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

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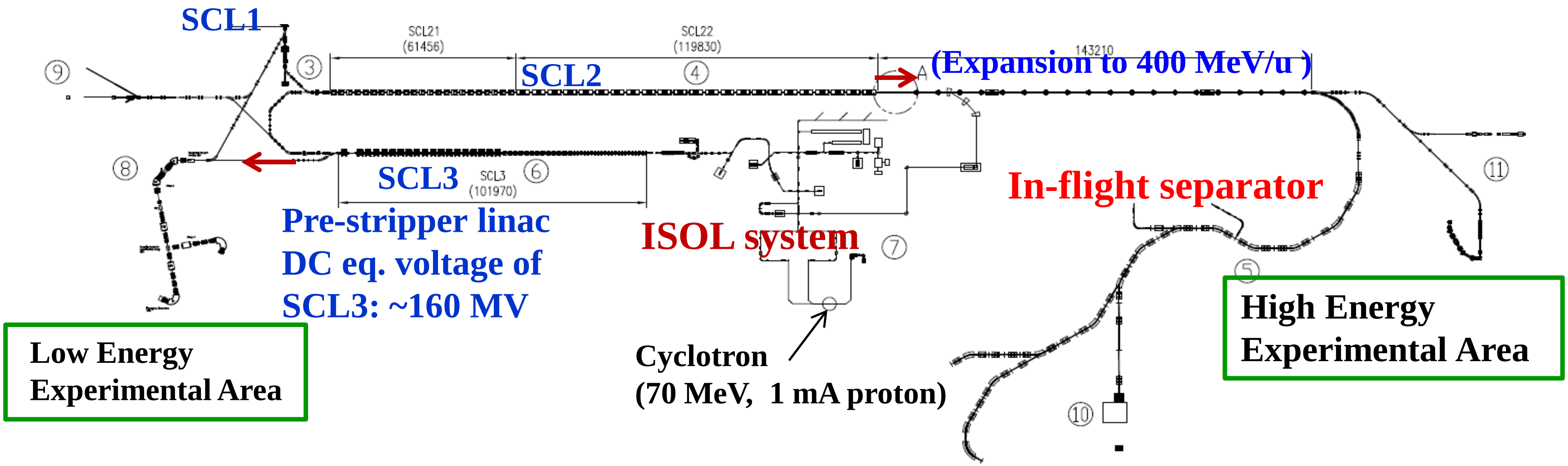
춘계원자력학회, 2017년 5월 18일

Layout of accelerator systems of RISP

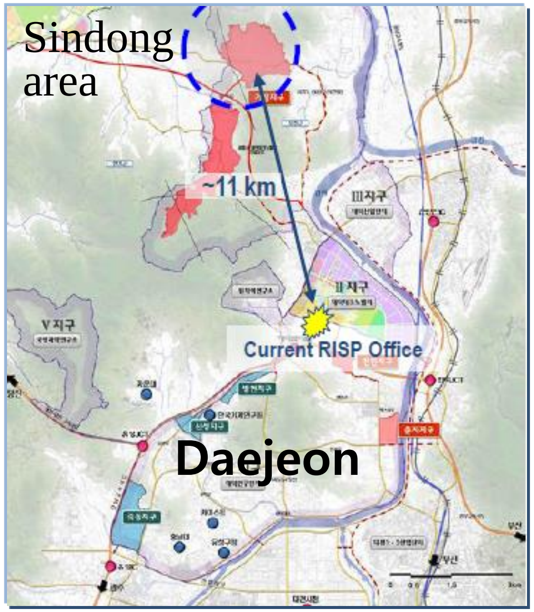
Total DC equivalent voltage: ~600 MV (SCL2+SCL3)

	Driver Sc-Linac (SCL1+SCL2)				Post (SCL3)	Cyclotron
Particle	**H**	**O**	**Xe**	**U**	SI, RI	proton
E (MeV/u)	**600**	**320**	**251**	**200**	> 18.5	70
I (pμA)	660	78	11	8.3	-	1000
Power (kW)	**> 400**	**400**	**400**	**400**	-	70



- IF (In-flight) separation
- ISOL (ISotope On Line) separation
- ISOL+IF

Aerial view of the RAON site in Sindong area



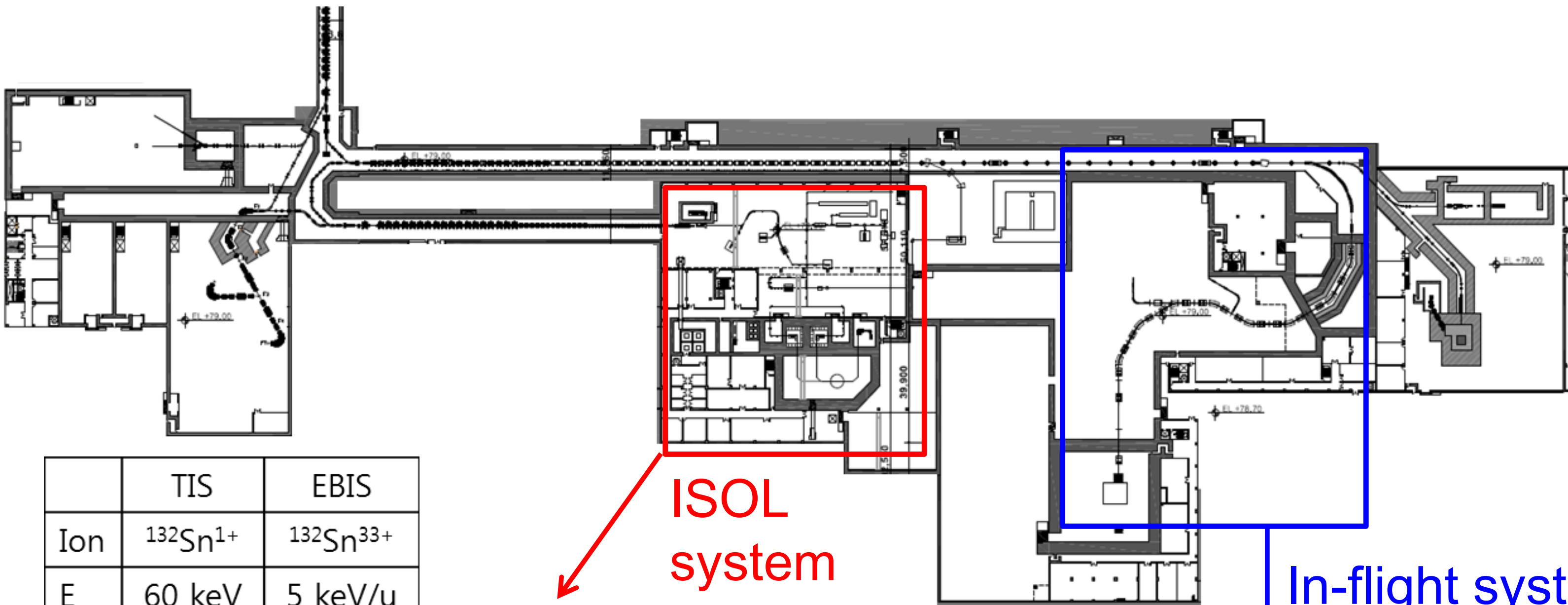
발표 요약

- **High-current heavy ion accelerator facilities based on superconducting linac** have been developed **for the next generation nuclear science study in different places**.

- **Rare isotope science project (RISP)** aims to provide 400-kW stable beams (^{238}U. 200 MeV/u) 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.

RI beam production systems of **RISP**: **ISOL** and **In-flight**



	TIS	EBIS
Ion	$^{132}Sn^{1+}$	$^{132}Sn^{33+}$
E	60 keV	5 keV/u

Pre-Separator
$m/\delta m = 300$

↓

MR-TOF

↓

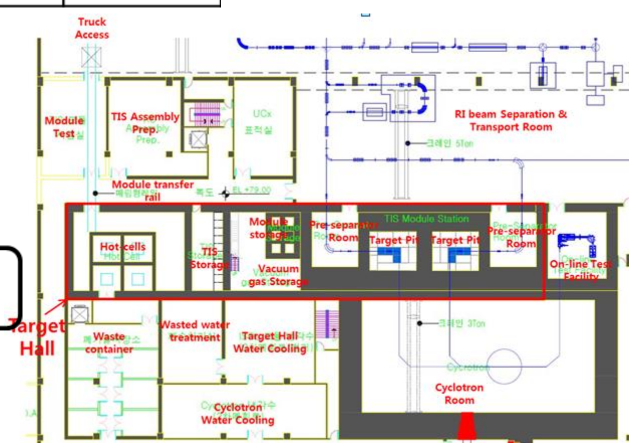
RFQ Cooler
3π mm mrad, 1 eV

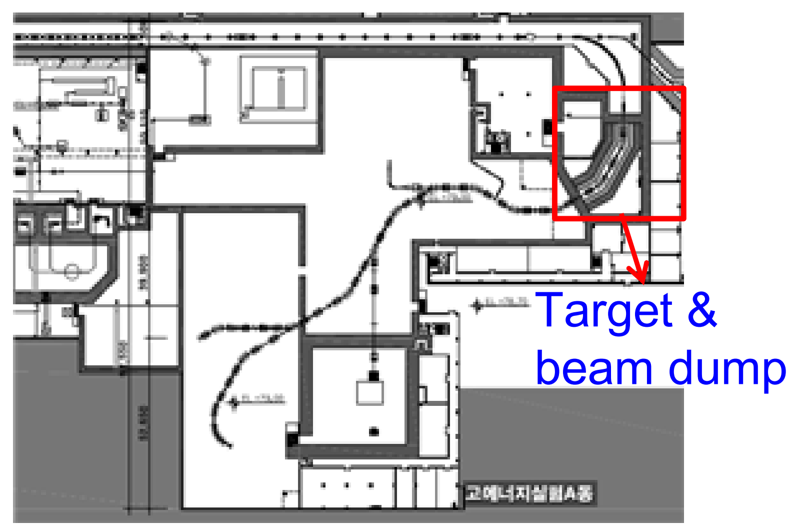
↓

EBIS

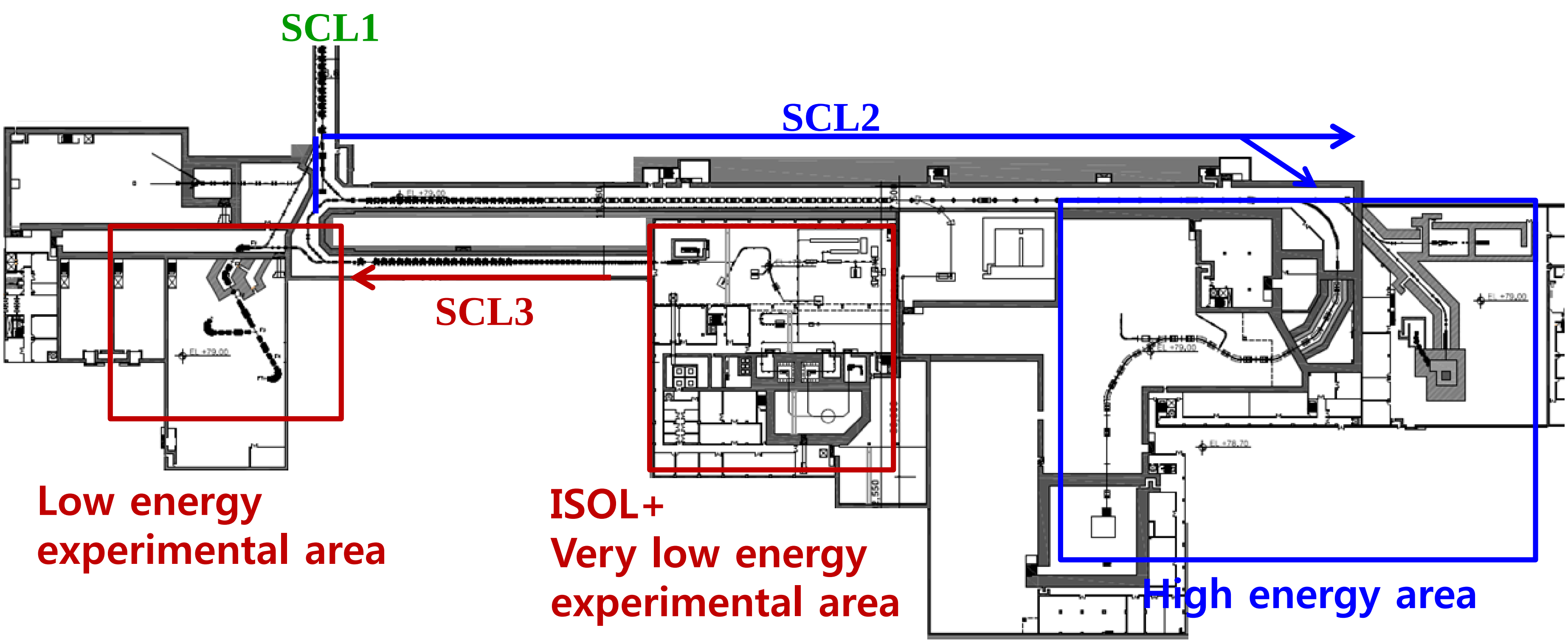
↓

Post linac





Staged construction



- **SCL3** → **SCL2** → **SCL1** according to the use of beams
- Beam power ramp-up: < 100 kW (2021) → 400 kW (in a few years after 2021)

