# Radioactive Ion Beam (RIB) Facility at VECC :

## Present & Future

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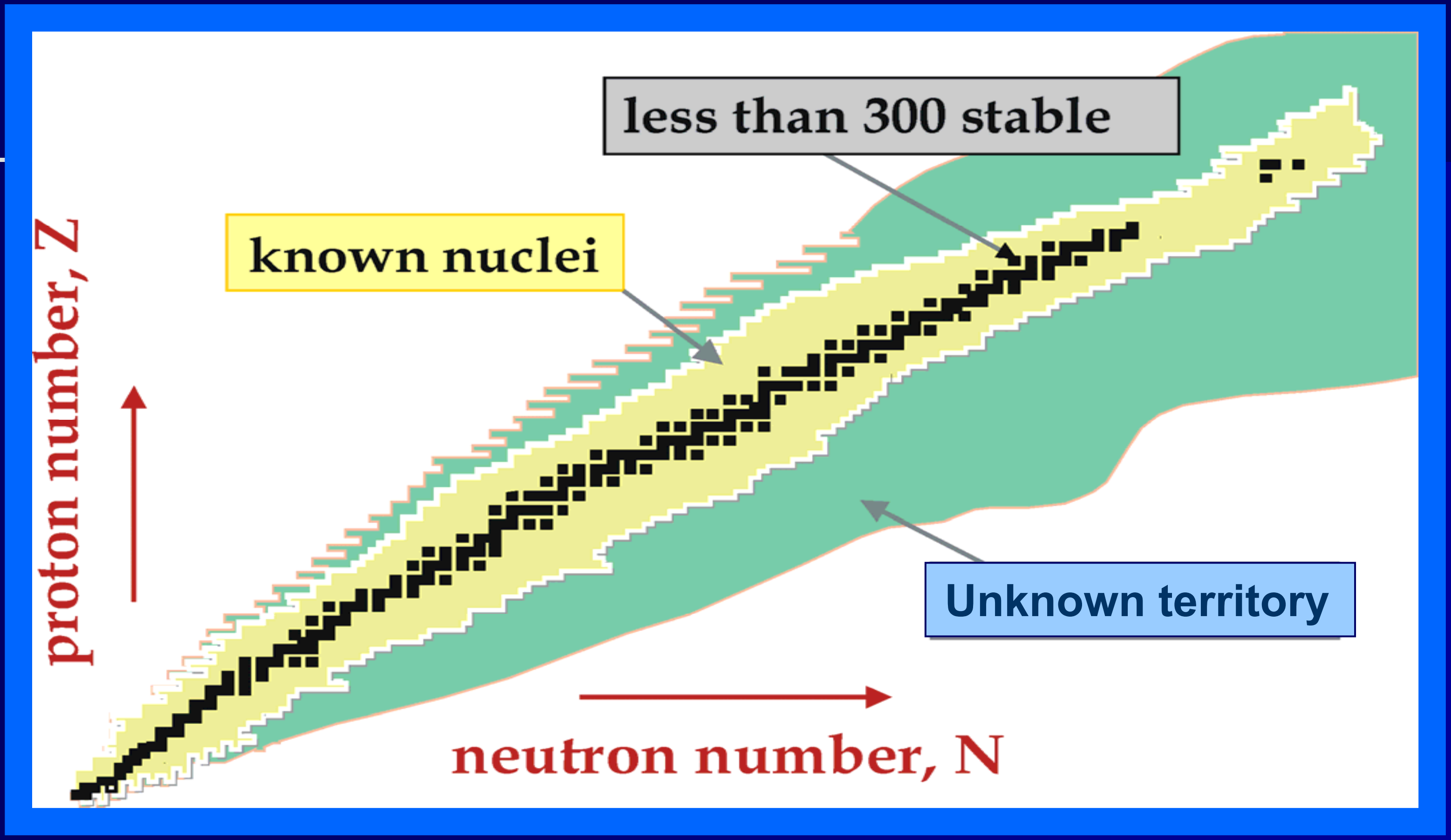
## Radioactive Ion Beams : Ions of β-unstable nuclei

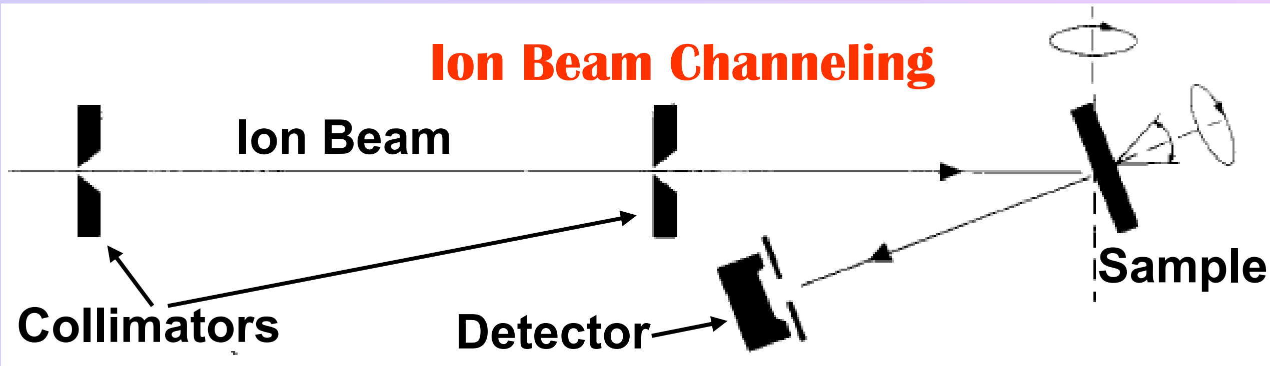



**Enormous increase in the no. of available projectiles**

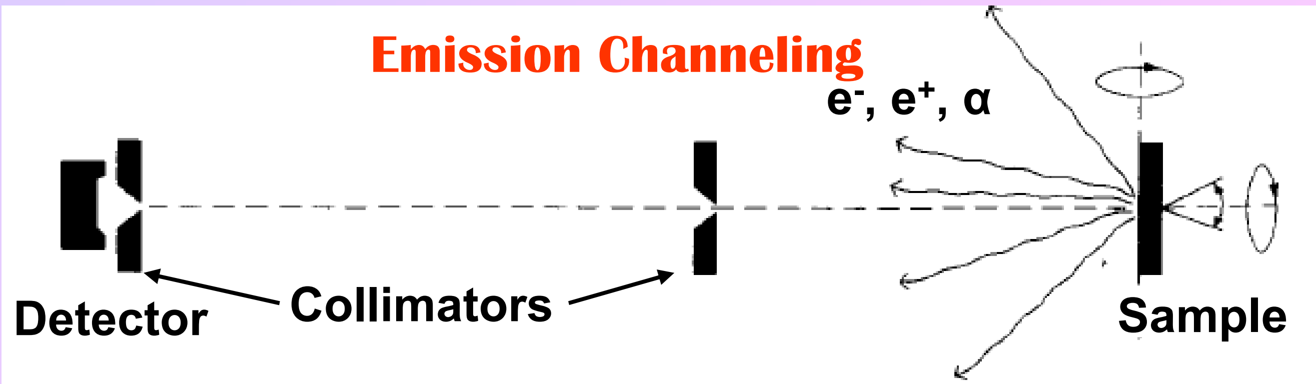
## Physics Motivation

## Material Science

### Study of formation & propagation of lattice defects




**Well collimated ion beam interacts with lattice & impurity atoms – backscattered yield is measured as a function of sample orientation**




**Yield of charged particles emitted by radioactive impurity atoms is measured as a function of sample orientation**

# Physics Motivation

## Material Science

**Advantages of EMISSION CHANNELING technique :**

**Req. implantation dose of radioactive atoms is significantly lower than that of ion channeling experiment.**

- **Radiation damage during channeling analysis negligible.**
- **Sensitivity of EC >> higher than ion channeling tech. (1E13 & 1E18 /cc)**

## Physics Motivation

- **Material Science**

**Mössbauer Effect (ME) : Study of recoil-free emission & absorption of g by a radioactive nucleus embedded in a solid.**

**ME allows measurement of Isomer Shift (IS) - relative shift of the emission and absorption lines proportional to the difference in electron density at the Mössbauer nucleus in the source and in the absorber matrix**

**→ Provides information about the lattice site of the Mössbauer atom & its charge state.**

# Physics Motivation

- **Material Science**

**Advantage of using RIB as a Mössbauer dopant are :**

➢ **Chemical incompatibility** of **Mössbauer atom is not an issue any more : possible to find a suitable compatible parent isotope which decays to the Mössbauer atom.**

➢ **Site selective doping which depends on the parent isotope**

**For example, $^{119}Sn$ – good Mössbauer dopant for group III-V compound semiconductors :**

**$^{119}In \rightarrow {}^{119}Sn$ (occupies group V lattice sites)**

**$^{119}Sb \rightarrow {}^{119}Sn$ (occupies group III lattice sites)**

## Physics Motivation

**Medical research**

**Radioisotope Therapy : A radionuclide is delivered to a tumor site using a biologically active molecule which decays via $\beta^-$ or $\alpha$.**

**Using RIB one can produce such nuclide with high specific activity as it will be carrier free or no-carrier-added form (suitable target+projectile & clean separation) + availability of new radioisotopes.**

**PET (Positron Emission Tomography) – medical imaging of tumors, mapping of human brain and heart function. Most of the PET isotopes are short lived for clinical use & research. Using RIB it is possible to produce longer lived PET isotopes ($^{72}As$ : $T_{1/2}$~ 26 hours) which are carrier free i.e. high sp. Activity.**

# Physics Motivation

- **Nuclear Physics**

## Study of nuclei away from line of β-stability

- **Neutron Halo** ($^{6,11}Li$, $^{14}Be$, $^{17}B$, .....)
- **β-delayed particle emission** ($^{21}Mg$, $^{16}C$, $^{22}Al$, $^{26}P$, ...)
- **Nuclr. Deformation & magicity** ( $^{80}_{40}Zr, ^{100}_{38}Sr$ )

- **Nuclear Astrophysics**

- **The nuclear processes responsible for nucleosynthesis**
- **When & where these processes took place**
- **Chracteristics (temperature, density, composition ..) of the nucleosynthesis sites**

# Primordial Nucleosynthesis

The Universe was created about 15 billion years back by gradual expansion from a state of extremely high density ($\rho \sim 10^{95}$ g/cc) & temperature ($T \sim 10^{32}$ K) → Big Bang Theory.

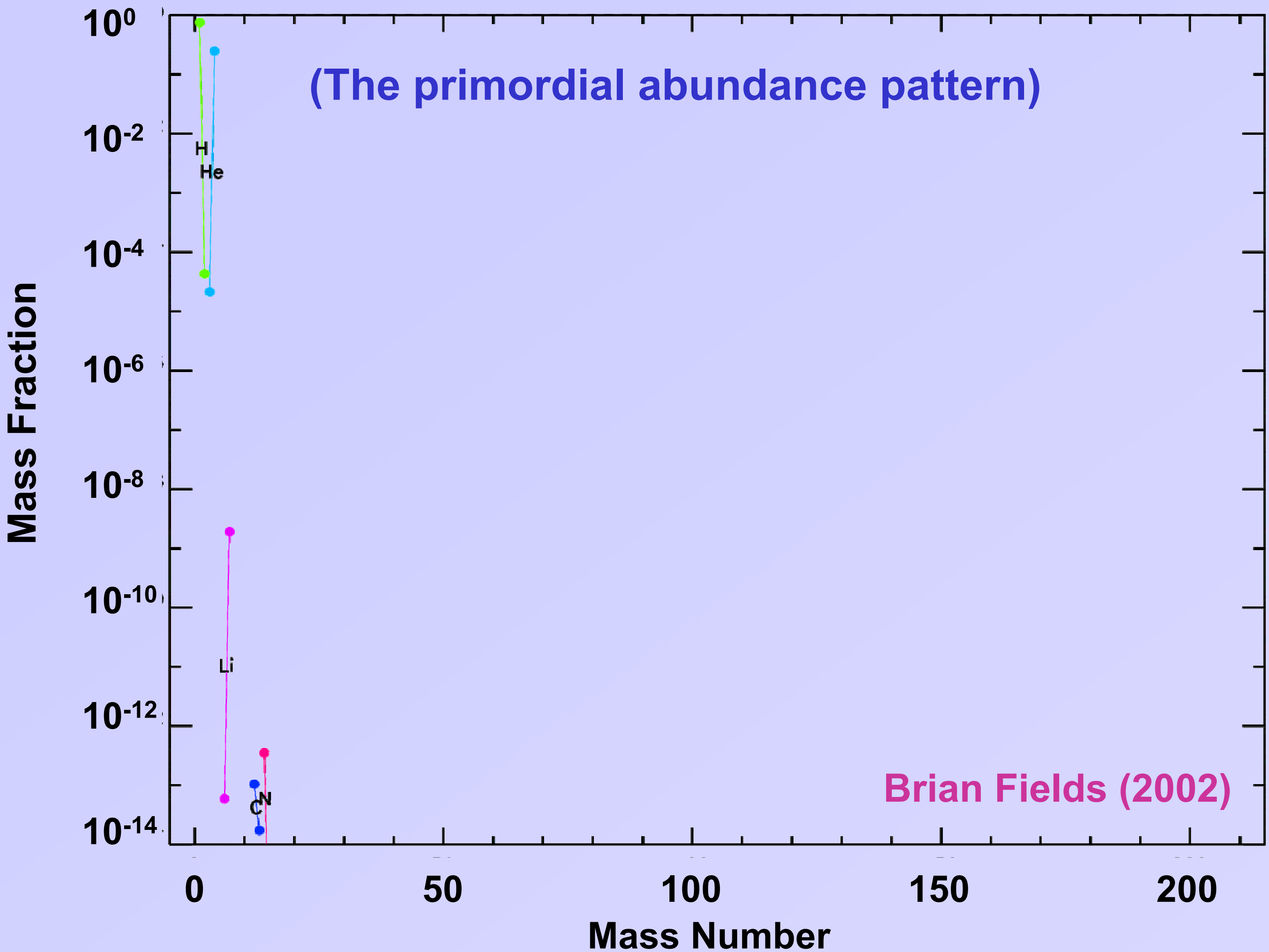
Nucleosynthesis could start ~ 3 minutes after the Big Bang when Deutorium (B.E. 2.23 MeV) stable against photo-dissociation at $T \sim 10^9$ K.

Nucleosynthesis could continue for a very short time after the big-bang because :

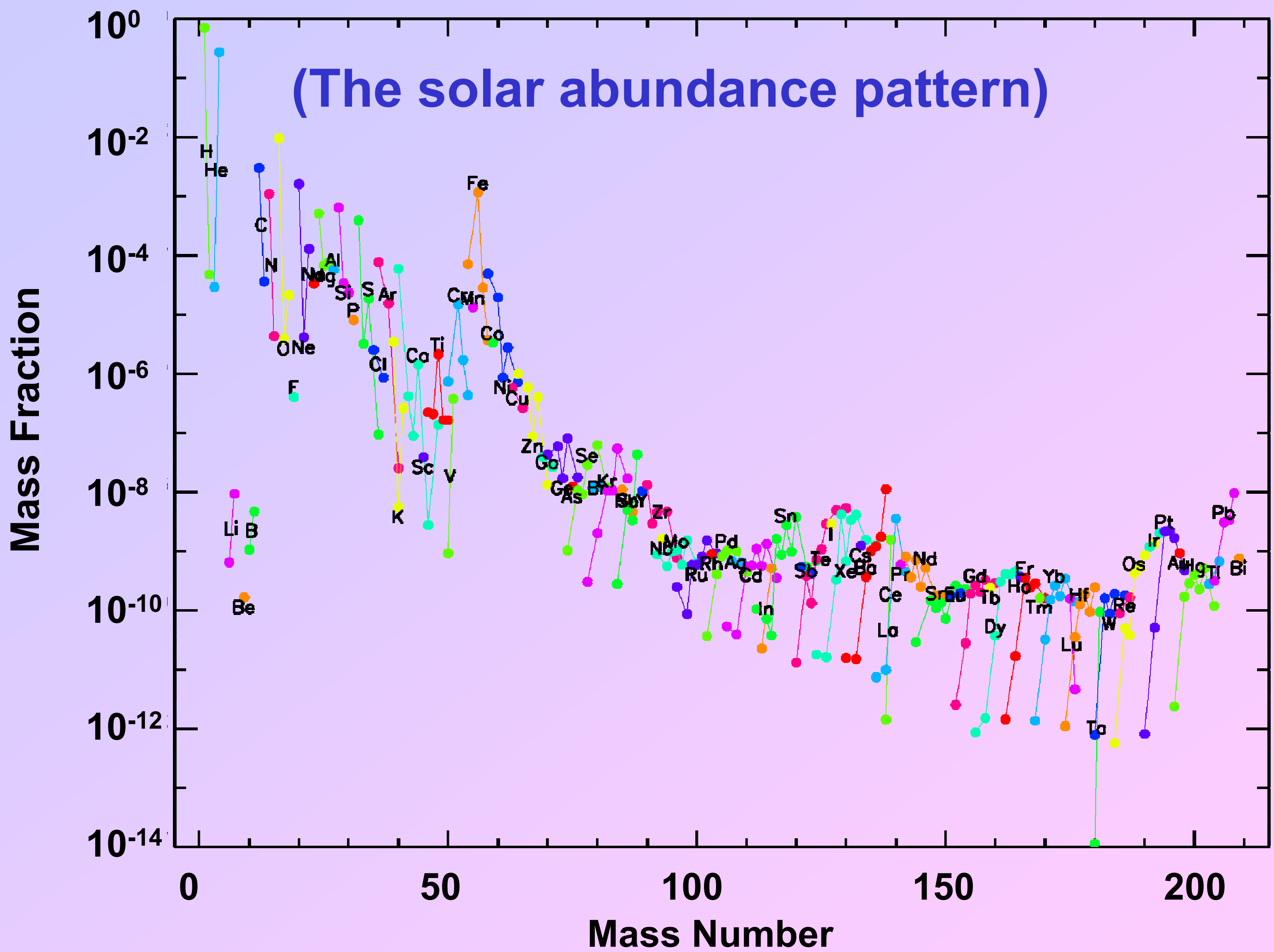
- All neutrons were used up for production of $^4$He
- No stable nuclei for A=5 and A=8
- Baryon density too low for 3 body reactions
- Temp. reduced due to expansion to sustain further nuclear reaction

| Mass Fraction | |
|---|---|
| $^1$H | 0.75 |
| $^2$H | (2.5±1.5)x10-5 |
| $^3$He | (4.2±2.8)x10-5 |
| $^4$He | 0.23±0.02 |
| $^6$Li | $300^{+300}_{-150} \times 10^{-12}$ |
| $^7$Li | $4600^{+4600}_{-2300} \times 10^{-12}$ |

# Primordial Nucleosynthesis



# Nucleosynthesis




Grevesse & Noels (1995)

# Nucleosynthesis in Stars

**Expanding Cosmological gas from Big Bang**

→ **Density Fluctuation** →

Denser zone will gravitationally attract material from outside → grows in density

↓

**Galaxies Formed (t > 500 million Yrs)**

↓

Within galaxy smaller clouds collapsed to form stars & other objects

**Gravitational Collapse of Star** → **Core Temp. of Star increases** → **$^{1}H$ fuses to $^{4}He$ releasing energy** → **Radiation pressure balances gravitational collapse**

**Hydrogen burning : Source of energy of Main Sequence Stars like Sun – continues for tens of millions of years**

# Nucleosynthesis in Stars

Elements are created in several stages where the products of one stage become the fuel for energy generation in the next stage.

## Hydrostatic burning stages

$M < 8M_{\oplus}$

After He burning stage, star will throw off its envelop as a planetary nebula & become a white dwarf.

