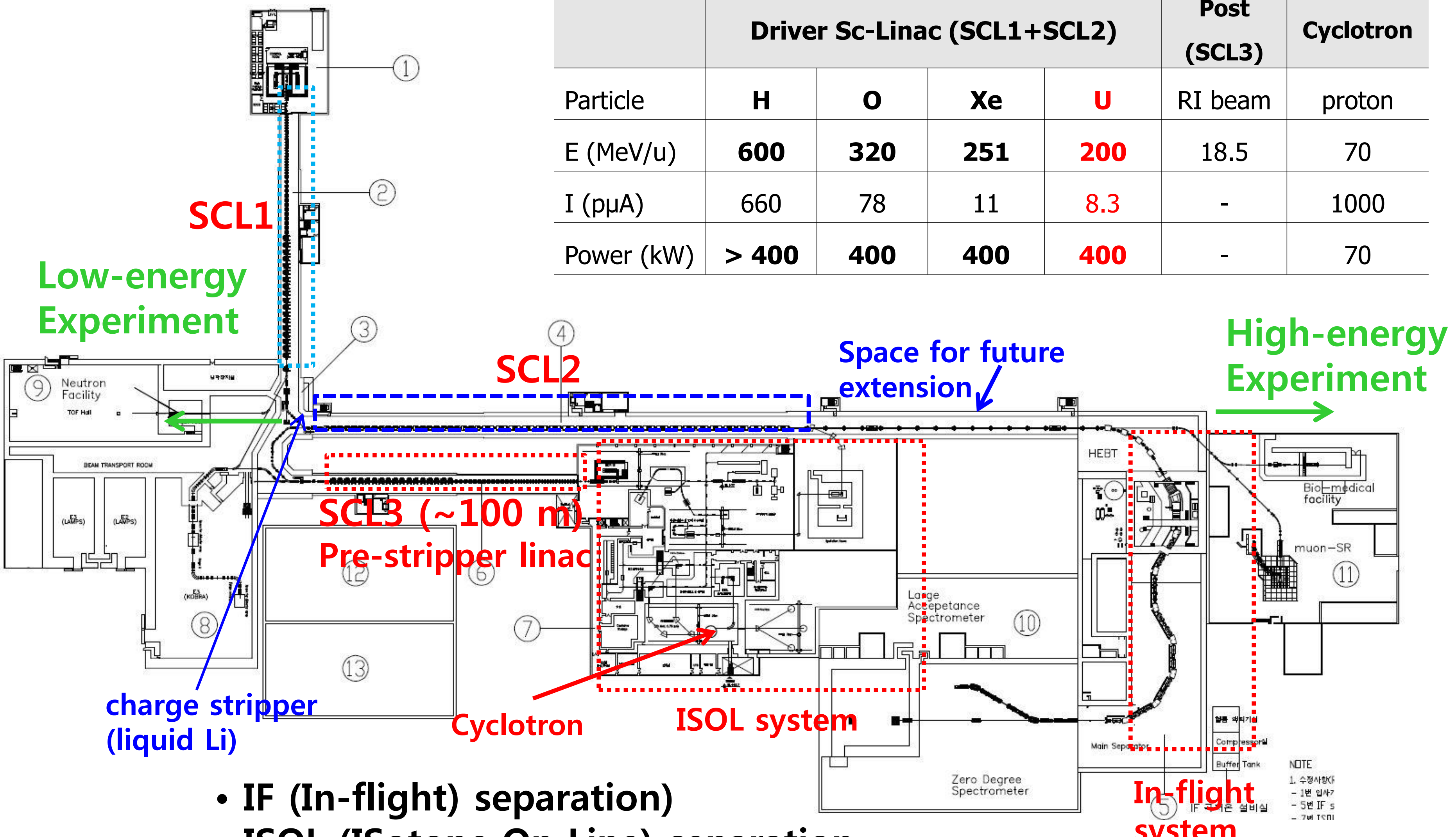
Rare isotope beam production systems for RISP

Jong-Won Kim

Rare Isotope Science Project
Institute for Basic Science
Pioneering Session of KPS, Oct. 24, 2015

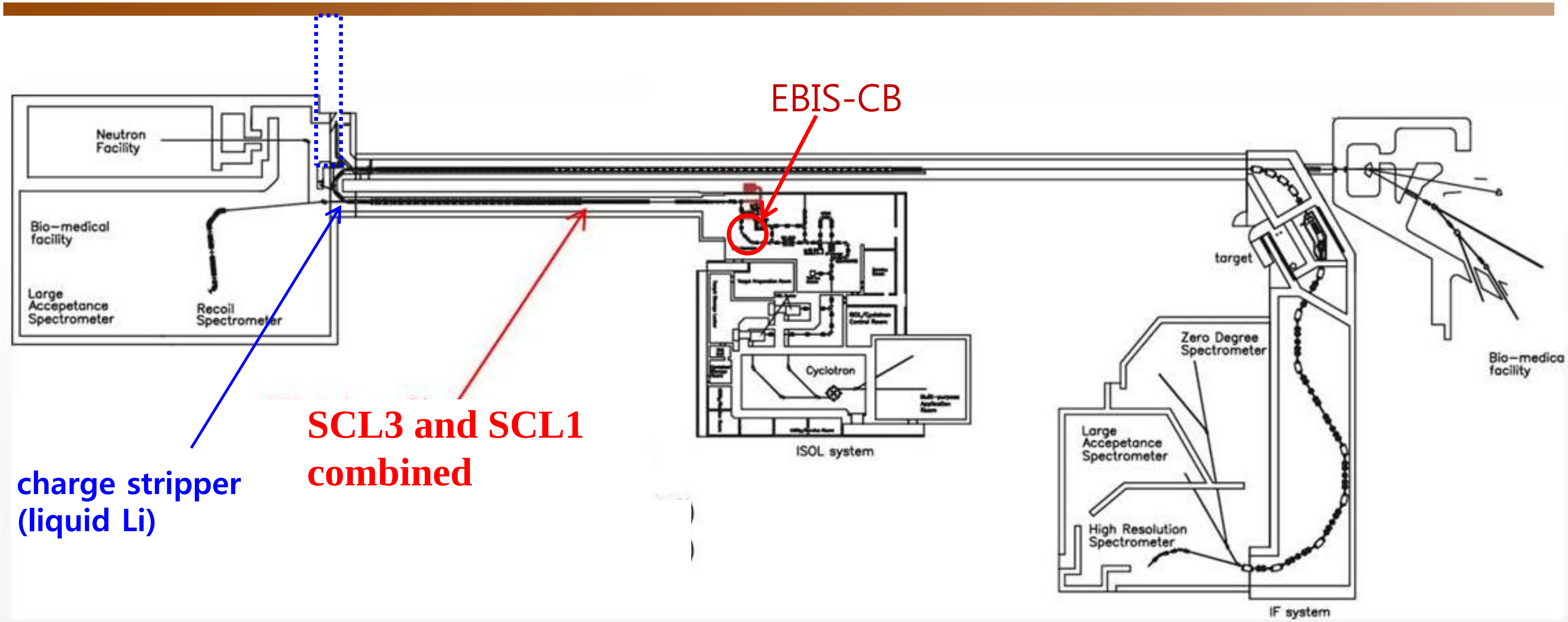
Layout of accelerators and RI beam production systems

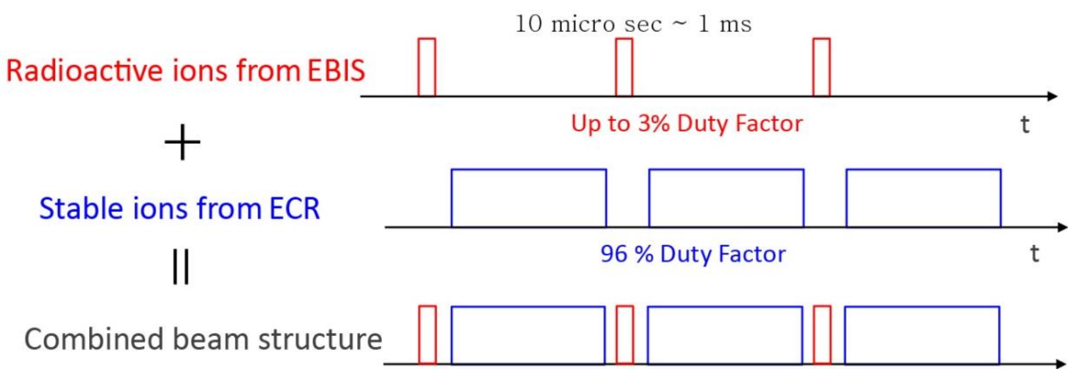
	Driver Sc-Linac (SCL1+SCL2)				Post (SCL3)	Cyclotron
Particle	**H**	**O**	**Xe**	**U**	RI beam	proton
E (MeV/u)	**600**	**320**	**251**	**200**	18.5	70
I (pμA)	660	78	11	8.3	-	1000
Power (kW)	**> 400**	**400**	**400**	**400**	-	70



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

A facility layout with a new concept





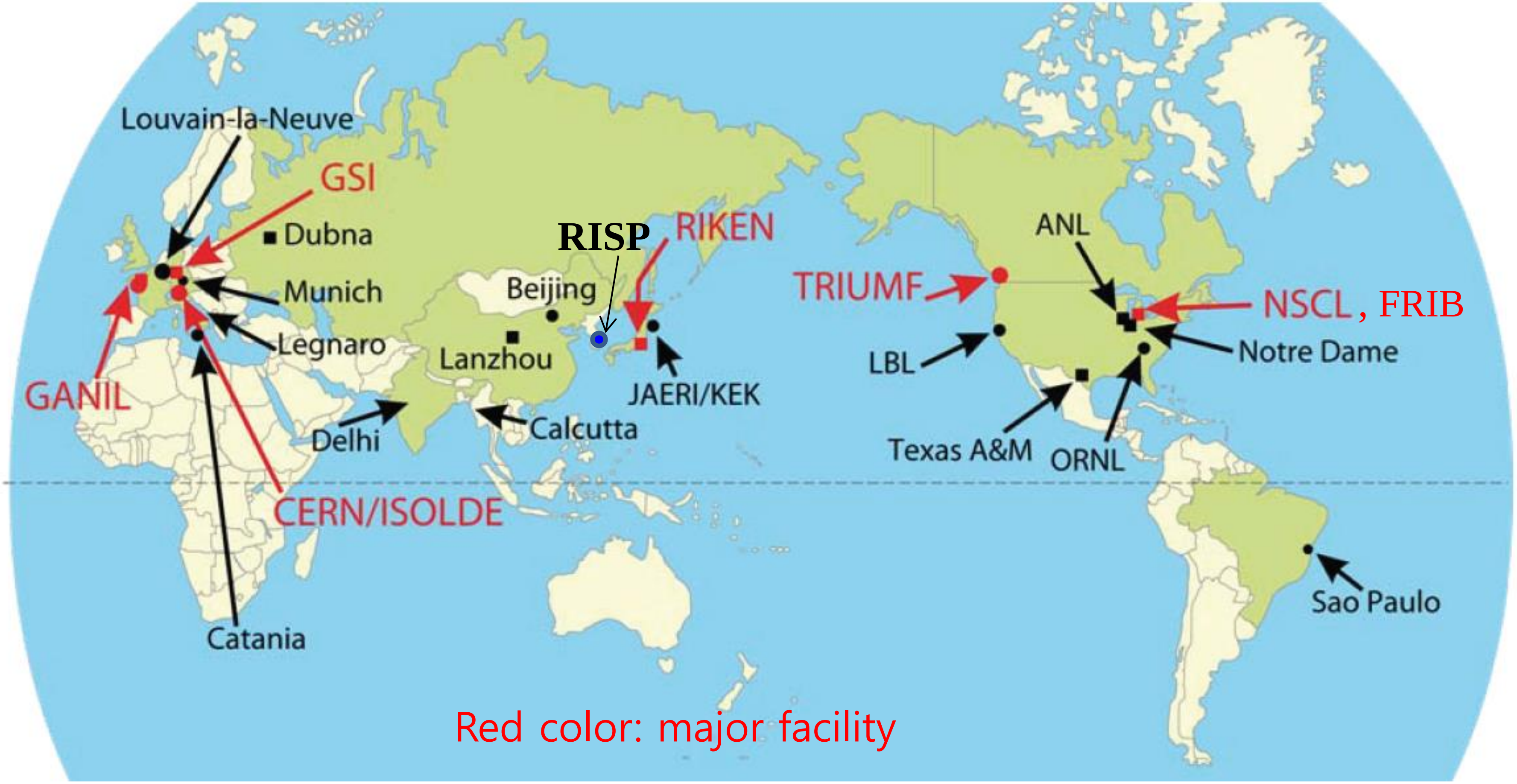
Simultaneous acceleration of stable and RI beams with similar q/A