Key technologies for high-intensity HI SC-linac system

1. **Design** of superconducting linac
2. **SC-cavity** especially for low-β beam
3. **SC-ECR ion source** to produce highly-charged and high-current heavy ions
4. **RFQ** for high-current heavy ion beams
5. **Charge stripper** for heavy ion beams
6. **EBIS**

1. **Design**: Injector+SCL3+SCL2 (current design)

Injector				SCL3			SCL2	
ECR	LEBT	RFQ	MEBT	SCL31	SCL32	STRIP	SCL21	SCL22
				QWR (81.25MHz)	HWR (162.5MHz)		SSR1 (325MHz)	SSR2 (325MHz)

→ IF separator and high-energy area

CAV QF QD — 22 cryomodules → Output 2.7 MeV/u

22 β=0.047 QWRs, 44 quadrupoles

CAV CAV QF QD — 13 cryomodules → Output 6.0 MeV/u

CAV CAV CAV CAV QF QD — 19 cryomodules → Output 18.5 MeV/u

98 β=0.12 HWRs, 64 quadrupoles

Stripper: charge state 33, 34 → 77,78,79,80,81 for Uranium

C C C QF QD — 23 cryomodules → Output 56.5 MeV/u

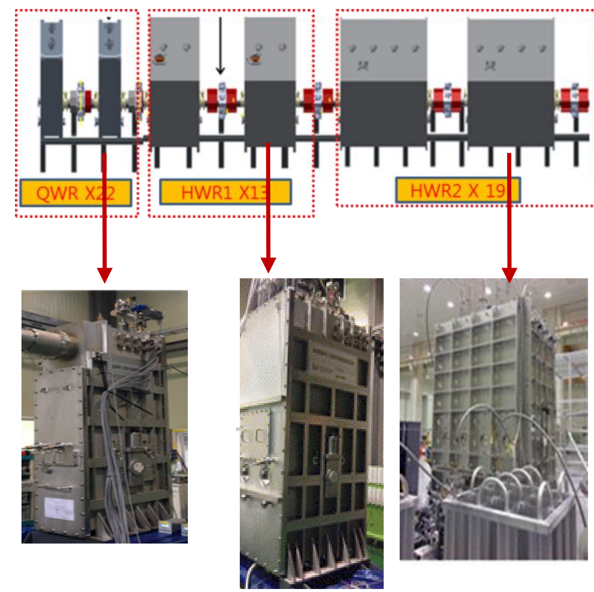
69 β=0.30 SSR1, 46 quadrupoles

C C C C C C QF QD — 23 cryomodules → Output 200 MeV/u

138 β=0.51 SSR2, 46 quadrupoles

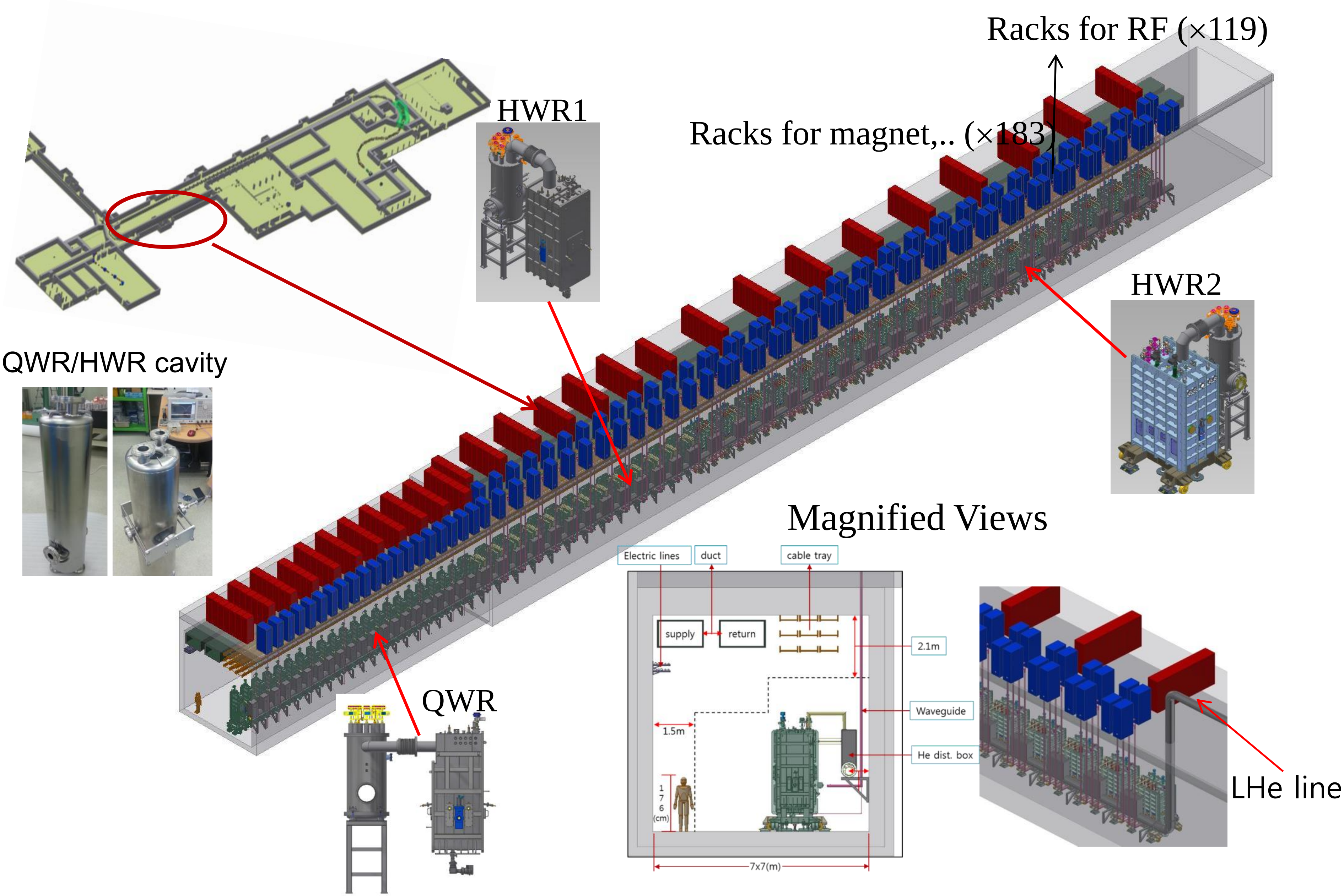
Total 331 cavities, 100 cryomodules, 196 quadrupoles

SCL3

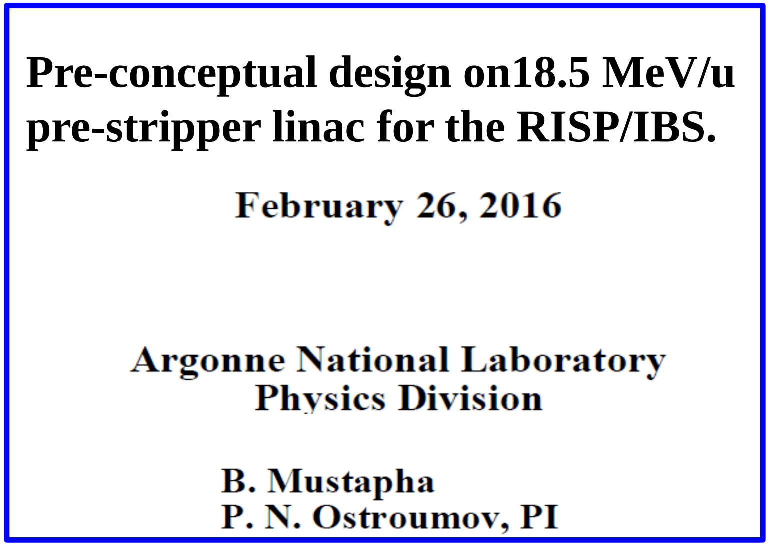


Length: SCL3+180° bending: 122 m, SCL2 181 m

1. **Design**: Tunnel design for SCL3



1. Design: Design study of SCL3 with ANL group (Feb. 2016)

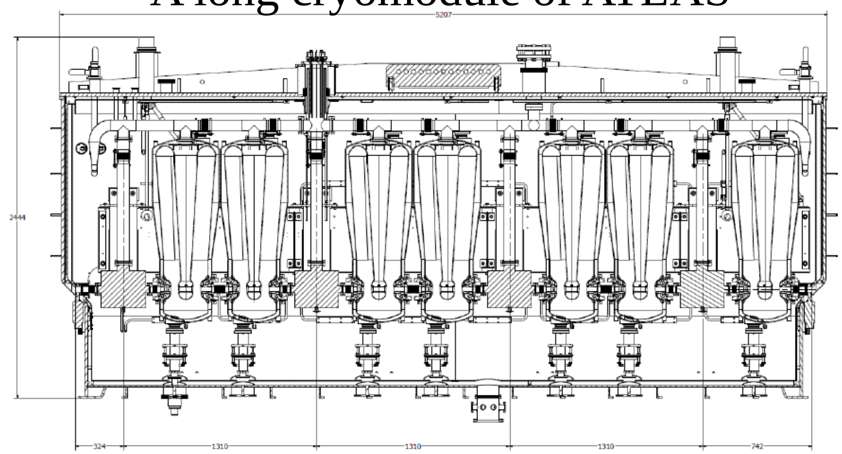

Pre-conceptual design on18.5 MeV/u pre-stripper linac for the RISP/IBS.

