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SPACE CHARGE AND ELECTRON CONFINEMENT IN HIGH CURRENT LOW ENERGY TRANSPORT LINES: EXPERIENCE AND SIMULATIONS FROM IFMIF/EVEDA AND ESS COMMISSIONING

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Abstract

The mechanism of space charge compensation given as a result of the residual gas ionization is a key factor for the emittance containment in the low energy beam transport (LEBT) lines of high intensity hadron injectors. A typical front end including an ion source, a LEBT and Radio Frequency Quadrupole (RFQ), is equipped with two repellers at each interface to prevent electrons from flowing back, to the source, or forward, to the RFQ. In this paper we will emphasize the importance of the ion source and LEBT repellers on giving the appropriate boundary conditions for the space-charge compensation build-up mechanism. The theory and simulations are supported by experiments performed in the high intensities facility such as ESS and IFMIF/EVEDA.

INTRODUCTION

The Linear IFMIF Prototype Accelerator (LIPAc) [1, 2] is a high intensity D^+ linear accelerator; demonstrator of the International Fusion Material Irradiation Facility (IFMIF). The final linac [3] will send 40 MeV of 125 mA deuteron beam onto a liquid lithium target, in order to reproduce the future fusion reactor neutron spectra. In summer 2019 the IFMIF/EVEDA Radio Frequency Quadrupole (RFQ) accelerated its nominal 125 mA deuteron (D^+) beam current to 5 MeV, with >90% transmission for pulses of 1 ms at 1 Hz, reaching its nominal beam dynamics goal [4, 5].

The European Spallation Source (ESS) [6], currently under construction in Lund, Sweden will send a 62.5 mA proton beam at 14 Hz and 2.86 ms pulse length will be accelerated to 2 GeV. The resulting average beam power of 5 MW will be used to drive the production of spallation neutrons, enabling ESS to become a flagship research facility and to carry out world class science. The normal conducting part is the first section of the machine to transition from installation to integrated testing and commissioning with beam. In spring 2022 the first DTL tank [7] was commissioned at full peak current reaching its nominal beam dynamics goal [8, 9].

Both of these high power high intensity facilities implement a similar low energy stage composed of:

- high intensity ion source of ECR (Electron Cyclotron Resonance) type
- magnetostatic LEBT (Low Energy Beam Transfer) line.

THE INJECTORS

In this paper we will focus on the extraction and LEBT optics of these two facilities (Fig. 1). The ESS ion source plasma phenomena are described in [10] and the beam modulation techniques in [11].

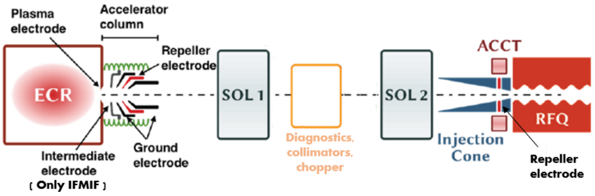

Figure 1: Common layout of the LEBTs of ESS and IFMIF/EVEDA.

The ion sources produce light ions beams: deuteron/protons for IFMIF, protons for ESS. The LEBT are based on a magnetostatic transfer line that uses two solenoids for transport and matching the beam into the RFQs. Two repellers are supplied, one in the extraction region, the other one at the RFQ entrance. As far as the diagnostics are concerned, both injectors are equipped with non intercepting current monitors that allows to read extracted beam current from the PE (Plasma Electrode) and to the RFQ injection point. Additionally, the ESS LEBT [12] is equipped with a Faraday Cup. In the following sections we will explain the differences between the injectors.

IFMIF Injector

The injector, an ECR source, in-kind contribution of CEA Saclay [13] consists of a 2.45 GHz RF power source with a two coil magnetic structure. The nominal CW beam extracted consists of 140 mA D^+ at 100 kV. For commissioning purposes, the source can also extract tens of mA of H^+ at 50 kV and can operate in pulsed mode. From the beam dynamics point of view, these beams are characterized by a high perveance beam transport: the general perveance (un-compensated) ranges from $5{\times}10^{-4}$ for the probe up to $5{\times}10^{-3}$ for the nominal beam. The extraction, differently to the ESS case, is characterized by a five-electrode system: the addition of an intermediate electrode can

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be used to unbalance the gap voltages between the plasma electrode and the first ground without changing the overall extraction output energy. There are no collimators in the LEBT other than the collimator cone before the RFQ.

ESS Injector

The ESS linac starts with a microwave discharge ion source [14] with a three coils magnetic structure producing a 75 keV, 90 proton beam with a flattop pulse length of 3 ms and 14 Hz repetition rate. The general perveance (uncompensated) ranges from $1.6{\times}10^{-4}$ for the probe beam up to $2.9{\times}10^{-3}$ for the nominal beam.

