Proposal to develop an accelerator facility for NE region by CUPAC NE Collaboration

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India-JINR workshop on elementary particle and nuclear physics, and condensed matter research
16-18 October, 2023
Joint Institute for Nuclear Research, Dubna, Russia

Introduction

- **Mission**
  - Develop 1st accelerator facility in the NE region
  - Train younger generation in accelerator & experimental technology and user research
- **Unique research capabilities (in national context):**
  - 5 MV Pelletron accelerator with ECRIS: 1st in the nation (200 keV to 100 MeV, 100s of μA current including Ne, A r, Xe,Kr)
  - Nuclear Astrophysics: **Recirculating supersonic gas jet** +RMS
  - Indigenous PIMS development **(PIMS CEC)**
  - **Neutron source** δE~50 keV, 10^4-10^5 /s,3-8 MeV
- **Potential Collaboration with JINR**

NORTH-EAST INDIA

Figure 1 *CUPAC-NE (Cotton University Particle Accelerator Centre and North East) Collaboration map.

The beautiful state of Assam, India

Cotton University

- **122** years of glorious existence
  - Established in **1901**
  - First higher-educational institute in the North-East
- Formerly Cotton College
- Educational hub of North-East, India

Science focus CUPAC-NE collaboration:

Domains:

D1: National Nuclear Astrophysics Facility: Gas jet + RMS, INO (UGL)

D2: Indigenous development of PIMS

D3: National Neutron Source: KNFS, solid Li target (BINP, Russia)

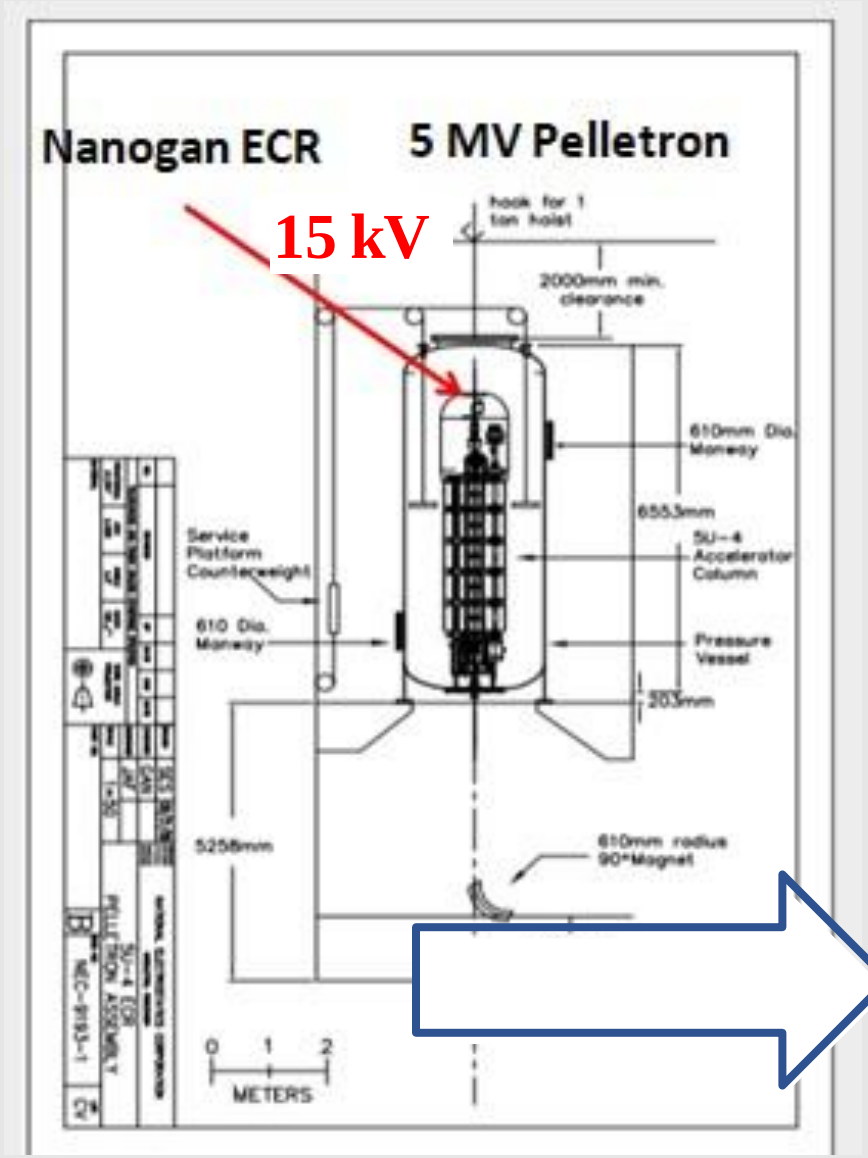
D4: Complement SHIM

- Gr-VIII, Heavy Ions*

***Enhancing MSV2035 Nuclear Physics**

Accelerator configuration for proposed Facility

Example :Ne-Na cycle
Gamow peak 200 keV



E=(qV+15) 215 keV

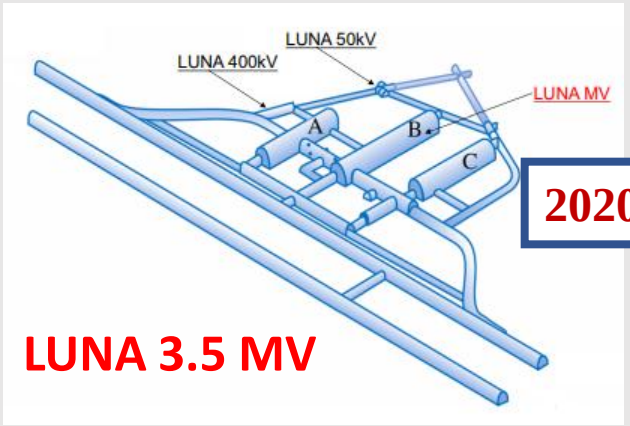
8 Beam Lines

Tandem cannot access
Ne, Gamow peak
E=(q+1)V+D 500 keV

Isotope Phase (2020-2030)

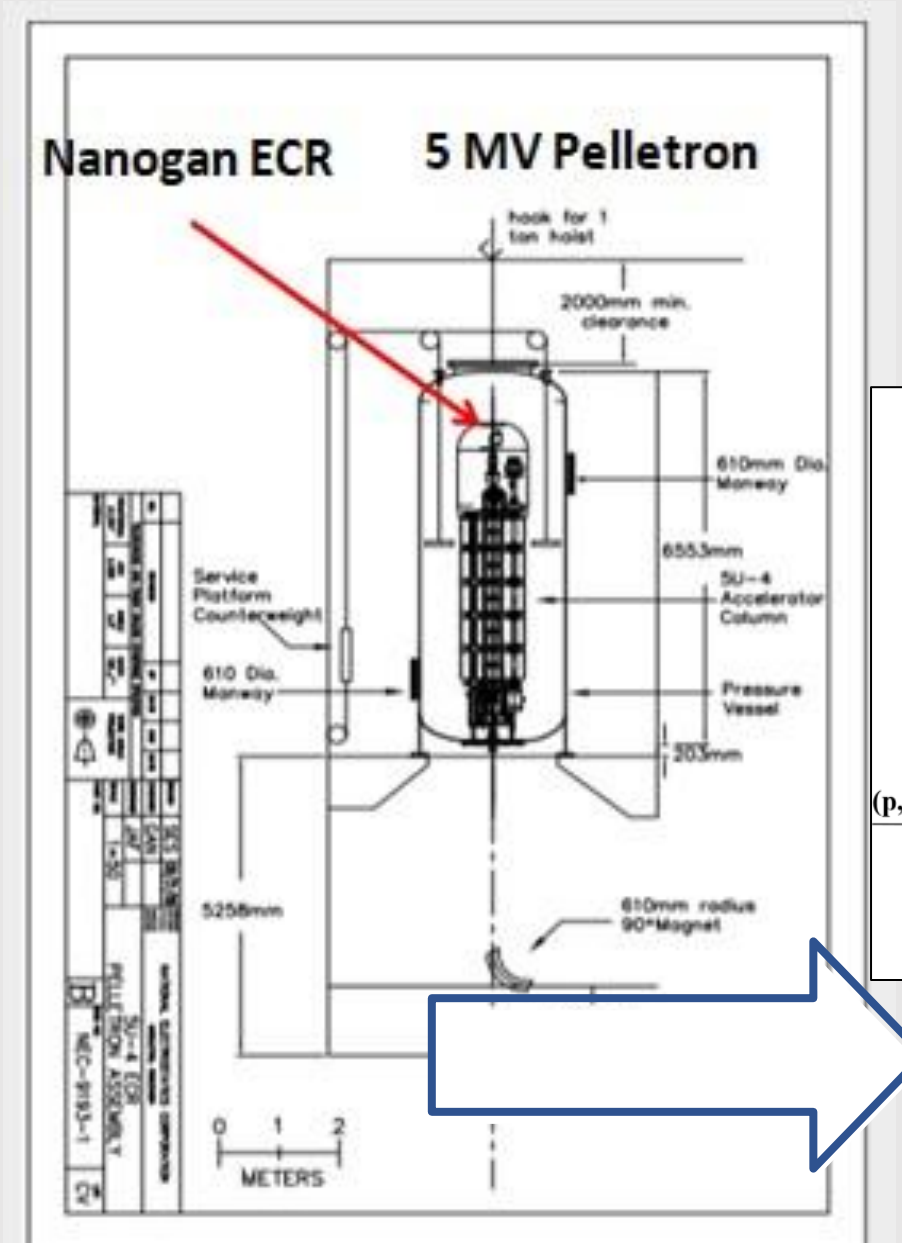
LUNA: Commissioning

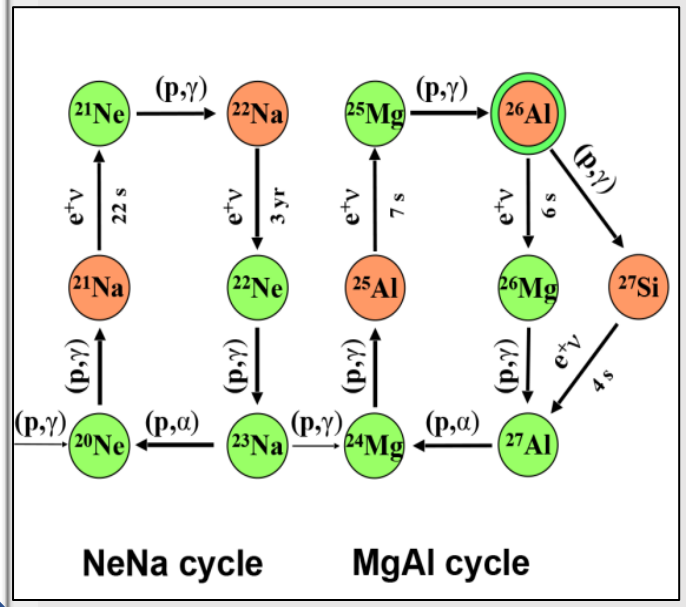
LUNA PAC approved experiment for first 10 yrs



2020-2030

Isotope Phase	Reaction	Gamow peak (E_0) (keV)	Gamow IKR(MeV)
CNO	$^{14}N(p,\gamma)^{15}O$	30	0.450
Neutron Source	$^{22}Ne(\alpha,n)^{25}Mg$	174	1.13
	$^{13}C(\alpha,n)^{16}O$	120	0.765
Al-Mg	$^{16}O(^{16}O,\alpha)^{28}Si$	274	0.548
Holy Grail	$^{12}C(\alpha,\gamma)^{16}O$	500	2.0

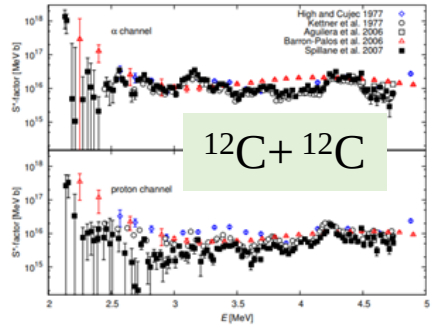




STRATEGY: IKR
RMS, Supersonic jet, Accelerator (E)

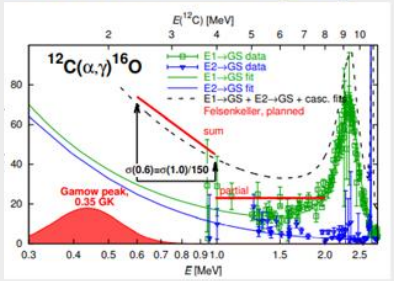
$^{12}C+^{12}C$ emission channels: γ, p, α, 2α

Frontier Research in Astrophysics – III
(Proc. Of Science 2018 008 (1-13)

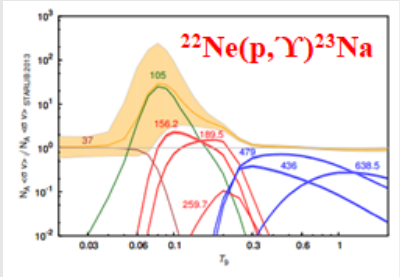


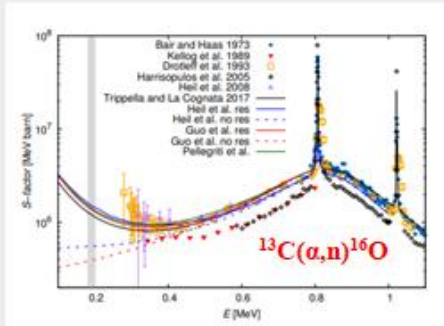
enkeller 5 MV underground accelerator: Towards the Grail of Nuclear Astrophysics $^{12}C(\alpha,\gamma)^{16}O$

HZDR: EPJ 178,01008 (2018)



$^{12}C\ (\alpha,\gamma)^{16}O$: IKR

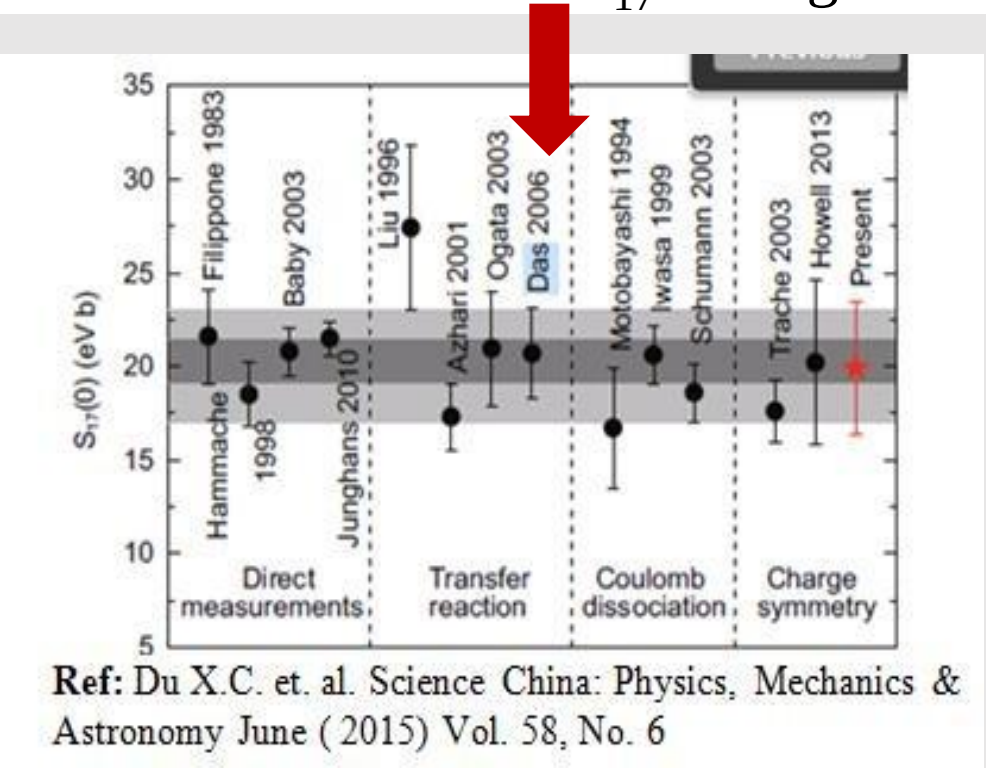




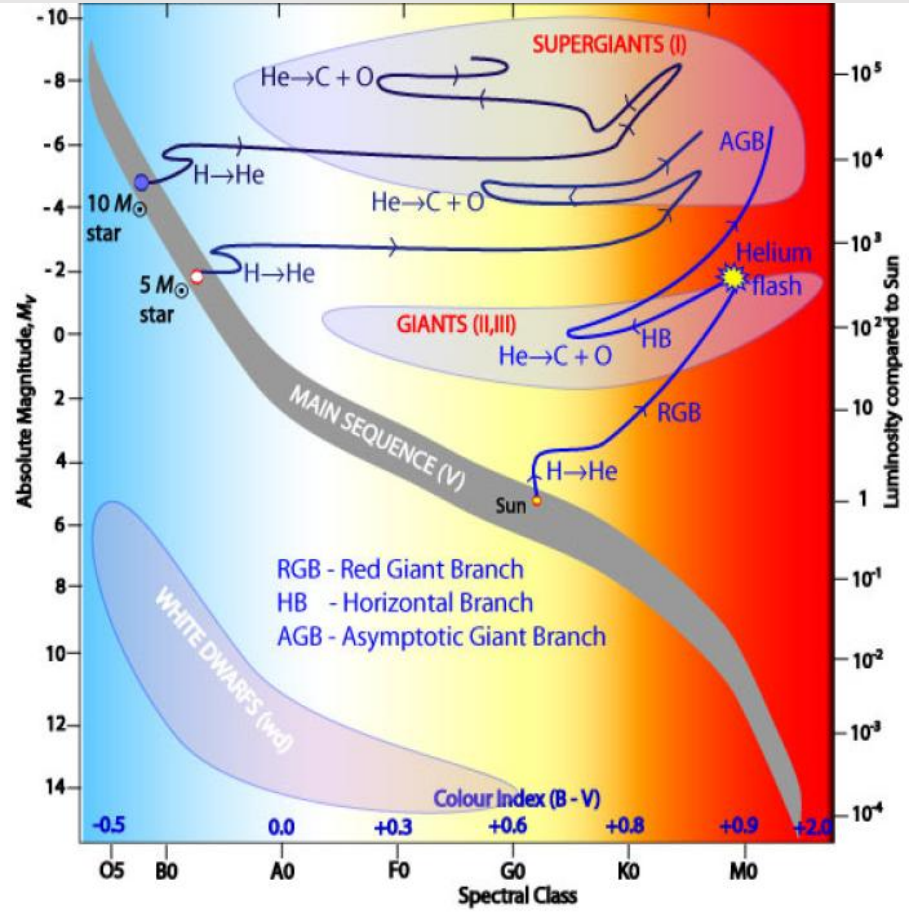
D1: Understanding isotopic abundances

- **Contemporary interest:** Accurate measurements in Ne-Na cycles and beyond
- **UGL**: (LUNA,JUNA,CASPER) or RMS (TRIUMF, UND)

- **Our contribution in main sequence stars :** Most accurate measurements to date in S_{17} through ANC



Ref: Du X.C. et. al. Science China: Physics, Mechanics & Astronomy June (2015) Vol. 58, No. 6



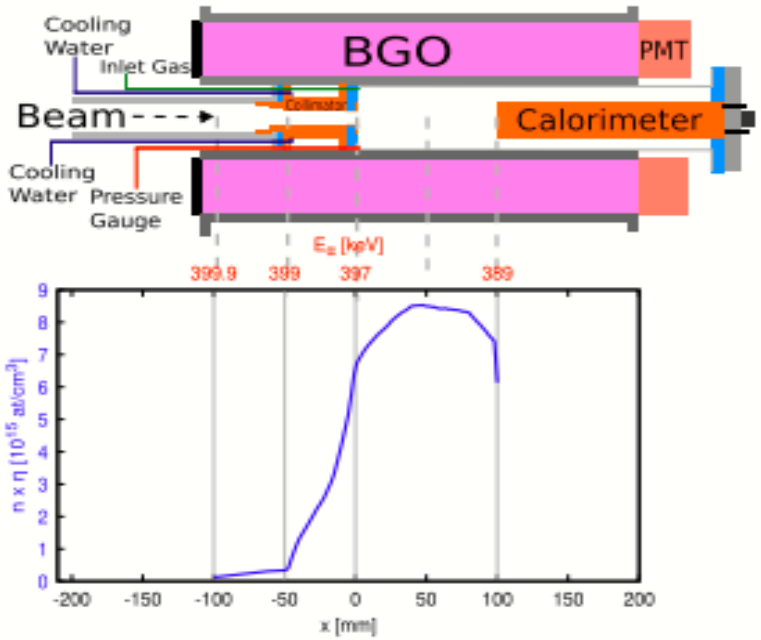
Recent measurements: LUNA and TRIUMF

Eur. Phys. J. A (2022) 58:194

LUNA,INFN

Target: P= 1 mb **Recirculation** (Ne),~10^{17}atoms/cm^2.