February 26, 2016

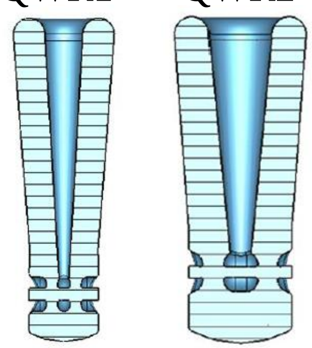
Argonne National Laboratory
Physics Division

B. Mustapha
P. N. Ostroumov, PI

A long cryomodule of ATLAS



Parameter	QWR1	QWR2
f (MHz)	81.25	81.25
β_{opt}	0.05	0.109
L_{eff} (cm)	18.5	40.2
Aperture (mm)	40	40
Height (cm)	103	115



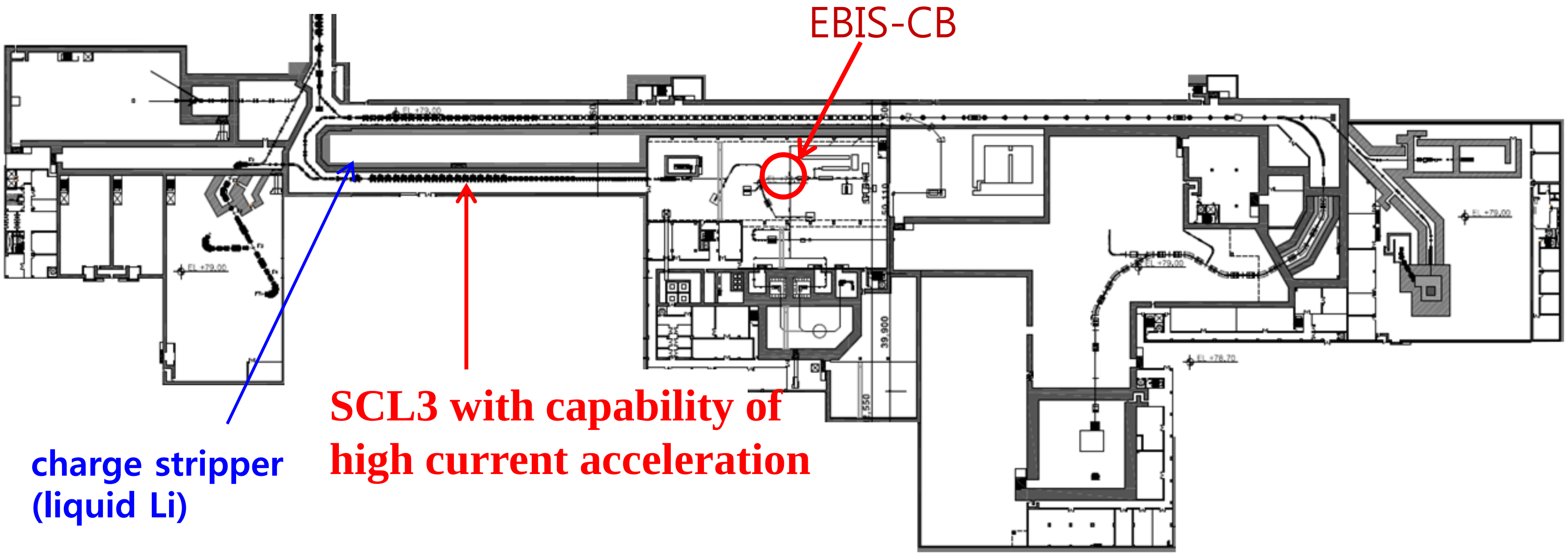
Comparison of SC Linac parameters.

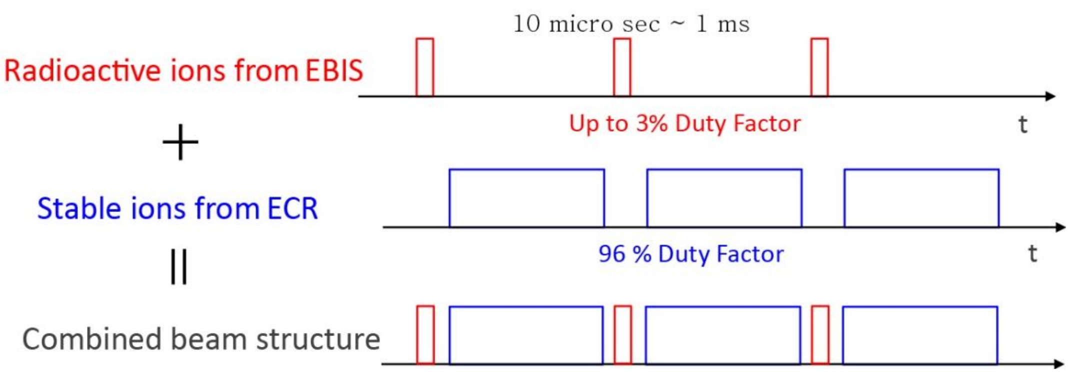
Parameters	RISP baseline	ANL proposal
Number of QWR (or QWR1)	22	15
Number of HWR (or QWR2)	102	49
Number of cryomodule	54	9
Total length	100 m	53.3 m

*E_p assumed for RISP: 35 MeV/m, ANL : 40 MeV/m

Capacity of cryogenic plant for ANL design: **2.5 kW at 4.4 K (4.2 kW for RISP baseline)**

1. **Design**: Two-beam acceleration with SCL3





Simultaneous acceleration of stable and RI beams with similar q/A

IF beam: $^{238}U^{33+,34+}$ (q/A≅0.14); ECR

ISOL beam: $^{132}Sn^{19+}$ (q/A≅0.14); EBIS-CB

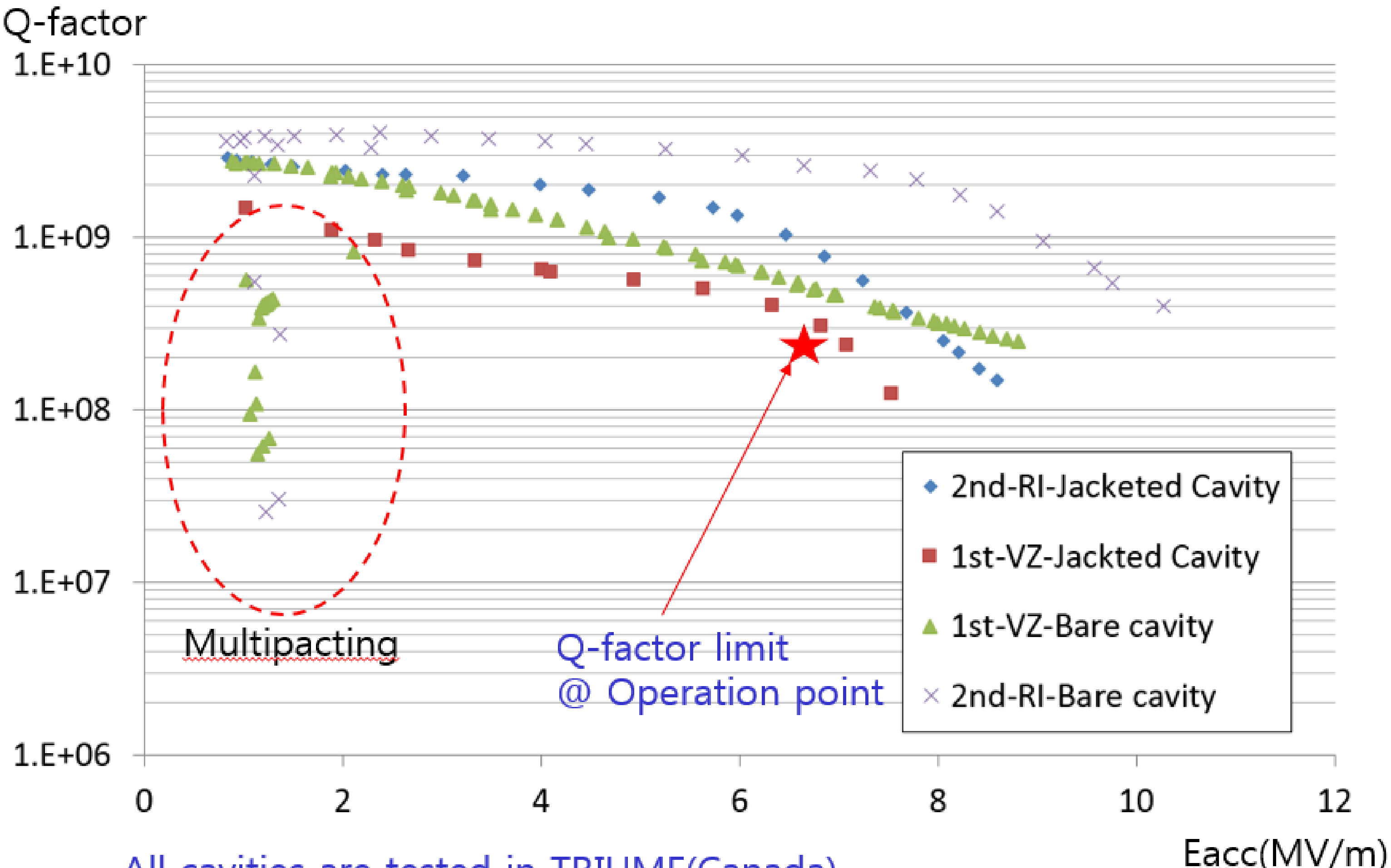
2. SC-cavity: Prototyping of SCL3 components

Item	1st Prototype	2nd Prototyping	Completion time or status
ECR Ion Source	RISP		Under test
RFQ	Vitzrotech(1)		Under test
QWR (β=0.047)	Vitzrotech(1)	Ongoing RI Instru. (2) Vitzrotech(2)	2016.4Q
QWR Coupler	Ongoing Toshiba(2) Mitubish(2)		2016.4Q
QWR Cryomodule	Vitzrotech(1)	Vitzrotech(1)	2016.4Q
HWR (β=0.12)	Vitzrotech(1)	Ongoing RI instru. (2) Vitzrotech(4)	2017.1Q
HWR Coupler	IHEP(2)		2017.1Q
HWR Cryomodule	Vitzrotech(1) SFA(1)	Ongoing	2017.1Q

***Parenthesis: number of the same element**

2. **SC-cavity**: QWR development of RISP

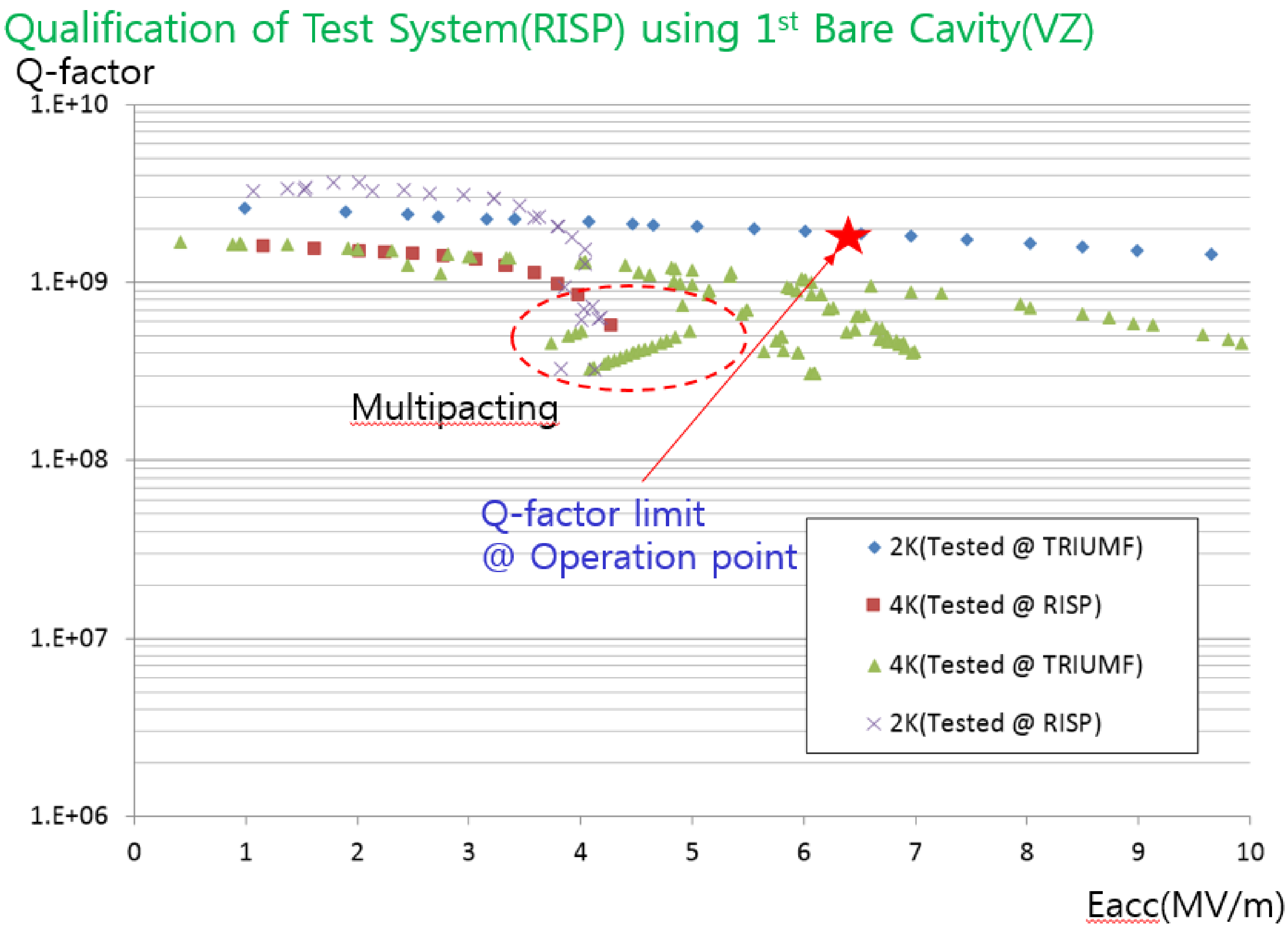
Bare cavity vs. Jacketed Cavity



All cavities are tested in TRIUMF(Canada)

