UPGRADE OF THE UNILAC HIGH CURRENT INJECTOR RFQ

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Abstract

For the operation of the GSI-accelerator chain as an injector for the future FAIR facility a considerable increase of the heavy ion beam intensity of up to a factor of 5 at the end of the UNILAC is required. The bottleneck of the whole UNILAC is the front-end system of the High Current Injector. It is shown that the transverse RFQ-acceptance can be significantly increased while the emittance growth can be reduced. Both goals are achieved with only a moderate change of the RFQ electrode geometry; the intervane voltage raised from 125 kV to 155 kV, but keeping the design limit of the maximum field at the electrode surface. The changed resonant frequency can be compensated with a relatively small correction of the carrying rings. The beam parameters in the final focusing elements of the LEBT were optimized together with the improved design of the input radial matcher; the length of the gentle buncher section was considerably increased to provide slow and smooth bunching resulting in a reduced influence of space charge forces. DYNAMION simulation with the modified electrode design resulted in an increase of the U^{4+}-beam current of up to 20 emA. It is planned to start the upgrade measure in spring 2009.

INTRODUCTION

In 1999 UNILAC passed a substantial upgrade - the Wideroe structure was replaced by the High Current Injector (HSI) [1]. The HSI consists of IH-type RFQ and two IH-DTL structures. The main goal of the upgrade project was to increase the U^{4+} beam current up to 15 emA. However the measured U^{4+} beam current behind the HSI never exceeded 6.5 mA. Detailed computer simulations using the DYNAMION code were performed to determine the source of beam intensity limitations [2]. The simulations were verified by beam parameters, measured during the whole period of HSI operation. The most important limitations were the following:

– lower brilliance of the injected beam in comparison with the design value;
– considerably mismatched beam at the RFQ-entrance due to the too high beam convergence required by original design;
– fast beam bunching in the RFQ gentle buncher section, leading to transverse emittance growth;
– strongly limited rf-voltage during the U^{4+} operation.

As a result, a partial RFQ upgrade program took place in 2004. It was mainly directed to the improvement of the rf-performance, but also included the new design of the input radial matcher (IRM), dedicated to optimize the beam dynamics in the focusing elements in front of the RFQ and to improve the matching itself [3].

The rf-performance of the HSI-RFQ was significantly improved after replacement of the electrodes. Minor changes in the IRM lead to 15% increase of the maximum beam intensity at the RFQ output (with the same beam, coming from the ion source). More than this, the results of the numerically calculated optimization of the RFQ electrode profile was confirmed and the beam dynamics codes were approved.

The FAIR program [4] requires increased beam intensities for the UNILAC as an injector. The HSI U^{4+} beam current has to be increased up to 18 mA. All previously obtained beam dynamics results confirmed that an essential RFQ electrode profile upgrade could provide for such requirements.

DESIGN OF THE HSI RFQ PROFILE

The main conditions for the new design are:

– maximum field at electrode surface should not exceed 320 kV/cm (existing design, U^{4+} -operation);
– total length of the electrodes must be exactly the same as in the existing design;
– operation frequency and other essential rf-parameters of the cavity must be kept, only minor adjustments of the resonant structure are acceptable.

It is clear, that an increase of the RFQ output beam current, keeping parameters of an injected beam, can be provided only by a corresponding increase of its transverse acceptance. The normalized transverse acceptance of the RFQ $\boldsymbol{V_k}$ can be expressed as:

$$V_k = \frac{1}{\lambda}\left(\frac{2}{m+1}\,\frac{R_0}{\rho_{\max}}\right)^2 \qquad (1)$$

with $\boldsymbol{\lambda}$ - wave length, $\boldsymbol{m}$ - modulation, $\boldsymbol{R_0}$ - average distance from axis to electrode, $\boldsymbol{\rho_{max}}$ - maximum value of the normalized matched envelope. The value of $\boldsymbol{\rho_{max}}$ is defined mainly by the focusing parameter $\boldsymbol{B}$, expressed through the maximum field at the electrode surface $\boldsymbol{E_{\max}}$:

