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DYNAMION—A Powerful Beam Dynamics Software Package for the Development of Ion Linear Accelerators and Decelerators

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Abstract: Numerous ambitious particle accelerator facilities, based on proton and ion linear accelerators, have recently been in development for fundamental research, as well as for industrial applications. The advanced design of such new machines, as well as the upgrade and optimization of existing linacs, requires adequate, precise and reliable tools to simulate beam dynamics. The software package DYNAMION, created about 30 years ago, is undergoing systematic improvement and further development in order to characterize modern ion linacs and to provide solutions for its intrinsic complex problems. The DYNAMION code features Front to End beam dynamics simulations under space charge conditions in a linac system, comprising an arbitrary sequence of accelerating-focusing structures and beam transport lines. The evolution of a macroparticle ensemble could be analyzed at a high level of specification. A 3D distribution of the external electrical field (RFQ, DTL) is modeled using integrated internal solvers. Optionally, a 3D electromagnetic field mapping, supplied by specialized external codes, could be used. The recent status of the DYNAMION software package is presented in this paper. Furthermore, the performance of the code is demonstrated on the basis of its application for various linear accelerator/decelerator projects.

Keywords: linear accelerator; linear decelerator; beam dynamics; electromagnetic field; computer software; linac design

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1. Introduction

The development and operation of modern linear proton and heavy ion accelerators is impossible without the use of advanced computer programs to simulate the acceleration and evolution of a charged particle beam. For this purpose, a very original version of the multiparticle code DYNAMION [1] was created more than three decades ago at the Linac Division of the Institute for Theoretical and Experimental Physics (ITEP, Moscow, Russia). The algorithms used for the code are based on the theory of particle motion in linear accelerators including space charge effects, developed by the founder of the ITEP Linac Division, Prof. I. M. Kapchinsky [2]. With the implementation of the DYNAMION software, various linac projects have been developed at ITEP [3–6]. Over the years the code has been expanded within the framework of the long-standing international cooperation with GSI Helmholtzzentrum fuer Schwerionenforschung (GSI, Darmstadt, Germany) [7,8].

However, development of the next generation of high intensity linear accelerators requires a tool adequate to modern tasks. In particular, an advanced beam dynamics simulation software should be able to work with any known accelerating/focusing structures and their combination, taking all details of particle motion, caused by space charge effects, coupling between oscillations in different phase planes and nonlinearities of external fields into account. Also, the obtained calculated data should allow for deep and flexible analysis of the evolution of the particle ensemble. For this purpose, the software package DYNAMION was thoroughly revised about twenty years ago. A high level of reliability was demonstrated by comparison of numerous measurement results obtained from operating linacs in several leading accelerator centers with corresponding simulations. Nevertheless, further code development is still in progress by adding different supplements in connection with the recent pioneer tasks.

The presented software package stands among other well-known computer codes as Beampath [9], TRACK [10], TraceWin [11] and BEAMDULAC [12]. However, a number of purposely developed modeling features, especially in their entirety, allow to solve unique and complex tasks, making DYNAMION code almost universal in the design and/or optimization of ion linear accelerators and decelerators.

Over the last few decades, DYNAMION has been widely used both for the development of new facilities and for the study and optimization of existing linacs at various accelerator centers around the world, namely at GSI (Darmstadt, Germany) [13–18], ITEP (Moscow, Russia) [3–6], HIM (Mainz, Germany) [19,20], ANL (Argonne, IL, USA) [21], HIT (Heidelberg, Germany) [22] and INR (Troitsk, Russia) [23]. Supporting beam dynamics investigations have been performed for linac projects at CERN (Geneva, Switzerland) [24], LNL-INFN (Legnaro, Italy) [25], SOREQ (Tel-Aviv, Israel) [26] and JINR (Dubna, Russia) [27]. Some of these projects are briefly described in this manuscript, illustrating various capabilities of the code.

A dedicated chapter is devoted to the design and successful commissioning of the RFQ-Decelerator for the HITRAP project at GSI [17].

2. Code Description

The multiparticle software package DYNAMION simulates beam dynamics in accelerating-focusing structures and transport lines under space charge conditions with high accuracy and reliability. Generally, the particle motion in the whole linac, potentially comprising an arbitrary sequence of RFQs (Radio-Frequency Quadrupole), DTLs (Drift Tube Linac) and beam transport lines, can be calculated in one run.

A detailed description of the external and internal fields in accelerating structures (RFQ, DTL) is provided by the software package itself. All geometrical data available from the specifications, tables for the machining, measurements or external calculations, including cell length, aperture, width and rounding of the electrodes for an RFQ, and tube and gap length, aperture and tube rounding for a DTL, can be used. Dedicated subroutines of the DYNAMION package precisely model the 3D electric field mapping, solving the Laplace equation for the potential on the grid by the finite element method.

2.1. RFQ Structure

For an RFQ section the electrical field is calculated separately for each cell. The eight-terms series for the potential is expressed at each node of the grid. The system of linear equations is solved by the least-squares method for the coefficients A_{ns}. The expression for the electrical field can be obtained by derivation of the formula for the electric potential:

$$\begin{aligned} U(r,\psi,z) &= -\frac{U_l}{2}\left[F_0(r,\psi) + \sum_{n=1}^{\infty} F_n(r,\psi)\ \sin(2n-1)\,kz\right] \\ F_0(r,\psi) &= \sum_{s=0}^{\infty} A_{0s}\left(\frac{r}{R_0}\right)^{2\,(2s+1)} \cos(2\,(2s+1)\,\psi) \\ F_n(r,\psi) &= \sum_{s=0}^{\infty} A_{ns}\, I_{4s}[(2n-1)\,kr]\ \cos 4s\psi \end{aligned} \tag{1}$$

where z, r, ψ—cylindrical coordinates, F_n, A_{ns}—Fourier-Bessel coefficients, $k = 2\pi/\beta\lambda$, β—relative velocity, λ—wavelength of rf field and R_0—average aperture of the RFQ.

By purpose, the obtained distribution of the potential (or electric field as a derivative) could be used directly by the software as a field mapping. In particular, the irregular electric field in the fringe areas of an RFQ is modeled taking the gap between electrodes and flange into account, and is represented as field mapping.

2.2. DTL Structure

For a DTL section the electrical field is calculated separately for each cell, combined by a gap and a drift tube. Assuming an axial geometry, the potential *U(r,z)* and the field components $E_z(r,z)$, $E_r(r,z)$ in a gap and inside a drift tube are approximated by a series with 30 coefficients A_n:

$$\begin{aligned} U(r,z) &= -V\left[\frac{z}{l} + \sum_{n=1}^{\infty} A_n \cdot \sin(2nkz) \cdot I_0(2nkr)\right] \\ E_z(r,z) &= -V\left[\frac{1}{l} + \sum_{n=1}^{N} A_n \cos(2nkz) \cdot 2nk \cdot I_0(2nkr)\right] \\ E_r(r,z) &= -V \cdot \sum_{n=1}^{N} A_n \sin(2nkz) \cdot 2nk \cdot I_1(2nkr) \end{aligned} \quad (2)$$

where r, z—coordinates, I_0, I_1—Bessel functions, l—half of cell length and $k = \pi/l$. The voltage distribution along the tank can be assumed from the design data or obtained from dedicated bead-pull measurements.

