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H^- beam transport experiments in a solenoid low energy beam transport[a)]

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The Front End Test Stand (FETS) is located at Rutherford Appleton Laboratory and aims for a high current, fast chopped 3 MeV H^- ion beam suitable for future high power proton accelerators like ISIS upgrade. The main components of the front end are the Penning ion source, a low energy beam transport line, an radio-frequency quadrupole (RFQ) and a medium energy beam transport (MEBT) providing also a chopper section and rebuncher. FETS is in the stage of commissioning its low energy beam transport (LEBT) line consisting of three solenoids. The LEBT has to transport an H^- high current beam (up to 60 mA) at 65 keV. This is the injection energy of the beam into the RFQ. The main diagnostics are slit–slit emittance scanners for each transversal plane. For optimizing the matching to the RFQ, experiments have been performed with a variety of solenoid settings to better understand the actual beam transport. Occasionally, source parameters such as extractor slit width and beam energy were varied as well. The paper also discusses simulations based on these measurements.
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I. INTRODUCTION

The Front End Test Stand (FETS) is located at Rutherford Appleton Laboratory (RAL) and has evolved in a test stand for future high power proton applications where injection into a ring is planned. An example might be the future upgrade for ISIS at RAL. This requires a chopped beam and the full–scale demonstration is one of FETS primary objectives. The main components of the FETS beamline are an H^- Penning ion source,[1] a LEBT to match the distribution into an RFQ, and a MEBT section, comprising buncher and quadrupole doublets including a novel design of a chopper. At the time being, the ion source and LEBT are fully operational and the RFQ design is almost finalized, and manufacturing is expected to start by the end of this year. A recent overview can be found in Ref. 2.

Earlier LEBT simulations based on ion source measurements have been indicated solenoid settings[3] at $S1 = 137$ A, $S2 = 123$ A and $S3 = 216$ A for this specific input distribution. This work is a kind of standard to match a nominal beam (65 keV and 60 mA) to the RFQ requirements. The emittance requirements at the entrance of the RFQ are the twiss parameters $\alpha = 0.84$ and $\beta = 0.032$ mm and an rms emittance not bigger than $0.25\,\pi$ mm mrad at an injection energy of 65 keV. More details about RFQ simulations and input parameters can be found in Ref. 4. To meet these requirements, ion source and LEBT have to be tuned very well but not many data about LEBT transmission and emittance output are available. To improve this situation, a comprehensive measurement program was launched, and this paper summarizes the first results. This program continues until the RFQ is ready for commissioning by early 2013.

II. EXPERIMENTAL SETUP

The general layout of the beamline is shown in Fig. 1. Currently, the end of the beamline is a diagnostics vessel hosting two slit–slit emittance scanners in the x and y plane. Additionally, the figure shows the apertures of the planned RFQ installation (transparent blue). Not shown is the slit extraction (10×0.8 mm) build as a diode system and usually operated with 17 kV. The jaws of the ground electrode are either 2.1 or 1.1 mm apart. The following sector magnet is mounted in a cold box which acts as Cs–trap and electron dump; bending angle, fringe field, and magnetic properties of the cold box are adjusted to deflect the beam 90°onto the horizontal axis. The ion source and extraction system is assembled under a microscope and a survey was carried out to align all the different components such as solenoids and vacuum vessel onto beam axis ($\leq 500\ \mu$m).

The PA supplies the remaining 48 kV to reach the required 65 keV beam energy. For the studies presented here, the gap was either 13 or 6 mm, while the PA is technically not part of the LEBT both beamline components have to be treated together to achieve an optimized LEBT output (for further information see Ref. 1).

