SLENA, SINP
January 16-20, 2006

Radioactive Ion Beam facility at VECC Kolkata

Alok Chakrabarti
Variable Energy Cyclotron Centre
Kolkata, India

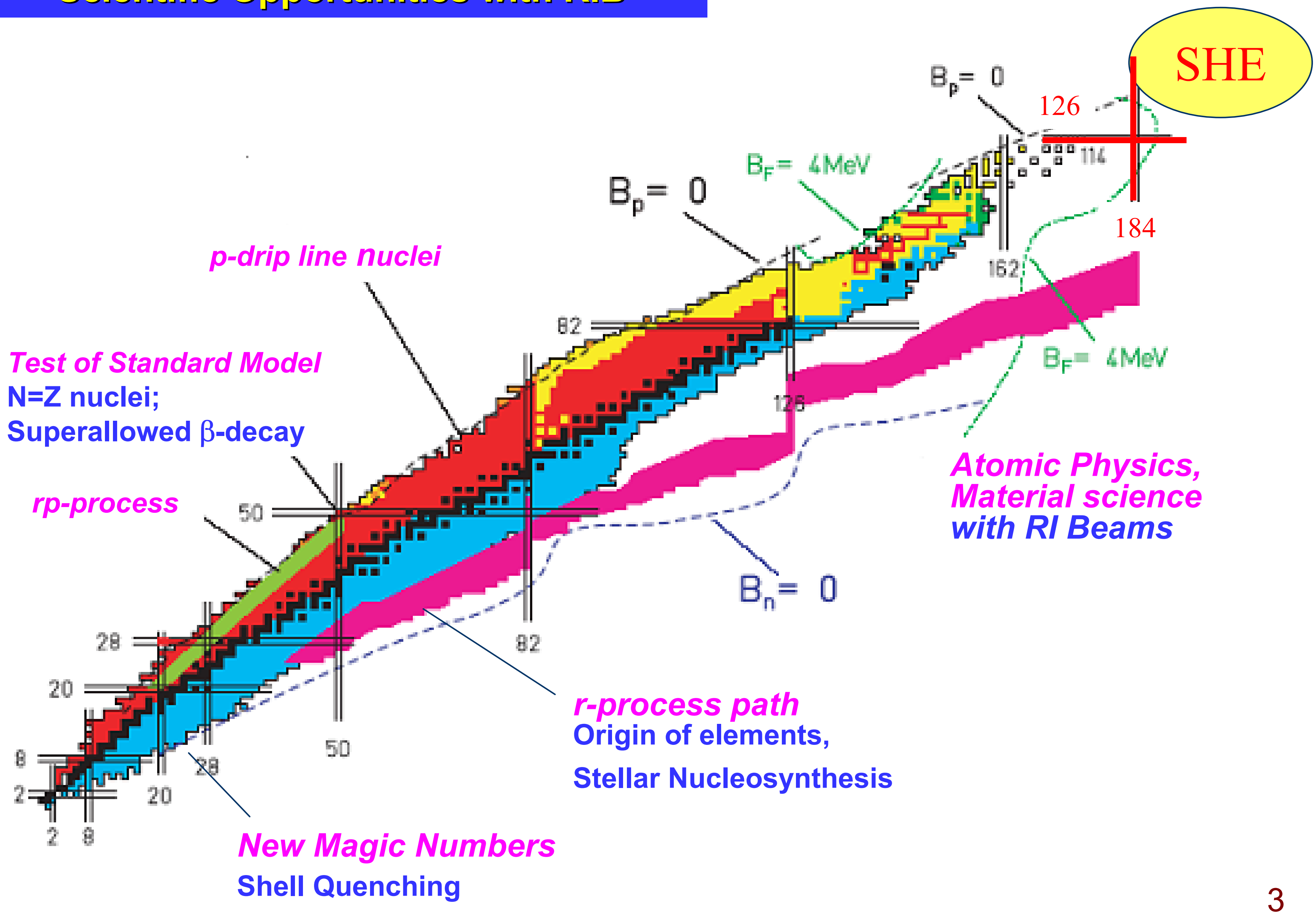
Plan of the talk

Introduction

RIB up to 2007 & its status

Future outlook

Scientific Opportunities with RIB



Intensity of RIB for various experiments (ISOL)

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

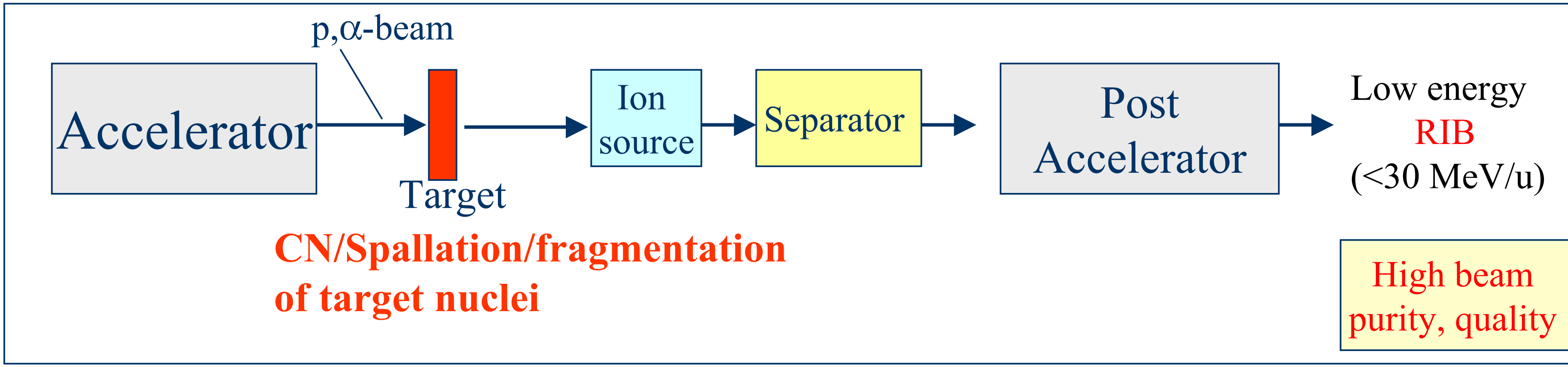
Physics Topics	Reaction & Techniques	Beams	Intensities (pps)	Energy (MeV/u)
Rapid Proton Capture (rp) Process	Transfer, Elastic, Inelastic, Radiative capture, Coulomb dissociation	^{14}O, ^{16}O, ^{26}Si, ^{34}Ar, ^{56}Ni	10^8 to 10^{11} 10^5 to 10^{11}	0.15 - 15
Studies of N=Z nuclei, symmetry studies	Transfer, Fusion, Decay Studies	^{56}Ni, ^{62}Ga, ^{64}Ge, ^{68}Ge, ^{67}As, ^{72}Kr	10^4 to 10^9	0.1 - 15
Decay Studies of ^{100}Sn	Decay	^{100}Sn	1-10	Low
Proton drip line studies	Decay, Fusion, Transfer	^{56}Ni, ^{62,66}Ge, ^{72}Kr	10^6 to 10^9	5
Slow n-capture (S-process)	Capture	^{134,135}Cs, ^{155}Eu	10^8 to 10^{11}	0.1
Symmetry studies with Francium	Decay, traps	^{A}Fr	10^{11}	Low
Heavy element studies	Fusion, decay	$^{50-52}$Ca, ^{72}Ni, ^{84}Ge, ^{96}Kr	10^4 to 10^7 10^6 to 10^8	5 - 8

Intensity of RIB for various experiments *cont…*

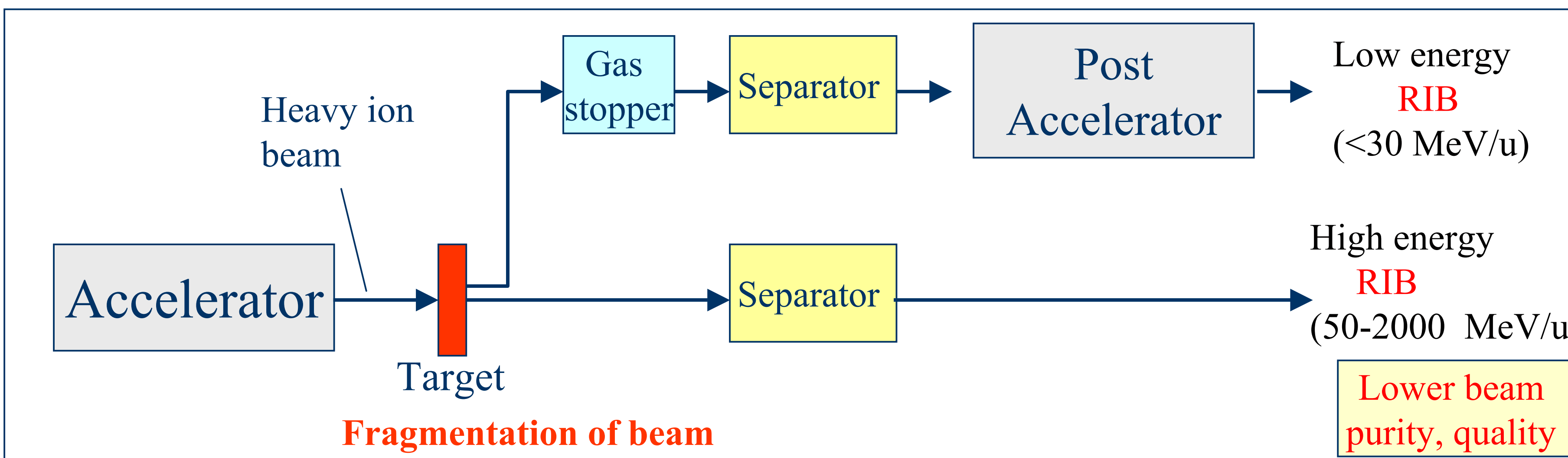
Physics Topics	Reaction & Techniques	Beams	Intensities (pps)	Energy (MeV/u)
Fission Limits	Fusion, Fission	$^{140-144}Xe$, $^{142-146}Cs$, ^{142}I, $^{145-148}Xe$, $^{147-150}Cs$	10^7 to 10^{11} 10^4 to 10^7	5
Rapid n-capture (r-process)	Capture decay mass measurement	^{130}Cd, ^{132}Sn, ^{142}I	10^4 to 10^9	0.1 - 15
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 to 10^{11} 10^2 to 10^7	5-15
Single particle states, effective nucleon-nucleon interaction	Direct reactions, Nucleon transfer	^{132}Sn, ^{133}Sb	10^8 to 10^9	5-15
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 to 10^9	1-10

Production of Radioactive Ion Beams

ISOL (ISOLDE, ISAC, SPIRAL, Oak Ridge, Louvain-la-Neuve, VECC, …)



Fragmentation (NSCL, GSI, RIKEN, GANIL, …)