2.3. Beam Transport Line

The beam transport lines can comprise magnetic and electrical elements (quadrupoles, octupoles, dipole magnets, solenoids, steerers ...), slits, apertures, etc. For any given purpose, the macroparticle ensemble could be rotated around the longitudinal beam axis by an arbitrary angle, as well as shifted and/or tilted horizontally and vertically by a given value.

2.4. Electromagnetic Fields from External Software

Generally, six-dimensional electromagnetic fields, calculated by external dedicated codes, or even directly measured, can also be applied for DYNAMION beam dynamics simulations. Such information, presented in form of a field map, can be used as input data.

2.5. Multiparticle Ensemble

DYNAMION simulations can be carried out under space charge conditions using an adequate macroparticle ensemble, which represents a mixture of ions with a different charge, mass, or energy. Such beams are usually delivered by an ion source, as well as produced by stripping of ions to different charge states. The charge stripping process increases the electric beam current by several times and leads to a wide spectrum of ions with different charge state, in particular for heavy projectiles. A theoretical or measured charge state distribution generated by charge stripping is used to calculate the behavior of the space charge dominated beam in a special section for the charge states separation. A generation of the input particle distribution of several types (KV, truncated Gaussian, uniform, etc.) is available inside the code. In addition, emittance measurement data can be used for generating the 6D input particle distribution, which represents non-uniformities of a real beam.

From the very first version of the code a special feature was implemented: a unique identifier is assigned to each macroparticle of the ensemble, which allows tracking not only the details of the trajectory of each particle, but also the fields acting on it during the transition through the entire accelerating-focusing channel.

2.6. Particle Motion Equations

The general three-dimensional equation of the charged particle motion in external electromagnetic fields and internal self fields is used in the most common form. DYNAMION solves the equations numerically by time integration:

$$\begin{aligned} \vec{r} &= \vec{r}_0 + \Delta t \cdot \frac{\vec{v} + \vec{v}_0}{2} \\ \vec{v} &= \vec{v}_0 + \Delta t \cdot \vec{A} \\ \vec{A} &= \frac{1}{\gamma} \cdot \frac{q}{m} \cdot \left(\vec{E} - \frac{\vec{v}_0}{c} \cdot \left(\frac{\vec{v}_0}{c} \cdot \vec{E} \right) + \left[\frac{\vec{v}_0}{c} \times \vec{H} \right] \right) \\ \vec{E} &= \vec{E}_{ext} + \vec{E}_{\text{int}} \\ \vec{H} &= \vec{H}_{ext} + \vec{H}_{\text{int}} \end{aligned} \tag{3}$$

where r, v, A—radius, velocity and acceleration vectors, q, m—charge and mass of ion, E_{ext}, H_{ext}—external electrical and magnetic fields, E_{int}, H_{int}—electrical and magnetic internal fields of the ions, t—time and c—speed of light.

2.7. Space Charge Solvers

Due to several reasons, the space charge forces during DYNAMION beam dynamics simulations are usually taken into account by calculation of the particle–particle interaction. With this, the most details of the non-uniform particle distribution are accounted for, despite high CPU time. However, with the ever-increasing capacities of modern computers and the development of parallel computing, this problem becomes less and less important. Moreover, as numerous comparisons of calculations with experimental data have shown, it is quite sufficient to use an ensemble of 10^3–10^4 particles to solve a wide range of typical problems for linacs [14,17,28–30]. In this case, the main and necessary condition for obtaining a reliable result is an adequate solving of the continuous equation of particle motion by discrete numerical methods, i.e., a sufficiently small timestep of integration, as well as the calculation of the Coulomb interaction between particles at each step.

The internal electrical and magnetic self fields are calculated as:

$$\begin{aligned} \vec{E}_j &= \sum_{i=1}^{N} \frac{q_i}{\left(r_{ij}^2 - R^2\right)^{\frac{3}{2}}} \cdot \vec{r}_{ij} \\ \vec{H}_j &= \sum_{i=1}^{N} \frac{q_i}{\left(r_{ij}^2 - R^2\right)^{\frac{3}{2}}} \cdot \vec{R} \\ \vec{r}_{ij} &= \left(x_j - x_i, y_j - y_i, z_j - z_i\right) \\ \vec{v}_j &= \left(v_x, v_y, v_z\right) \\ \vec{R} &= \left[\vec{r}_{ij} \times \frac{\vec{v}_j}{c} \right] \end{aligned} \tag{4}$$

where q_i—charge of the particle, v_j—velocity and r_{ij}—distance between two particles. Up to medium beam energies (relative velocity $\beta < 0.5$), the time of calculation can be remarkably decreased, neglecting the magnetic component. In order to prevent artificial collisions of particles after discrete steps of integration, a special routine is introduced [14]. Nevertheless, due to the relatively small size of the integration steps, the probability of such collisions is significantly low. Usually, more than 200 steps per characteristic length, corresponding to the phase length of 360°, are performed.

Mostly the simulations are carried out with one bunch, whose phase length (referred to the operating frequency) does not exceed ±180°. To prevent an artificial longitudinal widening of continuous beam or relatively long bunch under space charge influence, two additional virtual neighboring bunches are created. The distance from their centers to the reference particle is ±360° correspondingly. These virtual bunches are always identical to the original bunch; virtual bunches only serve to calculate space charge effects adequately.

Initially and all the time, the development of the DYNAMION software was exclusively targeted to the most detailed and reliable modeling of the dynamics of the ensemble (even at the expense of CPU time) but not for fast approximate calculations. Obviously, the calculation of the space charge effects takes up most of the entire process. Therefore, as a part of further code optimization, a fast solver of the Poisson equation is recently under development, as well as the adjustment of the code for parallel computing.

Additionally, a fast and precise Semi-Analytical space charge Solver (SAS) [31] was created for the DYNAMION software package. A continuous space charge density function, required for the semi-analytical solution, is reconstructed from the discrete particle coordinates by a polynomial interpolation using Chebyshev nodes for higher accuracy. Starting from a particle number above 5×10^3, SAS calculates space charge effects faster than the particle–particle method. In particular, SAS is about 24 times faster for 10^4 particles. This new solver allows for the calculations with a particle number of up to 10^6. The analysis of the simulated beam dynamics results shows a sufficient coincidence between SAS and the existing DYNAMION solver, which is already well proven by numerous benchmarking tests and by a comparison with measured data [28]. Therefore, an advanced "two-step" scheme for the beam dynamics simulation with the DYNAMION code is proposed: initial investigations by means of the fast and reliable SAS method with the final precise and detailed proof with the more time-consuming space charge solver.

2.8. Misalignments of the Linac Elements

Last but not least, the assumed or measured misalignments of linac elements can be defined for the advanced simulations. Horizontal/vertical shift and/or tilt could be specified for each linac section and even for a single element. As years of experience for commissioning and optimization of the accelerators have shown, the misalignment of the machine elements may have a significant and even critical impact on the performance of the entire accelerator facility and, therefore, must necessarily be taken into account [8,22].