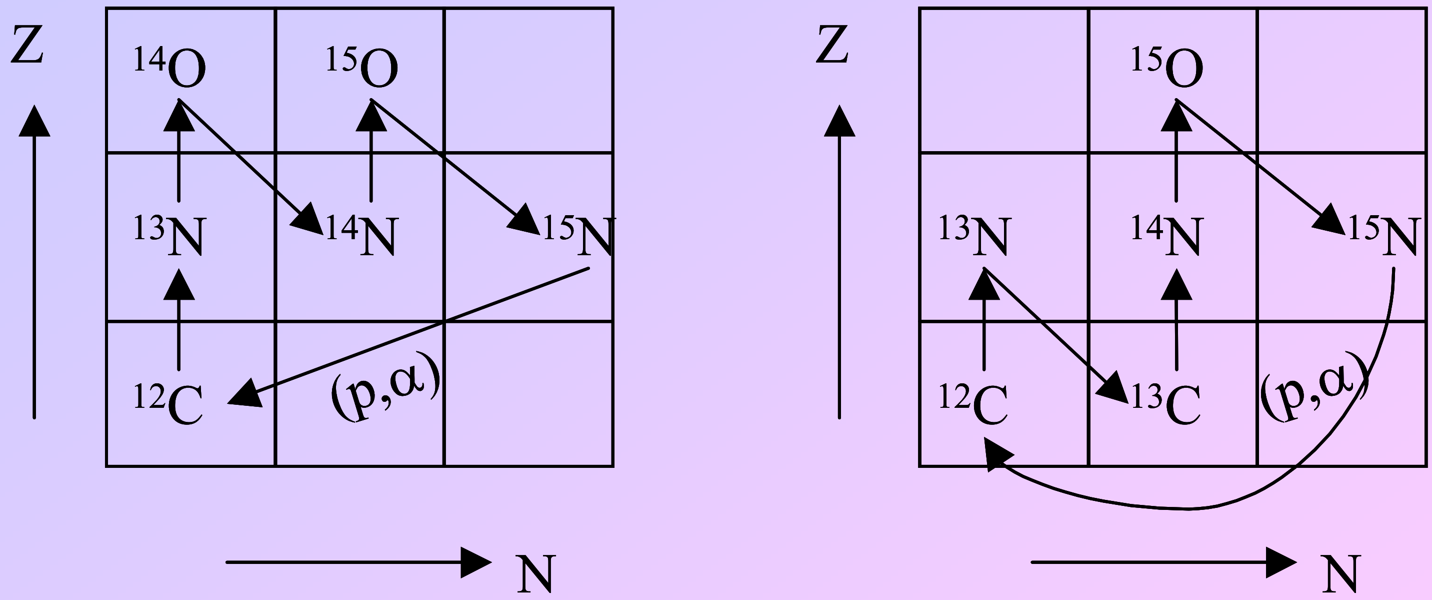
$M > 8M_{\oplus}$

Main sequence →Goes through all burning stages →Red Giant → Core of mostly Fe → gravitational collapse to super-density → Supernova explosion→ Blows off outer envelop→remnant as neutron star / black hole

| | |
|---|---|
| *H burning* | $4p \Rightarrow {}^{4}He + 2e^{+} + 2\nu + 26.7$ MeV |
| *He burning* | $\alpha + \alpha \Rightarrow {}^{8}Be$<br>${}^{8}Be + \alpha \Rightarrow {}^{12}C + \gamma + 7.2$ MeV<br>${}^{12}C + {}^{12}C \Rightarrow {}^{23}Na + p + 2.23$ MeV<br>$\Rightarrow {}^{20}Ne + \alpha + 4.6$ MeV |
| *C burning* | ${}^{12}C(p,\gamma){}^{13}N(e^{+}\nu){}^{13}C(\alpha,n){}^{16}O$ |
| *Ne burning* | ${}^{20}Ne + \gamma \Rightarrow {}^{16}O + \alpha$<br>${}^{20}Ne + \alpha \Rightarrow {}^{24}Mg + \gamma$ |
| *O burning* | ${}^{16}O + {}^{16}O \Rightarrow {}^{31}P + p$<br>$\Rightarrow {}^{28}Si + \alpha$<br>$\Rightarrow {}^{31}S + n$ |
| *Si burning* | ${}^{28}Si + \alpha \Rightarrow {}^{32}S + \alpha$<br>$\ldots + \alpha \Rightarrow {}^{56}Fe$<br>${}^{28}Si + \gamma \Rightarrow \alpha + Mg$ |

# Nucleosynthesis in Stars

**CNO Cycle**



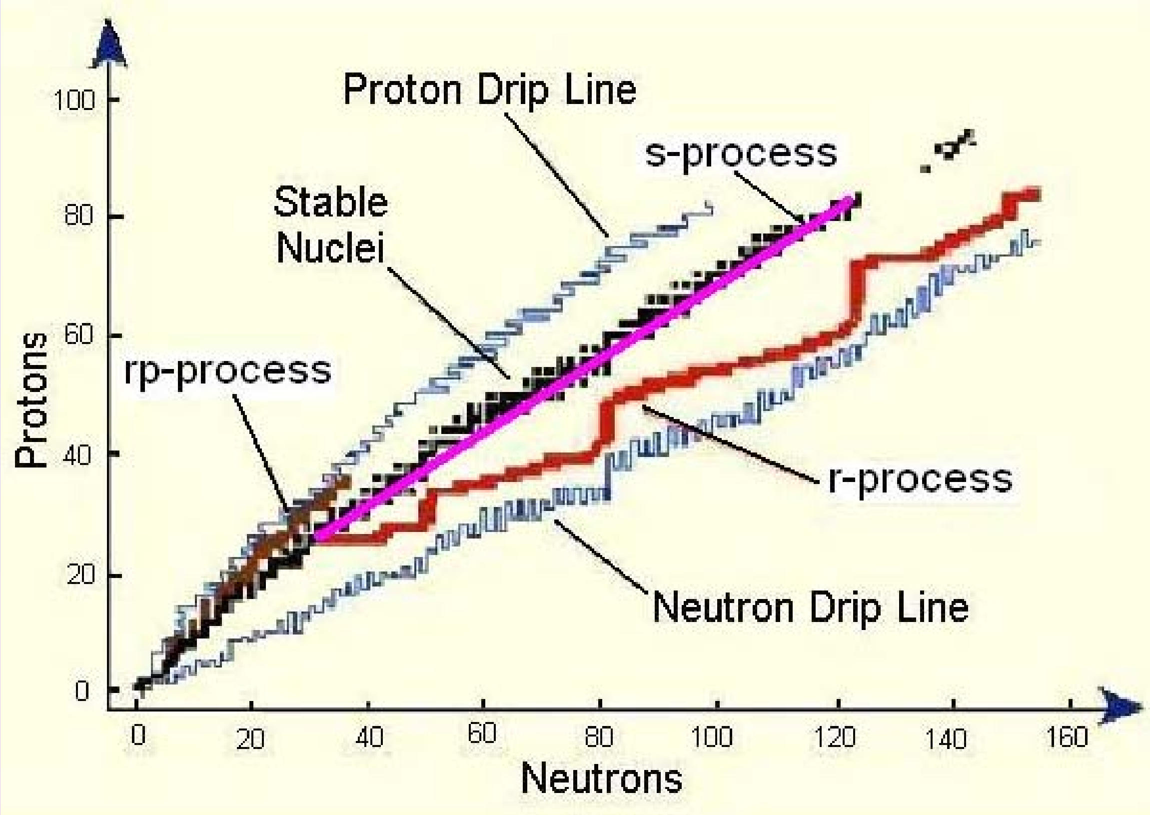

HOT CNO

COLD CNO

A form of Hydrogen burning chain reaction takes place in non-first generation stars where C is available to start with.

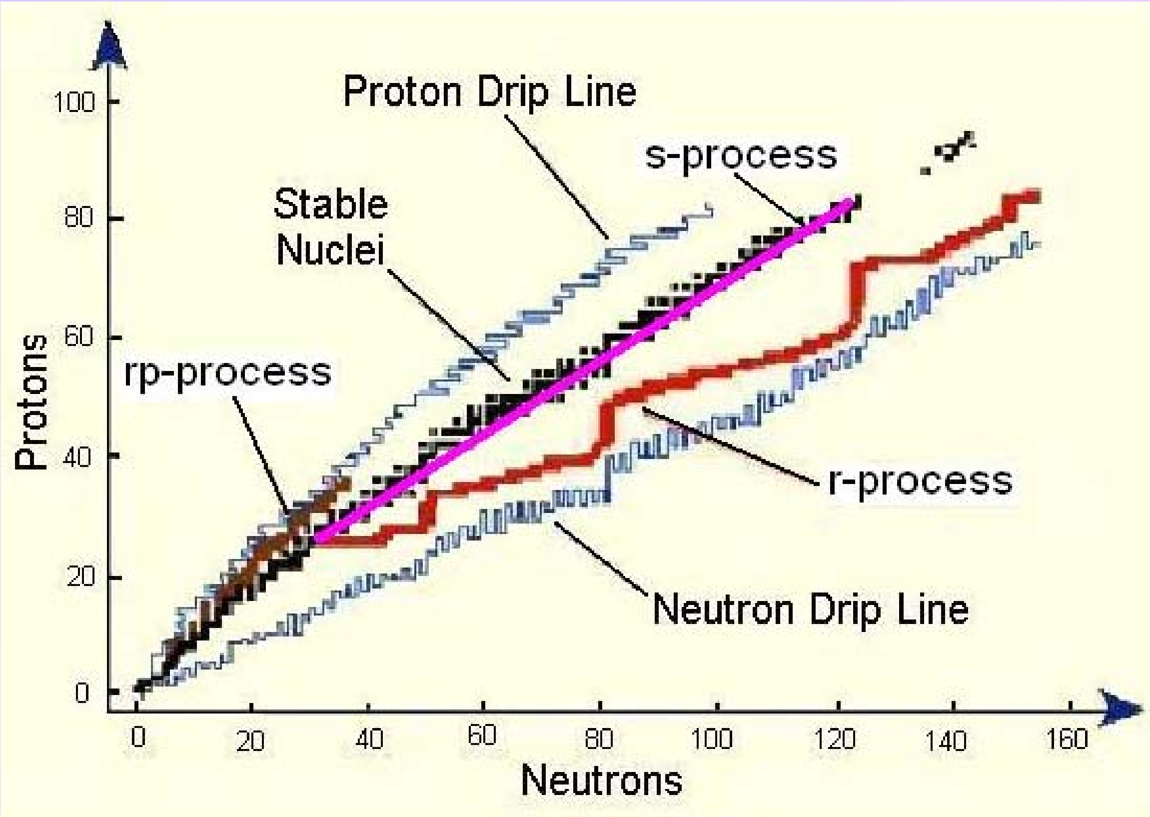
# Nucleosynthesis of elements beyond Fe

## r - Process




- Rapid successive n-capture (n,g) W/O intermediate a and b$^{-}$ decay
- Follows path closer to n-drip line
- Near magic nos. nutron BE is small – b$^{-}$ decay occurs – path moves towards stability line
- Produces n-rich nuclei between A=56 to 270 – beyond which fission sets in

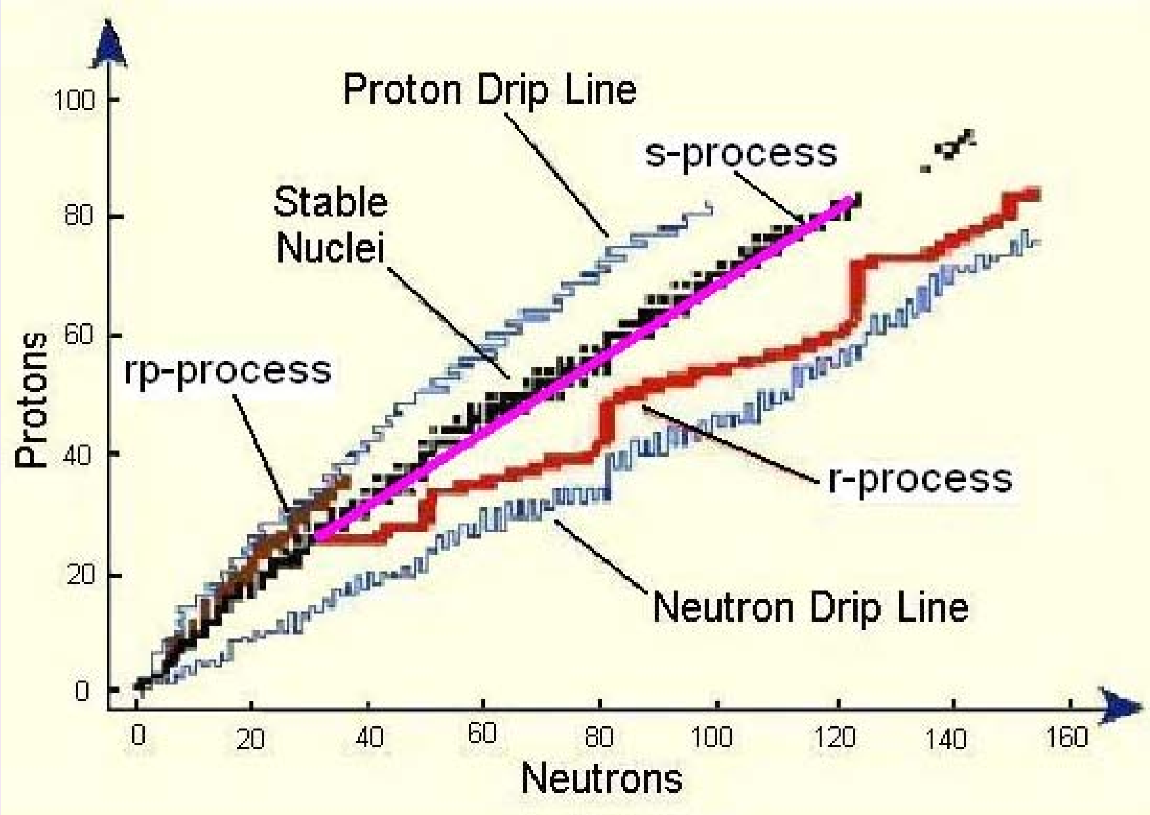
# Nucleosynthesis of elements beyond Fe




**s - Process**

- Slow n-capture : slow w.r.t. b$^{-}$ decay process
- Series of (n.g) processes and b$^{-}$ decays (sometimes b$^{+}$ and EC)
- Follows path closer to the stability line
- Produces n-rich nuclei between A=56 to 209 (Bi) – beyond which there are many short lived nuclei & slow process cannot compete.
- Red giants – being a good source of neutrons from $^{13}C(a,n)^{16}O$, $^{17}O(a,n)^{20}Ne$, $^{21}Ne(a,n)^{24}Mg$ … reactions– possible site for such processes.

# Nucleosynthesis in Stars




**rp - Process**

- Rapid p-capture process : fast w.r.t. b+ decay process
- Follows path closer to the proton drip line
- Produces p-rich nuclei up to  A ~ 100 – beyond which Coulomb repulsion prevents successive p-capture.

# Nuclear Astrophysics

- Reactions involving stable nuclei drive the evolutionary stage of main sequence stars
- Reactions involving unstable nuclei dominate the outcome of explosive events

## Major Challenges

- Number of target atoms/cm$^2$ is small as reactions have to be studied at a very low energy, thin targets have to be used
- Expected cross section is small near or below the Coulomb barrier
- Intensity of RIBs is generally less compared to stable beams
- Often the RIBs are not pure (mixed beam) & have large energy spread
- Background due to the decay of RIB

# Nuclear Astrophysics

## Major Detection Techniques Needed

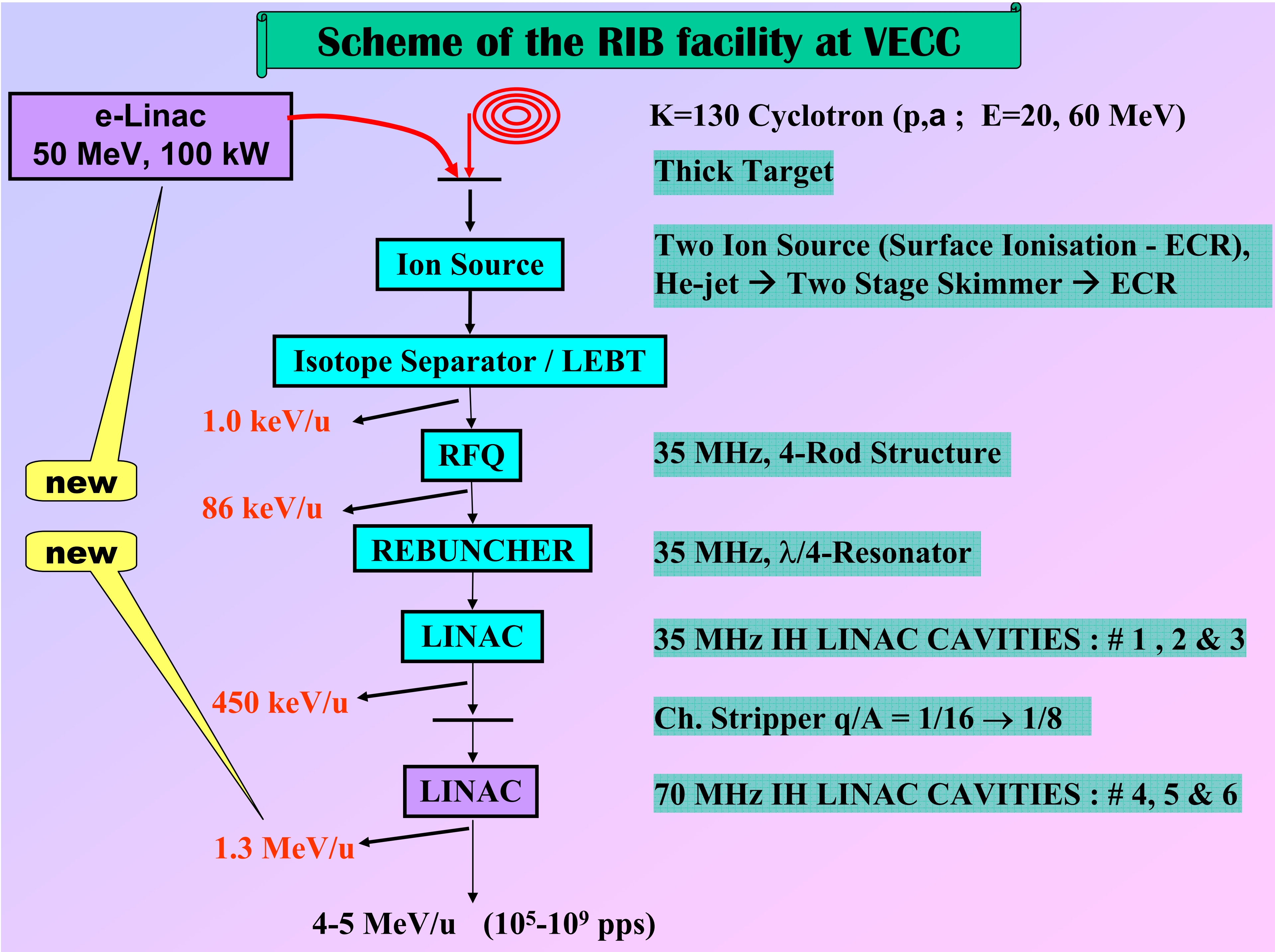
- Highly segmented high efficiency gamma ray detector array
- Large solid angle and good angular resolution silicon detector array
- Mass separator with high beam rejection efficiency
- Gas cell targets & targets of long lived radioactive nuclei

**GRETA (Gamma Ray Energy Tracking Array) - LBL**
**Solid angle coverage : 0.45 → 0.8**
**Detection Efficieny : 10→50 %**
**Position resolution : 20mm → 2mm**

**DRAGON (Detector of Recoils And Gammas Of Nuclear reactions)**
**Angular acceptance ≤ ±20 mrad**
**Energy acceptance ≤ ±4%**
**Separation is 1 in $10^{15}$**

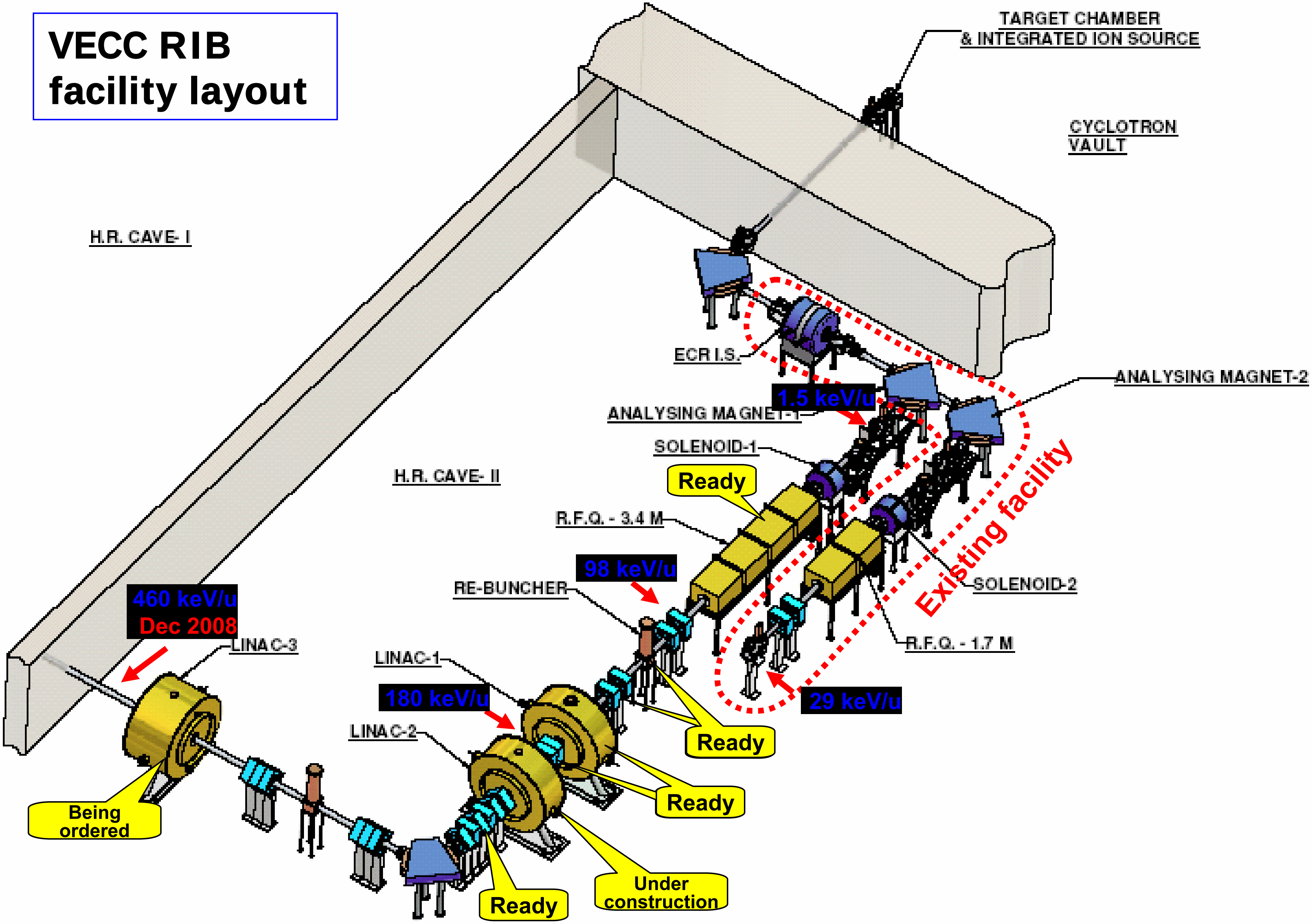
1. Radioactive Ion Beams will play an important role in all fields of accelerator based research for the next few decades
2. Nuclear astrophysics is a fascinating field of research of tracing back the evolution of the Universe. It requires information of different reactions using both stable and radioactive beams.
3. But --- it requires stretching the limits of present accelerator and detection technologies.

