Overview of Rare Isotope Beam Facilities in Asia

Sun Chan JEONG
RISP, IBS
on behalf of Asia Nuclear Physics Association

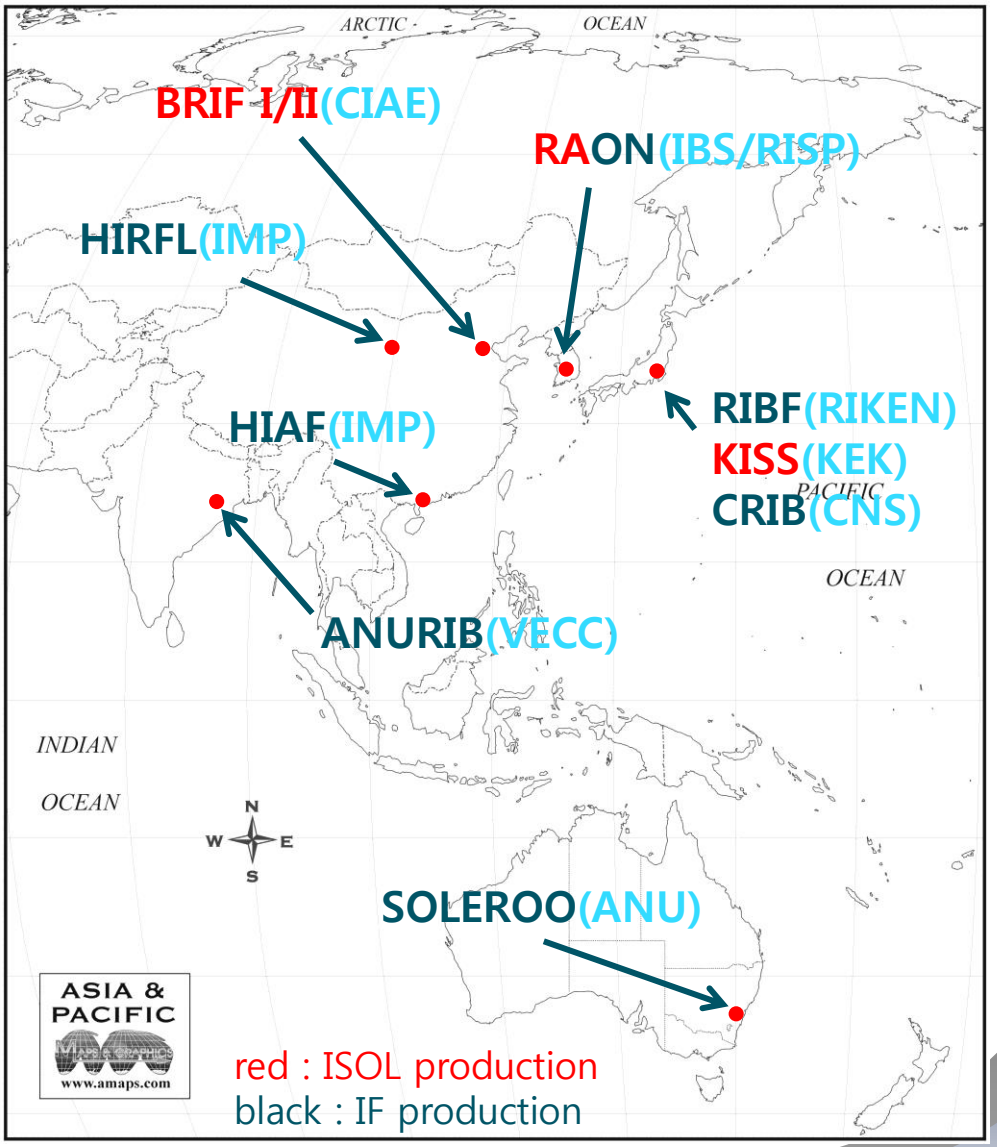
EURORIB'15

JUNE 7th – 12th , 2015 @ HOHENRODA / GERMANY

Major RIB Facility in the Asia & Oceania

- Activities at RIB facilities are growing rapidly in Asian countries.

- RIBF(RIKEN, Japan)
  CRIB (CNS, Japan)
  KISS (KEK, Japan)
  HIRFL(IMP, China)
  BRIF(CIAE, China)
  IUAC (VECC, India)
  Under successful operation

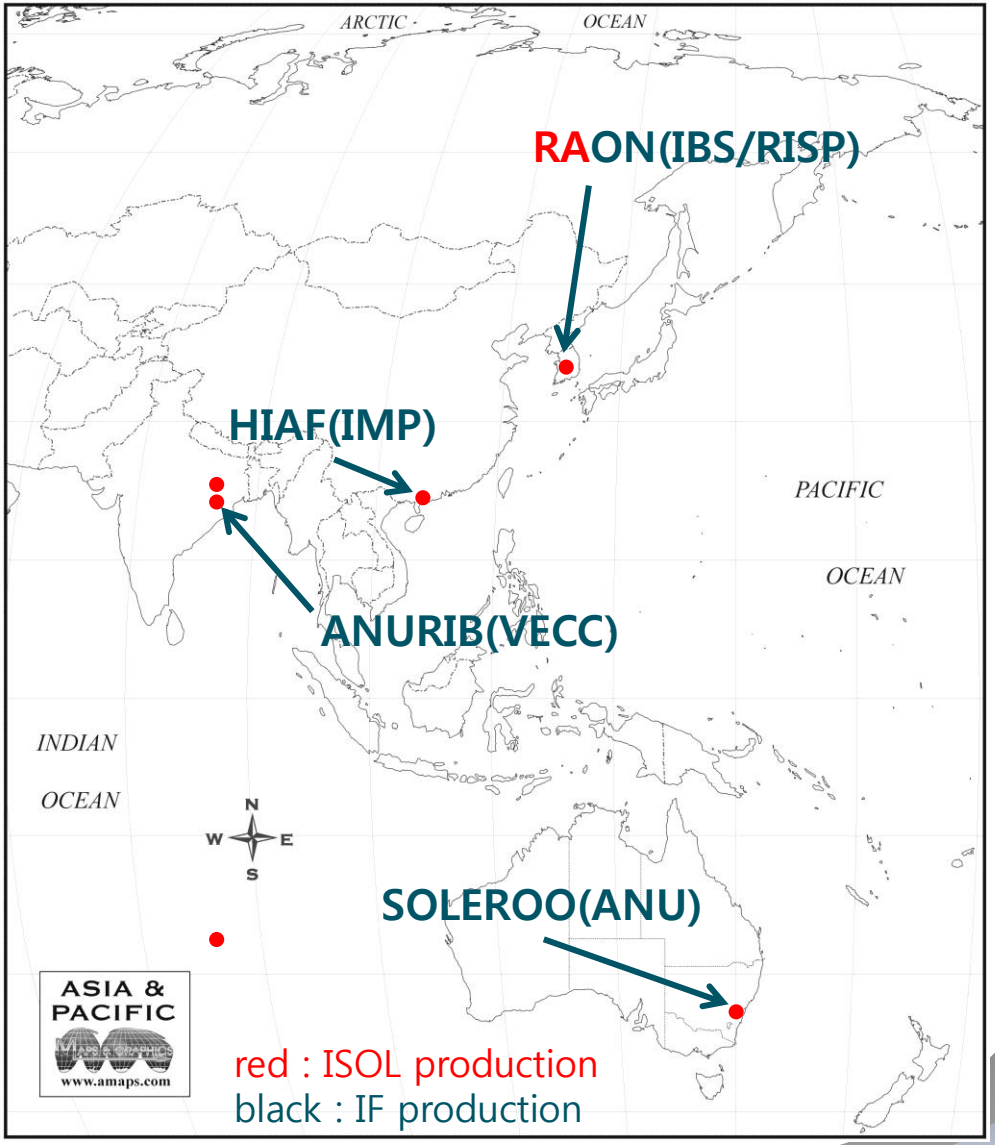


Major RIB Facility in the Asia & Oceania

- Activities at RIB facilities are growing rapidly in Asian countries.

- RIBF(RIKEN, Japan)
  CRIB (CNS, Japan)
  KISS (KEK, Japan)
  HIRFL(IMP, China)
  BRIF(CIAE, China)
  IUAC (India)
  are being successfully operated.

- The main focus of presentation will be on four RIB facilities under construction in Asia/Oceania :
  - RAON (IBS/RISP, Korea)
  - HIAF (IMP, China)
  - ANURIB (VECC, India)
  - SOLEROO (ANU, Australia)



Korea

- RAON
- Deajeon
- Institute for Basic Science / Rare Isotope Science Project (IBS/RISP)

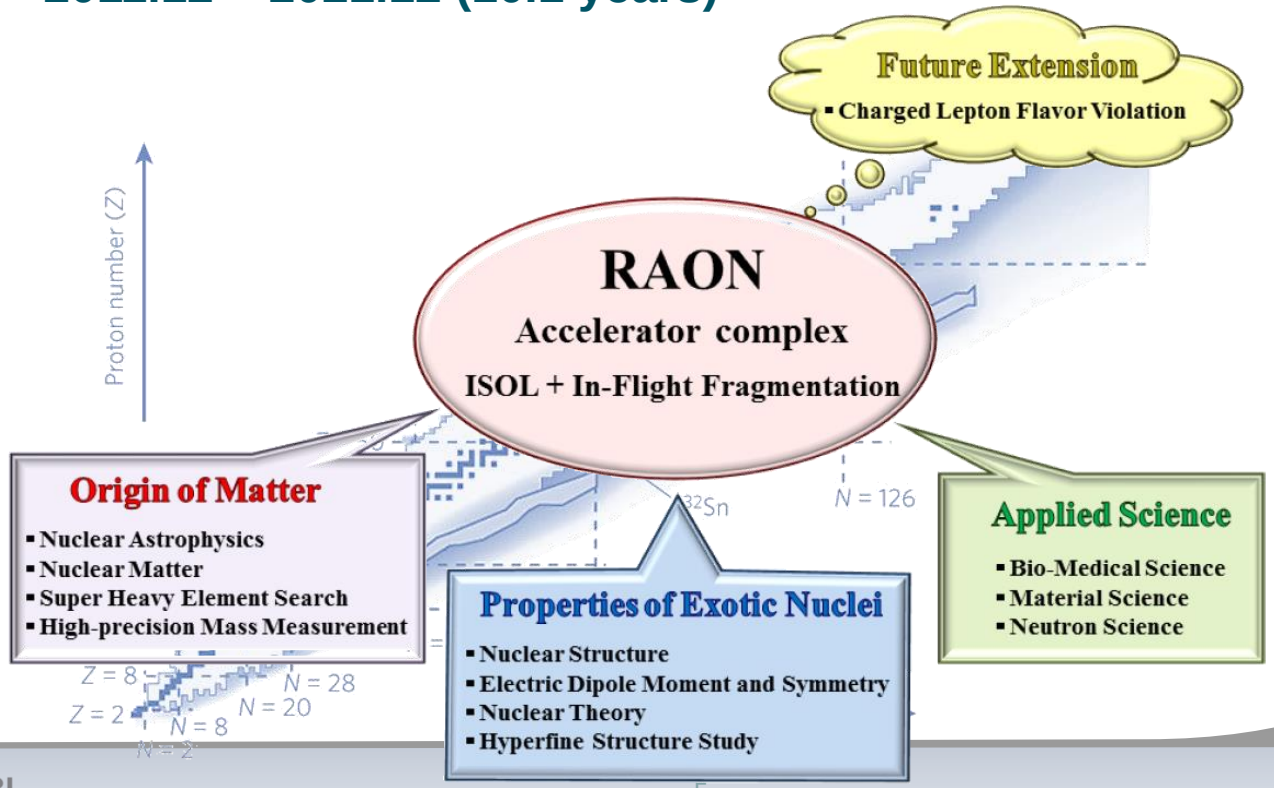
RAON

- **heavy ion accelerator complex**
  for **rare isotope science** research in Korea.

  * RAON: Pure Korean word meaning Delightful, Joyful, Happy

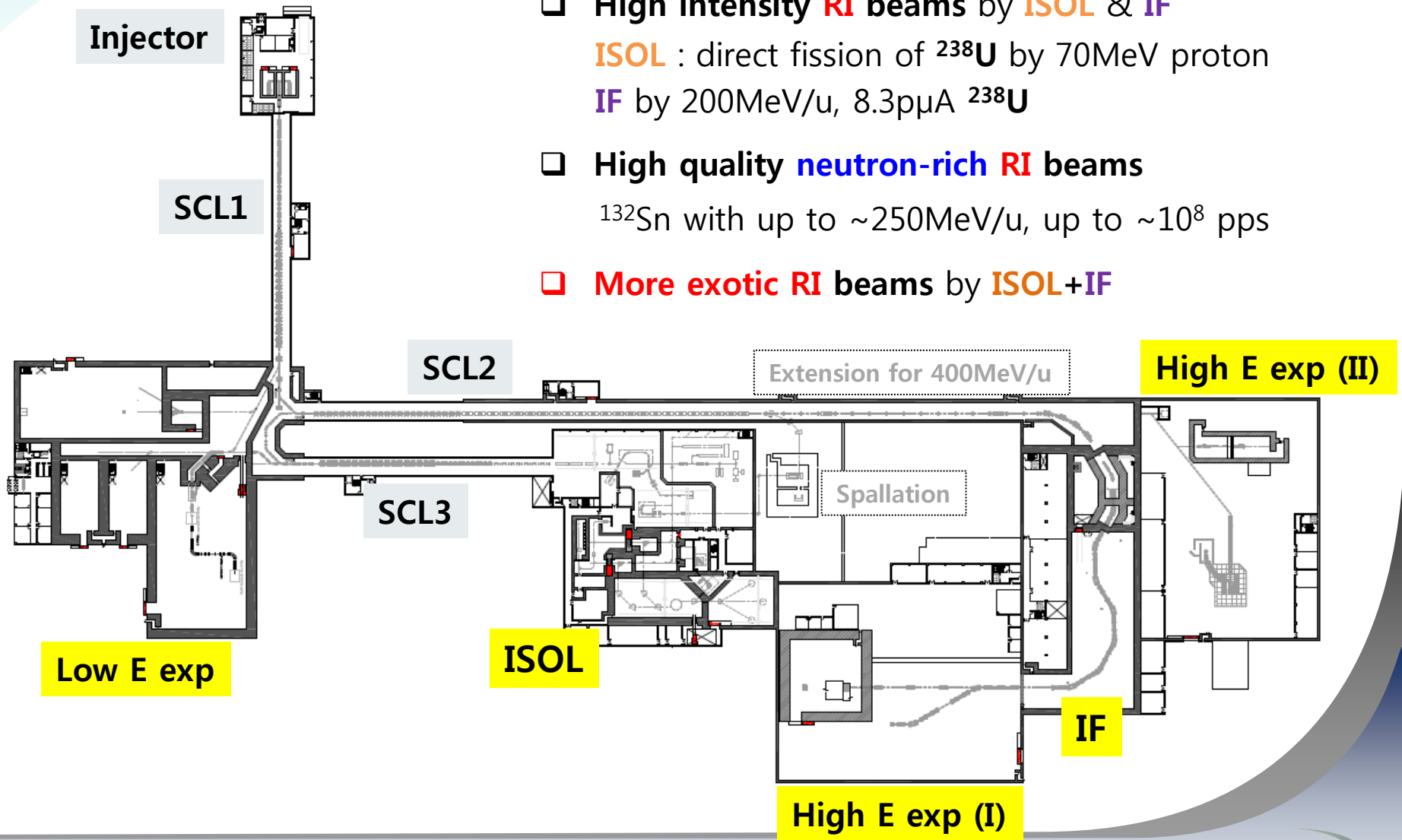
- **Budget: US$ 1.44 B** (1 B$~1T Won)
  - accelerators and experimental apparatus : 0.46 B$
  - civil engineering & conventional facilities : 0.98 B$ (incl. construction site purchase)

