TRIUMF / VECC collaboration towards ARIEL / ANURIB

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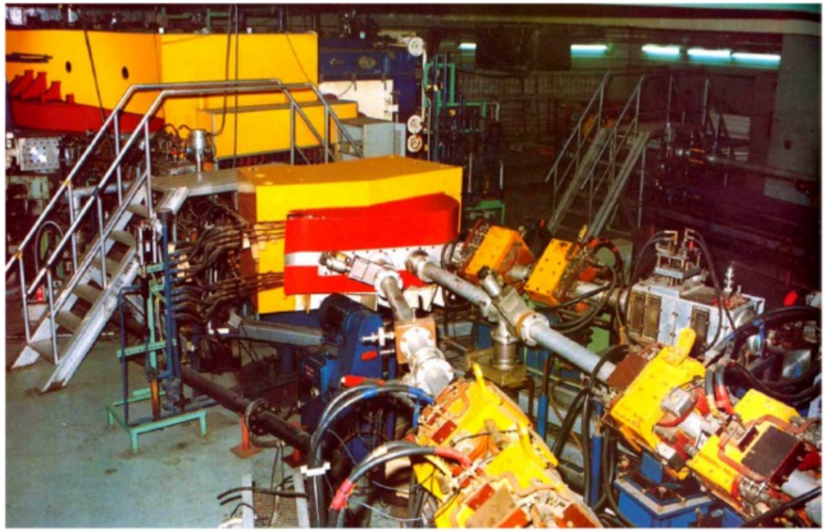
Professor – Homi Bhabha National Institute (HBNI)

TRIUMF SCIENCE WEEK – JULY 31ST TO AUGUST 4TH , 2023

Variable Energy Cyclotron Centre (VECC) – Our cyclotrons

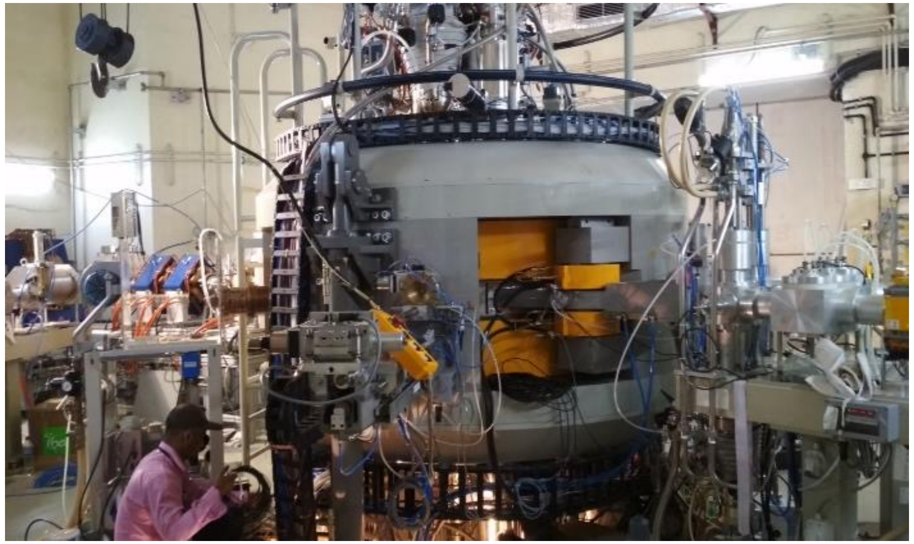


Room Temperature Cyclotron: June 1977

Proton	${}^{1}_{1}H$	7-12.5
Alpha	${}^{4}_{2}He$	28-50
Nitrogen	${}^{14}_{7}N$	105-140
Oxygen	${}^{16}_{8}O$	116-160
Neon	${}^{20}_{10}Ne$	145-192
Sulphur	${}^{32}_{16}S$	218

Superconducting Cyclotron: Dec 2020

Nitrogen	${}^{14}_{7}N$	252
Oxygen	${}^{16}_{8}O$	309
Neon	${}^{20}_{10}Ne$	360 - 436



Medical Cyclotron – September 2018

Proton	${}^{1}_{1}H$	15-30 MeV 350 μA

Beam energies are in MeV

Research goals of Variable Energy Cyclotron Centre (VECC)

Basic Sciences:
- Exp. Nuclear Physics (Low & High energy) using Accelerators
- Theoritical Nuclear Physics

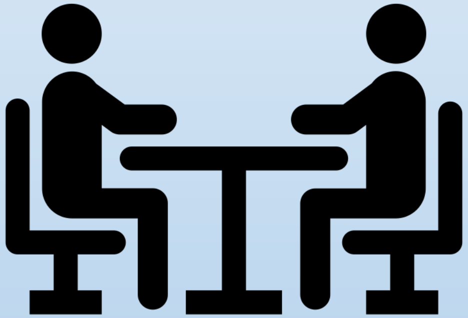
Accelerator based applied research:
- Material Science
- Radiation damage studies

Accelerator research:
- Indigenous accelerator development
- R&D on Advanced Accelerators

Accelerator applications:
- Medical cyclotron for radioisotope production

Technology development:
- RF / SRF
- Detector & DAQ
- Instrumentation
- Power Electronics
- Mechanical
- Cryogenics
- Computer, IT & Computer control

Collaboration



TRIUMF

Distance 11,431 km

Flying time 14h 20m + 2h

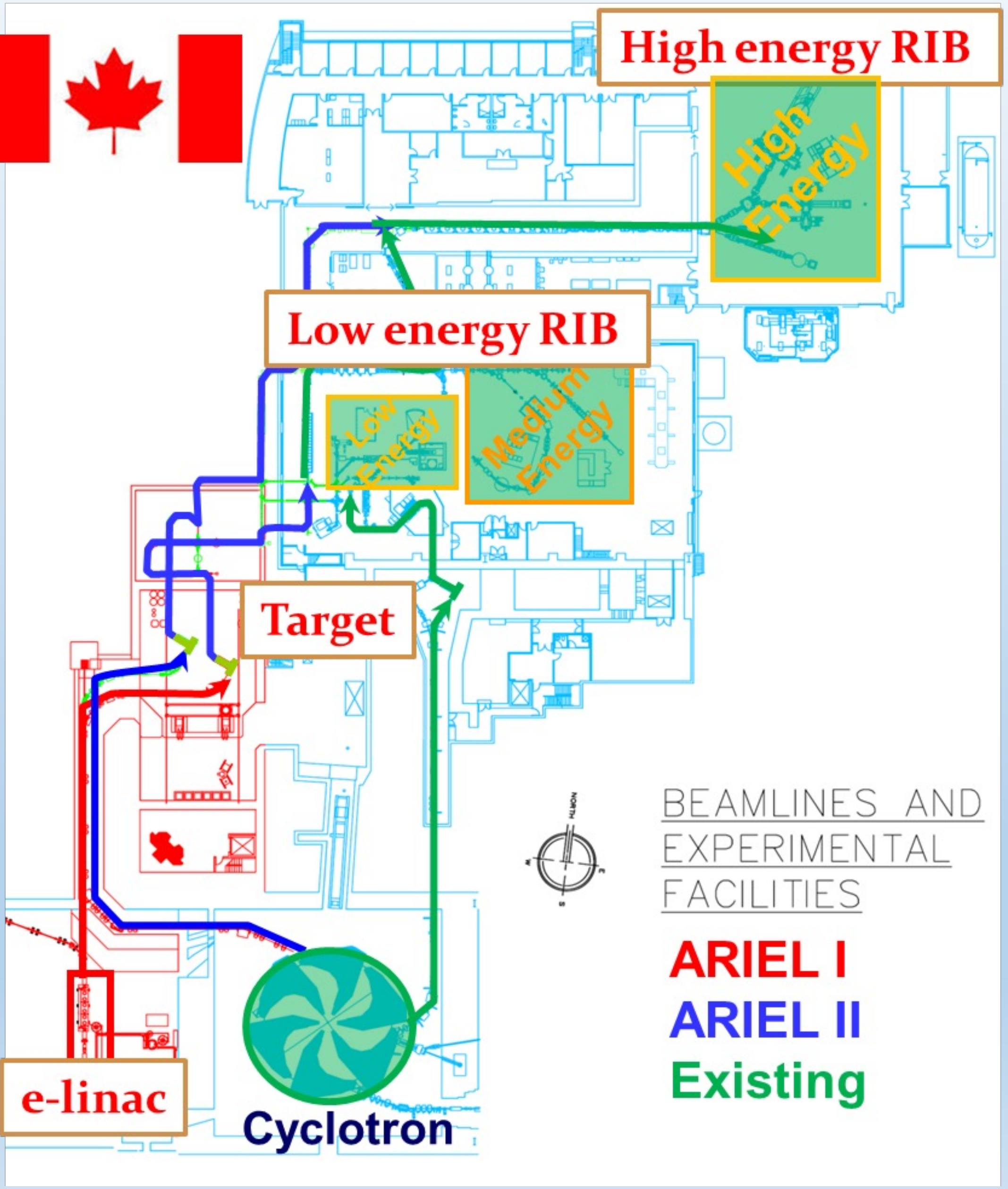
VECC

Advanced Rare Isotope Laboratory (ARIEL)

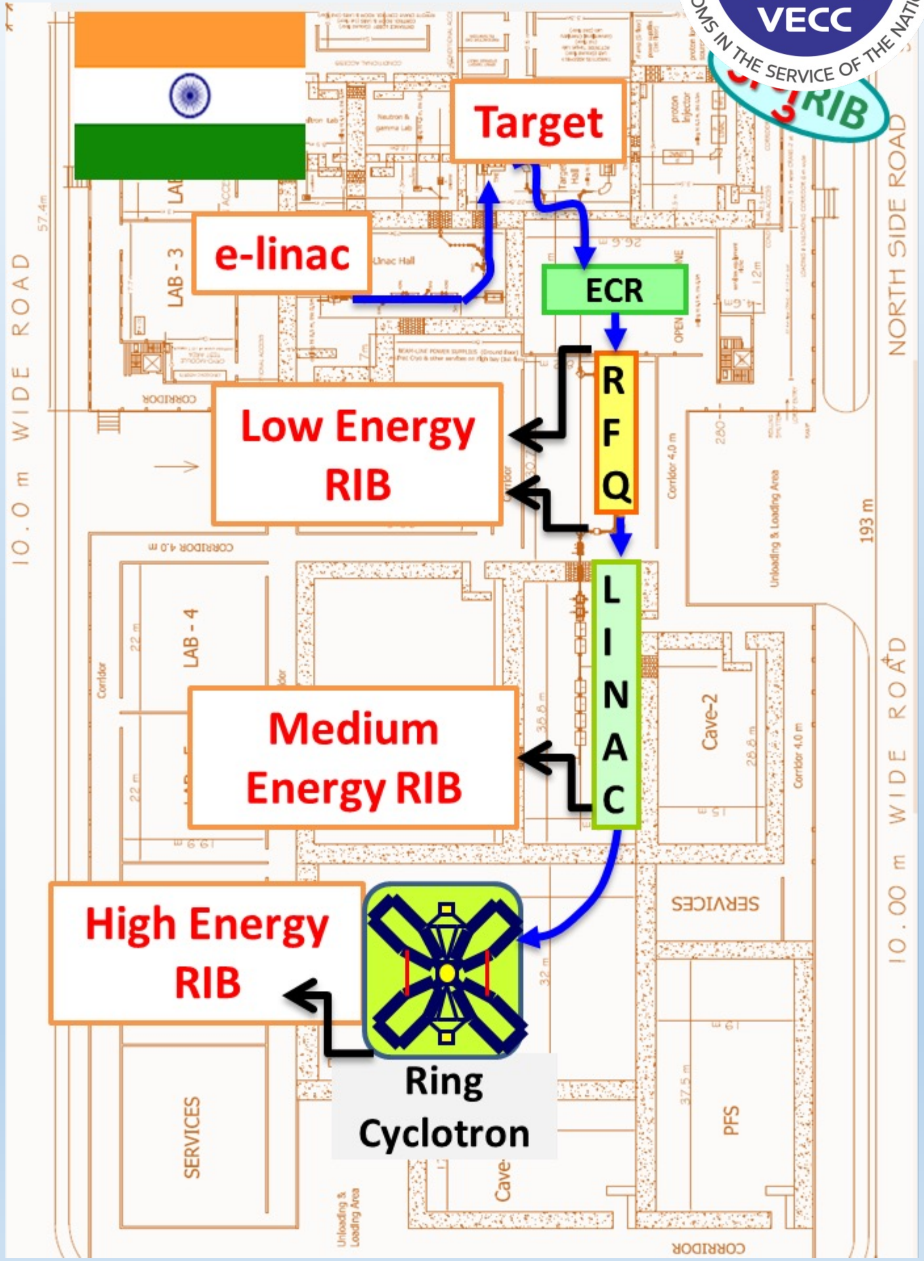
Applied and NUclear Research using Rare Isotope Beams (ANURIB)

- **ISOL Post-accelerator type of RIB Facility**
- **Cyclotron and e-LINAC are primary accelerators**
- **Specialised target stations and Separation stage**
- **Linear accelerators (NC & SC) as post-accelerators**

TRIUMF



High energy RIB
High Energy
Low energy RIB
Low Energy
Medium Energy
Target
e-linac
Cyclotron
BEAMLINES AND EXPERIMENTAL FACILITIES
ARIEL I
ARIEL II
Existing



Target
e-linac
ECR
RFQ
Low Energy RIB
LINAC
Medium Energy RIB
High Energy RIB
Ring Cyclotron
10.0 m WIDE ROAD
NORTH SIDE ROAD
LAB - 3
LAB - 4
Cave-2
SERVICES
PFS
193 m

International workshop on Production of Radioactive Ion Beams (PRORIB-2001), Puri, India

- ISAC operations
- Beam dynamics simulation For ISAC QWRs
- Design of IH LINAC for VECC

Bikash Sinha **Paul Schmor**

Umbrella MOU between VECC and TRIUMF → August 7th, 2008

Nigel Lockyer Bikash Sinha

TRIUMF Canada's National Laboratory for Particle and Nuclear Physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

VECC DAE

FOR IMMEDIATE RELEASE **AUGUST 07, 2008, 12:00PM PDT**

TRIUMF forges new research and technology partnership with India

VANCOUVER, BC (August 7, 2008) – TRIUMF, Canada's national laboratory for particle and nuclear physics, today announced the signing of a Memorandum of Understanding with the Variable Energy Cyclotron Centre (VECC) from Kolkata, India to establish a technology, research and trade partnership in advanced materials, physics, and life sciences technologies.

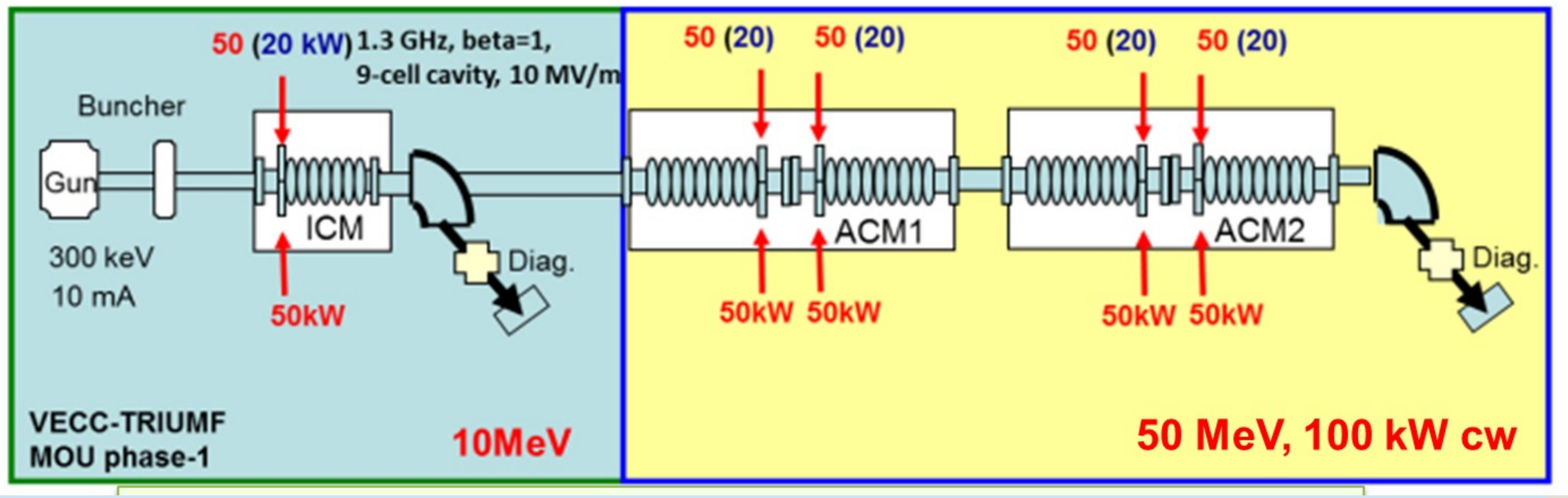
Addendum-1 to MOU

Addendum-2 to MOU between VECC and TRIUMF → July 9th, 2009

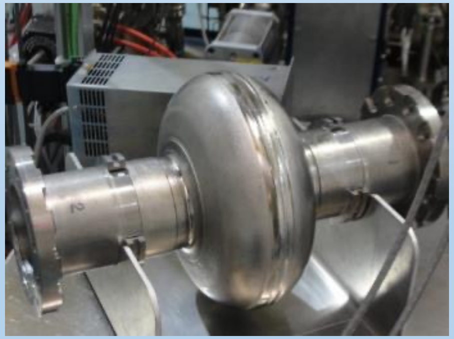
Goal of Addendum-2 to the MOU was to jointly develop & test Injector Cryo-module at TRIUMF – two units will be built & tested - One for VECC & for TRIUMF

Total project cost : 6.264 M CAN $ **Timeline : April -2012**

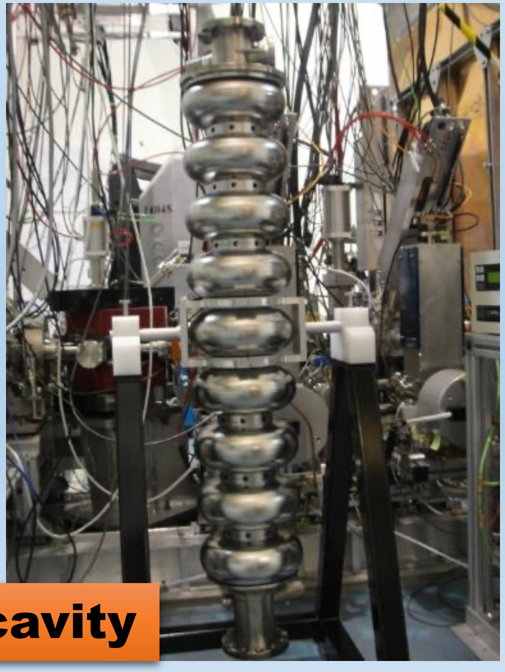
Super-conducting electron LINAC Development



Nine cell SC electron LINAC for production of RIBs using photofission route
Acc. Grad ~ 10 MV/m