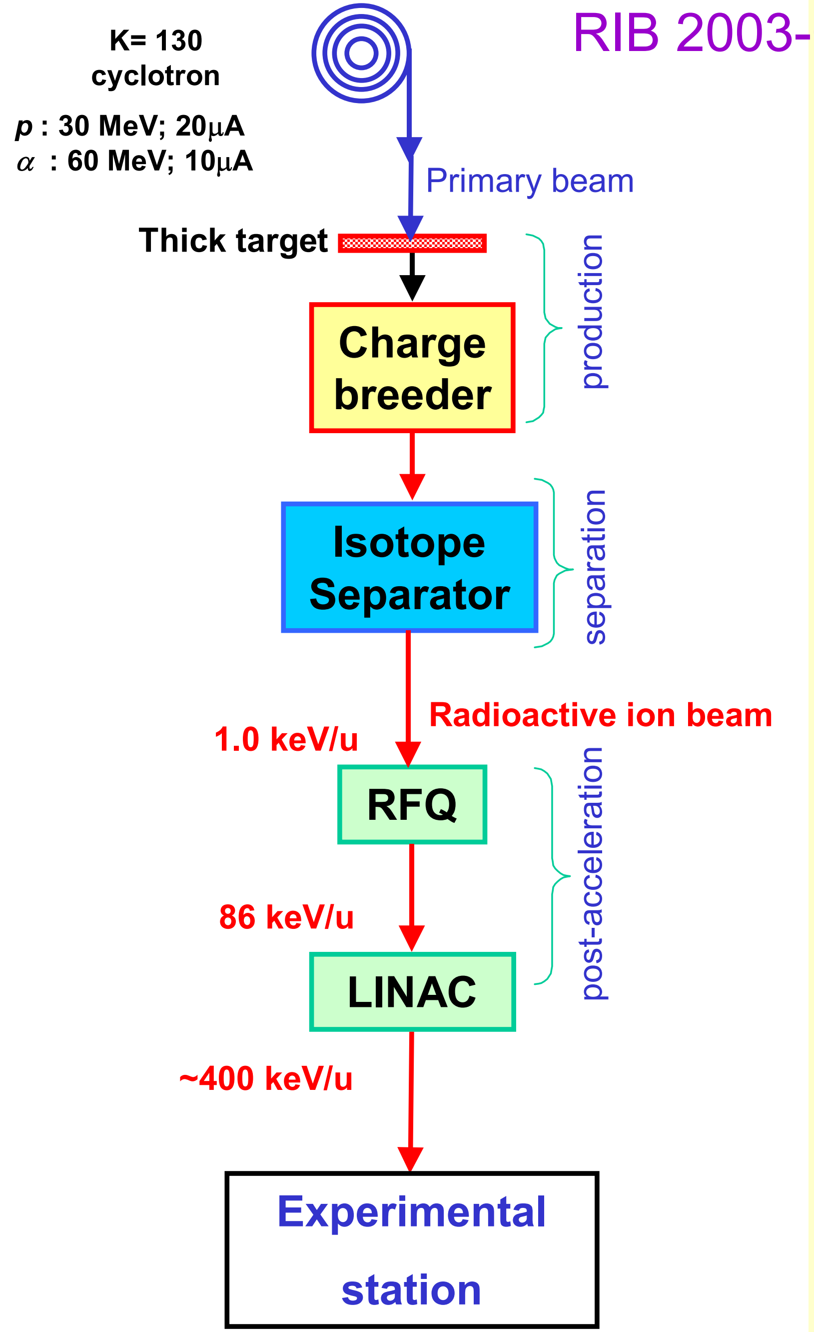
Accelerator Development

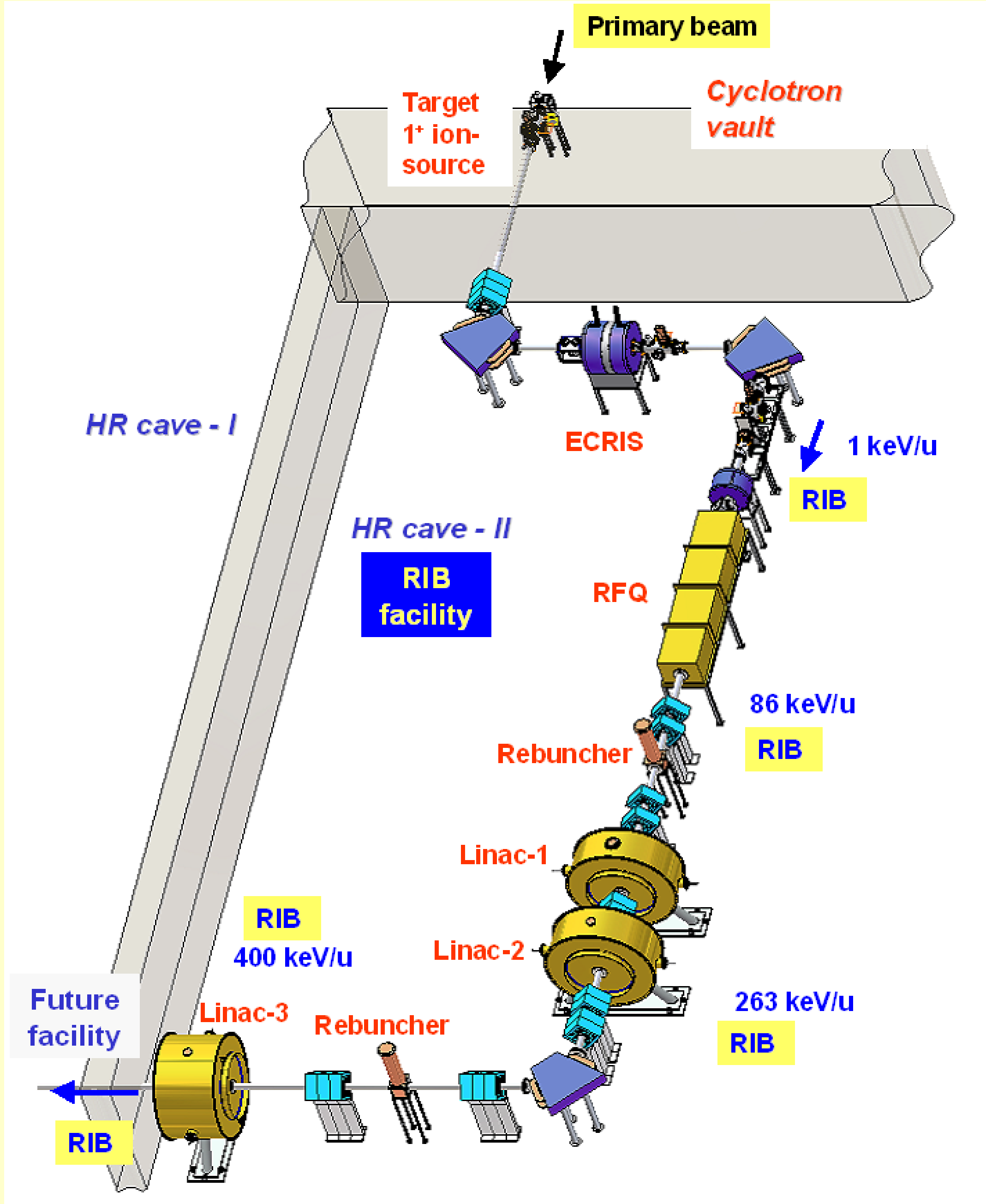
Aim High current stable ion acceleration & good enough intensity for a wide range of RI Beams

Challenges

- High power target
- Ion source/charge breeder
- Low energy accelerating structures
- Heavy Ion storage rings

RIB 2003-07


K= 130
cyclotron
p : 30 MeV; 20μA
α : 60 MeV; 10μA
Primary beam
Thick target
Charge
breeder
production
Isotope
Separator
separation
Radioactive ion beam
1.0 keV/u
RFQ
86 keV/u
LINAC
post-acceleration
~400 keV/u
Experimental
station



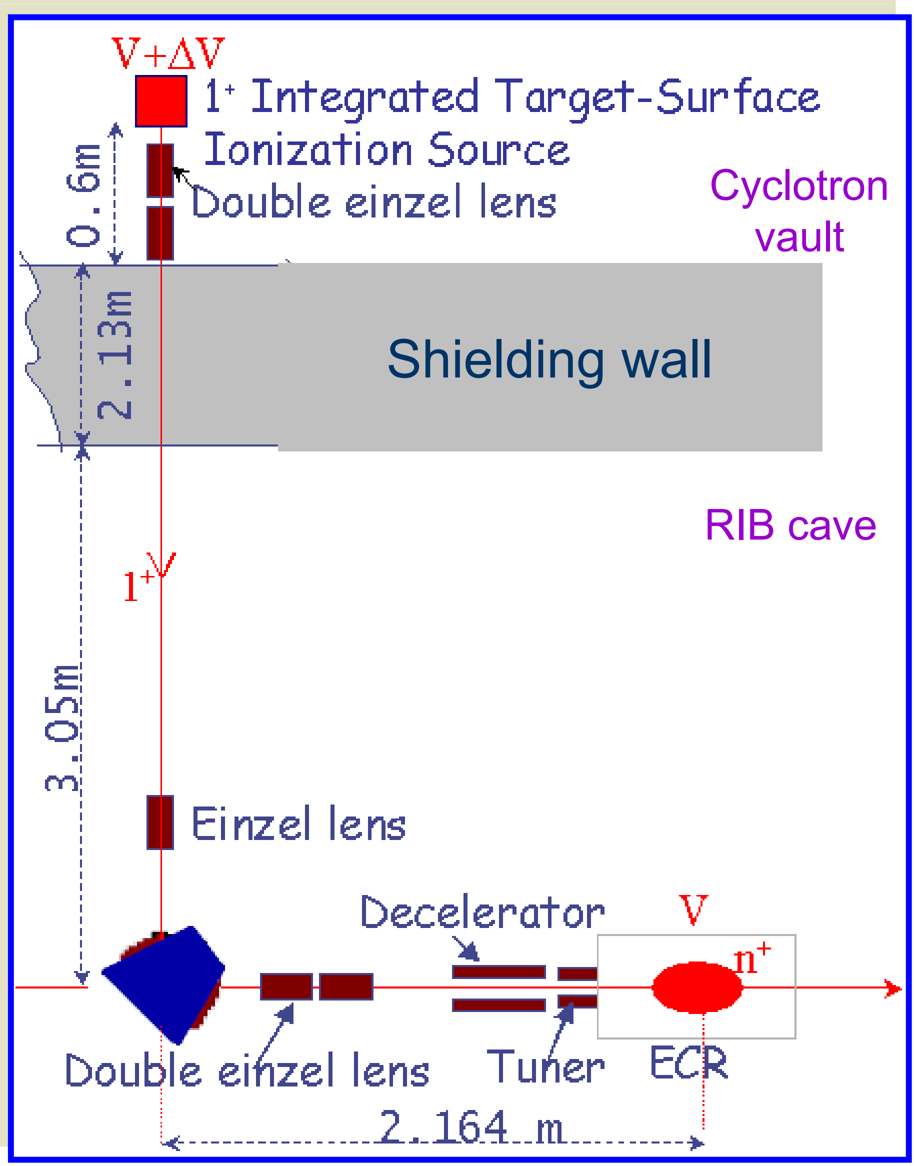
Primary beam
Target
1+ ion-
source
Cyclotron
vault
ECRIS
1 keV/u
RIB
HR cave - I
HR cave - II
RIB
facility
RFQ
86 keV/u
RIB
Rebuncher
Linac-1
Linac-2
RIB
400 keV/u
263 keV/u
RIB
Future
facility
Linac-3
Rebuncher
RIB