3. Linear Accelerators at GSI

Various projects have been developed and implemented at GSI over the past decades; some of them are briefly described below. However, the main attention and efforts have been focused on the further development and optimization of the workhorse of the entire facility, the heavy ion high current UNIversal Linear ACcelerator (UNILAC) (Figure 1) [32–34]. Each section of the UNILAC has been investigated in detail applying the DYNAMION software package. Numerous upgrade and optimization measures have been proposed, some of which have been already implemented, resulting in a significant improvement of the performance of the entire facility [14,35]. End-to-end simulations for the whole linac allow for the study and optimization of the overall machine performance, as well as for the calculation of the expected impact of different upgrade measures, proposed to improve the beam brilliance. However, the GSI-accelerator chain is recently undergoing a significant upgrade in order to serve as an injector for the Facility for Antiproton and Ion Research at Darmstadt (FAIR) [15]. Due to the exchange or upgrade of several major UNILAC sections, such end-to-end beam dynamics studies, based on the recent beam characteristics measured at the front of UNILAC, are under consideration.

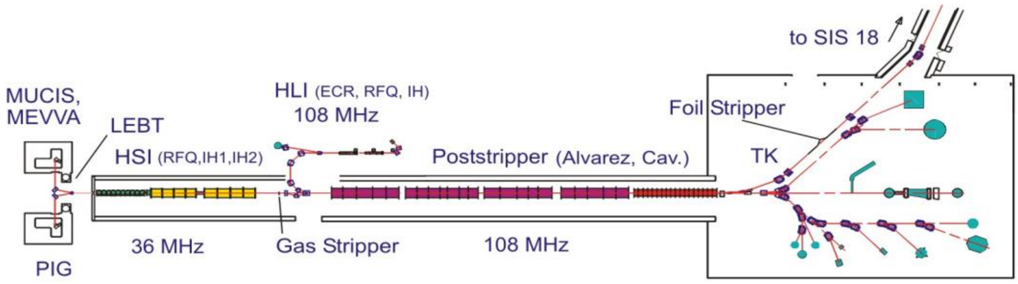

Figure 1. Schematic overview of the GSI UNILAC and the experimental area.

3.1. UNILAC as a Heavy Ion High Current Linac

The heavy ion linac UNILAC can accelerate the full spectra of ions from protons to uranium. Besides two ion source terminals and a low energy beam transport system (LEBT), the UNILAC high current injector (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 (Superlens). The IH-DTL, consisting of two separate tanks, accelerates the beam up to the final HSI-energy of 1.4 MeV/u. After beam stripping and charge state separation, the Alvarez DTL provides for beam acceleration without significant particle loss for the beam energy up to 11.4 MeV/u. The transfer line (TK) to the synchrotron SIS18 is equipped with a foil stripper and another charge state separator system [36]. Additionally, highly charged heavy ion beams are provided by the high charge state injector (HLI), accelerated to 1.4 MeV/u and, by means of a special bending section, injected into the main UNILAC beamline [37].

3.1.1. Beam Matching to the RFQ

Beam matching to the HSI-RFQ acceptance was performed by a Quadrupole Quartet (QQ), comprising four magnetic quadrupole lenses. Due to the short distance between the lenses and the relatively high aperture, an overlapping of the magnetic field from neighboring quadrupoles has a strong influence on the beam dynamics. Additionally, high magnetic gradients, being applied to a large beam spot, provide for a significant non-linear deformation of the 6D beam phase space. The absence of the beam diagnostics between QQ and RFQ allows for the optimization procedure only for the whole frontend. The used set of gradients was found experimentally in order to provide for the maximum beam current behind the HSI-RFQ.

The standard envelope codes for beam line optimization (with separately described quadrupoles) do not take an overlapping of magnetic field from neighboring quadrupoles into account. Also, the use of the paraxial approximation and matrix approach leads to a simplified description of the 3D particle motion in the magnetic field. Therefore, such codes can only provide for roughly estimated matching settings for the quadrupole lenses.

Usually only one four-parametric matched solution for the beamline settings is obtained by the use of a standard envelope software, while general theory predicts four solutions for a common case of four variable elements. As the polarity of the quadrupoles is technically fixed, the four focusing–defocusing elements might provide also two independent matching solutions.

Generally, the DYNAMION code is not foreseen for a typical many-elements beam line optimization. Nevertheless, with a slight adaptation DYNAMION can solve such specific problems by means of massive beam dynamics simulations (in automatic mode) with the Monte Carlo method for the magnetic gradients of four quadrupoles. A dedicated set of beam dynamics simulations was performed, randomly varying four quadrupole gradients in the full range (0–12 T/m). The distribution of the magnetic field has been measured for each quadrupole separately and was introduced into the DYNAMION code as input data. An overlapping of the field for the whole quadrupole quartet has been calculated automatically inside the code, in accordance with the random quadrupole settings for each run. The input particle distribution, generated from the emittance measurement data in front of the QQ, has been used as well.

As expected, two different QQ settings, leading to a high particle transmission for the system, have been found. One solution represents well the gradients for all four quadrupoles, which have been found experimentally during HSI-RFQ recommissioning in 2009. However, newly found QQ settings have been experimentally confirmed for different ions and beam intensities. For the low current argon beam, a 100% particle transmission for the entire HSI (LEBT, RFQ, MEBT and two IH-DTL) has been reached for the first time since commissioning in 1999, while previously achieved particle transmission did not exceed 85%. Also, a remarkable improvement for the HSI transmission was demonstrated experimentally for medium current heavy ion beams, in particular for a 4 mA Ta^{4+} ion beam [30]. Moreover, the corresponding DYNAMION beam dynamics simulations with the new QQ gradients showed after HSI-RFQ an about twofold increase of the transverse beam brilliance and a 60% higher longitudinal one. Mostly this result is explained by a significantly lower nonlinear deformation of the beam phase shape inside the QQ with newly found lower quadrupole gradients. Therefore, a better beam matching to the HSI-RFQ in turn leads to the correspondingly lower emittance growth along the RFQ channel.

3.1.2. UNILAC Stripper Section

In the UNILAC gas stripper section, the charge state of incoming ions at the energy of 1.4 MeV/u and a mass to charge ratio of $A/q \leq 65$ is increased by stripping in a nitrogen gas jet to allow further acceleration at $A/q \leq 8.5$. The design U^{4+} pulse beam current of 15 mA rises up to 7 times during the stripping process. The U^{28+} ions have to be purely separated from the neighboring charge states (and returned to the UNILAC axis) with the dispersion-free system of three dipoles (bending magnets) [34]. The code DYNAMION is well suited to completely simulate this specific problem, and thereby model an evolution of the particle ensemble, consisting of a mixture of many different charge states under space charge dominating condition, along the system of dipoles [14].

