Beam measurements at the PXIE LEBT

J.-P. Carneiro*
Fermilab, Batavia, IL 60510, USA

Abstract

This document summarizes the beam measurements performed at the PXIE LEBT from November 2014 to June 2015 during the conditioning of the beamline. These measurements which focus on transmission, beam size and emittance are compared with the 3D multi-particle code TRACK. The aim of these studies is to prepare the beam for an optimal operation of the RFQ and also to validate our simulation tools.

1 Introduction

The Proton Improvement Plan II (PIP-II) is an upgrade of the Fermilab injector complex with the primary goal of supporting MegaWatt operations for the Long-Baseline Neutrino Facility (LBNF). In its actual configuration PIP-II is considered to be a 2 mA CW, 800 MeV H^- linac that should be capable of working initially in a pulse (0.55 ms, 20 Hz) mode for injection into the Booster. One of the technical challenge of the PIP-II linac resides in its front-end with the transition from warm to superconducting section at low energy (2.1 MeV)

In order to study the feasibility of the PIP-II front-end, Fermilab has started since 2012 the construction of the PIP-II Injector Experiment (PXIE) which is expected to deliver in 2018 a 25 MeV H^- beam with an average current of 1 mA. The main components of the PXIE linac are a 10 mA, H^- Ion Source able to operate DC or pulsed, a Low Energy Beam Transport (LEBT) made of 3 solenoids, a Radio-Frequency Quadrupole (RFQ), a Medium Energy Beam Transport (MEBT), two superconducting cryomodules and a High Energy Beam Transport (HEBT) which brings the beam to a dump. The beam exits the Ion Source with an energy of 30 keV and is further accelerated to 2.1 MeV by the RFQ. The first cryomodule made of 8 Half-Wave Resonators cavities accelerates the beam to 10 MeV and the second cryomodule made of 8 Single-Spoke Resonators brings the beam to its final energy of 25 MeV.

The Ion source have been installed and is in operation at Fermilab since November 2013 and the LEBT have been in operation in its final 3 solenoids configuration since July 2014. This document presents the measurements (transmission, beam size and emittance) performed on the Ion Source and LEBT. Some of the measurements presented in this document are also described in Ref. [1].

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*carneiro@fnal.gov

2 LEBT design philosophy

The LEBT is made of 3 solenoids with the goal to transport and properly inject the beam into the RFQ by providing a centered and matched beam at the RFQ entrance with a transverse RMS normalized emittance ideally lower or equal to the RFQ design specification of 0.18 mm-mrad and the following TWISS parameters:

- α=1.6
- β=0.07 m/rad

The originality of the LEBT resides in its neutralization pattern. In fact, while all LEBTs operate fully neutralized to get benefits from a low space charge beam transport, the PXIE LEBT operates with a non-neutralized region starting downstream the middle of the second solenoid. There are two main reasons behind this long non-neutralized region: first following the observations reported in Ref. [2] we think that keeping a high vacuum region upstream the RFQ will help improving the RFQ operational stability and second we think that operating the chopper in an un-neutralized region will prevent optics perturbations during commissioning with a reduced duty factor.

3 Simulation tools

The preliminary design of the LEBT has been performed with the code VACO which has been developed at FNAL by V. Lebedev. VACO is a PIC code written with MATHCAD for axially symmetrical beamlines with simple space charge kicks. VACO is a powerful tool to use during the design of a beamline when repeated runs with varying parameters take place. The code is relatively easy to use and includes non-linear beam dynamics.

As presented in Ref. [3], the final design of the LEBT has been validated with the PIC code TRACEWIN [4] developed at Saclay, France. TRACEWIN is a full 3D tracking code which allows the use of 3D external fields and computes 3D space-charge fields at each integration step through the solving of the Poisson's equation. The tracking in TRACEWIN is usually performed with 100k macro-particles and the code allows to explore non–linear beam dynamics and its effects on for instance halo formation and emittance increase.

The code TRACK [5] developed at Argonne National Lab has been the main tool in use during the conditioning of the LEBT. The majority of the beam measurement presented on this document have been compared with TRACK. This code is similar in its functionality to TRACEWIN (full 3D) and TRACK has been successfully benchmarked with TRACEWIN for several projects as discussed in Ref. [4]. TRACK is found to be an excellent complement to TRACEWIN. Whereas TRACEWIN is easily settable and usable for matching purposes, TRACK does not offer at this stage of the code development an easy matching procedure. The powerful feature of TRACK resides in the fact that the code is simple to setup on a Grid through its Linux executable and hundreds to thousands of TRACK runs may be launched simultaneously. This feature is found to be particularly efficient when scanning parameters like solenoid currents. Even though feasible, the setup of TRACEWIN on a Grid is more difficult to achieve due to its licensing issue. TRACK is free of charge and does not require any license.

The three codes above-mentioned require an accurate description of the initial beam particle distribution. The initial distribution can either be internally generated in the codes through user

defined TWISS parameters (usually as 2D Gaussian, 2D Uniform, KV or Waterbag) or the distribution can be externally generated from a measured phase-space. During the design of the LEBT, the initial distributions were exclusively internally generated while during the commissioning we took advantage of the installation of the Allison Scanner at the ion source exit to convert the measured phase-spaces into initial beam particle distributions using PLOTWIN [6], a software from Saclay. Since the Allison Scanner could measure the phase space only in one plane, the generated beam is considered as identical in both planes.
The 3D solenoid and corrector field maps were generated with MicroWave Studio [7] and converted into TRACK and TRACEWIN input format with a simple Matlab macro. A more detailed description of the solenoid field maps is presented in Ref. [8]. A significant effort has been carried out to implement in the three codes a detailed aperture of the beamline. TRACK and TRACEWIN are able to handle aperture limitations inside solenoid fields. Finally it is important to mention that the codes do not support beam-residual gas interactions and therefore the neutralization effects occurring in the LEBT is modeled by a simple flag that homogeneously decreases the space charge current in the codes.

4 LEBT Layout and Modeling

4.1 Beamline description

A layout of the PXIE LEBT is presented in Figure 4.1. The H^{-} Ion Source has been delivered by D-Pace Inc. and is a filament driven source able to produce up to 10 mA initially as DC at an energy of 30 keV. A voltage modulation has been implemented at Fermilab on the ion source extraction electrodes to enable also its pulsed operation. When operated pulsed, the source can deliver bunches from 5 μs to 16 ms at a frequency of 60 Hz. As presented in Figure 4.1, upon exiting the ion source the beam is transported to a Faraday Cup by three identical solenoids. Upstream of the first solenoid, a shield of 34 mm diameter aperture protects the bellow connecting the ion source box to the solenoid. Inside the first and second solenoid, a water-cooled round Electrical Isolated Diaphragm is installed with the primary goal to confine the positive ions responsible for the beam neutralization between these two solenoids. The diaphragms, usually biased to +40V or +50V, also serve as beam scrapers and current monitors. In fact, the beam may be deviated into the diaphragms on purpose for beam size measurements or the beam can simply be scraped on which case the diaphragms provide a useful information on the amount of the beam lost. An electrostatic chopper is installed between the second and the third solenoid. The chopper is made of two parallel plates, each 16 cm long and 5 cm width, separated by a gap of 32 mm.

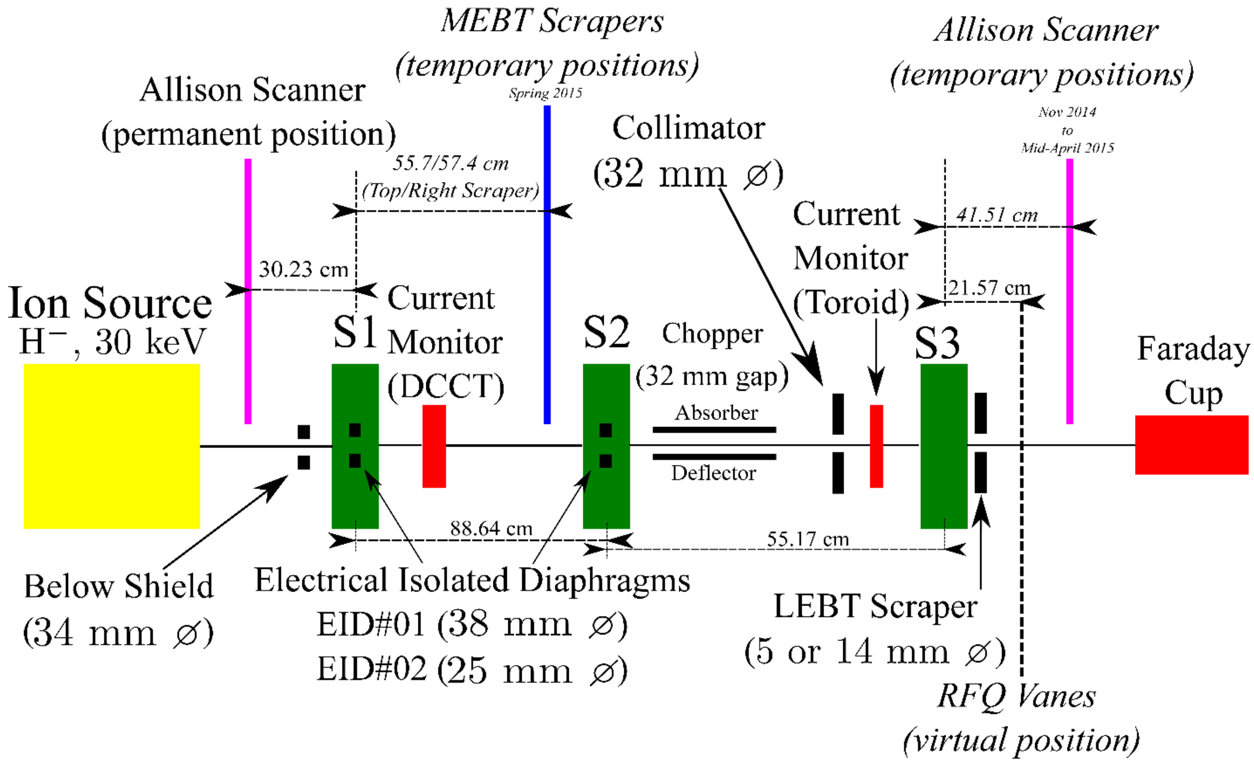

Figure 4.1: Layout of the PXIE LEBT (in italic elements temporary installed).

The chopper provides chopped pulses to the PXIE RFQ for commissioning purposes as well as for PIP-II dedicated studies. The chopper pulses range from 1 µs to 16 ms, at a rate of up to 60 Hz with rise and fall time below 100 ns. The lower plate of the chopper known as the Deflector is electrically isolated and is biased negatively at -5 kV. The upper plate also electrically isolated and known as the Absorber intercepts the deflected beam and reports its measured current. When an un-deflected beam is desired in the LEBT, the Deflector is usually brought to -300 V which allows for the clearing of neutralizing ions. As depicted in Figure 4.1, a collimator has been installed just downstream of the chopper. This collimator is a water-cooled, isolated round diaphragm similar to the ones installed inside the solenoids and its main purpose is to protect downstream elements (in particular the toroid ceramic break) from mis-steered particles. One of the last element that has been installed in the beamline is the LEBT scraper which is a water-cooled, electrically isolated vertical insert with three apertures: two holes of 5 mm and 14 mm diameter and a larger “D-Shape” hole. The smallest hole is meant for providing the RFQ with a “pencil-like” beam while the 14 mm hole has more a protective role of the vanes during normal operation of the RFQ. This 14 mm hole can also be used as part of a Machine Protection System. Would the beam present an abnormal excursion at the LEBT scrapers, the Deflector would then send the beam toward the Absorber. Concerning the “D-Shape”, it allows all the beam to pass through and its horizontal edge is used for beam size and profile measurement.

In regard to the diagnostics, an Allison Scanner has been extensively used downstream of the LEBT before its permanent installation at the ion source exit. When installed at the end of the LEBT, the Allison Scanner was measuring mainly horizontal phase-space portraits while in its permanent position the scans are vertical. Direct beam current measurements are performed using two non-interceptive current monitors (DCCT and Toroid) and at the end of the beamline using the Faraday Cup. As discussed in the previous paragraph, the beam current can also be monitored at the Absorber and/or at the isolated diaphragms (EID#01, EID#02, Collimator or LEBT scrapers). During routine operation of the LEBT, the current measured for instance at the DCCT would match appropriately the sum of the current measured at the Faraday Cup and at different scraping locations. As depicted in Figure 4.1, MEBT scrapers were temporarily installed between the first and second solenoid. These scrapers are intended to be used in the MEBT downstream of the RFQ and were initially installed in the LEBT for tests. We extensively used the MEBT scrapers to measure the beam size and beam profile as a function of the current of the first solenoid and for different ion source extraction voltages. These measurements are presented in Section 7.

4.2 Start-to-End Simulations

Figure 4.2(a) shows TRACK simulations of a 5mA beam along the PXIE LEBT, starting from the Allison Scanner slit location and matched into the RFQ (following the required TWISS mentioned in Section 2). The beam is considered fully neutralized up to the middle of the second solenoid and fully un-neutralized downstream of this point with the neutralization starting in TRACK as a step function. The initial TWISS were measured at the Allison Scanner on June 15, 2015 for an ion source extraction voltage of about 2.9 kV as α=-2.4 and β=46 cm/rad and the normalized RMS emittance at about 0.15 mm-mrad. Two initial distributions of 100k macro-particles were used in TRACK: a 2D Gaussian (Gaussian in both density and velocities) and a Uniform-Gaussian distribution (Uniform in density and Gaussian in velocities). The 2D Gaussian distribution (cut at 3 sigma) is internally generated in TRACK and the Uniform-Gaussian distribution was first generated by VACO and transformed into TRACK input distribution using a simple Matlab macro.