- **Period: 2011.12 ~ 2021.12 (10.1 years)**

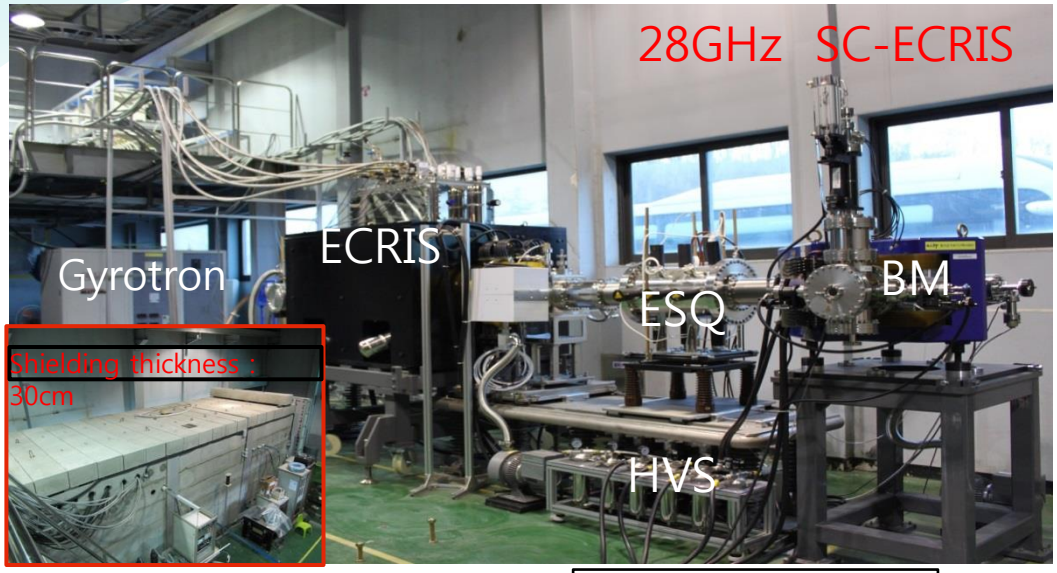


Layout of RAON

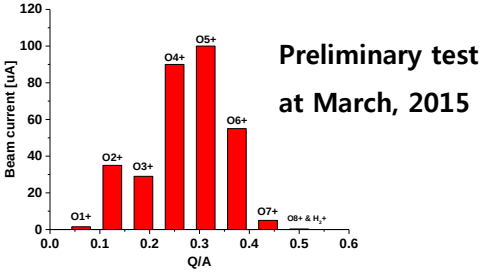
- **High intensity RI beams** by ISOL & IF
  ISOL : direct fission of ^{238}U by 70MeV proton
  IF by 200MeV/u, 8.3pμA ^{238}U
- **High quality neutron-rich RI beams**
  ^{132}Sn with up to ~250MeV/u, up to ~10^8 pps
- **More exotic RI beams** by ISOL+IF



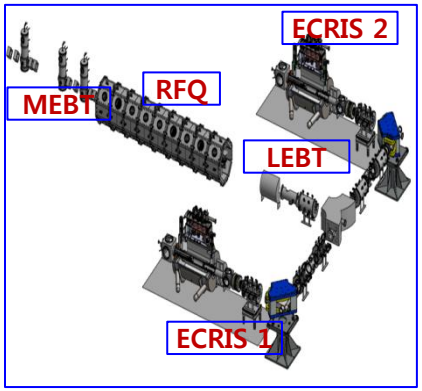
Injector System



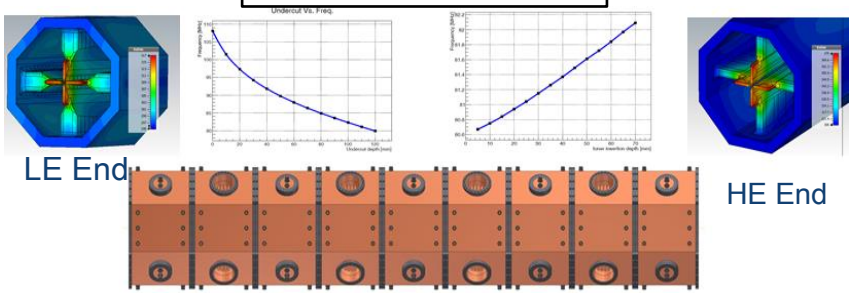
- ECR-IS
  - Output emittance: 0.12 π mm-mrad
  - Beam current: 400euA for $^{238}U^{33+} + {}^{238}U^{34+}$
  - Output beam energy: 10 keV/u
  - RF frequency : 28 GHz
  - Magnets : Fully superconducting NbTi

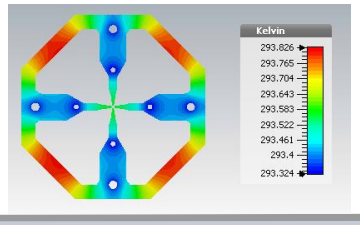


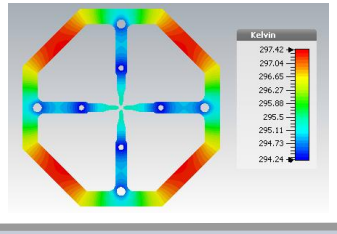
Injector layout



RFQ Engineering Design

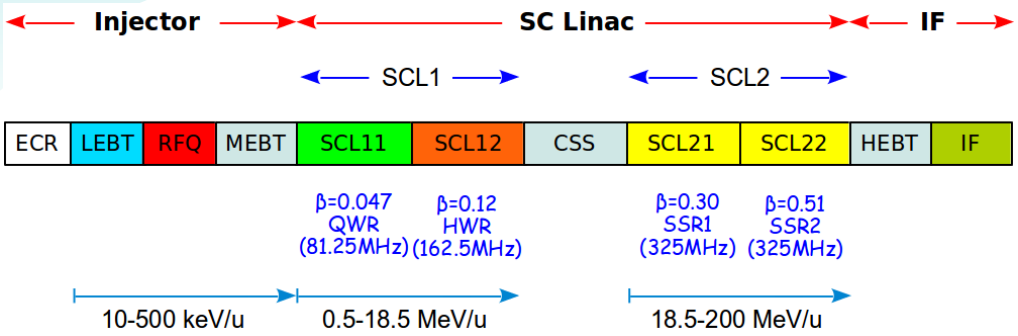




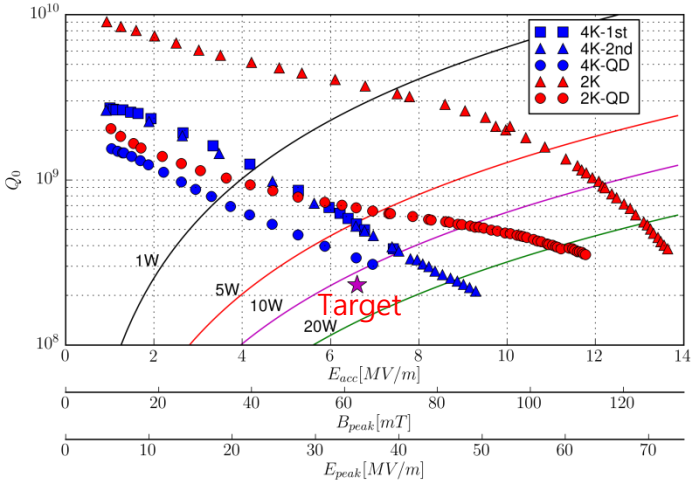


- RFQ
  - RF frequency: 81.25 MHz
  - Output beam energy: 500keV/u
  - 4 Vane types

Superconducting Linac (SCL)

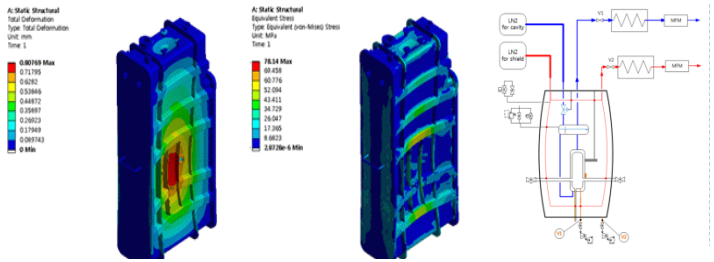


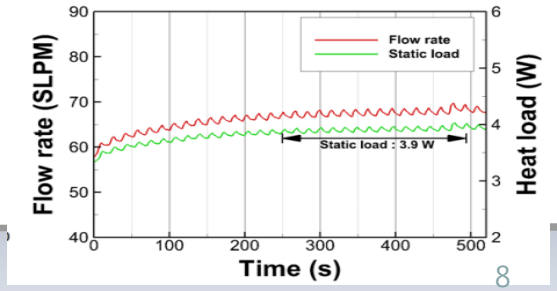
SC cavity development



RAON SCL Characteristics

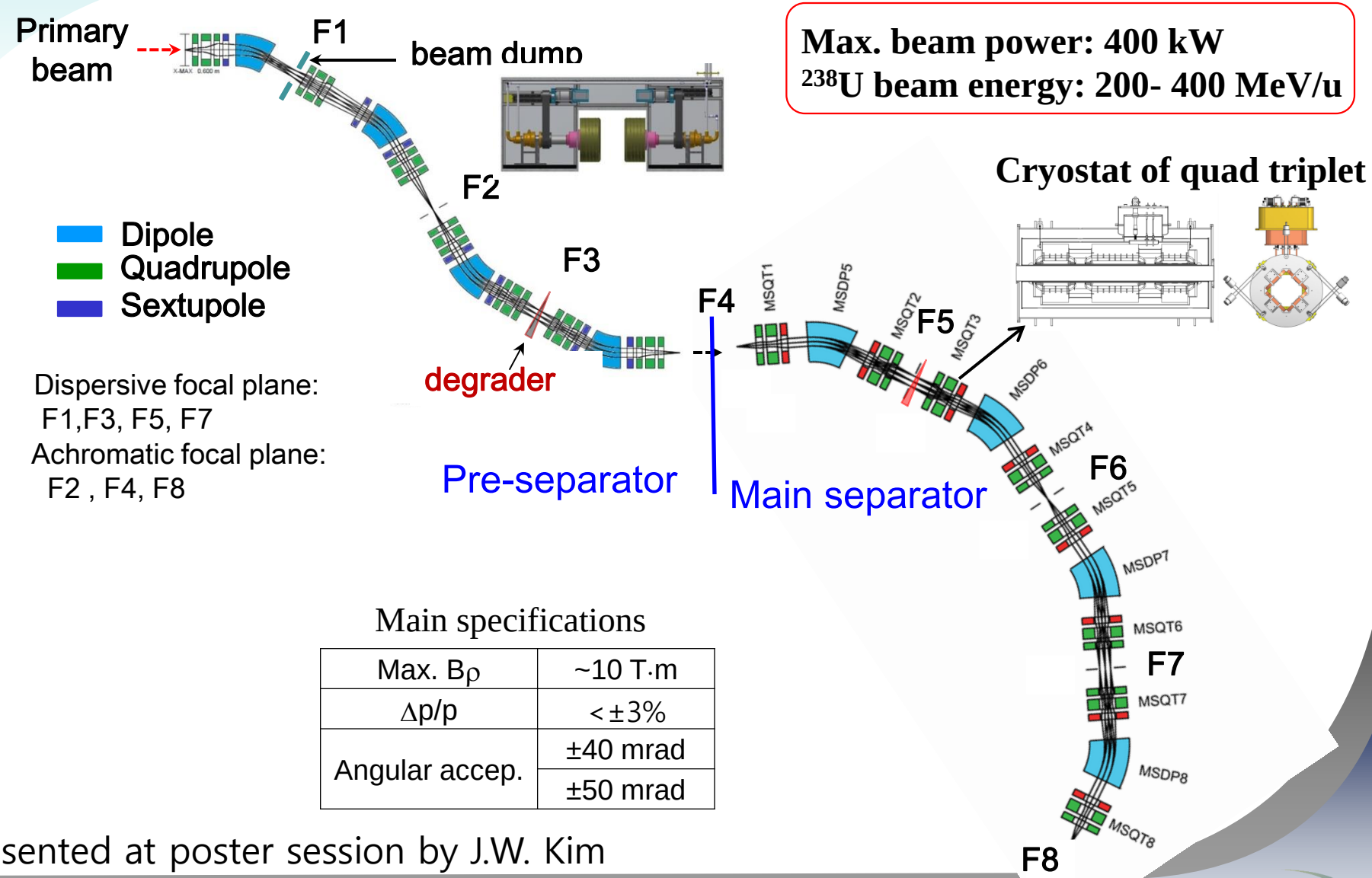
- Linac baseline frequency is 81.25MHz
- Niobium Cavities operating at 2K
- Focusing by normal conducting quad doublets
- Optimized geometric beta of SC cavities (0.047, 0.12, 0.30, 0.51)
- Employs larger aperture to reduce beam loss (4cm and 5 cm aperture)





In-Flight separator

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



Dispersive focal plane:
F1,F3, F5, F7
Achromatic focal plane:
F2 , F4, F8

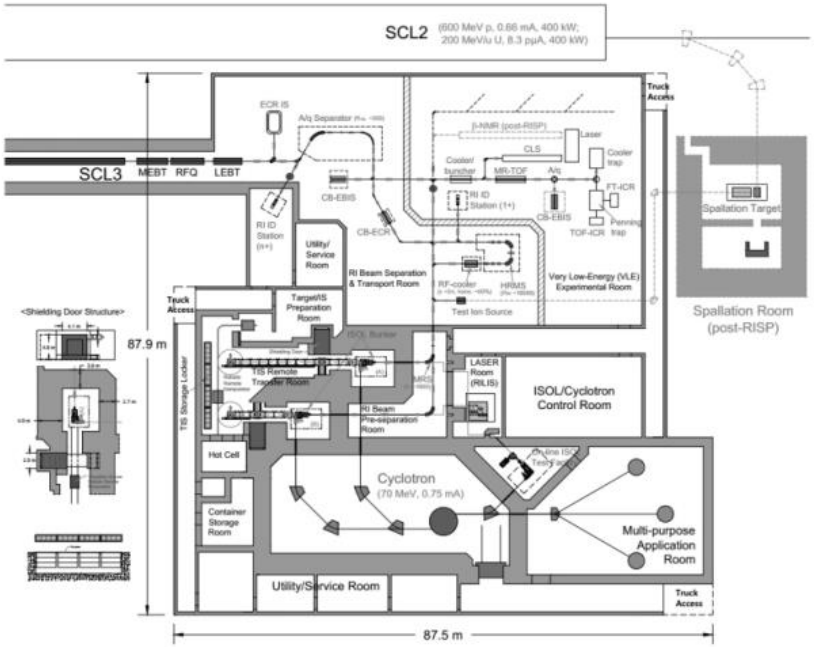
Main specifications

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

Presented at poster session by J.W. Kim

ISOL System

ISOL Driver: 35-70 MeV, H^- 1 mA cyclotron



The layout still evolving

	TIS	EBIS
Ion	1+	A/q < 4
E	40 keV	10 keV/u

Separator
$m/\delta m = 300$

↓

MR-TOF

↓

RFQ Cooler/Buncher
3π mm mrad, 1 eV

↓

EBIS

↓

Post linac

UCx target: 10 kW (Dia. 5 cm, 1.3 mm 19 disks)