The peak on-axis magnetic field B_i (T) of each solenoid is equal to $1.4085 \times 10^{-3}\ S_i$, where S_i is the solenoid coil current (A). The magnetic field distribution of each solenoid is represented as a field map in r-z co–ordinate space, and for the case of one solenoid it was verified that the on-axis field

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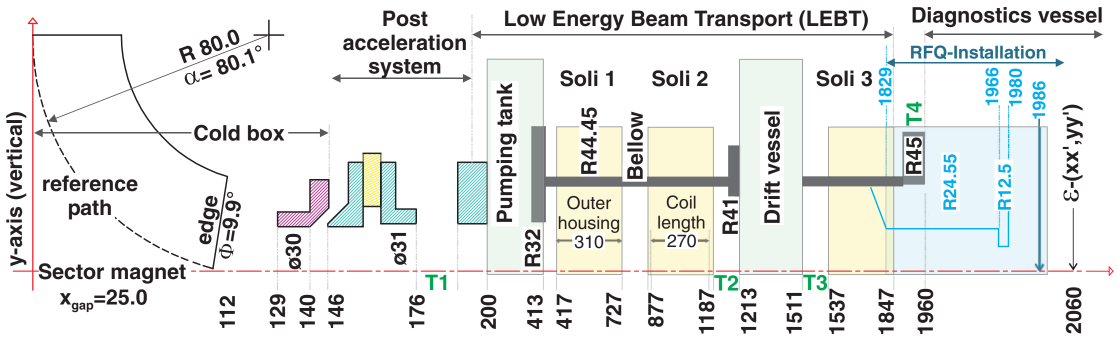

FIG. 1. (Color online) Current set-up of the FETS consisting of a Penning ion source, pumping tank, three solenoids and a diagnostics vessel at the end of the beamline. The LEBT stretches from the post acceleration (PA) through various drift sections and all three solenoids and the diagnostics vessel. The RFQ acceptance is 74 mm in front of the emittance measurement plane at $z = 1986$ mm. In total, four toroids are installed for beam current measurements and will be referred to as T1…T4.

component measured by a Hall probe agrees within 1% with the calculated value.[3] These field maps will be used in the simulations. The three solenoids are being referred to as S1 … S3, and currents will be given in units of Ampere in the following text.

A. Emittance measurements

In both the x and y plane, ISIS slit–slit scanners are used. The second slit that measures the angular distribution is built as a Faraday cup providing secondary electron suppression. Recent developments of the controller software are described in Ref. 5.

The raw data recorded by the electronics cannot be used directly to calculate the emittance because of background noise. To suppress the noise, usually a threshold is applied to cut off some data. Obviously, this can effect the tail of the beam. One possibility to overcome this fundamental problem is a more advanced algorithm called SCUBeX.[6,7] The SCUBeX approach provides a self–consistent way to calculate the 100% rms emittance without a possible subjective threshold to reduce data. But SCUBeX has shown some difficulties to converge if the beam has large filamentations.[8] Therefore, to check SCUBeX a threshold (typically ≤ 1 %) was applied to some results but the difference was never bigger than ≤ 2.5 %, all rms emittances shown in the text base on SCUBeX.

B. Measurement procedure

The emittance scanner is not directly located at the position where the RFQ (acceptance) will be; in fact, the

