HSI RFQ UPGRADE FOR THE UNILAC INJECTION TO FAIR

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Abstract

As an injector to the future FAIR facility, the UNILAC accelerator is required to deliver ion beams with high intensities as well as good beam quality. The electrodes of the current HSI RFQ are exhausted and the current RFQ itself is assigned to be one bottle-neck for improving the brilliance performance of the whole linac. Based on the so-called NFSP (New Four-Section Procedure) method, a new RFQ electrode design has been developed and optimized for 20 emA, U^{4+} beams at the RFQ entrance. Since only the electrodes will be replaced, the RFQ length has been kept unchanged. Even with a lowered inter-vane voltage, the new RFQ design has achieved better beam performance compared to the previous design. This paper will focus on the performed study with respect to beam dynamics.

BACKGROUND

A new international accelerator facility for antiproton and ion research, FAIR [1], is under construction at GSI in Germany. In order to make various unique physics experiments possible, the FAIR facility will need to provide particle beams with unprecedented intensity and quality, which brings challenges to the performance of the injectors.

Figure 1 shows the today's GSI (in blue) and the future FAIR (in red). FAIR will have two injectors: the existing UNILAC and the planned p-Linac. According to the current schedule, only the UNILAC will be available for the first beam commissioning of FAIR. Some parts of the UNILAC are more than 30 years old, so a series of dedicated upgrade programs have been started or prepared to ensure a reliable and satisfying injection to FAIR [2].

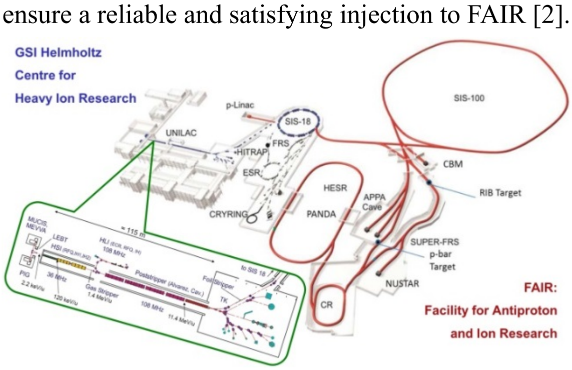

Figure 1: The FAIR Facility and the UNILAC injector.

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Covering the energy range from 2.2 keV/u to 120keV/u, the 36.136 MHz HSI RFQ is the first accelerating structure of the UNILAC. Therefore, its performance is crucial for the beam performance of the whole facility.

A brief overview on the history of the HSI RFQ is given below:

- 1996: the first HSI RFQ was started to be designed [3]
- 1998: the first HSI RFQ was produced
- 1999: the first HSI RFQ was tested with beam
- 2004: the radial matching section was redesigned, and new electrodes were produced
- 2008: the second set of electrodes for the HSI RFQ was designed and produced [4]
- 2009: the HSI RFQ with the second set of electrodes was put into operation
- 2015: the third set of electrodes for the HSI RFQ has been started to be developed

The second set of electrodes is currently still in use, but suffered from sparking (especially during mixed duty-cycle operation). Therefore, a new set of electrodes is being designed with the following requirements:

- Design beam intensity is 20 emA (for real operation, 18 emA and 16.2 emA will be expected at the entrance and the exit of the RFQ, respectively)
- Lower max. surface electric field ($E_{s,\,max}$)
- Same length (tolerance: ±1 mm, as the same tank will be used)
- Good beam performance, e.g. high transmission and high brilliance

The above-mentioned boundary conditions should be satisfied simultaneously, so the design study for this 9.2m-long RFQ accelerator, one of the longest RFQs in the world, is challenging. In this paper, the concepts adopted to reach the design goals as well as the beam dynamics design and simulation results will be presented.

DESIGN CONCEPTS & OPTIMIZATION

The design of 2008 for the HSI RFQ was made mainly following the traditional LANL Four-Section Procedure [5] which is characterized by a constant mid-cell aperture of the electrodes r_0 throughout the RFQ, a gentle main bunching, and a fast pre-bunching of the beam. For the new HSI RFQ, a different beam dynamics design method,

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the so-called New Four-Section Procedure (NFSP) [6, 7], was taken. The NFSP method uses instead:

- A varying transverse focusing strength which is adapted to the changing space-charge conditions along the bunching process
- A soft pre-bunching in order to maximally capture the input particles and form them into bunches with minimum longitudinal emittance growth
- A relatively fast main bunching which can help overcoming the increased space-charge forces in a gradually bunched beam

Figure 2 gives a comparison of the evolution of the mid-cell aperture between two designs. The new design starts with a bigger r_0 and then decreases it gradually to an end value which is smaller than that of the previous design and is afterwards held almost constant after z = 4 m. The average r_0 is only 0.02 cm smaller than before, but it allows reducing the inter-electrode voltage from 155 kV to 125 kV, which will not only lower $E_{s,\,max}$ but also save the RF power significantly. In addition, the slowly shrunk r_0 improves the transverse acceptance of the RFQ.

