END TO END SIMULATIONS OF THE GSI LINEAR ACCELERATOR FACILITY

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Abstract

During the last year several numerical investigations have been started at GSI in order to improve the performance of the linear accelerator facility. The main activities regard the upgrade of the high current UNILAC accelerator including the severe upgrade of the HSI injector, the HITRAP decelerator and, in the frame of the future FAIR project, the development of the new dedicated proton linac. End to end beam dynamics simulations are a powerful tool concerning the machine design, commissioning and optimization. Particle distributions, generated from beam emittance measurements, are transferred through the whole chain of accelerating structures and beam transport lines. Detailed calculations of space charge effects as well as external and measured mapping of the electromagnetic fields are used to provide the most reliable results. The paper presents a general overview of all activities performed at GSI concerning the linear accelerator complex.

INTRODUCTION

The scientific program at FAIR requires a sever upgrade of the existing GSI linear accelerator complex in terms of beam brilliance and absolute beam current. To fulfill the experimental heavy ion requirements the UNILAC must provide up to 3.3 x 10^{11} U^{28+}particles within macropulses of 100 µs long [1]. At the final energy of 11.4 MeV/u the beam will be injected into the SIS18 with a repetition rate up to 4 Hz.

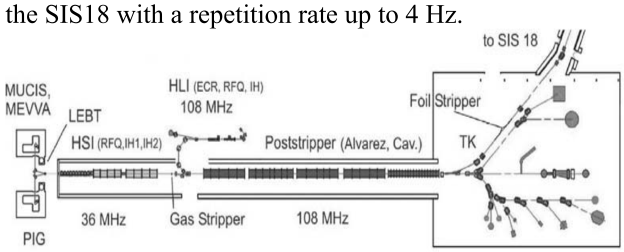

Fig.1: The present linear accelerator complex at GSI.

On the other side, FAIR will provide up to 7 x 10^{10} p-bar/h which, taking into account the antiproton production and cooling rate implies a primary proton beam of 2 10^{16} p/h. This intensity is far beyond the capabilities of the existing UNILAC and, for that reason, a new dedicated proton injector has to be built [2].

In parallel, activities on linear accelerators at GSI are not only focused on the FAIR project. Recently, in the frame of the atomic physics HITRAP project [3], a 4.00 Mev/u Ni^{28+} beam coming from the ESR was decelerated to 6 keV/u making available high charged and cooled beams for trapping experiments.

UNILAC UPGRADE

The next upgrade activities are mainly focused on the low energy front end which represented a bottleneck concerning operation with higher brilliance. The High Current Injector [4] consists of a 36 MHz IH-RFQ from 2.2 keV/u to 120 keV/u and a short 11 cell adapter RFQ called Super Lens. The following acceleration step is performed by two IH-DTL's which deliver a 1.4 MeV/u beam. After the stripping in a supersonic gas jet, uranium beams with charge state of 28+ are delivered to the Alvarez-DTL and accelerated to 11.4 MeV/u with minor losses.

Upgrades of the HSI

The first upgrade of the HSI-RFQ was performed in 2004 after five years of continuous operation. New electrodes were produced increasing the quality of surfaces and thus reducing the RF power consumptions from 650 kW to 380 kW. Additionally, the RFQ Input Radial Matcher (IRM) was redesigned to improve the beam transmission through the whole front-end system.

DYNAMION calculations were performed using particles distributions generated by measured emittances and predicted an intensity gain of up to 15% for high current uranium beam (15 mA). Those simulations were later on perfectly confirmed by measurements [5].

