ADVANCED BEAM DYNAMICS SIMULATIONS WITH THE DYNAMION CODE FOR THE UPGRADE AND OPTIMIZATION OF THE GSI-UNILAC

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Abstract

With the advanced multi-particle code DYNAMION it is possible to calculate beam dynamics in linear accelerators and transport lines under space charge conditions with high accuracy. Special features as data from the real topology of RFQ electrodes, drift tubes, quadrupole lenses, misalignment and fabrication errors and consideration of field measurements lead to reliable results of the beam dynamics simulations. Recently the DYNAMION code is applied to the upgrade and optimization of the GSI UNILAC as an injector for the Facility for Antiproton and Ion Research at Darmstadt (FAIR). An operation of the FAIR requires for the increase of the beam- intensity and -brilliance coming from the UNILAC (up to a factor of 5).

End-to-end simulations for the whole linac (from ion source output to the synchrotron entrance) allow for the study and optimization of the overall machine performance as well as for calculation of the expected impact of different upgrade measures, proposed to improve the beam brilliance. The results of the beam dynamics simulations by means of the DYNAMION code are compared with the recent measurements, obtained after upgrade of the High Current Injector (HSI) in 2009.

INTRODUCTION

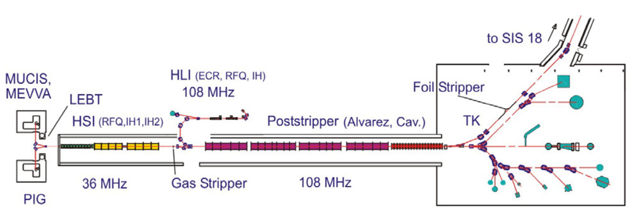

Figure 1: Schematic overview of the GSI UNILAC and experimental area.

Besides two ion source terminals and a low energy beam transport system (LEBT) the UNILAC-HSI comprises a 36 MHz IH-RFQ accelerating the ion beam from 2.2 keV/u up to 120 keV/u and a short 11 cell adapter RFQ (Super Lens). The IH-DTL, consisting of two separate tanks, accelerates the beam up to the final HSI-energy of 1.4 MeV/u. After stripping and charge state separation the Alvarez DTL provides for beam acceleration without significant particle loss. The transfer line (TK) to the SIS 18 is equipped with a foil stripper and another charge state separator system [1].

The HSI was commissioned in 1999 aiming for 15 mA of U^{4+} beam current. However the measured uranium beam current never exceeded 6.5 mA.

In 1999-2003 an extended experimental program dedicated to improve the overall UNILAC performance for heavy ion high current operation lead to an U^{73+} intensity of 2.0 emA at the injection to SIS 18. Before foil stripping 4.5 emA of U^{28+} beam intensity was achieved. An optimized total particle transmission of up to 50% was reached, while a design performance of about 90%was expected. The beam losses mainly happen in the front-end area of the HSI [2].

NUMERICAL INVESTIGATIONS AND FACILITY UPGRADE

Recently, for the operation of the GSI-accelerator chain as an injector for the FAIR facility, a considerable increase of the heavy ion beam brilliance of up to a factor of 5 at the end of the UNILAC is required [3].

HSI Upgrade I (2004)

Since 1999 detailed computer simulations using the DYNAMION code [4] were performed to determine the source of beam intensity limitations. The simulations were verified by beam parameters, measured during the UNILAC operation. It was demonstrated that the bottleneck of the whole facility is the front-end system of the HSI. 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 a new design of the input radial matcher (IRM), dedicated to optimize the beam dynamics in the focusing quadrupoles in front of the RFQ and to improve the matching itself [5].

The rf-performance of the HSI-RFQ was significantly improved after replacement of the electrodes. Minor changes of the IRM (approx. 1% of the RFQ length) lead to 15% increase of the maximum beam intensity at the RFQ output (with the same beam from the ion source). The prediction of the numerically calculated optimization of the RFQ electrode profile and beam matching was confirmed. The beam dynamics codes were approved.

