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A VIRTUAL CHARGE STATE SEPARATOR AS AN ADVANCED TOOL COUPLING MEASUREMENTS AND SIMULATIONS

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Abstract

A new Low Energy Beam Transport (LEBT) for multi-charge uranium beam will be built at GSI High Current Injector (HSI). All uranium charge states coming from the new ion source will be injected into GSI heavy ion high current HSI-RFQ, but only design ions U^{4+} will be accelerated to the final RFQ energy. A detailed knowledge about injected beam- current and -emittance for pure design U^{4+} ions is necessary for a proper beam line design commissioning and operation, while the measurements are possible only for a full beam including all charge states. Detailed measurements of beam current and emittance are performed behind the first quadrupole triplet at the beam line. A dedicated algorithm, based on combination of measurements and results of an advanced beam dynamics simulations, provides for an extraction of beam- current and -emittance for only U^{4+} component of a beam. The obtained results and final beam dynamics design for the new straight beam line are presented.

THE MEASUREMENTS CAMPAIGN

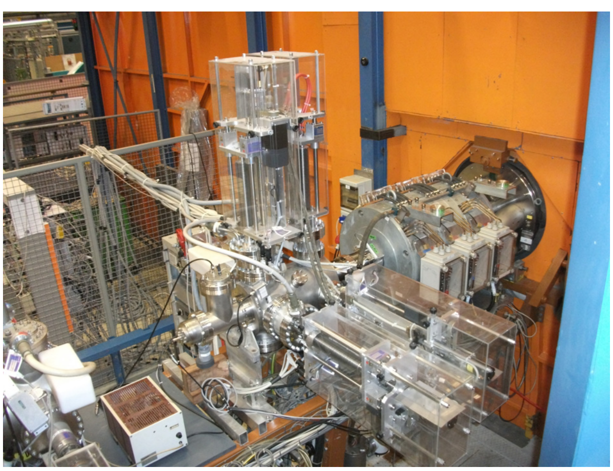

Figure 1: The setup for the measurements.

An intense experimental campaign was carried out in June-November 2013 at the existing North Terminal of the UNILAC (Fig.1) [1-3]. A set of beam emittance and current measurements behind the first quadrupole triplet (UL4QT1) of the LEBT has been performed. The beam current and emittance obtained with different settings of the ion source terminal were at that time in the range of 20-35 mA inside 300-450 mm*mrad respectively. These measurements have been performed in the frame of further upgrade and optimization for GSI heavy ion high current linac UNILAC [4-7].

As shown on Fig. 2 (left), a different focusing efficiency for the different charge states leads to a complicate shape of a composite beam emittance, measured behind quadrupole triplet. Obviously the standard diagnostics is not able to distinguish ions with different charge states. Nevertheless a macroparticle distribution in 2D vertical phase space (Fig. 2, right) was generated from the raw data of measured emittance. The density of macroparticles is proportional to the local intensity, measured with a slit-grid device inside each bin: **0.5 mm x 1.7 mrad**. The same procedure has been implemented for the horizontal measurements; a 4D transverse particle distribution has been created, assuming elliptical shape of the beam in real space of coordinates and velocities. A continuous beam has been assumed for the longitudinal phase space.

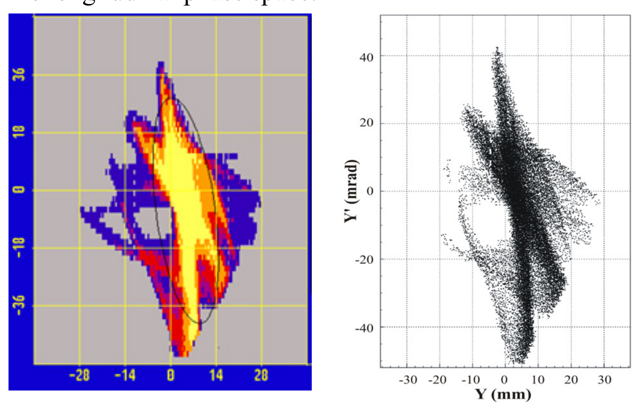

Figure 2: Measured vertical beam emittance (left) and generated macroparticle distribution (right).

DESCRIPTION OF THE METHOD

A set of beam dynamics simulations have been performed by means of DYNAMION code [8]. As the measured uranium beam emittance is formed by different charge states (mainly 4+ and 3+), the beam dynamics simulations have been done separately for the identical 6D phase space particle distribution, but with different charge state assigned to the particles. These input distributions have been transported backward (upstream a beam) through the quadrupole triplet. A magnetic field along the triplet has been represented by 3D mapping, obtained from detailed field measurements for each quadrupole. The gradients of the lenses have been taken from the machine settings.

