UPGRADE OF THE HIGH CURRENT HEAVY ION FRONT-END SYSTEM OF THE GSI UNILAC

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The FAIR Project requires an U^{4+} beam current above 18 emA behind the heavy ion high current RFQ. The measured intensity was a factor of two lower. The beam dynamics in the front-end system has been simulated with the DYNAMION code. New RFQ electrodes with an improved quality of the surface and a redesigned matching section were fabricated. Beam experiments after the RFQ upgrade confirmed the calculated gain in beam current.

PACS: 29.17.+w, 41.75.Lx

1. INTRODUCTION

For the Facility for Antiproton and Ion Research (FAIR) at Darmstadt the present GSI-accelerator complex, consisting of the UNIversal Linear ACcelerator (UNILAC) and the heavy ion synchrotron SIS 18, is foreseen to serve as a high current injector [1]. The UNILAC [2] was designed to accelerate all ion species with mass over charge ratio of up to 8.5. As shown in Fig.1, the main parts of the UNILAC are the 36 MHz High Current Injector (HSI), a gas stripper section at an energy of 1.4 MeV/u and a 108 MHz Alvarez type post-stripper (11.4 MeV/u).

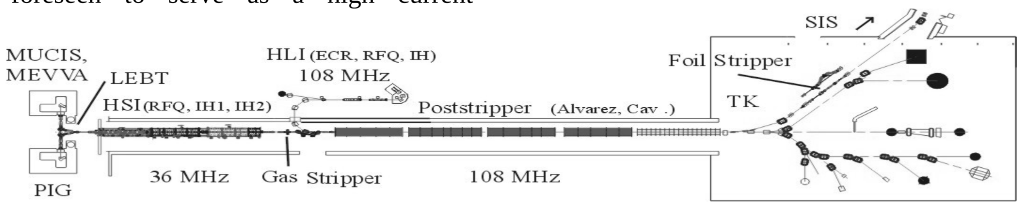

Fig.1. Schematic overview of the GSI UNILAC

The HSI consists of two ion source terminals (PIG and MUCIS/MEVVA), the Low Energy Beam Transport line (LEBT), a Radio Frequency Quadrupole accelerator (RFQ), a short matching section (superlens), and two Interdigital H-structure (IH) tanks. In the FAIR scenario the HSI has to deliver 18 emA of U^{4+}.

The HSI-RFQ is in operation since 1999 [3]. During operation with U^{4+} beam (V_{rf} = 125 kV), the measured rf power was about factor of two higher than calculated. The design voltage of 137 kV, required for the ions with higher mass to charge ratio, was not reached. New electrodes were fabricated and additionally copper-plated. A dedicated procedure for the control of the copper-plating and rf tuning of the RFQ resulted in an improvement of the rf-performance [4].

Additionally the new design of the first electrodes was implemented to improve the beam dynamics in the whole front-end system. The achieved uranium beam transmission through the RFQ was 55% (design value 90%). The design current of medium ions behind the RFQ has been obtained, but with a significant surplus of primary intensity.

2. BEAM MATCHING TO THE RFQ

Beam matching to the HSI-RFQ is carried out with four magnetic quadrupole lenses (Fig. 2).

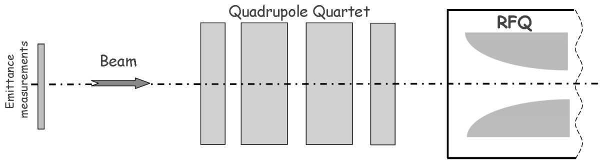

Fig.2. Matching line to the HSI-RFQ

Transverse beam emittances can be measured with a slit-grid device placed about 3 m before the RFQ. Due to the limited space between the Quadrupole Quartet (QQ) and the RFQ, beam transmission can be measured only for the whole front-end system.

A detailed beam dynamics study of the front end-system showed a significant gain in the particle transmission with only minor modification of the Input Radial Matcher (IRM), which length is about 1% of the total RFQ structure length.

3. BEAM DYNAMICS

Well-known codes for beam dynamics simulations PARMTEQM and PARMTRA don't provide the required accuracy of calculations due to intrinsic simplifications, namely paraxial approximation for the particle motion, calculations of the external field in the RFQ for ideal shape of electrodes and the representation of the space charge forces by a charged ellipsoid. The DYNAMION code has been chosen to provide for higher accuracy and reliability of the calculations.

3.1. MULTIPARTICLE CODE DYNAMION

The multiparticle code DYNAMION (DYNAMics of IONs) was written in ITEP for precise end-to-end beam dynamics simulations in high current linear accelerators and was implemented world-wide as for linac design and for study of linacs in operation as well. In collaboration between GSI and ITEP the DYNAMION code is in use since many years for the investigation of operation of the GSI high current heavy ion linac UNILAC. Significant development of the code was done under GSI support.