3.1.3. Proton Acceleration at Heavy Ion UNILAC

A high intensity primary proton beam, provided by a dedicated 70 MeV proton linac, is required for the experimental program at FAIR, mainly dedicated to antiproton physics [38,39]. According to the recent state, the GSI heavy ion linac UNILAC allows to deliver world record uranium beam intensities, but it is not dedicated for FAIR relevant proton beam operation. In an advanced machine investigation program, it was shown that high intensity CH_3-beam could be cracked and stripped in the UNILAC supersonic nitrogen gas jet into protons and carbon ions. During dedicated machine experiments in 2018, up to 3 mA of proton intensity (about 25% of the FAIR requirements) were measured behind the UNILAC [40,41].

Generally, proton beam acceleration at the heavy ion UNILAC requires special efforts for the settings of the rf-power. With a direct scaling from U^{28+} to protons, the amplifier, designed and normally operated at rf-power level at up to 2 MW, has to be adjusted to handle very low signal level of about 20 kW. However, a significant downshift of the synchronous (reference) phase in the Alvarez DTL gaps from the design value of about $-25°$ potentially results in an accelerating regime, but with correspondingly higher rf-power. Obviously, this reduces strongly the stability problem during rf-power operation.

A potential parameter area for the stable acceleration of protons at the heavy ion UNILAC under lower rf-power (rf-voltage) has been qualitatively investigated applying the dedicated DYNAMION features: an input particle ensemble representing a mixture of ions with different charge states and a unique identification for each macroparticle. For this, a specific input particle ensemble for the beam dynamics simulations in the last Alvarez type DTL tank (frequency f = 108 MHz, wave length $\lambda = c/f$, design relative velocity β = 0.134952) has been generated. To each set of 360 particles, uniformly distributed on longitudinal coordinate inside the characteristic length of $\beta\lambda$ (with 1° increment on phase), was assigned a charge number from +28 to +238 (with the increment 10), emulating a different tank rf-voltage with the increment of about 5%. The transverse coordinates and velocities of all particles were set to zero, i.e., a pencil-like beam has been simulated. With this approach, the full range of possible combinations of rf-voltage and rf-phase is scanned in one run and can be easily analyzed. In particular, the final energy of each particle as a function of its input phase is shown in Figure 2. Thus, the region of stable proton acceleration (rf-voltage and rf-phase) can be confidently localized and clearly visualized.

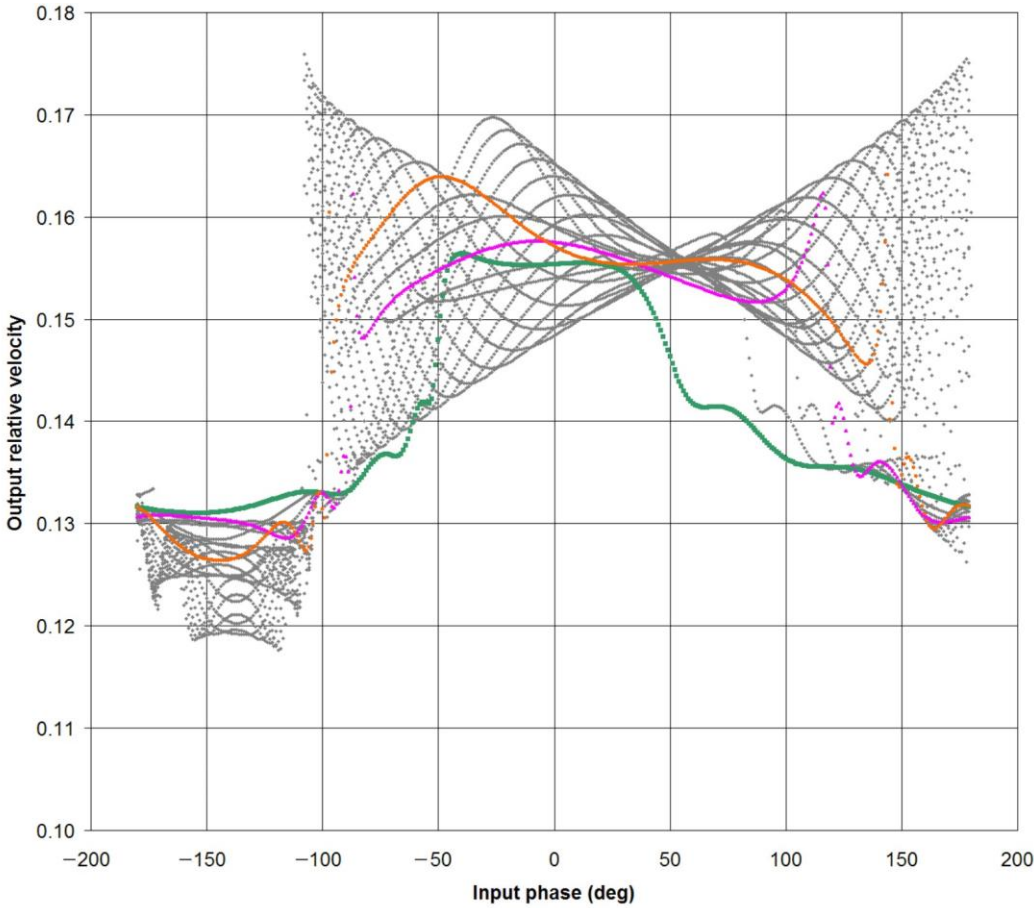

Figure 2. Final relative velocity of each particle as a function of its input rf-phase. Green points represent design ions with charge state 28+; magenta points represent charge state 58+ (emulating about twofold rf-voltage); orange points represent charge state 88+ (emulating about threefold rf-voltage); grey points represent all other charge states.

3.2. Superconducting Continuous Wave Heavy Ion Linac

Operation of the future GSI Facility for Antiproton and Ion Research at Darmstadt (FAIR) foresees the UNILAC as a heavy ion high intensity (but low duty-cycle) injector linac, which is not suitable for Super-Heavy Elements research (SHE) [42,43]. To keep the SHE program at GSI on a high competitive level, the development of the heavy ion superconducting (sc) continuous wave (cw) linac HELIAC (HElmholtz LInear ACcelerator) is in progress [20]. Such a machine provides for a significantly increased rate of SHE production, offering the beam for physics experiments with a smoothly varied output particle energy from 3.5 to 7.3 MeV/u. In accordance with the linac layout, a heavy ion beam with the design mass to charge ratio of A/q = 6 could be accelerated by twelve multi-gap CH cavities [44–47].

3.2.1. Protons Acceleration at Heavy ion HELIAC

A potential implementation of the HELIAC for acceleration of a wide spectrum of ions, from protons up to uranium, has been investigated by means of the DYNAMION software [48]. Due to the wide range of available rf-voltage and rf-phase settings for each CH-cavity, a variable beam energy could be provided by each cavity separately. In addition, an acceleration gradient, twofold compared to the initial design, has been experimentally reached in 2016 during commissioning of the first in the series CH-cavity [20]. Finally, under these conditions, an increased HELIAC output beam energy of up to 14.6 MeV/u for protons and up to 10.5 MeV/u for medium ions (mass to charge ratio A/q = 3) has been estimated.