Obviously the particles with different charge state are transported through the magnetic quadrupoles in a different way and form different beam emittance at the

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same position (Fig. 3, left). But in assumption that the beam parameters behind an ion source terminal are the same for every charge state, only a phase space overlapping of resulted particle distributions could be treated as an emittance formed by the complete beam (Fig. 3, right).

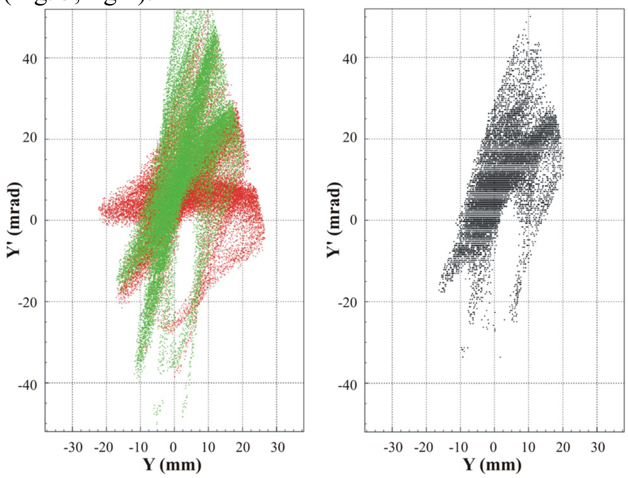

Figure 3: Left: particle distribution calculated through the triplet backward as U^{4+} (green) and as U^{3+} (red). Right: only overlapping of U^{4+} and U^{3+}.

The obtained "realistic" particle ensemble has been simulated forward (downstream a beam), again separately as U^{3+} and as U^{4+}. The transported particles at the position of measurements form separately beam emittances for different charge states which perfectly cover the originally measured phase space distribution (Fig. 4).

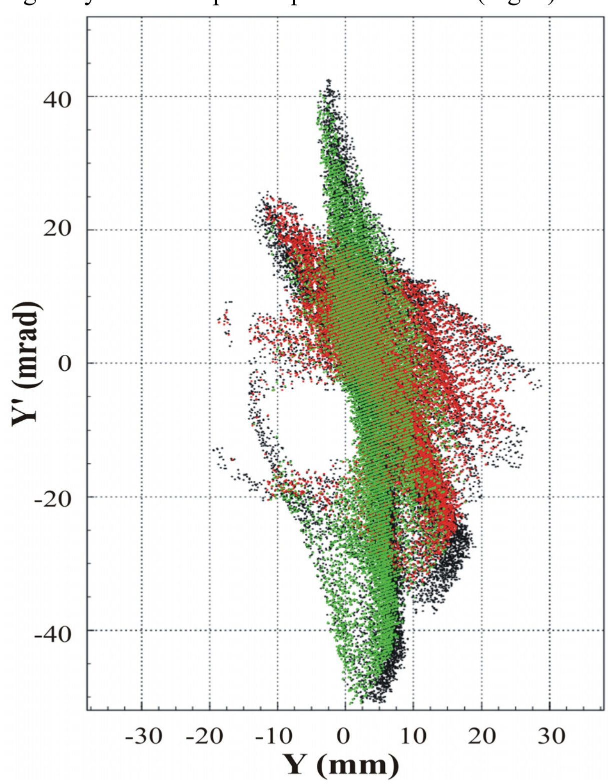

Figure 4: Original macroparticle distribution (black) and simulated ones for U^{4+} (green) and U^{3+} (red).

INTENSITY RATIO

Generally an Uranium beam from an ion source comprises different charge state: $U^{1+} + U^{2+} + U^{3+} + U^{4+} + U^{5+} + U^{6+}$... An amount of each charge state strongly depends on multi-parametric settings of the ion source and post-acceleration gap.

The mentioned above beam currents and beam emittances are measured behind magnetic quadrupole triplet for a mixture of Uranium charge states - mostly 3+ and 4+. Obviously nor current transformer neither emittance scanner are able to distinguish different charge states. But especially for new LEBT with straight beam injection into the RFQ (without charge state separation by dipole) an information about beam current and emittance only for design ion U^{4+} is essential.

The beam emittances have been measured with slit-grid device. As a raw data one obtains a local beam intensity for each bin (phase square) in some range of coordinates and angle. Measured local intensity in each bin is a sum of all charge states ***k***: $I_{ij} = \sum_k I_{ij}^{k+}$.

