SRF IN HEAVY ION PROJECTS

Dong-O Jeon[#] representing RAON
Institute for Basic Science, Daejeon, Republic of Korea

Abstract

SRF technologies are widely applied to heavy ion accelerator projects in the world such as the RAON, C-ADS, ATLAS Upgrade, SPIRAL2, ISAC-II, HIE-ISOLDE, FRIB, SARAF, HIAF, HIE-ISOLDE (EU), etc. In this paper, status report, design choices of projects on going in Asia along with ATLAS upgrade and SRF challenges met in heavy ion machines are presented.

INTRODUCTION

With its application to ATLAS, SRF technology is increasingly adopted for heavy ion accelerator projects around the world due to high field gradient and low operation cost. There are a few heavy ion accelerator projects under construction right now such as RAON, C-ADS and FRIB and ATLAS upgrade, SPIRA2. Also there are projects emerging on the horizon such as HIAF. All these projects are based on SRF technology. In this paper status report design choices and challenges met are presented.

CHALLENGES IN SRF LINAC

Among heavy ion accelerator projects, trend is to build high intensity superconducting heavy ion accelerators, providing hundreds of kilo watts of beam for users. Significant progress has been accomplished lately, making superconducting linacs more efficient and powerful. Challenges met in constructing heavy ion superconducting linacs are briefly mentioned.

Alignment and Beam Quality

It is known that elements in cryomodules move a few millimeters during cool down and attentions are paid to mitigate alignment issues related with this. Alignment tolerance matters as the beam intensity goes up and more stringent requirements need to meet. Some facilities such as ATLAS upgrade adopt optical devices to track elements movement, while others WPMs (wire profile monitors).

There are two camps. One camp adopts relatively long cryomodules with superconducting solenoids installed inside. ATLAS upgrade, C-ADS, FRIB, SARAF etc belong to this camp. This camp pays attention to accurate modeling and control of optical elements movement. The other adopts short cryomodules and normal conducting quadrupoles between cryomodules. SPIRAL2 and RAON belong to this camp.

It turns out that for RAON, detailed analysis shows that cost and cryogenic load of these two options do not differ much. Regarding cryogenic load, current leads of SC solenoids seem to compensate the benefit of long cryomodules.

Cavity Gradient

In SC cavity gradient front, there has been a significant improvement over years and now some low beta cavities reach E_{peak} > 80 MV/m [1]. With better understanding of cavity processing recipes including high temperature baking, both BCP and EP techniques seem viable solutions. EP can produce a very smooth surface compared with BCP, and is regarded slightly superior to BCP for maximum performance, although more expensive. ANL has successfully implemented EP in processing low beta cavities. ANL's low beta cavities employ double conical design, highly optimized EM design, minimizing ratio such as B_{peak}/E_{acc} and E_{peak}/E_{acc}.

High Efficiency

High efficiency frontier seeks mainly to increase the cavities' Q, especially at high field. Although not fully understood, Q slope is generated by several known causes like; 1) hydrogen in Nb leading to Q disease, 2) surface contamination by foreign materials leading to field emission, vacuum issues, 3) trapped magnetic field, and 4) surface roughness which creates local peak magnetic field. These issues are addressed through recipes such as high temperature baking, high pressure rinsing etc. Q disease can now be cured by heat treatment at 600 - 800 °C in vacuum, which removes hydrogen from Nb bulk. Magnetic shielding is used to minimize trapped magnetic field. This can be an issue particularly for a cryomodule design with SC solenoids in.

STATUS REPORT

Status report is summarized for RAON, C-ADS, and ATLAS upgrade projects for other on-going projects will be presented.

RAON

Heavy ion accelerator facility called RAON is under construction in Korea to support a wide range of cutting edge science programs in nuclear science, material science, bio & medical science, astrophysics, and atomic physics as well as interdisciplinary science programs. The RAON facility consists of accelerator systems [2] that support the 400 kW In-flight Fragmentation (IF) facility and Isotope Separator On-Line (ISOL) facility. There are also papers reporting progress in superconducting linac and RF system of the RAON [3-5].

