THE PERSPECTIVE OF JINR LU-20 REPLACEMENT BY A SUPERCONDUCTING LINAC

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Abstract

The new accelerator complex Nuclotron-based Ion Collider fAcility (NICA) is now under development and construction at JINR. Existing Alvarez-type DTL linac LU-20 now operates as injector of light ions, polarized protons and deuterons to Nuclotron for LHEP experimental program. It provides proton beam of 20 MeV energy and light ions of 5 MeV/u energy. In 2015 the cascade transformer 800 kV which is pre-accelerator of LU-20 had been replaced by the new RFQ linac. The proposal on Alvarez linac LU-20 upgrade by a superconducting light ion linac with energy up to 50 MeV is discussed in this report.

INTRODUCTION

NICA is new accelerator complex constructing at JINR [1-4]. The injection system of operating Nuclotron and new NICA is under upgrade now. Now it consists of old Alvarez-type DTL called LU-20. The pulse DC forinjector will replaced by new RFQ linac which is developed and constructed [5] and it is under commissioning at present. The possibility of LU-20 replacement by new superconducting linac of 25 MeV for protons [6] and up to 7.5 MeV/nucleon for deuterium beam is discussed now. Project should also include upgrade option up to 50 MeV for the proton beam. Beam intensity and quality could be sufficiently increased in Nuclotron and NICA after new linac commissioning. Such linac would to be consisting of a number of superconducting independently phased cavities and focusing solenoids. Technologies which are necessary for serial SC cavities manufacturing are now absent in Russia but JINR in cooperation with the Institute for Nuclear Problems of the Belarusian State University (INP BSU)and the Physical-Technical Institute of the National Academy of Sciences of Belarus (PTI NASB) have started the pilot project of elliptical cavities fabrication and testing [13-15]. Now a new collaboration of the Joint Institute for Nuclear Research, the National Research Nuclear University – Moscow Engineering Physics Institute (NRNU MEPhI), the Institute of Theoretical and Experimental Physics NRC "Kurchatov Institute", the INP BSU, the PTI NASB (PTI NASB), the Belarusian State University of Informatics and Radioelectronics (BSUIR), and the Scientific and Practical Material Research Center of NAS of Belarus (SPMRC NASB) is established. The new collaboration declares two main aims of cooperation: development of technologies for SC cavities production and construction of the new linac – the injector for the Nuclotron-NICA complex. First results of the linac general layout development and beam dynamics simulation are presented in the paper.

SC PROTON LINAC GENERAL LAYOUT AND BEAM DYNAMICS SIMULATIONS

Low to mid-energy linear accelerator development is challenging because of serious limitations imposed on non-relativistic beam accelerating and focusing systems. This task could be solved using RF accelerator with identical short SC cavities with independent phase control for high energy gain and focusing solenoids. This design is economically allowable in the case of identical cavities, otherwise the total accelerator cost dramatically increases. It means that RF wave for all cavities will have the same phase velocity value. Wave and particle synchronous motion will be not observed here due to of particles reference phase slipping. The slipping value should not exceed some allowable limits otherwise the rate of the energy gain decreases, both transverse and longitudinal beam stability disturbs and current transmission decreases. In this case there are a lot of cavities to be used in the accelerator. It is practical to divide them in several groups consisting of identical cavities. Number of cavities in every group should be limited which also leads to accelerator length and cost decrease. It should be noted that phase motion analysis problem is accentuated by the absence of synchronous particle. All SC accelerator layouts usually propose that beam focusing is provided by lenses (solenoids or quadrupoles) located between cavities. Analytical and numerical methods of beam dynamics study with accelerator layout optimization were developed at NRNU MEPhI [6-10]. These methods are implemented in BEAMDULAC–SCL simulation code and allow to reduce number of cavities.

The ion beam motion stability analysis show that with the slipping factor about 17,5% (see Fig. 1) the new SC linac will consists of four groups of cavities having geometrical velocities of β_g=0.07, 0.141, 0.225 and 0.314. First two groups of cavities should be two-gap QWR's and the other – four-gap CH-cavities. Using transfer matrix calculation method [12] and smooth approximation [11] the preliminary SC linac parameters were defined for minimal linac length and lowest cost. The simulation results are shown in the Table 1.

