Development of key technologies for a high-current superconducting heavy ion linear accelerator

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1. Introduction

High-current heavy ion accelerator facilities based on superconducting linac have been developed for the next generation nuclear science research in different places. Rare isotope science project (RISP) is underway in Korea under auspices of IBS, which aims to provide 400-kW stable beams as well as rare isotope beams produced by using both IF separation and ISOL methods. To realize high-current heavy ion accelerator, there are some key technologies needed to be developed and efforts made for RISP are described.

2. SC linac lattice design

To establish high-current accelerator system, SC cavities are used in consideration of reducing rf losses compared to conventional cavities especially in cw mode. In a low velocity regime usually adopted cavities are quarter wave and half-wave resonators (QWR, HWR). These two kinds are employed for RISP to achieve acceleration voltage of up to around 160 MV [1]. The cavities of RISP are shown in Fig. 1.

Fig. 1. (a) QWR, (b) HWR of RISP

The first heavy-ion SC linac in the world was built at Argonne, and they have lately completed the ATLAS upgrade adopting a new design of QWR, which operate at much higher voltages compared to the previous cavities. We have worked with the Argonne group on the post-linac design for the ISOL system, and suggested an alternative design with the major design parameters as listed in Table .1 [2].

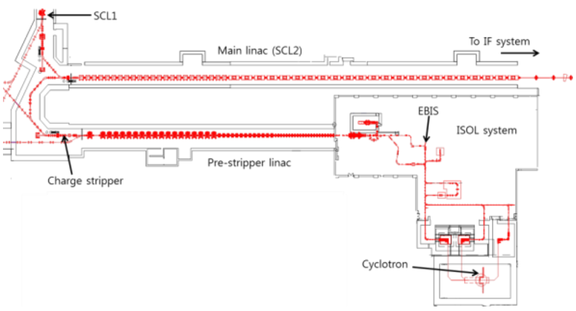

Fig.2. A layout of accelerator system of RISP.

Table 1: Linac parameters of the RISP baseline design in comparison to those of the alternative design

Parameters	RISP baseline (QWR, HWR)	Alternative design (QWR1, QWR2)
Number of low-β cavity	22	15
Number of high-β cavity	102	49
Total number of cryomodule	54	9
Total length	100 m	53.3 m

3. SC-ECR

It is crucial to develop a high-intensity ion source to produce highly-charged heavy ions for heavy ion accelerator, so as to efficiently utilize valuable acceleration voltages produced by rf cavities. SC-ECR is a sole kind of the ion source so far developed for this purpose, and efforts are ongoing to build SC-ECR operating at higher rf frequencies considering a scaling law $I_q \sim f^2$ (Electron resonance frequency for a given magnetic field $\omega = eB/m_e$). In fact a key technology of SC-ECR is to produce a high-field SC magnet system, which consists of mirror solenoids and SC hexapole magnets. Due to its complicated shape reliable construction of such SC coil system is not an easy task. SC-ECR operating at the highest field is currently VENUS as described in Ref. [3]

4. RFQ

RFQ is a low-energy linac for high-current acceleration and can have a section of adiabatic bunching prior to acceleration at a defined synchronous phase. This adiabatic bunching can allow high transmission efficiency, but the resulting beam quality may not be good enough for certain nuclear experiments. The RFQ of RISP has this section, and longitudinal emittance at the end is somewhat larger than that of the design value for FRIB. To avoid the increase of beam emittance, an external buncher utilizing multi-harmonic rf frequencies is employed, which was first demonstrated at Argonne.

The RFQ of RISP has a length of 5 m and is composed of nine modules [4]. According to optics simulation it seems possible to modify the first module to reduce emittance growth if needed with a multi-harmonic buncher (MHB) employed upstream.

5. SC cavity

For the velocity (β) range of around 0.1~0.5 half wave structures are used. Two kinds of such structure developed are 1) cylindrical shape called HWR, and 2) spoke shape namely spoke cavity. The spoke cavity has a merit in that the number of electrodes can be extended to allow multi gaps for acceleration.

RISP chose to use two kinds of single spoke resonator (SSR) for the high energy section of the SC linac called SCL2. The number of units are listed in Table 2. SSR has been studied from 90's, but is not operational in laboratory environment yet while double spoke resonator (DRS) was chosen for European Spallation Source (ESS) and for a high current proton linac at IMP in China. DSR can be more rigid than SSR with the use of two spokes in orthogonal direction besides one more acceleration gap. On the other hand, FRIB chose HWR for the similar velocity range and announced their cavities perform better than their specifications.

Table 2: Characteristics and numbers of SSR for RISP

Parameters	SSR1	SSR2
β_g	0.3	0.51
f (MHz)	325	325
V_{acc} (MV)	2.4	4.1
T_o(K)	2	2
# of cavity	69	138
# of cryomodule	23	23

6. Charge stripper

To efficiently use valuable acceleration voltage produced by SC cavities, it is important to remove the electrons of ions as much as possible at the ion source. However, there is a compromise between charge-state and beam current, so that a charge stripper is usually used at a beam energy to reach equilibrium charge state high enough for the efficient acceleration in the downstream linac. Low-Z material such as Be, Li, C is used for the stripper to reduce multiple scattering. Carbon foil or graphite has a merit in easy handling, but its lifetime for U beam is short.

In high current operation the charge stripper is heated, and thus liquid lithium in a high-pressure jet form was adopted for FRIB [5]. A similar design has been also worked for RISP. Due to its ability of enduring high-power beam, liquid Li jet has been developed as a high-flux neutron production target driven by deuteron accelerator.

7. Conclusion

The design of high current heavy ion linac requires a series of consideration on its lattice structure, low-energy injector, choices of rf cavities and so on. The accelerator system for RISP was laid out in 2013, and no major design changes have been made since. An alternative design of the ISOL post-linac was studied together with Argonne group in 2016, accommodating newly developed technologies in cavity and cryomodule. It seems this alternative design can significantly reduce the total numbers of cavity, cryomodule and the operation cost. Considering the previous examples of major changes in the middle of large-scale accelerator projects such as SNL and RIBF, it may be good to implement further refined designs and state-of art technology after careful evaluations if possible.

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