$$B = \frac{Ze}{A}\frac{1}{E_0}\frac{E_{\max}}{\chi R_0}\lambda^2 \qquad (2)$$

with $\boldsymbol{\chi}$ - field enhancement factor, $\boldsymbol{A,Z}$ - mass and charge numbers, $\boldsymbol{E_0}$ - rest energy. For flat electrodes with semicircular tips $\boldsymbol{R_e}$ it can be calculated by the formula

$$\chi = \sqrt{\left[\frac{1}{2}\left(1+\frac{R_e}{R_0}\right)\right]^2 + \left[\frac{2T}{\pi} k\, R_0\, I_0\left(k\frac{R_0+R_e}{\sqrt{2}}\right)\right]^2} \qquad (3)$$

with $\boldsymbol{T}$ - transit-time factor, $\boldsymbol{k = 2\pi/\beta\lambda}$ - wave number, $\boldsymbol{\beta}$ - relative velocity of the particle, $\boldsymbol{I_0}$ - modified Bessel function [5]. It follows from the expressions above, that the only way to keep the focusing parameter $\boldsymbol{B}$ constant,

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while $\boldsymbol{R_0}$ increases, is to keep the $\boldsymbol{\chi R_0}$ value. The last condition can be satisfied by decreasing the R_e/R_0 ratio.

The electrode geometry for the existing RFQ design (dotted lines) and the new one (dashed lines) is shown in Fig.1. The bottom lines represent the electrode curvature radius R_e, the middle lines the average radius R_0 and the upper ones the R_e/R_0 ratio.

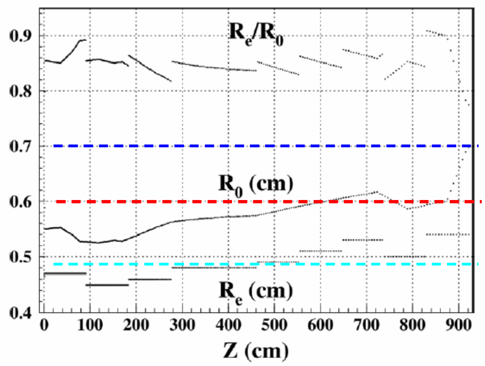

Figure 1: Electrode parameters of existing (dotted) and new (dashed) designs; the blue line represents the $\boldsymbol{R_e/R_0}$ ratio, the red line - $\boldsymbol{R_0}$ and the magenta line - $\boldsymbol{R_e}$.

The HSI-RFQ was designed with a variable $\boldsymbol{R_0}$ and $\boldsymbol{R_e}$ and with a constant voltage $\boldsymbol{U}$ along the structure. The design voltage of the existing RFQ ($\boldsymbol{U}$=125 kV) is limited by $\boldsymbol{R_0}$ near cell #100 (Fig. 1). According (2), it determines in total the relatively low acceleration rate and low focusing parameter $\boldsymbol{B}$ in the main part of the RFQ. The new electrode geometry is designed with constant $\boldsymbol{R_0}$ (6 mm) and $\boldsymbol{R_e/R_0}$ (0.7) along the whole RFQ structure. It allows to increase the voltage keeping the maximum field $\boldsymbol{E_{max}}$. The higher voltage allows to reduce the modulation in the main part of the RFQ and to optimize the beam dynamics in the gentle buncher to prevent excessive transverse emittance growth.

An increase of the high order terms in the RFQ electrical field due to the lower $\boldsymbol{R_e/R_0}$ ratio was investigated and a minor influence of this effect to the particle transmission (< 1.5%) was demonstrated.

The new RFQ-channel was designed using the DESRFQ code [6]. Modulation and synchronous phase for each RFQ-cell were chosen to provide the following conditions:

- capture of the particles into acceleration is not less then 90 %;
- separatrix is filled in the beginning of the gentle buncher as uniformly as possible;
- transverse phase advance is almost constant along the gentle buncher;
- tune depression in gentle buncher is almost equal its initial value.