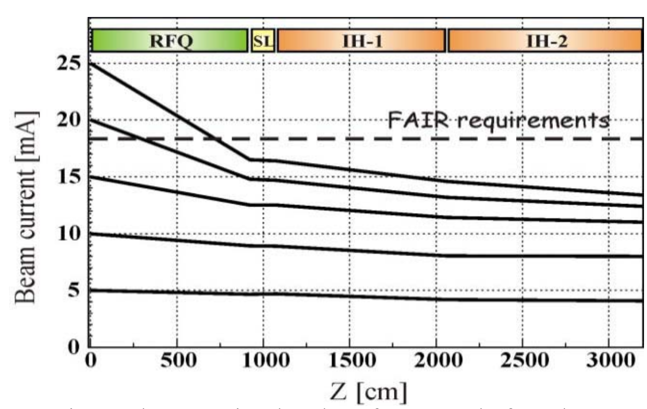

Fig.2: The HSI simulated performance before the 2009 upgrade for different input current in comparison with the requirements for FAIR.

This first upgrade increased the measured transmission up to 55 % but, as Fig 2 shows, even in simulations it was not possible to match the current requirements of FAIR. For this reason, in 2009 a new design of the RFQ was investigated in order to increase the phase advance and the acceptance of the accelerating focusing channel [6]. The new electrode profile was designed with higher voltage, keeping the maximum field at the electrode surface and with the same total length of the previous design. To compensate the change in resonance frequency the carrier ring design was consequently modified as well. The Input Radial Matcher was also redesigned in order to improve the beam matching to the RFQ by means of the LEBT quadrupole.

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. Dedicated code DESRFQ developed at ITEP, Moscow, was used to perform those studies.

A comparison between the new and the old design of the HSI RFQ is summarized in Tab.1.

Tab. 1: Comparison between the 2009 design and the old one of the HSI-RFQ.

Parameter	2009	1999
Voltage [kV]	155	125
Avr. Radius [cm]	0.6	0.55-0.50-0.7
Maximum Field [kV/cm]	312	318
Min. Aperture [cm]	0.41	0.38
Min Trans. σ [rad]	0.55	0.45
Norm Trans Accep. [mm rad]	0.86	0.73
Total Length [cm]	9217	9217
No. of modulated cell	394	343

Simulation Results

Particle simulations were performed with DYNAMION including integrated external 3D mapping of the electromagnetic fields. Exact topology of the Super Lens was included into DYNAMION and the intrinsic 8-terms field calculator was compared with the external 3D field mapping generated with EM Studio. The same method was applied as well to simulations of the HSI-RFQ high energy end. In particular, the use of EM Studio allowed to reproduce the exact geometry of the rods end, including curvature and shape as well as the real topology of the end flange. This combination between the intrinsic Laplace solver of DYNAMION and the external mapping generated with EMS resulted in reliable beam dynamics simulations.

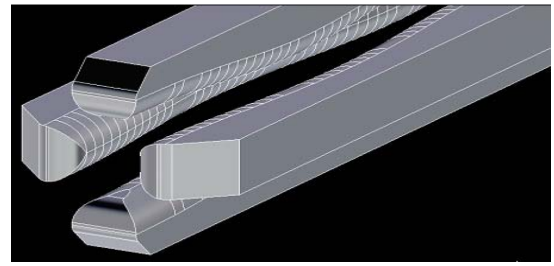

Fig.3: A detail of the modeling with EMS of the Super Lens RFQ. End flanges are not shown here but present in calculations.

Fig.4 shows the calculated the beam transmission through the new RFQ as a function of input beam current when input emittance or brilliance are kept constant. At the FAIR requirements of 18 mA transmission of around 85 % at constant emittance can be reached while 78 % of the beam reaches the end if the brilliance is preserved.

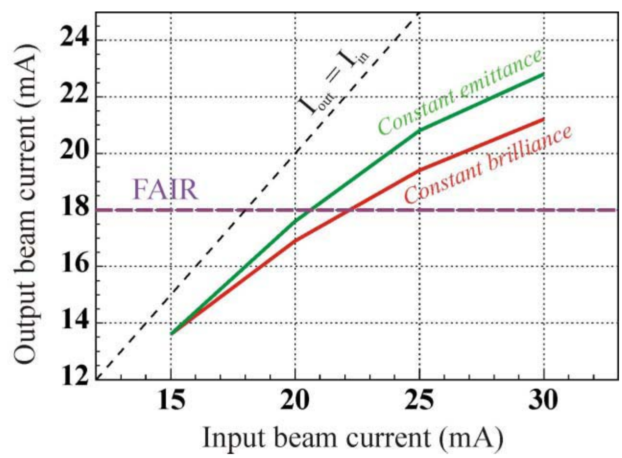

Fig.4: The transmission plot for the new HSI-RFQ when input emittance or brilliance are kept constant.

