Radioactive Ion Beam project

at VECC Kolkata

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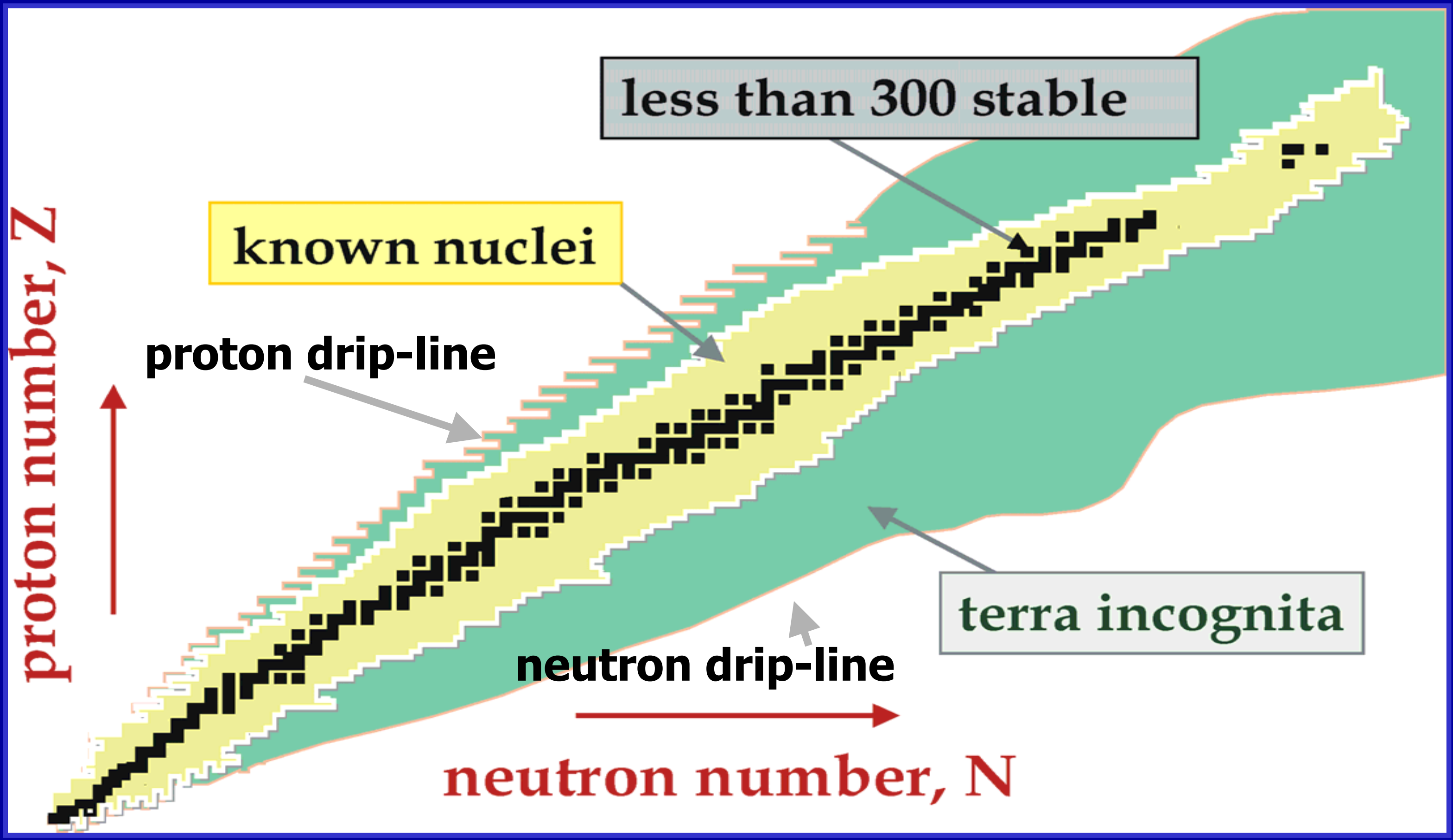
Plan of the talk

- Introduction
- Overview of the facility
- Present status of activities
- Future plans

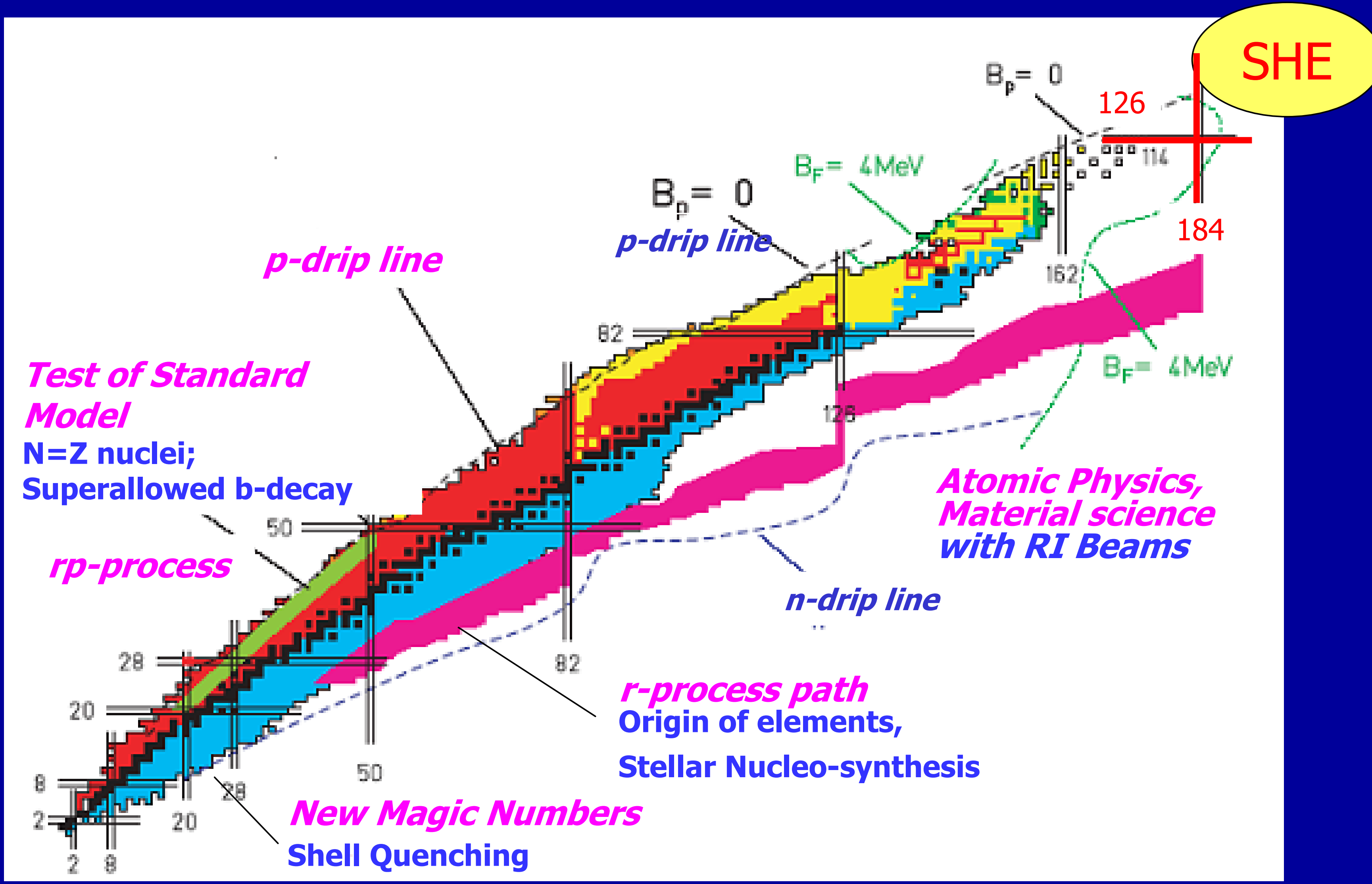
What is RIB?

RIB : Accelerated beams of β-unstable heavy-ions

→ **1 keV/u – 1 GeV/u**

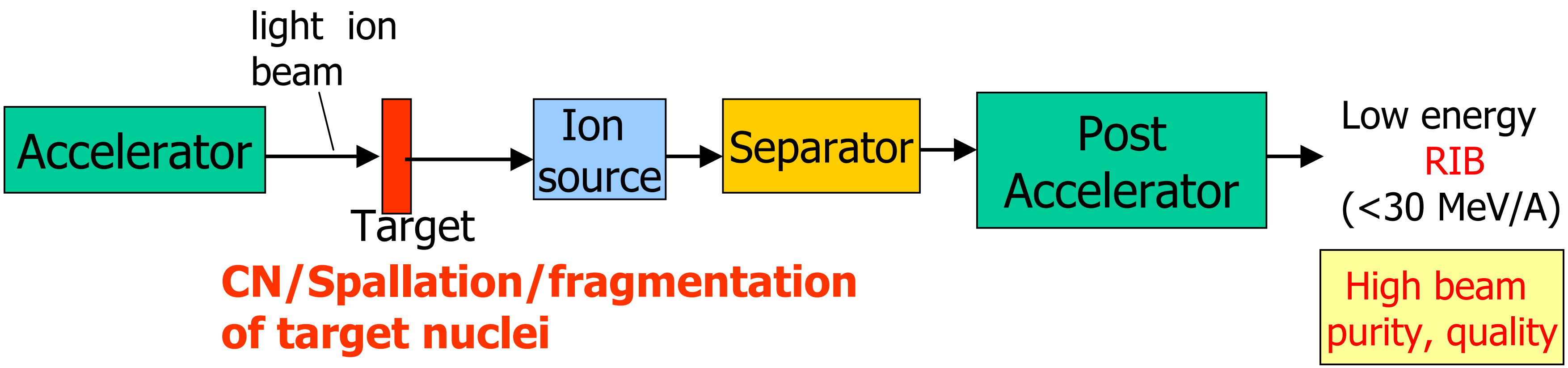


What can one study with RIB?

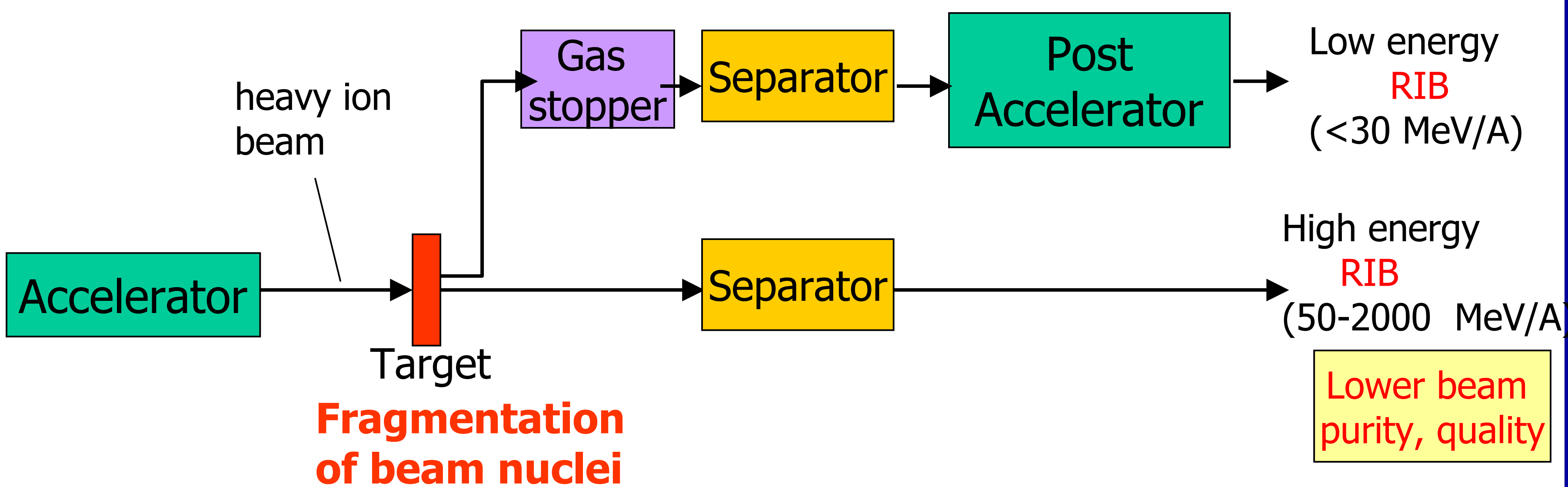


How to produce RIB?

ISOL method

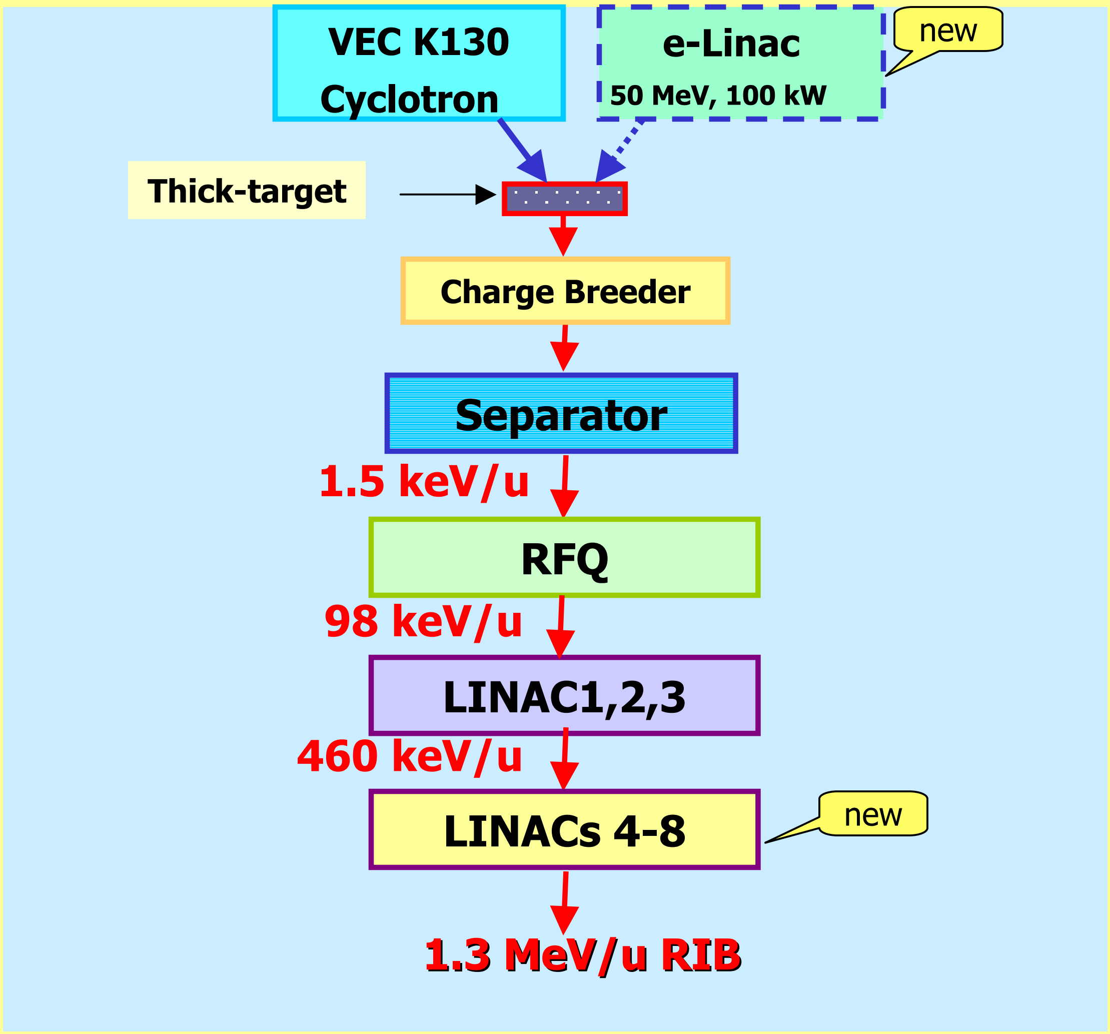


Fragmentation method



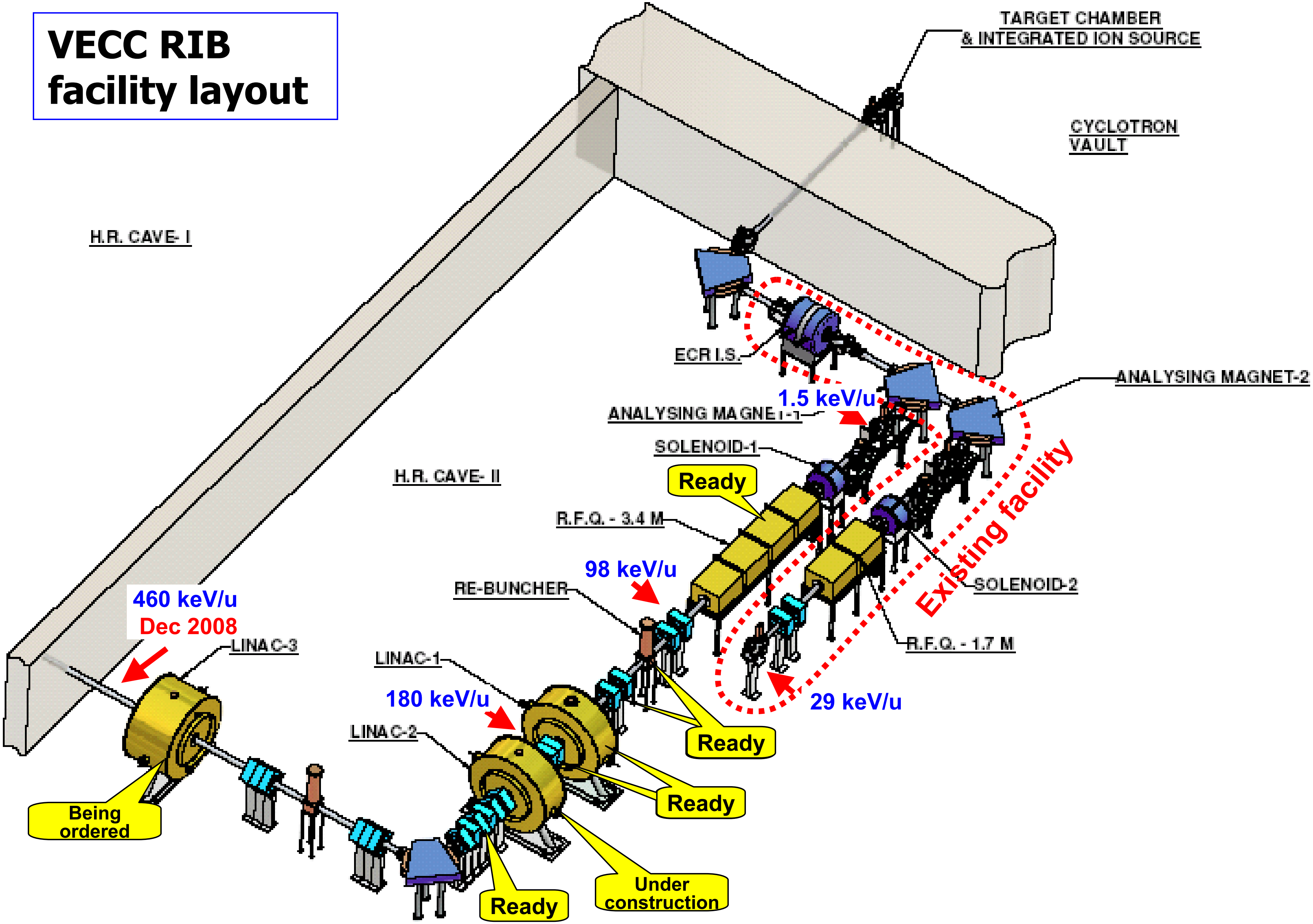
Proposal for acceleration to 1.3 MeV/u & Electron Linac as new primary accelerator