The driver accelerator for the IF facility is a superconducting linac that can accelerate up to 200

[#]jeond@ibs.re.kr

MeV/u in case of uranium beam and up to 600 MeV for proton beam with more than 400 kW beam power to the IF target and various other targets. The driver for the ISOL facility is an H^- 70-MeV cyclotron that delivers beam to the ISOL target. The cyclotron has dual extraction ports with thin carbon foils for charge exchange extraction of H^- beam. The rare isotope beams generated by the ISOL system is re-accelerated by a chain of post accelerators: RFQ, MEBT and superconducting linac SCL3 up to 18.5 MeV/u. The RI beams can be delivered to the low energy experimental hall or can be injected through P2DT to the driver linac to accelerate to higher beam energy. The schematic layout of the RISP facility is shown in Fig. 1.

Table 1: Parameters of RAON Accelerator Systems

Parameter	Value
Linac energy	200 MeV/u (uranium)
Linac ions	proton to uranium
Linac beam power	400 kW
Linac frequency	81.25/162.5/325 MHz
Duty factor	100%
Beam Loss	<1 W/m
Cyclotron energy	70 MeV
Cyclotron ion	H-
Cyclotron current	>700uA

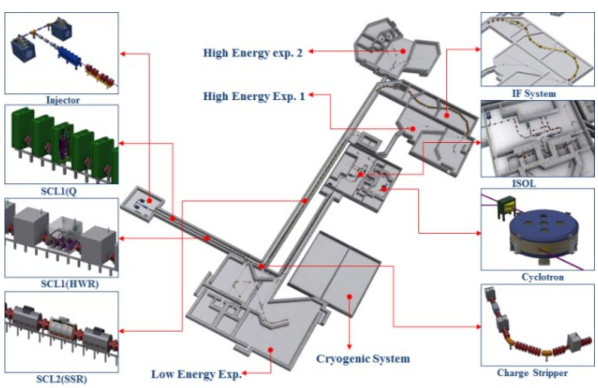

Figure 1: Plot of the RAON facility layout.

RAON driver linac consists of injector, low energy superconducting linac (SCL1), charge stripper section (CSS), and high energy superconducting linac (SCL2) delivering beams to the IF target and other targets. SCL1 accelerates uranium beam to 18.5 MeV/u and SCL2 to 200 MeV/u.

The driver SCL is designed to accelerate high intensity heavy ion beams and to meet the needs of various users. Large cavity apertures (4 and 5 cm) are chosen to reduce uncontrolled beam loss on the superconducting cavities. Cavity geometric betas are optimized and an optimum set of β = [0.047, 0.12, 0.30, 0.51] is obtained. Its results are shown in Fig. 2 and 3.

Figure 2: Plots of four types of superconducting cavities used for RAON superconducting linac.

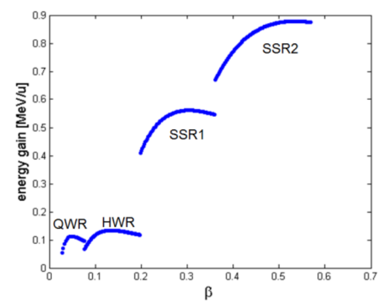

Figure 3: Plots of the optimized geometric betas of the superconducting cavities of RAON SCL.

Table 2: Cavity Parameters

Parameters	Unit	QWR	HWR	SSR1	SSR2
β_g	-	0.047	0.12	0.30	0.51
Resonant freq	MHz	81.25	162.5	325	325
No of cavities	-	21	98	69	120
Aperture	mm	40	40	50	50
QR_s	Ohm	21	42	98	112
R/Q	Ohm	468	310	246	296
V_{acc}	MV	1.05	1.52	2.22	4.20
E_{peak}	MV/m	35	35	35	35
B_{peak}	mT	58.1	57.4	50.1	64.6
Op. temp	K	2	2	2	2

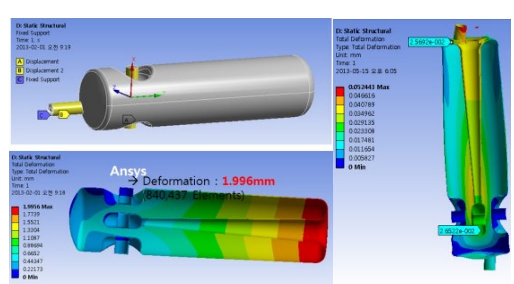

Figure 4: Plot showing thermal contraction due to cool-down to 2K and stiffeners reduces frequency shift by cool-down and pressure change.

