"THE LAUNCHING OF A 3-MeV PROTON RFQ LINAC"


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Summary

A 3 MeV RFQ linac has been constructed in the ITEP. Values of the linac design parameters attained in practice as well as some preliminary experimental results obtained at the machine launching with output current rising up to 100 mA are in the report below.

Introduction

The spatial uniform quadrupole focusing structures 2 or RFQ (this widespread abbreviation may include spatial periodic structures also) are now widely recognized as an effective mean for the acceleration of ions beams with low β values. Calculational and theoretical problems connected with the use of RFQ linac structures have been observed in the works of Soviet 3-6 and foreign 7-9 authors. The first RFQ linac had been put operational and investigated in 1977 10-12. In a number accelerator centers HP testing of models and full-scale RFQ resonators for light or heavy ions acceleration are under way 13-18.

The present report describes the course of RFQ linac launching in ITEP with obtaining 100 mA proton beam current accelerated up to energy of 3 MeV.

Parameters and design of the linac

An accelerating-focusing channel of the RFQ linac is a four-line structure supplied by the four-chamber H-type resonator with quadrupole mode of 148.5 MHz oscillations. The main physical parameters and properties of the resonator have been obtained earlier from testing of its full-scale model.

The RFQ vanes used in ITEP are strips restricted in the cross section by a semicircle with constant along the strip 10 mm radius. The distance from aperture axis to vane tips r is varied sinusoidally with gradually increasing period:

\[ r = R_0 (1 + \sin k z) \]

where \( R_0 \) - mean distance from the vane tip to the z-axis; \( m \) - modulation factor; \( k = 2\pi / \lambda \).

Minimal distance from the vane tip to the axis \( a = 2R_0/\sqrt{1+m} \) is bore radius, it determines the channel acceptance. The field and the vane tips shape were determined by an expression for ideal poles. The numerical study of the fields by a computer code POLE-1 20 shows that the distribution of the potential in the axis area for the vane tips of the mentioned form only slightly differs from the ideal (along the whole accelerating section, except its initial part). The fabrication of such vanes is not difficult, thus it is evident about optimum. In Los Alamos the same conclusion was reached recently 21.

The numerical analysis shows that peak vanes surface field \( E_{max} \) is reached either in the cross sections where vane tips are most closer to the z-axis if \( m < 1.2 \), or in the regions of the cross sections with precise quadrupole symmetry if \( m > 1.2 \). The value of \( E_{max} \) is determined basically by the field transverse component and it only slightly depends on the modulation depth. Thus spark limit value of the pole-gaps is practically the same for the parts of the channel with the same value of \( R_0 \), with the correct spacing of the vanes and equal quality of its surfaces.

In RFQ linac one can distinguish three sections: matching section, buncher and main accelerator. The manner of accelerating-focusing channel main parameters change in the matching section is shown in Fig. 1 and the buncher and accelerator - in Figs. 2 and 3, where \( V \) - minimal frequency of transverse oscillations on the scale of an indimensional time, \( E_0 \) - focusing efficiency, \( dW/dz \) - acceleration rate.

In the matching section of 22 cells transverse matching is realized by tapering of the average distance between the vanes. To attained a maximum capture in the first 12 cells the equilibrium phase is kept constant with the value and further its absolute value is reduced to 85°. By the end of the section uninterrupted beam is divided on bunches following each other at a small distance.

In the buncher quasistationary bunches are accelerated. A transit time factor 22 as well as equilibrium phase \( \phi \) are changing adiabatically along the z-axis with bunches length and longitudinal momentum absolute spread being constant. With the particles velocity growth bunches are separating leaving the spatial charge density constant.

In the accelerator section adiabatic decrease of the synchronous phase is stopped to prevent peak current reducing. With large distance between bunches its value is proportional to \( |\phi| \). A transit time factor and vanes modulation depth are becoming constant. The transit time factor and vanes modulation depth are becoming constant. The core of the bunch is pressed adiabatically and maximum spread is decreased to 12.2% and the phase length - to 74°.

The maximum value of the average current during the pulse \( I_{max} \) is limited by the output part of the buncher.

The 4.9 m long HP resonator of linac consists of 3 sections. The boundaries between sections are chosen in the places with the minimum field on the surface of modulated vanes, where the sparking possibility is less. The resonator has field restricting bottom ends. The diameter of each 4 resonator chambers is 200 mm. All sections are covered with the screws to fasten vanes properly, with the manual frequency tuning plates, alignment marks and measuring loops. Tuning plates enable to change a resonance frequency within ±1.5%. An unloaded resonator quality \( Q \) is 71000. Vanes have been milled by a special programme.