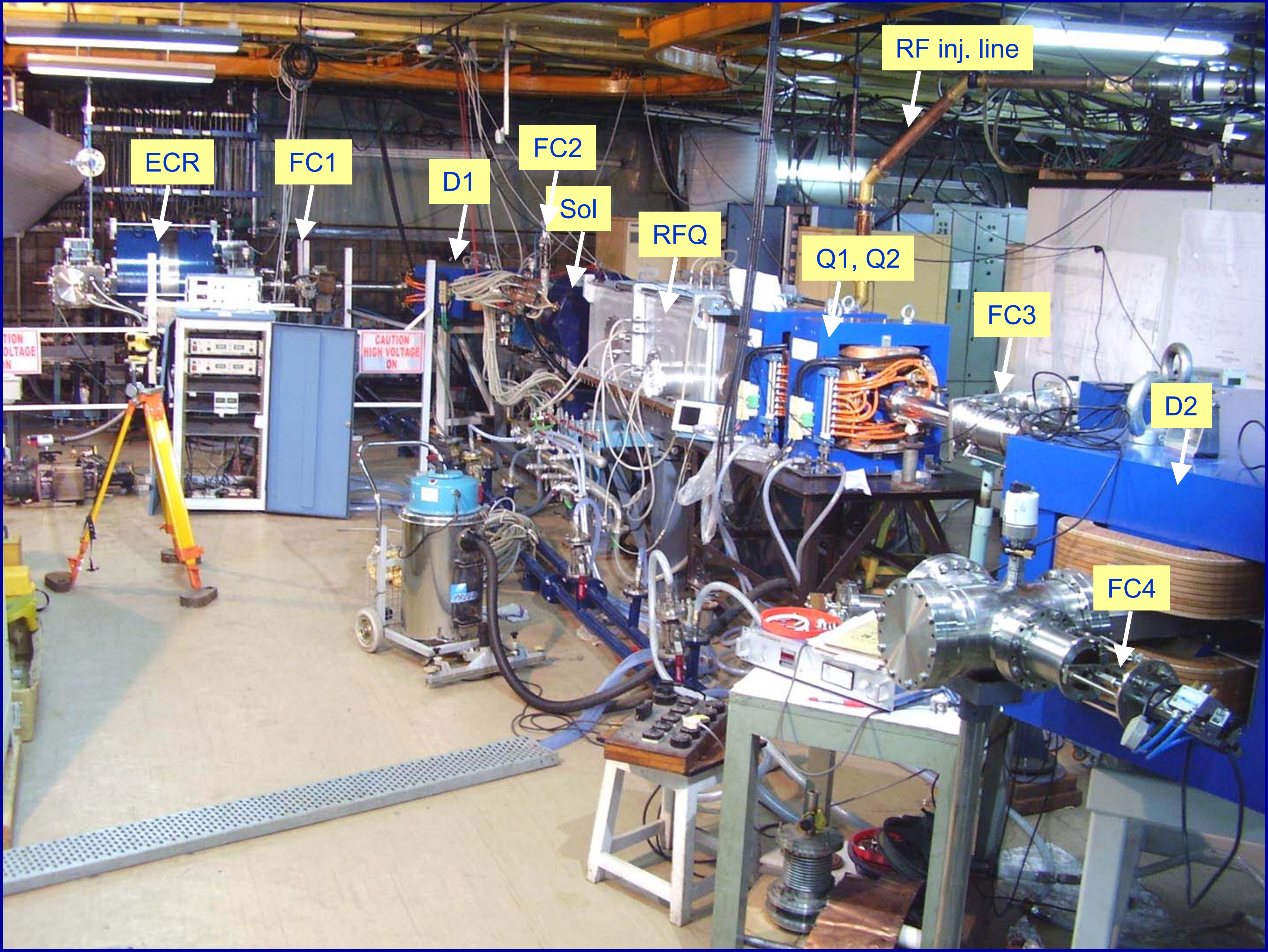
(newly funded)



What have we achieved so far?

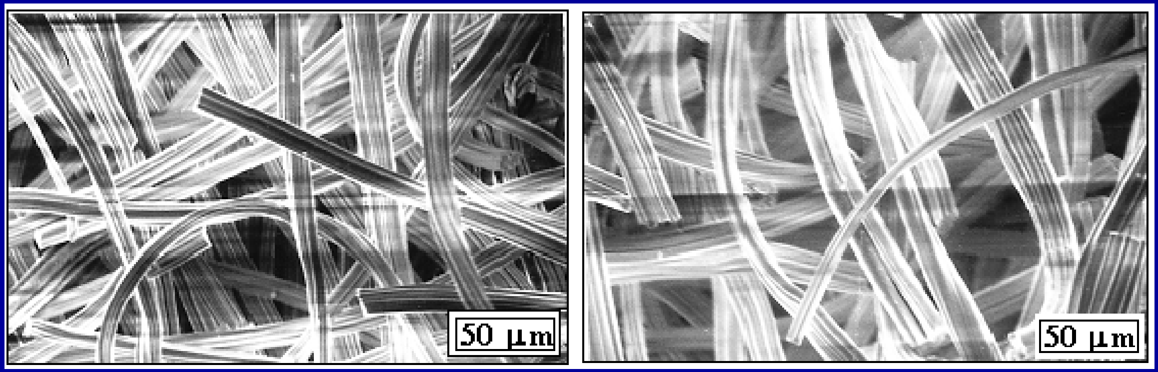
VECC RIB facility layout



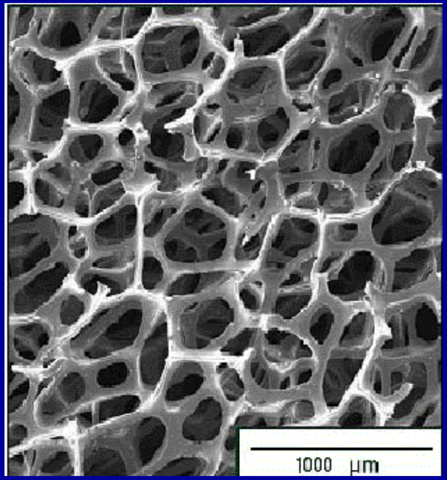

RF inj. line
ECR
FC1
FC2
D1
Sol
RFQ
Q1, Q2
FC3
D2
FC4
CAUTION
HIGH VOLTAGE
ON

Thick target R&D : first few targets

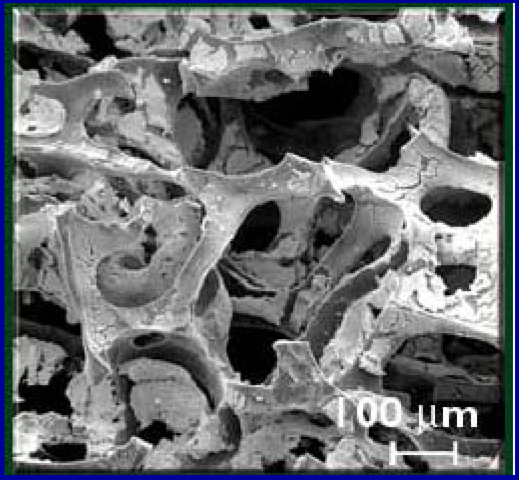
Carbon* , Al_2O_3, ZnO, HfO_2, BN, LiF, MgO, $CaCl_2$, ThC_2, UC_2, ZrO_2



SEM of Al_2O_3 & HfO_2



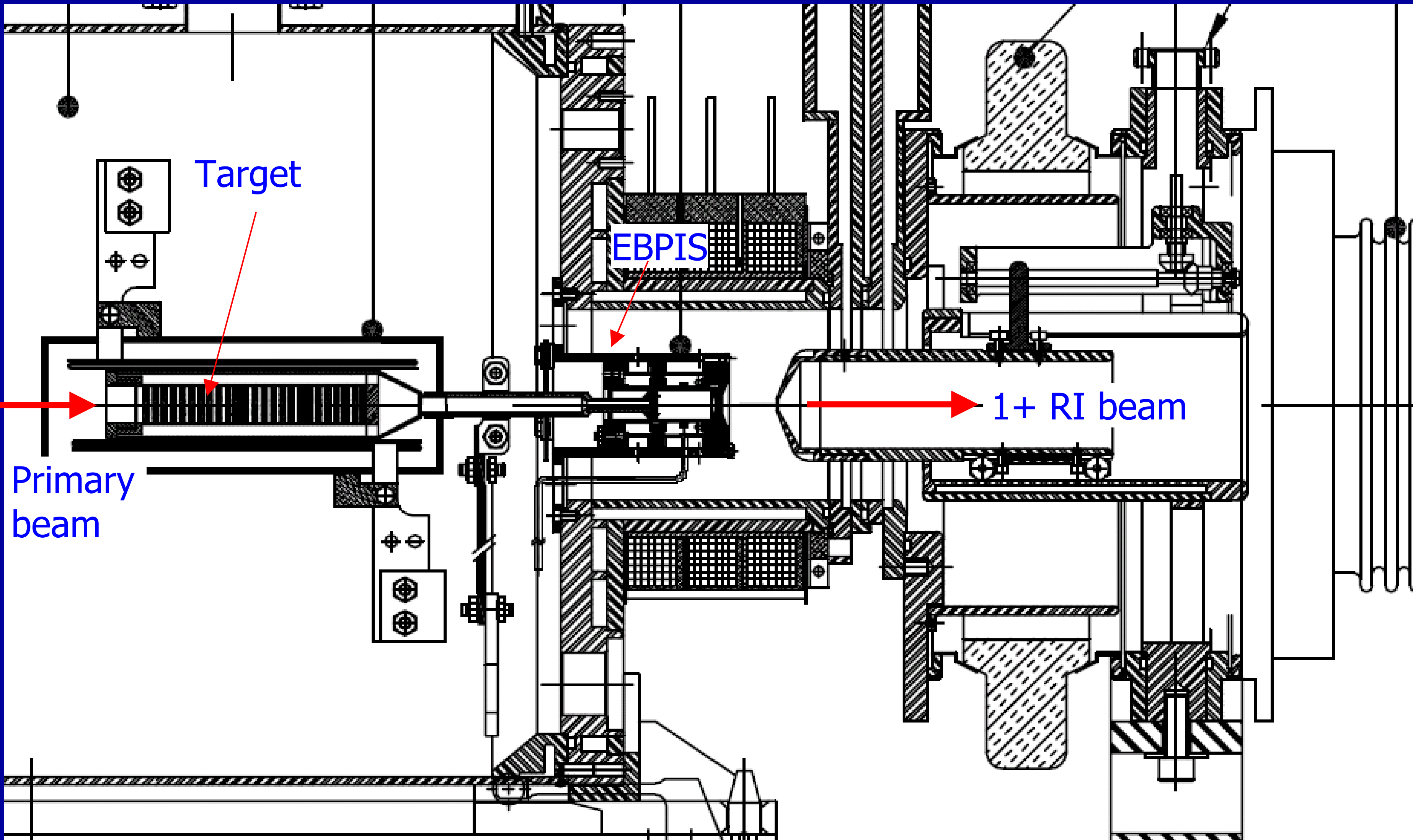
SEM of RVCF



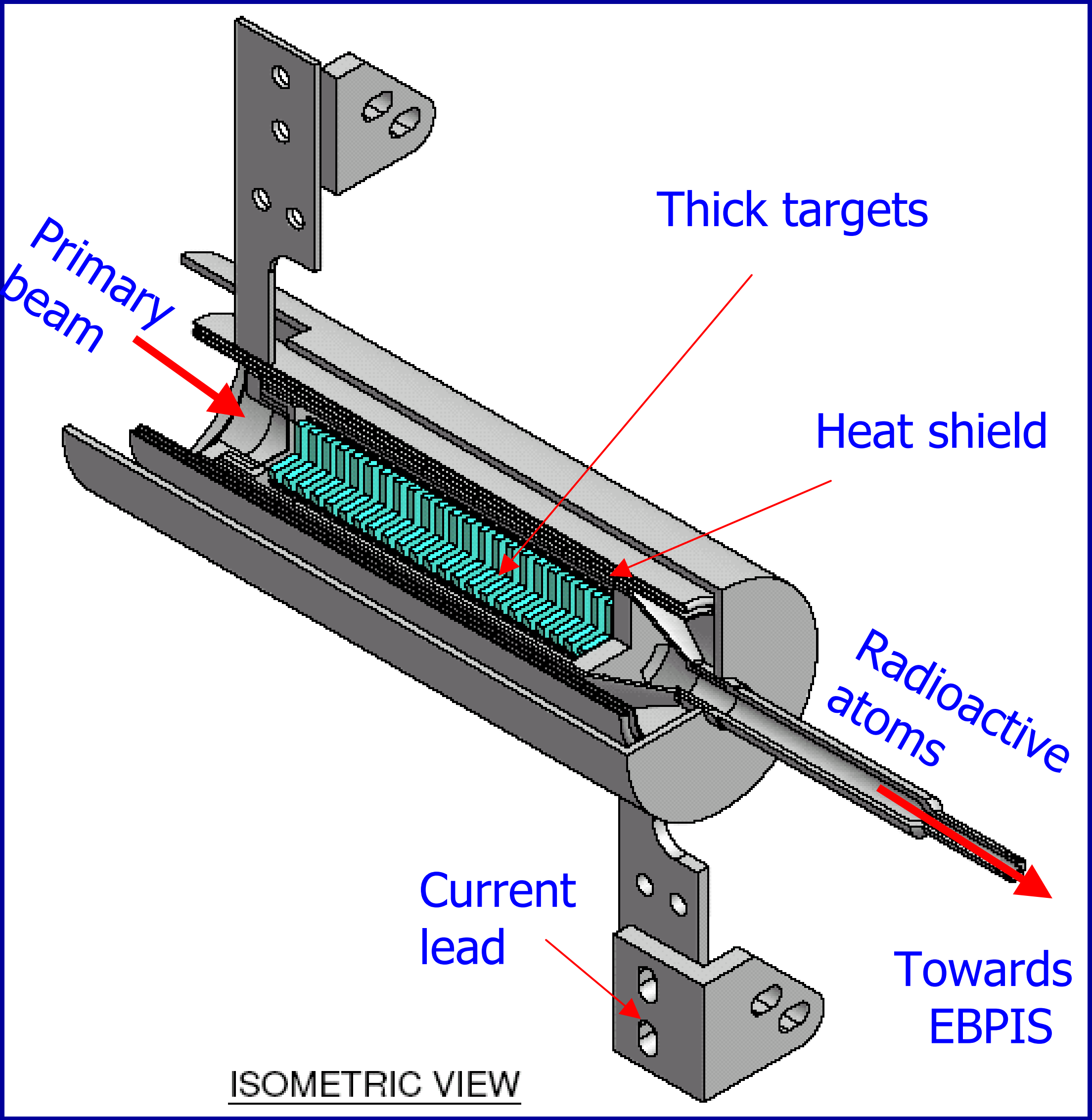
SEM of RVCF + Al_2O_3

*RVCF : Reticulated Vitreous Carbon Fiber

Integrated Thick-Target Electron Beam Plasma Ion-Source



Target holder



Ionization of Radioactive atoms in on-line

Needed : Good on-line ionization efficiency for desired charge state over a wide mass range

RFQ $\Rightarrow$ q/A =1/14 ; A=100, q>7^+

ECR ion-source best choice!

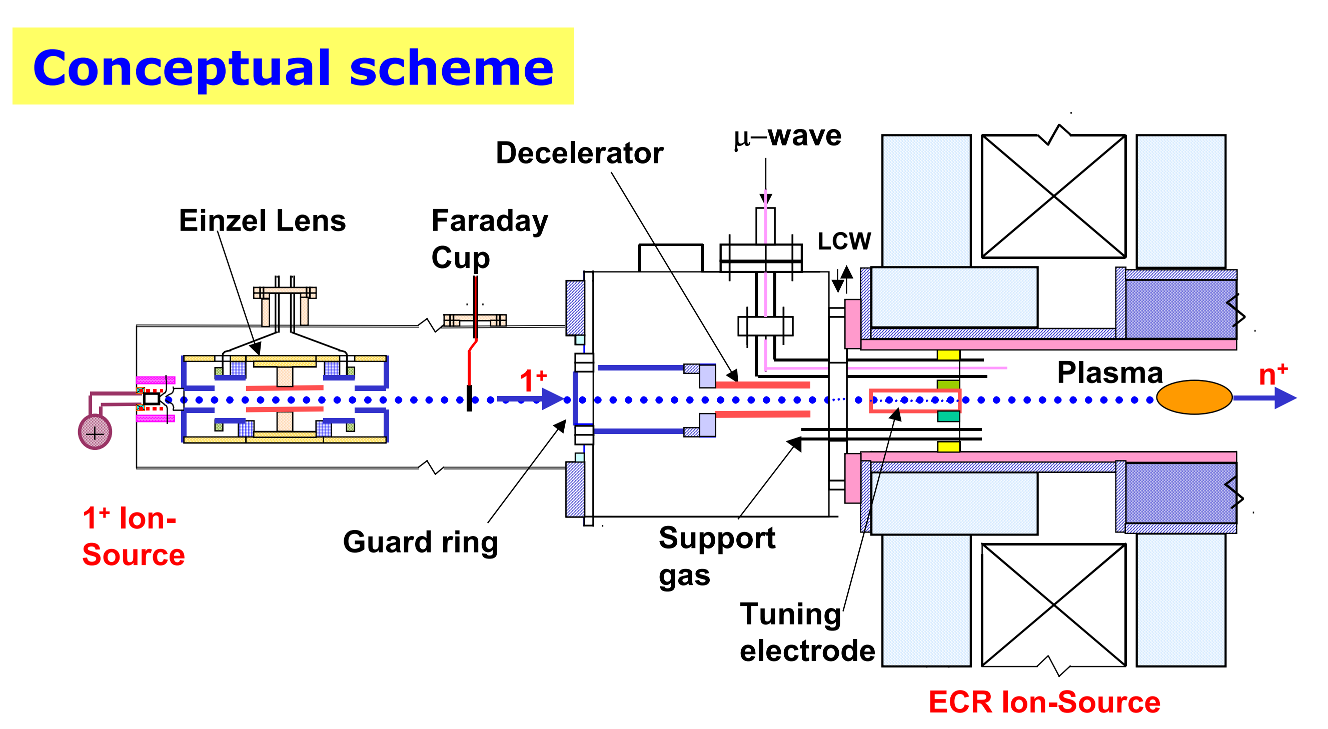
- **Stable operation over long time**
- **Good ionization efficiency, high charge states**

BUT !!!