Purity: 99.995 %



TRIUMF 8/22:

^{22}Ne(p, γ) ^{23}Na reaction and its role in AGB star and classical nova

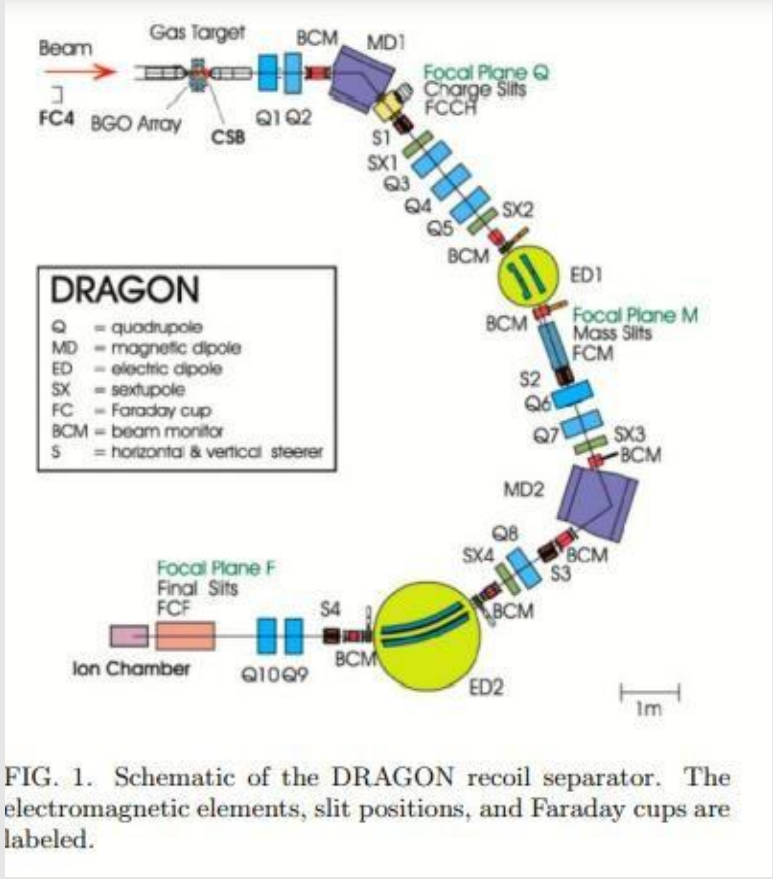
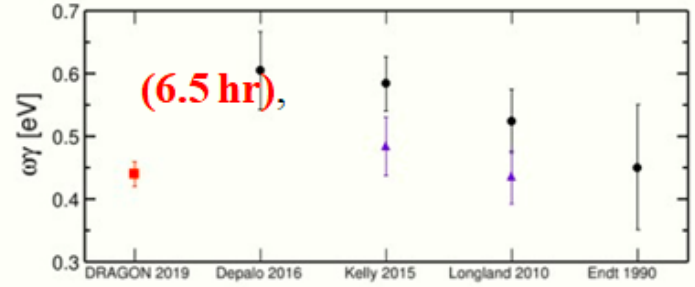
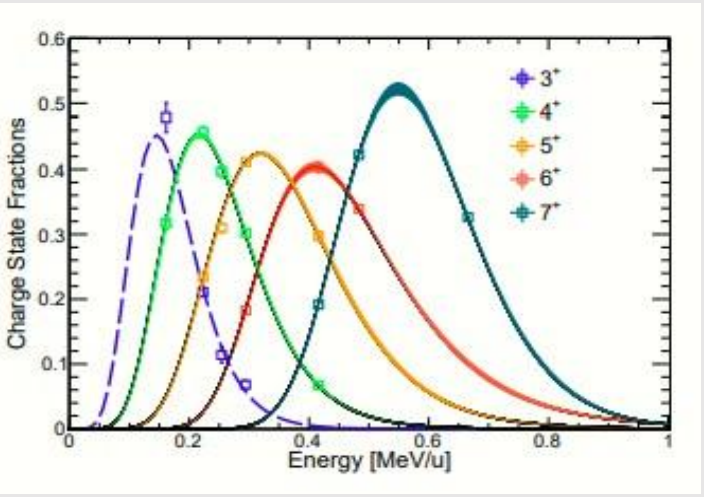


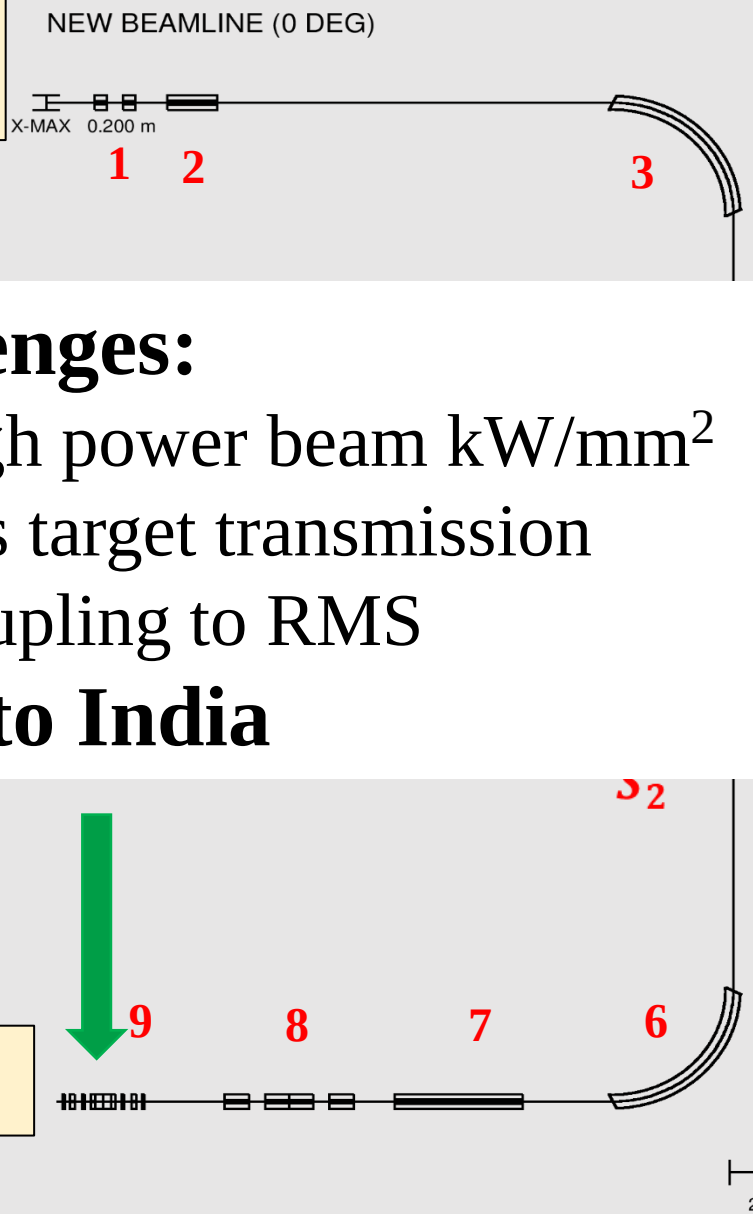
FIG. 1. Schematic of the DRAGON recoil separator. The electromagnetic elements, slit positions, and Faraday cups are labeled.





Nuclear astrophysics beam line

ACCELERATOR EXIT



Challenges:

- High power beam kW/mm^2
- Gas target transmission
- Coupling to RMS

- **New to India**

1. MQ Doublet:
- Effective Length : 0.15 m
- Aperture Radius : 25 mm

2. Switcher Magnet, S_1:
- Type 'A'
- Effective length: 0.6176 m
- Aperture Radius : 30 mm

3. Analyzing magnet, A_1:
- Radius: 1.5 m
- Effective length: 2.3562 m

4. MQ Doublet:
- Effective Length : 0.15 m
- Aperture Radius : 25 mm

5. Switcher Magnet, S_2:
- Type 'A'
- Effective length: 0.6176 m
- Aperture Radius : 30 mm

6. New bending magnet, A_2:
- Radius: 1.5 m
- Effective length: 2.3562 m

7. New switcher magnet, S_3:
- Type 'D'
- Effective length: 1.5886 m
- Aperture radius: 30 mm

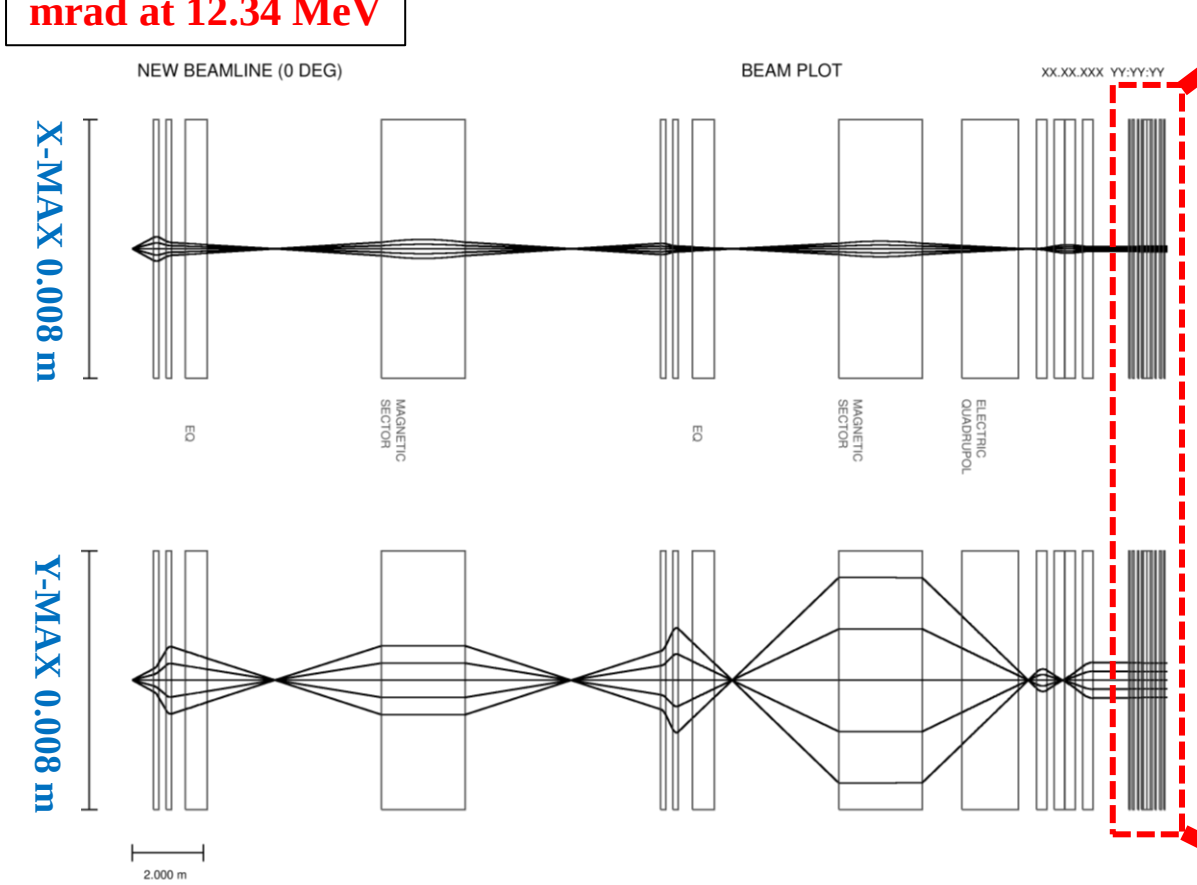
8. MQ triplet:
- Effective length: 0.3 m
- Aperture radius: 25 mm

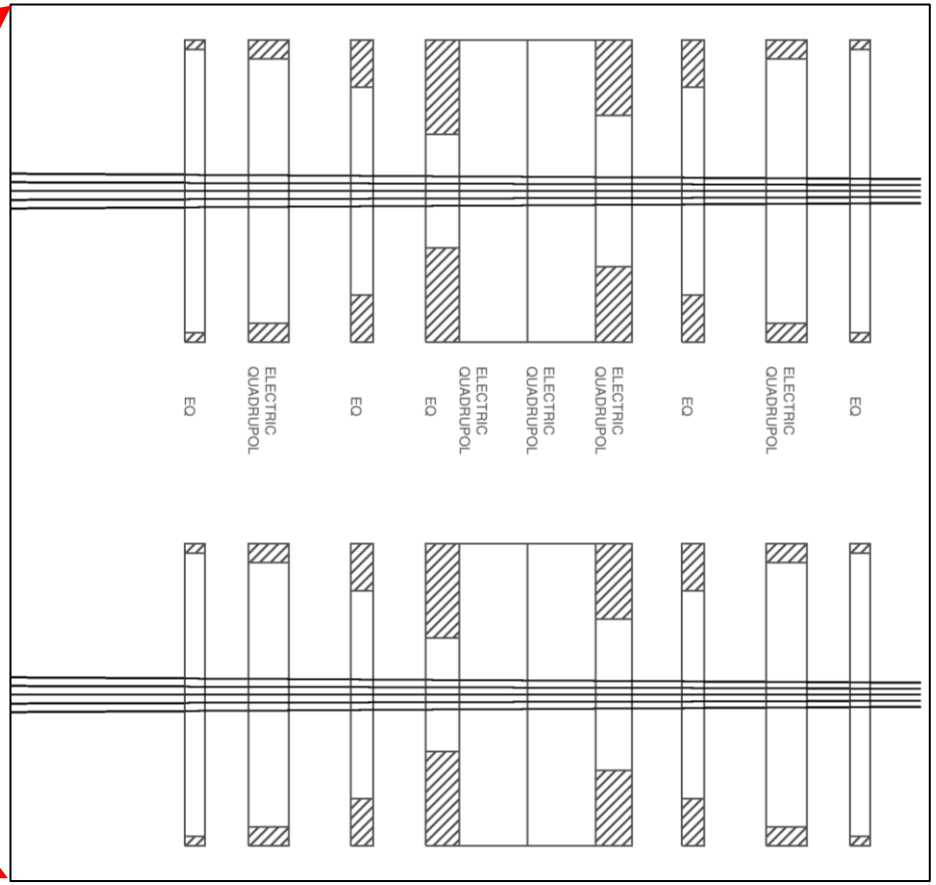
9. Gas target system:
- Windowless hydrogen gas target
- From ERNA, Italy
- Effective length: 1.016 m
- Gas target length: 0.202 m
- Target atom density: $\sim 10^{18}$ atoms/cm^2

Ref. : D. Schurmann et. al, "A Windowless hydrogen gas target for the measurement of Be-7(p, γ)B-8 with the recoil separator ERNA", Eur. Phy. J. A (2013)

First order Beam optics for gas target and RMS

ε = 0.117π mm mrad at 12.34 MeV





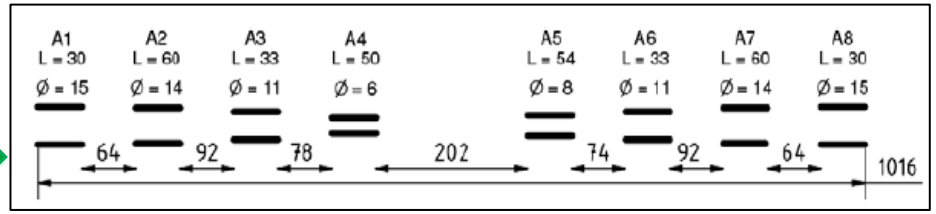
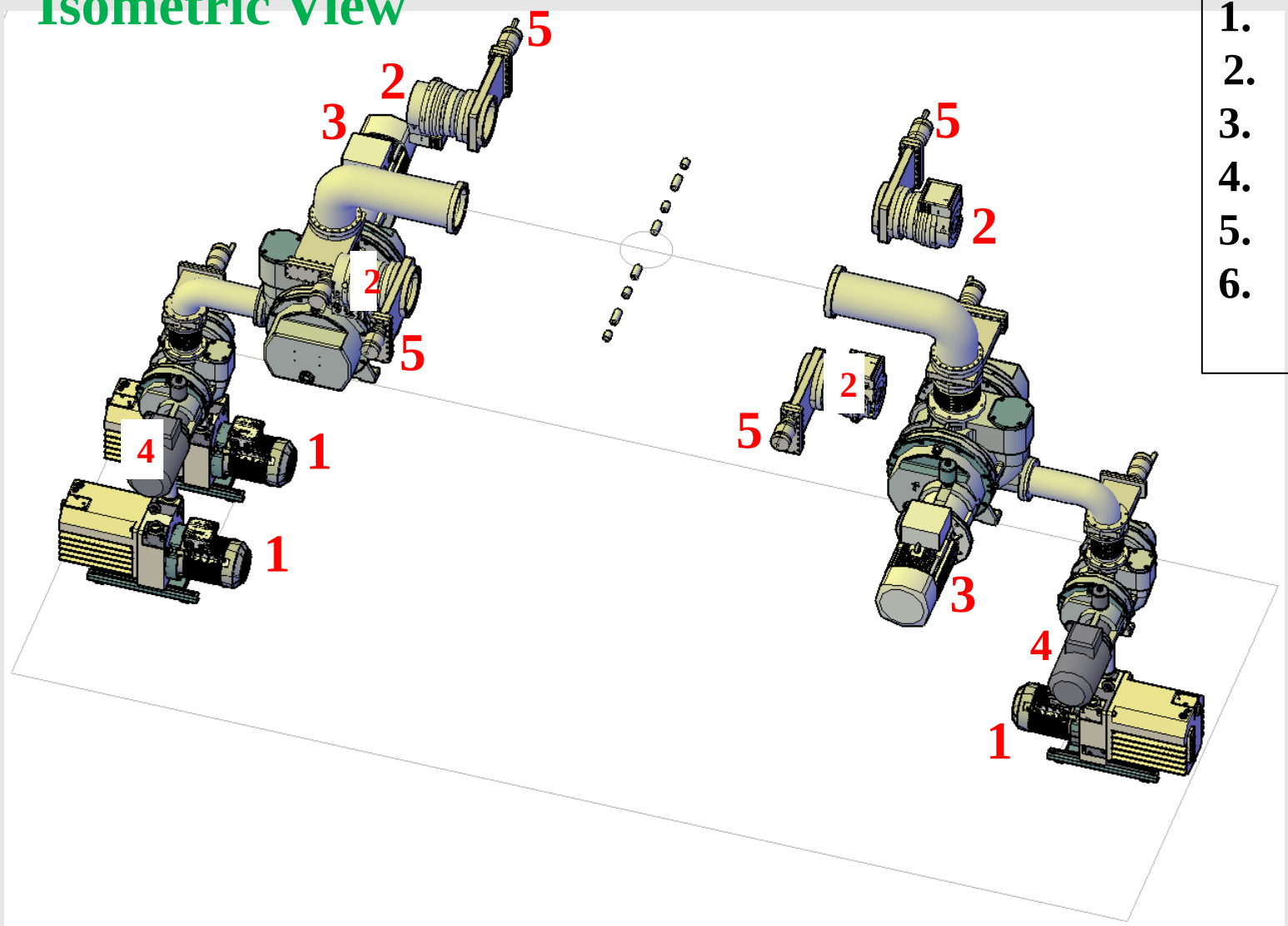