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

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

Discussion with P. Ostroumov in Nov. 2014, during ICABU workshop, Daejeon

Rare isotope beam facilities worldwide



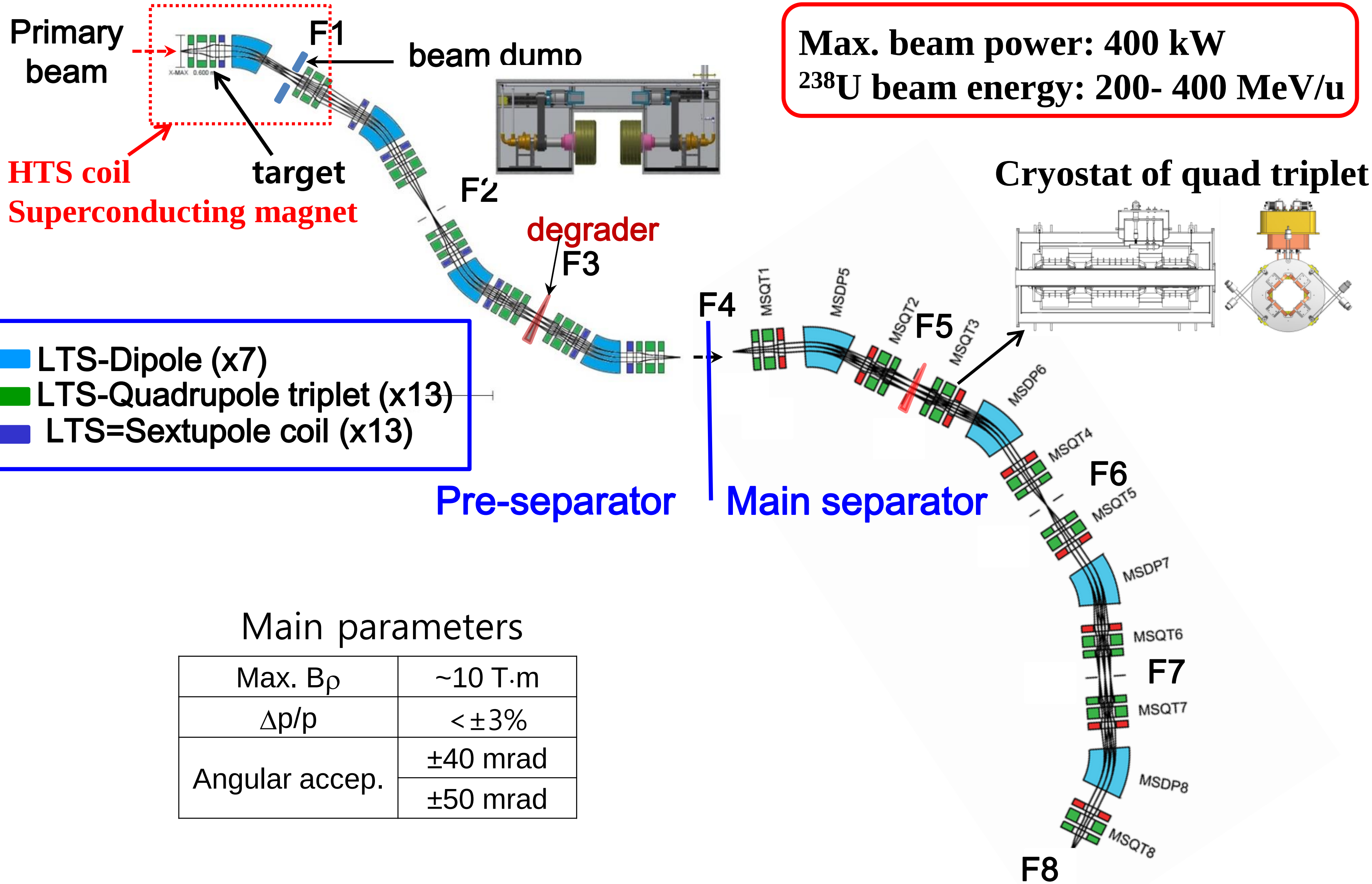
High power facilities
(> 50 kW)

Canada **TRIUMF ISAC**, **ARIEL(e linac)** **(ISOL)**
Japan **RIKEN RIBF (IF)**
France **GANIL SPIRAL2 (ISOL)**, Belgium **MYRRHA (ISOL)**
Germany **GSI FAIR (IF)**
USA **MSU FRIB (IF)**

Blue: under construction

Configuration and specification of the IF separator

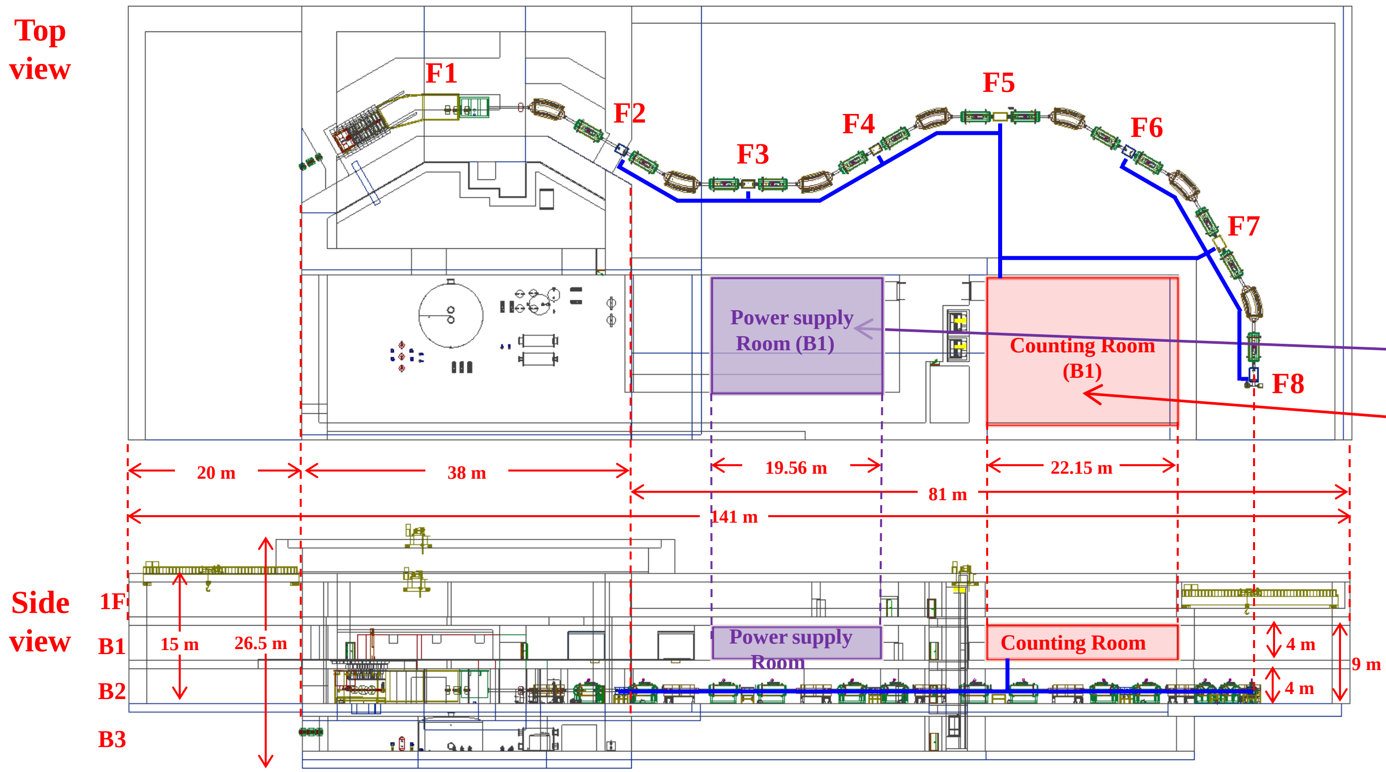
Max. beam power: 400 kW
^{238}U beam energy: 200- 400 MeV/u

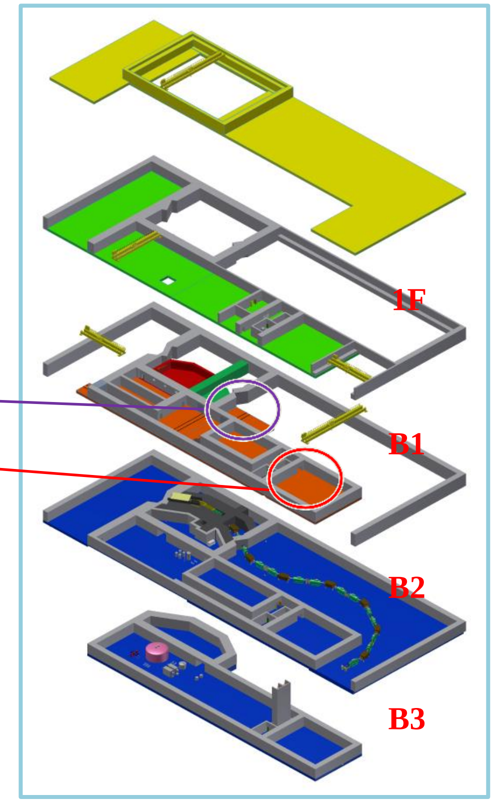


Main parameters

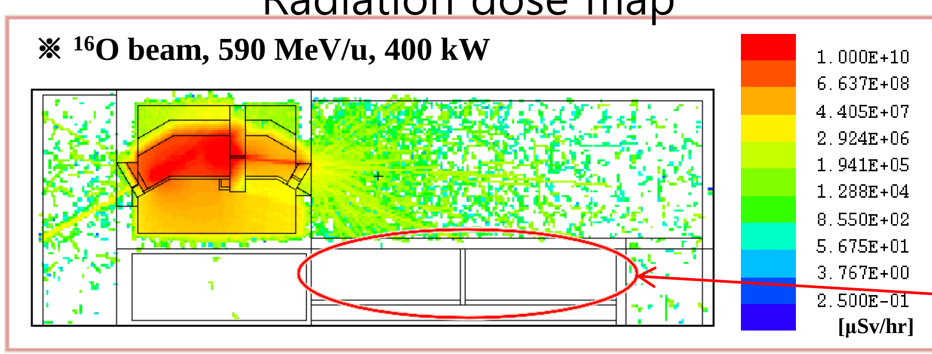
Max. Bρ	~10 T·m
Δp/p	< ±3%
Angular accep.	±40 mrad
	±50 mrad

Design of IF separator building





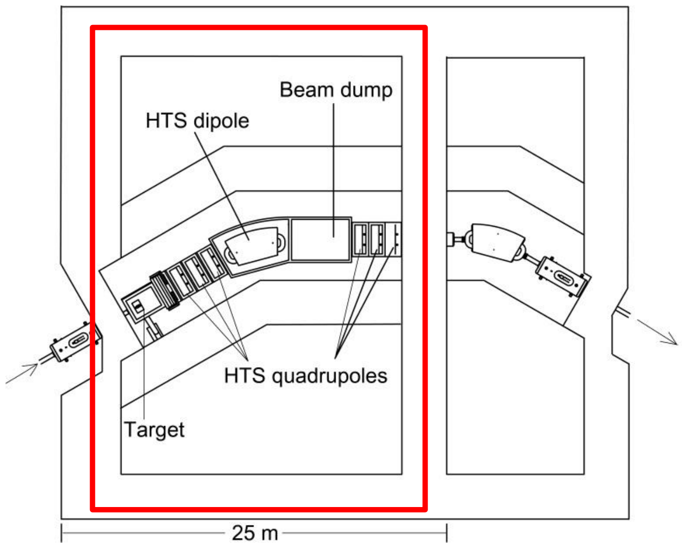
Radiation dose map



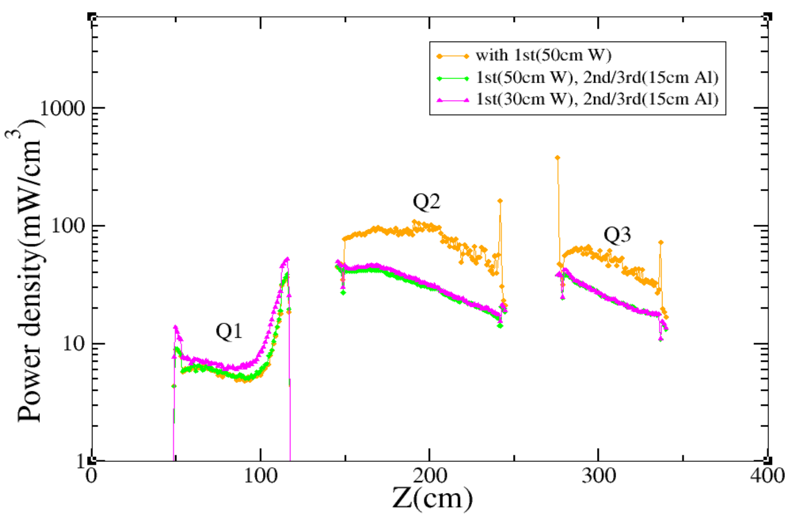
Power supply room and Counting room

Radiation transport and heating in the target area

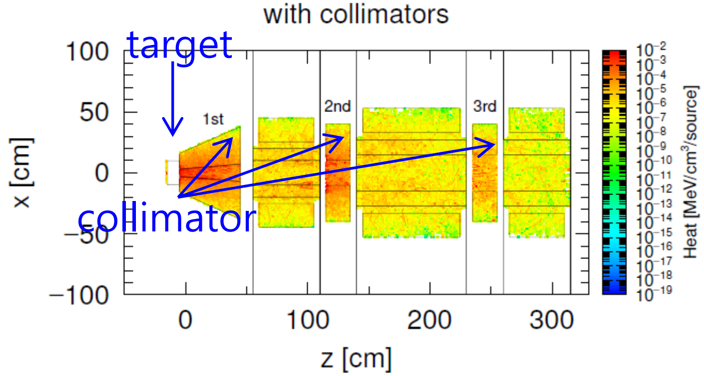
High radiation area (pre-separator)



Heat deposit along the HTS coils



Heat deposits downstream of target
Calculated using PHITS



Radiation heat deposit on HTS coils
(HTS: High temperature superconductor)

HTS coils	Max. power density [mW/cm³]		Dose desposit [MGy/yr]		Total heat depsoit [W]	
	^{40}Ar	^{238}U	^{40}Ar	^{238}U	^{40}Ar	^{238}U
Q1	13.1	4.0	30.2	9.3	32.5	9.6
Q2	6.1	1.8	14.1	4.2	23.4	7.0
Q3	4.4	2.1	10.0	4.8	9.4	2.8
Dipole	14.8	1.1	34.3	2.6	392	72.6
Q4	14.8	5.1	34.3	11.9	61.7	12.8
Q5	13.1	6.9	30.2	14.7	35.1	7.2
Q6	14.8	8.7	34.3	20.2	95.8	9.8

Major component development

1. High-power graphite target (~100 kW)

- high-power e-beam test for multi-slice target planed
- design of multi-layer target (ANSYS, Comsol.)