The baseline design was optimized for U^{4+} beam current of 20 mA and a total transverse emittance of 280 mm*mrad (unnorm.). These values were chosen on the base of the measurements in front of the RFQ (15 mA, 210 mm*mrad) assuming the same brilliance of the high current beam coming from the ion source. The main parameters of the new design are summarized in Tab. 1.

Table 1: Main RFQ Parameters

	New	Existing
Voltage, kV	155.0	125.0
Average radius, mm	6.0	5.2 ÷ 7.7
Electrode width, mm	8.4	9.0 ÷ 10.8
Max. field, kV/cm	312	318
Modulation	1.012 ÷ 1.93	1.001 ÷ 2.09
Synch. Phase, degree	-90 ÷ -28	-90 ÷ -34
Aperture, mm	4.1	5.5÷3.8÷4.8
Min. transverse phase advance, rad	0.56	0.45
Norm. transverse acceptance, mm*mrad	0.86	0.73
Electrode length, mm	9217.4	9217.4

SIMULATION RESULTS

The beam dynamics simulations for the final RFQ design were additionally carried out with the DYNAMION code. The RFQ output beam current in dependence on the input current (15 ÷ 30 mA) is shown in Fig. 2 for the case of a constant input emittance (210 mm*mrad, green line); additionally for the input emittances increased proportionally to the beam current (210 ÷ 420 mm*mrad, red line).

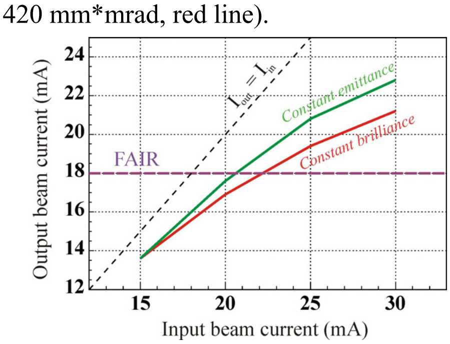

Figure 2: Simulated beam current at RFQ output in dependence on input current.

A comparison of the existing and the new RFQ channels is illustrated in Fig. 3. A beam current inside a given transverse emittance at the RFQ-output is shown for both designs. Beam dynamics simulations were done for the same beam current (25 mA) and emittance (210 mm*mrad), but with matched Twiss-parameters for each case.

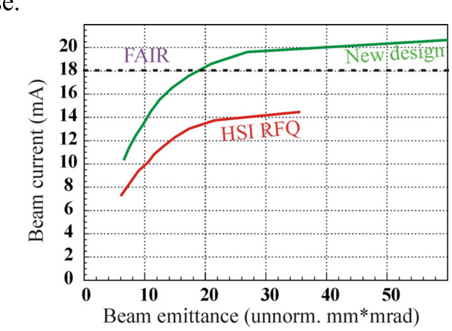

Figure 3: Beam current inside a given emittance at the RFQ-output for the existing design (red) and the new design (green).

The new RFQ design provides for more than 40% of the beam current compare to the old design. Higher beam emittance behind the new RFQ channel is formed by a few percent of the particles, while the core of the beam (20 mm*mrad) contains the required beam current.

An additional cross-check of the beam dynamics for the new RFQ was performed with the PARMTEQM code; a good coincidence of the results was demonstrated [7].

RESONANT STRUCTURE

For improved beam dynamics the average channel aperture $\boldsymbol{R_0}$ and the electrode half-width/curvature $\boldsymbol{R_e}$ have been specified constant along the channel. It leads to a different capacitive load, the appearing frequency shift must be compensated by other channel parameters. For the existing IH-RFQ a frequency of 35.96 MHz was calculated, what is in good agreement with the experimentally measured value. Then the height of the electrode "shoulder" ***h*** and the ring length ***L*** (Fig. 4) were used as free parameters to achieve the design frequency for the new channel.