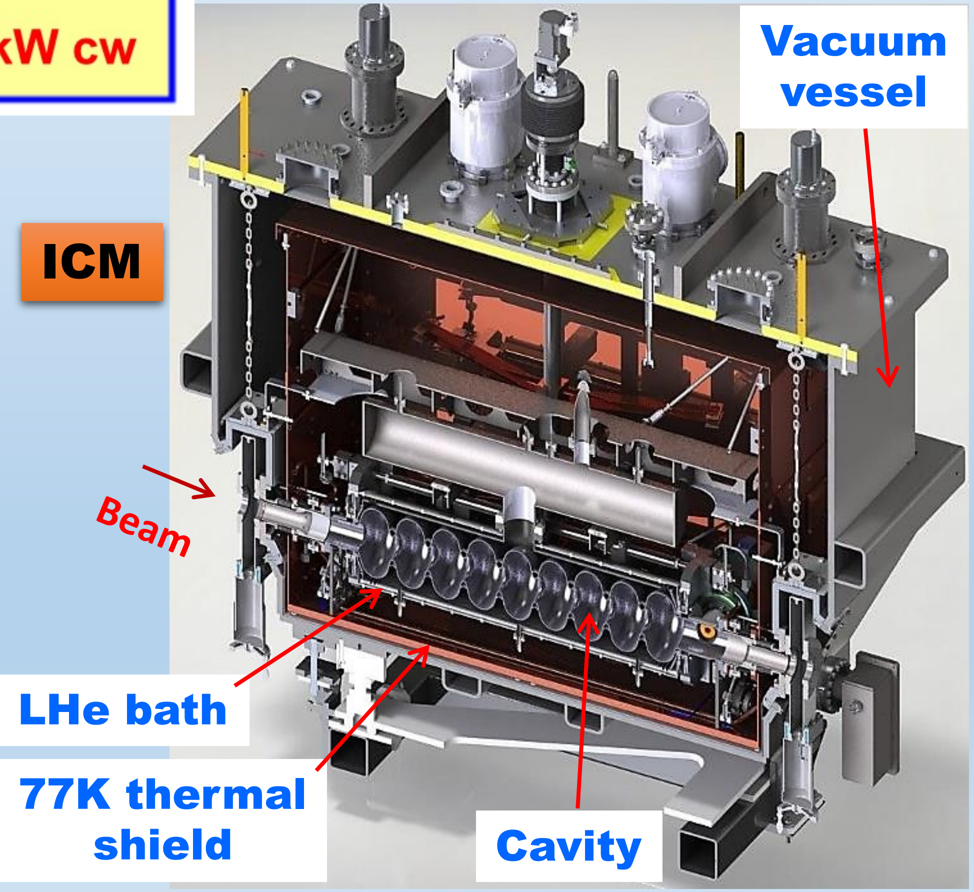


Single cell cavity



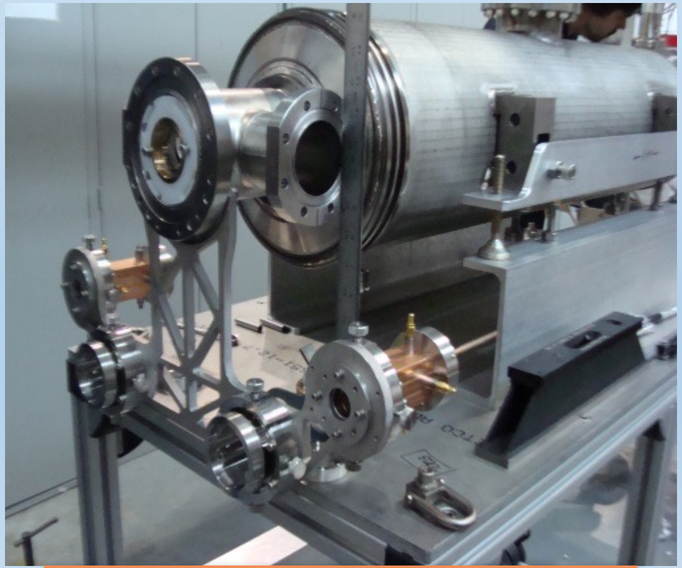
9-cell cavity

ICM

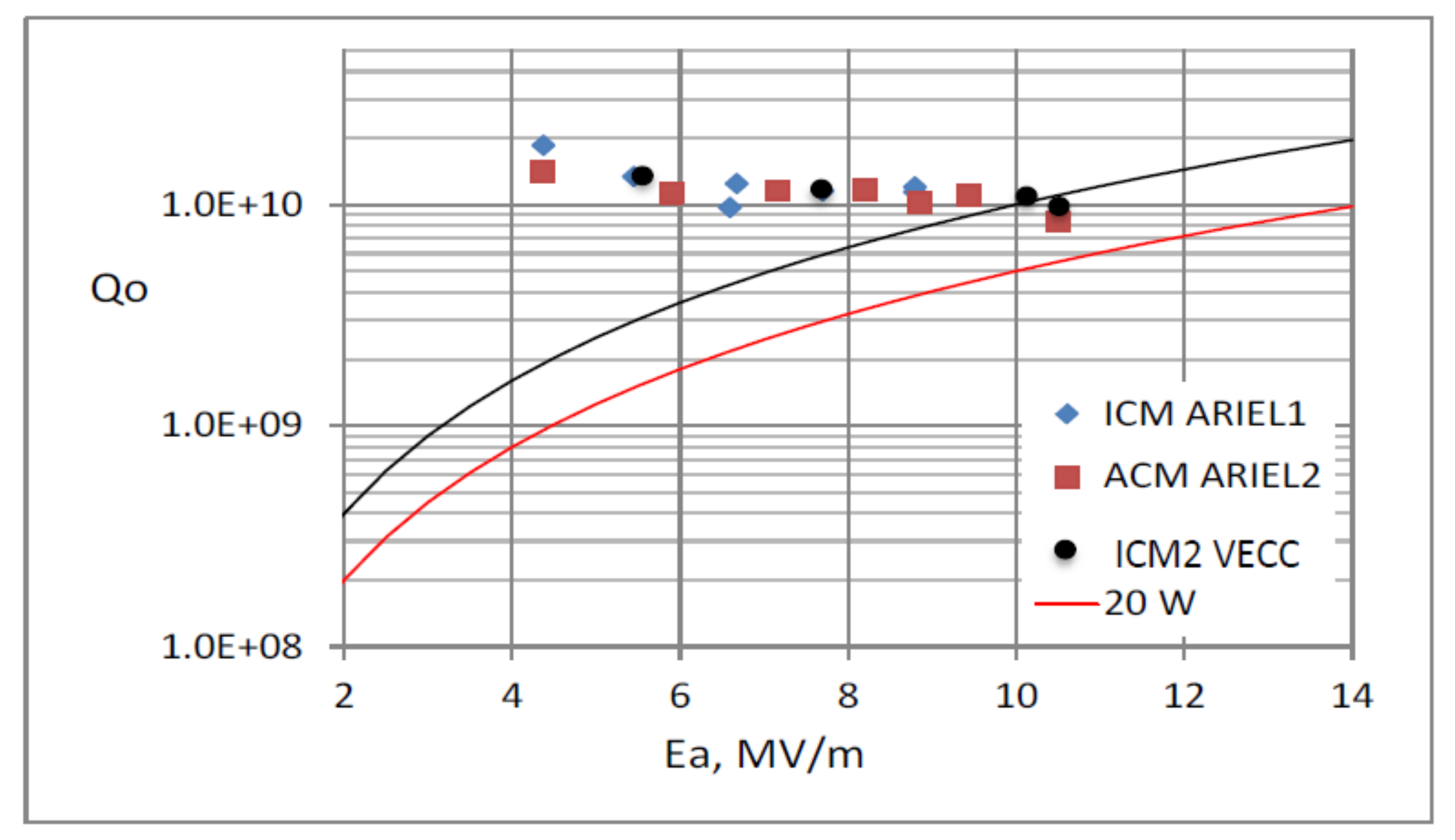


SC e- LINAC Development

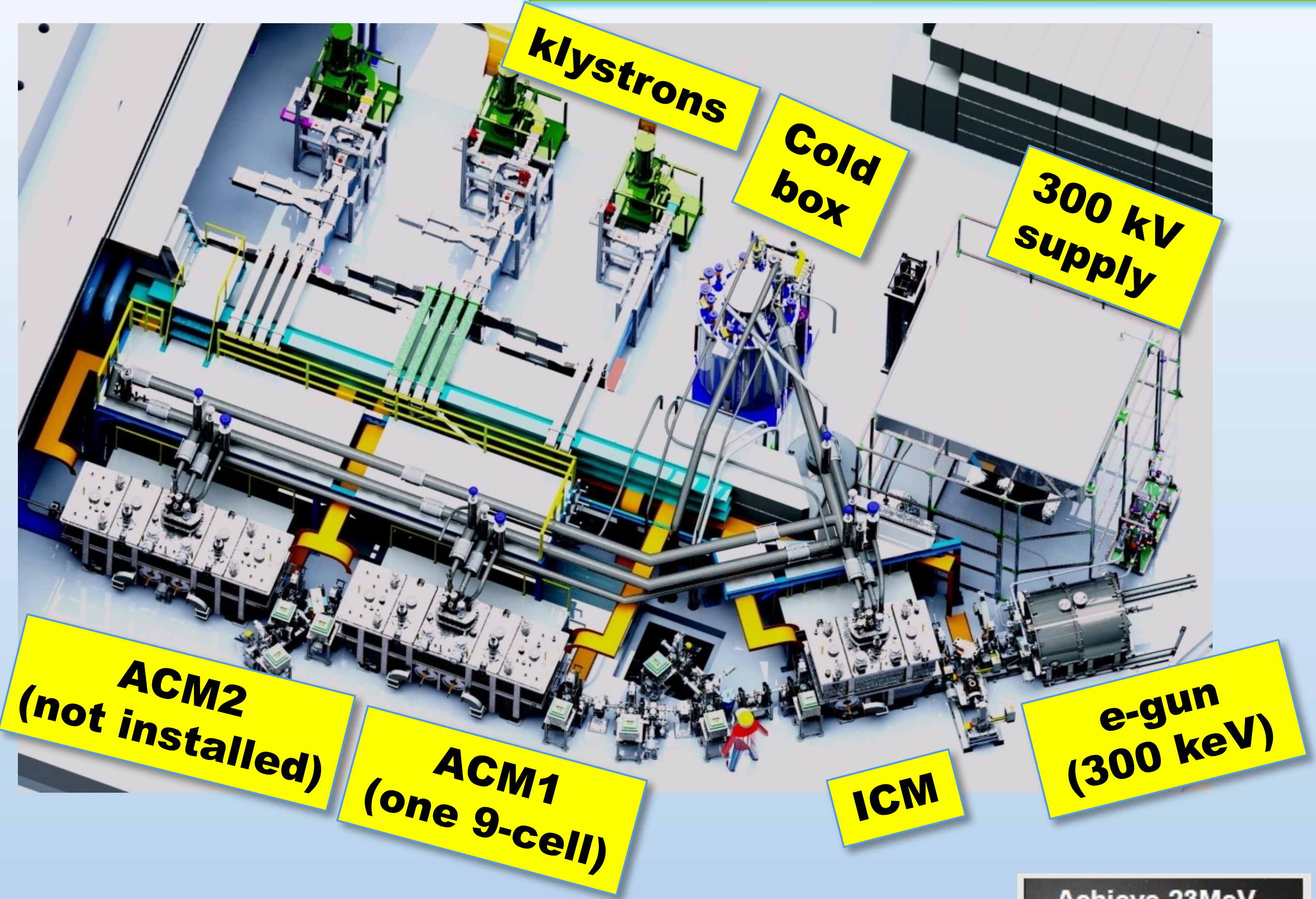
9-cell cavity inspection

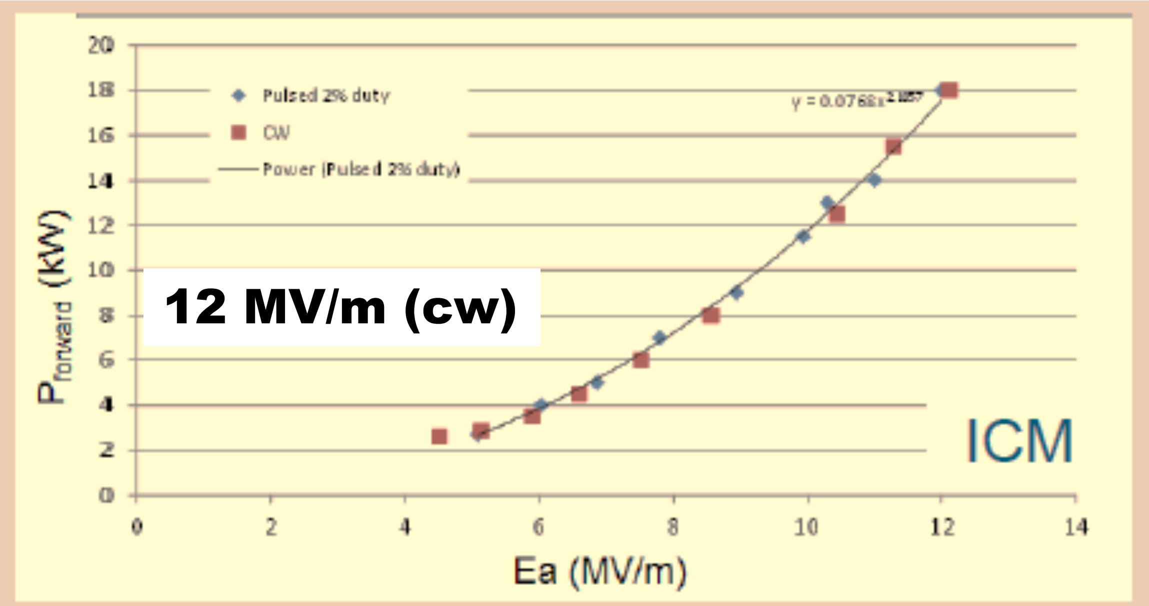


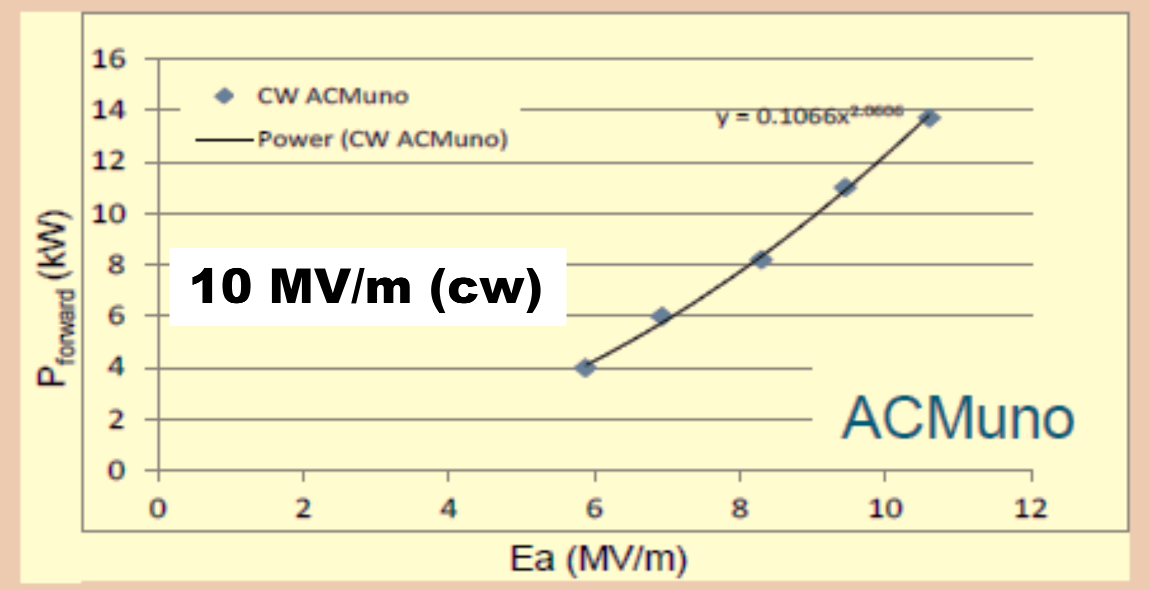
Dressed 9-cell cavity



Super-conducting electron LINAC Development







First beam accelerated to 22 MeV / 10 μA on 29th Sept 2014

Beam test of VECC cavity was done on 28th Oct 2016

Science with rare isotope beams (SCRIBE) organized at VECC in year 2012 & 2014

Addendum-3 to MOU between VECC and TRIUMF → August 8th, 2013

The goal of Addendum-3 to the MOU is to jointly design, develop and test

- **high power Actinide target/ converter modules – two numbers**
- **Radioactive ion extraction systems – two numbers**
- **Actinide target R&D, simulations and experiments**
- **One low beta heavy ion LINAC cryomodule**

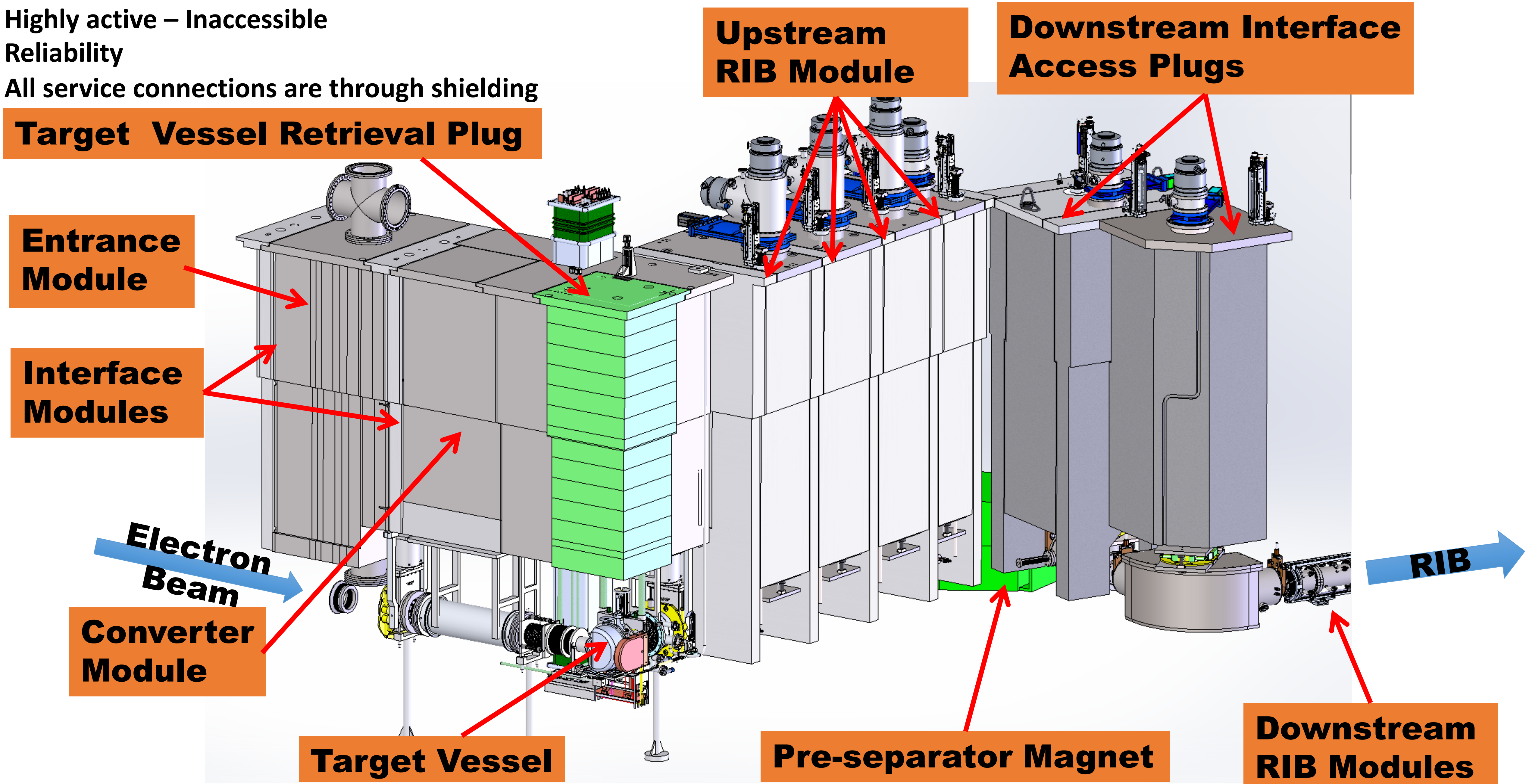
Total project cost : 6.3 M CAN$ **Timeline : Dec -2016**

D.K. Srivastava

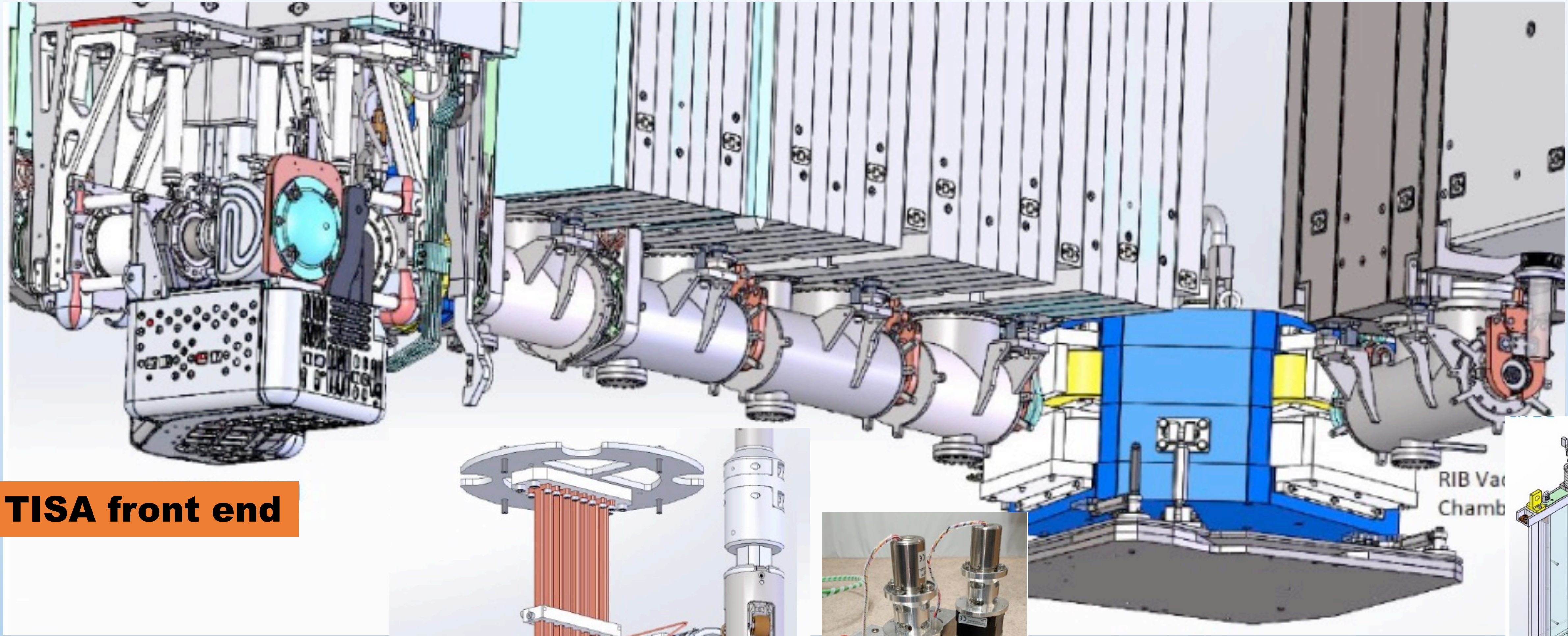
N. Lockyer

Target and Radioactive Ion Extractor Module

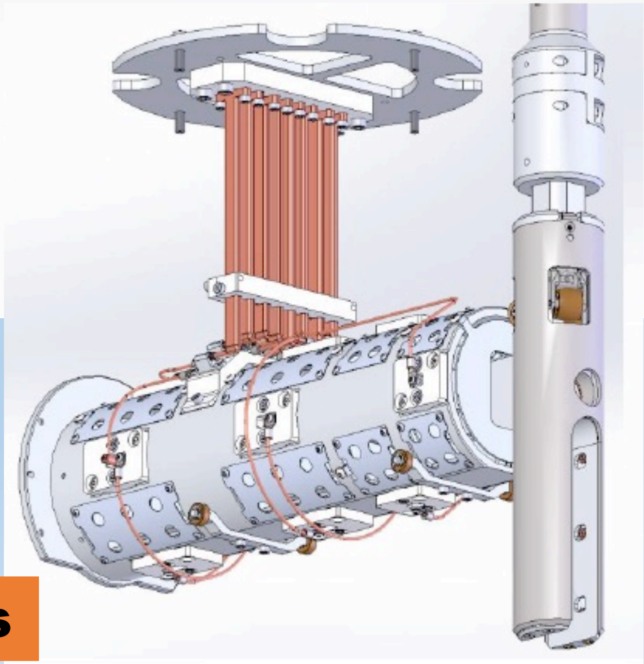
Highly active – Inaccessible
Reliability
All service connections are through shielding