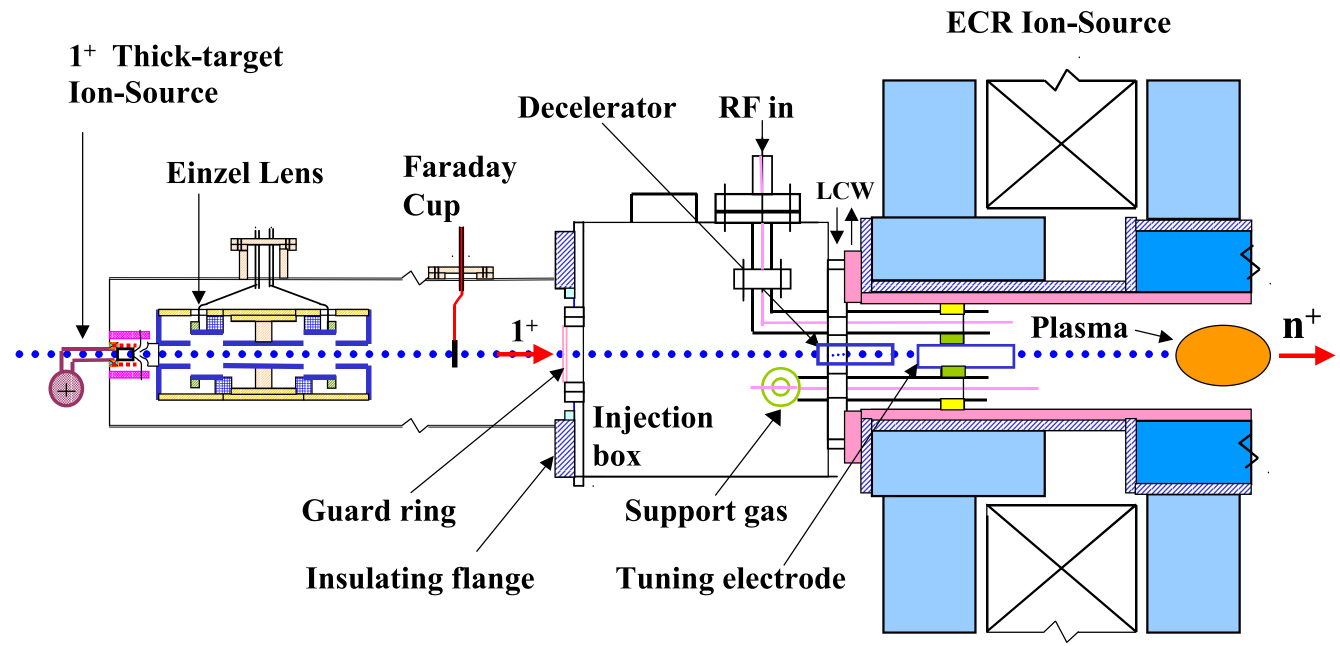
Two-Ion Source Charge Breeder

Integrated Target-ion source produces 1^+ RIB

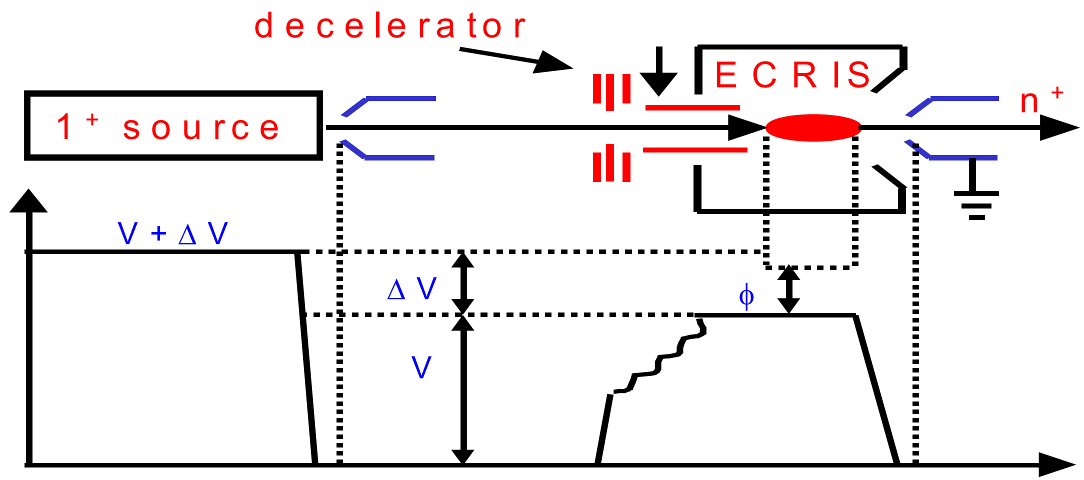
Inject 1^+ RIB into ECR ion-source $\Rightarrow n^+$ RIB

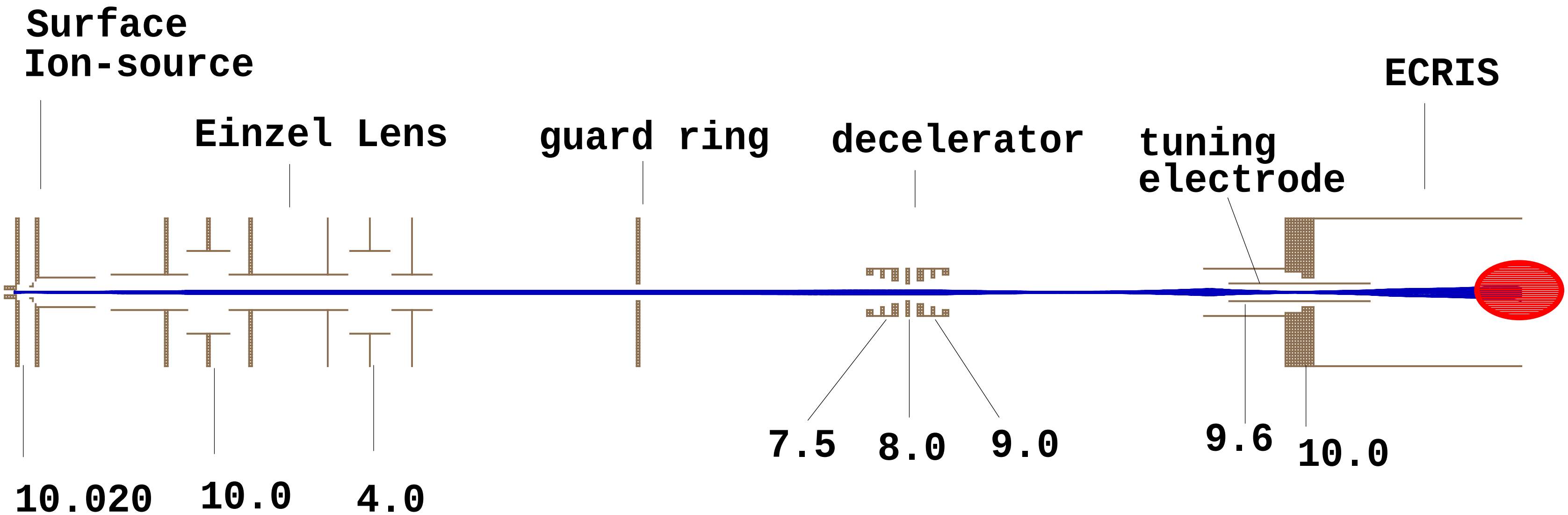
- ~ 10^{-6} mbar vacuum inside ECR ion source
- ECR permanent magnets protected from high radiation near target-ion source





Two-Ion Source Charge Breeder Schematic



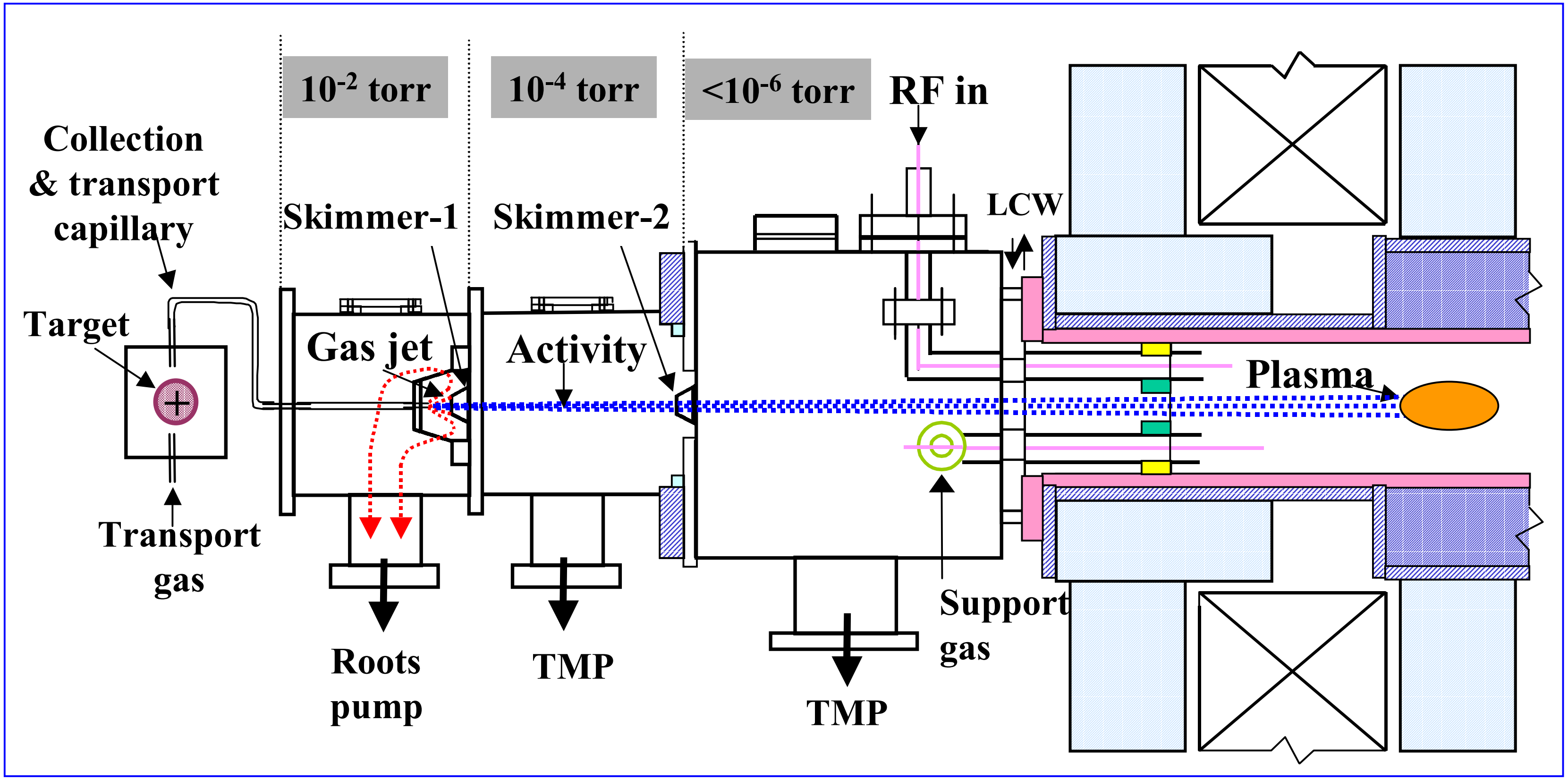


A=40 ; x=0.5mm ; theta=20mrad ; I=100nA ; final energy = 20eV
voltages in kilo volts