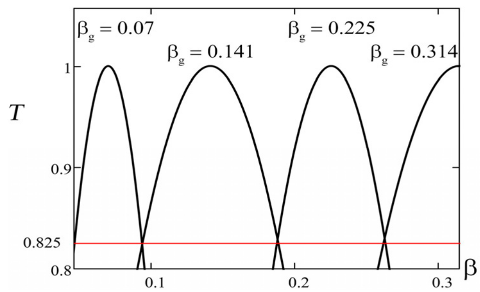

Figure 1: The slipping factor T for each cavities group.

Table 1: Parameters of SC Linac

Cavities group	1	2	3	4
β_g	0.07	0.141	0.225	0.314
W_{in}, MeV	1.0	4.1	17.2	34.3
β_{in}	0.046	0.093	0.189	0.263
W_{out}, MeV	4.1	17.2	34.3	50
β_{out}	0.093	0.189	0.263	0.314
T, %	17.5	17.5	17.5	17.5
K_T, %	100	100	100	100
f, MHz	162	162	324	324
N_{gap}	2	4	4	4
φ, deg	–20	–20	–20	–20
L_{res}, m	0.13	0.26	0.416	0.58
E, MV/m	3.08	10	12	11.21
U_{res}, MV	0.4	2.6	5	6.5
B, T	1.6	2	2.6	2.8
L_{sol}, m	0.2	0.2	0.2	0.2
L_{gap}, m	0.1	0.1	0.1	0.1
L_{per}, m	0.53	0.66	0.816	0.98
N_{per}	8	6	4	4
L, m	4.24	3.96	3.264	3.92

The proton beam dynamics in the polyharmonic field was simulated basing on the chosen parameters (see Fig. 2). We choose initial beam parameters (Fig. 2a) that provide particles matching with the longitudinal channel acceptance without dissipative effects (blue curve) and taking into account oscillations decay (magenta curve). Initial beam radius was taken equal to 3 mm, beam current being not taken into account. The protons beam acceleration, the oscillations decay and the slipping factor of the RF phase in dependence of the ratio between the particle velocity β and the phase velocity of the wave β_g should be taken into account for correct beam dynamics simulation. Results of beam dynamics simulation are presented in Fig. 2 (b–e).

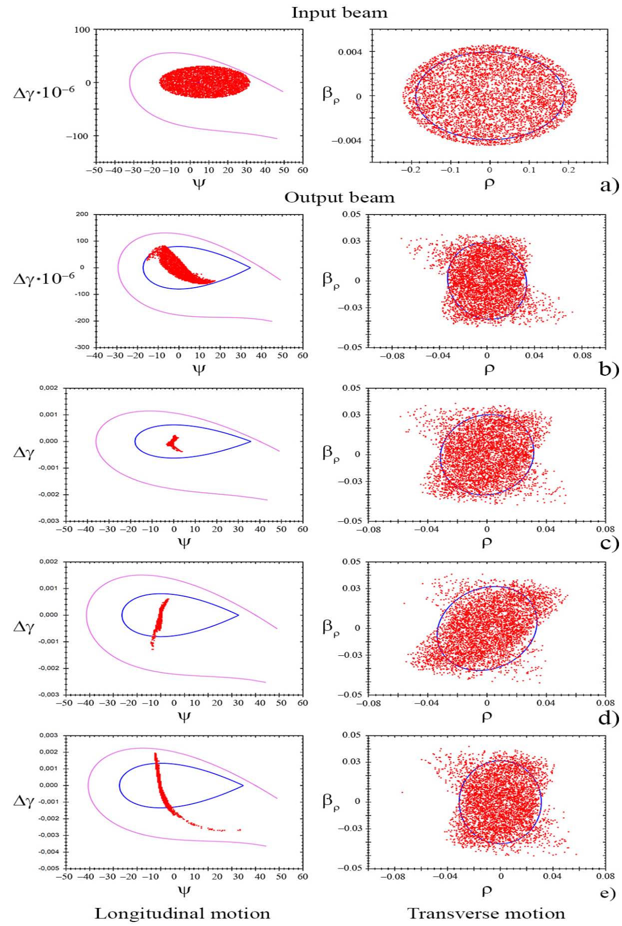

Figure 2: The longitudinal and transverse phase spaces after each section.

