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STATUS OF THE EMITTANCE TRANSFER EXPERIMENT EMTEX*

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Abstract

In order to improve the injection efficiency of the round UNILAC heavy ion beam into the asymmetric acceptance of the SIS18 it would be of great advantage to decrease the horizontal emittance by a so called emittance transfer to the vertical plane. In this contribution the present status of the emittance transfer experiment EMTEX at GSI will be reported. A short introduction about the theoretical background of the technique will be given, while the main part is dedicated to the practical solutions setting up a test beam line at GSI. Finally, the results of a first commissioning beam time will be presented. The scheduled beam time to apply the emittance transfer technique foreseen in spring 2014 had to be shifted to calendar week 26 in 2014, just after this conference as some components have not been delivered in time by the contractor. The results and comparison to the theoretical predictions you may find in later publications.

MOTIVATION

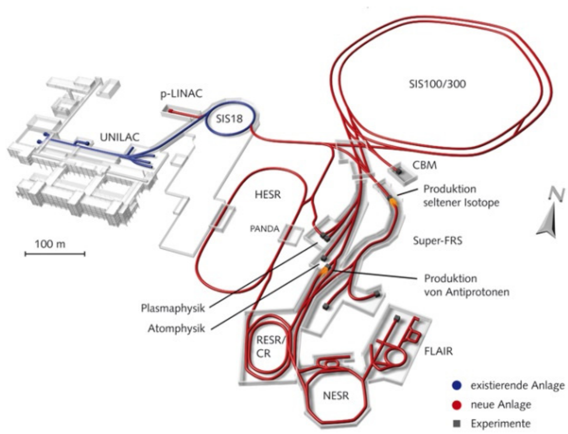

Figure 1: The planned facility for anti-proton and heavy ion research FAIR in red and the existing GSI facility that will serve as injector in blue.

GSI serves as injector for the FAIR Facility and thus the achievable FAIR intensities are directly linked to achievable SIS18 intensities. One of the bottlenecks herein is the injection efficiency of the Unilac beam into SIS18. Besides the strong requirements for a beam with low momentum spread to reach high rf capture efficiency inside the ring, the multi turn injection scheme benefits from so called flat beam with $\varepsilon_x \neq \varepsilon_y$ while the Unilac beam is round. Flat beams need to be specially formed as ion sources generally deliver round beams. The 36 MHz micro bunch structure delivered by the Unilac is lost during injection into the SIS18 and basically the beam behaves like a long mono energetic tube of approximately 100 µsec in length. Pretty much like winding up a tube the trajectories are put next to each other for each turn inside the ring as shown in Figure 2. This is the reason why the desired horizontal / vertical emittance ratio is approximately 1/3.

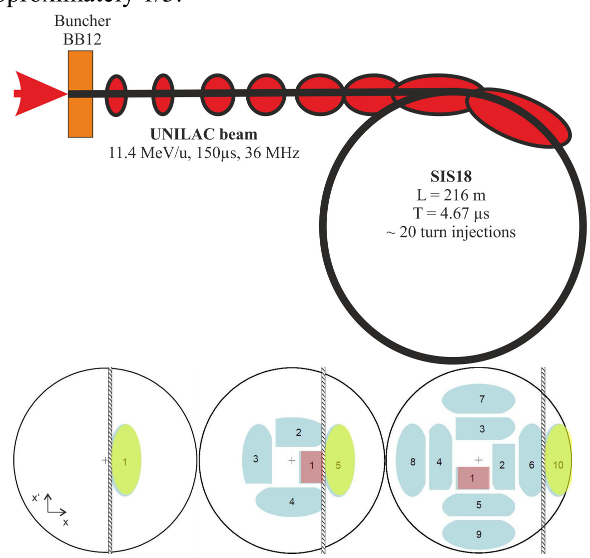

Figure 2: Multi turn injection scheme at SIS18. One turn at 11.42 MeV/u and 216 m circumference takes 4.67 µs thus approximately 20 turns are filled out of the 150µs UNILAC pulse length.