One of the main features of the DYNAMION code

* *Work supported by INTAS (Project 03-54-3543)*

is the possibility to simulate the 3D particle motion under space charge conditions in the whole linac, potentially consisting of RFQs, different types of DTLs, transport lines and other elements. The required accuracy and reliability were reached by an improved description of the external fields inside the code. Additionally, data from measurements or from calculations performed with external codes (e.g. focusing and accelerating fields, beam emittance, misalignments, etc.) are usable.

3.2. HSI PERFORMANCE BEFORE UPGRADE

First DYNAMION calculations of the particle motion in the RFQ were carried out with a design beam current of 16.8 emA for the uranium case. A beam transmission of 82% was shown, whereas the PARMTEQ code predicted up to 95% in the design stage [6]. Although the measured transmission was even lower.

Recent beam dynamics simulations in the front-end system were done with a beam current of 15 emA, which was measured before the matching quadrupoles. Results of the emittance measurements in the LEBT, the measured distribution of the magnetic field in the quadrupole lenses, the geometry of the electrodes "as fabricated" and measured misalignments of the ten RFQ sections were implemented. External electrical fields in the IRM as well as in the regular RFQ cells, were precisely calculated solving the Laplace equation for the potential in the area, formed by the surfaces of the electrodes and the tank. Behind the RFQ a beam current of 8.7 emA was calculated; the measured current was 8.3 emA.

The low transmission (55%) was caused by significant particle losses in the RFQ and 50% higher beam emittance (compare to the design value). Additionally, narrow matching conditions require strong beam convergence at the RFQ entrance. This leads to a significant deformation of the 6D beam phase volume, a large diameter of the beam in the QQ and remarkable particle losses. Therefore, machine settings were optimized to provide for maximum transmission through the whole front-end system (but not for the beam matching).

4. STUDY OF UPGRADE MEASURES

Strong magnetic fields in the QQ are required to reach high beam convergence simultaneously in both transverse planes at the HSI-RFQ entrance. The integration of the full 3D equation of the particle motion takes interaction of magnetic field in quadrupoles into account; not only with longitudinal, but also with transverse components of the particle velocity [5]. The transverse velocity of the outer particles inside the QQ reaches 20% of the longitudinal one. Even beam dynamics simulations in linear external magnetic field show a significant deformation of the 6D phase volume (Fig.3).

A lower beam convergence at the RFQ entrance should lead to easier beam matching, lower beam emittance perturbation and smaller particle losses in the quadrupole channel. Varying apertures (i.e. focusing strength) along the IRM change matched beam parameters at the RFQ entrance.

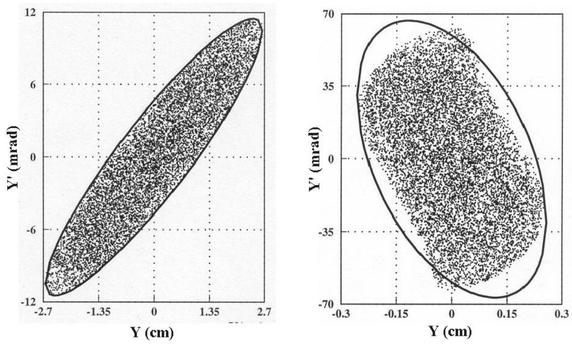

Fig.3. Vertical beam emittances before (left) and after (right) magnetic quadrupoles (linear magnetic field, no space charge effects, "open" apertures)

5. NEW IRM DESIGN

Originally the length of the electrodes with changing aperture was only 3 cells (3 $\beta\lambda/2$). The following 10 cells were designed with small modulation (amplitude less than 5 μm) not influencing the longitudinal particle motion. The aperture along the new increased IRM (13 cells) follows the special law to provide for improved beam matching (Fig.4); not in accordance with the classical model.

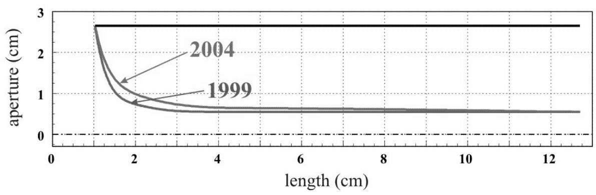

Fig.4. Apertures along IRM for original (1999) and for new (2004) design. Z=0 corresponds to the tank flange. Dashed line represents the RFQ axis

Several variants of the IRM design were considered and investigated with different codes: DYNAMION, TRACE-3D, DRAMA [7], and ABC [8]. In the original design width and rounding of the electrodes were constant in the original design. In the new design these parameters were changed in accordance with the aperture [4]. Correspondent modifications were introduced into DYNAMION field calculations. Matched Twiss-parameters for the 15 emA U^{4+} beam at the beginning of the regular part of the RFQ were obtained by the code ABC. The aperture in the IRM was defined in accordance with the required electrical rigidity along the channel. Beam Twiss-parameters were transformed back to the RFQ entrance by means of the code DRAMA including the distance from electrodes to the flange.

