An overview of Radioactive Ion Beam facility at VECC

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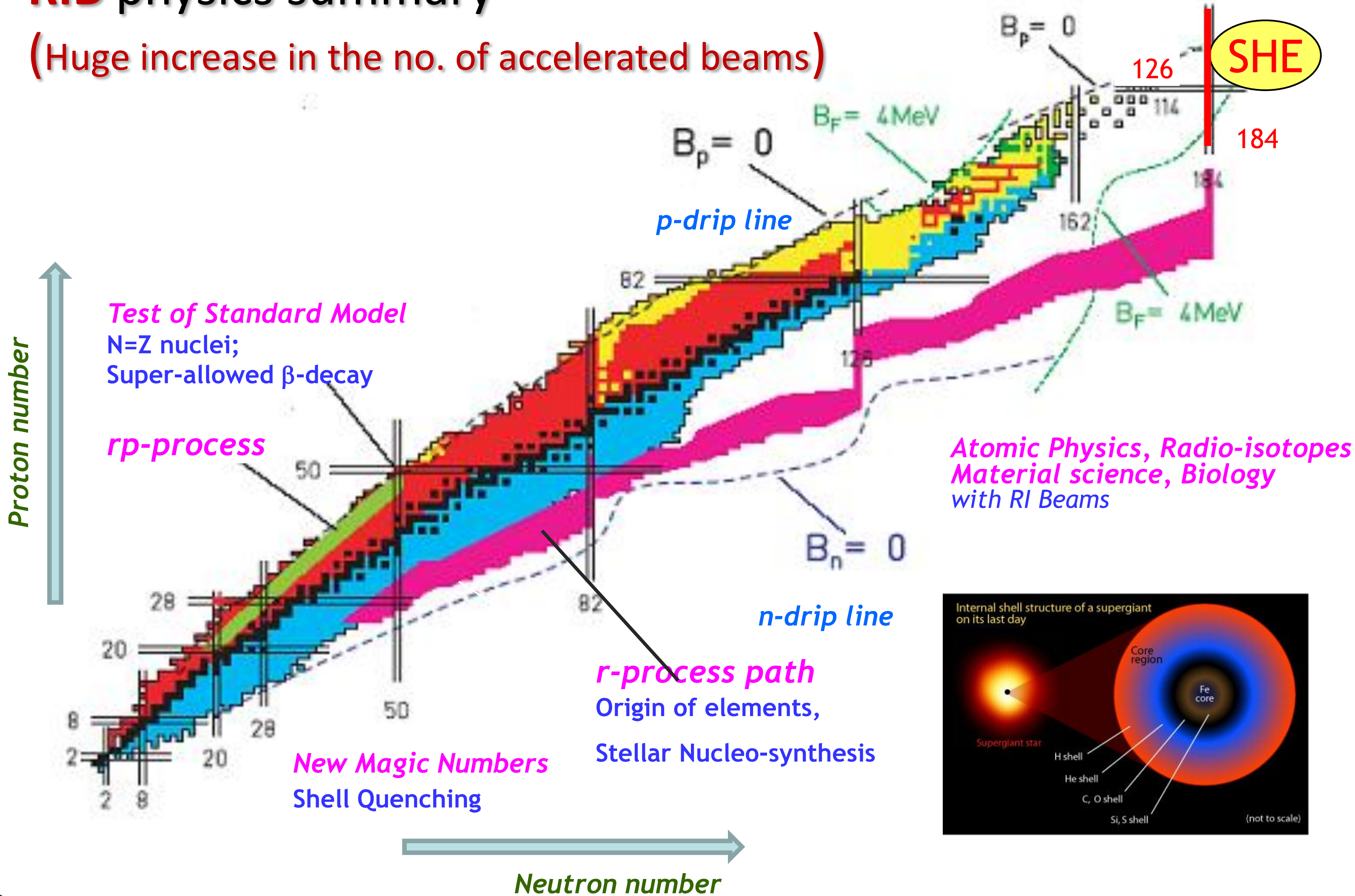
* On behalf of the VECC RIB group

RIB : the beginning of a new era in Nuclear Physics, Nuclear Astrophysics, Material Science, Biology, etc.

- **Nucleo-synthesis in normal stars and in explosive stellar events (we are but stellar dusts)**
- **Stellar evolution**
- **Nuclear structure: Study of exotic nuclei;**
- **Production and study of Super Heavy Elements**
- **Material properties using various radioactive beams as dopants**
- **Atomic physics, Biology; radioisotope production**
- **State of the art Accelerator technology**
- **Human Resource Development**
- **New / unanticipated findings**

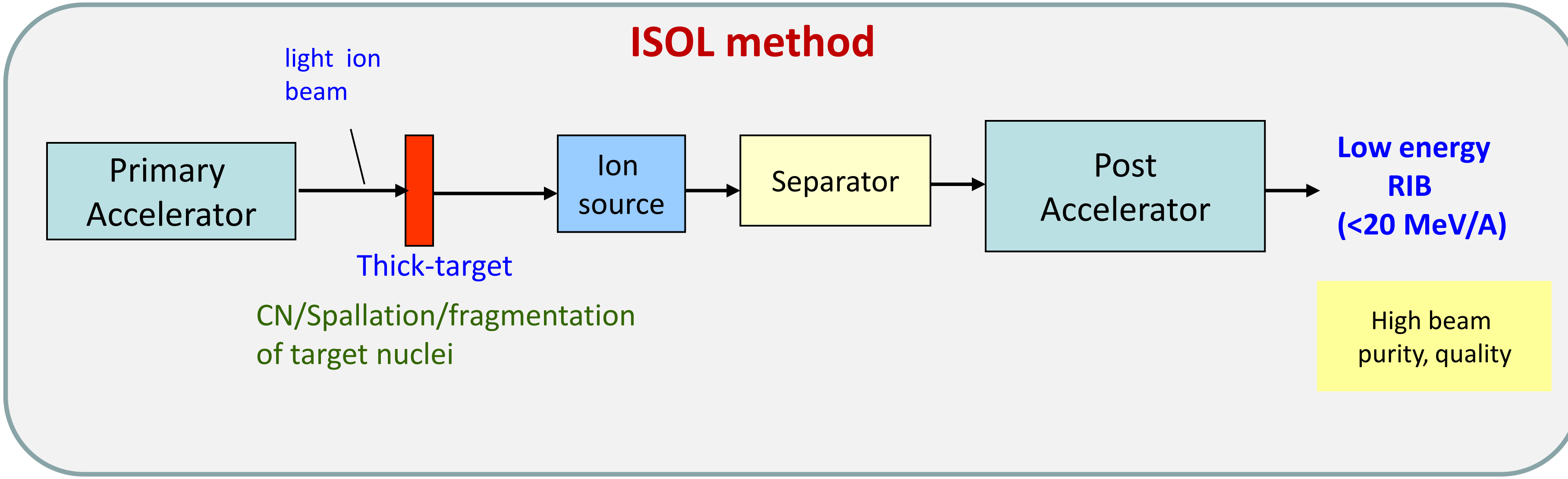
RIB physics summary

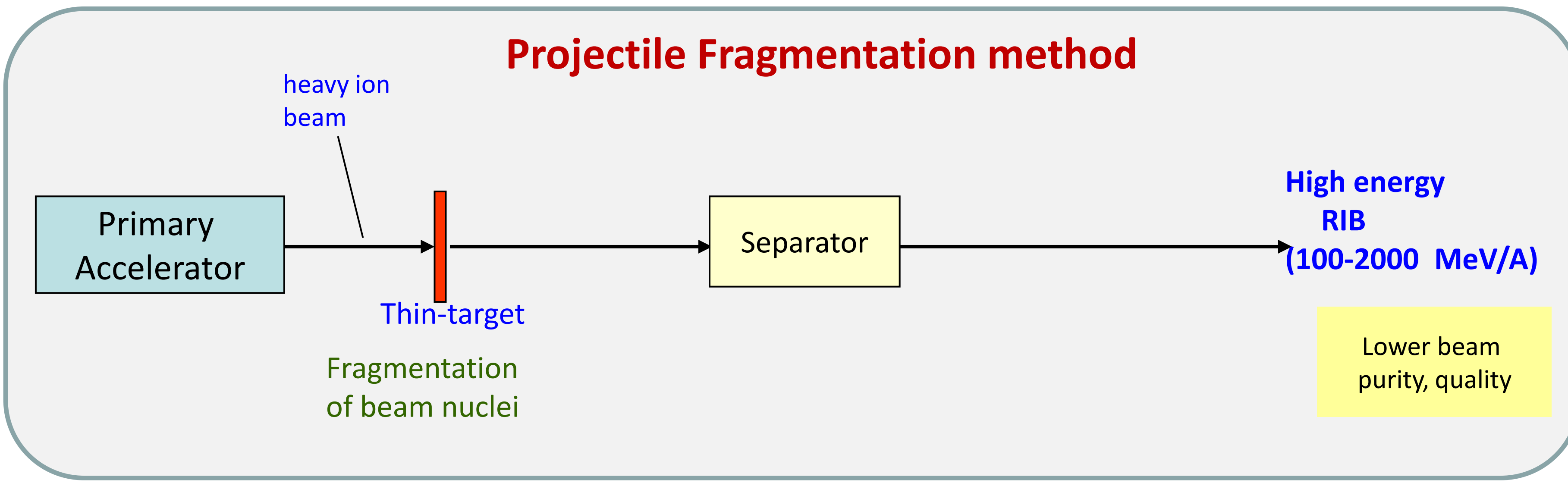
(Huge increase in the no. of accelerated beams)



Production of RIB: Two Complimentary ways

Intensity (RIB) = Intensity (primary beam) x production cross-section x no. of target atoms x efficiency factor





Challenges

- Int. (rib) should be adequate for various experiments ($1 – 10^9$ pps)

  Int. (rib) = Int. (primary Beam) x cross-section x No. of target atoms/cm^2 x efficiency factors (diffusion, ionization, separation, acceleration)

- High intensity primary beam (ADSS; accelerator-energy interface)

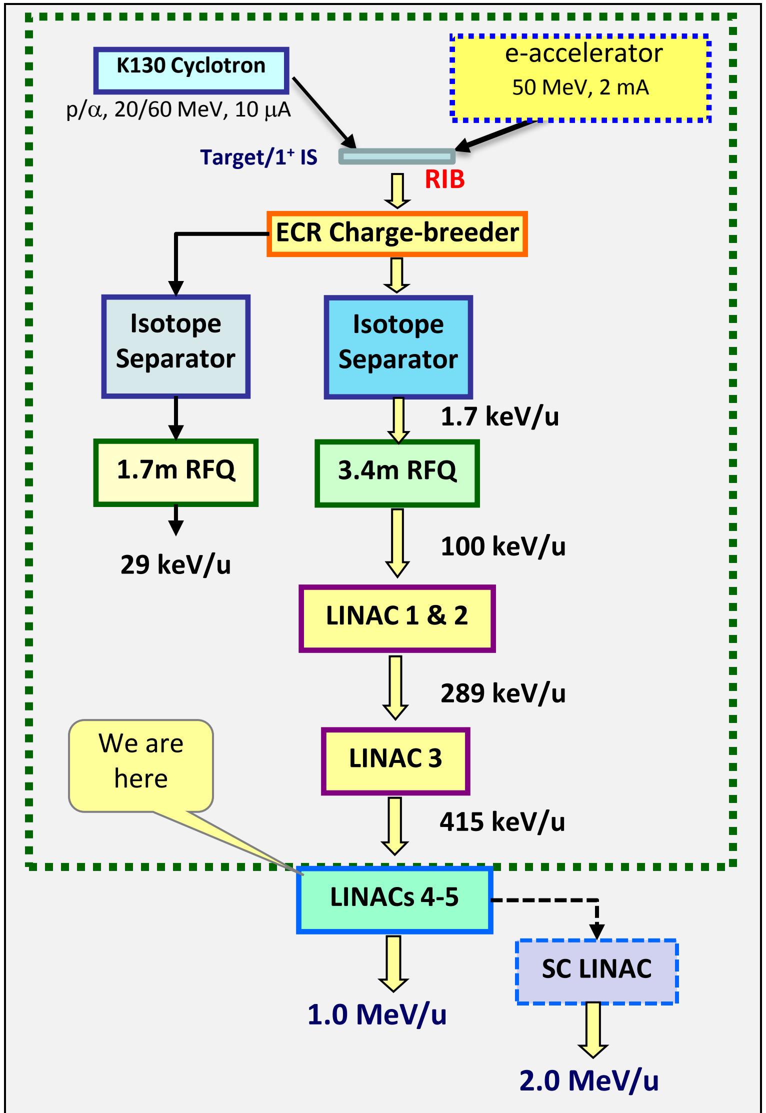
- Development of thick targets that can sustain high beam power (ADSS)

- Efficient ionization, separation & post-acceleration of RIB

- Both PFS & ISOL type facility to cover all ranges of half-life

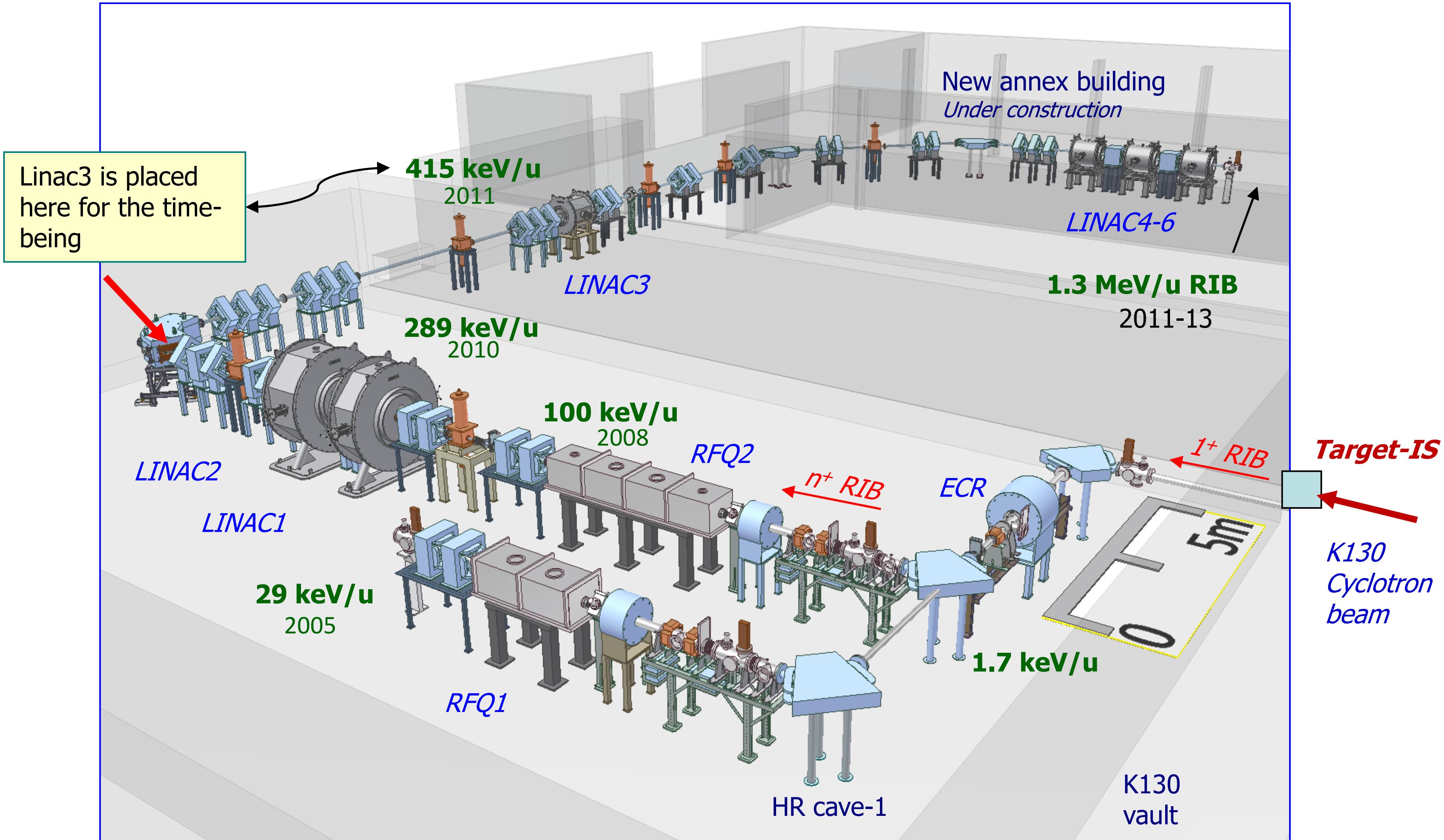
- State of the art detector systems (traps, arrays, ISOL, PFS, storage rings) & New ideas and detector arrays to improve S/N ratio

Towards our aim.. What have we achieved so far?