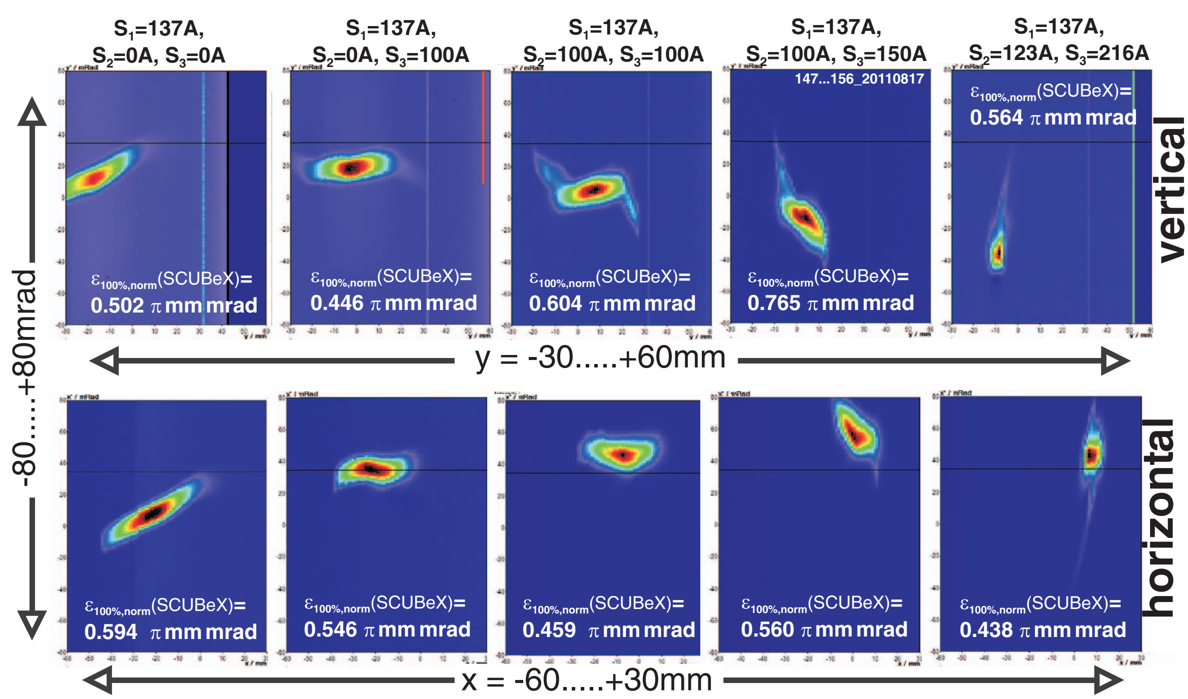

FIG. 2. (Color online) Horizontal and vertical emittances for a 65 keV beam with fixed B-field for S1 and increasing magnetic field from left to right, note the beam offset in both planes. The chosen setting for S1 is so that the measured beam current values along the LEBT only show marginal losses. The two scanner cover a different range in x and y.