Target and Radioactive Ion Extractor Module

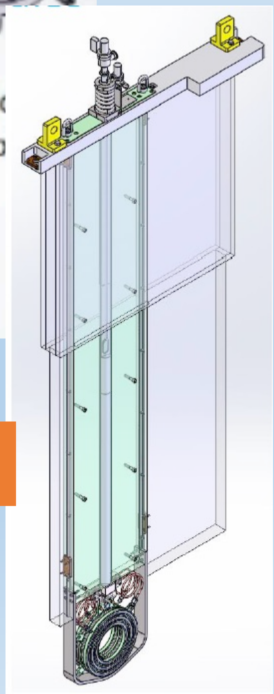


TISA front end



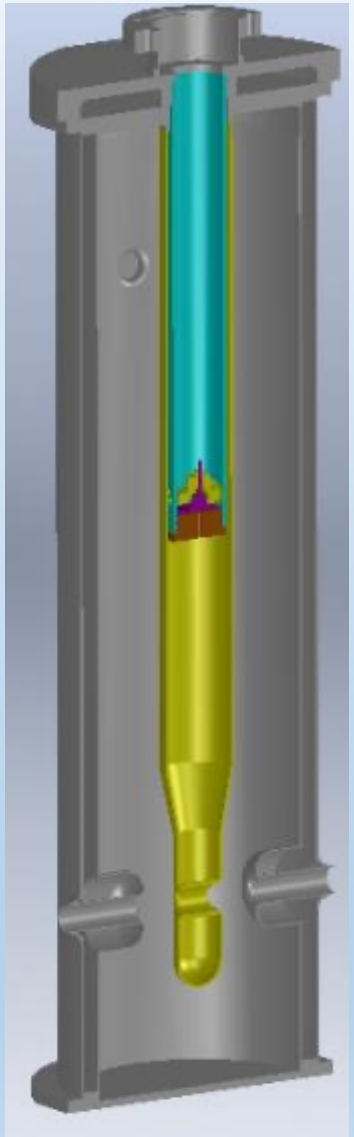
ES Quad Triplets

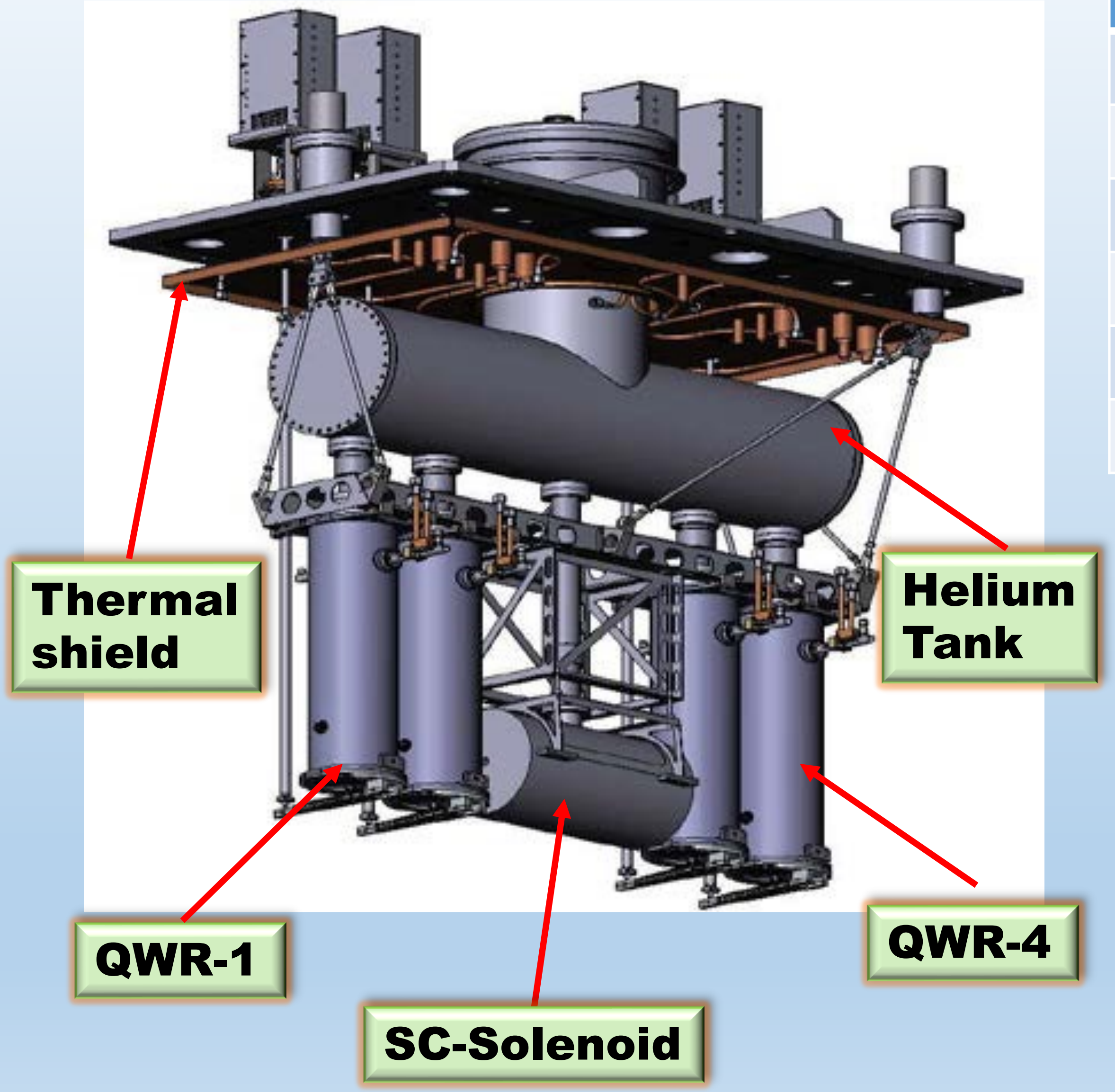
Diagnostics



Pillow seal

Super-conducting Quarter Wave Resonator (QWR) Development





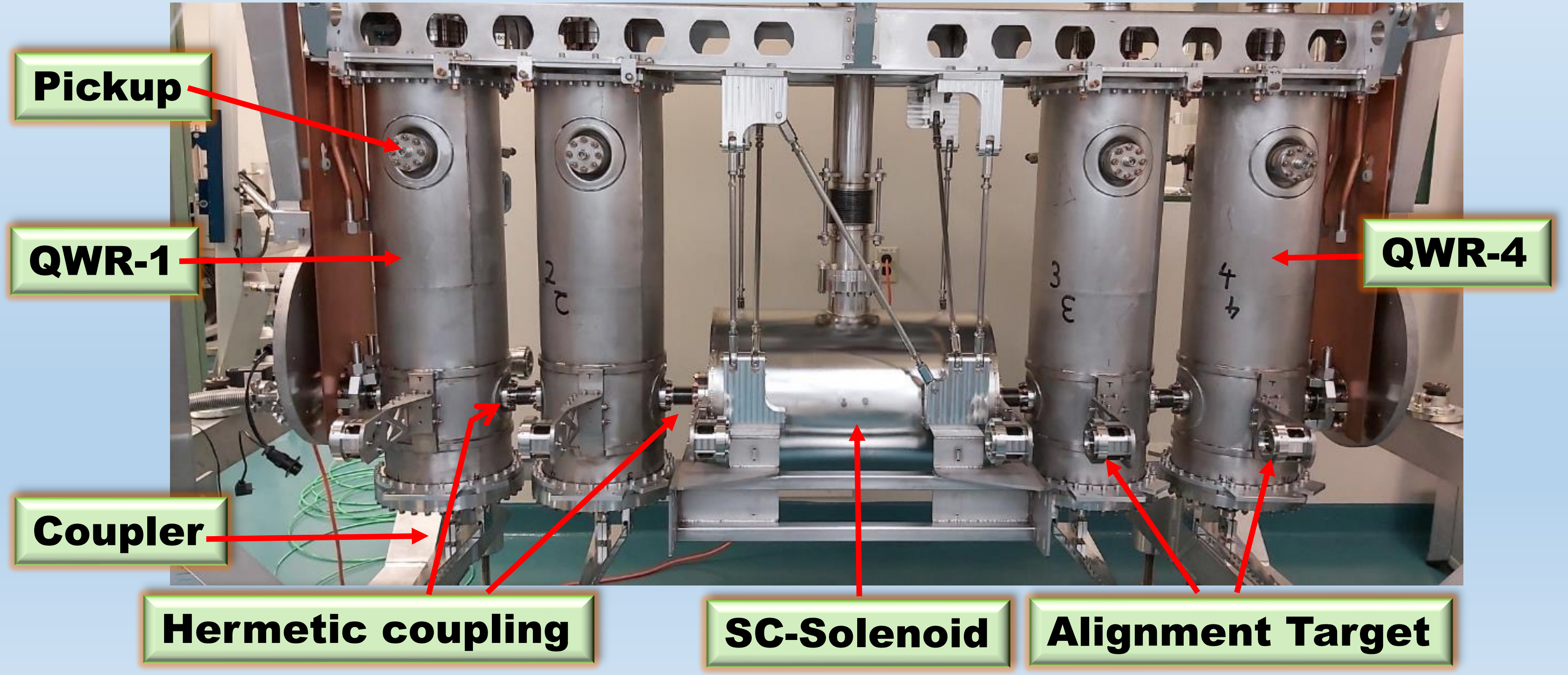
Design Parameters	Unit	Value
Frequency	MHz	113.61
β_0	%	5.5
No. of resonators		8
Energy @ Entry	MeV/u	1.038
Energy @ Exit	MeV/u	2.0
Acceln. Grad.	MV/m	5

Parameter	Unit	Value
$E_{Peak}/E_{Accel.}$	-	~4.6
$B_{Peak}/E_{Accel.}$	mT/(MV/m)	~8.5
$U/E^2_{Accel.}$	J/(MV/m)²	0.051
R_{Shunt}/Q	Ohm	491.3

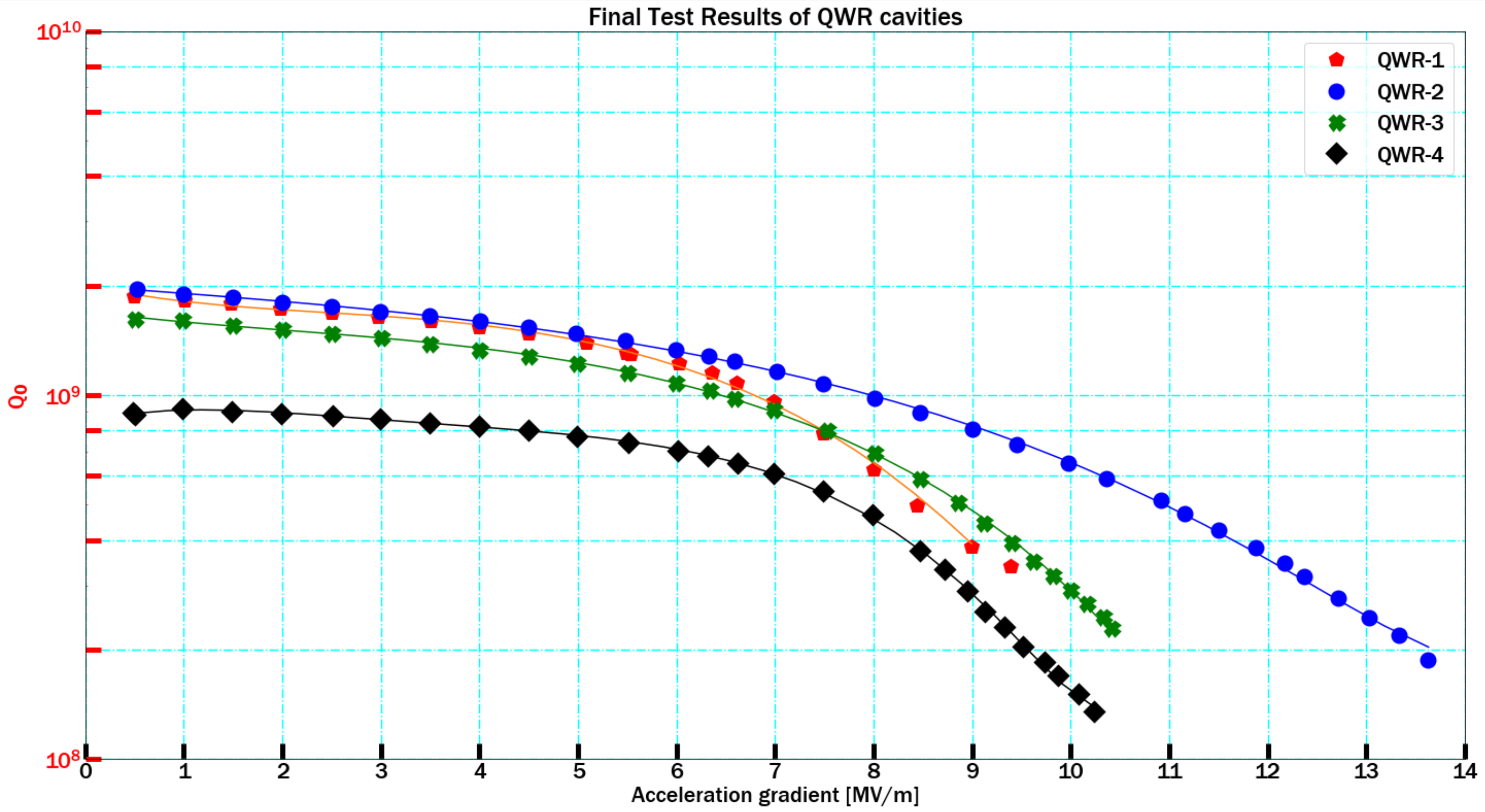
Super-conducting Quarter Wave Resonator (QWR) Development

The cryo-module vacuum and beam space vacuum are separate: Helps to avoid contamination of RF surfaces & long time performance degradation (??)

Only the "cold mass" needs to be assembled on the "strong back" & sealed inside class-100 clean room
The assembly within the cryo-module can be done inside class-1000 room with required infrastructure.



Super-conducting Quarter Wave Resonator (QWR) Development



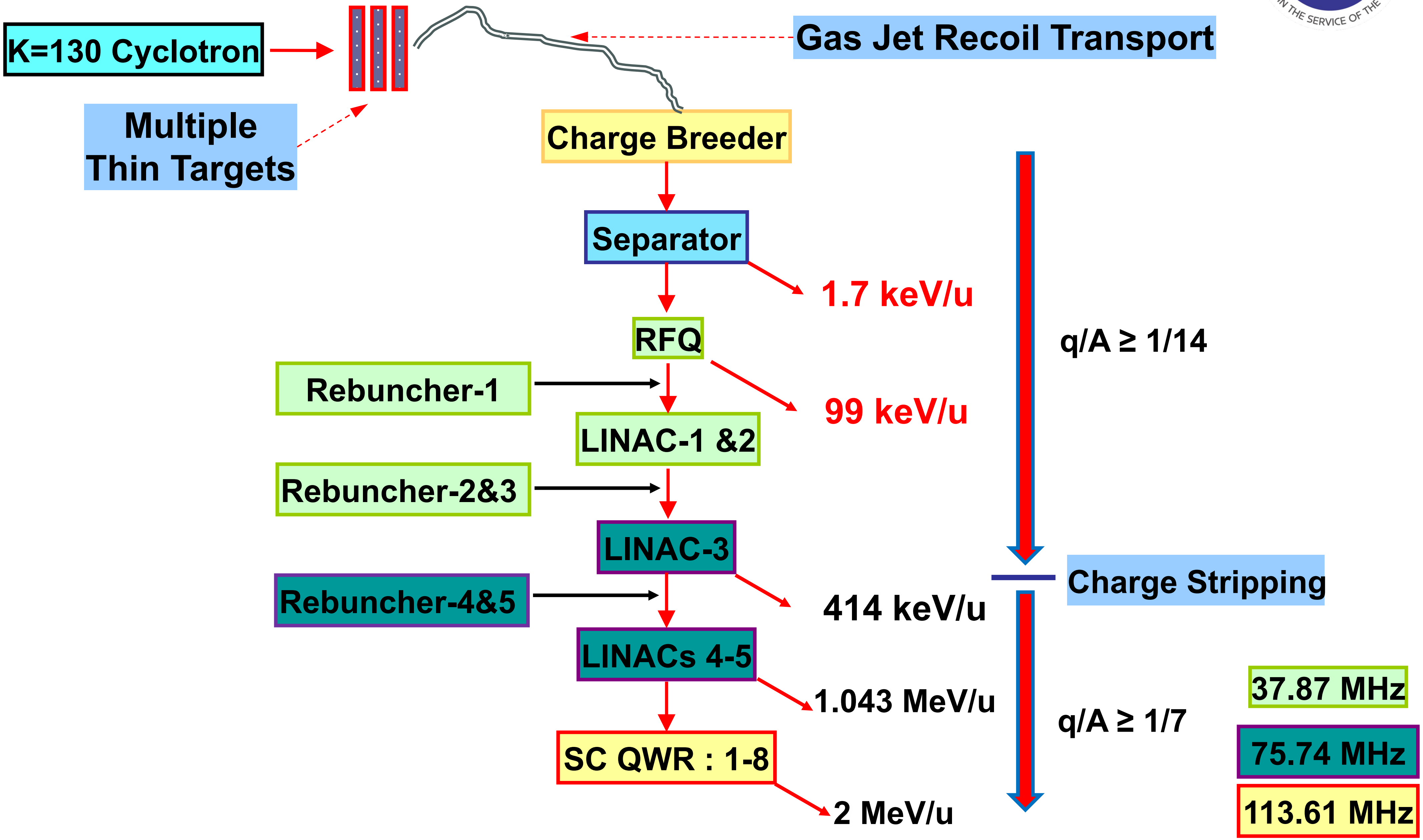
Static heat load	Quantity
LN2 (l/h)	5.08 (Flow rate)
Liq-He (W)	9.28 (Falling level)

Dynamic heat load	Quantity
QWR-2	1.59 W @E_{accln}=6.6 MV/m

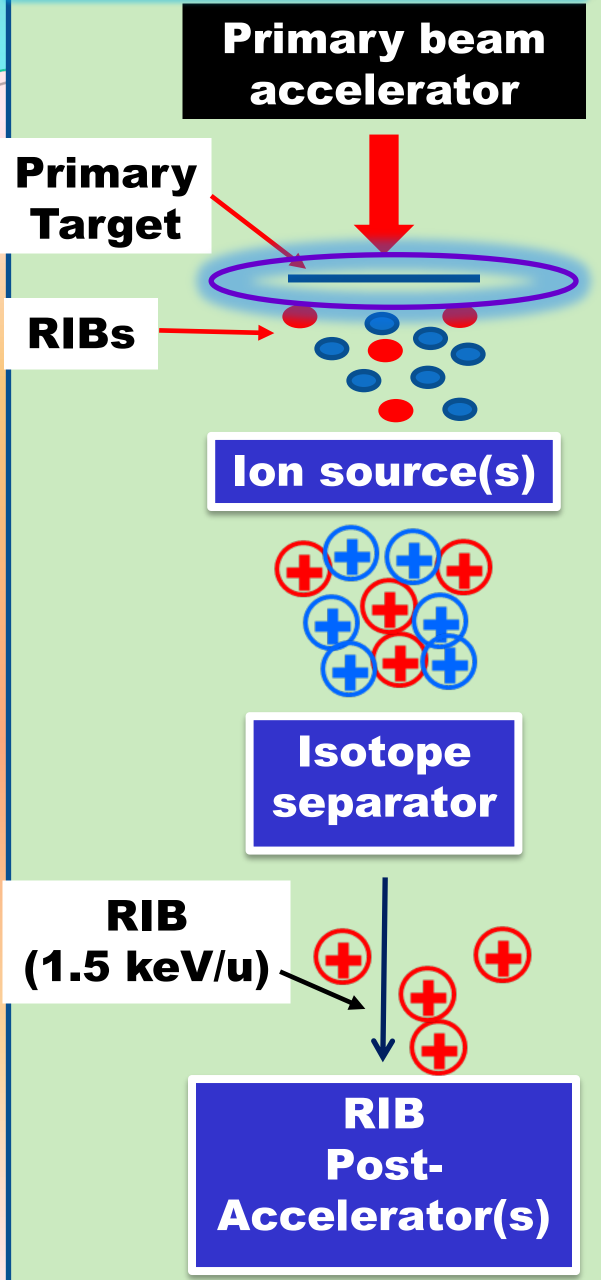
QWR-1 quenched @9.4 MV/m, QWR-3 & 4 did not quench till 10.2 MV/m and QWR-2 performed best – did not quench even at 13.5 MV/m.