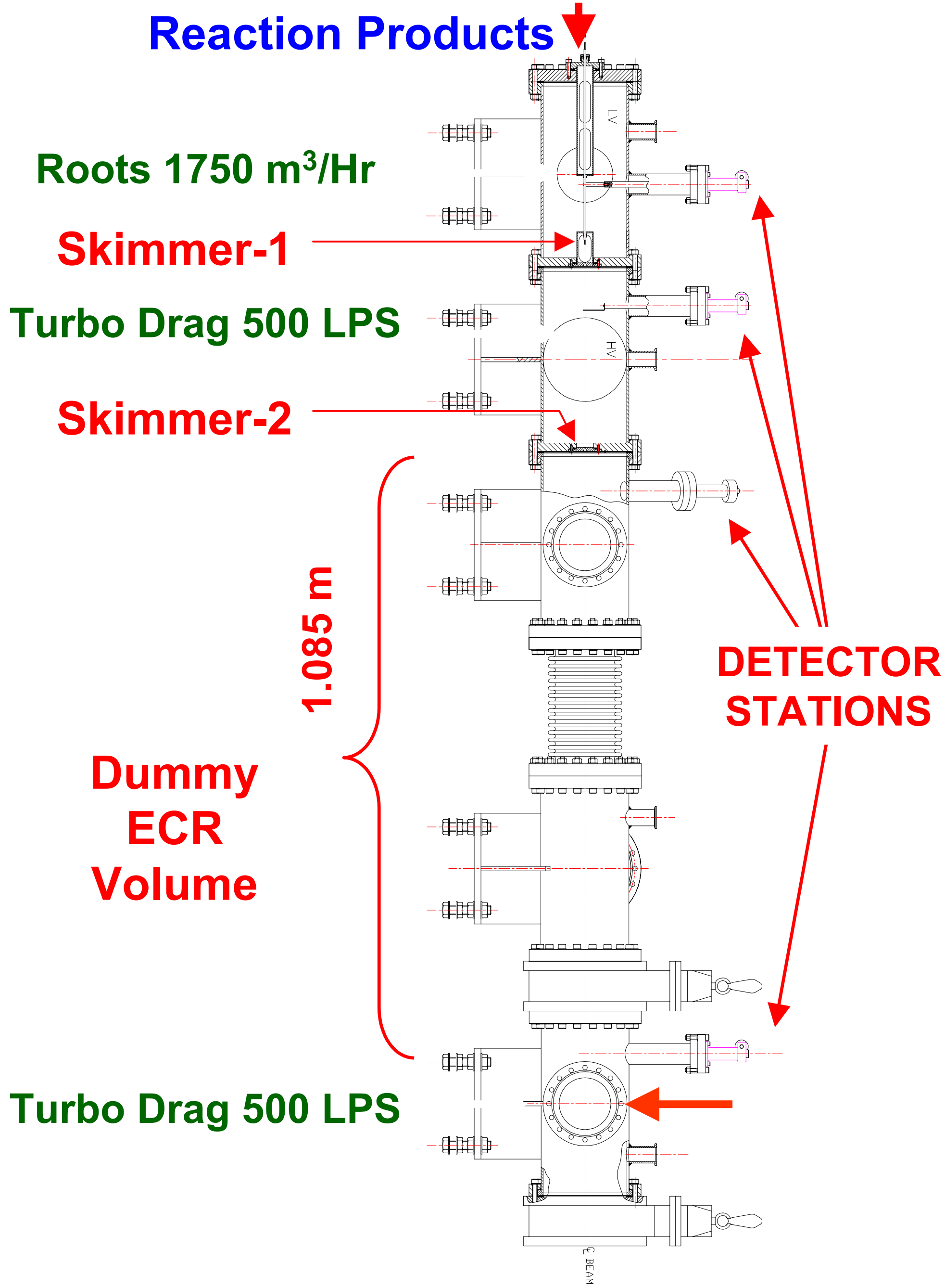
Two-Ion Source Charge Breeder Beam Dynamics results

SIMION

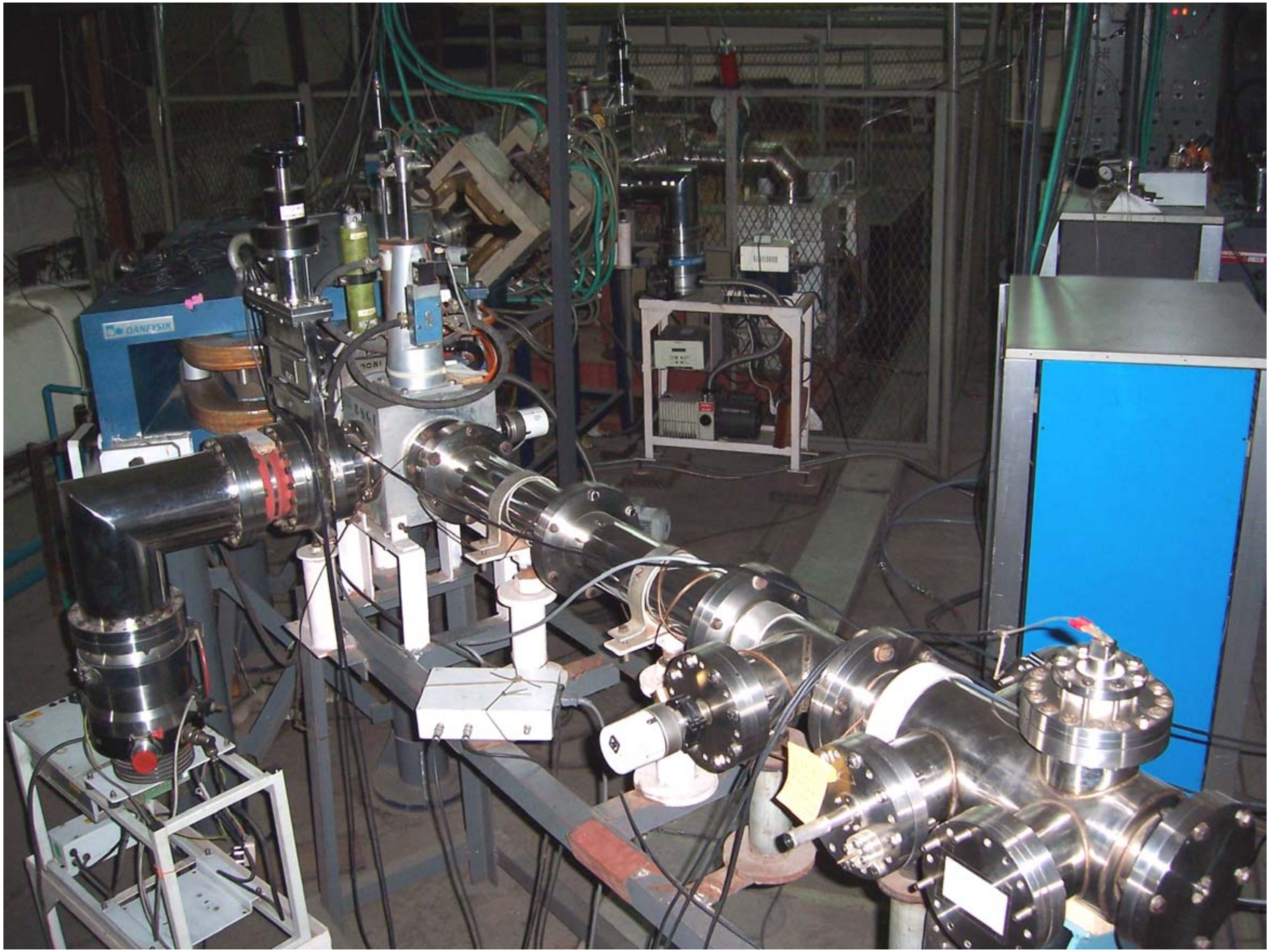
He-jet skimmer ECRIS- alternative to 2-IS



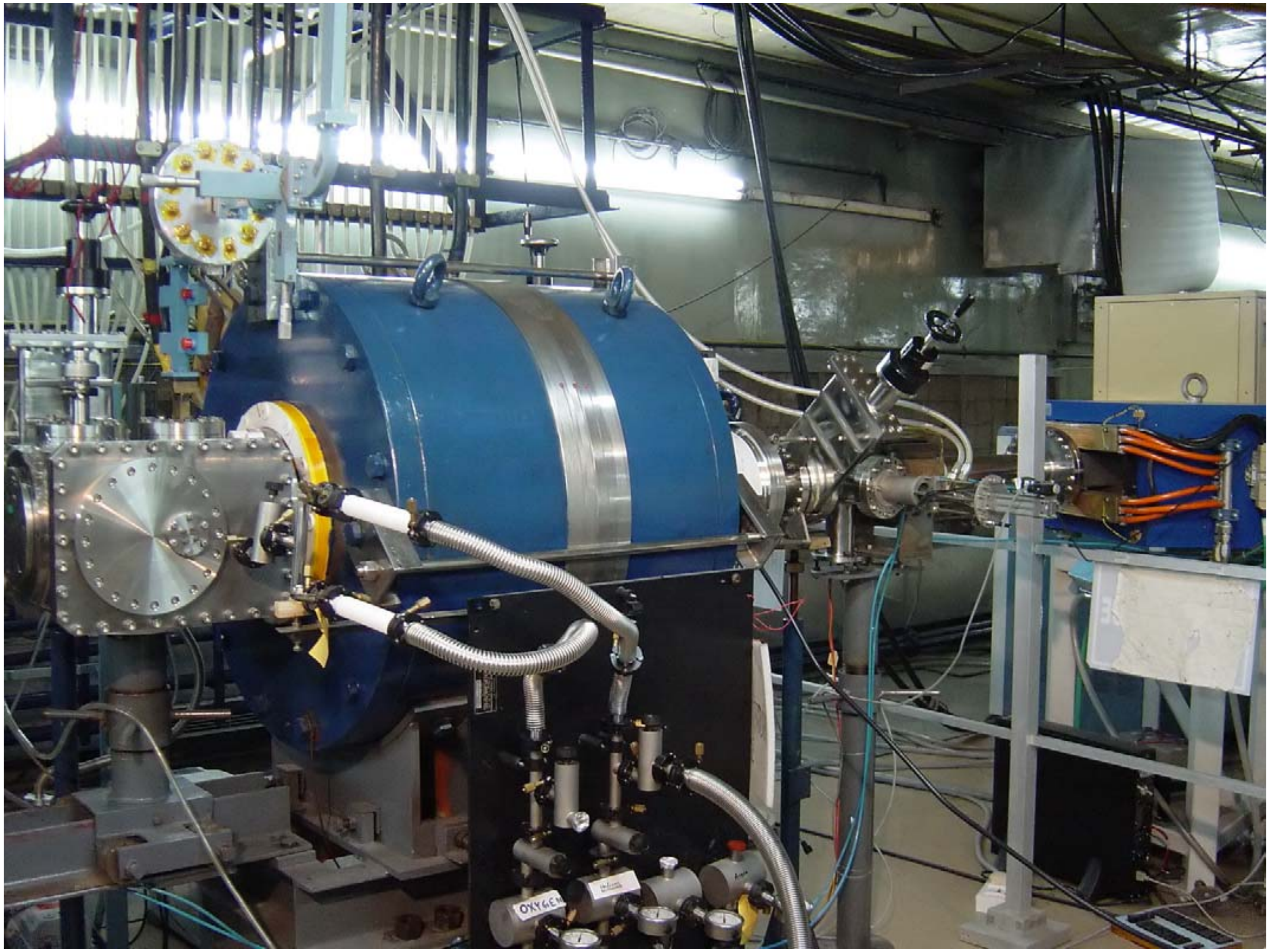
He-jet skimmer system



He-jet coupled Isotope Separator On-Line (ISOL) system @ VECC



6.4 GHz On-Line ECR ion-source @ VECC



ECR ion-source parameters

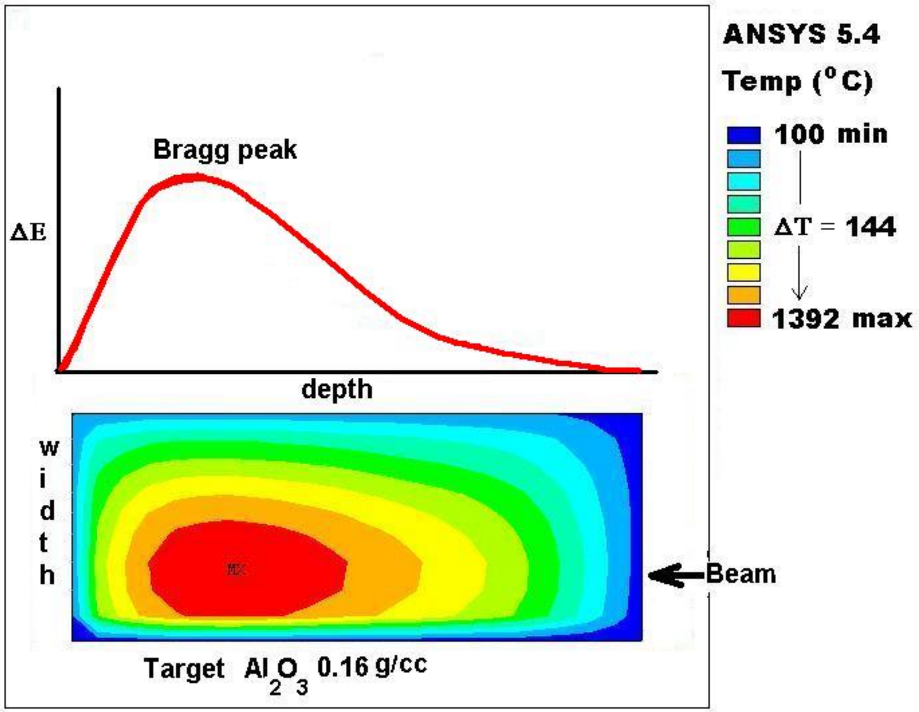
ECR parameters :	Value :
Frequency	6.4 GHz
RF Power (maximum)	3 kW
B_{ECR}	0.23 Tesla
Axial magnetic field (B_z) (Solenoid)	0.95 Tesla (inj.) ; 0.7 Tesla (ext.)
Radial mag. field at plasma chamber i.d. (B_r)	0.7 Tesla
Mirror ratio	5.9 (inj); 4.375 (ext)
Plasma chamber I.D	100 mm
ECR overall dimensions	0.98 m dia; 1m length
Power (both solenoid coils)	60 kW