2. Beam dump (~350 kW)

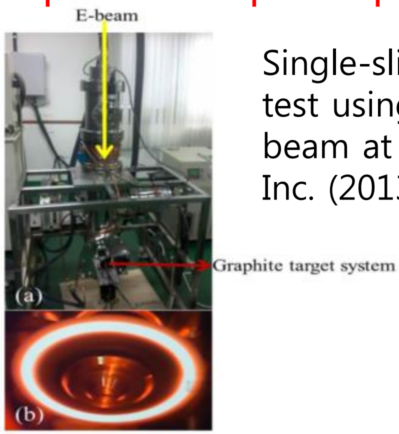
- thermo-mechanical analysis and mechanical design
- considerations on remote handling

3. Superconducting magnets with large aperture

- superferric quadrupole triplet and cryostat
- superferric dipole magnet design
- HTC coil quadrupole and dipole

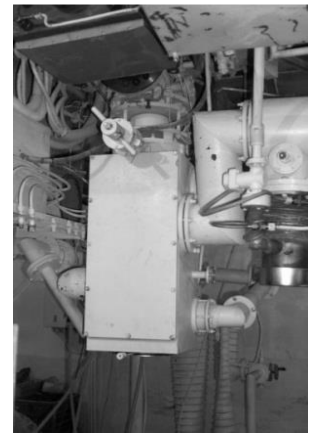
High-power graphite target development

Max. power deposit per slice: ~10 kW



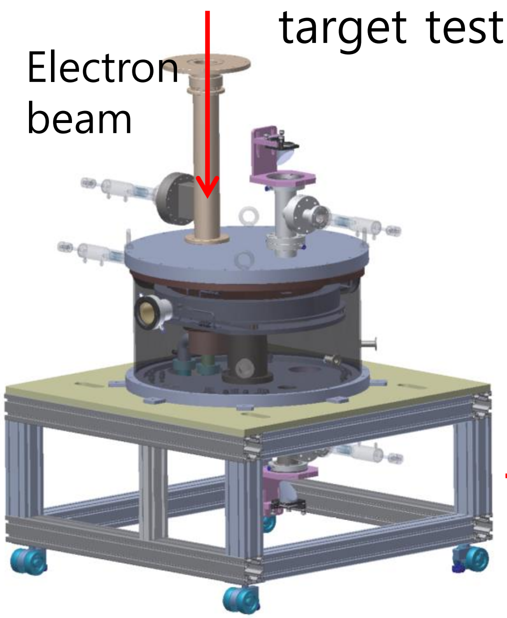
Single-slice target test using 50 kV e-beam at EB-Tech Inc. (2013)

Plan to use 100 kW ~1 MeV e-beam at Budker Institute of Nuclear Science (2016)

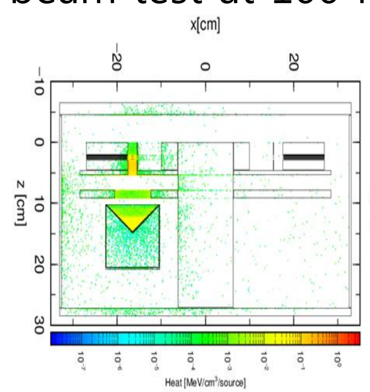


ELV series
1-1.4 MeV
100 kW
Min. beam dia.: 1 mm

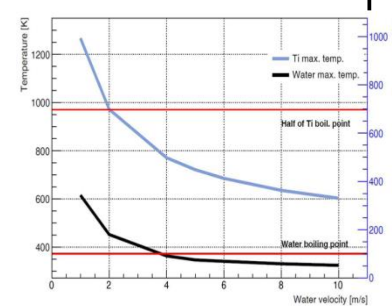
Vacuum chamber for multi-slice graphite target test (2015)



Beam dump design for e-beam test at 100 KW

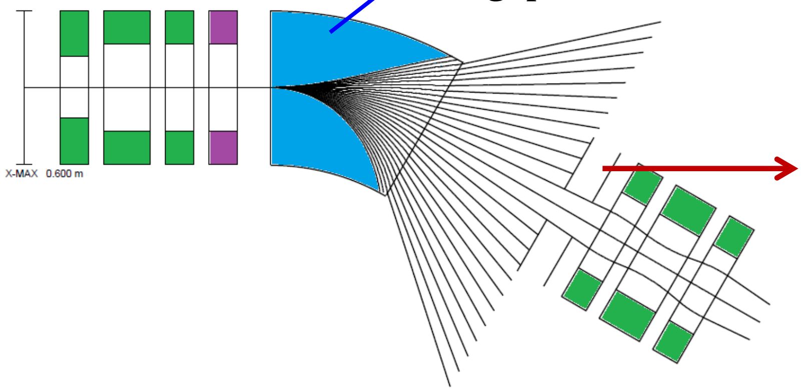


Temp. vs. water flow rate at e-beam dump



ΔT of water: < 10^0C
T_{max} on Ti-alloy: < 400^0C
Water flow: > 4m/s

Beam dump (350 kW) design

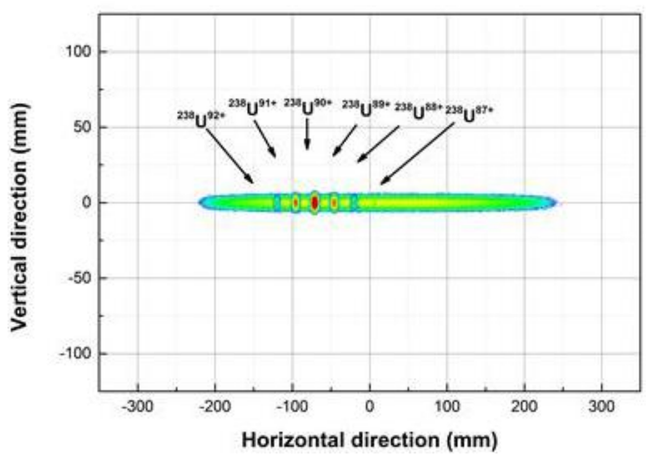


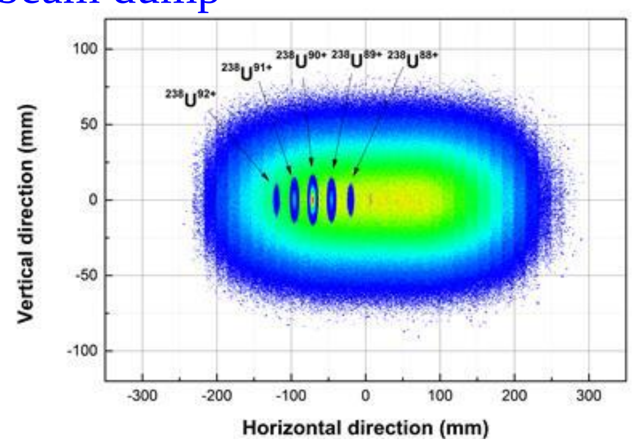
Dipole aperture
width: 60 cm
gap size: 15 cm

Beam dump
Horizontal coverage: ±82.8 cm
$\Delta p/p = \pm 36\%$,

Trajectories of primary beam with differing δp in steps of 3%

Defocus the beam on beam dump



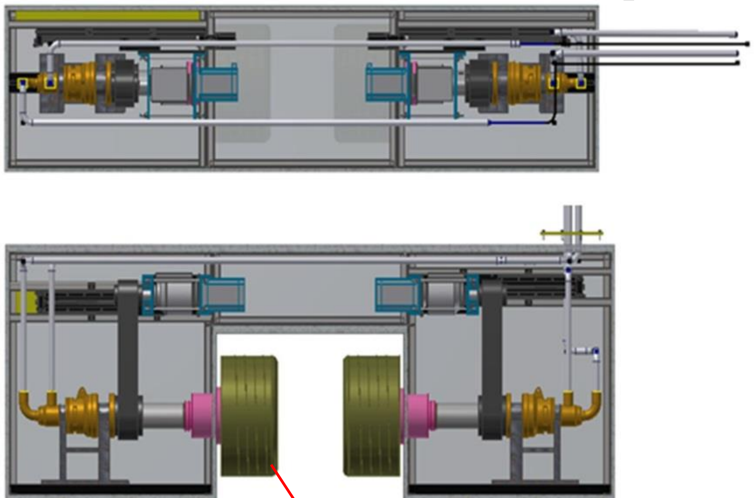


Beam power density at F1 of $^{238}U^{90+}$:
105.5 kW/cm^2 → 50.06 kW/cm^2

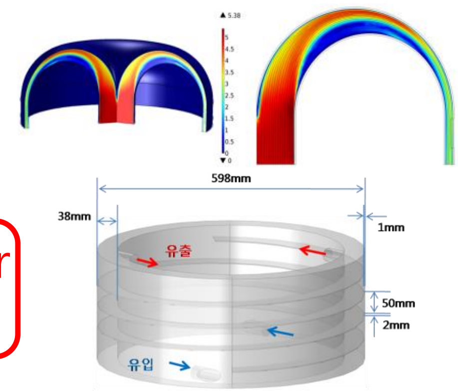
Beam dump development for high-power HI beam

Max. power deposit on beam dump: 350 kW

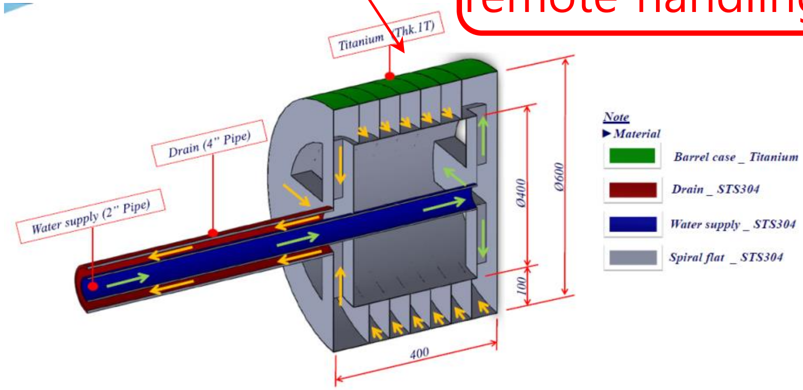
Sectional view of the beam dump



Max. beam power: 400 kW
Max. power density: ~ 100MW/m²
Radiation damage
long-lived life time >1 year or greater
5DPA/year
Barrel rotation speed < 400 rpm
Horizontal displacement : ± 20 cm
Water flow rate < 10 m/s



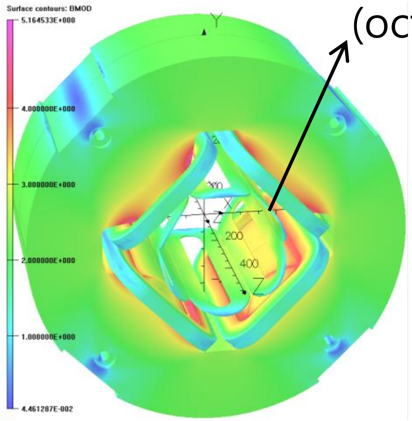
Design consideration underway for remote handling maintenance



Thermo-fluid-mechanical design using COMSOL multi-physics ('14~'15) → will continue

Beam dump barrel
Outer diameter: 600 mm
Length : 400 mm, 280 mm
Weight (water filled): 73 kg, 52kg

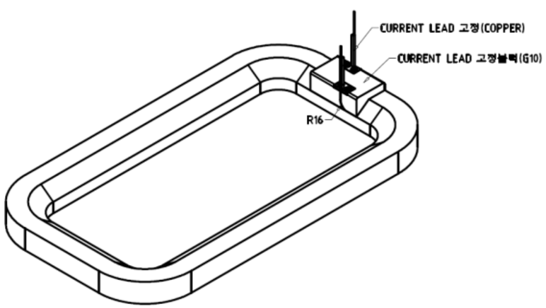
Design of superferric quadrupole magnet

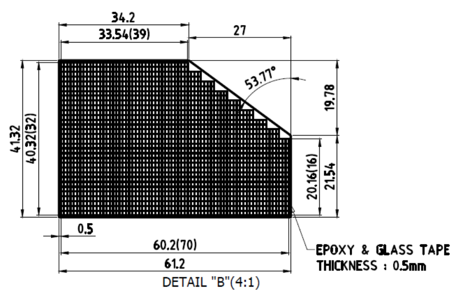


Hexapole coils for non-linear field effect correction (octupole coils not shown)