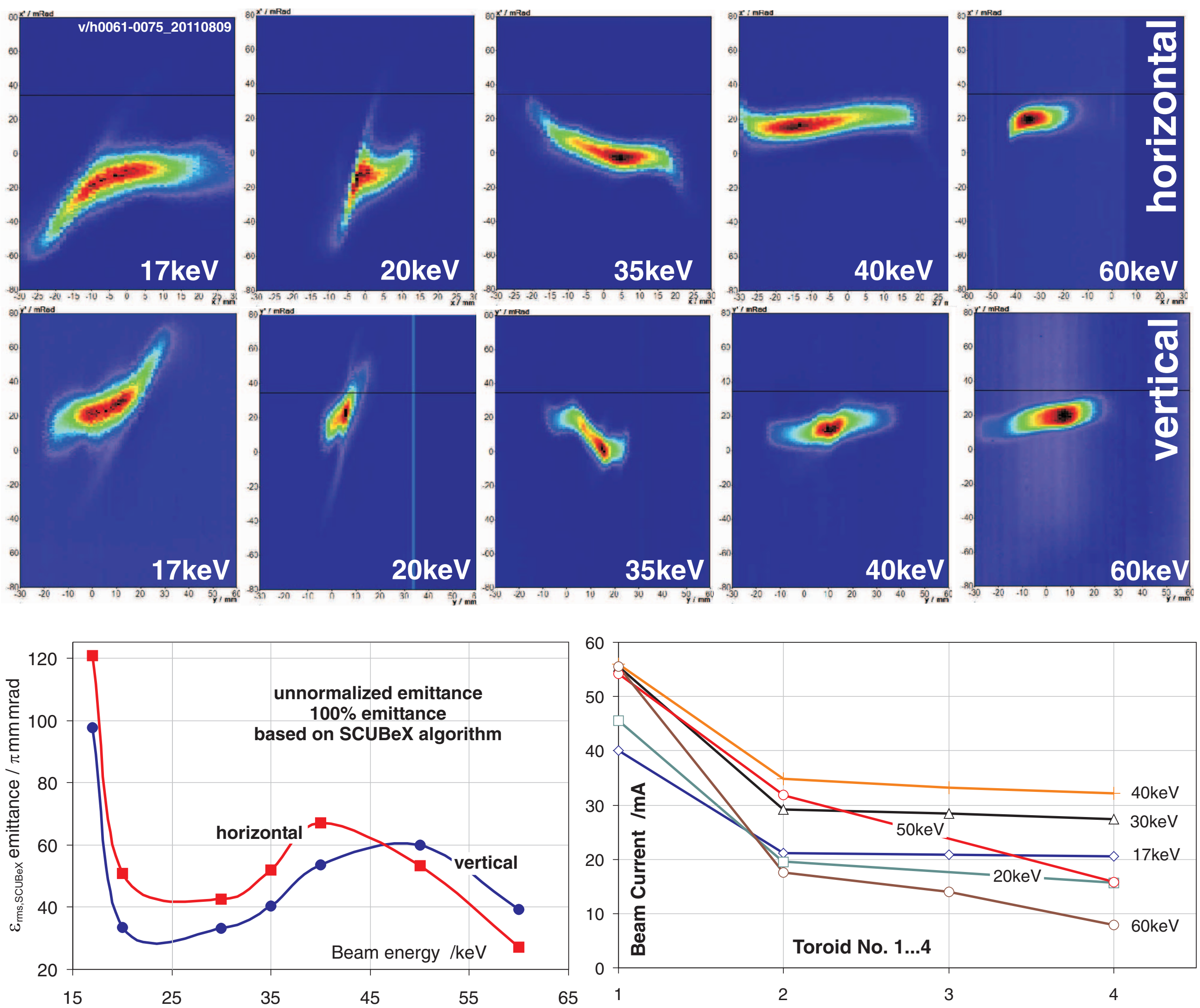

FIG. 3. (Color online) Variation of the beam energy vs. rms emittance and beam current, all three solenoids are constant at 70 A. The scanning range is for both x′ and y′ ± 80 mrad and for x = ± 30 mm and for y = –30…+60 mm. The lowest possible beam energy is the extraction voltage of 17 kV.

measurement plane is 74 mm further downstream. This is not ideal but due technical constraints this is as close as one can get with the given with the diagnostic vessel. On the other hand, it would be critical to measure a strongly focused beam very close to the focus because of possible -maybe very localized- damage on the slit caused by the high current density. A further problem is that the beam covers only a small portion of the phase space, hence the measurement error can be high due to the limited number of "phase space pixels."

The starting point are the LEBT simulations where the beam is matched into the RFQ as mentioned in I. If the emittance scanner were placed at the RFQ entrance the reasons mentioned would lead to various solenoid settings where the focus would be up– and downstream of the emittance instrument. This can be done also with the existing setup aside from considering the extra drift length when the solenoids are varied. This approach does not give an input distribution for RFQ simulations but should deliver enough knowledge about the beam behavior to find empirical LEBT settings to provide best performance when the diagnostics is not installed anymore but the RFQ.

III. EXPERIMENTAL RESULTS AND THEIR DISCUSSION

A. Focusing the beam with nominal energy

Here, the beam energy was kept constant at 65 keV with a 1.1 mm wide extractor slit and a gap length of the PA of 6 mm. The source provided an H^- current of T1 = 66 mA for all the emittance scans. The emittance plots are shown in Fig. 2 for both the vertical and horizontal plane at different solenoid settings. The focal strength of all three solenoids increases from left to right but the first one stays constant at S1 = 137 A.

An interesting aspect is how much the field strength steers the beam in both x- and y-plane. Due to skewed injection a variable offset can be measured in angle and position and if one likes the emittance plots are measurement points along the Larmour gyration[9] induced by a longitudinal B–field. It should be noted that the measured offset is always a combination of PA affecting the beam through an einzel lens effect[10] and solenoid settings. There are apparently some imperfections in the alignment of the different components ion

