COMPACT PROTON INJECTOR FOR SYNCHROTRONS

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Abstract

Compact proton linac comprising two sections of different RFQ structures was designed. The first section is conventional RFQ with output energy 3.5 MeV whereas the second one is RFQ with spatial periodic RF quadrupole focusing. The linac output energy is about 9 MeV. The both structures operate at frequency of 352 MHz. The total length of machine is less than 6 m. The output pulsed beam current is of 40 mA. The design is suitable for NICA injection complex and proton superconducting medical synchrotron.

INTRODUCTION

The design of proton linac was carried out in accordance with the NICA mega-project program at JINR [1]. There are two purposes to design of simple, reliable and compact proton machine: 1) proton injector for the Nuclotron (or it's booster) and 2) proton injector for medical synchrotron based on the Nuclotron-type technology [2,3]. The main parameters specified for the design are presented in Table 1.

Table 1: Linac parameters

Output beam energy, MeV	3.5…8.0
Pulse duration, microseconds	5…15
Average beam pulse current, mA	5.0…15.0
Pulse repetition rate, Hz	1…2

The particle energy range specified above can be reached with the use of well known scheme of a proton linac. The scheme comprise of a front end – RFQ structure operating at 325 – 433 МГц and the main accelerator part based on much more effective accelerating structures, nevertheless at the same frequency. The RFQ section provides bunch formation and acceleration of the particles up to an energy of 2.5…3.0 MeV. The accelerating structure of the most advanced proton linacs, such as SNS [4], J-PARC [5], Linac4 [6], followed after the RFQ, is the Alvarez-type one with permanent magnet quadrupoles. Compact linear accelerator has been proposed by the AccSys Company for the market also follows to the above mentioned scheme [7]. The list of beam parameters specified above is not full, because one should keep in mind also a number of other very important characteristics of any device aimed at application in medical treatment procedure, namely: high reliability, simple engineering design based on standard elements as much as possible, easy handling with low number of personal. Despite of a wide recognition, the scheme meets a lot of difficulties due to complexity of its manufacturing and high cost.

The goal of our paper is to demonstrate that a compact proton linac for the considering application area can be built using only RFQ structures.

LINAC SCHEME

The proposed injector scheme is shown in Figure 1. Injector consists of proton source (pS), matching channel (LEBT), conventional RFQ (RFQ1) and spatially – periodic RFQ (RFQ2). Design of all injector parts was aimed at providing compact and inexpensive linac with high transmission, which keeps initial beam brilliance and provides relatively small longitudinal output emittance.

Figure 1: General layout of the injector.

LEBT

Conventional LEBT function is beam transport from ion source to RFQ input and transverse matching with RFQ input. LEBT layout of compact injector is shown in Fig.2. It includes buncher and 4 quadrupole static lenses. RFQ input radial matcher is also shown in the picture because it is functionally part of matching channel.

Radial matcher is designed using optimizing computer code to reduce beam convergence at RFQ1 input and reduce beam envelope inside static lenses to minimize beam distortion in LEBT. Matcher has 12 $\beta\lambda/2$ cells. Twiss parameters at RFQ input are given in Table 2.

Table 2: Matched beam parameters at RFQ input

Beam current, mA	α	β, mm/mrad
10	0.10	0.032
20	0.11	0.038
30	0.12	0.042

Initial cell length at chosen frequency $\beta\lambda/2 = 4.4$ mm. Thus, it is a problem to design conventional drift tube buncher. A short RFQ structure consisted of 2 modulated cells with modulation coefficient m = 1.2 and of 6 cell input and output radial matchers is used as a buncher in our LEBT design. Transverse beam envelopes inside the LEBT are shown in Figure 2.