Main parameters of Q1&Q2

Item	Value
Max. B gradient	15 T/m
Bmax on coil	4.1 T
Jmax	158 A/cm^2
Total Amp. Turn	~300 kA
Pole tip radius	18 cm
Eff. Length Q1, Q2	55 cm, 90 cm
Yoke length Q1, Q2	45 cm, 80 cm
Yoke outer diameter	100 cm





Optimization using OPERA3D

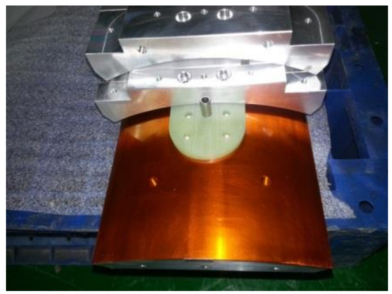
Parameters of hexapole coil

Inner radius (R1)	160 mm
Coil length	642.6 mm
Straight section (2*H1)	450 mm
Alpha (α), Beta (β)	70°, 90°

Construction of a prototype quadrupole magnet

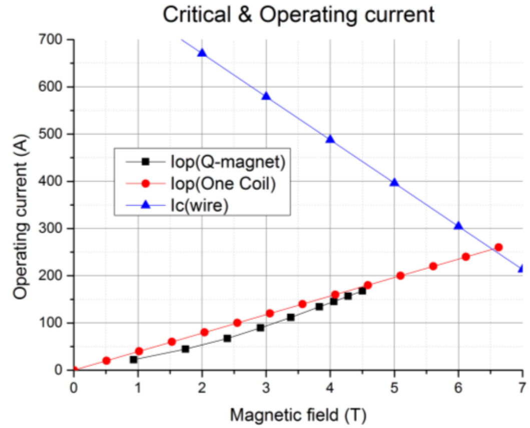
- Racetrack type
- epoxy molding on coil surface

Qudrupole coils



Hexapole coil

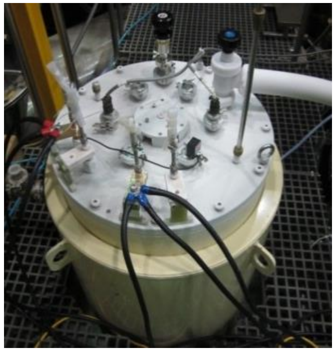
Quench currents of quadrupole coils



I_{op}: 162 A (I_{op}/I_c = 36%, 15 T/m)

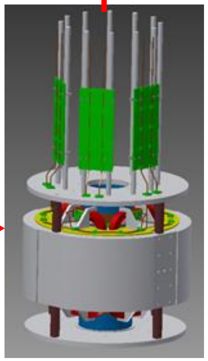
A large LHe dewar for quadrupole magnet test

Tests in LHe dewar and dewar with cryocoolers



A dewar with cryocoolers (1.5Wx2 at 4K)

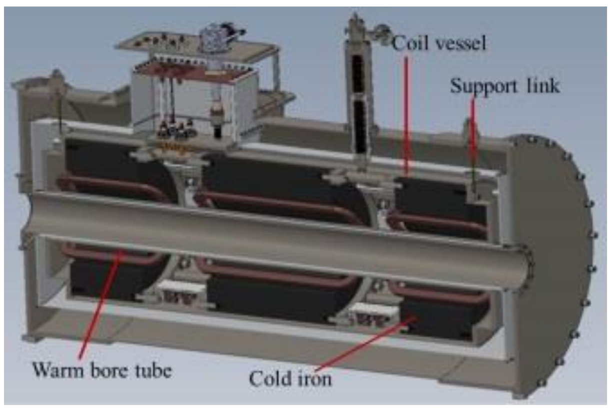
Iron yokes

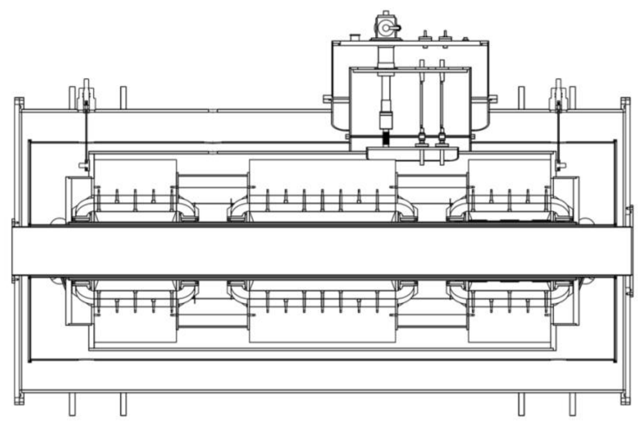


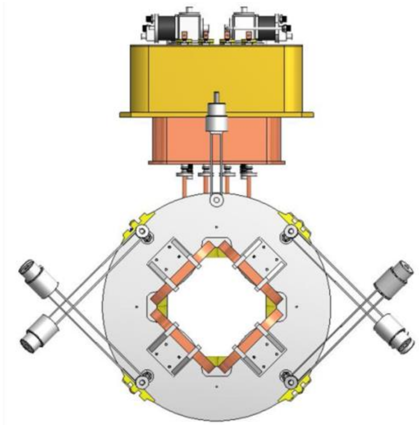
Quad singlet with multipole coils

Development of quadrupole triplet cryostat

Cryostat for quadrupole triplet with multipole coils





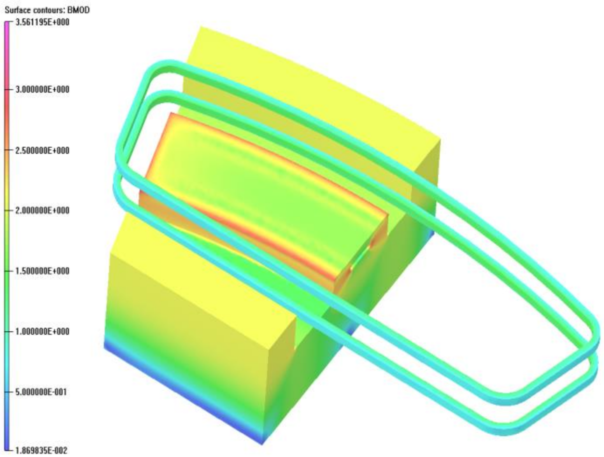


- Cryostat design: Korea Basic Science Institute
- Mechanical design: SFA Inc. → **To be constructed in 2016**

Design specifications

Coolant	Liquid He
Current leads	Vapor cooled type
Heat load (Shield)	~ 30 W (LN2)→ 40K He gas
Heat load at 4.5 K	~ 3.0 W

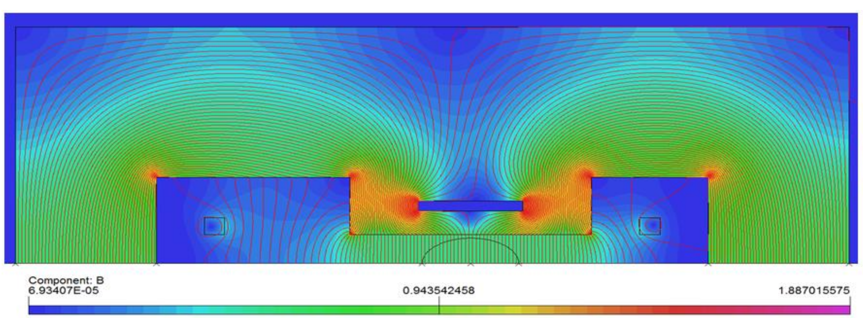
Design study of LTS dipole magnet

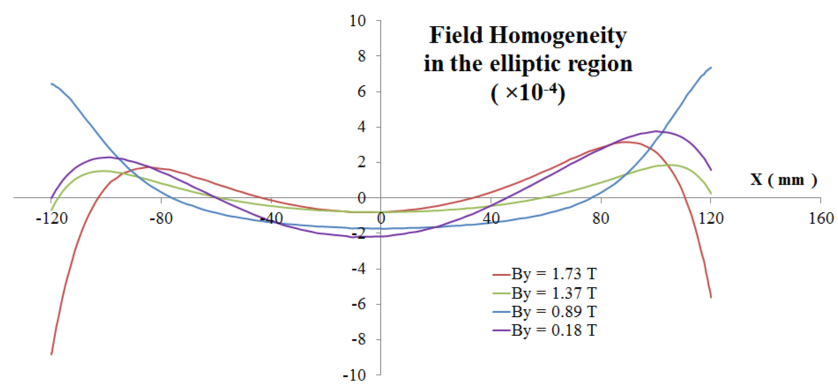


D-shaped LTS coils, Warm iron

Design parameters	
B_{max} , ρ	1.7 T, 6 m
Bending angle	30 degrees
Total Amp•turn	162 kA
B_{peak} on Coil	1.55 T
Stored energy	0.7 MJ
Yoke weight	60 tons
Gap height	17 cm
Gap width	68 cm

Magnetic flux density plot at B=0.89 T, J=15 A/mm^2



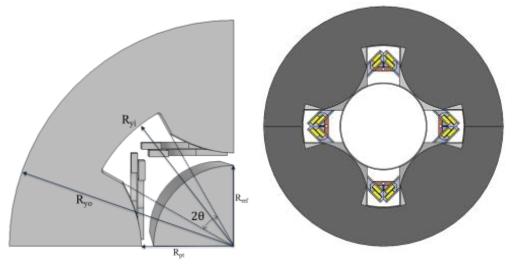


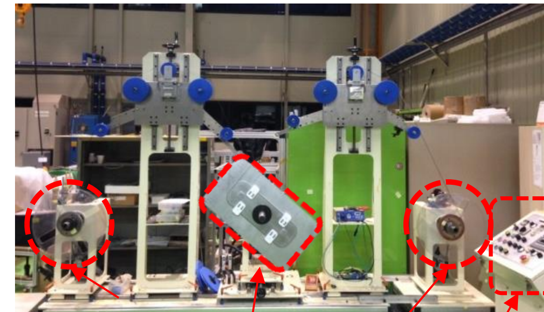
High-T_c superconductor (HTS) coil winding and test

Specification of prototype

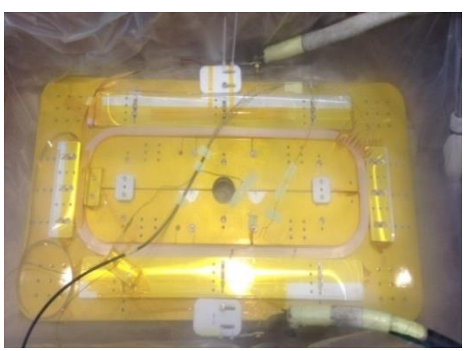
Aperture radius (mm)	120
Effective length (mm)	579
Yoke length (mm)	480
Field gradient (T/m)	15
Total current (kA)	121
Coil size (mm^2)	864 (36 mm x 12 mm x 2)
Current density (A/mm^2)	140
Turn number (N)	164 (per coil)
Operating current (A)	370
Critical current	640 A (SuperPower) 380 A(SuNam)
Inductance (H)	1.02
Stored magnetic energy (kJ)	69.8
Insulation / thickness (mm)	Stainless steel tape / 0.12

Working with Korea Electric Research Institute (KERI)