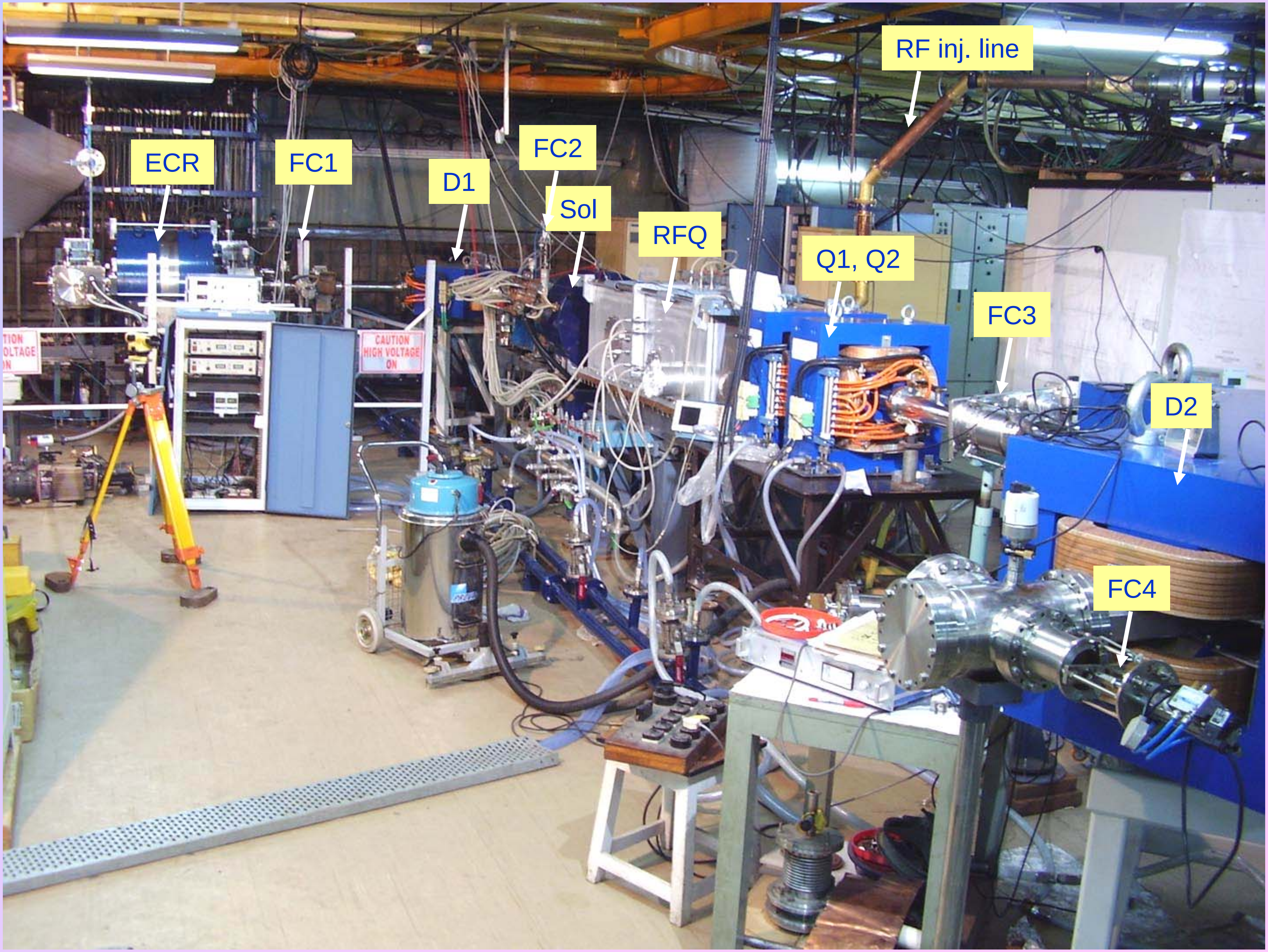
**How to produce RIB?**



Scheme of the RIB facility at VECC
e-Linac
50 MeV, 100 kW
new
new
K=130 Cyclotron (p,a ; E=20, 60 MeV)
Thick Target
Ion Source
Two Ion Source (Surface Ionisation - ECR),
He-jet → Two Stage Skimmer → ECR
Isotope Separator / LEBT
1.0 keV/u
RFQ
35 MHz, 4-Rod Structure
86 keV/u
REBUNCHER
35 MHz, λ/4-Resonator
LINAC
35 MHz IH LINAC CAVITIES : # 1 , 2 & 3
450 keV/u
Ch. Stripper q/A = 1/16 → 1/8
LINAC
70 MHz IH LINAC CAVITIES : # 4, 5 & 6
1.3 MeV/u
4-5 MeV/u (10$^5$-10$^9$ pps)

# VECC RIB facility layout




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

# Thick target development :

→Selection of suitable target material

ThermoCalc, Chemsage, HSC

(Data based thermo-chemistry & thermodynamic codes)

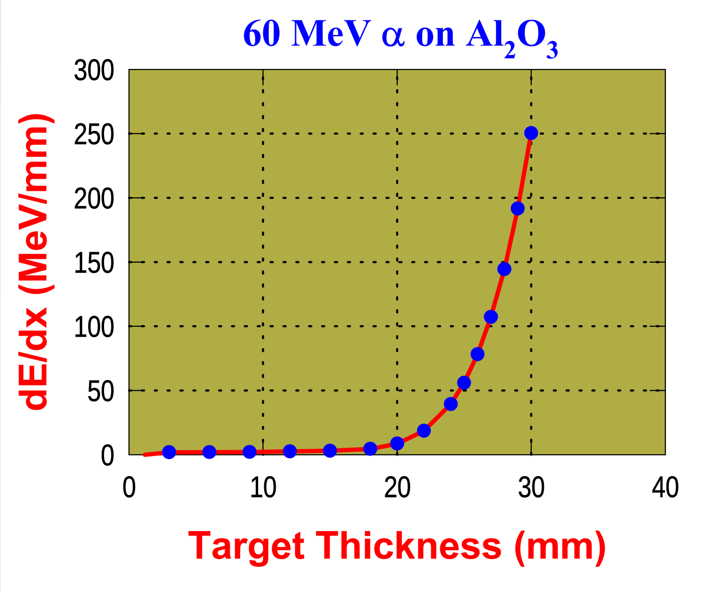
High dissociation temperature and low vapour pressure

→ Optimisation of the target geometry

Analysis of time dependent diffusion rate solving Fick's second equation for different symmetries like planner, cylindrical and spherical

→Optimising target thickness

Heat deposition in the target is calculated using TRIM – heat deposition within the target sharply increases near the Bragg peak window.

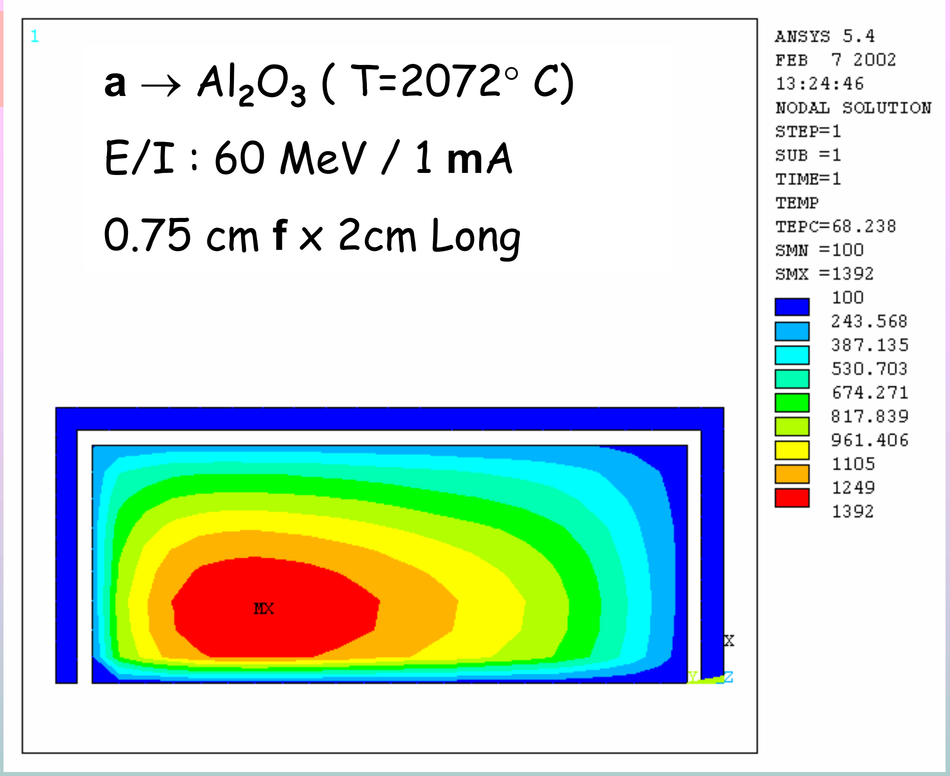


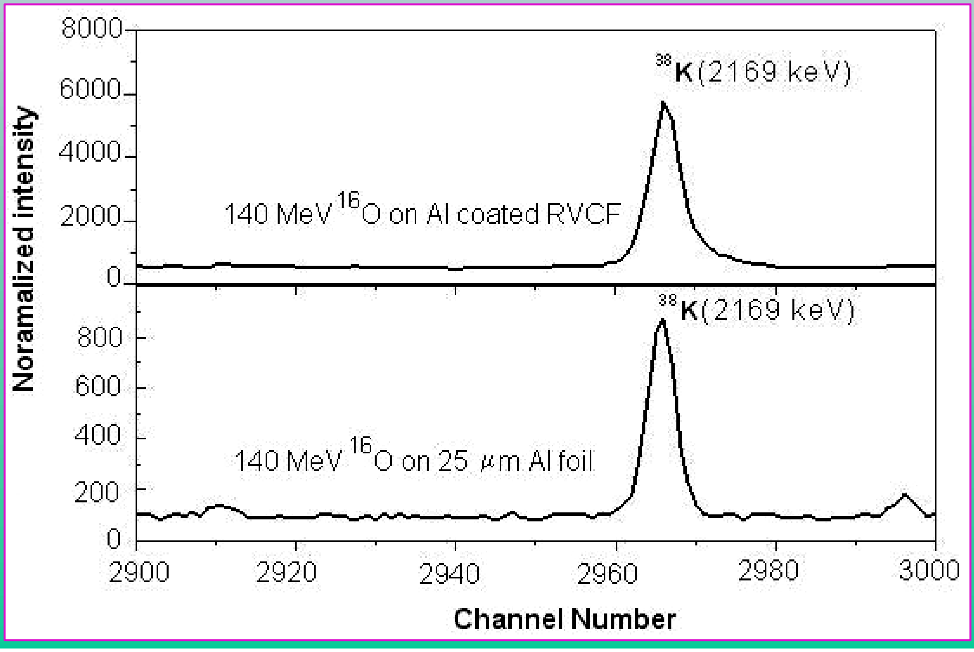
# Thick target development :

→ Temperature distribution (ANSYS)

The critical temperature is determined from critical vapour pressure

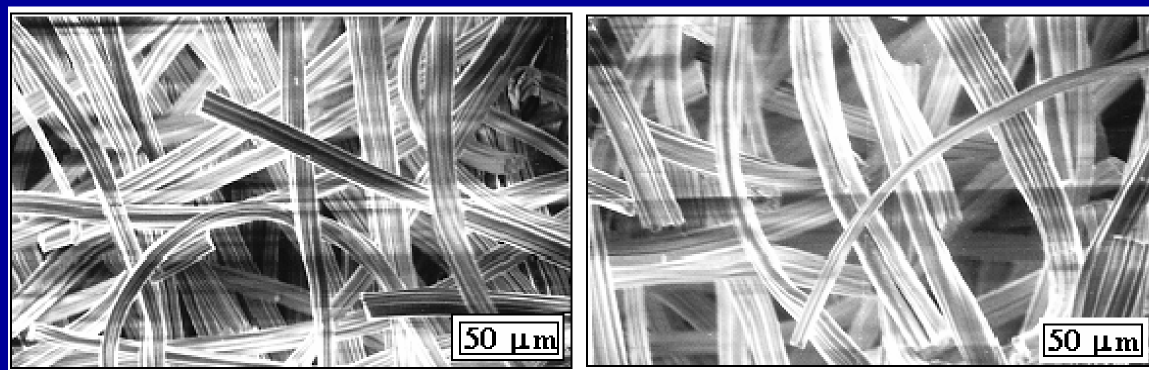
→ Maximise surface to volume ratio of the target i.e. porous / fiber like target matrix



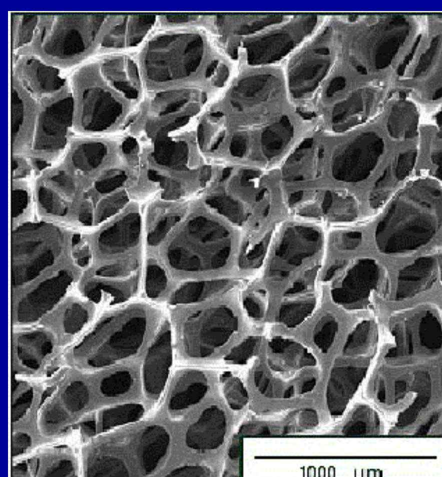



# Thick target R&D : first few targets

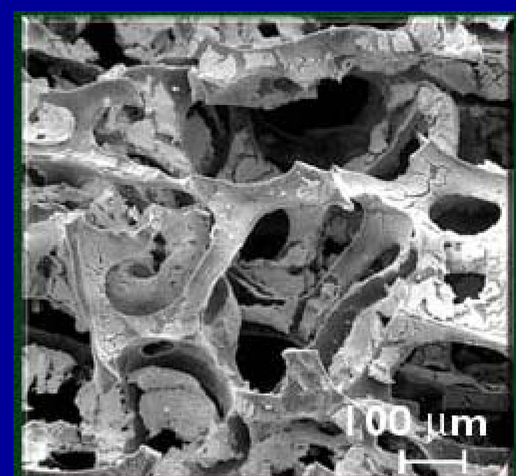
**Carbon* , $Al_2O_3$, ZnO, $HfO_2$, BN, LiF, MgO, $CaCl_2$, $ThC_2$, $UC_2$, $ZrO_2$**




**SEM of $Al_2O_3$ & $HfO_2$**




**SEM of RVCF**




**SEM of RVCF + $Al_2O_3$**

*RVCF : Reticulated Vitreous Carbon Fiber

## R&D Initiative on ion source :

- *Aim* → High On-line Efficiency for high charge States (q/A> 1/14)
- Apparent Choice → ECR ion source

**Problems**

- Poor vacuum (target evaporation) → high q !!!
- Neutron damage of permanent magnets

**Possible solution** → Two ion source philosophy

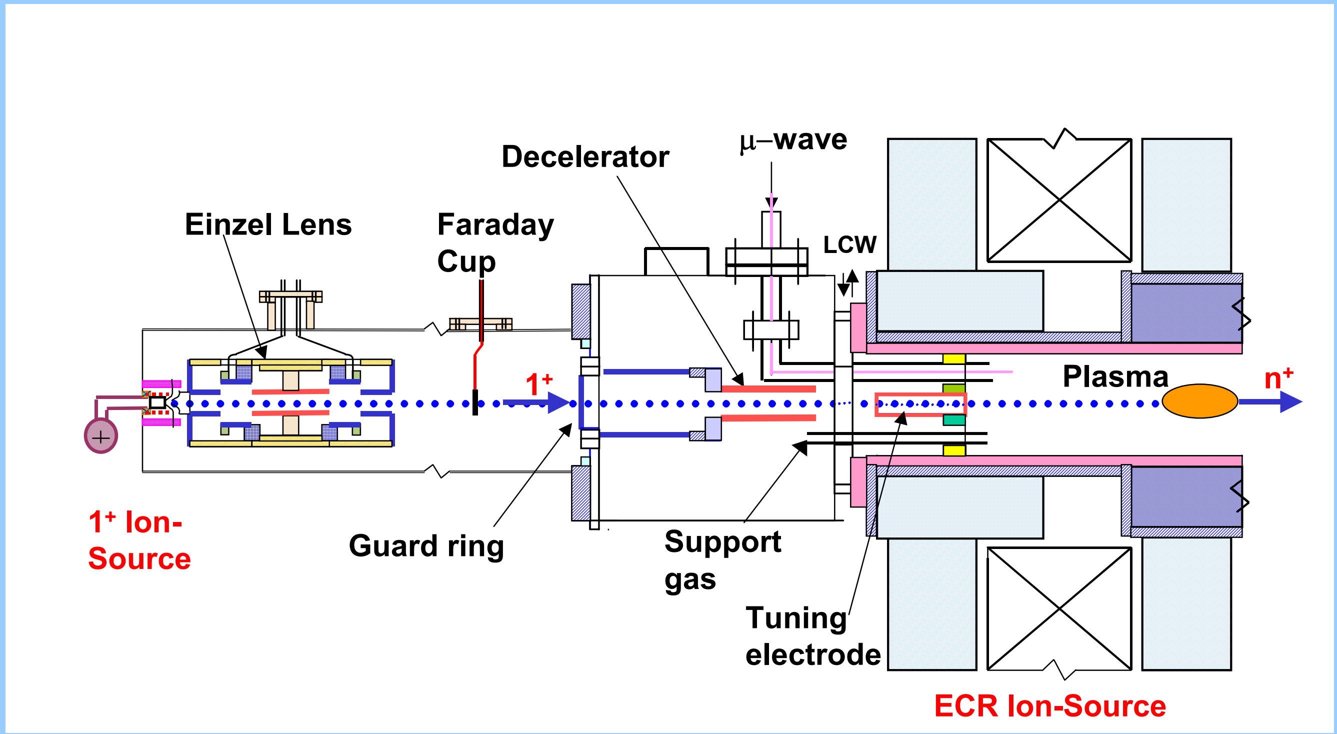
**Principle**

- Two I.S. in cascade – EBPIS & ECR in our case
- First I.S. provides $q=1^{+}$ even in poor vacuum
- Transported to ECR at a distance to get high q (Better vacuum and acceptable n-flux)