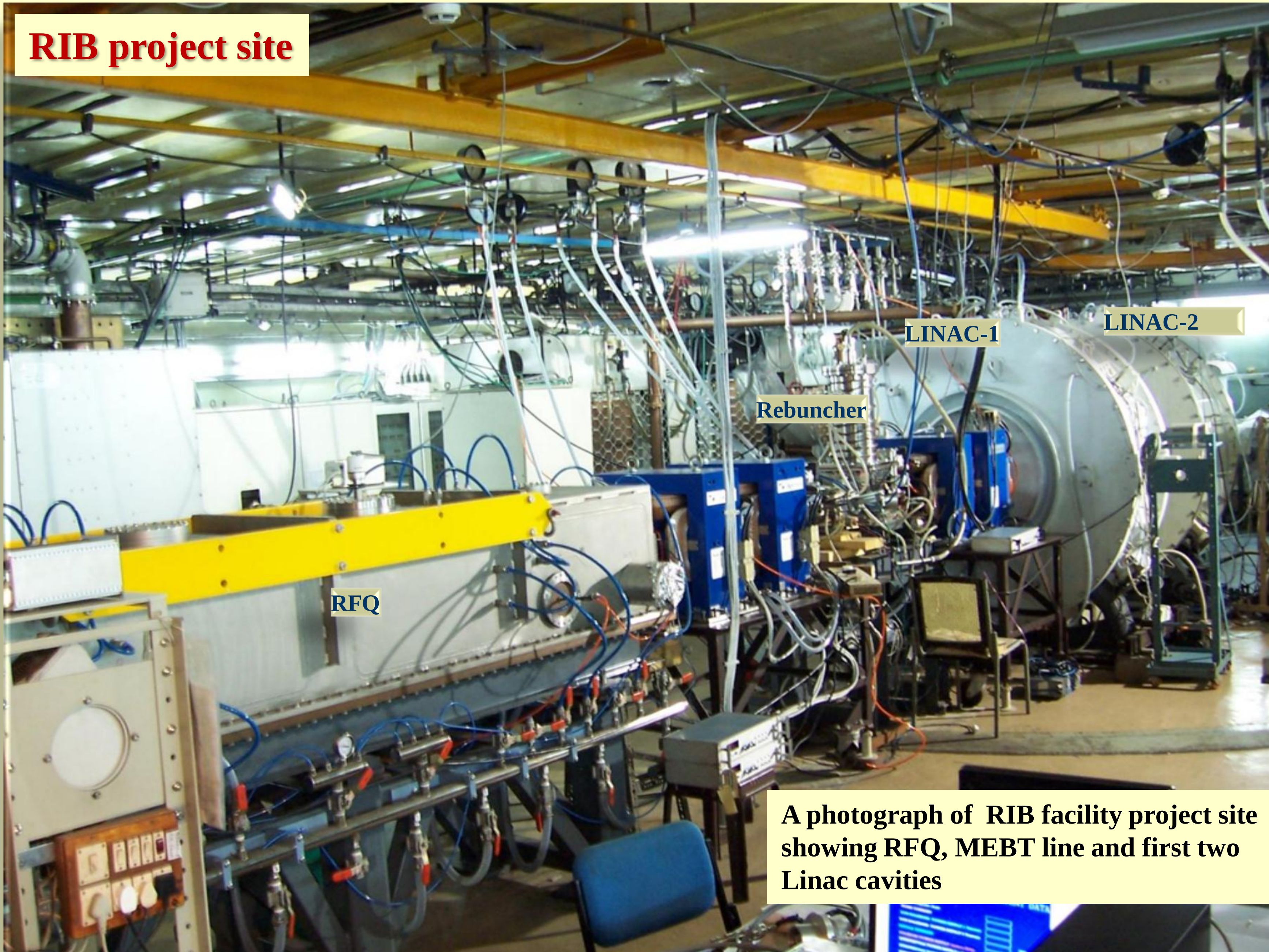


- Accelerated stable isotope beams to 415 keV/u
- Developed 1st RFQ in the country (29 keV/u). Second RFQ commissioned in 2008 (100 keV/u). Fully indigenous development.
- Developed 1st IH-Linac in the country. Linac-1 & 2 & 3 are already commissioned. Stable ion beams accelerated to 415 keV/u at the end of Linac-3.
- Linac 4 ready to be commissioned. Linac 5-6 being ordered. To be installed in new annex building by 2013
- Target R&D , on-line experiments ongoing.
- Experiments using cyclotron beam for acceleration of Radioactive Ion Beams are underway. $^{42,43}K$, ^{14}O, & ^{41}Ar beams are already produced
- Superconducting Electron Linac development started, in collaboration with TRIUMF Canada.
- Ion-beams from the facility have been used for material science experiments.
- Fragment Separator based experiment & PFS design (collaboration with RIKEN)

Schematic layout of RIB beam-line at VECC



RIB project site

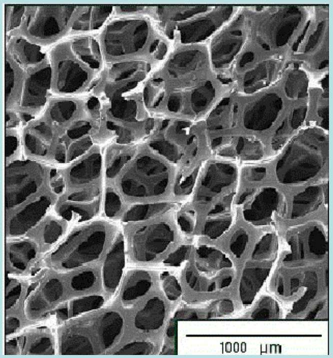


A photograph of RIB facility project site showing RFQ, MEBT line and first two Linac cavities

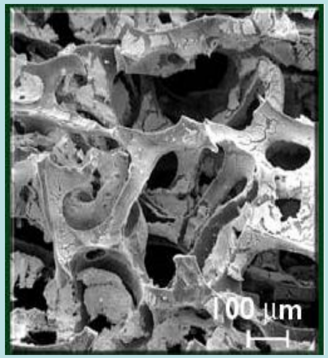
Production of RIB: R&D on Thick target

- Targets should be porous : Efficient & Fast release of radioactive atoms
- Targets should withstand beam irradiation for days together

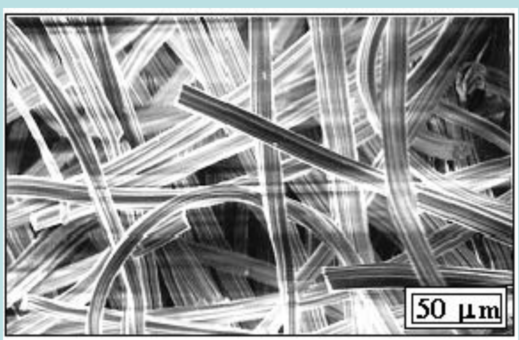
Target material coated on base matrix of RVC : Reticulated Vitreous Carbon



SEM of RVC Foam



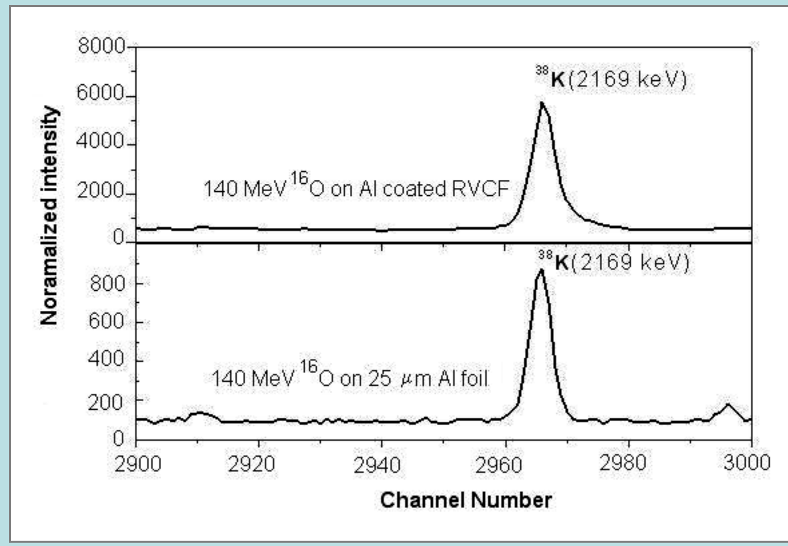
RVC Foam with Al_2O_3



RVC Fibres with Al_2O_3

Ceramics International, 34 (2008) 81

Target release experiments with Oxygen beam from K130 cyclotron



10 times Yield enhancement in Aluminum coated RVCF (top) as compared to Al foil (bottom) : effect of increase in surface to volume ratio is clearly seen

Nucl. Instrum. & Meth. A539 (2005)54

Grain growth studies in ZnO – R&D on high power targets

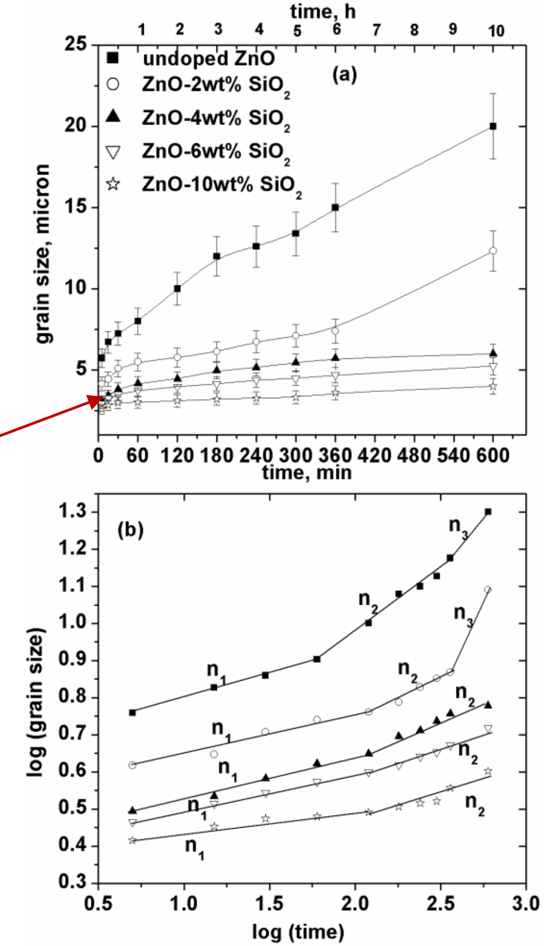
Ceramic International 34 (2008) 81; Ceramic International 37 (2011) 2679

- RIB intensity critically depends on radioactive isotope yield from the target.

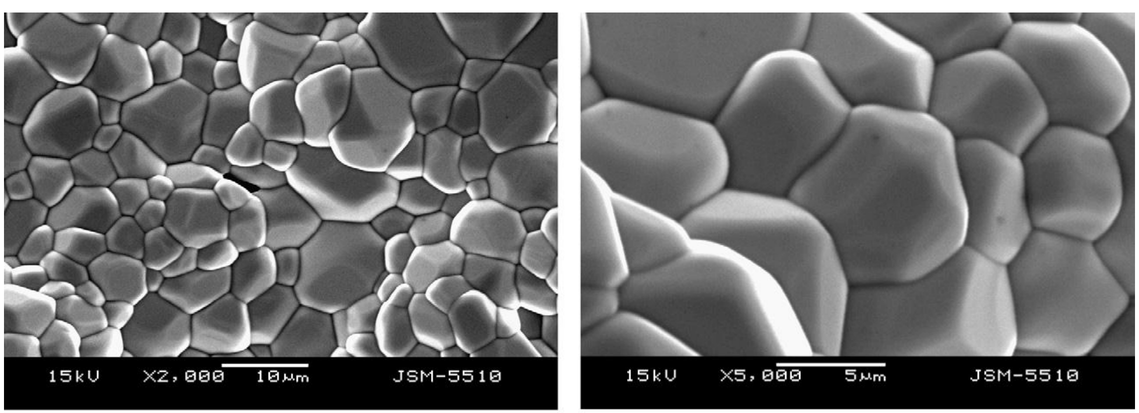
- Radioactive atoms should efficiently and quickly diffuse out of the target. Target should withstand high primary beam intensity without getting damaged.

- Sintering & grain growth in target due to beam heating hinders release of radioactive atoms and leads to localized heating which amplifies grain growth. Studies show that grain size of ≥ few microns reduces release efficiency.

- Our studies at VECC on ZnO have shown that grain growth can be controlled to< 20 micron grain size if one chooses nano-crystalline target compound. Grain growth can be further controlled to < 5 micron by Silica doping of 4 wt %.



(top) Grain growth for un-doped and Silica doped ZnO sintered at 1300 °C for 10 hours (bottom) Kinetics of grain growth changes due to silica doping

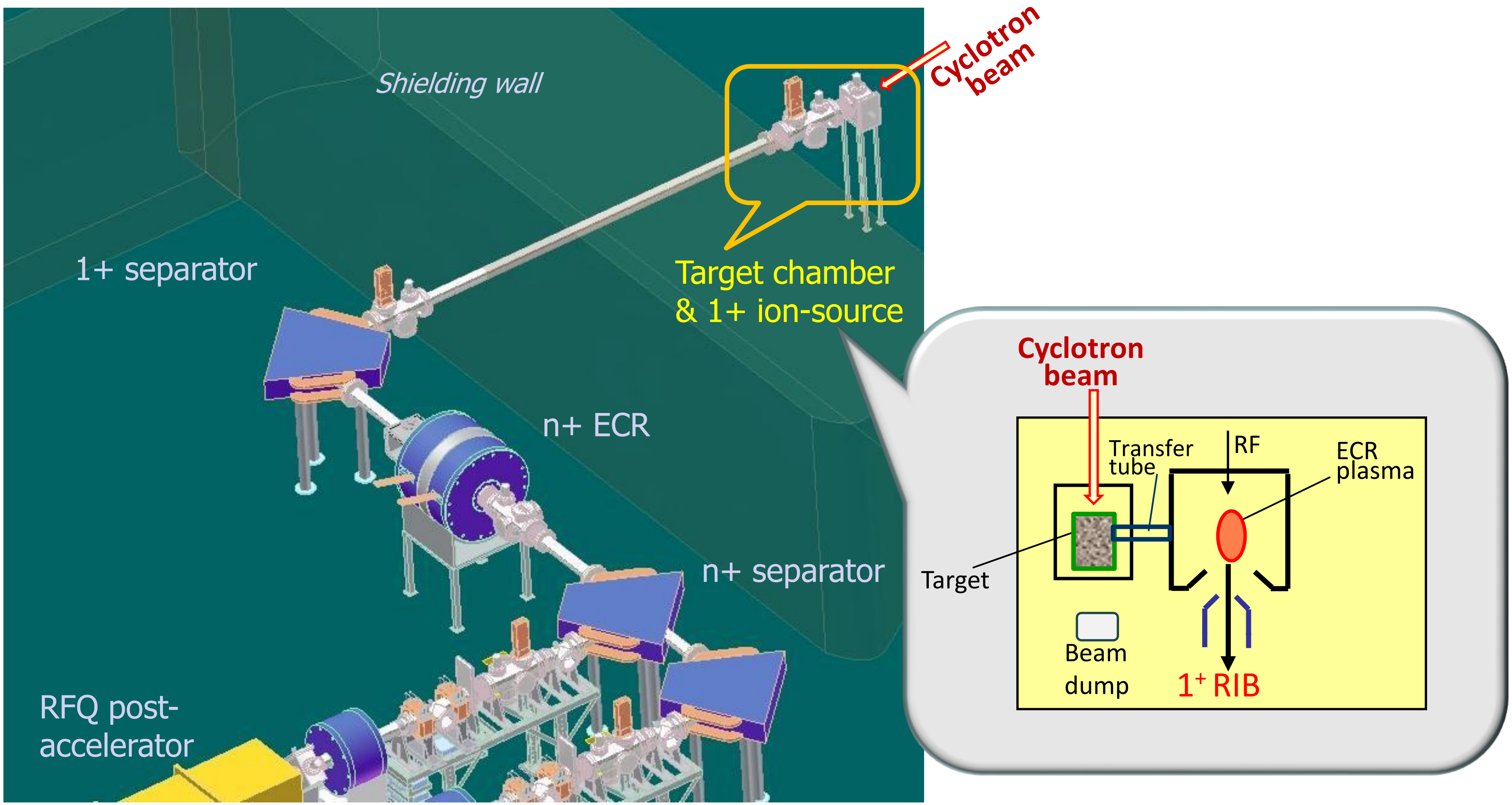


(a) (b)

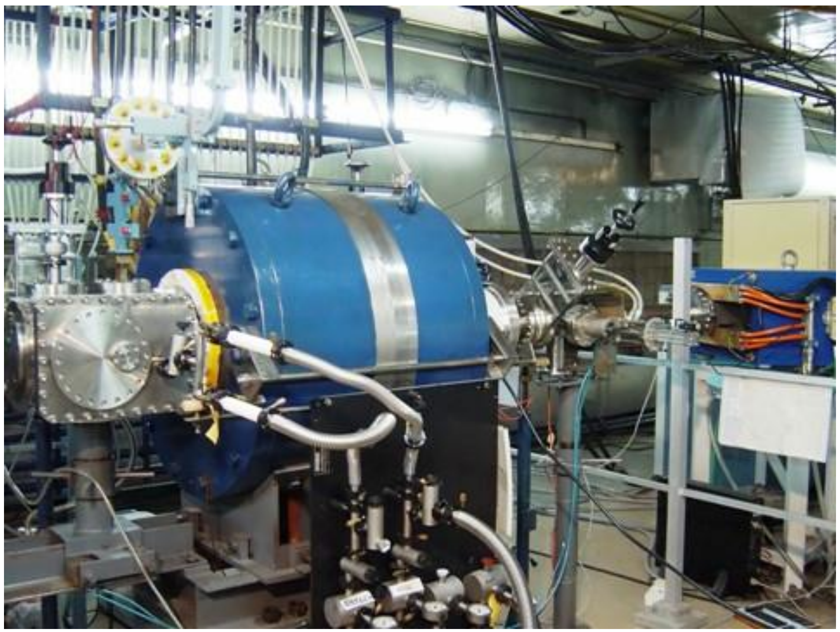
SEM image of nano-crystalline ZnO sintered at 1300 °C for 10 hrs. Grain size increase is ~ 20 micron size.