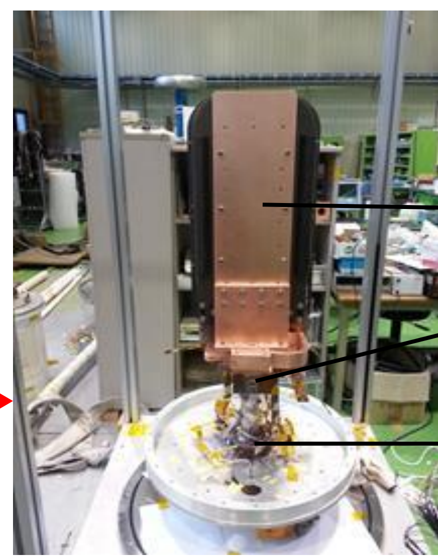




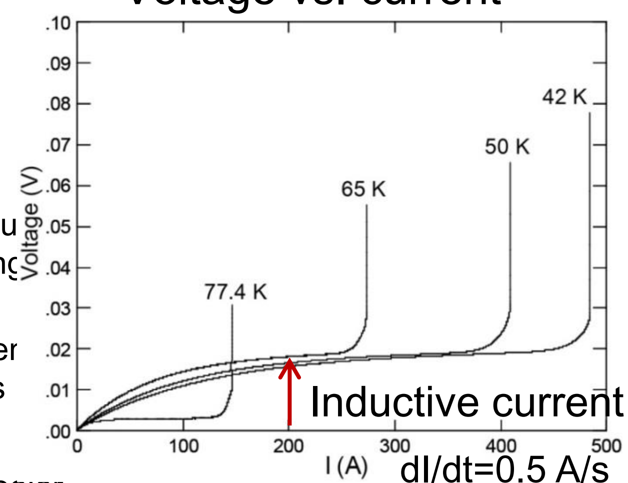
Test in LN$_2$



Test using cryocooler

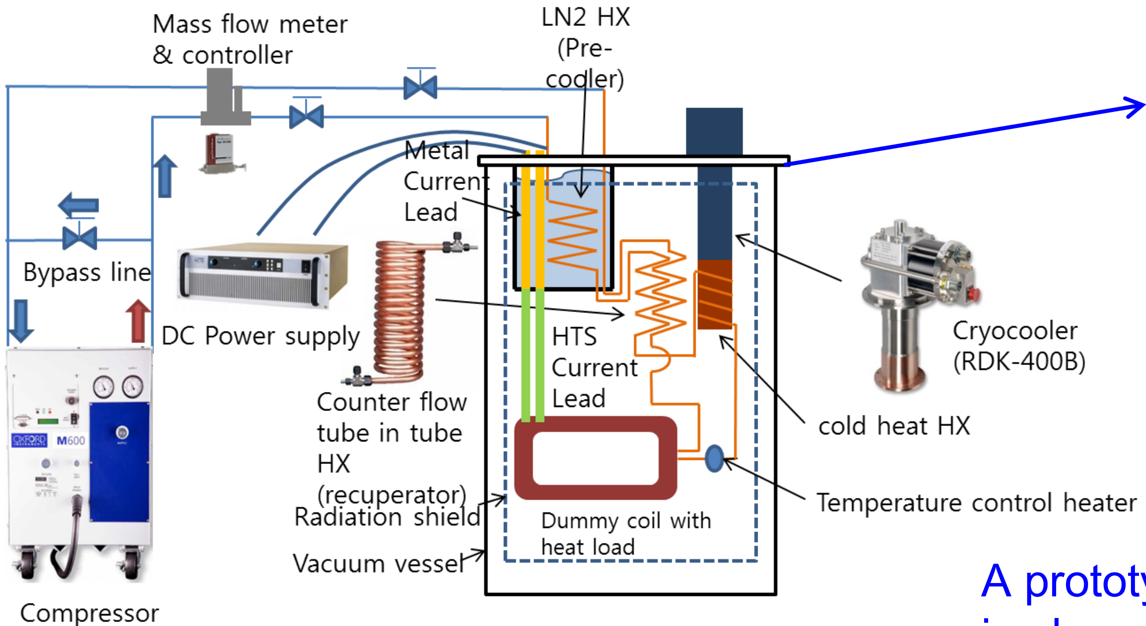


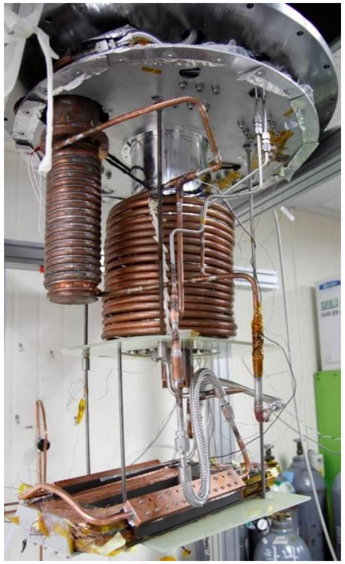
Voltage vs. current



Preparation of a prototype HTS-coil quadrupole

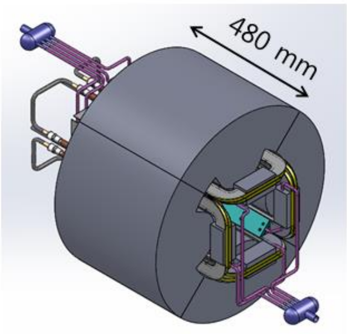
GHe cooling system at Changwon Univ.

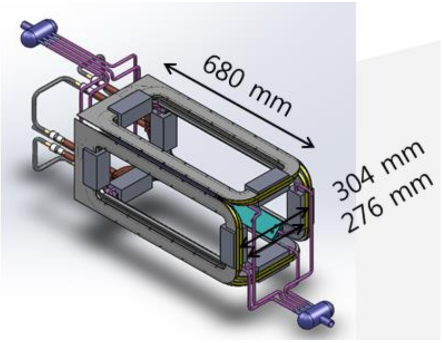


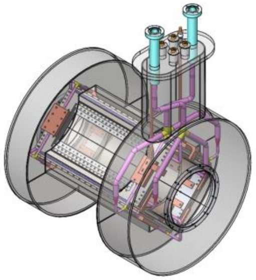


A prototype HTS quadrupole magnet is planned to be constructed and tested in 2016

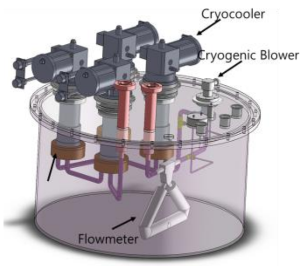
Cryostat for cold GHe cooling on HTS coil





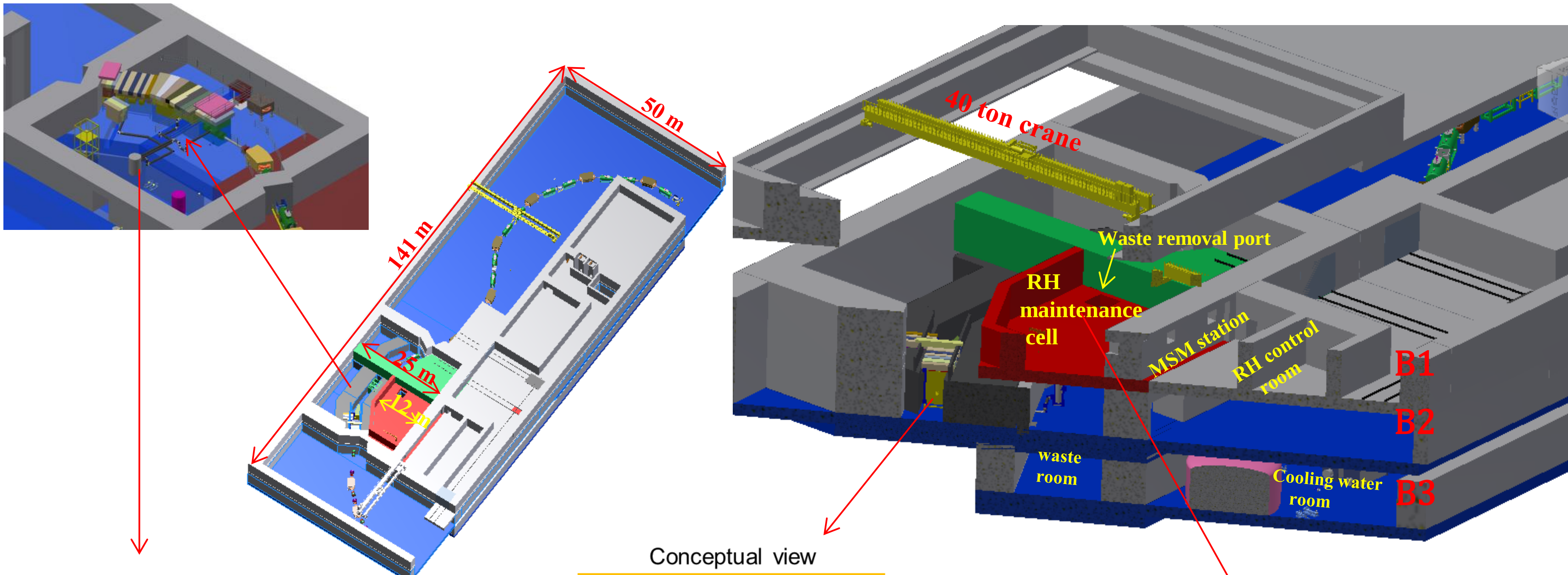


Cryostat (40 K) for quadrupole singlet

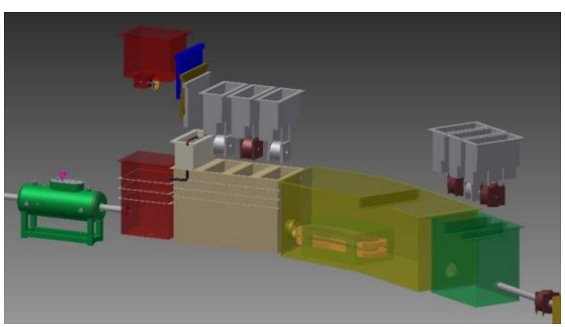


Cold He gas refrigerator system 40 K at 5 bar

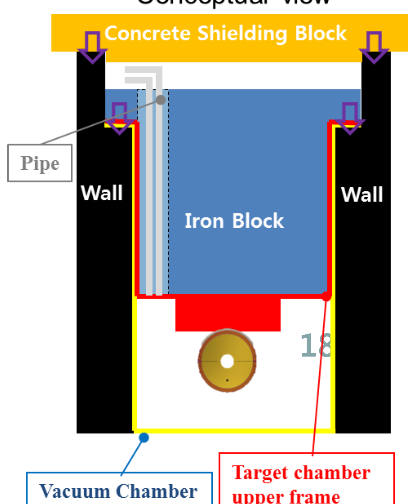
Building design for remote operation in target area



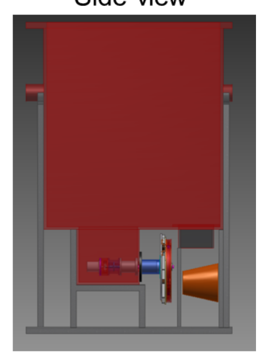
Vacuum chamber designed for RH

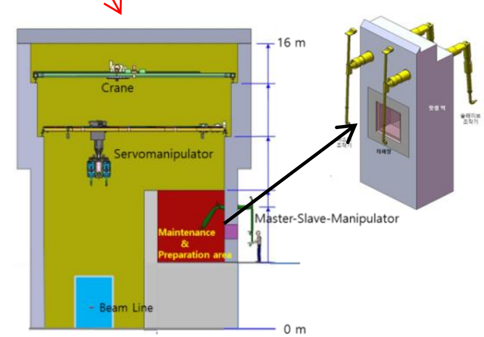


Conceptual view



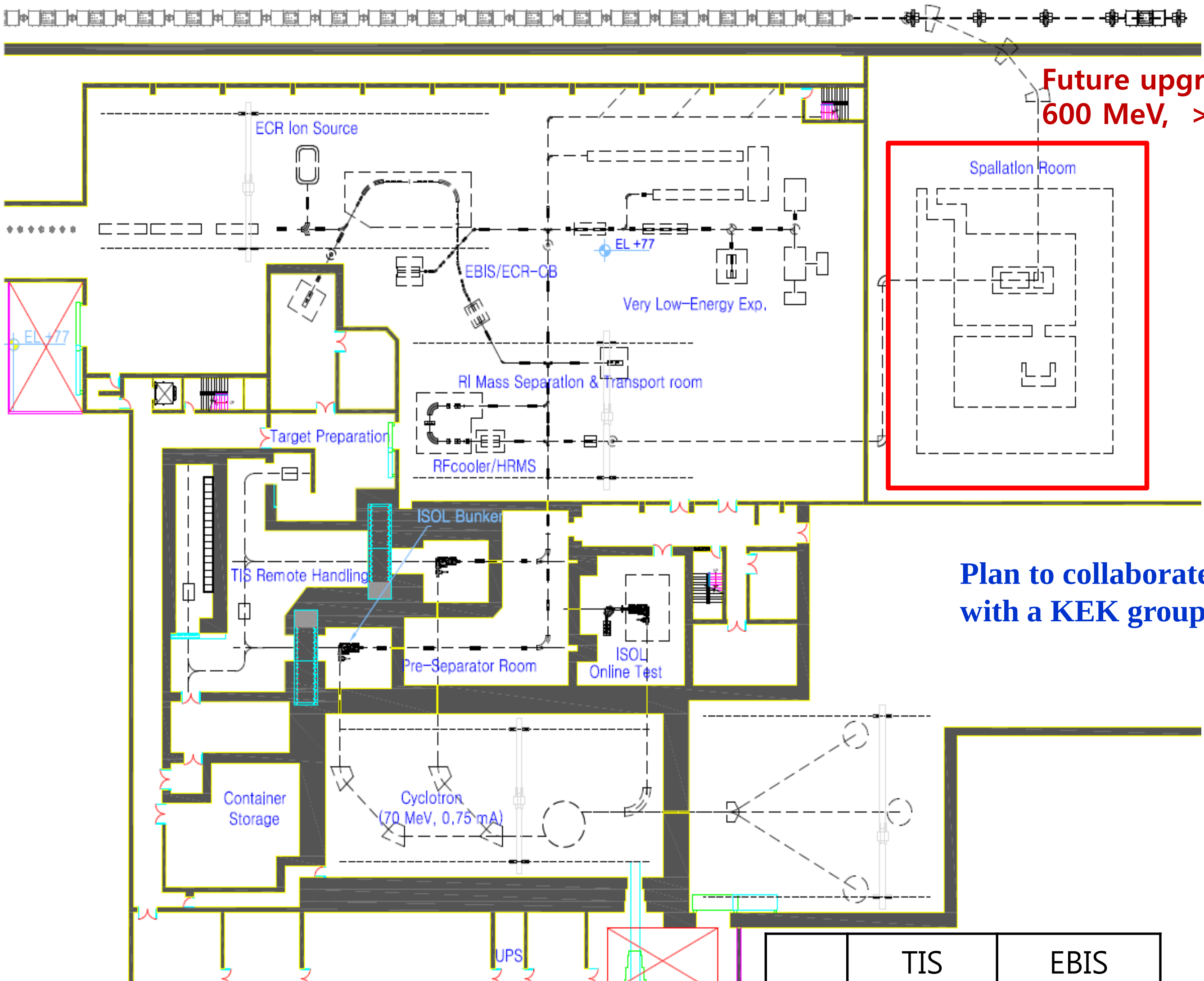
Side view

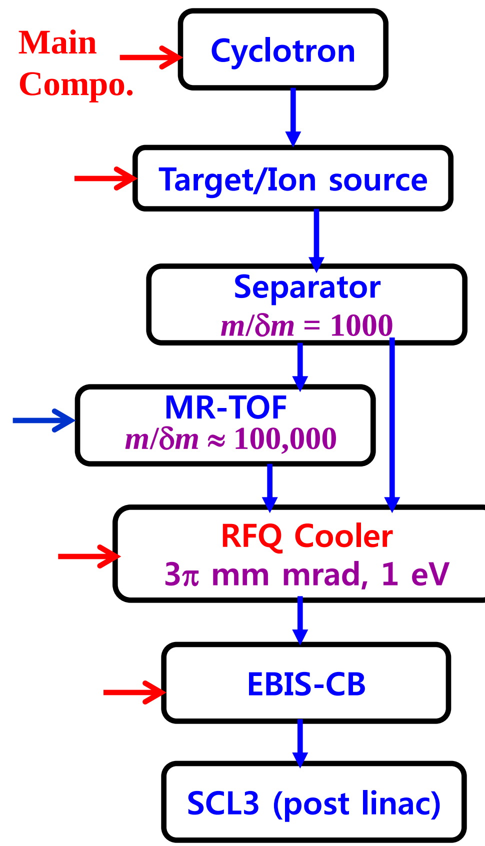




Working with a KAERI group

Layout of the ISOL system





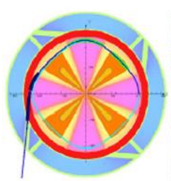
	TIS	EBIS
Ion	$^{132}Sn^{1+}$	$^{132}Sn^{33+}$
E	60 keV	5 keV/u