## R&D Initiative on ion source :

Integrated Target-ion source → $1^+$ RIB

ECR ion-source → $n^+$ RIB



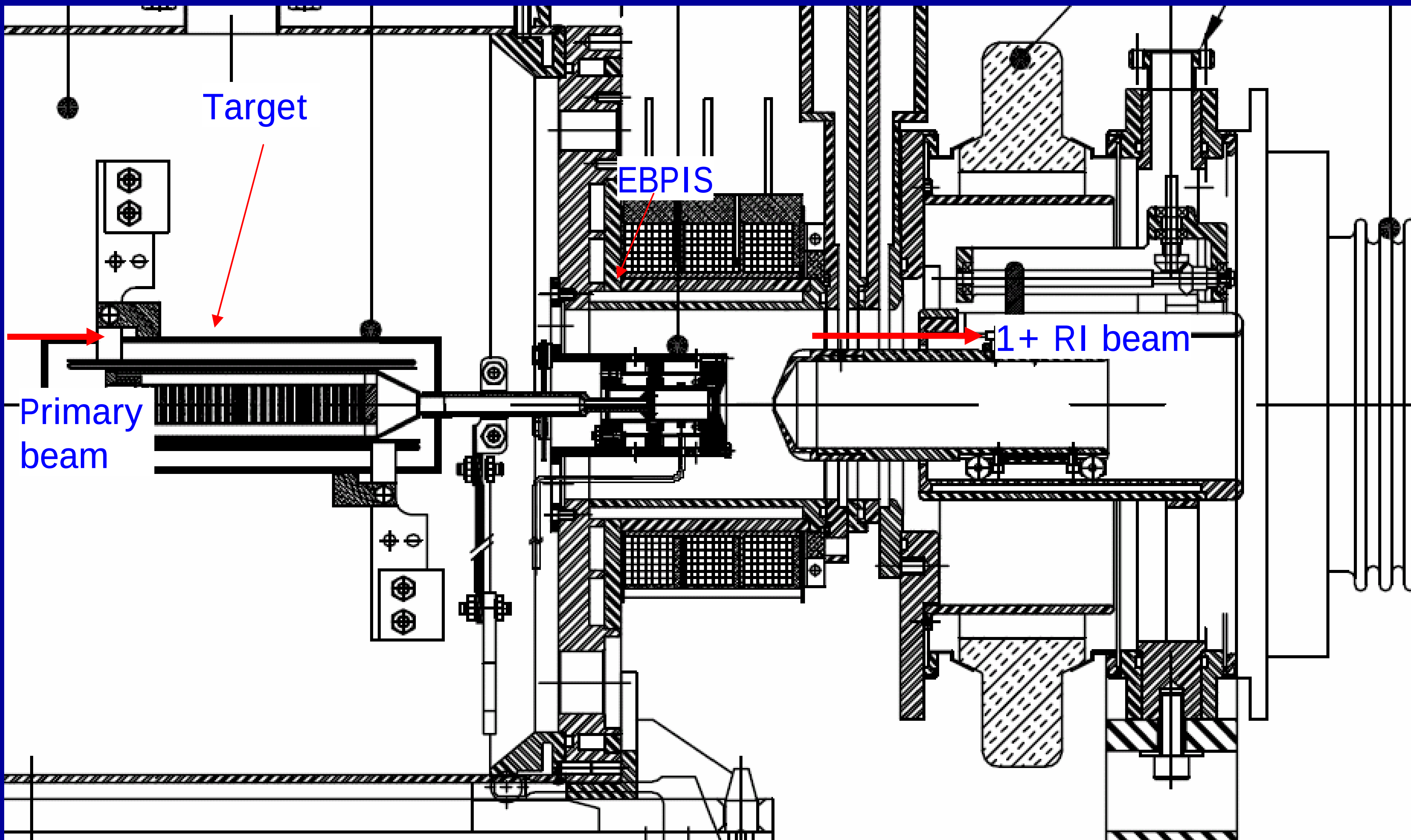

**Challenges**

- **Decelerate $1^+$ ions ~20 eV to ensure soft landing within ECRIS**
- **Optimised focussing to prevent beam loss**

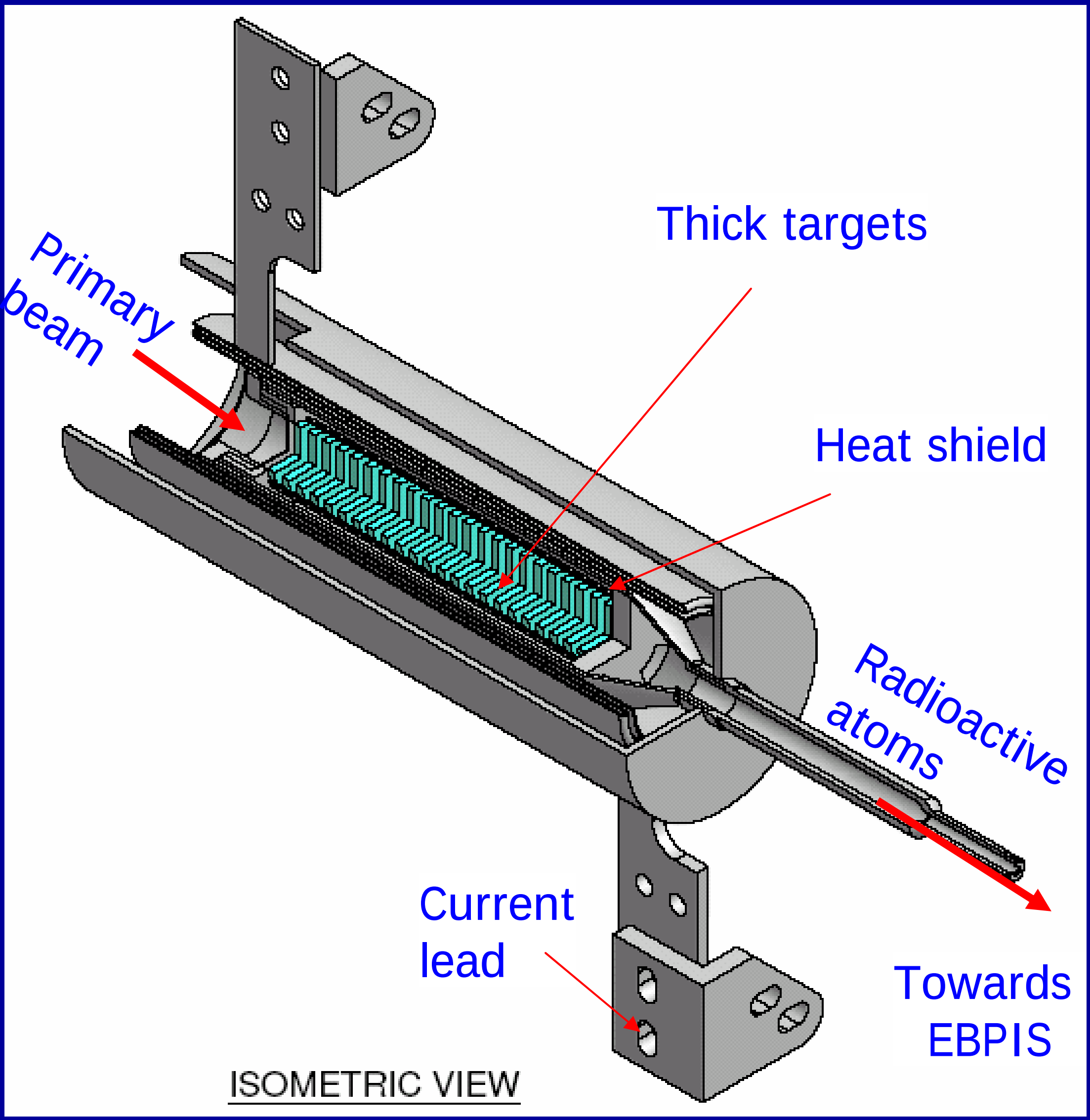
- **ECRIS : at safe distance ~ $10^{-6}$ mbar vacuum inside plasma chamber**
- **ECR permanent magnets protected from high radiation near target**

**R&D Initiative on ion source :**

# Integrated Thick-Target Electron Beam Plasma Ion-Source

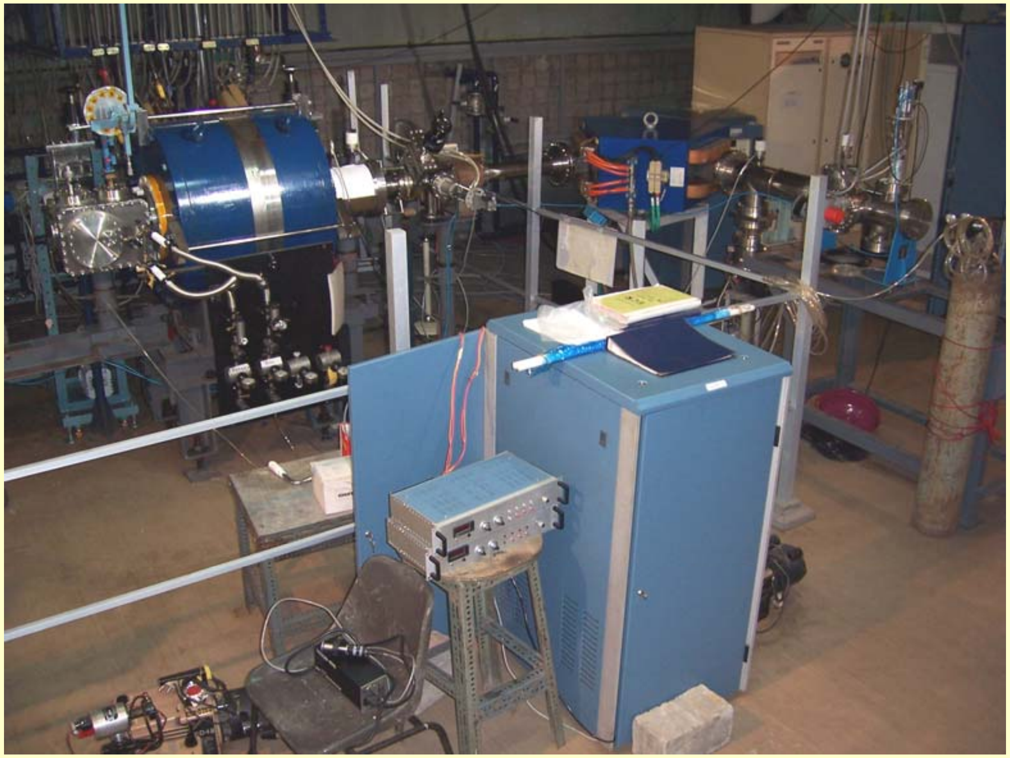


## R&D Initiative on ion source :



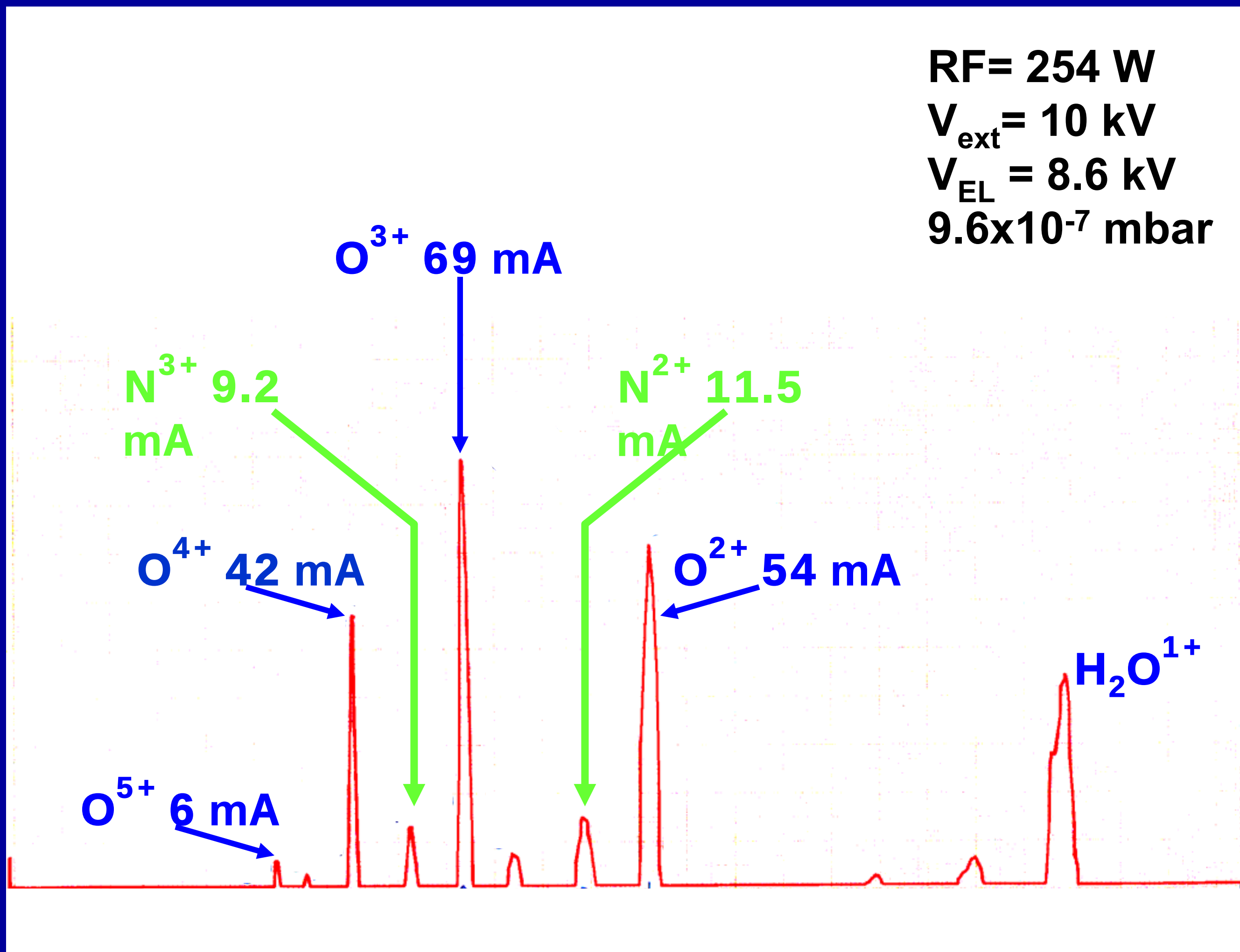

Target holder

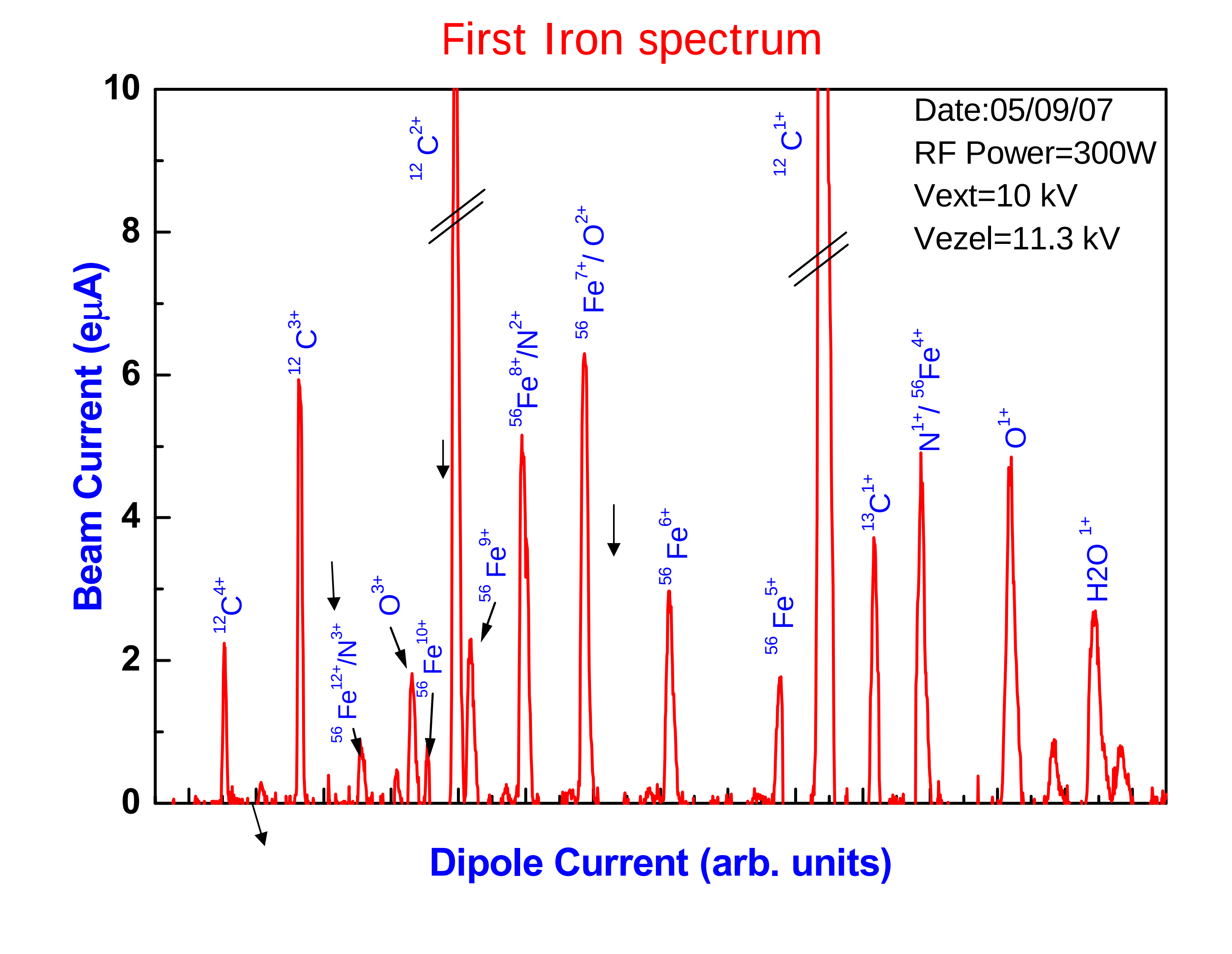
## R&D Initiative on ion source :



| | |
|---|---|
| Frequency | 6.4 GHz |
| Klystron / Sol. Power | 3 / 60 kW |
| $B_{ECR}$ | 0.23 T |
| $B_Z$(Inj) / $B_Z$(Ext) / $B_r$(r=R) | 0.95 / 0.7 /0.7 T |
| Mirror Ratio (Inj/Ext) | 5.9 / 4.375 |

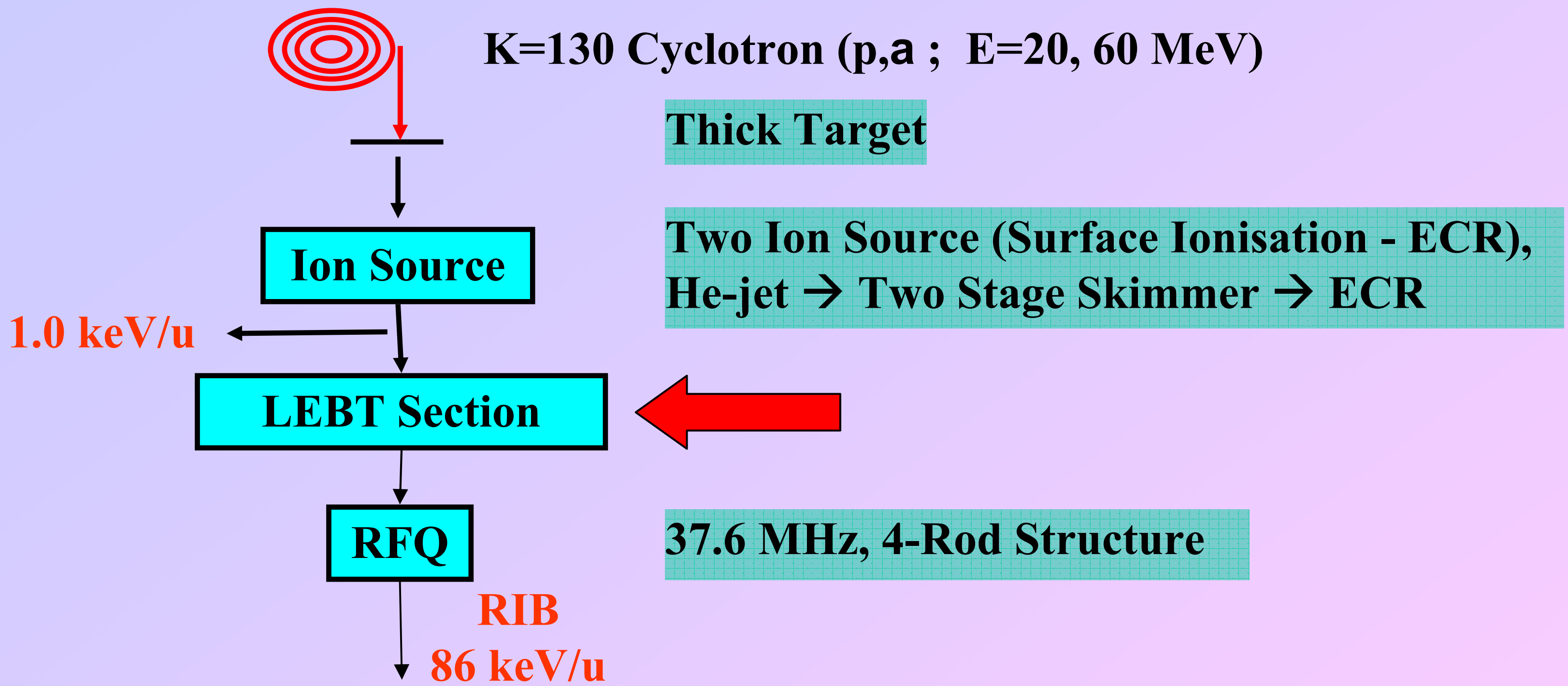
# Typical Oxygen spectrum from ECR ion-source