HSI Upgrade II (2009)

The FAIR program requires an increased HSI U^{4+} beam current of up to 18 mA. The results of numerical investigation demonstrated a necessity of an essential upgrade of the RFQ electrode profile for the FAIR requirements. Simulations, done by means of the

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DYNAMION code for the HSI with different input beam currents, are summarized in Fig. 2.

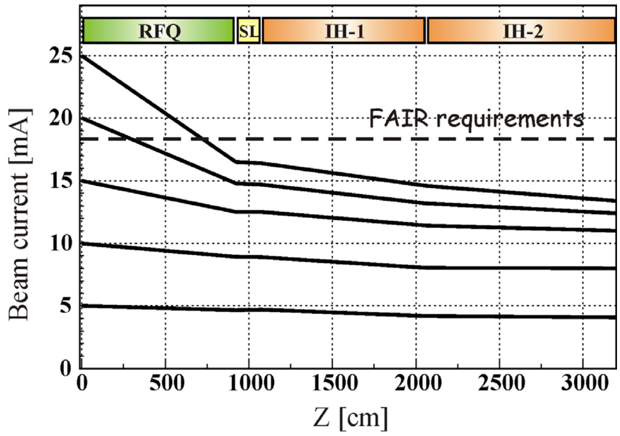

Figure 2: The HSI performance before the 2009 upgrade, simulated for different input beam current in comparison with the requirements for FAIR.

During further numerical investigations it was shown that the transverse RFQ-acceptance can be significantly increased while the emittance growth is reduced. Both goals are achieved with a change of the RFQ electrode geometry (aperture and modulation law) inside existing rf-cavity. The new RFQ accelerating-focusing channel was designed using the DESRFQ code [6]. The intervane voltage was increased from 125 kV to 155 kV keeping the design limit of the maximum field at the electrode surface. The changed resonant frequency was compensated with a relatively small correction of the carrying rings. A significant limitation for the channel design was a necessity to keep the total length of the electrodes (≈ 9 m) with an accuracy of less than 1 mm.

Design of the New HSI RFQ Electrode Profile

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 V_k can be expressed as:

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

with λ - wave length, m - modulation, R_0 - average distance from axis to electrode, ρ_{max} - maximum value of the normalized matched envelope [7]. The value of ρ_{max} is defined mainly by the focusing parameter B, expressed through the maximum field at the electrode surface $E_{\max}$:

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

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

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

with T - transit-time factor, $k = 2\pi/\beta\lambda$ - wave number, β - relative velocity of the particle, I_0 - modified Bessel function. It follows from the expressions above, that the only way to keep the focusing parameter B constant, while R_0 increases, is to keep the χR_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. 3. 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.

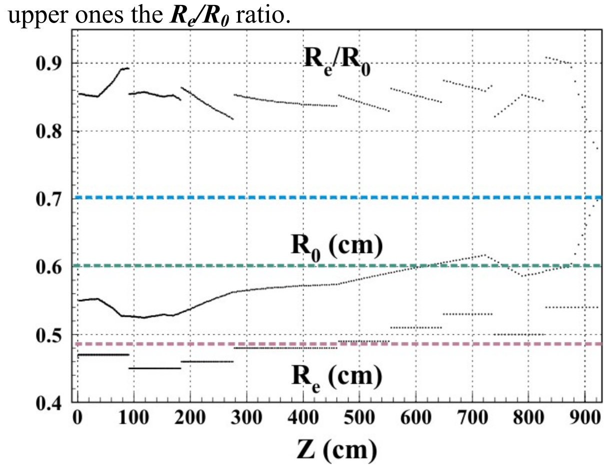

Figure 3: Electrode parameters of the old (dotted) and new (dashed) RFQ designs; the blue line represents the R_e/R_0 ratio, the green line - R_0 and the violet line - R_e.

