COMPARISON OF THE BEAM DYNAMICS DESIGNS FOR THE FAIR HIGH CURRENT PROTON LINAC-RFQ

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Abstract

The antiproton physics program for future Facility for Antiproton and Ion Research (FAIR) at Darmstadt is based on a rate of $7x10^{10}$ cooled antiprotons per hour. To provide sufficient primary proton intensities a new proton linac is planned. The proposed linac comprises a 100 mA proton source, a Radio Frequency Quadrupole (RFQ), and Crossed-bar H-cavities (CH-DTL). Its operation frequency of 352** MHz allows for an efficient acceleration to up to 70 MeV using normal conducting CH-DTLs. The beam pulses with a length of 36 mks, a current of 70 mA, and total transverse emittances of 7 mkm will allow to fill the existing GSI synchrotron SIS 18 within one multi-turn-injection up to its space charge limit of $7x10^{12}$ protons. Conceptual RFQ designs for two different RFQ types are proposed simultaneously: an RFQ of 4-rod type from the University Frankfurt (Institute for Applied Physics, IAP) and a 4-vane type (with coupling windows) RFQ from the Institute for Theoretical and Experimental Physics (ITEP) and from the Moscow Radio-Technical Institute (MRTI). Studies of the beam dynamics for both RFQ designs have been done with the versatile multi-particle code DYNAMION under space charge conditions. The topology of the RFQ tanks and electrodes is used "as to be fabricated" to provide for realistic calculations of the external electrical field. The results simulated for both designs will be discussed, as well as pros and cons. A comparison simulation results performed with DYNAMION and the results obtained from dedicated RFQ design codes PARMTEQM and LIDOS is presented.

INTRODUCTION

The FAIR proton linac [1] comprises a proton source, a RFQ, and a normal conducting Crossed-bar H-cavities DTL (Fig. 1).

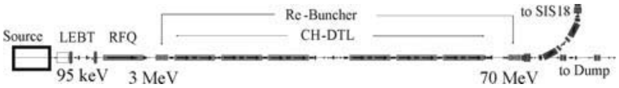

Fig. 1 Schematic view of the GSI proton linac

Recently (August 2006) the operation frequency of the linac was changed to 325 MHz, while the presented comparison was performed for 352 MHz. No significant difference in the beam dynamics performance is expected due to the slight modification of the linac design. The final energy of the linac is 70 MeV. The maximum output beam intensity is 70 mA at a total normalized transverse beam emittance of up to 2.8 mm*mrad [2].

In frame of a collaboration, IAP and ITEP proposed two RFQ designs. The design of the accelerating-focusing channel is different as well as the chosen rf structures: four-rod-type (IAP) [3] and four-vane-type with coupling windows (ITEP) [4]. One can distinguish two main directions in the design of an RFQ: beam dynamics involving accelerating channel only and development of the rf cavity. This paper is focused to comparison of the beam dynamics. Additionally, the beam dynamics simulations performed with the dedicated RFQ design codes are benchmarked.

GSI-PROTON-RFQ MAIN PARAMETERS

The required parameters of the GSI proton RFQ are presented in Table 1. All output parameters are assumed for accelerated particles only.

Table 1. Required parameters of the GSI proton RFQ

Operating frequency	352** MHz
Max. field strength	36.6 MV/m
Input beam energy	95 keV
Input beam current	100 mA
Input transverse beam emittance (rms, normalized)	0.3 mm*mrad
Output beam energy	3 MeV
Output transverse beam emittance (rms, normalized)	< 0.4 mm*mrad
Output long. beam emittance (rms)	< 150 keV*deg
Output beam current	> 90 mA
Particle transmission	> 90%

Table 2. Parameters of the RFQ designs.

	4-rod	**4-vane**
Length (cm)	317	307
Cell number	266	211
Voltage (kV)	90.0	95.7
Max. field (MV/m)	< 36.30	< 36.33
Modulation	1.0 ÷ 2.016	1.0 ÷ 1.901
Synchr. phase (deg)	-90 ÷ -30	-90 ÷ -30
Aperture (cm)	0.349 ÷ 0.210	0.330 ÷ 0.228
R_0 (cm)	0.350 ÷ 0.316	0.330
Rounding of the electrodes (cm)	0.279 ÷ 0.253	0.250

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** changed to 325 MHz in August 2006

Both proposed RFQ designs have similar main parameters, namely length, voltage, average aperture etc. but the laws of modulation and synchronous phase along the structure are significantly different. Additionally, in the 4-vane design the average aperture, the width, and the rounding of the electrodes are constant along the RFQ, while in the 4-rod design these parameters are significantly different along the channel (Table 2).