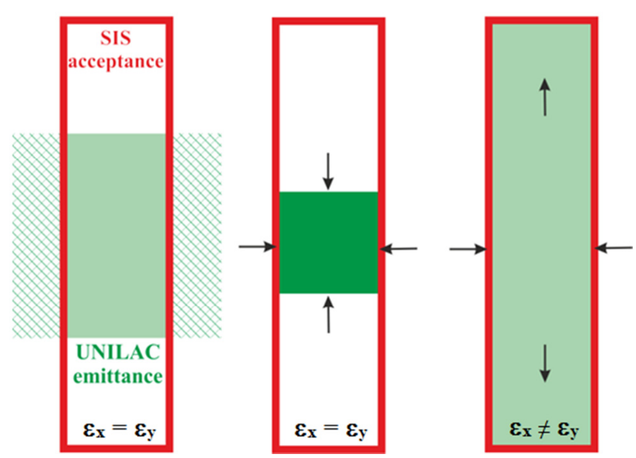

Figure 3: The UNILAC beam is generally round (left). In order to increase the injection efficiency one has to provide a brighter beam from the source (centre) or to perform an emittance transfer from one plane to the other, while keeping the product $\varepsilon_x * \varepsilon_y$ = const (right).

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FLAT BEAM CREATION

As shrinking the emittance in both planes is equivalent to providing a brighter beam with same current but not filling the offered acceptance, a flat beam ($\varepsilon_x \neq \varepsilon_y$) is desirable. In order to obtain a flat beam a non-Hamiltonian operation, changing the eigen-emittance [1] has to be performed on the beam. The two steps of emittance transfer are (1) coupling the planes and transferring eigen-emittance from one to the other and (2) decoupling the beam again.

Stand-alone solenoid axial fields and stand-alone solenoid fringe fields are not Hamiltonian since the Maxwell equation $\vec{\nabla}\vec{B} = \frac{\delta B_x}{\delta x} + \frac{\delta B_y}{\delta y} + \frac{\delta B_y}{\delta y} = 0$ forbids their existence. But of course complete solenoids do exist, they are Hamiltonian, and preserve the eigen-emittances. To achieve emittance transfer the eigen-emittances have to be changed in a non-Hamiltonian action that does not comprise “good” particle loss. A possible solution for coupling and transferring is a fake stand-alone solenoid fringe field that can be realized by placing a source [2], or as a special, for heavy ion beams, placing a stripper inside the solenoid [1], [3][1].

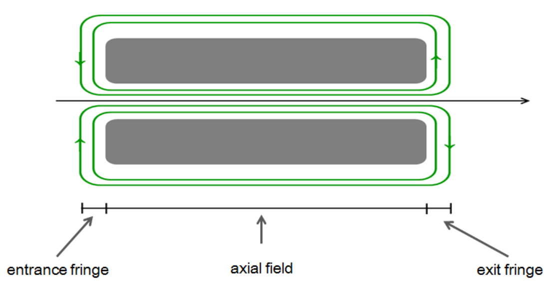

Figure 4: Schematic of a solenoid and its field lines.

The complete solenoid matrix can be split into: $M_{Sol} = M_{fo} * M_{||} * M_{fi}$, where M_{fi} is the entrance fringe, $M_{||}$ the axial and M_{fo} the exit fringe field with:

$$M_{fi} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & \kappa & 0 \\ 0 & 0 & 1 & 0 \\ -\kappa & 0 & 0 & 1 \end{bmatrix}, \quad M_{II} = \begin{bmatrix} 1 & -\frac{1}{2\kappa}\sin(\alpha) & 0 & \frac{1-\cos(\alpha)}{2\kappa} \\ 0 & \cos(\alpha) & 0 & -\sin(\alpha) \\ 0 & \frac{\cos(\alpha)-1}{2\kappa} & 1 & -\frac{\sin(\alpha)}{2\kappa}0 \\ 0 & \sin(\alpha) & 0 & \cos(\alpha) \end{bmatrix}, \quad M_{fo} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & -\kappa & 0 \\ 0 & 0 & 1 & 0 \\ \kappa & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

In here $\kappa := B/2(B\rho)$ is the focusing strength of the solenoid and $\alpha := -2\kappa L$ with L being the length of the axial field. For finally decoupling the planes again, quadrupoles tilted by 45° might be used.

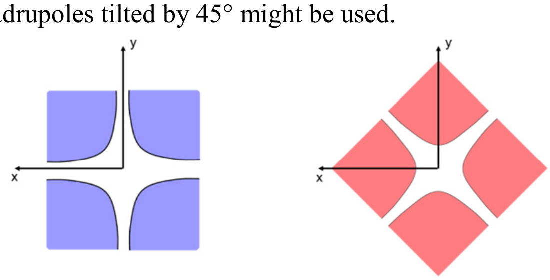

Figure 5: On the left a normal (non-coupling) quadrupole and to the right a quadrupole tilted by 45° (skew).

