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 injector 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 HW1 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 RF DESIGN
The beam dynamics simulation for superconducting part of the first linac layout was done using BEAMDULAC-SCL code designed at MEPhl [17-19]. According to the fourth version of SC linac design developed the accelerator is divided into two groups of cavities HW1 and HW2 with geometric velocities βC = 0.21 and 0.314. First group HW1 at βC = 0.21 accelerates protons to 20 MeV and light ions to 7.5 MeV/u. Second group HW2 at βC = 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 (HW1) are shown in Table 1.

Considerations on the SC cavity types choice and their RF design done at MEPhl 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 electrodynamic parameters of the cavities are presented in Table 2.
Table 1: Current Parameters of the HWR1 Group of SC Linac for Proton and Deuterium Beams Acceleration

<table>
<thead>
<tr>
<th>Cavity group</th>
<th>0 *</th>
<th>1**</th>
<th>2**</th>
<th>0 *</th>
<th>1**</th>
<th>2**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Proton beam</td>
<td>Deuterium beam</td>
<td>Proton beam</td>
<td>Deuterium beam</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta_p$</td>
<td>0.12</td>
<td>0.21</td>
<td>0.12</td>
<td>0.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_c$, MHz</td>
<td>162.5</td>
<td>325</td>
<td>162.5</td>
<td>325</td>
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<td></td>
</tr>
<tr>
<td>$T_r$, %</td>
<td>24.0</td>
<td>24.0</td>
<td>24.0</td>
<td>24.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_{gap}$</td>
<td>2</td>
<td>2x2**</td>
<td>2</td>
<td>2x2**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_{out}$, m</td>
<td>0.222</td>
<td>0.39</td>
<td>0.222</td>
<td>0.39</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_{in}$, m</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_{res}$, m</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
<td></td>
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<tr>
<td>$N_{sol}$, m</td>
<td>0.622</td>
<td>0.79</td>
<td>0.622</td>
<td>0.79</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Phi$, deg</td>
<td>3</td>
<td>8</td>
<td>8</td>
<td>3</td>
<td>8</td>
<td>8</td>
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<tr>
<td>$L_m$, m</td>
<td>1.87</td>
<td>4.98</td>
<td>6.32</td>
<td>1.87</td>
<td>4.98</td>
<td>6.32</td>
</tr>
<tr>
<td>$E_{acc}$, MV/m</td>
<td>4.50</td>
<td>5.86</td>
<td>6.4</td>
<td>4.50</td>
<td>5.86</td>
<td>6.4</td>
</tr>
<tr>
<td>$U_{acc}$, MV</td>
<td>1.0</td>
<td>1.3</td>
<td>1.25</td>
<td>1.0</td>
<td>1.3</td>
<td>1.25</td>
</tr>
<tr>
<td>$W_{rms}$, MeV</td>
<td>1.35</td>
<td>1.3</td>
<td>1.9</td>
<td>1.8</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$\beta_p$, %</td>
<td>0.073</td>
<td>0.102</td>
<td>0.168</td>
<td>0.073</td>
<td>0.088</td>
<td>0.133</td>
</tr>
<tr>
<td>$\beta_{sol}$, %</td>
<td>4.9</td>
<td>13.47</td>
<td>31.0</td>
<td>3.65</td>
<td>8.3</td>
<td>8.3</td>
</tr>
<tr>
<td>$K_2$, %</td>
<td>0.102</td>
<td>0.168</td>
<td>0.251</td>
<td>0.088</td>
<td>0.133</td>
<td>0.133</td>
</tr>
</tbody>
</table>

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

The operating frequency of SC sections is 325 MHz. Different confining 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 $\beta_g = 0.21$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWR type</td>
<td>Cylindrical</td>
</tr>
<tr>
<td>Operating frequency, $f_c$, MHz</td>
<td>325</td>
</tr>
<tr>
<td>Geometrical velocity, $\beta_g$</td>
<td>0.21</td>
</tr>
<tr>
<td>Cavity height, mm</td>
<td>431</td>
</tr>
<tr>
<td>Cavity radius, mm</td>
<td>97</td>
</tr>
<tr>
<td>Ratio of the peak electric surface field to the accelerating field, $E_{rms}/E_{acc}$</td>
<td>6.5</td>
</tr>
<tr>
<td>Ratio of the peak surface magnetic field to the accelerating field, $B_p/E_{acc}$, mT/(MV/m)</td>
<td>10.2</td>
</tr>
<tr>
<td>Effective shunt impedance, $R_s/Q$, Ohm</td>
<td>298</td>
</tr>
<tr>
<td>Geometric factor, $G=R_s/Q$, Ohm</td>
<td>57</td>
</tr>
</tbody>
</table>

Cavity body design was done by PTI NASB and EPFl 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 choose 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.

Figure 6: The Light Ion Linac SC cavity design.
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 RRR300 bulk niobium 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-N2 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].
REFERENCES