Present Status of RIB Facility at VECC

Variable Energy Cyclotron Centre (Bidhan Nagar)
Rare Ion Beam Facility



RIB facility in VECC-Bidhan Nagar Campus

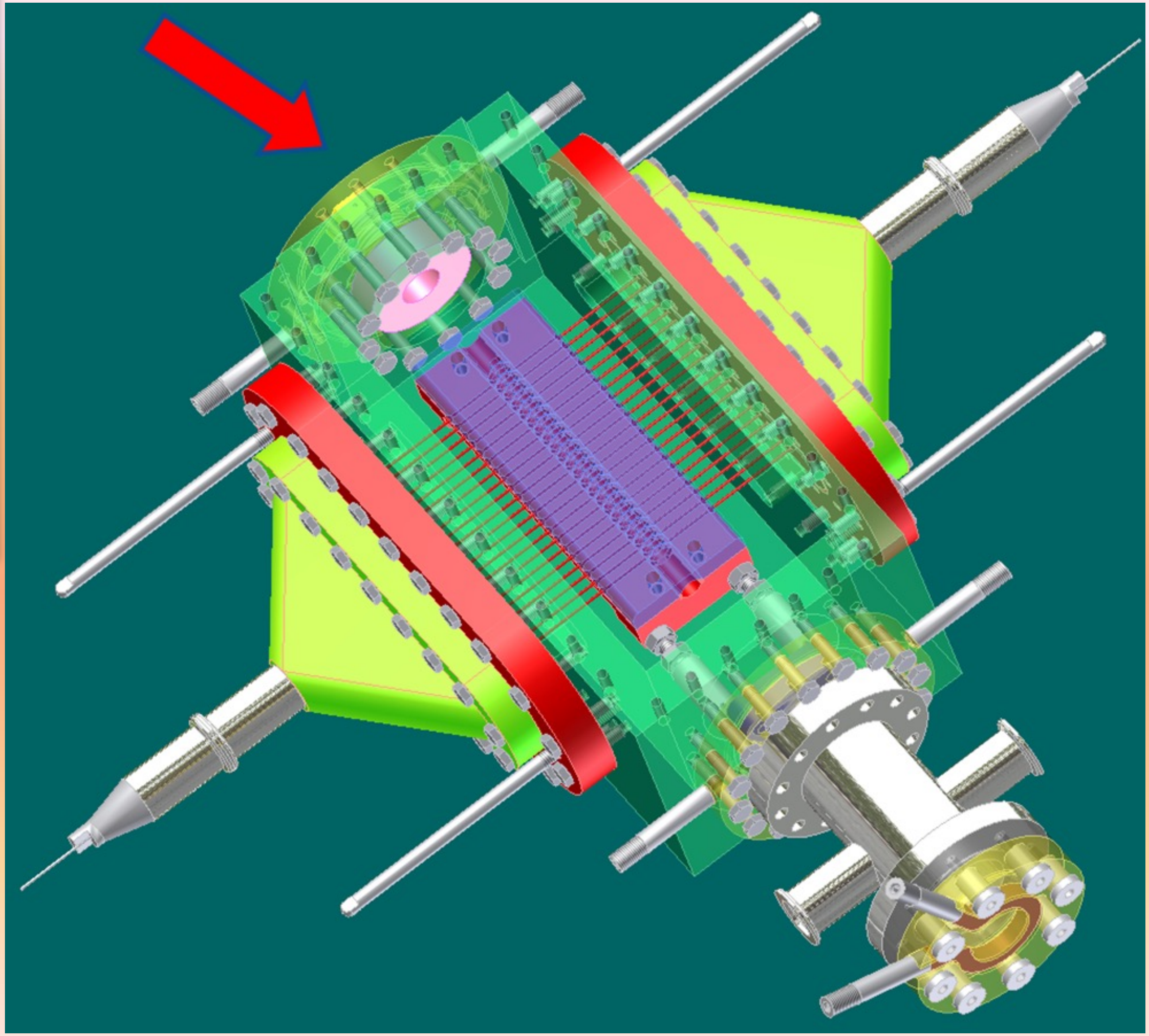


RIB Production & Transport

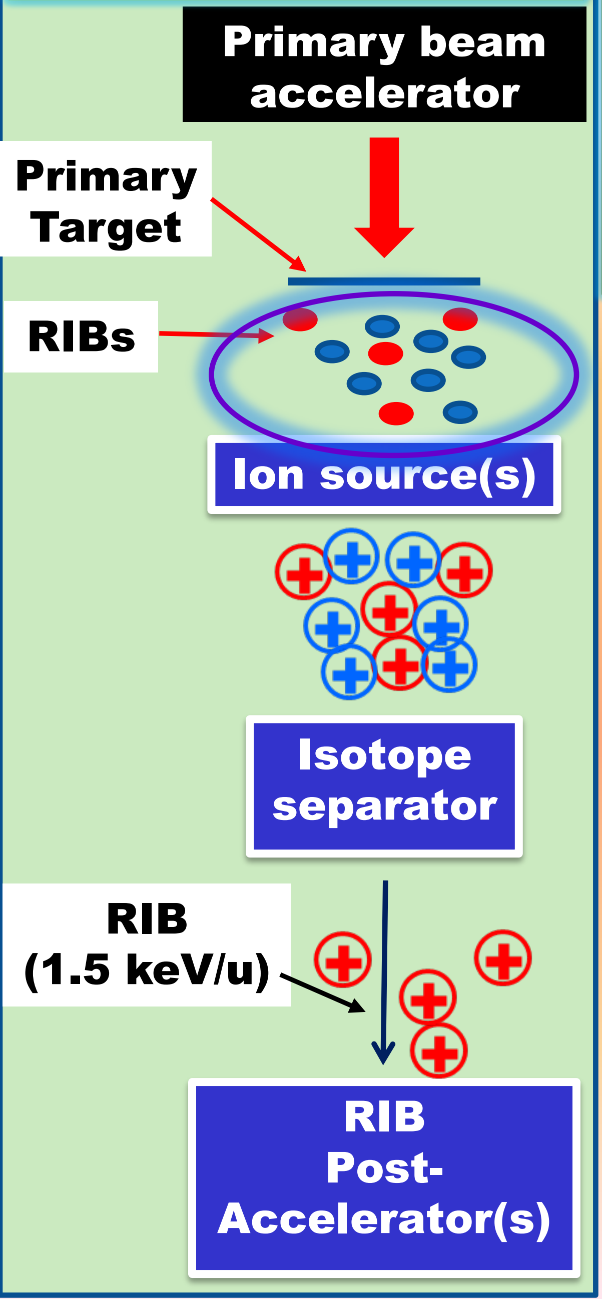
RIB production target chamber is located inside cyclotron vault

Multiple thin targets are used to maximize the RIB intensity

$$I_{RIB} = I_{Pri} N_t \sigma \eta$$

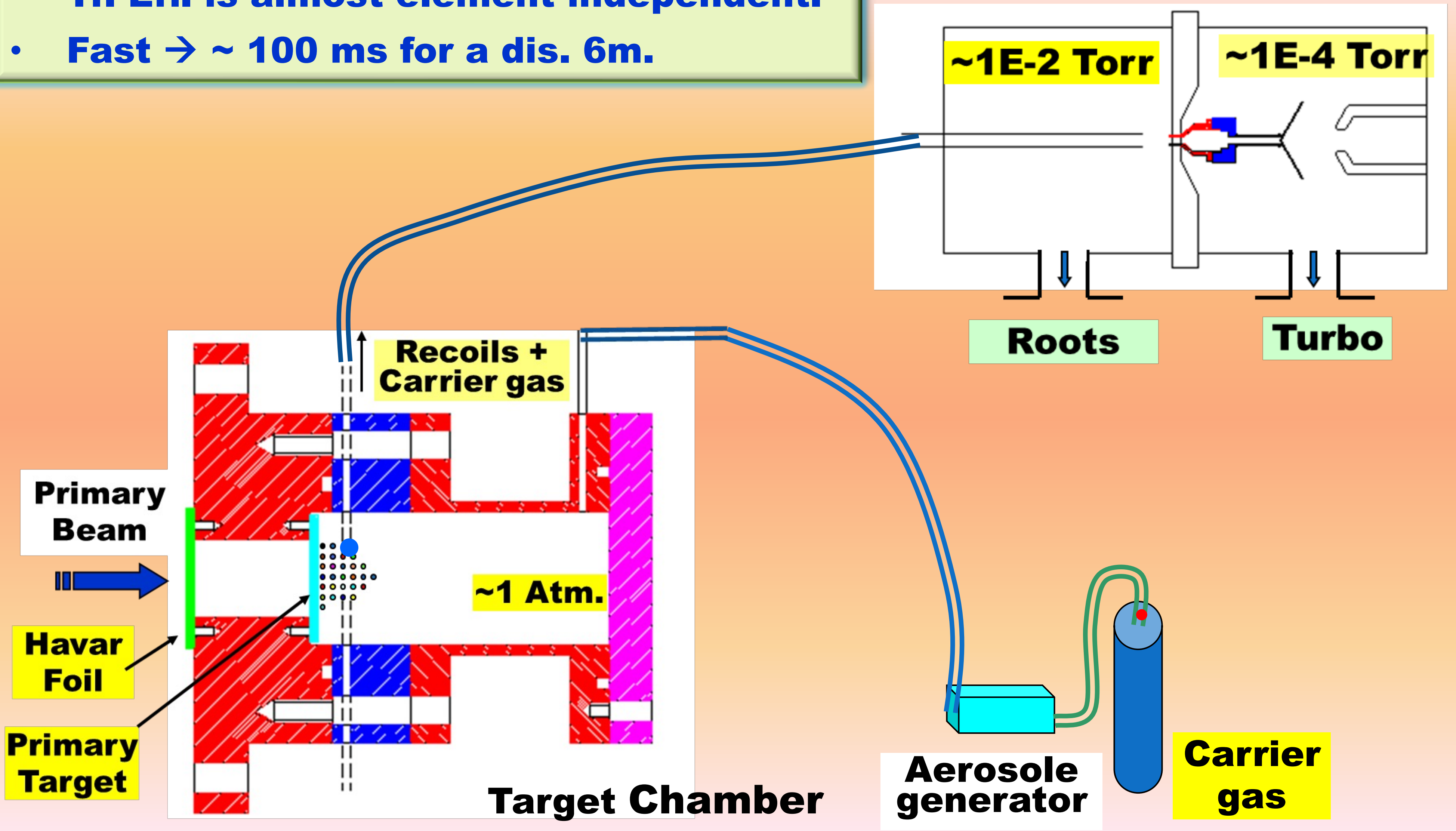


RIB facility in VECC-Bidhan Nagar Campus

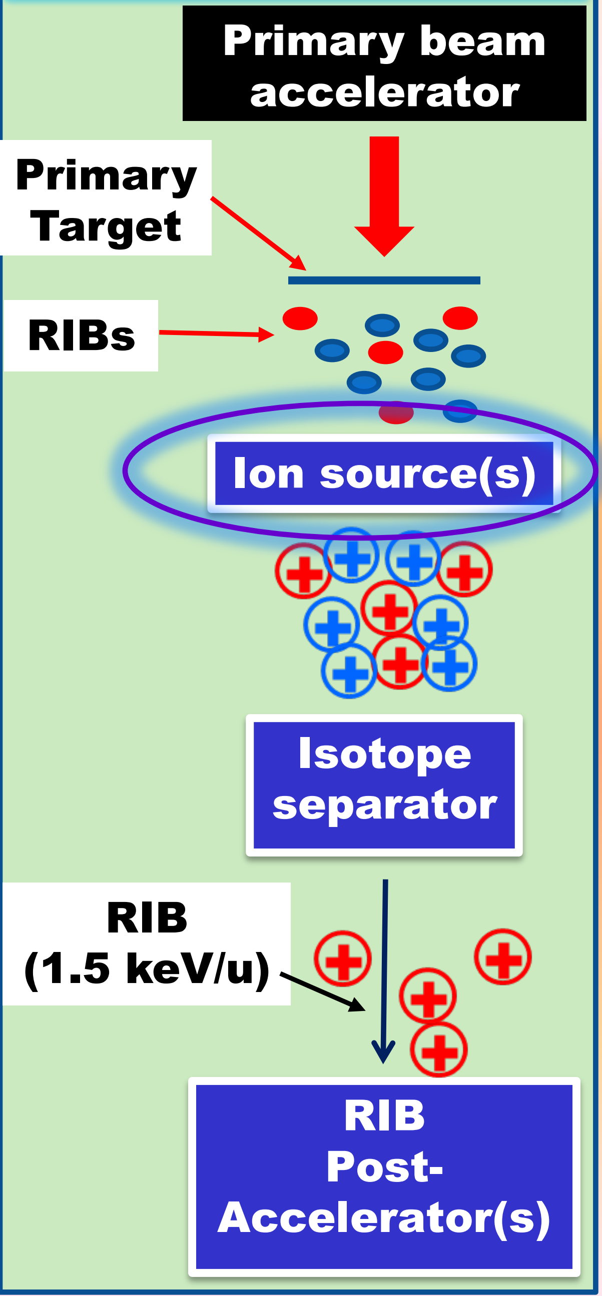


RIB Transport→ Gas jet recoil transport technique

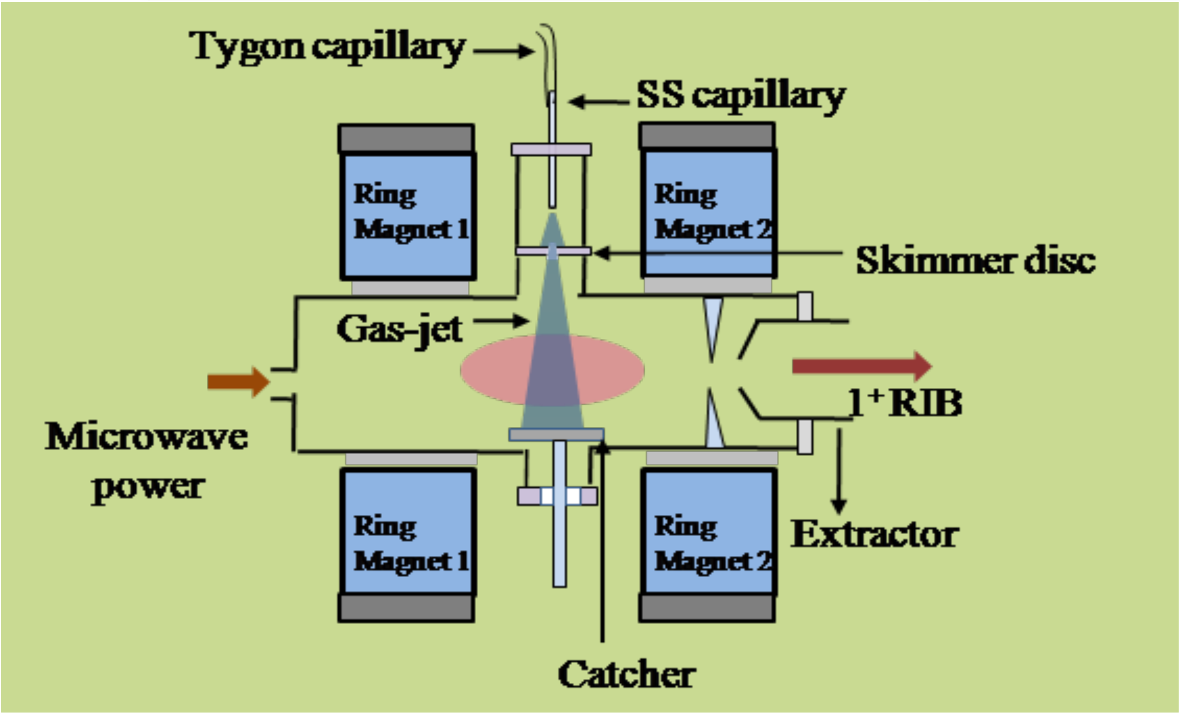
- Thermalisation of recoils
- Transport due to differential pumping
- Tr. Eff. is almost element independent.
- Fast → ~ 100 ms for a dis. 6m.



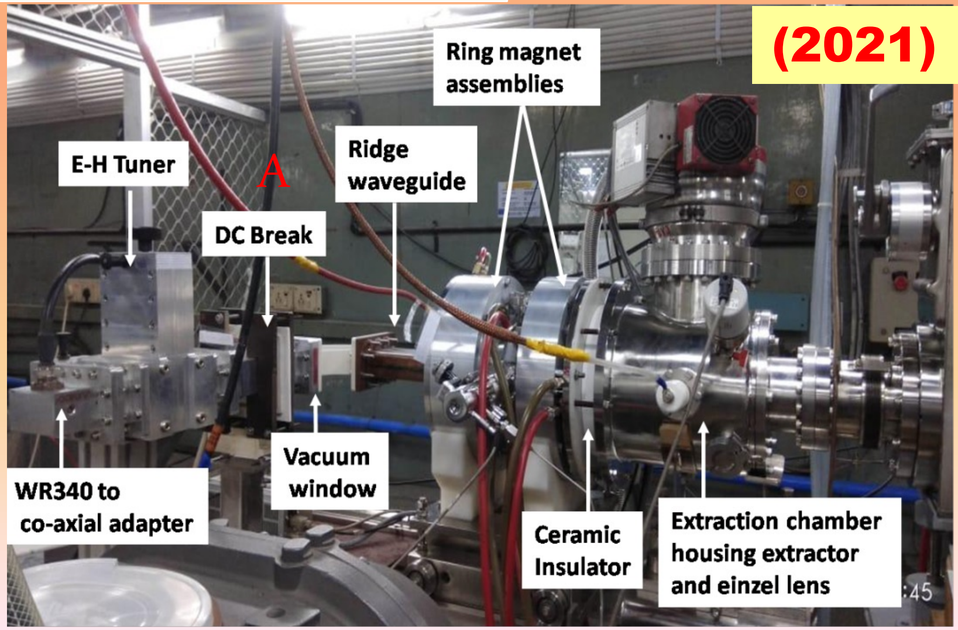
RIB facility in VECC-Bidhan Nagar Campus



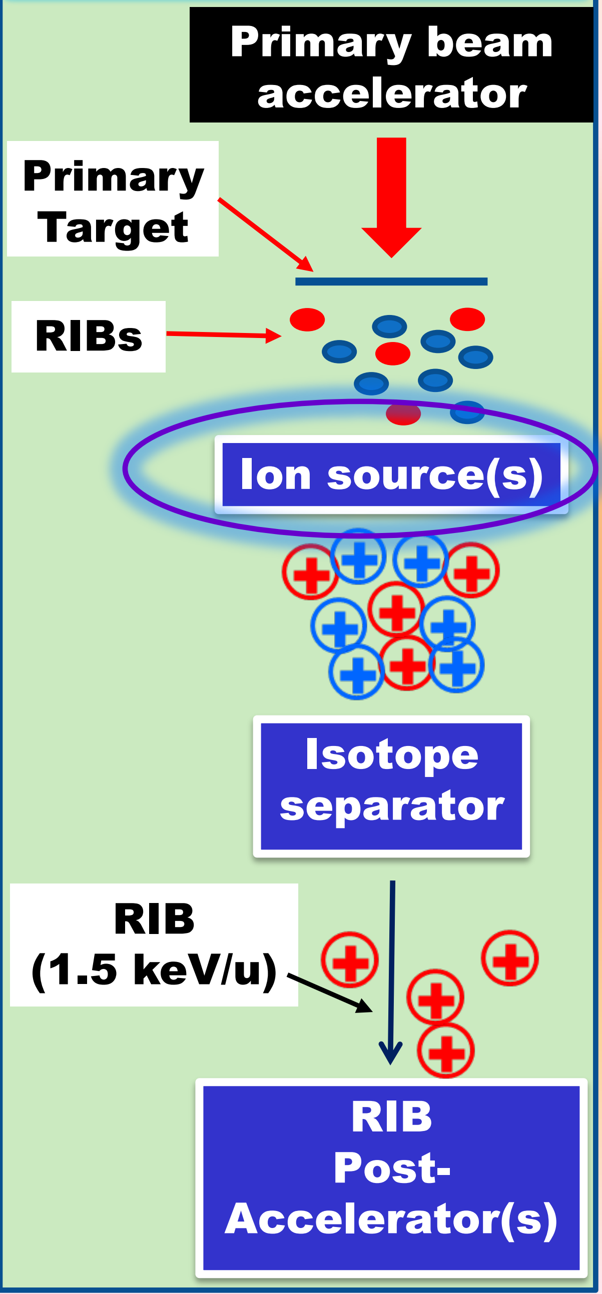
Ionisation: 1^+ Ion Source



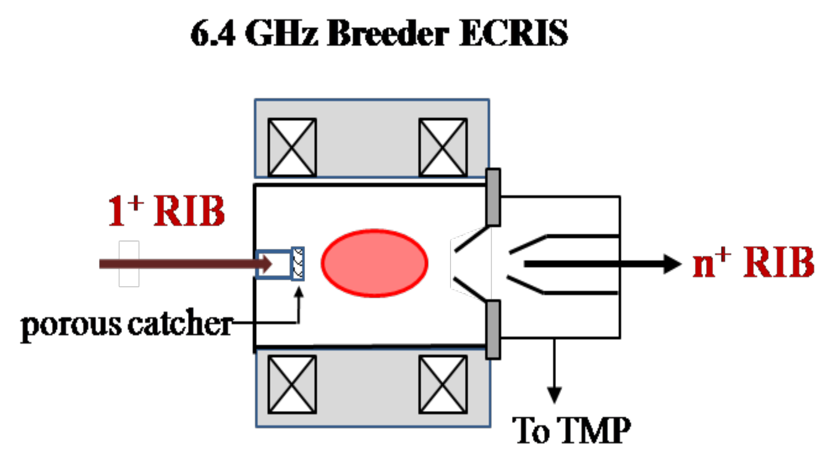
1^+ ECR	
Frequency	2.45 GHz
Microwave source	450 W (SS µ-wave generator)
Axial confinement	Permanent magnets B_in=1.84 kG B_ext=1.35 kG
Radial confinement	1.2 kG @r=45 mm