The transport matrix of a thin, horizontally focussing, quadrupole of focusing length 1/q, rotated clockwise by 45° is given by:

$$M_{SkewQuad} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & -q & 0 \\ 0 & 0 & 1 & 0 \\ -q & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

In principle all components to administer emittance transfer are available now. We use a solenoid for non-Hamiltonian coupling of the x and y plane by putting a stripper foil inside the solenoid for imposing effective stand-alone fringe fields. The eigen-emittance transfer is from changing the beam Bρ, i.e. the different action of the entrance and exit fringe fields on the beam. Finally, we use tilted quadrupoles to decouple the x and y plane again. This decoupling is Hamiltonian. Table 1 summarizes the effect of various beam line elements on the emittances.

Table 1: Emittance Changing Capability of Ion Optical Elements

Element	**$rms_{x,y}$**	**4d-rms**	**$Eigen_{1,2}$**
Drift	no	no	no
Quadrupole	no	no	no
tilted quadrupole	yes	no	no
Dipole	no	no	no
tilted dipole	yes	no	no
Solenoid	yes	no	no
solenoid fringe	yes	no	yes
solenoid axial field	yes	no	yes

DECOUPLING

Defining a coupling parameter $t := \frac{\varepsilon_x \varepsilon_y}{\varepsilon_1 \varepsilon_2} - 1 \geq 0$, with t = 0 there is no inter-plane coupling, i.e. the beam is fully decoupled. Herein $\varepsilon_{x,y}$ are the projected rms emittances and $\varepsilon_{1,2}$ are the Eigen-emittances [3]. A plot of *t* versus the longitudinal magnetic field along the solenoid is shown in Fig. 6 and Fig. 7 for simulations using two different codes.

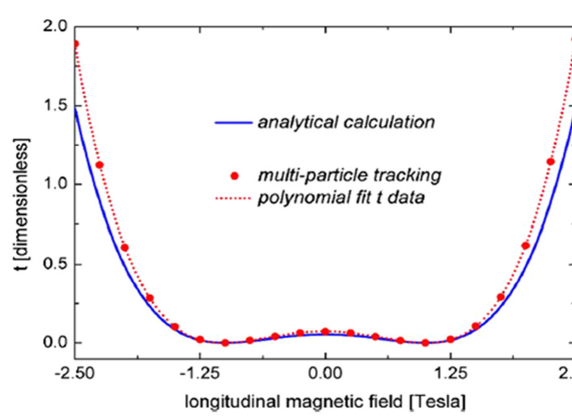

Figure 6: The coupling parameter *t* as a function of the longitudinal magnetic solenoid field as published in [3].

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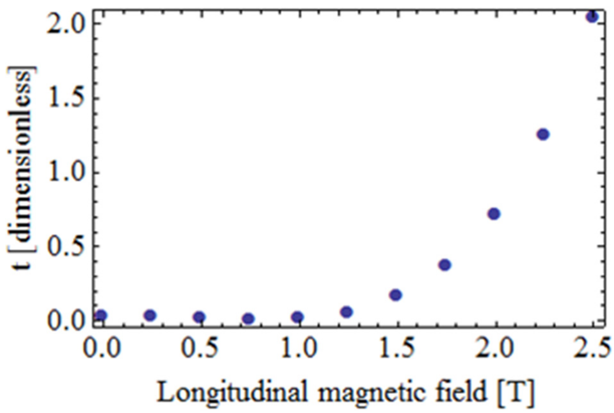

Figure 7: The same coupling parameter calculated using another code by applying an innovative 4d-envelope model as published in [4].

The decoupling is very convenient since it does not require any re-adjustment of the decoupling quadrupoles behind the solenoid. The *t*-values shown in Figs. [6-7] have been obtained by keeping the de-coupling gradients constant. Moreover, the decoupling also delivers constant Twiss parameters β and α in both planes. More details on these convenient decoupling features are given in [5].