From presentation of H.C. Jung, KPS spring meeting April, 2017

2. **SC-cavity**: HWR development of RISP



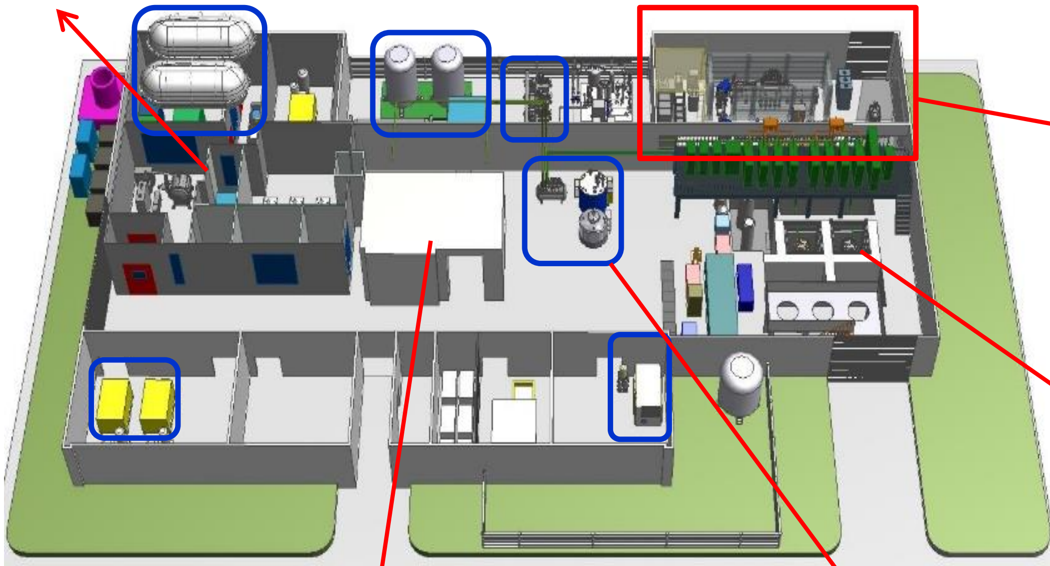
From presentation of H.C. Jung, KPS spring meeting April, 2017

2. **SC-cavity**: SRF test facility at Munji campus of KAIST

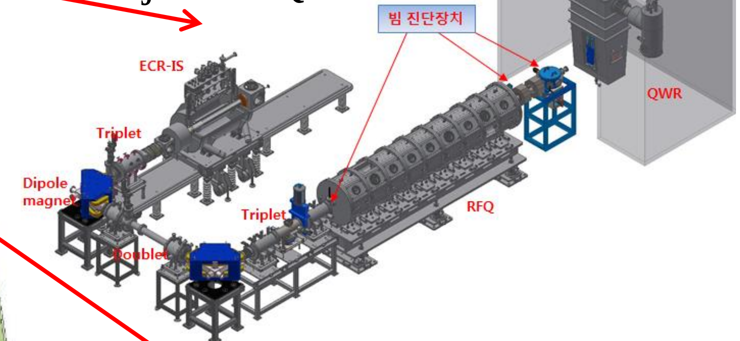
Clean room
up to class 10

Completion date: June, 2016

SCL-demo project



Beam test for
Injector+QWR



Cryomodule test room

LHe system (330 W at 4.5 K)

Vertical cavity test

2. **SC-cavity**: comparison with FRIB cavities

Parameters of RISP cavities

Parameters	Unit	QWR	HWR	SSR1	SSR2
β_g	-	0.047	0.12	0.30	0.51
Resonant frequency	MHz	81.25	162.5	325	325
No of cavities	-	22	98	69	138
Aperture diameter	mm	40	40	50	50
QR_s	Ohm	21	42	98	112
R/Q	Ohm	470	300	230	300
V_{acc}	MV	1.0	1.5	2.2	4.2
E_{peak}	MV/m	35	35	35	35
B_{peak}	mT	57	55	58	64
Operating temp	K	4.5	2	2	2

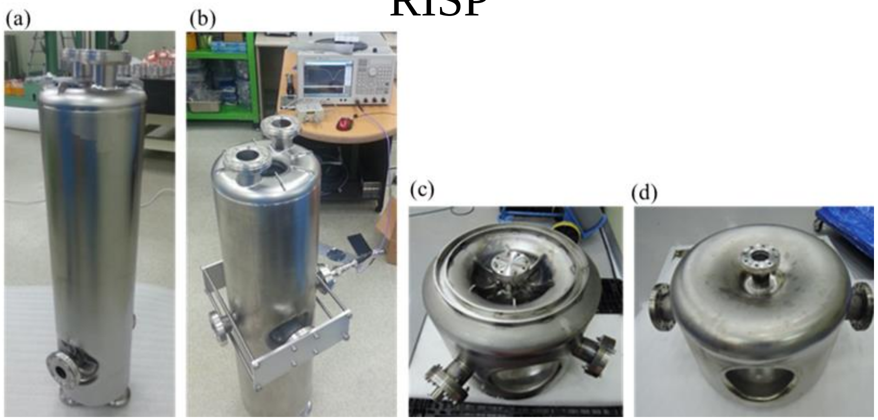
Table 1: FRIB SRF Cavity Parameters

Cavity Type	QWR	QWR	HWR	HWR
β	0.041	0.085	0.285	0.53
f [MHz]	80.5	80.5	322	322
V_a [MV]	0.810	1.80	2.09	3.70
E_{acc} [MV/m]	5.29	5.68	7.89	7.51
E_p/E_{acc}	5.82	5.89	4.22	3.53
B_p/E_{acc} [mT/(MV/m)]	10.3	12.1	7.55	8.41
R/Q [Ω]	402	455	224	230
Γ [Ω]	15.3	22.3	77.9	107
Aperture [m]	0.036	0.036	0.040	0.040
$L_{eff} \equiv \beta\lambda$ [m]	0.153	0.317	0.265	0.493
Lorenz detuning [Hz/(MV/m)^2]	< 4	< 4	< 4	< 4
Specific Qo @VT	1.4×10^9	2.0×10^9	5.5×10^9	9.2×10^9

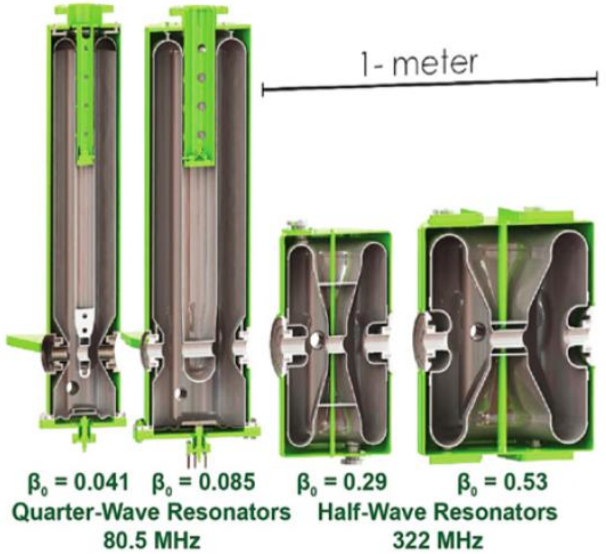
Operating temp all cavities at 2 K

2. **SC-cavity**: comparison with FRIB cavities

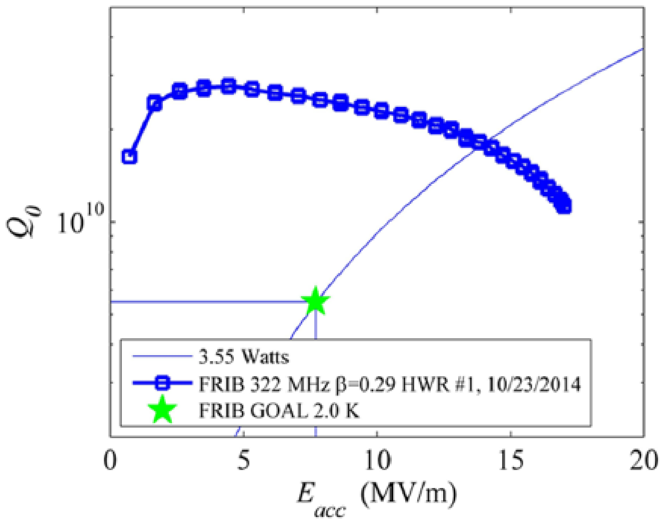
RISP



Four types of the prototype cavities; (a) QWR, (b) HWR, (c) SSR2, (d) SSR1



FRIB SRF cavity families with helium jacket.



From presentation of J. Wei, LINAC Conf. 2016

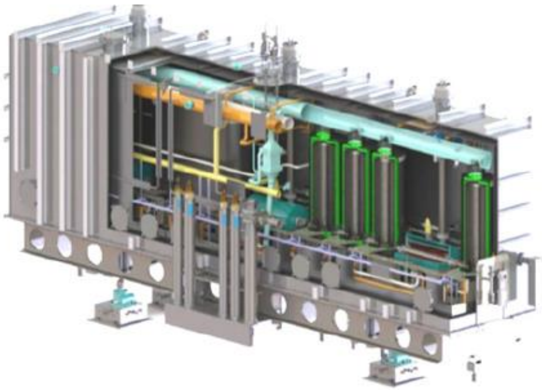
2. **SC-cavity**: 1st assembled QWR cryomodule test ('17, April)