Test stand for target ion source, front-end mass separator on HV platform

Experimental Facilities at RAON

Field	Facility	Exp. hall	Characteristics	Remark
Pure science	Recoil spectrometer – KOBRA	Low E	High resolution, Large acceptance function, RIBs production with in-flight method	Mass resolution; ~ 200 Large acceptance; ~ 80 msr
	Large acceptance Spectrometer – LAMPS(L&H)	Low & High E (I)	High efficiency for charged particle, n, and γ	High E: solenoid spectrometer (TPC; 3π Sr), neutron wall, dipole spectrometer (upgrade) Low E: Si-CsI array, neutron array
	High resolution Spectrometer	High E (I)	High resolution, Precise scattering Measurement to the focal plan, Rotatable	Momentum resolution ; 1.5×10^4
	Zero-degree Spectrometer	High E (I)	Charge and mass separation, Good mass resolution	Momentum resolution ; 1200~ 4100
	High precession mass measurement system	Ultra low E	Penning trap, Multi-reflection Time of flight	Mass resolution ; 10^{-5}~ 10^{-8}
	Collinear laser Spectroscopy	Ultra low E	High Resolution Laser Spectroscopy System	Spectral resolution ; ≤ 100 MHz
Applied science	β-NMR/μ-SR	Low / High E (II)	High intensity ^{8}Li & muon production	^{8}Li & muon > 10^8 pps
	Bio-medical facility	Low & High E (II)	Irradiation system for stable & radio ion beam	Uniformity ; < 5%
	Neutron science Facility	Low E	Fast neutron generation & measurement system of fission cross section	Uncertainty ; < a few %

KOBRA (KOrea Broad acceptance Recoil spectrometer and Apparatus)

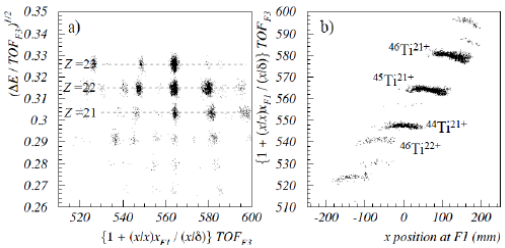
RAON

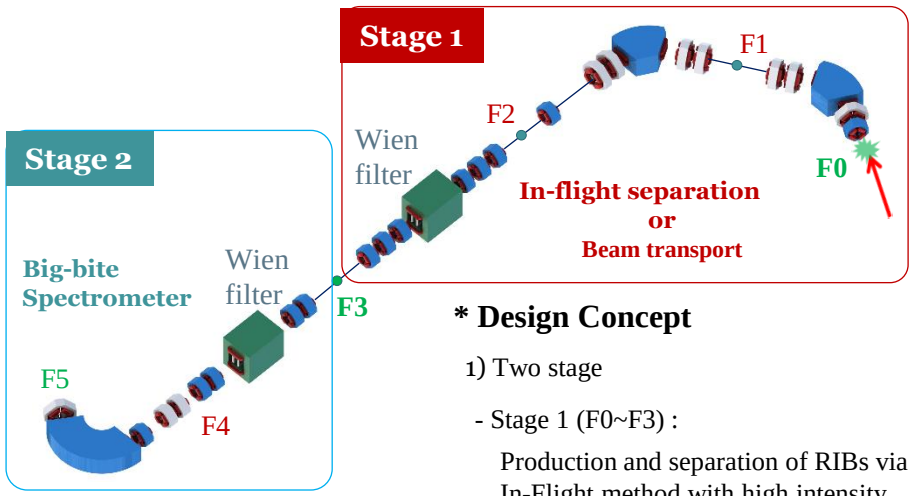
Main facility for nuclear structure and nuclear astrophysics studies with low-energy stable and rare isotope beams

● Main Research Subject :

1) Nuclear structure of exotic nuclei near the drip lines
2) Astrophysically important nuclear reactions
3) Rare event study - Super Heavy Element (SHE), New isotopes
4) Nuclear phyiscs with polarized beam/target etc

- RIBs production via low-E in-flight method by multi nucleon transfer reaction (ex. ^{44}Ti)





*** Design Concept**

1) Two stage

- Stage 1 (F0~F3) :

  Production and separation of RIBs via In-Flight method with high intensity SIBs from SCL

- Stage 2 (F3~F5) :

  Big-bite spectrometer with Wien filter
  → large acceptance

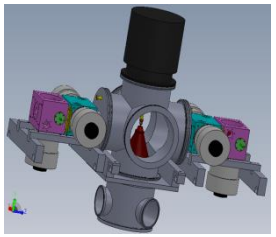
*** Associate equipments**

FP	Equipments
F0	RI production target,
F3	gas-jet target, gamma-array, detection system, β-NMR
F5	Focal plane detection system

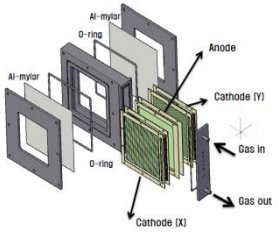
- Main Specification

Maximum magnetic rigidity (Tm)	~3
Mass resolution ($m/\Delta m$) @ stage 1	~700
Dispersion (cm/%) @ stage 1	4.2
Momentum acceptance (%) @ stage 1	±4
Angular acceptance (mrad) @ stage 2	40 (H) and 200 (V)

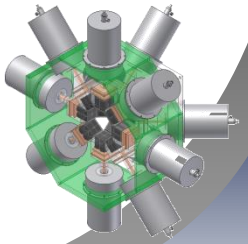
- Ion optics calculation was done using K-trace code (ray tracing)
- Rotation of 'stage 2', variable position of Q-magnets in 'stage 2' are under consideration
- Technical design is in progress
- Design of associate equipment



[Gas-jet target]



[PPAC]



[Gamma array]

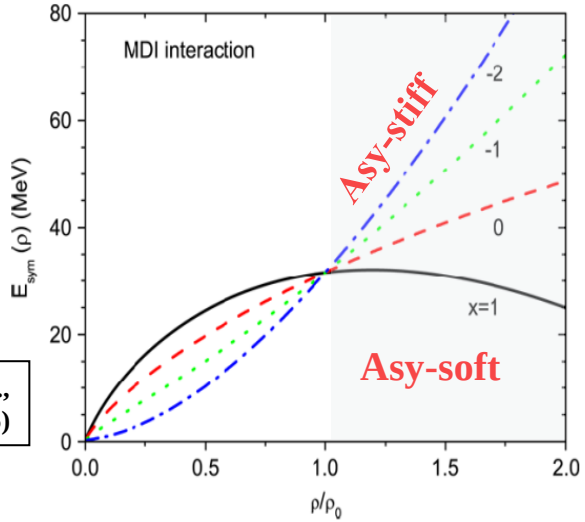
LAMPS (Large Acceptance Multi-Purpose Spectrometer)

RAON

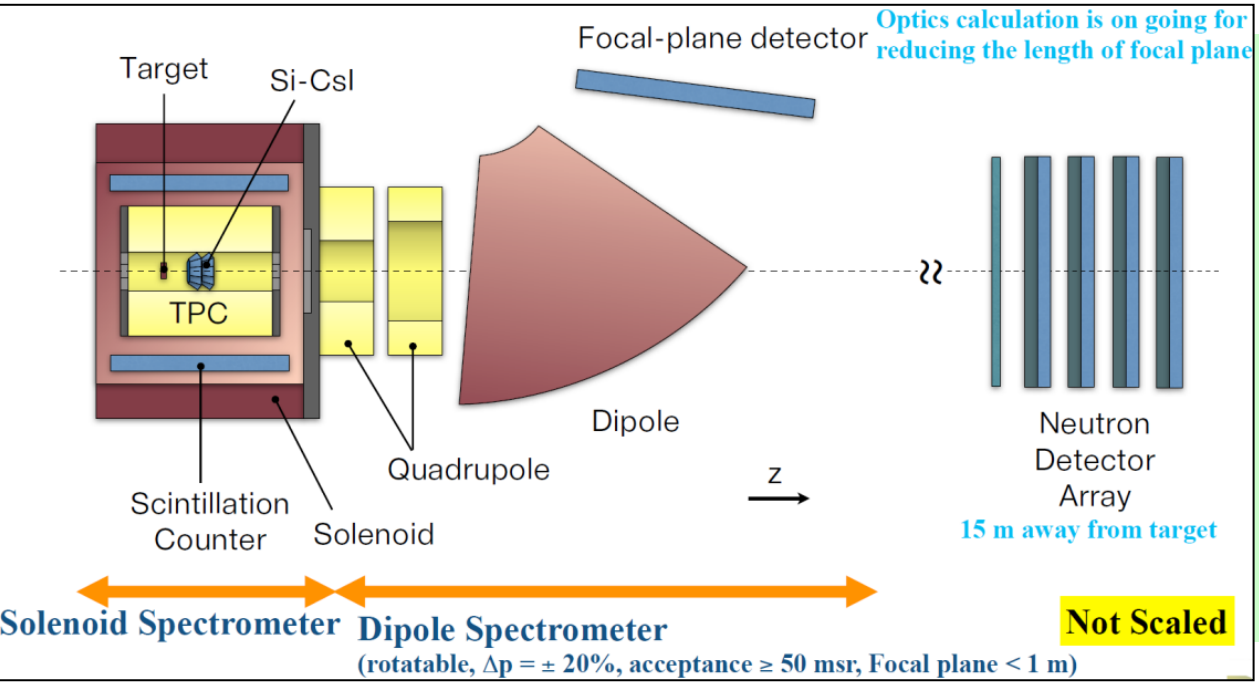
Main facility for nuclear matter and nuclear reaction studies with intermediate energy stable and rare isotope beams

Main Research Subject:

Study of nuclear symmetry energy at supra-saturation density via heavy-ion collision experiment



L.W. Chen et al., PRL 94, 032701 (2005)



- **Beam Energy: up to 250 MeV/u**
- **Solenoid Spectrometer**

- Max. 1T solenoid magnet
- TPC (~ 3π sr acceptance, charged particle tracking)
- Scintillation counter (trigger & ToF)
- Si-CsI (measure heavy fragment using ΔE-E method)

- **Dipole Spectrometer**

- Rotatable dipole magnet and focal plane detector (capable to study nuclear reaction)

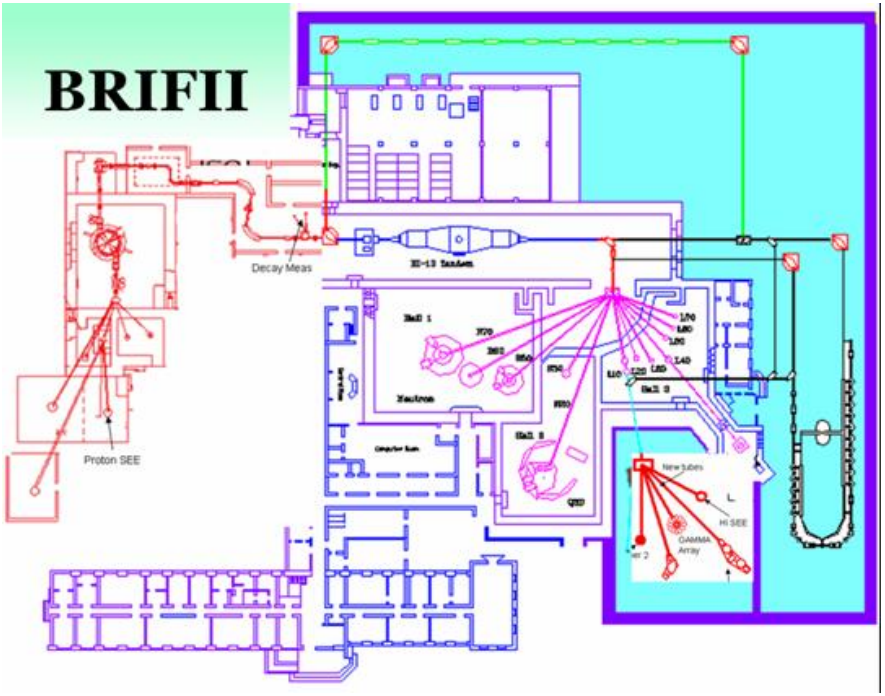
- **Neutron Wall (neutron tracking)**

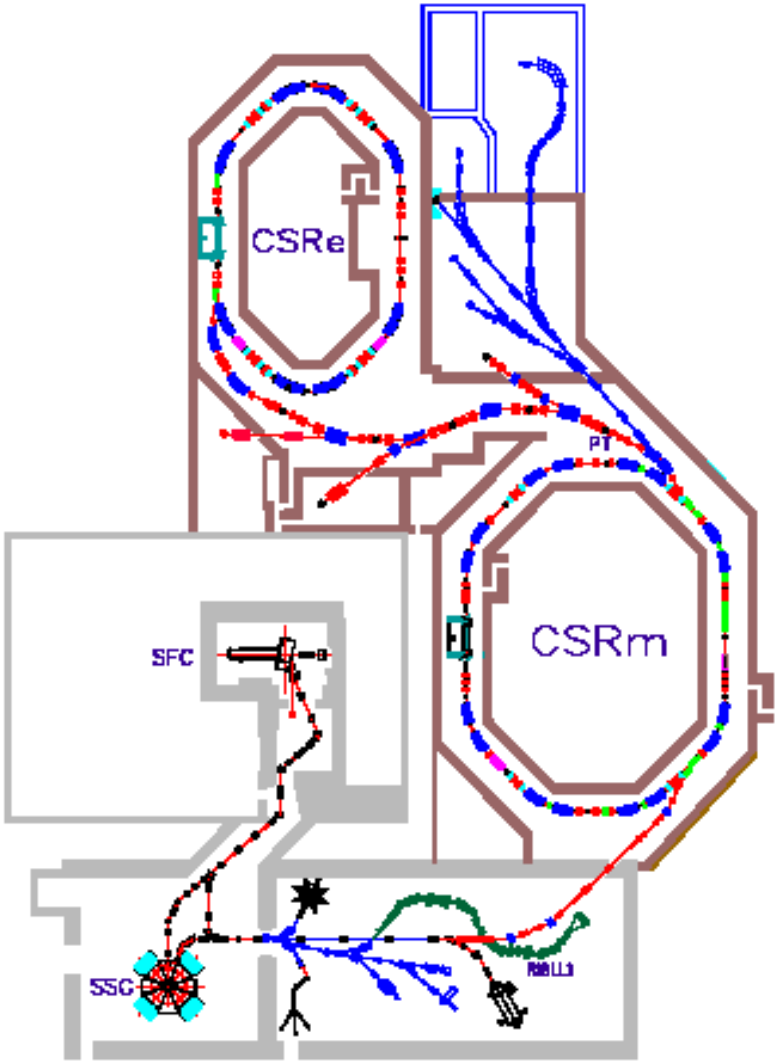
China

- Heavy Ion Research Facility in Lanzhou (HIRFL)
- Lanzhou
- Institute of Modern Physics (IMP)