- **Poor vacuum close to target chamber (~10^{-3} mbar)**
- **Radiation damage of permanent magnets**

SOLUTION ! **Charge Breeder** Two ion sources in cascade

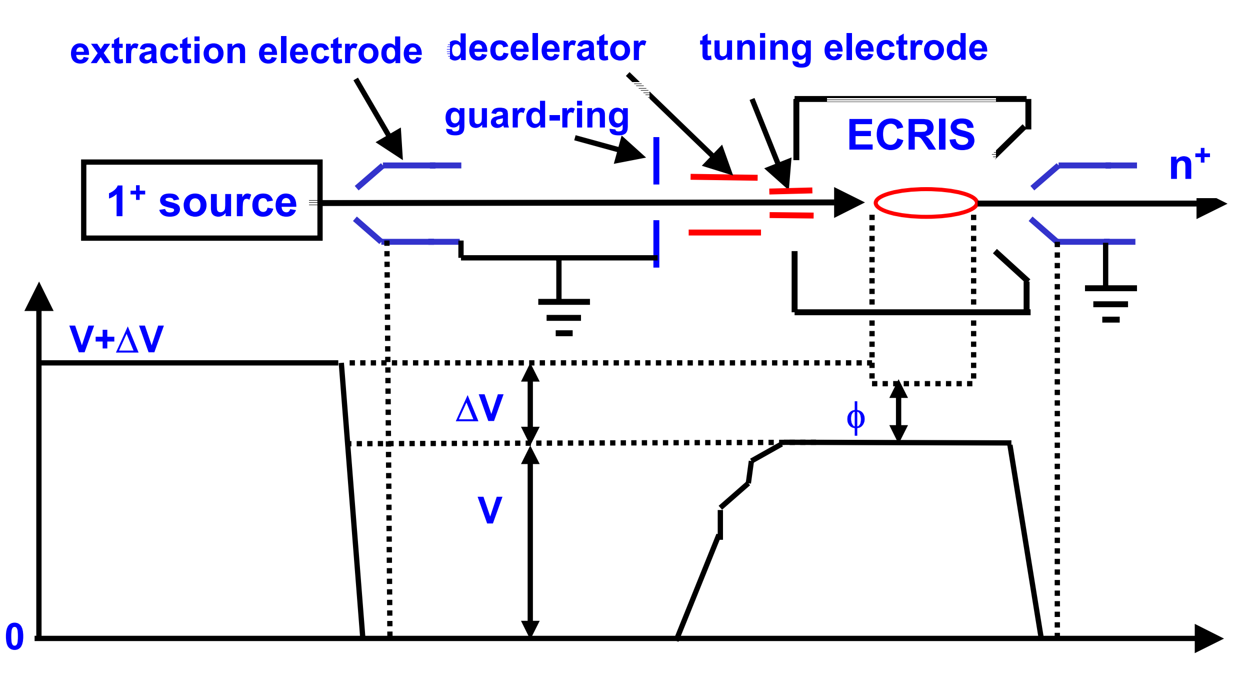
Integrated Target-ion source → 1^+ RIB | ECR ion-source → n^+ RIB



- ECRIS : at safe distance ~ 10^{-6} mbar vacuum inside plasma chamber
- ECR permanent magnets protected from high radiation near target

- 1^+ ions : typical energy 1.5 keV/u; ions need to be decelerated or
- else will pass through the ECR plasma without being captured

- Decelerate 1^+ beam to ~ 20 eV (plasma potential)



Deceleration ⇒ high transverse emittance growth

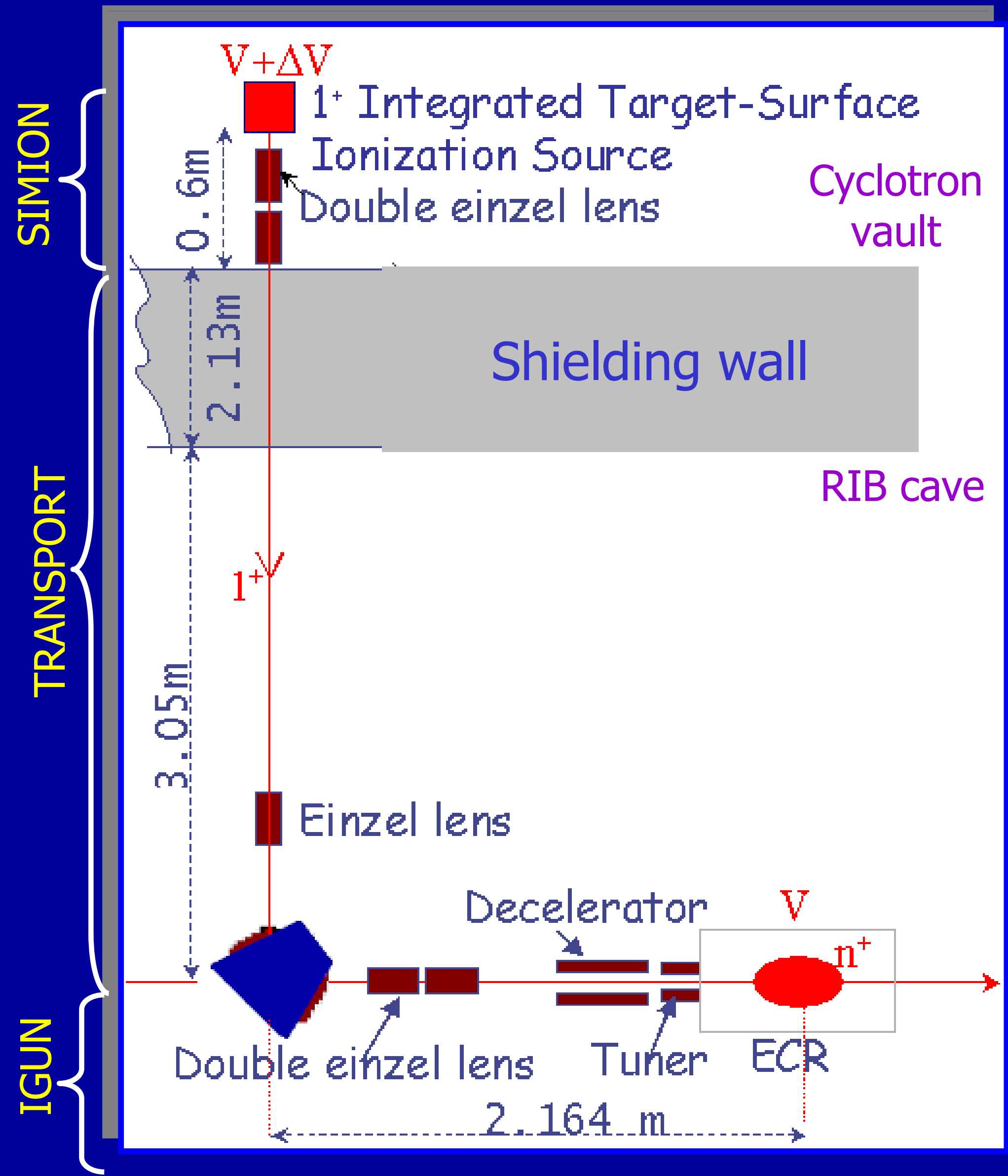
Gradual deceleration ⇒ soft landing inside ECR plasma, high capture

Two-Ion Source Charge Breeder : design calculations

- 1^+ beam Surface ion-source
  e=10 π.mm.mrad ; E= 15 keV

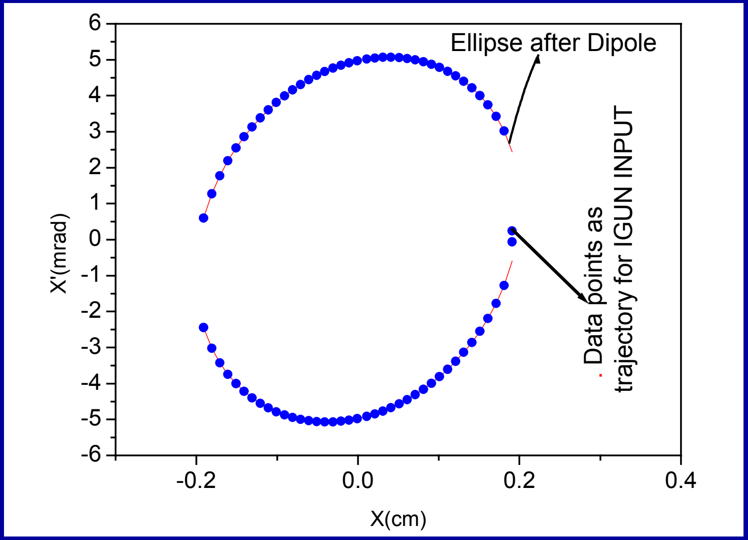
- point-to-point beam transport
  1^+ ion-source to end of dipole

- deceleration & injection of
  1^+ beam into ECR ion-source

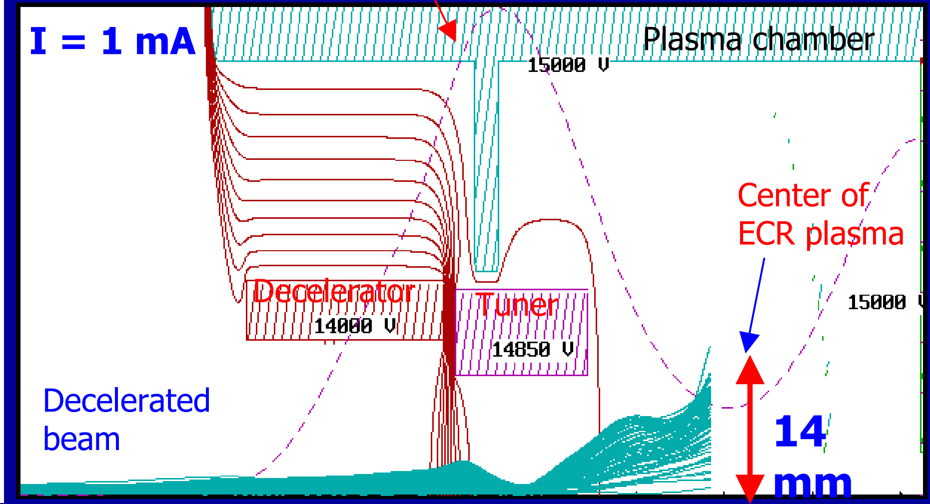


2-IS charge breeder beam-dynamics simulation

- 1^+ beam from the Surface ion-source injected into 6.4 GHz ECR ion-source for further ionization to n+
- Gradual deceleration of 1^+ beam (~ 20 eV) & soft landing inside ECR



Input beam



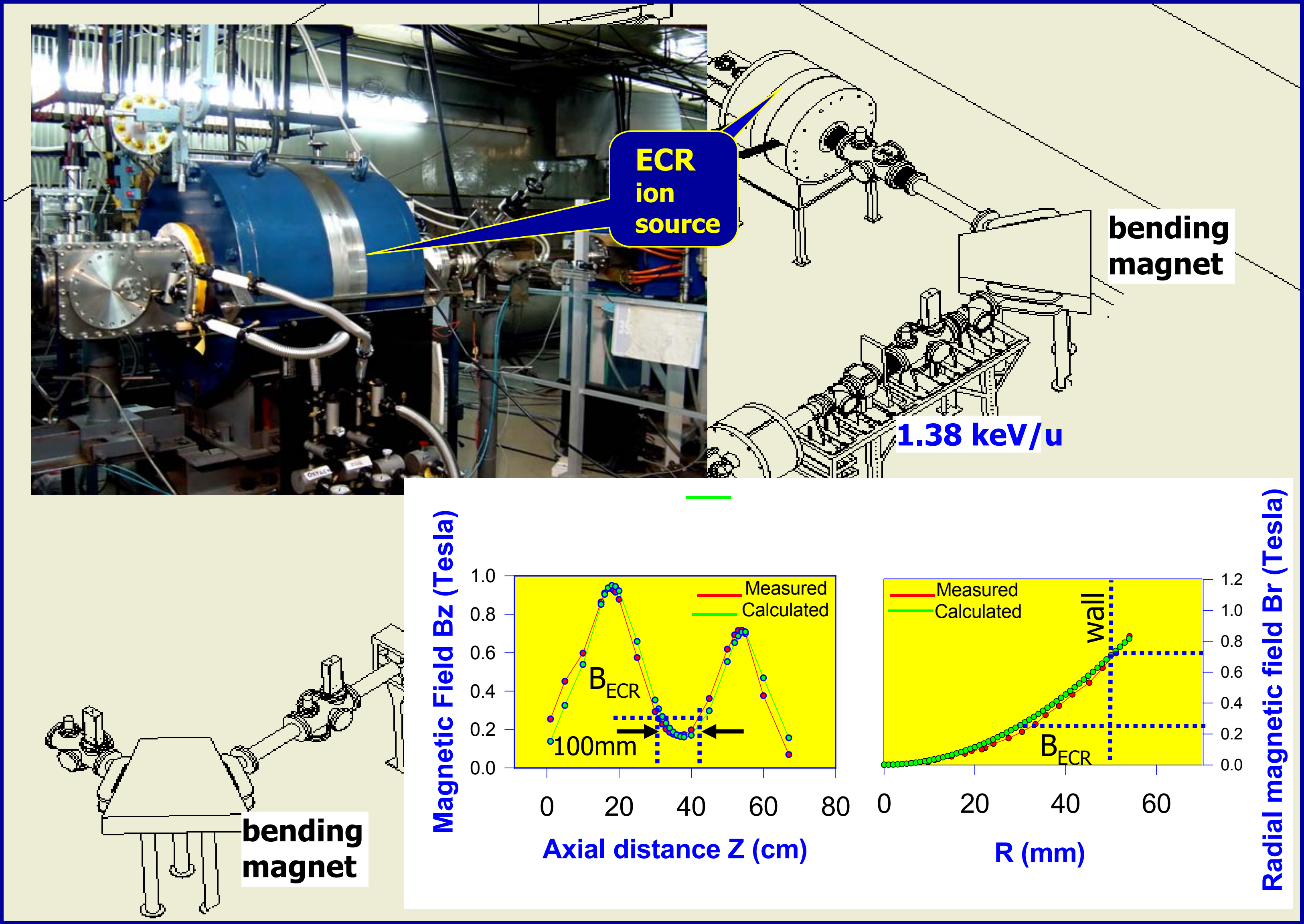
RESULTS

IGUN simulation for A=100, 100 nA & 1μA beam current, space charge effect considered

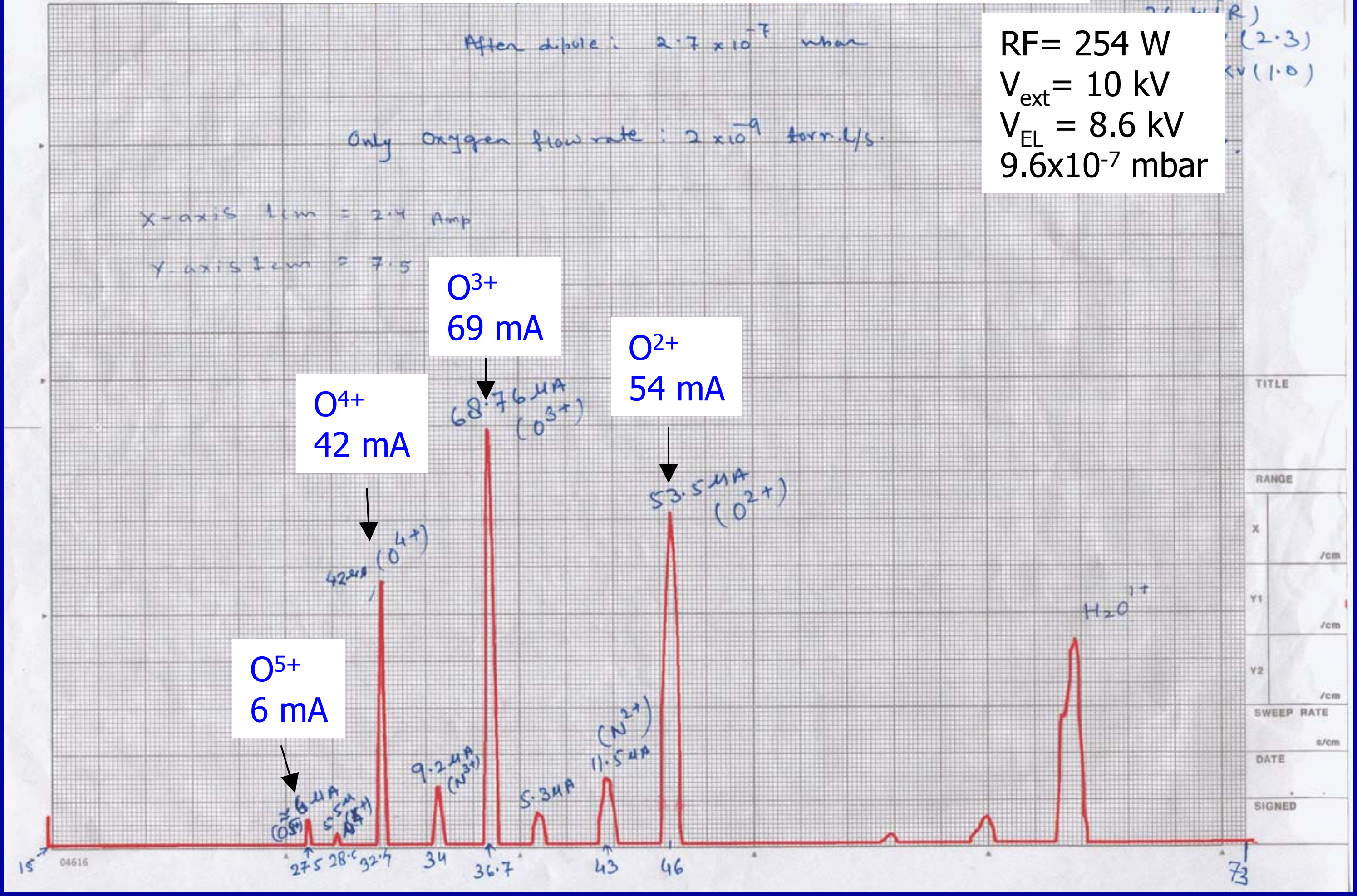
- Beam size at the center of ECR plasma zone = 12 mm (100 nA) & 28 mm (1 mA)
- Beam size less than ECR plasma zone extent (50 mm)
- Coulomb repulsion ⇒beam size larger for 1μA