Consideration on a new cyclotron for ISOL driver

70 MeV, 1mA H- commercial cyclotron in Baseline Design

	BEST	IBA	Sumitomo*
Emax, Imax	35~70MeV 1mA*	30~70MeV 750uA	(Fixed) 70MeV 1mA
B (H/V)	1.6T, 0.12T	1.7T, 0.12T	1.7T, 0.5T
Operating Site	INFN(Legnaro) (2015)	ARRONAX, Zevacor, CDMN,..	N/A

1st Workshop on Compact Cyclotrons for High Power Ion Beams (CC2015)



Date: June 26 (Fri.) and 29 (Mon.), 2015
Place: RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198

The 1st workshop on Compact Cyclotrons for High Power Heavy Ion Beams will be held at the RIKEN Nishina center for accelerator-based science (RNC) on June 26 and 29, 2015. The workshop is co-hosted by RNC and the institute of basic science (IBS).
CC2015 is a by-invitation-only workshop for intensive discussions on feasibility study of compact cyclotrons for high power ion beams for applications ranging from RI beam production to neutrino science. CC2015 will cover the following topics:

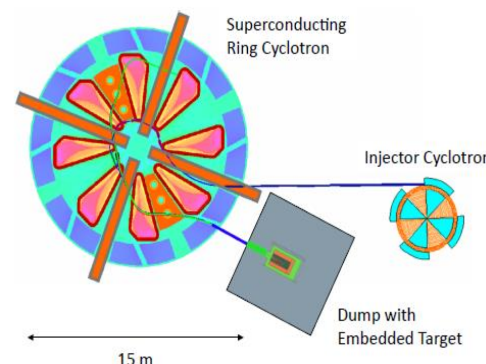
1: M/Q=2 60 MeV/u cyclotron for ISOL production
2: Compact cyclotrons for neutrino science
3: Pre-accelerator cyclotrons for high energy uranium ion beams

Organizing committee
Jong-Won Kim (IBS)
Luciano Calabretta (INFN)
Hiroki Okuno (RIKEN, Okuno@riken.jp)

RIKEN NISHINA CENTER ibs RISP

Supported by Sumitomo Heavy Industries, Ltd

Sterile Neutrino Search



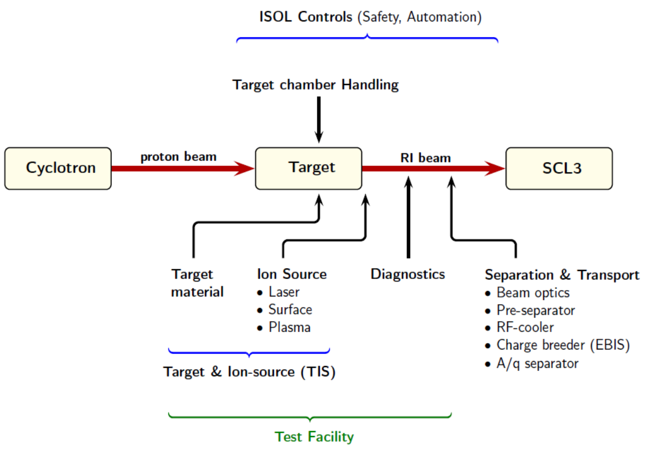
Neutron Production in Be target (7Li(n,ν)8Li)

60 MeV/u 5 mA H_2^+ Cyclotron

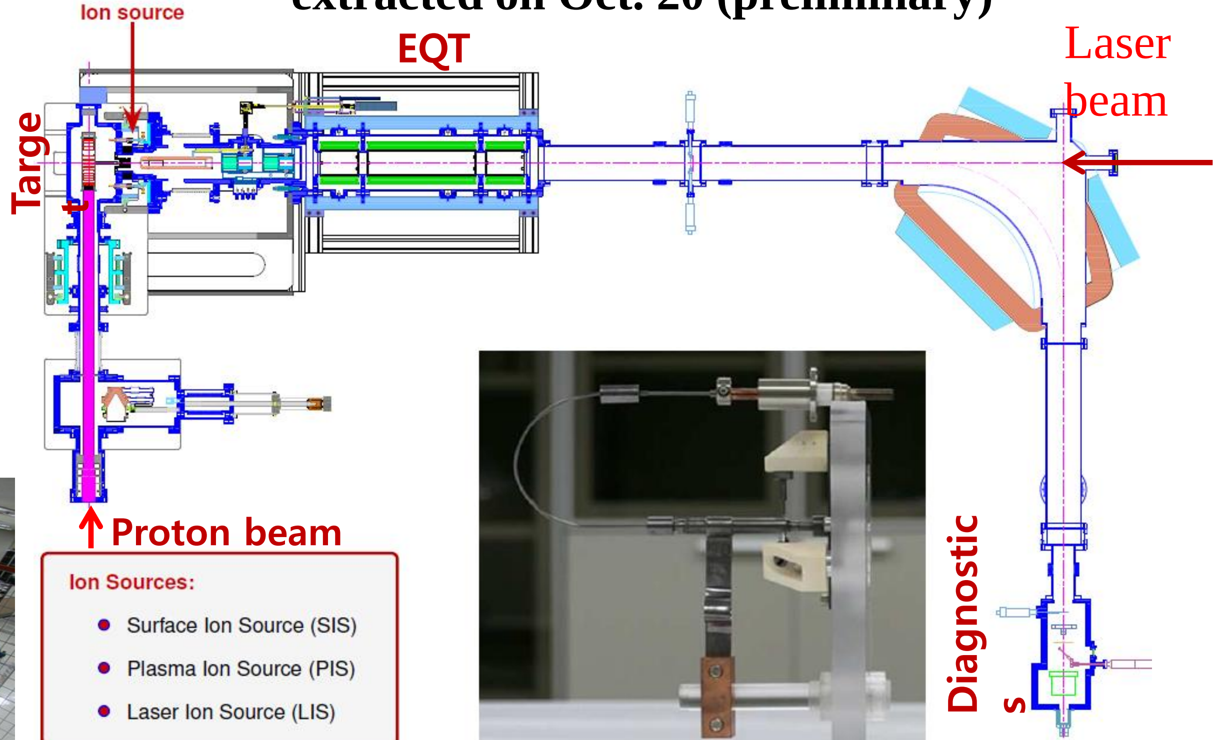
IsoDAR @ KamLAND

IsoDAR	**RISP (A/q=2)**	RISP (H^-)
H2+	**H2+, D+ ,..**	H-
60 MeV/u	**40 MeV/u**	35-70 MeV
5 mA	**1 mA**	1 mA
2.3 Tm	**1.9 Tm**	1.2 Tm
1.99 m	**1.64 m**	
1.16 T	**1.16 T**	
450 ton	**~300 ton**	~150 ton

Construction of ISOL test facility for TIS development



$^{120}Sn^{1+}$,~5nA ionized with Laser and extracted on Oct. 20 (preliminary)

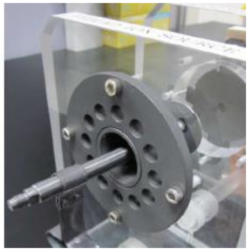


Ion Sources:

- Surface Ion Source (SIS)
- Plasma Ion Source (PIS)
- Laser Ion Source (LIS)

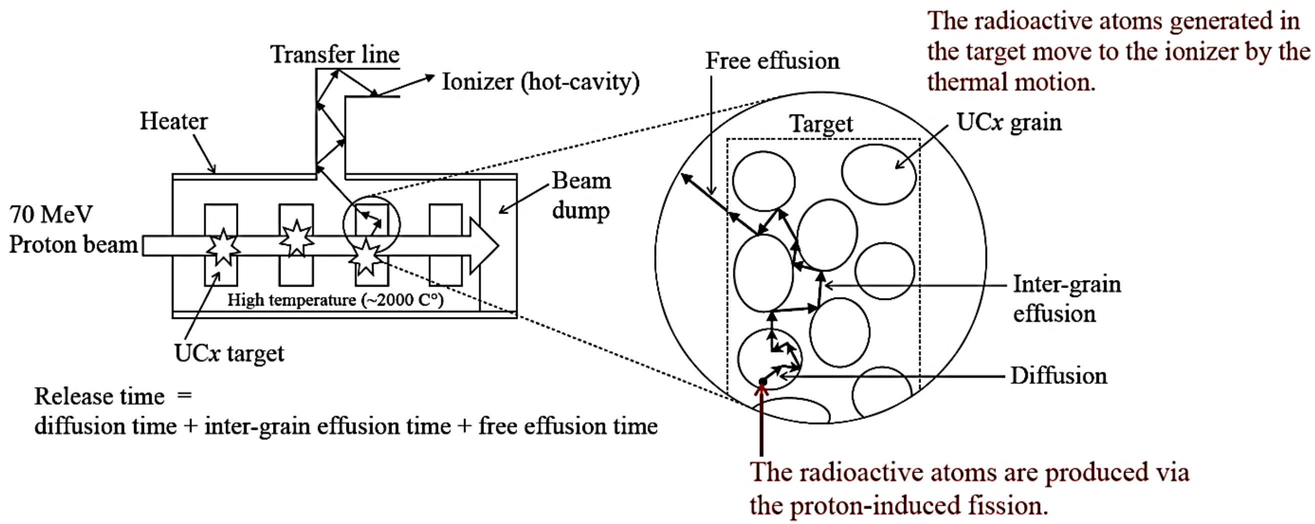
Surface Ion Source

Plasma Ion Source

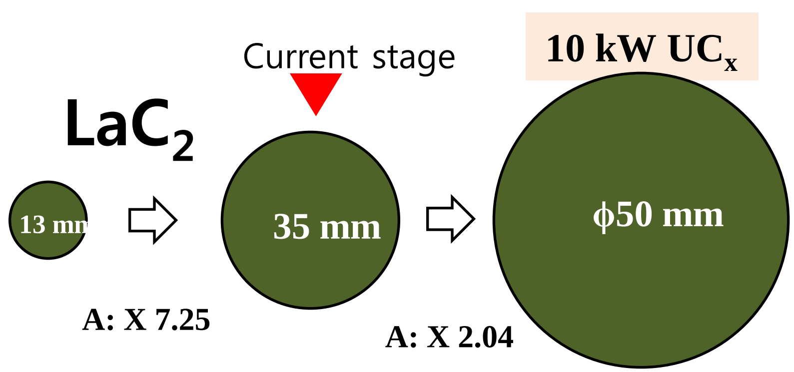


Laser Ion Source

UCx Target development

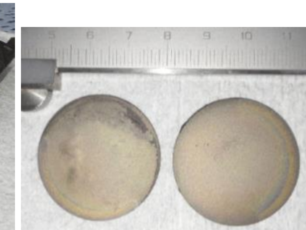


	LaC_2	UC_2
Density (g/cm^3)	5.20	11.28
Melting Temp. (˚C)	2360	2427
Structure	HT β: FCC LT α: Tetragonal	HT β: FCC LT α: Tetragonal