TECHNICAL LAYOUT OF EMTEX

The complete EMTEX setup, shown in Fig. 8, has been designed to allow for the regular SIS18 injection as well as to allow for emittance transfer by not altering the existing beam line, only adding devices that can be switched off. This setup is an experimental beam line attempting to prove the principle of emittance transfer on ion beams. The EMTEX beam line consists of two doublets shown in Fig. 9 and Fig. 10, matching the beam to the split solenoid (small beam spot) and the stripping foil herein shown in Fig. 11, to mitigate four-dimensional rms emittance growth from scattering during the stripping process. In the solenoid centre a 20 $\mu g/cm^2$ carbon foil is placed to strip the 11.4 MeV/u D_6^+ molecule beam [6], [7] to $3D_2^+$. Behind the solenoid there are three triplets, depicted in Figs. [12-14] of which the middle one is the skew triplet ,i.e. tilted by 45°. The beam line as well comprises a slit grid emittance scanner with an angular resolution of 0.1 mrad (wire distance of 1mm at approximately 10 m distance) and a spatial resolution of 0.5 mm, given by the width of the high current slits.

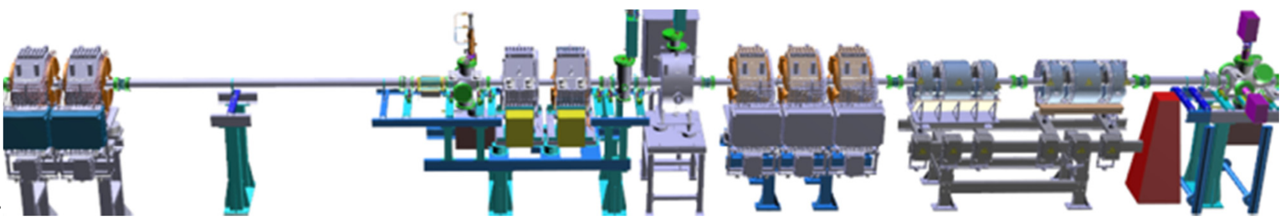

Figure 8: The overall EMTEX beam line. From left to right it is consisting of two doublets, the split solenoid with the stripping foil in its centre and the three triplets of which the middle one is the skew triplet rotated by 45°. In the end the slit box of the slit grid emittance scanner is located.

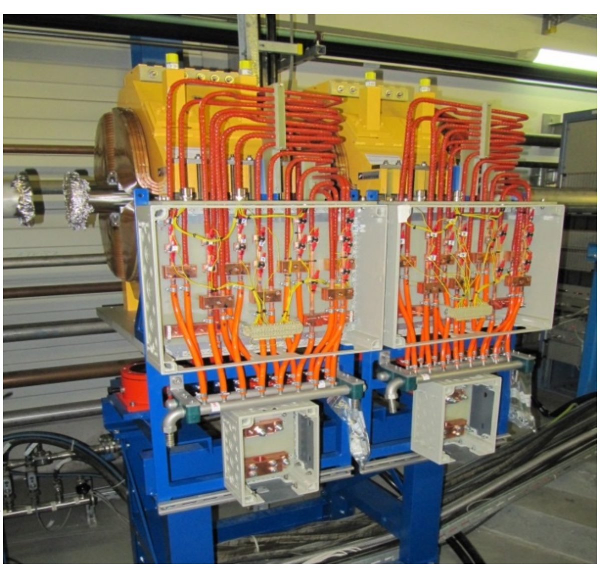

Figure 9: TK5QD4, the new quadrupole doublet delivered in March 2014 for matching the beam together with TK5QD5 in Figure 8 in to the solenoid.

Figure 10: TK5QD5, the already existing quadrupole doublet, together with QD4 it provides a small beam spot and a double-waist on the foil to mitigate emittance growth from scattering during stripping.

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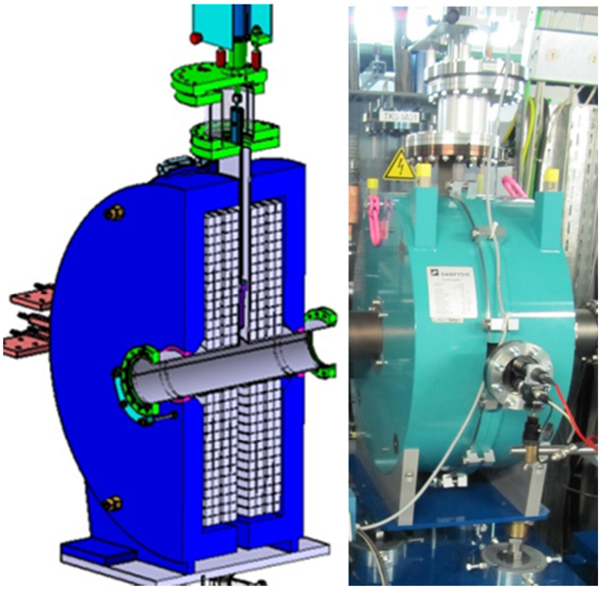

Figure 11: The split solenoid [8] TK5MO1 with the foil carrier from the top. Attached to the solenoid chamber a camera for non-destructive online foil observation from the right is installed.