§ Advantages of gradual deceleration scheme

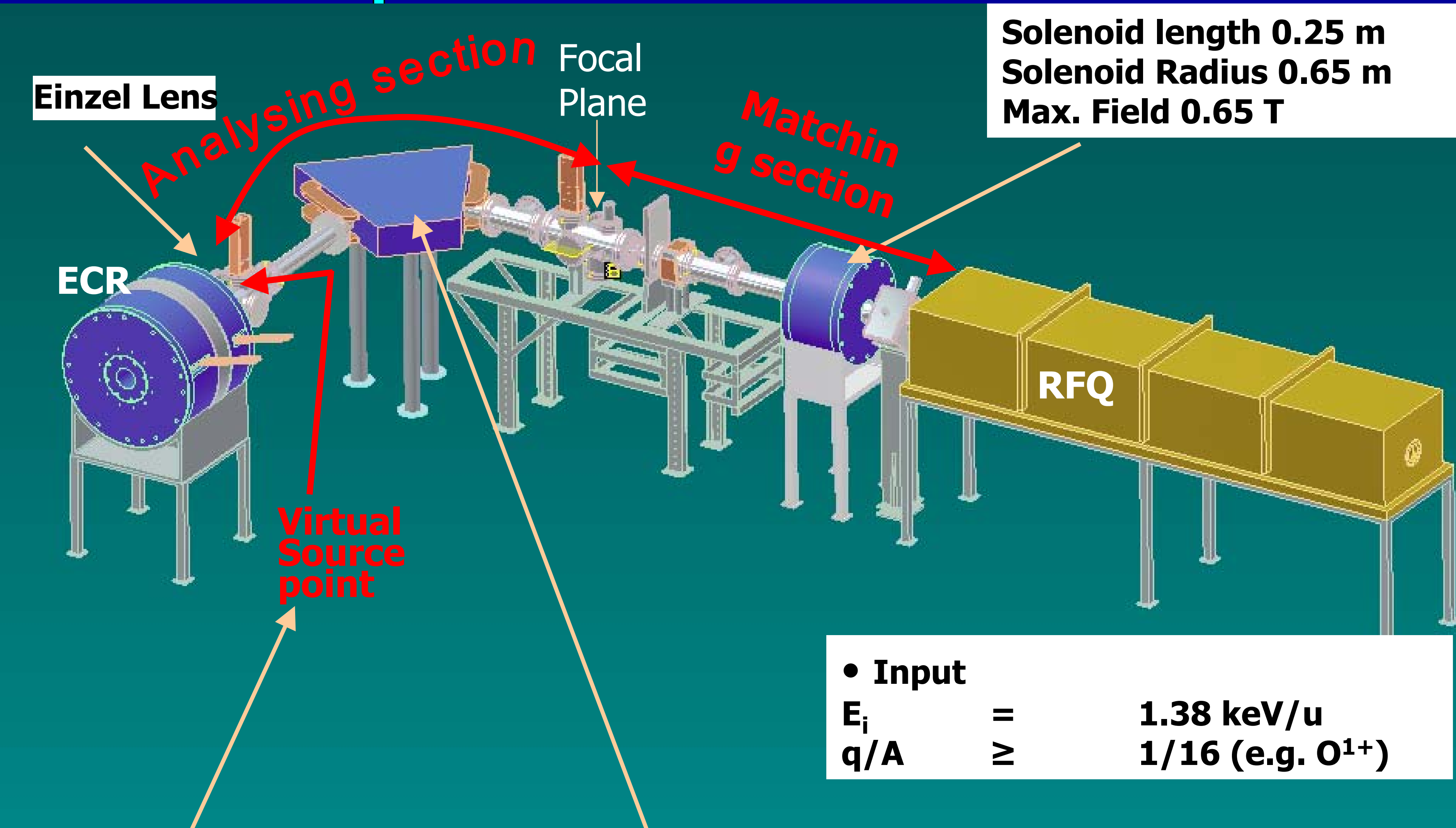
- beam size less than ECR injection hole (26 mm ϕ)
- decelerated beam focused well inside the radial extent of ECR plasma
- negligible parasitic extraction towards injection side
- calculation should be considered a guideline for actual experiments


ECR
ion
source
bending
magnet
1.38 keV/u
bending
magnet
Magnetic Field Bz (Tesla)
Measured
Calculated
B_ECR
100mm
Axial distance Z (cm)
Measured
Calculated
wall
B_ECR
R (mm)
Radial magnetic field Br (Tesla)

Typical Oxygen spectrum from ECR ion-source



Low Energy Beam Transport line



Solenoid length 0.25 m
Solenoid Radius 0.65 m
Max. Field 0.65 T

- **Input**

E_i	=	1.38 keV/u
q/A	≥	1/16 (e.g. O^{1+})

Erect Ellipse
ε = 120 π mm mrad
(± 1.2 cm / ± 10 mrad)

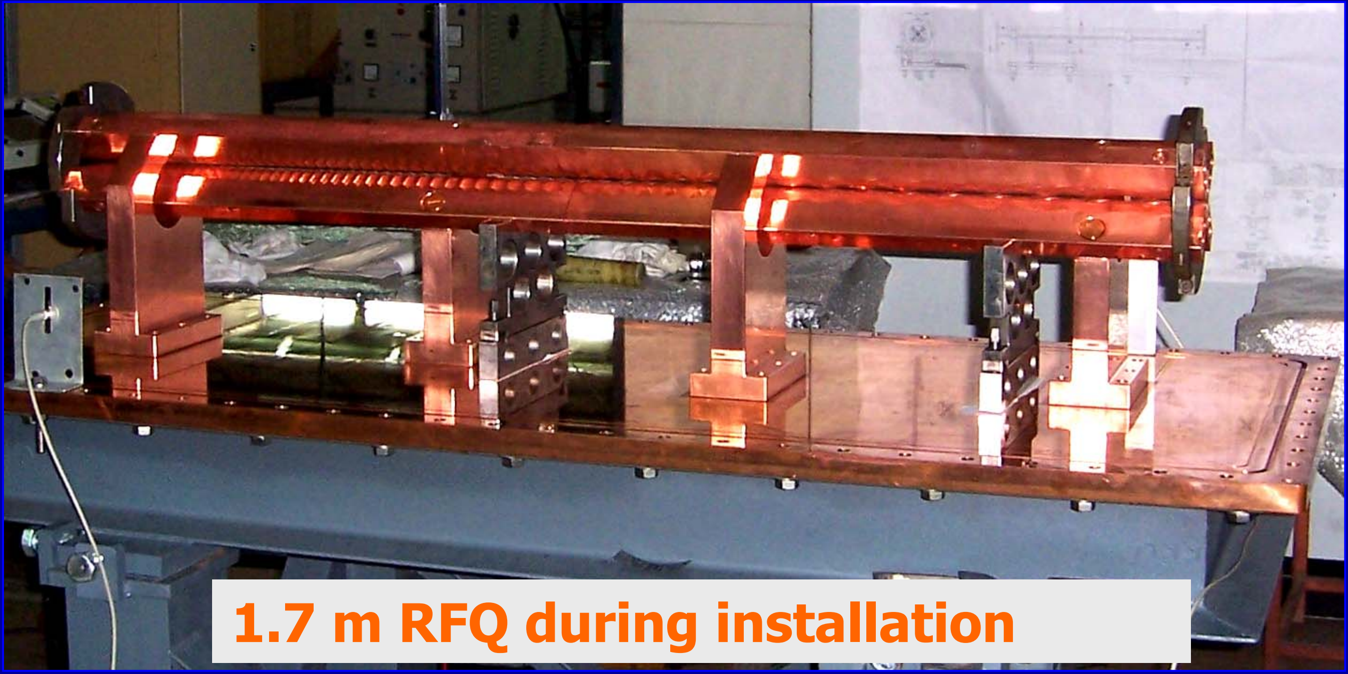
Bending Angle 90°
Bending Radius 0.5 m
Max. Field 0.25 T
Entry / Exit angle 27.141° / 27.107°

A.Bandyopadhyay,
S. De Choudhury et. al.

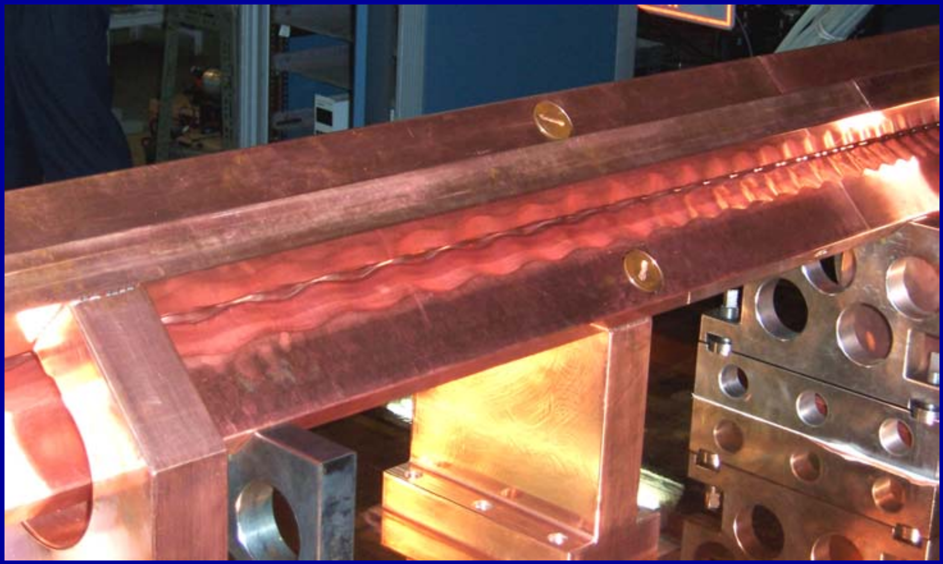
RADIOFREQUENCY QUADRUPOLE (RFQ): first post-accelerator

- **Acceleration of RIB from 1.5 to 98 keV/u**
- **Heavy Ion RFQ q/A ≥ 1/14 ; f ~ 35 MHz**
- **Extended rod structure ; Vane Length 3.1 m ; Vane Voltage 49.5 kV**

RFQ development ⇒ stage 1 ⇒ ½ scale model
stage 2 ⇒ 1.7 m RFQ (vane length = 1.55m)
stage 3 ⇒ 3.4 m RFQ (vane length = 3.1m)



1.7 m RFQ during installation

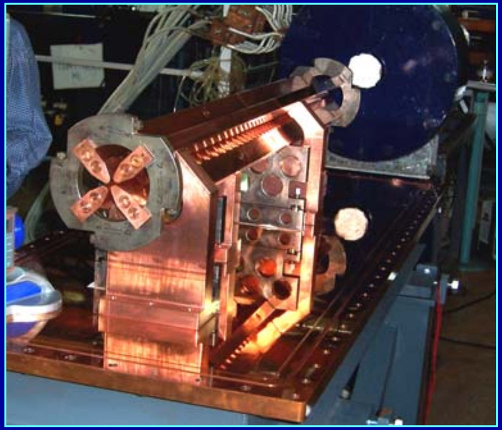


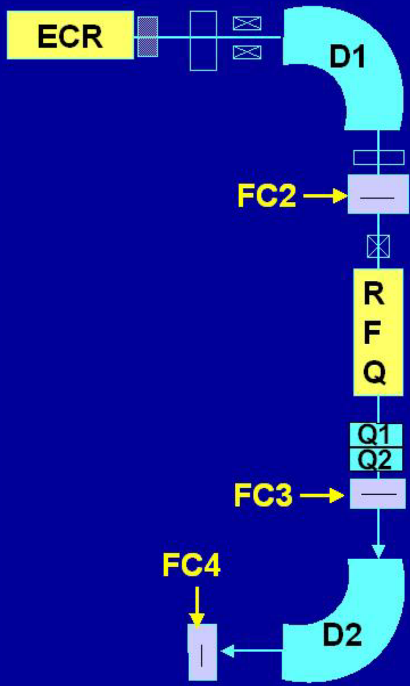
Result of 1.7 m RFQ Full power tests

Quantity	Measured
f	33.7 MHz
Q	5250
Vane voltage	16.5 kV
Power	1.1 kW
O^{3+} beam transmission η	~ 85 % (RFQ exit)

Rev Sci Instrum. Vol78 (2007) 043303.

Nucl. Instrum. & Meth. VolA535 (2004)599.