The LEBT includes an electrostatic chopping system [15] (fixed, different to the IFMIF/EVEDA case) and an adjustable iris between the two solenoids. Even with its full aperture, the iris decreases the aperture between the solenoids down to around 35 mm radius, protecting the devices downstream from unwanted losses. The extraction system is composed by 4 electrodes: change of the extraction voltage or the beam current density is unavoidable in order to probe the optics of the extraction. The IS and the LEBT are in-kind contributions from INFN Catania in Italy [16].

IFMIF/EVEDA EXPERIENCE WITH RFQ REPELLER

Close to the RFQ injection point there is an electron repeller. Following the LEDA experience [17], it was placed in order to boost the space charge compensation in this last LEBT section. As a matter of fact, there are two beam envelope minimums r_{min} along the LEBT: one close to the plasma electrode and one at the RFQ entrance. In such points:

1. The space charge field ϕ_{self} possesses the larger values with respect the other part of LEBT domain.
2. The decompensation due to the Columbian collisions [18] has also their maxima ϕ_{scc}/ϕ_{self} in those positions, where $\phi_{scc} = \phi_{self}(1-\eta)$.
3. The maxima of the beam self-field potential attracts the electrons generated via residual gas ionization and collisions with pipes. For positive ion even at the steady state, there is a residual uncompensated beam potential that drives the electrons dynamics $-\nabla\phi_{scc}$ [19].

Therefore, on both points, there are effective longitudinal electron flows that reduce the electron density for several cm after or ahead of the r_{min}. As such, the s.c.c. degree decreases significantly.

The effect can be seen in Fig. 2: two simulations were performed with WARP code [20] of the IFMIF/EVEDA LEBT, with nominal beam perveance. The total potential ϕ_{tot} along axis is shown at the steady state of the simulation for two cases. In one of these simulations we kept the RFQ repeller "off", while in the other it was "on". At steady state, the residual potential for the "off" case ϕ_{self} is roughly two times larger than the "on" case, but in the exact point of r_{min}.

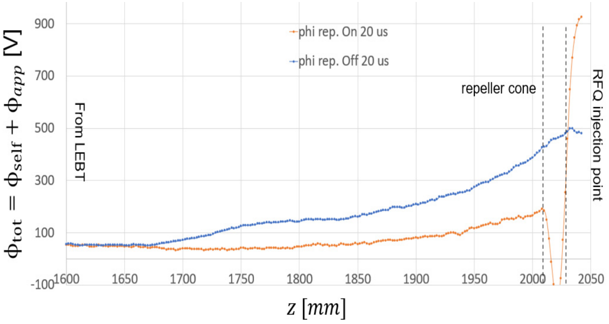

Figure 2: IFMIF/EVEDA simulated total potential close RFQ injection point with the WARP code, for repeller on (orange curve) and off (blue curve). Repeller cone voltage effect on potential is highlight.

If we look to the predicted emittance growths, we calculate a +38% larger emittance at RFQ injection in case of (RFQ) repeller off, meaning that the small gain of compensation at the r_{min} position, at the cost of a constant electron longitudinal outflow, does not preserve the beam emittance. Another interesting effect given by this electron outflow, is that the non-intercepting beam current measurement at the RFQ entrance (such as an ACCT) leads to under estimation of the current at the entrance of the RFQ, if no potential on the repeller is applied. Therefore, an overestimation of transmission through RFQ is expected in such a case. In IFMIF/EVEDA, we measured 15 mA of such electron outflow for nominal proton beam (70 mA) and we had to apply -1 kV at RFQ repeller to disrupt it.

ESS EXPERIENCE WITH SOURCE REPELLER

Similar phenomena can be found at the other r_{min} position, at the extraction column. Different to the RFQ case, the electrons flow is opposite to that of the proton beam. Therefore, the extracted current read is overestimated by the transformer. At this place, it is commonly added an electron repeller in order to avoid this electron flow entering into the plasma chamber, damaging the electrodes or the boron-nitride disks (Fig. 3).

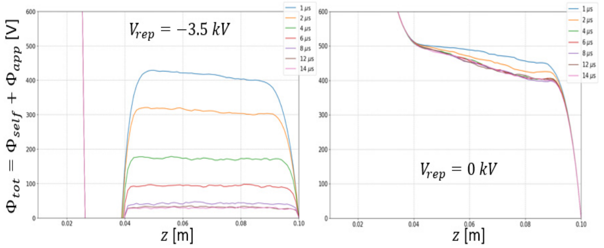

Figure 3: Simulated total potential close to the extraction with the WARP code, for repeller on (left plot) and off (right plot). The potentials are shown with respect time needed for compensation to build up.

The source repeller also disrupts the backward flow of electron (reflecting the electrons) and builds up the space-charge compensation in the extraction region. The effect on the emittance growth, however, is far more important with respect to that of the RFQ repeller: if the beam is divergent from the extraction (due to the uncompensated space charge or bad extraction optics) for this type of ion sources, the larger emittance growth contribution may rise form the solenoid spherical aberrations [21], which occurs when the beam occupies more than 50% of solenoid bore.