Ionization: Target-ion-source (1+) and 2 ion-source Charge Breeder (n+)

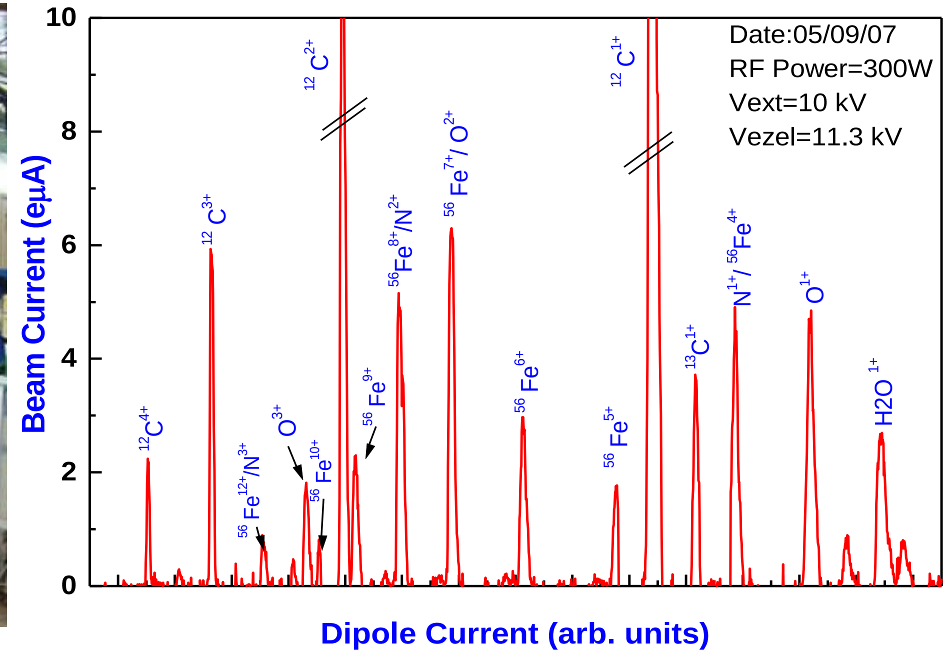
NIM A547 (2005)



Electron Cyclotron Resonance ion source



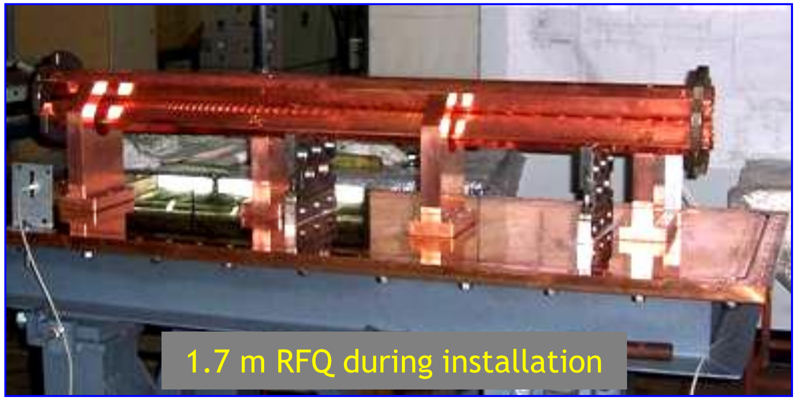
6.4 GHz on-line ECR ion-source

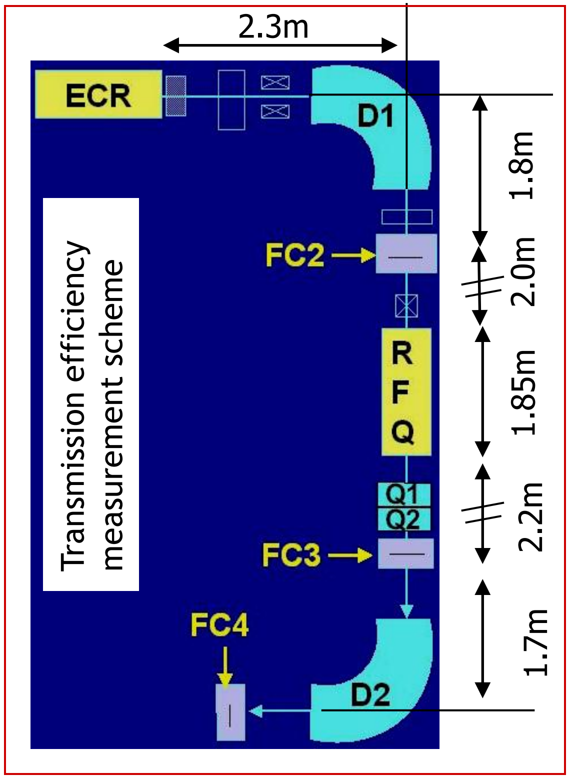


Typical spectrum from ECR ion source

Acceleration: 1.7 m RFQ commissioned in Sept. 2005 *India's first RFQ*

Rev Sci Instrum. 78 (2007) 043303 ; Rev. Sci. Instrum. 80, (2009) 103303





Measured Parameters	*Value*
Frequency	33.7 MHz
Q- value	5200
RF power for $^{16}O^{4+}$ (V_{vane}=11.45 kV)	670 W
RF power for $^{16}O^{3+}$ (V_{vane}=15.27 kV)	1.2 kW
RF power for $^{16}O^{1+}$ (V_{vane}=45.9 kV)	*10.8 kW
Typical transmission at RFQ exit (FC3/FC2)	#85 %
Typical transmission of analyzed beam (FC4/FC2)	#80 %
** Duty factor 20%* *# Electron suppressed FC*	

- RFQ constructed with complete indigenous technology
- Machining of Vane, post & other components at Central Mechanical Engineering Research Institute (CMERI), Durgapur (200 km from Calcutta)
- RF transmitters made by SAMEER, Mumbai ; RIKEN's (Japan) help in physics design

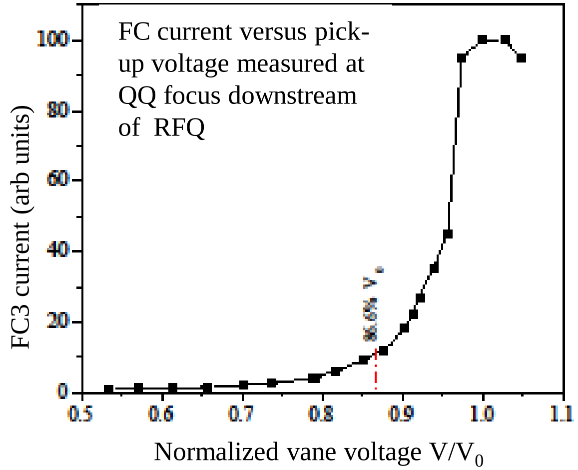
3.4m RFQ: commissioned in July 2008

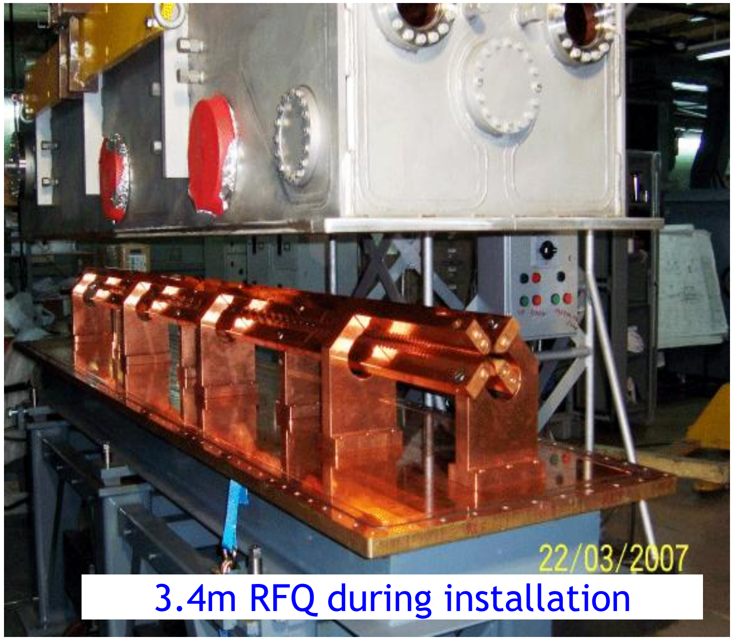
Rev Sci Instrum. 81 (2010) 023301

- $q/A=1/14$; input = 1.75 keV/u;
output = 100 keV/u, 3.4m long,
vane length ~ 3.12m, resonating at 37.83 MHz

- RFQ made at CMERI Durgapur, Cavity,
Cu plating at GSI, Darmsadt via Danfysik

- Measured transmission efficiency at
RFQ exit for O^{5+} ~ 90 %

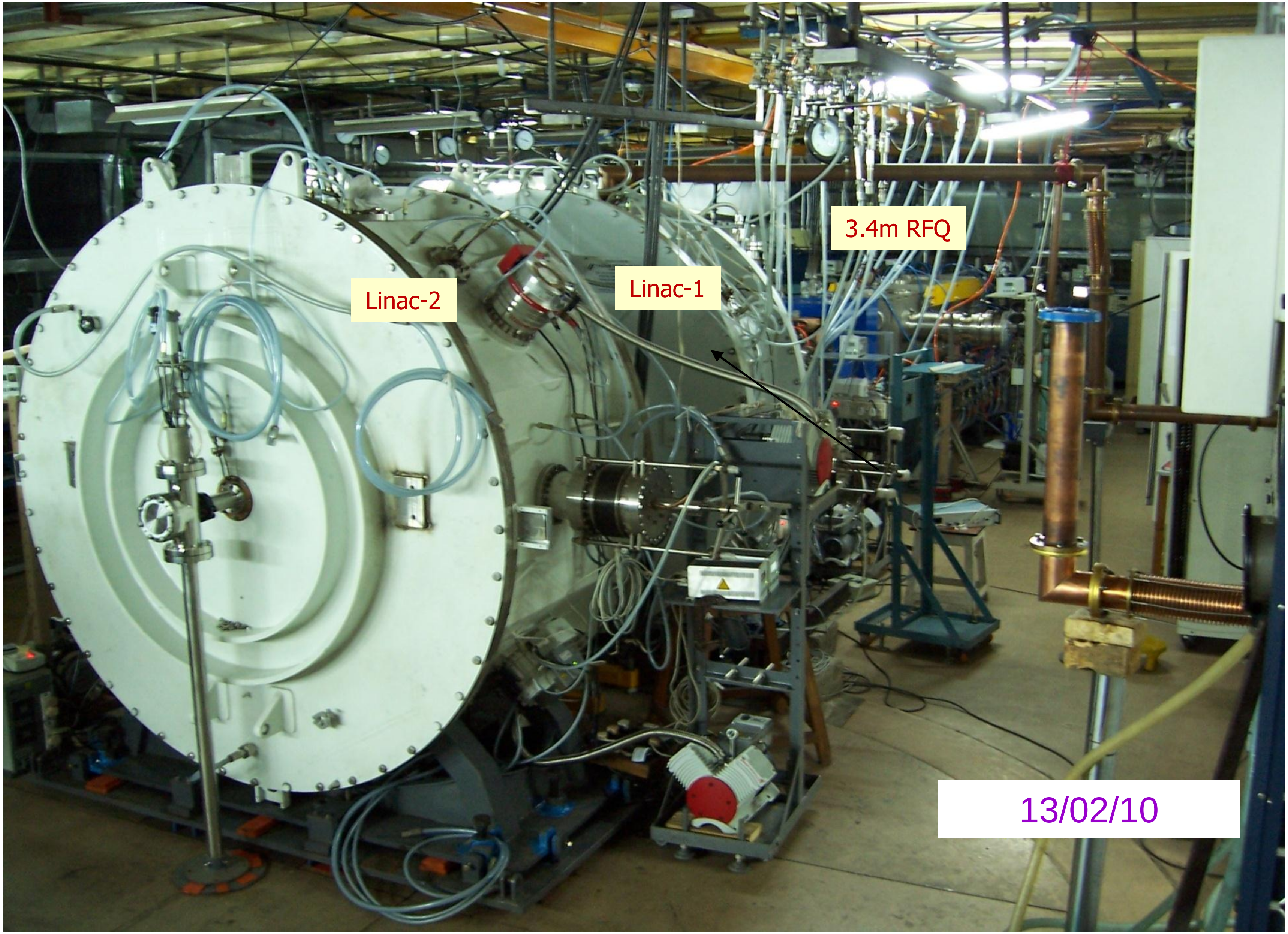




3.4m RFQ during installation

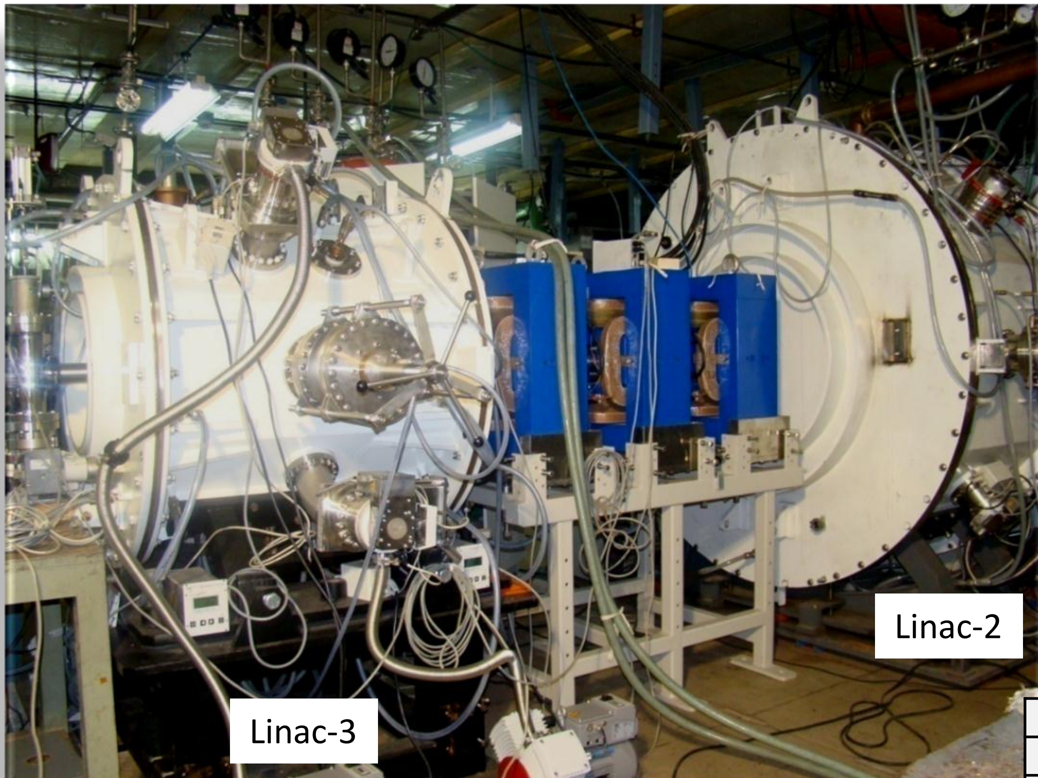
RIB project site

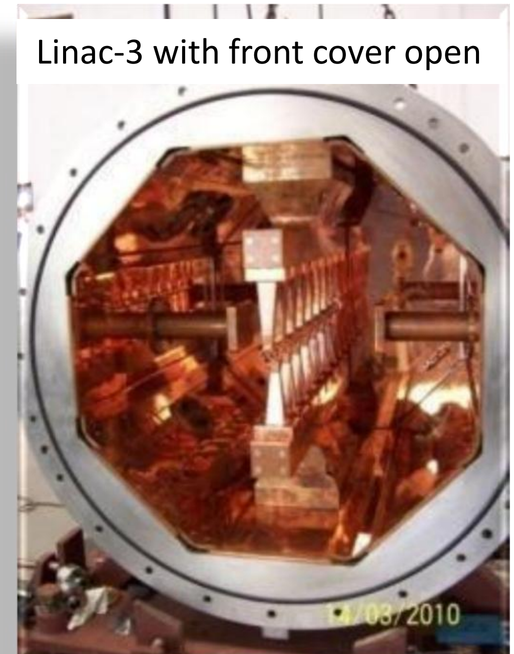
Linac Modules



LINAC-3 Commissioned in March 2011

414 keV/u (5.8 MeV), 400 nA $^{14}N^{4+}$ beam accelerated through LINAC-3





Linac-3 with front cover open

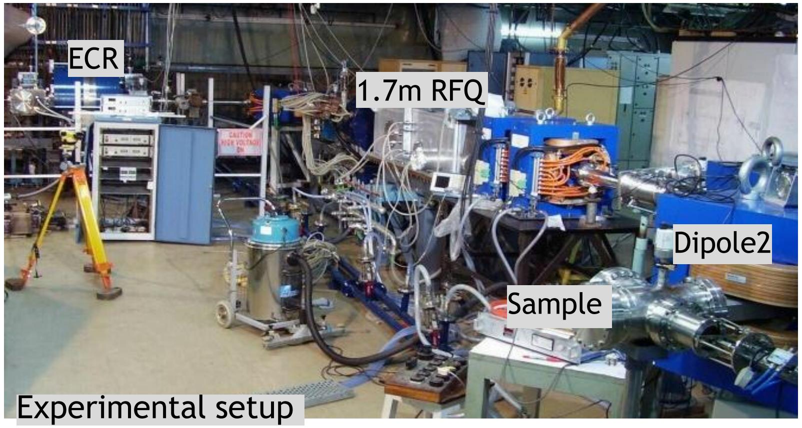
A photograph of Linac-3 installed downstream of Linac-2 for beam test;
Eventually will be moved to adjacent cave

Parameter	Unit	Linac-2	Linac-3
Frequency	MHz	37.8	75.6
q/A	>=	1/14	1/14
E(in)	KeV/u	186.2	289.1
E(out)	KeV/u	289.1	413.9
Peak Vol.	kV	±107.8	±75.8
Length	m	0.871	0.913
Inner Dia	m	1.72	0.8
Accln. Grad.	MV/m	1.79	1.99
Power (Calc)	kW	9.84	11.5