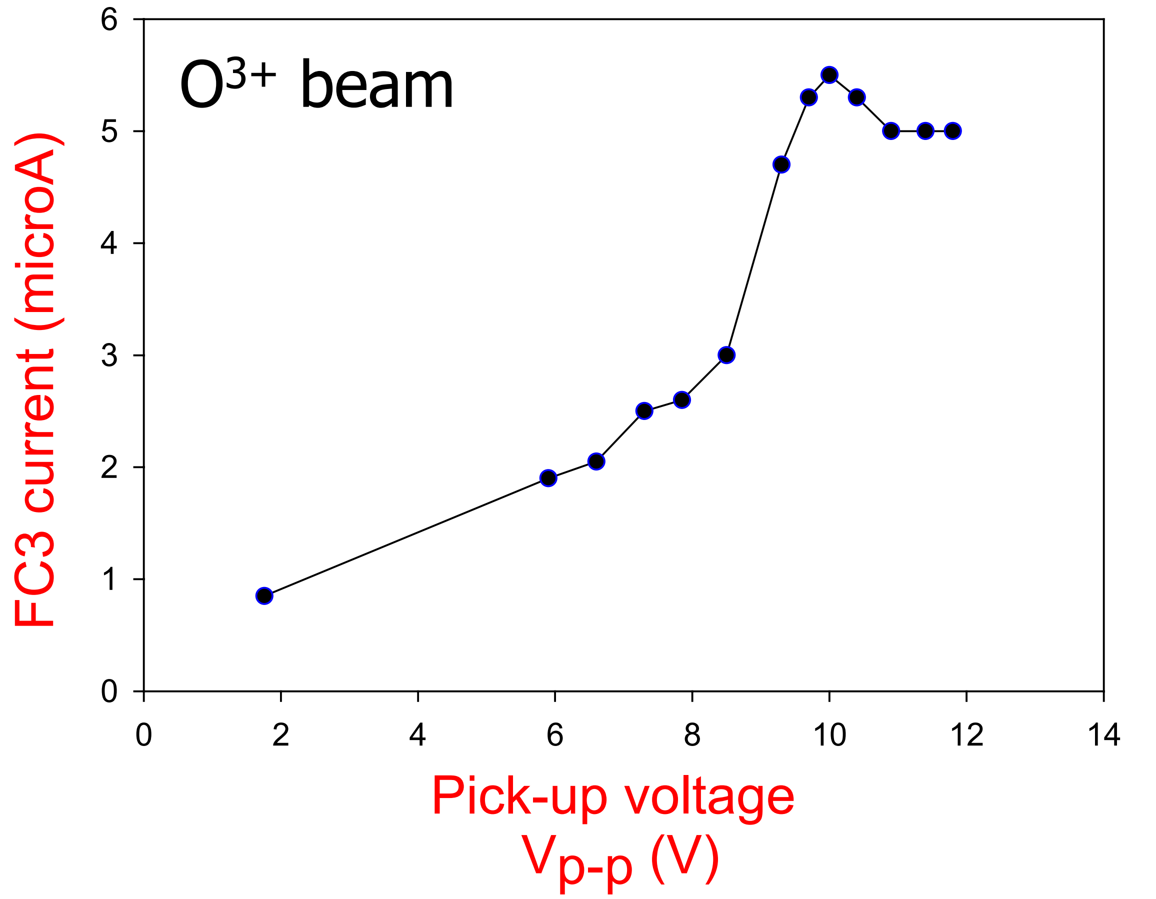




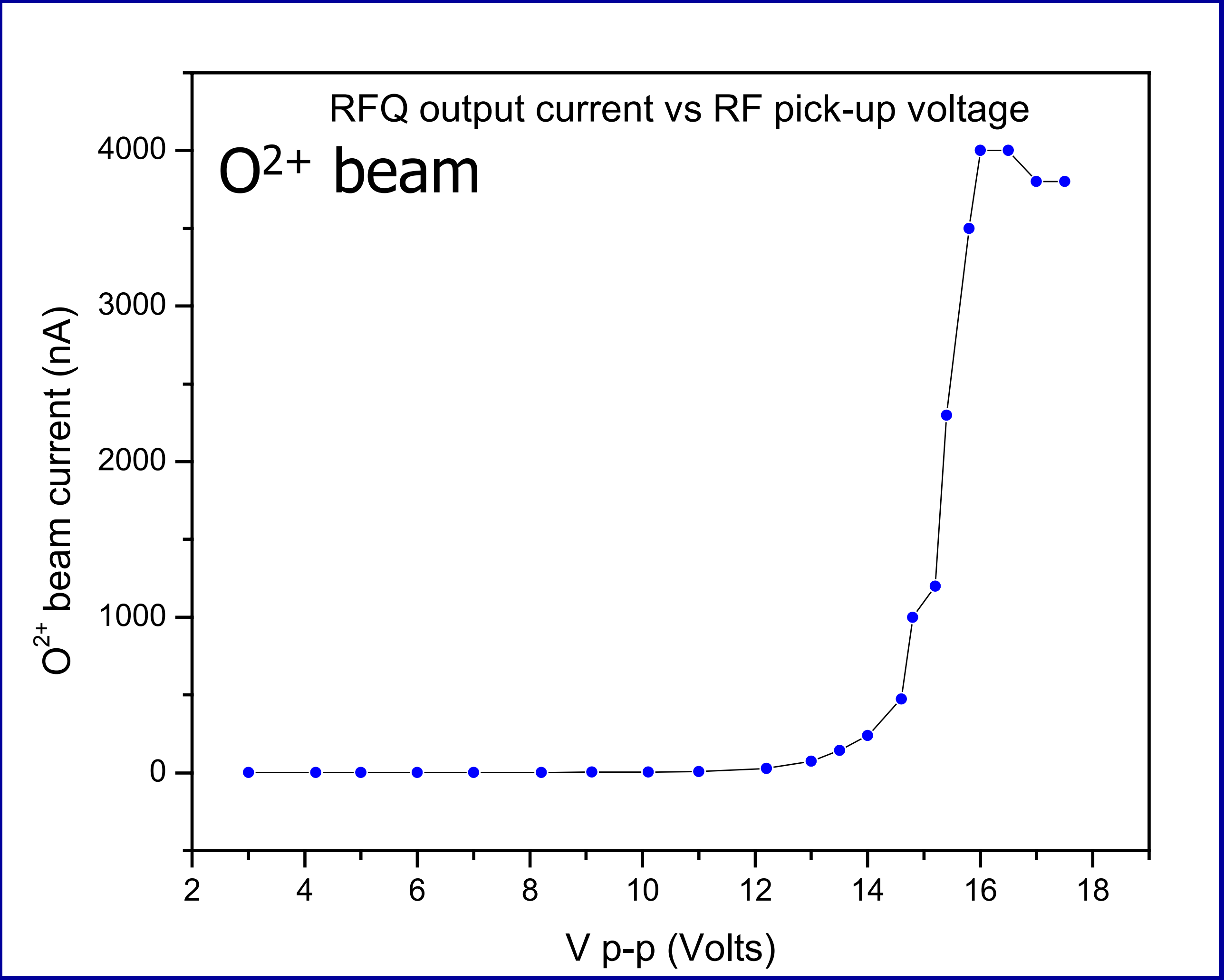
Experimental Results: Test Beam: Ar 4+

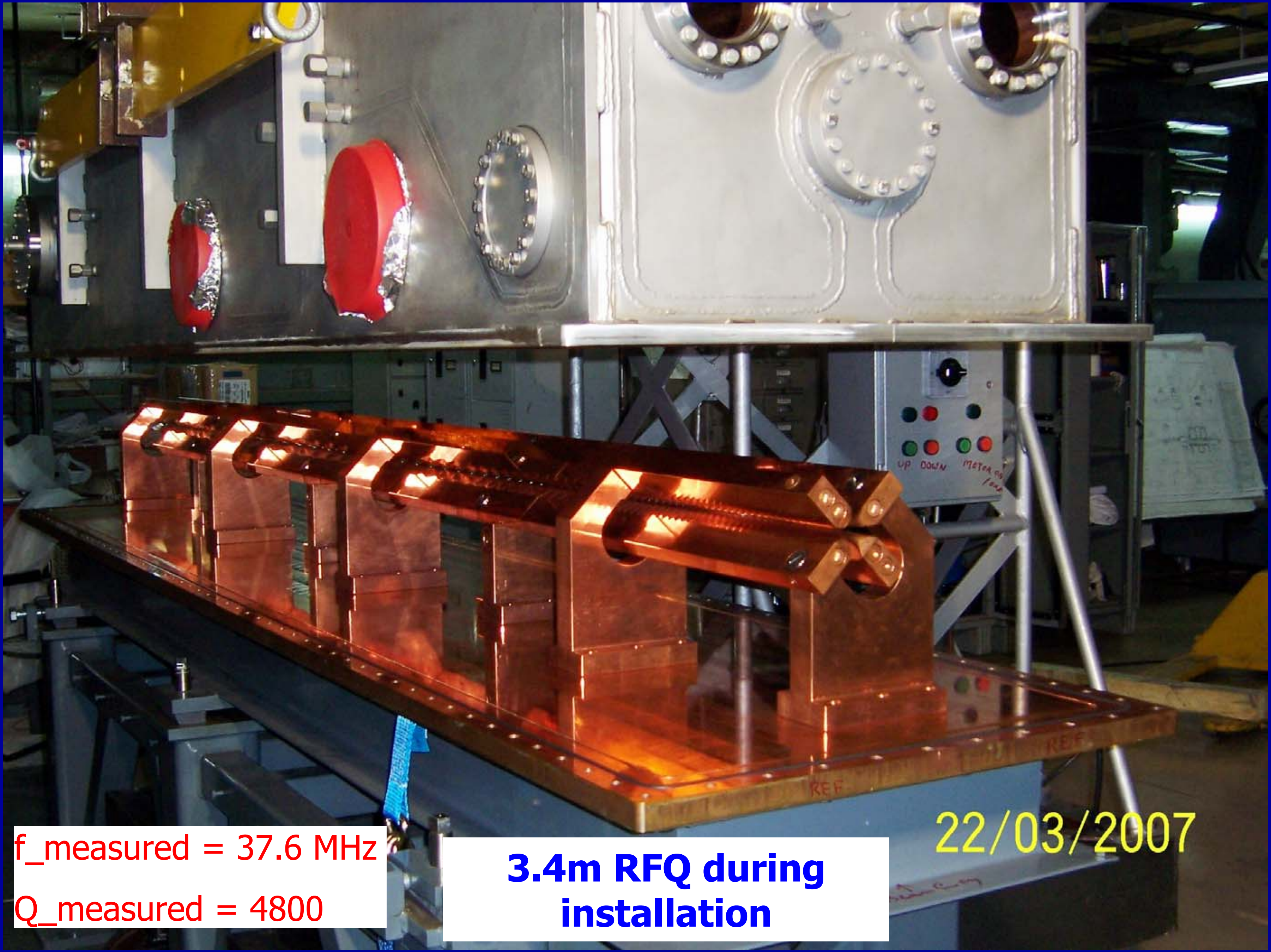
Calculated magnetic strength (kG) (29.06 keV/u)	Experimental magnetic strength (kG)	Transmission Efficiency* % *with electron suppression
Q1: -1.528 Q2: 1.065	Q1: -1.53 Q2: 1.057	~81% FC3/FC2
Q1 : -1.07 Q2: 0.7 D2 : 2.058	Q1: -1.058 Q2: 0.82 D2: 2.058	~80% FC4/FC2

Beam current *vs* RFQ power : 1.7m RFQ (FC3 at RFQ exit)



FC at QQ focus after RFQ





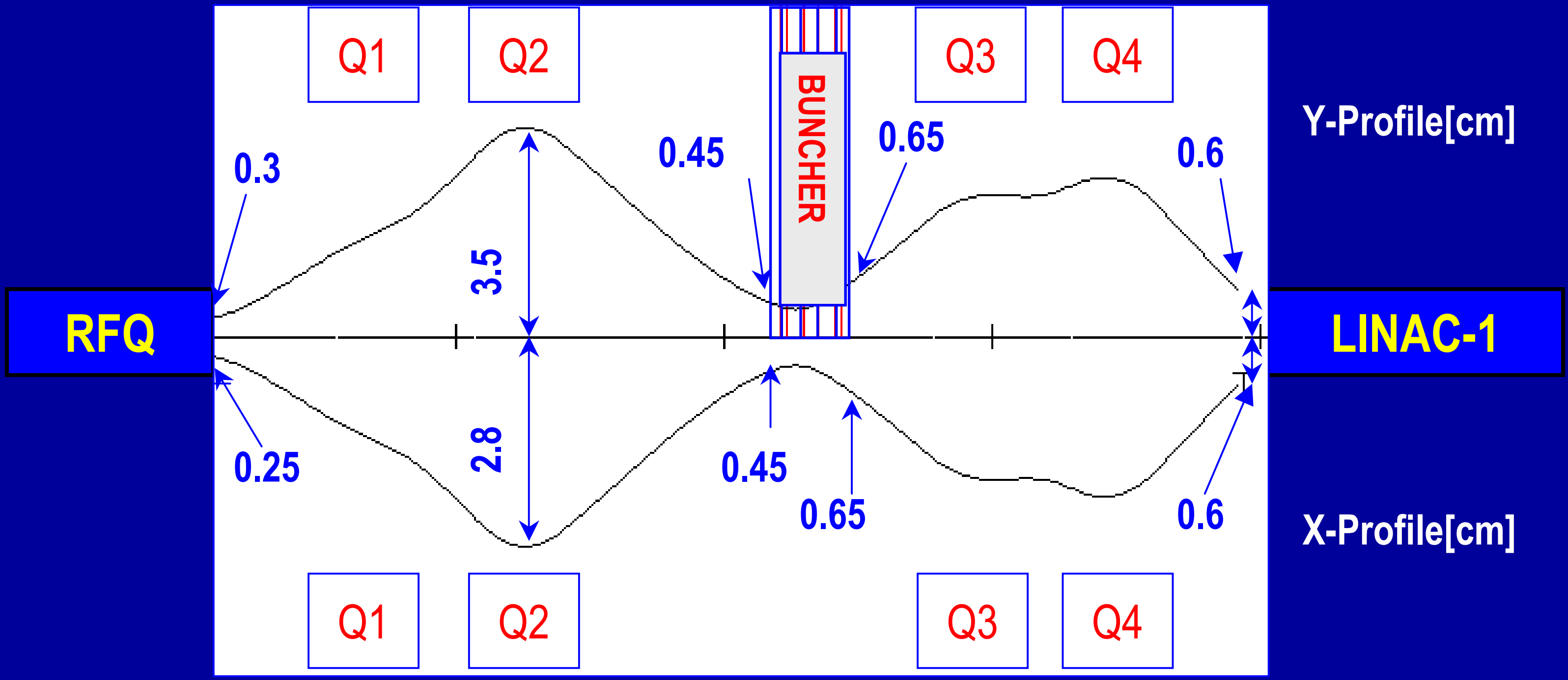
f_measured = 37.6 MHz

Q_measured = 4800

3.4m RFQ during installation

RFQ to Linac-1 beam-line

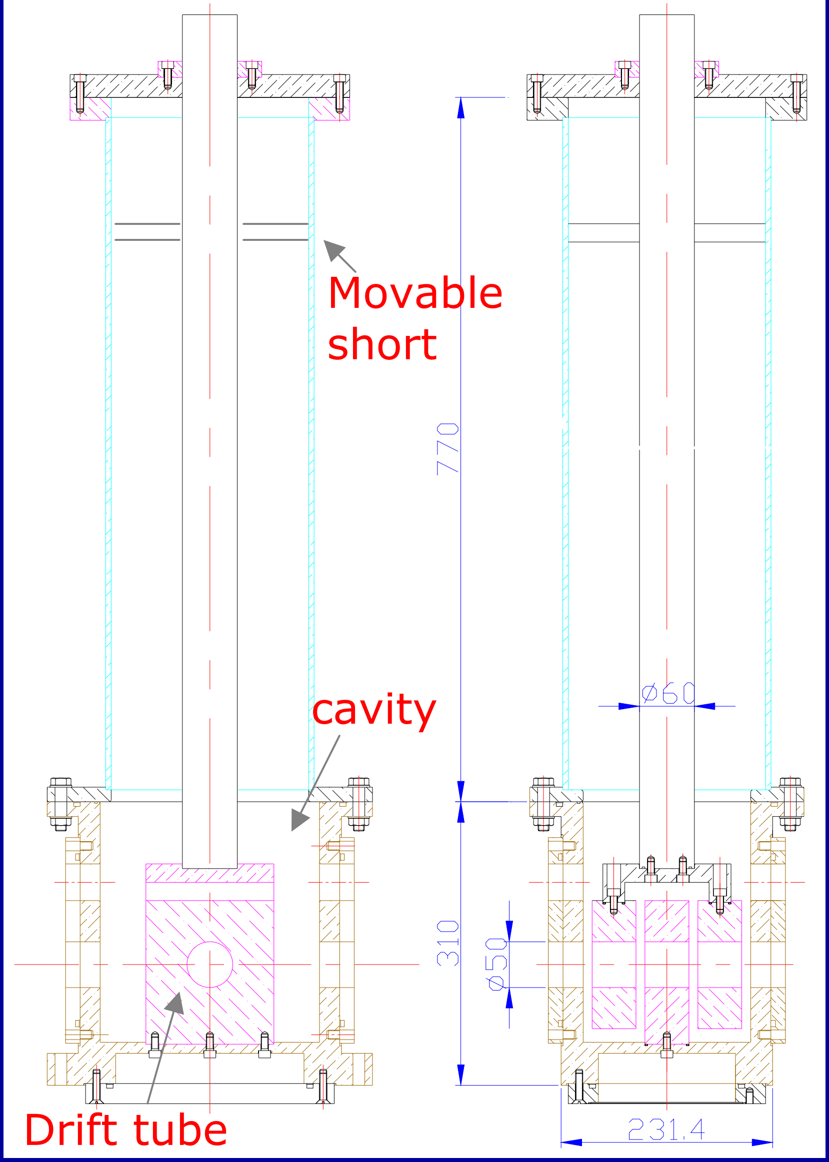
- Configuration : QQ-Buncher-QQ
- Total length : 3.934 m



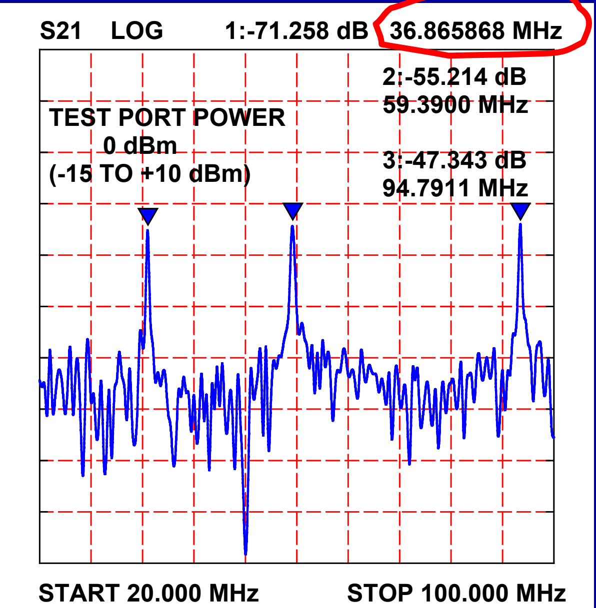
Re-buncher parameters

- **Frequency : 35 MHz**
- **Max. gap vol. : 13.75 kV**
- **No. of gaps : 4**
- **Drift tubes : 140 x 140 sq. mm**

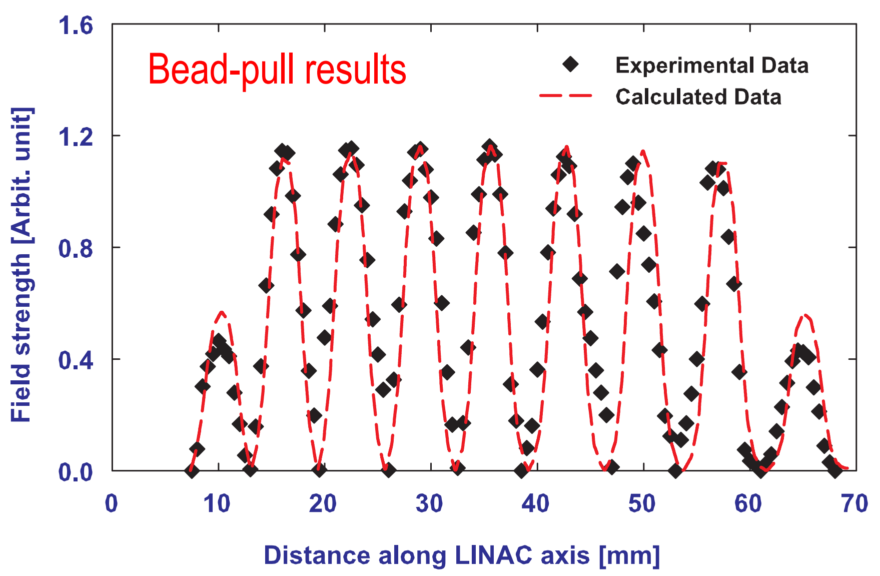
  50mm dia. hole
  48 mm long
- **Drift tube gaps : 9.85 mm**



IH –Linear Accelerators : post-accelerators after RFQ
100 keV/u ⇒ 460 keV/u in 3 linac tanks

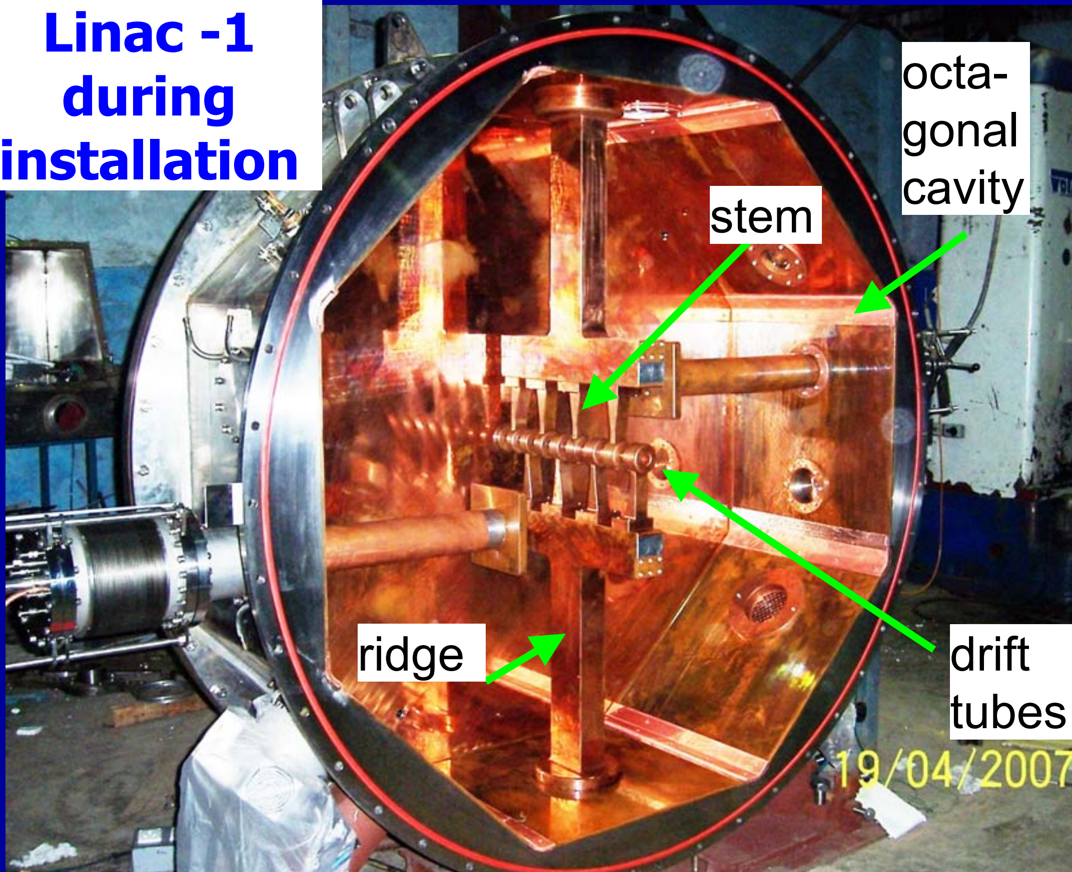


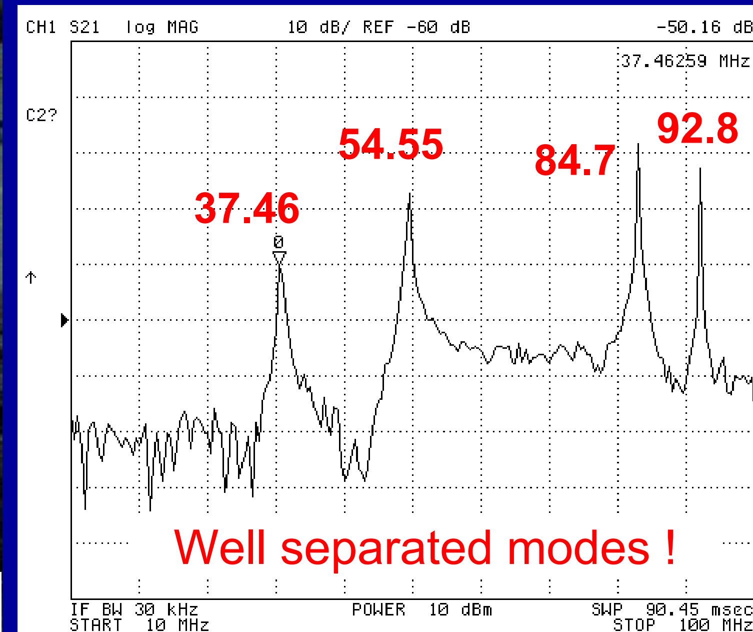
36.86 MHz



Linac -1 full scale prototype

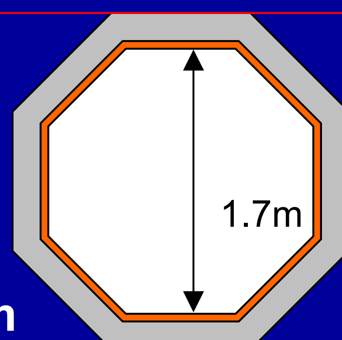
Linac -1 during installation

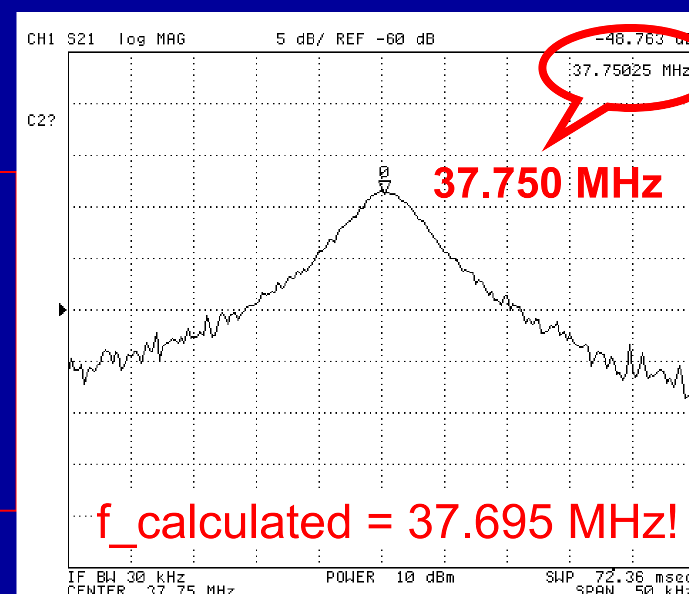




CAVITY :