Short Cryomodule

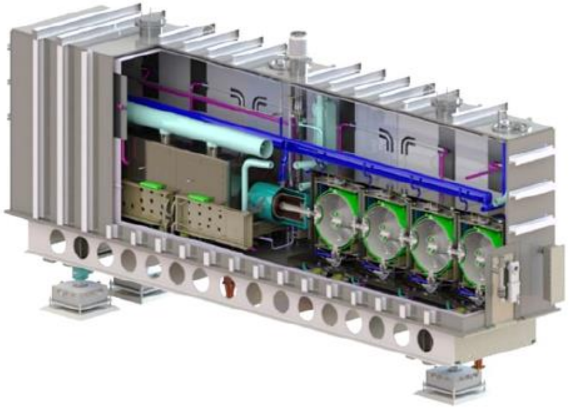
RISP

Installed QWR module in Test Bunker

Long Cryomodule

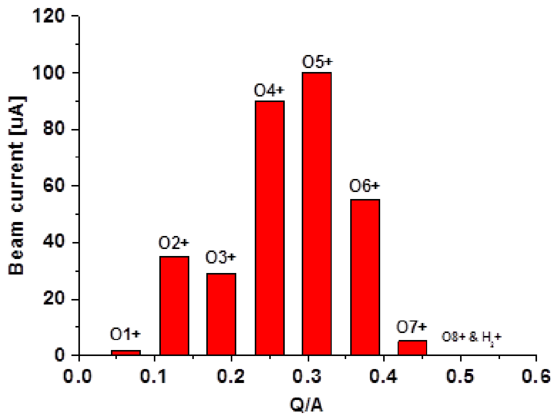


FRIB 0.85QWR cryomodule design



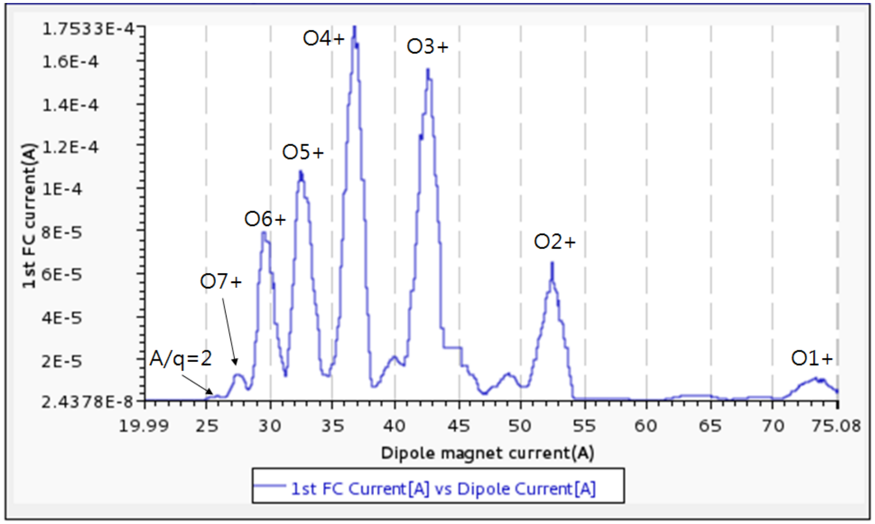
FRIB 0.53HWR cryomodule design

3. SC-ECR: beam test of 28 GHz SC-ECR, RISP

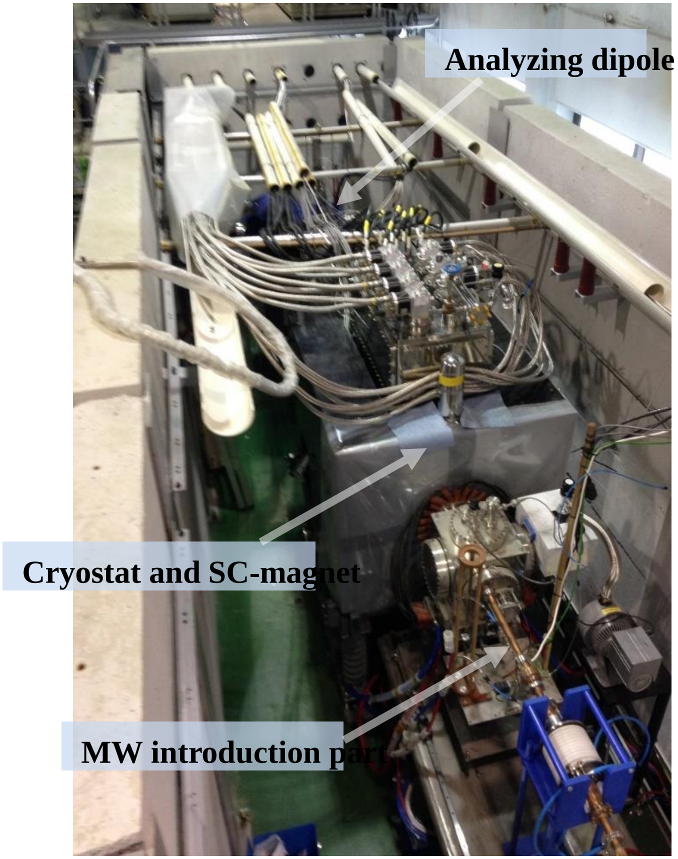


Oxygen beam test in 2015

Frequency (GHz)	28
RF Power (kW)	10 + 2
Plasma Chamber ID (mm)	147
V_{ecr} (kV) = V_{ext} (kV) + V_{acc} (kV)	70 = ~ 30 + ~ 50
Number of Solenoid Coils	4
B_{inj} (T)	~3.5
B_{ext} (T)	2
B_{min} (T)	0.4 ~ 0.8



O^{7+} beam extraction at 10 keV/u, 10uA (Oct. 2016)



3. SC-ECR : comparison with SC-ECR of SECRAL

R&D for HIAF — **SECRAL High Intensity Beams**

The world best performance ECRIS

SECRAL beam intensities

Ion Beam	SECRAL (eμA)
$^{16}O^{6+}$	5000
$^{40}Ar^{11+}$	1620
$^{40}Ar^{16+}$	350
$^{40}Ca^{11+}$	710
$^{40}Ca^{14+}$	270
Xe^{26+}	1100
Xe^{30+}	320
Xe^{42+}	10
$^{209}Bi^{31+}$	680
$^{209}Bi^{41+}$	100
$^{209}Bi^{50+}$	10
$^{238}U^{33+}$	202

The world record beam intensities (5000 – 10)

LBNL VENUS 400 eμA ($^{238}U^{33+}$)

From presentation of Hongwei Zhao, Jan. 2017, AFAD

3. SC-ECR : comparison with VENUS at LBL

Design characteristics of the VENUS magnet structure

ID of plasma chamber	15 cm
Mirror field on axis	4.0 T (at injection), 3.0 T (at extraction)
Mirror-mirror spacing	50 cm
Central field	0.2 -1.0 T (variable)
Max. radial field, plasma wall	2.4 T
Min. field, plasma wall	2.0 T

TABLE II. Recent VENUS results.

Ion	Charge state	Intensity (eμA)	Method
^{124}Xe	30+	211	Gas
^{124}Xe	42+	1	Gas
^{209}Bi	31+	300	HiT oven
^{209}Bi	50+	5.3	HiT oven
^{16}O	6+	3000	Gas
^{16}O	7+	925	Gas
^{40}Ca	11+	400	LoT oven

J. Benitez et al., RSI 83 (2012)

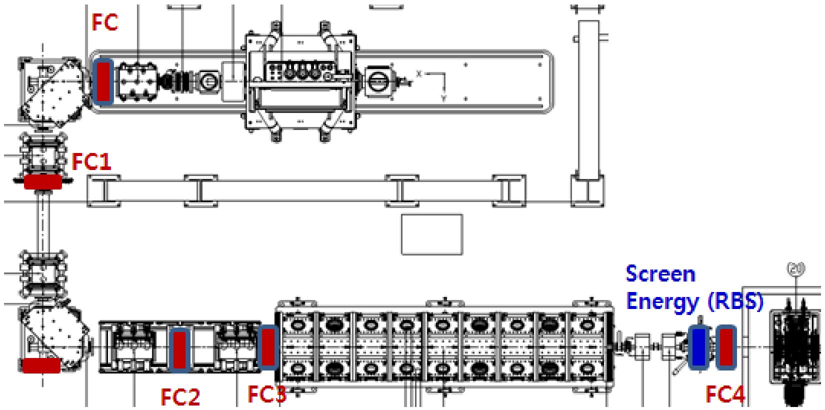
Ion	Charge State	Intensity (eμA)
4He	1+	20 emA
4He	2+	11 emA
16O	6+	3 emA
40Ar	11+	860 eμA
40Ar	16+	270 eμA
40Ca	11+	400 eμA
40Ca	12+	400 eμA
124Xe	35+	37.5 eμA
209Bi	31+	300 eμA
209Bi	50+	5.3 eμA
209Bi	51+	3.3 eμA
238U	33+	450 eμA
238U	50+	13 eμA
238U	56+	0.79 eμA

VENUS Records

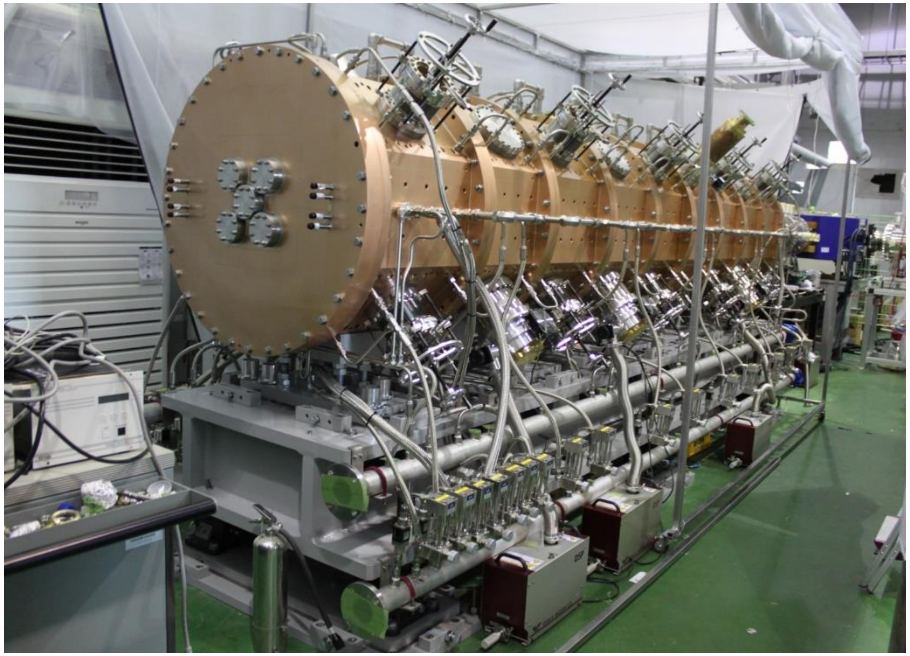
From 88inch cyclotron Website (May, 2017)

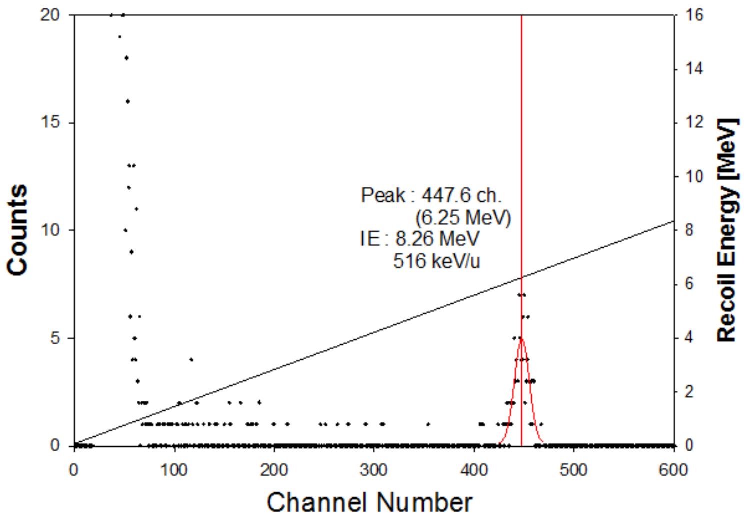
4. RFQ: O^{7+} beam first accelerated by RFQ on Nov. 30, 2016

Parameter	Value
f	81.25 MHz
E_{in}	10 keV/u
E_{out}	0.507 MeV/u
ε_{out}	0.0125 .cm. mrad ~26 keV/u-degree
Transmission	~98 %
P_{loss}	94 kW
Duty factor	100%