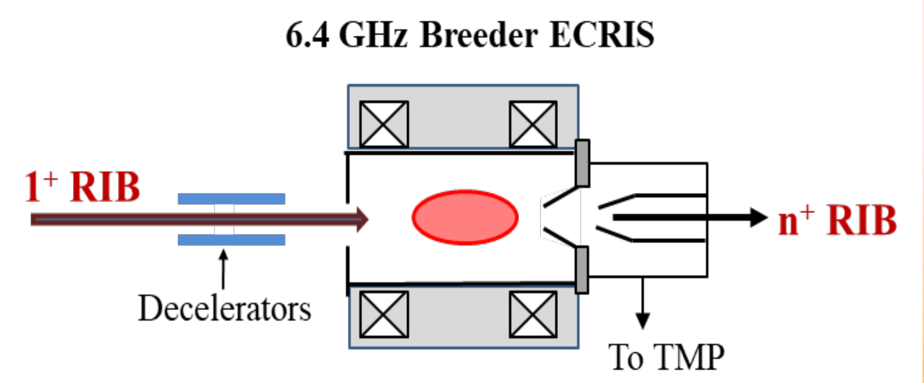
RIB facility in VECC-Bidhan Nagar Campus



RIB Production & Ionisation

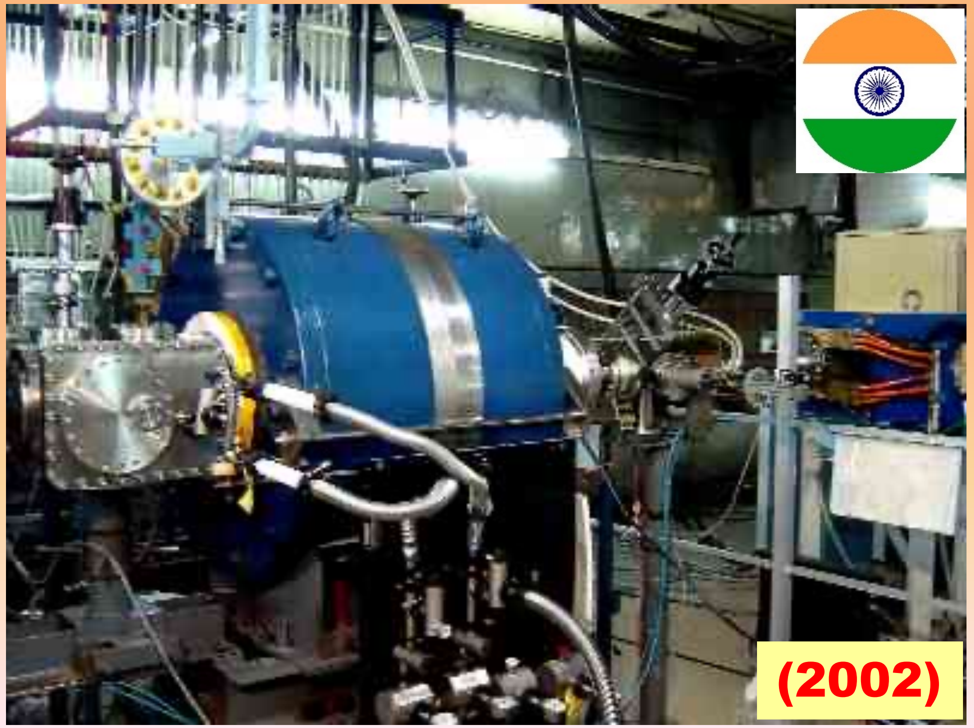


Decelerated to 2-8 keV → fall on porous catcher → Diffusion



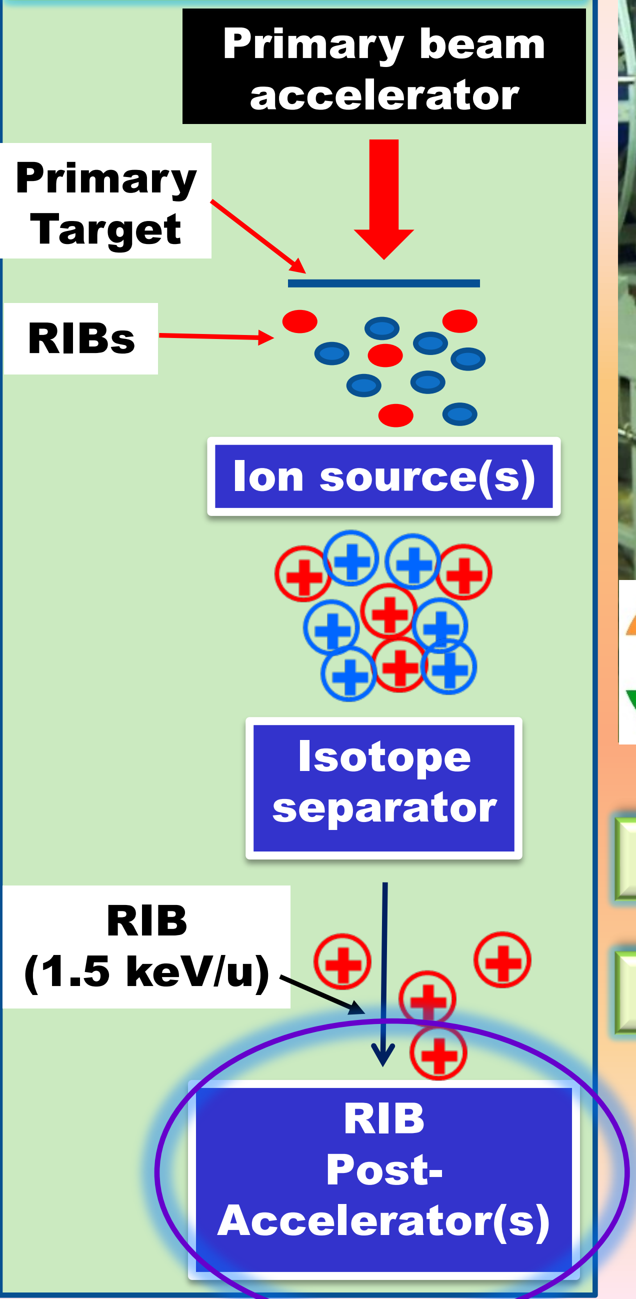
Decelerated to 20 - 30 eV → Inject into ECR plasma

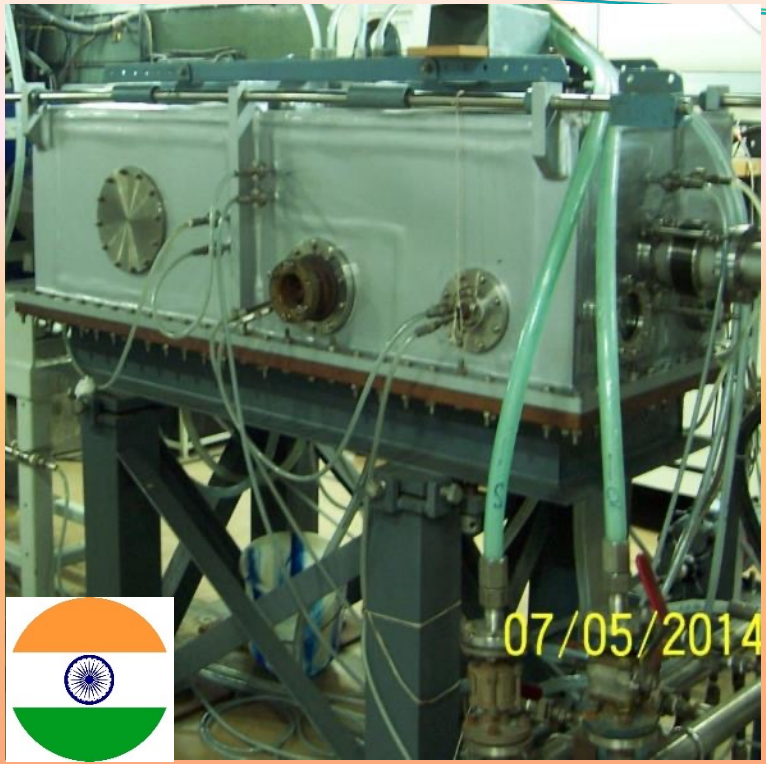
n^+ ECR	
Frequency	6.4 GHz
Microwave source	3 kW (Klystron)
Axial confinement	Solenoid coils B_in=0.95 T B_ext=0.7 T
Radial confinement	Permanent magnets 0.7 T @r=50 mm



Radio Frequency Quadrupole (RFQ)

RIB facility in VECC-Bidhan Nagar Campus





Freq. : 33.7 MHz | **q/A ≥ 1/16**

Energy : 1.38 → 29 keV/u

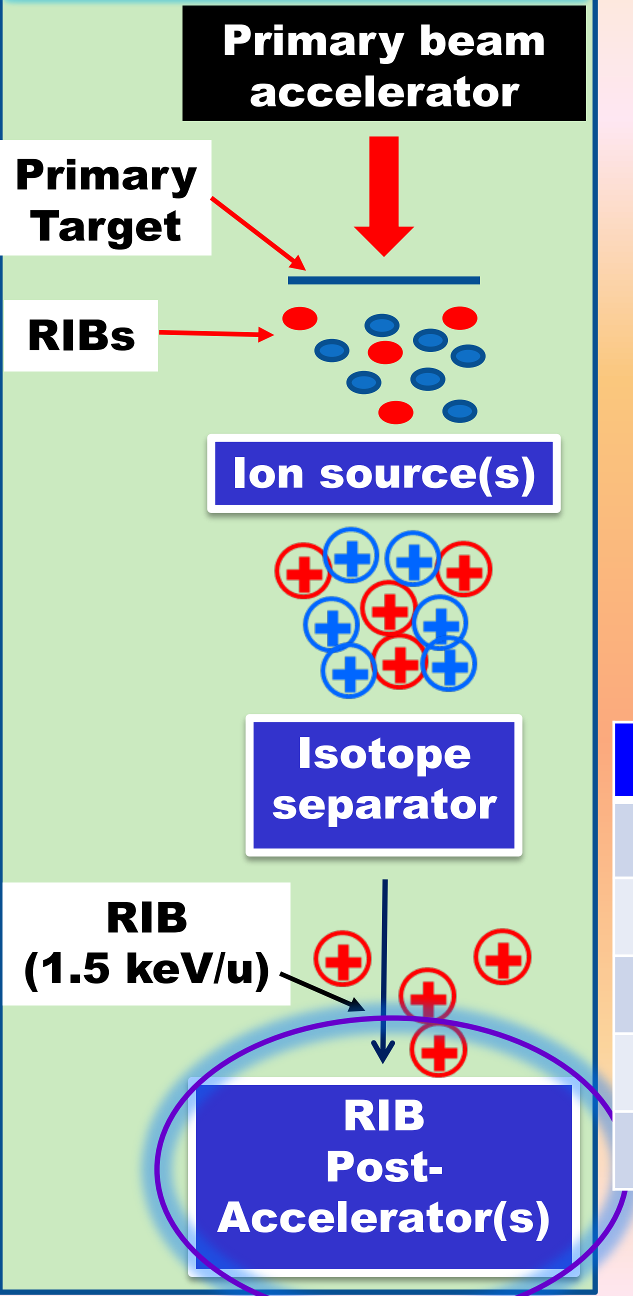
Commissioned in 2005

Freq.: 37.8 MHz | **q/A ≥ 1/14**

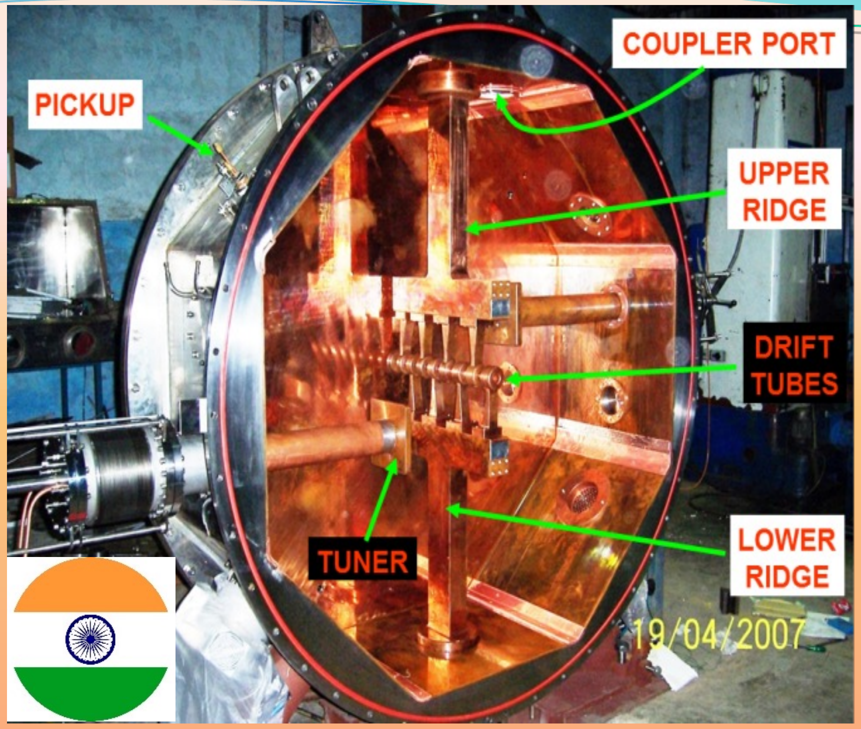
Energy : 1.73 → 98.8 keV/u

Commissioned in 2008

RIB facility in VECC-Bidhan Nagar Campus

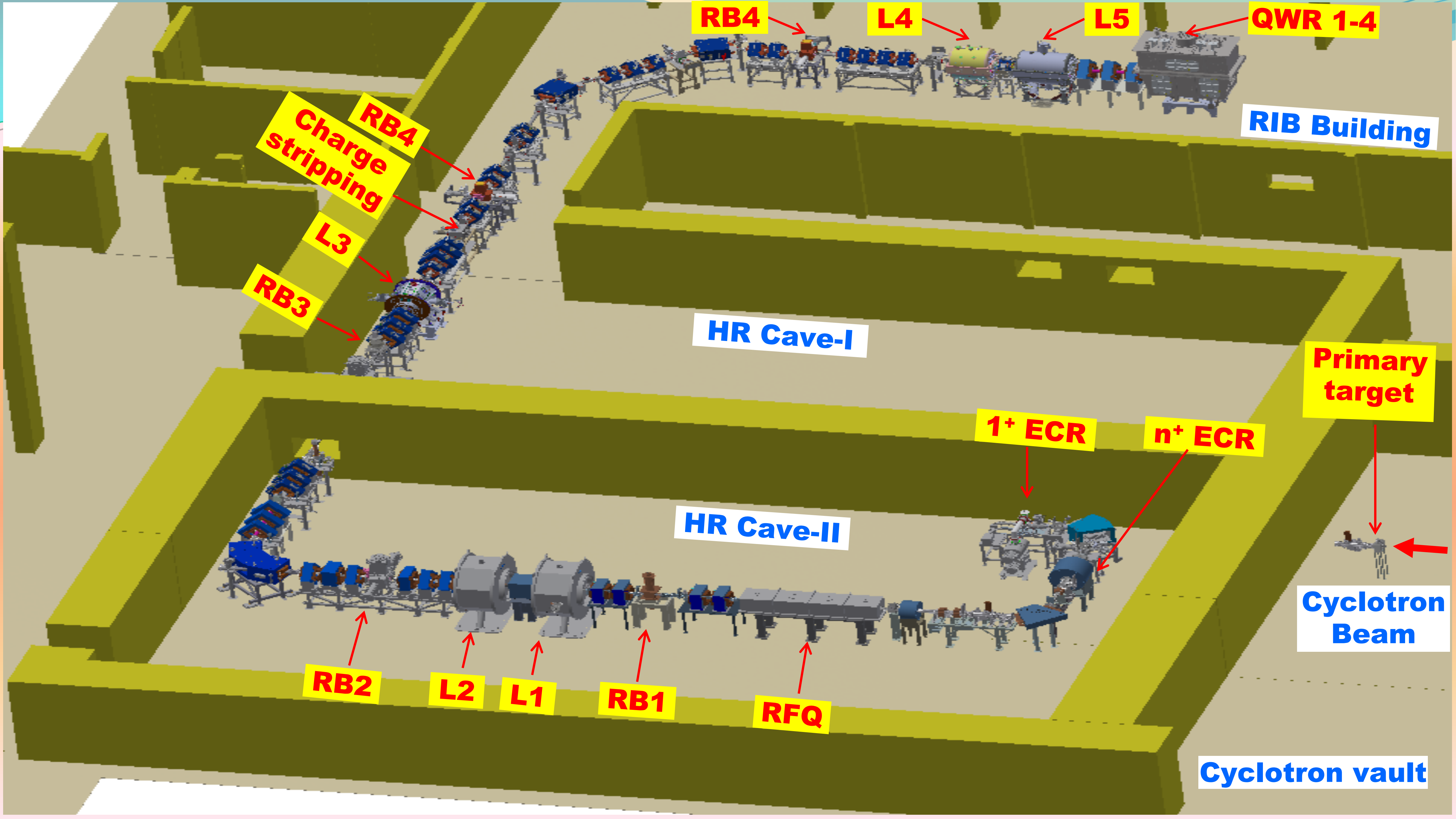


IH LINACs

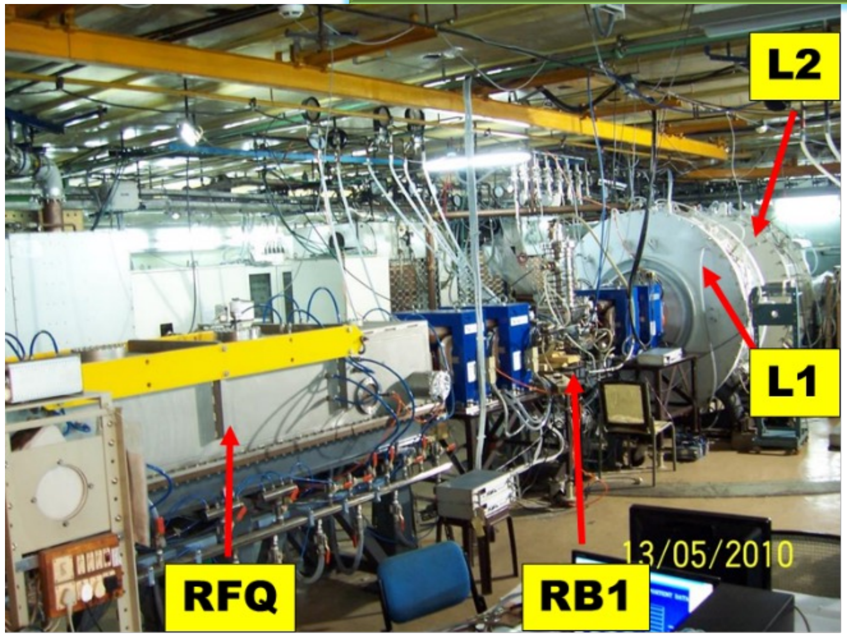


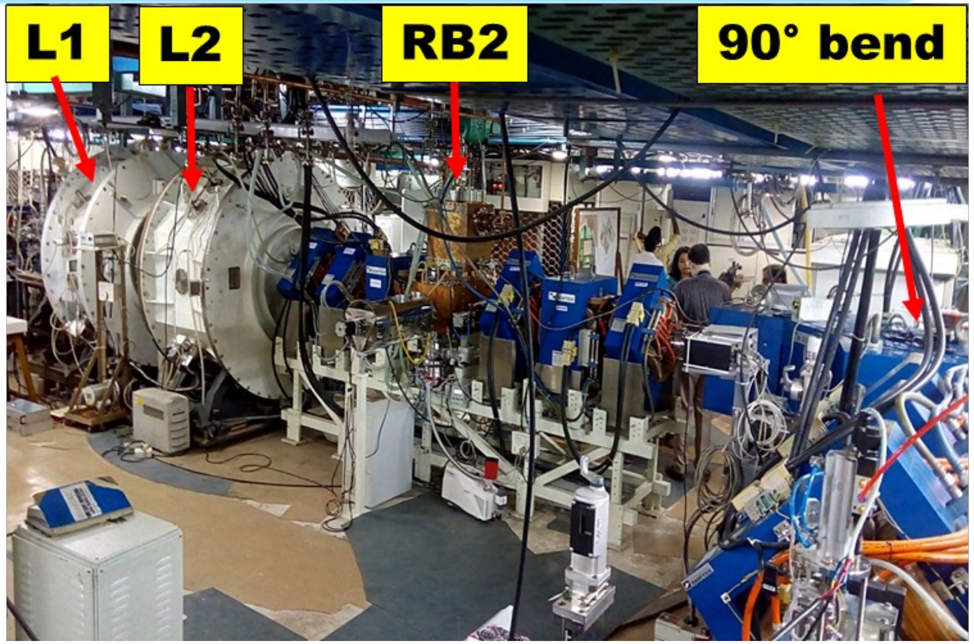
IH LINAC Accelerators for accelerating from 99 kev/u to 1.04 MeV/u