Thick target R&D

$$I_{rib} = I_{pri} \cdot N_t \cdot \sigma \cdot \eta_{release} \cdot \eta_{ionization,separation,acceleration}$$

10^{13} 10^{22} 10^{-27} 10^{-2}

maximize!



How ?

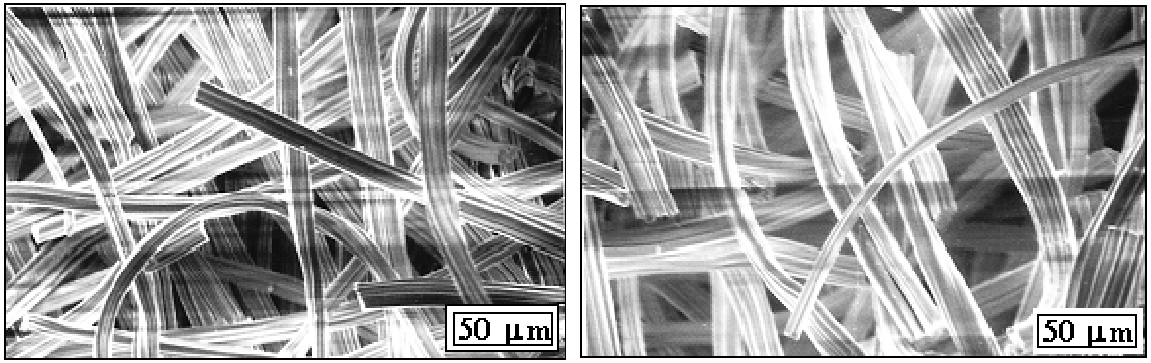
- Maximize surface to volume ratio and porosity
- Minimize density

Choose appropriate target geometry
- Fiber
- Powder
- Multiple thin foils

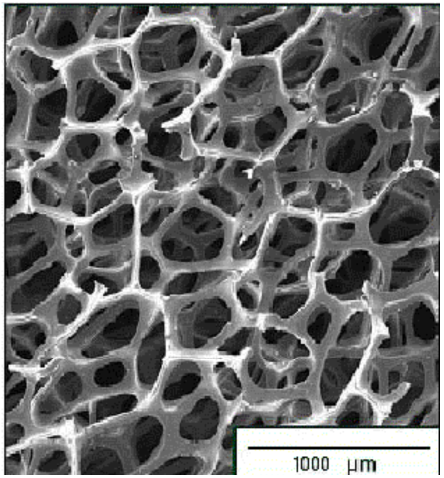
- **First few targets**

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

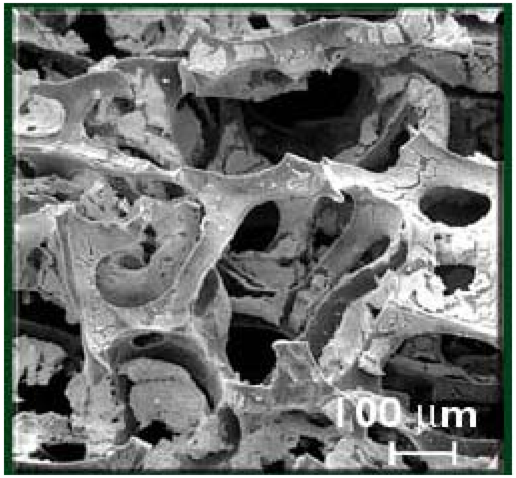
*RVCF : Reticulated Vitreous Carbon Fiber



SEM of Al_2O_3 & HfO_2



SEM of RVCF

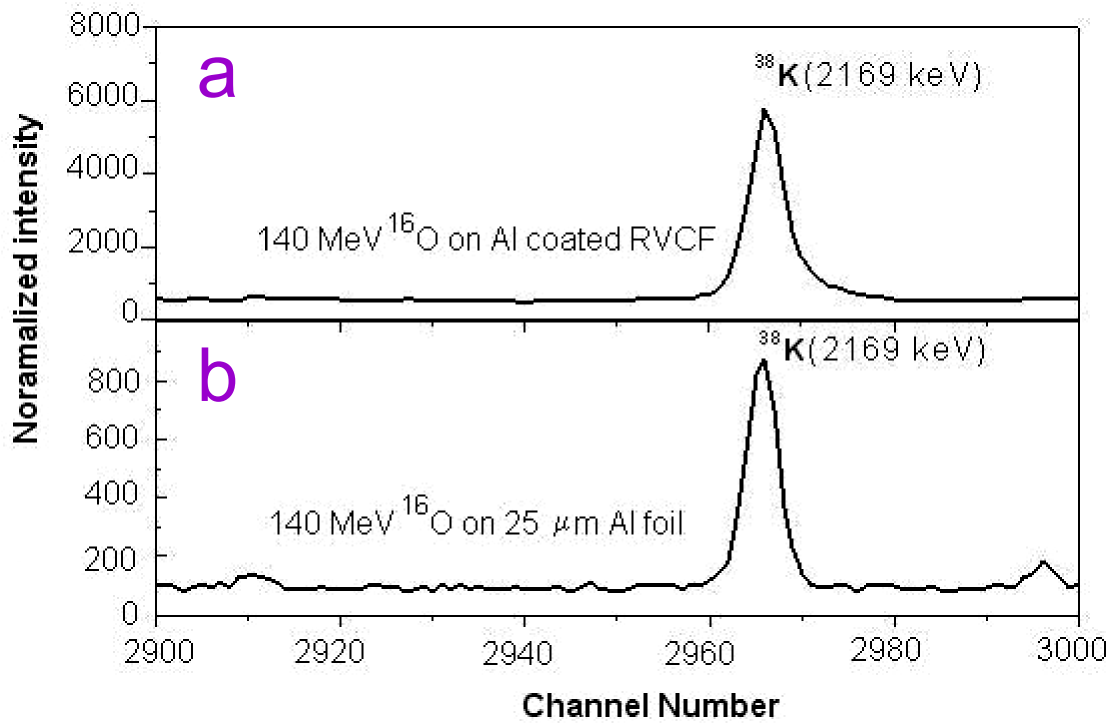


SEM of composite target : RVCF + Al_2O_3

First few RI beams

RIB	$T_{1/2}$	Reaction	Target
^{11}C	20 min	$^{11}B(p,n)$	BN
^{13}N	10 min	$^{13}C(p,n)$	Graphite
^{17}F	1 min	$^{14}N(\alpha,n)$	BN
^{18}F	110 min	$^{16}O(\alpha,n)$	HfO_2,Al_2O_3
^{19}Ne	17 sec	$^{19}F(p,n)$	LiF
^{35}Ar	1.7 sec	$^{35}Cl(p,n)$	$CaCl_2$
^{38}K	7.6 min	$^{35}Cl(\alpha,n)$	$CaCl_2$
^{90}Kr	32 sec	$U/Th(\alpha,f)$	UC/ThO
^{93}Rb	6 sec	-do-	-do-