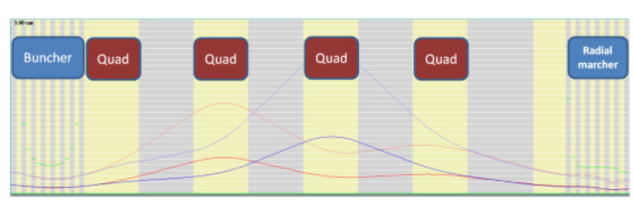

Figure 2: LEBT layout and simulated envelopes

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RFQ 1

RFQ1 is designed as a conventional RFQ structure. Main design goal was providing initial formation of the beam and its acceleration to intermediate energy with minimum vane length. External buncher in front of RFQ [8] and relatively low design beam current value allow us to provide high transmission and low longitudinal emittance at RFQ output using considerably reduced length of gentle buncher. Trapezoidal vane modulation profile is used in accelerating part to reduce total length.

Last RFQ1 cells are designed to match longitudinal emittance with RFQ2. The main RFQ1 parameters are given in Table 3.

Table 3: Basic RFQ1 design parameters

Parameter	Value
Input beam energy, MeV	0.05
Output beam energy, MeV	3.52
Frequency, MHz	352.2
Mean radius, mm	3.6
Voltage between electrodes, kV	93.2
Electrodes thickness	0.8 R_0
Vane modulation profile	Sin + Trapezoid
Maximum surface electric field, kV/cm (Kilpatrick value)	340 (1,85)
Transverse phase advance, deg	31
Transverse acceptance, mm mrad	6.6
Cell number	252
Length of vanes, mm	3000

Beam dynamics in RFQ1 was studied using multi particle simulation code TRANSIT. Simulation results are given in Table 5.

RFQ1 resonant structure is 4-vane with coupling windows. Cavity parameters are given in Table 6.

RFQ2

Voltage and, hence, the rate of acceleration in conventional RFQ is defined by transverse stability requirement. Transverse phase advance μ is inversely proportional to average radius R_0. Energy gain in RFQ cell ΔW is in turn proportional to R_0.

$$\mu \approx \frac{E_{\max}}{R_0}, \quad \Delta W \approx E_{\max} \cdot R_0$$

Increasing R_0 within certain limits keeping transverse motion stability can be provided by increasing focusing period length using spatially periodic structure. RFQ2 is based on the structure described in more details in [9].

The structure consists of 4-vane segments separated by a number of round drift tubes. 4-vane segments have different transversal displacements of vertical and horizontal vanes from axis. It means that there is nonzero electric potential on the quadrupole axis that forms accelerating gap between quadrupole and axially symmetrical drift tubes. Structure with focusing period length $S = 5\beta\lambda$ is shown schematically in Figure 3.

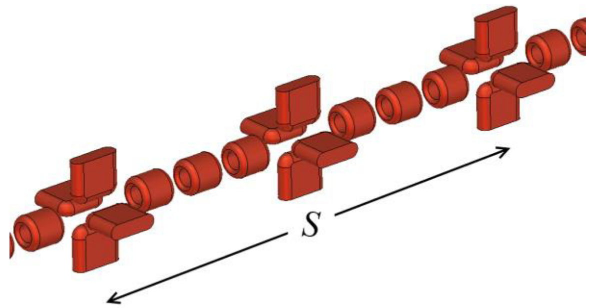

Figure 3: Spatially periodic RFQ structure (S = 5βλ)

Basic design parameters of RFQ2 structure are given in Table 4.

Table 4: Basic RFQ2 design parameters

Parameter	Value
Input beam energy, MeV	3.52
Output beam energy, MeV	9.05
Frequency, MHz	352.2
Drift tubes aperture, mm	8.0
Gap length, mm	20.0
Quadrupole average radius, mm	10.0
Voltage between electrodes, kV	220
Maximum surface electric field, kV/cm (Kilpatrick value)	340 (1.85)
Transverse phase advance, deg	44
Length of structure, mm	2000

Beam dynamics in spatially – periodic structures with RF focusing is more complicated due to dependence of particle transverse motion on phase of field at moment particle crosses quadrupole center. This effect imposes limitation on phase width of bunch at RFQ2 input. Figure 4 shows dependence of transverse RMS emittances on bunch phase width at RFQ2 input calculated by TRANSIT code. It illustrates that there is no emittance growth up to $\Delta\Phi = \pm 20°$ in X plane and only 13% growth for Y plane. It confirms that RFQ1 output beam can be accelerated in RFQ2 without considerable deterioration.