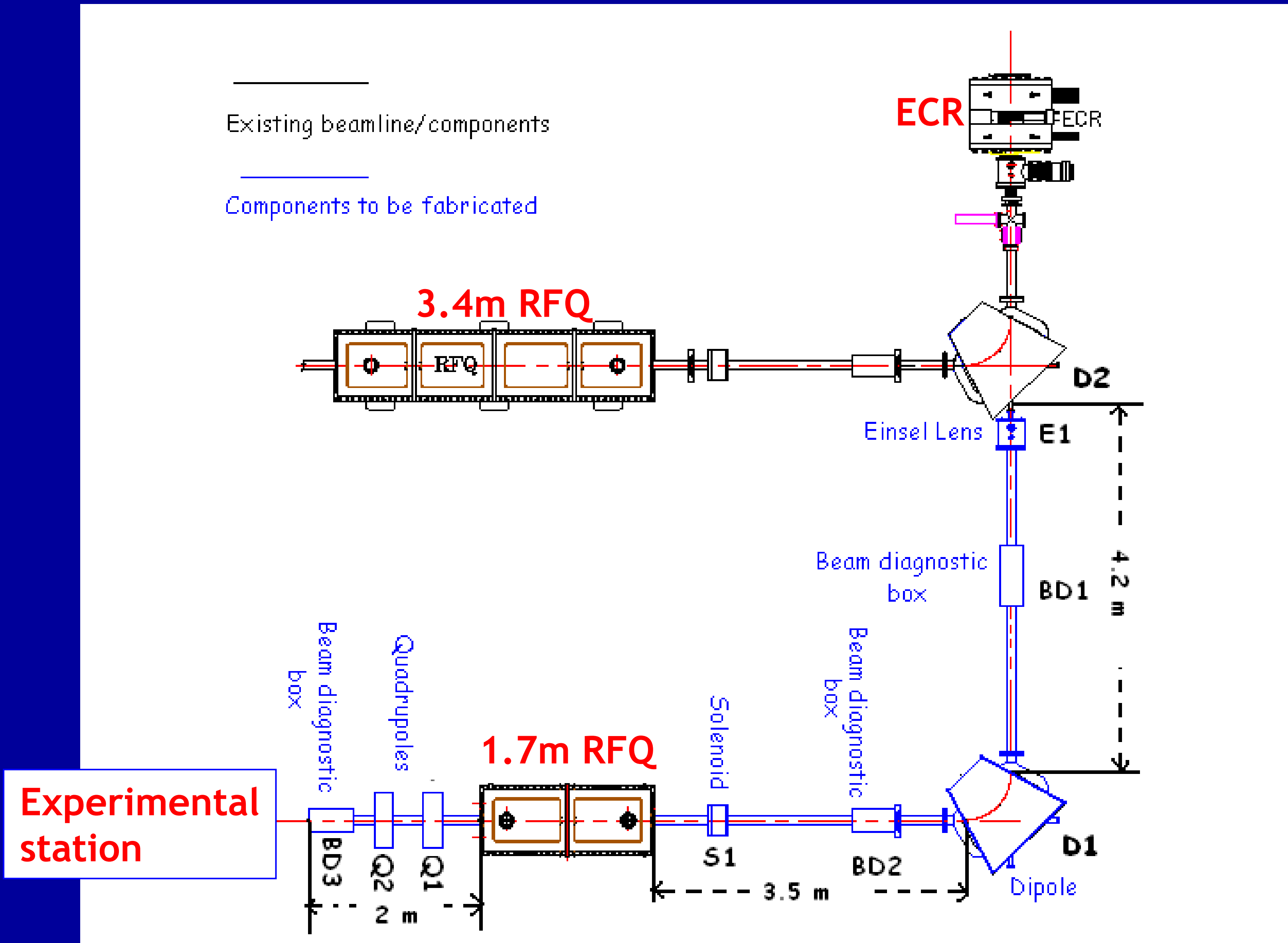
- 25 mm thk. SS304L
- cladded with 5 mm thk. Cu
- Diameter ~ 1.7m ; Length ~ 0.6 m

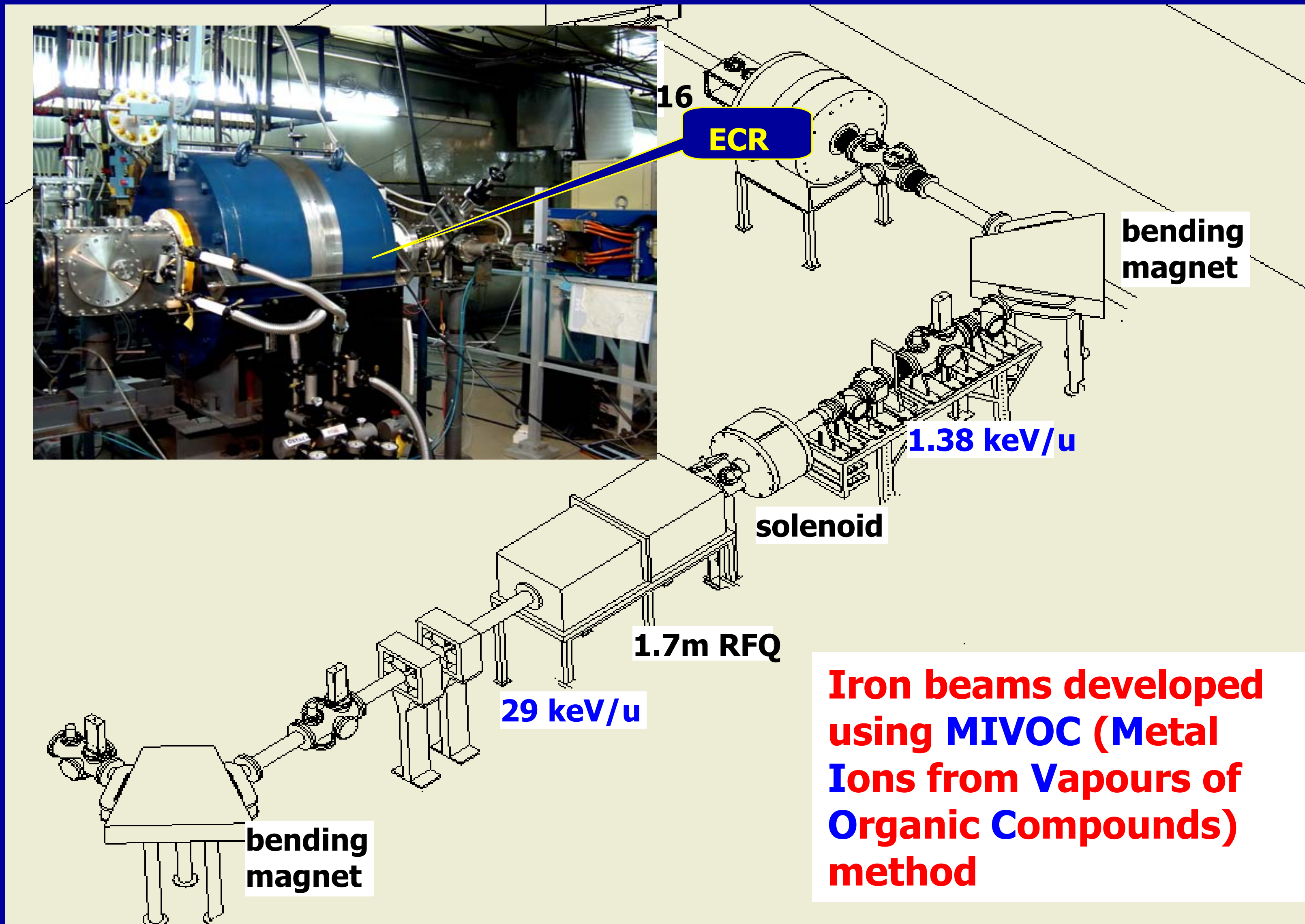




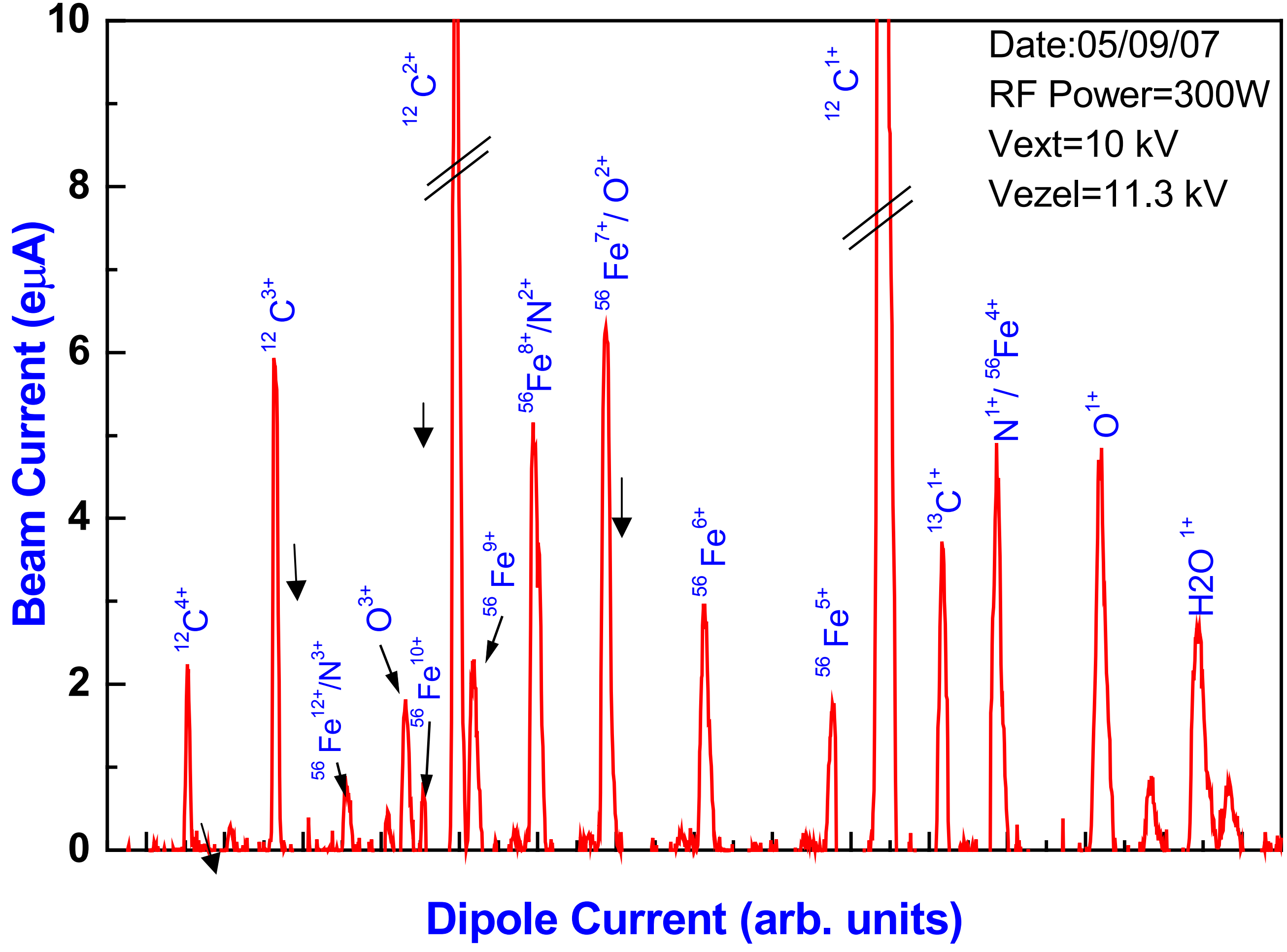

VACUUM TECHNIQUES PVT.LTD.
03/12/2007

New dedicated beam-line for material science & low energy spectroscopy experiments




16
ECR
bending magnet
1.38 keV/u
solenoid
1.7m RFQ
29 keV/u
bending magnet
Iron beams developed using MIVOC (Metal Ions from Vapours of Organic Compounds) method

First Iron spectrum



Beams available from the RIB facility

- **Oxygen : up to 120 keV (after ECR); 464 keV (after RFQ)**
- **Nitrogen : up to 100 keV (after ECR); 406 keV (after RFQ)**
- **Argon : up to 160 keV (after ECR); 1.16 MeV (after RFQ)**
- **Iron : up to 220 keV (after ECR); 1.6 MeV (after RFQ)**
- **Also H, Helium, O2, Carbon, …**

Typical measured currents: O^{3+} ~ 70 μA; O^{4+} 40 μA; O^{5+} ~ 6μA; Ar^{4+} ~ 4 μA; He^{1+} ~ 100 μA; Fe^{6+} ~ 7 μA; Fe^{10+} ~ 1 μA

optimization of ECR continuing

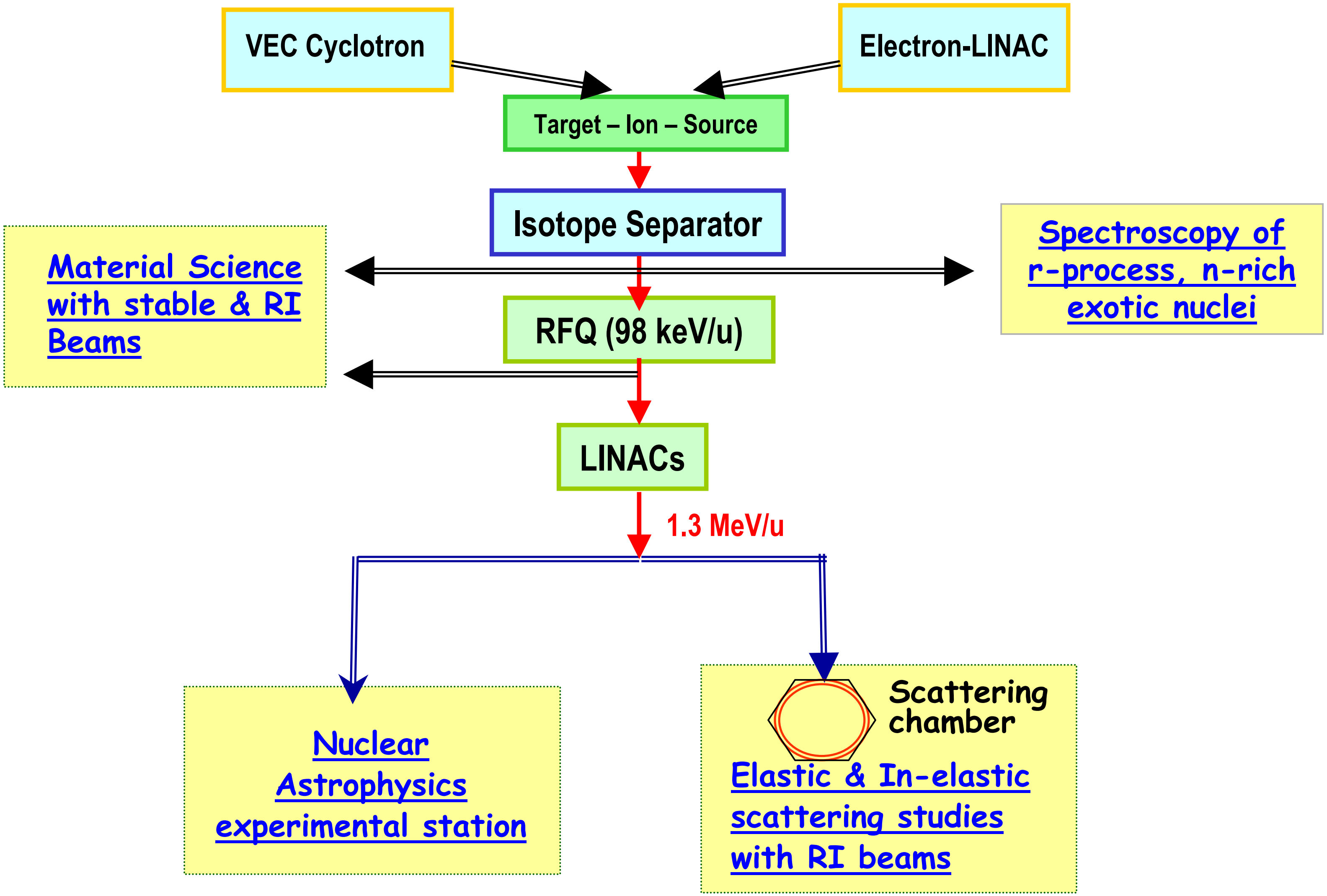
Recent publication from RIB project group

(in international peer review journals)

1. Phys. Lett. (in press), 2007. *Experiments*
2. Nucl. Instrum. & Meth. B261(2007)1018. *RIB facility status*
3. Rev Sci Instrum. Vol78 (2007) 043303. *RFQ results*
4. J of Phys. Condensed Matter 19, (2007) 236210. *Experiments*
5. Ceramics International, (in press). *Target*
6. Nucl. Instrum. & Meth. VolA560 (2006)182. *Linac design*
7. Nucl. Instrum. & Meth. VolA562 (2006)41. *Beam-line*
8. Nucl. Instrum. & Meth. VolA539 (2005)54. *Target*
9. Nucl. Instrum. & Meth. VolA547 (2005)270. *Charge breeder design*
10. J. of Mat. Sc. 40 (2005) 5265. *Experiments*
11. Nucl. Instrum. & Meth. VolA535 (2004)599. *RFQ design*
12. Physica C, Vol416, (2004) 25. *Experiments*
13. Nanotechnology 15 (2004) 1792. *Target*
14. Nucl. Instrum. & Meth. VolA447 (2000)345. *Charge breeder design*

Physics with VECC facility

- Nuclear astrophysics with stable and unstable beams
- Condensed matter physics with stable & unstable ions
- Spectroscopy of n-rich *r* process nuclei