3.2.2. Commissioning of the First HELIAC rf-Cavity

The Ar^{9+} beam energy behind the first HELIAC superconducting CH-cavity has been measured for the full range of rf-phase and compared with the corresponding DYNAMION beam dynamics simulations (Figure 3). Besides perfect coincidence of the experimental and simulated results, these data were used to calibrate the rf-power (rf-voltage) of the cavity.

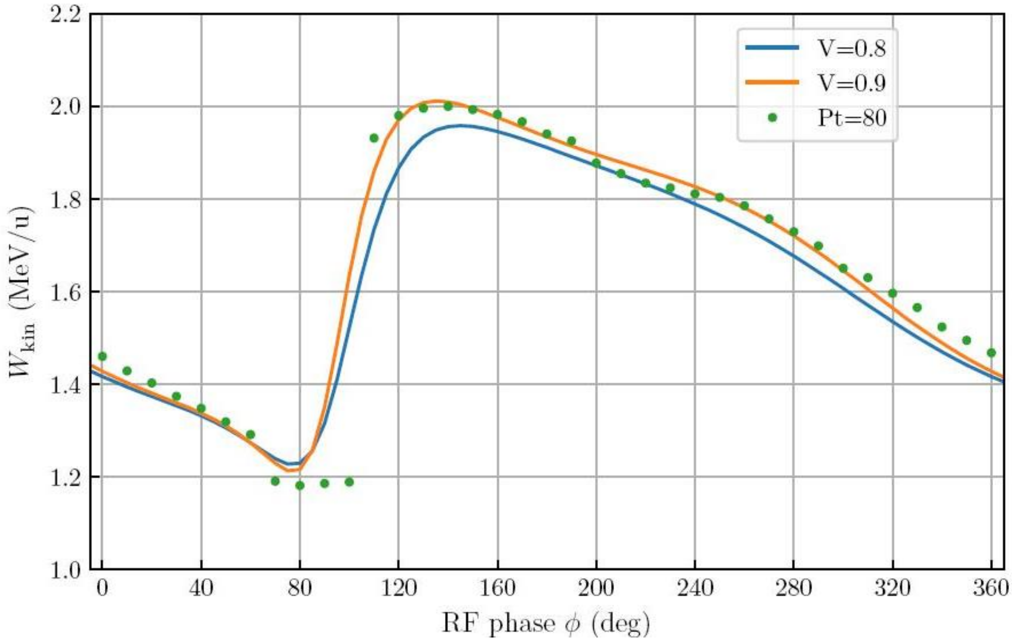

Figure 3. Ar^{9+} beam energy W_{kin} behind the first HELIAC cavity, powered at Pt = 80 mW, as a function of the rf-phase Φ (dotted line). The corresponding simulation results are shown for 80% and 90% of the design voltage V (solid lines).

3.2.3. Normal Conducting HELIAC Injector Linac

In parallel with the commissioning of the superconducting main part of HELIAC, the normal conducting injector linac is under consideration. The newly developed linac comprises an ECR ion source, an RFQ and two Interdigital H-mode (IH) DTL cavities [49,50]. Both such cavities were designed on the base of an Alternating Phase Focusing (APF) beam dynamics scheme in order to accelerate ions with the maximum mass to charge ratio of A/q = 6 from 300 keV/u to 700 keV/u (tank 1) and from 700 keV/u to 1400 keV/u (tank 2). The APF concept allows for a stable and effective magnet-free accelerating-focusing channel, enabling an efficient and compact design. Only one external quadrupole triplet between the DTL cavities is foreseen.

Generally, the APF scheme requires a complicate nonlinear variation along the channel for the synchronous phase in the gaps to provide for both longitudinal and transverse beam focusing [51–53]. As a global optimization method, minimizing the performance function, a random search strategy has been implemented in order to optimize the synchronous phases in each gap. This function combines several requirements, namely high beam acceleration in a given number of gaps, as well as low transverse and longitudinal emittance growth. A dedicated interface for massive parallel computations, using multi-core application of the multiparticle code DYNAMION, has been developed and implemented. The search boundaries were manually adjusted at each iteration to progressively shrink the search range, keeping full control for the convergence of the problem. Simultaneously the nonlinear voltage profile along the DTL cavity was updated by means of the recent CST-Studio [54] model.

The finally obtained layout of the cavities provides for an acceleration gradient of 3 MV/m with a sufficiently low beam emittance growth of less than 5% in each cavity in all three (transverse and longitudinal) phase planes. Recently the APF-based DTL cavities are in fabrication.

4. RFQ-Decelerator for the GSI HITRAP Facility

A wide range of experiments in different areas of physics research require ions, slowed down to the energy range below a few keV/u. Therefore, a facility for acceleration, stripping and subsequent deceleration of such ions is of strong interest for the scientific community. The antiproton decelerator facility ASACUSA has been built and successfully commissioned at CERN [55]. To fulfill a request of the user community for the experiments with slow highly charged or even bare heavy ions, the Heavy Ion Trap (HITRAP) linear facility (Figure 4) for deceleration of such ions has been designed under major support of the Institute of Applied Physics (IAP, Goethe University Frankfurt, Germany) and has been built at GSI [17]. The entire GSI accelerator complex, comprising UNILAC and the synchrotron SIS-18, provides for acceleration of various ions to 400 MeV/u and adjacent foil stripping. In the Experimental Storage Ring (ESR), the ions with a mass to charge ratio of $A/q \leq 3$, for instance U^{92+}, are cooled and decelerated down to 4 MeV/u. At the HITRAP setup these ions should be further decelerated to 6 keV/u. The slow ions could be captured in a Penning trap, cooled further to cryogenic temperatures and transported to various experiments for atomic, nuclear and solid-state physics.

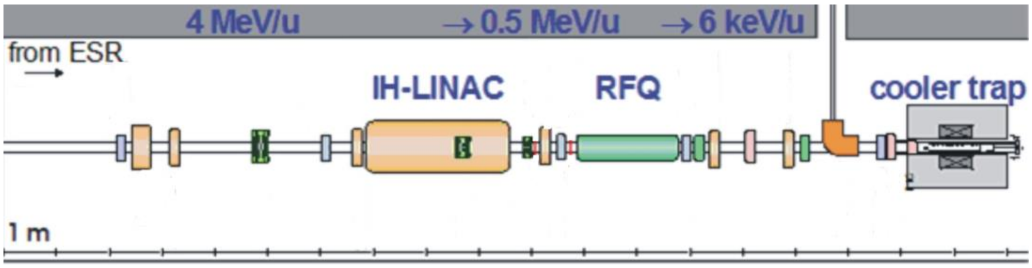

Figure 4. Schematic overview of the HITRAP setup.

4.1. Observed Problem

The ion beam, delivered by the GSI accelerator complex with an energy of 4 MeV/u, is primary decelerated in a 108 MHz Drift-Tube-Linac of Interdigital H-type (IH-DTL) down to 500 keV/u. The RFQ-Decelerator (RFQD) should further decelerate the ions to an energy of about 6 keV/u. During the commissioning stage a deceleration down to 500 keV/u was successfully demonstrated, while all efforts providing for a complete deceleration to the design value of 6 keV/u failed, despite long-term systematic experimental investigations. In order to explain these experimental results, and in a second step to solve this general problem, an investigation program by means of the software package DYNAMION has been initiated.