Fig. 2: Beam optics of the beamline using **GICOSY**

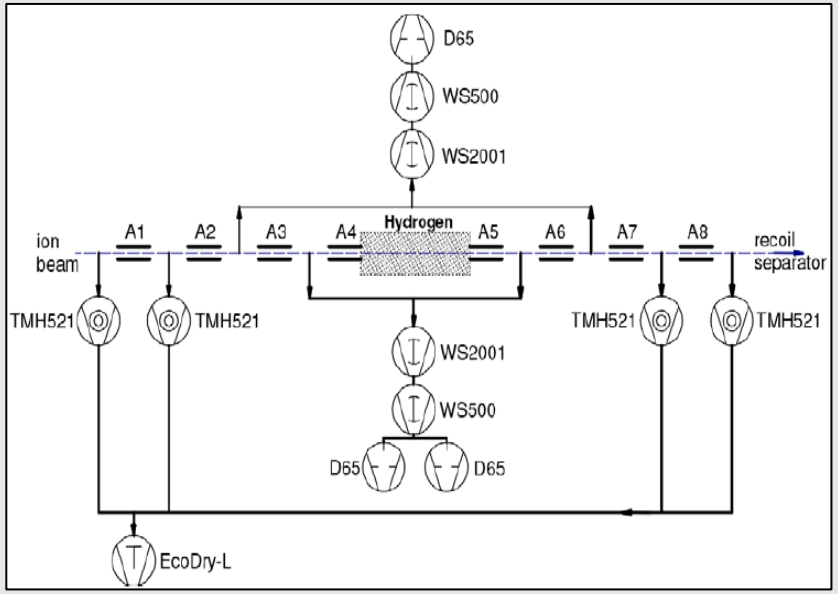
Ref. : D. Schurmann et. al, "A Windowless hydrogen gas target for the measurement of Be-7(p, γ)B-8 with the recoil separator ERNA", Eur. Phy. J. A (2013)

Preliminary 3D CAD design of the gas target system

Isometric View



1. Duo 65, Rotary vane pump: 3
2. TMH 521, Turbomolecular pump: 4
3. Okta 2000, Roots blower: 2
4. Okta 500, Roots blower: 2
5. Gate valves: 4
6. EcoDry-L: 3D CAD file isn't obtained yet



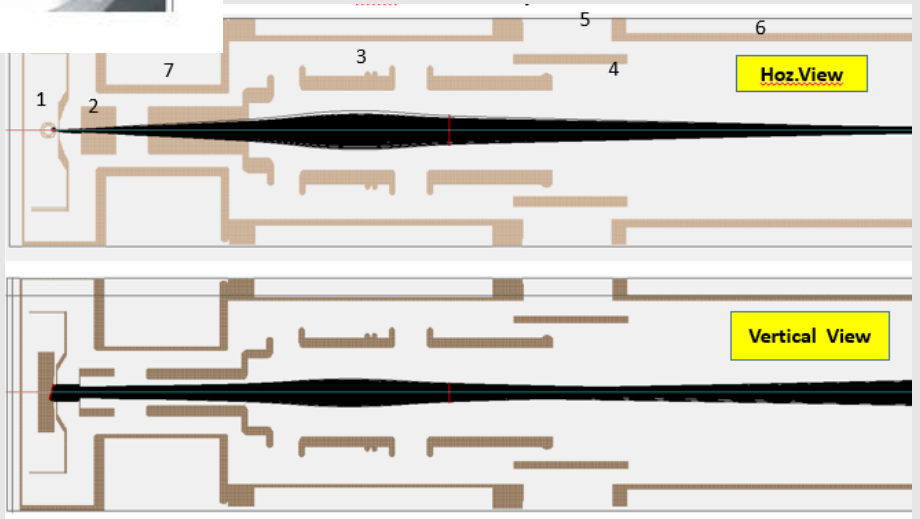
Commissioning results of ISTF3, ORNL

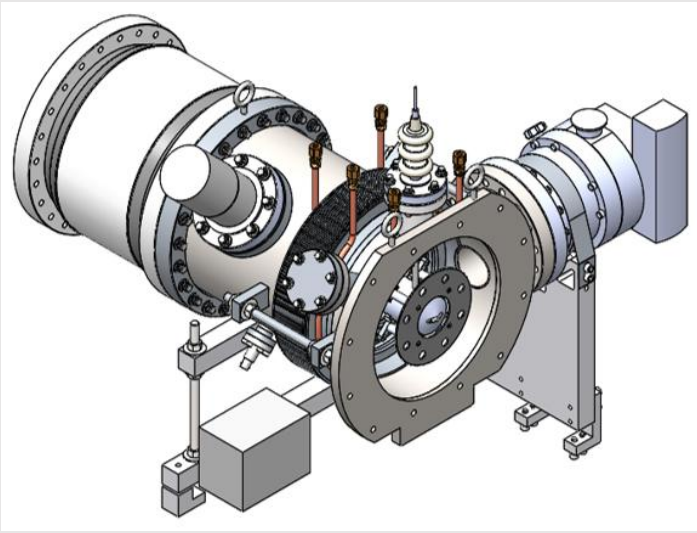
[Das2013] JJ Das, HK Carter, JR Beene, BM Sherrill
Journal of Physics: 420 (1), 012165 1 2013

PIMS /Pelletron ECRIS optics

ISTF3 Extraction optics:

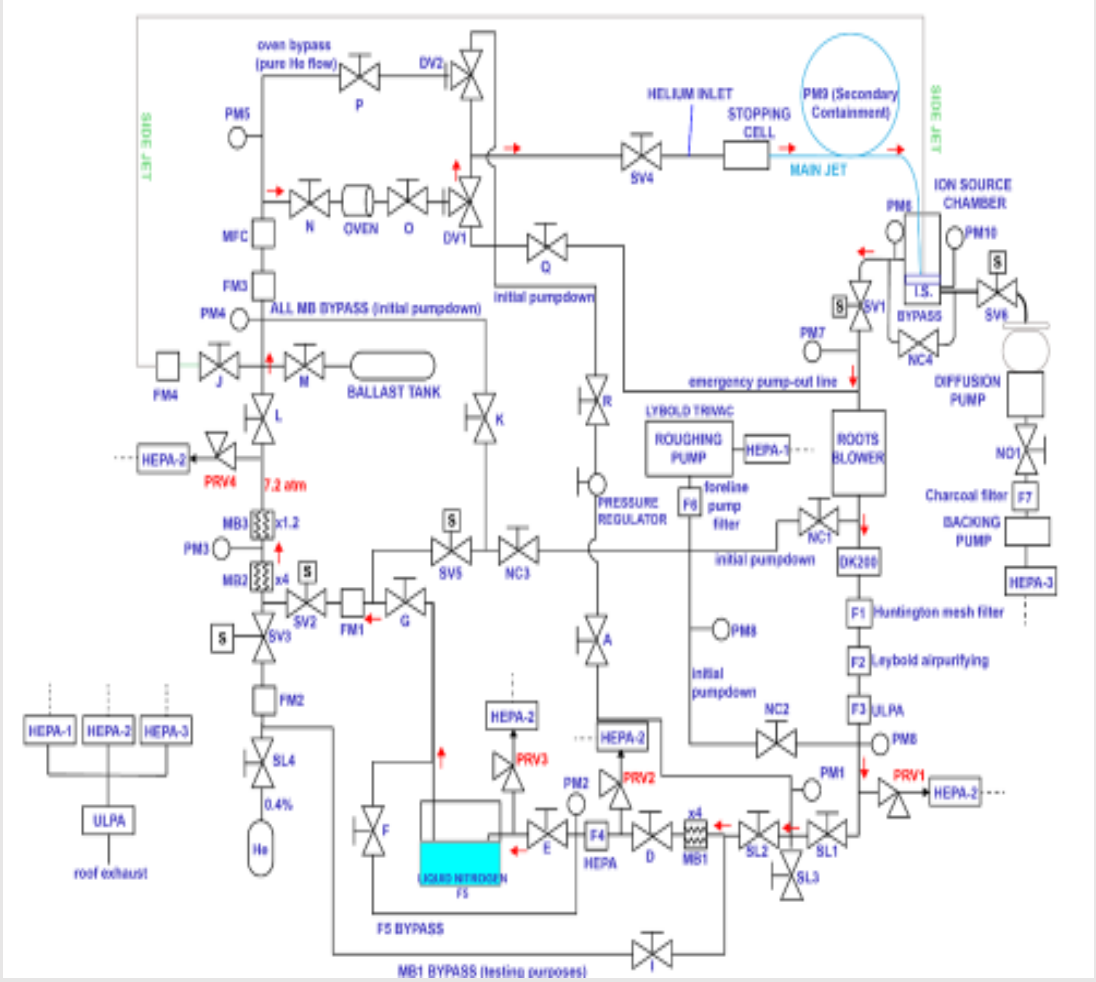
- Space charge compensated
- SIMION8.0
  - Full 3D: no symmetry
  - ECRIS: 2D cylindrical



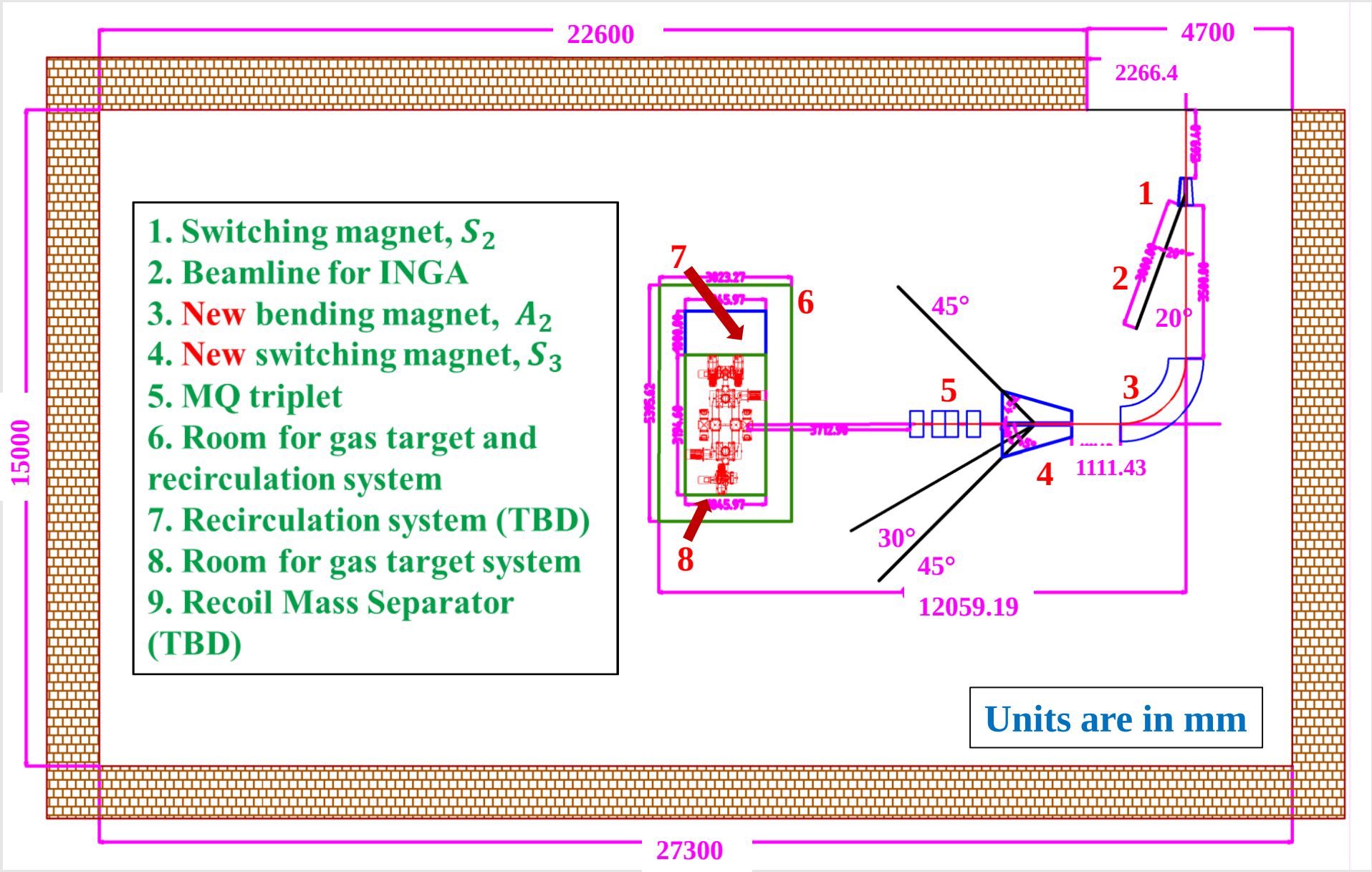


•Recirculating system

- **99.6% recirculated**
- **Enriched/radioactive** targets:
  - ^{3}He,^{3}H,enriched N,Ne, etc.
- **Challenges:**
  - Purification and compression
  - Accurate control and reproducibility



Layout of the beam-hall

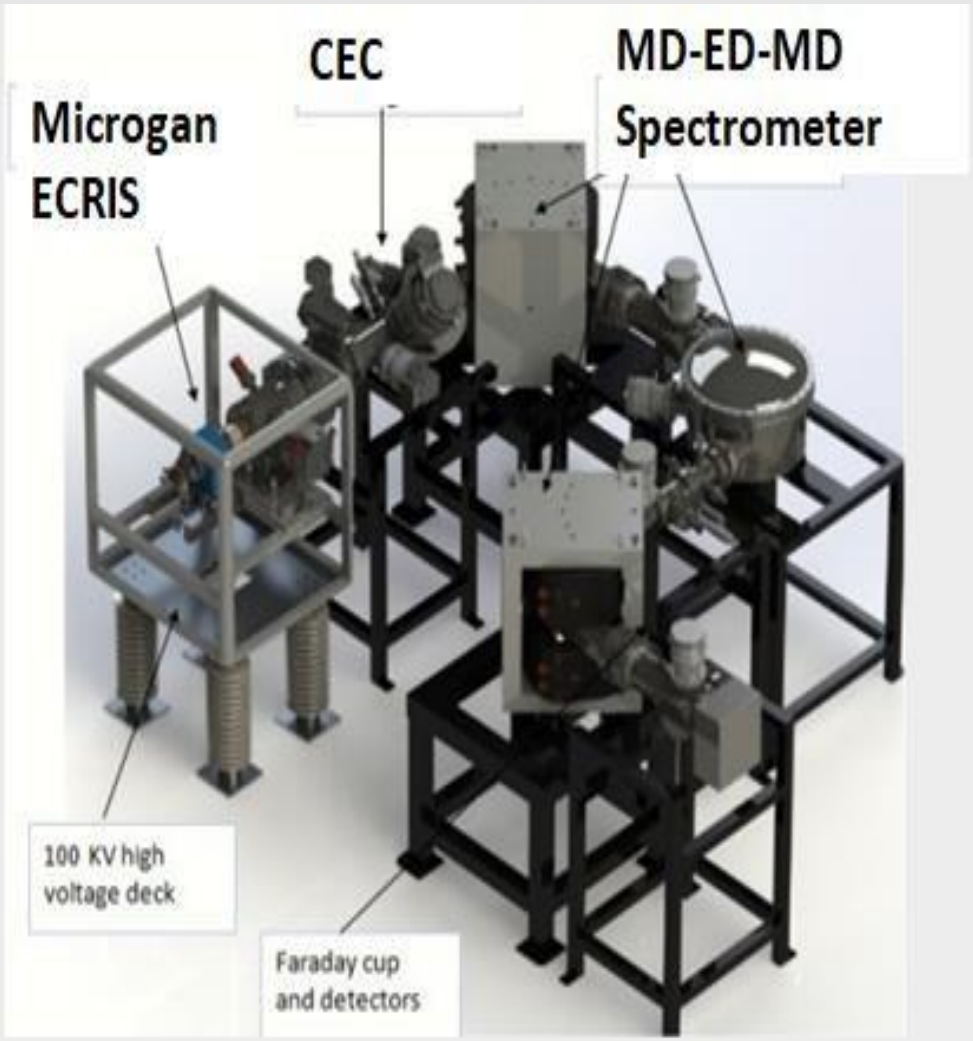


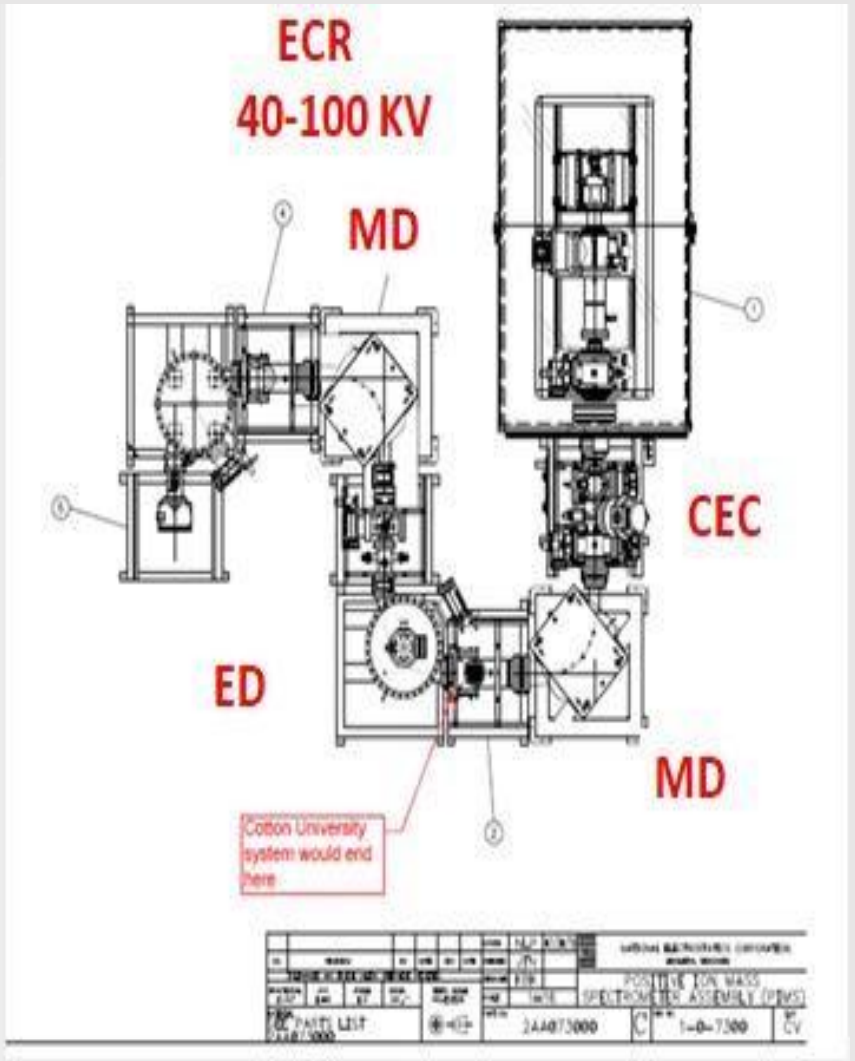
FIRST ORDER OPTICS: BARC-COTTON-SINP NUCLEAR ASTROPHYSICS BEAM-LINE

P C Rout, S Santra: Nuclear Physics Division, Bhabha Atomic Research Centre
Rasna Baruah, Bhargab Boruah, A Barthakur, M Baro, J J Das, A K Nath, M Patgiri, G C Wary:
Dept. of Physics, Cotton University, Guwahati
A Banerjee, C. Ghosh, S Chattopadhyay: SINP, Kolkata
T. Ghosh: VECC, Kolkata
V.M. Datar : IMSc, Chennai