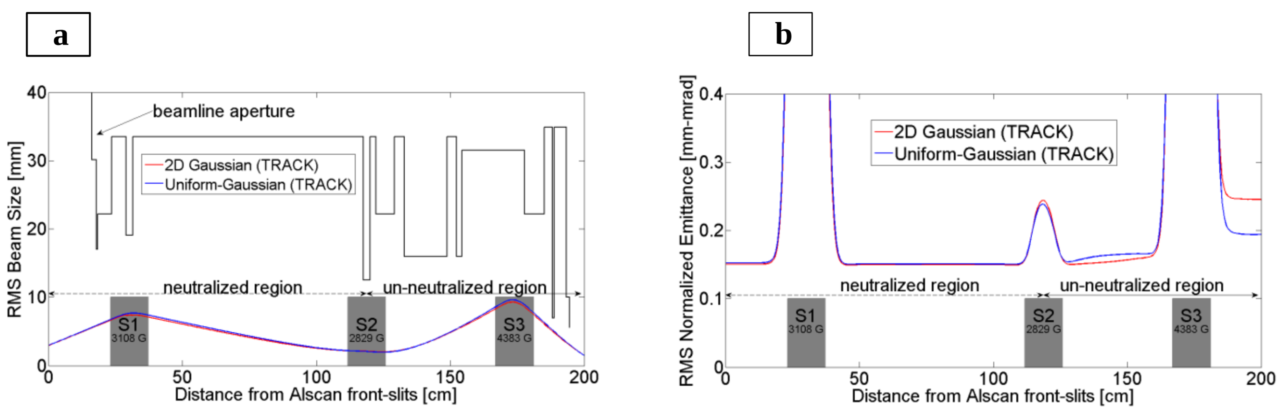

Figure 4.2: (a) Matched envelope and (b) Corresponding emittance evolution of a 5 mA beam along the PXIE LEBT for two initial distributions (2D Gaussian and Uniform-Gaussian). The beam is considered fully neutralized up to the middle of the second solenoid and fully un-neutralized after this point. The black line represents the beamline aperture and the gray boxes the solenoid fields. From TRACK.

Two observations can be made from Figure 4.2(a): first whether the initial current distribution is considered Gaussian or Uniform does not impact the overall RMS beam size along the LEBT and second the LEBT is able to properly match at the RFQ entrance these two initial current distributions. The LEBT aperture was implemented in detailed in TRACK as reported in Figure 4.2(a) to monitor beam losses. It was found that the Uniform-Gaussian distribution is transported along the LEBT without losses while the 2D Gaussian distribution reports minor losses (about 2%) inside the first solenoid. Since the beam sizes are identical in both horizontal and vertical planes, only the horizontal sizes are reported in Figure 4.2(a).

The corresponding emittances are reported in Figure 4.2(b). The distribution with the Uniform current density presents a lower emittance increase (about 30%) in the un-neutralized section compared to the one with a Gaussian current distribution (about 60%). This observation has already been made and is reported in Ref. [9]. The beam with a Gaussian current distribution presents strong non-linear space-charge forces outside of the beam core. The tail particles experience a lower space charge kick compared to the core of the beam which distorts the beam phase space leading to an emittance increase. This effect is less pronounced with the Uniform distribution for which the space charge field is linear along the transverse dimension of the bunch. As reported in Ref. [9] a solution to avoid this emittance dilution in the un-neutralized section of the LEBT is to tune the ion source to create a uniform current density at its exit. Another solution is to start at the ion source exit with a beam having a Gaussian current distribution and scrape the beam early in the LEBT so that only its core enters the un-neutralized section.

5 Estimated Stripping losses and Neutralization time

Table 1 gives in its second column an estimate for the neutralization time of the H^- beam as a function of the pressure along the LEBT and in its third column an estimate for the corresponding beam loss per meter due to the stripping of the slightly bound (0.75 eV) electron. The residual gas is considered to be molecular hydrogen.

During typical operation, the first half of the LEBT (from the ion source exit to the middle of solenoid 2) is desired to be fully neutralized as reported in Figures 4.2. This region is usually operated with a vacuum which we consider to be in the order of 5×10^{-6} torr. In such configuration and according to Table 1, the beam is expected to be neutralized after ~157 µs and the corresponding beam losses due to the stripping are minimal to about 2%.

The second half of the LEBT (from the middle of solenoid 2 to the end of the LEBT) is typically operated with a high vacuum which is measured at the chopper to be in the order of 1×10^{-7} torr. According to Table 1, this high vacuum leads to a neutralization time of about 7.8 ms which for a typical operation of the LEBT with a pulse of 1 or 2 ms does not leave enough time for neutralization to occur. This section of the LEBT is then expected to be un-neutralized as depicted in Figures 4.2

Table 5.1: Estimated neutralization time and stripping losses versus pressure.

Line Pressure	Estimated neutralization time*	Estimated stripping losses** (for a 1 meter long section)
1. 10^{-4} torr	7.8 µs	35 %
7. 10^{-5} torr	11 µs	25 %
5. 10^{-5} torr	16 µs	18 %
2. 10^{-5} torr	39 µs	7 %
1. 10^{-5} torr	78 µs	3.5 %
7. 10^{-6} torr	112 µs	2.5 %
5. 10^{-6} torr	157 µs	1.8 %
2. 10^{-6} torr	393 µs	0.7 %
1. 10^{-6} torr	785 µs	0.35 %
7. 10^{-7} torr	1.1 ms	0.25 %
5. 10^{-7} torr	1.6 ms	0.18 %
2. 10^{-7} torr	3.9 ms	0.07 %
1. 10^{-7} torr	7.8 ms	0.035 %

*

$\tau = 1/(n_g \cdot \sigma_i \cdot v)$ **[Reiser, page 274] where $n_g[m^{-3}] = 3.54 \times 10^{22} \times p[torr]$ is the density of the residual gas, p its pressure, σ_i the ionization cross-section for the residual gas H_2 by 30 keV H^- and $v = 0.08 \cdot c$. For 30 keV H^- on H_2, $\sigma_i \cong 1.5 \times 10^{-20}\ m^2$ [10].**

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$1/L = n_g \cdot \sigma_{-10}$ **[Reiser, page 274] where $n_g[m^{-3}] = 3.54 \times 10^{22} \times p[torr]$ is the density of the residual gas, p its pressure and σ_{-10} the single stripping cross-section. For 30 keV H^- on H_2 $\sigma_{-10} \cong 1 \times 10^{-19}\ m^2$ [11].**

6. Measurement with the Allison Scanner near the ion Source

On June 15, 2015 the beam phase space have been recorded with the Allison Scanner at the exit of the ion source for 16 different ion source extraction voltages, ranging from 1.68 kV to 4.99 kV with all other ion source parameters kept constant at their regular values: the Arc Voltage and Current were respectively 122 V and 13 A, the Plasma Electrode at 3.3 V and the filament at 175.4 A. The ion source correctors were set to -1 A for the horizontal and +2 A for the vertical. A pulsed beam of 1.5 ms was exiting the source. Figures 6.1 show the corresponding measured beam size, TWISS parameters and Image integral at the end of the pulse, with a 1% threshold reduction in the Allison scanner. We can observe from these figures that the beam parameters at the ion source exit present a strong dependence with the extraction voltage with two distinct regions appearing below and above 3 kV. At 1.68 kV the beam exiting the ion source is large and strongly divergent to become smaller and less divergent as it approaches 3 kV. At this value, the beam presents its smallest size and divergence before starting growing and diverging again beyond 3 kV.

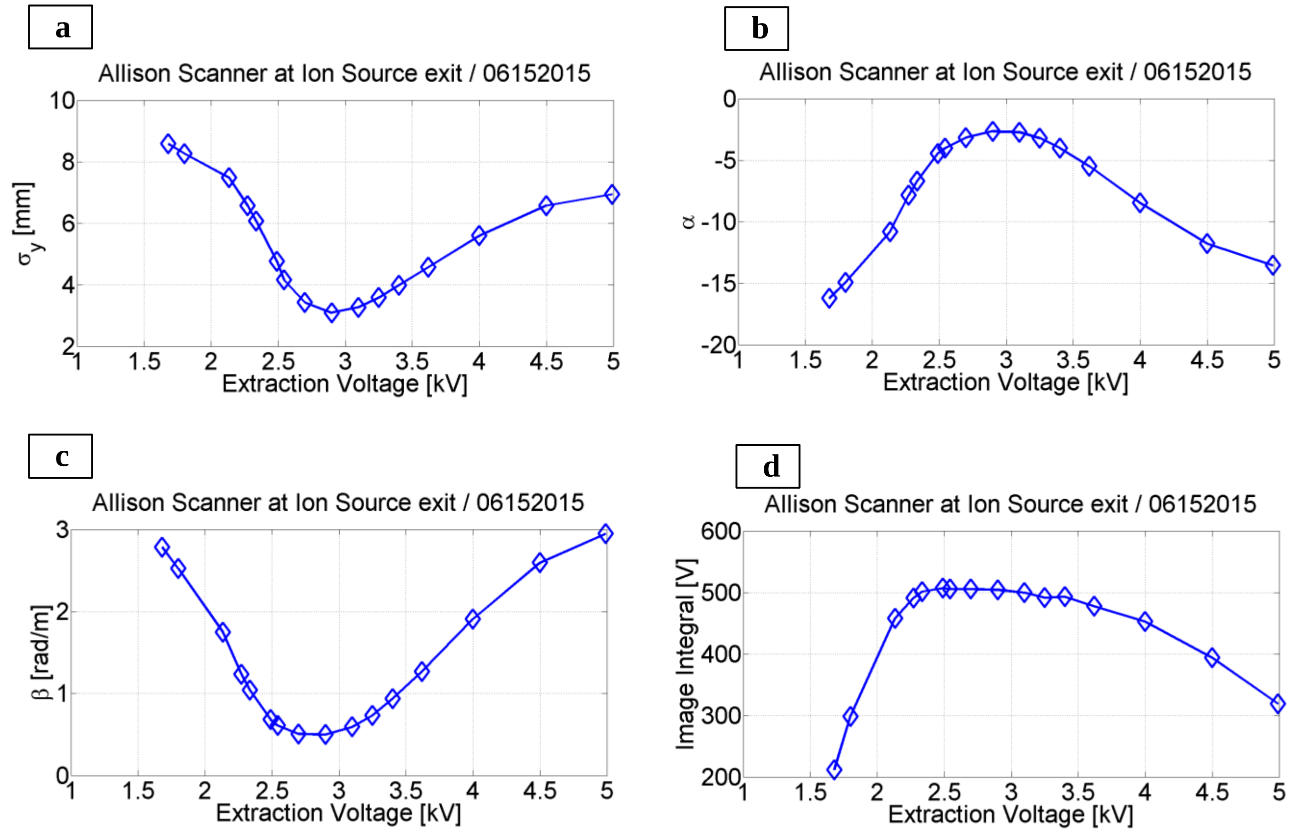

Figure 6.1 (a) Beam size, (b) and (c) TWISS parameters and (d) Image integral measured with the Allison scanner at the ion source exit as a function of the extraction voltage. Other ion source parameters are described in the text.

Each one of these 16 measured phase space have been transformed into TRACK and TRACEWIN input distributions using the code PLOTWIN, as discussed in Section 3. Figures 6.2(a) and 6.2(b) show the PLOWIN reconstructed phase spaces with 100k macro-particles at 2.54 kV and 3.62 kV and the corresponding current density are reported in Figures 6.2(c) and 6.2(d). We can observe in these last two Figures that a Gaussian distribution is a reasonable representation of the current density as built by PLOTWIN and used in the simulation codes for initial distributions. The corresponding beam angular distribution (not reported in this document) shows also a Gaussian distribution. These 2 extraction voltages are a good representation of the remaining 14 ones and we can conclude from this study that the input distributions built by PLOTWIN from a measured phase space and used in the simulations codes have a distribution in density and velocity which is approximately Gaussian.

