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STATUS OF THE SC HWR CAVITIES PRODUCTION FOR NICA PROJECT

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Abstract

Since 2015 the superconducting (SC) linac-injector development for Nuclotron NICA (JINR, Dubna, Russia) is carried out by the collaboration of JINR, NRNU MEPhI, INP BSU, PTI NASB. This new SC linac is to accelerate protons up to 20 MeV and light ions to 7.5 MeV/u with possible energy upgrade up to 50 MeV for proton beam. This paper reports the current status of the development and manufacturing of superconducting accelerating cavities for a new linear accelerator of the injection complex of the Nuclotron-NICA project.

INTRODUCTION

Nuclotron-based Ion Collider fAcility (NICA) is new accelerator complex under construction at JINR [1-5]. It was proposed for ion collision and high-density matter study. NICA facility will include the existing ion synchrotron Nuclotron together with new booster and two collider rings being under construction. The injection system of Nuclotron-NICA was upgraded in 2011-2016. The pulse DC linac forinjector of Alvarez-type DTL LU-20 was replaced by the new RFQ developed and commissioned by JINR, ITEP and MEPhI [6]. New RFQ linac can accelerate ions with charge-to-mass ratio Z/A>0.3. The first technical session of Nuclotron with new injector was ended on 2016 [7]. The LU-20 with new RFQ for-injector is used for p, p↑, d, d↑, He, C and Li ions acceleration till now. The other heavy ion linac for particles with Z/A=1/8-1/6 was developed by joint team of JINR, Frankfurt University and BEVATECH and commissioned in 2016.

It must be noted that LU-20 operation causes many technical issues because of its age: it was commissioned in 1972. The possibility of LU-20 replacement by the new linac of 20 MeV energy for protons [8-12] and 7.5 MeV/nucleon for deuterium beam is discussed now. Project also include an option of the proton beam energy upgrade up to 50 MeV by installing several cavities in additional section. New linac will include a number of superconducting (SC) cavities.

The general layout of new light ion linac (LILac) for the NICA collider is presented in Fig. 1 [13]. LILac consists of 5 cavities: RFQ, re-buncher, two Interdigital H-mode Drift-Tube-Linacs (IH-1 and IH-2) and a de- buncher [14]. The operating frequency is 162.5 MHz and the final energy at the IH-2 exit is 7 MeV/u. After IH-2 the beam is transported towards the Nuclotron (bending magnets shown in blue). SPI stands for Source of Polarized Ions [15]. In future the extension of LILac is expected with normal-conductive cavities up to 13 MeV/u (marked green) and followed by SC HWR 1 cavities (light blue at Fig. 1) up to 20 MeV for protons and to 7.5 MeV/u light ions and by SC HWR 2 cavities up to 50 MeV for protons [16].

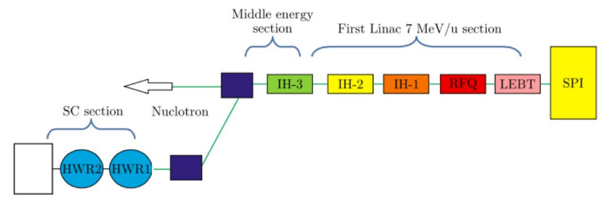

Figure 1: The Light Ion Linac.

The problem with SC cavities and SC linac construction for Nuclotron-NICA was the absence of SRF technology in Russia. The development of the SRF technologies is the key task of the new Russian - Belarusian collaboration launched in March 2015. For testing purposes, the test beamline is proposed with two HWR1 cavities installed. A test cryostat for two cavities HWR 1 is developing now by a joint team of JINR, GSI (Germany) and BEVATECH (Germany). Cryostat for 4 cavities HWR 1 is developing by JINR and IMP (China).

BEAM DYNAMICS AND FR DESIGN

The beam dynamics simulation for superconducting part of the first linac layout was done using BEAMDULAC-SCL code designed at MEPhI [17-19]. According to the fourth version of SC linac design developed the accelerator is divided into two groups of cavities HWR 1 and HWR 2 with geometric velocities β_G = 0.21 and 0.314. First group HWR 1 at β_G = 0.21 accelerates protons to 20 MeV and light ions to 7.5 MeV/u. Second group HWR 2 at β_G = 0.314 accelerates particles up to 50 MeV.

The beam dynamics of proton and deuterium ions beam was studied at [9]. Parameters of the first group of cavities (HWR 1) are shown in Table 1.

Considerations on the SC cavity types choice and their RF design done at MEPhI and JINR are presented in detail in [20]. HWR cavities were proposed because they could provide proper consent to electrodynamic parameters and beam dynamics [16, 20].

The operating frequency of SC sections is 325 MHz. Different concurring HWR cavity designs were considered one with ordinary cylinder-shaped central conductor and the second with cone-shaped one [21]. Geometric and electrodynamics parameters of the cavities are presented in Table 2.