- Beijing Rare Isotope Facility (BRIF)-II
- Beijing
- China Institute of Atomic Energy (CIAE)

Two major RIB facilities in China





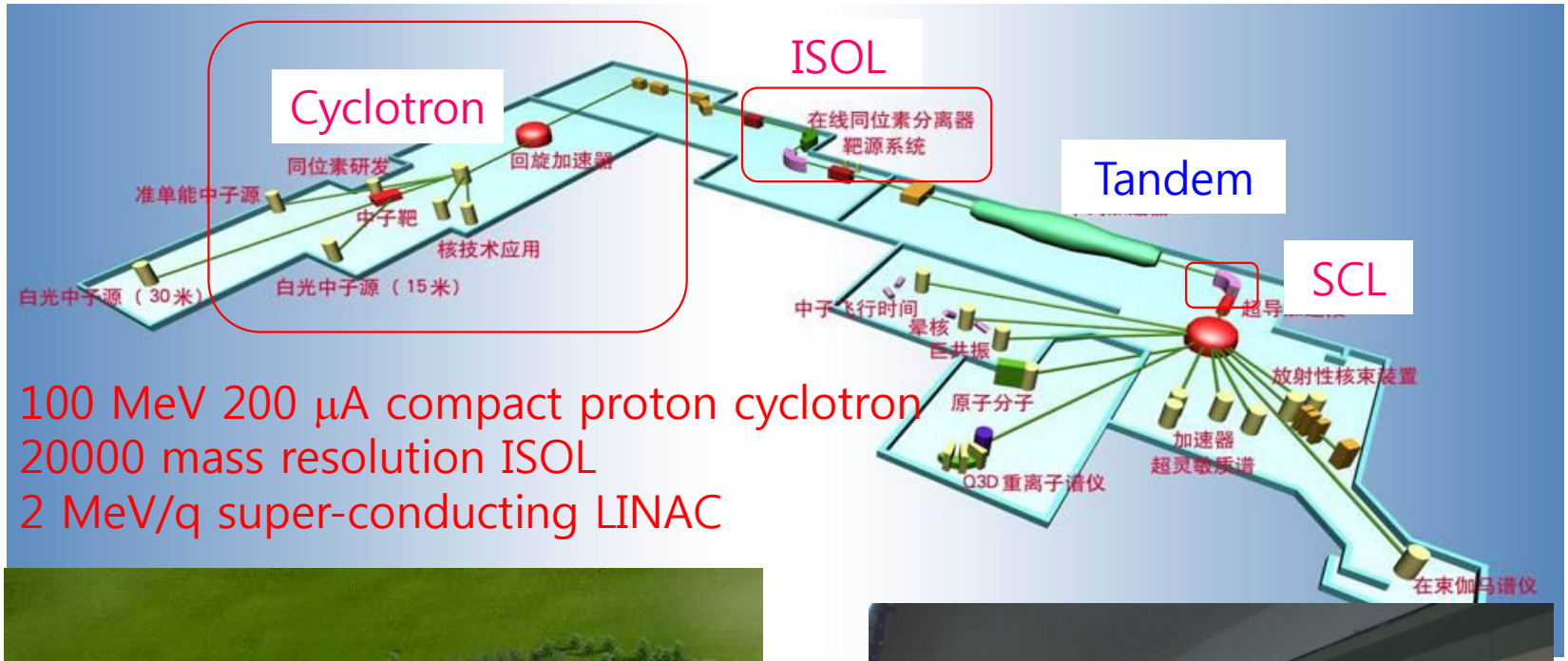
Beijing
BRIF, BRIF II ,
Low E HI, RIB, 2014

Lanzhou, HIRFL
Med E HI, RIB, 2008

Status of BRIFII

BRIF-(Beijing Rare Ion beam Facility)

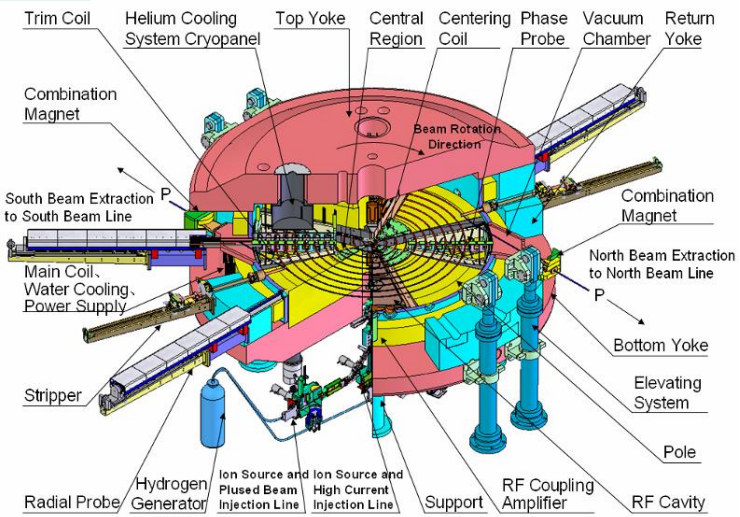
1987: Operation & Experiments 2001-2002: update to HI-15

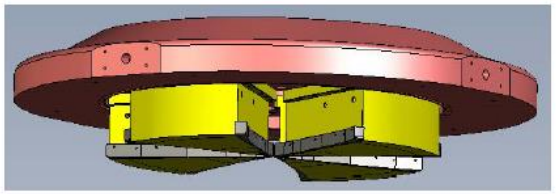


- 100 MeV 200 μA compact proton cyclotron
- 20000 mass resolution ISOL
- 2 MeV/q super-conducting LINAC

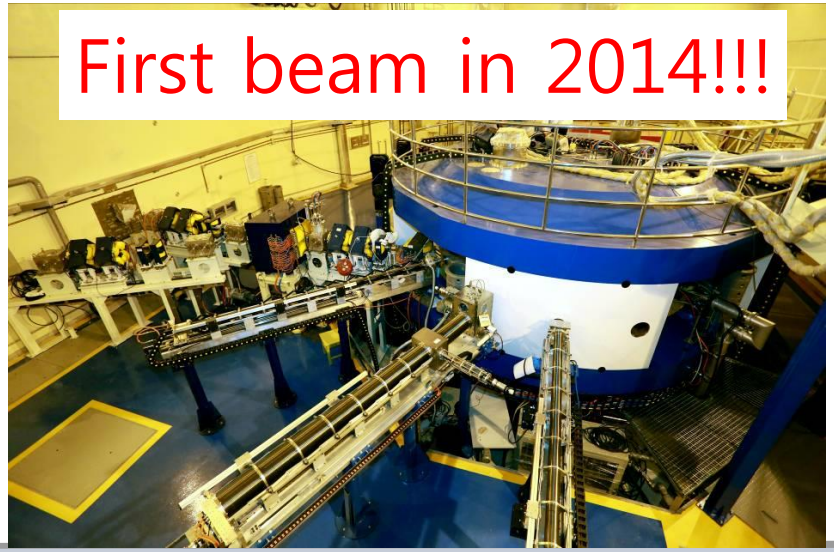
Brief idea in 1990,
Supported in 2009 (0.36B),
First beam in 2014

Status of BRIFII





Dia.: 6160 mm
Height: 2820 mm
Weight: 435 t



Magnet design and fabrication

2015, May 4, ISOL separated ^{38}K RI delivered

Status of HIRFL

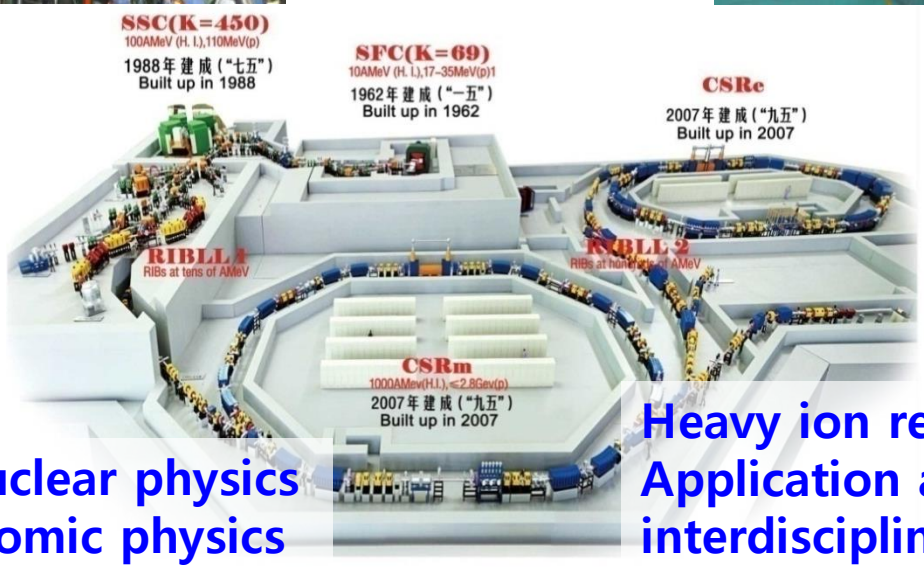
Heavy Ion Research Facility in Lanzhou (HIRFL)

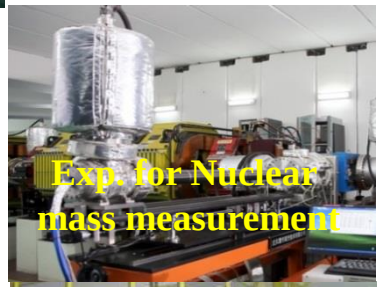
National Laboratory of Heavy Ion Accelerator in Lanzhou(1991)

1998	Approved
2000-2005	Construction
2006-2007	Commissioning
2008	Operation

Status of HIRFL

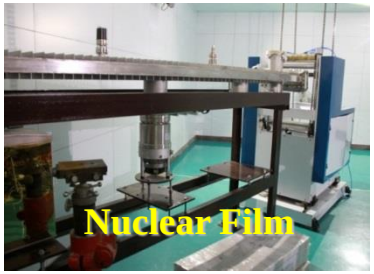
Main Setups

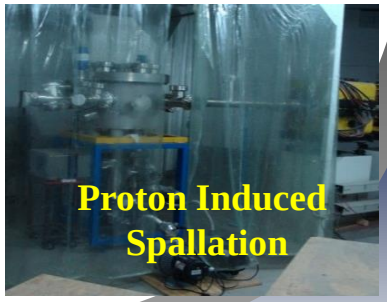




Nuclear physics
Atomic physics

Heavy ion related
Application and
interdisciplinary



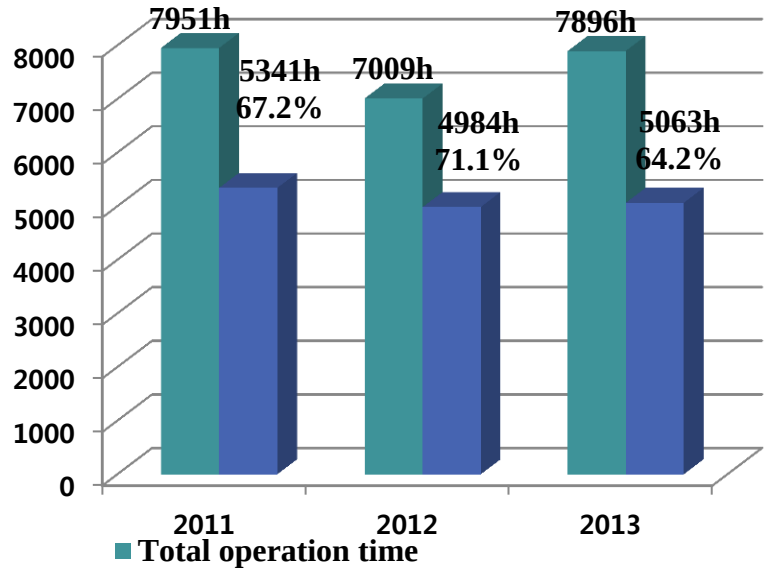


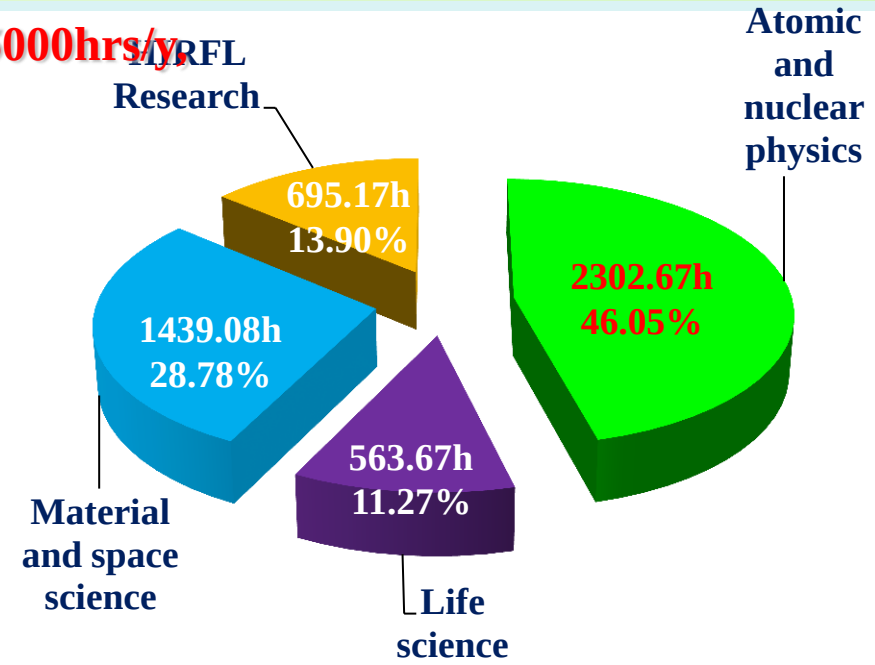
About 20 apparatuses for heavy-ion physics and applications

Status of HIRFL

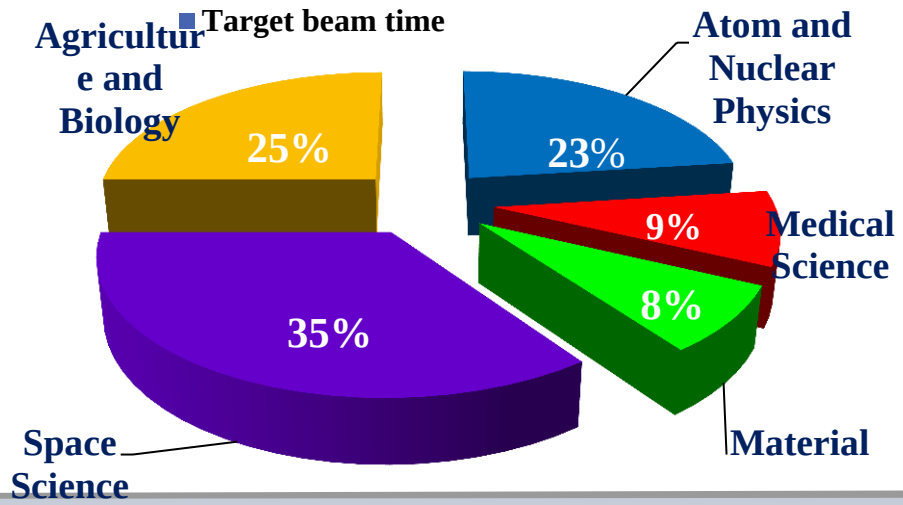
HIRFL statistics

Operation time >7000hrs/year, target time ~5000hrs/y, applied for beam time >1400hrs/y