Study on room temp. ferromagnetism in ZnO; effect of Fe Ion-implantation

Nucl. Instrum. & Meth. B267 (2009) 1783 ; Phys. Lett. A371 (2007) 482

Ion implantation of Fe beam accelerated in RFQ

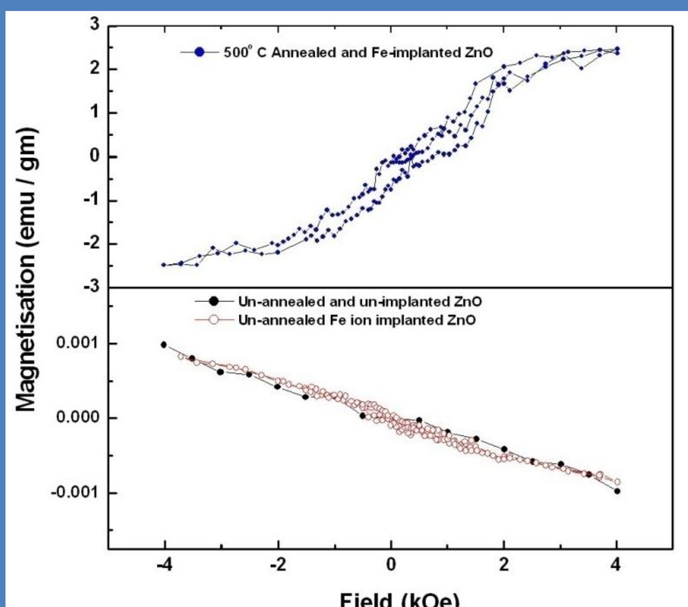


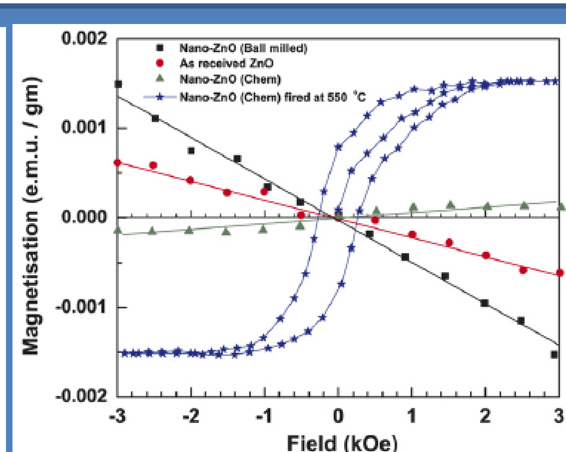
Spintronics : ZnO - potential candidate ; prediction that it may show ferromagnetic ordering at room temperature

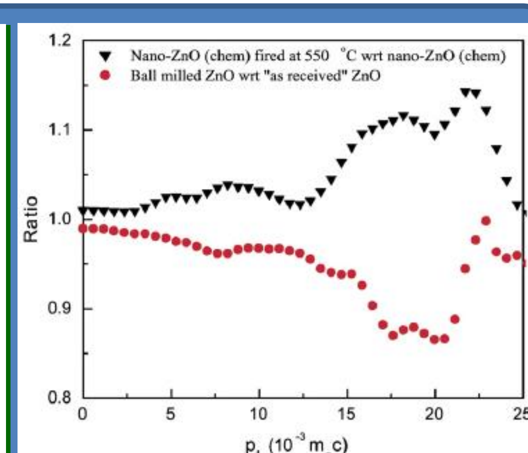
• Positron annihilation studies at VECC show clearly that defects govern room temperature ferromagnetic properties of nano-crystalline ZnO.

• Enhanced positron annihilation with core electrons of Zn observed in 500 °C annealed ZnO ; strong correlation between defects and ferromagnetism seen experimentally

• Two orders enhancement in saturation magnetic moment seen in Fe ion-implanted ZnO (500 °C annealed). For this study 10^{16} $^{56}Fe^{6+}$ ions of 1.63 MeV were implanted in 0.75 micron ZnO sample.







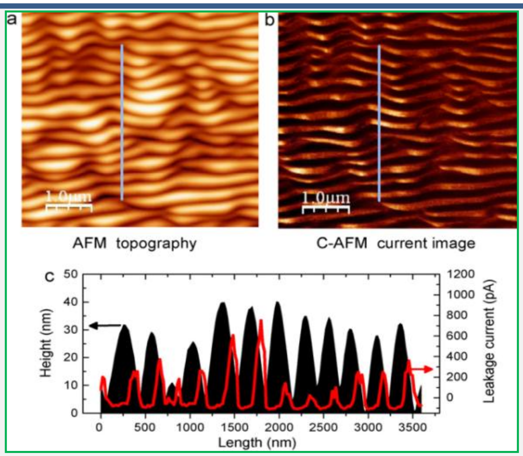
(left) Enhanced saturation magnetic moment in 500 °C annealed Iron implanted ZnO, compared with un-implanted annealed ZnO (top)

Ratio of electron-positron momentum distribution for various samples. Enhancement in higher momentum region indicates preferred annihi-lation with Zinc 3d core electrons

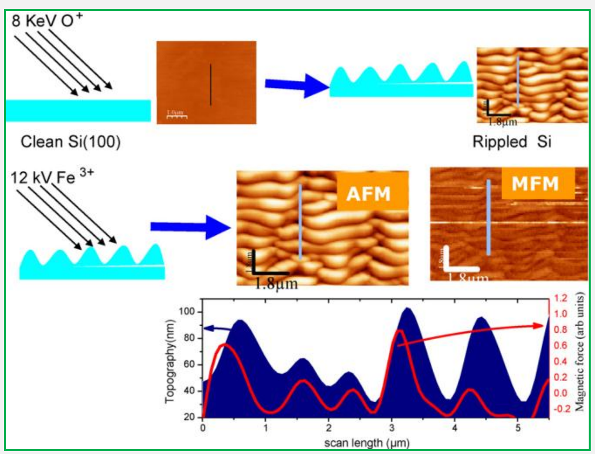
Surface science studies using ion-beams from the facility

Appl. Surf. Sci. 257, 6775 (2011), Appl. Surf. Sci. (2011) doi:10.1016/j.apsusc.2011.07.038; Nucl. Instr. & Meth. xx, xxx (2012)
S. Bhattacharjee, et.al., AIP Conf. Proc.**1349**,611 (2011); J. Phys. Cond. Matt. 22, 175005 (2010).

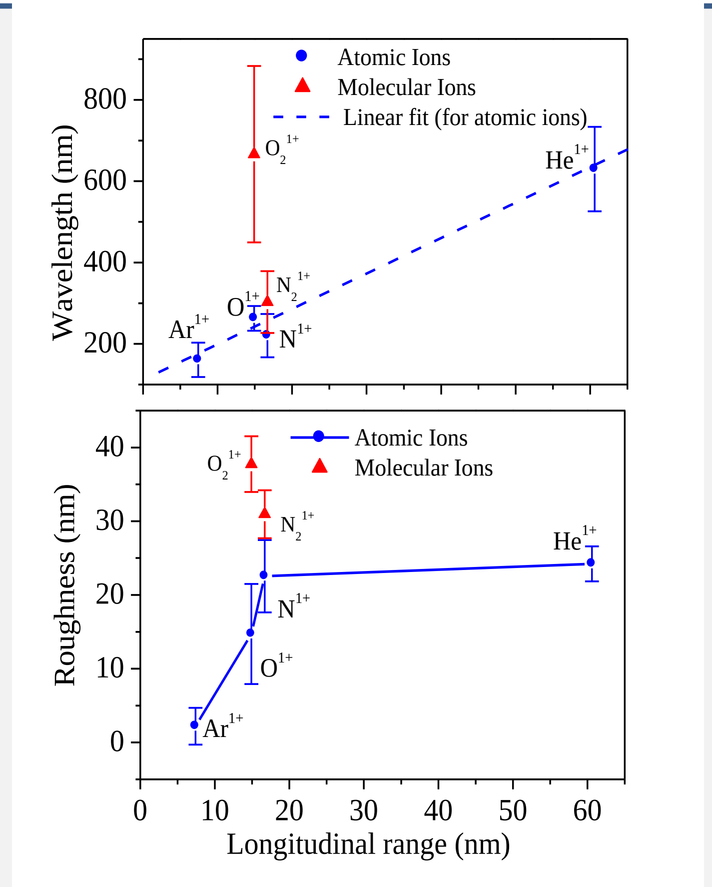
Ion beam induced nano-pattern formation and coulomb sputtering studies on Silicon oxide, Zinc Oxide, Carbon films etc. using oxygen, carbon, argon, nitrogen ion beams from the facility.



Periodic semiconducting insulating stripes formation by keV oxygen ion bombardment



Periodic magnetic non magnetic stripe formation by ion implantation



Effect of projectile's chemical reactivity on nano-patterning. Oxygen and nitrogen show enhanced effect on nano-patterning.

A novel detector & technique for delayed proton measurement

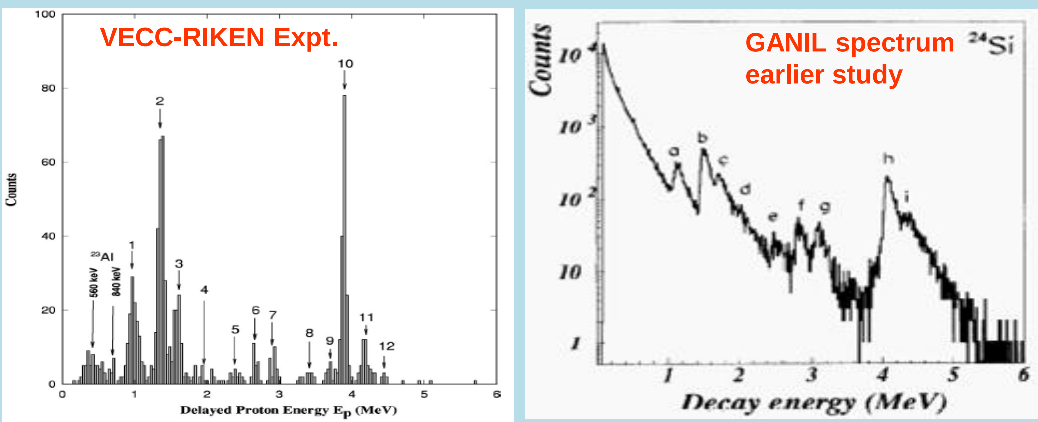
Phys. Rev. C 63, 024307 (2001) ; Phys. Rev. C 80, 044302 (2009) ; Eur. Phys. J. A 42, 375-378 (2009)

- VECC group established a new technique for beta delayed-proton spectroscopy of proton-rich exotic nuclei.

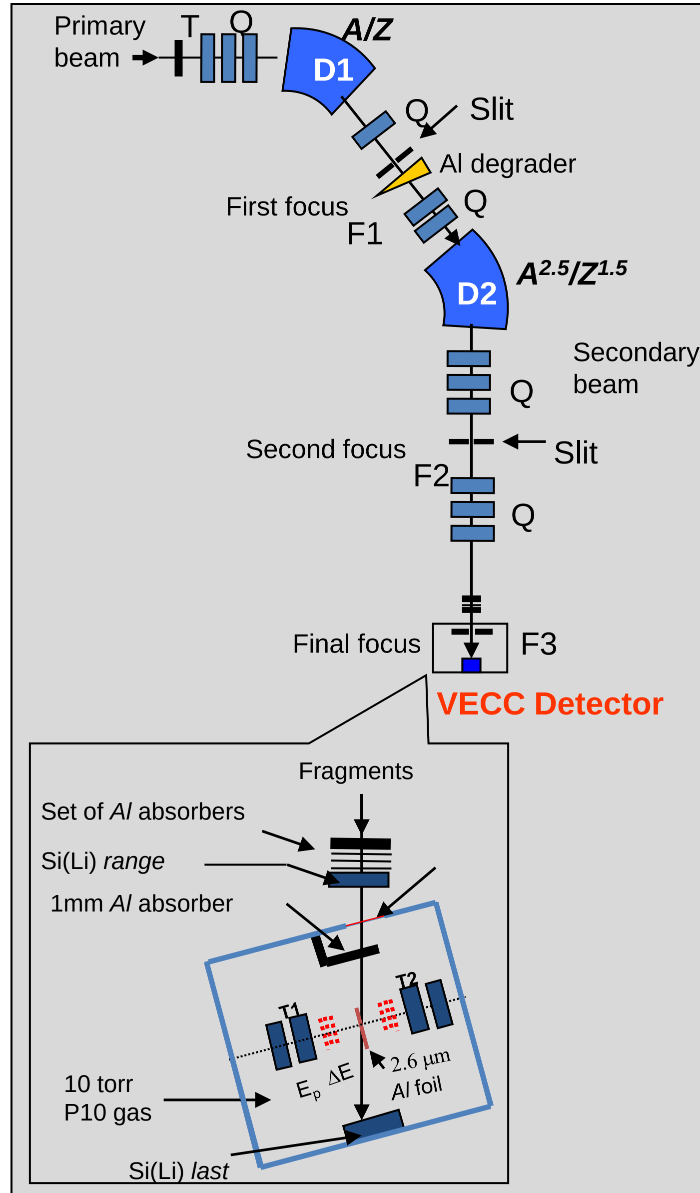
- VECC made detector was used at RIKEN projectile-fragment separator facility to study decay of 140 msec ^{24}Si.

- RIKEN is now using this technique for studying other proton-rich nuclei. The studies have lead to two PhD thesis – one from VECC & another from RIKEN.

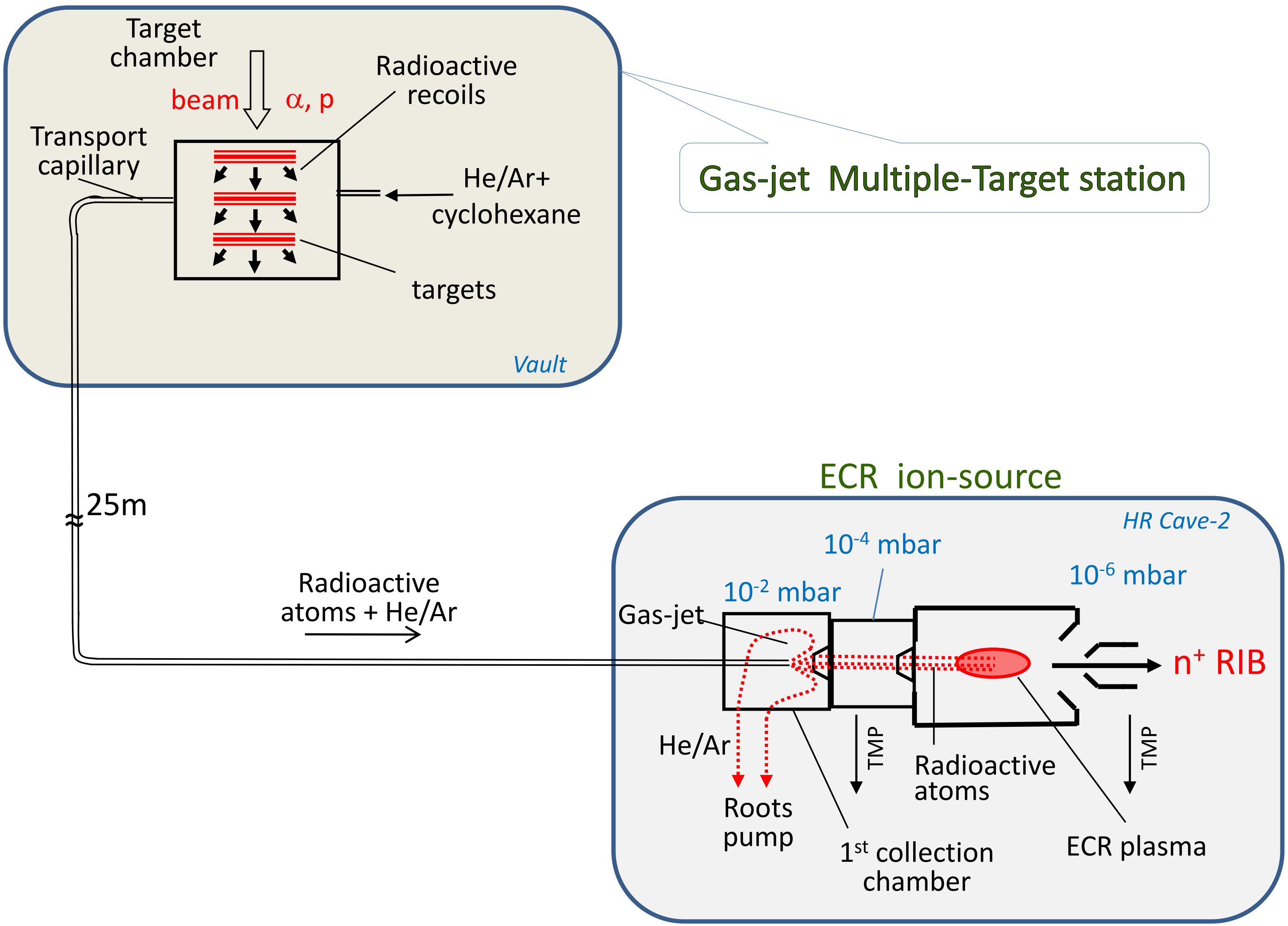
Delayed proton spectra of ^{24}*Si* ($T_{1/2}$ 140ms)



New technique for delayed proton measurement at RIKEN RIPS facility: **Dramatic improvement in quality of delayed proton spectra**