Ferrocene $C_5H_5FeC_5H_5$

# Design & Development of LEBT section between on-line ECRIS & RFQ



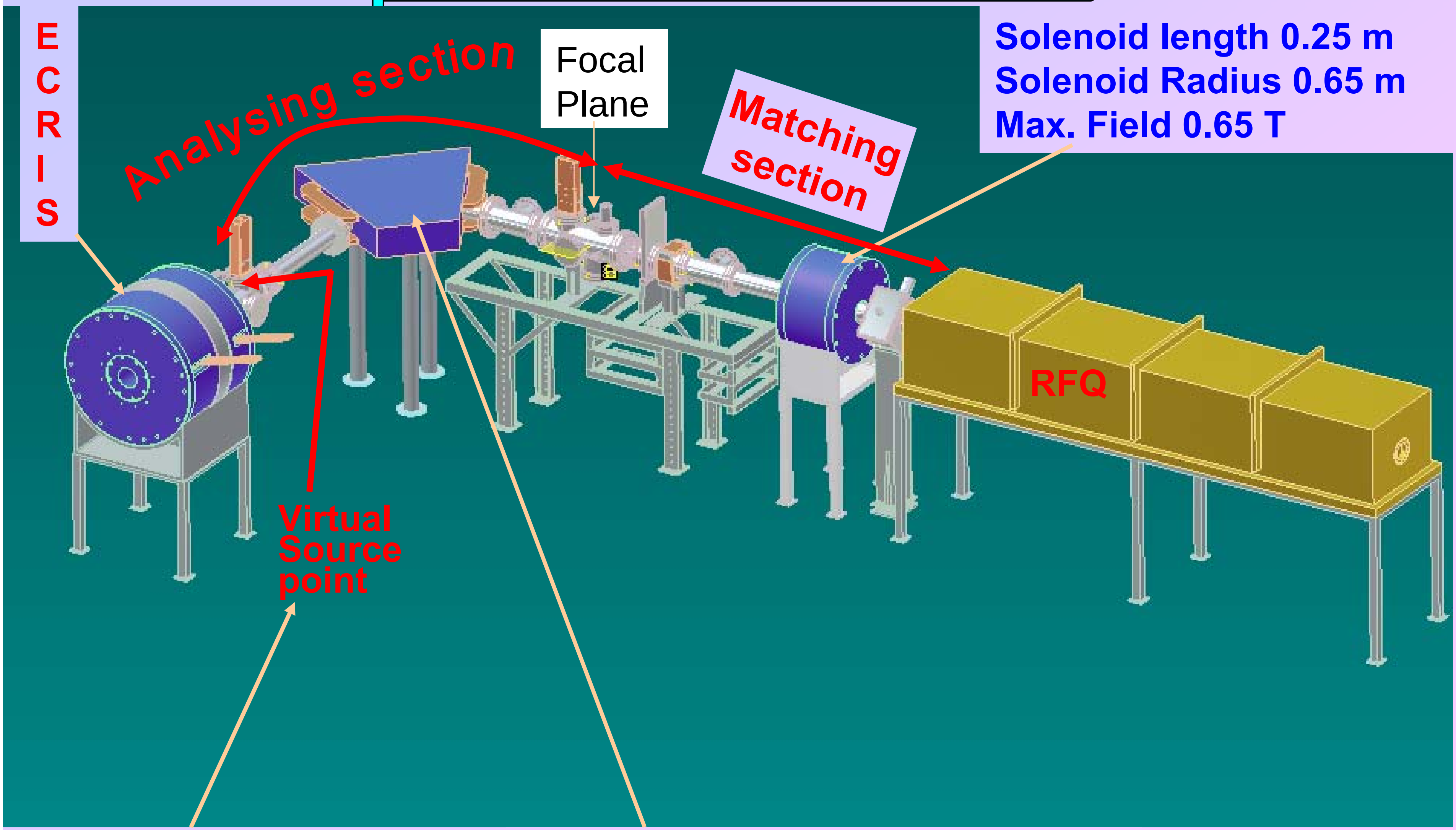

## Design Aims :

- Initial separation of the RIB of interest having optimum q from the rest.
- Transverse matching of the selected RIB to the acceptance of the RFQ.

## Challenges :

- Maximum transmission & RP even with high emittance beam from IS (ECR).
- Minimum floor space & number of optical elements.

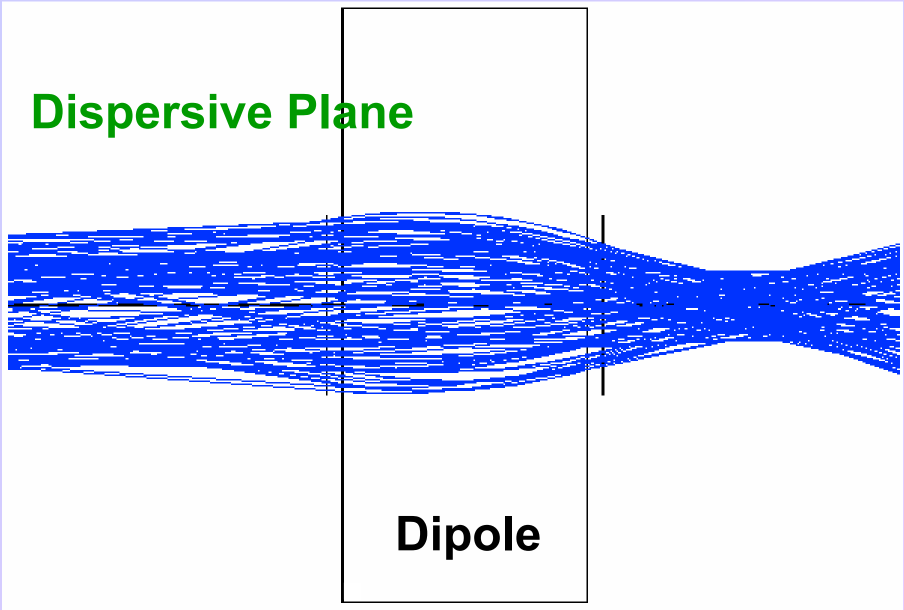
# Low Energy Beam Transport section

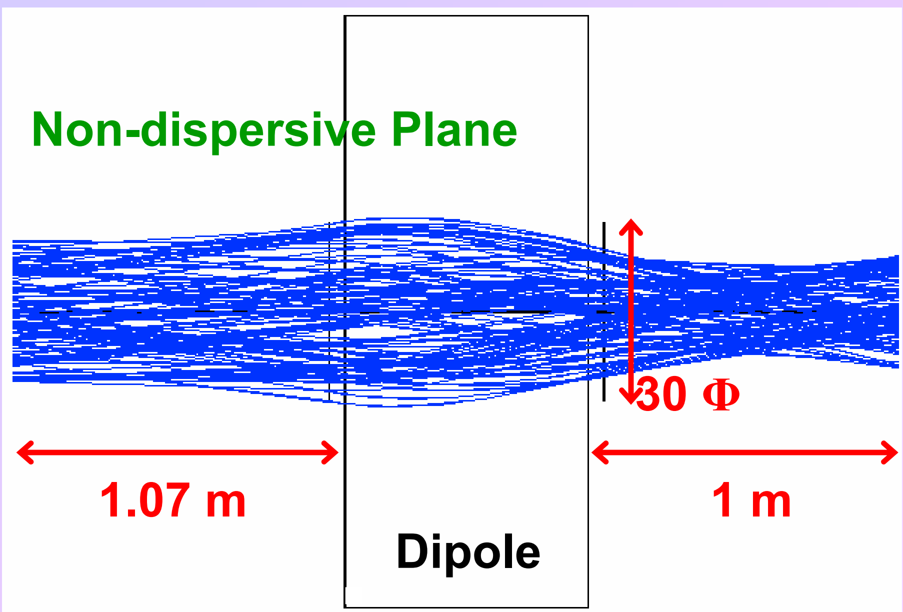


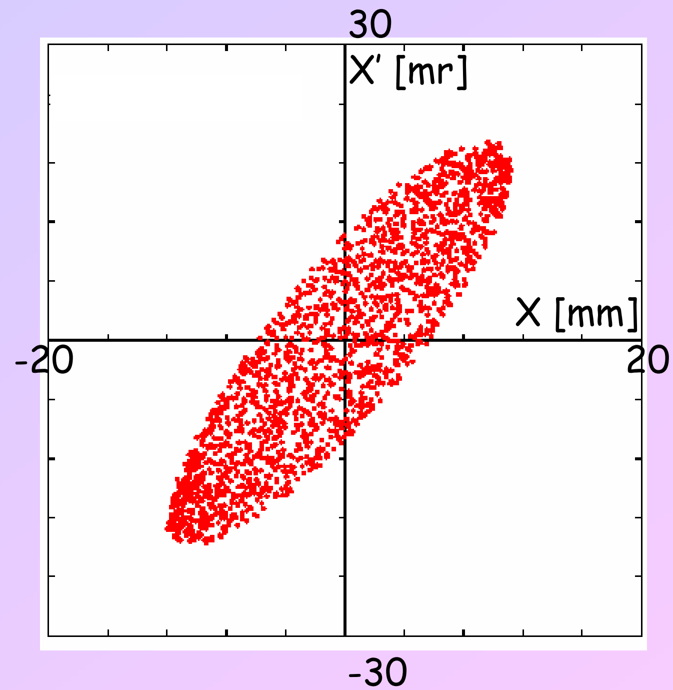

**Erect Ellipse**
**e = 120 π mm mrad**
**(± 1.2 cm / ± 10 mrad)**

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

# Optics for the analysing section of the LEBT design

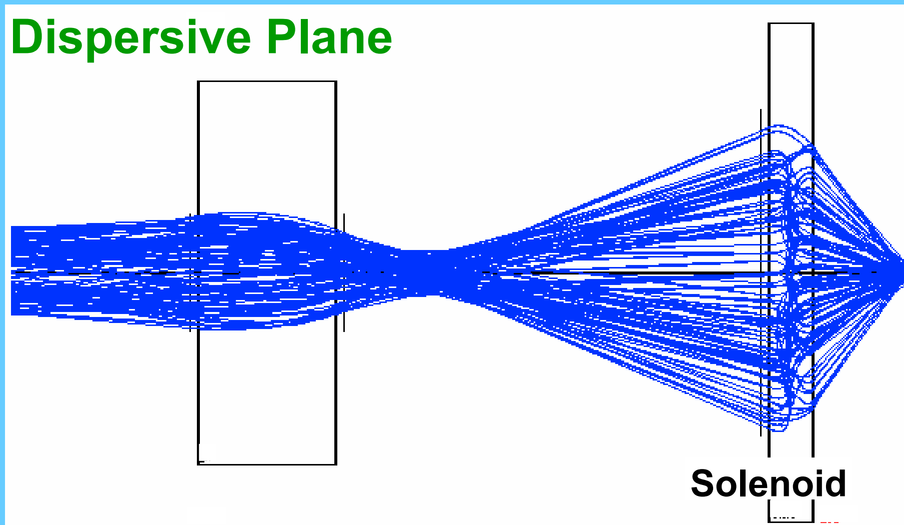


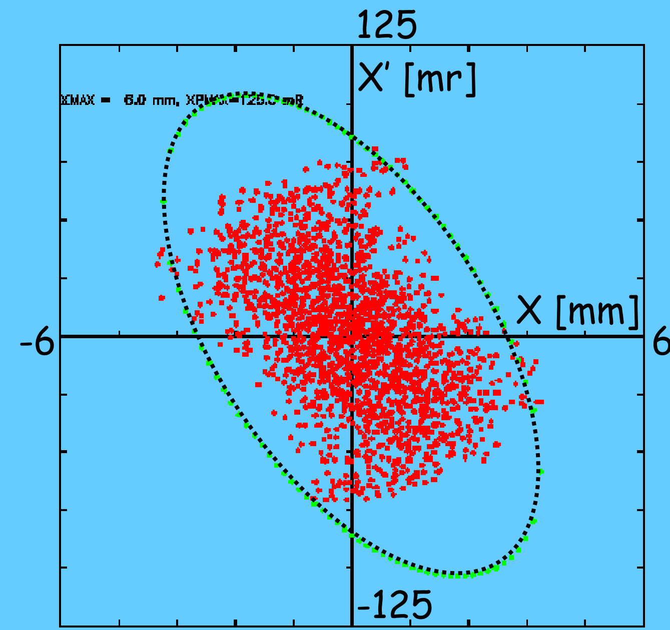



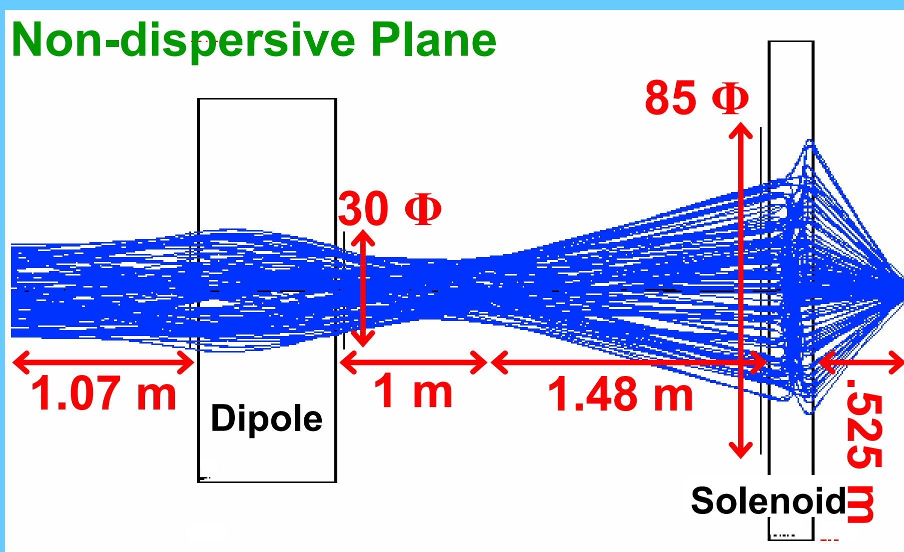

| | |
|---|---|
| Configuration | Drift-Dipole-Drift |
| Acceptance | 120 π-mm-mr. (Full Transmission) |
| System Length | 2.855 m |
| Dispersion | 1.98 m (for 100% rigidity change) |
| Mass R. Power | 43 (3rd order) |
| Magnification | -0.95 |

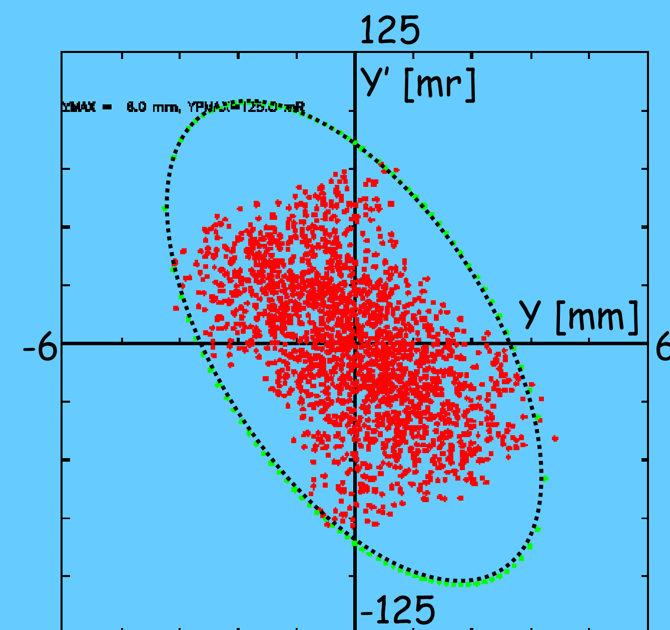
# Optics for the LEBT section




**Transmission 98.8 %**



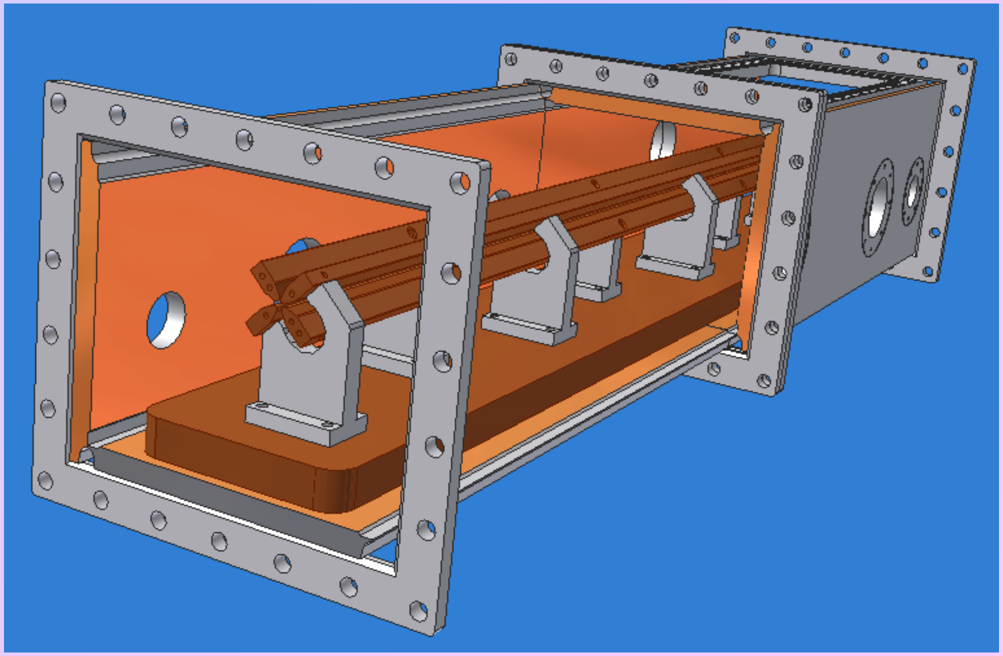



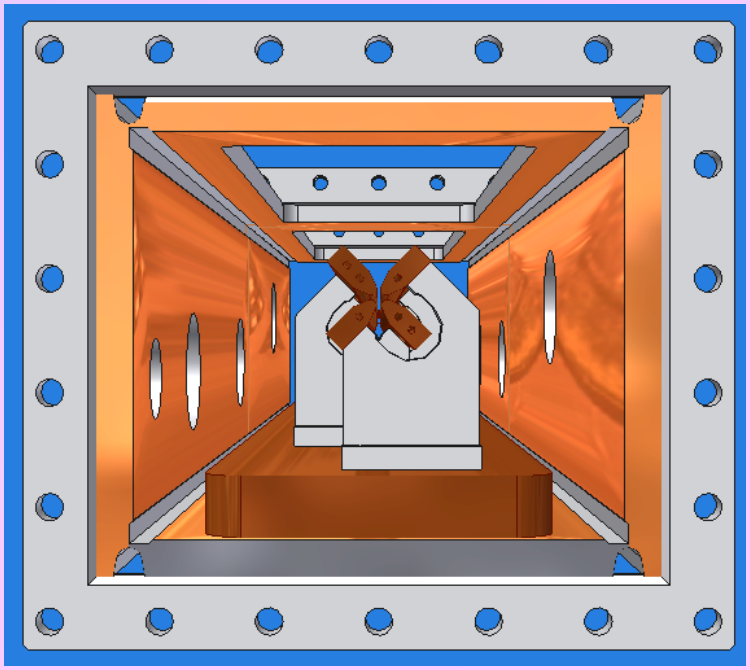
# Design of Radio Frequency Quadrupole (RFQ)

**Design Aim : Acceleration of RIBs (q/A≥1/16) from 1 keV/u to about 90keV/u**

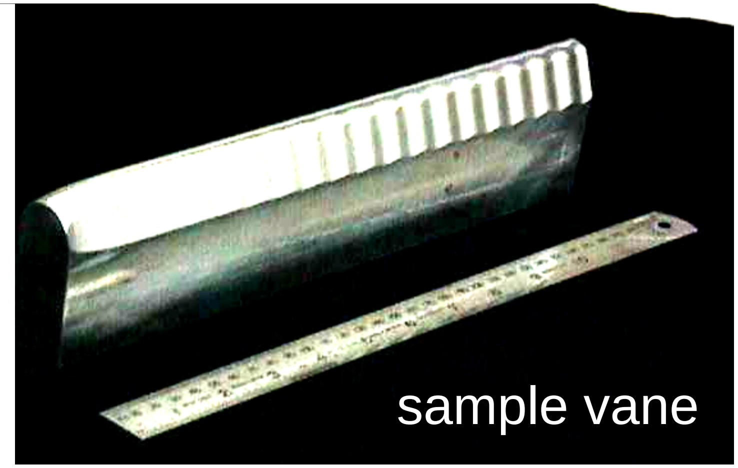
**RFQ : Single RF structure capable of bunching, focussing and accelerating low energy ( ~ keV) ions**

**However → Designing Machining and aligning**





# Vane mac




Vane profile from PARMTEQ

⇓

Co-ordinates of Surface

⇓

3D modelling of profile

⇓

Optimum tool path generation

⇓

Machining of vane

⇓

Check co-ordinates (CMM)
&
surface finish (Talysurf)

| Requirement | Sample vane |
|---|---|
| $\Delta/r_0 \leq 0.5\%$ for good transmission : $\Delta \sim 30 \mu m$ | ~20 mm |
| Skin Depth d~11 mm<br>Rt ≤ 2.2 mm | ~2mm |

# RADIOFREQUENCY QUADRUPOLE (RFQ) : 1$^{st}$ in India

আনন্দবাজার পত্রিকা ১৫ আশ্বিন ১৪১২ শনিবার ১ অক্টোব

সংক্ষেপে ...