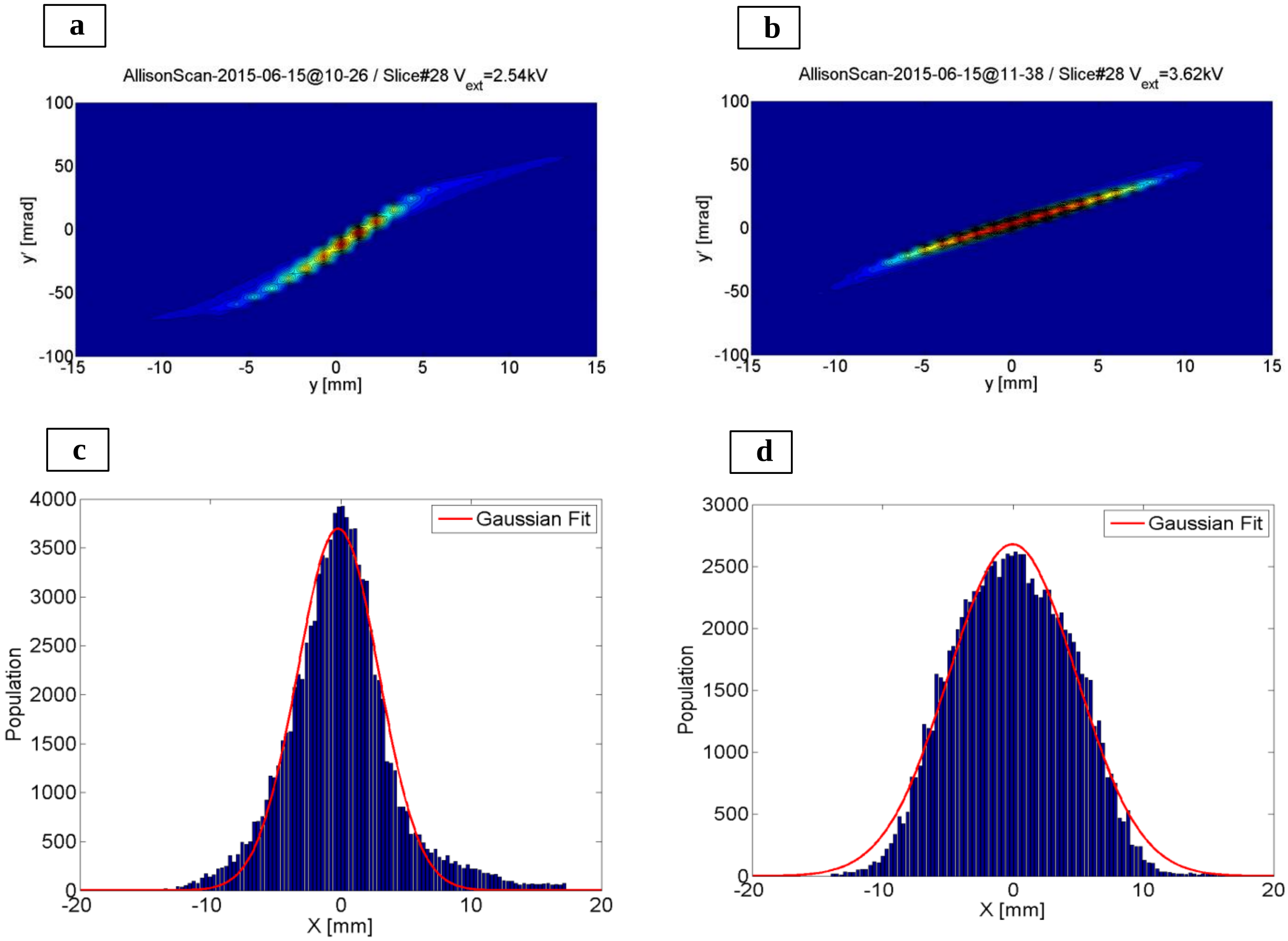

Figure 6.2 PLOTWIN reconstruction of the measured beam phase space with the Allison scanner at the ion source exit for an ion source extraction voltage of (a) 2.54 kV and (b) 3.62 kV and corresponding beam density (c) and (d) with a Gaussian fit. These distributions contain 100k macro-particle and are used as TRACK and TRACEWIN inputs.

Figure 6.3 shows the measured beam current at the DCCT downstream of the first solenoid for the 16 distributions above-mentioned. The current in the first solenoid was kept constant at 141.4 A. Also reported in this Figure are the estimated beam current at the Allison Scanner and the predicted from TRACK at the DCCT. In order to determine the current for each distribution at the Allison Scanner we used an integral-to-current conversion coefficient that was calculated when the diagnostic was installed downstream of the LEBT with current readings from the DCCT and the Faraday Cup. The error bars reflect 5% of uncertainty in the calculated conversion coefficient calibration. The simulations with TRACK used as input distributions the measured phase spaces reconstructed with PLOTWIN and the assumption were made that the beam is fully neutralized in this section and that the Allison scanner doesn’t affect significantly the neutralization pattern. We can observed in Figure 6.3 that the overall shapes of the measured beam current at the DCCT and predicted by TRACK give a reasonable agreement. The measured beam current is nevertheless about 10% lower than expected from TRACK. We looked at the neutralization pattern and found that it cannot be taken responsible for this 10% discrepancy. In fact, TRACK predicts that a fully un-neutralized section would lead to the same beam transmission. We estimated the stripping losses resulting from the residual gas to be in the order of 1% or 2% between the Allison Scanner location and the DDCT (as reported in Table 1). Remains therefore between 8% and 9% difference between the measurement and the prediction which we think may be due to the calibration of the integral-to-current conversion coefficient of the Allison Scanner which may inaccurately report the initial beam current.

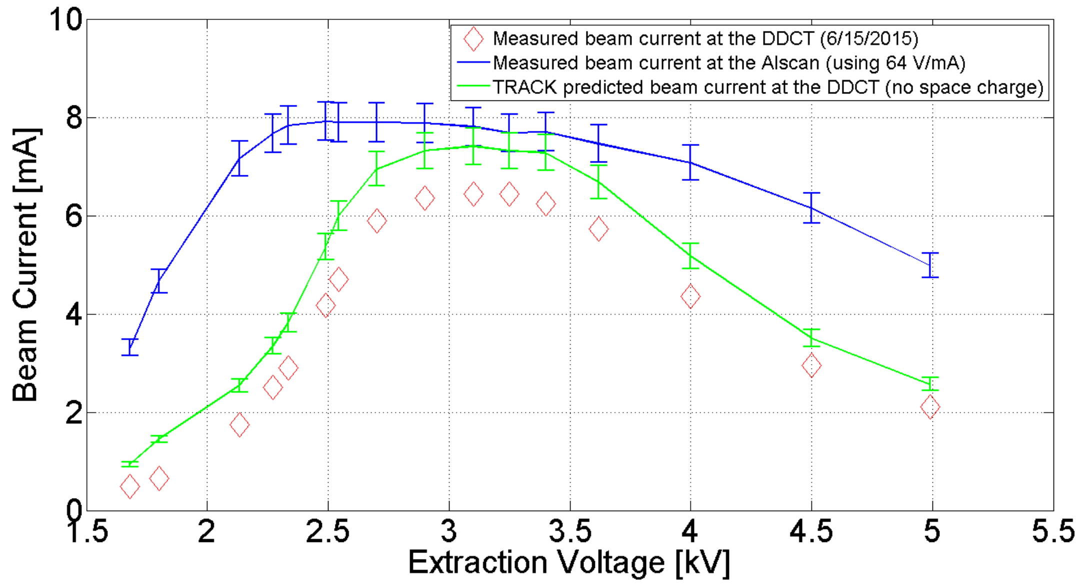

Figure 6.3 Measured beam current at the DCCT as a function of the ion source extraction voltage and Predicted from TRACK.

Another important conclusion that can be drawn from Figure 6.3 is that the beam scraping in the first solenoid can be significant, reaching up to 70% at low extraction voltages. TRACK simulations have shown that the majority of the scraping occurs in the 34 mm bellow shield located upstream of the first solenoid as depicted in Figure 4.1. Unfortunately this shield does not provide a read-back for the current intercepted. This drawback is expected to be corrected in future upgrades of the LEBT. Figure 6.4 shows the impact, as predicted by TRACK, of the scraping in the first solenoid on the beam emittance. We can observe that the scraping does significantly reduce the emittance by cutting off the beam halo. While the emittance at the ion source exit can reach up to 0.28 mm-mrad, it does not exceed 0.15 mm-mrad at the exit of the first solenoid, which meet the expectation for the RFQ design, as discussed in Section 2. The beam scraping in the first solenoid (also reported in left axis of Figure 6.4) does have a positive impact on the overall beam dynamics in the LEBT by providing at the exit of the first solenoid a beam with a more uniform current distribution favorable to less emittance increases as discussed in Section 4.2.

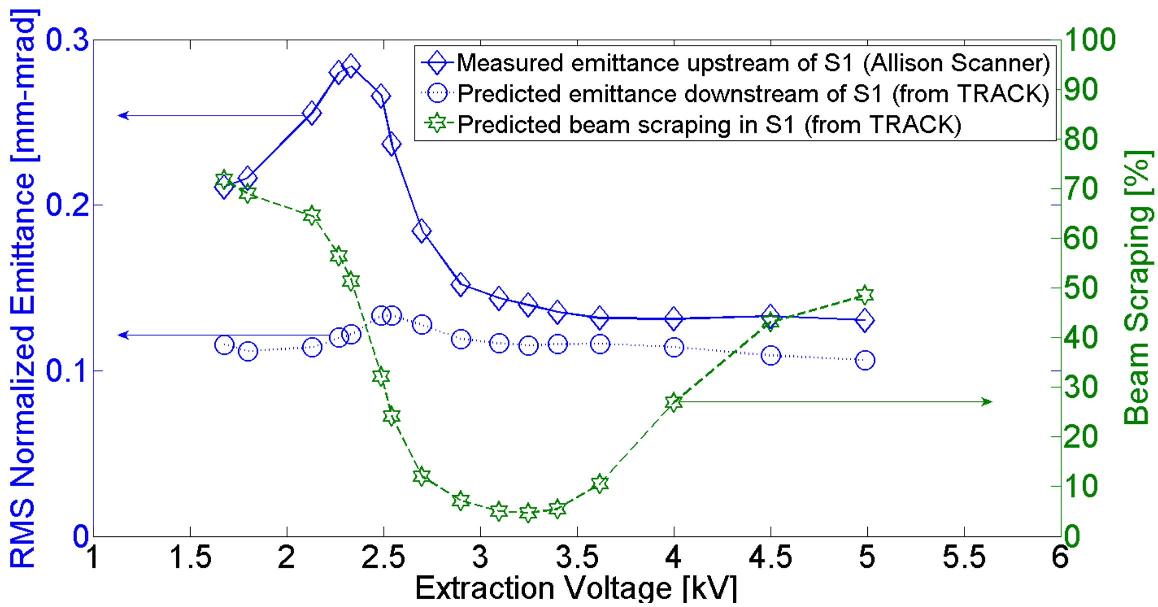

Figure 6.4: Left axis: Measured emittance with the Allison Scanner at the ion source exit as a function of the extraction voltage and Predicted emittance downstream of the first solenoid. Right axis: Predicted beam scraping in the first solenoid (bellow shield and diaphragm). Predictions are from TRACK taking a fully neutralized section and a current of 141.4 A in the first solenoid.

7. Measurement of beam sizes with the MEBT scrapers

A set of four MEBT scrapers (Top, Bottom, Left, and Right) have been installed in the LEBT during the spring 2015, between solenoid 1 and solenoid 2. These scrapers, initially installed for tests, have been used for beam size measurements. Figure 4.1 shows the position of the upstream face of the Top and the Right scraper, respectively at 55.7 cm and 57.4 cm from the middle of solenoid 1. These two scrapers have been extensively used in May 2015 to measure the beam size as a function of the current in solenoid 1 for 14 different ion source extraction voltages ranging from 1.68 kV to 4.5 kV. The ion source was producing a 2 ms pulse and the scrapers sampling the tail of the bunch. The current in solenoid 1 was scanned during the measurement by 5 A steps, typically from 130 A to 190 A.

Each one of these 28 sets of beam size measurement have been compared with simulations from TRACK, taking the RMS beam size in the code at the upstream face of the scrapers. As input distribution in TRACK, we used a PLOTWIN reconstructed distribution from the phase-space measurements performed at the ion source exit with the Allison Scanner on June 15, 2015 as discussed in Section 6. We made a particular attention on June 15 to acquire the phase-space portrait for each one of the 14 extraction voltages used during the MEBT scans so that our simulations could start with a measured distribution. The simulations with TRACK were performed on the Fermi Grid as a set of 101 runs of 100k macro-particles, scanning solenoid 1 from 120 A to 220 A with 1 A step. The field integral of Solenoid 1 was set in TRACK to match the measured field integral and of course the full details of the beamline aperture were implemented in the code.

Figures 7.1(a) to 7.1(d) present the measurement of the beam size at the Top MEBT scraper as a function of the Solenoid 1 current for an ion source extraction voltage of (a) 1.68 kV, (b) 2.27 kV, (c) 2.54 kV and (d) 3.62 kV. These measurements were compared with TRACK taking different neutralization scenarios. The starting current for the 1.68 kV, 2.27 kV, 2.54 kV and 3.62 kV distributions was respectively 3.3 mA, 7.67 mA, 7.89 mA and 7.4 mA, as shown in Figure 6.3.

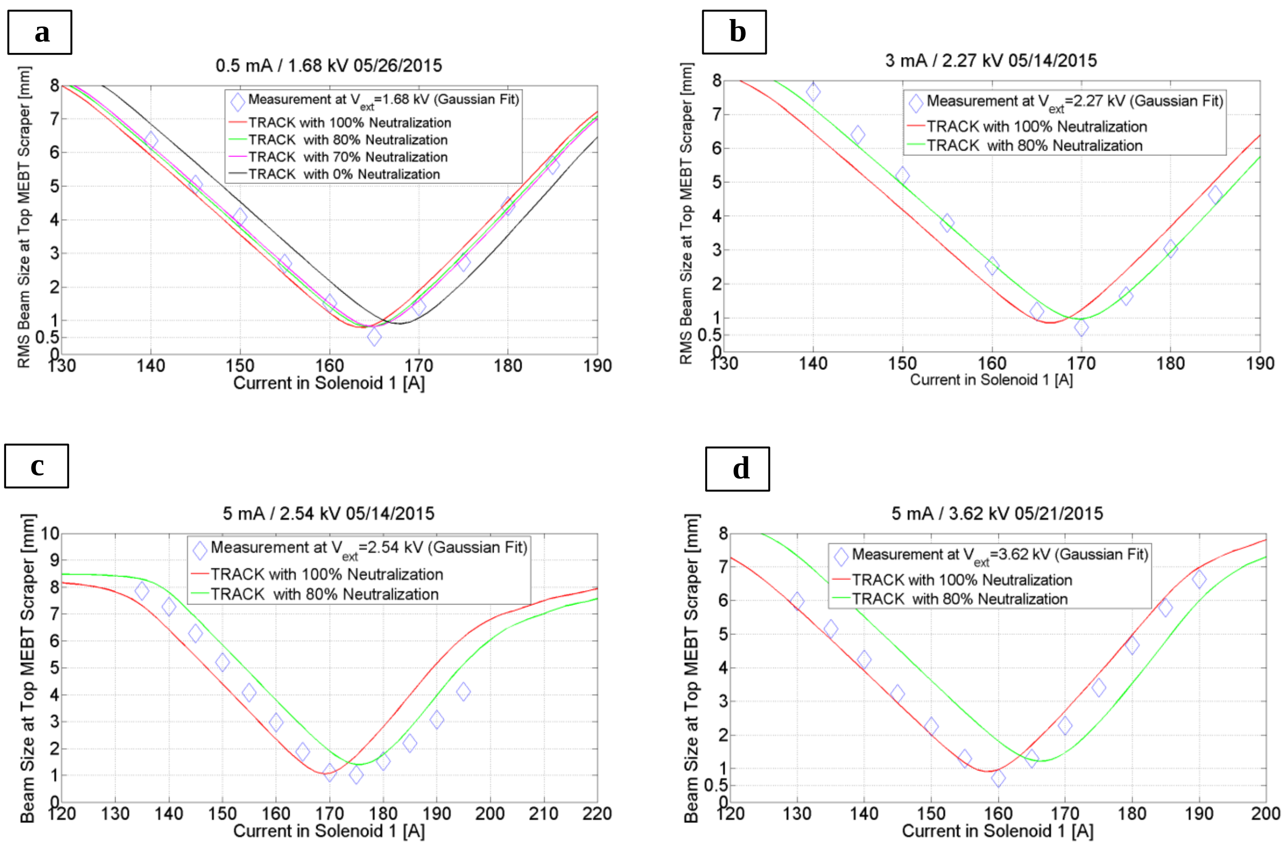

Figure 7.1 Measured (blue diamond) beam sizes with the Top MEBT Scraper as a function of the current in solenoid 1 for an ion source extraction voltage of (a) 1.68 kV (b) 2.27 kV (c) 2.54 kV and (d) 3.62 kV. The red and green curves correspond to TRACK simulations for a section respectively fully neutralized and 80% neutralized. Beam size measurements were performed on May 2015 and the TRACK input distributions were measured on June 15, 2015.

