NEW SUPERCONDUCTING LINAC INJECTOR PROJECT FOR NUCLOTRON-NICA: CURRENT RESULTS

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Abstract

The joint collaboration of JINR, NRNU MEPhI, INP BSU, PTI NASB, BSUIR and SPMRC NASB started in 2015 a new project on the development of superconducting cavities production and test technologies and new linac-injector design. This linac intend for the protons acceleration up to 25 MeV (up to 50 MeV after upgrade) and light ions acceleration up to ~7.5 MeV/u for Nuclotron-NICA injection. Current status of linac general design and results of the beam dynamics simulation and SRF technology development are presented in this report.

INTRODUCTION

Nuclotron-based Ion Collider fAcility (NICA) is new accelerator complex developing and constructing at JINR [1-4]. The injection system of operating Nuclotron and new NICA is under upgrade now. It was consisted of old Alvarez-type DTL called LU-20. The pulse DC forinjector was replaced by new RFQ linac which was developed and constructed by joint team of JINR, ITEP and MEPhI [5] and commissioned on December, 2016. The first technical session was done on May-June, 2016, with new injector [6] and the first experimental session is under operation at present (November, 2016). The other heavy ion linac for beams with charge-to mass ration Z/A=1/8-1/6 was developed by joint team of JINR, Frankfurt University and BEVATECH and it is under installation and commissioning at present.

The possibility of LU-20 replacement by new superconducting (SC) linac of 25 MeV for protons [7, 8] 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.

Technologies which are necessary for serial SC cavities manufacturing are now absent in Russia. JINR in cooperation with the INP BSU and the PTI NASB done the pilot project of elliptical cavities fabrication and testing [9-11]. Now a new collaboration of the JINR, the NRNU MEPhI, the ITEP NRC "Kurchatov Institute", the INP BSU, the PTI NASB, the Belarusian State University of Informatics and Radioelectronics and the Scientific and Practical Material Research Center of NAS of Belarus 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. The first results of the linac general layout development and beam dynamics simulation are presented in the paper.

NEW SUPERCONDUCTING LINAC GENERAL SCHEME AND THE FIRST VERSIONS OF LAYOUT

Superconducting linac would to be consisting of a number of superconducting independently phased cavities and focusing solenoids. 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. Such linac design was called modular. 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 [12-13].

Starting 2014 two SC linac designs were proposed, discussed and simulated [7]. The first preliminary design was done with the following assumptions: the injection

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energy of proton beam after new RFQ for-injector is 1.6 MeV (particles velocity is 0.058c), total length of linac not higher than 20 m and accelerating gradient not higher than 3 MV/m in the low energy part and <10 MV/m in medium energy one. For the chosen type of accelerating elements and the admissible slipping factor < 20%, it was determined that the accelerator should be divided into five groups of cavities with the geometric velocity $\beta_G = 0.072$, 0.105, 0.15, 0.217, and 0.314. The analysis of the stability conditions for longitudinal and transverse oscillations showed that, for example, for the first group of cavities, the stability is achieved for the field strength E=2.26 MV/m, entrance phase φ = –20°. Such field limitation is caused by transverse and longitudinal stability but not by RF limitations for the cavities. Solenoid field amplitude not higher than ≈3 T is necessary for the effective beam transverse focusing with such RF field limitations. Cavities types for all groups were not choused in [7] but QWR or HWR were discussed for the first two or three groups of cavities and CH- or Spoke cavities were discussed for the other groups.

The second version of linac layout was done on first half 2016 [8]. The ion beam motion stability analysis show that with the slipping factor about 17.5% 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. The first two groups of cavities should be two-gap QWR's and the other – four-gap CH-cavities or Spoke-cavities. Using transfer matrix calculation method and smooth approximation [12-14] the preliminary SC linac parameters were defined for minimal linac length and lowest cost. The total length of the linac was reduced from 17.8 to 15.5 m and the number of cavities was also reduced from 32 to 28.

CURRENT SC LINAC LAYOUT AND BEAM DYNAMICS

After a number of meetings the linac general layout was sufficiently modified. At the first it was stated that the injection energy for SC part of linac will increased up to 5 MeV (as it is for LU-20 at present), the normal conducting part will consist of 2.5 MeV proton linac (which also should be designed for beams with charge-to-mass ratio Z/A<1/3 acceleration up to 2.5 MeV/nucleon) and a number of identical cavities for acceleration from 2.5 to 5 MeV. The RF field was limited by 4.5 MV/m for QWR (and HWR if they will be necessary) and by 7.5 MV/m for CH- and Spoke cavities designed. The solenoid field limitation was contrariwise increased to 2.5 T and a beam envelope limitation was also increased form 3 to 5-6 mm.