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Table 1: Current Parameters of the HWR1 Group of SC Linac for Proton and Deuterium Beams Acceleration

Cavity group	0 *	1**	2**	0 *	1**	2**
	Proton beam			Deuterium beam		
β_g	0.12		0.21	0.12		0.21
F, MHz	162.5		325	162.5		325
T, %	24.0		24.0	24.0		24.0
N_{gap}	2		2x2**	2		2x2***
L_{res}, m	0.222		0.39	0.222		0.39
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		0.79	0.622		0.79
N_{per}	3	8	8	3	8	8
L, m	1.87	4.98	6.32	1.87	4.98	6.32
E_{acc}, MV/m	4.50	5.86	6.4	4.50	5.86	6.4
U_{res}, MV	1.0	1.3	1.25	1.0	1.3	1.25
Φ, deg	–20	–20	–20	–20	–20	-90
B_{sol}, T	1.35	1.3	1.9	1.8	2.0	1.0
W_{in}, MeV	2.5	4.9	13.47	2.5	3.65	8.3
β_{in}	0.073	0.102	0.168	0.073	0.088	0.133
W_{out}, MeV	4.9	13.47	31.0	3.65	8.3	8.3
β_{out}	0.102	0.168	0.251	0.088	0.133	0.133
K_T, %	100	100	100	100	100	100

* these cavities are normal conducting;
** SC cavities;
*** two 2-gap HWR per one period.

The operating frequency of SC sections is 325 MHz. Different concurring HWR cavity designs were considered one with ordinary cylinder-shaped central conductor and the second with cone-shaped one [21]. Geometric and electrodynamics parameters of the cavities are presented in Table 2.

It was shown that both designs satisfy the requirements for the accelerating gradient. The second design with the conical central conductor cavity has much better performance with respect to multipactor discharge. This discharge is observed for coaxial cavities for low RF field levels and leads to the conditioning time increase.

Table 2: RF Parameters of 325 MHz HWR for $\beta g = 0.21$

Parameter	Value	
HWR type	Cylindrical	Conical
Operating frequency, f, MHz	325	
Geometrical velocity, β_g	0.21	
Cavity height, mm	431	474
Cavity radius, mm	97	97
Ratio of the peak electric surface field to the accelerating field, E_p/E_{acc}	6.5	5.9
Ratio of the peak surface magnetic field to the accelerating field, B_p/E_{acc}, mT/(MV/m)	10.2	9.6
Effective shunt impedance, R_{sh}/Q_0, Ohm	298	306
Geometric factor, $G=R_s/Q$, Ohm	57	57

Cavity body design was done by PTI NASB and MEPhI research groups taking into account thermal and mechanical cavity performance considerations during cooldown. Cavity was designed in classical coaxial HWR configuration with integrated helium vessel [22, 23]. PTI NASB production facility expertise in deep-drawing and EB welding of high purity niobium allowed us to choice in favor of more complicated but yet much more promising design with conical inner conductor. HWR cavity with integrated cryostat vessel design is presented on Fig. 2.

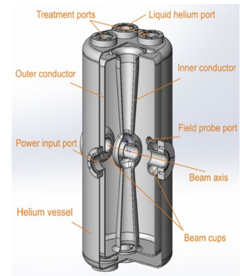

Figure 2: The Light Ion Linac SC cavity design.

COPPER PROTOTYPE

Design study and manufacturing of copper prototype cavity (Fig. 3) were carried out from 2019 to 2020 at PTI NANB and INP BSU. Tooling for hydroforming of central conductor parts, side beam ports and housing covers were developed. The cavity was assembled using the clamping system shown in Fig. 3a, that allowed one to align, precisely adjust and securely fix cavity parts before welding. This clamping system also was used for cavity RF performance intermediate measurements as shown in Fig. 3c.

Copper prototype cavity (see Fig. 4) was manufactured and tested in 2020 [24]. Resonant frequency measurements and vacuum tests showed cavity desired performance [25]. Intermediate measurements and frequency control procedure used at production site allowed us to get the necessary frequency value. This multistage tuning took us several weeks as the cavity parts were manufactured and matched. Cavity RF test port reflection and resonant frequency dependence on temperature are presented on Fig. 5.

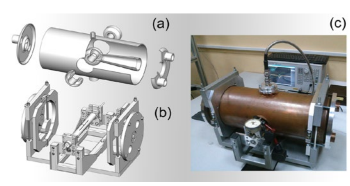

Figure 3: (a) Six parts of the cavity body, (b) assembling frame and (c) complete assembly with fixtures for RF measurements.

Copper prototype cavity (see Fig. 4) was manufactured and tested in 2020 [24]. Resonant frequency measurements and vacuum tests showed cavity desired performance [25]. Intermediate measurements and frequency control procedure used at production site allowed us to get the necessary frequency value. This multistage tuning took us several weeks as the cavity parts were manufactured and matched. Cavity RF test port reflection and resonant frequency dependence on temperature are presented on Fig. 5.

Plunger with precise mechanical actuator for slow frequency tune was developed and manufactured at INP BSU. [25]. Tuner design and prototype manufactured are shown on Fig. 6. This tuner was successfully tested on copper cavity and showed to deliver 13 kHz/mm frequency shift.