4.2. RFQD Description "as Fabricated"

An accelerating-focusing channel of RFQ-type, as well as a decelerating-focusing channel of an RFQ-Decelerator, is formed by four modulated rods (vanes). The period of modulation (cell length), the average distance between adjacent rods and the channel aperture vary along the structure, following the dedicated laws. As the machining data for the HITRAP RFQD rods were not available anymore, the original rods were disassembled from the tank and precisely measured, in order to get a basis for reliable beam dynamics simulations. The photometric data were used to build a 3D surface of the rods "as fabricated" (Figure 5).

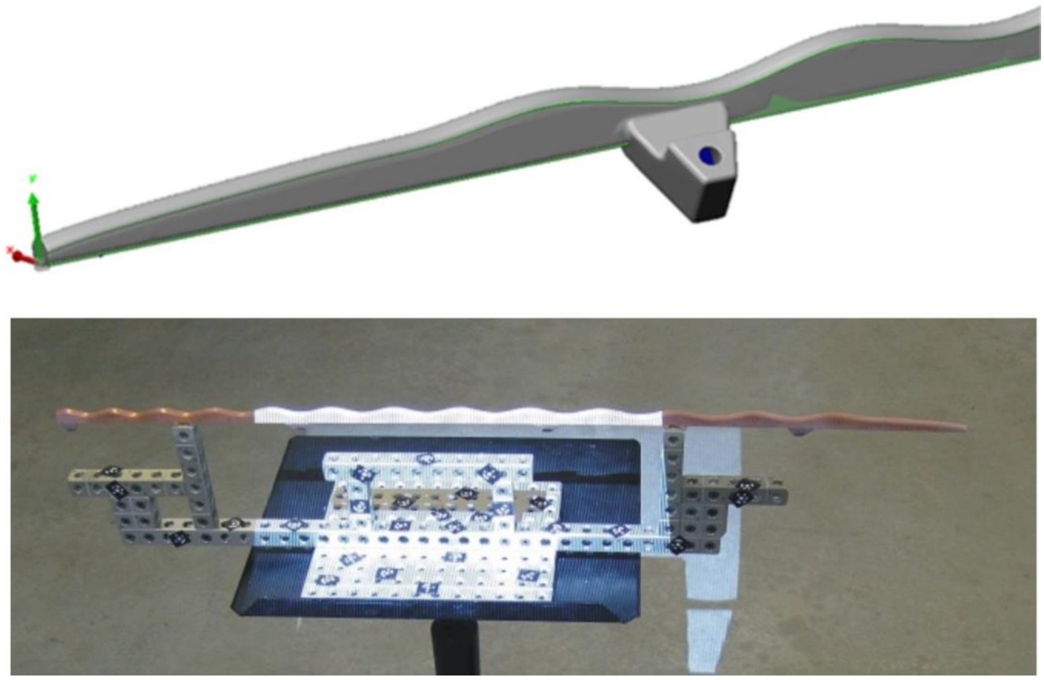

Figure 5. 3D surface of the original RFQD rod (**top**), reconstructed from the photometric measurements (**bottom**).

Based on the measured shape of the rods, a detailed distribution of the electrical potential inside the RFQD channel was built solving the Laplace equation by means of dedicated routines of the DYNAMION package. The boundary conditions were formed by all four rods, as well as by the input and output flanges. The 3D electrical field mapping was obtained as a derivative of the 3D electrical potential. The input and output fringe fields are represented as a 3D field mapping, while for the regular RFQD cells the calculated 3D field mapping is approximated with the well-known eight-term series [14]. It is essential that the bead-pull measurements of the rf-voltage along the tank have been taken into account. Finally, such represented external electrical field is used as an input for macroparticle beam dynamics simulations.

Obviously, inside the RFQ channel a distribution of the electrical field is determined by the shape of the rods and the cavity. As a consequence, the electrical field is the same, regardless of beam injection from the low or high energy end, i.e., when RFQ(D) would be operated in accelerating or decelerating mode. Therefore, the 3D field mapping, already calculated for an RFQD in decelerating mode, could be easily transformed (mirrored) to a field mapping for the same channel but operated in accelerating mode (and vice versa).

4.3. Beam Dynamics Investigations

The acceptance of an accelerating-focusing channel could be obtained from DYNAMION beam dynamics simulations, using a broad 6D phase space input particle distribution, in particular $\pm 180^\circ$ in beam phase length, emulating the full range of the cavity rf-phase. Every macroparticle, used for DYNAMION simulations, has its own ID-number, stored in a file together with particle coordinates and velocities. The macroparticles, accelerated to the desired energy, are marked and then selected from the input distribution to represent the acceptance of the channel at its entrance. Obviously, such an algorithm could be used for a decelerating channel as well. Therefore, this method has been implemented to the HITRAP RFQD to calculate firstly the longitudinal acceptance. For this purpose, the transverse coordinates and velocities of all particles were set to zero, i.e., a pencil-beam on axis was simulated.

The results of beam dynamics simulations in a wide range of rf-tank voltages clearly indicated a serious discrepancy with the design parameters of the RFQD: only particles with an input energy of 525 $\pm$ 10 keV/u could be potentially decelerated with the fabricated RFQD channel, while the design energy range is significantly lower at about 500 $\pm$ 10 keV/u. It can be clearly identified that not even a partial overlap of the required energy range with the corresponding simulated results could be observed.

A supplementary set of experimental and numerical studies has shown that the HITRAP IH-DTL structure, when operated at nominal settings, credibly decelerates ions of 4 MeV/u to the design energy of about 500 $\pm$ 10 keV/u required at the RFQD input. At the dramatic costs of reduced beam transmission for decelerated particles, the IH-DTL section could be detuned to provide for ions with a final energy of up to 515 keV/u, but not higher. Therefore, the energy of the beam that could be decelerated with the IH-DTL structure under all possible settings does not match the RFQD input energy that was reliably calculated based on the actual shape of the manufactured rods. For this reason, it must be concluded that the original RFQ decelerator on the HITRAP setup was not capable to deliver a decelerated beam under these conditions.

4.4. RFQD Test at an External Facility

In a next step the obtained simulation results were confirmed experimentally. The HITRAP RFQD was transported to MPI-K (Heidelberg, Germany) and tested at the beam line behind the Pelletron accelerator, which provides for an almost mono-energetic H_2^+ beam with a variable energy, in particular inside the required range from 450 keV/u to 550 keV/u at a sufficient repetition rate to carry out the necessary investigations. Additionally, the energy-analyzing detector, usually installed behind the HITRAP IH-DTL at GSI, has been calibrated at MPI-K facility with several beams of precisely known energy. Furthermore, the data, taken during previous beam times at GSI facility, has been proved. In particular, the beam energy behind IH-DTL, operated in a nominal mode, has been confirmed as only a few keV/u below 500 keV/u, which is well consistent with the design parameters [15].