## পরমাণু বিজ্ঞানে নয়া সাফল্য ভারতের

স্টাফ রিপোর্টার ✧ কলকাতা

জাপানের পরে এ বার ভারতেও রেডিও ফ্রিকোয়েন্সি কোয়াড্রুপল 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।

THE HINDU

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

## National

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National

### India joins select club in particle technology

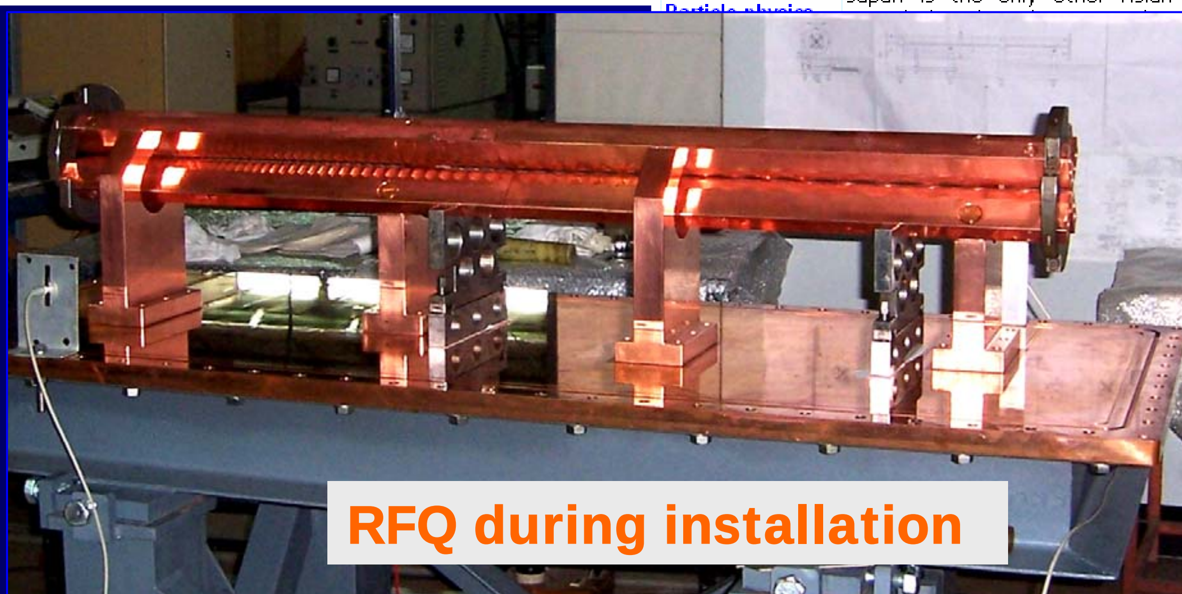
Special Correspondent

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.

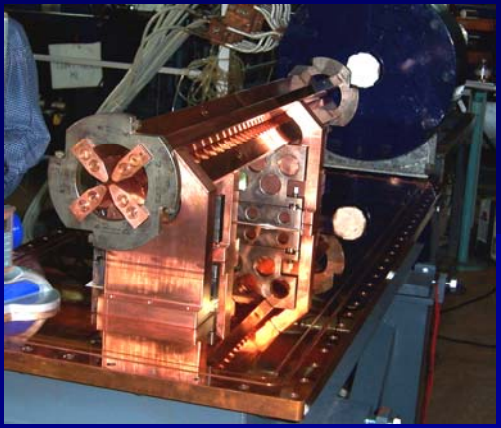
Scientists from across the world have acknowledged the achievement as a hall-mark development in particle accelerator technology in the country, VECC officials told *The Hindu* on Tuesday.

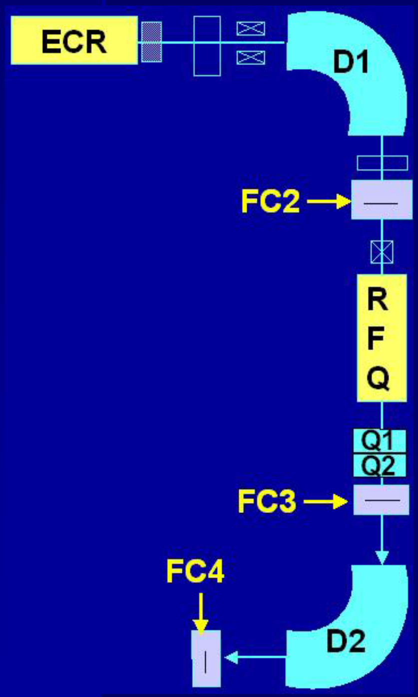
Japan is the only other Asian country to have successfully ... r which was tried out on a ... st time in the United States of ...

... lz] cavity of very pure copper ... ed vanes which takes care of ... using of ion beams", according



RFQ during installation






## Experimental Results: Test Beam: Ar 4+

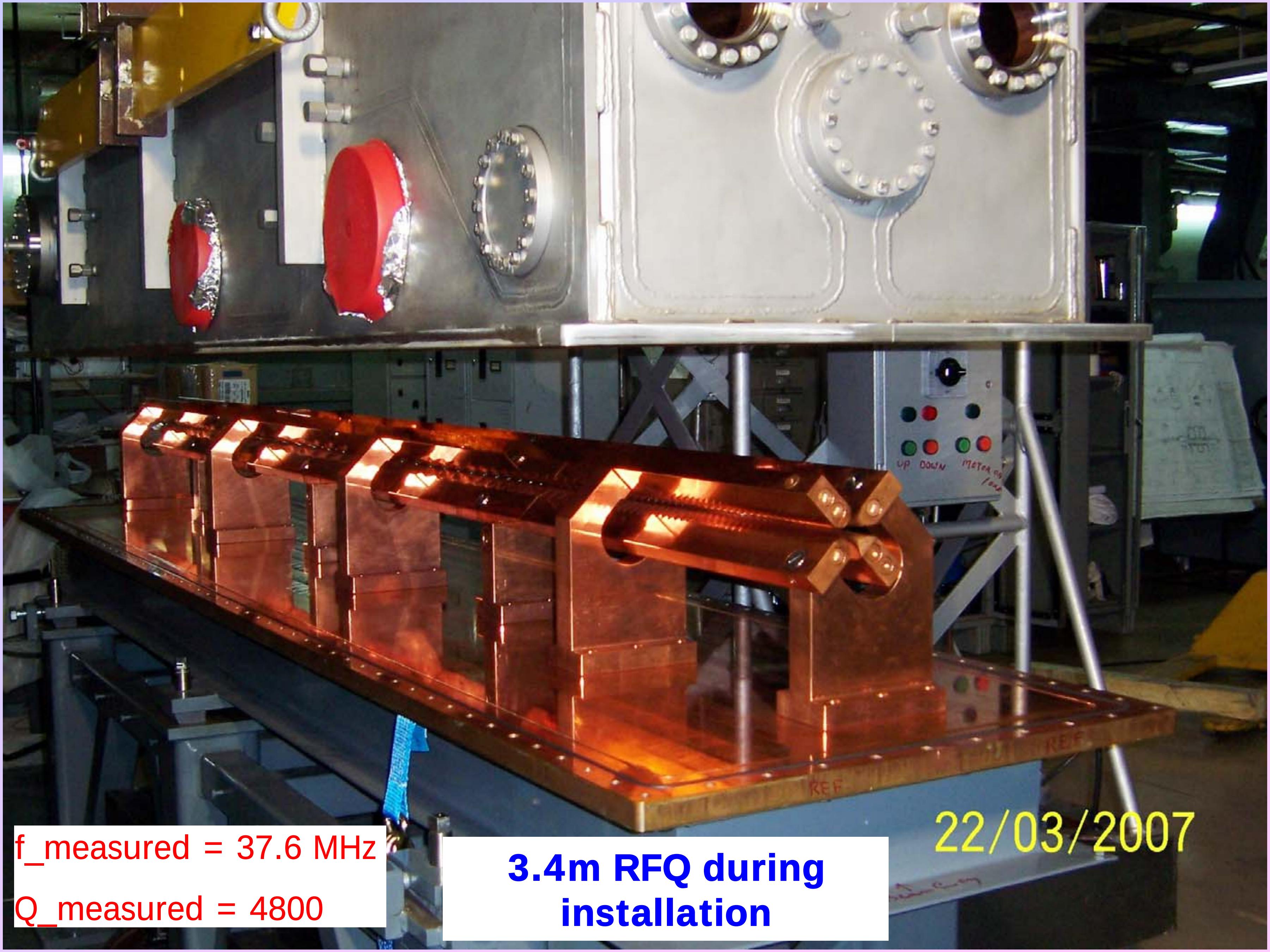
| Calculated magnetic strength (kG) (29.06 keV/u) | Experimental magnetic strength (kG) | Transmission Efficiency* % *with electron suppression |
|---|---|---|
| Q1: -1.528<br>Q2: 1.065 | Q1: -1.53<br>Q2: 1.057 | ~81%<br>FC3/FC2 |
| Q1 : -1.07<br>Q2: 0.7<br>D2 : 2.058 | Q1: -1.058<br>Q2: 0.82<br>D2: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

## 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*

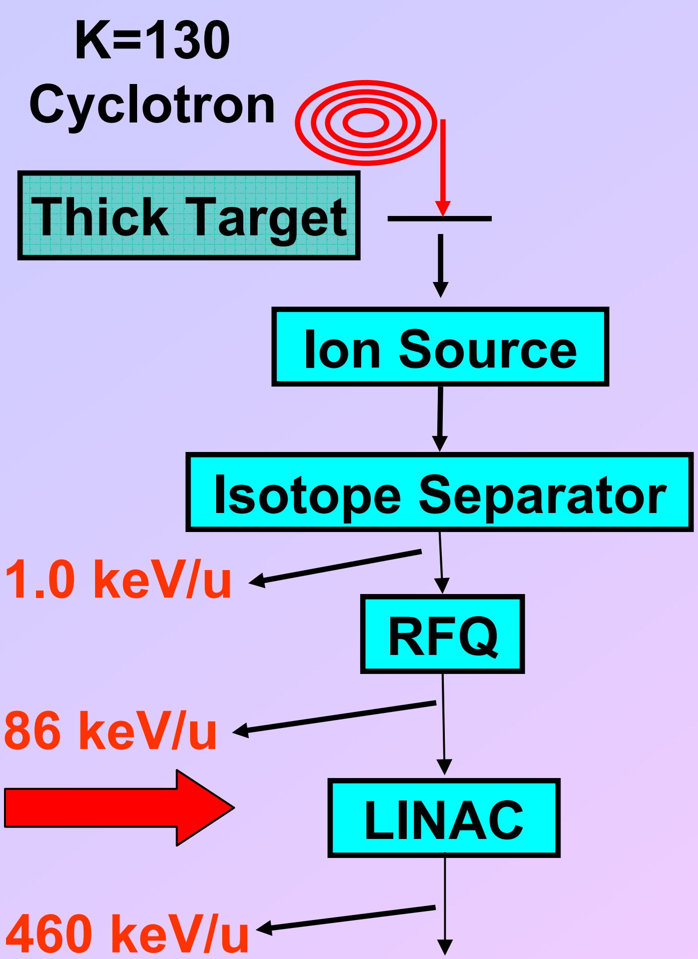



f_measured = 37.6 MHz

Q_measured = 4800

**3.4m RFQ during installation**

# Design of LINAC cavities




**Design Parameters**

- q/A ≥ 1/14
- $e_n$ ≥ 0.5 p-mm-mr
- $T_{in}$ = 86 keV/u

**Design goals**

**Beam Dynamics :**

→ Maximising Transmission

→ Energy tunability

→ Good beam quality (DE, Dt)