Fig.5 shows a comparison between the old and the new design of the beam current inside a given emittance at exit of the RFQ: the requirements for FAIR are fulfilled within a reasonable emittance of 20 mm mrad . Moreover, the behavior of the beam curve is a serious proof that the core of the beam remains well compact during the acceleration process.

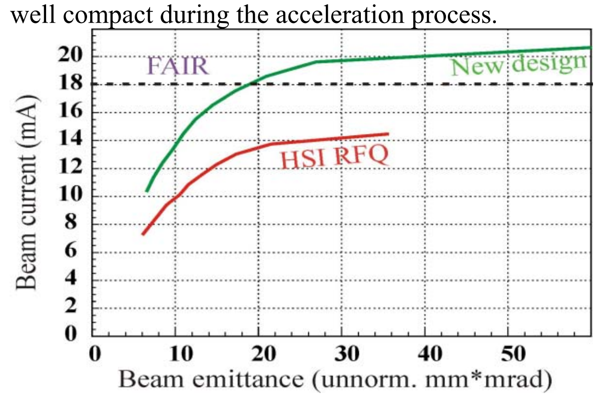

Fig.5 Beam current as function of the emittance for the old and the 2009 design.

The new HSI RFQ has been commissioned in July with high current Argon beam. Experimental results are in agreement with the calculations performed with DYNAMION and a detailed comparison is in preparation

The FAIR Proton Injector

A significant part of the scientific program at FAIR will be dedicated to antiproton physics. The acceleration chain for the production of the intense p-bar beam is shown in Fig.6 and it starts with a dedicated proton linac.

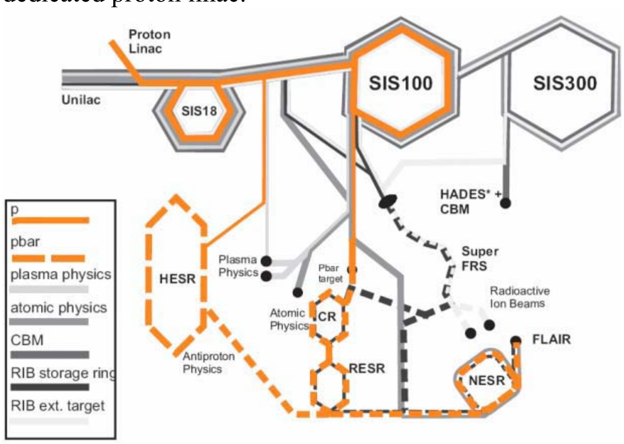

Fig.6: The FAIR accelerator chain showing the path for the production of cooled antiproton beams.

Tab.2: The main parameter of the FAIR proton injector

Source	H^+, 95 keV, 100 mA
LEBT (2 solenoids foc.)	95 keV, 100 mA
RFQ (4-rod)	3 MeV, ε= 2 μm
CH-DTL 325 MHz	70 MeV
Current [mA]	35 in operation
RF Pulse [μs]	70
Beam Pulse [μs]	36
Repetition Rate [Hz]	4
Norm. Transv. Emitt. [μm]	< 2.8
Relative Momentum Spread	< 1 ‰
Length [m]	~ 23
Total Length [m]	< 40

This new injector will be operated at 325 MHz and it has to provide a 35 mA beam pulse of 36 μs. The final energy is fixed at 70 MeV in order to avoid any jump in resonance frequency and to allow an efficient and fast cooling rate. The ion source will be an ECR 2.45 GHz delivered by CEA, Saclay, and can provide 100 mA of proton beam at the extraction energy of 95 keV. Afterwards a four rod RFQ designed by Frankfurt University will accelerate the beam to 3 MeV where the main linac begins. Even if 35 mA are required for the multiturn injection into the synchrotron, the design of the linac assumes higher current, up to 100 mA from the ion source.