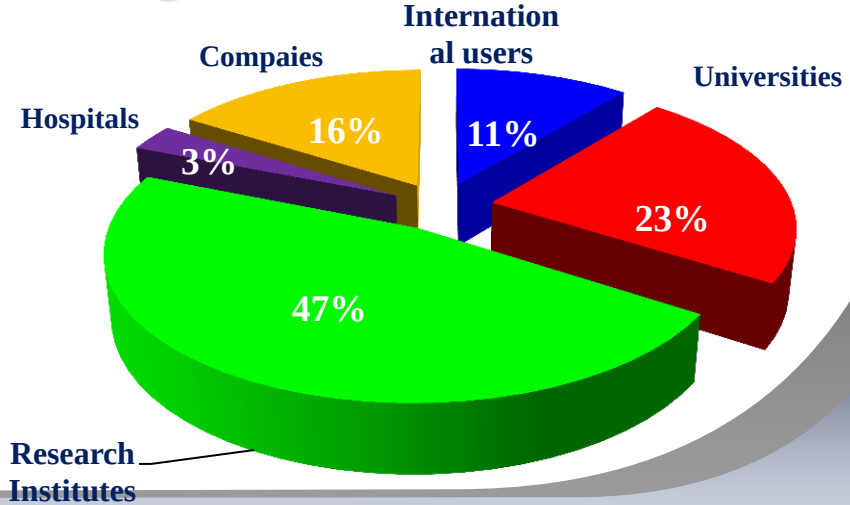




Average beam time distribution



Distribution in Research Fields



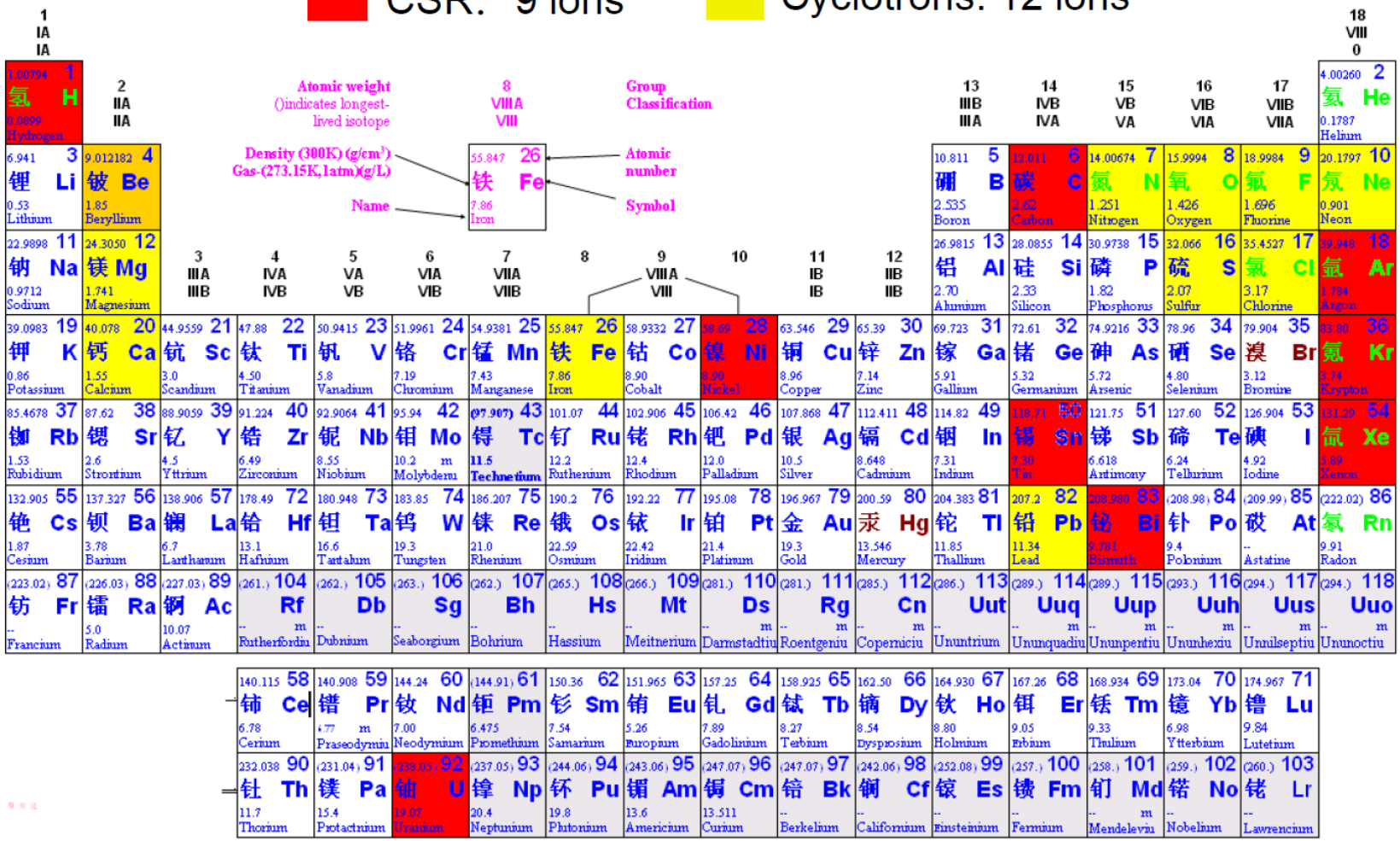
Distribution of ~200 Users Units

Typical beam

p ~ U, Total accelerated elements: 21

CSR: 9 ions

Cyclotrons: 12 ions

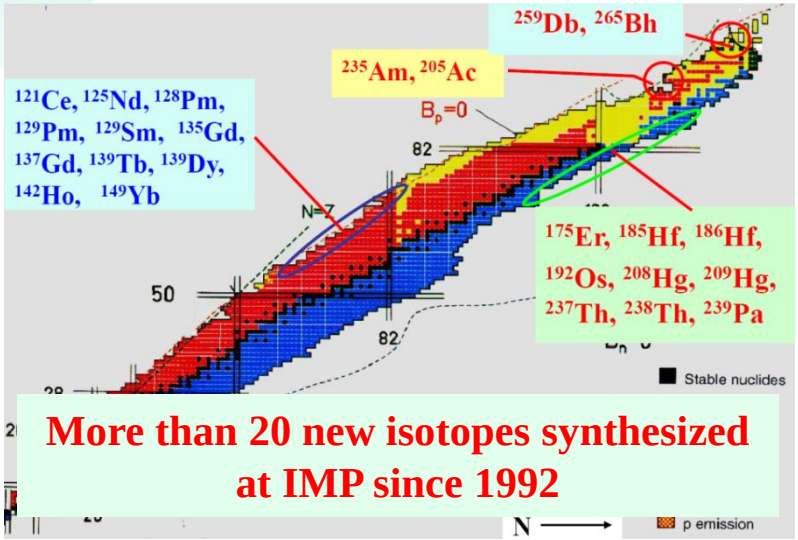


~23 different beam species (~10 new) provided by HIRFL every year

Status of HIRFL

Highlights progress

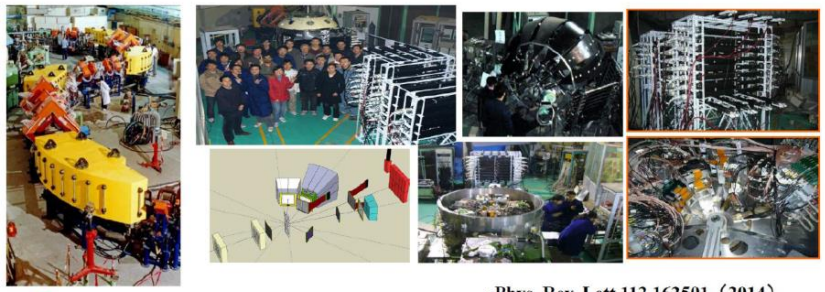
Synthesis of New Isotopes



More than 20 new isotopes synthesized at IMP since 1992

RIB physics

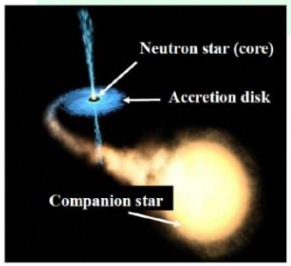
RIBLL Collaboration established in 2011, including >16 institutions

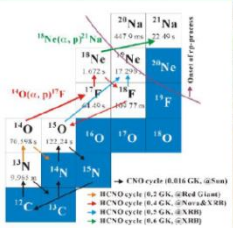


–Phys. Rev. Lett 112,162501（2014）
–Phys. Rev. C90, 014606(2014)
–Phys. Rev. C87, 024312（2013）
–Phys. Rev. C87, 044613（2013）
–Phys. Lett. B727, 126（2013）
–Phys. Rev. C84, 037603（2012）
–Phys. Rev. C85, 024621（2012）
–Phys. Rev. C81, 054317（2010）
–Phys. Rev. C82, 064316（2010）
–Phys. Rev. C80, 054315（2009）
–Phys. Rev. C80, 014310（2009）

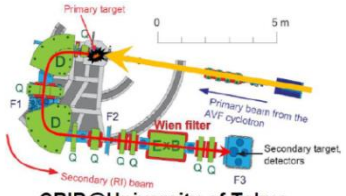
Nuclear Astrophysics

Studies of key (α,p) reactions in Type I X-ray bursts at RIBLL and CRIB





RIBLL1@IMP



CRIB@University of Tokyo

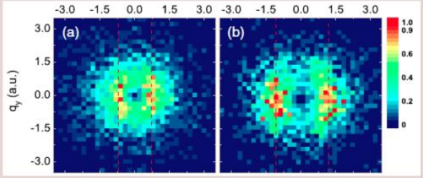
Publications

1. J.J. He *et al.*, Eur. Phys. J. A47(2011)67
2. J.J. He *et al.*, Phys. Lett. B725(2013)287
3. J.J. He *et al.*, Phys. Rev. C88(2013)012801R
4. J. Hu *et al.*, Phys. Rev. C90(2014)025803
5. L.Y. Zhang *et al.*, Phys. Rev. C89(2014)015804
6. J.J. He *et al.*, Nucl. Instr. Meth. A680(2012)43
7. S.Z. Chen, Nucl. Instr. Meth. A735(2014)466

Atomic Physics

Two-center interference observed in a collision between H_2^+ projectile used as a double slit and helium target atoms using kinematically complete technique

IMP and MPIK collaboration

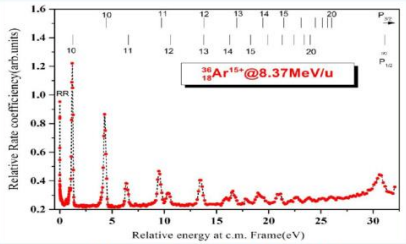


Momentum transfer pattern @ inter-nuclear distances

Theoretical optical interference patt

Dielectronic recombination spectroscopy at cooler storage ring

The resolution of dielectronic recombination spectroscopy is of 100meV. Paved the way to precision spectroscopy at CSR.



- Phys. Rev. Lett. 112, 023201 (2014)
- Phys. Rev. A 90, 022706 (2014)
- Nucl. Instr. Meth. A736, 75 (2014)
- Phys. Rev. A 87, 062510 (2013)
- Phys. Rev. A 86, 012709 (2012)
- Phys. Rev. A 84, 042710 (2011)

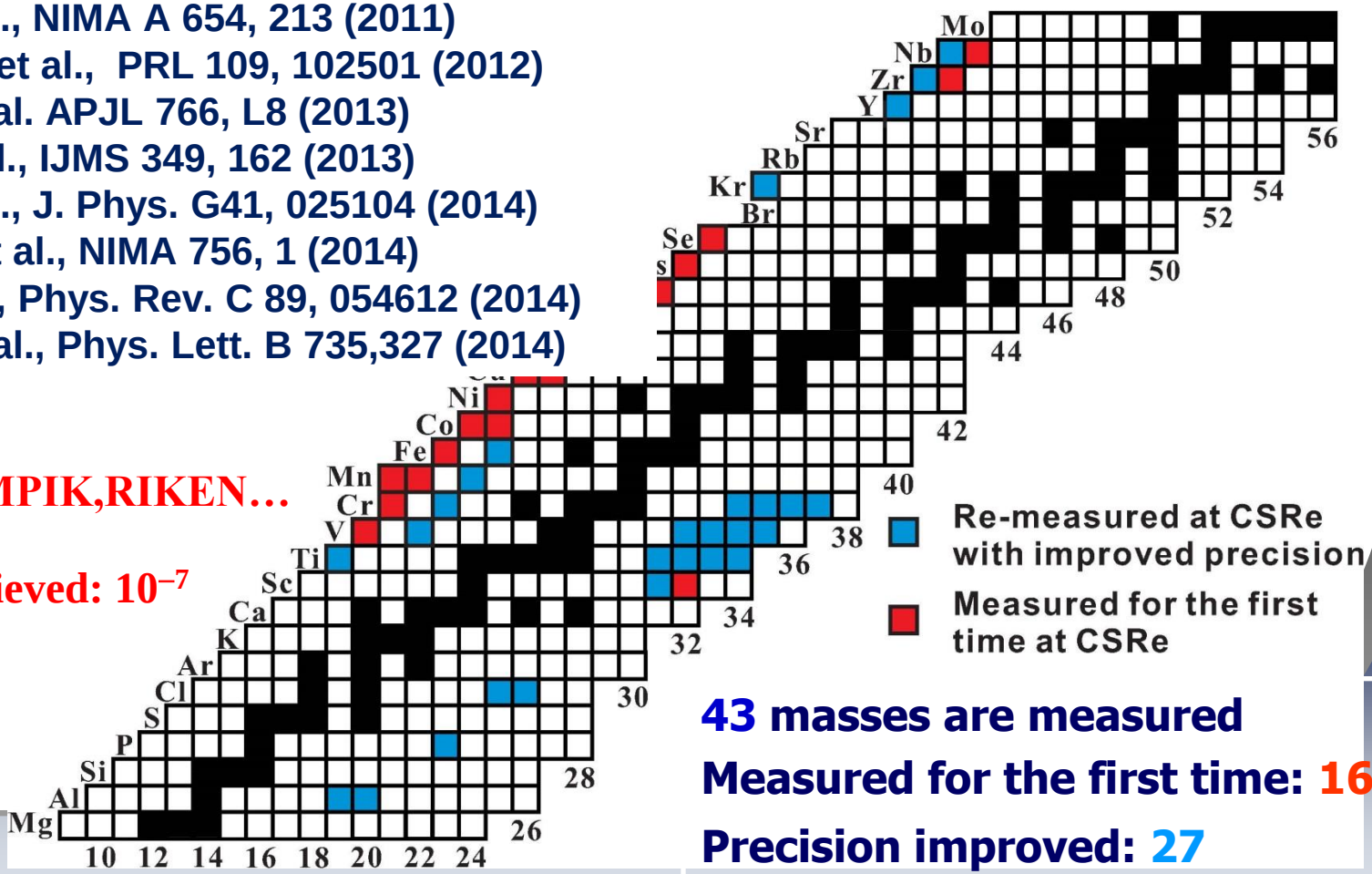
Mass Measurements

Primary Beams: ^{56}Ni, ^{78}Kr, ^{86}Kr, ^{112}Sn

1. B. Mei et al., NIMA A 624, 109 (2010)
2. X.L. Tu etal., PRL 106, 112501 (2011)
3. X.L. Tu et al., NIMA A 654, 213 (2011)
4. Y.H. Zhang et al., PRL 109, 102501 (2012)
5. X.L. Yan et al. APJL 766, L8 (2013)
6. H.S. Xu et al., IJMS 349, 162 (2013)
7. X.L. Tu et al., J. Phys. G41, 025104 (2014)
8. W. Zhang et al., NIMA 756, 1 (2014)
9. B. Mei et al., Phys. Rev. C 89, 054612 (2014)
10. P. Shuai et al., Phys. Lett. B 735,327 (2014)