The original HSI-RFQ was designed with a variable R_0 and R_e and with a constant voltage U along the structure. The design voltage of the RFQ (U=125 kV) was limited by minimum of R_0. According (2), it determines in total the relatively low acceleration rate and low focusing parameter B in the main part of the RFQ. The new electrode geometry is designed with constant R_0 (6 mm) and R_e/R_0 (0.7) along the whole RFQ structure. It allows an increased tank voltage keeping the maximum field 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 R_e/R_0 ratio was investigated and a minor influence of this effect to the particle transmission (< 1.5%) was demonstrated.

The baseline design was optimized for an U^{4+} beam current of 20 mA and a total transverse emittance of 280 mm*mrad (2.2 keV/u, 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 Table 1.

The beam dynamics simulations for each iteration of the design were additionally carried out with the codes DYNAMION (RFQ) and LORASR (Superlens and IH-section) [8]. The beam envelopes in the final focusing quadrupoles 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.

Table 1: Main RFQ Parameters

	New	Old
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
Average aperture, mm	4.1	5.5÷3.8÷4.8
Norm. transverse acceptance, mm*mrad	0.86	0.73
Electrode length, mm	9217.4	9217.4

The RFQ output beam current, calculated for the final design in dependence on the input current (15 ÷ 30 mA) is shown in Fig. 4 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).

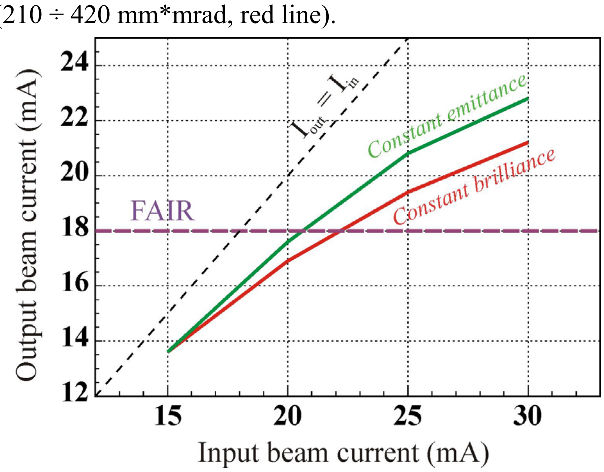

Figure 4: The RFQ output beam current as a function of injected one.

For the new RFQ design the beam transmission is 40% higher. Relatively increased 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.

Improved Description of the High Energy RFQ-end

The low energy RFQ-end is described in the code DYNAMION as a 3D filed mapping, obtained from the solution of the Laplace equation for the given topology of the Input Radial Matcher including distance from flange to the electrodes. The external electric field for the regular RFQ part is described by the well-known 8-term potential with approximated coefficients obtained from the solution of the Laplace equation for the real topology of each RFQ cell. The additional improvement was implemented for the high energy RFQ-end. The last two cells (including distance from electrodes to the flange) were described independently by the dedicated code from the DYNAMION package and EM-Studio. An obtained 3D field mapping was introduced into DYNAMION.

As expected, the comparison of the beam dynamics simulations for the improved description of the RFQ-end with standard ones showed only minor difference for the final particle energy and beam shape behind the HSI-RFQ. Nevertheless, this measure is a further improvement of the reliability of the code and additionally confirms earlier DYNAMION simulations. Similar detailed calculations of the external electrical field in the Superlens (short 11-cells RFQ section) were done and also used for advanced beam dynamics simulations.

"High Current" RFQ Acceptance

Assuming low beam current and smooth approximation [7], a local normalized acceptance V_k for each RFQ cell can be calculated from the Floquet functions, which are the solution of the Mathieu-Hill equation for the particle motion:

$$V_k = \nu_f \frac{a^2}{\lambda}, \; \nu_f = \frac{1}{\rho^2},$$

where ρ is a module of the Floquet function, a - aperture (radius) of the cell, λ - wave length of the operating frequency; ν_f can be treated as a minimum of the phase advance μ on the focusing period.