An example of two RFQ output distributions are shown in Fig.7 where 45 mA and 100 mA, respectively, are injected into an RFQ optimised for 45 mA. As once can see there are no major differences between the two distributions, showing that the RFQ design is very robust against higher current intensity.

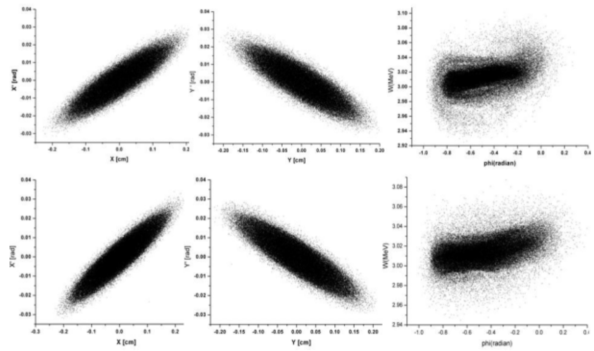

Fig.7: A 45 (top) and a 100 mA RFQ output distribution.

Tab3.: RMS emittance for two RFQ output distributions at different current

	45 mA	100 mA
RMS ε norm hor	0.26	0.25
RMS ε norm ver	0.26	0.25
RMS ε norm Δϕ ΔW	1.29	1.25

After the RFQ the beam is matched into the main linac by mean of an independent phase buncher; the MEBT includes an XY steerer and a current transformer placed immediately after the RFQ. Two focusing elements placed in front and beyond the buncher, respectively, ensure the full transmission while the diagnostics is completed by a compact phase probe placed just in front the main linac.

Status of the Project

In the frame of FAIR the proton injector is well advanced. Agreement with CEA, Saclay, has been reached regarding the ion source while IAP Frankfurt has sent in production the second resonator of the DTL. The first 2.5 MW klystron from Toshiba was delivered in 2008 and, presently, the design of a high power RF test bench is in progress at GSI. Measurements on the first coupled CH are expected to be started in 2010.

Beam Dynamics through the DTL

The main linac is based on 12 CH cavities developed at Frankfurt University [7]. Those kind of cavities in combination with the KONUS beam dynamics allow an extremely efficient acceleration process in the low-medium beta range. In order to reduce the RF requirements the 12 CH cavities are grouped in six independent coupled resonators. A 1:2 scaled model built at Frankfurt University [ref] has demonstrated the validity of this concept while construction of the FAIR second resonator is at the moment in preparation.

An extended diagnostics section is integrated into the DTL after the 3rd coupled module. This section will also include scrapers to dump of outer particles and keep the beam core as compact as possible.

Fig.8 shows the general layout of the proton linac including an alternative design discussed later on

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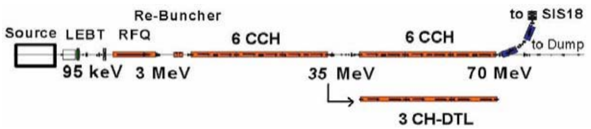

Fig.8: The general layout of the FAIR Proton injection showing the two options under discussion

Fig.9 shows a comparison of the 99% beam envelopes for 45 and 100 mA, respectively. The design reveals to be very stable against current intensity variation and, even with quadrupoles optimized for the 45 mA case, 100 mA are transported with less than 1 % beam losses.