ISBN 978-3-95450-143-4

EM/mechanical characteristics of the superconducting cavities are analyzed using the CST and ANSYS codes to study and to ensure that the cavity design meets the requirement of Lorentz force detuning, detuning due to helium pressure fluctuation (df/dP), microphonics detuning etc. EM design has been conducted to reduce B_{peak} and E_{peak} which in turn reduces the Lorentz force detuning. Stiffening the cavity endwalls and shell reduces the Lorentz force detuning and detuning due to helium pressure fluctuation. Endwalls of spoke resonators are reinforced with two types of ribs: donut ribs and daisy ribs. Figure 4 shows the contraction due to cool-down and the modeling of stiffening structure of the QWR cavity. Figure 5 shows the mechanical vibration modes and its characteristic frequencies of bare QWR cavity.

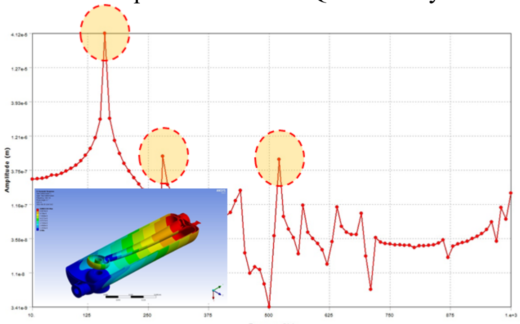

Figure 5: Analysis of mechanical vibration modes and characteristic frequencies of QWR cavity with He jacket. Lowest mode frequency is 160 Hz and the next 280 Hz.

Multipacting analysis is conducted for the combined structure of the cavity and power coupler. Analysis is done and shows that some multipacting bands can be found at low cavity field.

Figure 6: Drawing of QWR with helium jacket.

Prototyping of superconducting cavities are under way right now and Fig. 6 shows a drawing of QWR with helium jacket. Four types of superconducting cavities are optimized by the IBS. Fabrication of cupper and niobium cavities is proceeding through vendors for each type of cavities and it is under bidding process. The other track is to do prototyping in collaboration with international laboratories. Prototyping of cryomodules are on going as well and Fig. 7 shows schematic drawing of QWR cryomodule.

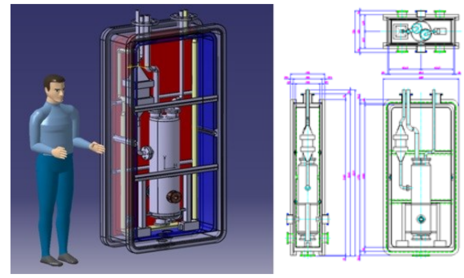

Figure 7: Plots of the QWR cryomodule.

Chinese ADS Project

Supported by the Chinese Academy of Sciences (CAS), the Chinese ADS project is now on-going based on the collaboration of several Chinese institutions. The proton accelerator of Chinese ADS is a superconducting CW linear accelerator. Its energy is 1.5GeV, with beam current of 10mA. Institute of High Energy Physics (IHEP) and Institute of Modern Physics (IMP) are responsible for developing the two injectors respectively and IHEP is the leading institute for the developing of the main Linac [6].

Two different injector schemes are under development by IHEP and IMP respectively and the final solution will be chosen based on the R&D results. IHEP is developing one injector based on 325 MHz RFQ and beta=0.12 Spoke SC cavity; IMP is developing the other based on 162.5 MHz RFQ and beta=0.10 HWR SC cavity.

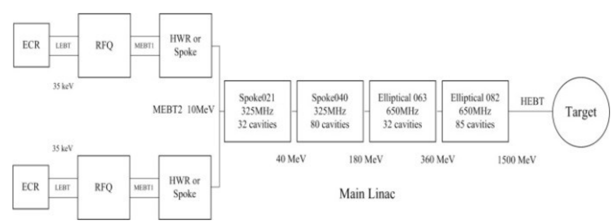

Figure 8: Layout of Chinese ADS Proton Accelerator.

Table 3: Specifications of Chinese ADS Proton Accelerator (Courtesy of IHEP)

Parameter	Value
Energy	1.5 GeV
Current	10 mA
Beam power	15 MW
Frequency	162.5/325/650 MHz
Duty factor	100%
Beam Loss	<1 (0.3) W/m
Beam trips/year	<25000 for 1s<t<10s <2500 for 10s<t<5m <25 for t>5m

Table 3 shows the main parameters of Chinese ADS proton accelerator SC cavities. 162.5 MHz half-wave resonator (HWR) is developed for the injector-II, 325

MHz Spoke cavities and Elliptical cavities are developed for the injector-I and the main accelerator.