Due to magnetic focusing of the particles into a frame of emittance scanner, a contribution $\boldsymbol{I_{ij}}^{\boldsymbol{k+}}$ from each charge state ***k*** to a local intensity $\boldsymbol{I_{ij}}$ significantly differs from bin to bin. The number of particles for each beam dynamics simulation with different uranium charge states is fixed. But during simulations an unknown ratio of real intensities can't be represented in advance by a different number of particles. Nevertheless as result of simulations one can count a number of particles $\boldsymbol{N_{ij}}^{\boldsymbol{k+}}$ for each charge state inside each bin. This amount of simulated particles with different charge states varies from bin to bin. Ideally in the same way as real contribution of each charge states to the measured local intensity at each bin. From the simulation results the intensity in each bin can be expressed as $I_{ij} = \sum_k x_k N_{ij}^{k+}$, where $\boldsymbol{x_k}$ are the unknown coefficients for relative total intensity of charge state ***k***.

Let us consider an equation:

$$A(N,M)X(M) = B(N),$$

where $A(N,M) = \begin{pmatrix} a_{11} & \dots & a_{1M} \\ \dots & \dots & \dots \\ a_{N1} & \dots & a_{NM} \end{pmatrix}$ - matrix of coefficients, $X(M) = \begin{pmatrix} x_1 & \dots & x_M \end{pmatrix}$ - vector of variables, and $B(N) = \begin{pmatrix} b_1 \\ \dots \\ b_N \end{pmatrix}$ - vector of meanings. Then a well-known "solution" of such over-defined linear system one can get as $P = (A^T A)^{-1} A^T B$.

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For our case a_{nm} is a number of simulated particles with charge state m inside bin n, b_n - measured intensity in bin n, and x_m - relative total intensity of charge state **m**.

Based on an experimental experience and on the simulations results, we limit ourselves by only two charge states 3+ and 4+. Intensity of all other charge states is assumed as neglectable. Then the matrix transforms to A(2,N), where N is number of bins with non-zero amount of simulated backward-forward U^{3+} or U^{4+}.

Two transverse phase planes X-X' and Y-Y' were under consideration independently. These two "solutions" of such over-defined linear systems give the most probable intensity ratio of U^{3+} and U^{4+} for the measured beam emittances (Tab.1). Also an evaluation of the horizontal and vertical measurements together has been performed and good coincidence in the range of few percent has been reached.

Table 1: Calculated Relative Intensity

Plane	U^{4+}	U^{3+}
Vertical	64%	36%
Horizontal	61%	39%

Independently, for only two charge states, a direct enumeration has been done as a cross-check. Assuming an uranium 4+ intensity of a given level from 1% to 100% a discrepancy (using least squares method) between result of simulation (particle number inside a bin) and measured data has been calculated. Such scan leads to a smooth optimum at approximately 60-65% of U^{4+} intensity (Fig. 5).

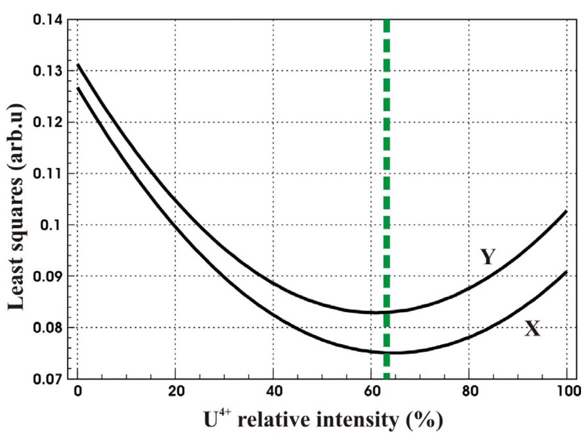

Figure 5: Least squares direct enumeration assuming given ratio of U^{4+} intensity from 1% to 100%.

CONCLUSION

- To distinguish between different charge states coming from an ion source a dedicated method has been proposed, developed and realized.
- A macroparticle distribution was generated from the raw data of an emittance measurements, taking into account detail of intensity distribution inside 4D transverse phase space.
- Accurately measured distribution of a magnetic field along the quadrupole triplet provides for the realistic results of beam dynamics simulations.
- With use of this method one can extract from the measurements for the mixed beam (U^{3+} and U^{4+} mainly) the detailed beam parameters and macroparticle distribution for the design ion U^{4+} only.
- Additionally an algorithm, based on the solution of an overdefined system of linear equations, could provide for an estimated U^{4+} intensity inside the measured one for all charge states together (1+, 2+, 3+, 4+, 5+, 6+).
- Generally, the proposed coupling of detailed measurements and precise beam dynamics simulations with versatile DYNAMION code, acts as a virtual charge state separator. Finally it provides for beam parameters (emittance and current) which can't be measured directly with standard beam diagnostics.
- An obtained information has been already used for the final design of the new GSI heavy ion Compact-LEBT for a straight injection of the beam into the HSI-RFQ [1].
- The developed procedure will be implemented for further investigation and optimization of the existing UNILAC beam lines. Also it will be used for the commissioning, tuning and operation of the new GSI high current uranium ion source terminal and Compact-LEBT.

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