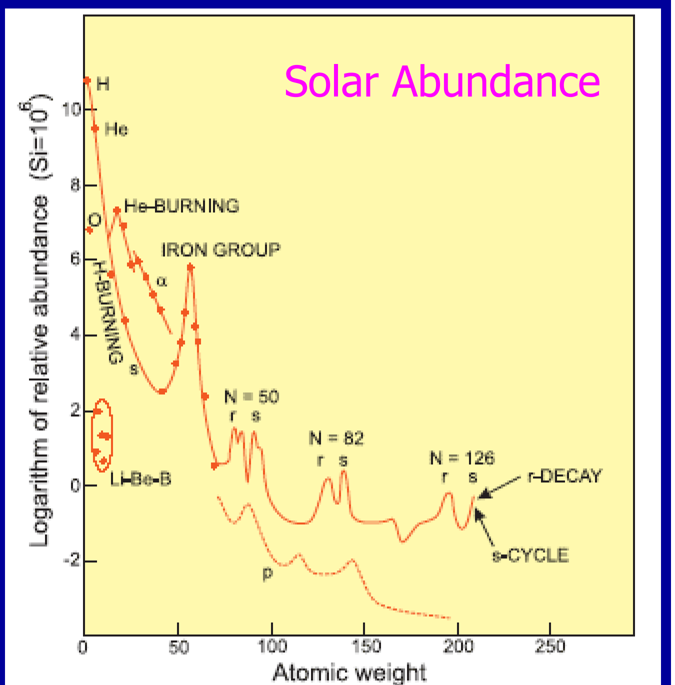


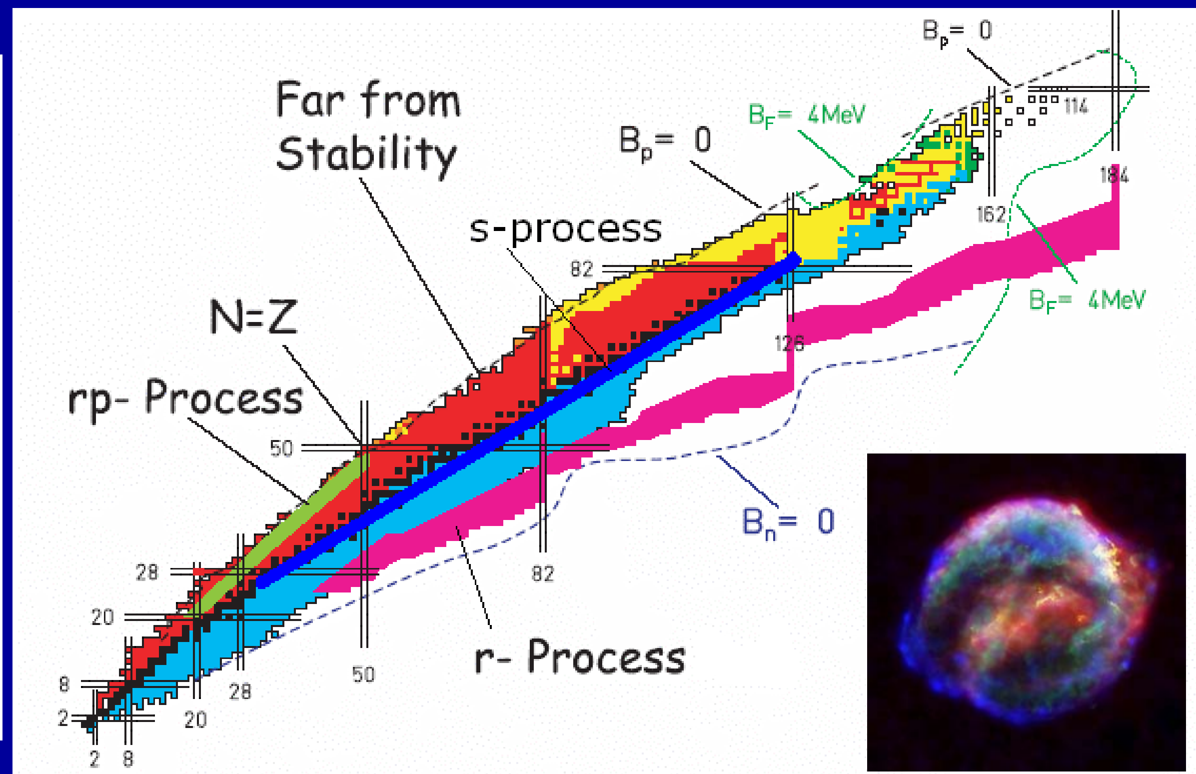
VEC Cyclotron
Electron-LINAC
Target – Ion – Source
Isotope Separator
Material Science with stable & RI Beams
Spectroscopy of r-process, n-rich exotic nuclei
RFQ (98 keV/u)
LINACs
1.3 MeV/u
Nuclear Astrophysics experimental station
Scattering chamber
Elastic & In-elastic scattering studies with RI beams

Element synthesis in the Universe

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

Beyond Bi, only r-process





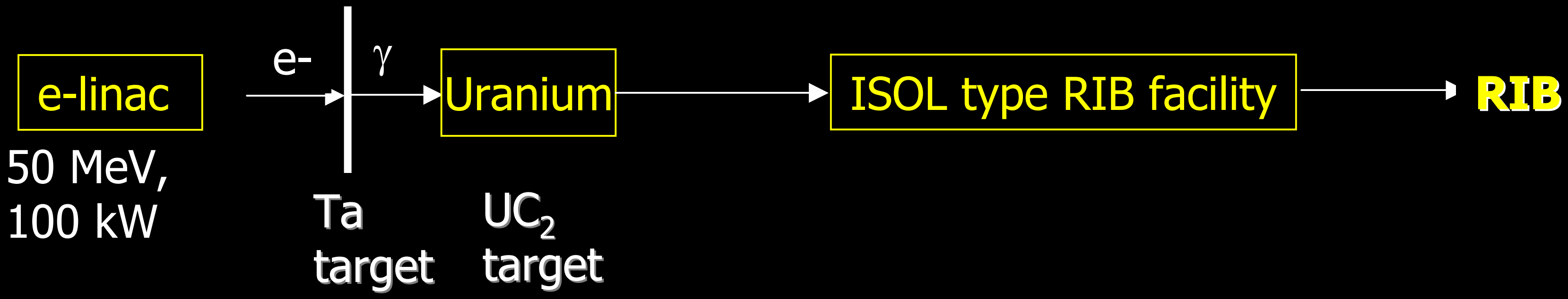
Type of nuclear astrophysics studies with various accelerators

	Stellar Burning				Explosive Burning				
FACILITY/REACTIONS	H	He	HI	s	r	rp	αp	γ	ν
Low-E Stable Beam	■	■	■	■				■	
High-E Stable Beam	■	■				■	■	■	■
RIB-ISOL	■				■	■	■	■	
RIB-Fragmentation	■	■		■	■	■	■	■	■
Spallation n (ν) source				■	■			■	■
Free Electron Laser		■		■				■	

Experimental facilities needed for astrophysics experiments

	LE-SB	HE-SB	RIB ISOL	RIB FRAG	SNS	FEL
Gamma array-segmented	■	■	■	■	■	
Silicon-Strip Arrays	■	■	■	■	■	■
Neutron Array	■	■	■	■		■
Spectrograph		■	■	■		■
Mass Separator	■		■	■		
Gas/Liquid Targets	■	■	■	■		
Radioactive Targets	■				■	
Traps			■	■		

This table shows the general types of apparatus that will be required by experiments with various types of facilities. Of course, the precise nature of a particular device will differ depending on the facility. Here LE-SB and HE-SB stand for low and high energy stable beam facilities; RIB ISOL and RIB FRAG stand for the two types of radioactive beam facilities (ISOL and Fragmentation); SNS stands for Spallation Neutron Source but for some purposes includes linacs and other neutron sources; FEL stands for Free Electron Laser.



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

average photo-fission cross-section = 160 mb

Expected yield of some very neutron-rich exotic nuclei at target

^{78}Ni : 2 x 10^{9} pps; ^{132}Sn : 2 x 10^{11} pps

^{91}Kr: 1 x 10^{12} pps; ^{94}Kr: 3 x 10^{10} pps

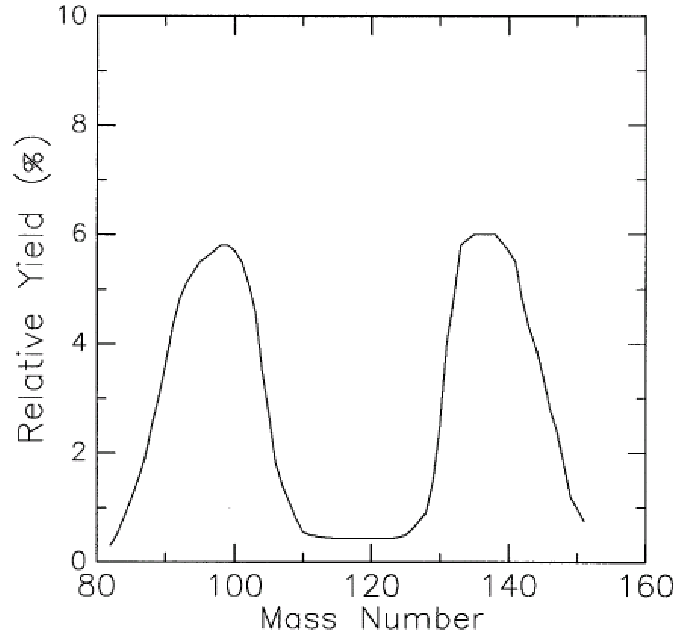
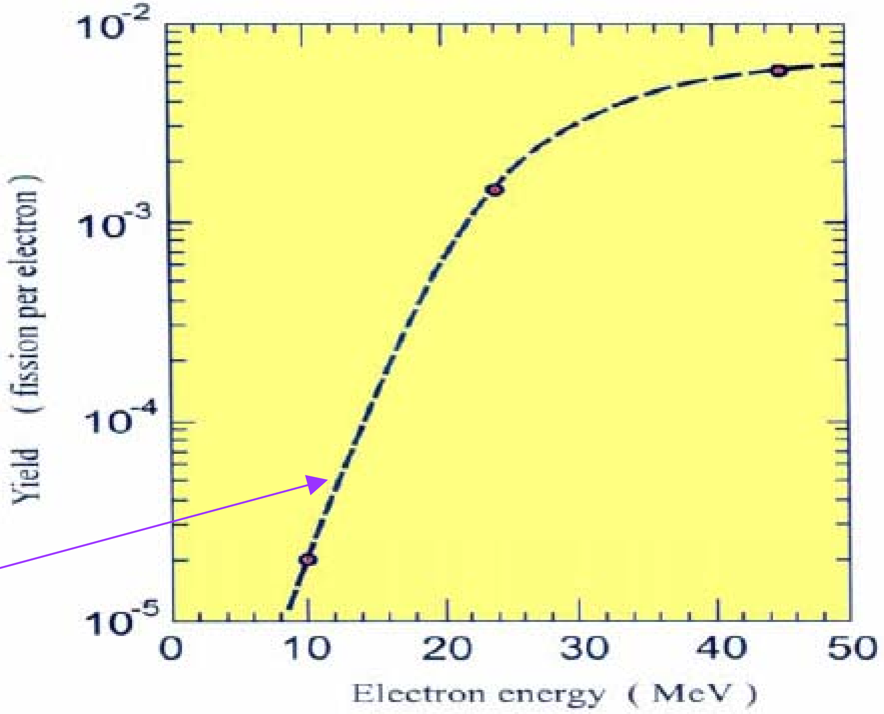


Fig. 10. The mass yield of fission fragments from electron-induced fission of ^{238}U produced by 30 MeV electrons [32].

238U photo-fission fragments mass distribution

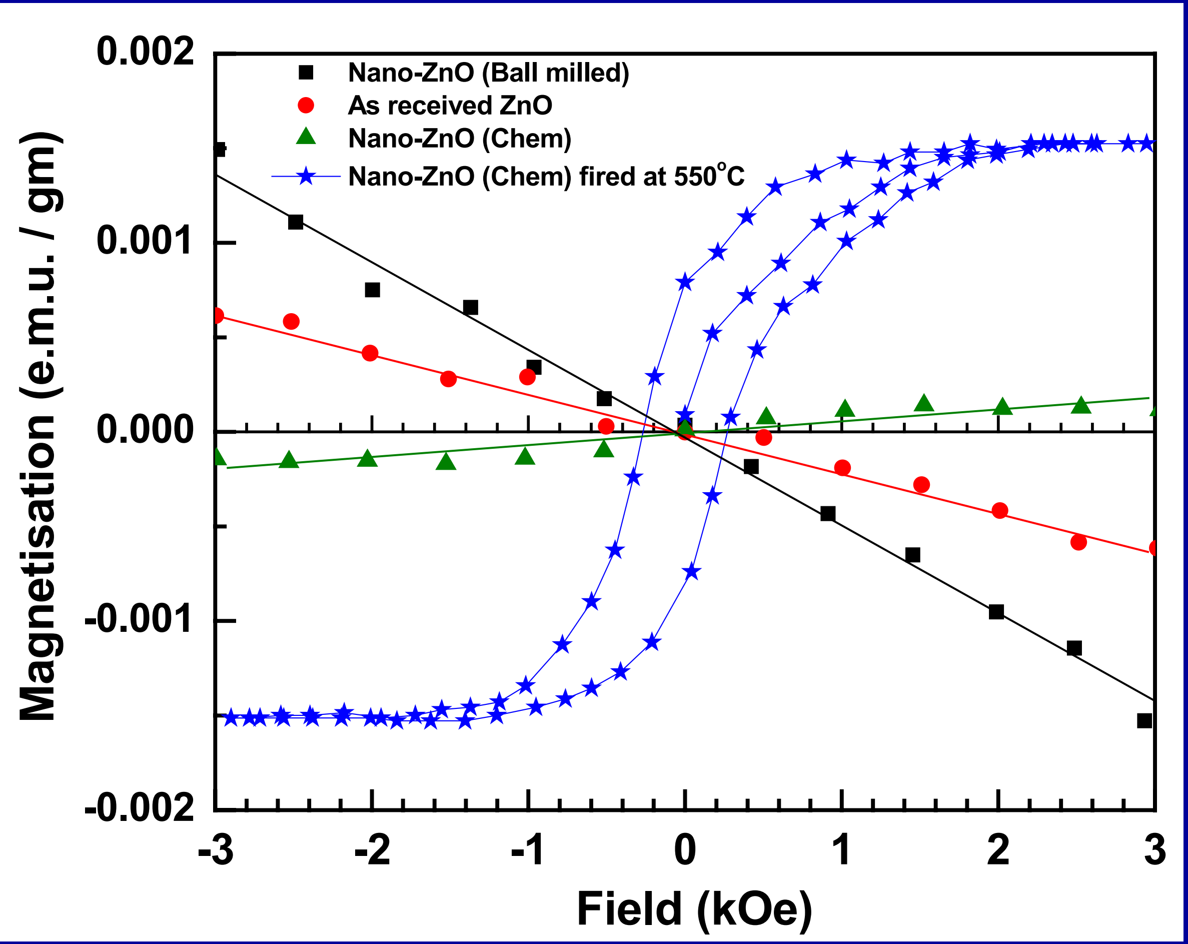


fission yield per electron for 238U as a function of electron energy

Ferromagnetism in Nano-crystalline Zno

Nano-crystalline ZnO ⇒ paramagnetic at room temperature

Ferromagnetic with oxygen defects



Phys. Lett. (in press), 2007

What happens when iron is implanted in Nano-crystalline Zno??

Summary

- 29 keV/u stable beams available from the facility

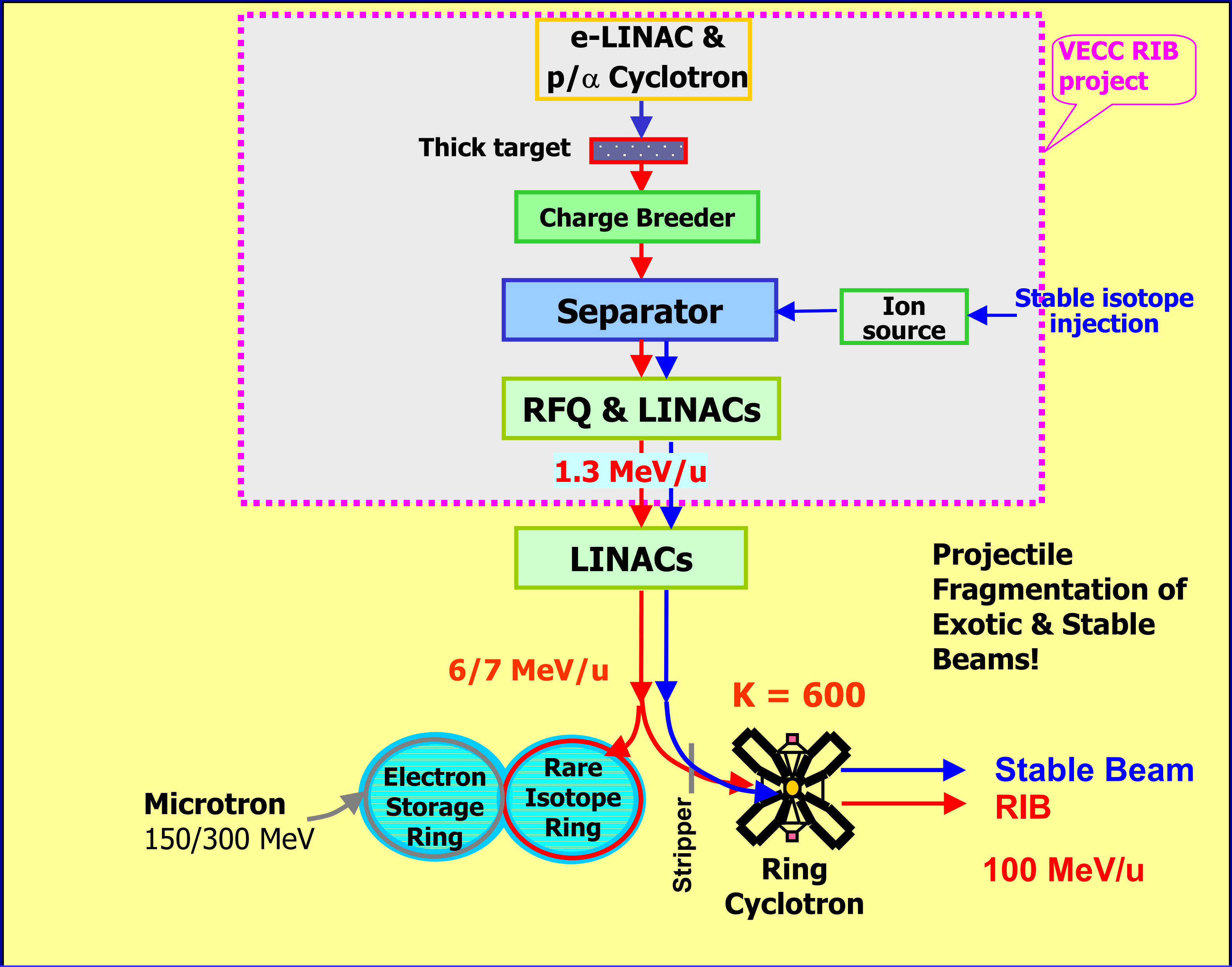
- beams available : oxygen, nitrogen, carbon, argon, iron, molecular beams (O_2 ; N_2 (after ECR))

