BEAM DYNAMICS STUDY FOR THE NEW CW RFQ

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Abstract

A compact "university scale" research CW proton accelerator, as well as driver linac with three branches of experimental beam lines, delivering beam energy of 2, 10 and 30 MeV for dedicated experiments, are recently under development in Russia. A proposed front-end system of both linacs comprises a 2 MeV CW RFQ, which is foreseen to bunch and accelerate up to 10 mA proton beam. The RFQ design is presented. The beam dynamics simulation results, obtained by means of different software, are discussed and compared.

INTRODUCTION

The development of a CW high-power proton linacs 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. Also compact research facilities are the modern trend for high intensity CW proton and deuteron linac development [1,2].

The Russian accelerator-driver concept has been already developed by the collaboration of researchers from MEPhI and ITEP of NRC Kurchatov Institute [3-6]. The proposed linac layout is close to the conventional scheme: an RFQ and a normal conducting DTL with transverse focusing by integrated RF sections up to 30 MeV. The independently phased SC cavities are foreseen for medium and high beam energies. Three branches of experimental beam lines, delivering a beam energy of 2, 10 and 30 MeV for dedicated experiments, are foreseen as the main feature of the proposed facility concept [7,8].

Research and development of CW applications is an important step in RFQ design. A 2 MeV RFQ is under investigation for the compact CW research proton accelerator, as well as for the planned driver linac in Russia. The maximum beam current is fixed to 10 mA; the operating frequency has been set to 162 MHz; the RF potential should be limited by 1.3-1.5 of Kilpatrick criterion for the CW mode. The main RFQ parameters are shown in Tab.1.

The beam dynamics simulations for the new RFQ channel, as well as an analysis of the RFQ characteristics, have been performed with the codes BEAMDULAC [9] and DYNAMION [10], providing for a cross-check of the design features and the calculated results. The first results of the beam dynamics simulations have been briefly discussed in [12].

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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 (total)
Particle transmission	> 99%

A preliminary design of a CW RFQ linac has been already started at MEPhI and ITEP [11,12]. 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 and ITEP [13,14], as well as decades of GSI expertise in construction, optimization and routine operation of ion linac facilities [15-21]. Most recently, the prototype for a heavy ion CW linac with a SC main part is under construction at GSI and HIM [22-26].

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 $\boldsymbol{E_{max}}$ has been limited by the 1.5 Kilpatrick criterion.

The average radius $\boldsymbol{R_0}$ = 0.530 cm and the vanes half-width/rounding $\boldsymbol{R_e}$ = 0.412 cm have been defined together with the RFQ voltage of 90 kV. The Kilpatrick criterion $\boldsymbol{E_{kp}}$ = 148 kV/cm for the given operating frequency of 162 MHz has been calculated using modified Kilpatrick equation:

$$R_0 E_{kp}^3 \cdot \left(1-\exp\left(-\frac{48.6 E_{kp}}{R_0 f^2}\right)\right) = 1.8\cdot 10^5 \cdot \exp\left(\frac{170}{E_{kp}}\right)$$

with average radius $\boldsymbol{R_0}$ given in cm, frequency $\boldsymbol{f}$ in MHz and the Kilpatrick criterion $\boldsymbol{E_{kp}}$ in kV/cm [27].

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The maximum electrical field on the vane surface E_{max} (Fig. 1) could be calculated for the real topology of each RFQ cell. Almost constant electrical field strength E_{max} provides the most effective focusing and acceleration along the whole channel. In particular this is important, as RF voltage and RF power should be strongly limited for a CW regime.

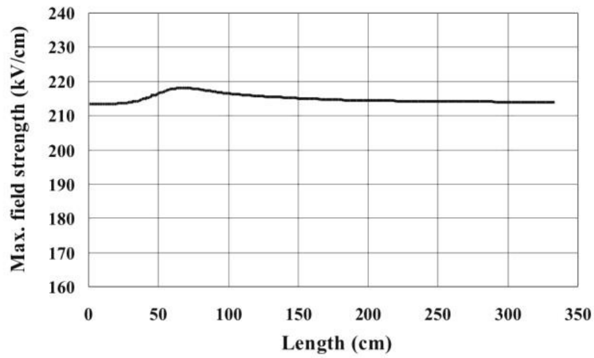

Figure 1: Maximum strength of electrical field on the vane surface along the RFQ channel, calculated for each cell separately.

Assuming a low beam current and a smooth approximation [28], the normalized local acceptance V_k for each RFQ cell can be calculated using the Floquet functions from a solution of the Mathieu-Hill equation for particle motion:

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

where $\nu_f = 1/\rho^2$, ρ is a module of the Floquet function, a - aperture radius of the cell, λ - wave length of the operating frequency; ν_f can be treated as a minimum of the phase advance μ on the focusing period.

Assuming a given beam current phase density (beam brilliance) for a uniformly charged beam (KV distribution), a tune depression can be calculated semi-analytically for each RFQ cell. Then a local acceptance along the channel under space charge conditions could be evaluated as:

$$V_k = V_{k0}\left(\sqrt{1+h^2} - h\right), \quad h = j \cdot \frac{B\lambda}{\mu_0 \beta I_0}$$

where the Coulomb parameter h combines parameters of the beam and the accelerating channel: $j = I / V_p$ - beam brilliance, I - beam current, V_p - normalized beam emittance, B - ratio of the peak to the pulse currents, I_0=3.13·10^7·A/Z - characteristic current, A, Z - mass and charge numbers, μ_0 - phase advance for low current, β - relative velocity of particle.

The lowest value of the local "cell"-acceptance estimates the transverse acceptance of the whole RFQ channel. As illustrated in Fig. 2, the RFQ acceptance under design space charge conditions (Tab. 1), is decreased on a few percent only, 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 energy might lead to a slightly compacter RFQ, but will result in stronger space charge effects, especially inside the gentlebuncher.

