BEAMDYNAMICS SIMULATIONS AND CODE COMPARISON FOR A NEW CW RFQ DESIGN

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Abstract

Research and development of CW applications is an important step in RFQ design. The RF potential should be limited by 1.3-1.5 of Kilpatrick criterion for the CW mode. A 2 MeV RFQ is under development for the compact CW research proton accelerator, as well as for planned driver linac in Russia. The maximum beam current is fixed to 10 mA; the operating frequency has been set to 162 MHz. The new RFQ linac design will be presented and beam dynamics simulation results will be discussed. Calculations of the beam dynamics are provided using the codes BEAMDULAC (developed at MEPhI for linac design) and DYNAMION. A comparison of the software performance is presented.

INTRODUCTION

The development of CW high-power proton linacs with 1.0-2.0 GeV beam energy is a very actual aim of crucial accelerator technology. Such linac is useful for large scale research complexes as spallation neutron sources or accelerator driven systems. Low or medium-energy linacs can be used for several applications as boron-neutron capture therapy (BNCT), high productivity isotopes generation and material science [1-4]. Also compact research facilities, for example SARAF at Soreq Centre [5], are the modern trend for high intensity CW proton and deuteron linac development.

In 2013 the Russian accelerator-driver concept has been developed by the collaboration of researchers from MEPhI, ITEP and Kurchatov Institute [6-9]. The proposed linac layout is close to the conventional scheme: an RFQ and an RF focusing section up to 30 MeV as normal conducting part [10] and independently phased SC cavities for medium and high beam energies. Three different RF focusing methods were discussed: RF crossed lenses [11], radio-frequency quadrupoles with modified profile of electrodes [12] and axi-symmetrical RF focusing (ARF) [13]. Three branches of experimental beam lines, delivering beam energy of 3, 30 and 100 MeV for dedicated experiments, are foreseen as the main feature of the proposed concept.

A preliminary design of a CW RFQ linac has been already started at MEPhI and ITEP [14, 15]. The recent detailed layout of the presented 2 MeV CW RFQ is based on a preliminary concept, exploiting long-term experience for proton and heavy ion linac development at MEPhI [16], ITEP [17,18], as well as decades of GSI expertise in construction, optimization and routine operation of linac facilities [19-24]. Most recently, the prototype for a heavy ion CW linac with a SC main part is under construction at GSI and HIM in frame of a collaboration with IAP (University Frankfurt) [25].

The beam dynamics simulations for the new RFQ accelerating-focusing channel, as well as an analysis of the RFQ characteristics, have been performed by means of different software to provide for a cross-check of the design features and the calculated results. The main RFQ parameters are summarized in Tab.1.

Table 1: Main Parameters of the CW RFQ

Ions	protons
Input energy	46 keV
Output energy	2.0 MeV
Frequency	162 MHz
Voltage	90 kV
Length	345 cm
Average radius	0.530 cm
Vanes half-width	0.412 cm
Modulation	1.000 - 2.250
Synchr. phase	-90° - -33°
Max. input beam current	10 mA
Max. input beam emittance	6 cm·mrad
Particle transmission	> 99%

DESCRIPTION OF THE CODES

The presented RFQ accelerating-focusing channel has been designed at MEPhI by means of the BEAMDULAC code [26]. A cross-check, including calculations of RFQ characteristics and beam dynamics simulation, was performed by use of the DYNAMION software [27].

The BEAMDULAC code has been developed at MEPhI for self-consistent beam dynamics investigations in RF linacs and transport channels. The motion equation for each particle is solved under implementation of the external electromagnetic fields and the inter-particle Coulomb field simultaneously. The BEAMDULAC code utilizes the cloud-in-cell (CIC) method for accurate treatment of the space charge effects. It allows consideration of the shielding effect, which is sufficiently important for transverse focusing in the narrow channel. The fast Fourier transform (FFT) algorithm is used to solve the Poisson equation on a 3D grid. The obtained Fourier series for the space charge potential can be analytically differentiated, and thus each component of the Coulomb electrical field can be found as a series with known coefficients. The dedicated version of the

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BEAMDULAC code was created for fast RFQ channel design and beam dynamics simulations.

The multiparticle code DYNAMION calculates beam dynamics in linear accelerators and transport lines under space charge conditions with high accuracy and reliability. A detailed description of the external and internal fields is provided by the DYNAMION package. Also the use of measured data or electromagnetic fields, calculated by external codes, is possible. Generally, the particle motion in the whole linac, potentially comprising RFQ(s), DTL(s) and transport lines, can be calculated in one run. Simulations of high intensity beam dynamics are performed taking space charge forces into account (by different dedicated routines).

All geometrical data, available from the external calculations, measurements, specifications and tables for the machining, can be used: cell length, aperture, width and rounding of the electrodes for an RFQ; tube and gap length, aperture, and tube rounding for a DTL. Dedicated subroutines of the DYNAMION package precisely calculate the 3D electrical field mapping, solving the Laplace equation for the potential:

RFQ Input/Output Radial Matcher: the area for the grid is formed by the surface of electrodes / flange of the tank.