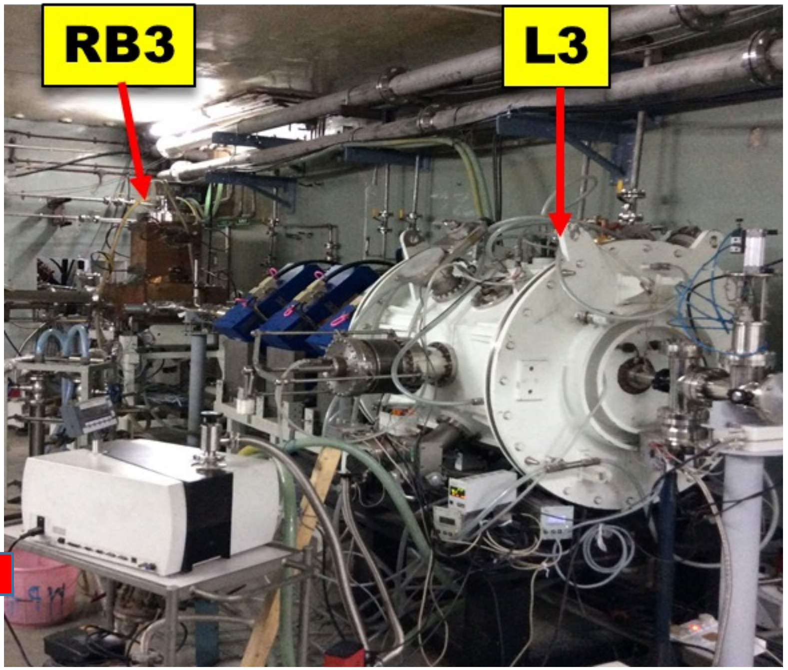
IH #1	98.8 → 186.2 keV/u	37.87	Copper cladded steel	Conventional LINAC beam dynamics	2009
IH #2	186.2 → 289.1 keV/u	37.87			2010
IH #3	289.1 → 413.9 keV/u	75.74			2012
IH #4	413.9 → 717.8 keV/u	75.74	Copper plated MS	KONUS beam dynamics	2023
IH #5	717.8 → 1038.0 keV/u	75.74			2024


RB4
L4
L5
QWR 1-4
RB4
Charge stripping
L3
RB3
RIB Building
HR Cave-I
Primary target
1⁺ ECR
n⁺ ECR
HR Cave-II
Cyclotron Beam
RB2
L2
L1
RB1
RFQ
Cyclotron vault

Walking around the facility





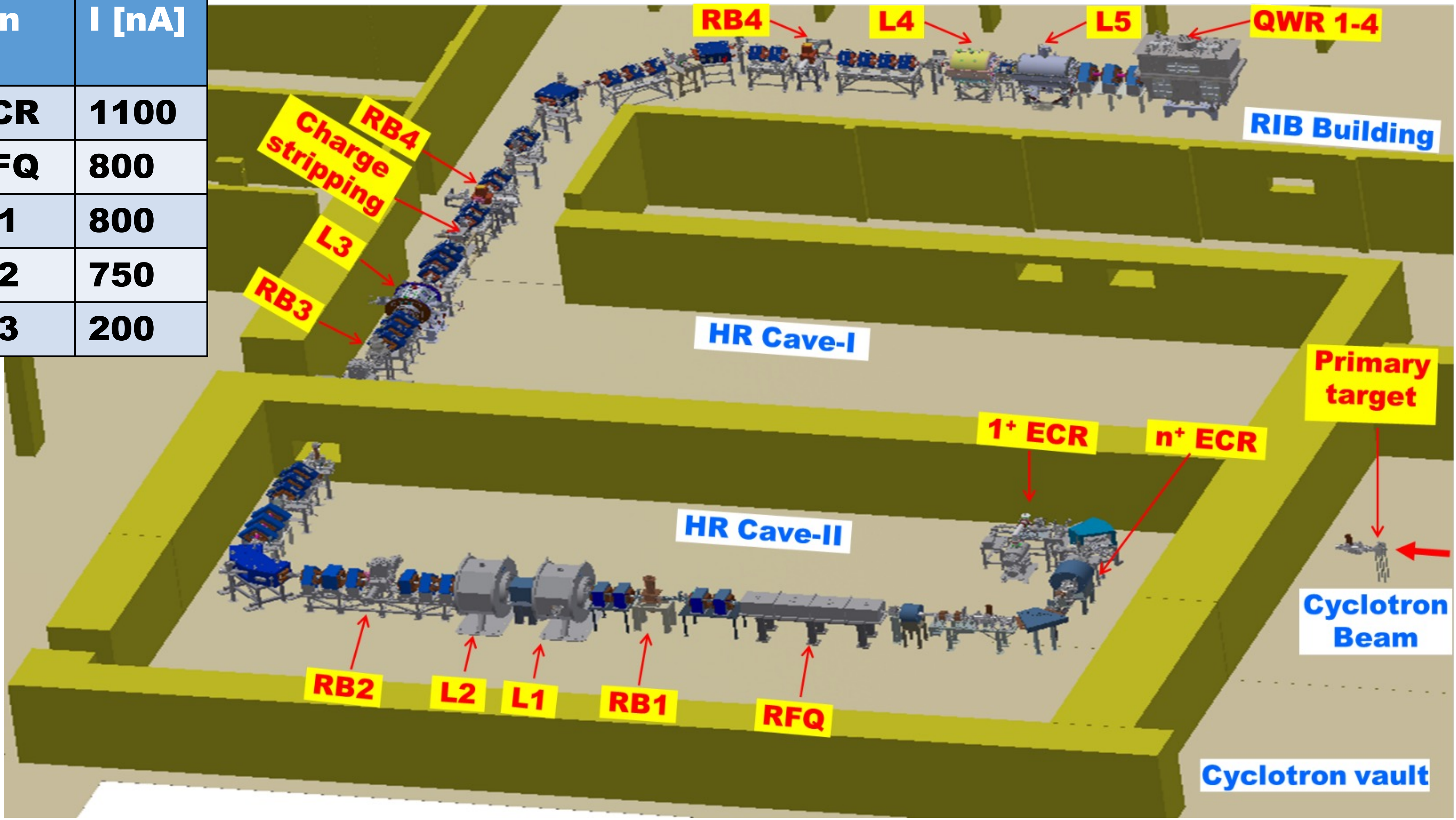


Measurement results for stable beam acceleration

Energy [kev/u]	Location	I [nA]
1.5	After ECR	1100
99.2	After RFQ	800
188.4	After L-1	800
289.6	After L-2	750
415.3	After L-3	200

N^{4+}

Regulatory clearance up to 415 keV/u (L-3)



C-12, N-14, O-16, He-4, Ar-40, Fe-56, Ni-58, In-115, Zn-64, B-11 : Currents ~ 0.01 – 100 µA Typ.

RIB produced to demonstrate commissioning of low energy facility

RIB	T_1/2	PPS	Reaction
${}^{11}_{6}C$	20.3 m	5x10³	${}^{14}_{7}N(p,\alpha)$
${}^{14}_{8}O$	71 s	5x10³	${}^{14}_{7}N(p,n)$
${}^{42}_{19}K$	12.4 h	2.7x10³	${}^{40}_{18}Ar(\alpha,pn)$
${}^{43}_{19}K$	22.3 h	1.2x10⁵	${}^{40}_{18}Ar(\alpha,p)$
${}^{41}_{18}Ar$	109 m	1.3x10³	${}^{40}_{18}Ar(\alpha,2pn)$
${}^{111}_{49}In$	2.8 d	1.6x10⁵	${}^{Nat}_{47}Ag(\alpha,xn)$

→ 3.2E3 after RFQ

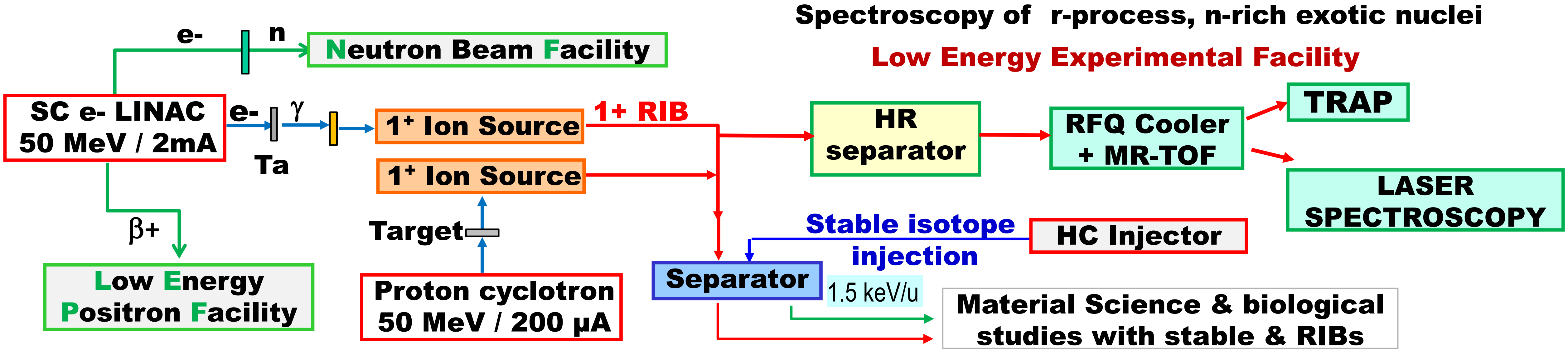
Rare ion beams up to 415 keV/u (Regulatory clearance) for a few cases – the list will grow as and when we can increase the intensity in the production stage

A few possibilities

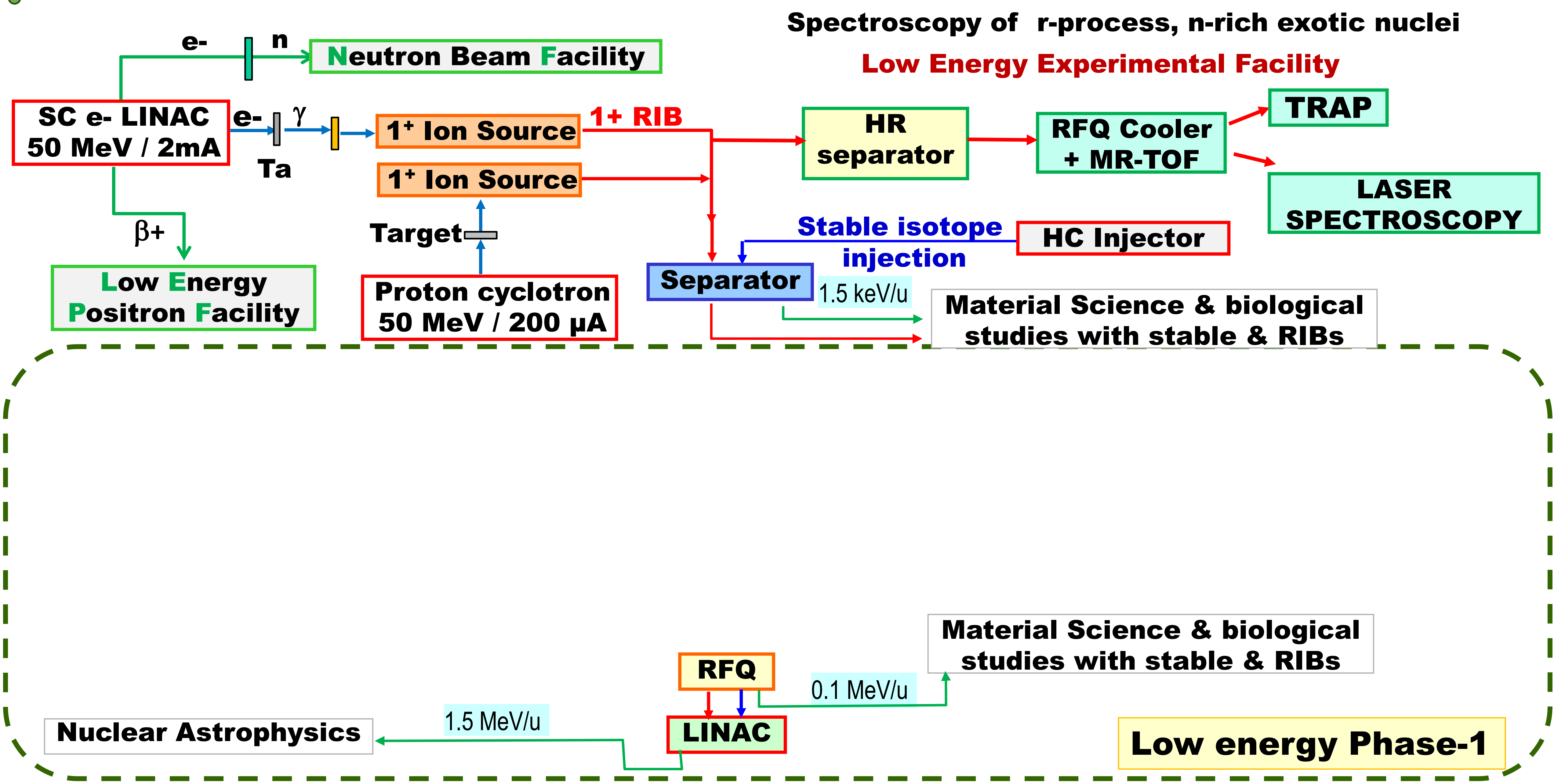
RIB	T_1/2	Reaction
${}^{15}_{8}O$	2.03 m	${}^{14}_{7}N(d,n)$
${}^{87}_{36}Kr$	76 m	${}^{232}_{92}U(\alpha,f)$
${}^{90}_{37}Rb$	4.3 m	
${}^{135}_{54}Xe$	9 h	
${}^{138}_{55}Cs$	32 m	

Applied and NUclear Research using Rare Isotope Beams (ANURIB)

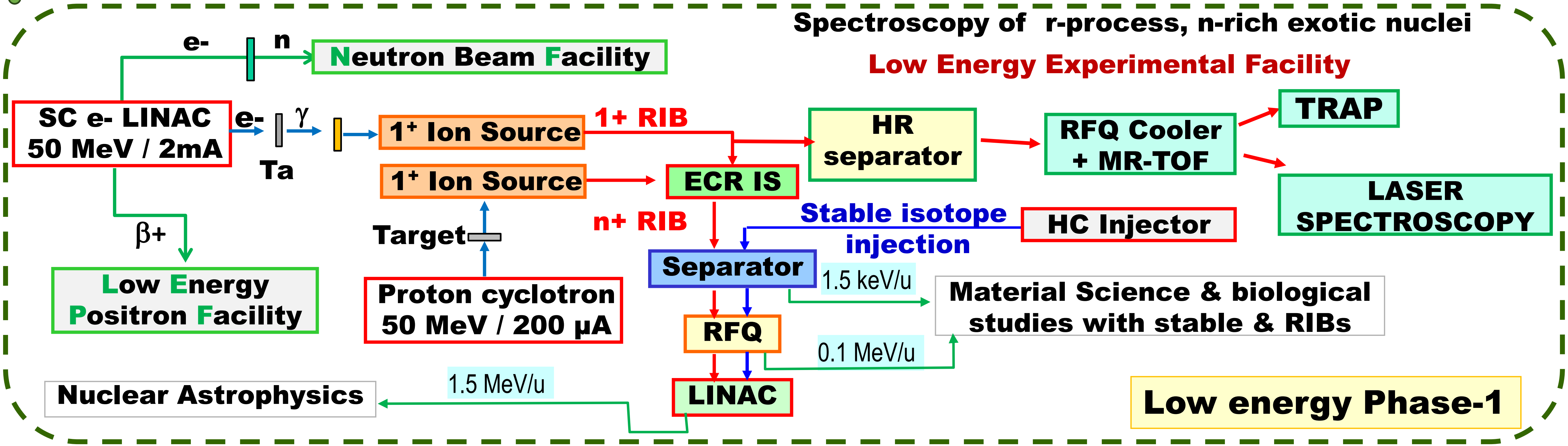
Applied and NUclear Research using Rare Isotope Beams (ANURIB)



Applied and NUclear Research using Rare Isotope Beams (ANURIB)



Applied and NUclear Research using Rare Isotope Beams (ANURIB)



Applied and NUclear Research using Rare Isotope Beams- Technology Readiness Level

1	Primary Accelerator	Cyclotron	Research Development
2		e-LINAC	Development Deployment
3	RIB Production & Transport	Multiple thin target & Gas jet transport	Deployment
4		Thick target methodology	Research
5	Ionisation	1+ ion source	Deployment
6		n+ ion source	Deployment
7		Charge breeding	Development
8	Separation	On-line isotope separator	Development
9	Post-acceleration	Radio Frequency Quadrupole	Deployment
10		IH LINACs	Deployment
11		Super-conducting Quarter Wave Resonators	Development Deployment
12		Rebunchers	Deployment