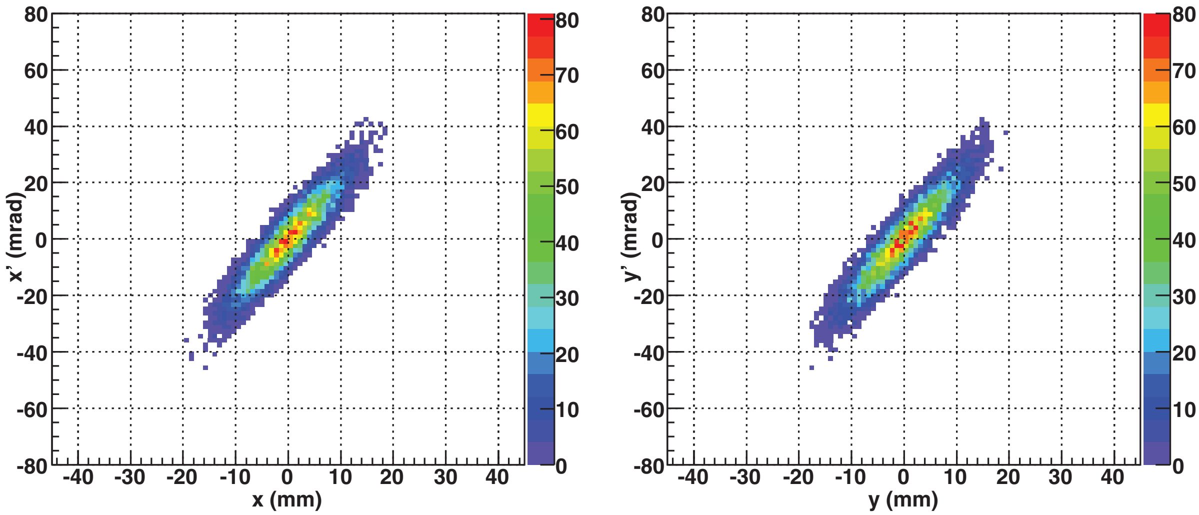

FIG. 4. (Color online) Initial beam distribution used in the GPT simulations.

source, sector magnet, PA and LEBT beam line and small errors of ≤1.0 mm sum up to this large offset. Most likely, misalignment appears at the intersection of the different elements, e.g., transition from sector magnet to PA or first vacuum vessel of the LEBT.

Further experiments at this energy have been performed with slightly different ion source settings extracting a current of above 80 mA in T1 and transporting 60 mA to T4 and can be found in Faircloth *et al.*[11]

B. Variation of the beam energy

These measurements have been performed with a PA gap of 6 mm and an extraction slit width of 2.1 mm. Figure 3 shows the phase space plots and rms emittance (SCUBeX) including toroid measurements. To compare the different beam energies directly the solenoids were all set to 70 A and cannot be more than a compromise. The extraction energy was 17 keV, hence defining the lowest possible beam energy.

It is not fully understood why the rms–emittances show a minimum at lower energies. So far, this is not verified in simulations[12] but the beam is obviously collimated and this makes a judgment on rms emittance always difficult. The drop in rms emittance at higher energies is probably also spoiled by beam losses. The toroid measurements imply that this should happen in the first solenoid because both 50 and 60 keV show significant higher losses between T2 and T4. Both emittance and current show that the PA probably needs some changes (e.g., longer gap) to perform at 65 keV as good as between 35 and 45 keV.

IV. PARTICLE SIMULATIONS WITH GPT

Simulations using the General Particle Tracer software package (GPT) (Ref. 13) have been performed in order to understand the behaviour of the H^- beam passing through the LEBT. The geometry shown in Fig. 1 is implemented in the simulation, from the location of the first toroid (T1) up to the position of the downstream emittance scanner. The solenoidal field is as a field map implemented in the simulations.[3]

Drift sections between the solenoids are represented as pure vacuum regions. The initial 65 keV H^- beam distribution, shown in Fig. 4, is based on a waterbag distribution with Twiss parameters $\alpha_{x,y} = -2.3$ and $\beta_{x,y} = 1.3$ mm, with a normalized emittance of $\epsilon_{x,y} = 0.35\pi$ mm mrad. Space charge effects (equivalent to a current of 6 mA, i.e., 80–90% compensation is assumed) are included in the beam transport calculations. Figure 5 shows the x and y beam envelope as a function of z for the nominal solenoid current settings of 137, 123, and 216 A (equivalent to the on-axis fields of 0.19 T, 0.17 T, and 0.30 T).