We found a good agreement between the measured beam sizes at the Top and Right MEBT scrapers and the predictions from TRACK for relatively low beam currents, typically below 2 mA as measured at the DCCT. These currents correspond to extraction voltages on the ion source below 2.1 kV, as depicted in Figure 8.3. Such result is shown in Figure 7.1(a) that presents the measured beam size at the Top MEBT scraper as a function of the current in solenoid 1 for an ion source extraction voltage of 1.68 kV. In this Figure is also shown the corresponding TRACK simulations taking the section 100%, 80% and 70% neutralized. Two major conclusions may be drawn from Figure 7.1(a):

- First, Figure 7.1(a) shows that the beam in the LEBT front-end seems to have, as expected, a high degree of neutralization, at 70% or higher.

- Second, we can see in Figure 7.1(a) that the location of the beam waist (at around 165 A) is adequately reproduced by TRACK which means that the solenoid seems to be properly modeled in the code.

For higher extraction voltages corresponding to higher beam currents at the DCCT it is difficult to draw clear conclusions. We highlight below two major observations:

- We found for extraction voltages ranging from 2.2 kV (about 2.5 mA at the DCCT) to 2.7 kV (about 6 mA at the DCCT) that the agreement between the measured beam size and TRACK gets worse. This observation, valid for Top and Right scrapers, is depicted in Figures 7.1(b) and 7.1 (c). Figures 7.1(b) and 7.1(c) tend also to confirm a beamline neutralization of about 80%, as shown by the location of the beam waist between the measurements and TRACK. We may conclude from Figure 7.1(c) that the simple model for neutralization in TRACK (taking a uniform current decrease across the bunch) may not be adequate for beam current higher than 2 mA).

- We also found for "high extraction voltages" (typically 3 kV or above) that the agreement between the measured beam size and TRACK (taking a beamline fully neutralized) is suddenly getting much better, as depicted in Figure 7.1(d) for an extraction voltage of 3.7 kV. We do not have for the moment any clear explanation for such good agreement at these high extraction voltages but we have observed that for "high extraction voltages" the beam appears to be more neutralized as shown in Figure 7.1(d) where TRACK predicts almost 100% neutralization at 3.7 kV.

Figure 7.2 shows the measurement performed on March 17, 2015 of the beam intercepted with the Left MEBT scraper (with its upstream face located 56.8 cm from the middle of solenoid 1, not shown in Figure 4.1) and compared with TRACK, taking a section fully neutralized and 80 % neutralized. The ion source extraction voltage was 3.7 kV for a Solenoid 1 current of 141.4 A. TRACK offers the possibility to insert a scraper and to monitor the beam it intercepts. Simulations shown in Figure 7.2 were performed in the Fermi Grid taking 101 runs, inserting the scraper by a fraction of a millimeter in each run. We can conclude from Figure 7.2 that TRACK reproduces well the overall measured beam shape for this high extraction voltage and that the beam seems to be fully neutralized, as previously observed and discussed with Figure 7.1(d).

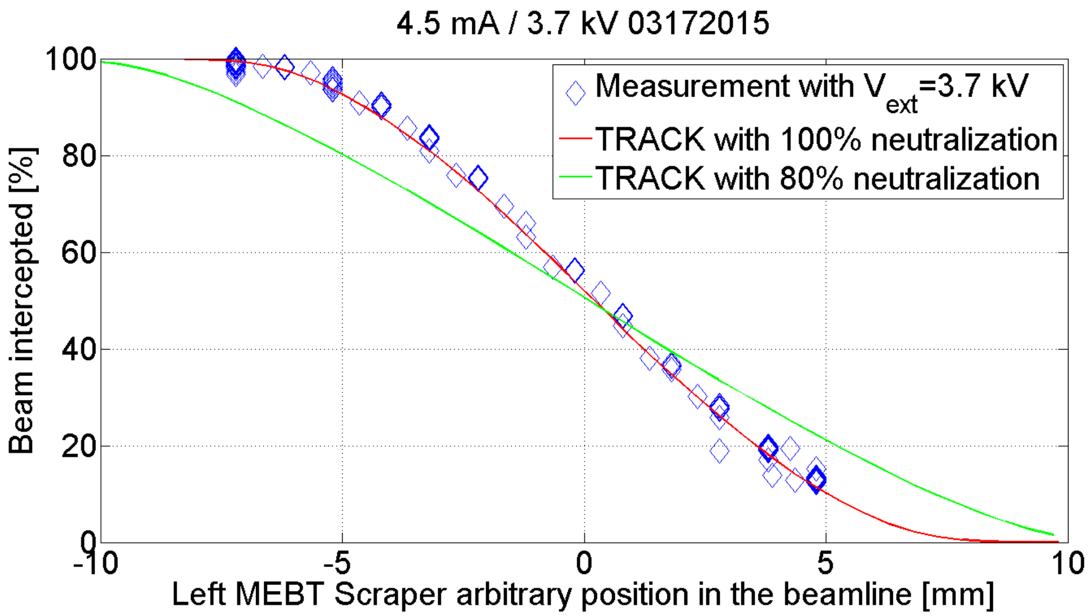

Figure 7.2: Measured (blue diamond) beam interception by the LEFT MEBT scraper for an ion source extraction voltage of 3.7 kV and comparison with TRACK for a section fully neutralized (red curve) and 80% neutralized (green curve). The current in solenoid 1 was 141.4 A. Beam size measurement was performed on March 17, 2015 and the TRACK input distributions was measured on June 15, 2015.

8. Measurements with the Allison scanner at the end of the beamline and comparison with TRACK

We present in this section emittance and beam size measurements taken with the Allison Scanner located 41.51 cm downstream from the middle of Solenoid 3 (as shown in Figure 4.1). These parameters are reported as a function of the current in Solenoid 3 for the LEBT operating in 7 different conditions (1 mA CW, 5 mA CW, 5.3 mA / 2 ms (chopper off) vacuum degraded, 4.5 mA / 1 ms chopped with two different extraction voltages at the ion source, 0.5 mA / 1 ms chopped and finally 5.5 mA / 60 µs chopped).

Reference [12] mentions that the emittance measured and reported by the Allison Scanner needs to be corrected to account for the effect of finite slit sizes on the case of an incoming beam with a Gaussian spatial and angular distribution. The corrected emittance ε_0 is expressed as:

$$\varepsilon_0^2 = \varepsilon_m^2 - \varepsilon_m \left(\beta_m \cdot \frac{{d_1}_{full}^{\,2} + {d_2}_{full}^{\,2}}{12L^2} + \frac{(1+\alpha_m^2)}{\beta_m} \cdot \frac{{d_1}_{full}^{\,2}}{12} - \alpha_m \cdot \frac{{d_1}_{full}^{\,2}}{6L} \right) + \left(\frac{{d_1}_{full}^{\,2} \cdot {d_2}_{full}^{\,2}}{144L^2} \right)$$

with ε_m, β_m, α_m the measured emittance and TWISS as reported by the Allison scanner, $L = 118 \times 10^{-3}$ m the distance between the slits, ${d_1}_{full} = 0.2 \times 10^{-3}$ m and ${d_2}_{full} = 0.65 \times 10^{-3}$ m the full aperture of respectively the first and second slit. The measured and corrected emittance is reported for each measurement on the sections below together with simulations from TRACK

8.1 Measurement of a 1 mA CW beam (11212014)

Figure 8.11(a) shows the RMS beam size measurement performed on 11/21/2014 at the Allison Scanner for a 1 mA (measured at the DCCT, see Figure 4.1) CW beam. Figure 8.11(a) reports 20 slices ranging from 25 µs to 500 µs. A quadratic fit of the square of the beam size has been performed for each one of the 20 slices in order to fetch the value of the current in Solenoid 3 that would correspond to the minimum beam size and this analysis is reported in Figure 8.11(b). The vacuum for this experiment was optimal (low in the first half of the LEBT and high in its end). The ion source was operating at 1.75 kV of extraction voltage.

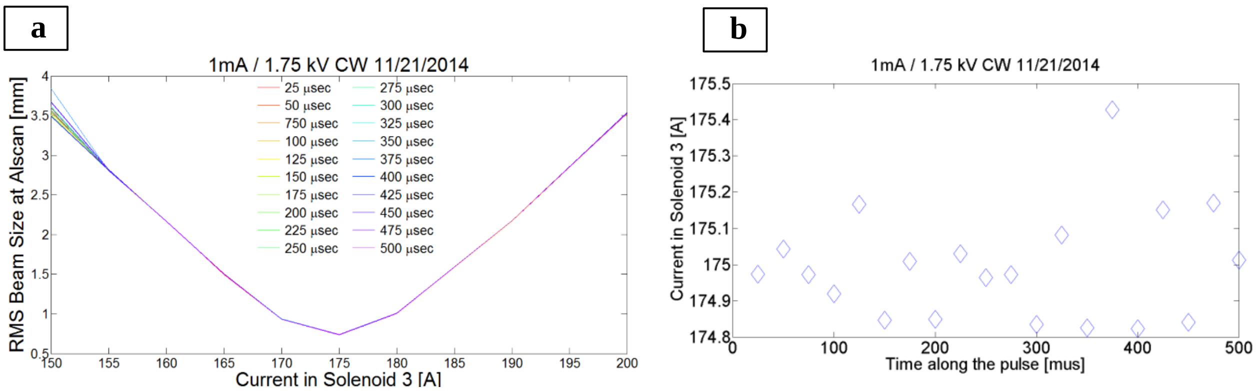

Figure 8.11(a): Measured beam size along the pulse at the Allison scanner located downstream of S3 (S1=150.7A, S2=189A) as a function of the current in S3 for 500 µs of a 1mA CW beam. The current in S3 corresponding to the minimum beam size along the pulse is reported in Figure 8.11(b). Measurement performed on 11/21/2014.

Figure 8.12(a) shows the first and last slice of Figure 8.11(a) and the comparison with TRACK taking different neutralization scenarios. The corresponding RMS emittance (as measured by the Allison Scanner and after correction) is reported in Figure 8.12(b) together with TRACK.

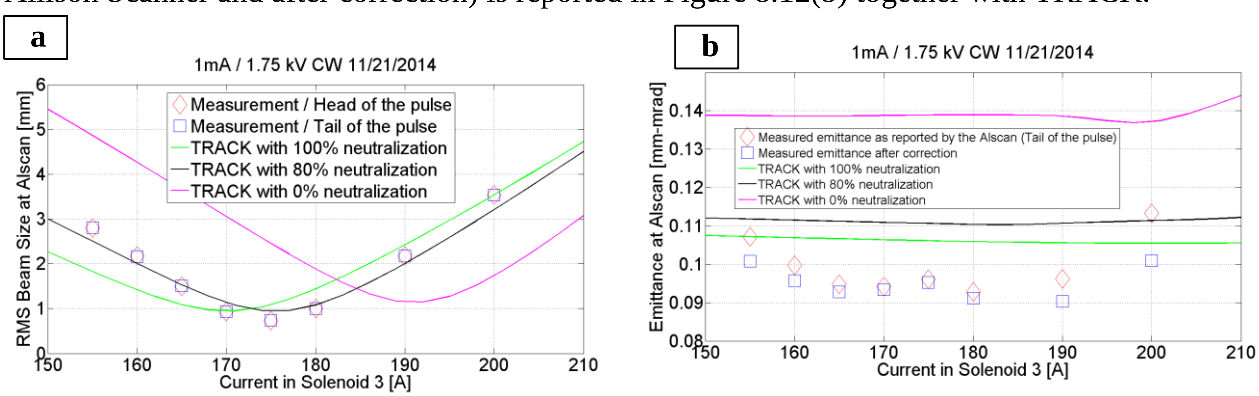

Figure 8.12(a): Measured beam size at the Allison Scanner located downstream of S3 as a function of the current in S3 (S1=150.7A, S2=189A) for the Head (25 µs) and the Tail (500 µs) of a 1mA CW beam and comparison with TRACK taking 3 neutralization scenarios. Corresponding RMS normalized emittance (as reported by the AS and after correction) and TRACK simulations are reported in Figure 8.11(b). Measurement performed on 11/21/2014.