For a significant injected beam current the values of μ and ν_f decrease (tune depression). Quantitatively it can be calculated by using the Coulomb parameter h, which combines the parameters of the beam and the accelerating channel:

$$h = j \cdot \frac{B\lambda}{\mu_0 \beta I_0},$$

where $j = I/V_p$ - beam brilliance, I - beam current, V_p - normalized beam emittance, B - ratio of the peak current to the pulse current, I_0=3.13·10^7·A/Z - characteristic current, A, Z - mass and charge numbers, μ_0 - phase advance for "zero" current, β - relative velocity of particle. Phase advance and, correspondingly acceptance of the channel can be evaluated as

$$\mu = \mu_0 \left(\sqrt{1+h^2} - h\right),$$
$$V_k = V_{k0} \left(\sqrt{1+h^2} - h\right).$$

The minimum of the "zero" current local acceptance along the new RFQ channel is 0.856 mm*mrad for an U^{4+} beam [6]. It corresponds to the total unnormalized acceptance at the RFQ entrance (2.2 keV/u) of about 400 mm*mrad. The Coulomb parameters reaches its maximum value along RFQ channel in the gentlebuncher, where the peak current is already high (B ≈ 2), while the beam energy is low.

Previous measurements show an U^{4+} beam current of up to 37 mA, coming from the ion source. The uranium beam current measured before injection to the RFQ is 15 mA only, while beam emittance is about 200 mm*mrad. A significantly higher beam emittance coming from the ion source can explain the observed particle losses in the complicate LEBT (including mass-separation).

The new compact line for the straight injection of uranium beam to the HSI-RFQ is already planned [2]. The potentially possible matching of the beam emittance to the acceptance of the new HSI-RFQ was investigated in a wide range of expected beam brilliance. An increase of the beam brilliance leads to a decrease of the RFQ acceptance. The calculated dependence of the acceptance on the injected beam- current and -emittance defines a brilliance limitation for the new HSI-RFQ design (Fig. 5). With a beam current of about 25 mA at the RFQ entrance and the transmission of 80% the FAIR requirements are fulfilled. For this current the acceptance of the RFQ and the emittance of the injected beam are limited to 300 mm*mrad.

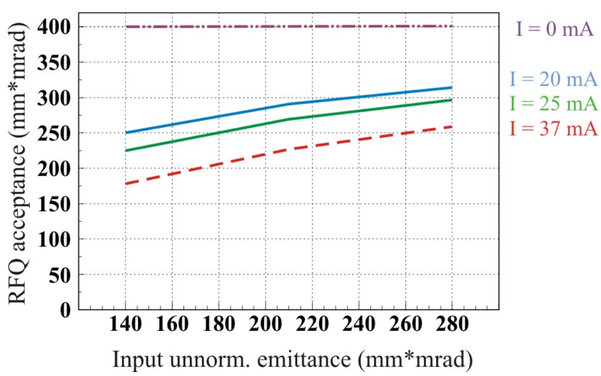

Figure 5: "High current" acceptance of the HSI-RFQ as a function of the beam emittance (for different current).

Optimization of the LEBT with Measured Emittances

Beam matching to the HSI-RFQ is carried out with four magnetic quadrupole lenses (Quadrupole Quartet, QQ). Transverse beam emittances can be measured with a slit-grid device, placed 3 m in front of the RFQ. Due to the limited space between the QQ and the RFQ, beam transmission can be measured only for the whole front-end system (QQ and RFQ).

Originally the aperture of the quadrupoles was defined for the design beam emittance of 140 mm*mrad. The recently measured data is up to 2 times higher, leading to significant beam losses in the matching quadrupoles (set to design gradients). Changed settings of the quadrupoles improve the particle transmission through the lenses, but instantly make worse the matching to the RFQ. This leads to additional particle losses in the RFQ channel. Therefore experimental beam matching to the RFQ is a complicate task.