D2: (PIMS) (Patented)

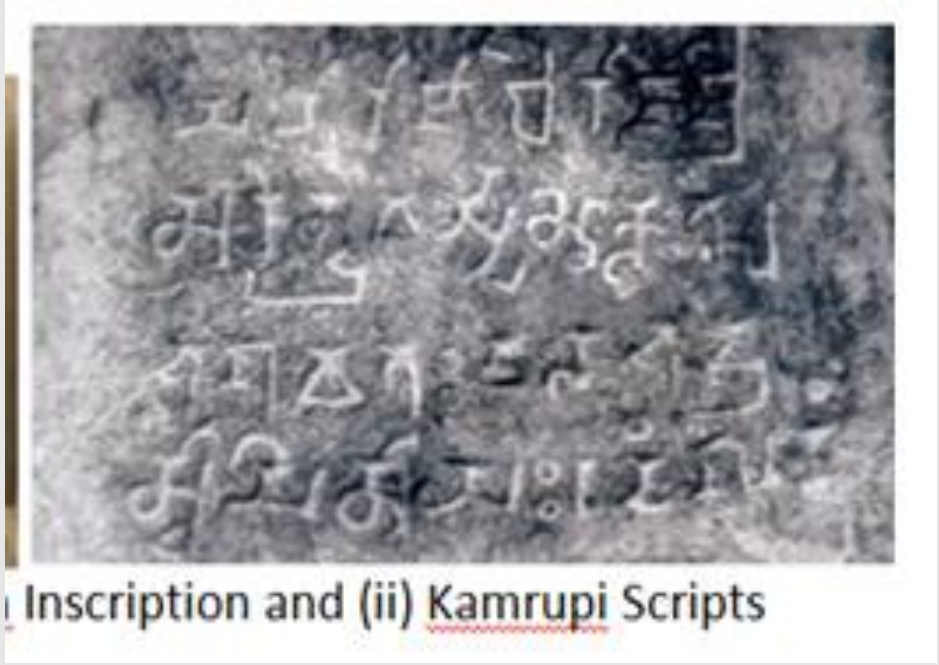
$^{14}C^{+}/^{14}N^{+}$ → $^{14}C^{-}/^{14}N^{+}$ → $^{14}C^{-}$





Scientific opportunities with PIMS

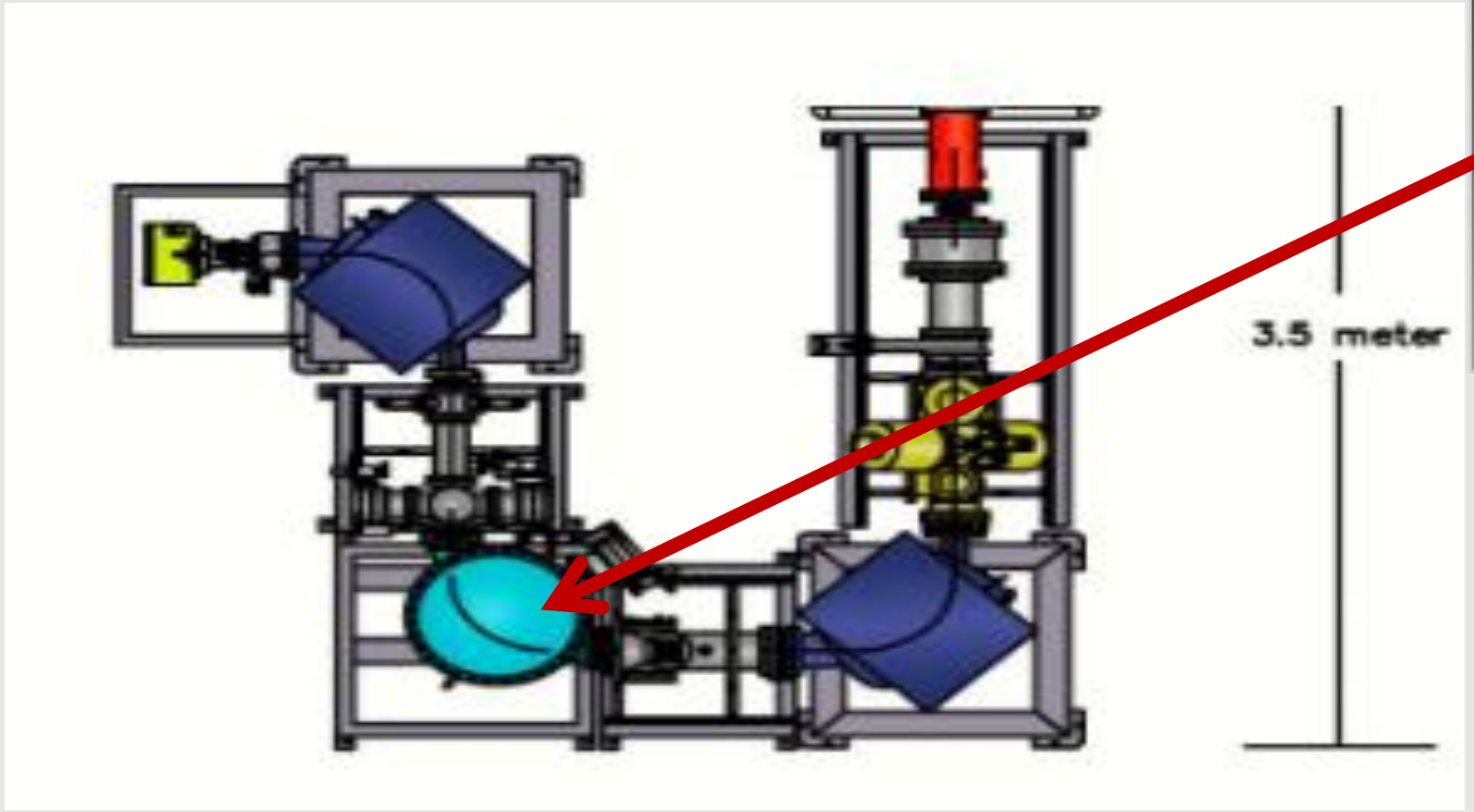
- Ambiguity jn Questions of recent history: need 100 yr separation
  - Who wrote this manuscript A or B
  - Whether Assamese lipi underwent changes post Arian migration is written
- The uncertainties in AMS:
  - Transmission through tandem and graphitization are absent in PIMS

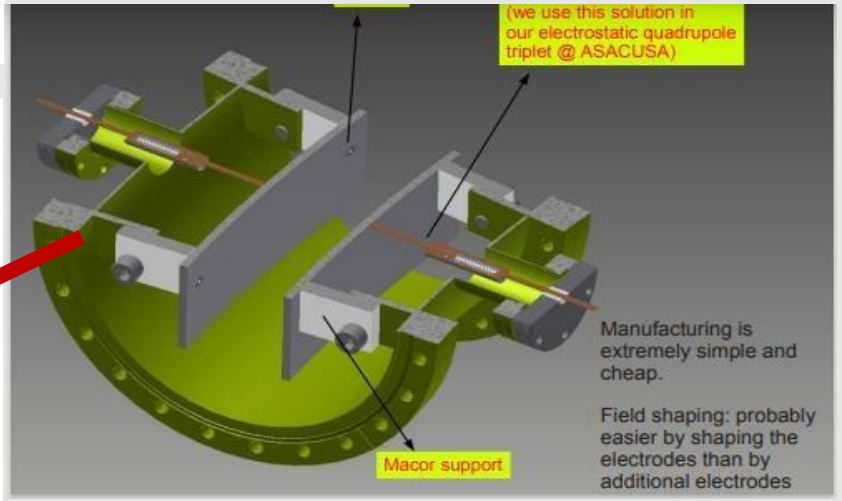


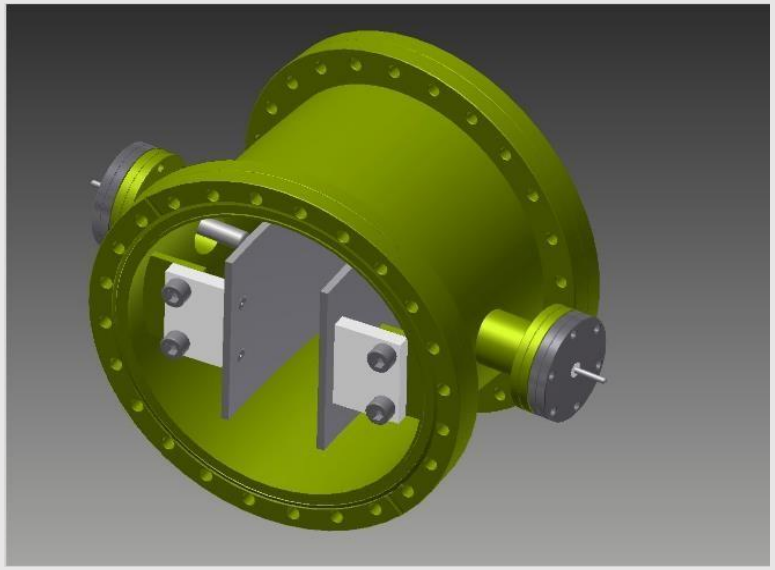
Inscription and (ii) Kamrupi Scripts

•New ideas for PIMS

- •Slotted electrode like HIRA anode



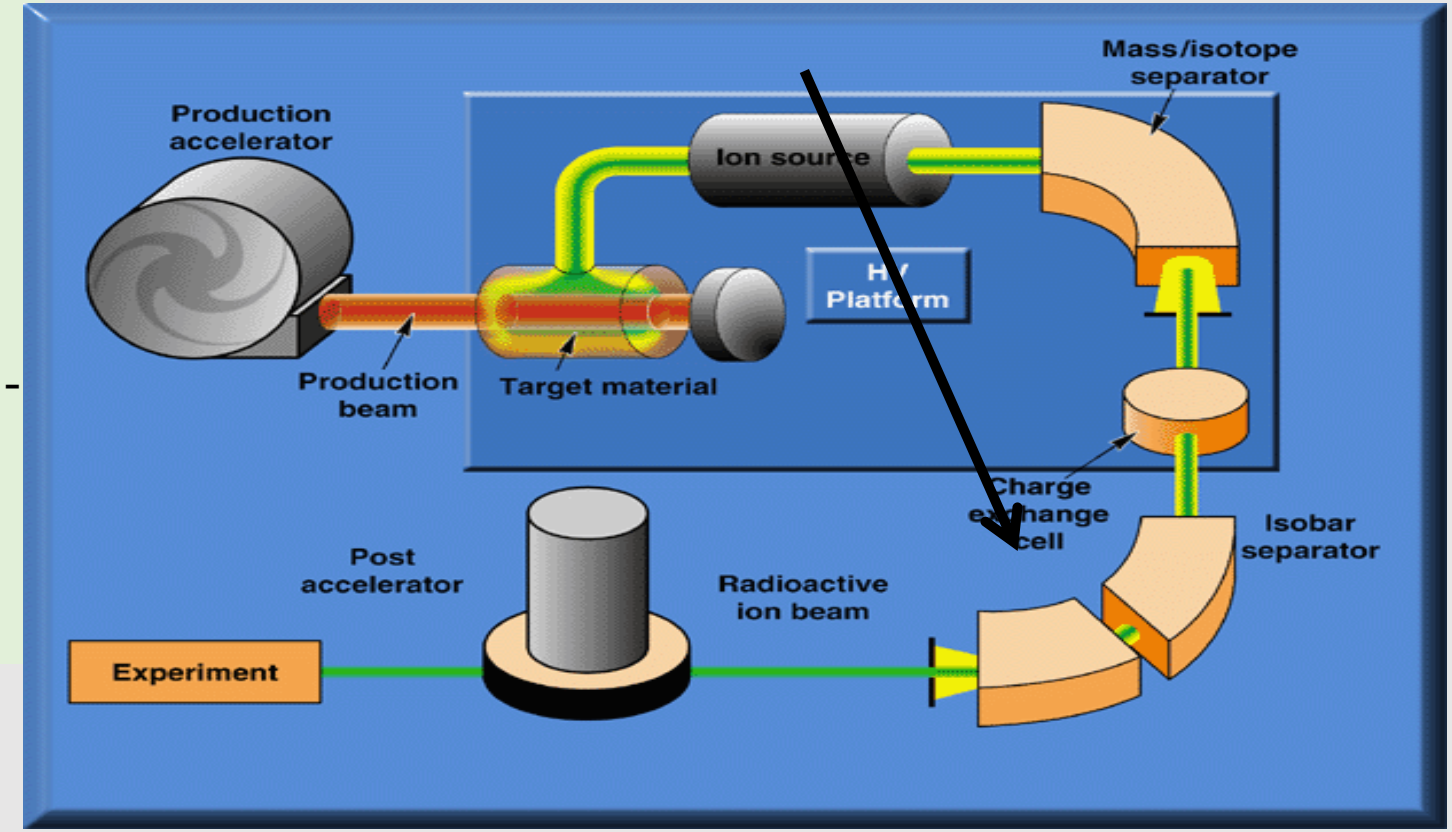




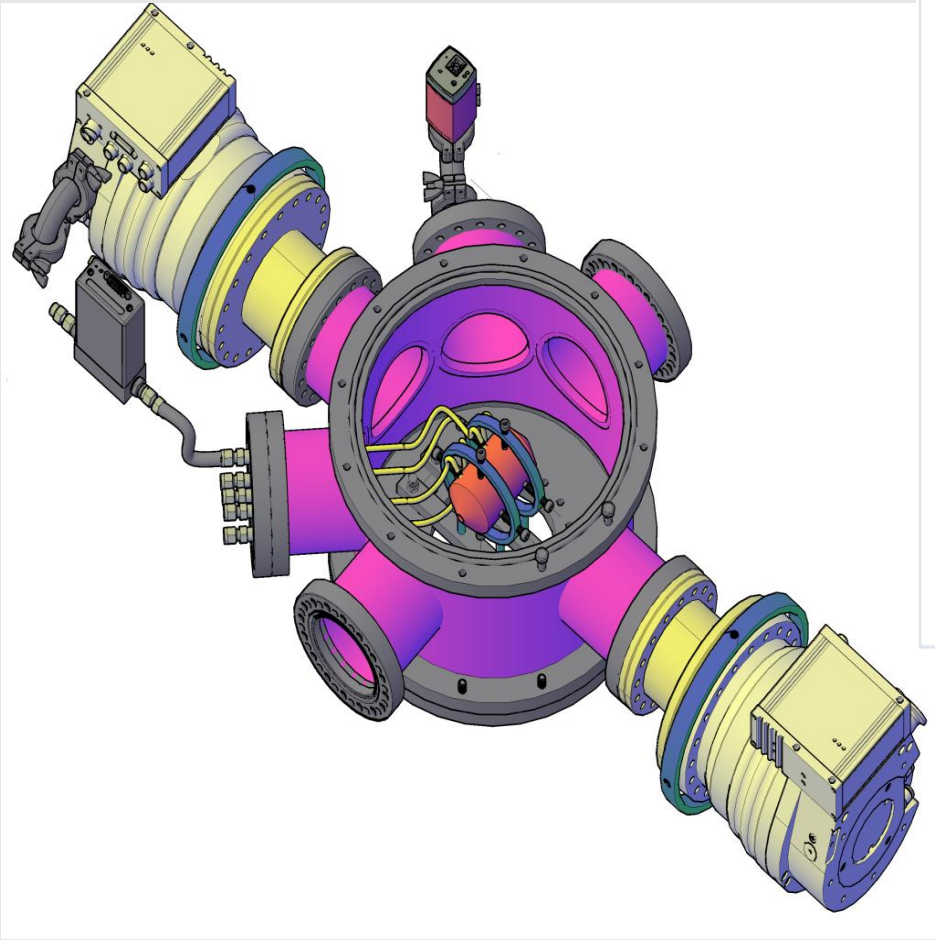
Discovery potential with PIMS

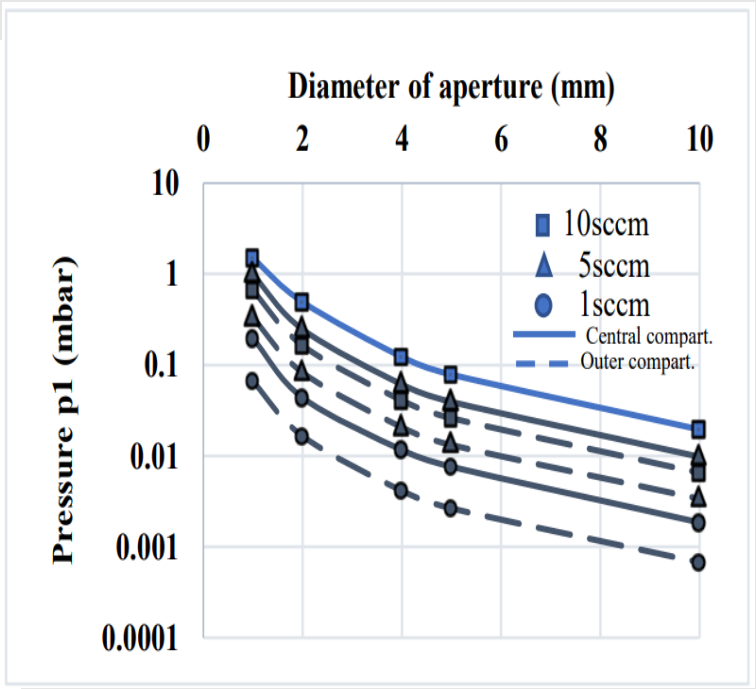
- **Radio Carbon Dating (60 k yrs)**
  - Nobel prize (1960) William Libby
  - Clock for millions of yrs
- **RIB (Radioactive Ion Beam) R&D at ORNL**

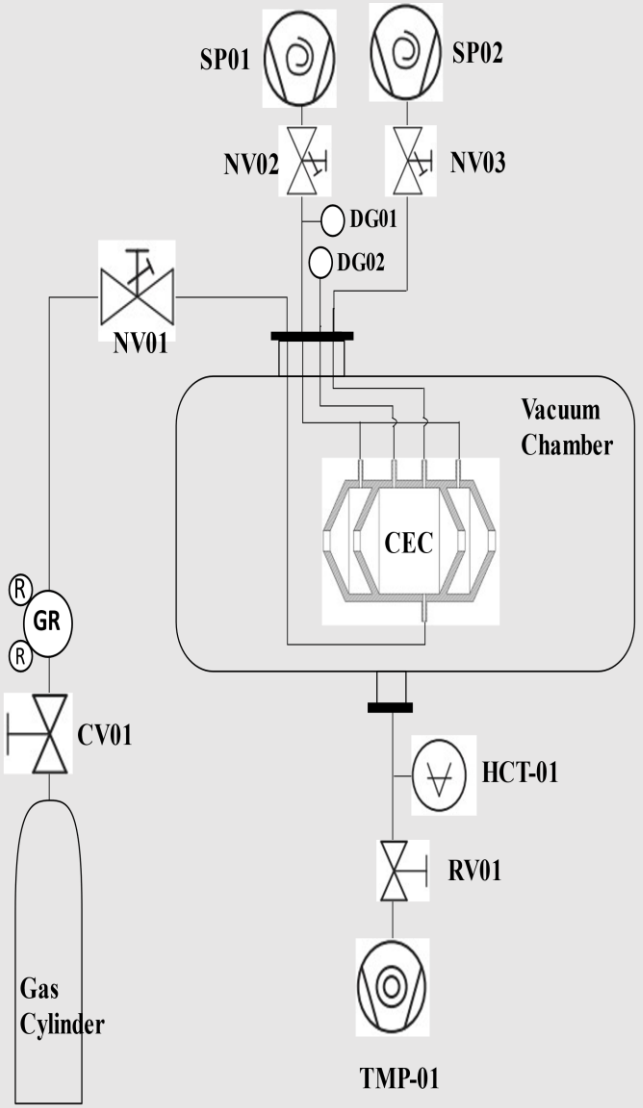
Isotope of interest	Half life (year)	Dating (year)	Isobaric contaminant
^{14}C	5730	60,000	^{14}N
^{10}Be	1.5 m	15 m	^{10}B
^{26}Al	0.71m	7 m	^{26}Mg
^{36}Cl	0.3 m	3 m	^{36}S
^{41}Ca	0.1 m	1 m	^{41}Sc
^{129}I	15.7 m	157 m	^{129}Xe