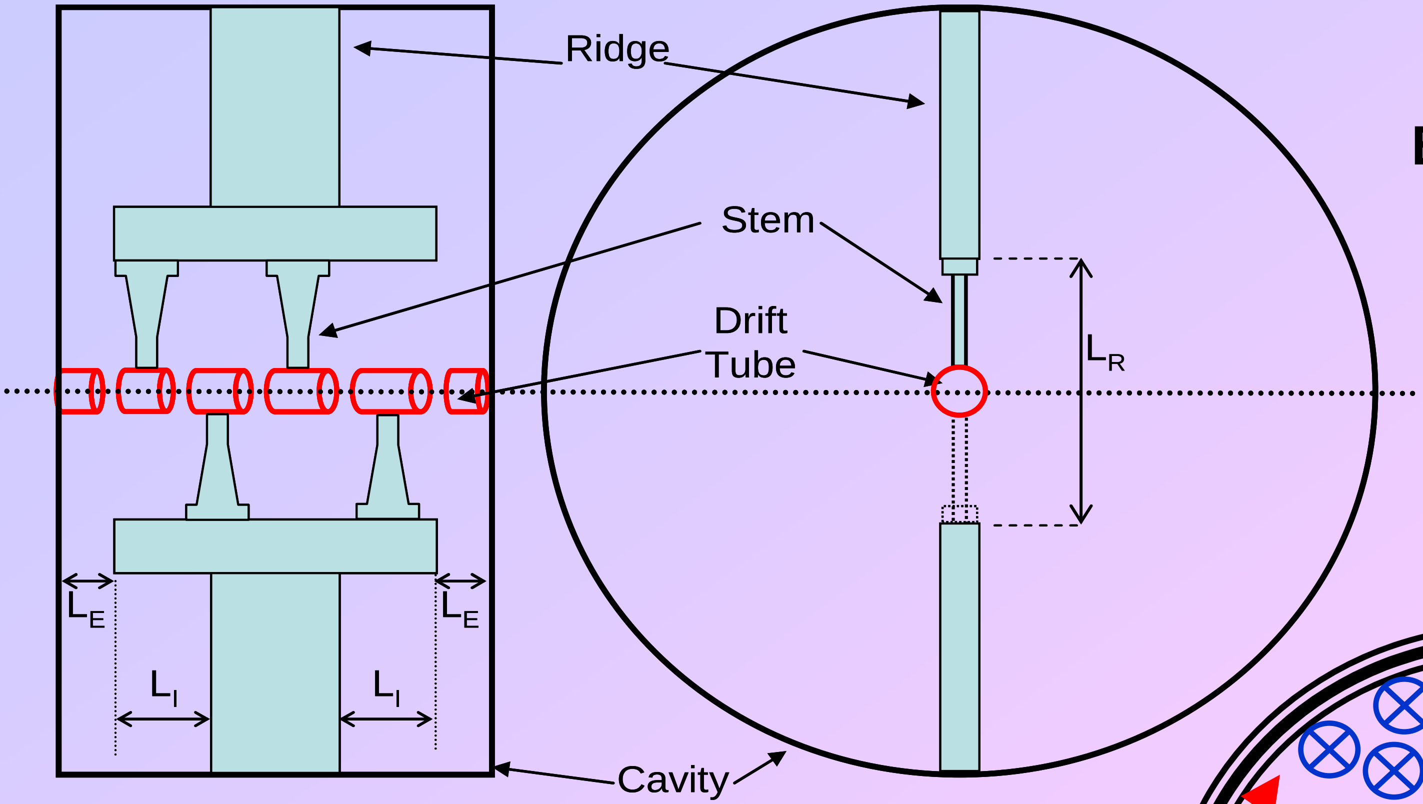
**RF Analysis :**

→ Getting the desired frequency

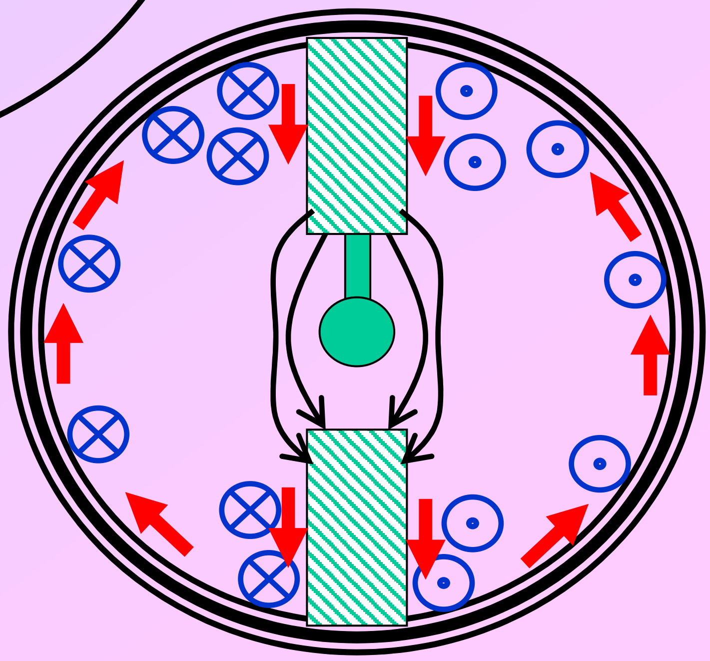
→ Optimisation for best shunt impedance

→ Surface current density at the junction of two components should not be high

# IH - LINAC :




**Excitation mode :**
**TE111 or H**



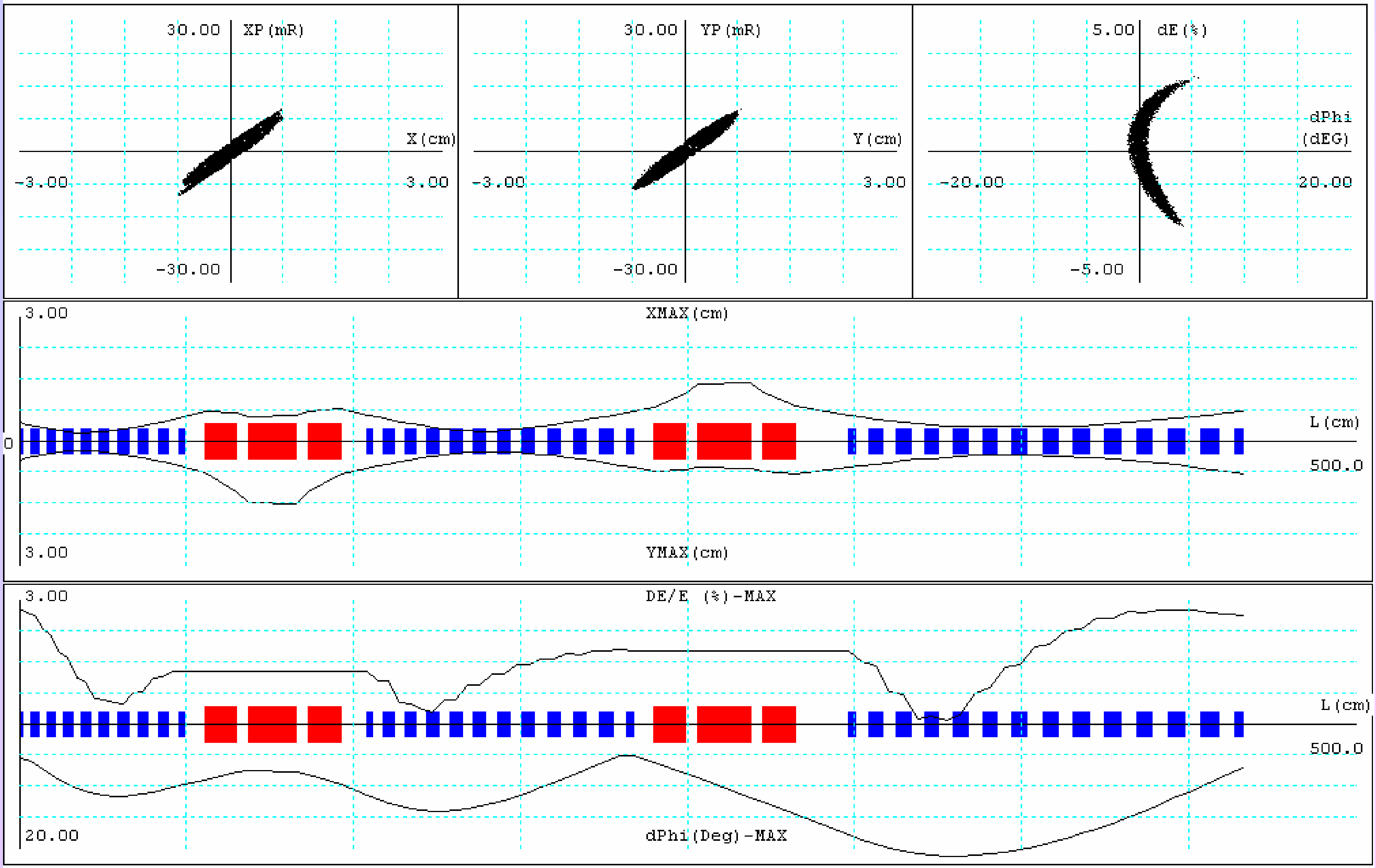
Magnetic Flux

Electric flux

RF Current

# VECLIN Snap shot

**$\varepsilon_{x/y}$ = 0.5 π mm mrad & $\varepsilon_z$ = 10 π-deg-%  A=16**

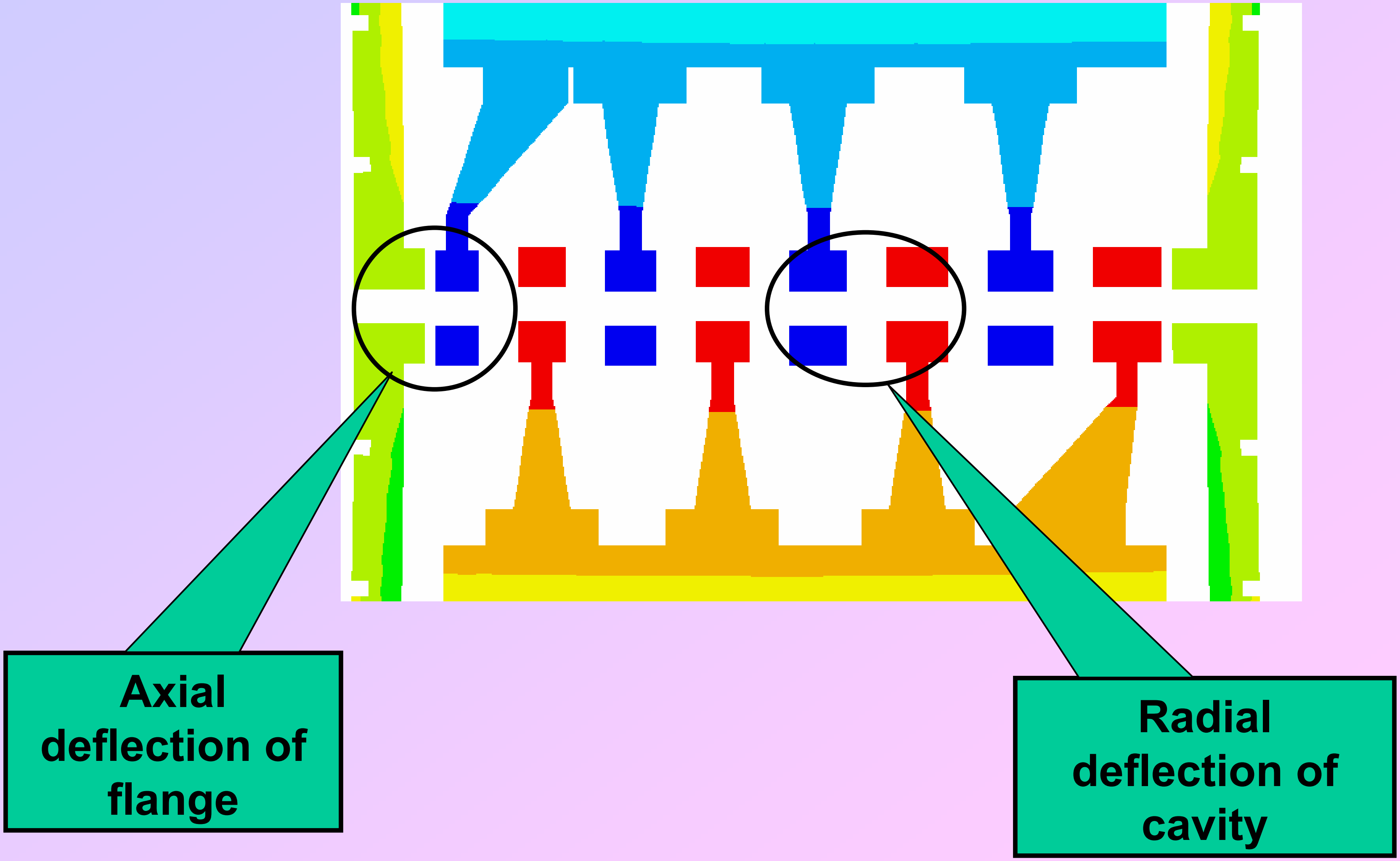



**Inter-tank space 75 cm**
**Quads → L=21+14+21 cm / Aperture rad 2.85 cm / Gradient 30 T/m**

## IH - LINAC : The design details

**6. Engineering Analysis** **ANSYS**

**Structural deflection under various loads :**
**(a) Atmospheric pressure (b) Self weight (c) Thermal flux due to RF**



## IH - LINAC : The design details — Structural Deflection

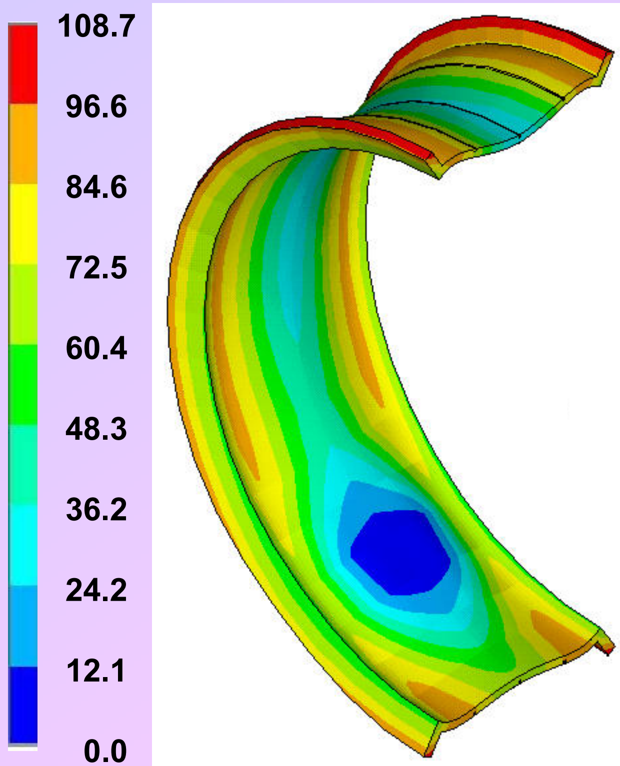
**The effects have been tried to minimise using :**

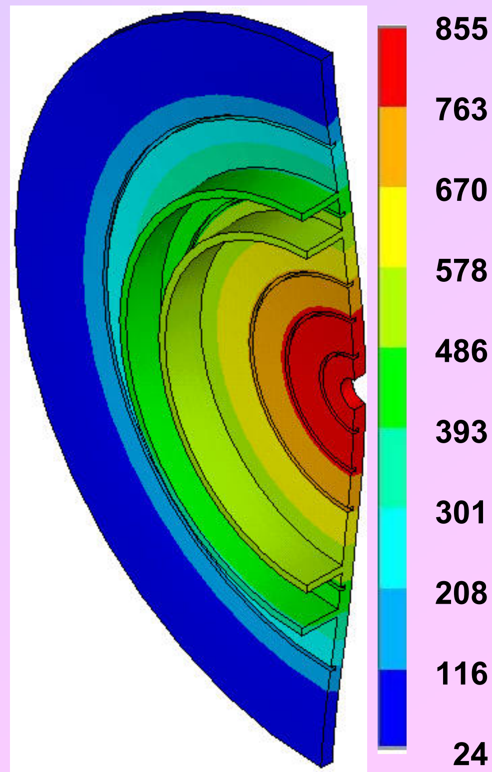
**(a) Proper thickness of the cavity materials :**
**Mild Steel – 25 mm (cavity) & 35 mm (End covers)**

**(b) Circular stiffeners on end covers : Two Nos.**

**(c) Cooling**

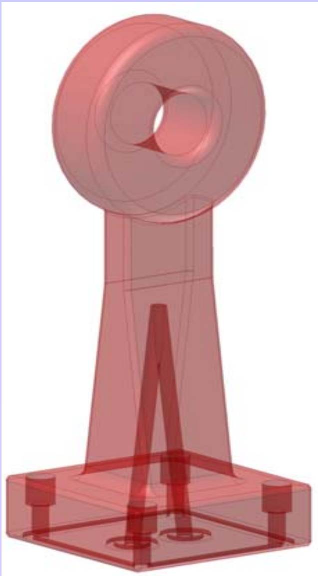
Vertical Deflection (mm)

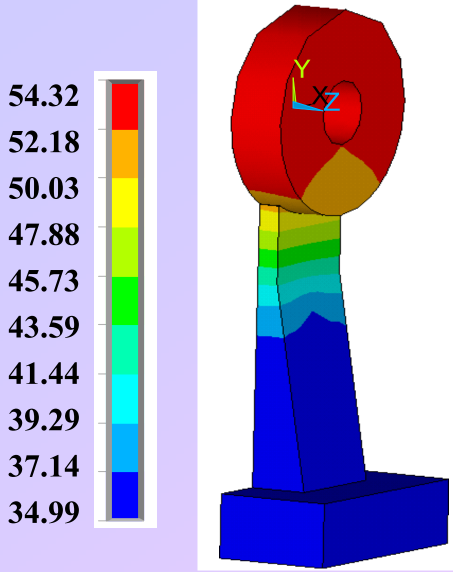


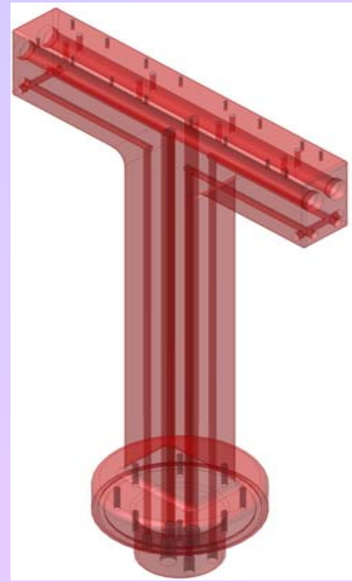



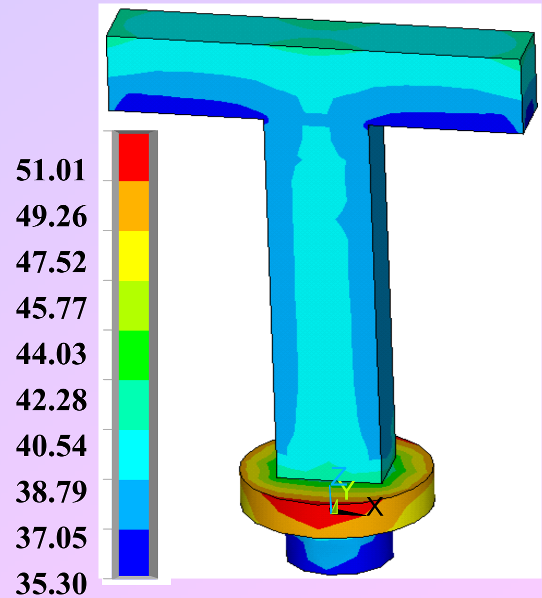

Axial Deflection (mm)

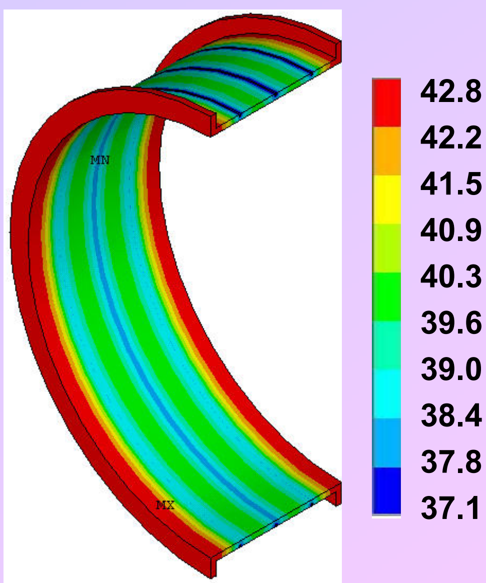
# IH - LINAC : The design details Temperature Distribution



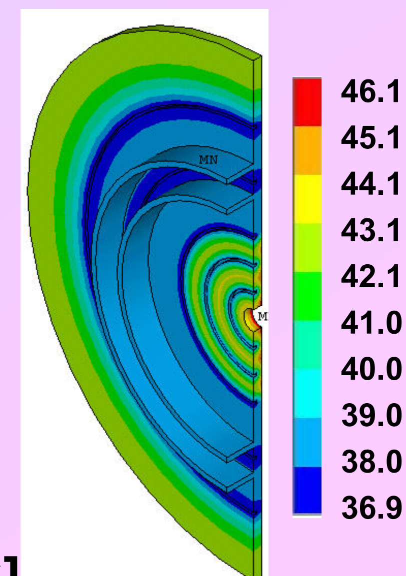




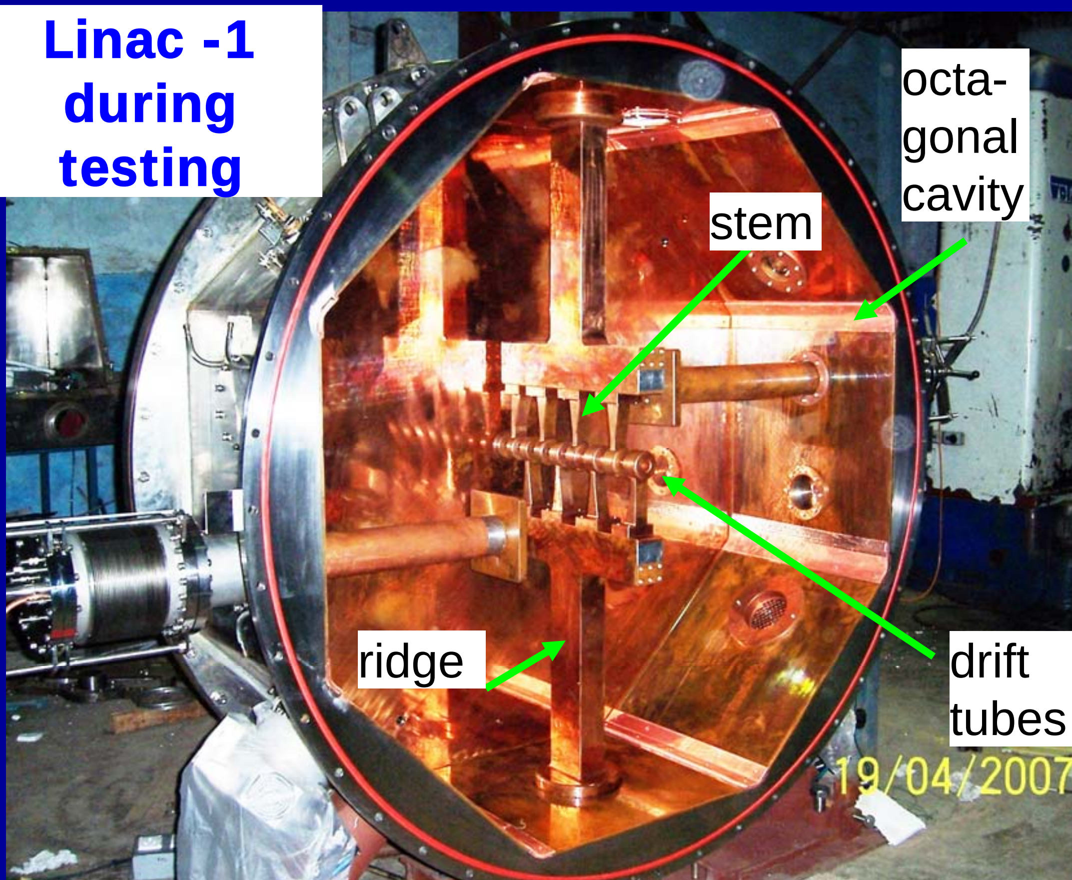

Temperature [°C]

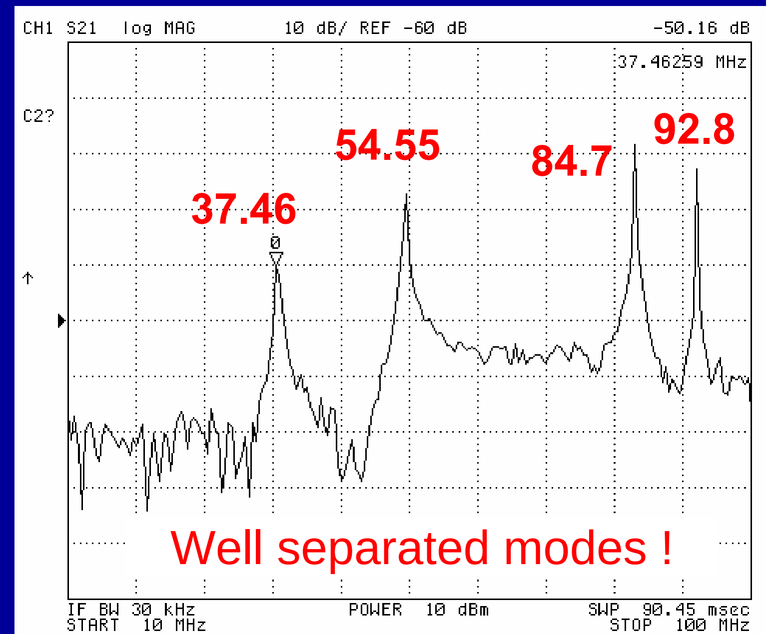


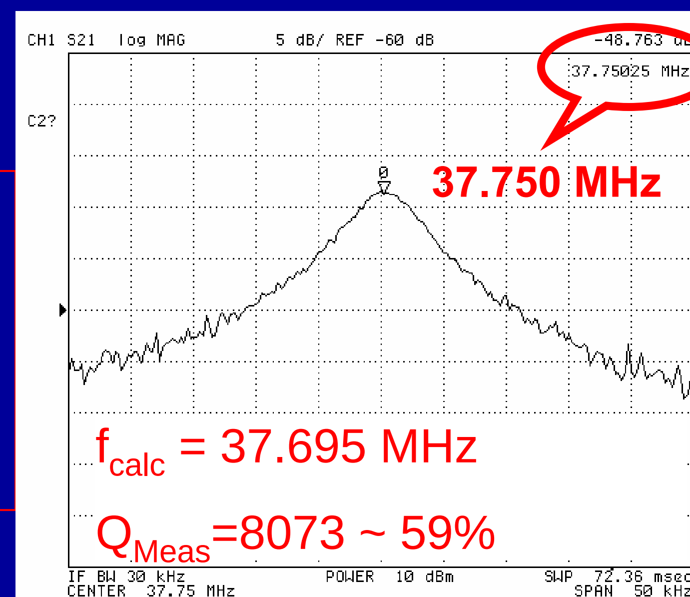
# LINAC-1 : Important Parameters

| | | |
|---|---|---|
| Frequency | MHz | 37.6 |
| q/A | | $\geq$ 1/14 |
| $T_{in} \rightarrow T_{out}$ | keV/u | 98.785 → 183.56 |
| $\beta_{in} \rightarrow \beta_{out}$ | % | 1.456 → 1.985 |
| Accelerating gaps | # | 9 |
| Drift tube I/D & O/D | mm | 25 & 69.5 |
| Drift tube gap | mm | 29.2 |
| Cell legth | mm | 58.4 → 78.8 |
| Peak D.T. voltage | kV | 101.24 kV |
| Max. Field | | 1.4 x $E_{Kilpatrick}$ |
| Transit Factor | | 0.789 → 0.843 |
| Sync. Phase | Degree | -24 |
| Cavity Length | M | 0.6182 |
| Accln. Gradient | MV/m per q | 2.102 |
| Shunt Impedance | MΩ/m | 342 |
| Q-Value | | 13765 |
| Power | kW | ~ 15 |