The vacuum pumping is provided by 12 l/min 250 l/s pumps, turbomolecular pump of 500 l/s and roughing mechanical pump with a trap. Stainless steel vacuum tank has diameter 70cm.
volume 3 m³ and consists of 5 sections joined with metallic seals.

Preparation and tuning of a resonator

The resonator was prepared by following steps: assembling of a separate sections; their mechanical cleaning; washing in a vibrating bath with freon; final assembling of the resonator within a clean plastic tent; check of its tuning and the placing of the resonator into a vacuum tank (Fig.4). Alignment of the sections in the tank was fulfilled with the help of alignment gear attached to a tank wall and passing a shift in vacuum. Each section has 16 holding gears. Sections of the resonator are placed in the tank with rms deviation of 100 pm. Many cycles of pumping and filling of the tank have not shifted the resonator.

HF preparation of the resonator included its own frequency tuning for the working quadrupole mode of oscillations, leveling of the field along the tank by chambers, dipole modes suppressing. Dipole modes suppressing with a slot excitation of the resonator used in Los Alamos at a frequency of 425 MHz 13 in our case is not convenient because of a lower working frequency and hence larger geometrical dimensions. Besides of that, with the slot excitation the tank of resonator walls cooling becomes very complicated. Four-chamber resonator in the ITEP excites with the help of four loops placed by one in each of the chambers and properly phased. With that way of excitation and quality of the resonator in a loaded condition $Q = 4700$ it was possible to adjust fields so, that dipole field components were not felt within the measurement accuracy 2%. Field disturbances in the longitudinal as well as azimuthal directions was not more than 10%. At the same time it was found that small displacement of sections (about 100-150 µm) caused noticeable changes of a reached magnetic field distribution along the resonator as well as by separate chambers. Preliminary estimations show that requirements to accuracy of the vanes placement from the point of view of HF resonator tuning might be more rigid than those, which are defined by tolerances on transverse field distortions.

Launching of the linac

During the preparation of the linac to physical start-up all technological systems were adjusted individually. The pressure after 36 hours of pumping was $3 \cdot 10^{-6}$ torr and in the course of following several days did not change notably.

The output power of HF generator while working with a load equivalent at pulse duration of 120 µsec and rate of 0.25 pps reached 1.5 MWT. For the first time HF power was put into the resonator at $2.6 \cdot 10^{-6}$ torr (later it was being done at $6 \cdot 10^{-6}$ torr).

The process of vanes surfaces training was followed by some HF oscillations instability in the resonator. At rising the resonator sparking occurred more often in the aperture area between the adjacent vanes or in the places of next vanes junction. Sparking did not cause sharp falling of HF envelope and fast local discharge of the whole stored in the resonator HF energy.

Maximum voltage between adjacent vanes $U_L$ measured in the units of a threshold level $U_{thr}$ calculated to be about 225 kV was $U_L = 1.3 U_{thr}$. Equilibrium phase $-35^\circ$ in the main accelerator section was at $E_b$ max $\approx 250$ kV/cm and $U_v = 185$ kV. Actually multipactoring effects have not shown off.

A modified version of ion gun described earlier 22 was used at the injector. The ion source was a hollow cold cathode duoplasmatron with pulsed gas eject. The control of apparatuses under 100 kV pulse voltage was realized by optronic channels. The nominal injector parameters were obtained on the stand in advance. An ion source unit was placed at minimal distance (0.3 m) from linac input. The final ion gun alignment in respect aperture channel was conducted by proton beam passing through accelerating channel at low HF field levels. The acceleration was reached immediately after HF voltage rising up to level $U_v = 150$ kV (average value from 20 of resonator measuring loops) it corresponds a calculating value of the threshold level. The existence of 3 MeV protons was affirmed by their passing through a 70 m stainless steel foil. With some HF envelope falling in was shown, sharp increase of γ-ray intensity and scintillation screen brilliance.

At the measurements of particles capture value a collimator was used so as to eliminate the loss through Coulombian repulsion. It restrict a normalized beam emittance of 0.06 cm-rad. The Fig.5 shows the change of accelerated (passing through a cutting foil) current $I_{acc}$ (dotted lines) versus of vanes voltage $U_v$ (in the units of threshold voltage $U_{thr}$). A part of accelerated particles in output beam increases with rising of $U_v$ and at $U_v = 1.22 U_{thr}$ (that corresponds calculated equilibrium phase value $\phi = -35^\circ$) reached $\approx 95\%$ (Fig.6).

Measured value of optimal injection energy (92 kV) and estimation of a momentum spread on the output (<3%) are closed to calculated values. The maximum accelerated current was 100 mA with pulse duration of 25 µsec.

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Fig.4. The RFQ Linac resonator in a vacuum tank.