Low Energy Experimental Facility

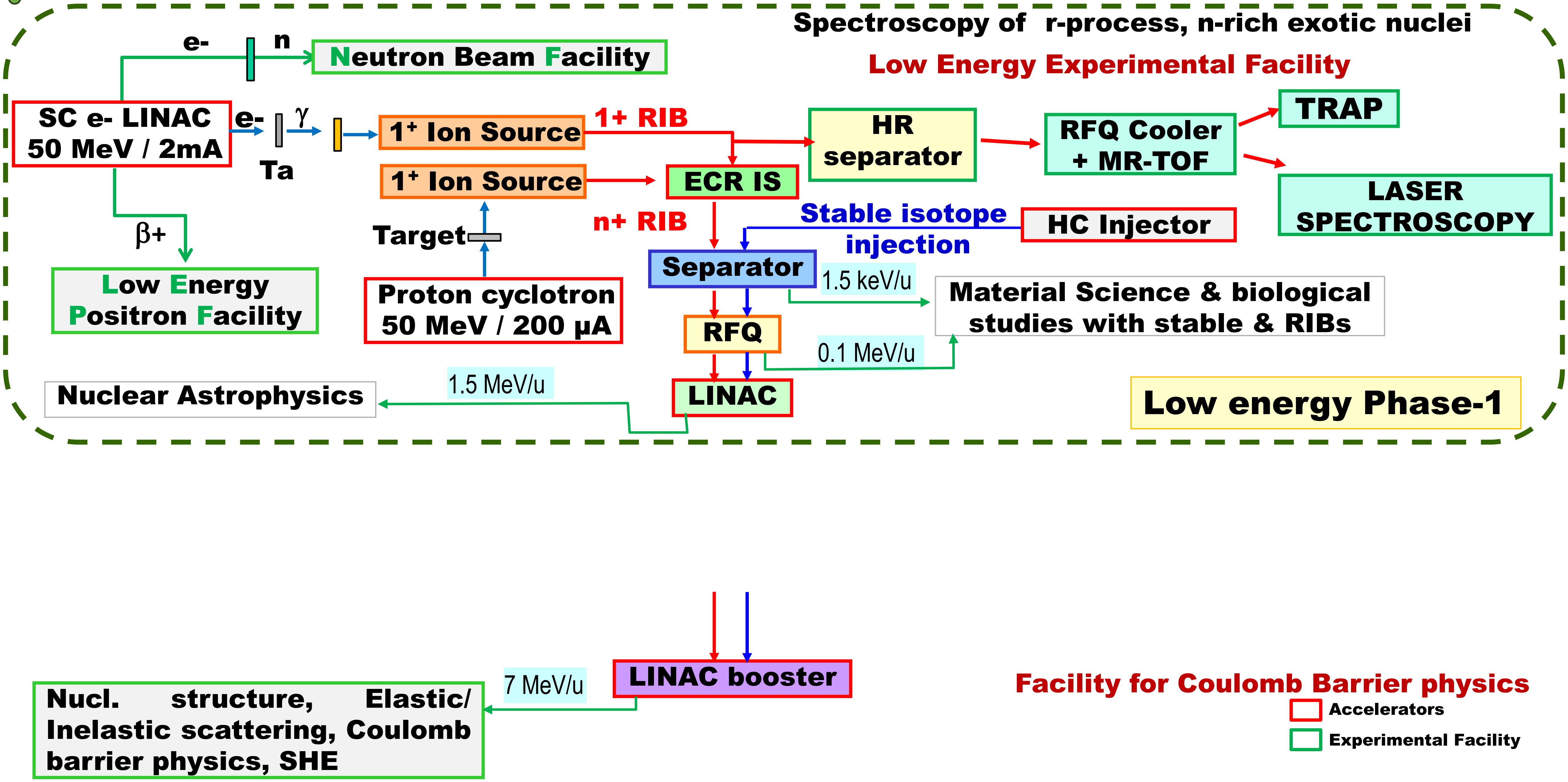
HR separator

RFQ Cooler + MR-TOF

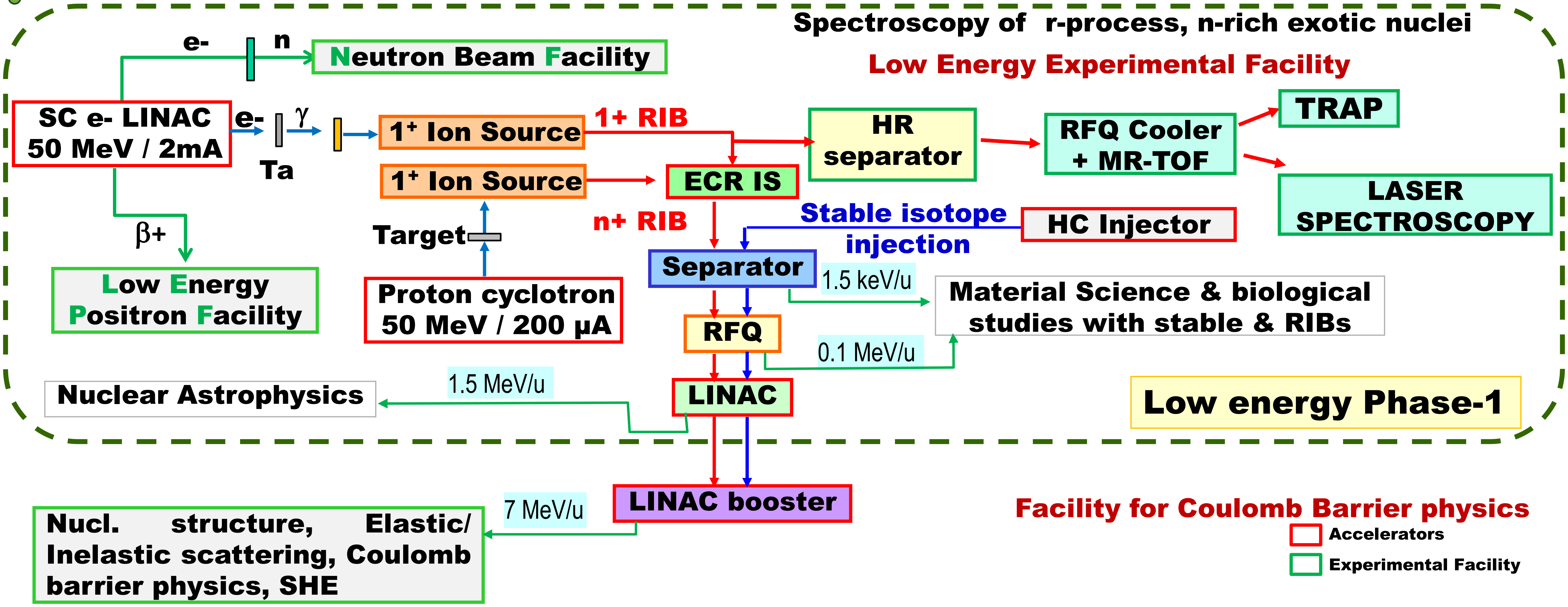
TRAP

LASER SPECTROSCOPY

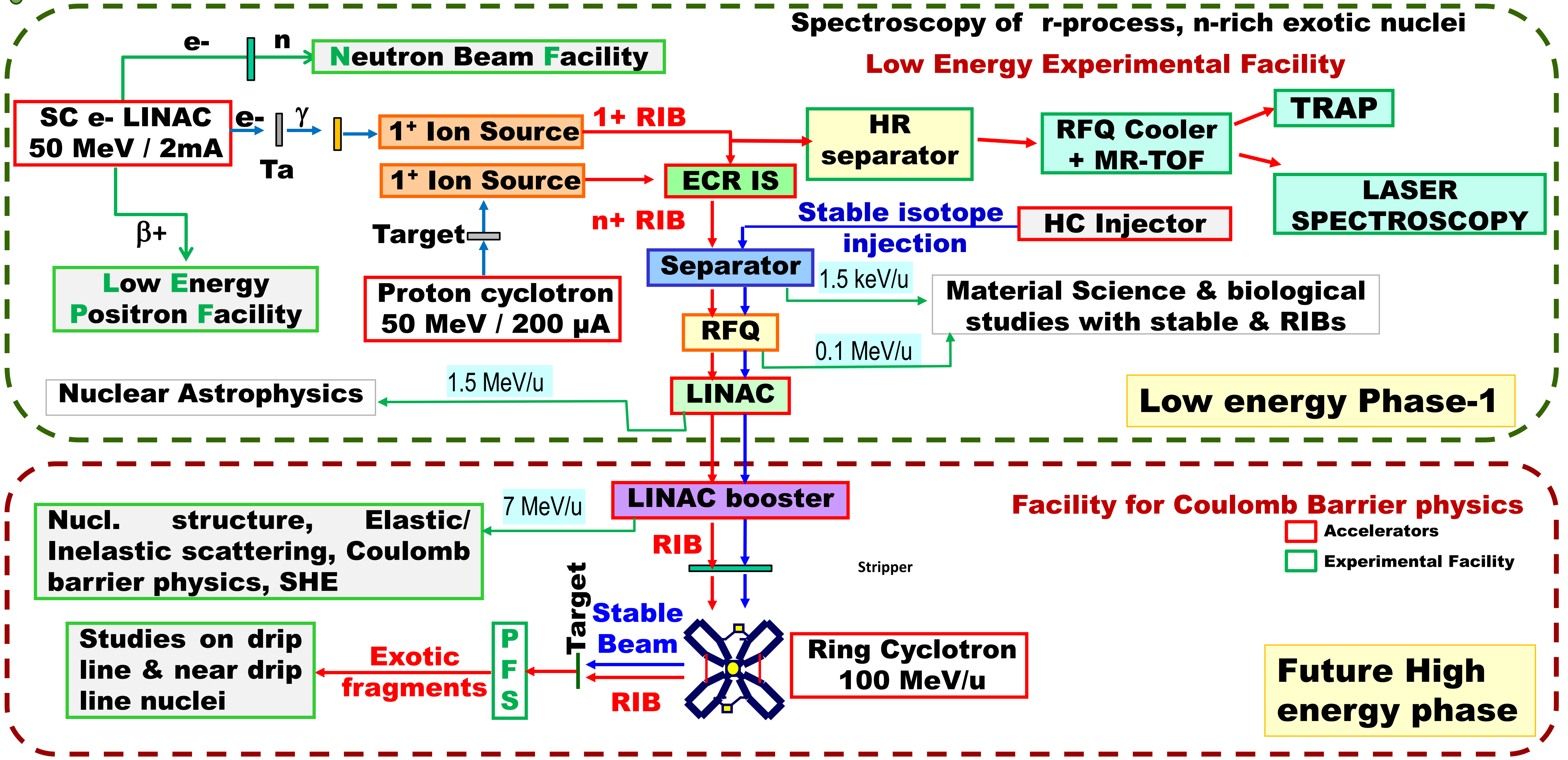
Applied and NUclear Research using Rare Isotope Beams (ANURIB)



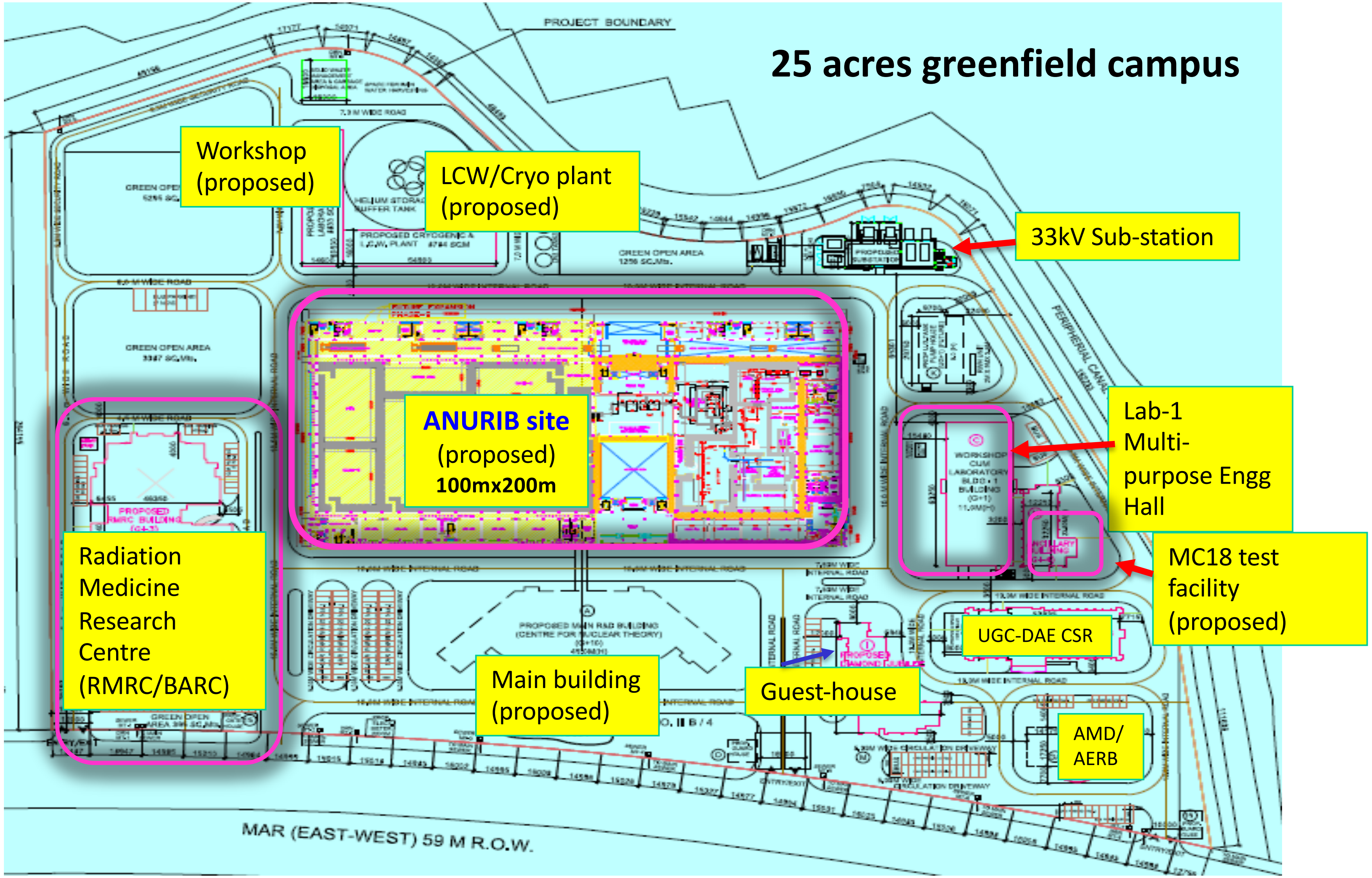
Applied and NUclear Research using Rare Isotope Beams (ANURIB)



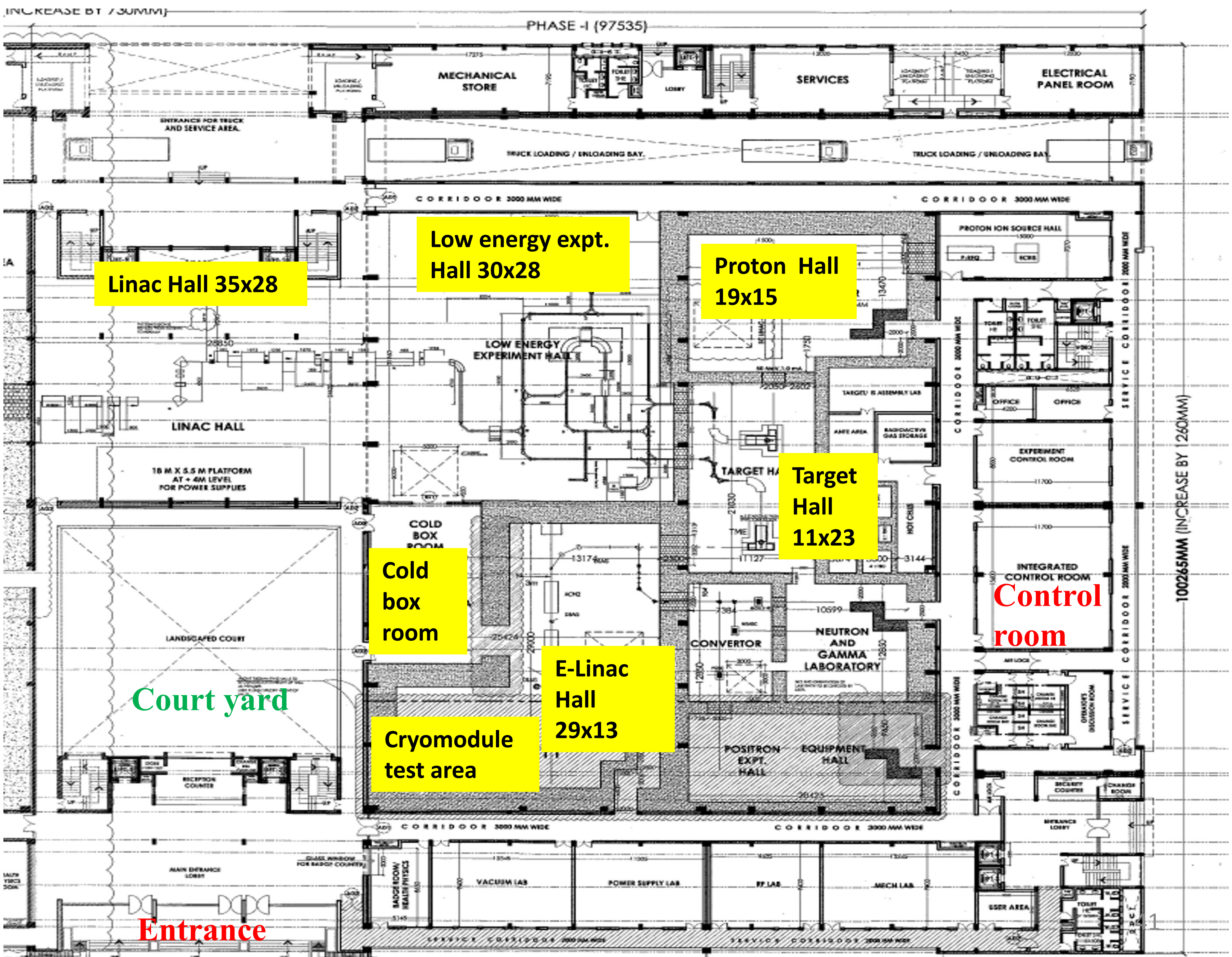
Applied and NUclear Research using Rare Isotope Beams (ANURIB)



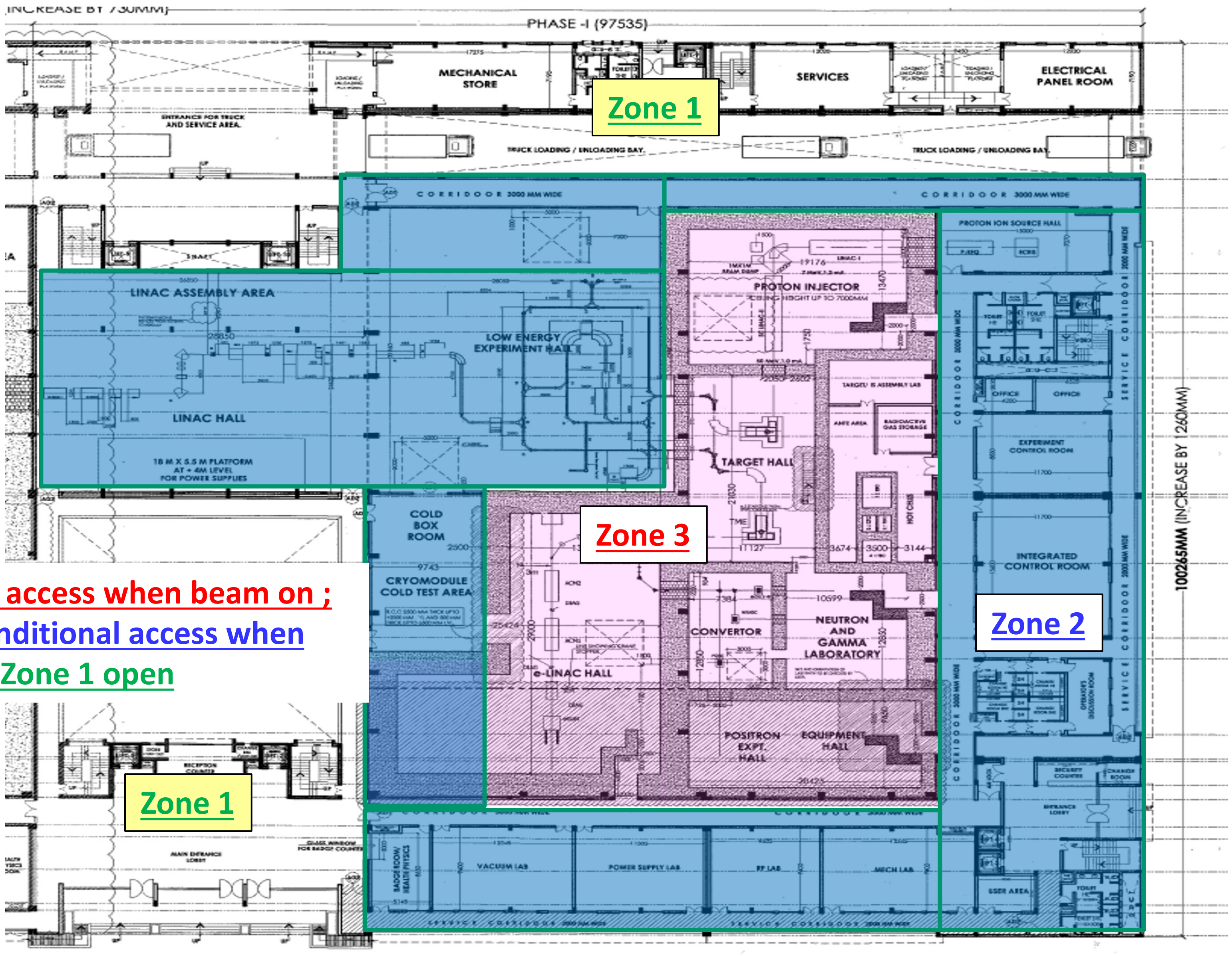
VECC RAJARHAT CAMPUS MASTERPLAN



ANURIB building Floor plan



ANURIB building radiation zoning



Zone 3 no access when beam on ;
Zone 2 conditional access when beam on; Zone 1 open

COST ESTIMATE & PHASING

Sl. No.	Major Activity	Cost (Rs. Crore)	Cost (Rs Bilion)	
1	ANURIB Phase-I including building	675.00	6.75	
2	Acceleration of RIB to 7 MeV/A	140.00	1.4	
3	Beam transport lines to caves	185.00	1.85	
	Total (Rs. in Crore)	1000.00	10	161 M CAN $

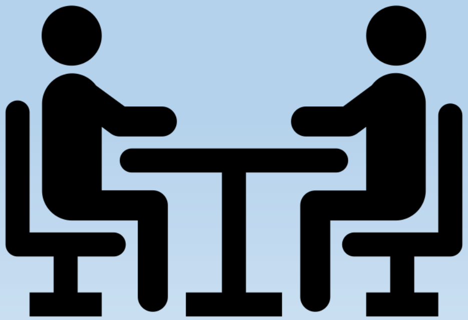
Time-line	Major Activity
T=0	Financial Sanction of project
T+5 Y	Building & Services / Bringing all activities to deployment level
T+10 Y	Installation & commissioning In phases • Primary accelerators • Low energy experimental facilities • Post-accelerators
T+12 Y	Beam delivery & first experiment

Very productive Collaboration so far

Injector Cryo-module for e-LINAC, QWRs &
Cryo-module for VECC, Target & RIE module

Present status of RIB development at VECC

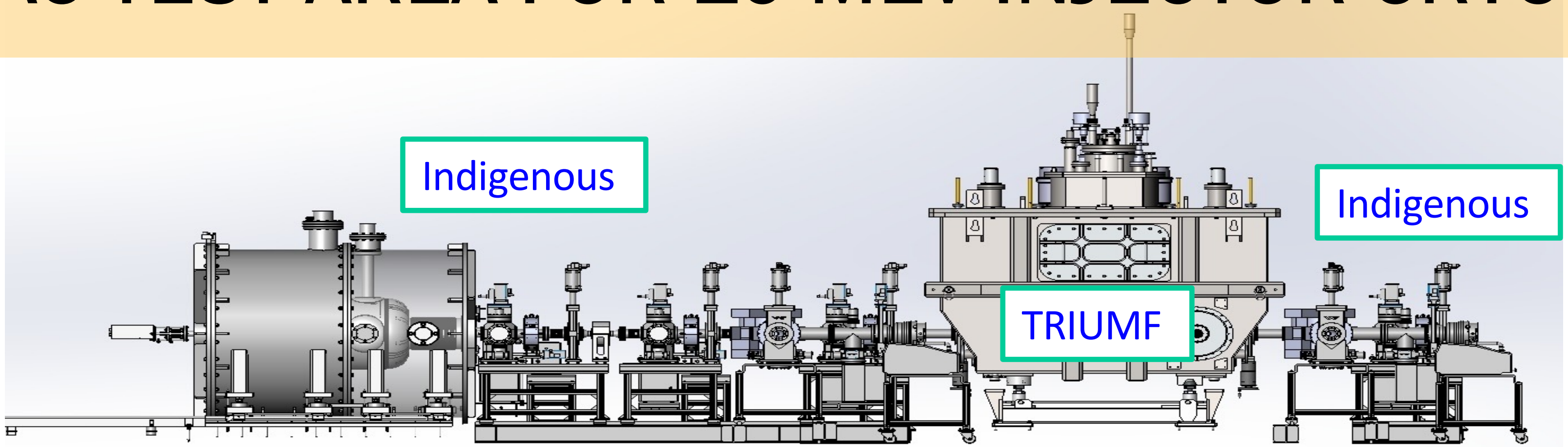
Plan for ANURIB in VECC



Collaboration

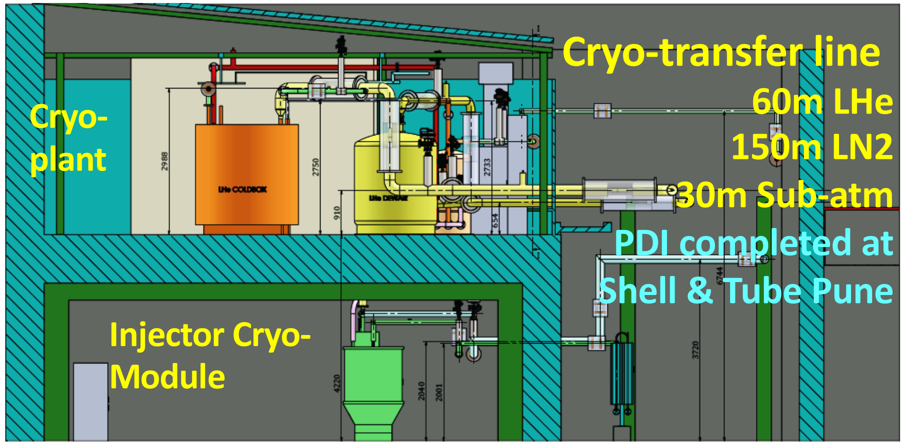

THANK YOU

E-LINAC TEST AREA FOR 10 MEV INJECTOR CRYOMODULE



300 kV Electron gun | Low Energy Beam Transport (LEBT) line | Injector Cryo-Module | Analyzing section