Figure 6 shows a comparison of the measured beam distribution at the downstream emittance scanner with GPT simulations for different solenoid current settings. Note that the scanner distributions have not been corrected for missalignment between the beam direction and the z axis of the experimental set-up. In general, the scanner data show a beam with a larger core than the simulations, with more

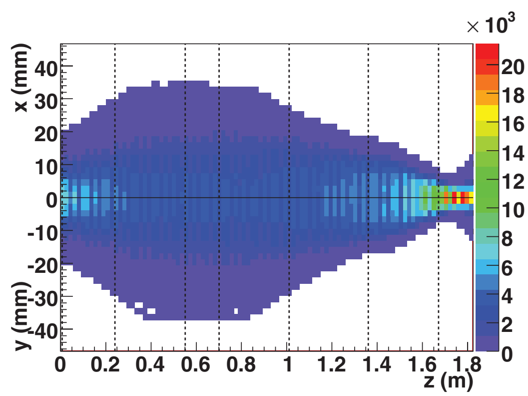

FIG. 5. (Color online) The x and y envelope of the beam along the length of the LEBT, up until the location of the RFQ entrance, based on the GPT simulation results for the nominal solenoid settings (137 A, 123 A, 216 A). Here $z = 0$ is near to the location of the first toroid (T1 in Fig. 1), while the dotted vertical lines show the boundaries of the solenoids.

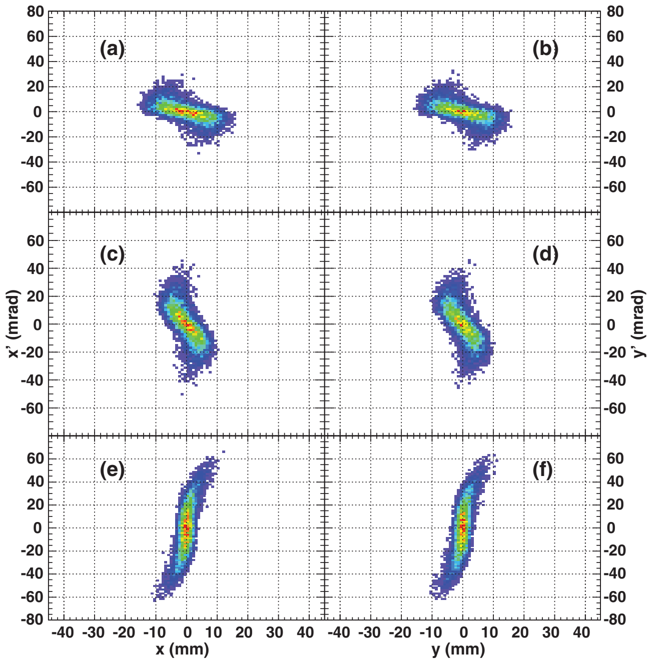

FIG. 6. (Color online) Beam emittance distributions, in x and y from GPT simulations. The solenoid current settings are as follows: (137 A, 100 A, 100 A) for plots a and b; (137 A, 100 A, 150 A) for plots c and d; (137 A, 123 A, 216 A) for plots e and f. The equivalent measurements can be found in Fig. 2.

exaggerated, asymmetric filamentation as a result of the beam passing through the solenoid fields. However, the change in the orientation of the emittance distribution, as well as the increase in beam filamentation as the solenoid currents increase, is predicted reasonably well by the simulation. Better agreement should be possible by using an asymmetric (i.e., offset) initial distribution that more closely matches the beam emerging from the post–acceleration aperture, which will be investigated for future studies.

V. SUMMARY AND OUTLOOK

The existing H^- beam needs to be transported through the LEBT matching as close as possible the RFQ input parameters. To achieve that a series of slit–slit emittance scans have been carried out. First results are presented and show a sufficiently high current of 60 mA at the RFQ entrance; however, the emittance needs to be reduced to meet the requirements of the RFQ simulations.

The achieved emittances depend on ion source settings and on the PA where the applied voltage amplifies a slight off-centered beam due to an einzel effect. Further increase of this effect is caused by the solenoid and depends similar to the PA of the settings. This problem needs to be addressed in the near future and possibly the survey improved.

Concerning the simulations it is planned to carry out calculations with 4D particle distributions close to measurements, considering steering effects and implementing the correct aperture between PA and first solenoid in order to learn more about the low transmission between the two first toroids.

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