From the 1m A / CW results presented in Figure 8.11 and 8.12 we draw the following observations:

- Figure 8.11(a) shows that the RMS beam size from the 20 slices overlap and Figure 8.11(b) shows that the minimum beam size range from S3=174.8 A to S3=175.4 A with an RMS deviation for S3 of 0.15 A.

- Figure 8.11(a) shows that the best agreement between the measured beam size and TRACK is for a beamline neutralized uniformly at 80%. The observed steady-state does not seem to correspond to a fully neutralized beam, but to a beam neutralized at 80%.

- Figure 8.11(b) shows that the measured emittance (as reported by the Allison Scanner and after correction) is lower by about 10% to 15% than predicted by TRACK at respectively 100% and 80% neutralization. Figure 6.4 predicts that for an ion source extraction voltage of 1.75 kV about 70% of the beam get scraped at the 34 mm bellow shield upstream of Solenoid 1 (See Figure 4.1), cutting the emittance from > 0.2 mm at the ion source exit to around 0.11 mm-mrad downstream Solenoid 1. This low emittance is reported by TRACK in Figure 8.11(b). The reason why the Allison Scanner reports and emittance lower by 10% to 15% than predicted will need further investigation.

8.2 Measurement of a 5 mA CW beam (02122014)

Figure 8.21(a) shows the RMS beam size measurement performed on 12/02/2014 at the Allison Scanner for a 5 mA (measured at the DCCT, see Figure 4.1) CW beam. Figure 8.21(a) reports 24 slices ranging from 25 µs to 600 µs. A quadratic fit of the square of the beam size has been performed for each one of the 24 slices in order to fetch the value of the current in Solenoid 3 that would correspond to the minimum beam size and this measurement is reported in Figure 8.21(b). The vacuum for this experiment was optimal (low in the first half of the LEBT and high in its end). The ion source was operating with an extraction voltage of 2.4 kV

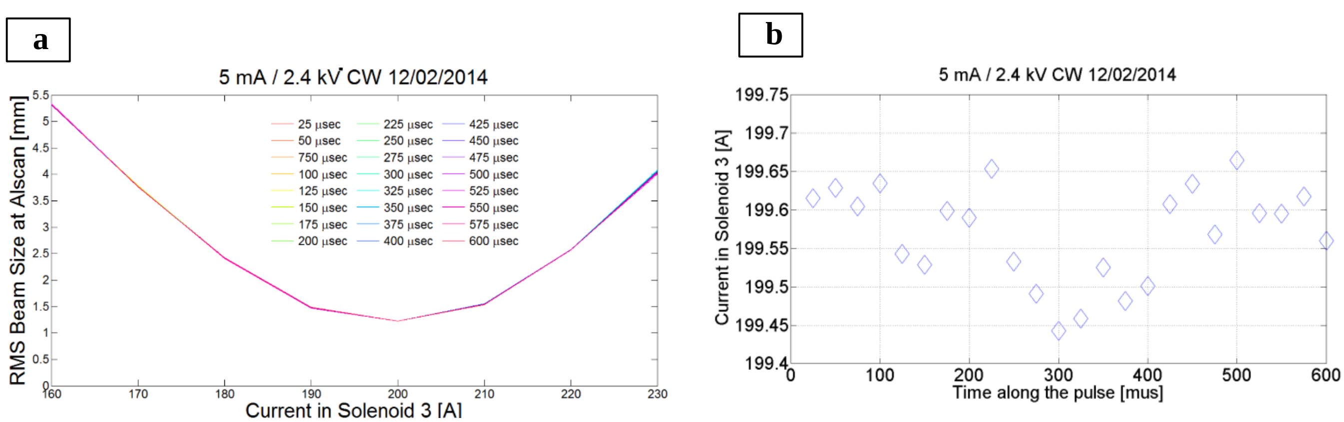

Figure 8.21(a): Measured beam size along the pulse at the Allison scanner located downstream of S3 (S1=154.7A, S2=189A) as a function of the current in S3 for 600 µs of a 5mA CW beam. The current in S3 corresponding to the minimum beam size along the pulse is reported in Figure 8.11(b). Measurement performed on 12/02/2014.

Figure 8.22(a) shows the first and last slice of Figure 8.21(a) and the comparison with TRACK taking different neutralization scenarios. The corresponding RMS emittance (as measured by the Allison Scanner and after correction) is reported in Figure 8.12(b) together with TRACK.

a **b**

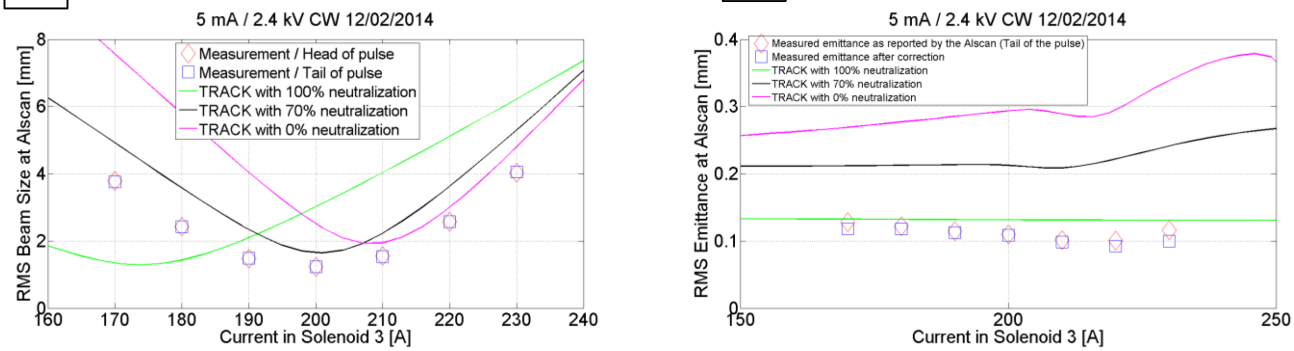

Figure 8.22(a): Measured beam size at the Allison Scanner located downstream of S3 as a function of the current in S3 (S1=154.7A, S2=189A) for the Head (25 μs) and the Tail (600 μs) of a 5mA CW beam and comparison with TRACK taking 3 neutralization scenarios. Corresponding RMS normalized emittance (as reported by the AS and after correction) and TRACK simulations are reported in Figure 8.22(b). Measurement performed on 12/02/2014.

From the 5m A / CW results presented in Figure 8.21 and 8.22 we draw the following observations:

- Figure 8.22(a) shows that the RMS beam size from the 24 slices overlap and Figure 8.21(b) shows that the minimum beam size range from S3=199.45 A to S3=199.65 A (0.2 A scatter) with an RMS deviation for S3 of 0.06 A.

- Figure 8.22(a) shows that TRACK is able to reproduce the position of the minimum beam size taking a neutralization pattern of 70% along the LEBT but TRACK does not match the RMS beam size values. At 5mA CW with 70% neutralization, TRACK predicts an RMS beam size about 30% higher than measured. While at 1mA / CW (Figure 8.12(a)) the agreement between TRACK (with 80% neutralization) and the measured RMS beam size was reasonable, at 5 mA / CW (with 70% neutralization) a disagreement of about 30% is observed. Further investigation is needed to understand this disagreement.

- Figure 8.22(b) shows that the measured emittance of a 5mA / CW beam is low at the end of the LEBT, about 0.10 to 0.11 mm-mrad. Figure 6.4 predicts that for an extraction voltage at the ion source of 2.4 kV about 40% of the beam gets scraped at the 34 mm bellow shield (see Figure 4.1) decreasing the RMS emittance from > 0.27 mm-mrad (before S1) to about 0.12 mm-mrad after S1. As for the 1mA/CW case, the reason why the measured emittance is lower by 10% to 15% compared with TRACK taking a fully neutralized LEBT needs further investigation. We can also note from Figure 8.22(a) and 8.22(b) that the information we get from the beam size measurement is an LEBT neutralized at around 70% while the RMS emittance measurement favors a 100% neutralized LEBT.

*8.3 Measurement of a 5.3 mA / 2ms (chopper off) pulsed beam with **degraded vacuum** downstream of the second solenoid and an extraction voltage of 2.98 kV in the ion source (03272015-PM)*

Figure 8.31(a) shows the RMS beam size measurement performed on 03/27/2015 at the Allison Scanner for a 5.3 mA beam (measured at the DCCT, see Figure 4.1) with a degraded vacuum downstream of Solenoid 2 (the turbo pump located at the Chopper and Allison Scanner were turned off). The measured vacuum was around 4.6×10^{-6} torr downstream of the ion source and about 6.5×10^{-6} torr downstream of the LEBT. Figure 8.31(a) reports 24 slices ranging from 25 µs to 2 ms. A quadratic fit of the square of the beam size has been performed for each one of the 24 slices in order to fetch the value of the current in Solenoid 3 that would correspond to the minimum beam size and this measurement is reported in Figure 8.31(b). The ion source extraction voltage was set to 2.98 kV and the chopper was off (including the -300V clearing voltage). All the other biasing (EID#01 and EID#02, see Figure 4.1) were turned on at their nominal values.

a **b**

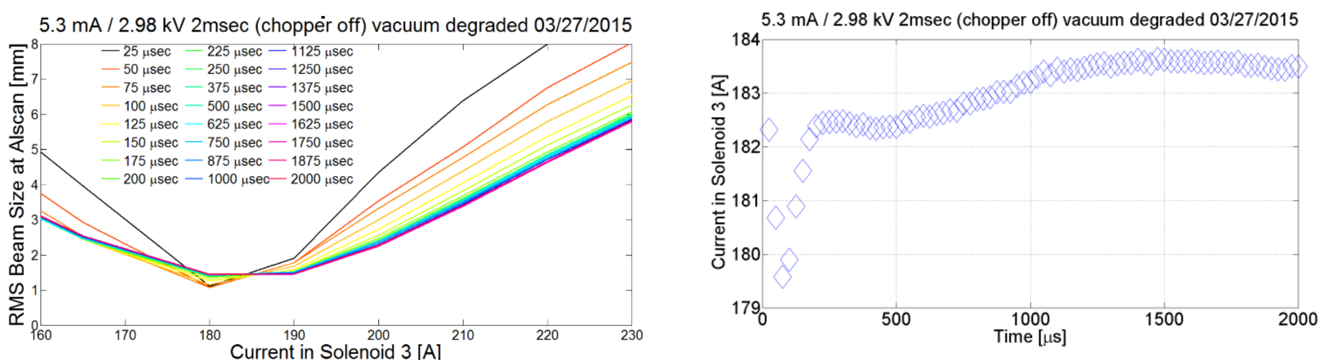

Figure 8.31(a): Measured beam size along the pulse at the Allison Scanner located downstream of Solenoid 3 as a function of the current in Solenoid 3 for a 2 ms / 5.3 mA (DCCT) pulse (S1=152.4A, S2=252.5A). The vacuum downstream of the LEBT was degraded to 6.5×10^{-6} torr. The current in Solenoid 3 corresponding to the minimum beam size along the pulse is reported in Figure 8.31(b). Measurement performed on 03/27/2015.

Figure 8.32(a) shows the first and last slice of Figure 8.31(a) and the comparison with TRACK taking different neutralization scenarios. The corresponding measured RMS emittance (as reported by the Allison Scanner and after correction) is reported in Figure 8.32(b) together with TRACK simulations.

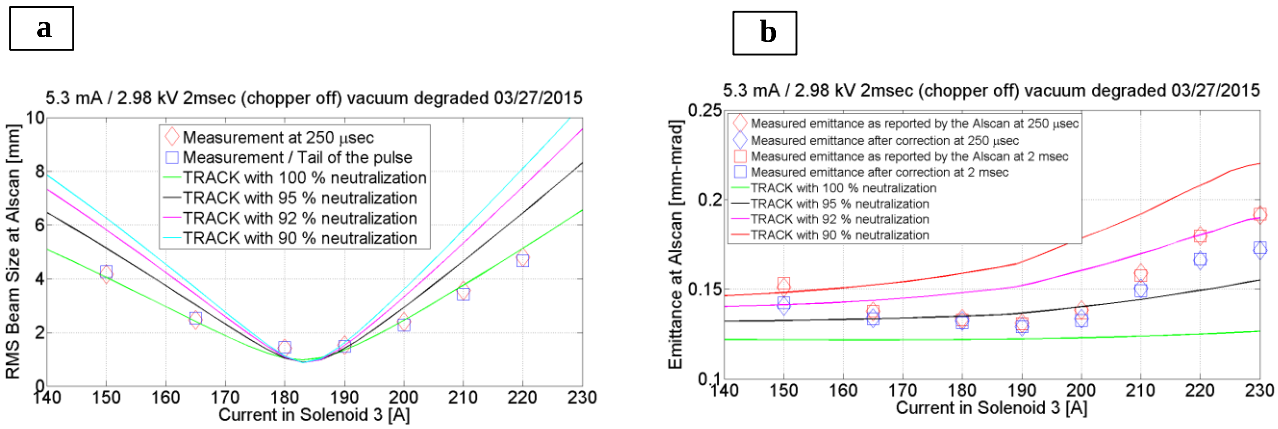

Figure 8.32(a): Measured beam size at the Allison scanner located downstream of Solenoid 3 as a function of the current in Solenoid 3 for the Head (250 µs) and the Tail (2 ms) of a 2 ms (chopper off) / 5.3 mA (DCCT) pulse and comparison with TRACK taking 3 neutralization scenarios. The vacuum downstream of the LEBT was degraded to 6.5×10^{-6} torr. Corresponding RMS normalized emittance (as reported by the AS and after correction) and TRACK simulations are reported in Figure 8.32(b). Measurement performed on 03/27/2015.