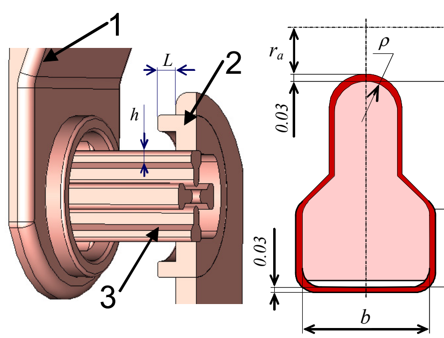

Figure 4: Regular cell of IH-RFQ structure (left) and electrode cross-section (right). 1 - stems; 2 - carrier rings; 3 - electrodes (mini-vanes).

The length of the carrier rings is the most efficient parameter for frequency adjustment, available at every cell of the structure. The frequency dependence on the length of the carrier ring edge, calculated for the structure with the modified channel, is shown in Fig. 5.

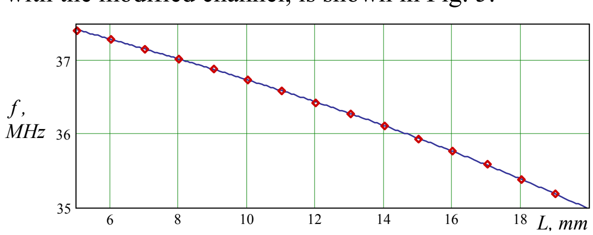

Figure 5: IH-RFQ frequency as a function of the length of the carrier ring edges.

A desired frequency of 35.96 MHz without tuners may be realized with the structure cell parameters given in the Tab. 2, while the operating frequency of 36.136 MHz will be reached with inductive tuning plungers.

Table 2: Main Dimensions of the IH-RFQ Cell

R_0, mm	R_e, mm	*b*, mm	*h*, mm	*L*, mm
6.0	4.2	16.0	7.0	14.8

In order to reduce dark current contributions [3], the electrode surface has to be covered by a 0.03 mm layer of electrolytic copper (Fig. 4, right). The electrodynamics simulations for the final geometry showed that additional 10 micrometers of copper layer lead to a frequency shift of about 0.023 MHz, which is comparable to the effect of one plunger. The frequency sensitivity to the radial displacement of the electrode is considerably less (0.0006 MHz/μm).

CONCLUSION

The new electrode profile for the HSI-RFQ was designed with higher transverse acceptance and phase advance, keeping the maximum field at the electrode surface of the recently operating machine. The new design of the Input Radial Matcher allows for an improved beam matching to the RFQ by means of the LEBT quadrupole lenses. Beam dynamics in the beginning of the gentle buncher was optimized to provide for rapid and uniform (as possible) separatrix filling. To avoid an excessive rf-defocusing and a significant space charge influence, the modulation and the synchronous phase in the gentle buncher increase considerably slower compare to the existing RFQ-design. The maximum modulation in the main RFQ part is also reduced.

The shift of the resonant frequency of the cavity with increased average radius and reduced electrode thickness can be compensated with minor changes of the topology of the mini-vane and the connecting ring.

Beam dynamics in the new channel were studied with the DYNAMION code. It could be shown, that the beam intensity at the HSI-RFQ output (18 mA of U^{4+} ions), required for the FAIR program, can be reached.

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REFERENCE

[1] W. Barth, "Commissioning of the 1.4 MeV/u high current heavy ion linac at GSI", LINAC 2000, USA.
[2] S. Yaramishev et al., "Development of the versatile multi-particle code DYNAMION", NIM A, 2005.
[3] S. Yaramyshev et al., "Upgrade of the high current heavy ion front-end system of the GSI UNILAC", IWCPA 2005, Prob.Atomic Sci.Technol., 2006.
[4] W. Barth et al., "Upgrade Program of the High Current Heavy Ion UNILAC as an Injector for FAIR", ICAP 2006, NIM A, 2007.
[5] A. I. Balabin, Preprint ITEP 81-107, 1981.
[6] Physical Review Vol. 5, 060101 (2002).
[7] A. Schempp, IAP Int. Rep. UF-IAP-S-08-1307.
[8] R. Tiede, IAP Int. Rep. IAP-DYNA-010708.