Beam emittance measurements (Fig. 6, top) in the LEBT in October 2009 were analyzed and used for the optimization of the U^{4+} beam matching to the RFQ. A 6D particle distribution was generated from the measured emittance data, taking into account an elliptical shape of the beam in real space. The number of particles is proportional to the measured intensity of each bin (Fig. 6, bottom). The longitudinal distribution is uniform (±180° without energy spread). Simulations of the particle motion through the matching quadrupoles and through the RFQ (assuming the measured beam current) were done using the measured shape of the focusing gradient along the axis. Measurements of the magnetic field were done for each quadrupole separate. Overlapping of the magnetic field from neighboring quadrupoles was calculated by DYNAMION for each set of gradients, taken from the machine settings. A discrepancy of the calculated particle transmission (about 10-20% lower than measured one) was observed.

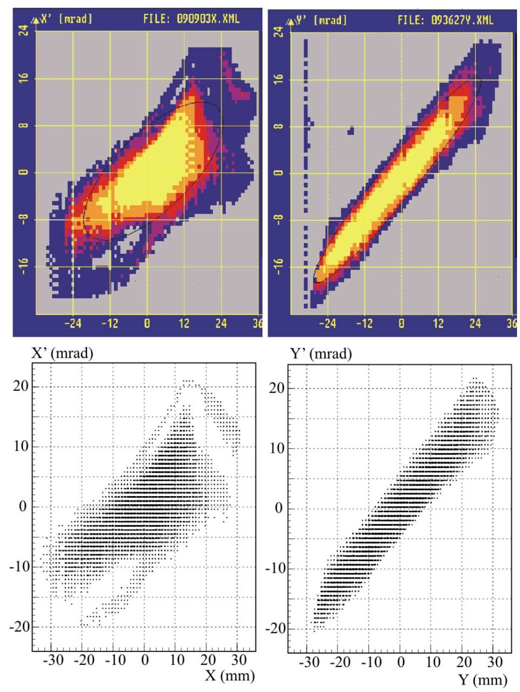

Figure 6: Measured hor. and vert. U^{4+} beam emittances (top) and related generated particle distribution (bottom).

Results of the calculated particle motion within the area of the diagnostic box were analyzed, reconstructing measurements of the horizontal and vertical emittances separately. It was verified, that during measurements of the vertical emittance (with vertically moving horizontal slit and grid) the full range of vertical coordinates Y and angles Y' was observed. At the same time, calculations show remarkable particle losses at the slit and at the grid due to their limited horizontal size. During measurement of a horizontal emittance the limitation of the vertical size of the moving horizontally slit and grid also leads to the particle losses. As a consequence the real transverse 4D beam emittance and its projections on the phase planes are much more peaked, than evaluated from the measurements. The amount of such particles might be estimated up to 40% (for both vertical and horizontal planes). With relatively high probability these particles pass through the quadrupoles and RFQ, forming the measured transmission significantly higher than the calculated one.

The importance of the computer investigation and the optimization of the beam matching was demonstrated and experimentally verified during the successful HSI-RFQ upgrade in 2004. Incompletely measured emittances hamper strongly a numerical optimization of the beam matching to the HSI-RFQ. A size, shape and orientation of the real beam might differ from the measurements. Consequently, the settings of the matching quadrupoles should be corrected.

During machine experiments (2009-2010) with an U^{4+} beam current of 7 mA, the complex LEBT (including mass-separation) was optimized for a smaller beam- size and -divergence at the position of emittance measurement device. Certainly this optimization was done for both transverse phase planes simultaneously. Nevertheless recent divergence of about ±20 mrad is relatively high. In 2004 a measured divergence was about ±12 mrad only, even for higher beam current of 15 mA. This issue can be explained by a bigger and/or deformed beam emittance.