CAD design and gas flow simulations







PIMS test system:

- Test with existing ED of LEIBF at low current
- Needed modifications of chamber
- Low intensity it should work

Revised Experimental setup

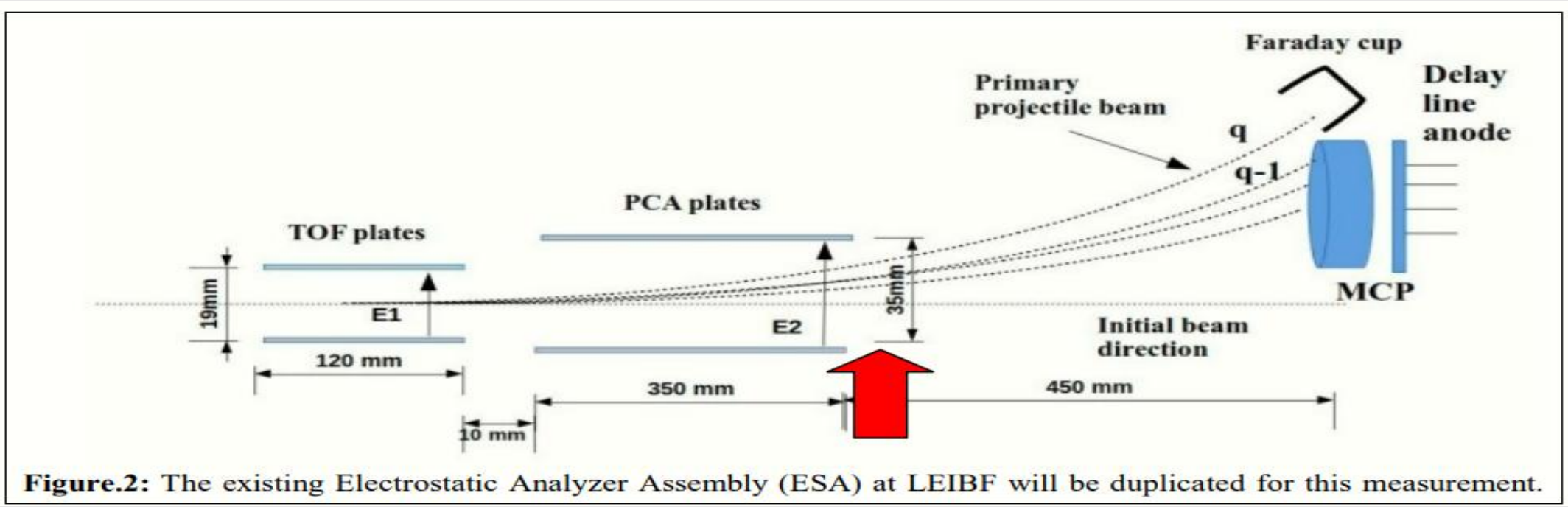
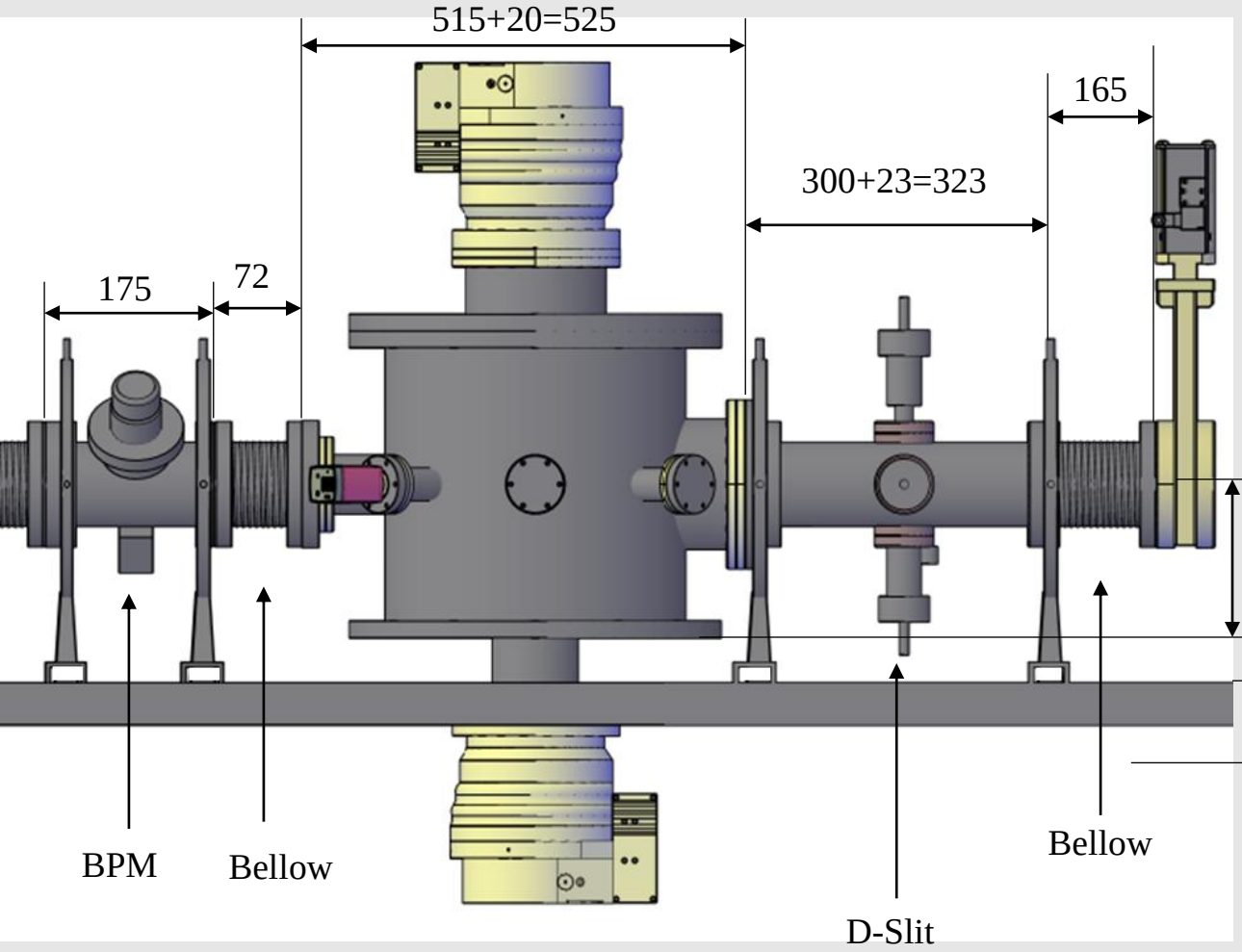
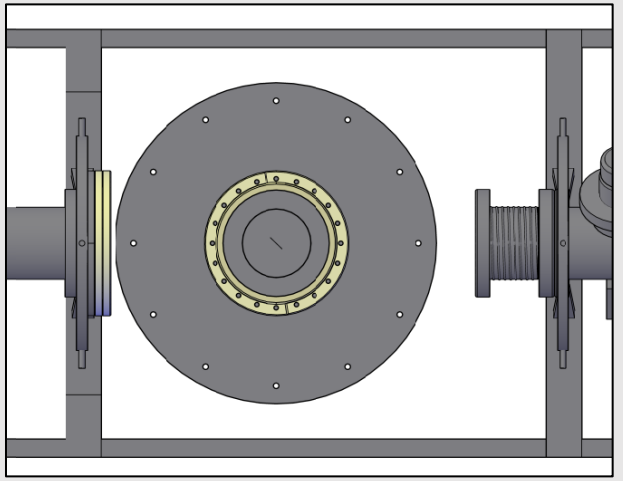
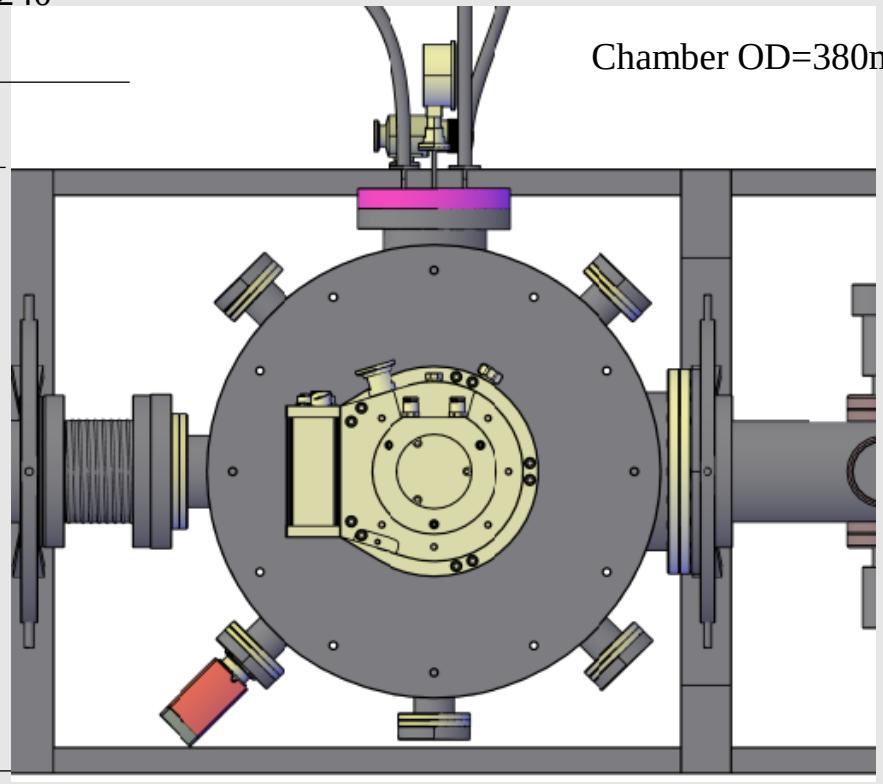


Figure.2: The existing Electrostatic Analyzer Assembly (ESA) at LEIBF will be duplicated for this measurement.