• ***Spoke012 Cavity:*** The 325 MHz spoke012 cavity for the 3~10MeV injector-I is designed and first two cavities have been fabricated by IHEP-PKU-HIT joint group.

Figure 9: Two fabricated spoke012 prototype cavities (Courtesy of IHEP).

The post-processing and vertical tests of the two prototype cavities have finished at the end of 2012. There are no serious multipacting effects observed, and the VT tests results are quite promising (Figure 10).

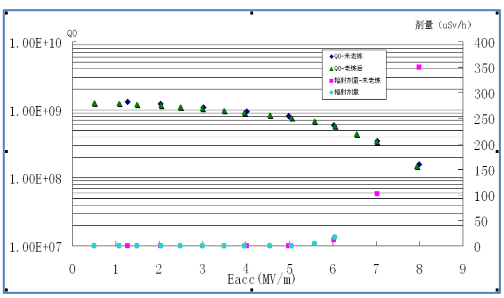

Figure 10: Vertical test result of Spoke012: $Q_0 = 5.8\text{x}10^8$ @ 6MV/m, 4K; $Q_0 = 3.4\text{x}10^8$ @ 7MV/m, 4K (Courtesy of IHEP).

• ***HWR009 Cavity:*** The 162.5 MHz HWR010 cavity for 2.1~10 MeV injector-II is being constructed by IMP. Four HWRs have been tested at IMP. Two of them are ready for helium-vessel welding. Figure 11 shows fabricated HWR cavity and Figure 12 shows vertical test results of HWR010.

Figure 11: HWR010 cavity (Courtesy of IHEP).

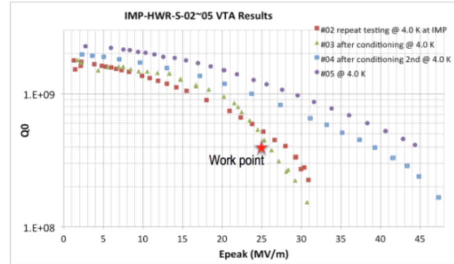

Figure 12: Vertical test results of HWR010 (Courtesy of IHEP).

• ***Spoke021 Cavity:*** The 325 MHz spoke021 cavity (Figure 9) has been designed for the main accelerator in the range of 10~40 MeV. Fabrications of two prototype cavities have been finished and vertical test is planned to carry out at the middle of 2013.

Figure 13: The spoke021 cavities parts (Courtesy of IHEP).

ATLAS Upgrade

The ongoing ATLAS upgrade project requires several substantial developments in accelerator technologies: a CW heavy ion RFQ and a high-performance cryomodule with seven low-beta cavities [1,7]. For ATLAS upgrade project, on-line commissioning is planned November-December 2013.

For a high performance cryomodule, new innovative superconducting cavity fabrication and surface treatment technologies are applied. The cryomodule consists of seven $\beta_G = 0.077$ QWRs at 72.75 MHz SC cavities and four 9-Tesla SC solenoids. The engineering 3D model of the cavity string suspended from the cryostat lid is shown in Fig. 14. New cryomodule features include the separation of the cavity and the cryogenic vacuum systems, and top-loading of the cleaned and sealed cavity-string subassembly. The new QWRs will create accelerating gradients a factor of three higher, on average, whose test results are shown in Fig. 15, achieving E_{peak} over 80 MV/m.

A key processing step for the cavities was the heavy, 150 um, electropolishing on the complete cavity. Two separate rounds of polishing are performed. First, after fabrication, the cavities were electropolished on consecutive days, removing 65 um of niobium each day. Total polishing time was about 12 hours. The cavities were then baked under vacuum at Fermilab for 14 hours at 625°C in order to degas hydrogen. Last, the cavities

ISBN 978-3-95450-143-4

were returned to Argonne for a final light 20 um electropolish.

Improvements other than electropolishing have been made since the 2009 upgrade. Electromagnetic (EM) optimizations of the 72 MHz QWR accounts for about 20% of the performance increase relative to the previous 109 MHz ATLAS Energy Upgrade cavities. However, the most substantial new feature is the conical-shaped outer housing which reduces by 20% compared to a straight cylindrical housing. No additional beam-axis space is needed since the expanded volume occupies the empty space already needed to join cavities together.