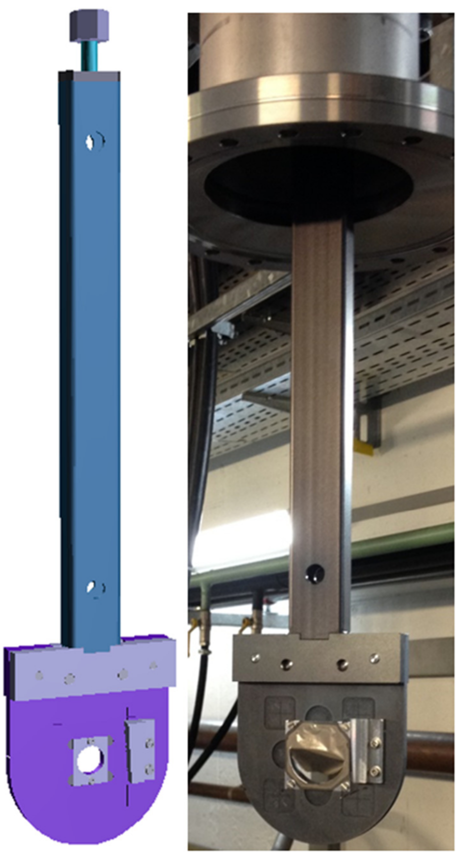

Figure 12: The stripper foil arm installed inside the solenoid is equipped with a polished stainless steel block to reflect the foil image for non-destructive online observation of the foil condition.

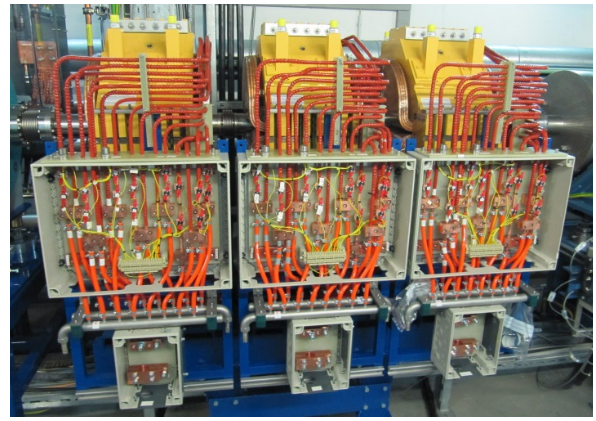

Figure 13: TK5QT5, the new quadrupole triplet, delivered in March 2014.

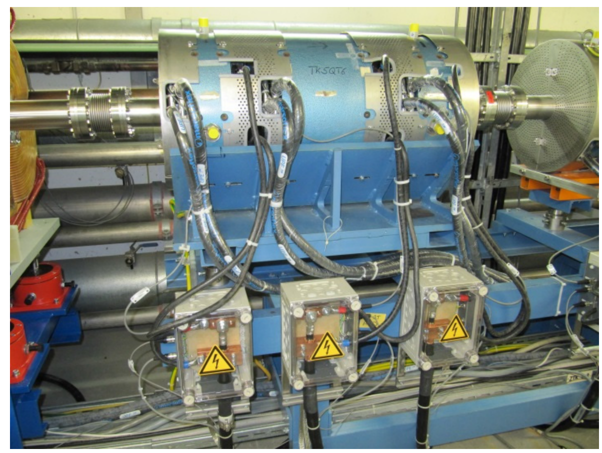

Figure 14: TK5QT6, the skew quadrupole triplet, an overhauled and modified existing GSI triplet. This is the so called “skew” triplet rotated by 45° to decouple the beam.

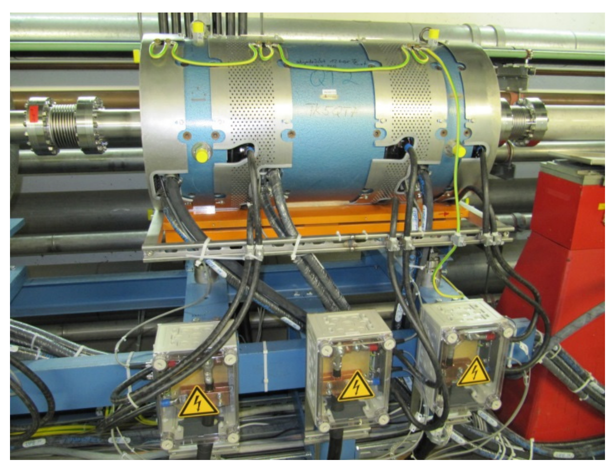

Figure 15: TK5QT7, the last quadrupole triplet, an overhauled existing GSI triplet.