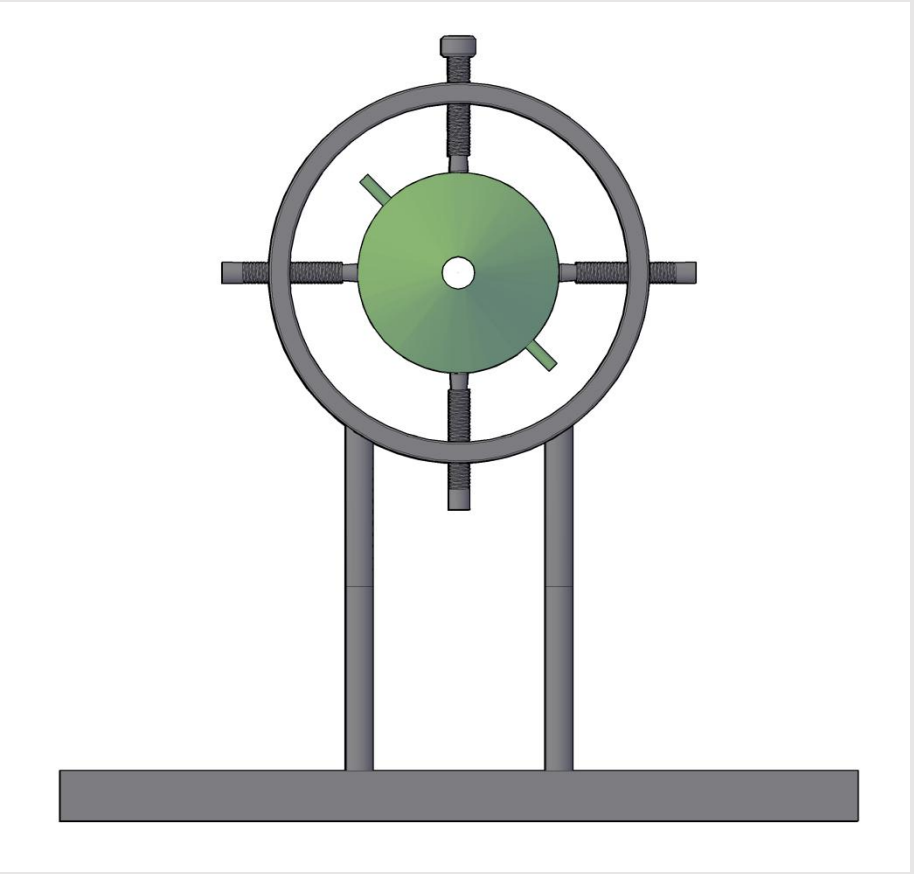


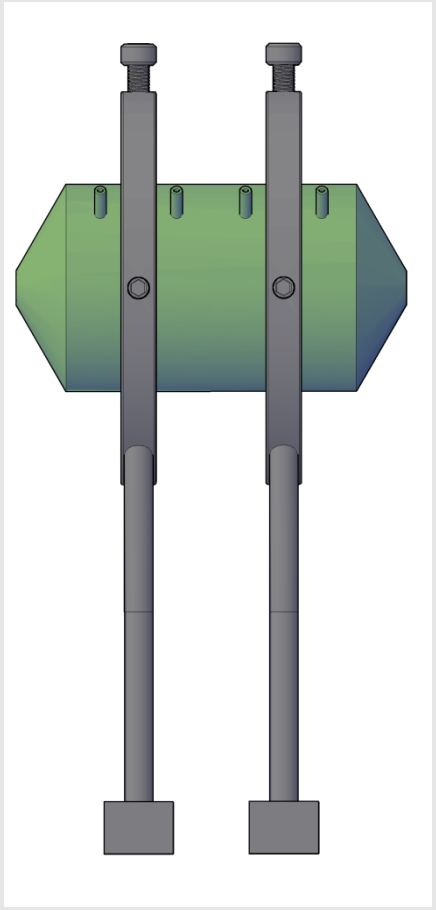
Top view of Chamber bottom and stand

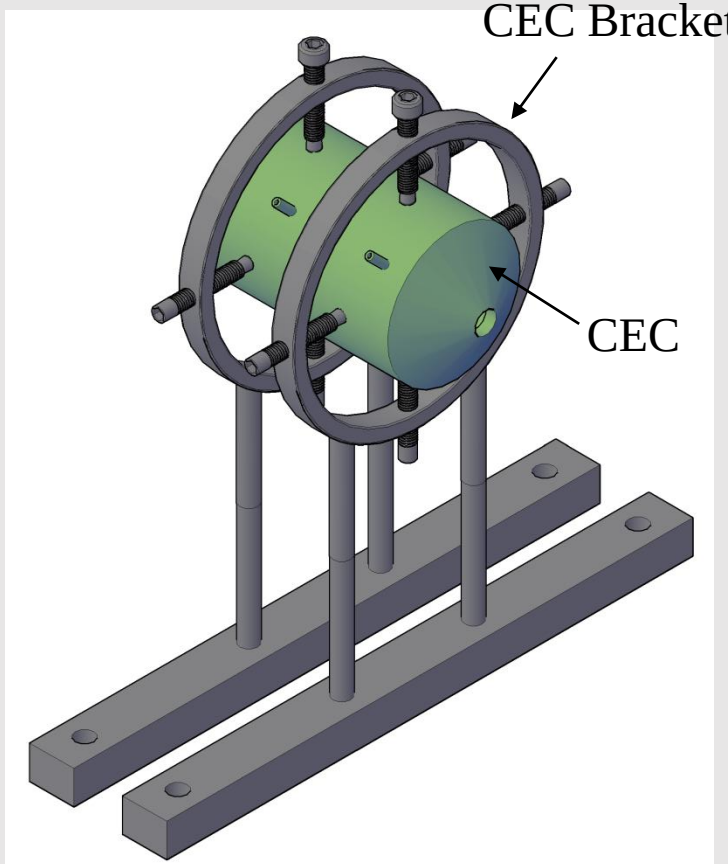


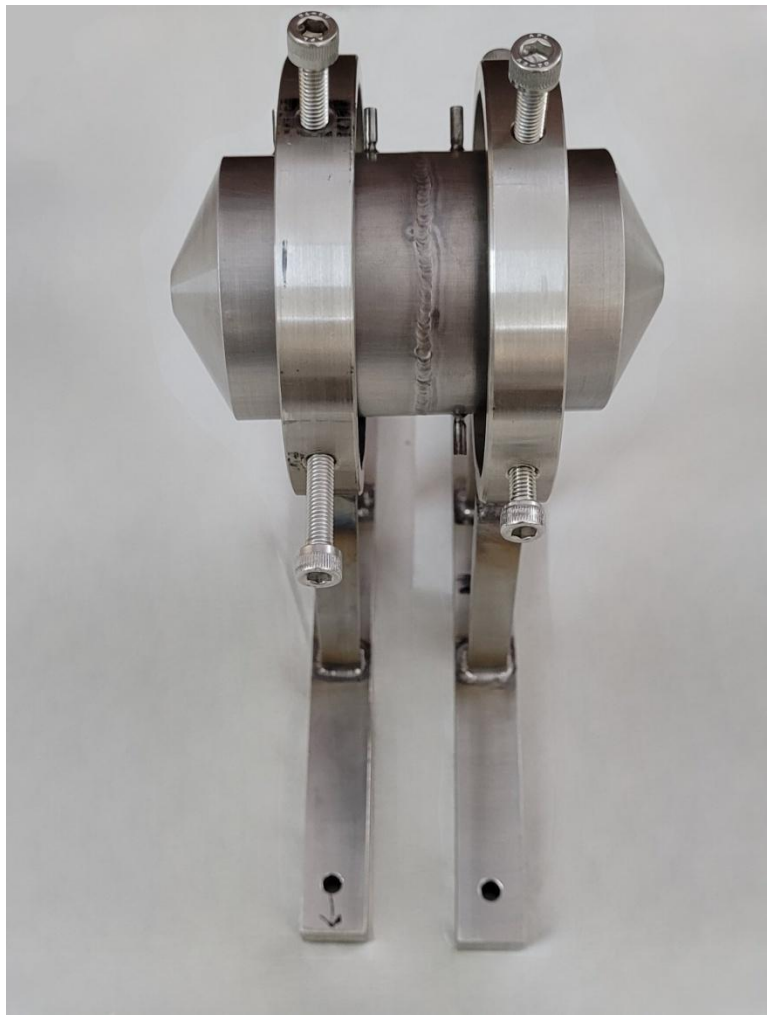


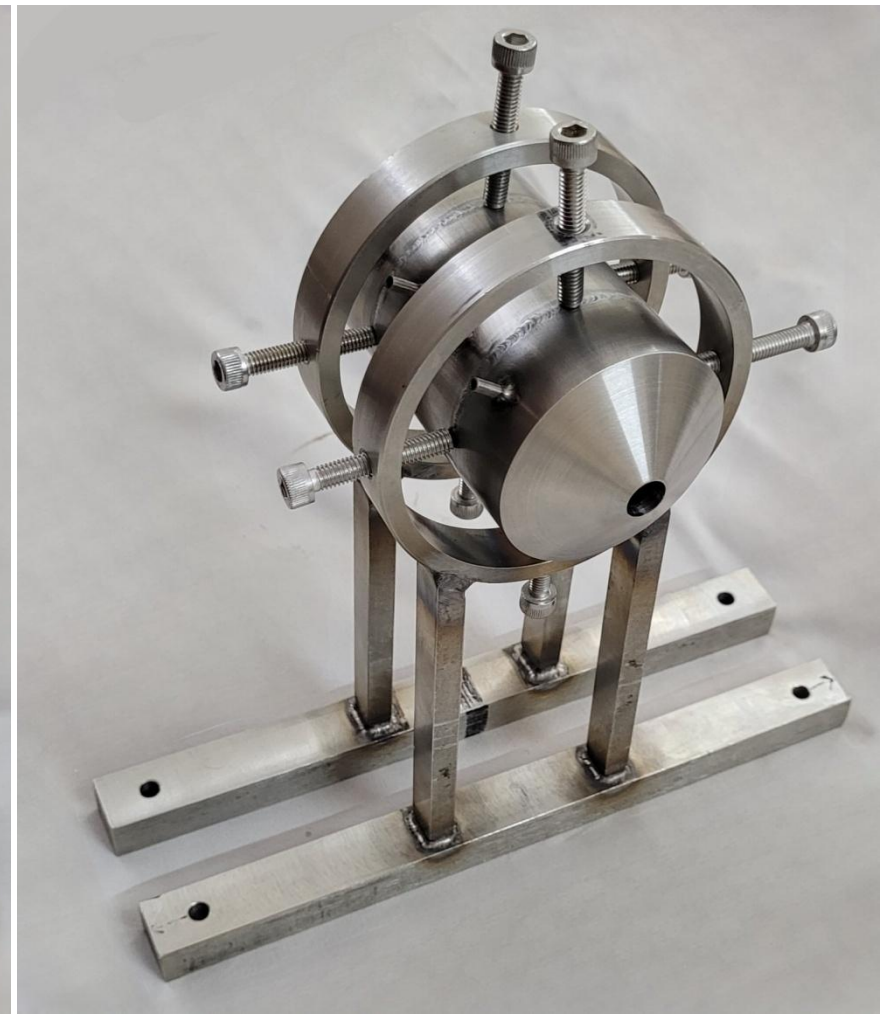
CEC with bracket AutoCAD model



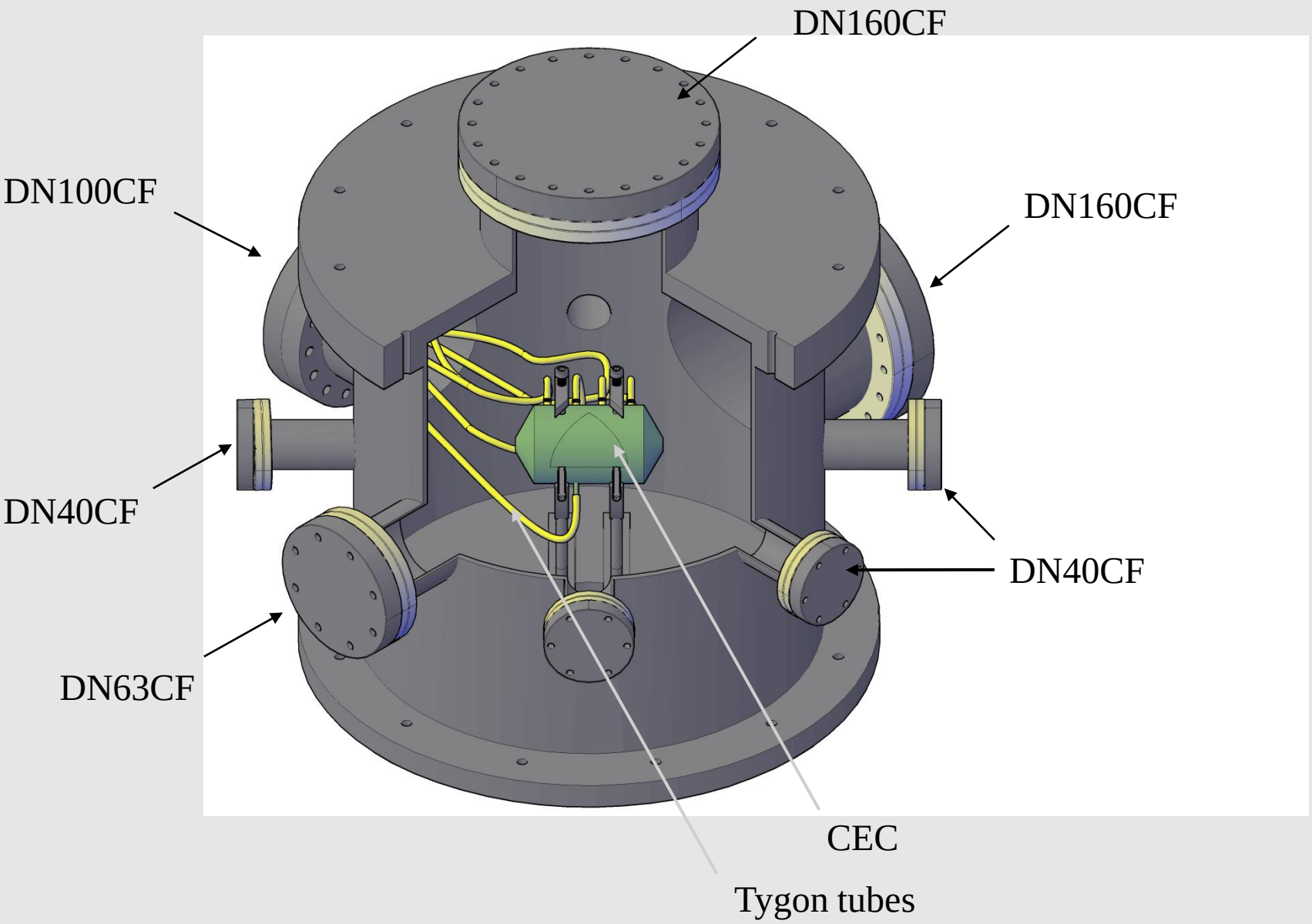




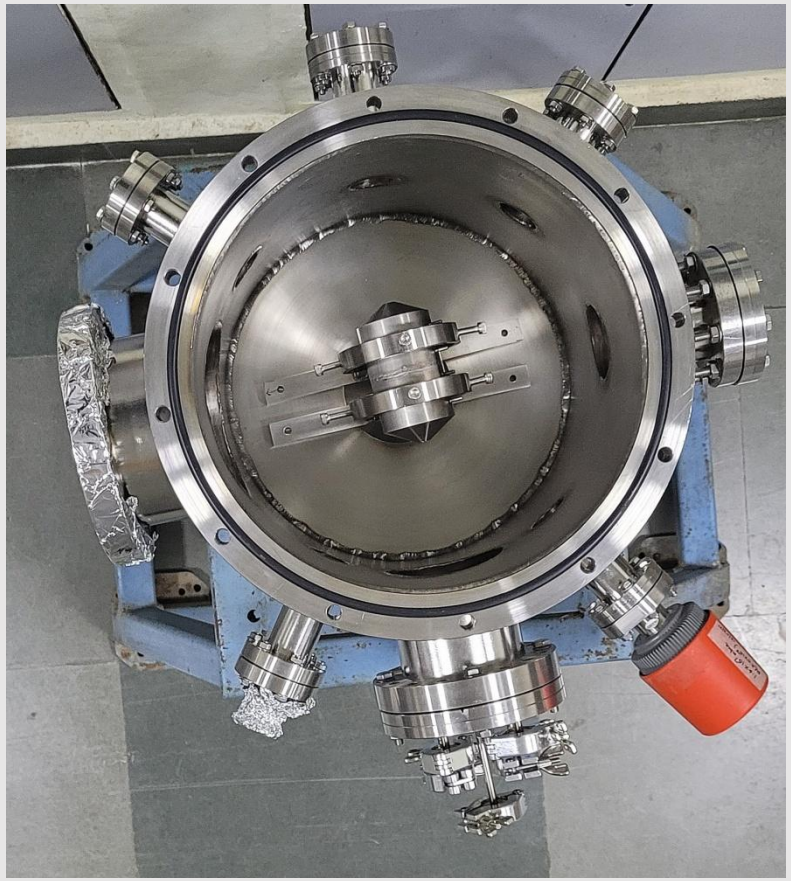




Chamber with CEC AutoCAD model



The photographs of CEC assembly for offline testing



Neutron Source-I :

- H(^{7}Li,^{7}Be)n reaction in IKR
- Neutrons counted in coincidence with ^{7}Be
- HIRA ToF (~ 400 ns) of Be used correct En to 50 keV

HIRA facility in IKR optics

Rotating target

Exit channel	Q-value	Threshold energy
$n_0 + {}^{7}Be$	-1.644 MeV	13.098 MeV
$n_1 + {}^{7}Be^{*}$(0.429 MeV)	-2.073 MeV	16.513 MeV
$n_2 + {}^{3}He + {}^{4}He$	-3.230 MeV	25.726 MeV
$n_3 + {}^{7}Be^{*}$(4.57 MeV)	-6.214 MeV	49.489 MeV

Results of simulations [1]

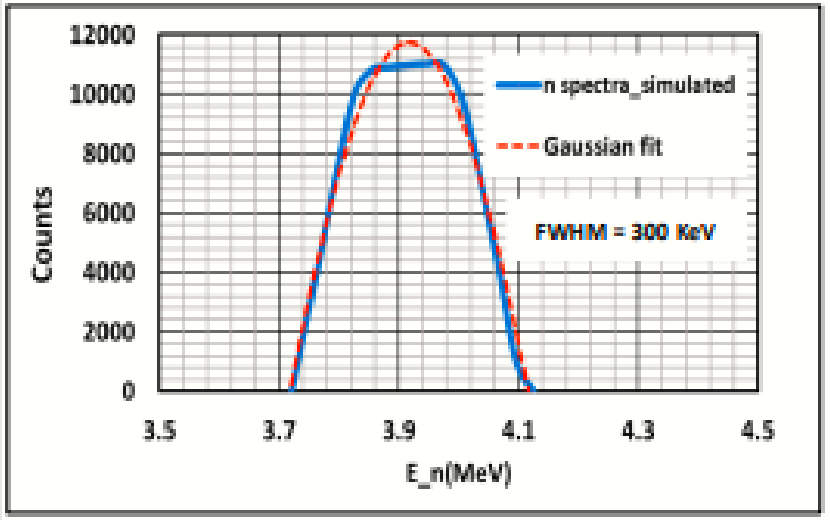


Fig. 20: Simulated result of neutron energy spread due to energy loss of ^{7}**Li** inside the target

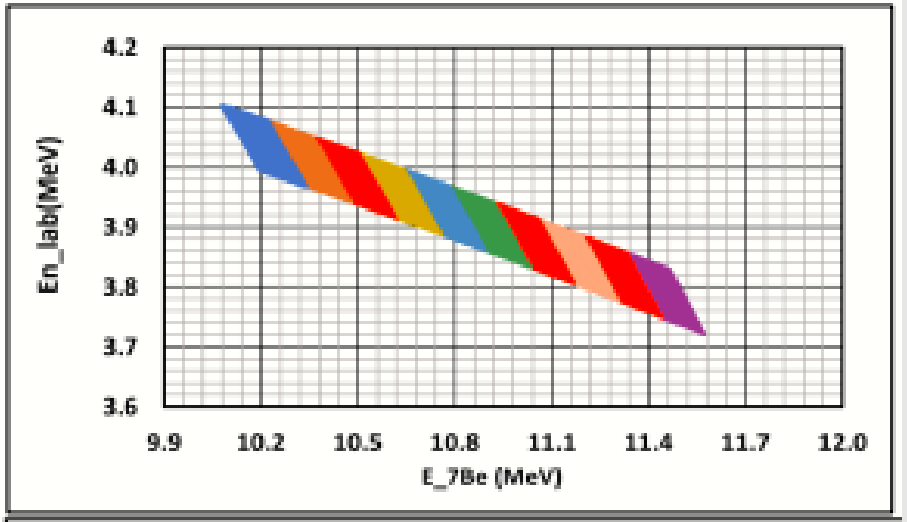
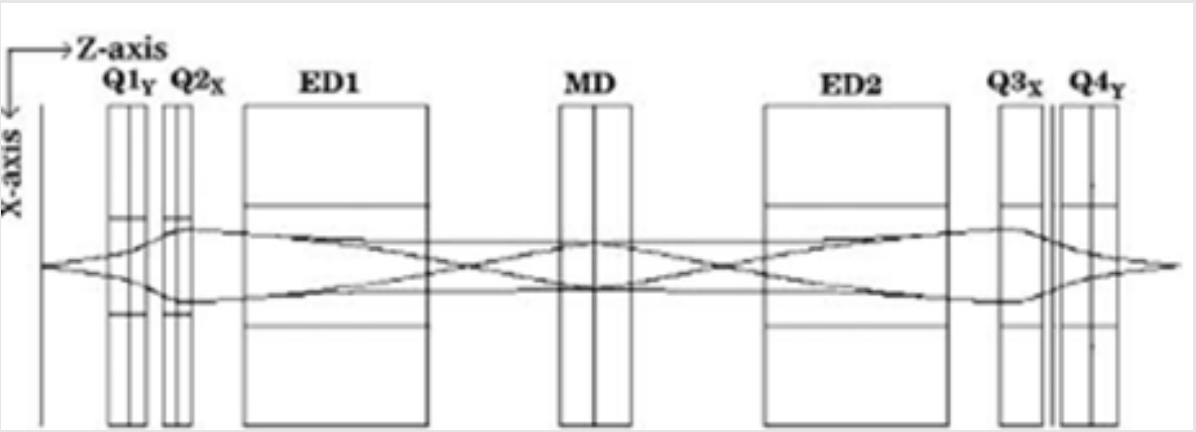
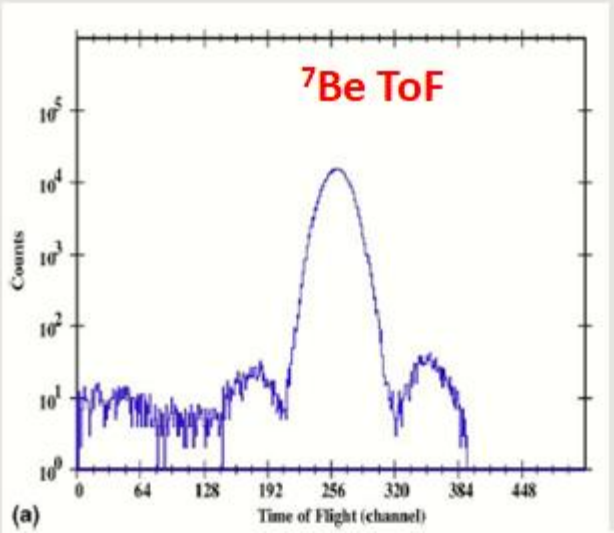


Fig. 21: Scatter plot for n energy and ^{7}**Be** energy coming out from different layers of the target. Different colors are used to distinguish different layers of the target

Ion optics for IKR tested at 9 degree





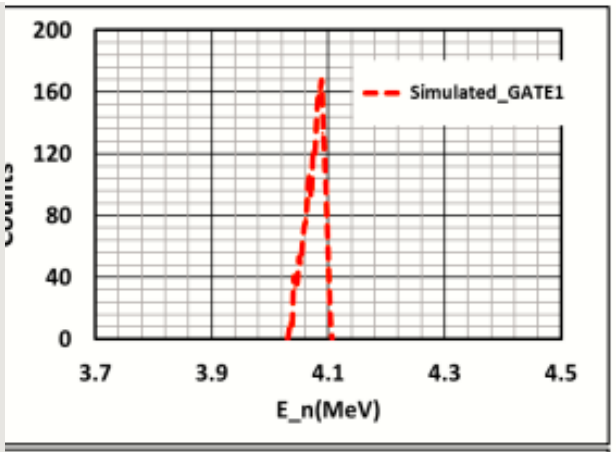
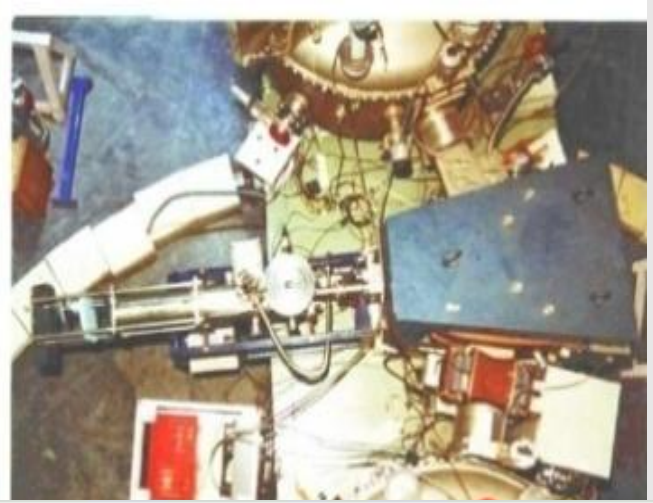


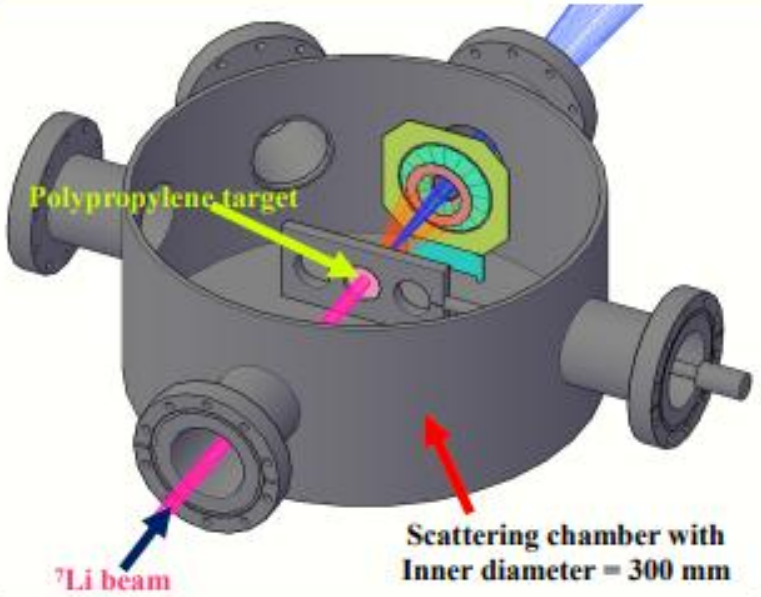
Fig. 24: Neutron energy spectrum corresponding to 80 keV gate in ^{7}Be energy in the range **10.077-10.157 MeV**

Neutron source-II

- **IPN Orsay tried first**
  - Low background due to inverse kinematics
  - target burnt in 1 hr
- **CUPAC contribution**:
  - Rotating target
  - ToF RMS, ~25 MeV
  - Absolute normalization of neutron flux
  - Ray tracing



Experimental setup(3D)