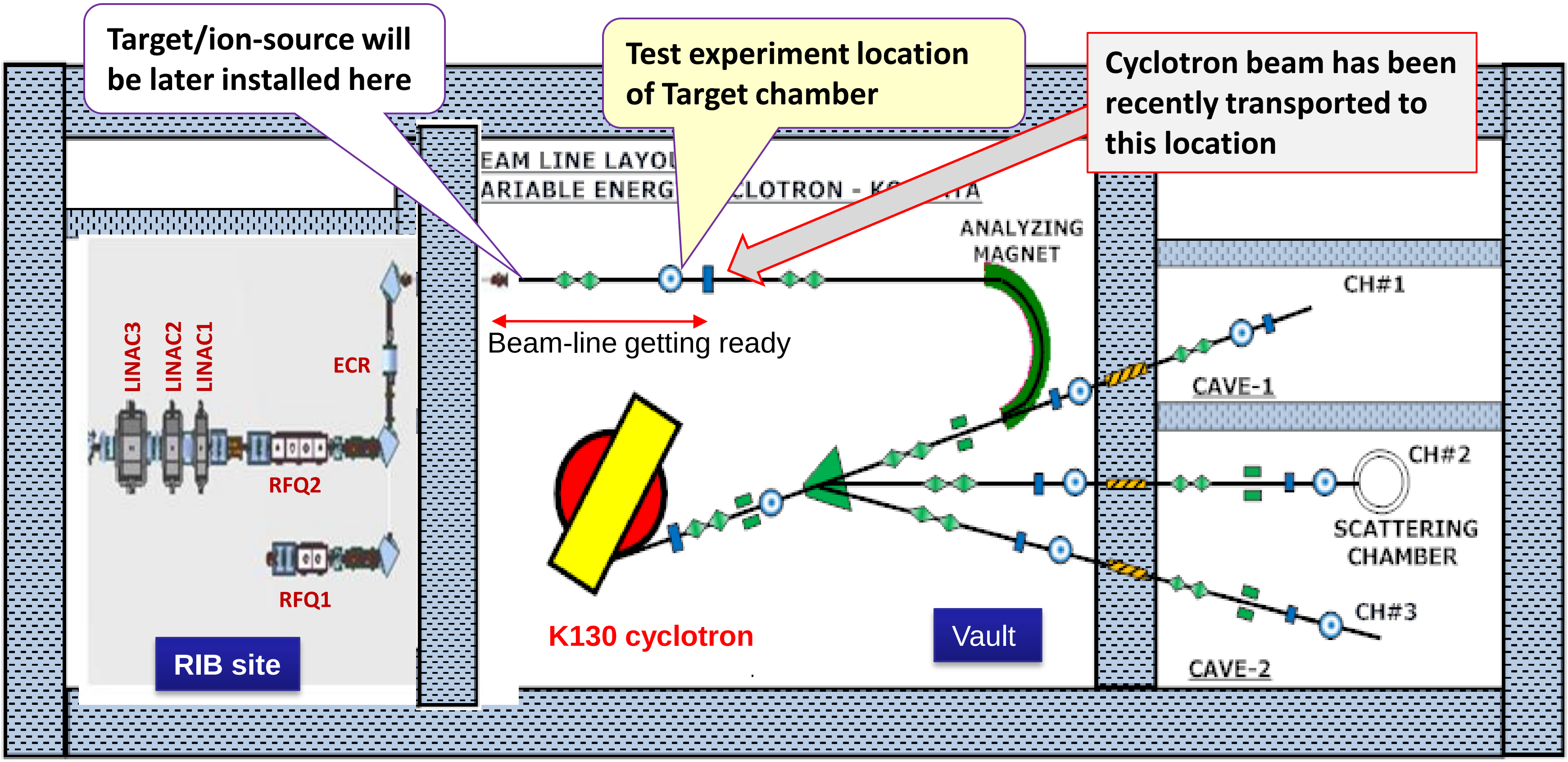
Transport and production of RIB- a new approach



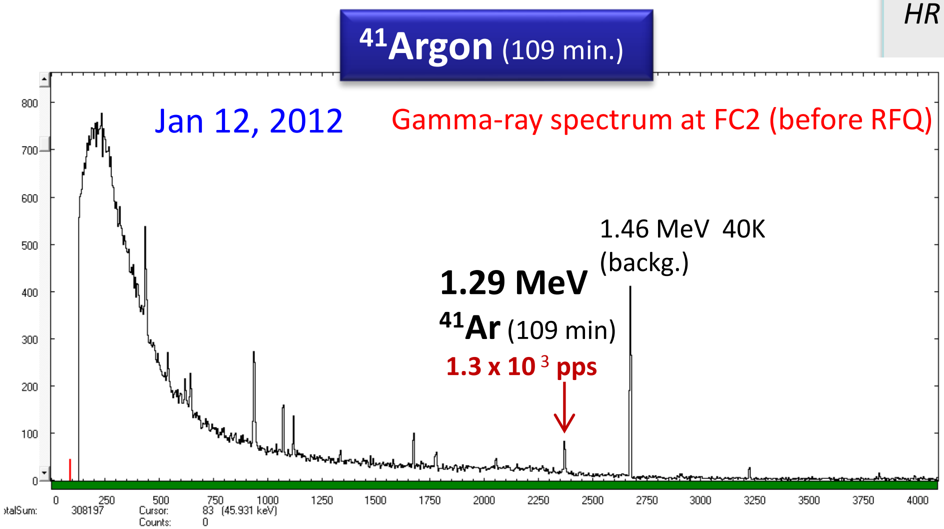
Successful production of RIB – first test experiments

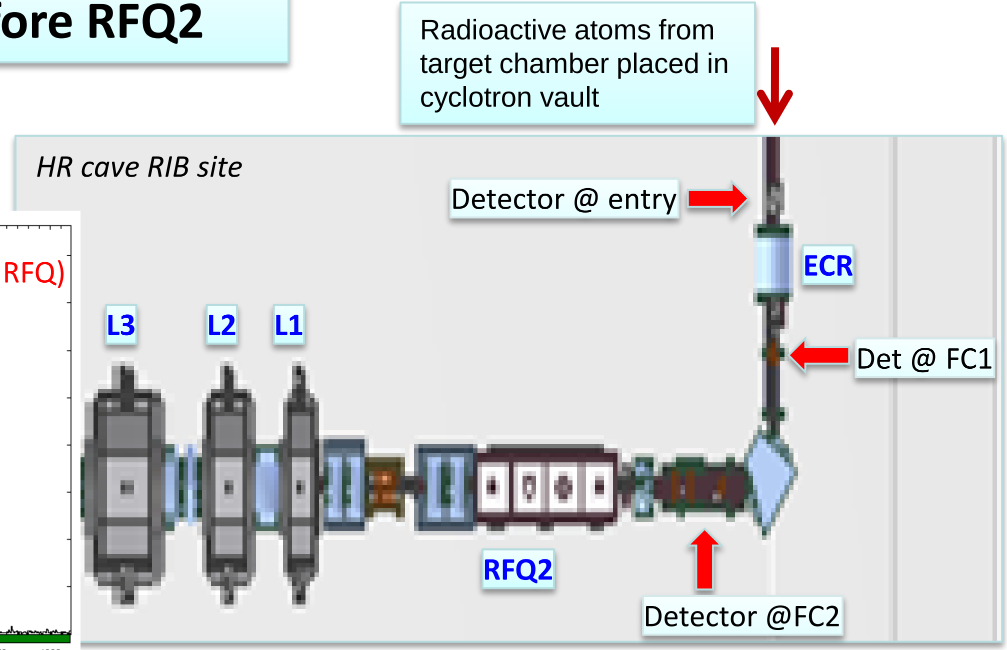
Aim:

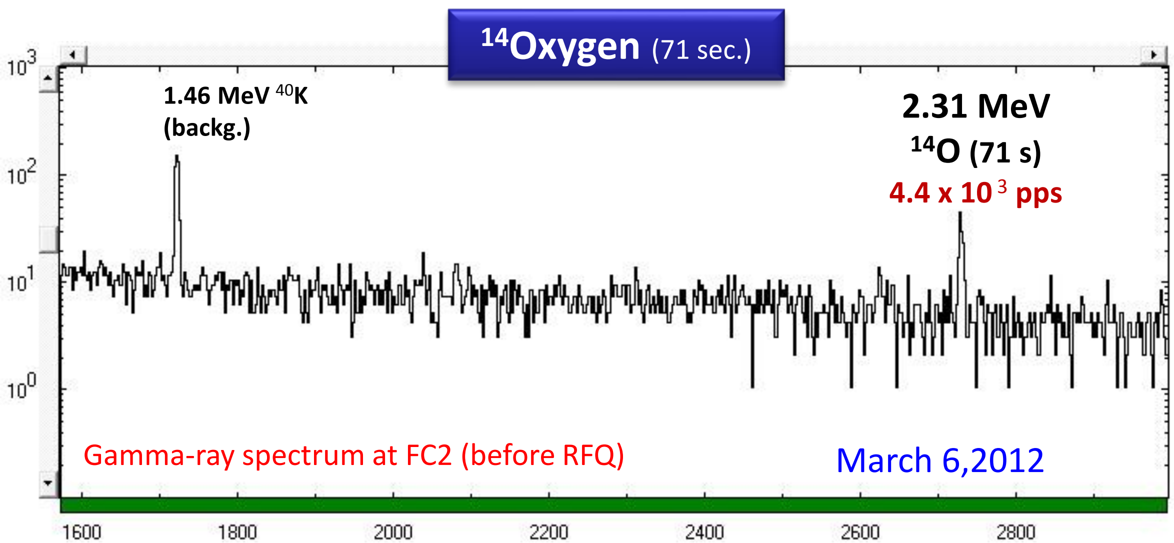
1. To transport radioactive atoms to RIB site using Gas-jet Transport system √
2. Production of low energy RIB and measurement of yield at FC2 (before RFQ2) √
3. Acceleration of RIB to 100 keV/u



Measured RIB decay-spectra before RFQ2



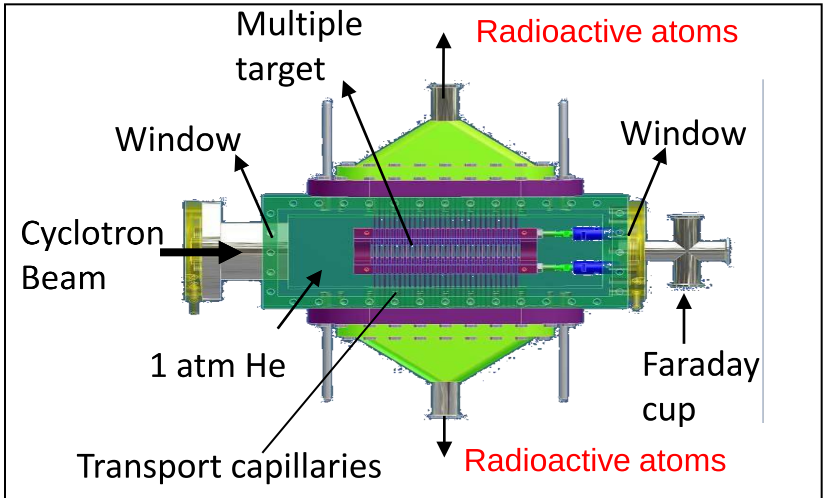




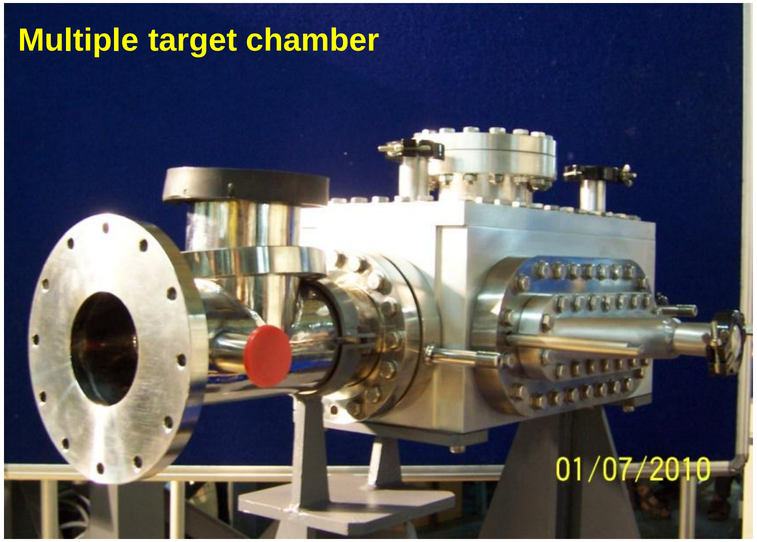
RIB	Prod. route	T1/2	pps @ FC2
^{14}O	^{14}N(p,n)	71 s	4.4 x 10^3
^{42}K	^{40}Ar(α,pn)	12.36 hr	2.7 x 10^3
^{41}Ar	^{40}Ar(α,2pn)	109 min	1.3 x 10^3

RI beams to be developed

RIB	$T_{1/2}$	Reaction	Target
^{14}O	71 sec	$^{14}N(p,n)$	N_2
^{41}Ar	109 min	$^{40}Ar(\alpha,2pn)$	Ar
$^{42,\,43}K$	12.4 hrs, 22 hrs	$^{40}Ar(\alpha,pxn)$	Ar
^{111}In	2.8 days	$^{109}Ag(\alpha,2n)$	Ag
^{19}Ne	17 sec	$^{16}O(\alpha,n)$	HfO_2,Al_2O_3
^{66}Ga	9.4 hours	$^{63}Cu(\alpha,n)$; $^{64}Zn(\alpha,pn)$	Cu foils, Zinc Oxide
^{68}Ga	68 min	$^{65}Cu(\alpha,n)$	Cu foils



He-jet multiple target system



Publications from RIB project group*

(*in international journals)

(Since the year 2000)

Accelerator development

1. Ceramics International, (2011) 2679. Target
2. Nucl. Instrum. & Meth. A 631 (2011) 1 MEBT
3. Pramana 75 (2010) 485. MEBT
4. Rev. Sci. Instrum. 81, 023301 (2010); RFQ2
5. Rev. Sci. Instrum. 80, (2009) 103303. RFQ2
6. Ceramics International, 34 (2008) 81. Target
7. Nucl. Instrum. & Meth. B261(2007)1018. RIB facility status
8. Rev Sci Instrum. 78 (2007) 043303. RFQ1
9. Nucl. Instrum. & Meth. A562 (2006)41. Beam-line
10. Nucl. Instrum. & Meth. A560 (2006)182. Linac
11. Nucl. Instrum. & Meth. A547 (2005)270. Charge breeder
12. Nucl. Instrum. & Meth. A539 (2005)54. Target
13. Nucl. Instrum. & Meth. A535 (2004)599. RFQ1
14. Nucl. Instrum. & Method A 533 (2004) 37. RFQ1
15. Pramana 59 (2002) 923. RIB facility
16. Pramana 59 (2002) 957. RFQ1
17. Nucl. Instrum. & Meth. A 447 (2000) 345. charge breeder

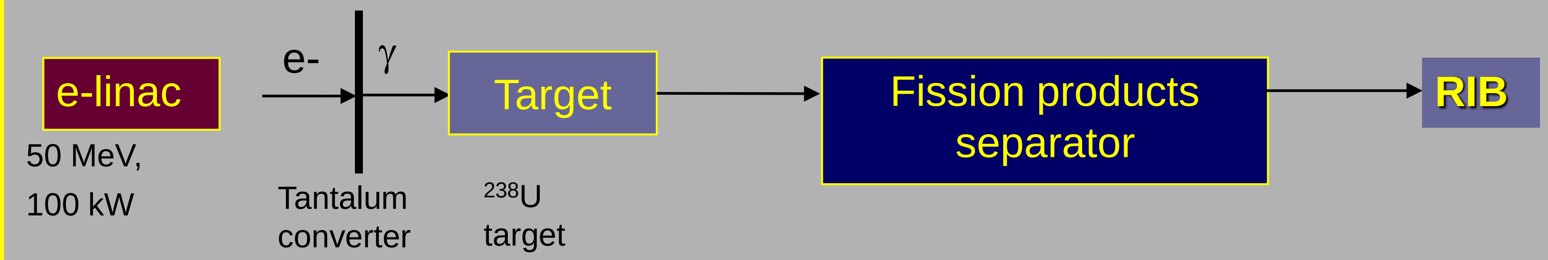
Nuclear Physics & Material Science Experiments

1. Nucl. Instr. & Meth. xx, xxx (2012)
2. Materials Science Forum, 699 (2012) 1-38
3. J of Phys. Cond. Matt. 23 (2011) 155801
4. Appl. Surf. Sci. 257 (2011) 6775
5. Solid State Communications, 150, (2010) 2266.
6. J. Phys.: Condens. Matter 22 (2010) 175005
7. Nuclear Instru. & Method B267 (2009) 1783.
8. Phys. Rev. C 80, 044302 (2009)
9. Eur. Phys. J. A 42, 375-378 (2009)
10. J. of Phys: Cond. Matt. 21 (2009) 445902
11. Appl. Phys. Lett. 93, (2008) 103102.
12. Materials Characterization 60 (2009) 1014.
13. J. of Phys. D 41 (2008) 135006.
14. Appl. Phys. Letts. 93 (2008) 103102
15. J of Phys. C 20 (2008) 45217
16. J of Phys. D 41 (2008) 135006.
17. Phys. Lett. A371 (2007) 482.
18. J of Phys. C 19, (2007) 236218.
19. J of Phys. C 19, (2007) 236210.
20. J. of Mat. Sc. 40 (2005) 5265.
21. Physica C, Vol416, (2004) 25.
22. Nanotechnology 15 (2004) 1792.
23. Physica C 416 (2004) 25.
24. Phys. Rev. C 63 (2001) 024307.