BENCHMARKING OF THE CODES

The well-known code PARMTEQM [5] was used in IAP for the RFQ design, while ITEP implemented dedicated code LIDOS [6], created in MRTI. Both codes provide for the geometrical parameters of the RFQ electrodes (cell length, modulation, aperture, etc.) as well as for the beam dynamics study in the created structure.

Results of the calculations were compared with simulations done by means of the multiparticle code DYNAMION [7], created in ITEP and developed in GSI. The advanced code DYNAMION calculates beam dynamics in linear accelerators and transport lines under space charge conditions with high accuracy. The method of the particle-particle interaction is implemented. A dedicated routine prevents artificial particle collisions. Virtual bunches (before and after the main one) are introduced for an adequate calculation of the space charge influence for the continuous beam, the bunching process, and behavior of the sequence of the bunches in an RFQ. Reliability of the results simulated with the DYNAMION was verified experimentally for several linacs in the leading accelerator centers as well as by a comparison with the analytical models.

In a first step, an adequate description of the RFQs had been carried out. All geometrical data, available from the technical specifications, were used. The electrodes were described "as to be fabricated". The voltage in each cell was assumed constant. Dedicated subroutines of the DYNAMION code precisely calculate the 3D external electrical field solving the Laplace equation for the potential:

- *RFQ Input Radial Matcher:* the area for the grid is formed by the surface of the electrodes and of the flange of the tank.
- *RFQ cells:* the area for the grid for each cell is formed by the surface of the modulated electrodes. The calculated potential is approximated with classical 8-term series assuming the quadrupole symmetry. The coefficients of the series are introduced into calculations as input data. The 3D electrical fields are calculated as corresponding derivatives of the potential.

For the benchmarking of the codes the PARMTEQM / LIDOS input particle distributions (4000 macroparticles) were directly used for the calculations with the DYNAMION code. The comparison of the output beam parameters is presented for the 4-rod (Table 3) and the 4-vane (Table 4) RFQ designs.

The DYNAMION code calculates about 10% lower transmission than PARMTEQM. Mainly the treatment of the space charge influence is responsible for this effect. The longitudinal rms emittance, calculated with DYNAMION, is significantly higher (30%) than the PARMTEQM value even with lower particle transmission. The discrepancy between results of the codes LIDOS and DYNAMION is less than the difference between PARMTEQM and DYNAMION due to the sophisticated FFT space charge solver, used in the LIDOS code.

Table 3. Input / output beam parameters of the 4-rod RFQ design calculated by means of PARMTEQM and DYNAMION.

	PARMTEQM	**DYNAMION**
Input beam current	100 mA	
Input beam emittance - total, unnormalized - rms, normalized	150 mm*mrad 0.352 mm*mrad	
Transmission - accelerated particles	100 % > 95 %	87 % 85 %
Output transv. beam emittances (rms, norm.)	0.352 mm*mrad 0.352 mm*mrad	0.302 mm*mrad 0.302 mm*mrad
Output long. beam emittance (rms, norm.)	134 keV*deg	176 keV*deg

Table 4. Input / output beam parameters of the 4-vane RFQ design calculated by means of LIDOS and DYNAMION.

	LIDOS	**DYNAMION**
Input beam current	100 mA	
Input beam emittance - total, unnormalized - rms, normalized	141 mm*mrad 0.264 mm*mrad	
Transmission - accelerated particles	100 % 94 %	97 % 88 %
Output transv. beam emittances (rms, norm.)	0.280 mm*mrad 0.280 mm*mrad	0.276 mm*mrad 0.262 mm*mrad
Output long. beam emittance (rms, norm.)	180 keV*deg	180 keV*deg

MACRO-PARAMETERS OF THE RFQ DESIGNS

A normalized acceptance V_k for each RFQ cell can be calculated from the solution of the Floquet equation as

$$V_k = \nu_f \frac{a^2}{\lambda}$$

where ν_f is the minimum of the phase advance μ on the focusing period, a - aperture of the cell, λ - wave length of the operating frequency [8]. In case of an intense beam, assuming uniformly charged KV particle distribution, the phase advance μ and correspondingly acceptance V_k can be estimated as

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

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

where μ_0 and V_{k0} - phase advance and acceptance without current. Coulomb parameter h is

$$h = \frac{1}{4\mu_0}\frac{\lambda}{\beta\varepsilon}\frac{I_{peak}}{I_0},$$

with β - relative particle velocity, ε - total unnormalized beam emittance, $I_0 = 3.13 \cdot 10^7$ A, $I_{peak} \sim 1/\Delta\Phi$ - beam peak current, $\Delta\Phi$ - phase spread [8].

The local acceptances of the proposed RFQ designs along the accelerating-focusing channels are presented in Fig. 2 for low (0 mA) and high beam current (100 mA).