# Linac -1 during testing

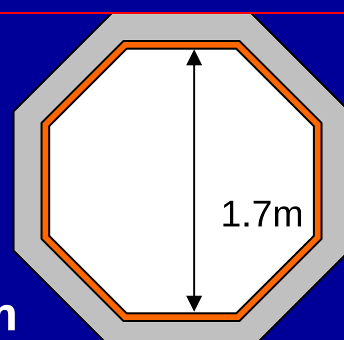



## CAVITY :

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

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03/12/2007

# LINAC-2 : Important Parameters

| | | |
|---|---|---|
| Frequency | MHz | 37.6 |
| q/A | | ≥ 1/14 |
| $T_{in} \rightarrow T_{out}$ | keV/u | 183.56 → 286.8 |
| $\beta_{in} \rightarrow \beta_{out}$ | % | 1.985 → 2.481 |
| Accelerating gaps | # | 10 |
| Drift tube I/D & O/D | mm | 25 & 60 |
| Drift tube gap | mm | 39.8 |
| Cell legth | mm | 79.6 → 98.4 |
| Peak D.T. voltage | kV | 107.5 kV |
| Max. Field | | $1.3 \times E_{Kilpatrick}$ |
| Transit Factor | | 0.8045 → 0.8506 |
| Sync. Phase | Degree | -25 |
| Cavity Length (Inner) | M | 0.871 |
| Accln. Gradient | MV/m per q | 1.79 |
| Shunt Impedance | MΩ/m | 432 |
| Q-Value (Calc.) | | 18856 |
| Power (Calc.) | kW | ~ 10 |


MVR35
MITSUBISHI
13/02/2008

# First few beams →

| RIB | T1/2 | Production | 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- |

$$I_{RIB} = I_{Pri} \cdot N_t \cdot \sigma \cdot \eta_{release} \cdot \eta_{IS} \cdot \eta_{separation} \cdot \eta_{transport}$$

$$= \frac{10^{-6}}{\left(1.6 \cdot 10^{-19}\right)} \cdot \left(6 \cdot 10^{23}\right) \cdot \left(50 \cdot 10^{-3} \cdot 10^{-24}\right) \cdot \underbrace{0.1 \cdot 0.05 \cdot 0.6 \cdot 0.5}_{0.15\%} \approx 10^{9}\ pps$$

1mA    $1 g/cm^2$    50 mb

**Expected average yield at experimental station ~ $10^6$-$10^8$**

# Future Plans

# LINAC : What Next ???

**LINAC-1 : 98.785 → 183.56 keV/u**

- Installation at VECC have started : To be completed by 15th Oct, 2007
- Installation in beam line : April 2008

**LINAC-2 : 183.6 → 286.8 keV/u**

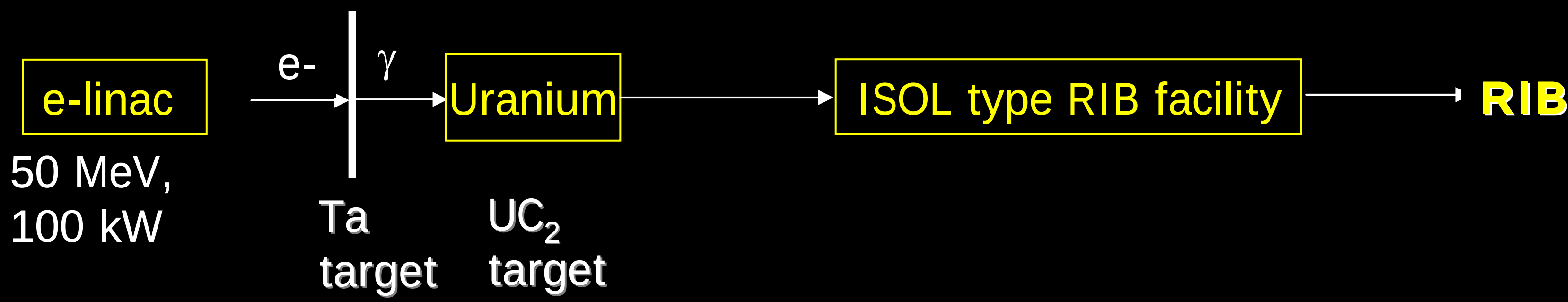
- PO placed
- Delivery schedule : Mar 2008
- Installation in beam line : Sep 2008

**LINAC-3 : 286.8 → 450 keV/u**

- Advanced stage of design
- Likely completion date : Dec 2008

**LINAC-4 to LINAC-8 : (To be completed by 2012)**

- Frequency 75.2 MHz
- 450 keV/u to 1.3 MeV/u
- Physics design stage




$\gamma$- 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

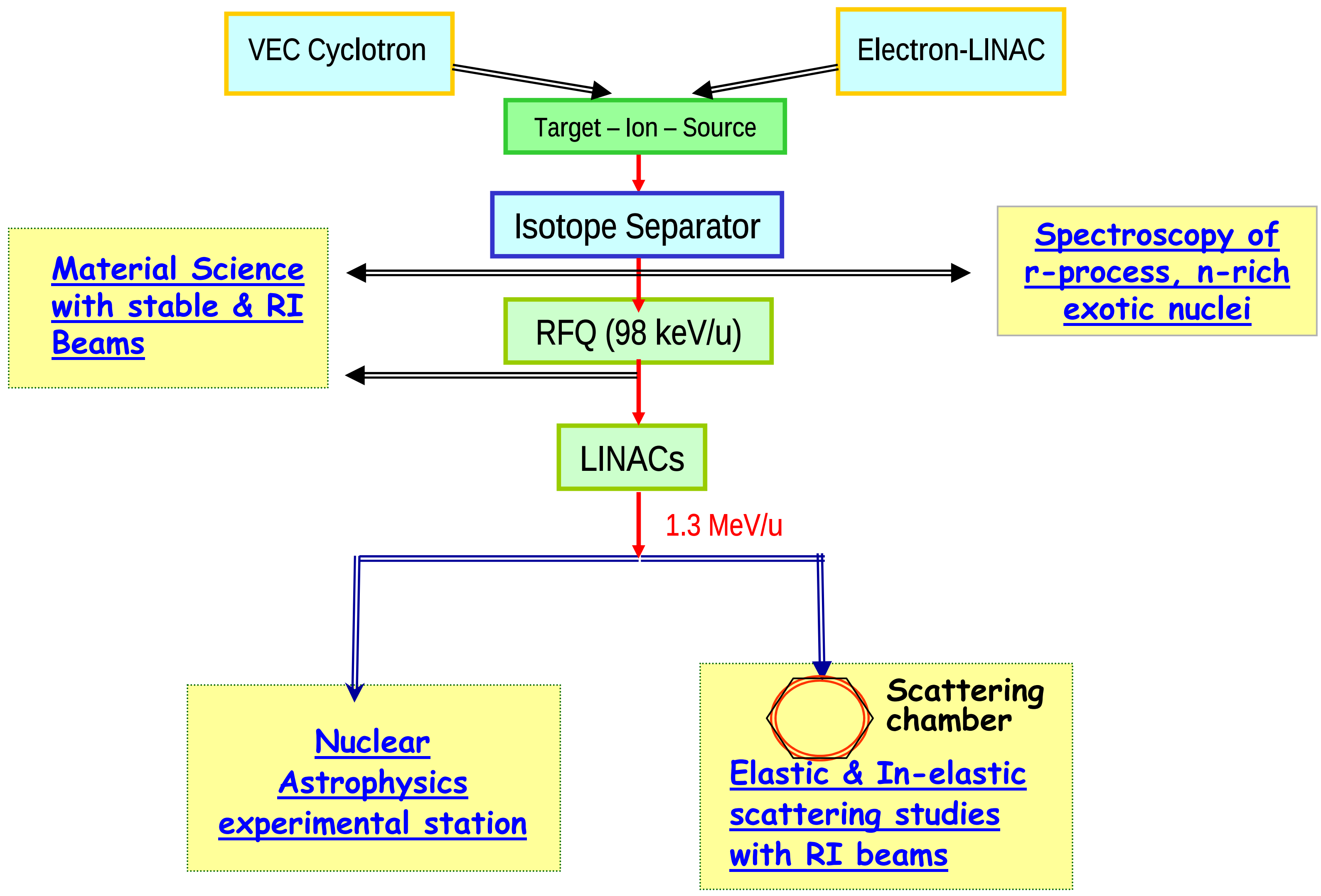
$^{91}Kr$: 1 x $10^{12}$ pps; $^{94}Kr$: 3 x $10^{10}$ pps

## 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*

Thank You!



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

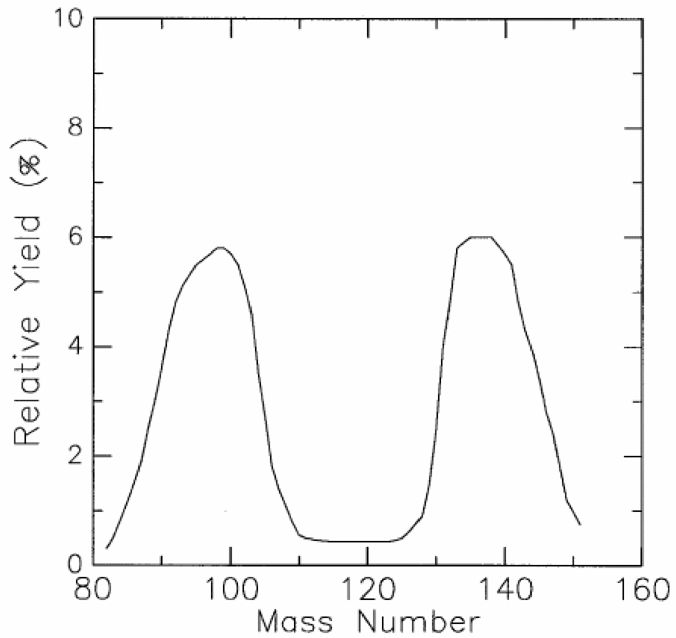
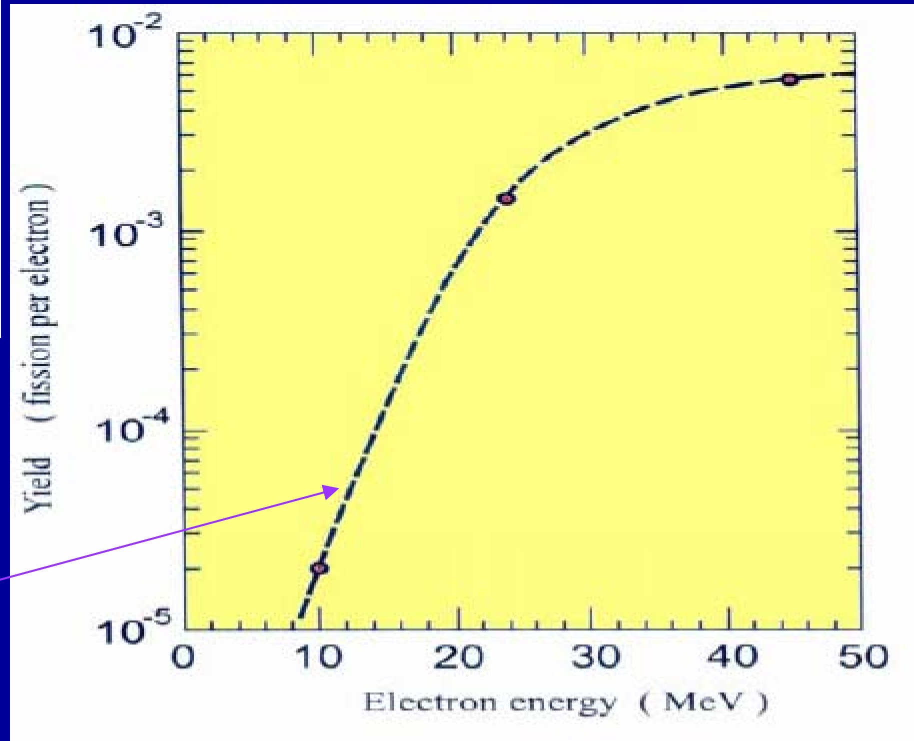



Fig. 10. The mass yield of fission fragments from electron-induced fission of $^{238}U$ produced by 30 MeV electrons [32].

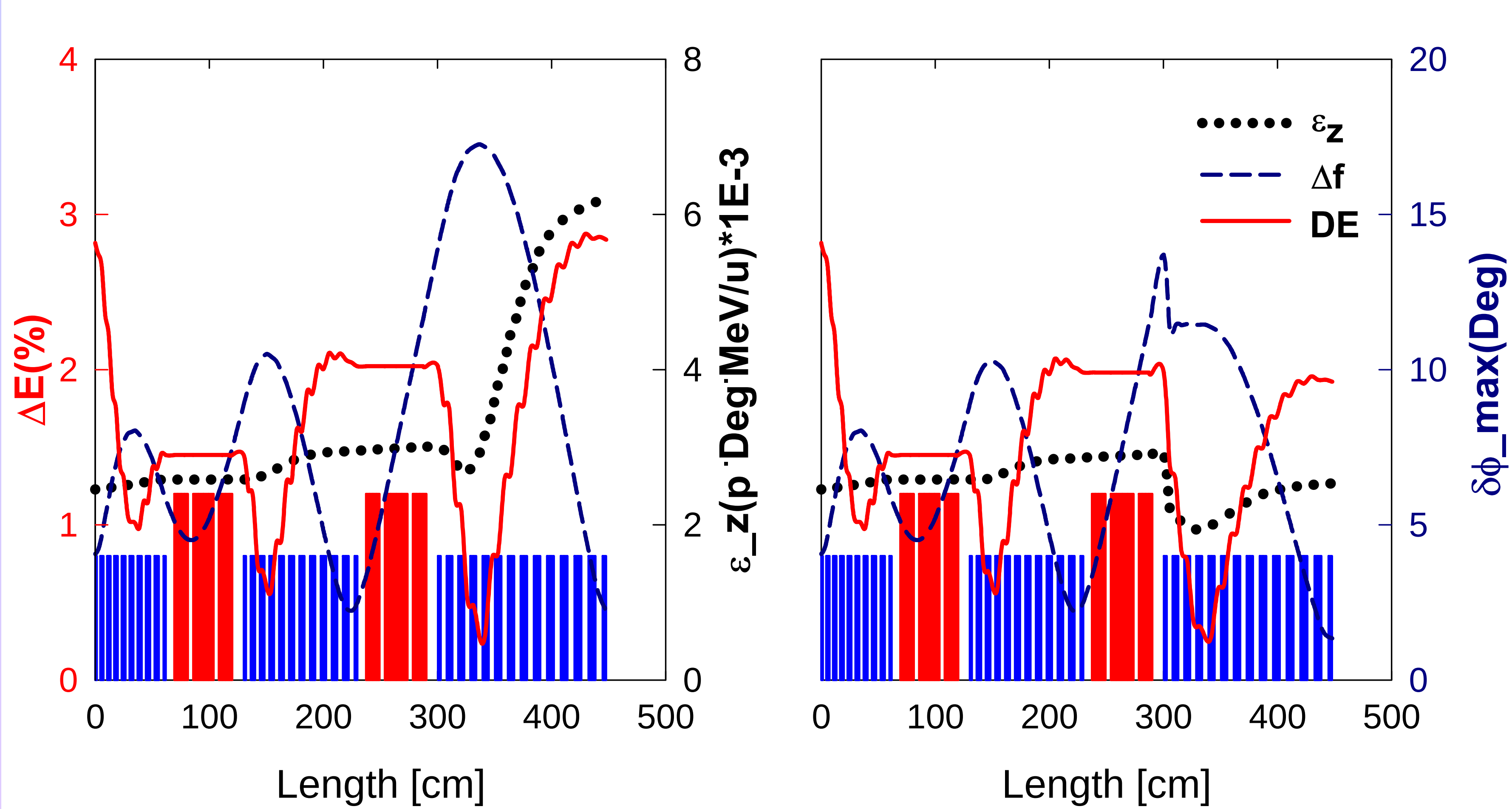
238U photo-fission fragments mass distribution




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

# IH - LINAC : The design details → Beam Quality

**Better Intensity (95% transmission)** | **Better Beam Quality**




**Better Intensity (95% transmission)**
- εz-rms : increased by 2.5 times
- ΔE : No change
- Df : 4.06°→2.23°

**Better time structure (66% transmission)**
- No change
- 2.8 → 1.9% (2*rms energy width)
- 4.06°→1.34°(2*rms phase width)

# IH - LINAC : The design details → Energy Tunability

**Possible set of energy tunes**

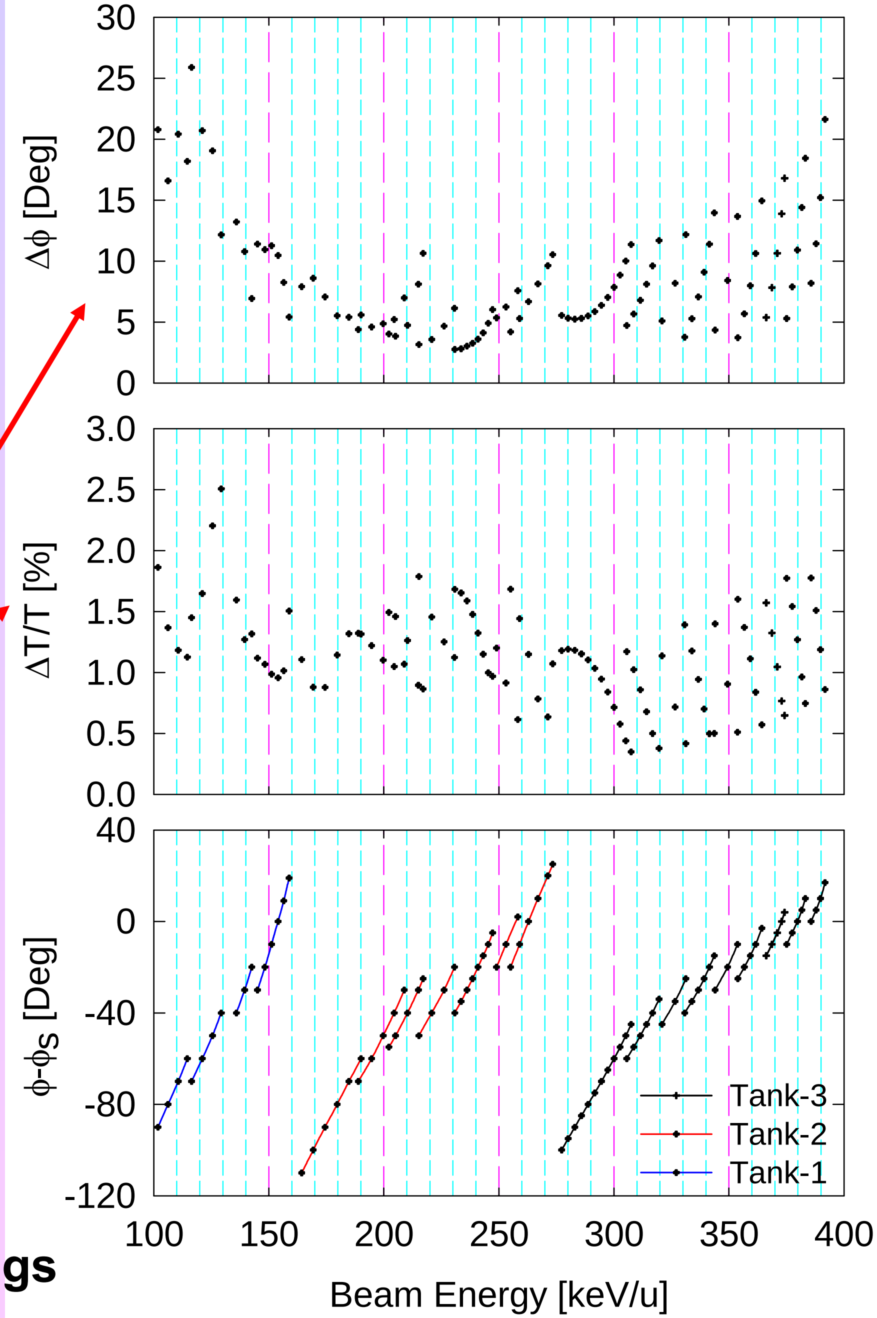
**Knobs : RF voltage & phase**

| Energy (keV/u) | Tank-1 | Tank-2 | Tank-3 |
|---|---|---|---|
| 263 – 397.5 | Design | Design | Knobs |
| 158.2 – 263 | Design | Knobs | Buncher |
| 100 – 158.2 | Knobs | Off | Buncher |

**Captures >90% of beam** { **2*ΔΦ_rms**, **2*(ΔT/T)_rms** }

**Typ. Energy widths ~ ± 0.5-1%**

**Typ. time widths ~ ± 1 nS**




**Voltage & Phase settings**