QWR AND CH-CAVITIES SIMULATIONS

The operating frequency of the linac was chosen equal to 162 MHz with further increase twice to 324 MHz. QWR and CH-cavities were simulated using CST Studio Suite and it's electrodynamics characteristics were preliminary optimized. Used models are presented in Fig. 3. Electrodynamics models of QWR cavities were designed for β_g=0.072, 0.105 and 0.150 and resonant frequency of f=162 MHz. The tuning and optimization goals were traditional: resonant frequency tuning, transit time factor T and effective shunt impedance R_a/Q maximization, and peak magnetic field B_p/E_a and overvoltage E_p/E_a minimization. As an example, optimal QWR characteristics for f=162 MHz and β_g=0.072 are the following: cavity height h = 480 mm, central conductor length l=439 mm, central conductor radius R_i= 18 mm, cavity internal radius R_o=67 мм, central drift tube length d=118 m, gaps length g=24 mm, B_p/E_a=10.83 mT/(MV/m), E_p/E_a = 6.36, T=0.912, R_{sh}/Q=650.27 Ohm. Optimizations were done for all β_g noted above.

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Four-vane CH-cavities models were also developed and tuned for β_g=0.150, 0.217 and 0.314 and f=324 MHz. Main cavities characteristics are presented in the Table 2.

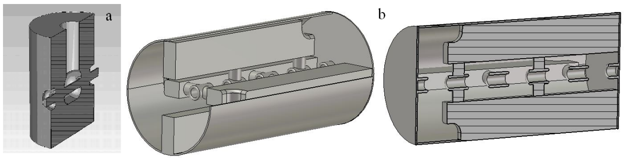

Figure 3: Models of QWR (a) and four-vane CH-cavity used for RD simulations.

Table 2: Characteristics of SC CH-cavities, f=324 MHz

β_g	0.150	0.217	0.314
Period length (D=βλ/2), mm	69.4	100.4	145.3
Cavity length, mm	347.0	502.0	726.4
Cavity radius, mm	150.0	164.0	170.5
Aperture, mm	30.0	30.0	30.0
Pylon width, mm	40.0	50.0	50.0
Pylon length, mm	295.0	430	620
E_{max}/E_{acc}	3.9	4.8	5.0
B_{max}/E_{acc}, mT/(MV/m)	7.5	8.6	9
$R_{sh.eff}/Q$, Ohm	867	686	572
E-field amplitude variation, %	< 5	< 5	< 5

SC CAVITIES FABRICATION TECHNOLOGY

SC cavities fabrication technologies are under development in PTI NAN and BSU last years. In the framework of joint activities with JINR manufacturing technologies of elliptical single-cell SC 1.3 GHz niobium cavities was studied [13-14]. In the PTI NASB work on shaping and electron beam welding (EBW) of resonators parts are performed, methods of the inner surface processing are studied. In the INP BSU with cryogenic support of the SPMRC NASB tests of the resonators was carried out.

A number of areas in the field of metal forming, in particular stamping of sheet materials, are traditional for PTI NASB. For the manufacture of elliptical cavities very pure niobium (production of Ningxia OTIC with RRR=300) 2.8 mm thick sheets have been used. Forming operations of the manufacture of half-cells have been performed using liquid impact forging on the equipment of the institute's own production. In the PTI NASB EBW equipment with 15 kW beam power and 2500 × ø1350 mm working chamber dimensions is used. Currently there are works on commissioning of plants for EBW with a beam power of 30 kW and the volume of the working chamber of 40 m^3.

The weld width is not less than 4 mm for the niobium welding (base metal thickness 2.8 mm) have a thickness of 1.7 mm and the penetration bead thickness not exceeding 100-120 µm. Superconducting characteristics of the weld metal are maintained at the level of the metal did not subjected to welding [15]. A number of experimental models of single-cell 1.3 GHz niobium cavities was manufactured, the tests of which have shown the set specified geometric dimensions and the quality of the resonator material. Previously the model cavities made of copper and aluminum also have been made, and the tests confirmed the receipt of the required cell geometry. Some examples of the produced components are shown in Fig. 4.

Figure 4: Examples of components produced by impact hydroforming at PTI NASB.

CONCLUSION

First results of SC proton linac development for JINR LU-20 upgrade were discussed. Beam dynamics simulation results and preliminary design of SC QWR and CH-cavities were presented. Problems of SC cavities production were discussed.

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