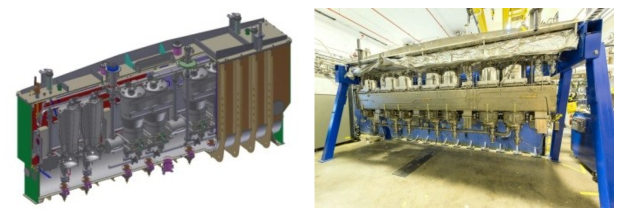

Figure 14: ATLAS upgrade cryomodule drawing on the left and photograph of cryomodule assembly on the right (Courtesy of ANL).

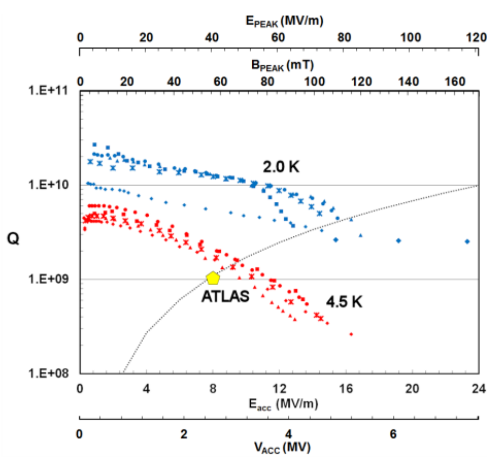

Figure 15: Plots of 5 QWRs tested for ATLAS upgrade (Courtesy of ANL).

HIAF (Heavy Ion Accelerator Facility)

A heavy ion accelerator facility, High Intensity Heavy Ion Accelerator Facility (HIAF), has been promoted by Institute of Modern Physics in China. The injector of the accelerator facility is a superconducting linac. It is a high intensity heavy ion linac and works on pulse mode. The final energy is 100 MeV/u [8]. The accelerated species are from Proton to Uranium. The designed current is 1.0 emA. This linac consists of SC cavities with beta [0.041, 0.085, 0.21, 0.40]. Table 4 lists some parameters of HIAF injector SCL.

Table 4: HIAF SCL Cavity Parameters

Parameters	Unit	QWR	QWR	SSR1	SSR2
β_g	-	0.041	0.085	0.21	0.40
Resonant freq	MHz	81.25	81.25	325	325
No of cavities	-	18	88	90	72
E_{peak}	MV/m	31.25	31.25	35	35

CONCLUSION

Although there are many challenges met in the SRF technology, the SRF technology maturing and superconducting heavy ion linacs become a preferred choice. There are many superconducting linacs are under construction at present such as RAON, C-ADS, ATLAS upgrade and so on. Brief status reports are presented along with challenges met.

ACKNOWLEDGEMENT

This work is made possible by the support of the Ministry of Science, ICT and Future Planning (MSIP) and Technology and the National Research Foundation (NRF) of the Republic of Korea under Contract 2011-0032011. Thanks go to Y. Chi (IHEP) for providing information about C-ADS and P. Ostroumov for information about ATLAS upgrade.

REFERENCES

[1] M.P. Kelly et al, “Cold testing of superconducting 72 MHz Quarter Wave cavities for ATLAS”, Proc. of 2012 LINAC conference, p. 348, Tel-Aviv, 2012.

[2] Dong-O Jeon, “Status of the RAON accelerator systems”, Proc. of 2012 LINAC conference, p. 3898, Tel-Aviv, 2012.

[3] H.J. Kim et al, “RAON Superconducting Linac”, this conference.

[4] H.J. Cha et al, “Design progress of SSR1 single spoke resonator for RAON”, this conference.

[5] Heejin Do et al, “Design of LLRF system for RAON”, this conference.

[6] Y. Chi et al, “Progress of injector-I and main linac of Chinese ADS proton accelerator”, Proc. of 2013 International Particle Accelerator Conference, p. 3854, Shanghai, 2013.

[7] P.N. Ostroumov et al, “ATLAS Upgrade”, Proc. of 2011 Particle Accelerator Conference, p. 2110, New York, 2011.

[8] Z.J. Wang et al, “Conceptual design of superconducting heavy ion linear injector for HIAF”, Proc. of 2012 LINAC Conference, p. 561, Tel-Aviv, 2012.