4 Ph. D theses during 2004-2007 ; 2 PhD thesis submitted recently ; 2 M.Tech Thesis

Superconducting Electron Linac (VECC-TRIUMF Collaboration)

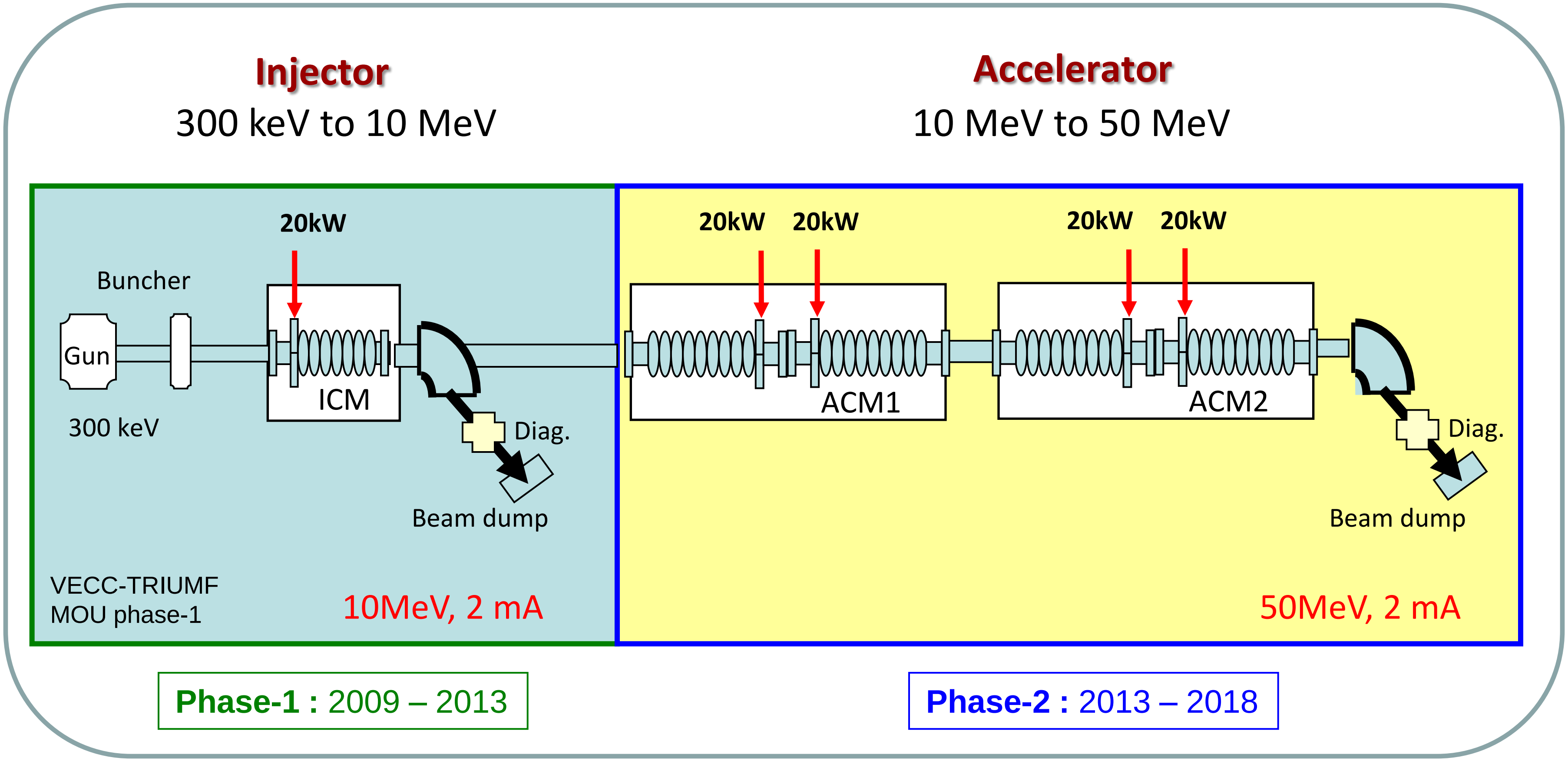
- 50 MeV, 2 mA; 100 kW CW, 1.3 GHz, 2 deg K
- For production of neutron rich nuclei through photo-fission of Uranium
- Also a strong neutron source of intensity 10^{14} per sec



γ - induced fission (photo-fission); GDR peak at ~13.5 MeV

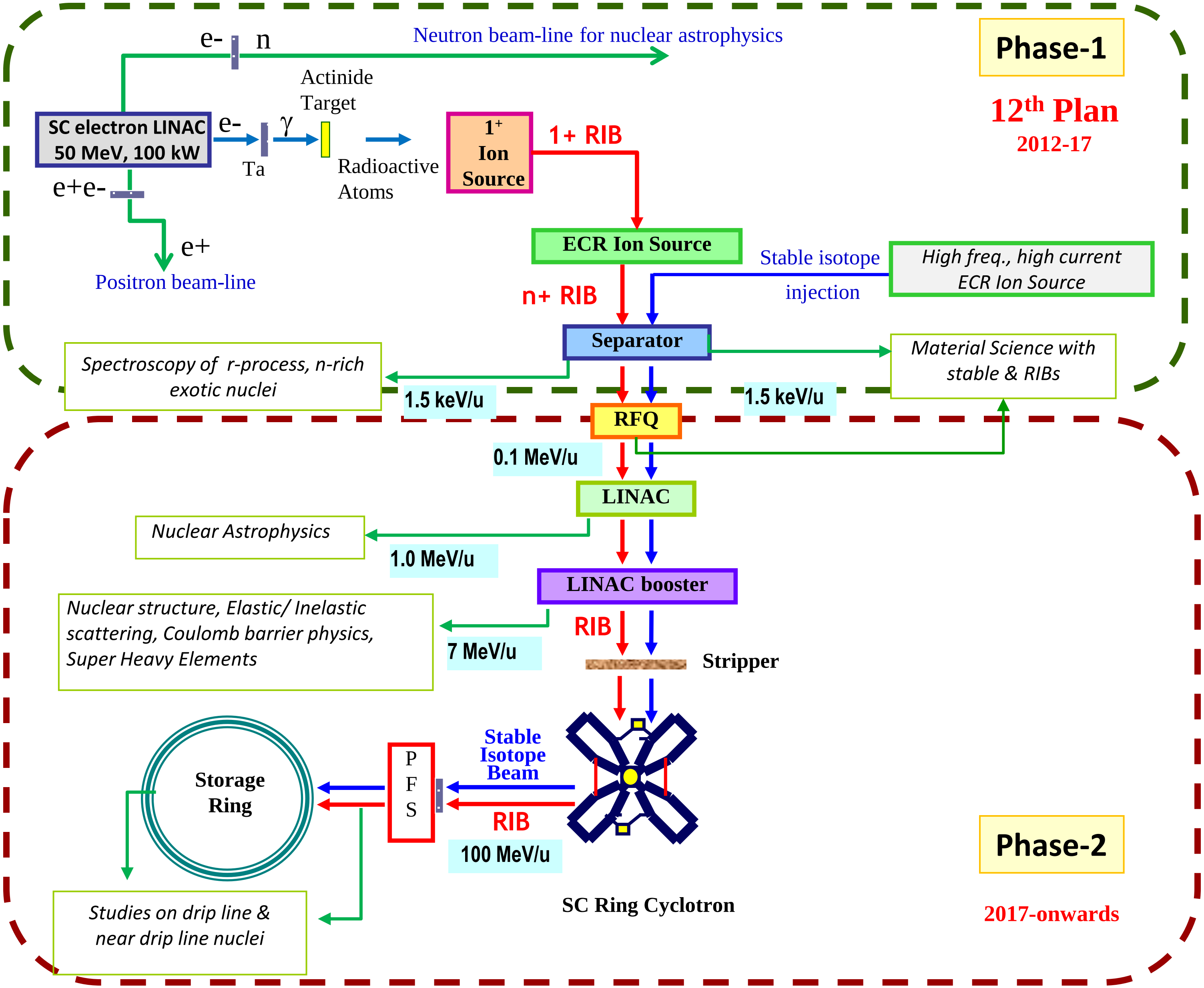
peak photo-fission cross-section for $^{238}U/^{235}U$= 168/400 mbarn

50 MeV Superconducting Electron Linac - Schematic

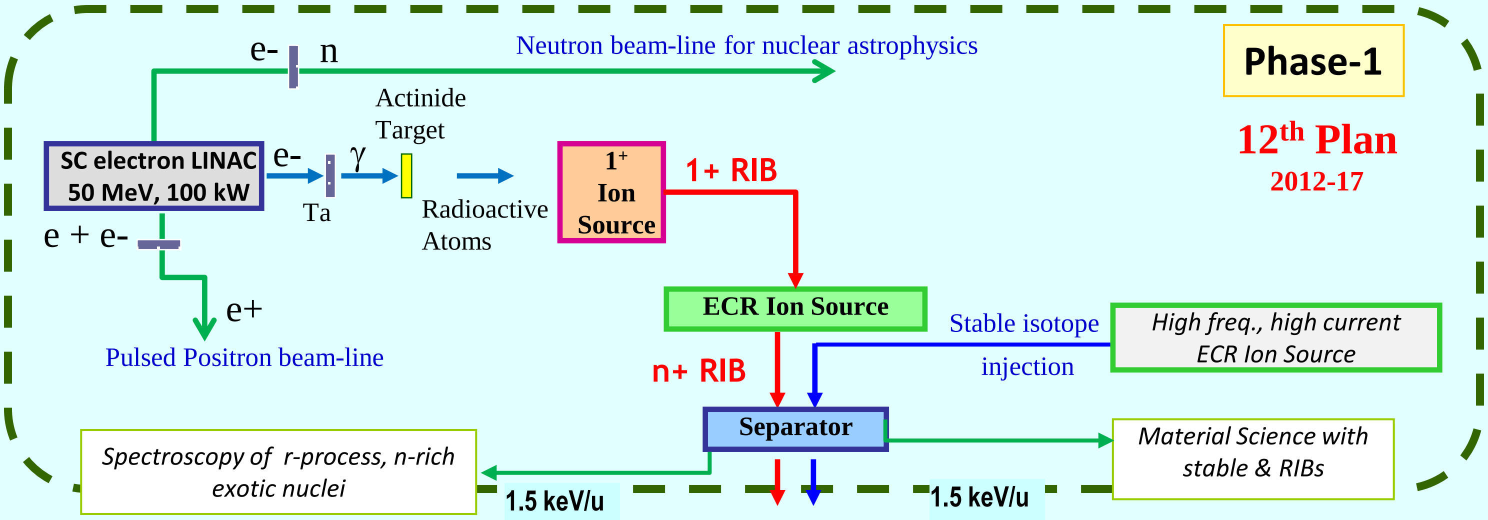


The ultimate goal : ANURIB facility

A National Facility for Unstable and Rare Isotope Beams



12th plan Project: ANURIB phase-1



Financial outlay of ANURIB phase-1

No.	Major Activity	Expenditure (Rs. Crore)
1.	Target Modules, Remote handling, High Power Beam Dumps	27.00
2.	ECR ion-sources, LEBT line, Acc. R&D, Isotope Separator facility & other expt. facility	38.00
3.	Electron Linac Accelerator Cryo-Module (ACM) for acceleration from 30 to 50 MeV; R&D on High current injector (comprising of ECR, RFQ, & Linac delivering beam energy up to 2.5 MeV) & Misc	25.00
4.	Building (phase-1) and Services : electrical power, air-conditioning, LCW plant, Cryogenic & other infrastructure services	75.00
	Total (Rs. in Crore)	**165.00**

12^{th} plan ANURIB phase-1 activities

1. Physics & Engineering Design of entire ANURIB facility (both phases)

2. Construction of high power actinide target modules, Accelerator Cryo-Module (ACM) for electron-linac, ECR ion-source, low energy beam-line (Isotope Separator),

3. Experimental facility for 1.5 keV/u beams – nuclear spectroscopy of r-process nucleo-synthesis nuclei, laser spectroscopy, ion-beam based material science

4. Design of phase-1 building & AERB clearance

5. R&D on high current injector, prototype development

6. Construction of Phase-1 building that will house the following:
(i) Electron linac (ii) Target stations (iii) ECR ion-source (iv) Isotope separator (v) Neutron facility cave (vi) Misc. expt. cave (vii) positron cave

7. Identification & development of vendors

8. Collaborations : national & international; Workshop/Symposium on ANURIB

Thank You!

Intensity of RIB for various experiments (ISOL method)

$$I_{RIB} = I_{primary} * N_t * \sigma * \eta$$

Physics Topics	Reaction & Techniques	Beams	Desired Intensities particles/s	Energy Range MeV/u
1. Rapid proton capture (*rp*-process)	Transfer, elastic, inelastic, radioactive capture, Coulomb dissociation	^{14}O, ^{15}O, ^{26}Si, ^{34}Ar, ^{56}Ni	10^8 - 10^{11} 10^5 - 10^{11}	0.15 - 15
2. Studies of N = Z nuclei, symmetry study	Transfer, fusion, decay studies	^{56}Ni, ^{62}Ga, ^{64}Ge, ^{68}Ge, ^{67}As, ^{72}Kr	10^4 – 10^9	0.1 - 15
3. Decay studies of ^{100}Sn	decay	^{100}Sn	1 - 10	low
4. Proton drip-line Studies	decay, fusion, transfer	^{56}Ni, $^{62,66}Ge$, ^{72}Kr,	10^6 – 10^9	5
5. Slow neutron capture *s*-process	capture	$^{134,135}Cs$, ^{155}Eu,	10^8 - 10^{11}	0.1
6. Symmetry studies with Francium	decays, traps	^{A}Fr	10^{11}	low
7. Heavy element studies	fusion, decay	$^{50\text{-}52}Ca$, ^{72}Ni, ^{84}Ge, ^{96}Kr,	10^4 – 10^7 10^6 – 10^8	5 – 8

Intensity of RIB for various experiments cont..

8. Fission limits	fusion, fission	$^{140-144}$Xe, $^{142-146}$Cs, ^{142}I, $^{145-148}$Xe, $^{147-150}$Cs	10^{7} - 10^{11} 10^{4} – 10^{7}	5
9. Rapid neutron capture (*r*-process)	capture decay mass measurement	^{130}Cd, ^{132}Sn, ^{142}I,	10^{4} – 10^{9}	0.1 – 5
10. Nuclei with large Neutron excess	Fusion, transfer, deep inelastic	$^{140-144}$Xe, $^{142-146}$Cs, ^{142}I, $^{145-148}$Xe, $^{147-150}$Cs,	10^{7} – 10^{11} 10^{2} – 10^{7}	5 - 15
11. Single-particle States, effective Nucleon-nucleon interactions.	direct reactions, nucleon transfer	^{132}Sn, ^{133}Sb	10^{8} – 10^{9}	5 - 15
12. Shell structure, Weakening of gaps, Spin-orbit potential	mass measurement, Coulomb excitation, fusion, nucleon transfer, deep inelastic	^{A}Kr, ^{A}Sn, ^{A}Xe,	10^{2} – 10^{9}	0.1 - 10

RFQ : India joins the select club

THE HINDU

Online edition of India's National Newspaper
Wednesday, Oct 05, 2005

National

National

India joins select club in particle technology

Special Correspondent

KOLKATA: India's first heavy ion Radio Frequency Quadruple [RFQ] accelerator has been commissioned at the Department of Atomic Energy's Variable Energy Cyclotron Centre [VECC] here.

Scientists from across the world have acknowledged the achievement as a hall-mark development in particle accelerator technology in the country, VECC officials told *The Hindu* on Tuesday.

Japan is the only other Asian country to have successfully commissioned such an accelerator which was tried out on a "proof-of-principle" basis for the first time in the United States of America in 1980.

"RFQ is a radio frequency [33.7MHz] cavity of very pure copper that houses four precisely machined vanes which takes care of the acceleration, bunching and focusing of ion beams", according

natureINDIA

Welcome back: vaish

doi:10.1038/nindia.2010.77; Published online 14 June 2010

Science news

Cosmos and cancer

Biplab Das

A big indigenously built machine sits in the campus of the Variable Energy Cyclotron Centre (VECC) in Kolkata. It hums into action occasionally prying open many secrets of the universe with its energetic radioactive ion beams (RIB).

The RIB project site at VECC.

Alongside cracking puzzles like how chemical elements were born in the fiery cauldron of stars, the RIB technology also generates energetic particles to selectively kill unruly cancer cells.

Researchers at VECC have designed the radio frequency quadrupole (RFQ) accelerator that accelerates low energy heavy ions[1]. "It is a three-in-one accelerator — it accelerates, bunches and focuses the ion beam," says Alok Chakrabarti of VECC.

The VECC team has created the facility in collaboration with

আনন্দবাজার পত্রিকা

১৫ আশ্বিন ১৪১২ শনিবার ১ অক্টোবর ২০০৫

সংক্ষেপে ...