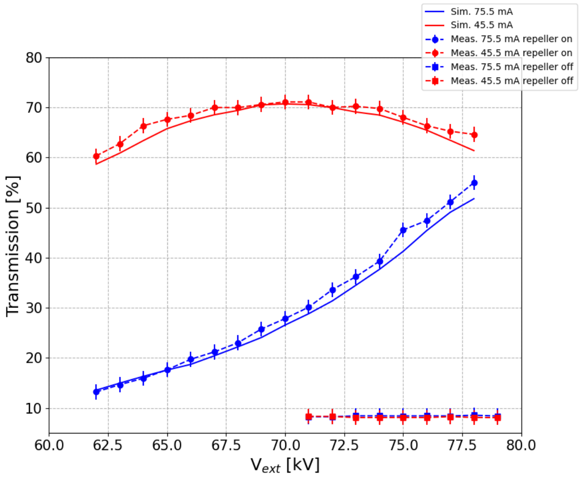

Figure 4: Simulated and measured transmission at FC for 75.5 mA and 45.5 mA at different extraction voltages, with/without the source repeller. Dotted marked line are the measurements, while the continuous lines are the simulations. The square marks are the measurements without repeller.

At ESS we performed an experiment that allowed us to probe the optics of the extraction for different electrode voltages with different repeller voltages. Keeping the solenoid 1 off, we change the platform voltage between 60-80 kV with the repeller off and at -3.5 kV (Fig. 4). For different extracted currents (75.5 mA and 45.5 mA) while changing the potential, we kept the extracted current constant adjusting slightly the RF and the gas. We then looked at the ratio between the extracted current (measured by a transformer) and the current reaching the FC between the two solenoids. This quantity is related to the beam dimensions and thus of the divergence at the source. The measurements were benchmarked with a dedicated code [22] based on IBSIMU [23] and WARP. It is possible to see that the curves with the repeller on (dot marks) follow the well-known trend driven by the source perveance, while in the other case (no voltage applied on the repeller) it is completely independent from them. This means that the space charge compensation does not reach higher enough levels (also as expected by Fig. 3). The divergence is therefore largely amplified (a factor of 3 roughly) if the electron flow is present. From preliminary simulations, this can led to a factor of 4 of higher emittance between the two solenoids with respect the nominal case.

This effect can be studied also looking at the current reaching the FC for different repeller voltages at fixed extracted current, 75.5 mA (Fig. 5).

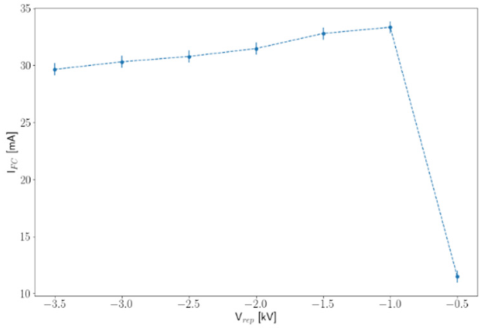

Figure 5: Current at the FC for 75.5 mA extracted current for different repeller voltages.

The current at the FC increases up to the point where the repeller potential does not anymore disrupt the electron flow through the plasma electrode hole. Therefore, the s.c.c. does not build up anymore and the transmission reduces abruptly due to the low s.c.c. . Not only do the electrons close to the extraction contributes to these phenomena, the electrons from the LEBT may also potentially contribute as shown in Fig. 6.

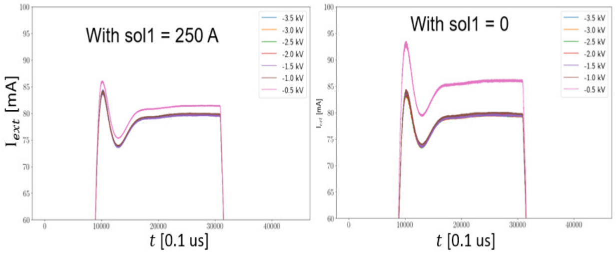

Figure 6: Extracted current waveforms for different repellers and with and without solenoid 1 on.

The extracted current waveforms for different repellers and with/without the solenoid 1 are shown in Fig. 6. It is possible to see that in both cases, when the repeller voltage is below 1 kV, the current transformer measures the electron outflow (as an increase of extracted current). Its magnitude is different depending on the field of solenoid. This can be explained by the fact that the contribution from the electrons of the LEBT to the outflow is limited by the solenoid field, which partially removes their contributions.

CONCLUSION

In this paper, we explored the role of the repellers in the space charge compensation of high intensity positive light ion facilities of IFMIF/EVEDA and ESS. Besides their main roles, as protection devices for the source and RFQs they carry out a very important function in the longitudinal confinement of the electrons, an essential mechanism for a good quality beam at the RFQ entrance.

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