IMP,GSI,MSU,MPIK,RIKEN…

Precision achieved: 10^{-7}



43 masses are measured

Measured for the first time: 16

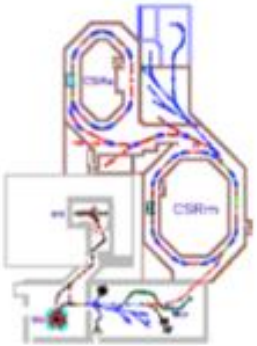
Precision improved: 27

Nuclear physics road map in China

1986
Beijing Tandem
HI-13

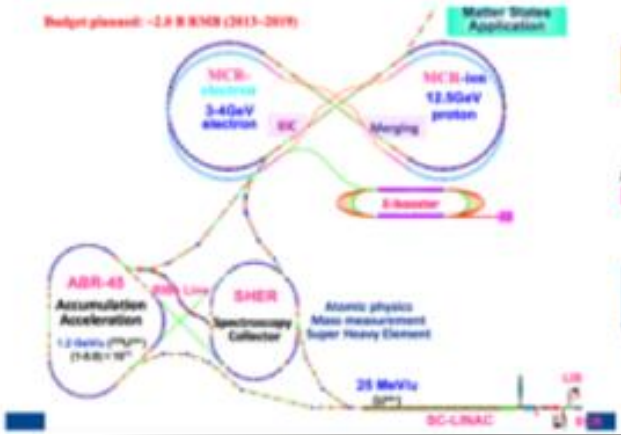
1988
Lanzhou cyclotron
SSC

2008
Lanzhou storage ring
CSR



2015
Beijing rare ion beam
BRIF

2020
Heavy ion application
HIAF



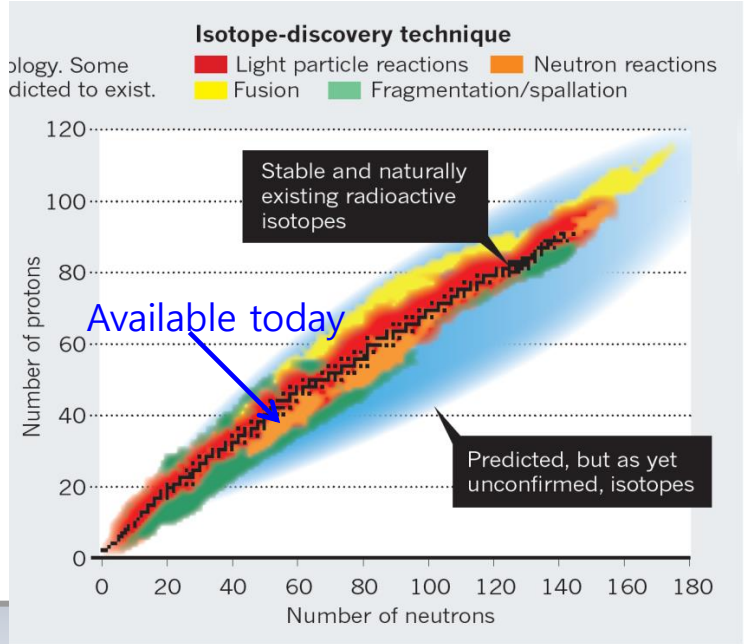
2025
:Beijing ISOL

High Intensity heavy ion Accelerator Facility

HIAF: One of 16 large-scale research facilities proposed in China in order to boost basic science, now under design optimization and technical R&D

- Proposed by IMP in 2009.
- Approved in principle by the central government in the end of the 2012 (700MUS$).
- Design Report(v1.0) was published in July 2014

Next-generation high intensity facilities are required for advances in nuclear physics and related research fields:



Fascinating and crucial questions

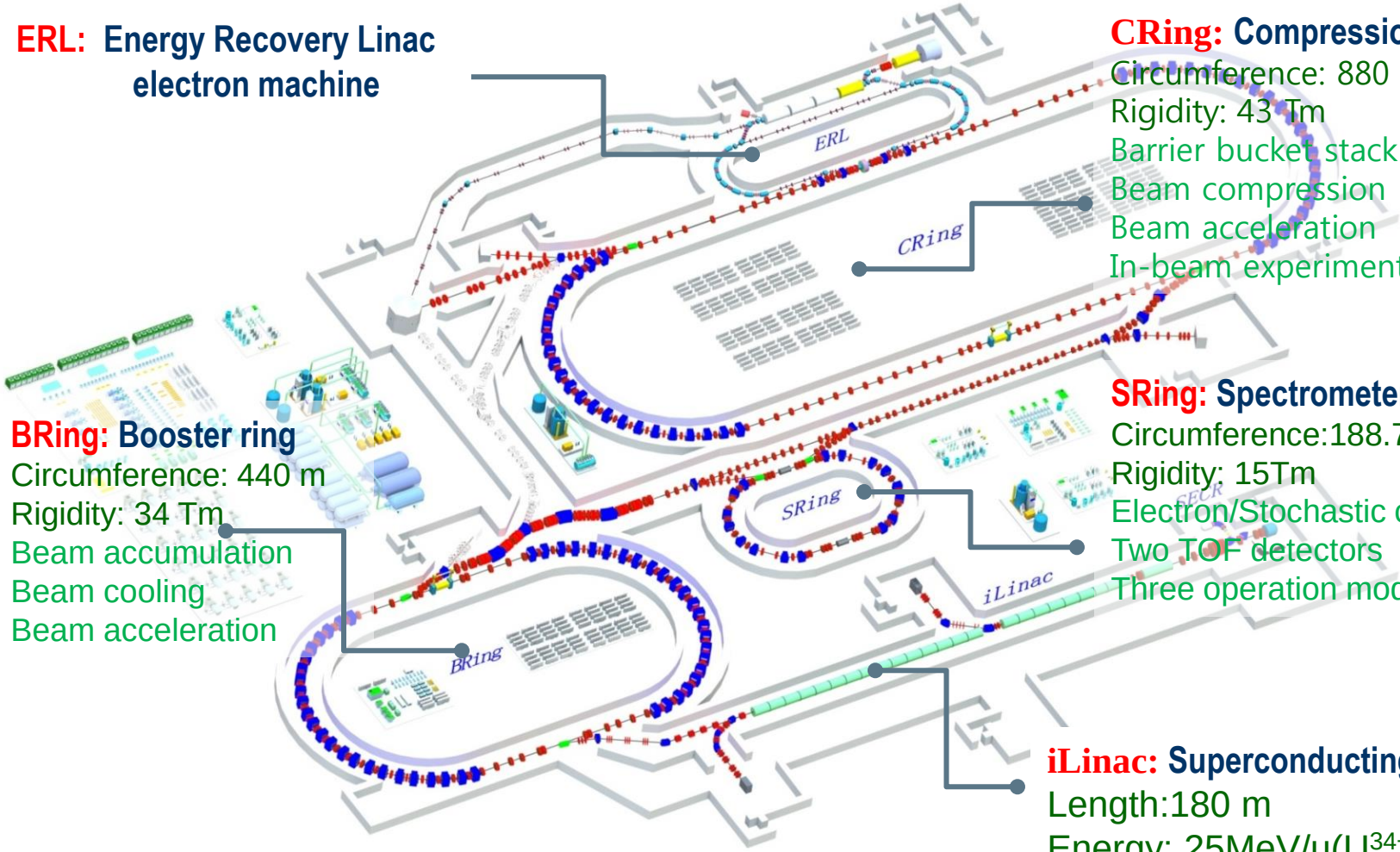
- To explore the limit of nuclear existence
- To study exotic nuclear structure
- Understand the origin of the elements
- To study the properties of High Energy and Density Matter

……

HIAF: Multi-purpose facility with unprecedented parameters

ERL: Energy Recovery Linac electron machine

CRing: Compression ring
Circumference: 880 m
Rigidity: 43 Tm
Barrier bucket stacking
Beam compression
Beam acceleration
In-beam experiment



BRing: Booster ring
Circumference: 440 m
Rigidity: 34 Tm
Beam accumulation
Beam cooling
Beam acceleration

SRing: Spectrometer ring
Circumference:188.7m
Rigidity: 15Tm
Electron/Stochastic cooling
Two TOF detectors
Three operation modes

iLinac: Superconducting linac
Length:180 m
Energy: 25MeV/u(U^{34+})

Multi-purpose facility with unprecedented parameters

Unprecedented beam Intensity(Comparison with HIRFL):

- Primary beam intensity increases by x 1000 – x 10000
- secondary beam intensity increases by up to x 10000

Precisely-tailored beams

- beam cooling (*Electron, Stochastic, laser; high quality, very small spot*)
- Beam compression (*Ultra-short bunch length: 50-100ns*)
- super long period slow extraction (*Super long, high energy, quasi-continuous beam*)

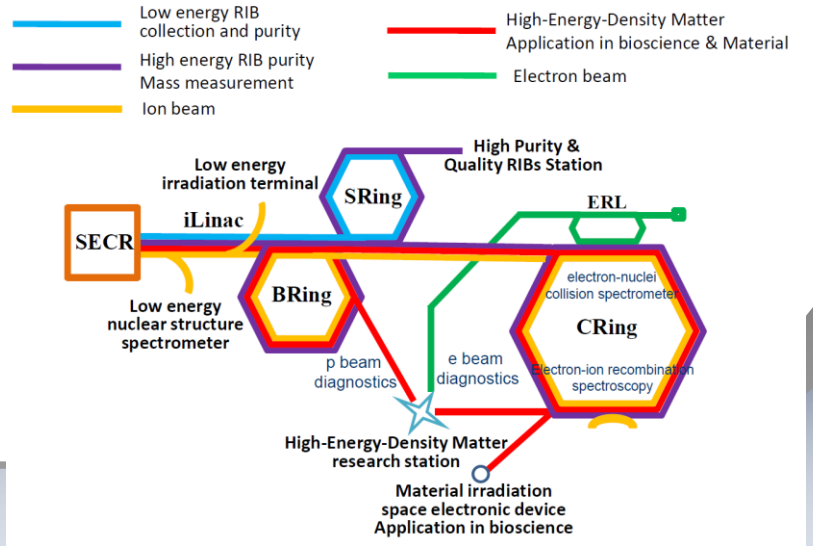
Wide beam Energy:

- heavy-ion energy : x 10 – x 15

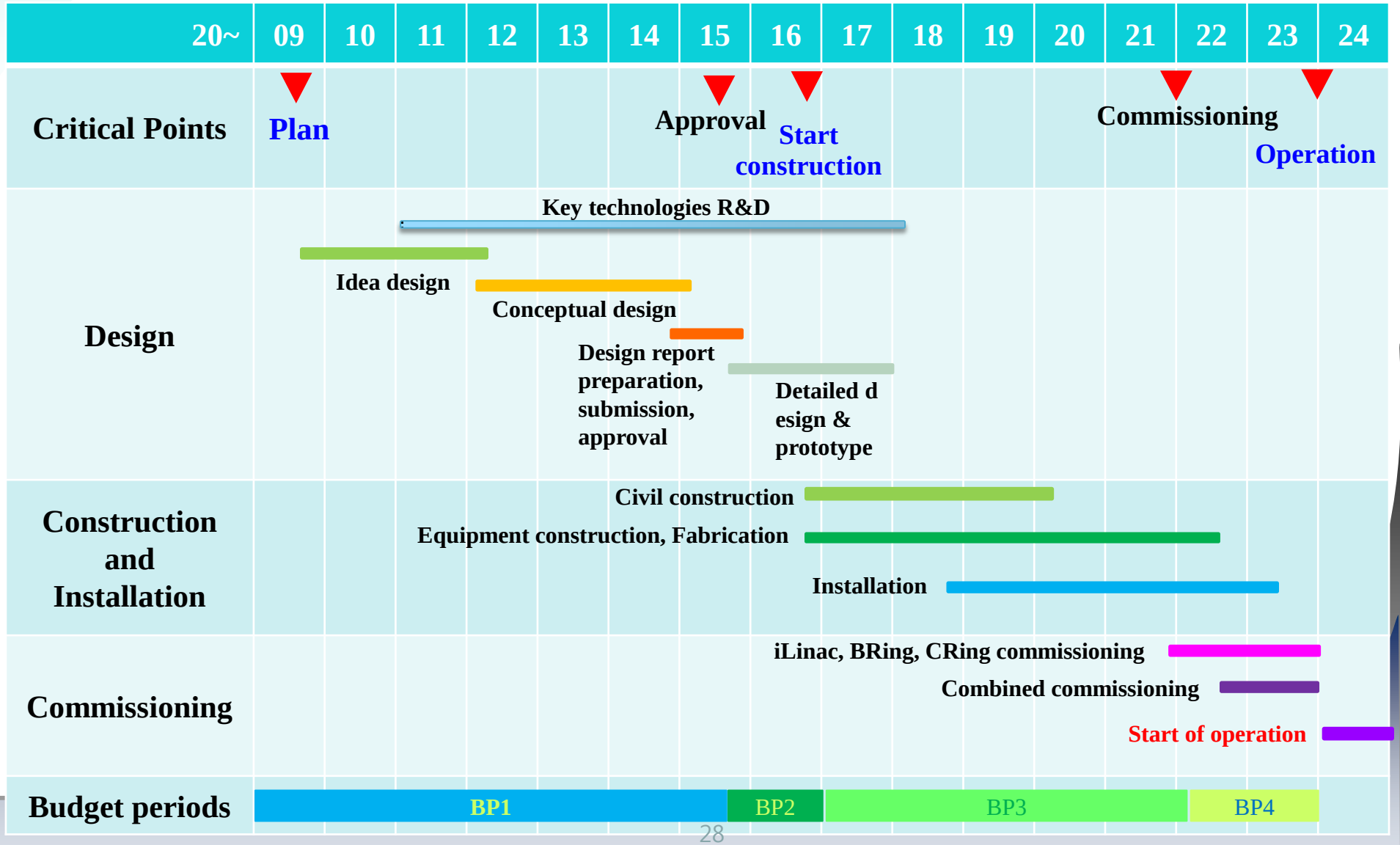
Versatile operation modes:

- parallel operation, beam splitting (*increase of target time, high integrated luminosity*)

	Ions	Energy	Intensity
SECR	U^{34+}	14 keV/u	0.05 pmA
iLinac	U^{34+}	25 MeV/u	0.028 pmA
BRing	U^{34+}	0.8 GeV/u	~1.4×10^{11} ppp
CRing	U^{34+}	1.1 GeV/u	~5.0×10^{11} ppp
	U^{92+}	4.1 GeV/u	~2.0×10^{11} ppp



Schedule for the HIAF (1st phase)



India

- Advanced National facility for Unstable and Rare Isotope Beams (ANURIB)
- Kolkata
- Variable Energy Cyclotron Center (VECC)

Main features of ANURIB facility
(Green field project costing around 200M US$)

1. 50 MeV, 2 mA electron linac photo-fission driver for production of neutron-rich RIBs

2. Proton-rich nuclei will be produced using a 50 MeV proton Cyclotron

3. Neutron & Positron Beam Facility

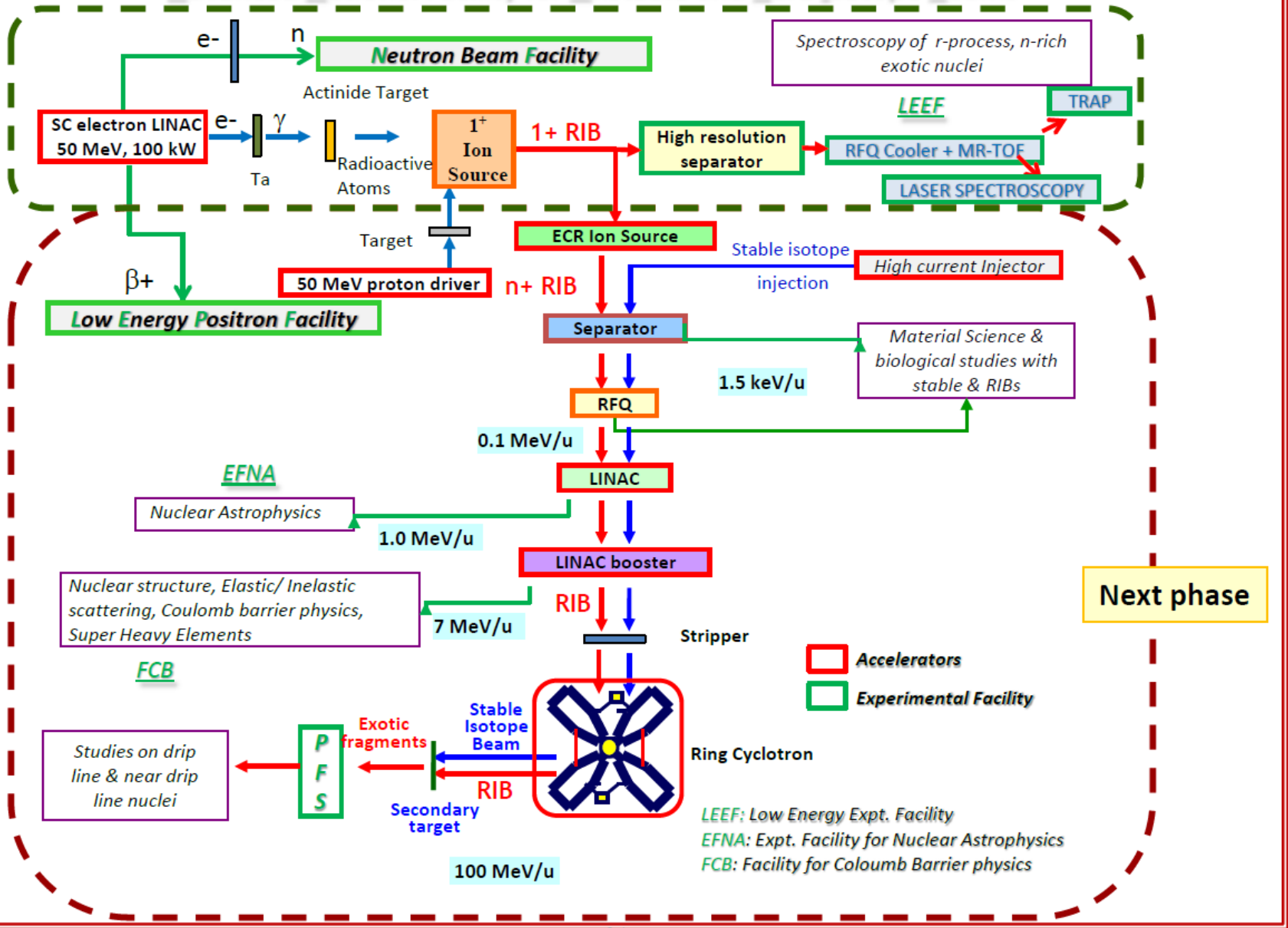
4. Both ISOL and Projectile Fragment Separator type facility

5. Will accelerate both radioactive and high intensity stable isotope beams

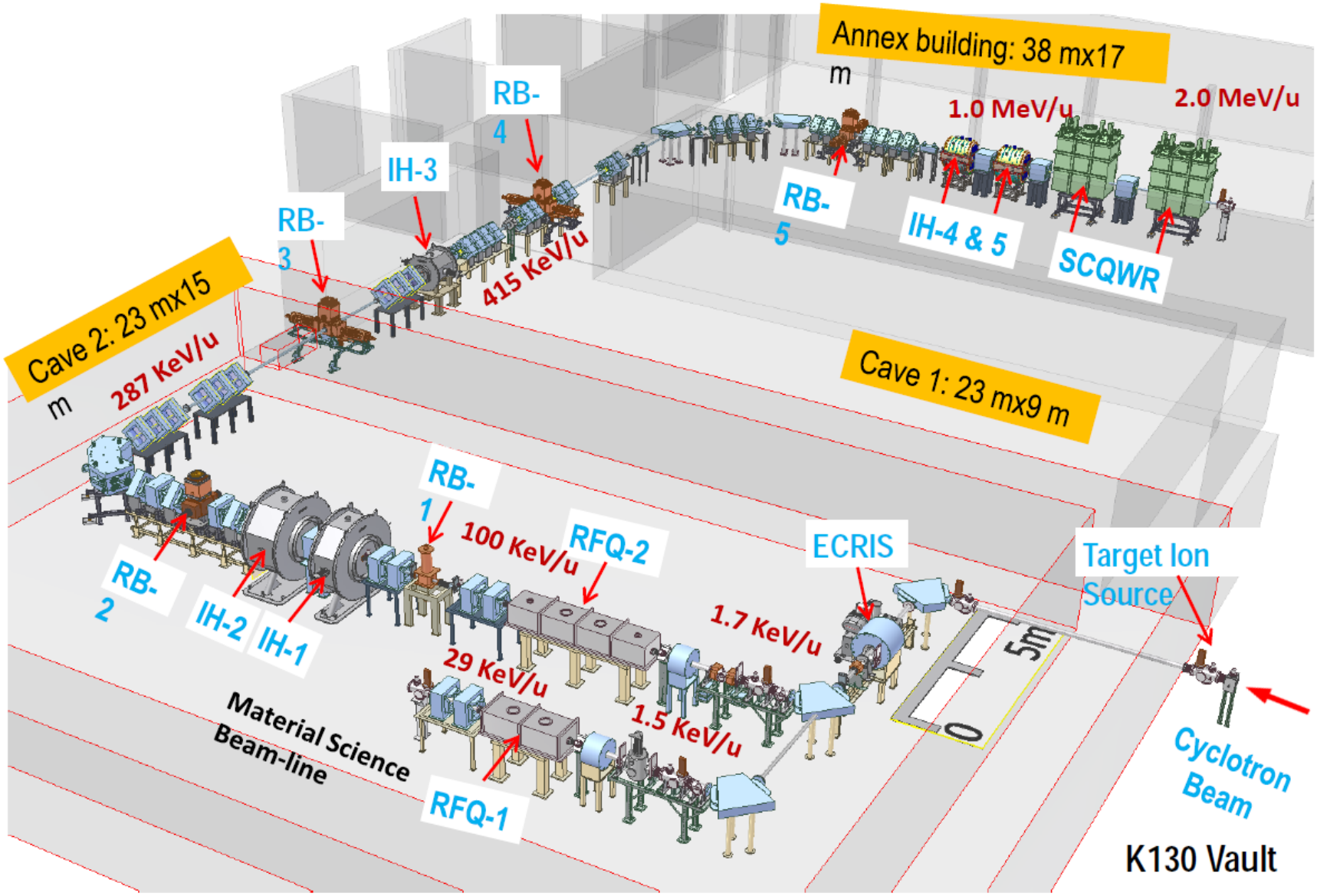
6. Fragmentation /fusion of radioactive ion beams to produce near drip-line n-rich /p-rich nuclei.

Schematic layout of ANURIB facility

Advanced National Facility for Unstable and Rare Isotope Beams

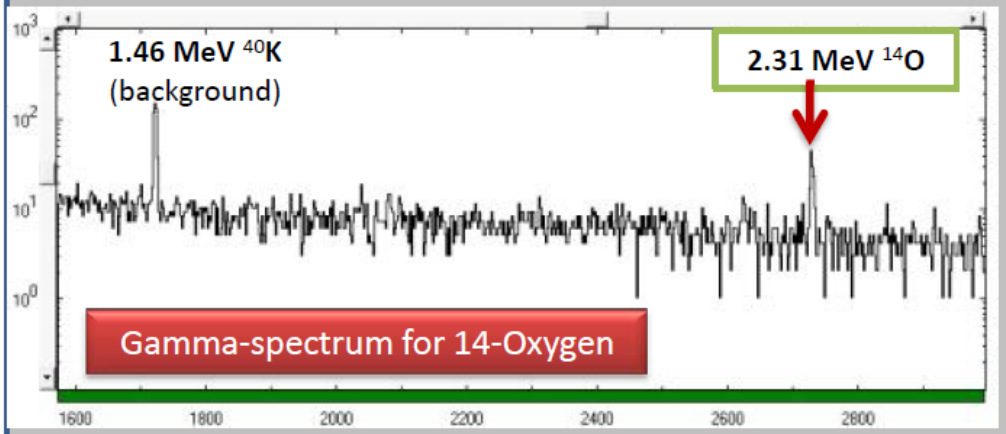


RIB facility at VEC Campus



RIBs produced so far

RIB	Prod. route	T1/2	I(pps) @ before RFQ	I(pps) @ after RFQ	Applications
^{14}O	$^{14}N(p, n)$	71 s	5.0×10^3	3.2×10^3	super-allowed beta decay, test of standard model; break-out reaction from hot CNO cycle to rp-process
^{42}K	$^{40}Ar(\alpha,pn)$	12.36 hr	2.7×10^3	-	bio-medical tracer
^{43}K	$^{40}Ar(\alpha,p)$	22.3 hr	1.2×10^3	-	bio-medical tracer
^{41}Ar	$^{40}Ar(\alpha,2pn)$	109 min	1.3×10^3	-	tracer used in engineering ; wear studies
^{111}In	$^{nat}Ag(\alpha,xn)$	2.8 days	1.6×10^3	-	Perturbed angular correlation spectroscopy, medical radio-tracer



Gamma-spectrum for 14-Oxygen

Optimized parameter	value
beam	$^{14}O^{2+}$
ECR ext. vol.	12.3 kV
RFQ power	10 kW cw
RFQ vane vol.	27 kV

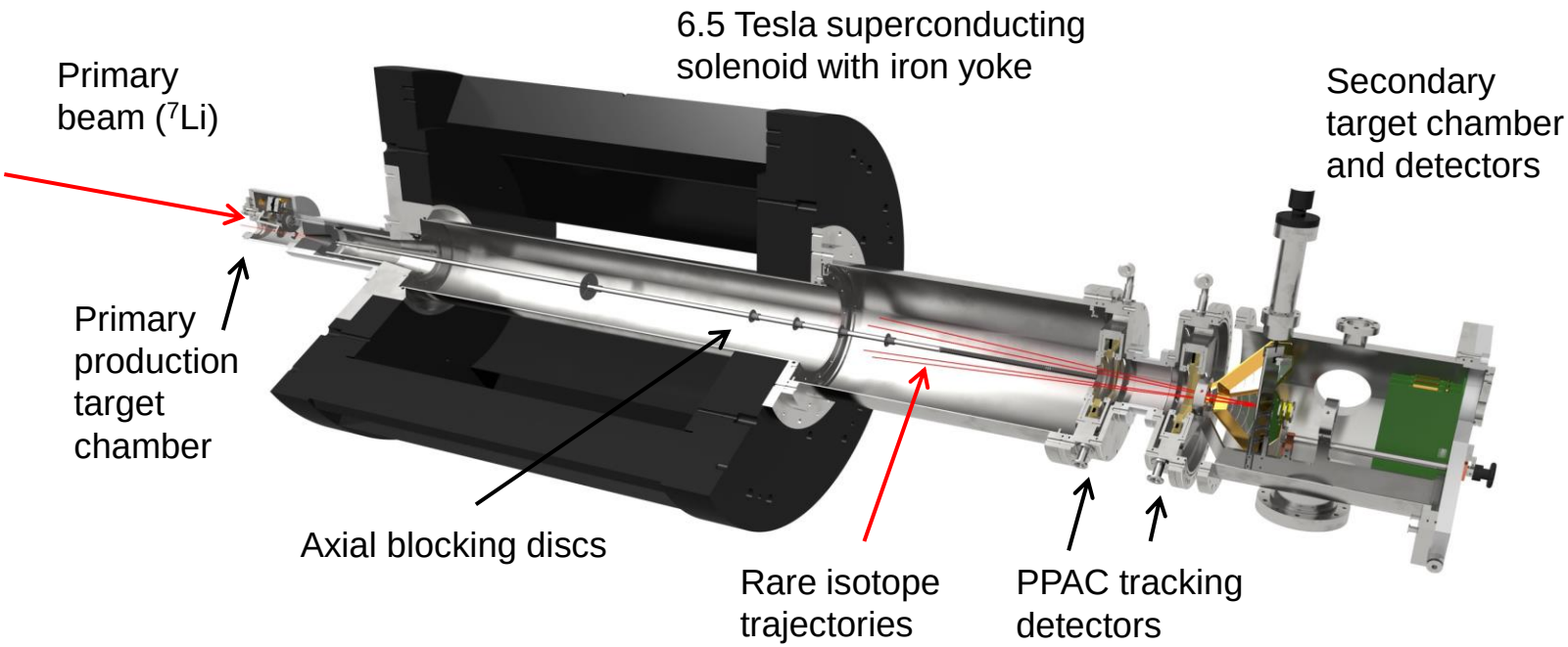
RFQ parameters for 14-Oxygen

Australia

- SOLenoid Exotic Rare iSOtOpe separator (SOLEROO Separator)
- Canberra
- Australian National University (ANU)