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FIRST COMMISSIONING RESULTS

As the two triplets at the end of the beam line shown in Figure 14 and Figure 15 were already available in house, they were the first to be installed in the beam line. The split solenoid including the special stripping foil chamber has been delivered in December 2013 and was installed before the first beam time block in 2014. Thus those components are already tested with beam and were found to be working within the specifications.

The solenoid has been tested without using the stripper foil during this beam time as well and as expected the effect of the solenoid field on the beam is small. As during the tests there is no stripping, there is also no emittance transfer and the focussing effect as well as the coupling is negligible for the $^{40}Ar^{8+}$ beam available during this beam time. In an independent test the camera systems to observe the stripping foil have been commissioned successfully.

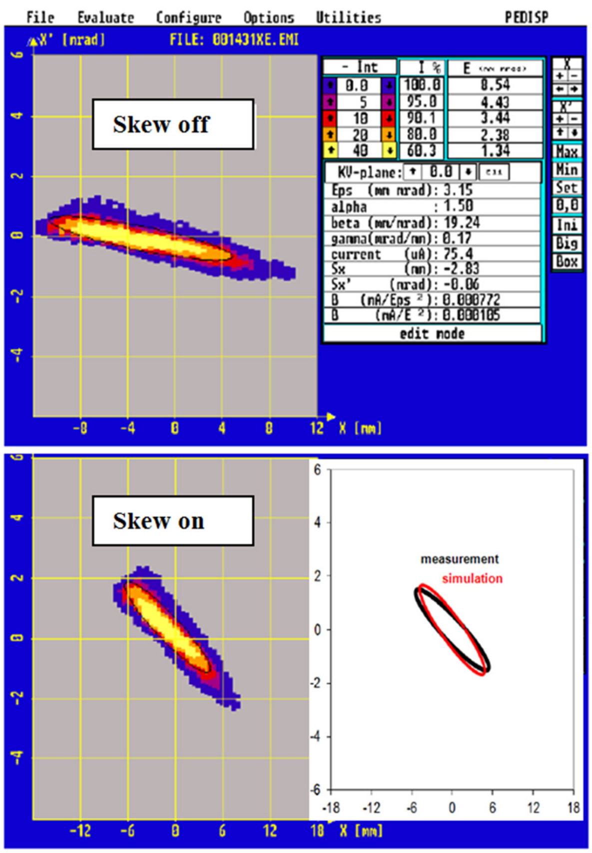

Figure 16: Comparison of the measured horizontal emittance behind the skew triplet with the simulation result.

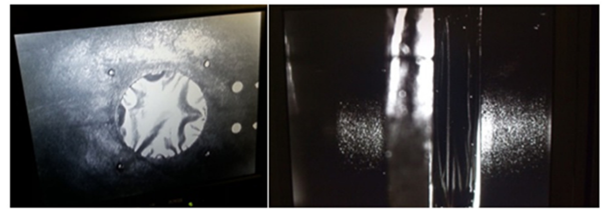
Figure 17: The stripping foil inside the solenoid seen from the diagnostics chamber in front of the solenoid (left) and via the non-destructive lateral view port pointing toward the solenoid centre (right).

OUTLOOK

The first EMTEX beam time with all its components installed to test emittance transfer is scheduled for end of June 2014. We will use an 11.4 MeV/u D_6^+ molecule beam stripping it to $3D_2^+$. On the later we will attempt to administer the emittance transfer. According to our tracking simulation results summarized in Table 2 it should be possible to reach an emittance ratio of about ¼.

Table 2: The beam parameters at the entrance and exit of the EMTEX beam line. An initial water-bag distribution was assumed for the tracking simulations [3].

Parameters	Entrance	Exit
α_x / α_y	-1,21 / -2.28	0.0 / 0.0
β_x / β_y	21.80 / 15.01	7.18 / 7.13
ε_x / ε_y	0.509 / 0.510	0.256 / 1.144

In case this experimental proof-of-principle is successful, it might be envisaged to apply the technique to an intense uranium beam as needed for the new linac that shall replace the existing Alvarez DTL [9-11]. First simulations delivered promising results.

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