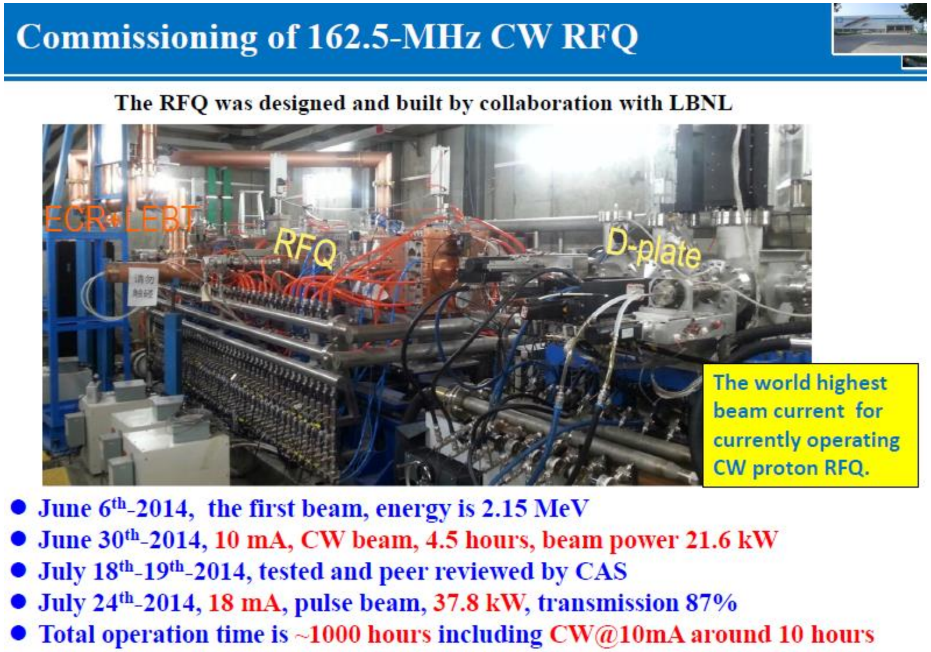
Repetition rate : 1Hz
- RF pulse width: 250 μsec
- Beam pulse width: 110 μsec





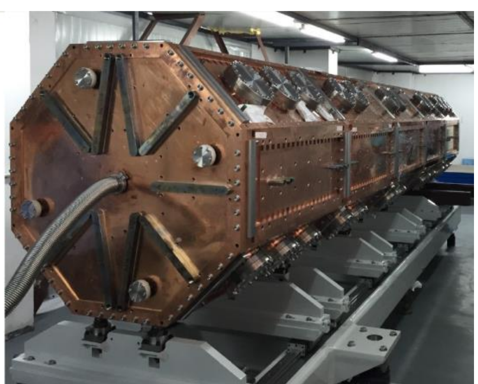
Rutherford Back Scattering method used

4. **RFQ**: comparison with other RFQ's



From presentation of Hongwei Zhao, Jan. 2017, AFAD

80.5 MHz, 5-segment, 4-vane RFQ tuned
(2016 Linac Conf., J. Wei)



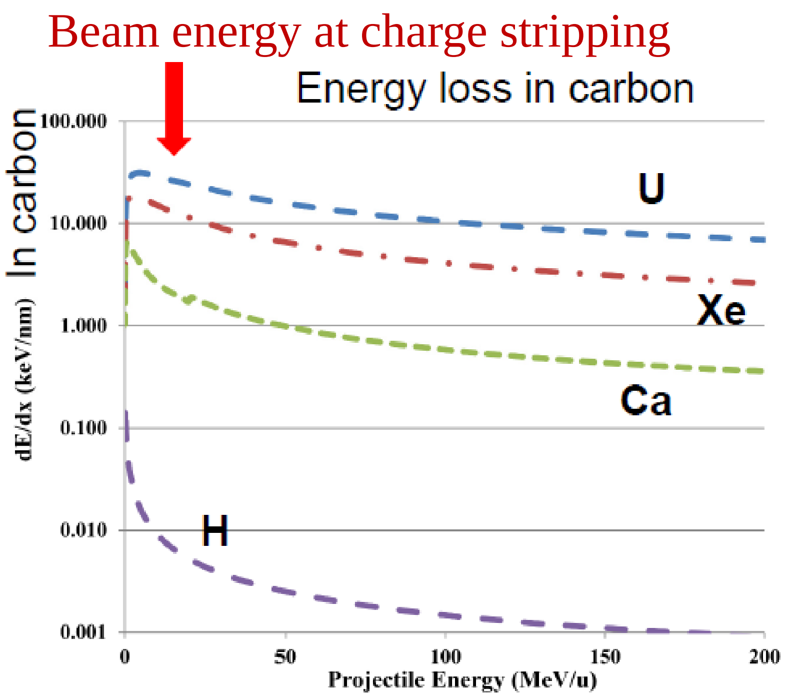
SPIRAL2 at GANIL

- Proton ~5 mA CW (Dec. 2015) trans. ~100 %
- A/Q=2 ($^{4}He^{2+}$) ~1 mA CW (June 2016) trans. > 99 %
- RFQ always operated in CW

From presentation in July. HB2016

5. Charge Stripper: Carbon, Liquid Li, He

The energy loss of the heavy ions in material is much higher than for protons. It is a challenge to dissipate the power.



Solid carbon foils can be used only with low mass ions at low intensities

Two options are available for high intensity: flowing liquids and gases

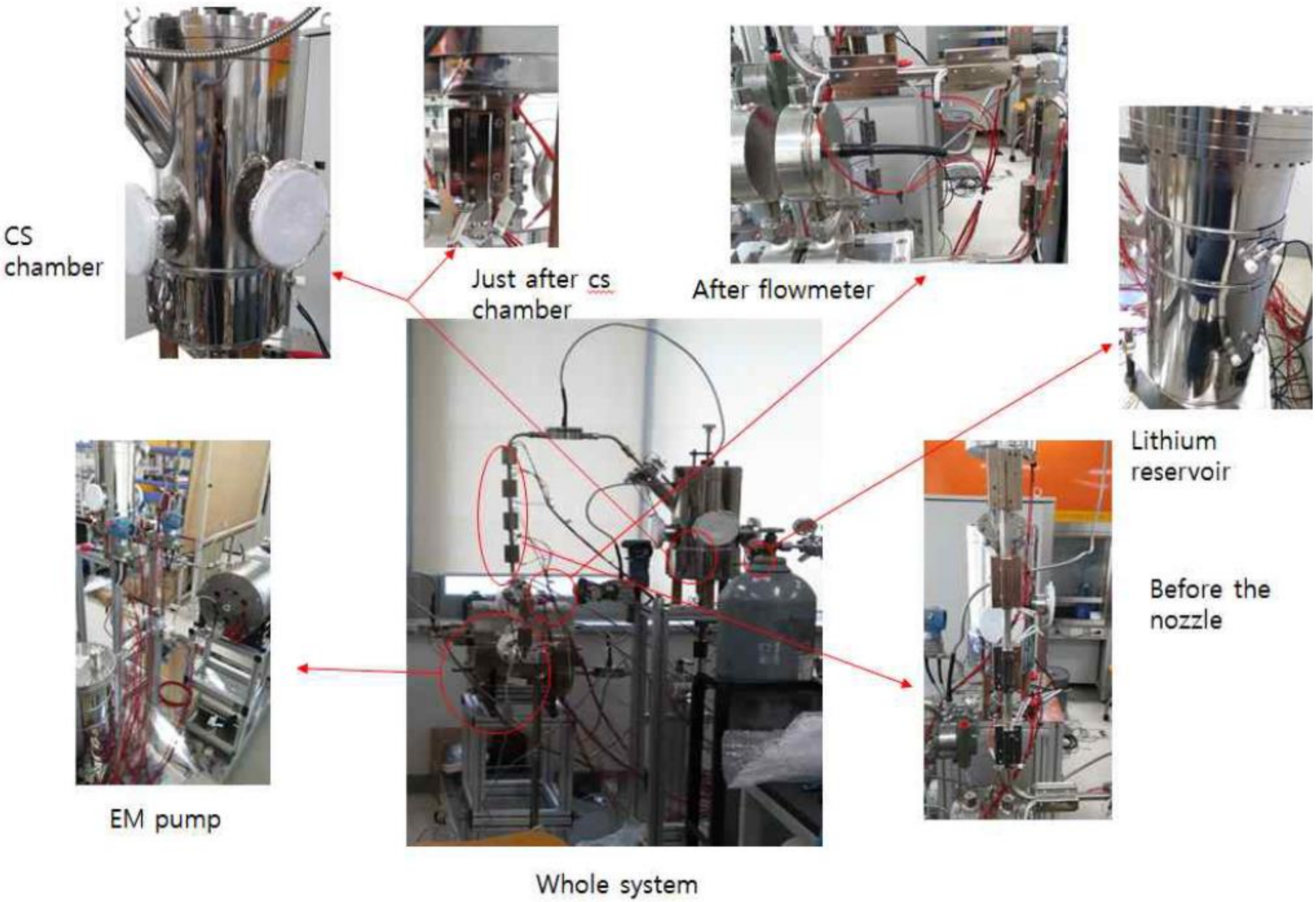
-For liquids, lithium is the best option. (The average charge state after stripping is higher than for heavier mass gases like N2 or Ar)

-For gases, helium is the best candidate.

F. Marti, From presentation at HB2016

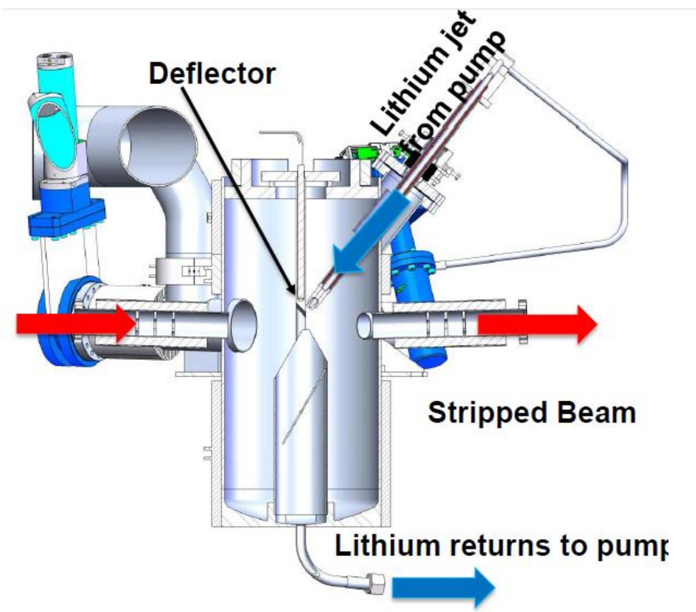
5. Charge Stripper: 액체 리튬 stripper개발

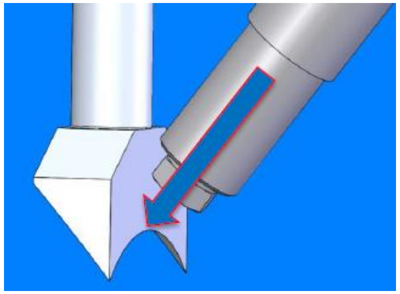
EM pump 개발 (2016, 6월), 대전 문평동 실험실

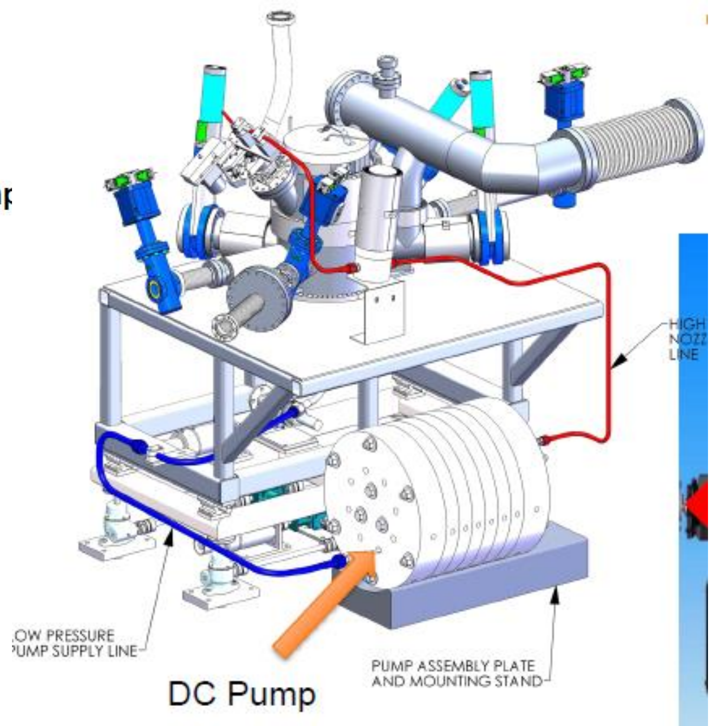


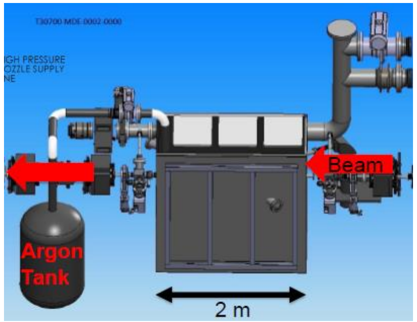
5. Charge Stripper: Liquid Li at FRIB

- Film thickness: ~12 μm
  stability: ±5% for ϕ1 mm spot
- Speed of liquid Li: ~ 50 m/s) to remove heat
- High pressure: ~15 bars
- Nozzle diameter: ϕ0.5 mm