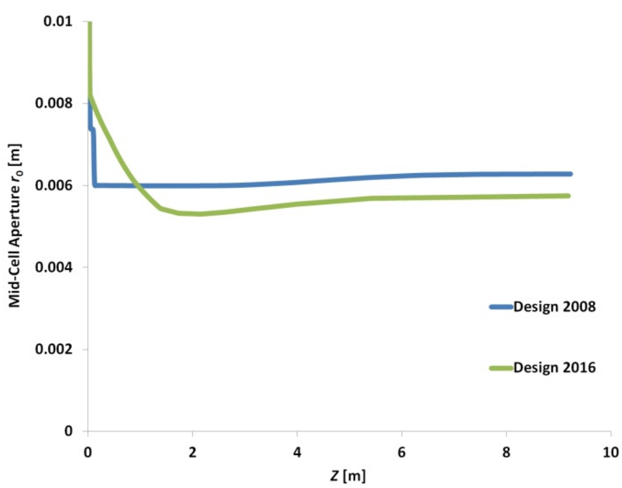

Figure 2: Evolution of mid-cell aperture of electrodes along the RFQ channel.

Figure 3 shows the evolution of the acceleration efficiency along the RFQ channel. The acceleration efficiency is defined by Eq. (1) [8], where a is the minimum aperture and m is the modulation of the electrodes for each cell, respectively:

$$A \equiv \frac{m^2 - 1}{m^2 I_0(ka) + I_0(mka)} \qquad (1)$$

The new design has an NFSP-style beam bunching:

- fairly soft at the beginning for the pre-bunching, which improves the longitudinal acceptance of the RFQ
- and afterwards much faster for the main bunching, which can not only balance the increasing transverse defocusing effects but also compensate the length increase caused by the slowed-down pre-bunching

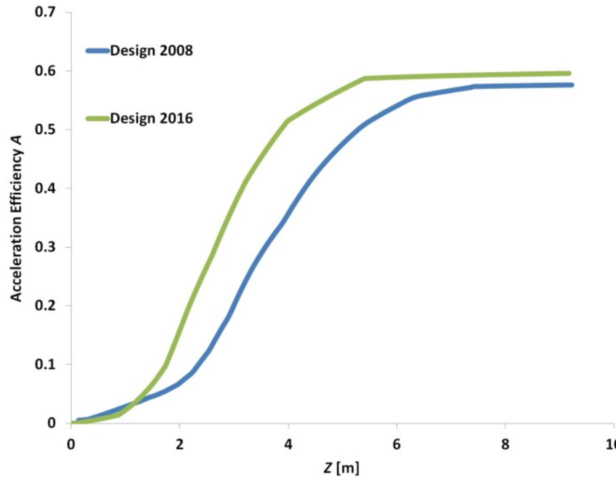

Figure 3: Evolution of acceleration efficiency along the RFQ channel.

In Fig. 4, one can see that both designs have achieved the same energy gain within almost identical distance.

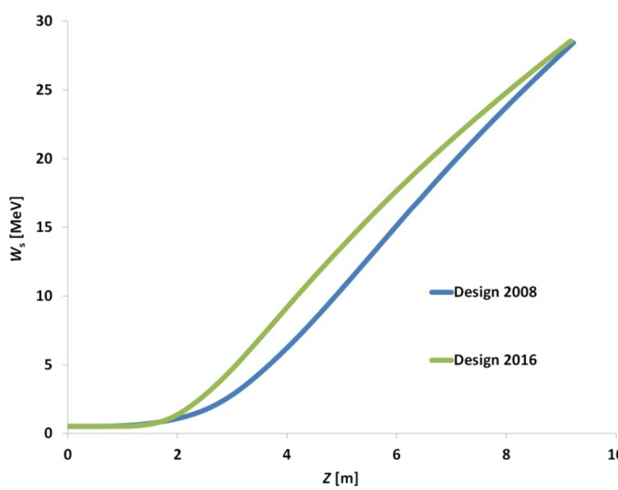

Figure 4: Evolution of synchronous energy along the RFQ channel.

DESIGN RESULTS & COMPARISON

The detailed parameters of the two designs for the HSI RFQ, Design-2016 and Design-2008, are compared in Table 1.