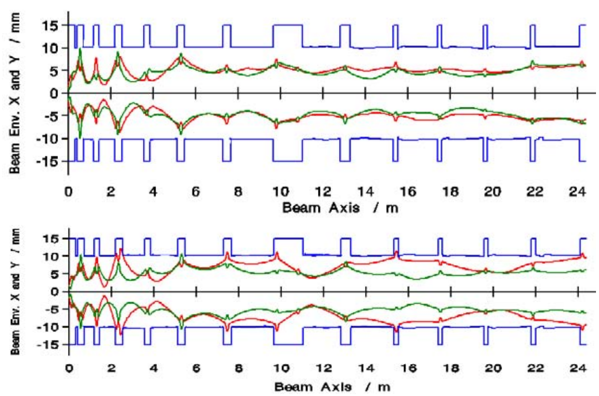

Fig.9: 99 % beam envelopes for two different RFQ output distributions. On top, 45 mA and bottom 100 mA

Examples of the output distribution for those two cases are shown in Fig.10 while Tab.4 summarizes the 100 % RMS at the output energy. In both cases the emittance requirements for the multiturn injection into the SIS18 are fulfilled

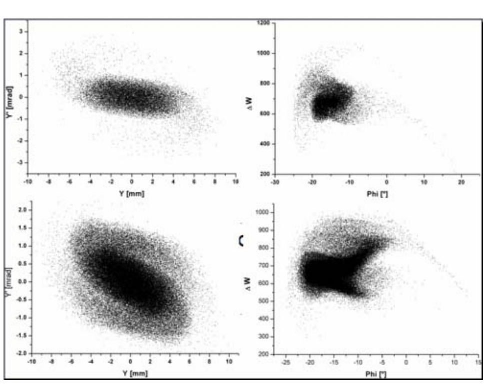

Fig.10: The transversal and longitudinal distribution for 45 mA (top) and 100 (bottom).

Tab.4: The rms parameters as dependence of the input current at the output of the proton linac

Parameter	45 mA	100 mA
RMS ε norm X-X' mm mrad	0.40	0.383
RMS ε normY-Y' mm mrad	0.44	0.409
RMS ε normΔΦ- ΔW keV/ ns	2.09	2.09

Alternative Layout

The use of the KONUS allows to build long accelerating sections without any focusing element. For the proton linac, this feature could be fully exploited in the second part of the DTL after the diagnostics section where the space charge effect is already strongly reduced. The coupled cavity could be replaced by long standard CH-DTL leading to a general simplification of the mechanical design and to a reduction of the number of focusing elements. This concept is under investigation at GSI and preliminary results with a beam current of 45 mA are promising [8]. As one can see from Fig.11 and Fig.12, the beam is full transmitted through the long sections and the output distribution and RMS emittances are comparable with the original design. At present further investigations are in progress in order to test the robustness of this solution with higher current and against possible misalignments and operational errors.

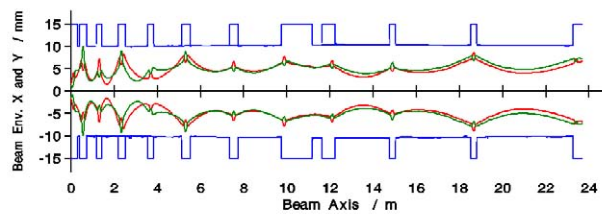

Fig.11: 99% beam envelopes for the alternative design

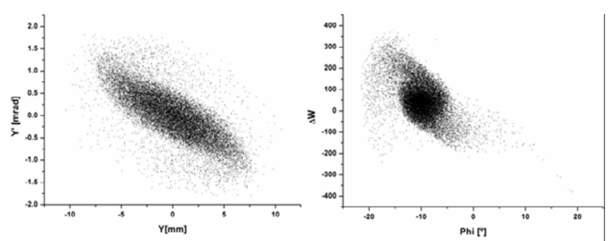

Fig.12: The output distributions for the alternative design for an RFQ output current of 45 mA.

Tab5: Rms emittance for the alternative design at 45 mA

RMS ε norm X-X' mm mrad	0.383
RMS ε normY-Y' mm mrad	0.409
RMS ε normΔΦ- ΔW keV/ ns	2.09

HITRAP

In the frame of the atomic and nuclear physics program a new cooling trap called HITRAP, Heavy Ion TRAP, is under commissioning at GSI. The scientific program aims for investigations of high charged ions in the region of $Z\alpha \approx 1$ where no perturbation method can be applied. The experimental area which can be covered by HITRAP is wide and includes, among others, investigation of the g-factor of bound electrons and alpha particles, hyperfine and X ray spectroscopy, mass measurements and surface interactions.