PROBLEMS OF ATOMIC SCIENCE AND TECHNOLOGY. 2006. № 2.
Series: Nuclear Physics Investigations (46), p.64-66.

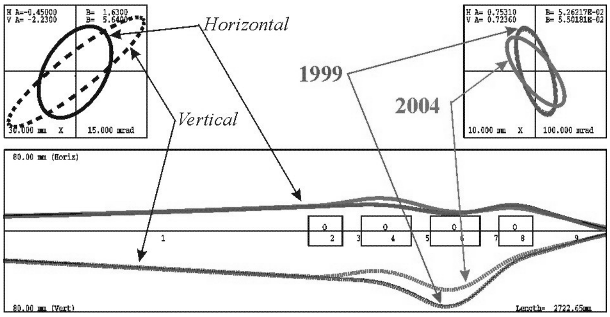

Fig.5. Beam envelopes and emittances in the LEBT for original (1999) and for new (2004) IRM design

Starting at the position of emittance measurement device the beam was matched to the RFQ entrance with four quadrupole lenses, optimized with TRACE-3D code (Fig.5). Finally, the particle motion in the whole front-end system was simulated with the DYNAMION code. For the final design a 15% higher transmission was predicted by calculations for the 15 emA U^{4+} beam.

6. EXPERIMENTAL RESULTS

After recommissioning of the RFQ, measurements for a high current argon beam (16 emA) and a low current uranium beam (< 0.5 emA) had been carried out. A high current uranium beam was not available at that time.

For the U^{4+} beam 100% transmission was reached for the first time since commissioning in 1999. Before the upgrade the transmission was up to 85%.

On Fig. 6 the Ar^{1+} transmission before and after the upgrade is presented as a function of the intervane voltage. As shown, the calculated gain of up to 15% is verified.

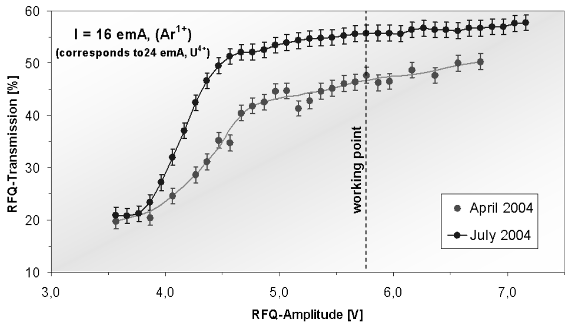

Fig.6. Measured transmission for a high current argon beam before and after the upgrade of the RFQ

CONCLUSION AND OUTLOOK

The main goal of the RFQ upgrade has been achieved: the measured rf power for the acceleration of the $^{180}Ta^{3+}$ beam decreased from 650 to 380 kW. A detailed computer study for the improvement of the beam dynamics in the HSI front-end system was done by means of the DYNAMION code. Small changes of the aperture in the beginning of the RFQ electrodes had been proposed, investigated and realized. Experiments with high current beam verified the calculated gain of up to 15% in transmission and in brilliance.

Nevertheless the existing front-end system can not provide the beam current of 18 emA for the FAIR requirements. Recently the design of a compact LEBT and new RFQ is under investigation.

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МОДЕРНИЗАЦИЯ СИЛЬНОТОЧНОЙ НАЧАЛЬНОЙ ЧАСТИ УСКОРИТЕЛЯ ТЯЖЕЛЫХ ИОНОВ UNILAC, GSI

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Для проекта FAIR после сильноточного RFQ нужен ток пучка U^{4+} больше 18 emA. Измеренная интенсивность была в два раза меньше. В начальной части динамика пучка моделировалась по программе DYNAMION. Были изготовлены новые RFQ электроды с улучшенным качеством поверхности и реконструирована согласующая секция. Эксперименты с пучком после модернизации RFQ подтвердили расчетное увеличение тока пучка.

МОДЕРНИЗАЦІЯ СИЛЬНОТОЧНОЇ НАЧАЛЬНОЇ ЧАСТИНИ ПРИСКОРЮВАЧА ВАЖКИХ ІОНІВ UNILAC, GSI

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Для проекту FAIR після сильнострумового RFQ потрібний струм пучка U^{4+} більше 18 emA. В той же час інтенсивність пучка до реконструкції структури RFQ була в два рази менше. В початковій частині динаміка пучка моделювалась за допомогою програми DYNAMION. Виготовлені нові RFQ електроди, що мають підвищену якість поверхні, і реконструйована узгоджуюча секція. Експерименти з пучком після модернізації RFQ підтвердили розраховане збільшення струму пучка.