From the results of the 5.3 mA / 2 ms pulse with degraded vacuum presented in Figure 8.31 and 8.32 we draw the following observations:

- Table 5.1 predicts for a vacuum pressure of 6.5×10^{-6} torr a neutralization time ranging from 100 µs to 150 µs. Figure 8.31(b) shows that the current in Solenoid 3 leading to a minimum beam size tend to stabilize after 200 µs at around 182.5 A. This observation therefore agrees with our expectations. Further investigation is needed to explain the reason why the current reported in Figure 8.31(b) increases after 500 µs to reach and stabilize at around 183.5 A after 1 ms.

- Figure 8.32(a) shows a reasonable agreement between the measured RMS beam size and TRACK taking a beamline fully neutralized. Also we can observed in this Figure 8.32(a) that the Head and Tail present a rather similar size which tend to indicate that the beam may be fully neutralized after > 250 µs.

- Two observations can be made from Figure 8.32(b). First, the measured emittance is in reasonable agreement with the expected one from TRACK taking a neutralization pattern along the LEBT of about 92% to 95%. Second an increase in the measured emittance is observed for values of the current of Solenoid 3 above 190 A and this increase is also reported by TRACK at the condition to implement some space charge (about 5% to 8%) in the code. While the measured RMS beam size tend to confirm a fully neutralized LEBT, the measured RMS emittance favors an LEBT with remaining space charge effects. Further investigation is needed to explain this observation.

*8.4 Measurement of a 4.5 mA / 1ms chopped pulsed beam with **high vacuum** downstream of the second solenoid and an extraction voltage of 2.5 kV at the ion source (03162015-PM)*

Figure 8.41(a) shows the RMS beam size measurement performed on 03/16/2015-PM at the Allison Scanner for a 4.5 mA (measured at the DCCT, see Figure 4.1) / 1 ms chopped pulse. Figure 8.41(a) reports 20 slices ranging from 50 μs to 1 ms. The vacuum for this experiment was optimal (low in the first half of the LEBT at around 5×10^{-6} torr and high in its end at around 1×10^{-7} torr). The ion source was operating with a pulse of 2 ms and an extraction voltage of 2.5 kV. All the biasing were turned on to their nominal values.

A quadratic fit of the square of the beam size has been performed for each one of the 20 slices in order to fetch the value of the current in Solenoid 3 that would correspond to the minimum beam size and this analysis is reported in Figure 8.41(b). An exponential decay curve fit is presented in Figure 8.41(b) following the analysis reported in Ref. [13] where the compensation time is defined as $\tau \approx 2 \cdot \tau_{decay}$.

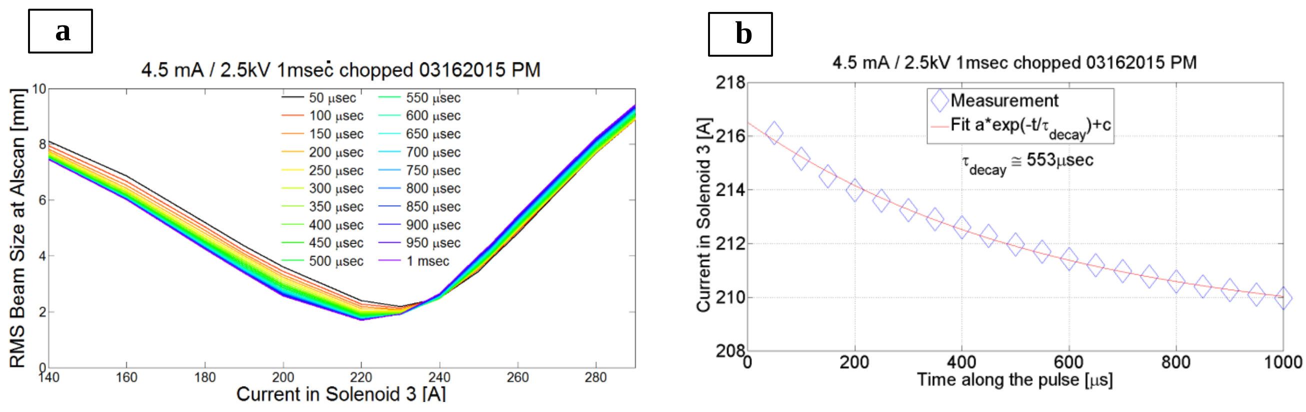

Figure 8.41(a): Measured beam size along the pulse at the Allison Scanner located downstream of S3 (S1=141.4 A, S2=158 A) as a function of the current in S3 for a 4.5 mA (DCCT) / 1 ms (chopped) pulse and 2.5 kV at the ion source. The vacuum downstream of the LEBT was high at around 1×10^{-7} torr. The current in S3 corresponding to the minimum beam size along the pulse is reported in Figure 8.41(b). Measurement performed on 03/16/2015-PM.

Figure 8.42(a) shows the first and last slice of Figure 8.41(a) and the comparison with TRACK taking different neutralization scenarios. The corresponding measured RMS emittance (as measured by the Allison Scanner and after correction) is reported in Figure 8.42(b) together with TRACK simulations.

From the 4.5 m A / 1ms (chopped pulse) / 2.5 kV results presented in Figure 8.41 and 8.42 we draw the following observations:

- Figure 8.41(b) predicts that the beam is close to reaching a steady-state after 1 ms, which is significantly lower than the 7.8 ms reported in Table 5.1 for a high vacuum pressure of 1×10^{-7} torr. We may conclude from Figure 8.41(b) that the estimated neutralization time from measurements seems to be several times shorter than expected.

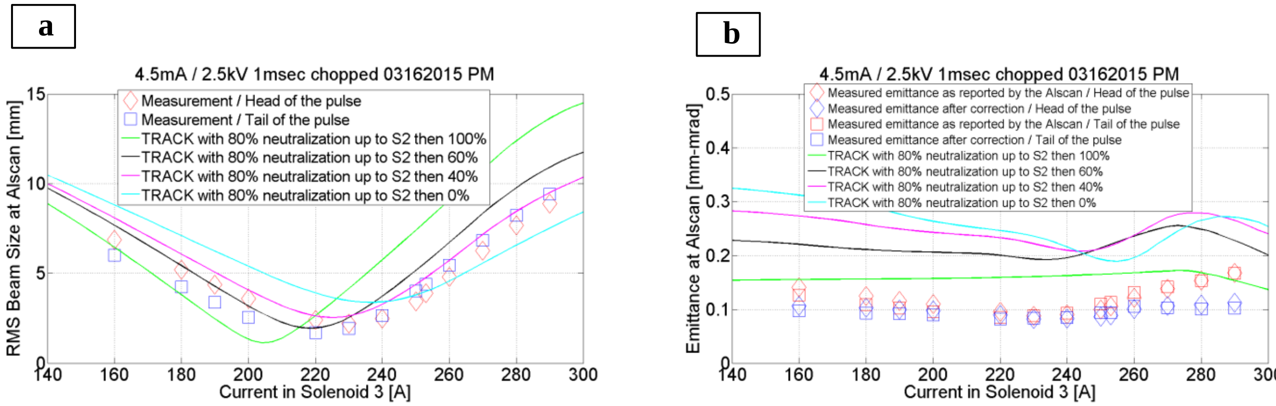

Figure 8.42(a): Measured beam size at the Allison scanner located downstream of S3 as a function of the current in S3 (S1=141.4 A, S2=158 A) for the Head (50 µs) and the Tail (1 ms) of a 4.5 mA (DCCT) / 1 ms (chopped) pulse and comparison with TRACK taking 4 neutralization scenarios. The ion source extraction voltage was 2.5 kV. Corresponding RMS normalized emittance (as reported by the Allison Scanner and after correction) and TRACK simulations are reported in Figure 8.42(b). Measurement performed on 03/16/2015-PM.

- Figure 8.42(a) shows the measured RMS beam size at the Head and Tail of the pulse together with TRACK simulations for 4 different neutralization patterns. The measured RMS beam size for the Head and the Tail of the pulse give a reasonable agreement with TRACK taking a partially neutralized beamline downstream of Solenoid 2, about 40% for the Head of the pulse and about 60% for its Tail. Two conclusion may be drawn from these observations: first the Head of the pulse does not seem to be un-neutralized and second if we consider from Figure 8.41(b) the Tail of the pulse to be close to a steady-state, this steady-state would then correspond to a partially (around 40%) neutralized beam.

- The main observation that we can make from Figure 8.42(b) is that the measured RMS emittance is significantly lower (by 30% to 40%) than the lower emittance predicted by TRACK (taking a fully neutralized section downstream of the second solenoid). According to Figure 6.4, TRACK predicts that at 2.5 kV around 30% of the beam is cut at the bellow-shield of Solenoid 1 which decreases the emittance from >0.25 mm-mrad upstream of solenoid 1 to about 0.13 mm-mrad downstream. Taking 80% neutralization in the first half of the LEBT (as presented in Figure 8.42(b)) increases the emittance to about 0.15 mm-mrad which is then transported to the end of the beamline taking a fully neutralized beam downstream of Solenoid 2. Would we consider the section downstream of the LEBT partially neutralized at 40% or 60% as suggested from the observations in Figure 8.42(a), the emittance at the end of the LEBT would then increase to > 0.2 mm-mrad and the difference between the measured emittance and expected from TRACK would then disagree by a factor or 2. Further work is needed to understand why the measured emittance for this 4.5 mA / 2.5 kV / 1 ms (chopped) pulse is lower than expected by the code.

*8.5 Measurement of a 4.5 mA 1ms chopped pulsed beam with **high vacuum** downstream of the second solenoid and an extraction voltage of 3.7 kV at the ion source (03162015-AM)*

The measurements presented in this section concern a 4.5 mA (measured at the DCCT, see Figure 4.1) / 1 ms (chopped) pulse and were performed on the same day than the measurement presented in Section 8.4. The only noticeable difference between these 2 set of measurements in that in this section the 4.5 mA beam was achieved with an extraction voltage in the ion source of 3.7 kV while in the previous section the extraction voltage was set at 2.5 kV.

Figure 8.51(a) shows the RMS beam size for 20 slices along the 1 ms pulse and Figure 8.51(b) presents the predicted current in Solenoid 3 that leads to the minimum beam size of the measurements presented in Figure 8.51(a). As discussed for Figure 8.41(b), an exponential decay curve fit is presented in Figure 8.51(b) where the compensation time is defined as $\tau \approx 2 \cdot \tau_{decay}$.

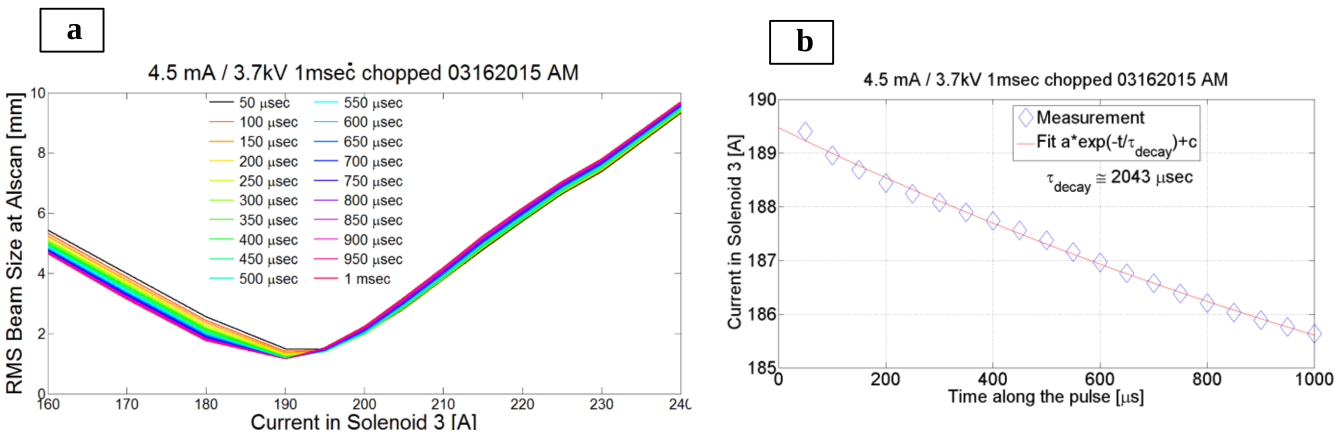

Figure 8.51(a): Measured beam size along the pulse at the Allison scanner located downstream of S3 (S1=141.4 A, S2=158 A) as a function of the current in S3 for a 1 ms (chopped) / 4.5 mA (DCCT) pulse and 3.7 kV at the ion source. The vacuum downstream of the LEBT was optimal. The current in solenoid 3 corresponding to the minimum beam size along the pulse is reported in Figure 8.51(b). Measurement performed on 03/16/2015-AM.

Figure 8.52(a) shows the first and last slice of Figure 8.51(a) and the comparison with TRACK taking two neutralization scenarios. The corresponding measured RMS emittance (as reported by the Allison Scanner and after correction) is reported in Figure 8.52(b) with TRACK simulations.

From the 4.5 m A / 1ms (chopped pulse) / 3.7 kV results presented in Figures 8.51 and 8.52 we draw the following observations:

- Comparing Figure 8.51(b) with Figure 8.41(b), it is interesting to notice that the compensation time along the pulse seems to be a factor of 4 larger when operating with an extraction voltage of 3.7 kV rather than 2.5 kV. Further investigation is needed to explain why for the same current and vacuum profile the beam presents a different compensation time.