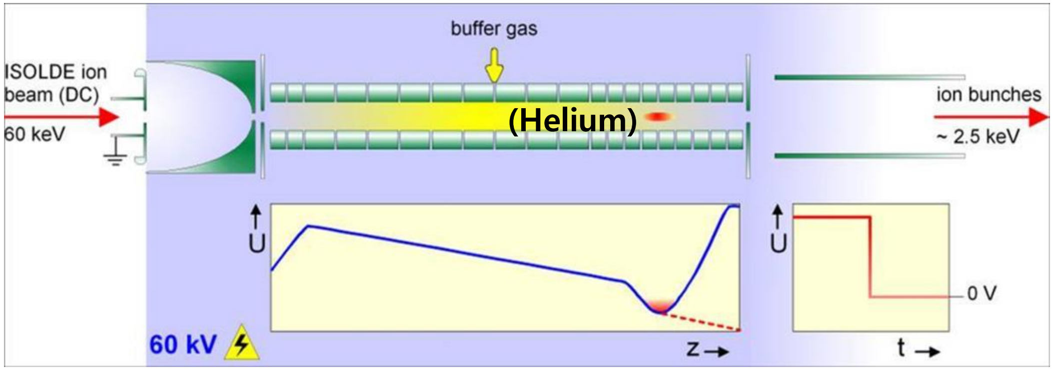
After annealing of 35 mmϕ LaC_2 disc

Density	1.97 g/cm^3
Porosity	56 %



RFQ cooler for beam cooling

Principle of RFQ cooler

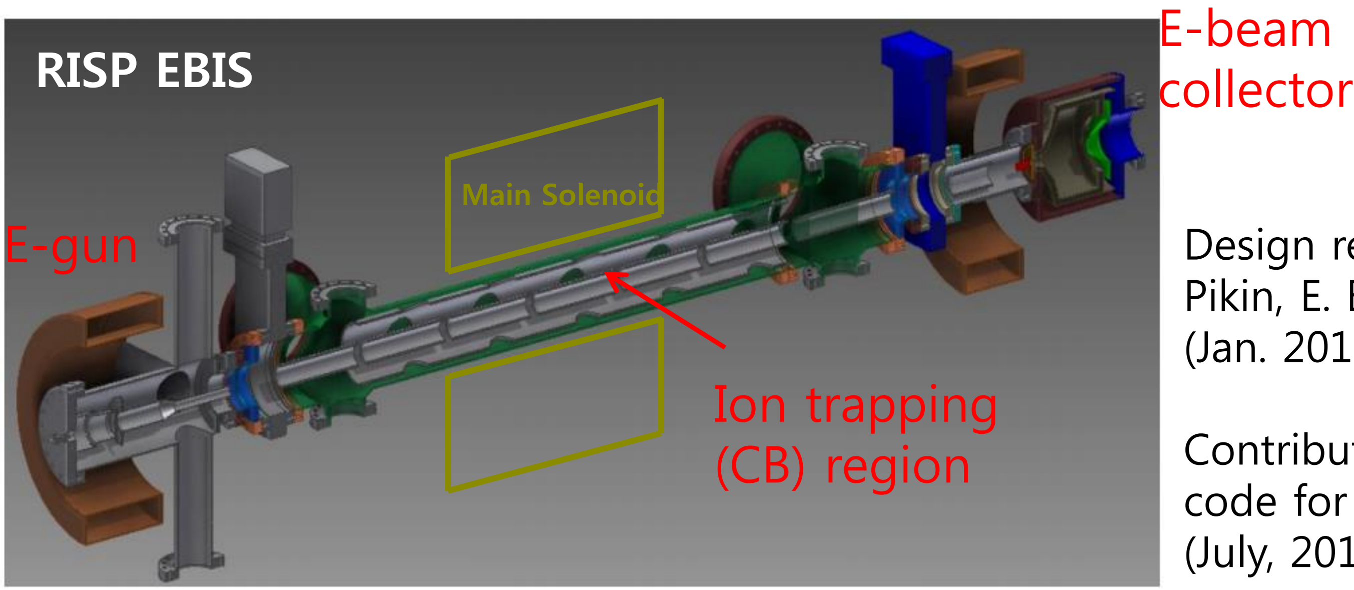


An RFQ cooler developed at LPC-CAEN for SPIRAL2, June, 2015

Specification of RF cooler

Parameter	Value
Beam energy	10-60 keV
Beam current	10^8 pps
Transverse emittance (injected beam)	30-40 π mm mrad
Emittance reduction factor	10
Energy spread	< 5 eV
Cooling time	1-10 ms
Transmission efficiency	> 80% CW beam, >50% bunched beam
Buffer gas	Helium
RF Voltage	500 Vpp (max)
RF frequency	1 MHz (max)

Design Parameters for EBIS



Design review at BNL: A. Pikin, E. Beebe, J. Alessi (Jan. 2015)

Contribution on control code for off-line test: ANL (July, 2015)

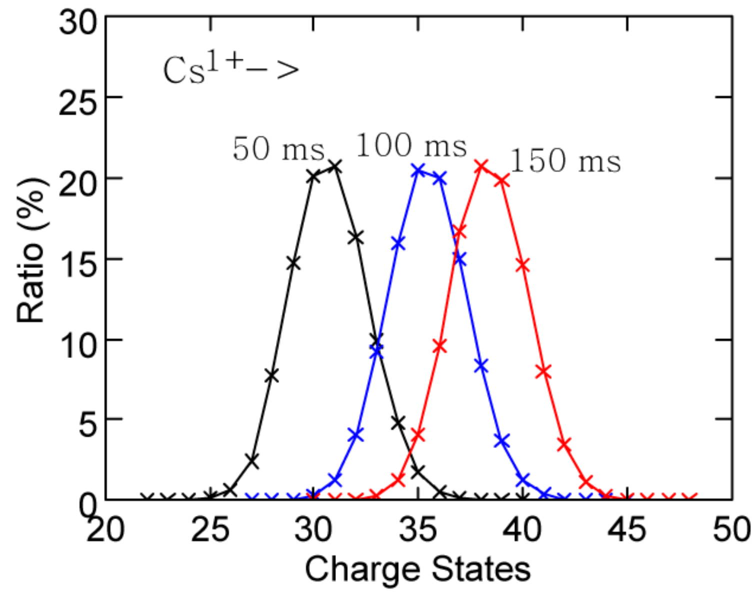
Design parameters @ RISP

Electron beam current	Electron beam current density	Electron beam energy	B-field in Trap region
0 ~ 3 A	500 A/cm^2	~ 20 keV	6 T
A/q	Ion beam intensity	Breeding time	Breeding efficiency
2 ~ 7	~ 10^8	50 ~ 100 ms	15 %
Repetition rate	Pulse width	Ion Trap Length	Electron Beam Dia.
> 10 Hz	10 ~ 20 μs	~ 0.7 m	0.9 mm

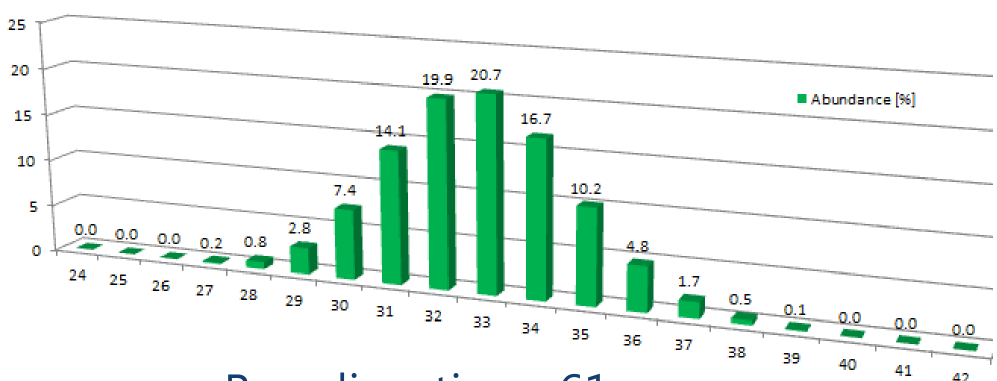
Calculation of charge breeding (CBSIM)

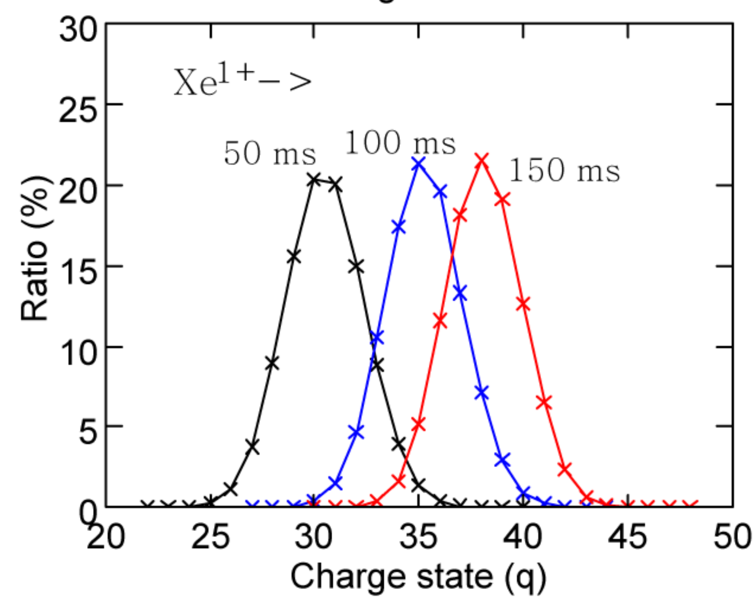
Electron Beam Energy : 20 KeV
E-Beam Current : 3 A
E-beam Current Density : 493.5 A/cm²

Isotopes of interest	Emittance	
	with rfq cooler	without rfq cooler
^{132}Sn, ^{142}Xe, ^{95}Sr, ^{15}O, ^{126}Al	3 π mm mrad	30 π mm mrad



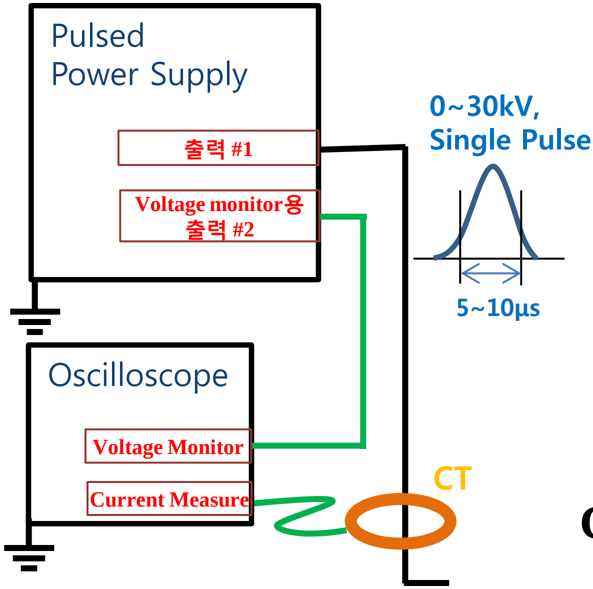
Sn1+ →





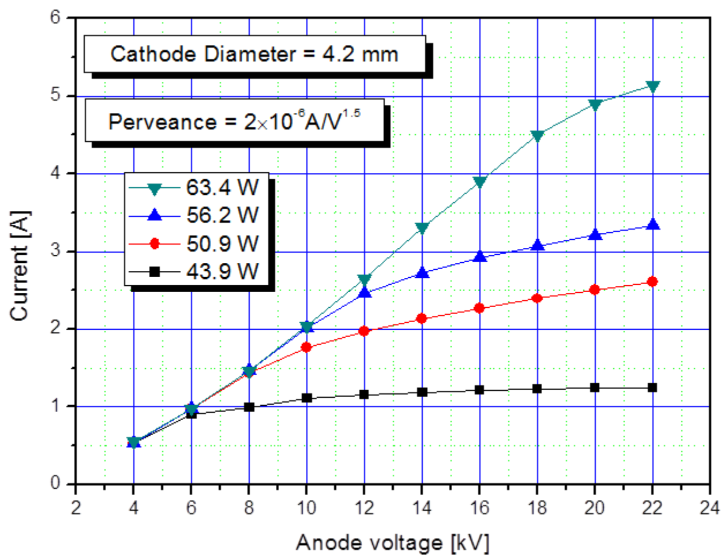
Breeding time: 61 ms

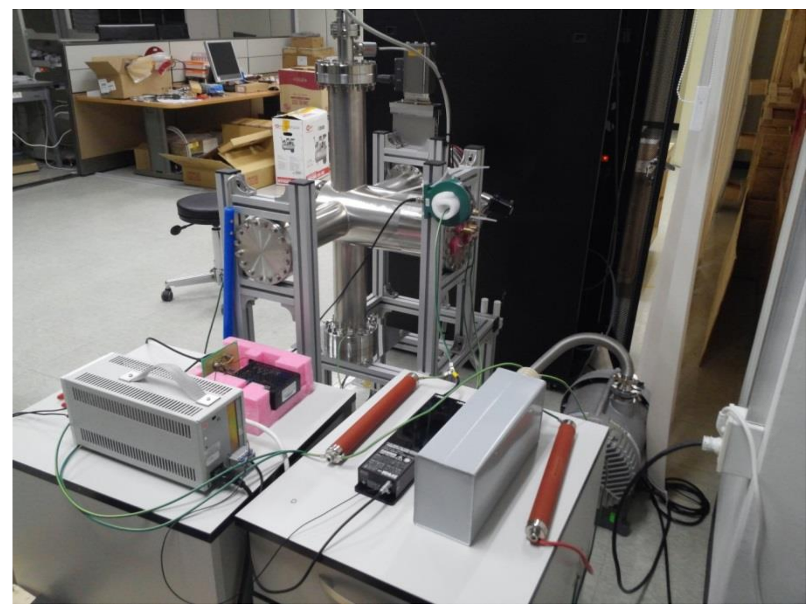
Electron gun test



E-Gun Cathod Diameter: 5.6 mm
Cathod Material: IrCe
E-Beam Current: 3 A
Current Density at Cathod: 12 A/cm^2
Magnetic Filed at Cathod surface : 0.2 T
Manufactured by BINP

Cathode with 4.2 mm dia.

