BEAM DYNAMICS SIMULATION FOR THE 1 GeV HIGH POWER PROTON LINAC

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Abstract

The design of high energy and high power proton linacs for accelerating driven systems (ADS) is one of the accelerator technology frontiers. Such linacs are under developing in EU, Japan, PRC but not discussed in Russia previous ten years. The driver linac and the breeder conceptual designs were funded by the Ministry of Science and Education of Russian Federation in 2013. The 2 MeV RFQ linac was proposed as the first accelerating section. A number of RF focusing sections types (by RF crossed lenses, modified electrode profile RFQ, axi-symmetrical RF focusing) were discussed for medium energies. The conventional modular scheme linac based on spoke-cavities and 5-cell elliptical cavities was designed for higher energies. The results of beam dynamics simulation in this linac will present.

INTRODUCTION

The designing of a high-power proton linac for 1.0 GeV was performed by collaboration of MEPhI, ITEP and Kurchatov institute researchers in 2013. Such linac is useful for spallation neutron sources and drivers for accelerator driven system (ADS). Operation in the CW mode is preferable for an ADS linac. Accelerator-driver design was done more that ten years ago in the Russian Federation last time. This project was supported by the Ministry of Science and Education of the Russian Federation. The conceptual design of the linac is presented in Fig. 1.

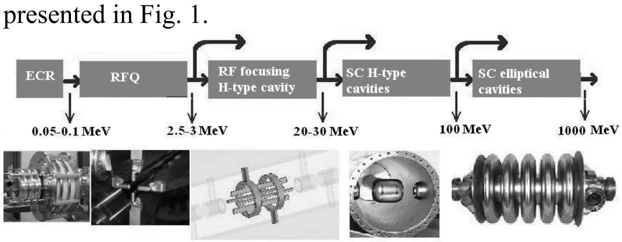

Figure 1: The linac general layout

The linac will consist of an RFQ, RF focusing section(-s) and SC modular configuration sections. Several different types of RF focusing linacs were discussed for the medium energies. There are RF crossed lenses [1], modified electrode profile RFQ [2], axi-symmetrical RF focusing (ARF) [3] and the short SC cavities system was also discussed. The conventional modular scheme linac [4] based on spoke-cavities and 5-cell elliptical cavities were designed for higher energies. The linac layout have three intermediate energy beam lines which can be used by step-by-step linac construction to different experiments with neutron production targets or for radiation testing of reactor construction materials..

BEAM DYNAMICS SIMULATION IN RFQ

Beam dynamics simulation in RFQ section was done using the BEAMDULAC-RFQ code [5] and is detail discussed in ref. [6]. The CW RFQ linac section operates at 162 MHz and accelerates the beam to 2 MeV. It should be noted that accelerating potential between the RFQ electrodes will limited by 1.5-1.7 of Kilpatrick criterion value for the CW mode (~130-150 kV for 100-200 MHz band). The accelerating channel consists of three regions as was proposed in [7-8]: the dynamic matcher, the gentle buncher and the main accelerating region. The main RFQ channel parameters are the following: operating frequency 162 MHz, channel length 2400 mm, matcher length 160 mm, buncher length 1100 mm, synchronous phase on main accelerating region 36 ^{o}, maximal electrodes modulation 2.25, maximal aperture size (on matcher start) 9 mm, maximal aperture size in main accelerating region 5.5mm, injection energy 0.047±1 % MeV, injection transverse emittance 2π mm·mrad output energy 2.0MeV. It was shown that for the injection energy (47 keV) and the electrode potential (120 kV) current transmission decreases very slowly with injection current growth: ~96 % for zero current and ~94 % with 20 mA

BEAM DYNAMICS IN MEDIUM ENERGY RANGE

The different types of RF focusing sections as RF crossed lenses, modified electrode profile RFQ and axi-symmetrical RF focusing were studied for medium energy region with short SC cavities system. Brief results of beam dynamics simulation were presented in [9].

RF Crossed Lenses

A method of ion focusing in linac by RF decelerating fields of crossed lenses (RFCL) [1] permits to obtain energy-independent focusing strength and high acceleration rate. The crossed lens (CL) is a set of plane electrodes with rectangular apertures such that the apertures in the neighbouring electrodes are rotated 90^{o} each other (see Fig. 2).

The ratio of sides for the rectangular apertures equals 3 (chosen under a/b<<1) then an electrical field component directed along the slit is negligible as compared with a component across the slit. Within the considered method

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the two-electrode RF crossed lenses with decelerating fields are arranged in accelerating gaps of a drift tube with round apertures linac. The focusing period with arrangement of the CL through two gaps (FOODOO) of the accelerating system formed by drift tubes with round apertures are shown in Fig. 3.