The beam experiments with the HITRAP RFQD, performed at MPI-K for a wide spectrum of the input beam energy and rf-power (rf-voltage), have impressively confirmed the results of the DYNAMION simulations:

- RFQD steadily decelerates ions from 525 keV/u to the design energy of 6 keV/u;
- the acceptable input energy of ions varies from 520 to 530 keV/u;
- no deceleration was observed in the vicinity of the design energy of 500 keV/u.

Therefore, in addition to the DYNAMION simulations, this machine study also confirms why the decelerated ions behind the fabricated original RFQD could not be observed during dedicated experimental campaigns at the GSI-HITRAP setup.

4.5. Further Design Issues

As described in [56], the RFQD channel was developed at IAP in the standard RFQ acceleration mode. Then, applying the original designers code, the particle motion was simulated backward, i.e., in deceleration mode. In accordance with this backtracking simulation, such an RFQD channel should decelerate particles from 500 keV/u to 6 keV/u.

To develop an RFQ decelerator, it is certainly a suitable procedure to apply a traditional algorithm cell by cell, starting with the design procedure at the low-energy end and considering the unique characteristics and special properties of a decelerating RFQ. However, the motion of the reference (synchronous) particle and the evolution of the whole particle ensemble (under condition of full particle transmission) along an RFQ in an acceleration mode for obvious reasons are identically mirrored with the beam dynamics for a deceleration mode, independently of the design algorithm.

During investigation of the originally designed RFQD with the DYNAMION code, the particle motion was modelled in both accelerating and decelerating modes for validation purposes. As expected, the obtained results—beam deceleration from 525 keV/u to 6 keV/u and acceleration from 6 keV/u to 525 keV/u—are fully mirrored.

4.6. New RFQD Design Applying the DESRFQ Code

On the basis of the carried-out numerical study and the experimental confirmation, the new RFQD decelerating-focusing channel has been developed. The main design goal was to decelerate U^{92+} ions with the energy of 495 keV/u, corresponding to the optimum IH-DTL decelerator settings, down to the design beam energy of 6 ± 1 keV/u. Simultaneously, the longitudinal acceptance of the RFQD should be increased to provide for a higher yield of the decelerated ions. Due to the already fixed input- and output-energies and with the fixed overall length of the rods (to be mounted into the same tank), such requirements lead to a nontrivial designing process and require the use of an advanced and reliable beam dynamics code.

The image-oriented interactive code DESRFQ [34] was developed for advanced RFQ design efforts with a high level of reliability and visualization during all stages of the design process. The beam dynamics in each RFQ cell are calculated immediately after the definition of its parameters. Therefore, characteristics of the next cell can be chosen in accordance with the beam evolution in all previous cells. A typical screenshot (see Figure 6) illustrates the final stage of an interactive design process.

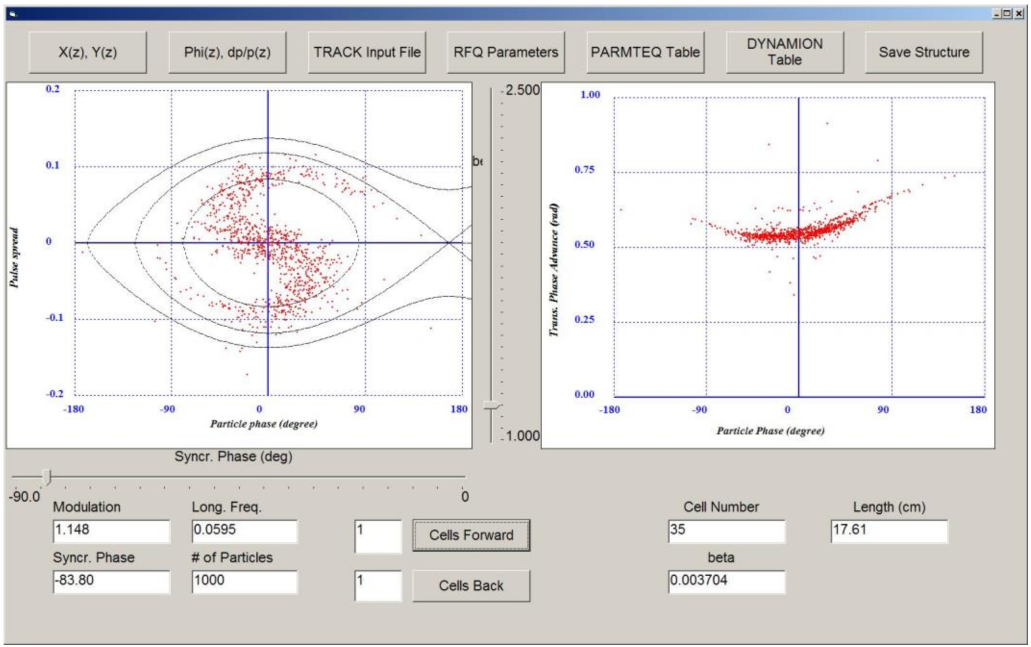

Figure 6. A typical screenshot, illustrating cell-by-cell design process with the DESRFQ code; the longitudinal beam phase portrait (**left**) and the stability diagram (**right**) are shown.

The new HITRAP-RFQD channel was designed with the standard "acceleration" approach. Nevertheless, following the statements mentioned above, in a smart way such approach could be also implemented for the design of an RFQ Decelerator. New rods (mini-vanes) were developed with the constant average radius (average aperture) and the constant width/rounding of the mini-vanes along the channel. This simplifies the fabrication of the mini-vanes, as well as further machine tuning. The rf-voltage was increased from 77.5 kV to 89.5 kV, following experimental tests and dedicated calculations for the maximum electric field strength on the surface of the rods [57]. The main parameters for the original and the new RFQDs are presented in Table 1. The corresponding beam phase portraits, depicting the acceptance for each accelerating-focusing channel, are shown in Figure 7.

Table 1. Main design parameters of the original and the new RFQD channels.

	Original	New
Input energy (keV/u)	525	495
Output energy (keV/u)	6 ± 1[(1)]	6 ± 1
Voltage (kV)	77.5	89.5
Average radius (cm)	1.0–0.58–0.68	0.65
Rods rounding and width	variable	constant
Max. modulation	3.0	2.35
Min. aperture (cm)	0.34	0.39
Frequency (MHz)	108.408	108.408
Max. field strength (kV/cm)	220	238
Kilpatrick factor (criterion 125 kV/cm)	1.76	1.94
Transv. total acceptance, 90% (cm mrad)	0.65	0.58
Long. total acceptance, 90% (keV/u·deg)	177	357
Electrode length (cm)	198.1	198.1

[(1)] No decelerated ions were observed behind the original RFQD, installed at HITRAP setup.