পরমাণু বিজ্ঞানে নয়া সাফল্য ভারতের

স্টাফ রিপোর্টার ✧ কলকাতা

জাপানের পরে এ বার ভারতেও রেডিও ফ্রিকোয়েন্সি কোয়াড্রু
পল চালু হল। এশিয়ার মধ্যে ভারতই হল দ্বিতীয় দেশ,
যেখানে এই 'অ্যাক্সিলারেটর' বা ত্বারক চালু করা হয়েছে।
শুক্রবার ভেরিয়েবল এনার্জি সাইক্লোট্রন সেন্টারের অধিকর্তা
বিকাশ সিংহ এক লিখিত বিবৃতিতে এ কথা জানান। এটি একটি
জটিল এবং অত্যাধুনিক ত্বারক। এর মাধ্যমে পরমাণু কণাকে
প্রচণ্ড গতিশীল করে তোলা যাবে। ১৯৮০ সালেই প্রথম মার্কিন
যুক্তরাষ্ট্র এই ত্বারক চালু করে। তার পর থেকে খুব বেশি দেশ
এই ত্বারক চালু করতে পারেনি।

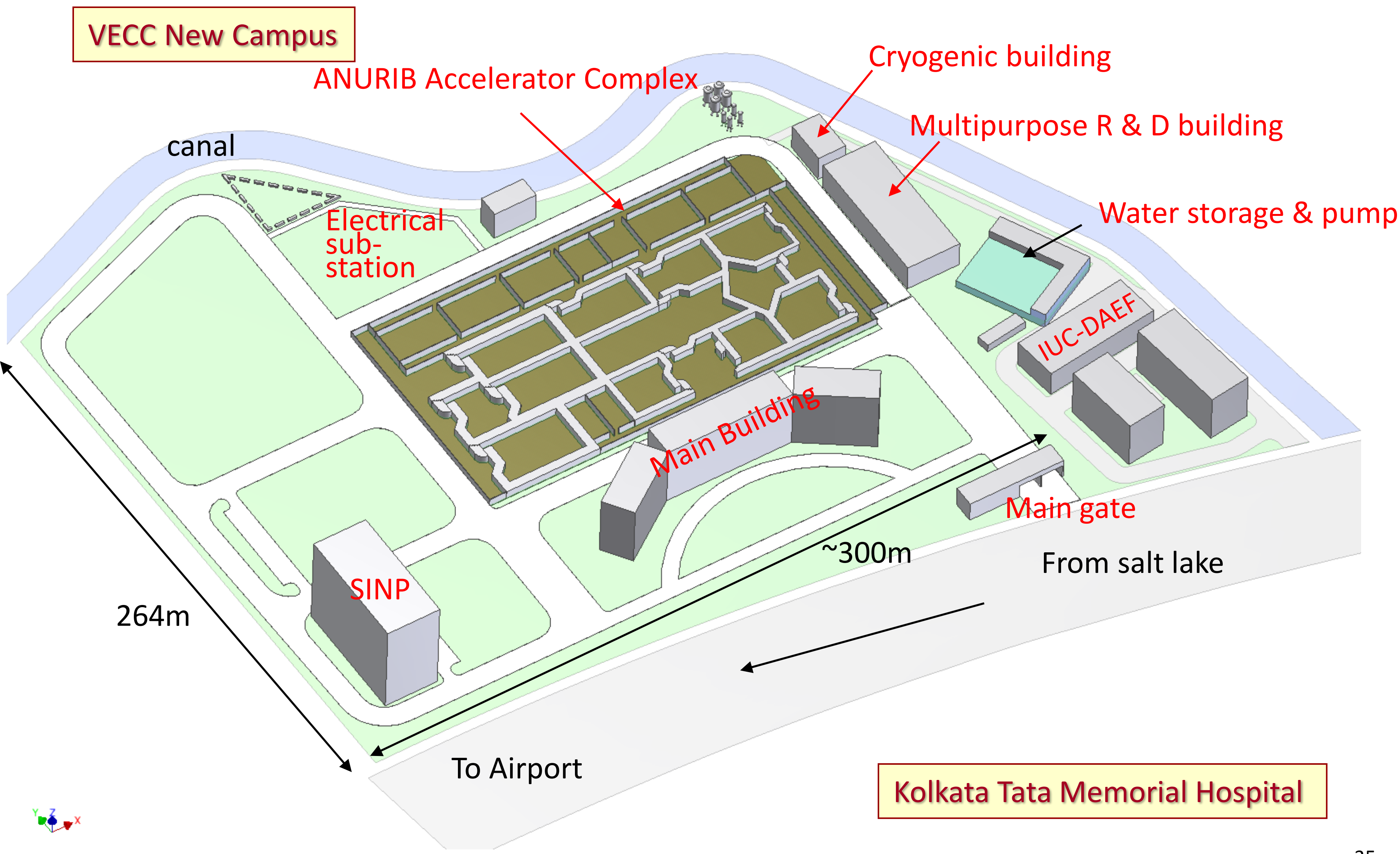
Major components of total ANURIB project and Tentative Cost projection

No.	Major Activity	Expenditure (Rs. Crore)
1.	Super Conducting Electron Linac, acceleration from 30 to 50 MeV, high Power Actinide Target Module, Remote handling, Waste Management, High Power Beam Dumps	60.00
2.	Production and Acceleration of RIB to 6 - 7 MeV/A	140.00
3.	Super Conducting Ring Cyclotron for 100 MeV/A acceleration	140.00
4.	Experimental facilities for nuclear physics, nuclear astrophysics, material science, & PF Separator, ion storage ring,	180.00
5.	Building comprising of Accelerator Complex and Services - electrical power, air-conditioning, LCW plant, Cryogenic plant & other infrastructure services	350.00
	Total : Rs. in crore (million US Dollar)	870.00 (174)

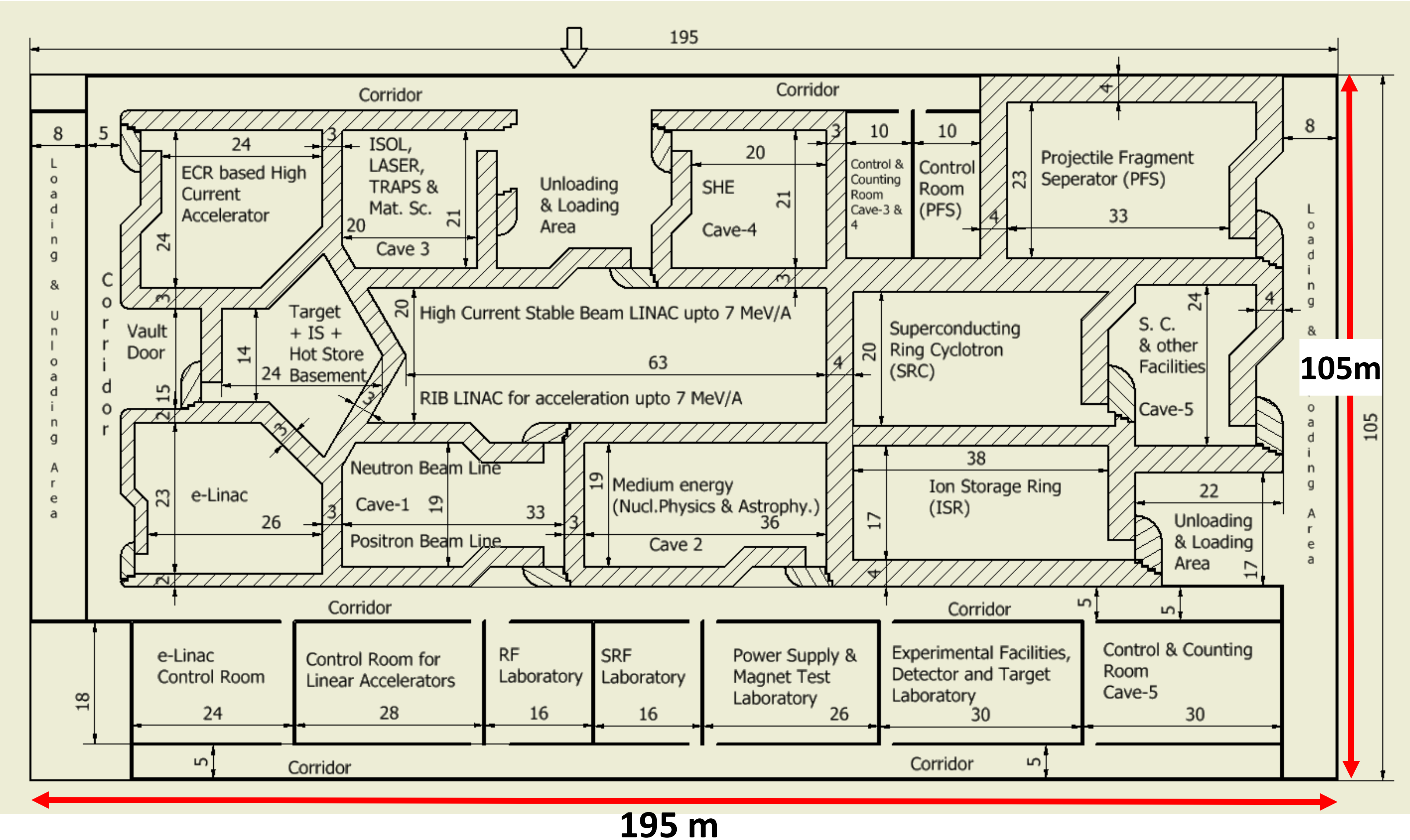
Phasing of Expenditure (Rs. Crore)

2012-13	2013-14	2014-15	2015-16	2016-17	Total 12th Plan	Spill over 13th & 14^{th} Plan
2.00	5.00	8.00	75.00	75.00	165.00	600.00 (13^{th} plan) 105.00 (14^{th} plan)

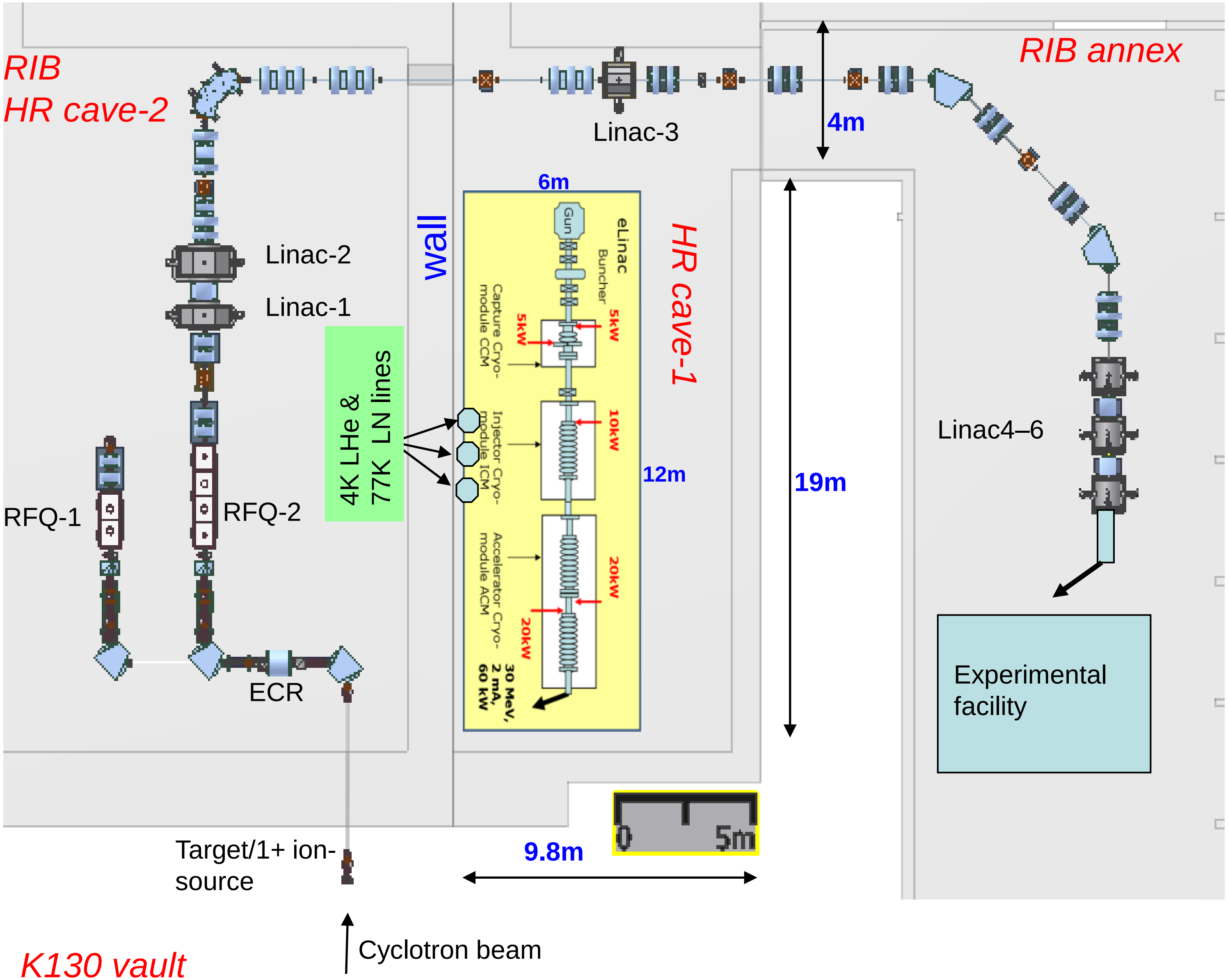
VECC Rajarhat site layout (tentative)



Floor layout of ANURIB Accelerator Complex (tentative)



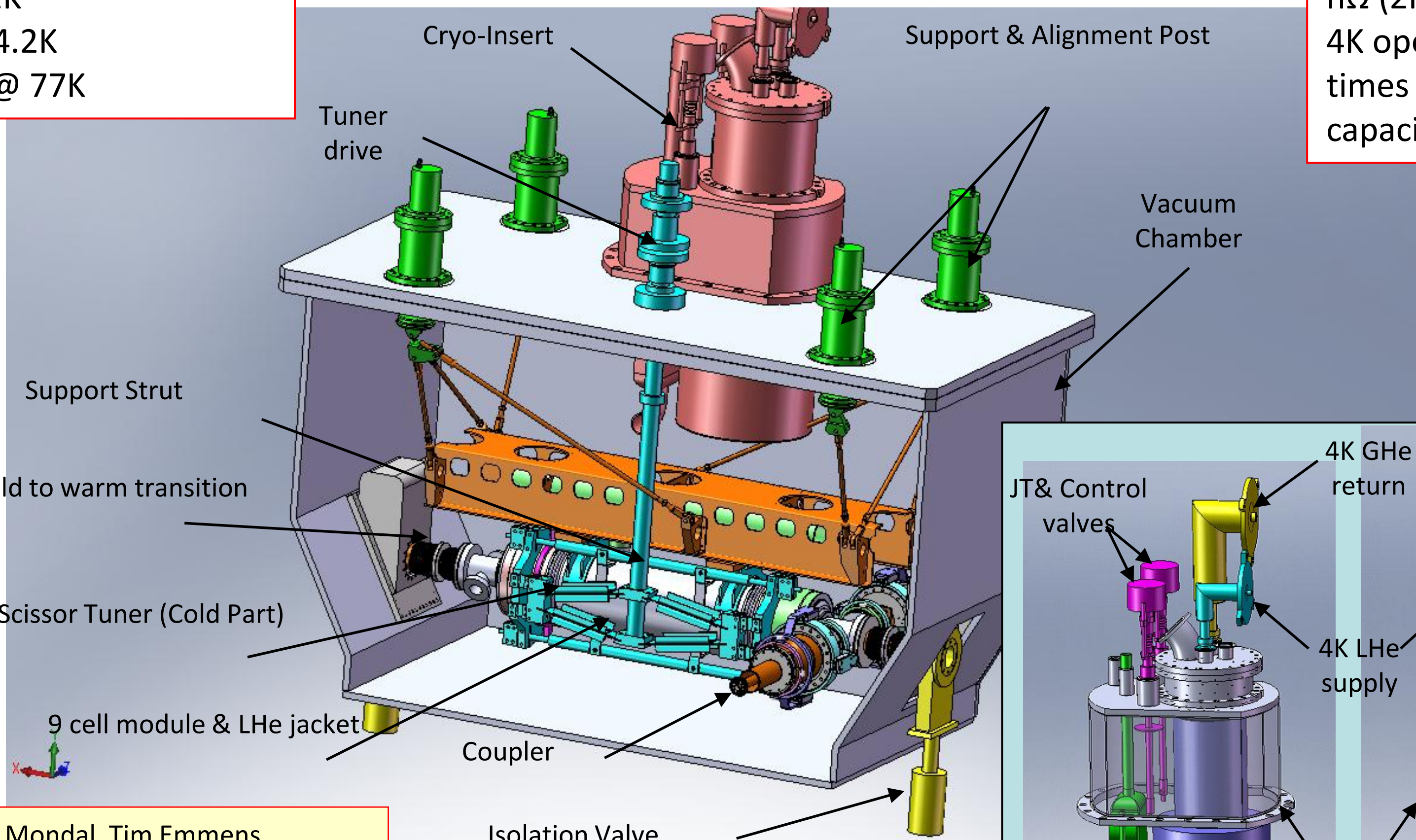
Location for Electron Linac in HR Cave 1

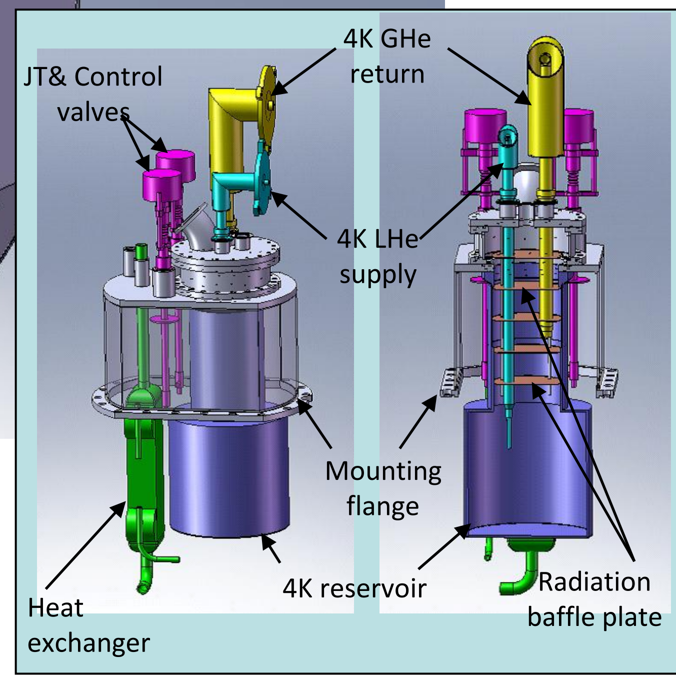


Est. heat load 10 MV/m ICM
Static + Dynamic
15 W @ 2K
+ 6 W @ 4.2K
+ 275 W @ 77K

Injector Cryo- Module details

2K operation important
RF surface resistance 20 nΩ (2K) but 800 nΩ at 4K.
4K operation will need 10 times higher Cryo-plant capacity.