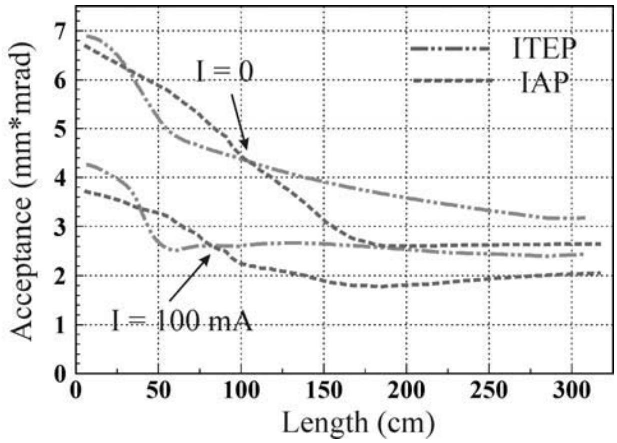

Fig. 2 The local acceptances along structures for low and high beam current.

The acceptance of the 4-rod RFQ at the main part is about of 30% below the acceptance of the 4-vane one in the high current case. This fact is also confirmed by beam dynamics simulations with higher beam emittance presented below.

COMPARISON USING DYNAMION CODE

In a second step, the comparison of the two RFQ designs was performed using DYNAMION code (Table 5).

Table 5. Comparison of the beam parameters for of the RFQ designs; input particle distribution generated by DYNAMION.

	4-rod	4-vane
Input beam current (mA)	100	
Input beam emittance - total, unnormalized (mm*mrad) - rms, normalized (mm*mrad)	 130 0.3	
Input beam radius (mm)	2.4	3.1
Input beam angle (mrad)	81	101
Transmission (%) - accelerated particles (%)	87 86	95 85
Output beam emittance (rms, norm.) - horizontal plane (mm*mrad) - vertical plane (mm*mrad) - longitudinal plane (keV*deg)	 0.238 0.245 175	 0.281 0.278 175

The beam dynamics for the both RFQ designs was simulated solving the same particle motion equation and space charge conditions. The same input beam characteristics were used except the matched Twiss-parameters, which were calculated individually for each RFQ in accordance with the Input Radial Matcher design and the beam- current and -emittance. A Gaussian input distribution (truncated at 2σ) was generated in both transverse planes and uniform in the longitudinal plane.

Results for the RFQ designs are very similar due to the particle transmission and the longitudinal rms emittance. A slight difference is observed for the transverse rms emittance (13%). The transverse and the longitudinal output phase-space distributions are shown in Fig. 3.

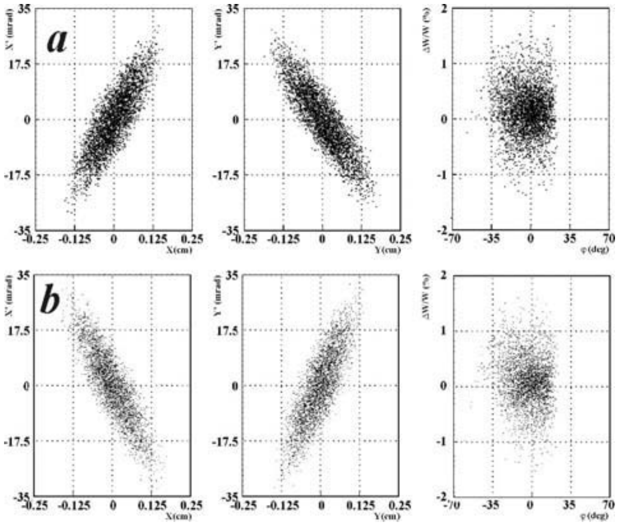

Fig. 3 Four-rod (***a***) and four-vane (***b***) transverse and longitudinal output phase-space particle distributions.

Additional series of the beam dynamics simulations were carried out for different combinations of the input beam current and emittance:

- different beam emittance with a constant beam current of 100 mA (Fig. 4);
- different beam current and emittance with a constant beam brilliance, i.e. ratio of the current to the emittance of 100 mA / 0.3 mm*mrad (Fig.5).

The particle transmission for both RFQ designs at the working point is the same and differs by less than 10% in the wide range of the input parameters.