The input beams used by them have same beam intensities, emittance, and Twiss parameters as well. With a 20% lower inter-electrode voltage, the RFQ is now even ~5 cm shorter, which will be corrected in the last fine-tuning phase. Another result is the lowered $E_{s,\,max}$, which helps to reduce the risk of sparking. Meanwhile, the beam transmission efficiency is ~5% higher than the previous one. Also, some non-design cases have been checked for the new design. For example, the input emittance and input intensity were increased from 210 π mm-mrad to 280 π mm-mrad and from 20 emA to 35 emA, respectively, both calculated beam transmission

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efficiency were still 84%, which showed the robustness of the new design.

The brilliance B for 80% center particles of the output beam given by the new design is 61.5 emA/mm-mrad, which is ~2 times bigger than the expected value.

$$B \equiv \frac{I}{\varepsilon} \qquad (2)$$

Table 1: Comparison of the HSI-RFQ Designs

	Design 2016	Design 2008
W_{in} [keV/u]	2.2	2.2
W_{out} [keV/u]	120	120
U [kV]	125	155
$r_{0,\ avg.}$ [cm]	0.58	0.60
$E_{s,\ max}$ [MV/m]	30.2	31.2
g_{min} [cm]	0.53	0.60
I_{in} [emA]	20	20
$\varepsilon_{in,\ trans.,\ unno.,\ real}$ [π mm-mrad]	210	210
$\alpha_{twiss,\ in,\ trans.}$	0.6	0.6
$\beta_{twiss,\ in,\ trans.}$ [cm/rad]	13.6	13.6
$\#_{Cells}$	384	409
L [cm]	916.4	921.7
T [%]	94.1	88.5

The previous design was made eight years ago, so many simulation results cannot be easily found. One available output particle distribution of Design-2008 was given by a simulation using 25 emA as the input beam intensity and 10000 macro-particles.

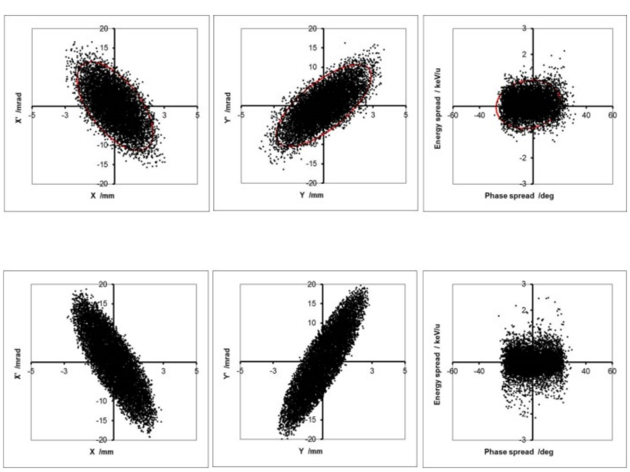

Figure 5: Output phase spaces of the two designs at 25 emA (top: Design-2008; bottom: Design-2016).

For a good comparison, the new design was simulated also using a 25 emA input beam with a same number of macro-particles. The output distributions for the two cases are plotted together in Fig. 5.

The output distribution of the previous design contains 8300 particles (only accelerated) which resulted in the output emittances, $\varepsilon_{x,\ n.,\ rms}$ = 0.066 π mm-mrad, $\varepsilon_{y,\ n.,\ rms}$ = 0.069 π mm-mrad, and $\varepsilon_{z,\ rms}$ = 0.325 keV/u-ns, respectively. As the not-well-accelerated particles were removed from the simulation, the output transverse emittances are smaller than the input one $\varepsilon_{in,\ n.,\ rms}$ = 0.076 π mm-mrad. Keeping all transported particles, the new design led to an output distribution consisting of 9328 particles which are all accelerated. The calculated output emittances are, $\varepsilon_{x,\ n.,\ rms}$ = 0.076 π mm-mrad, $\varepsilon_{y,\ n.,\ rms}$ = 0.074 π mm-mrad, and $\varepsilon_{z,\ rms}$ = 0.327 keV/u-ns, respectively. It can be seen that there are no emittance growth in the transverse planes and the emittances are comparable for the both designs in the longitudinal plane.

CONCLUSIONS

Benefitting from the efficient NFSP method, a new beam dynamics design has been developed for the HSI RFQ accelerator. Though the inter-electrode voltage has been lowered by 20%, the new design has fulfilled all design goals with improved beam quality. As parallel activities for the UNILAC upgrade, a new LEBT (Low Energy Beam Transport) section dedicated for uranium ions and a new MEBT (Medium Energy Beam Transport) section in front of and behind the RFQ, respectively, have been also designed. The optimization of input and output matching for the HSI RFQ is now ongoing. It is foreseen that the construction of the RFQ rods will be started in this year.

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