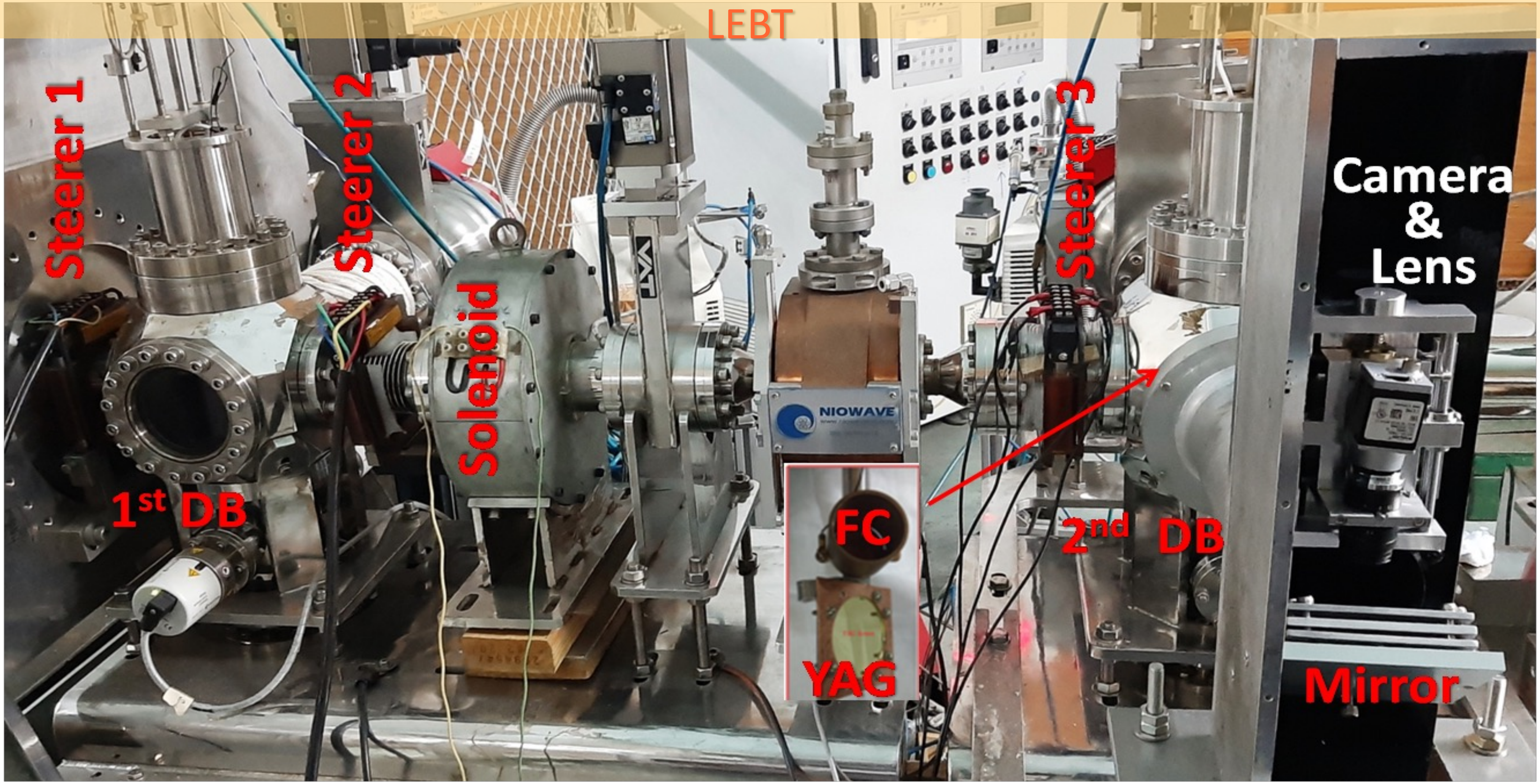
Cryogenic plant, IOT, HV power supply installed on 1st floor; Injector Cryomodule at ground floor



Liquid Helium Plant 540 [W], 115 [l/h]

ELECTRON GUN AND LOW ENERGY BEAM TRANSPORT LINE

LEBT

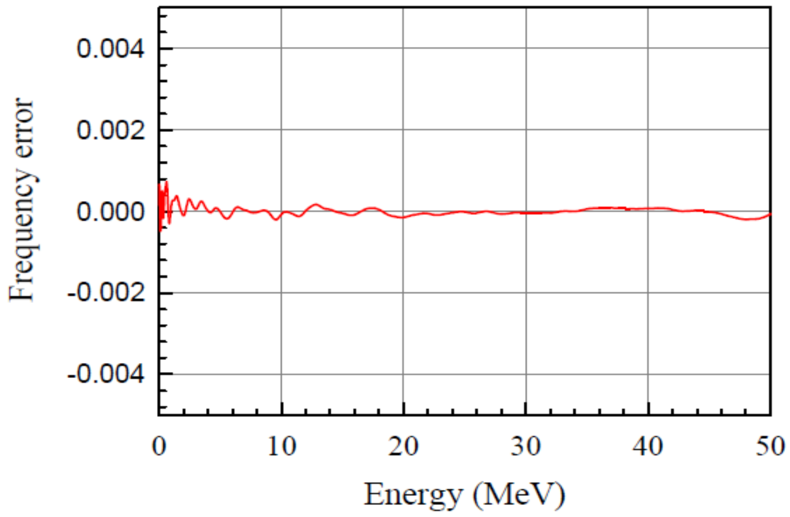


VACUUM JACKETED, LN2 COOLED LIQ. HELIUM TRANSFER LINE

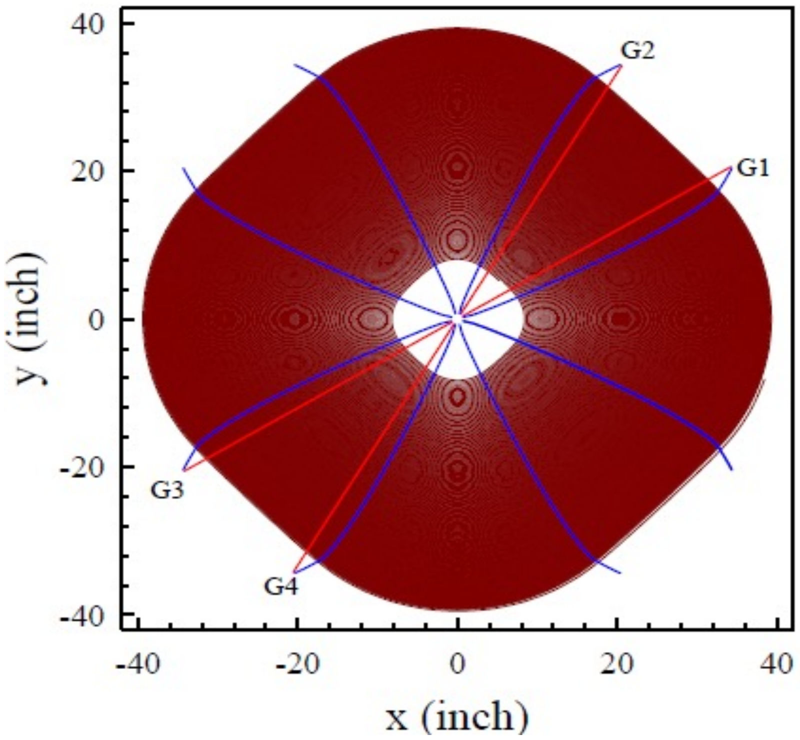
50 MEV PROTON CYCLOTRON FOR ANURIB

Key points:

1. Size is compact (R = 101.5 cm)
2. Tune values away from resonance
3. Frequency error less than 0.04 %
4. Integrated phase shift within ± 5^0

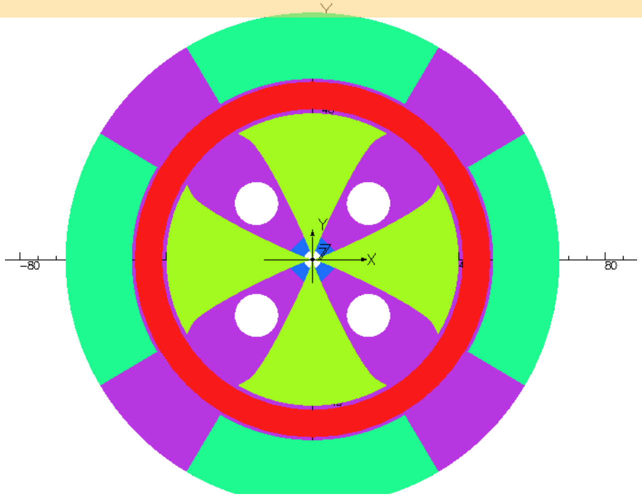


Current Density	0.56 A/mm²)
Ampere-turns/coil	30697.3
No of coils	2
Coil ID	209 cm
Coil OD	247 cm
Coil Height	29 cm
Coil Width	19 cm
No of turns	504
Operating Current	61 A
Magnet OD	343 cm
Magnet Height	160 cm
Iron Weight	77 Ton

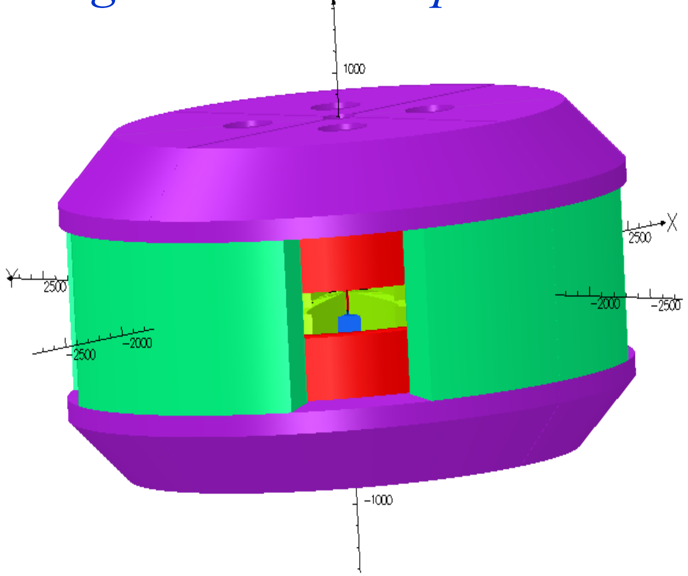


Accelerated Orbit up to 50 MeV

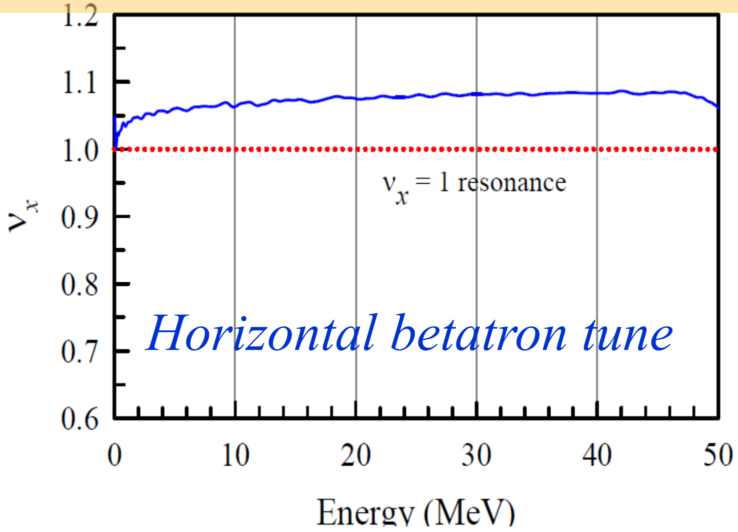
PROTON CYCLOTRON MAGNET DESIGN

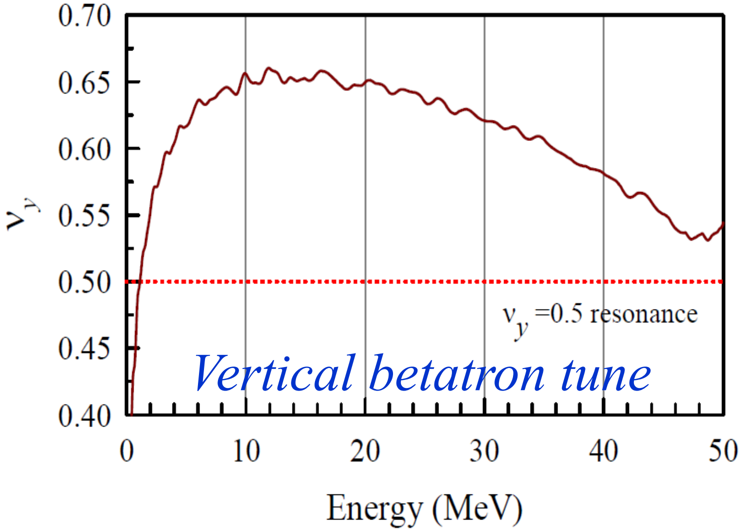


Magnet model in Opera 3D

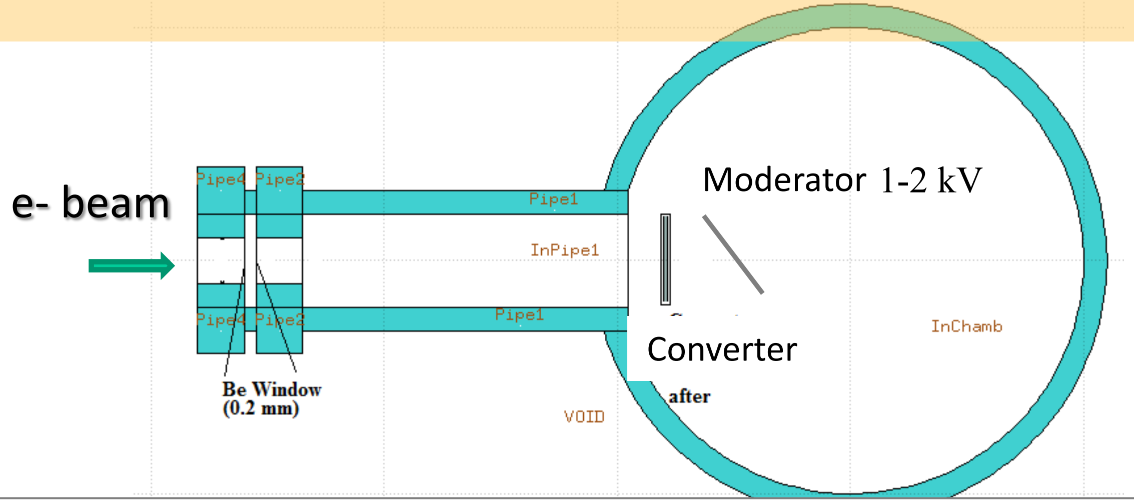


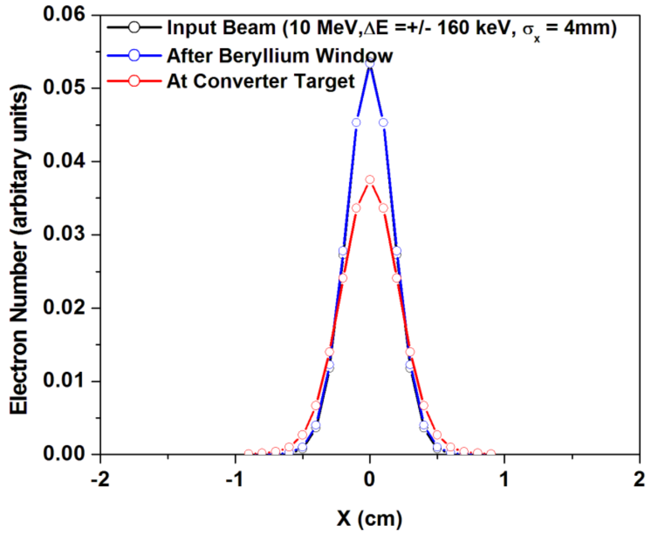
Parameter	Value
No of sector	4
Hill Gap (mm)	30
Valley Gap (mm)	800
Hill field (max)	17 KG
Pole radius	101.5 cm
Valley field (approx)	1 KG
Ion revolution frequency	16 MHz
Harmonic mode	4
RF Frequency	64 MHz
Required Dee voltage	50 kV
No of Dee	2



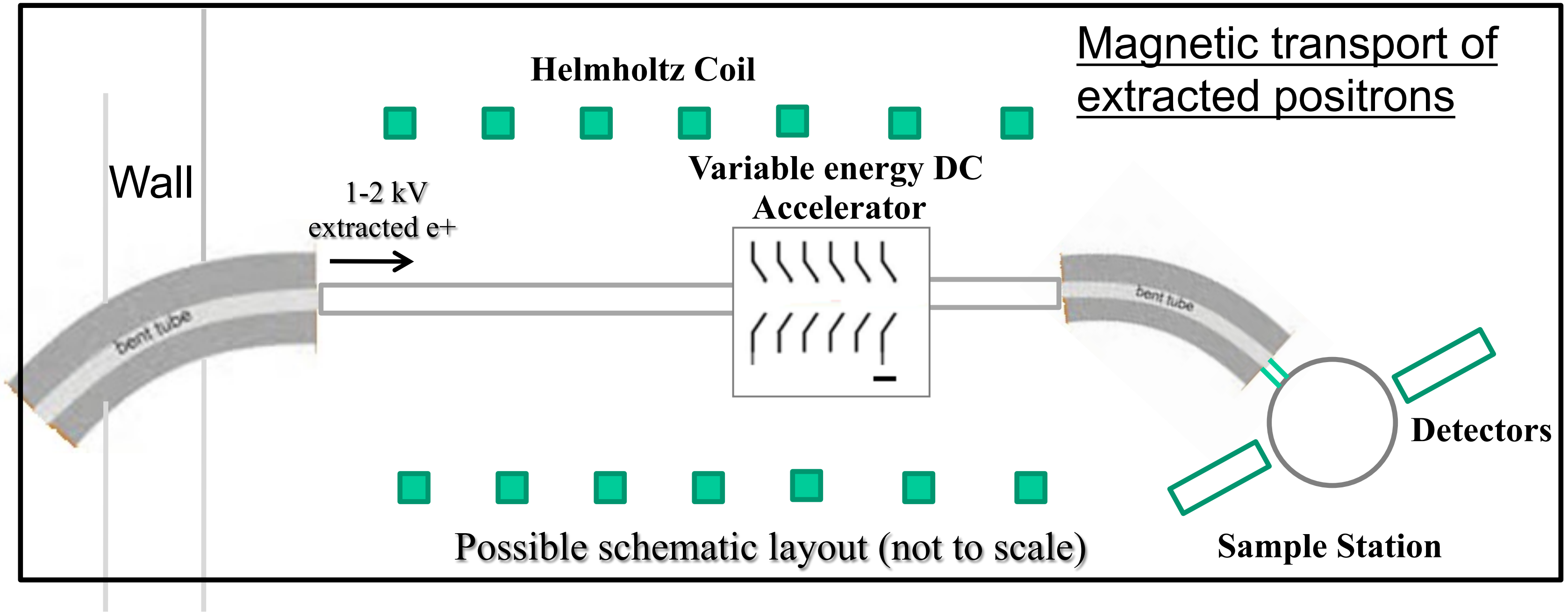


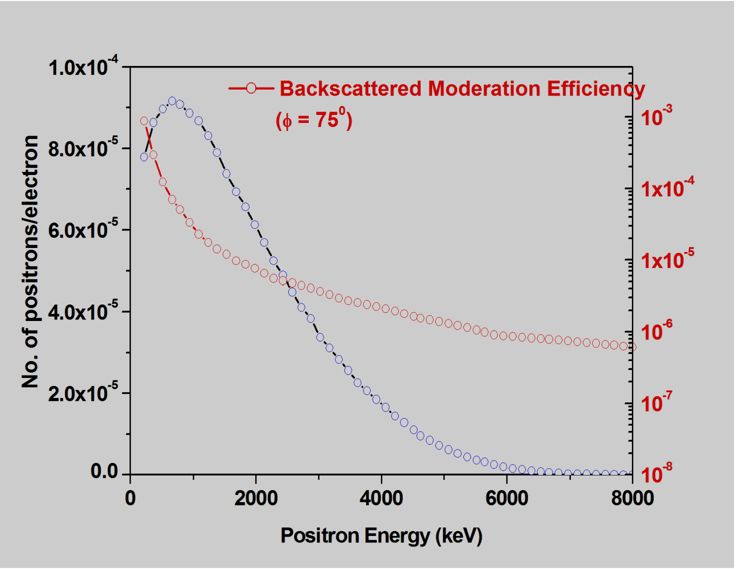
SLOW POSITRON BEAM FROM 10 MEV ELECTRONS





Estimate of moderated positron for 100μA , 10 MeV electron beam ~ $8x10^7$ e+/s





NEUTRON BEAM FROM THE ELECTRON ACCELERATOR

Nuclear Data Measurements:
n-cross section measurement (total, capture, fission, elastic, scattering γ ray, n production) for fission, fusion materials, ADS, transmutation of minor actinides and s process nucleo-synthesis.

Solid State Physics: n provides access to magnetic structure and dynamics of solid

Material Science:
n sensitive imaging will provide new information pertaining to real scale tomography & radiography

Neutron Scattering :
Diffraction data for structural modes of crystals, glass & liquids

Biology & Biotechnology :
n sensitive to dynamics of molecules & single atoms

Estimated neutron flux from 1 mA, 50 MeV electron beam at a measurement station ~ 4m away from converter

Electron energy / MeV	Radiator source strength / s^{-1}	Flux density at measuring position / $cm^{-2} s^{-1}$
20	$7.9 \cdot 10^{12}$	$4.3 \cdot 10^{6}$
30	$1.9 \cdot 10^{13}$	$1.0 \cdot 10^{7}$
40	$2.7 \cdot 10^{13}$	$1.5 \cdot 10^{7}$