Target release experiments with 140 MeV Oxygen beam at He-jet system

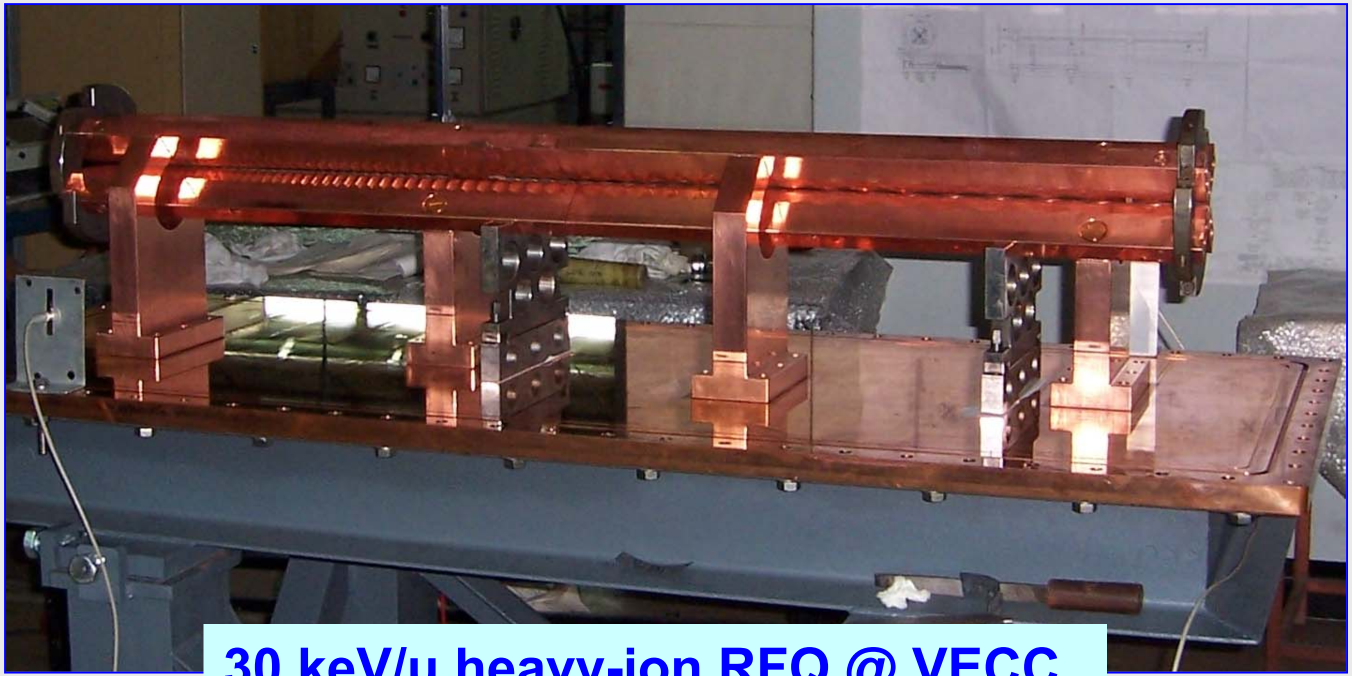


Yield enhancement due to increase in surface to volume ratio

RADIOFREQUENCY QUADRUPOLE (RFQ): first post-accelerator

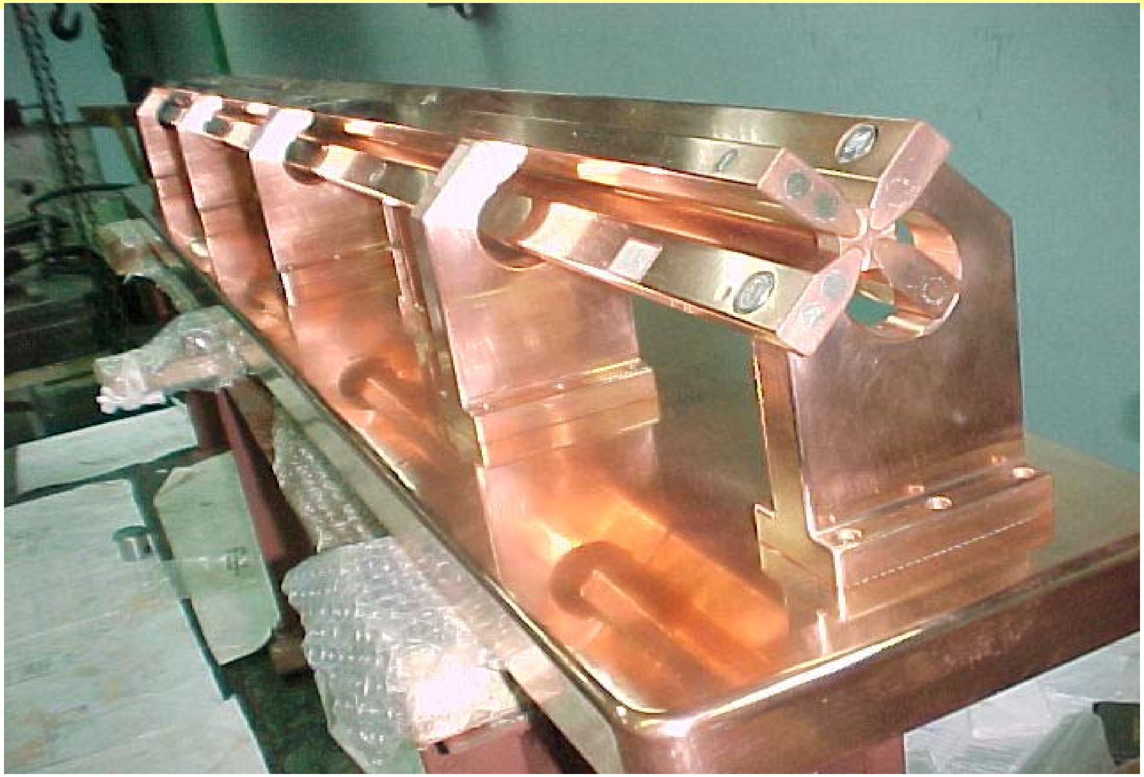
- Acceleration of RIB from 1 to 86 keV/u
- Heavy Ion RFQ → q/A = 1/16 ; f = 35 MHz
- Extended rod structure → Vane Length 3104 mm ; Vane Voltage 49.5 kV
- Transmission ~ 83 % with external pre-buncher

RFQ development ⇒ stage 1 ⇒ ½ scale model
stage 2 ⇒ 30 keV/u RFQ
stage 3 ⇒ 86 keV/u final RFQ

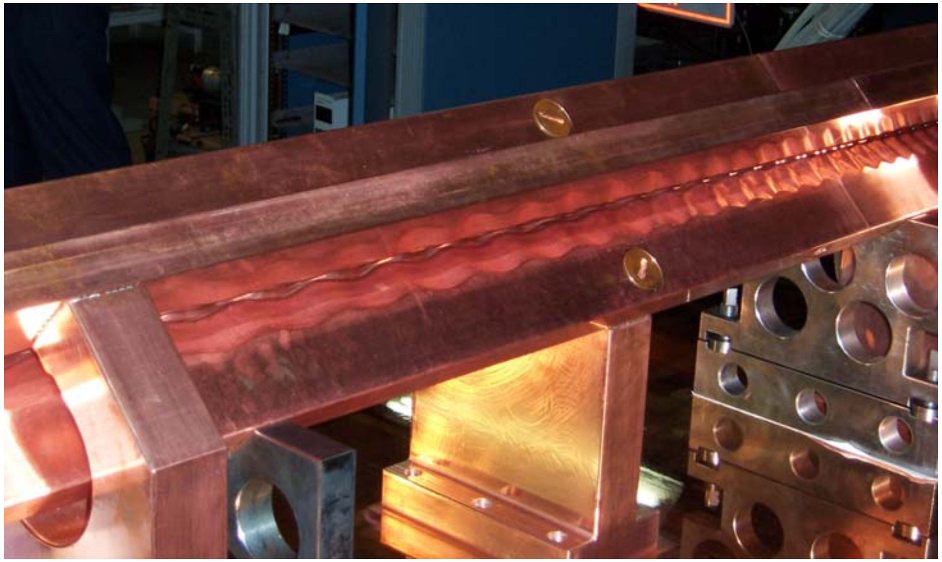


30 keV/u heavy-ion RFQ @ VECC

Result of RFQ ½ scale model tests



Quantity	Measured	Expected (theoretically)
f (MHz)	73.00	70.00
Q	3500	6951
R_p (kΩ)	35	61.52

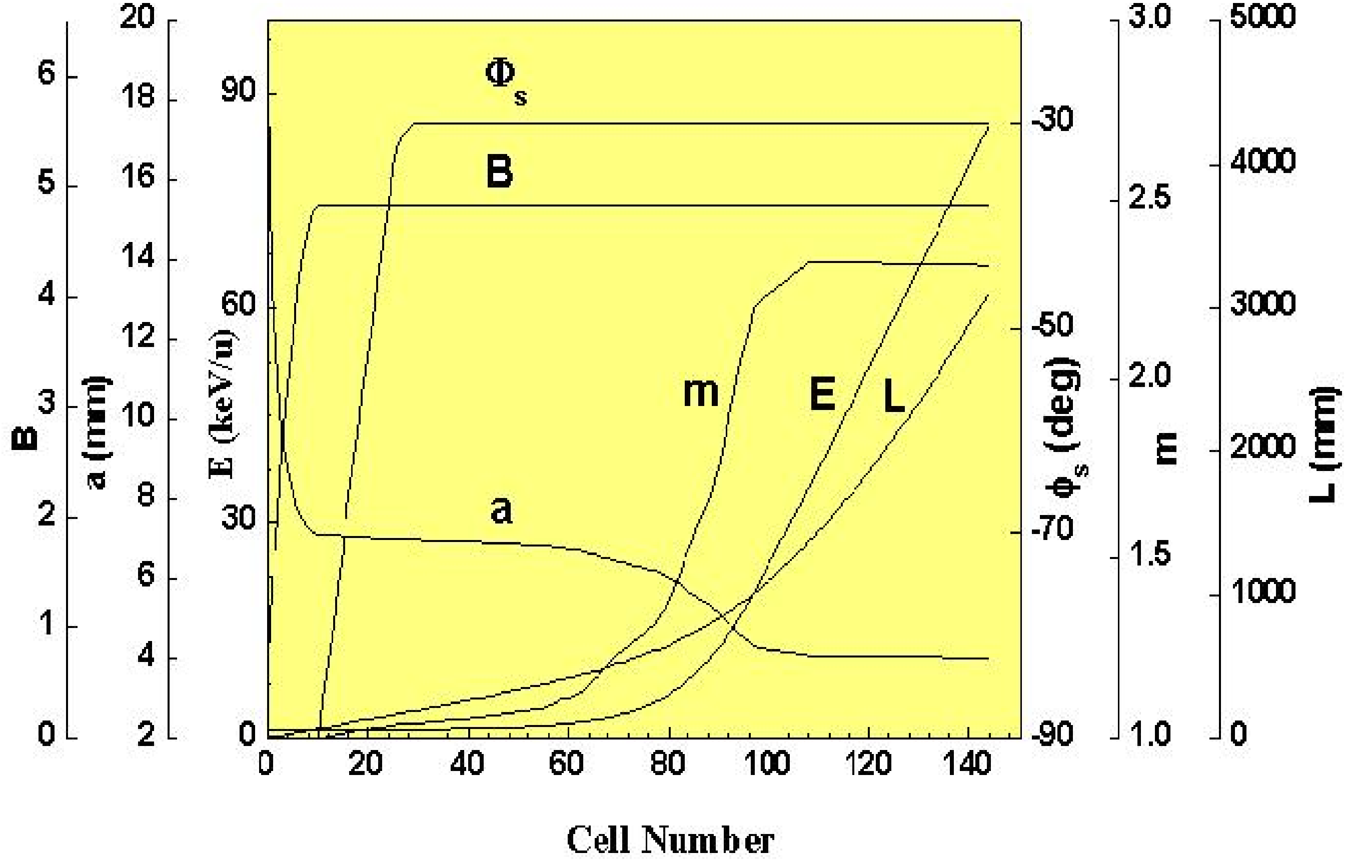


30 keV/u heavy-ion RFQ (close-up)

Result of Full power tests 30 keV/u RFQ

Quantity	Measured
f	33.7 MHz
Q	5250
Vane voltage	15.3 kV
Power	1.1 kW
O^{3+} beam transmission η	~ 85 %

Optimized beam dynamics parameters for RFQ with external pre-buncher



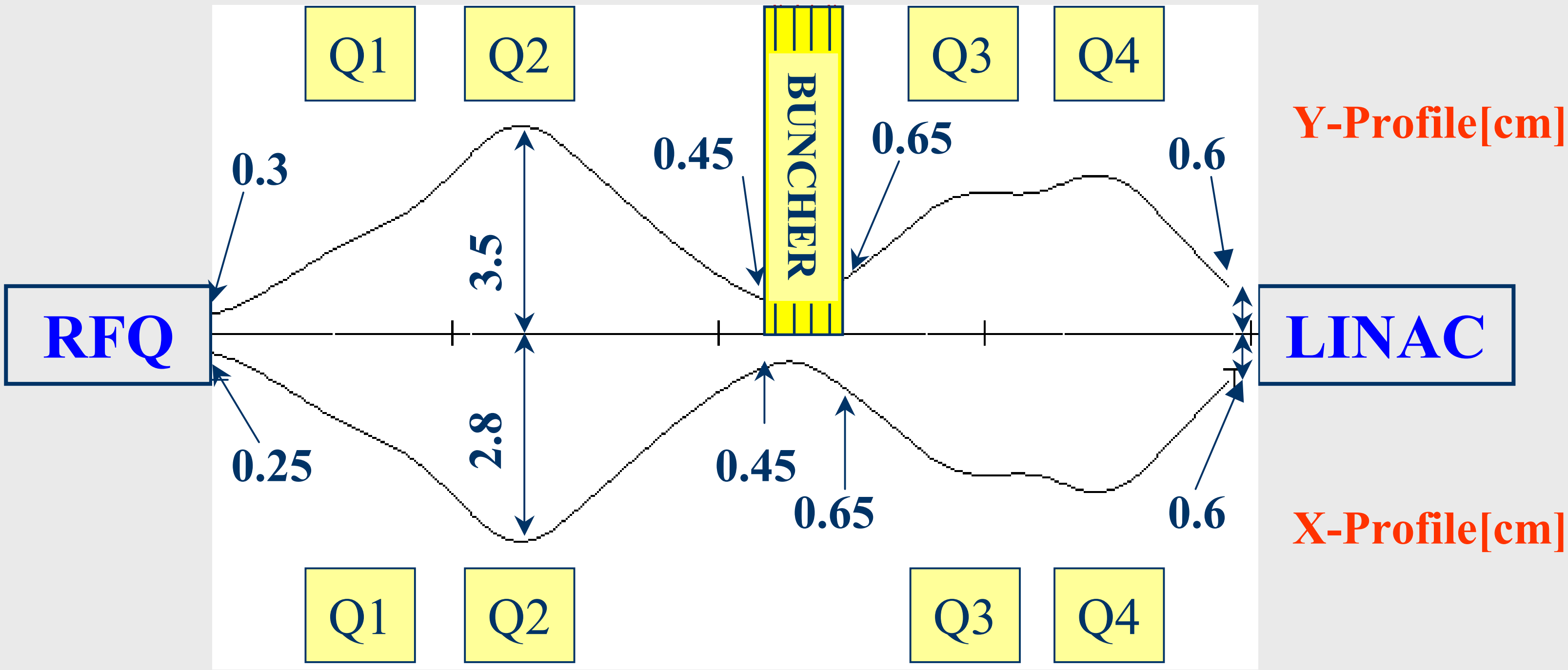
RFQ : list of optimized parameters

Basic parameters		Basic physical parameters	
Operating frequency	35 MHz	Cavity length	3250 mm
Input energy (keV/u)	1.0 keV/u	Cavity width & height (inner)	600 mm X 520 mm
Output energy *(keV/u)*	85.56 keV/u		
Charge to mass ratio *q/A*	1/16		