RFQ cells: the area for the grid for each cell is formed by the surface of modulated electrodes; the potential is approximated with a classical 8-term series assuming the quadrupole symmetry; 3D electrical fields are calculated as corresponding derivatives of the potential.

DTL gaps: the area for the grid is formed by the surface of tubes; the potential and the 3D electrical fields for each gap, including the slack of the field into tubes, are approximated with 30-term series assuming axial symmetry; coefficients of the series are introduced into calculations as input data.

The transport line elements (quadrupole lenses, bending magnets, solenoids, etc.) are described inside the code or can be represented by measured or calculated field mapping. Several additional features are developed for more reliable simulations: slits, strippers, apertures, beam shift and rotation, breeding of particles, etc.

The assumed or measured misalignments of the linac elements can be defined for the simulations.

Input particle distribution of several types (KV, truncated Gaussian, uniform, etc.) are available inside the code. The data of an emittance measurement can be used for generating of the input particle distribution which includes non-uniformities of a real beam.

A multiparticle distribution, which represents *the mixture of ions* with a different charge, mass and energy can be carried out under space charge conditions.

ANALYSIS OF RFQ CHARACTERISTICS

The maximum electrical field strength on the vane surface along the channel strongly influences on all RFQ parameters. For the presented CW RFQ design the field strength has been limited by the 1.5 Kilpatrick criterion E_{kp} = 148 kV/cm.

The average radius of 0.530 cm and the vanes half-width/rounding of 0.412 cm have been defined together with the RFQ voltage of 90 kV (Tab. 1). The maximum electrical field on the vane surface, calculated for the real topology of each RFQ cell, is shown in Fig. 1.

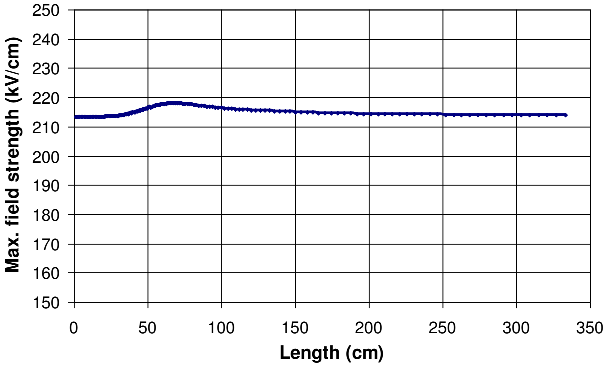

Figure 1: Maximum strength of electrical field strength on the vane surface, calculated along the RFQ channel (for each cell separately).

Almost constant electrical field strength along the channel provides for effective focusing and acceleration, especially as RF voltage and RF power are strongly limited due to the CW regime.

Assuming a low beam current and a smooth approximation, the phase advance μ (Fig. 2) and the normalized local acceptance V_k (Fig. 3) for each RFQ cell can be calculated from a stable solution of the Mathieu-Hill equation for particle motion, using the Floquet functions:

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

where ρ is a module of the Floquet function, $\nu_f = 1/\rho^2$, 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.

Additionally a tune depression can be semi-analytically calculated for each RFQ cell, assuming a given current phase density (beam brilliance) for a uniformly charged beam (KV distribution).

The Coulomb parameter h combines 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. The phase advance and acceptance of the channel under tune depression could be evaluated as

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

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

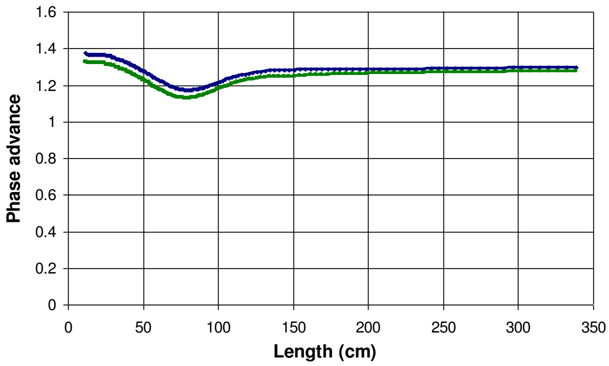

Figure 2: Phase advance for low beam current (blue) and under space charge conditions (green), calculated along the RFQ channel (for each cell separately).