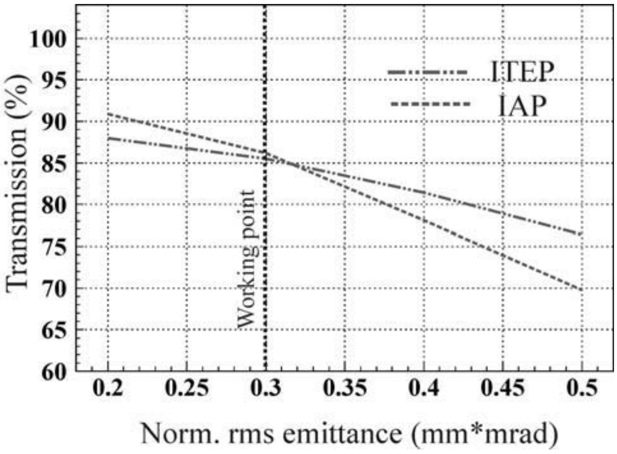

Fig. 4. Particle transmission as a function of the input emittance with an input beam current of 100 mA.

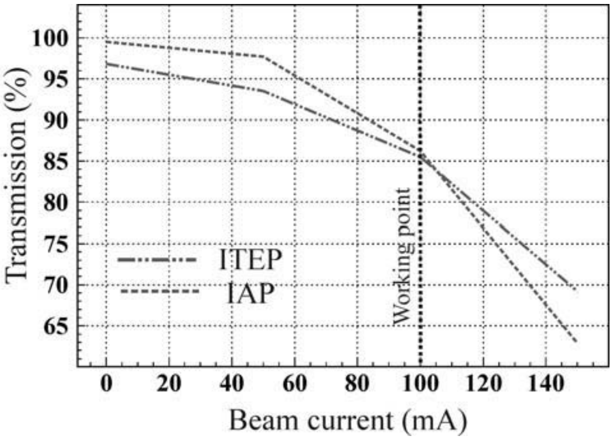

Fig. 5. Particle transmission as a function of input beam current with constant input beam brilliance.

CONCLUSION

The versatile simulation code DYNAMION was chosen for the comparative study. The investigation was carried out using artificial input particle distributions. No misalignments and/or fabrication errors were taken into account. The following main results of the DYNAMION simulations can be mentioned:

- DYNAMION calculates a particle transmission 10% lower than PARMTEQM and 6% lower than LIDOS (for the design input beam current of 100 mA);
- both RFQ designs results in particle transmission close to the required one;
- for both RFQ designs the transverse rms emittance is calculated below 0.3 mm*mrad, while the required maximum is 0.4 mm*mrad;
- for both RFQ designs the longitudinal output rms emittance is about 175 keV*deg, while the required maximum is 150 keV*deg;
- for the 4-rod RFQ design a high caption of particles into the acceleration process is performed;
- no significant gain with variable average aperture compare to constant one was observed, but more efforts to reach the same fabrication accuracy for 3D machining compare to standard milling tool are expected.

OUTLOOK

In the frame of the design study for the GSI proton linac the slight modification of the RFQ designs due to the change of the operating frequency from 352 MHz to 325 MHz should be performed. No significant change in the beam dynamics results is expected. Additional RFQ beam dynamics simulations are foreseen including:

- fabrication errors;
- misalignments of the rods / vanes;
- beam mismatching;
- use of the input particle distribution, obtained from measurements [9] or calculated [10] by the external KOBRA code (Fig. 6).

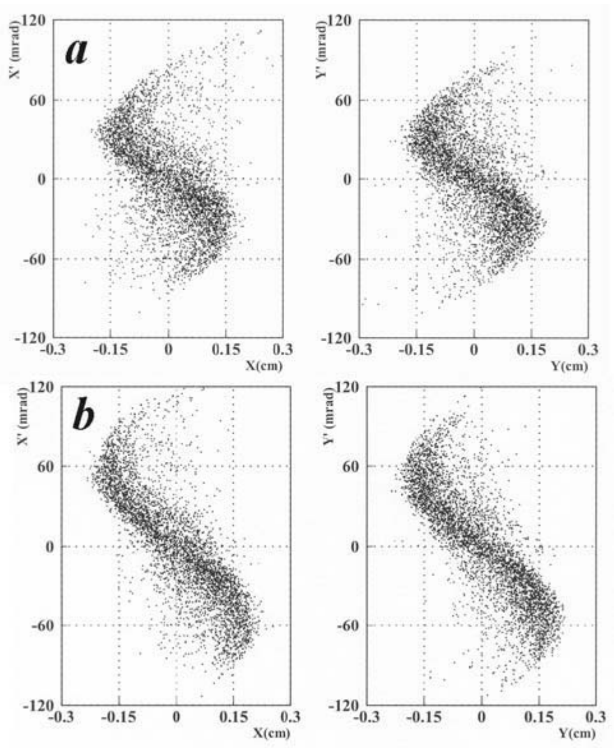

Fig. 6. Input rms-matched transverse particle distribution for the 4-rod (***a***) and the 4-vane (***b***) RFQ designs based on the SILHI ion source performance.

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