Beam dynamics parameters		RF structure parameters	
Length of vanes	3104 mm	Calculated Q value of the cavity	9830
Synchronous phase	-90° to –30°	Calculated R_p value	87.12 kΩ
Total number of cells	145	Total power loss (calculated)	14.3 kW
Characteristic bore radius r_o	7.1 mm		
Minimum bore radius a_{min}	4.0 mm		
Maximum modulation m_{max}	2.329		
Focusing strength B	4.83		
Inter-vane voltage	49.5 kV		
Kilpatrick factor	1.2		
Transmission (< 1 mA)	74% (buncher voltage 40 V)		
	84% (buncher voltage 78 V)		
Minimum energy width $\Delta E/E$	0.28% (buncher voltage 40 V)		
(FWHM)	0.56% (buncher voltage 78 V)		

Transfer of RIB from RFQ to LINAC

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

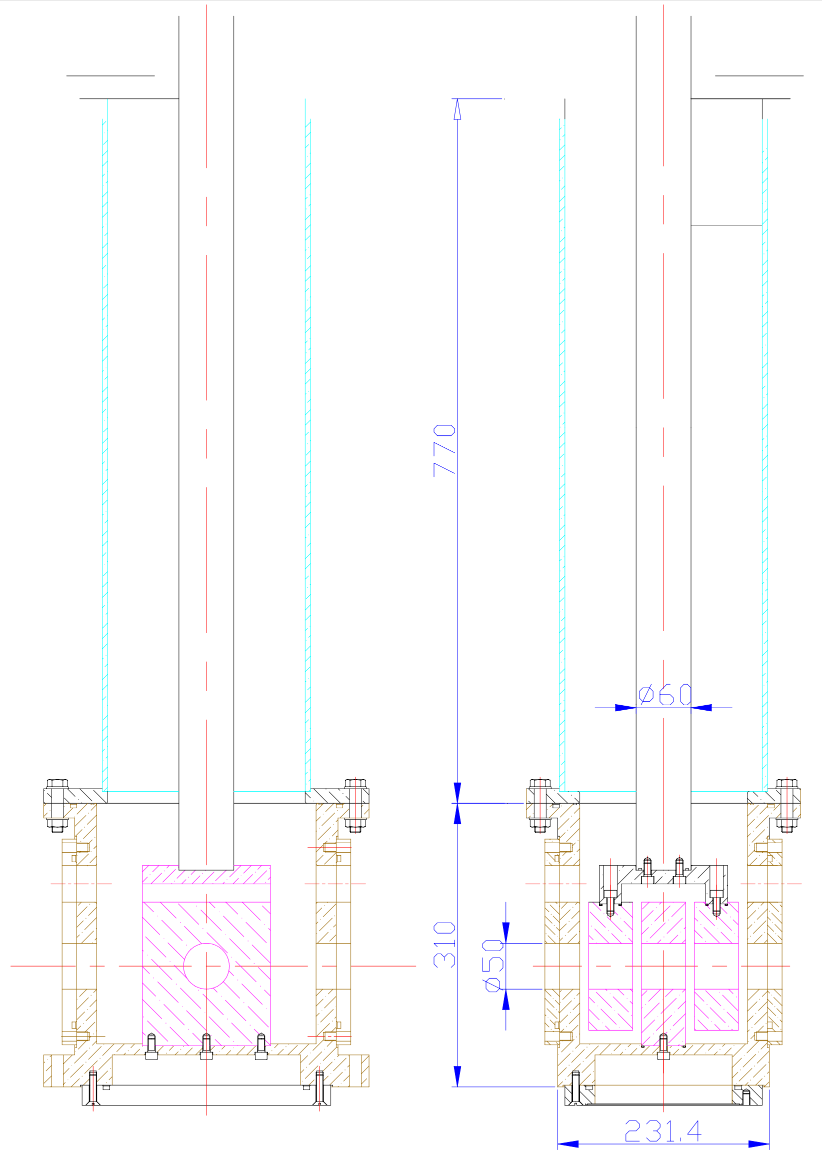


Re-buncher

Between RFQ & Linac-1

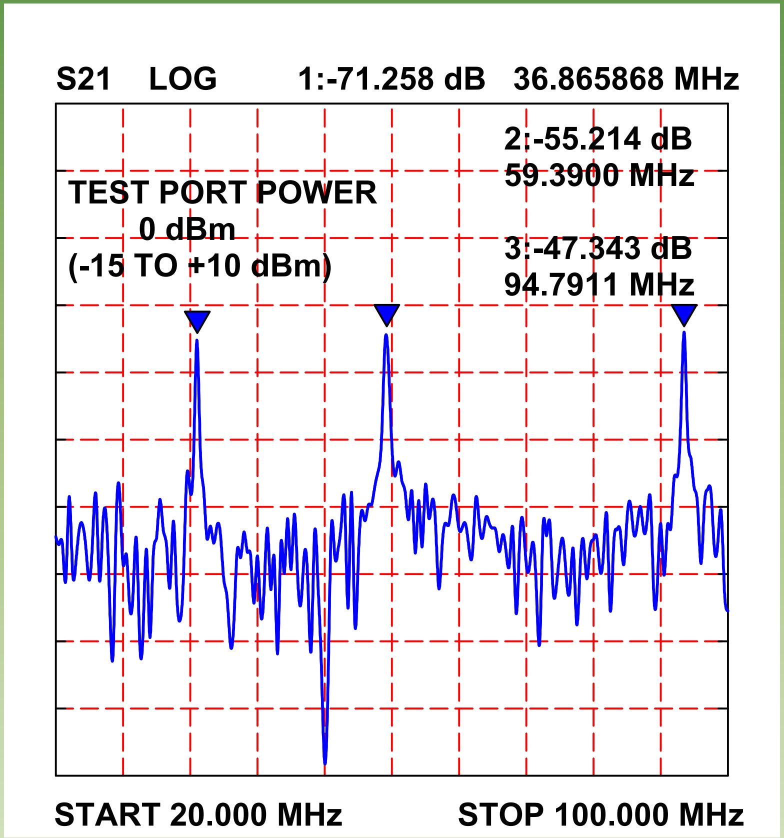
Re-buncher parameters

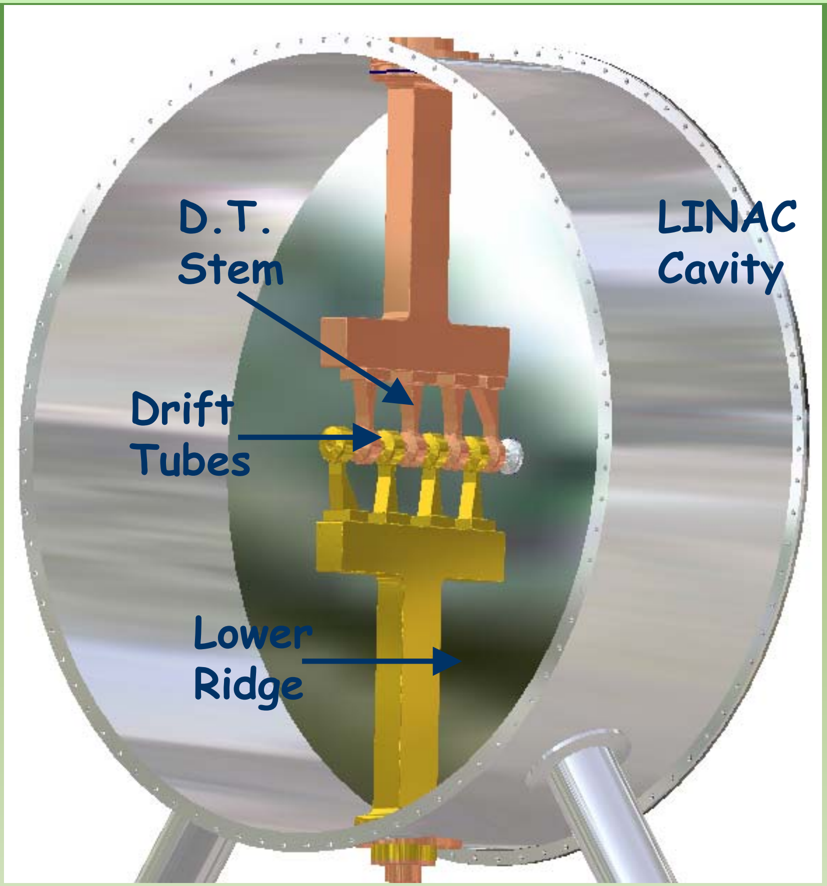
- **Frequency : 35 MHz**
- **Max. gap vol. : 13.75 kV**
- **No. of gaps : 4**
- **Drift tubes : 140 x 140 sq. mm**
- **Beam aperture: 50mm dia.**
- **Drift tube gaps : 9.85 mm**



Heavy-ion IH LINAC for RIB

- Acceleration of RIBs after RFQ from 86 keV/u to 400 keV/u
- IH LINAC → q/A = 1/16 ; f = 35 MHz ; E_max ~ 1.3*E_K (=10.2 MV/m)
- Transmission ~ 100 % ; Normalised acceptance ε_n = 0.5 π-mm-mrad