Manas Mondal, Tim Emmens

Status of 10 MeV Injector & ICM

- Beam dynamics design of e-Linac completed
- Mechanical engineering design of ICM and ACM completed
- Cryogenic-line design underway

Hydrostatic burning stages leading to ^{56}Fe

H burning → $4p \Rightarrow {}^{4}He + 2e^{+} + 2\nu + 26.7\ \text{MeV}$

He burning → $\alpha + \alpha \Rightarrow {}^{8}Be$

$^{8}Be + \alpha \Rightarrow {}^{12}C + \gamma + 7.2\ \text{MeV}$

C burning → $^{12}C + {}^{12}C \Rightarrow {}^{23}Na + p + 2.23\ \text{MeV}$

$\Rightarrow {}^{20}Ne + \alpha + 4.6\ \text{MeV}$

$^{12}C(p,\gamma){}^{13}N(e^{+}\nu){}^{13}C(\alpha,n){}^{16}O$

Ne burning → $^{20}Ne + \gamma \Rightarrow {}^{16}O + \alpha$; $^{20}Ne + \alpha \Rightarrow {}^{24}Mg + \gamma$

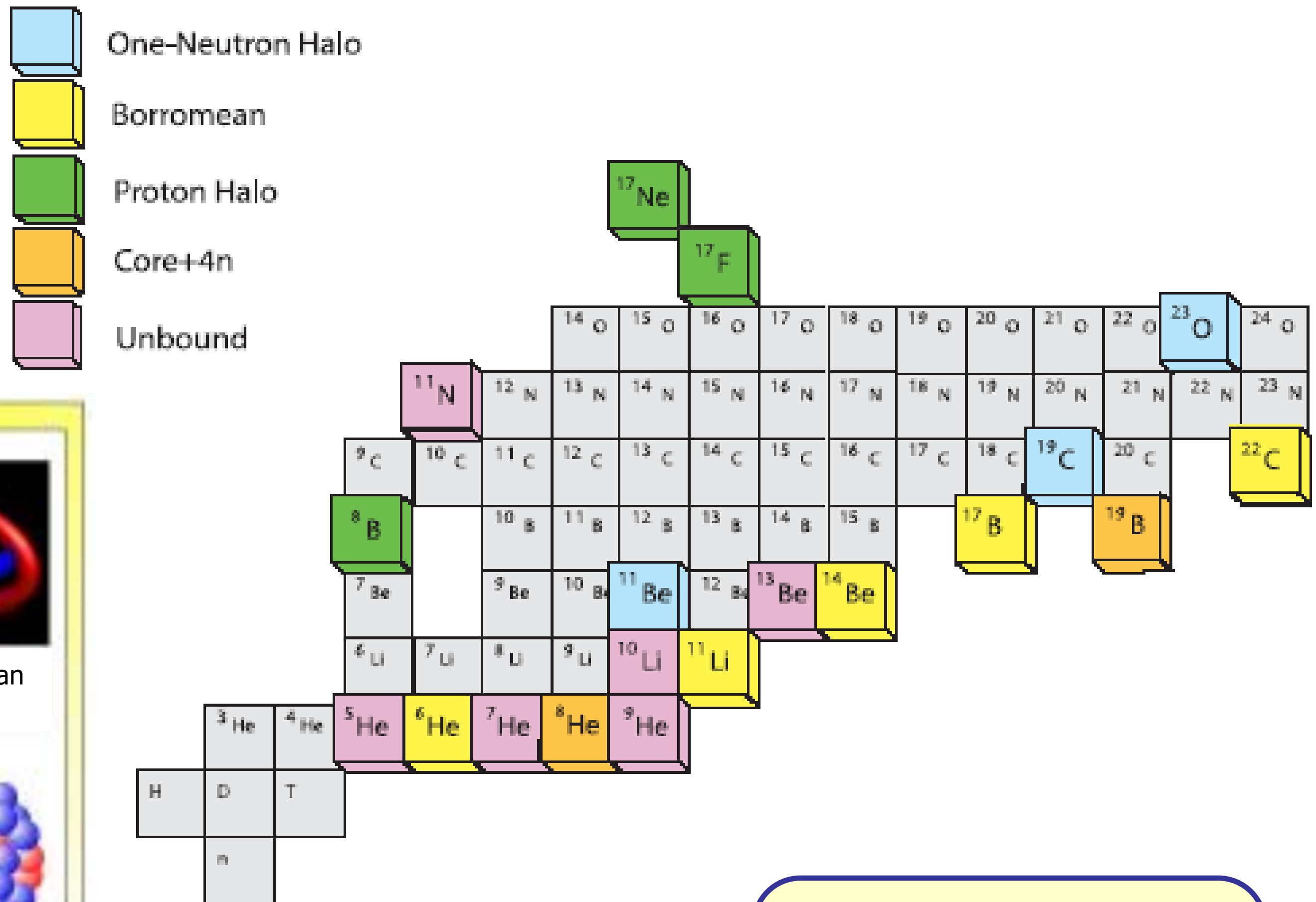
O burning → $^{16}O + {}^{16}O \Rightarrow {}^{31}P + p \Rightarrow {}^{28}Si + \alpha \Rightarrow {}^{31}S + n$

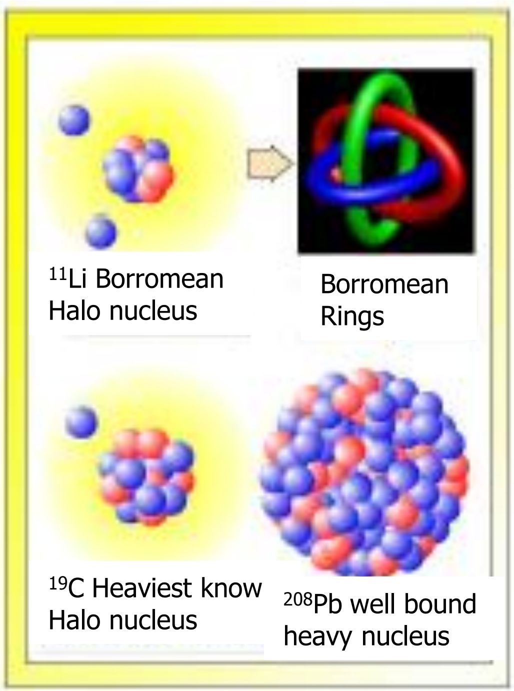
Si burning → $^{28}Si + \alpha \Rightarrow {}^{32}S + \alpha + \alpha \ldots + \alpha \Rightarrow {}^{56}\mathbf{Fe}$

$^{28}Si + \gamma \Rightarrow \alpha + Mg$

(*main source of* α)

Halo Nuclei – nuclei with unusually large matter distribution





Halo universality?
Halo in excited states?

Halo in excited states

- Excited states close to particle threshold in stable or near stable nuclei may exhibit **halo structure**

- $^{12}C\ (n, \gamma)\ ^{13}C$; $^{16}O\ (\gamma, n)\ ^{17}O$

  Reaction rate (expt.) ≈ 100 x Reaction rate (1/v)

  $\Rightarrow$ Reduction of neutrons in the Helium-burning stage of a star

  $\Rightarrow$ significant effect on *s* process (n, γ) nucleo-synthesis rates

Beta-decay of Fully/highly stripped ions & Cosmo-chronology

- $^{163}Dy^{66+}$ (Z=66) → $^{163}Ho^{66+}$

(Half-life = 47 days when fully stripped; stable if neutral)

- $^{187}Re^{75+}$ (Z=75) → $^{187}Os^{75+}$

(Half-life = 33 yrs when fully stripped; 4×10^{10} yrs if neutral)

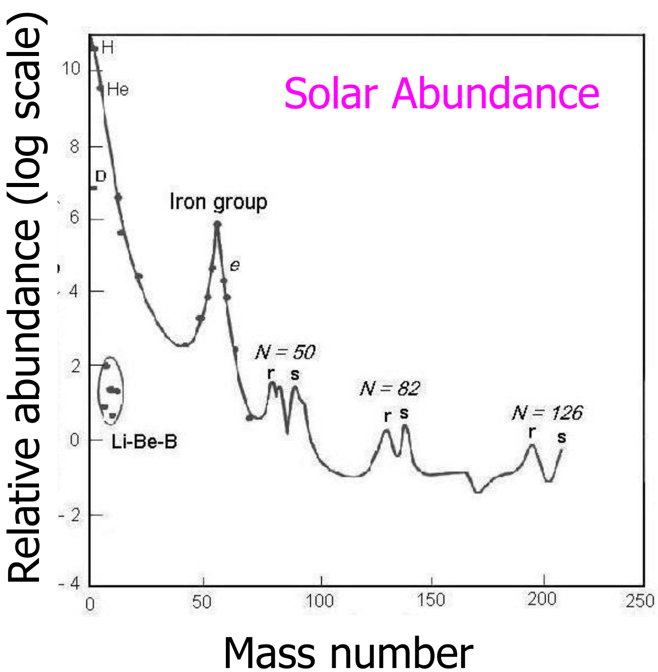
- correction in galactic age determination

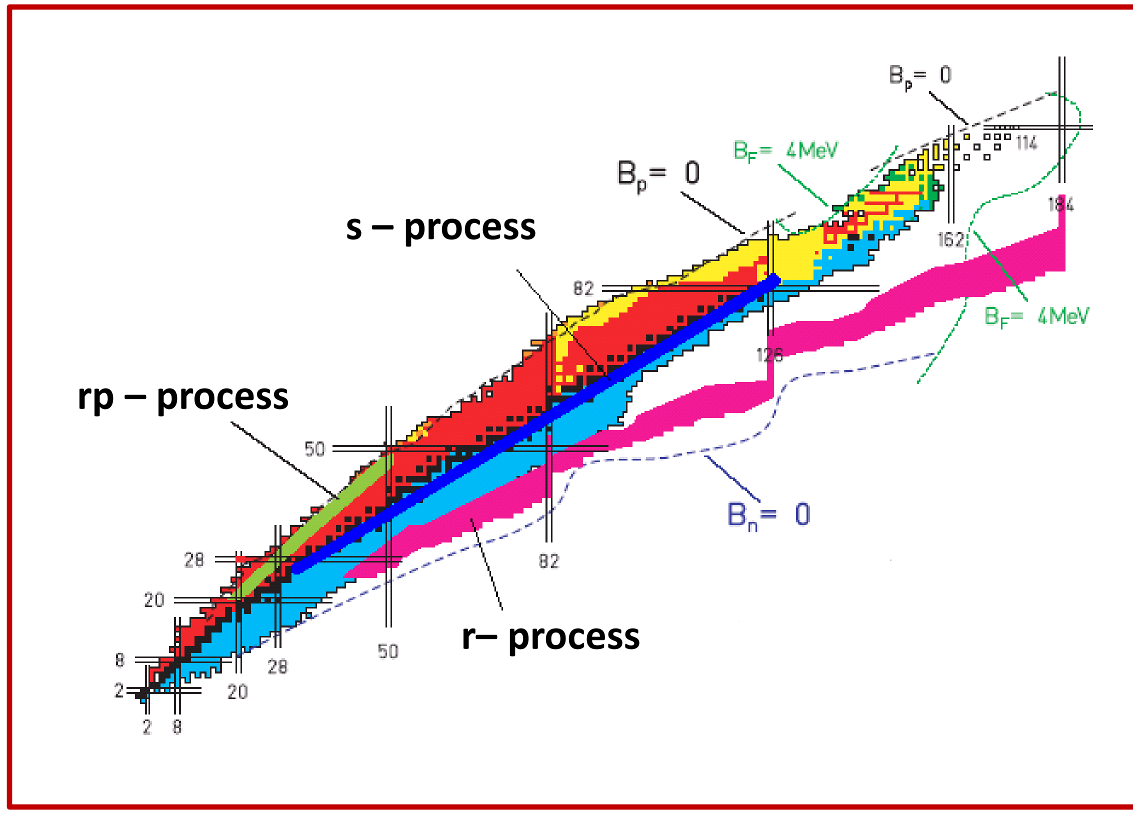
Element synthesis & Exotic Nuclei

(we are but stellar dust)

fusion stops at ^{56}Fe ; S-process : up to ^{209}Bi

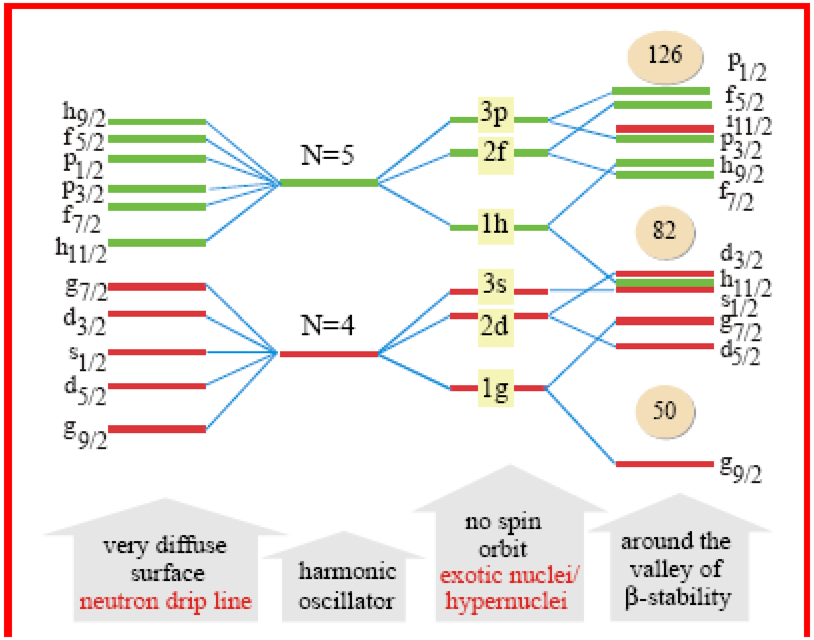
Beyond Bi, only r-process

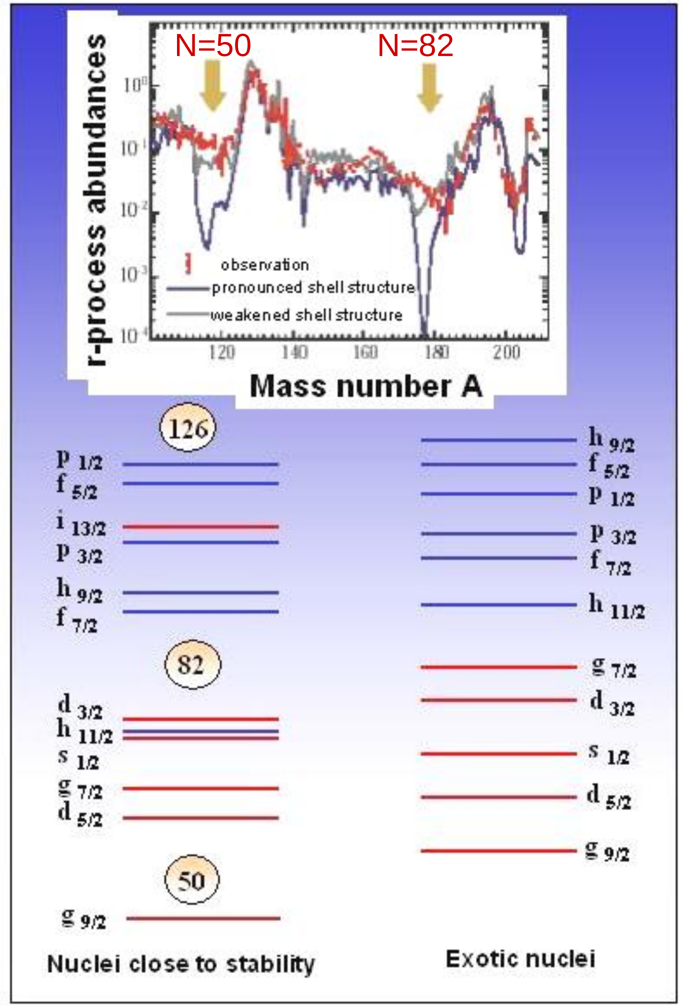




Weakening of shells away from beta-stability

Moving towards neutron-drip line





Calculations with weakened shell structure show a reduced discrepancy between measured and calculated r-process abundances at N=50 and N=82 shell closures

Synthesis of Super Heavy Elements (SHE)

- prediction

 shell closure at *N= 184*
Z=114/118/120/126
(depending on the model)

- with stable beams it is not possible to reach these closed shells