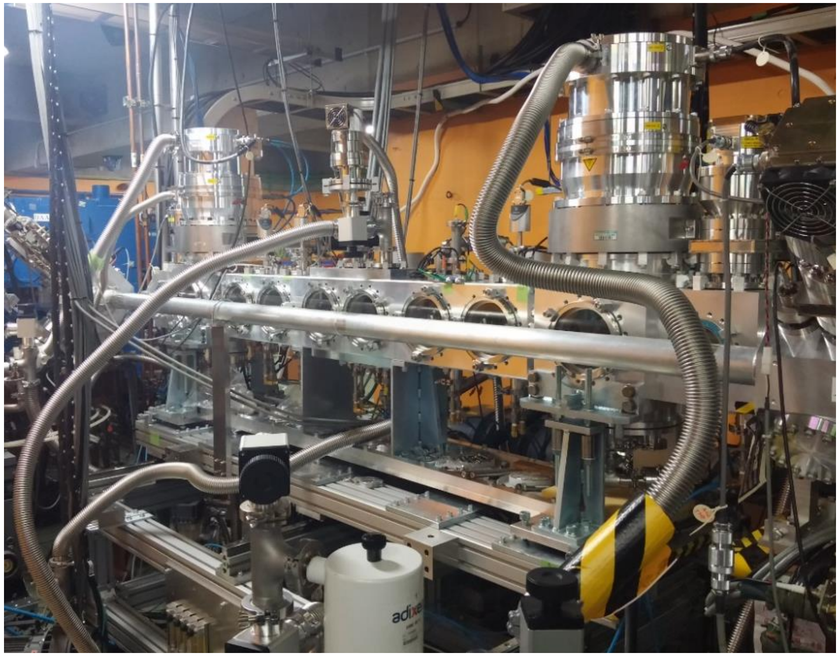


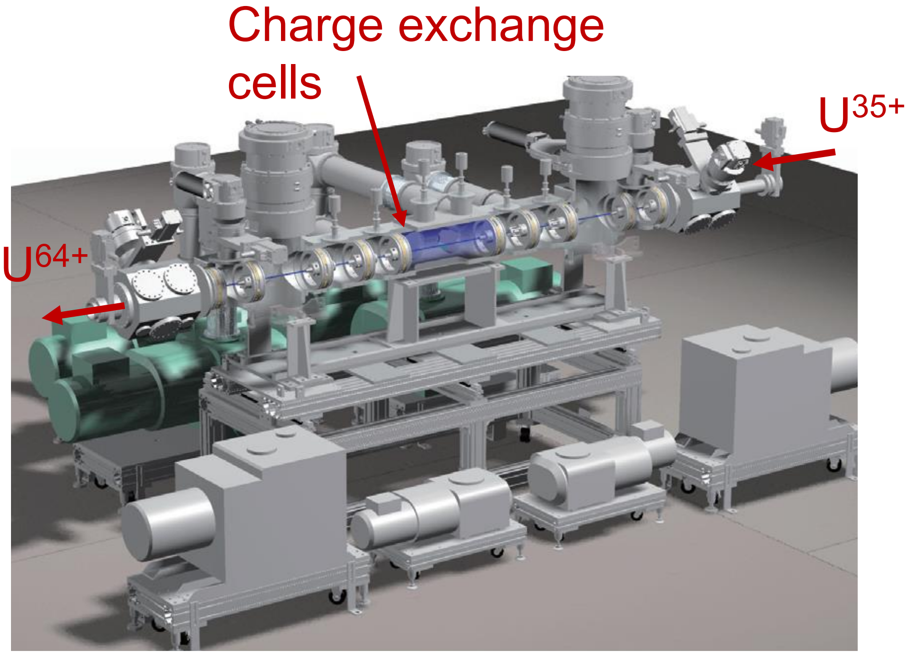


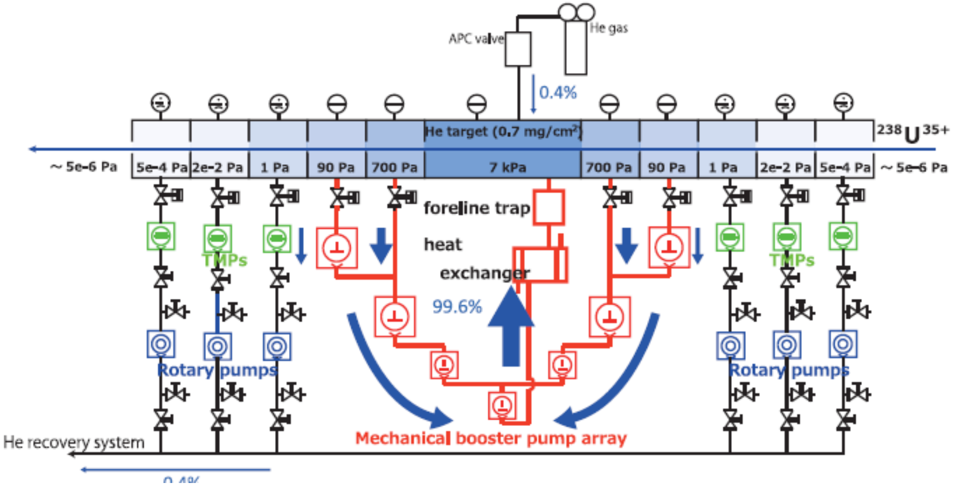


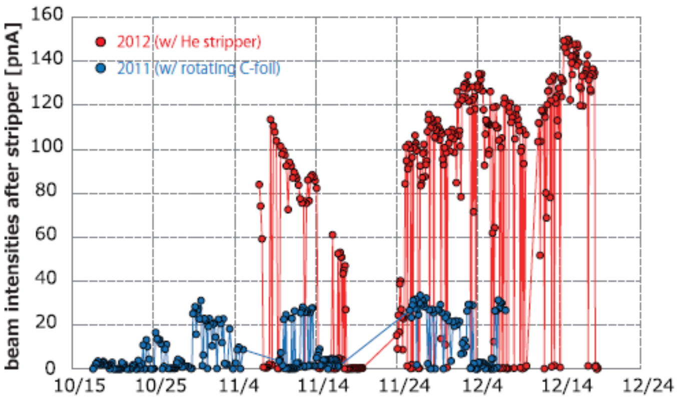
F. Marti, From presentation at HB2016

5. Charge Stripper: He gas stripper at RIKEN







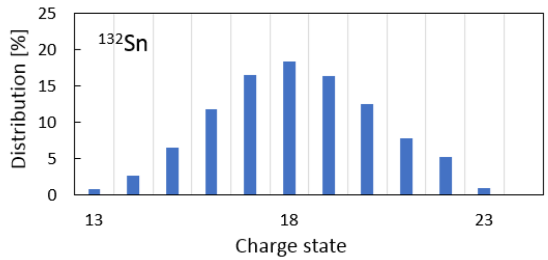


H. Imao et al., Proc. of Cyclotron 2013

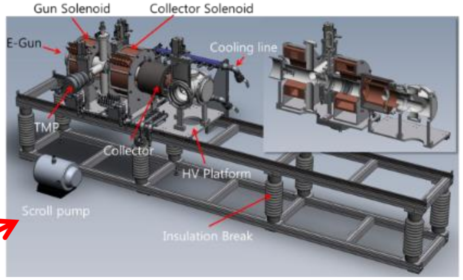
6. EBIS: EBIS-CB and ISOL system

	TIS	EBIS
Ion	$^{132}Sn^{1+}$	**$^{132}Sn^{33+}$**
E	60 keV	**10 keV/u**

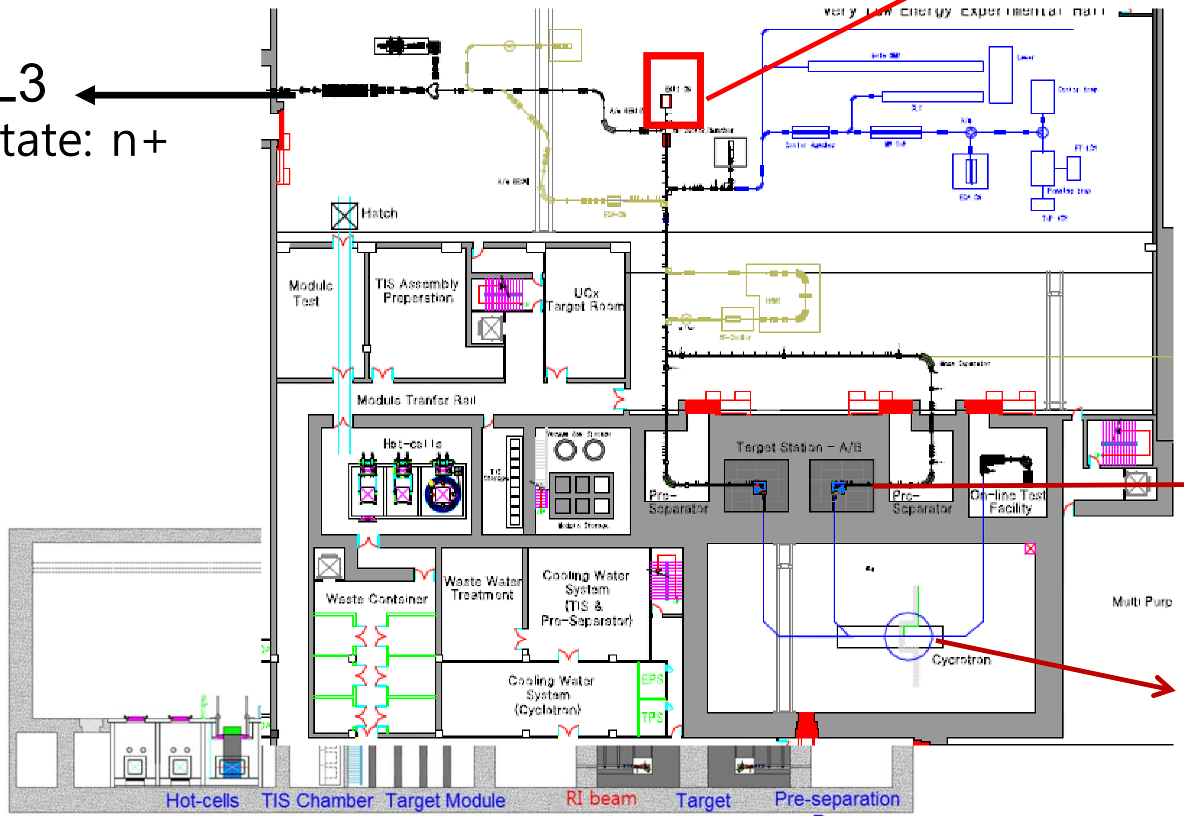
After charge-breeding of 5 ms



EBIS-CB



SCL3
charge state: n+



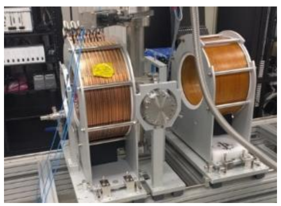
Target Ion Source (TIS)

Proton cyclotron (70 MeV)