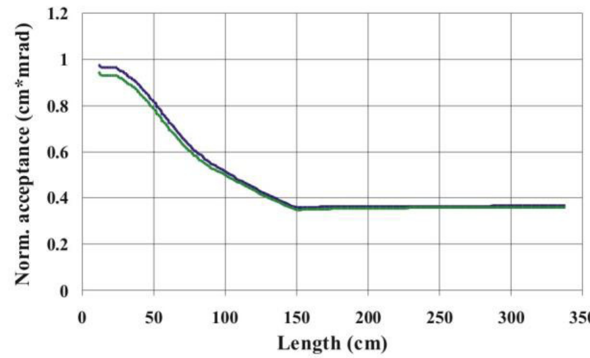

Figure 2: Normalized local acceptance for low beam current (blue) and under space charge conditions (green) along the RFQ channel, calculated for each cell separately.

BEAM DYNAMICS SIMULATIONS

The shape of the RFQ input radial matcher has been optimized for a smooth matching of the beam emittance to the RFQ acceptance. The matched Twiss-parameters have been obtained from the results of dedicated simulations for the RFQ acceptance. The same 6D phase space input macroparticle distribution (truncated Gaussian in transverse phase planes and continuous in longitudinal one) has been introduced into both codes for beam dynamics simulations with low beam current.

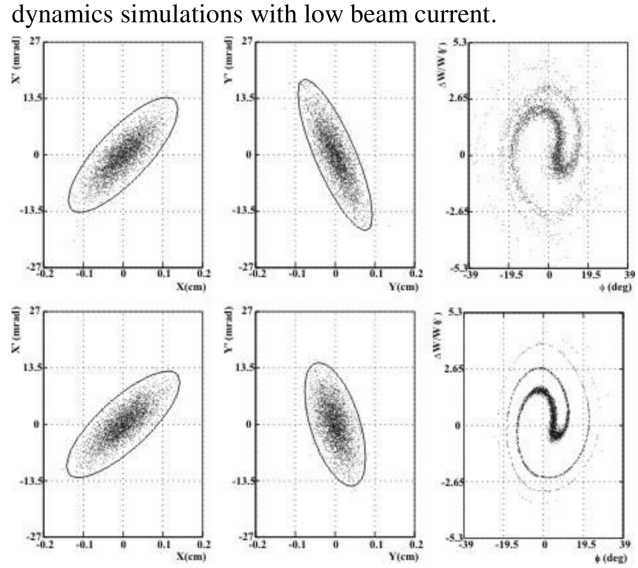

Figure 3: The beam phase portraits behind RFQ for transverse and longitudinal phase planes, simulated by the codes BEAMDULAC (top) and the DYNAMION (bottom); ellipses represent 99% of the particles.

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The resulted particle distributions behind the RFQ (Fig. 3) demonstrate good coincidence between the codes BEAMDULAC and DYNAMION.

Also a set of simulations under space charge conditions, even taking low tune depression of only few percent into account, is recently under consideration together with the final optimization of the modulation and synchronous phase along the RFQ accelerating-focusing channel.

CW RFQ CAVITY

The 4-vane RFQ with coupling windows [29] can be utilized as a front-end for a high-energy high-power linac. A segmented vane RFQ type (SVRFQ), successfully commissioned in 2016 for the new NICA injector at JINR (Dubna) [30], was also proposed to be used for CW application [11].

The described RFQ cavity comprises 13 RF-cells. Magnetic coupling windows have to be optimized by six parameters to achieve high RF field uniformity and to improve the transverse shunt impedance and Q-factor: the shell radius, the transverse and conjugate diameters of windows, the transverse diameter of the endmost windows (EWs) and the lengths of both end regions.

The corresponding 3D model of the proposed SVRFQ structure with optimized elliptical vane windows is shown in Figure 4. Optimal geometry parameters for SVRFQ design normalized to the RF-cell length (L_{cell}) or shell radius (R_{shell}) as well as main electrodynamics characteristics are given in Table 2.

Table 2: Geometry for an optimal SVRFQ design and main electrodynamics characteristics

Parameter	
Frequency, MHz	162
Shell radius, mm	196
Transverse window length, $\%L_{cell}$	75.5
Transverse EW length, $\%L_{cell}$	37.0
Conjugate window length, $\%R_{shell}$	42.2
1st end region length, $\%L_{cell}$	26.3
2nd end region length, $\%L_{cell}$	26.3
Power loss, kW	61.9
Q-factor, 10^4	1.65
Transverse shunt impedance, kΩ	150.4

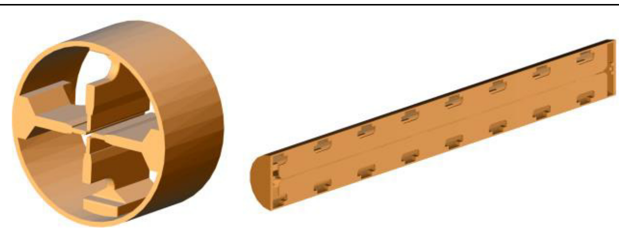

Figure 4: Optimized design of the SVRFQ cavity with elliptical coupling windows.

CONCLUSION

A new CW 2 MeV RFQ linac design is proposed. The maximum field strength is limited by the 1.5 Kilpatrick criterion. The proposed RFQ linac can accelerate a 10 mA proton beam with a particle transmission close to 100%. The codes BEAMDULAC and DYNAMION have been used for beam dynamics simulations. The results of the codes are in good agreement. Final optimization of the RFQ channel is in progress. The electrodynamics simulations for the RFQ resonator have been already started. The mechanical layout for a new CW RFQ cavity is recently under consideration.

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