The general scheme of HITRAP is shown in Fig.13. A 4 MeV/u beam with q/A =1/3 covering $^{238}U^{92+}$ is extracted by the ESR, bended by two dipole magnets, focused by a quadrupole duplet and decelerated to 500 keV/u by a 108 MHz IH-DTL. A 4-rod RFQ performs the last stage of deceleration to 6 keV/u. The phase and energy matching from the ESR to the IH is ensured by two independent bunchers resonating at 108 and 216 MHz, respectively.

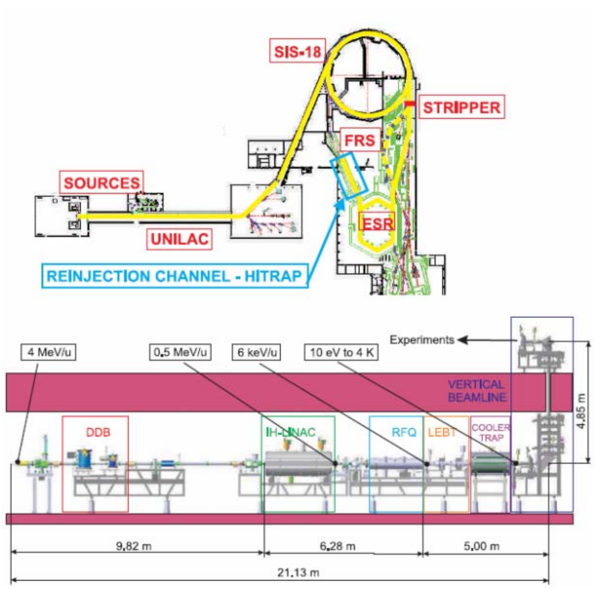

Fig.13: The location of HITRAP at GSI and a detail of the decelerator complex after the ESR.

Beam Dynamics and Ion Optic

The starting point for the optics calculations was the extracted beam from the ESR. Concerning the matching the acceptance of the IH (2.2 and 2.3 mm mrad) was used even if the emittance of the ESR is expected to be smaller (by a factor two or more). Fig. 14 shows the beam envelopes, from the exit of the ESR to the IH entrance.

The first 4 gap buncher accepts (into a single bucket) 100° out of the cw beam corresponding to 28% of intensity. The following rebuncher, operating at double frequency, reduces further the phase spread to 10° before the injection into the IH. It's important to remark that particles escaping the first RF bucket are not necessarily lost but will be transported without full deceleration through the IH.

The IH consists of 25 gaps for a total voltage of 11.15 MV. The focusing scheme is based on a KONUS lattice with an internal triplet placed behind 15 gaps.

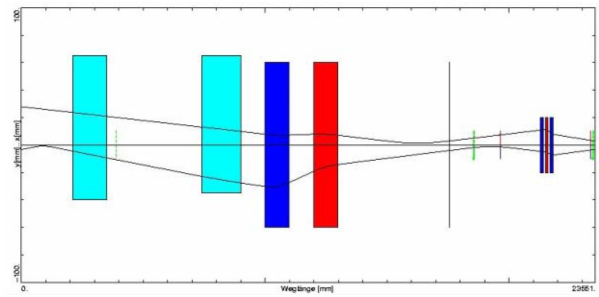

Fig.14: The beam envelopes between the ESR and the IH.

The total length is around 4 meter and the power consumption is kept lower than 180 kW. Fig.15 shows the beam distribution for a single RF bucket at the beginning of the deceleration line and at 500 keV/u after the IH.