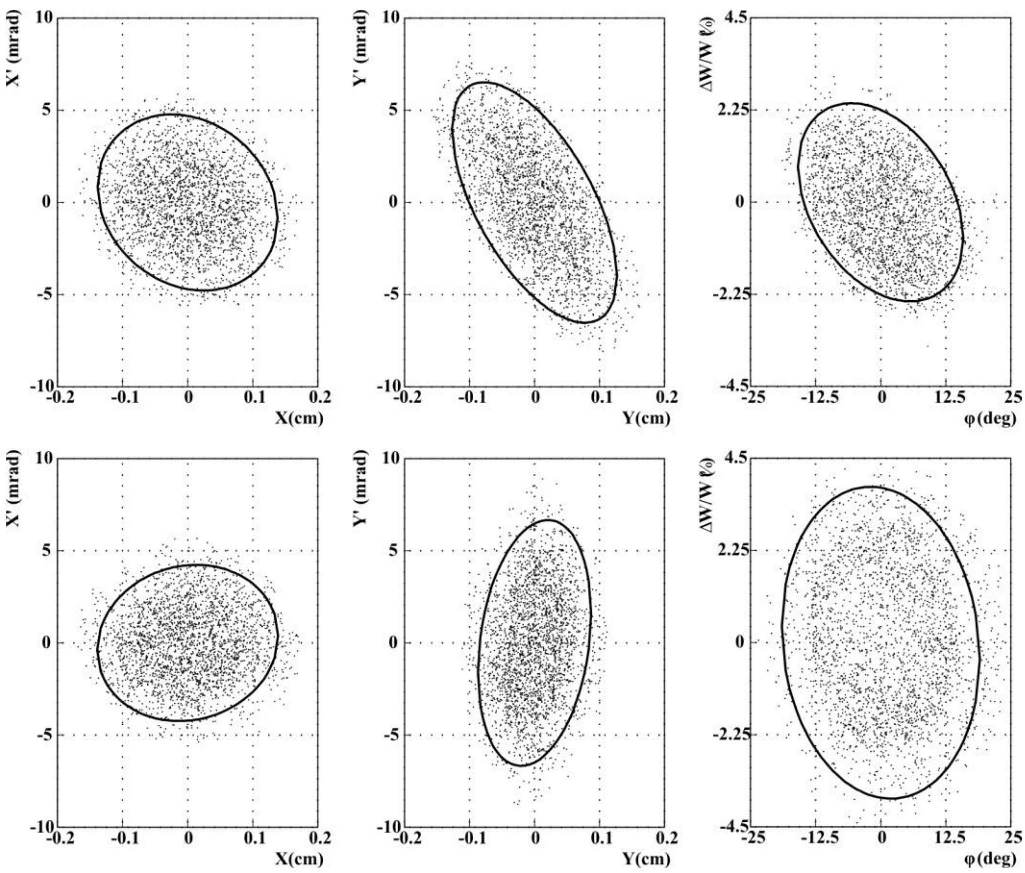

Figure 7. Beam phase portraits depicting the acceptance of the original (**top**) and new (**bottom**) accelerating-focusing channels. The ellipses represent 90% of the beam intensity.

The RFQD with newly fabricated rods was commissioned and successfully tested at the HITRAP setup with heavy ion high charged beams [17]. A sufficient amount of heavy ions, decelerated to the design energy of 6 ± 1 keV/u, were detected (Figure 8, upper spot). Due to unavoidable beam mismatch between IH-DTL and RFQD sections at the recent setup, a significant fraction of the beam could not be decelerated (Figure 8, lower spot). Therefore, a completely revised RFQD design has been recommended for a potential future upgrade of the HITRAP heavy ion linear decelerator.

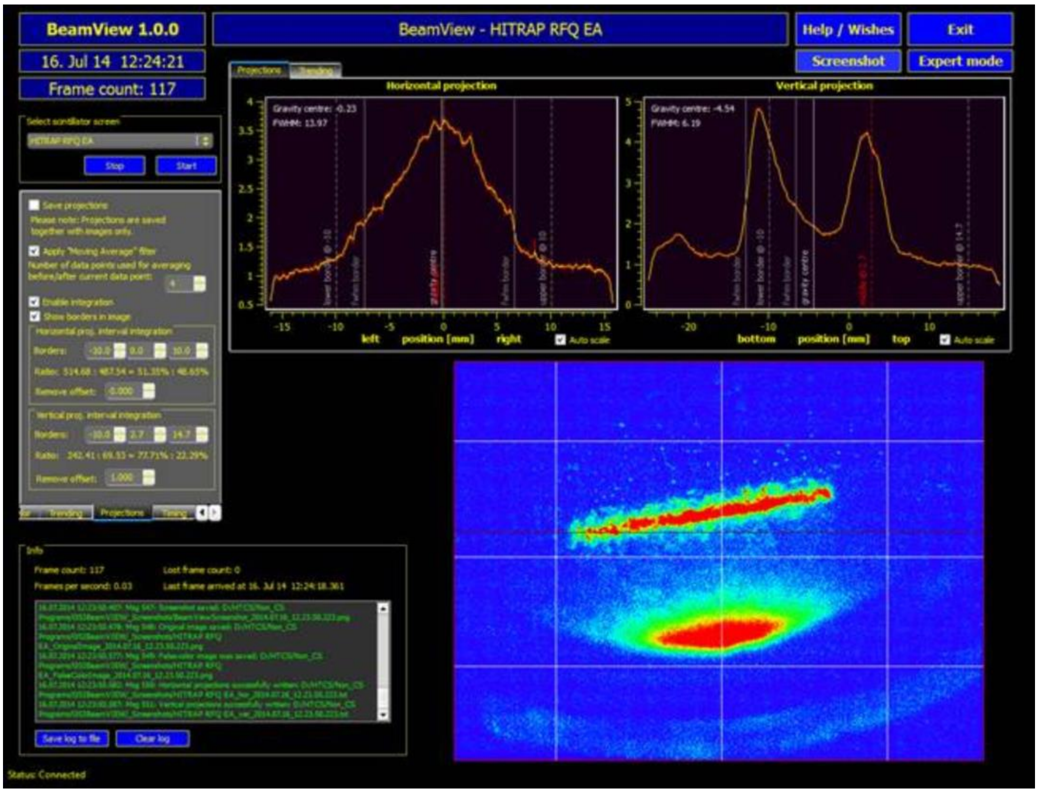

Figure 8. Measured output of the energy analyzer: the upper red spot represents heavy ions decelerated to about 6 keV/u; the lower red spot represents the non-decelerated fraction of the beam (500 keV/u); the histograms show beam intensity profiles in horizontal and vertical directions (the low energy peak is on the left).

5. Conclusions

The ideas, methods and features, implemented in the software package DYNAMION, allow for efficient solving of a large number of problems in ion linac physics and technology. The code is therefore of major interest to the accelerator community. The multiparticle beam dynamics simulations code DYNAMION has been widely used for numerous novel linac projects, as well as for facilities in operation at different leading accelerator centers around the world. According to its embedded philosophy, the DYNAMION software package can be directly applied to the design and further investigation of linear ion decelerators just as successfully as for linear ion accelerators. Moreover, the DYNAMION software is constantly under development to meet further challenges emerging in the field of linear proton and heavy ion accelerators.

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