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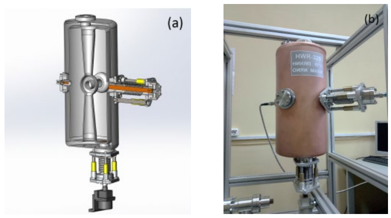

Figure 4: (a) 3D model of the coaxial half-wave resonator with field probe, power input antennas and plunger-based frequency tuning system; (b) manufactured copper prototype [24].

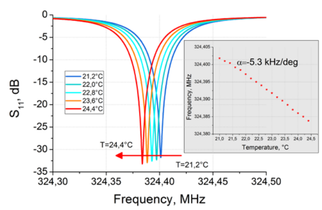

Figure 5: The reflection coefficient S_{11} for the power input in the critical coupling conditions for different ambient temperatures; (inset) resonant frequency dependence on temperature.

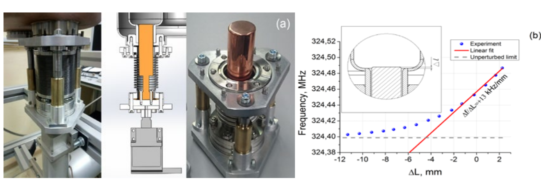

Figure 6: (a) The slow frequency tuning system; (b) experimentally measured frequency shift Δf vs plunger penetration depth ΔL [25].

NIOBIUM CAVITY PRODUCTION

Pilot full performance SC cavity is being manufactured in 2020-2021. The cavity is made of RRR300 bulk niobium and has titanium cryogenic vessel permanently attached. Technology of niobium sheets deep drawing, hydroforming, electron beam welding at several production facilities at Minsk were developed. The intermediate frequency measurements and control of niobium cavity (Fig. 7) were performed based on copper prototype-based experience. Fig. 8 illustrates the Nb cavity core sealed and equipped for RF and vacuum tests. Weld seals leak rate was under 3.8×10^{-9} Pa·m^3/s. Cavity outer shell for cryogenic system was made of titanium and welded to the cavity. Cavity low power RF tests at room temperature were carried out [26] and showed the expected results.

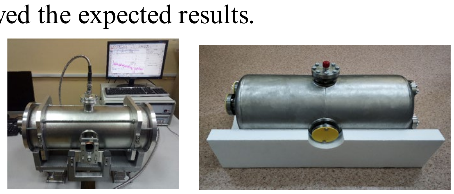

Figure 7: Niobium cavity core under intermediate RF test and cavity Nb core with outer Ti shell assembly.

Cryostat for cavity testing was developed in collaboration of JINR and INP BSU, Fig. 8 [27]. At September 2021 first tests of cavity cooled down to liquid nitrogen temperature were done. Resonant frequency shift measured during cooldown at selected temperatures is shown on Fig. 9. Helium tests are scheduled to the end of 2021.

As soon as the first cavity tests would be fully completed two cavities for Nuclotron-NICA injector will be made. Their production is already launched, Fig. 10 shows two sets of Nb parts for these cavities.

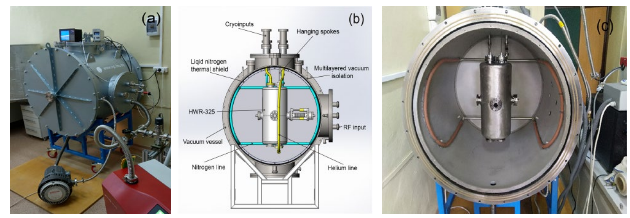

Figure 8: (a) Fabricated test cryostat, (b) the main parts and subsystems of the cryostat, (c) test cryostat with a cavity inside [27].

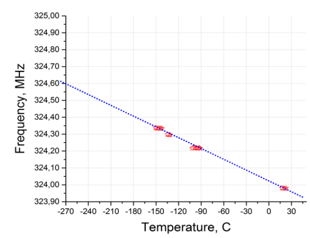

Figure 9: Resonant frequency vs. temperature dependence measured during cavity cooldown.

Figure 10: Nb parts for two Nuclotron-NICA cavities.

CONCLUSION

HWR SC cavity with frequency tuner for Nuclotron-NICA injector was designed. Dedicated tooling and technologies were developed and certified for production of high performance SC cavities. Core parts are made of high RRR bulk niobum sheets by deep drawing and hydroforming and then electron beam welded. Titanium cryogenic shell is permanently attached to cavity core. Full production line procedures for intermediate measuring, testing and adjustment of cavity parts was developed. Cryostat for cavity tests under L-He temperature was designed and manufactured.

Copper prototype and niobium pilot cavity were manufactured. Vacuum and low power RF tests at room temperature and Liquid-N_2 conditions were carried out and showed the cavity expected performance. Production of two Nb cavities for NICA beamline is launched.

Next steps scheduled to 2021/2022 will be cavity cold tests at 4K and fast frequency tuning system development [28].

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