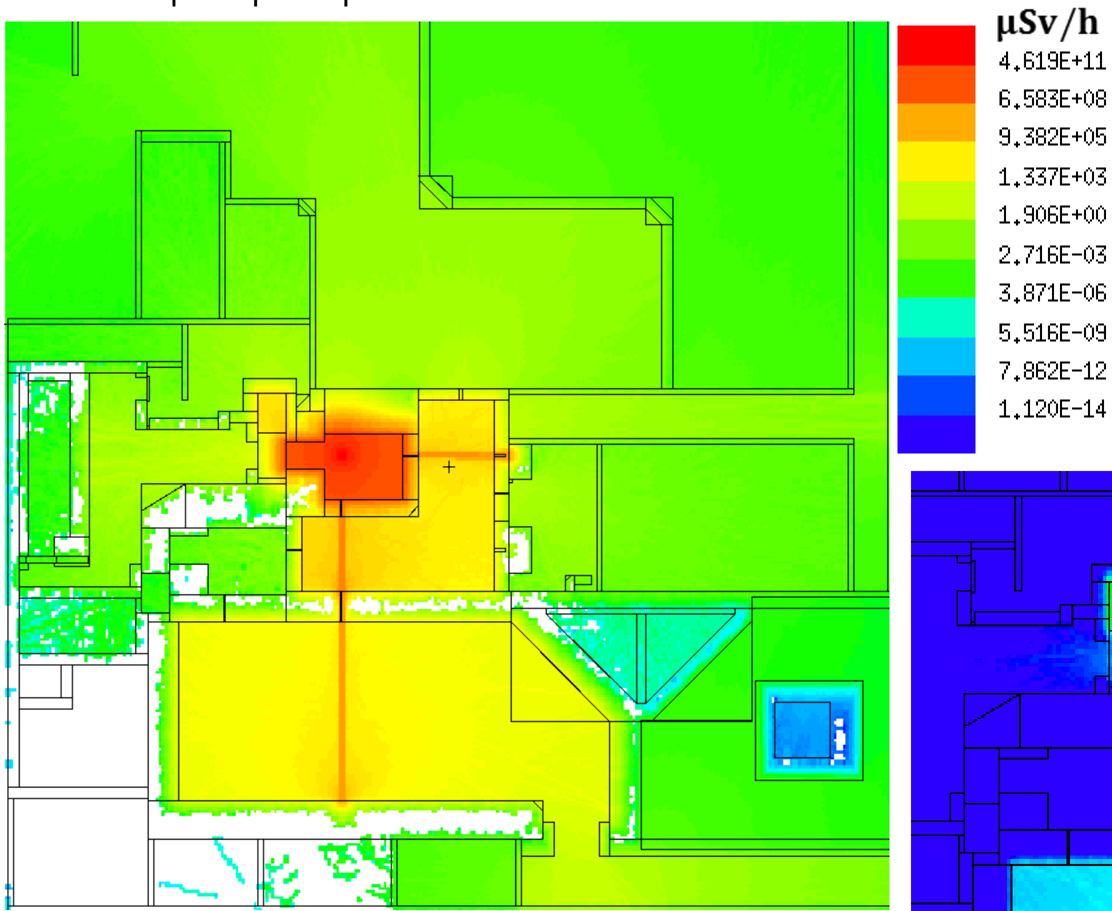




E-gun test (with a cathode of ϕ4.2 mm on Oct. 15, test with ϕ5.6 mm underway)

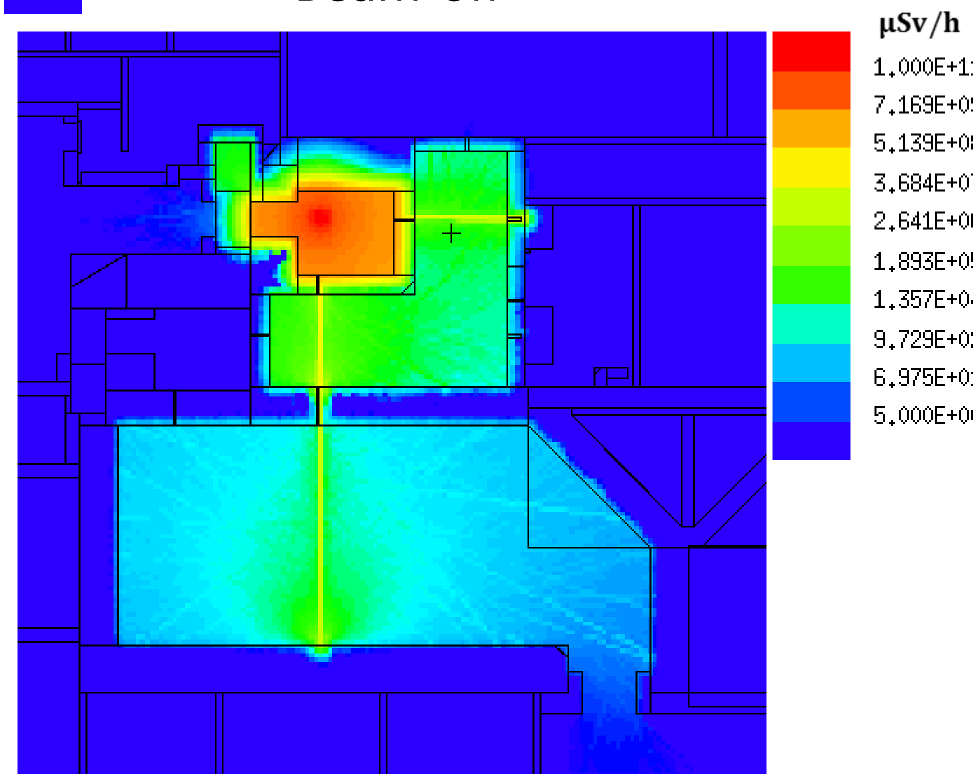
Radiation dose calculations using MCNPX

Dose map of prompt radiation with 70 kW beam



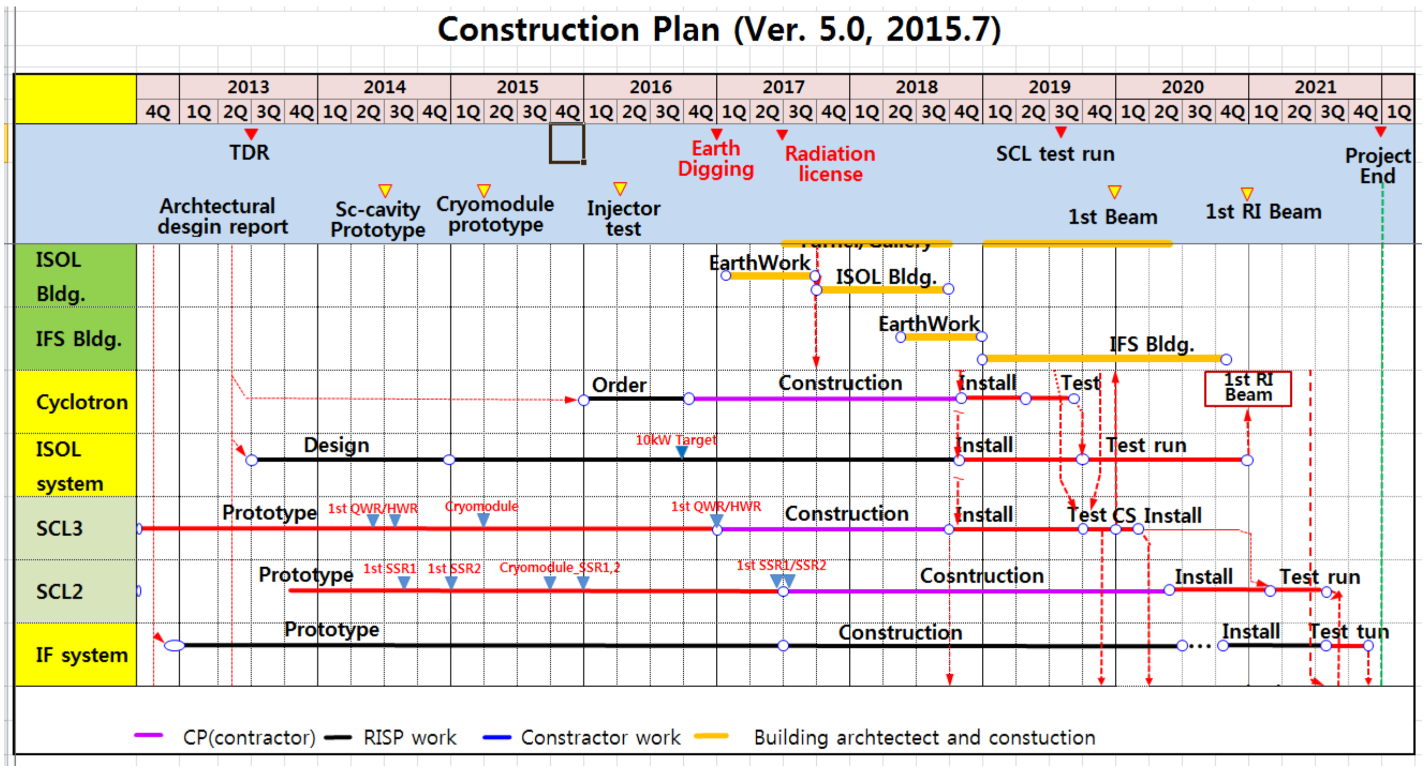
Beam on

Beam off

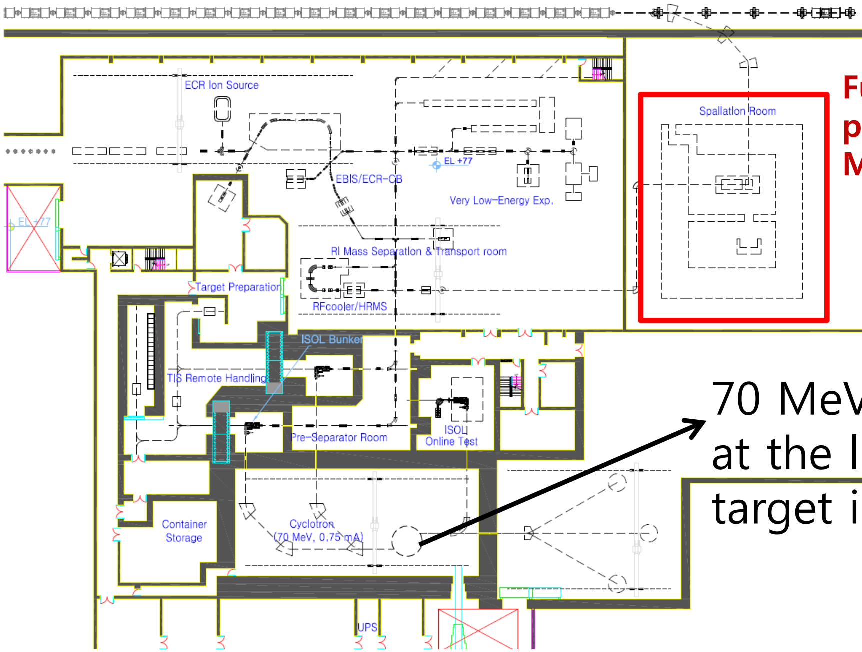


Concluding remarks

- In-flight separator and ISOL systems are being designed along with building design, and prototyping is underway for major components.
- Components in the high radiation area require design consideration for maintenance and remote handling.
- We put our efforts more on the ISOL system to meet the RISP schedule



A thought

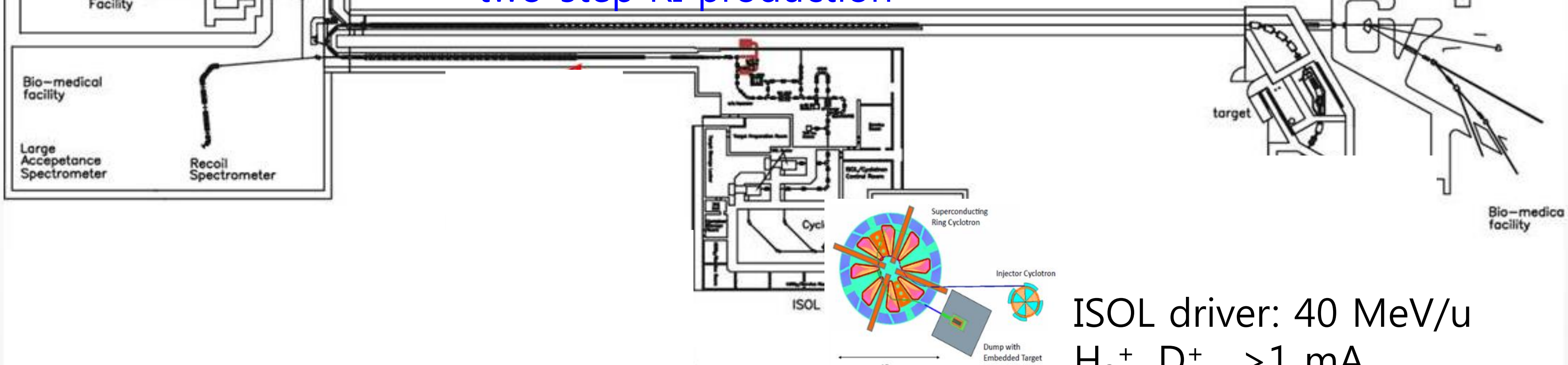


Future upgrade, proton 600 MeV, >400 kW

IF separator cannot be used when SCL2 accelerates protons.

70 MeV, H- beam can be used at the level of 10 kW on UCx target in current technology

RI beams to IF separator for two-step RI production



ISOL driver: 40 MeV/u H_2^+, D^+ , >1 mA