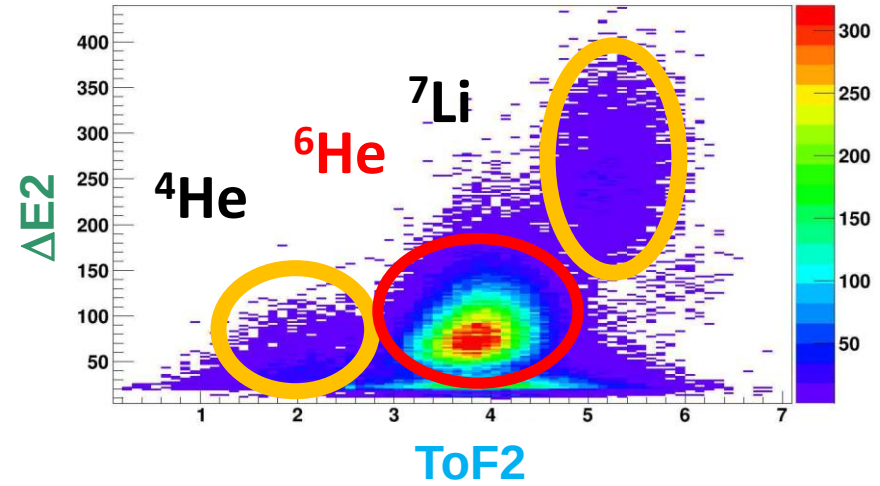
SOLEROO separator – solenoidal exotic rare isotope separator

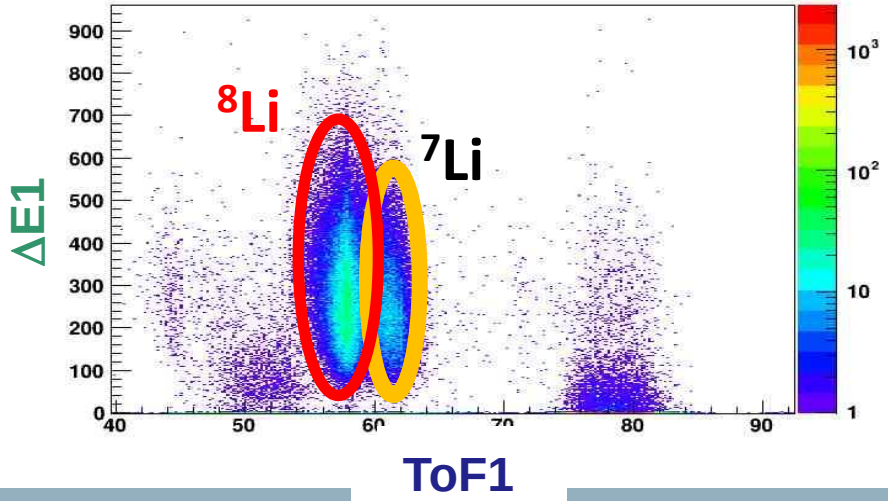
- ANU 15 MV tandem electrostatic accelerator
- ^{6,7}Li beams 10 to 60 MeV; ^{9}Be production target 2.8 mg cm^{-2}
- Superconducting solenoid: beam rejection and RIB refocusing
- Tracking detectors: trajectory reconstruction and particle i/d

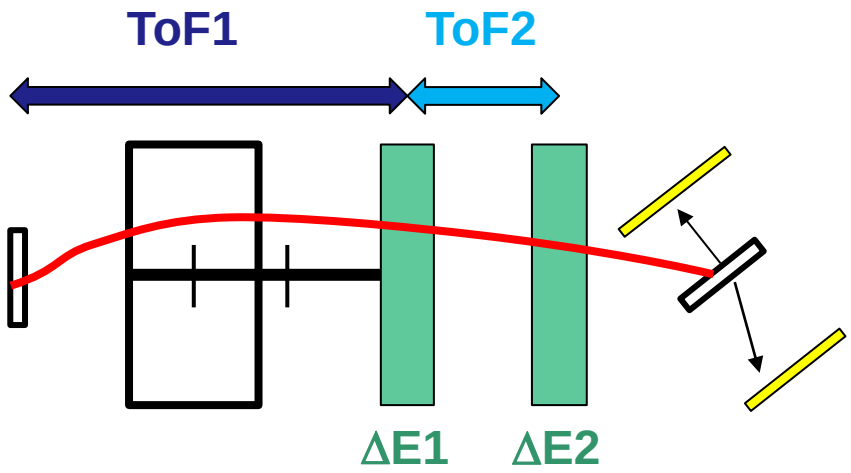


Another operating mode of SOLITAIRE (gas-filled fus-ev residue spectrometer)

PPAC Tracking detectors: time, 1mm position resolution







- $ToF \propto \sqrt{\frac{m}{E}}$
- $\Delta E \propto \sqrt{\frac{mz^2}{E}}$

PPACs handle rates > 10^6 /sec

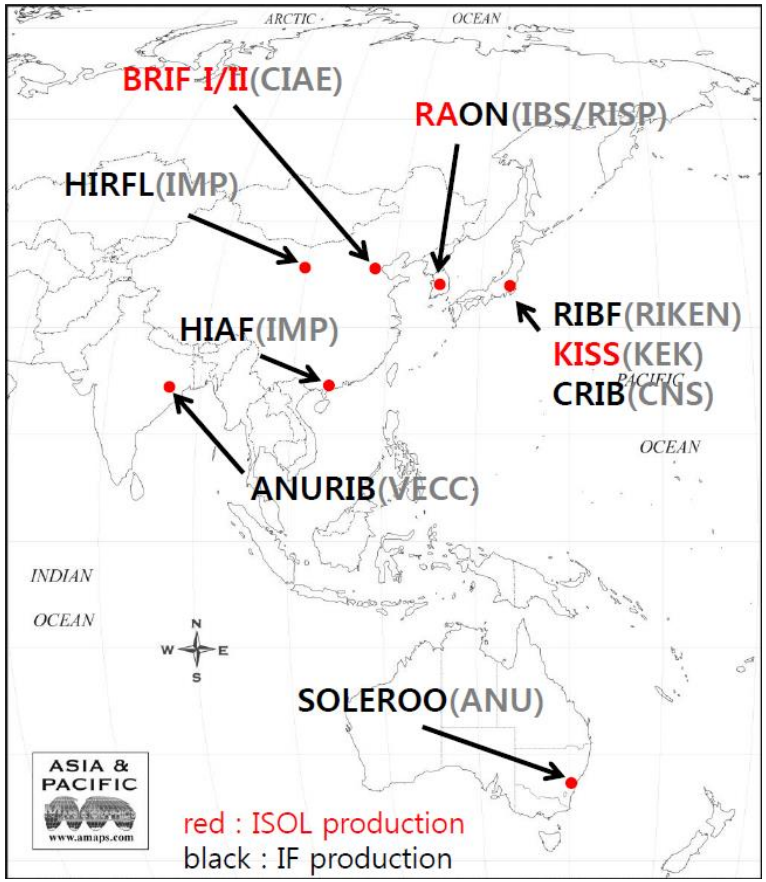
Provide tagging of desired RIB

- RIB intensities:
  - $^{6}He > 10^{5}$/sec
  - $^{8}Li > 10^{6}$/sec
- Tracking detectors:
  - Particle i/d: ΔE, ToF (DC or pulsed beam)
  - Reconstruction of trajectories:
    - Focal length ➡ energy resolution < 1 MeV
    - Secondary target interaction position < 2 mm
- Physics: compact DSSD 512 pixel detector array
- First physics experiment April 2015

In summary

- We can expect a fantastic landscape of RIB facilities in Asian within a decade, hopefully allowing our access to the edge of a large unknown area on the nuclear chart.
- Facility itself does not mean the success of science research: User-oriented management and organizations highly required and should be more largely expanded in Asia, starting from Japan to China, Korea, India, Australia …

Thanks to…



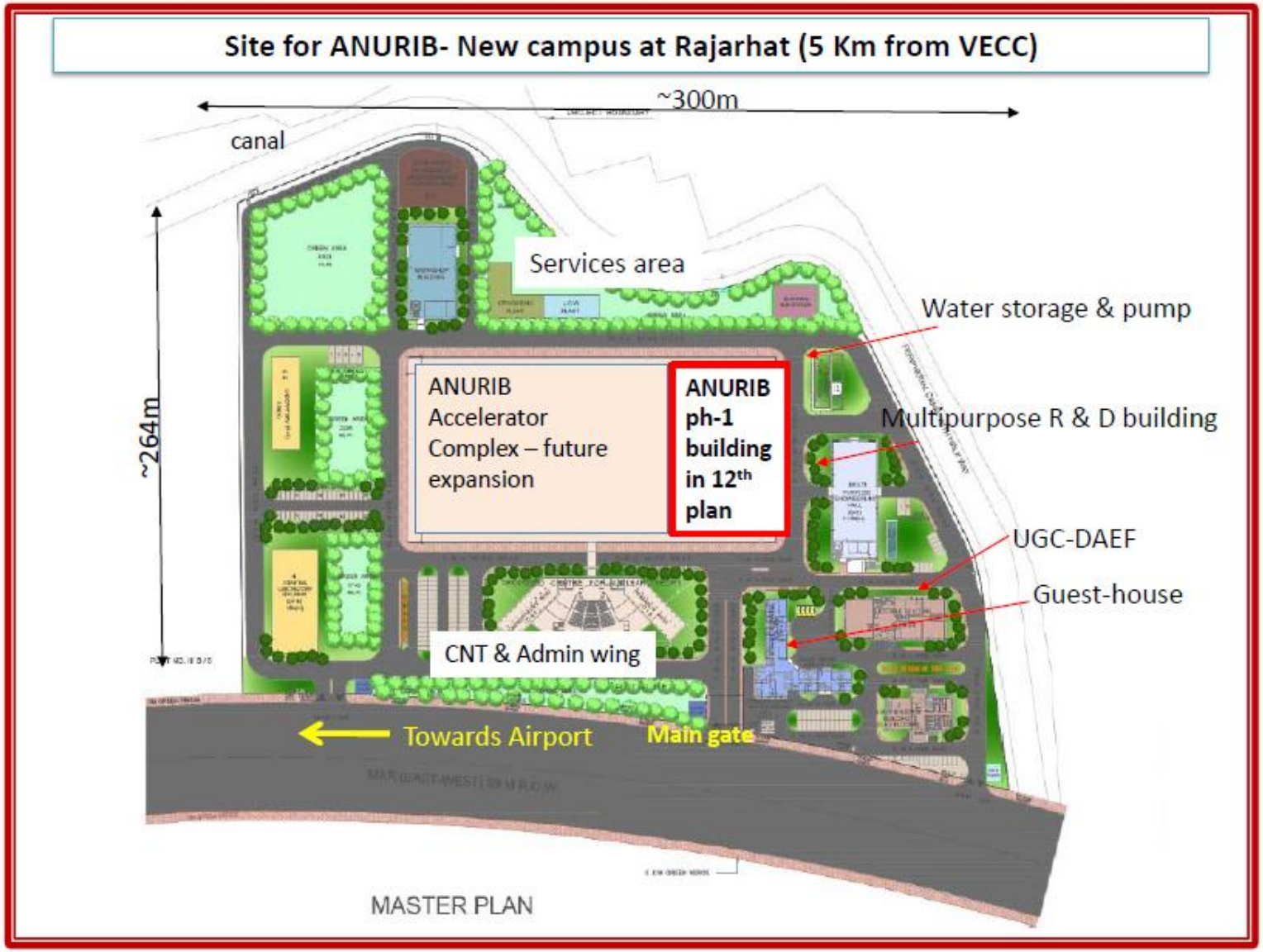
Korea: Yeong-Kwan Kwon (RISP)
China: Jiancheng Yang (IMP), Weiping Liu (CIAE)
India: Alok Chakrabarti (VECC)
Australia: David J. Hinde (ANU)
and others

Facilities under construction at a Glance

Facility	Institution (Country)	Driver	Post-acc.	Operation	RI production
RAON	IBS/RISP (Daejeon, Korea)	SC-Linac (IF) up to 200AMeV (^{238}U)		2021~	**ISOL+IF**
		Cyclotron (ISOL) proton, 70MeV, 70kW	SC-Linac up to20AMeV, up to 200AMeV		
HIAF	IMP (Huizhou, Guangdong China)	i-Linac up to 25AMeV (^{238}U) BRing – CRing up to 4.1AGeV (^{238}U)	Synchrotron	2024~ (Phase I)	**IF** & **ECS**
ANURIB	VECC (Kolkata, India)	SC electron Linac Electron, 50MeV, 100kW	Linac booster up to 7AMeV Cyclotron up to 100AMeV	2017~ (Phase I)	**ISOL** (photo-fission)
SOLEROO	ANU (Canberra, Australia)	Tandem 10 to 60 MeV (^{6,7}Li)		2015~	**IF**

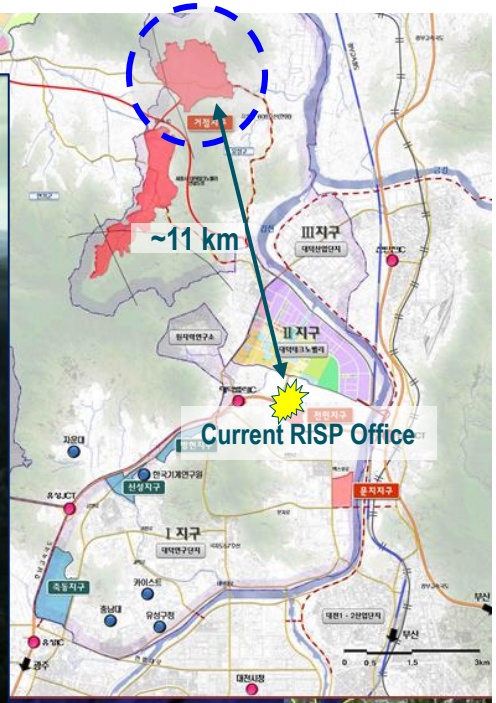
Thank you for your attention !

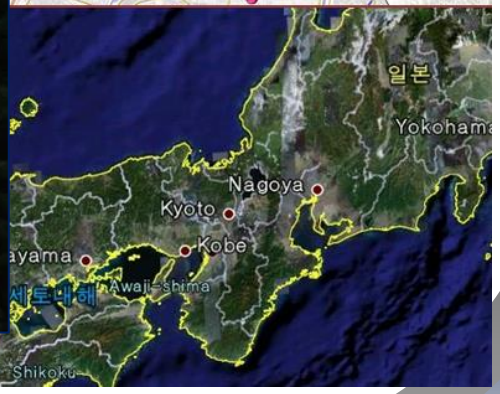
Closing by Bird's-eye site view…



RAON Site


Bird's-eye view
Area (Lot/Bldg): 952,066 m² / 130,257 m²


~11 km
Current RISP Office
III지구
II지구
I지구


일본
Yokohama
Nagoya
Kyoto
Kobe
Awaji-Shima
Shikoku
Fukuoka

Site of HIAF project-new campus

Huizhou, Guangdong

Site of HIAF project-new campus