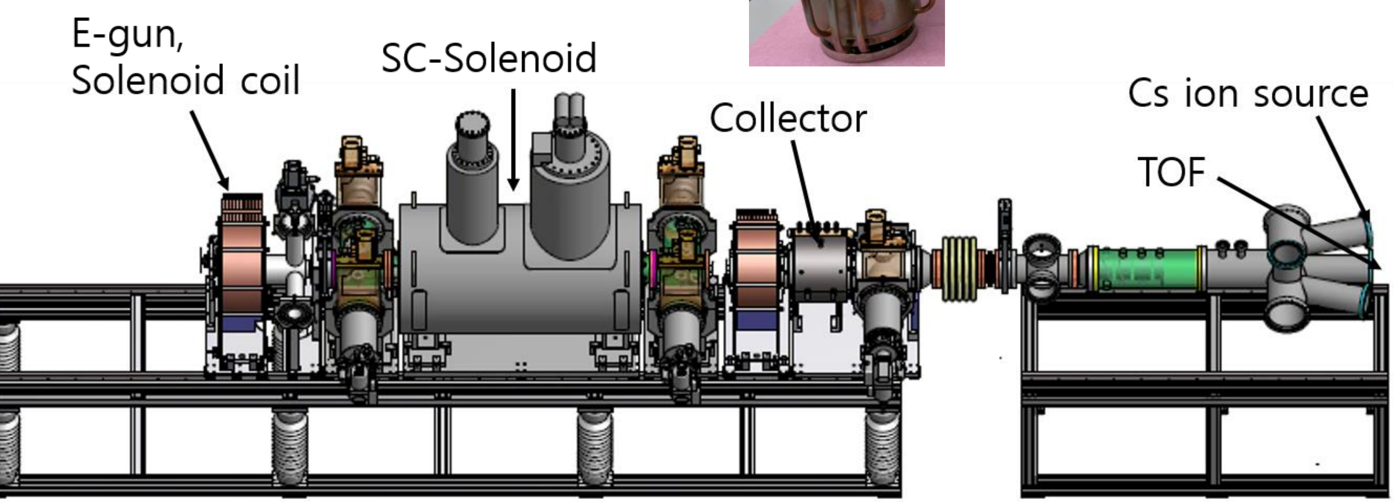
6. **EBIS**: EBIS development

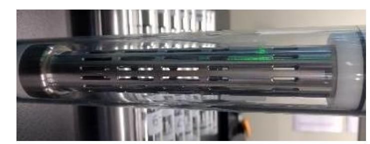
- EBIS (Electron beam ion source) is a key component for the multi-user capability
- Major components are ready to be assembled in 2017.

High vacuum: $10^{-10\sim11}$ torr
High current e-beam: 3 A
High voltage: ~40 kV



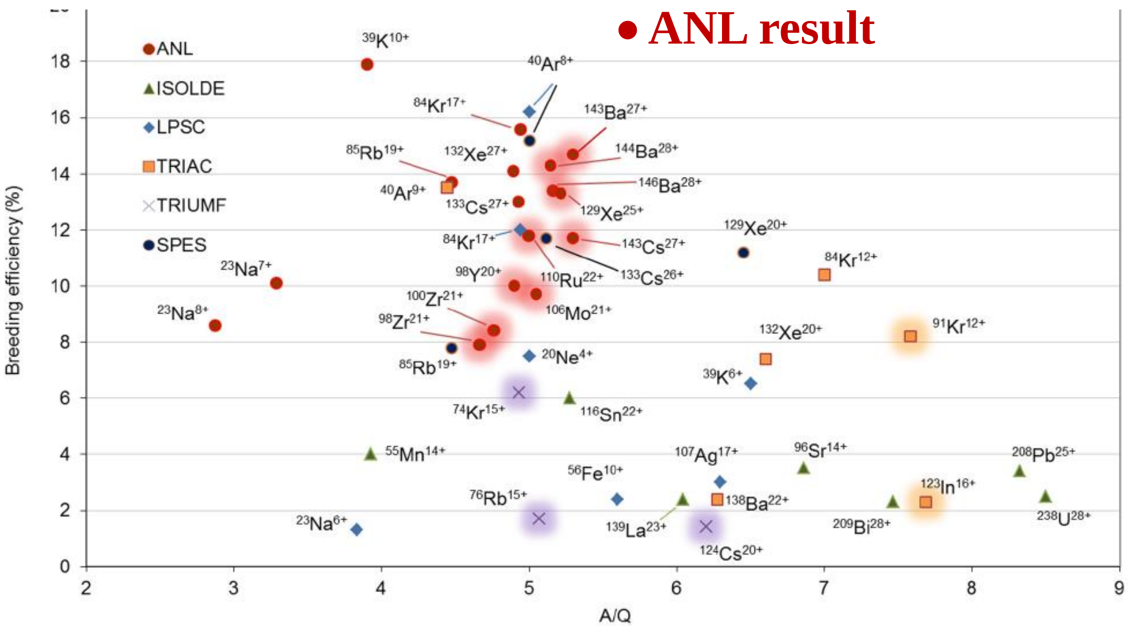




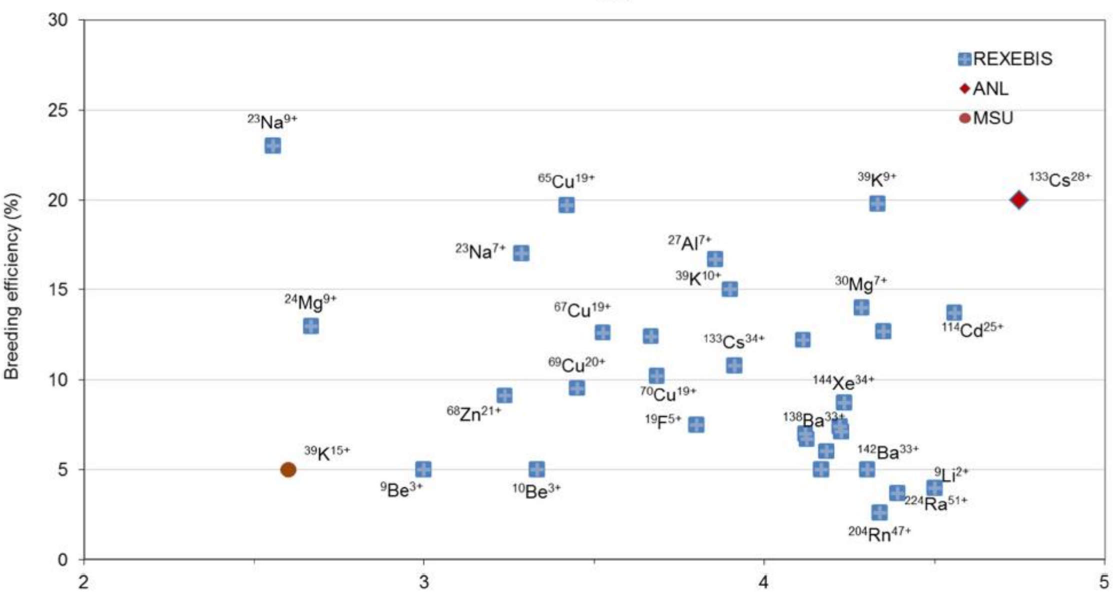
Drift tube

Cryopump

6. **EBIS**: experimental results



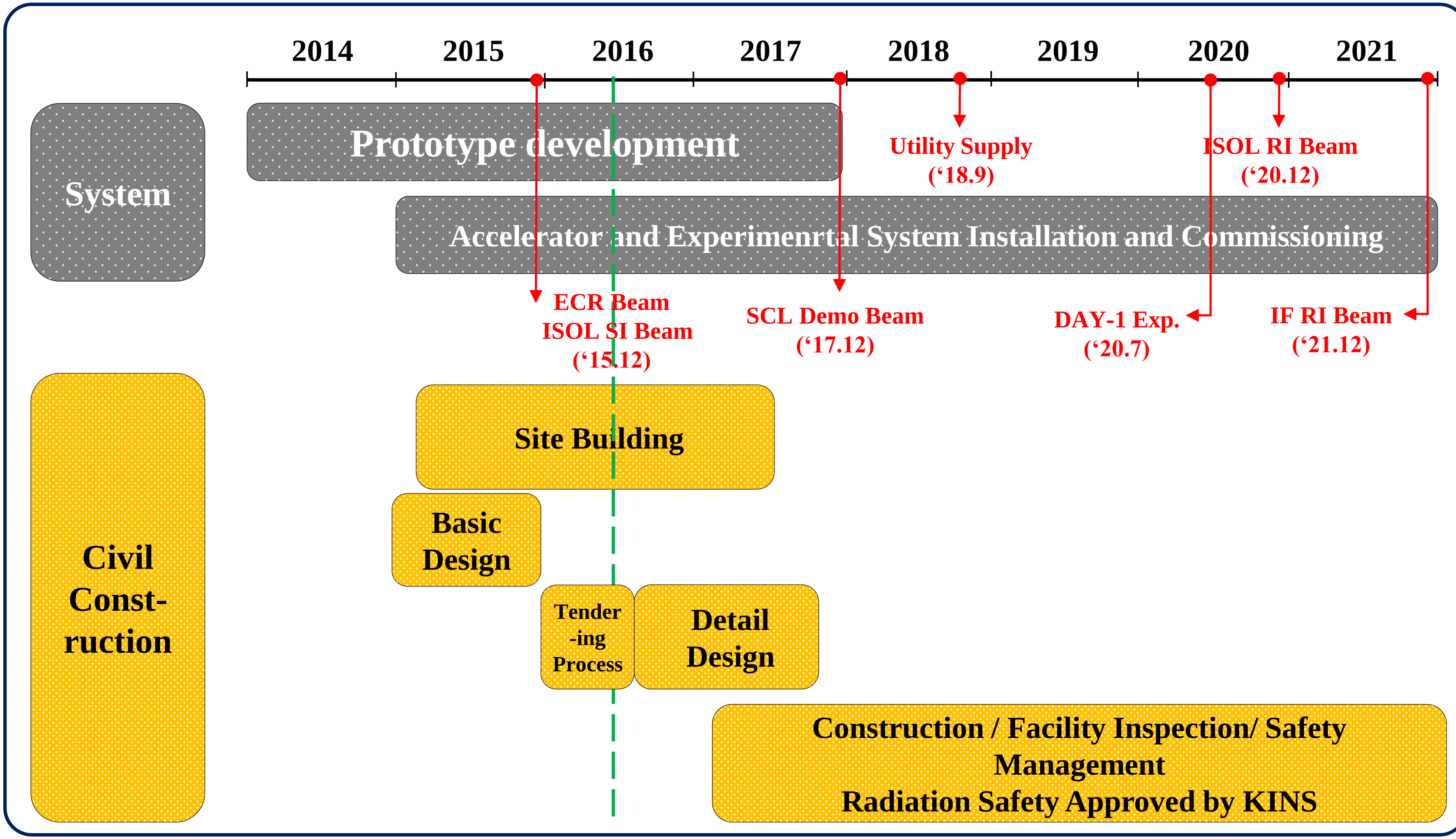
Charge breeding performance for the Phoenix ECR sources tested at ISOLDE and LPSC, the TRIAC source, the TRIUMF source, the ANL source, and the recently commissioned SPES charge breeder (built by LPSC for the LNL group). The radioactive beam species are denoted with a halo around them.



Present EBIS charge breeding performance for the REX-EBIS group, a potassium beam produced by the MSU ReA EBIT in 2013 and a cesium beam recently produced by the ANL EBIS.

R. Vondrasek, NIM B 376 (2016)

Major milestones of RISP



7. Concluding remarks

- SCL3 will be the first SC-linac for RISP
- Key technologies in the SC-linac development for nuclear science research are identified and discussed: 1) Design of SC-linac, 2) SC-cavity, 3) SC-ECR, 4) RFQ, 5) Charge stripper, 6) EBIS
- **Further efforts are needed for RISP to achieve the design goals and required performance to compete with similar facilities in other countries**