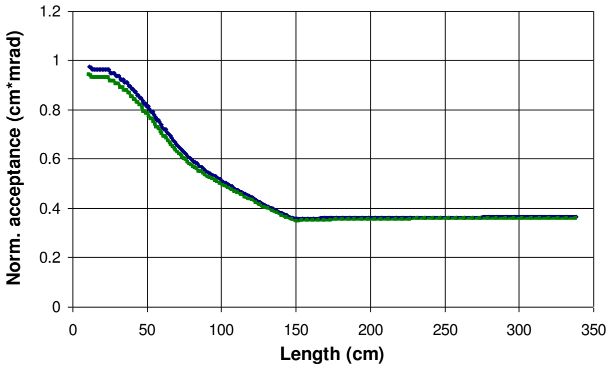

Figure 3: Normalized local acceptance for low beam current (blue) and under space charge conditions (green), calculated along the RFQ channel (for each cell separately).

As follows from Figures 2 and 3, under design space charge conditions (beam current 10 mA, total unnorm. beam emittance 6 cm·mrad), the decrease of the RFQ phase advance and acceptance is only a few percent, thus an influence of the space charge effects is neglectable.

In particular, this is ensured by the chosen relatively high input particle energy of 46 keV. A lower input RFQ energy might lead to a slightly compacter RFQ, but results in much stronger space charge effects, especially inside the gentlebuncher. Obviously this would lead to nonlinear effects, emittance growth and a degradation of the beam quality.

BEAM DYNAMICS SIMULATIONS

Assuming low tune depression, the results of beam dynamics simulations are recently presented only for low beam current, demonstrating the coincidence between the used codes. A set of simulations under space charge conditions is now under consideration, in parallel to the final optimization of the modulation along the RFQ.

A profile of the RFQ input radial matcher has been defined in the way to provide for a smooth matching of the beam emittance to the RFQ acceptance. The matched Twiss-parameters have been obtained from the results of dedicated beam dynamics simulations for the RFQ acceptance. The same 6D phase space input macroparticle distribution, continuous in longitudinal phase plane, has been introduced into both codes (Fig. 4).

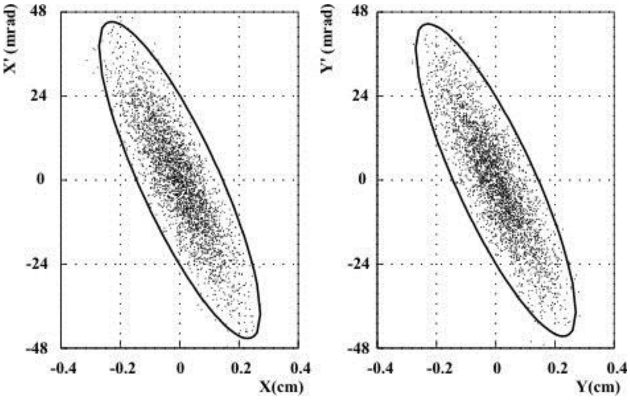

Figure 4: The transverse beam phase portraits at the RFQ entrance; ellipses represent 99% of the particles.

The resulted particle distributions behind the RFQ (Fig. 5) illustrate good similarity. Possible sources of minor discrepancy are recently under investigations.

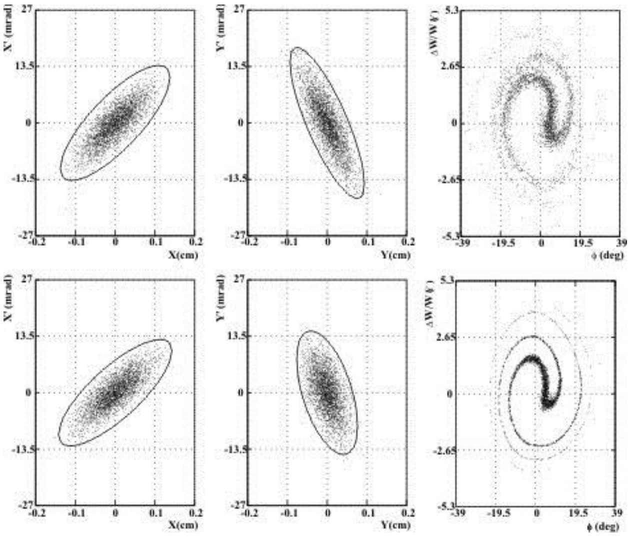

Figure 5: The beam phase portraits behind RFQ for transverse and longitudinal phase planes, simulated by the BEAMDULAC-RFQ (top) and the DYNAMION (bottom) codes; ellipses represent 99% of the particles.

CONCLUSION

A new CW 2 MeV RFQ linac design is proposed. The maximum field strength is limited by the 1.5 Kilpatrick criterion. The machine can accelerate a 10 mA proton beam with a particle transmission close to 100%. Beam dynamics simulations were performed by means of the codes BEAMDULAC and DYNAMION. A preliminary design of an RFQ modulation can be efficiently performed by the BEAMDULAC-RFQ code. The DYNAMION code, which uses an accurate treatment of the external electrical field, is useful for the detailed beam dynamics simulations. The results of the codes are in good agreement. The electrodynamics simulations, as well as mechanical layout for a new CW RFQ cavity are in progress. Final optimization of the RFQ channel has been already started.

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