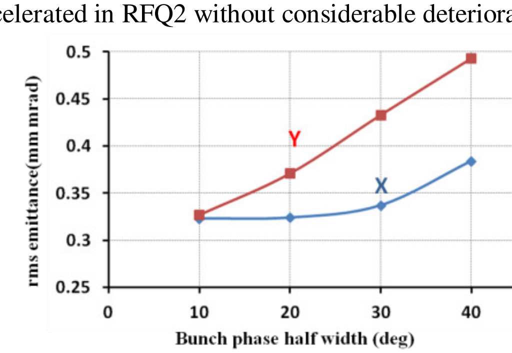

Figure 4: The dependences of transverse emittance on bunch phase width

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Figure 5 shows screenshot from TRANSIT with transverse envelopes calculated with initial bunch phase width $\Delta\Phi = \pm 20°$and beam current I = 20 mA. Figure 6 shows simulation results for dependence transverse phase advance on beam current.

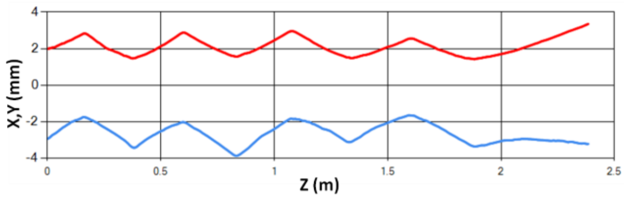

Figure 5: Transverse envelopes in RFQ2

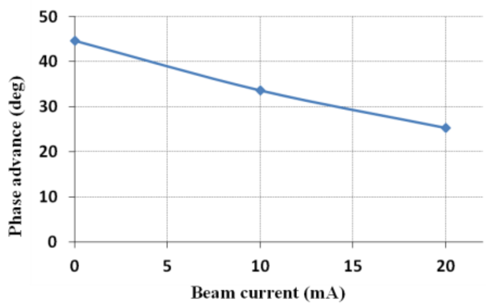

Figure 6: Transverse phase advance vs beam current

The results of beam simulation in injector are given in Table 5. It presents emittance growth through sections of injector-relatively to the corresponding values at output of preceding part. Data are obtained from simulation using TRANSIT code for initial transverse emittances $\varepsilon_x = \varepsilon_y$ = 2.0 mm mrad and beam current I = 20 mA.

Table 5: Transverse emittance evolution through injector

	LEBT	RFQ1	RFQ2
Transmission, %	100	95	100
X rms, norm, mm mrad	1.01	1.04	1.05
X 99%, norm, mm mrad	1.00	1.03	1.19
Y rms, norm, mm mrad	1.04	1.03	1.25
Y 99%, norm, mm mrad	1.02	1.02	1.24

The spatially – periodic RFQ2 can be based on IH cavity as well as 4-vane cavity. 4-vane option allows us to simplify mechanical design of cavity whereas IH cavity provides lower RF losses. Opposite vanes in 4-vane cavity are connected by drift tubes so there is no problem to provide mode separation. The 4-vane cavity is shown in Figure 7. Calculated parameters of RFQ1 and RFQ2 cavities are given in Table 6.

Table 6: Section parameters

	RFQ1	RFQ2
Cavity type	4-vane + cw	4-vane
Frequency	352.2	
Cavity diameter, mm	160	276
Q factor	8500	13890
Specific RF power loss	120 kW/m	183 kW/m
Total RF power loss	360 kW	366 kW

Figure 7: 4-vane spatially – periodic RFQ cavity

CONCLUSION

Compact proton injector for NICA facility has been designed. It consists of conventional RFQ structure and newly proposed spatially – periodic RF quadrupole focusing structure with FODO lattice. The injector total length is about 5.3 m at output energy of 9 MeV. The proposed injector can accelerate proton beam with current up to 40 mA. The injector structures based on 4-vane cavities consume less than 800 kW RF power. The proposed modification of accelerating structure allows to built relatively simple and inexpensive accelerator that can be used for different applications.

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