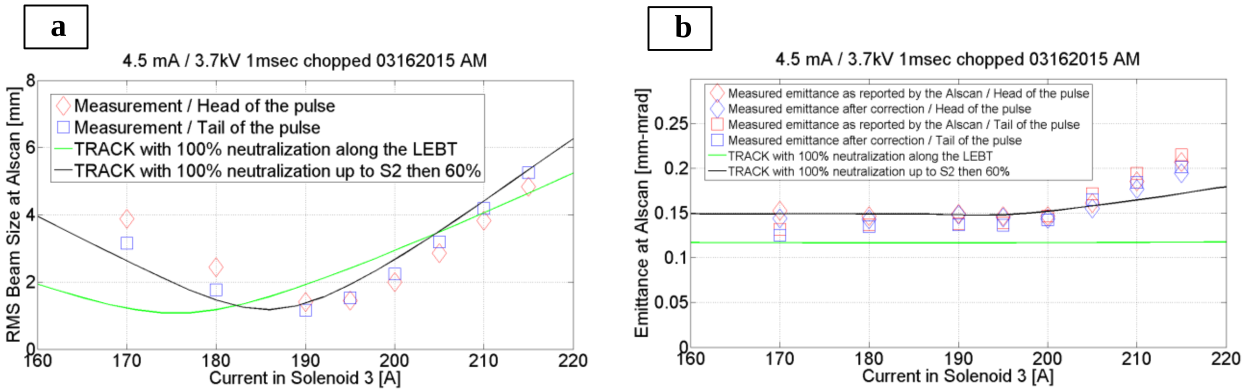

Figure 8.52(a): Measured beam size at the Allison scanner located downstream of solenoid 3 as a function of the current in solenoid 3 (S1=141.4 A, S2=158 A) for the Head (250 µs) and the Tail (1 ms) of a 1 ms (chopped) / 4.5 mA (DCCT) pulse and comparison with TRACK with 2 neutralization scenarios. The ion source extraction voltage was 3.7 kV. Corresponding RMS normalized emittance (as reported by the AS and after correction) and TRACK simulations are reported in Figure 8.52(b). Measurement performed on 03/16/2015-PM.

- Figure 8.52(a) shows that TRACK gives a better agreement with the measured Head and Tail RMS beam size when using a beamline 60% neutralized downstream of Solenoid 2 rather than a section fully neutralized. From these observations, we may expect an even better agreement if taking 50% or 40% neutralization downstream of the second solenoid. It is interesting to notice in this Figure 8.52(a) that the Head of the pulse does not seem to be un-neutralized. This observation has also been done for Figure 8.42(a).

- Figure 8.52(b) shows a good agreement between the measured RMS emittance and the predicted one from TRACK, taking a section 60% neutralized downstream of the second solenoid. It interesting to notice that the minimum measured RMS emittance for the same current (4.5 mA) is about 30% higher when operating the ion source with an extraction voltage of 3.7 kV (Figure 8.52 b) than 2.5 kV (Figure 8.42 b).

- The overall agreement between the measured beam parameters (neutralization time, RMS beam sizes and RMS emittance) seems to be in better agreement for an ion source operating with an extraction voltage of 3.7 kV than 2.5 kV. In particular the RMS emittance. Further analysis is necessary to explain such observation. Figure 6.4 predicts that at 3.7 kV about only 10% of the beam is getting scraped in the bellow shield of Solenoid 1 while at 2.5 kV the scraping is about 30%. Figure 6.4 also predicts that this scraping reduces the RMS emittance from 0.13 mm-mrad to 0.12 mm-mrad at 3.7 kV and from about 0.25 mm-mrad to 0.13 mm-mrad at 2.5 kV. We could extrapolate this observation to state that the less beam is scraped in Solenoid 1 the better the agreement with TRACK seems to be.

*8.6 Measurement of a 0.5 mA / 1ms chopped pulsed beam with **high vacuum** downstream of the second solenoid and an extraction voltage of 1.7 kV at the ion source with the biasing (EID#01, EID#02 and -300 V chopper) On (03232015-AM) and Off (03232015-PM).*

Figure 8.61(a) shows the measured RMS beam size at the Allison Scanner located downstream of Solenoid 3 (see Figure 4.1) for the Head (200 µs) and the Tail (1 ms) of a 0.5 mA (measured at the DCCT, see Figure 4.1) / 1 ms (chopped) pulse. The ion source was operating with a 2 ms pulse and an extraction voltage of 1.75 kV. Two operating scenarios are presented in Figure 8.62(a): a first set of measurement was performed on 03/23/2015-AM having all the biasing of the LEBT (EID#01, EID#02 and -300 V chopper) turned On at their nominal values and a second set on 03/23/2015-PM with all the biasing turned off (keeping all other LEBT settings unchanged). The corresponding RMS emittance (as reported by the Allison Scanner and corrected) is reported in Figure 8.42(b) for the Tail of the pulse only. TRACK simulations are reported in Figures 8.62 taking two neutralization scenarios.

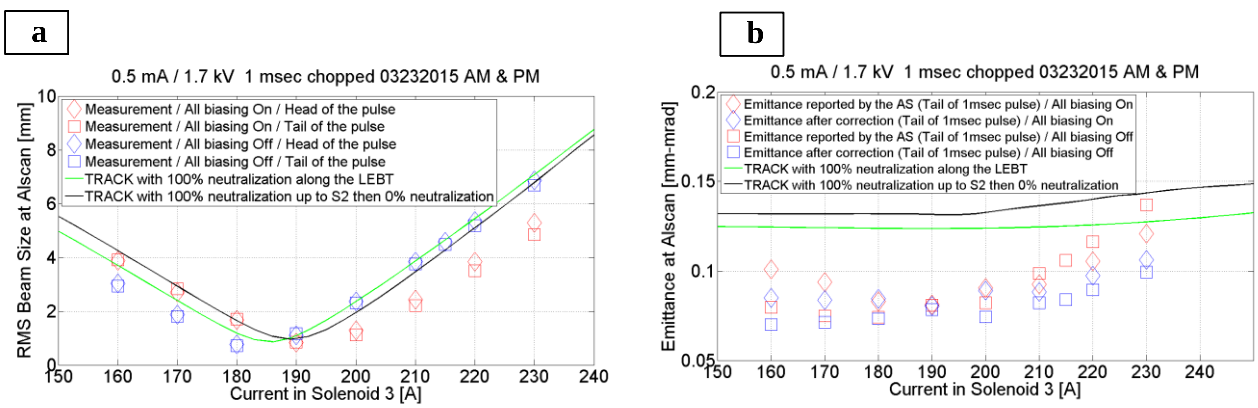

Figure 8.61: Measured beam size at the Allison scanner located downstream of solenoid 3 as a function of the current in solenoid 3 (S1=141.4 A, S2=158 A) for the Head (200 µs) and the Tail (1 ms) of a 1 ms (chopped) / 0.5 mA (DCCT) pulse and comparison with TRACK taking 2 neutralization scenarios. The biasing (EID#01, EID#02 and -300 V chopped) was On and Off. Corresponding RMS normalized emittance (as reported by the AS and after correction for the Tail of the pulse) and TRACK simulations are reported in Figure 8.62(b). Measurement performed on 03/23/2015.

From the 0.5 m A / 1ms (chopped pulse) / 1.75 kV / Biasing On and Off results presented in Figures 8.61 we draw the following observations:

- Figure 8.61(a) shows a shift of about 10A in Solenoid 3 current for the position of the minimum RMS beam size while having the biasing Off (S3=180A) and On (S3=190A). It is interesting to see from Figure 8.61(a) that having the biasing On shifts the measured RMS beam size curve to the right, a shift that indicates that the beam may be experiencing more space charge. This observation is counterintuitive, since we would expect with the biasing turned on a neutralization more effective and therefore a shift of the RMS beam size curve to the left (values of current of Solenoid 3 lower than 180 A).

- We can also see in Figure 8.61(a) that the measured RMS beam size with the biasing off agrees reasonably well with TRACK taking a section downstream of the second solenoid fully neutralized. When the biasing are turned on, the measured RMS beam sizes seems to agree with TRACK taking the section downstream of Solenoid 2 fully un-neutralized.

- Figure 8.61(b) shows that the measured RMS emittance is lower by about 30% than expected from TRACK. At 1.7 kV, Figure 6.1 predicts that about 70% of the beam is scraped in the bellow shield of Solenoid 1, decreasing the emittance from > 0.2 mm-mrad upstream of Solenoid 1 to about 0.12 mm-mrad downstream. The low emittance measured and reported in Figure 8.61(b) cannot be reproduce with the present setup in TRACK.

Figures 8.62 reports the current in Solenoid 3 that correspond to the minimum beam size along the 17 slices of the pulse ranging from 200 µs to 1 ms. As reported in previous sections, the position of the minimum was obtained by performing a quadratic fit of the square of the measure RMS beam size as a function of the Solenoid 3 current.

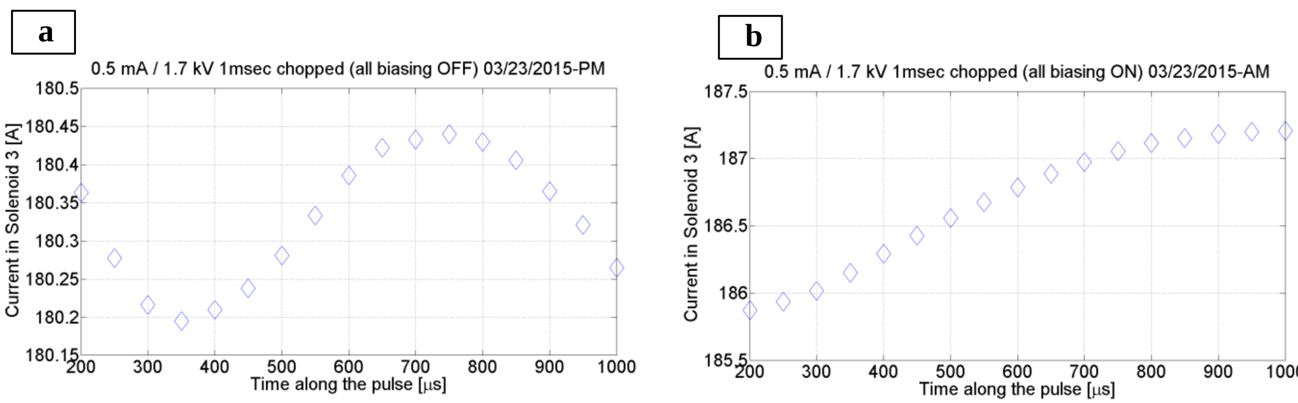

Figure 8.62(a): The current in solenoid 3 corresponding to the minimum beam size along a 1 ms / 0.5 mA (DCCT) pulse with all biasing off (EID#1, EID#2 and -300V chopper). Same measurement with all biasing ON are reported in Figure 8.62(b). Measurements performed on 03232015 using the Allison scanner located downstream of solenoid 3.

From the 0.5 m A / 1ms (chopped pulse) / 1.75 kV / Biasing on and off results presented in Figures 8.62 we draw the following observations:

- Figure 8.62(a) shows a sinusoidal behavior for the position of the minimum beam size along the pulse with a period of about 700 µs when the biasing are turned off. This very interesting result will require more analysis to be fully explained.

- It is interesting to see in Figure 8.62(b) that the sinusoidal motion of Figure 8.62(a) is not anymore observed and that when the biasing is turned on the beam seems to reach a steady state at about 1ms with a steady increase (of about 1A) in the position of the minimum starting from 200 µs. This increase in the position of the minimum beam size has already been observed in Figure 8.31(b) for a 5.3 mA / 2 ms beam operating with a degraded vacuum downstream of the beamline.

8.7 Measurement of a 5.5 mA 60 µsec chopped pulsed beam with high vacuum downstream of the second solenoid and an extraction voltage of 2.98 kV at the ion source (01302015)

Figure 8.71(a) shows the RMS beam size measurement performed on 01/30/2015 at the Allison Scanner for a 5.5 mA (measured at the DCCT, see Figure 4.1) / 60 µs chopped pulse. Figure 8.71(a) reports 16 slices ranging from 12 µs to 57 µs. The vacuum for this experiment was optimal (low in the first half of the LEBT at around 5×10^{-6} torr and high in its end at around 1×10^{-7} torr). The ion source was operating with an extraction voltage of 2.98 kV. All the biasing were turned on to their nominal values.

Figure 8.71(b) presents the predicted current in Solenoid 3 that leads to the minimum beam size for the 16 slices presented in Figure 8.71(a). The current in Solenoid 3 was obtained by performing a quadratic fit of the square of the RMS size for each slice.

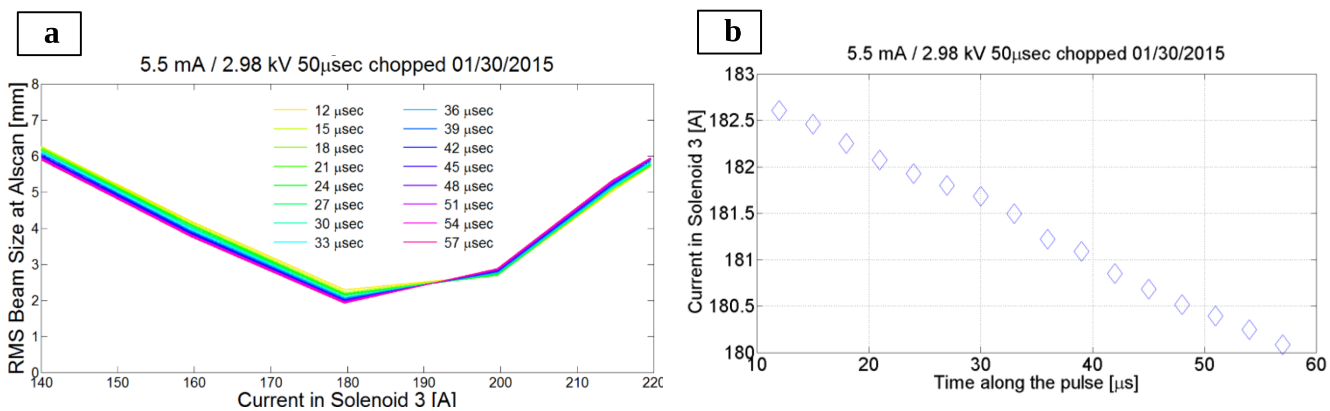

Figure 8.71(a): Measured beam size along the pulse at the Allison scanner located downstream of solenoid 3 (S1=151.1A, S2=137.3 A) as a function of the current in solenoid 3 for a 60 µsec (chopped) / 5.5 mA (DCCT) pulse. The vacuum downstream of the LEBT was optimal. The current in solenoid 3 corresponding to the minimum beam size along the pulse is reported in Figure 8.71(b). Measurement performed on 01/30/2015.