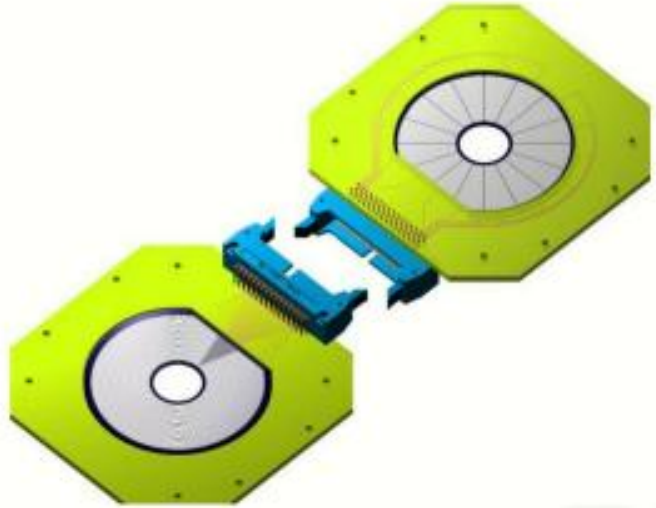
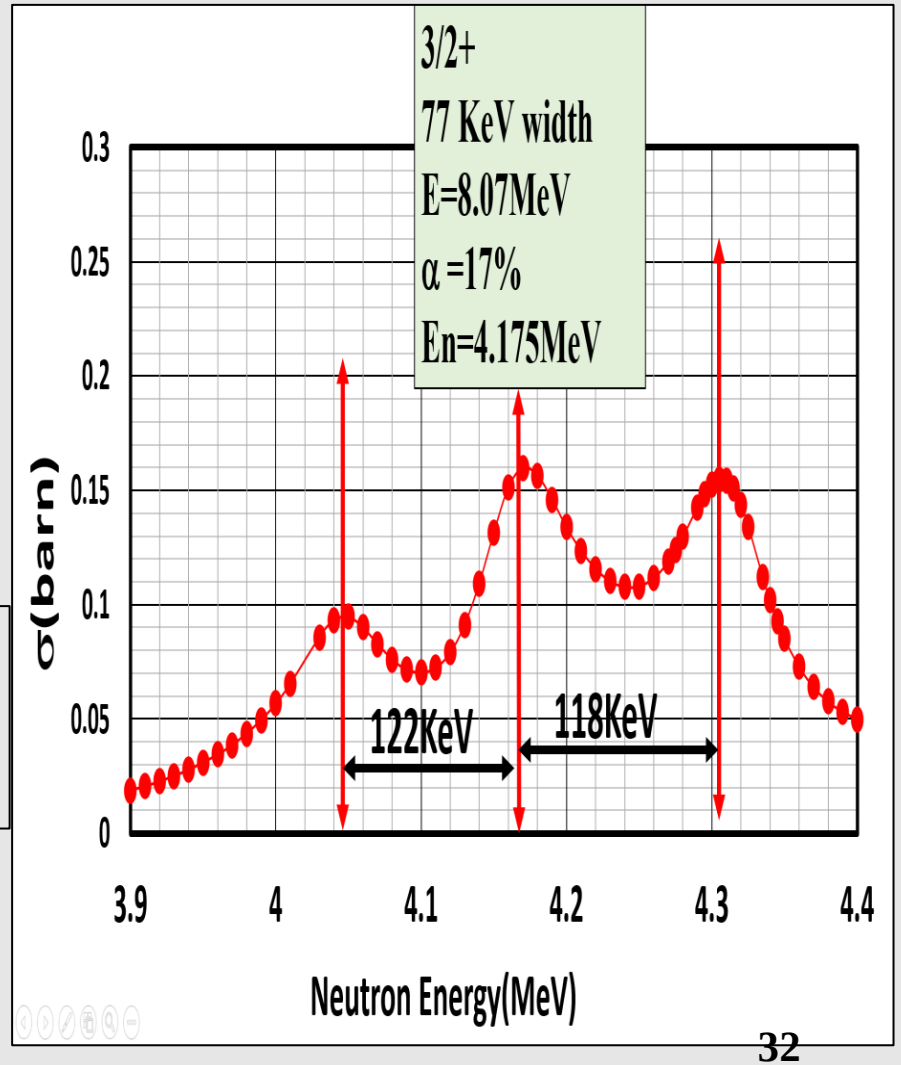


Fig. 6: The proposed experimental set-up in 3D for neutron beam energy of **4.053 MeV**

Fig. 7: Annular silicon strip detector(ASSD) from Micron Semiconductor of **ID=20 mm** and **OD=76mm**

D3: Neutron source strength in AGB stars: $^{13}C(\alpha,n)^{16}$ in time reversal method

- Absolute normalization errors & background (30%-50%)
- Background effects R matrix analysis
- Novel technique
  - Overall errors: 10% (stat 6%, syst. 8%)
  - Prove: Reproduce existing measurements



"**The Importance of the $^{13}C(\alpha,n)^{16}O$ Reaction in Asymptotic Giant Branch Stars**" by S. Cristallo et. al. in The Astrophysical Journal, 859:105 (14pp), 2018 June 1 **n_ToF: Measurements of key reactions of interest to AGB stars** by C. Massimi et. al. in Universe 2022 8 100

THE ASTROPHYSICAL JOURNAL, 859:105 (14pp), 2018 June 1

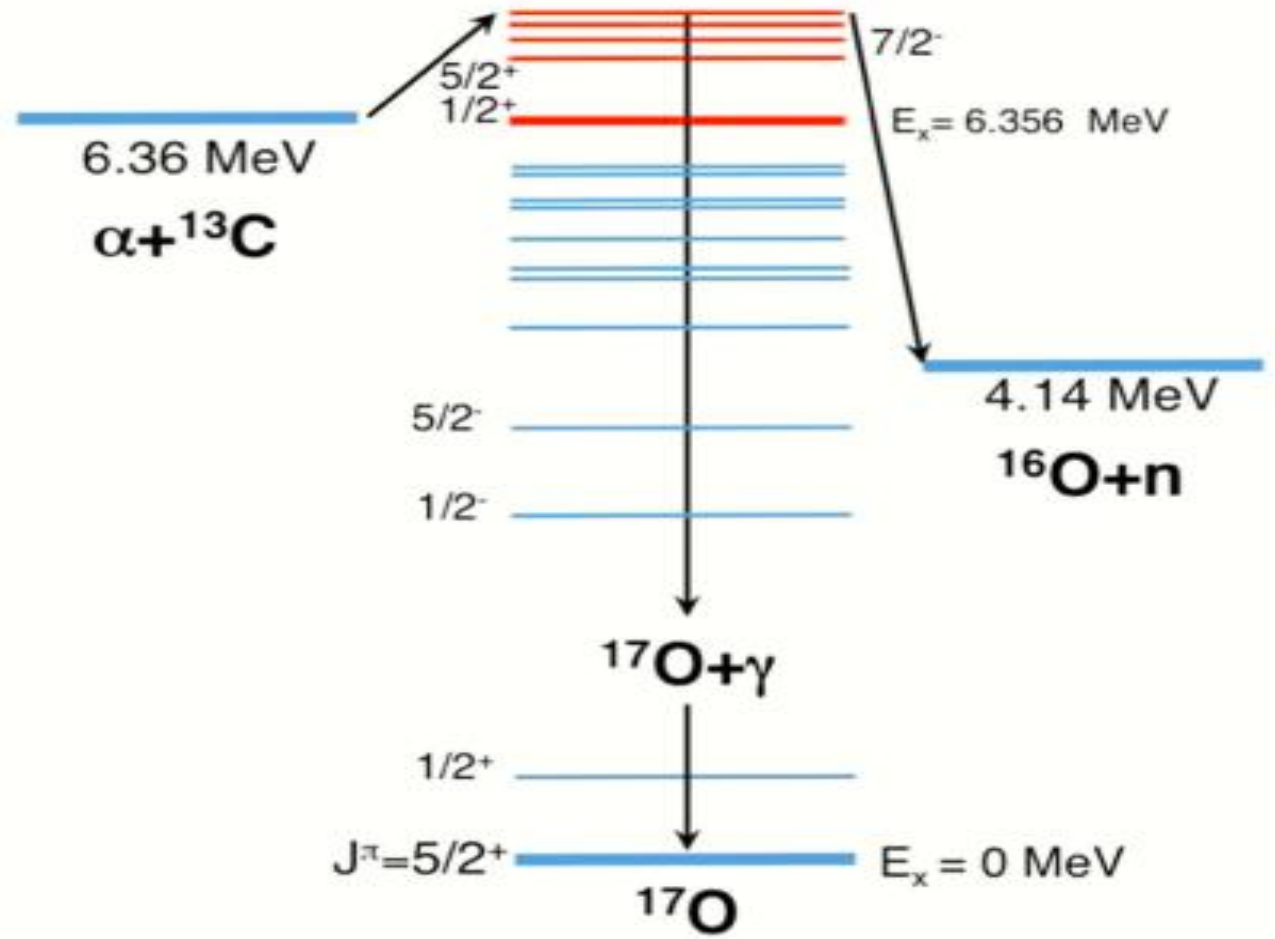


Figure 1. Schematic diagram of the ^{13}C(α,n) ^{16}O nuclear reaction process, together with the competing exit channel ^{17}O+γ. Neutrons are produced via α-particle capture on ^{13}C through a resonant process involving the formation of the ^{17}O compound nucleus. The excited states of interest for AGB nucleosynthesis are shown in red.

Simulations of the experimental set-up and feasibility

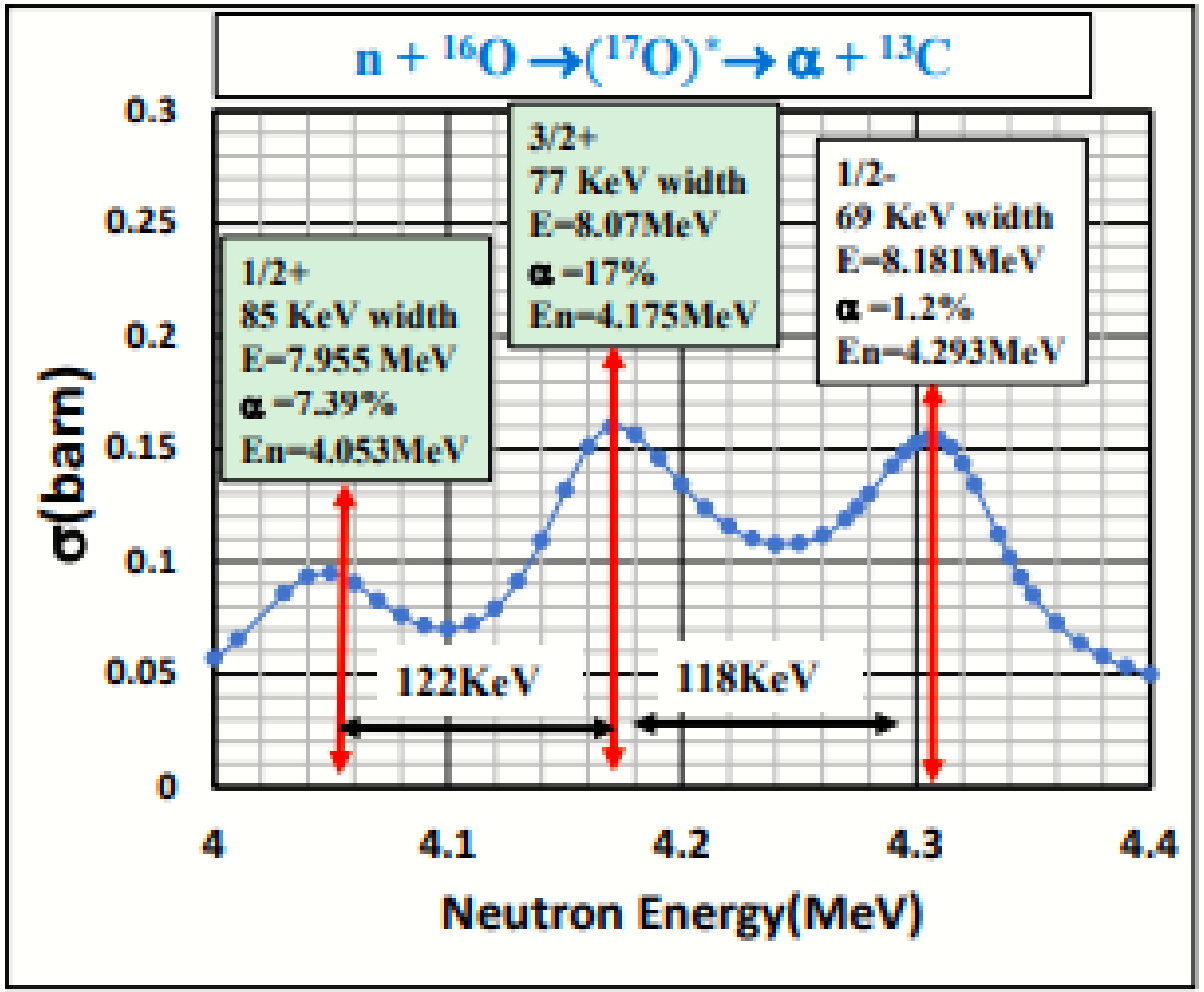


Fig. 8: $^{16}O(n,\alpha)^{13}C$ cross-section plot

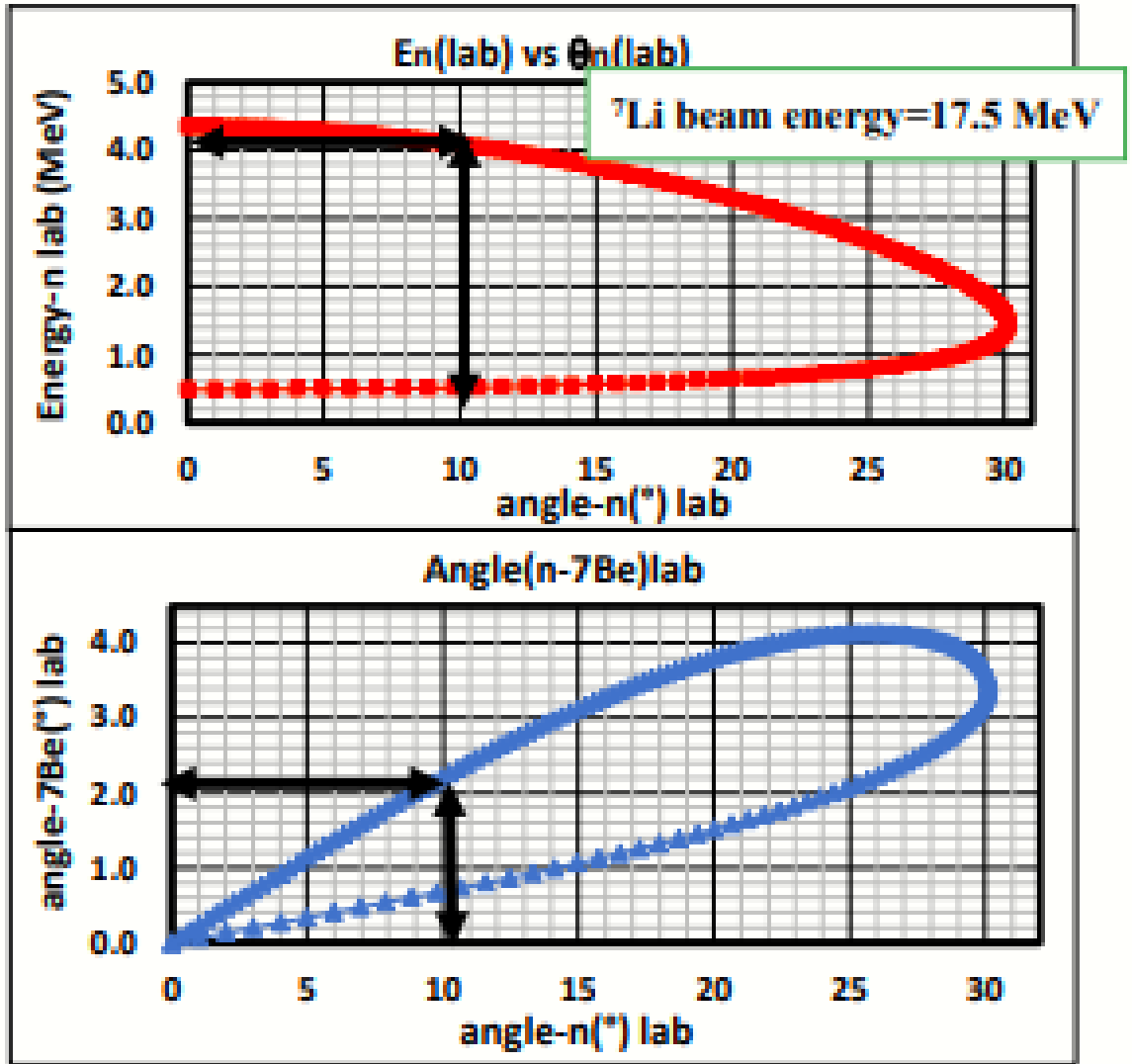
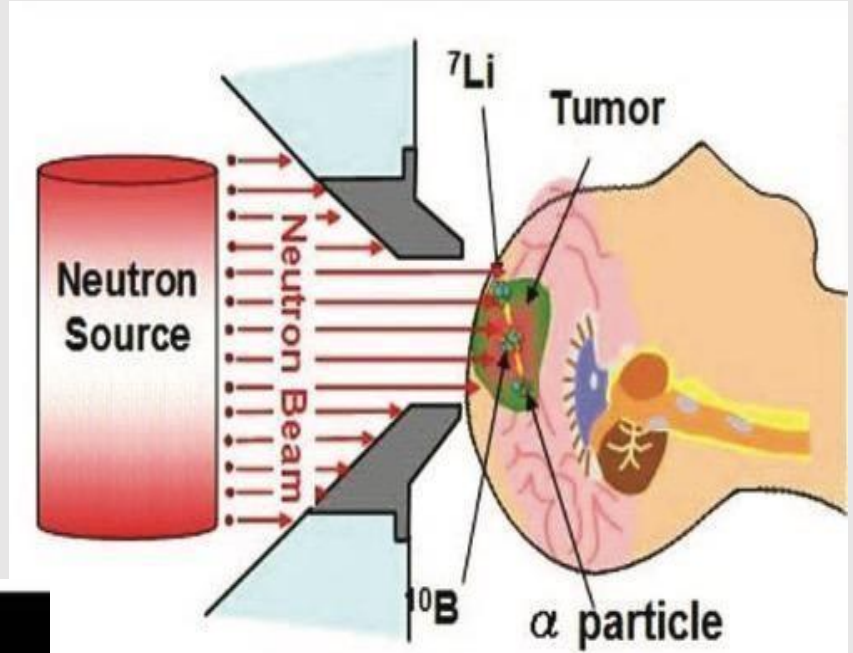


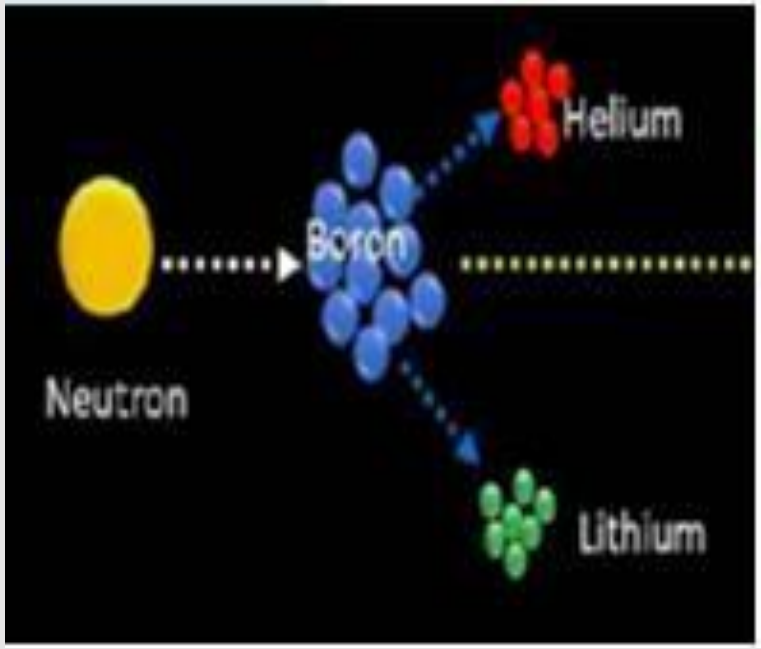
Fig. 9: p(^{7}Li,^{7}Be)n reaction kinematics plot