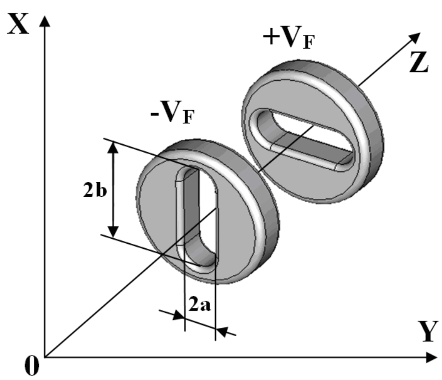

Figure 2: Two-electrode crossed lens

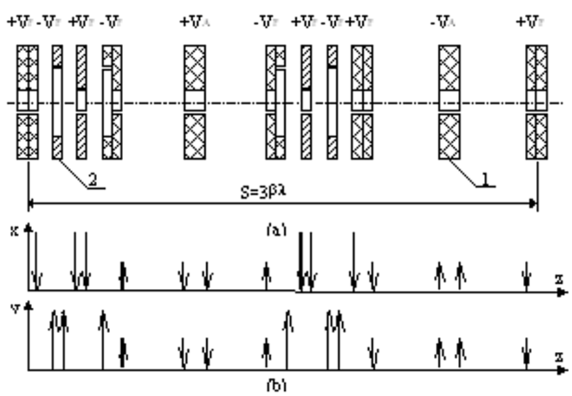

Figure 3: FOODOO focusing period with RF crossed lenses (a) and focusing gradients (b): 1 - round aperture drift tubes; 2 - two-electrode crossed lenses.

The lenses are identically aligned within limits of the focusing half-period and rotated 90º in the subsequent one. RF voltage is applied to lens electrodes to form in phase and anti-phase electrical fields in gaps between the lenses and inside the lenses respectively in relation to the accelerating fields in the initial gaps. Thus RF decelerating 3D-quadrupole field areas are created inside the lenses. Drift tube and lens electrode voltages (V_A and V_F see Fig. 3) are provided in the RF resonant system operating in π -mode. A spatial distribution of focusing gradients in the FOODOO period is presented in Fig. 3b. The transverse particle motion is determined by transverse components of accelerating fields and quadrupole fields of the CL. The accelerating field causes RF beam defocusing for an autophasing mode. The design parameters of a 30 MeV proton section with RF CL are the following: energy 2÷32.64 MeV, operating frequency162 MHz, peak field 250 kV/cm (1.8 Kp), peak field in gap 100 kV/cm, focusing period 3βλ (FOODOO), number of periods 8, number of lenses in period 2÷6, aperture radius 6.5 mm, pulse current limit 60 mA, acceleration rate 4.4 MeV/m, linac length 7.0 m.. The normalized acceptance of the RFCL channel is 0.33 π cm mrad, which is three times more than the beam emittance from the RFQ. Thus, the conditions for transverse recapture are performed.

We consider the stability of proton motion in the FOODOO focusing periods with described above parameters at the following parameters: the radio frequency of 162 MHz, , the field amplitudes in the accelerating and decelerating gaps 100 kV/cm, normalized transverse acceptance of 0.33π cm·mrad, the separatrix phase length of 75º, and the current limit of 60 mA. Dependencies of the minimum number of CL providing stable transverse motion of particles within limits of the separatrix on the proton energy and acceleration gain are presented in Fig. 4. Two lenses in the focusing period require for first three periods up to energy 8.64 MeV. In the following two periods of up to 16.4 MeV are needed four lenses. Total for this section will be used 32 RF crossed lenses.

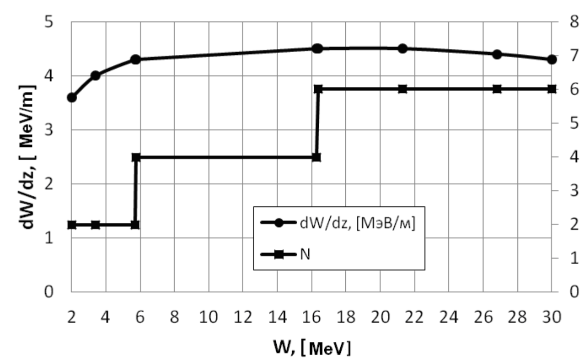

Figure 4: Dependencies of the minimum number of the crossed lenses and acceleration rate on the proton energy.