Figure 8.72(a) shows the measured RMS beam size as a function of the current in Solenoid 3 for the Head (12 µs) and the Tail (57 µs) of the pulse together with TRACK simulations taking a beamline fully neutralized and fully un-neutralized. The measured RMS emittance (at 30 µs) is reported in Figure 8.72(b) (before and after correction).

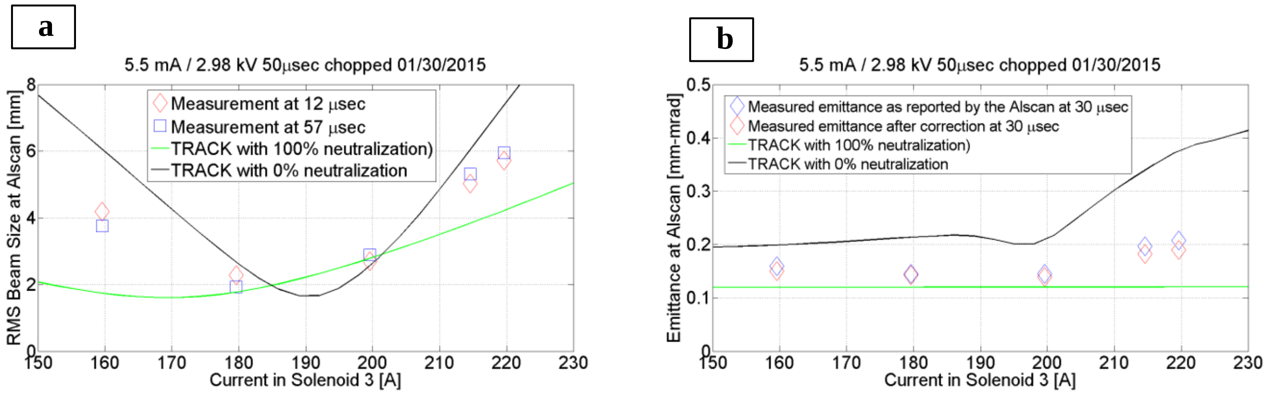

Figure 8.72(a): Measured beam size at the Allison scanner located downstream of solenoid 3 as a function of the current in solenoid 3 (S1=151.1A, S2=137.3 A) for the Head (12 µs) and the Tail (57 µs) of a 60 µs (chopped) / 5.5 mA (DCCT) pulse and comparison with TRACK taking 2 neutralization scenarios. The RMS normalized emittance at 30 µs (as reported by the AS and after correction) and TRACK simulations are reported in Figure 8.72(b). Measurement performed on 01/30/2015.

From the 5.5 m A / 60 µs (chopped pulse) / 2.98 kV results presented in Figures 8.71 and 8.72 we draw the following observations:

- Figure 8.71(b) shows a decrease in the position of the minimum RMS beam size by about 2.5 A in the current in Solenoid 3, from the Head (12 µs) and the Tail (57 µs) of the pulse. This observation indicates that some neutralization may take place in the first 50 µs of a pulse.

- Figure 8.72(a) shows a reasonable agreement between the measured RMS beam size and TRACK taking a beamline fully un-neutralized in the code. These results is interesting since previous observations from longer pulses (1 ms) at 4.5 mA presented for instance in Figures 8.42(a) and 8.52(a) seems to suggest a pulse Head significantly neutralized.

- Figure 8.72(b) shows that the measured RMS emittance does not agree with the simulations from TRACK taking, as suggested from the beam size observations, the pulse fully un-neutralized. The position of the emittance increase (at around S3=200 A) is nevertheless properly reproduced in the code.

9. RFQ Matching

As presented in the previous section, we performed a series of emittance and TWISS parameters measurement with the Allison Scanner located at the end of the LEBT, about 20 cm downstream of the virtual location of the RFQ vanes (see Figure 4.1). Figure 9 reports the measured TWISS parameters as a function of the current in Solenoid 3 for a beam current at the DCCT of 4.5 mA (ion source extraction voltage of 2.5 kV, see Section 8.4) and 0.5 mA (ion source extraction voltage of 1.7 kV, see Section 8.6). These two set of measurements correspond to the nominal operation of the LEBT at high and low beam current with a low vacuum upstream of the LEBT favoring neutralization (about 5×10^{-6} t downstream of the ion source) and a high vacuum downstream (about 1×10^{-7} t at the Allison scanner box) to avoid neutralization. The Allison scanner was sampling for both measurement a 1 ms chopped pulse (2 ms at the ion source) for a current in the first and second solenoid of respectively 141.4 A and 158 A. The measured TWISS parameters at the end of the 1 ms pulse are reported in Figure 9.

The design of the RFQ has been performed for a nominal input matched beam at the RFQ vanes of α=1.6 and β=0.07 m/rad and, as mentioned in Section 2, an input RMS normalized emittance below 0.18 mm-mrad. These matched TWISS at the RFQ vanes translate to about α=-12 and β=1.9 m/rad at the Allison scanner location considering a drift of 20 cm at 4.5 mA. For a beam current of 0.5 mA the matched RFQ TWISS parameters translate to about α=-9 and β=1.5 m/rad at the Allison scanner. These TWISS target at the Allison scanner are reported in Figure 9 from which two major observations can be made:

- We were able to find settings for the LEBT that would provide a matching close to the desired alpha and beta at the Allison scanner.

- We can match the beam in beta with a slight mismatch in alpha of about 10% at low charge and 20 % at high current.

Previous simulations discussed in Ref. [3] showed that the quality of the match into the PXIE RFQ tends to be more sensitive to the beam size (β) than the beam divergence (α). Preliminary simulations of the PXIE RFQ with TRACK showed that a mismatch in alpha of about 20% does not impact the output transverse emittance of the RFQ. It is also important to remind that, as shown in the Section 8.4 and Section 8.6, the measured emittance presented in Figure 9 is around 0.13 mm-mrad for the 4.5 mA case and 0.11 mm-mrad for the 0.5 mA, significantly lower than the 0.18 mm-mrad limit.

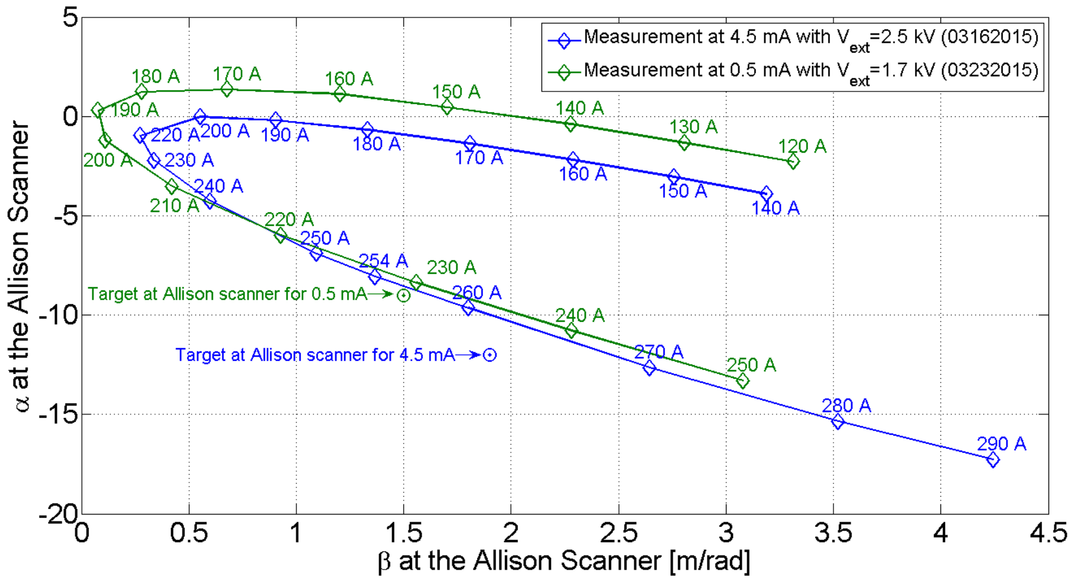

Figure 9: Measured TWISS parameters at the Allison scanner located at the end of the LEBT as a function of the current in solenoid 3 for a 4.5 mA beam (03162015-PM) and 0.5 mA beam (03232015). Sampling the end of a 1 ms chopped pulse (2 ms at the ion source). For a current of 141.4 A in Solenoid 1 and 158 A in Solenoid 2. With standard biasing (+40 V in the EID#1 and #2) and standard vacuum profile (about 4.5×10^{-6} t downstream of the ion source and 7.1×10^{-8} downstream of the LEBT). Target goal TWISS are reported for 0.5 mA and 4.5 mA.

10. Predicted RFQ transmission using the measured distribution at the Allison scanner (4.5 mA, 2.5 kV 03162015-PM)

As presented in Section 8.4, a set of 17 phase space portraits were acquired at the Allison Scanner downstream of Solenoid 3 for a 4.5 mA / 1 ms (chopped) beam. The ion source was operating with a 2 ms pulse and an extraction voltage of 2.5 kV. The vacuum was optimal (low in the first half and the LEBT and high downstream of Solenoid 2) and the biasing turned on at their nominal values.

Figure 4.1 shows that, during this set of measurement, the Allison Scanner was positioned at about 20 cm downstream the virtual location of the RFQ vanes. We took advantage of a feature in TRACK that allows to back-propagate the beam in the presence of space-charge to transform with PLOTWIN the 17 measured phase-space portrait into TRACK input distributions and back-propagate to the RFQ vane position these distributions at 4.5 mA. At this location, each TRACK output was then transformed into an input distribution and sent into the RFQ, modeling the RFQ in TRACK with 3D fields. The RFQ vane tip voltage was set in TRACK to the nominal 60 kV.

Figure 10 shows that TRACK predicts an excellent transmission at the RFQ output of about 97.5% taking as above-mentioned the measured phase-space portrait at the Allison Scanner.

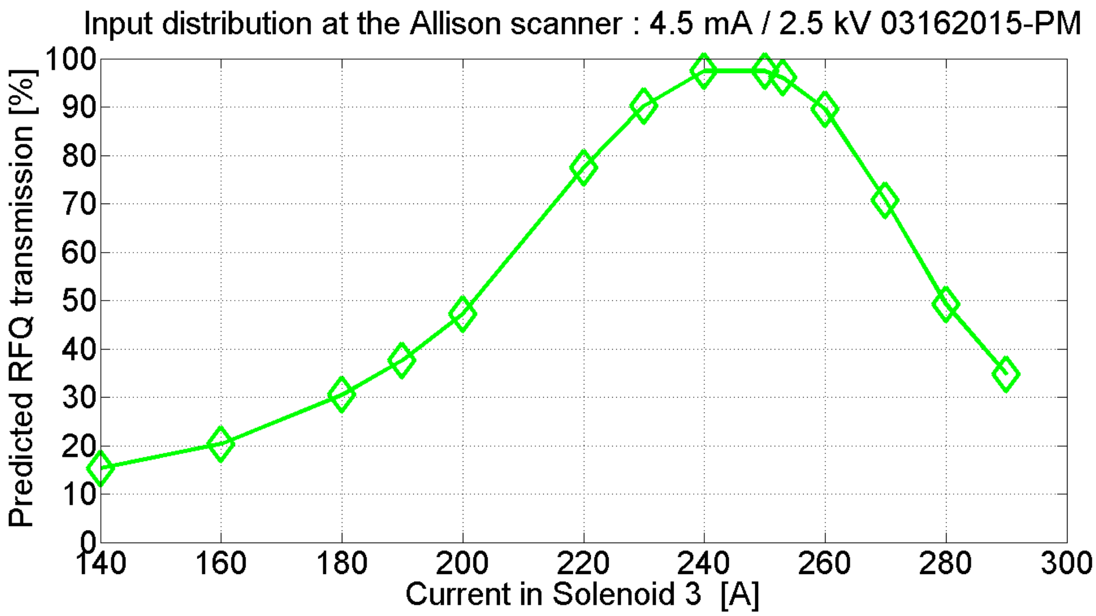

Figure 10: Predicted RFQ transmission (from TRACK) taking as input the 4.5 mA phase-space portraits at the Allison Scanner located downstream of solenoid 3 measured on 03162015-PM.

11. Summary

We presented in this document beam measurements performed on the LEBT from November 2014 to June 2015. These measurements were compared with the beam dynamics code TRACK. We were able to experimentally find in the LEBT settings that allow to match the required TWISS at the RFQ entrance. For a low charge beam (0.5 mA), we were able to match the beam in beta with a mismatch in alpha of about 10% and at high charge (5 mA) we were able to match the beam in beta with a mismatch in alpha of about 20%. For both cases, the measured emittance at the end of the LEBT was kept below the target goal of 0.18 mm-mrad. Our measurements confirm that the LEBT reaches its goal and also our measurements validate its original design consisting in a long un-neutralized section at its end.

Concerning the agreement between the measured beam parameters and TRACK our conclusions are more mitigated. First we observed at the start of the LEBT that the measured transmission is about 10% lower than the transmission predicted by TRACK. We also observed that the measured emittance at the end of the LEBT as a tendency to be lower (by 10% or higher) than the one expected from TRACK. These two points will need further investigation in the future. TRACK confirms that the first half of the LEBT is properly neutralized (by 70% or higher). There are indications from TRACK that the end of the LEBT may experience some degree of neutralization, even for short (about 50 µs) pulses. More efforts are needed to further explore the neutralization pattern in the PXIE LEBT.

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