -1000\,\text{V}$, which is approximately the beam axis potential, all electrons are captured in the LEBT and losses occur only on Solenoid 4. In Fig. 4 it is seen that the electrons stay almost completely within the Solenoid 4. This causes a long distance of uncompensated transport which allows the ion beam a long time to thermalise and therefore an emittance growth for an non-homogeneous beam will occur.

For a potential of $\Phi_{\text{Cone}} = -250\,\text{V}$, the majority of electrons is hold back in the beam, as visible in Fig. 5. Here, the electrons stay in the LEBT, as seen in Fig. 3 and a few are lost on Solenoid 4 and within the RFQ vessel. As the beam axis potential is more than four times higher as the repeller voltage, still some electrons may travel into the RFQ. Compared to the case in fig. 4, the repeller potential is lower and hence the electrons can compensate the beam into the RFQ vessel, which is indicated grey, leading to a distance of less than 80 mm between the beginning of uncompensated transport and the beginning of the rods.

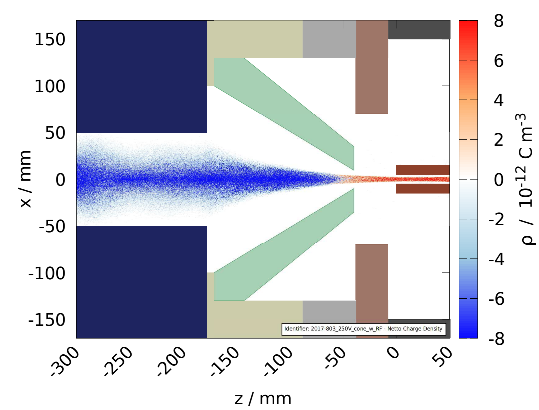

Figure 5: Netto charge densities for the injection with cone. $\Phi_{\text{Cone}} = -250\,\text{V}$. Key see Fig. 2

CONCLUSION

Simulated scenarios will help to understand the physical situation in reality. Minor changes in the cone settings can lead to important issues for the beam dynamics.

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