Axi-symmetrical RF Focusing

ARF linac [3] can be useful for medium energy range. Such focusing type was studied for 2-5 MeV proton linac section. It was shown that the rate of the energy gain can reaches to 2.5 MeV/m and section can be very compact. But the transverse emittance growth is very serious (more than 70 % with 10 mA initial beam current).

Modified Electrode Profile RFQ

The modified electrode form RFQ [10] can be used as the second section to accelerate the beam in 2-15 MeV energy range. Beam loses are absent, the averaged rate of the energy gain is equal to 1.3 MeV/m. It should be noted that such sections provide the lowest transverse emittance growth: about 5 % for 1 mA and 70 % for 100 mA.

BEAM DYNAMICS IN HIGH ENERGY SECTION

The BEAMDULAC-SCL code [4] was used to study the beam dynamics in the high energy range. Linac consisting of independently phased SC cavities (spoke and elliptical type) and focusing solenoids was designed. The synchronous phase slipping is the serious difficulty in

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Table 1: SC Section Design Parameters

Energy range	1	2	3	4	5
Geometrical velocity, β_g	0.31	0.36	0.48	0.65	0.875
Injection energy, W_{in}, MeV (β_{in})	20 (0.203)	49 (0.311)	91 (0.411)	184 (0.549)	456(0.740)
Output energy, W_{out}, MeV (β_{out})	49 (0.311)	91 (0.411)	184(0.549)	456 (0.740)	1000(0.875)
Slipping factor, T, %	20	20	20	20	23
Phase bunch size, $\Delta\varphi_{out}$, grad	36 (-16÷20)	34 (-15÷19)	40 (-18÷22)	29 (-12÷17)	32 (-16÷16)
Energy spread, $\Delta\gamma_{out}$	0.0006	0.0015	0.0028	0.01	0.018
Current transmission coefficient,%	100	100	100	100	100
Frequency, f, MHz	324	648	648	648	648
Wave length, λ, m	0.93	0.46	0.46	0.46	0.46
Gaps per cavity, N_{gap}	2	5	5	5	5
Injection phase φ, grad	–20	–20	–20	–20	–24
Cavity length, L_{res}, m	0.2883	0.414	0.552	0.7475	1.0063
RF field amplitude, E, MV/m	5.3	5.3	8.5	10.3	12.5
Solenoid length, L_{sol}, m	0.2	0.2	0.2	0.2	0.2
Solenoid field, B, T	1.4	1.8	2.4	2.4	2.6
Period length, L_{per}, m	0.69	0.81	0.95	1.15	1.40
Period's number per range, N_{per}	20	24	22	40	52
Stage length, L, m	13.76	19.54	20.94	45.92	72.80
Current transmission, %			100		

such linac because it provides to longitudinal stability degradation and energy gain decreasing. The phase slipping factor was limited by 20 %. It was shown that linac should consist of five groups of identical cavities with phase velocities 0.31, 0.36, 0.48, 0.65 and 0.875 (see Fig. 5). First group are 2-gap (or 3-gap) spoke cavities with 324 MHz operating frequency, other groups – 5-cell elliptical cavities operating on 628 or 972 MHz. Total length of SC linac part is 173 m, it consist of 158 cavities. The solenoid fields necessary for focusing not exceeds 2.6 T and the beam loses are absent. Main parameters of the high energy section are described in Table 1.

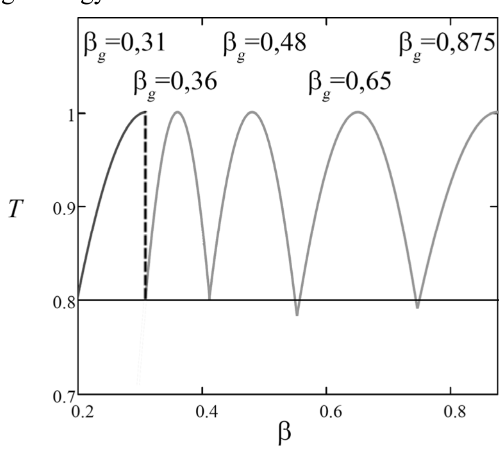

Figure 5: Slipping factor T versus beam velocity β in the high energy stage

CONCLUSION

Results of beam dynamics simulation of high energy high power proton linacs for accelerating driven systems were discussed. Main results for low (RFQ), medium (RFCL, ARF, modified electrode profile RFQ or shot SC cavities system) and high (SC) stages are presented.

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