- acceleration of RI Beams : *December 2008*

- First RI beams planned: ^{13}N, ^{19}Ne

Future plans

Scheme for Advanced RIB Facility



Scientific Opportunities

Physics can be done at each stage of development

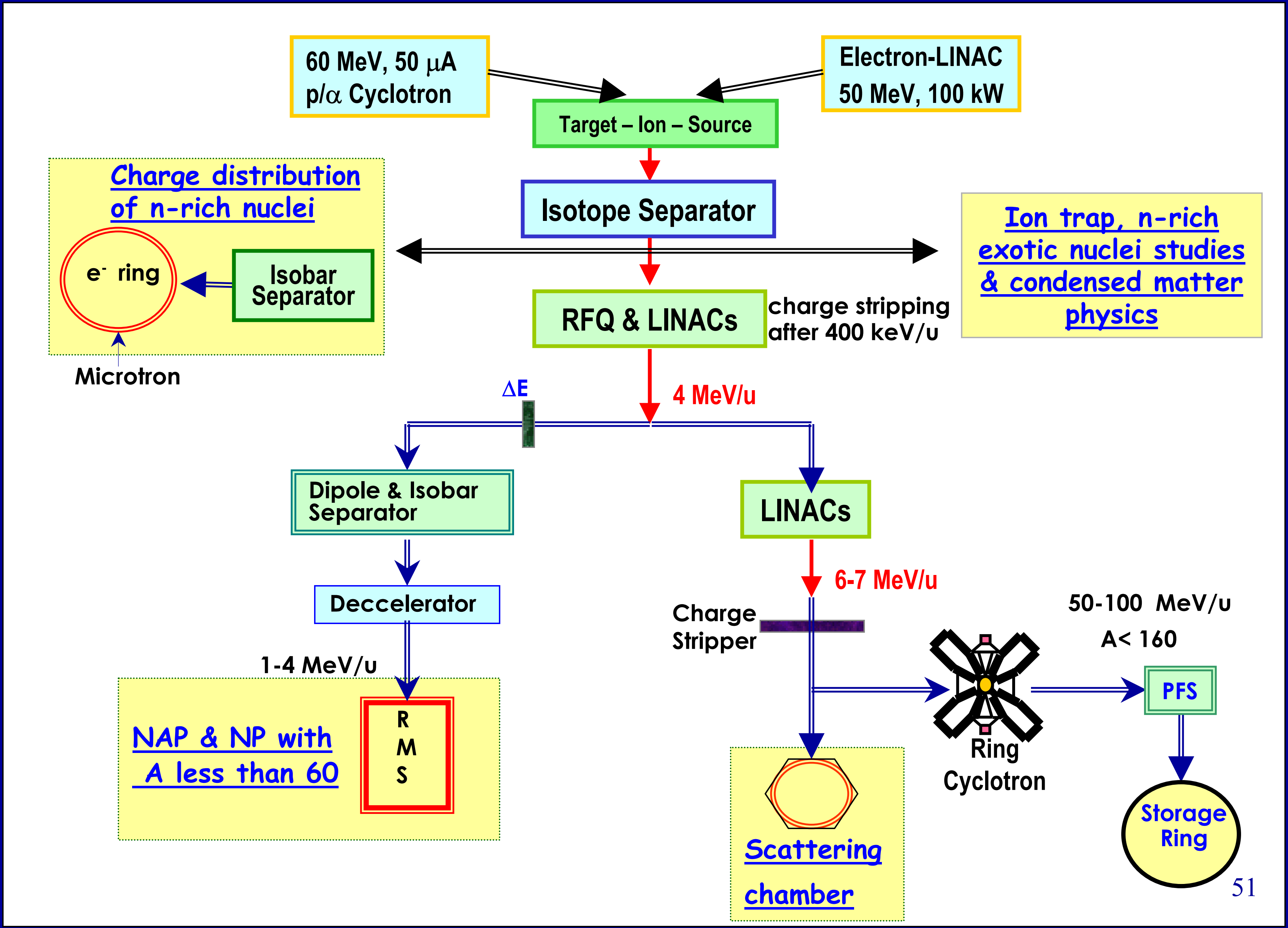
Physics with low energy RI Beams : 1.5 keV/u to 1.3 MeV/u

- Material Science, Atomic Physics
- Spectroscopy of r-process nuclei & mass measurements in Ion-trap
- Nucleo-synthesis & Nuclear Structure studies

Physics at higher energies : 1.3 to 100 MeV/u

- All of above
- Synthesis & study of Super Heavy Elements
- Nuclear charge distribution of neutron-rich nuclei
- Precision mass measurements in Storage Rings
- Reaching Drip-lines, study of Halo nuclei, spectroscopy of very short lived nuclei using projectile fragmentation of stable & radioactive ion beams

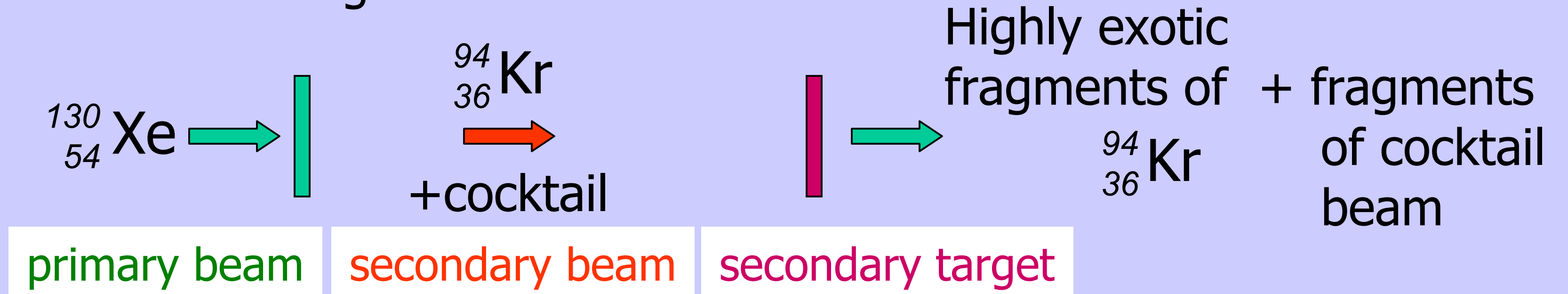
Physics at each stage



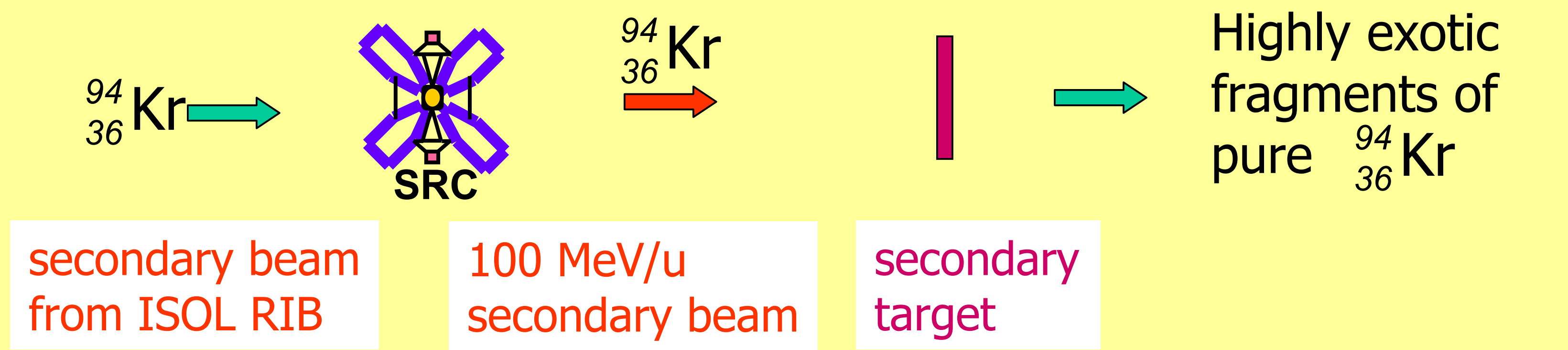
Unique features of the proposed advanced RIB facility

1. 2 – primary accelerators ⇒ Low cost option for producing a large number of RI Beams
2. RIB accelerated in SRC ⇒ Fragmentation of pure secondary RIB

a. Usual fragmentation scheme



b. Advanced facility fragmentation scheme

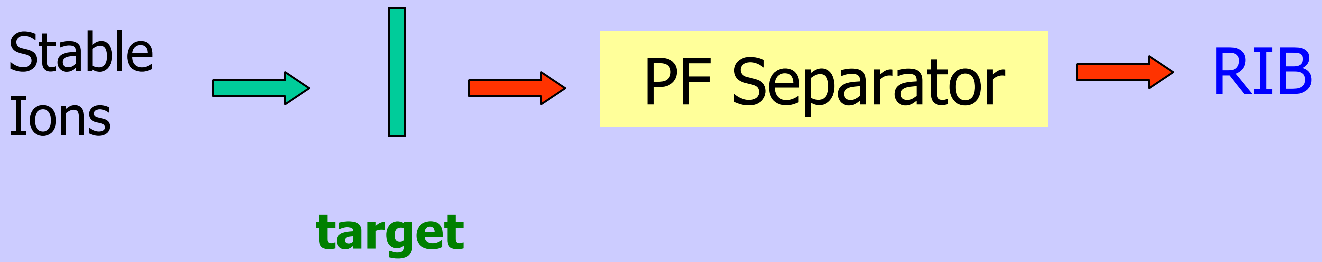


Unique features cont …

3. Acceleration of intense stable-ion to 100 MeV/u

⇓

Projectile fragmentation type RIB facility : no limitation in half-life!

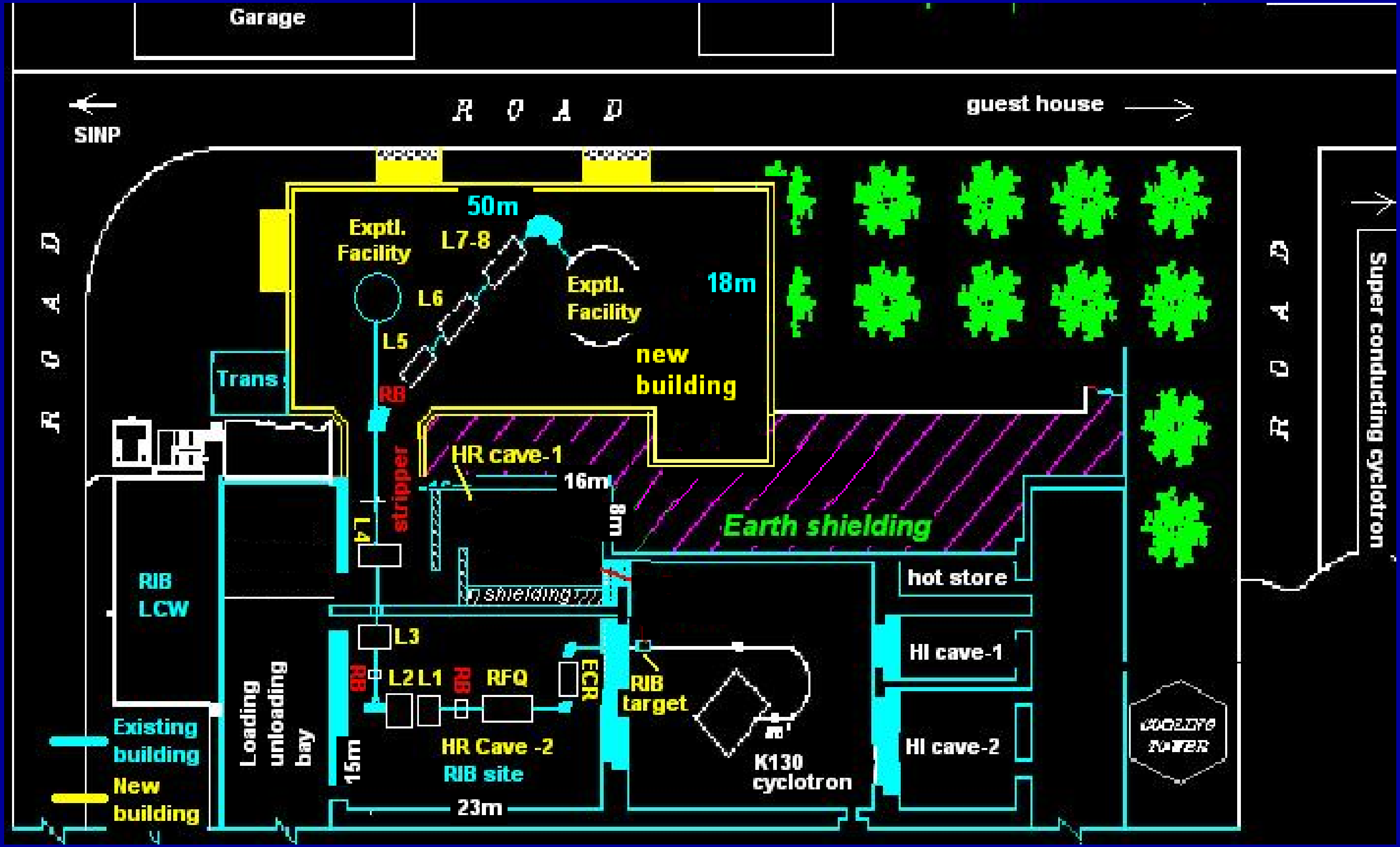


Cost projection for Advanced RIB facility

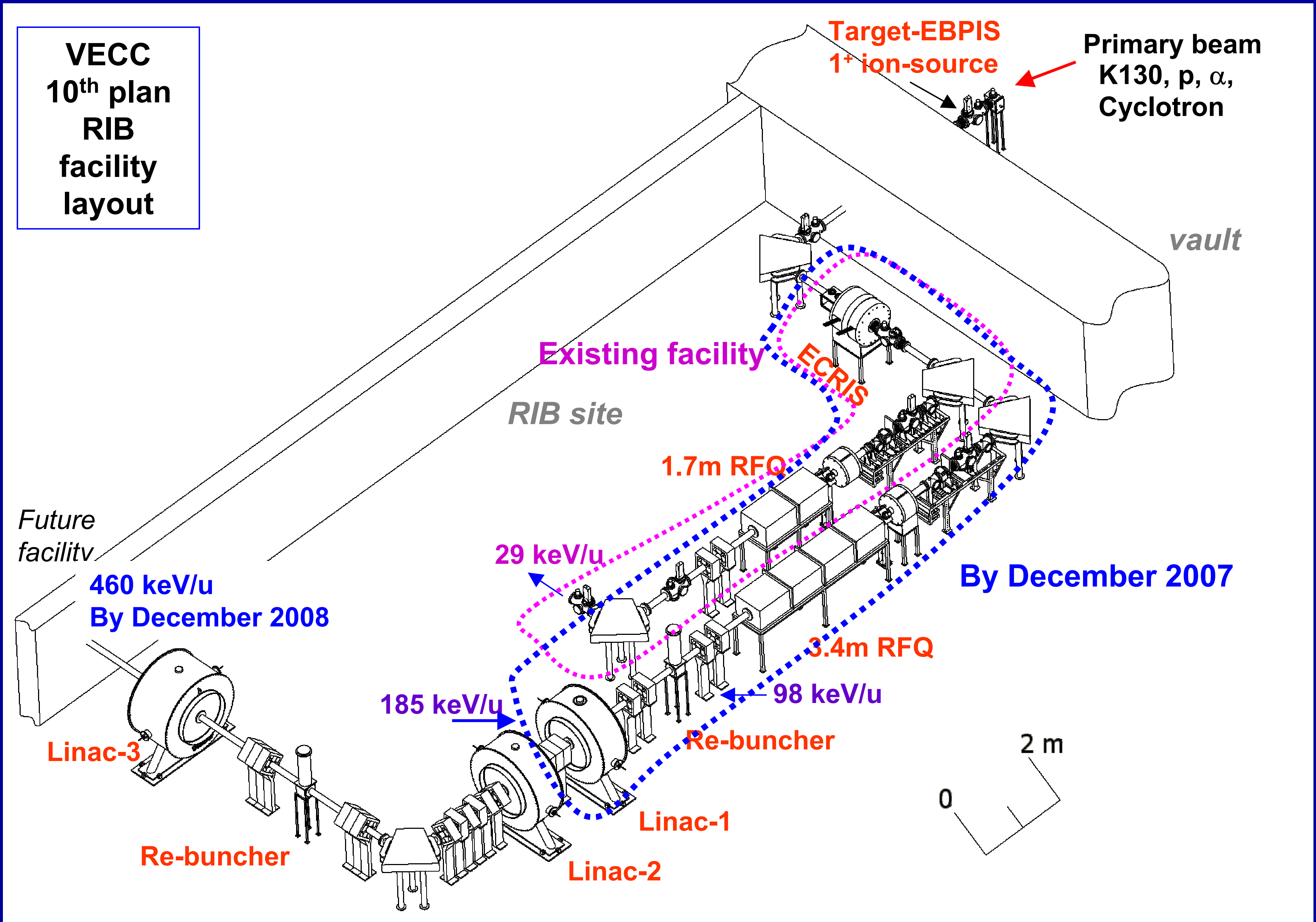
Major activity	Expenditure (Rs. Crore)
Building, infrastructure, electrical power	110.00
Acceleration of neutron-rich RIB (e – Linac) & proton-rich RIB to 6/7 MeV/u	180.00
60 MeV p/α Cyclotron	45.00
Microtron & Electron Storage Ring (ESR) & Rare Isotope Storage Ring (RIR)	80.00
Experimental facilities for nuclear & astrophysics, mat. science	75.00
Ring Cyclotron & PF Separator	80.00
Total (Rs. Crore)	**570.00**

Thank You!

New extension building for Advanced RIB Facility



Sl. No.	Major Activity (financials) for 11th plan VECC RIB	Cost (Rs. lakh)
1.	Linac4,5,6,7,8, Re-bunchers	800=00
2.	RF Transmitters/Amplifiers for Linac 4-8 & Re-bunchers	600=00
3.	Building, power, LCW & other infrastructure, Misc.	600=00
4.	Experimental facilities (detectors, New beam-line for material science, data acquisition system, computation system etc.,)	300=00
5.	Electron-Linac	3,300=00
6.	Target development, remote handling system for target	200=00
7.	Advanced charge-Breeder, beam-line, He-jet multiple target system	600=00
8.	Beam-lines, beam diagnostics equipment, Magnets & power supplies, Vacuum system	370=00
9.	Computer control, Management Information System	100=00
10.	R&D on SCC rf structures (1.3 to 1.8 MeV/u)	180=00
11.	Consultancy	176=70
12.	Salary	116=80
13.	Travel	100=00
14.	Motor vehicle	15=00
15.	Office expenses	14=50
16.	Contingency expenses	27=00
	Total (Rupees lakh)	**7,500=00**



VECC
10th plan
RIB
facility
layout
Target-EBPIS
1+ ion-source
Primary beam
K130, p, α,
Cyclotron
vault
Existing facility
ECRIS
RIB site
1.7m RFQ
Future
facility
29 keV/u
460 keV/u
By December 2008
By December 2007
3.4m RFQ
98 keV/u
185 keV/u
Re-buncher
Linac-3
2 m
0
Re-buncher
Linac-1
Linac-2