As a consequence new slits and grids with extended size are already ordered. This measure can generally improve a quality of the measurements and increase an efficiency of the numerical optimization.

RECENT HSI COMMISSIONING AND OPTIMIZATION

Beam commissioning (Ar^{1+} high current beam) of the new HSI-RFQ started in July 2009 [9]. A beam energy of 119.64 keV/u has been measured using the TOF method. The design value calculated with DYNAMION code is 119.60 keV/u. Re-commissioning of the complete HSI, including Superlens and IH, verified the correct RFQ beam energy. First measurements showed a significant gain in particle transmission through the quadrupole quartet and the new RFQ (Fig. 7).

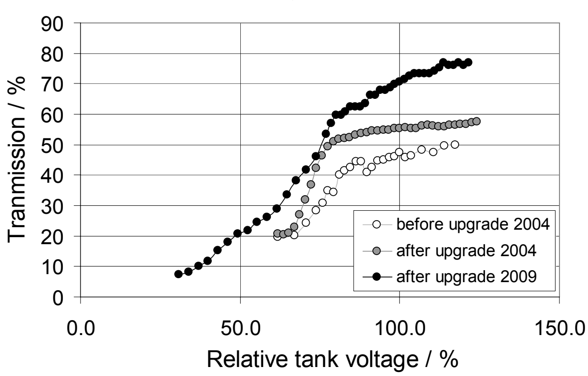

Figure 7: Measured HSI-RFQ transmission (Ar^{1+}, input current 16 mA).

The improved performance of the new HSI-RFQ was also demonstrated with an uranium beam. After three weeks for conditioning the design level of the tank voltage (155 kV) was reached. An additional optimizations of the LEBT with 7 mA U^{4+} beam current in 2010 results in a maximum transmission of 95% through the quadrupole quartet and the RFQ (Fig. 8).

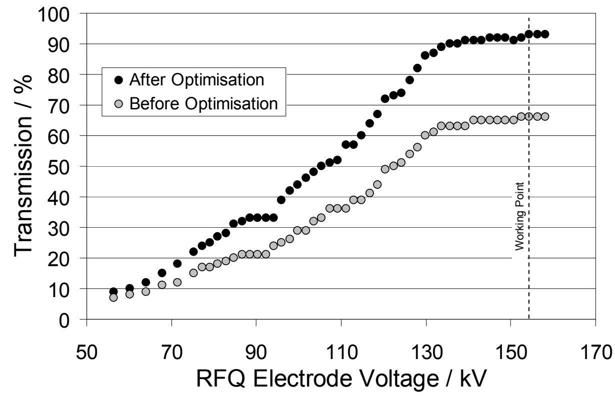

Figure 8: Measured transmission after the 2009 upgrade and after additional optimization of the LEBT during machine experiment in 2010 (U^{4+} input beam current 7 mA).

CONCLUSION

The HSI-RFQ with a newly designed electrode profile has been successfully commissioned in 2009. The beam dynamics in the channel was studied with the DYNAMION code. It was shown, that the beam intensity (18 mA of U^{4+} ions) behind new HSI-RFQ, required for the FAIR program, can be reached.

The HSI-RFQ upgrade resulted in a significant increase of high current transmission. In particular, 95% RFQ transmission for a 7 mA U^{4+} beam was reached. Recently a bottleneck of the HSI is shifted to the beam matching to the IH-section. Nevertheless a machine record of 8.5 mA Ar^{1+} beam current behind the whole HSI was established. Future upgrade steps will provide for full performance as required for FAIR.

Corresponding beam dynamics studies for the whole UNILAC facility are in progress. An end-to-end simulation for the whole linac is an advanced tool for the study and optimization of the overall machine performance as well as for the calculation of the expected impact of different upgrade measures. The comparison of the calculated and measured data proved the high reliability and accuracy of the code DYNAMION.

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