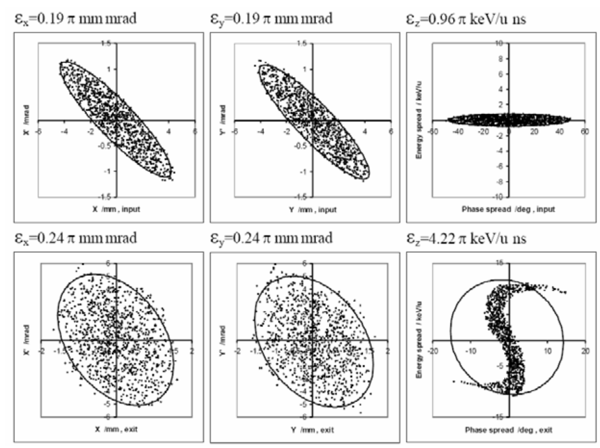

Fig.15: The beam distribution at the beginning of the decelerating line, namely in front of the first buncher (top), and after the IH (bottom) within a single RF bucket.

The design of the 4 rod-RFQ is modelled along the GSI HLI RFQ, which serves as injector for moderate charge states (q/A > 1/9). The HITRAP decelerator is designed for high charge states of q/A> 1/3, which reduces the RF-power requirements and allows for a shorter structure. The RF consumption is 80 kW and the total length is around 1.9 m with an aperture of 4 mm in radius.

The crucial RFQ-design parameters are the longitudinal emittance, the energy spread, and the phase width of the beam. The required output emittance restricts the possible input phase width and energy spread. A value of an energy spread of $\Delta W/W$=1% at the RFQ-high energy input would translate to 66% at the low energy end.

The developed deceleration scheme reduces the output-energy spread to ± 6%. With an input-phase width of $\Delta\varphi < 20°$ and asynchronous deceleration, the beam pulse can be kept compact with reduced phase oscillations. An energy spread of 2% is the upper useful limit while, for the radial emittance, a value of 0.24 π mm mrad has been used for input.

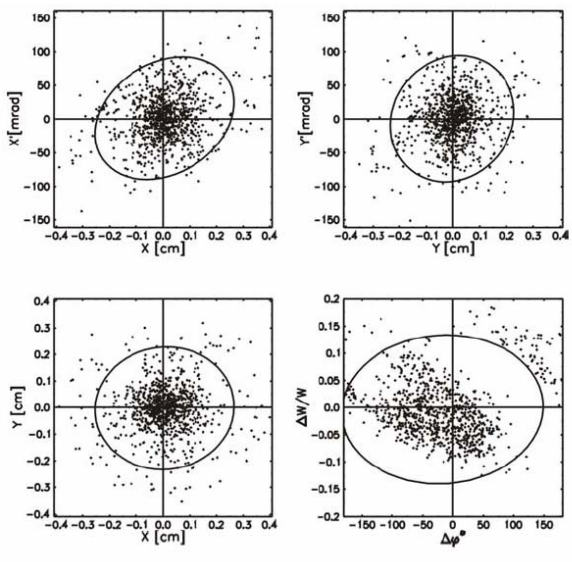

Fig.16: Particles distribution at the exit of the RFQ assuming an energy spread of 2 % as input parameters

Presently, the HITRAP facility is under commissioning at GSI [9] and in early 2009 6 keV/u Ni^{28+} particles were detected at the end of the RFQ.

MILESTONES AND CONCLUSIONS

At GSI several activities run in parallel concerning the linear accelerator complex. The high intensity beam requirement of the FAIR project was the main motivation for a new concept design of the HSI RFQ which has been successfully commissioned in 2009. This new design was accomplished by an intense simulation campaign. Particle distributions were generated by measured emittances and external 3D mapping reproducing the exact topology of the accelerator components were integrated into the simulations code.

The R&D activities for FAIR are not limited to the existing facility since the antiproton program requires a complete new dedicated proton injector. Beam dynamics simulations are in progress applying different beam current and, concerning the structure development, the first coupled CH cavity is under fabrication. The first RF klystron has already been delivered and a high power test bench is going to be prepared at GSI.

Beside the FAIR project, recently a decelerating beam line called HITRAP has been commissioned delivering highly charged ions for trapping experiments.

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