For the chosen types of accelerating elements and the assumptions noted above the third version of SC linac design was developed. The slipping factor should be not higher than 24% (see Figure 1) and the accelerator should be divided into three groups of cavities with the geometric velocity β_G = 0.12, 0.21 and 0.314. Current characteristics of the SC linac are shown in Table 1. Note that now only one group of QWR is necessary and correct choice of cavities of 2nd and 3rd groups (CH-cavities, Spoke-cavities or HWR) should be done. 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 Figure 2 (b–e).

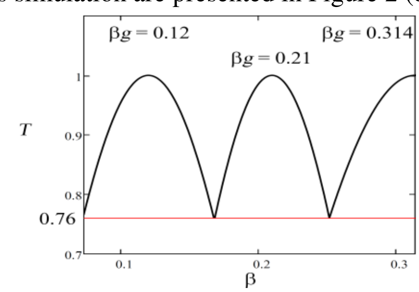

Figure 1: The slipping factor T for each cavity group.

Table 1: Current Parameters of the SC Linac

Cavity Group	0 *	1	2	3
β_g	0.12	0.12	0.21	0.314
W_{in}, MeV	2.50	4.90	13.47	31.00
β_{in}	0.073	0.102	0.168	0.251
W_{out}, MeV	4.90	13.47	31.00	50.00
β_{out}	0.102	0.168	0.251	0.314
T, %	24	24	24	24
K_T, %	100	100	100	100
F, MHz	162	162	324	324
N_{gap}	2	2	4	4
Φ, deg	–20	–20	–20	–20
L_{res}, m	0.222	0.222	0.39	0.58
E. MV/m	4.50	7.52	7.70	7.76
U_{res}, MV	1.0	1.67	3	4.32
B, T	1.35	1.4	1.9	2.3
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	0.622	0.622	0.79	0.98
N_{per}	3	5	7	5
L, m	1.87	3.11	5.53	4.90

* 0th group cavities are normal conducting.

SC CAVITIES DESIGN

The operating frequency of the linac was chosen equal to 162 MHz with further increase twice to 324 MHz for CH- or Spoke cavities. QWR and CH-cavities were simulated (see more in [15]).

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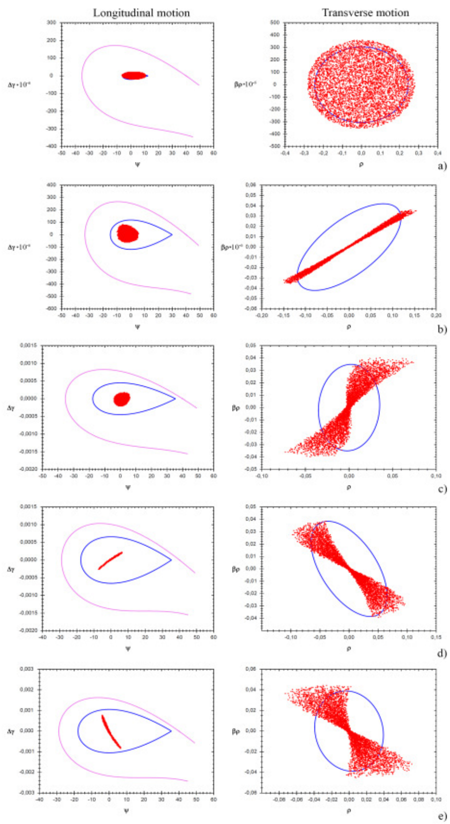

Figure 2: The longitudinal and transverse phase spaces after each section.

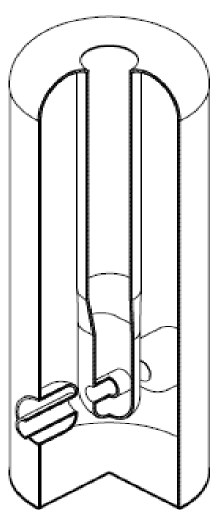

Figure 3: Model of QWR.

SC CAVITIES FABRICATION TECHNOLOGY

SC cavities fabrication technologies are under development in PTI NASB and BSU last years [9-11] but it were developed for 1300 MHz elliptical SC cavities.

Now we start to develop fabrication technologies for 162 MHz quarter-wave resonators. Preliminary QWR construction has been developed based on the simulated model. Then we identified the key units in the construction of a QWR and divided them into elementary components in terms of the possibility of their production. The QWR components were analyzed for the ability to use semi-finished products that are produced in the industry (tubes having a required diameter, sheets, etc.) to reduce the cost of the resonator fabrication. For the resonator components high requirements to quality of the internal surface, purity of a superconducting niobium, accuracy of geometrical parameters are imposed. The best way to ensure these requirements is impact hydroforming technology. A feature of the method is use of liquid as the forming tool that ensures absence of damage and contamination of the surface and high precision of stamping [16]. Current version of the QWR design for 162 MHz and β_G=0.07 is shown in Figure 3.

CONCLUSION

Current results of new SC proton linac development for JINR LU-20 upgrade were discussed. Beam dynamics simulation and preliminary design of SC cavities results were presented and problems of SC cavities production technologies were discussed.

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