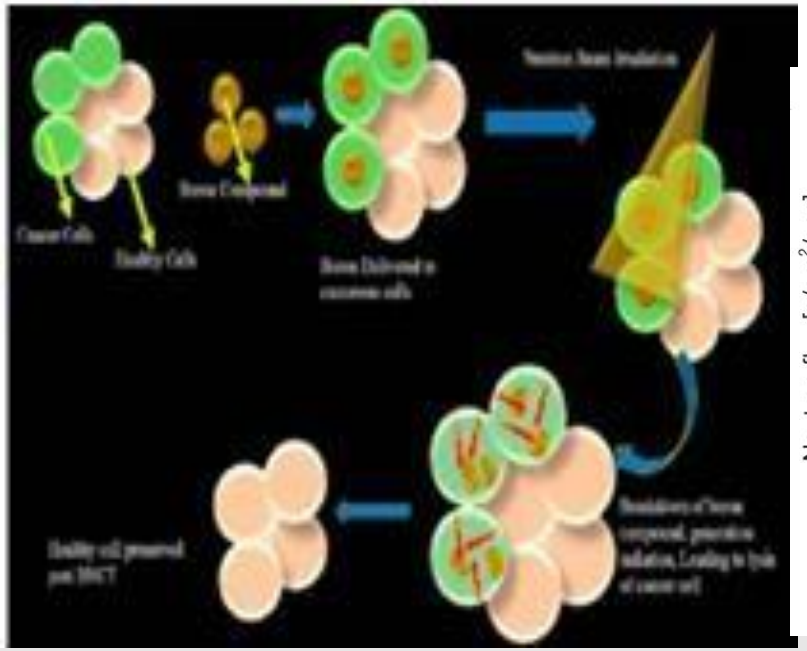
D4: AD-BNCT investigations

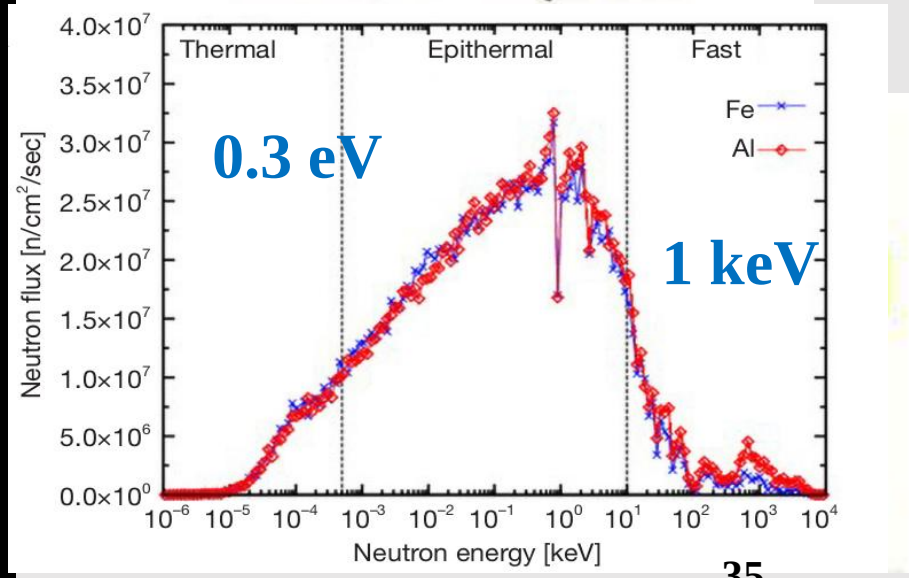
Investigate AD-BNCT:

- Requires epithermal neutron beam
- Must meet strict IAEA quality control

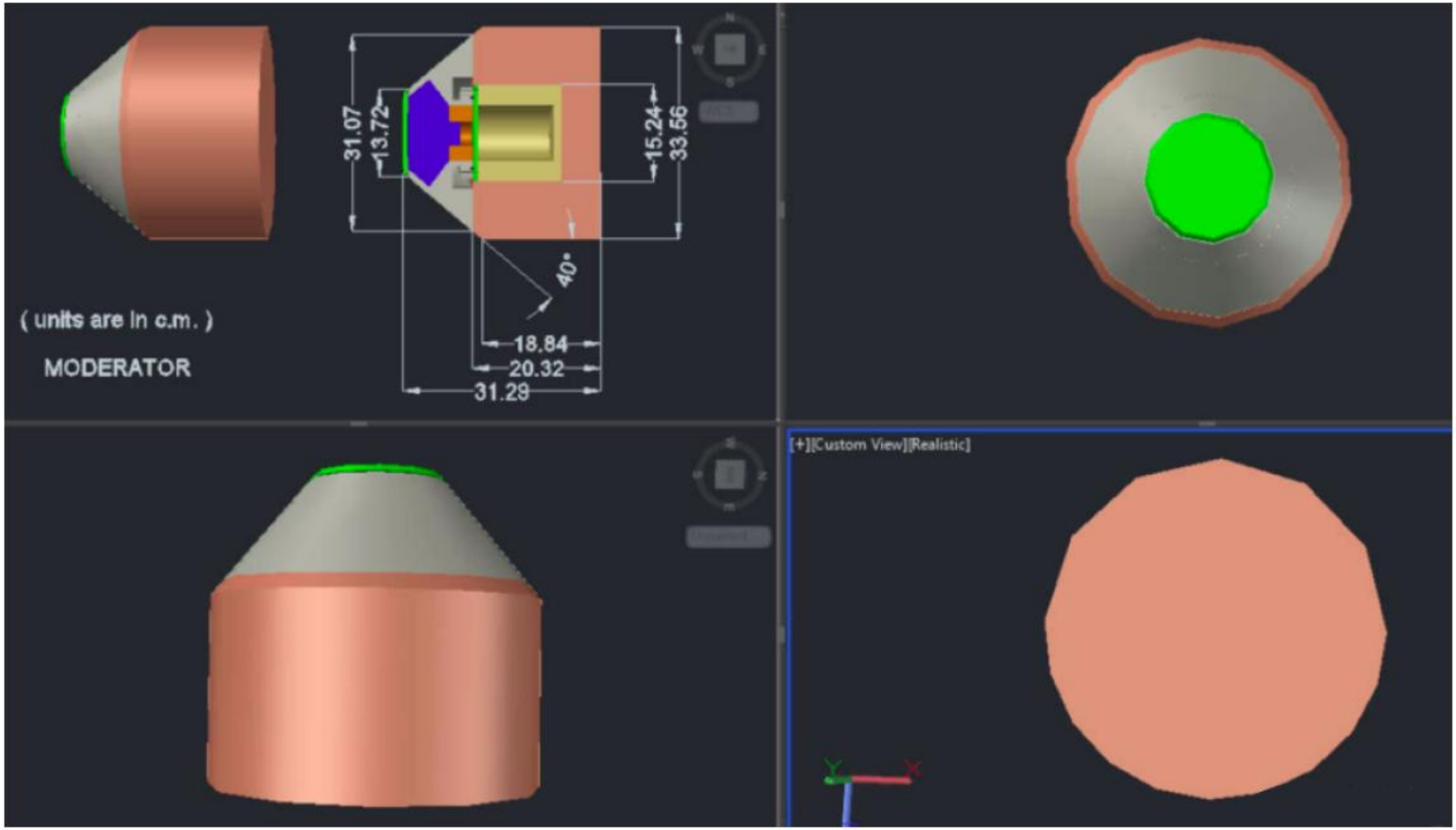




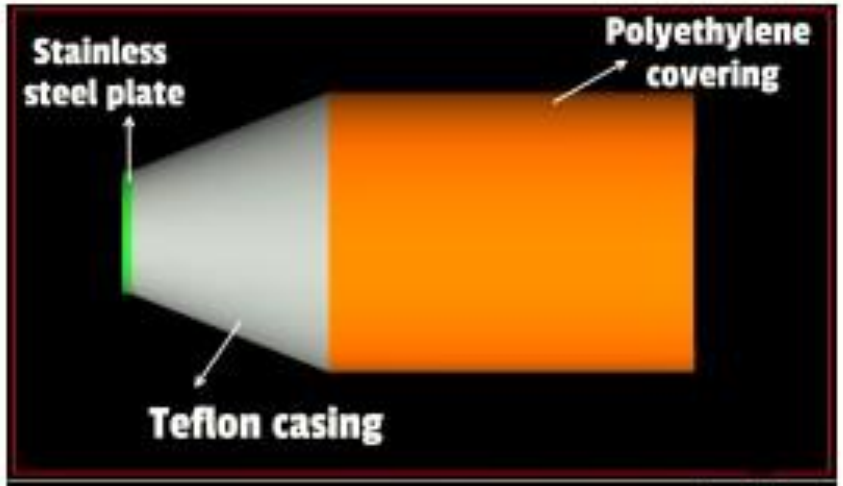


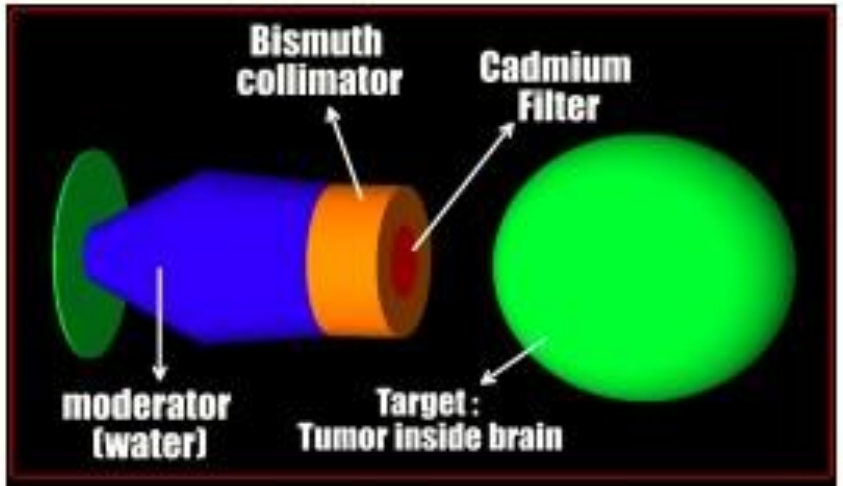


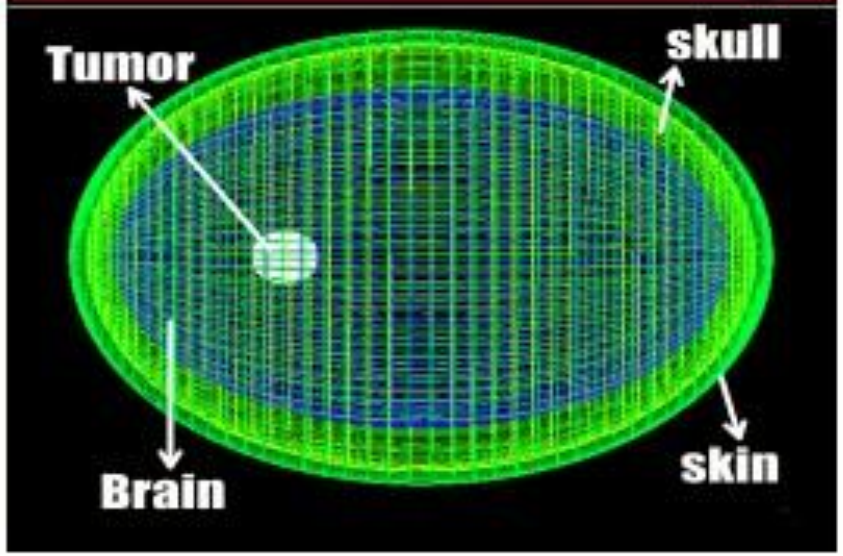
Design of the Neutron Moderator



Complete Geometry of the Moderator







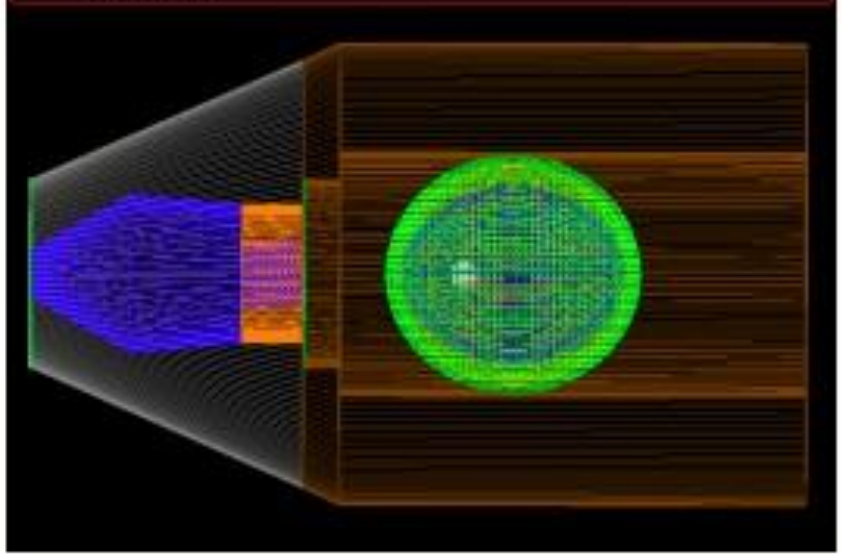
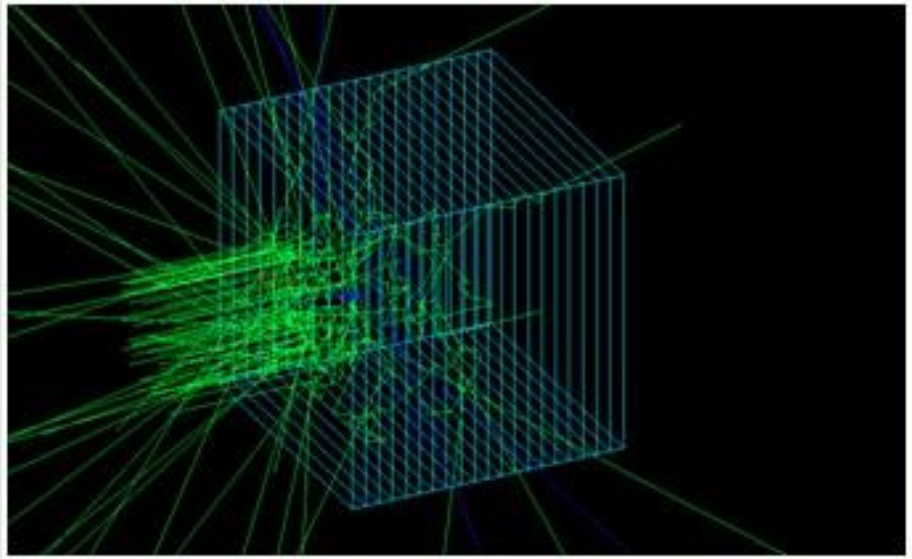
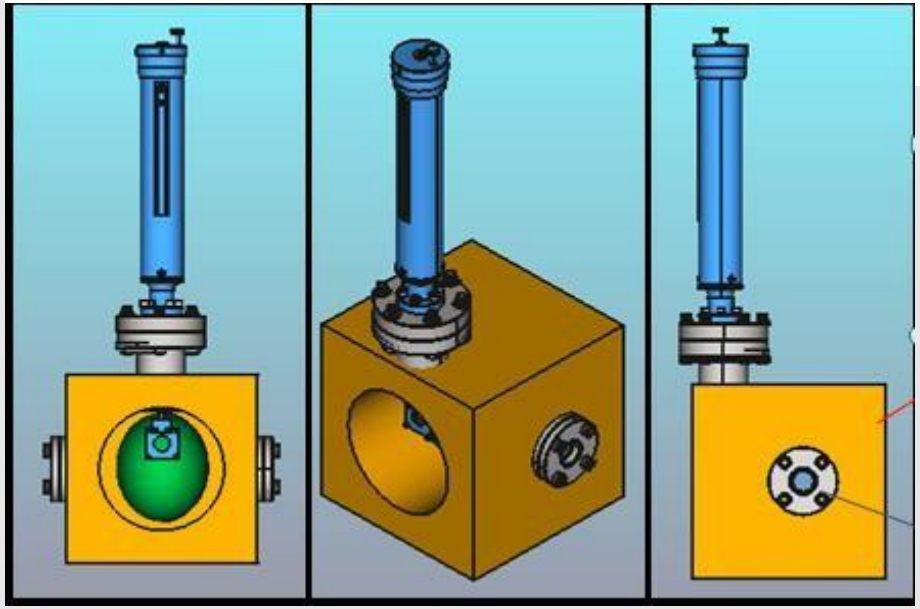


Figure 6: From top left: The Exterior & Interior of the moderator
From bottom left: Details of brain tumor & Completed geometry

GEANT4 simulation of Head phantom





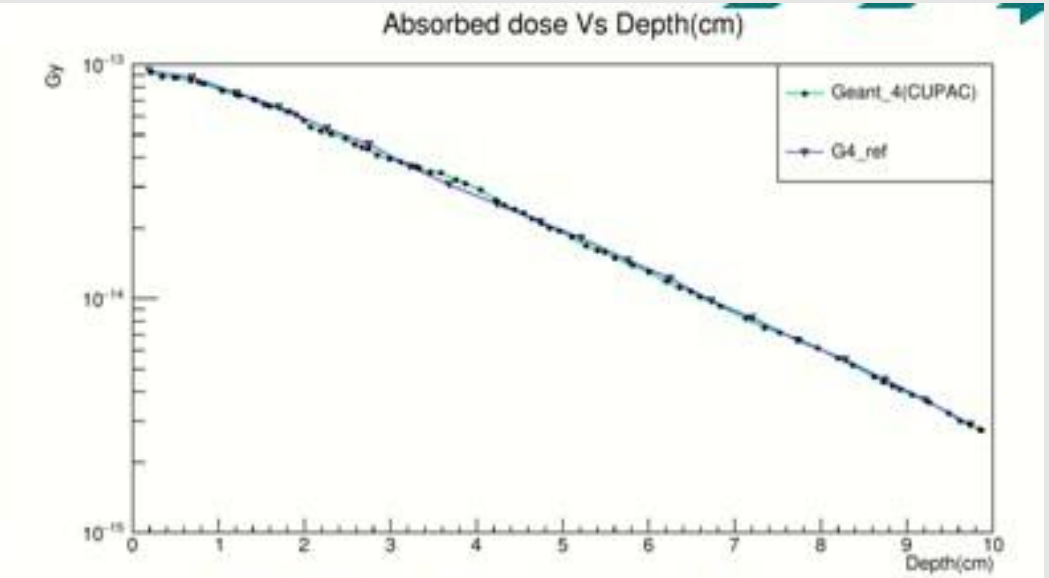


Fig .9 Absorbed dose vs depth

Potential co=operation with JINR

- **Experiment UGL:**
  - Construction 400 kV ECR with supersonic
  - Layout already made for INO jet (US $3 m)
- **Theory**
  - **Atomic physics:** Charge exchange cross-section with MED (minimum energy defect)
  - **Nuclear Physics:** R matrix analysis
  - **Nuclear Astrophysics:** Stellar modeling codes like FUNC

Conclusion

- Status: construct an accelerator and experimental system. Significantly enhance national research capabilities: Nuclear Astrophysics, **PIMS**, **AD-BNCT** and SHIM
  - Design of supersonic **gas jet target** coupled to an RMS is presented
  - **PIMS** system R&D: waiting for beam-time at IUAC/BARC
  - KNFS to be tested soon at IUAC
  - AD-BNCT" CAD design complete fast neutron moderator and Snyder head phantom is complete. Validation of the design using GEANT4 is near completion
- **Mission statement:**
  - all these works were done entirely by our dissertation students in last 3 yrs
  - skills: High level excel programming, CAD for UHV, accelerator p[tics, SIMION,GEANT4
- **Possible collaboration with JINR in UGL, atomic and nuclear theory**

Green: World's first

Red: India's First

EXTRA SLIDES

Assembly of the drive