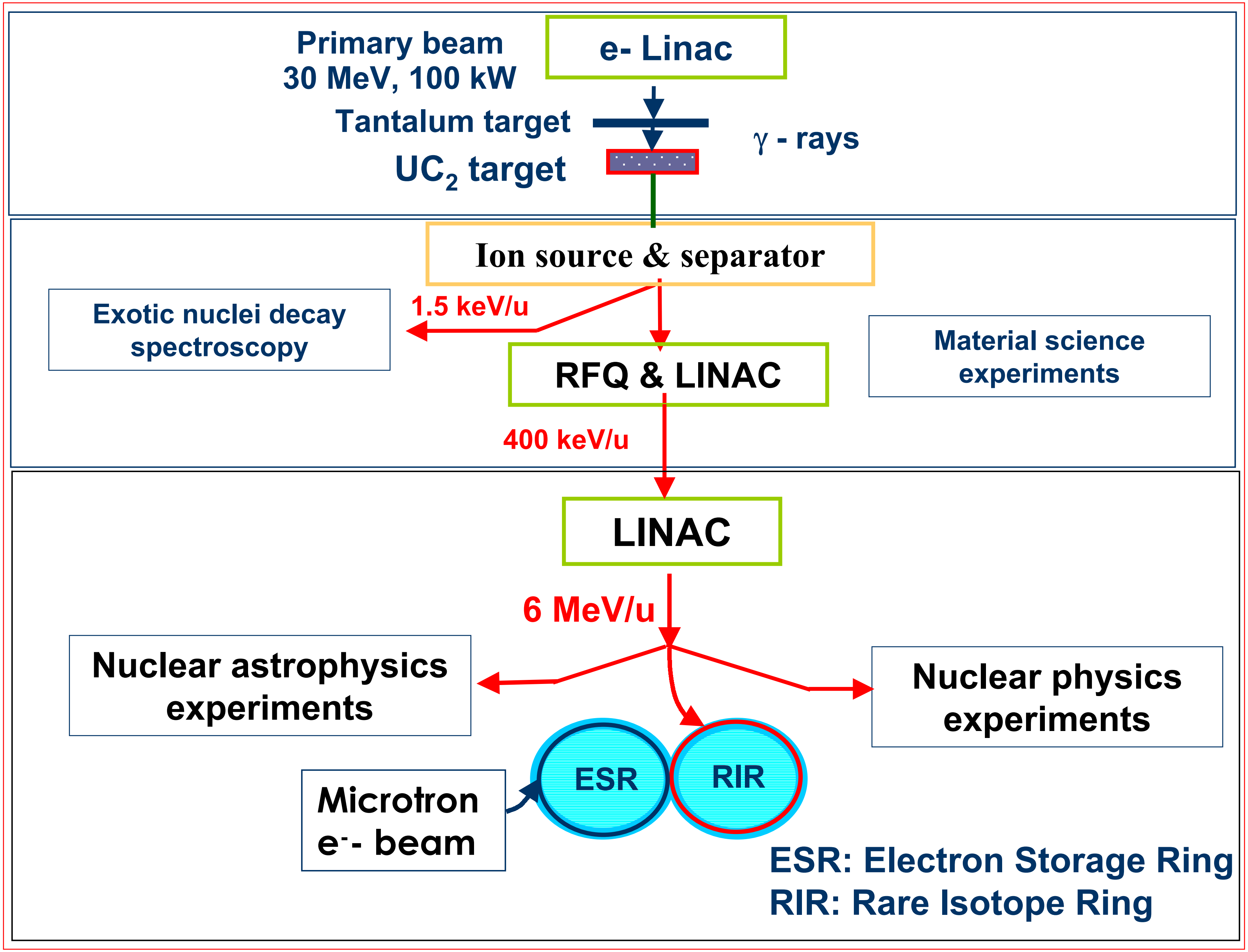
Important Parameters for the first three LINAC cavities

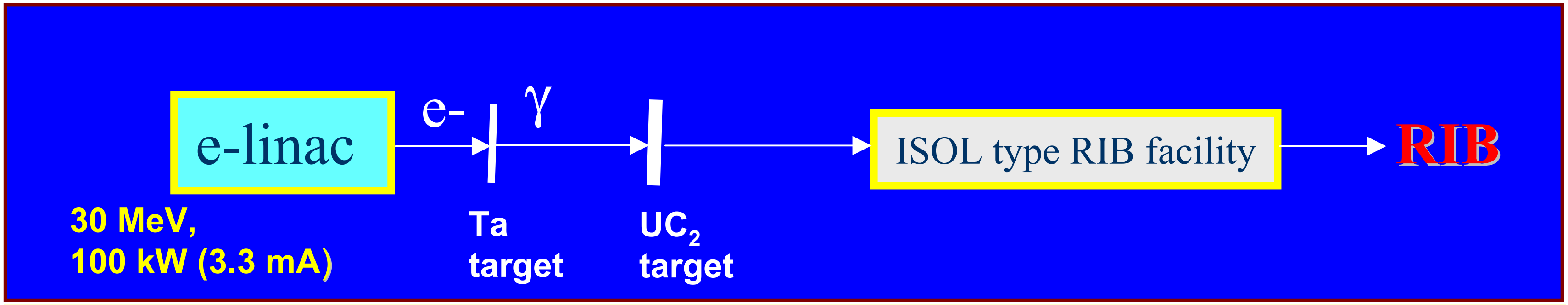
Parameter	Unit	Tank-1	Tank-2	Tank-3
Frequency	MHz	35	35	35
q/A	>=	1/16	1/16	1/16
E(in) → E(out)	KeV/u	86.0 → 158.2	158.2 → 263.0	263.0 → 397.5
β(in) → β(out)	%	1.36 → 1.84	1.84 → 2.38	2.38 → 2.92
# of Cells & gaps		9	11	13
Bore radius	cm	1.25	1.25	1.25
Gap length	cm	2.92	4.0	5.1
Cell length	cm	5.84 → 7.9	8 → 10.13	10.2 → 12.46
Peak Vol. On drift tubes	kV	171.8	202.0	217.6
Transit Factor		0.79 → 0.84	0.80 → 0.86	0.82 → 0.86
Sync.Phase	Deg	-25	-25	-25
Cavity Length	m	0.618	0.996	1.476
Cavity Diameter	m	1.72	1.72	1.72
Shunt Impedance	MΩ/m	369	487	474
Quality Factor		15878	21571	26284
Power	kW	10.5	10.2	11.5

Project schedule

- RFQ $\Rightarrow$ 30 keV/u — Sept 2005
- RFQ $\Rightarrow$ 86 keV/u — Jun 2006
- Linac 1 — Dec 2006
- Linac 2 — Jan 2007
- Linac 3 — Jan 2008

The Next Step ! (2007-2016)





- RIB production route $\quad$ *$^{238/235}UC$ Photo-fission*

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

  ^{78}Ni (doubly magic): 2 x 10^{9} pps

  ^{132}Sn (doubly magic): 2 x 10^{11} pps

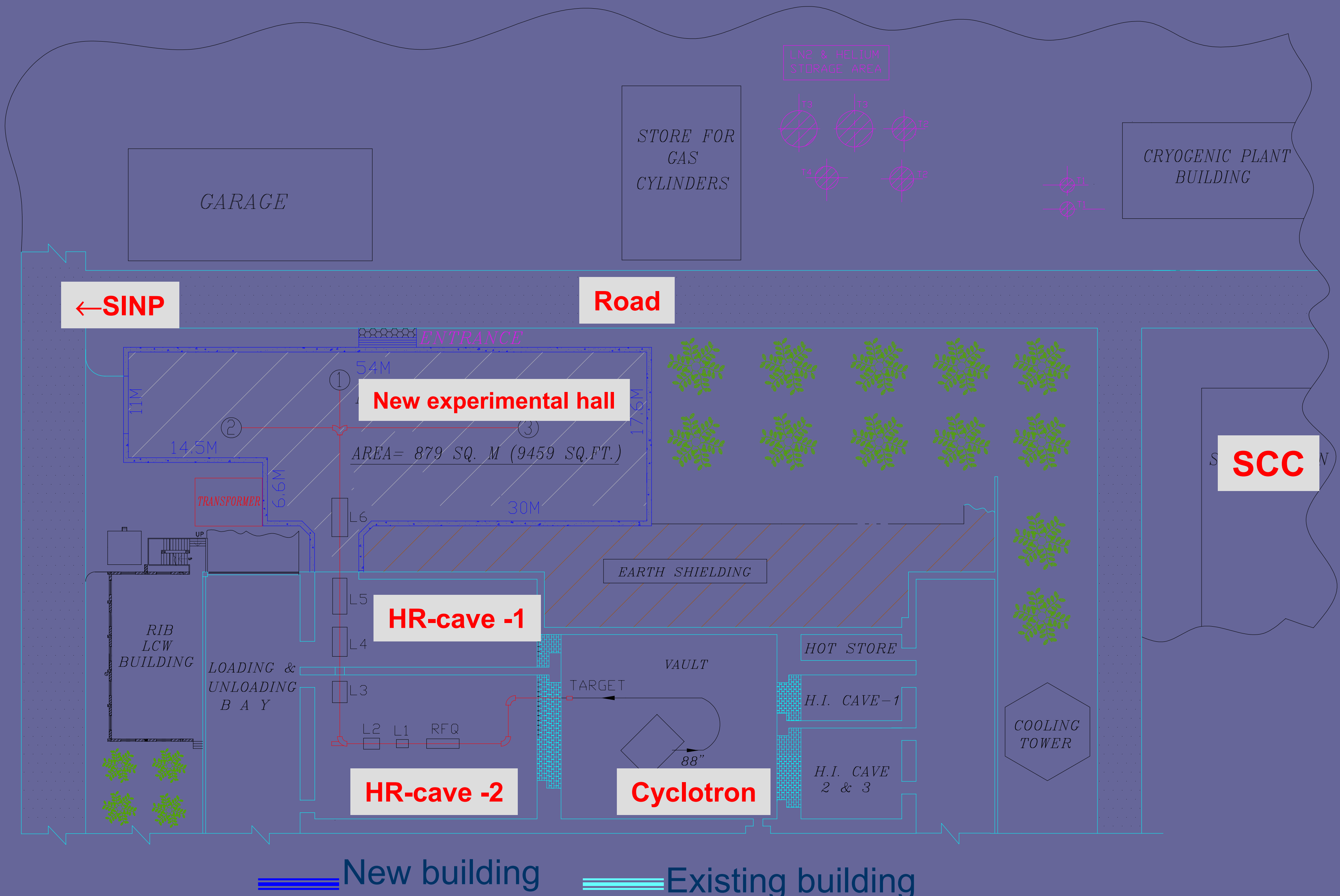
  ^{91}Kr (for SHE production): 1 x 10^{12} pps

  ^{94}Kr (for SHE production): 3 x 10^{10} pps

Implementation strategy

- **yr 2007-2010**
  - ¤ ***Acceleration of stable & RI Beams using K=130 cyclotron upto 1.5 MeV/u at VECC***
  - ¤ ***Design of accelerators & experimental facilities for 6 MeV/u advanced RIB facility***
  - ¤ ***Experiments using 1.5 MeV/u RI Beams at VECC***
  - ¤ ***Building, services, procurement for advanced RIB facility & installation of e-Linac at new campus***
- **yr 2010-2012**
  - ¤ ***Installation & part commissioning of advanced RIB facility & associated experimental facilities***
- **yr 2012-2016**
  - ¤ ***Full commissioning of advanced RIB facility***
  - ¤ ***Full commissioning of experimental facilities and experiments with 6 MeV/u advanced RIB facility***
  - ¤ ***Commissioning of the ESR & RIR storage rings***

XIth PLAN RIB PROJECT ACTIVITY AT VECC



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  - ¤ ***Commissioning of the ESR & RIR storage rings***

Cost Projection

Plan period		Expenditure (Rs Cr)
11th plan	Additional fund for completing 10th plan activities	3.00
(2007-2010) at VECC	LINAC, Buncher Cavities & RF Transmitter	17.00
	Beam lines, magnets etc	6.00
	Detectors & experimental facilities for 1.5 MeV/u	4.00
	Target R&D,Two ion source R&D	5.00
	Small Building for R&D facilities, Services & misc.	5.00
(2007-2012) at New Campus	Building, Infrastructure at New Campus	(2007-2010) 40.00
	Electron LINAC	(2010-2011) 30.00
	RIB from 1.5 to 3 MeV/u	(2010-2012) 10.00
	Experimental facilities	(2010-2012) 10.00
	Total 11th plan	**130.00**
12th plan (2012-2016) at New Campus	RIB from 3 to 6 MeV/u	(2012-2014) 30.00
	Experimental facilities	(2012-2014) 20.00
	Small storage rings for HI & electrons	(2012-2016) 80.00
	Total 12th plan	**130.00**
TOTAL Project Cost (Rs. Crores)		**260.00 ~ 50 Million US$**

Thank you

Particle energy distribution