A proposal for an underground facility for nuclear astrophysics

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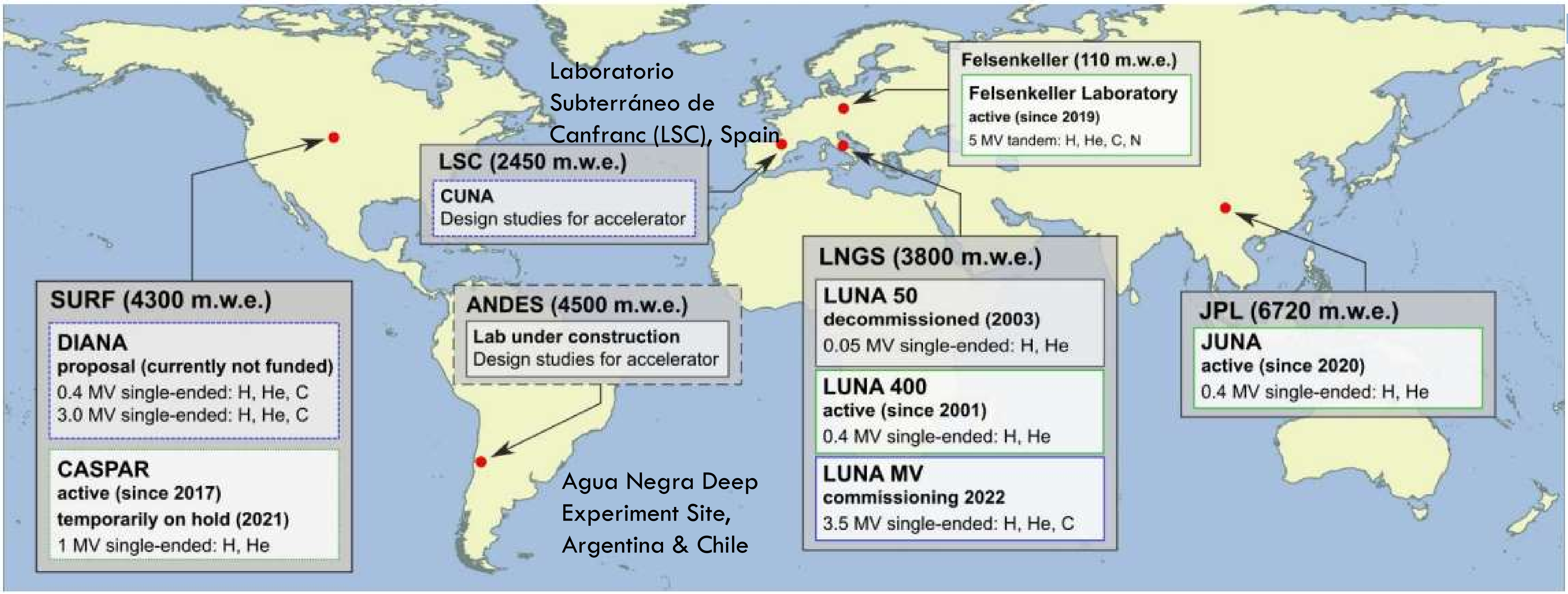
Discussion meeting on underground facility in India

Outline of the presentation

- Underground facilities for nuclear astrophysics
- Reactions of interest
- Present status of a few
- Proposed accelerator
- Proposal for AJT & RMS
- Summary

Underground accelerator facilities around the World



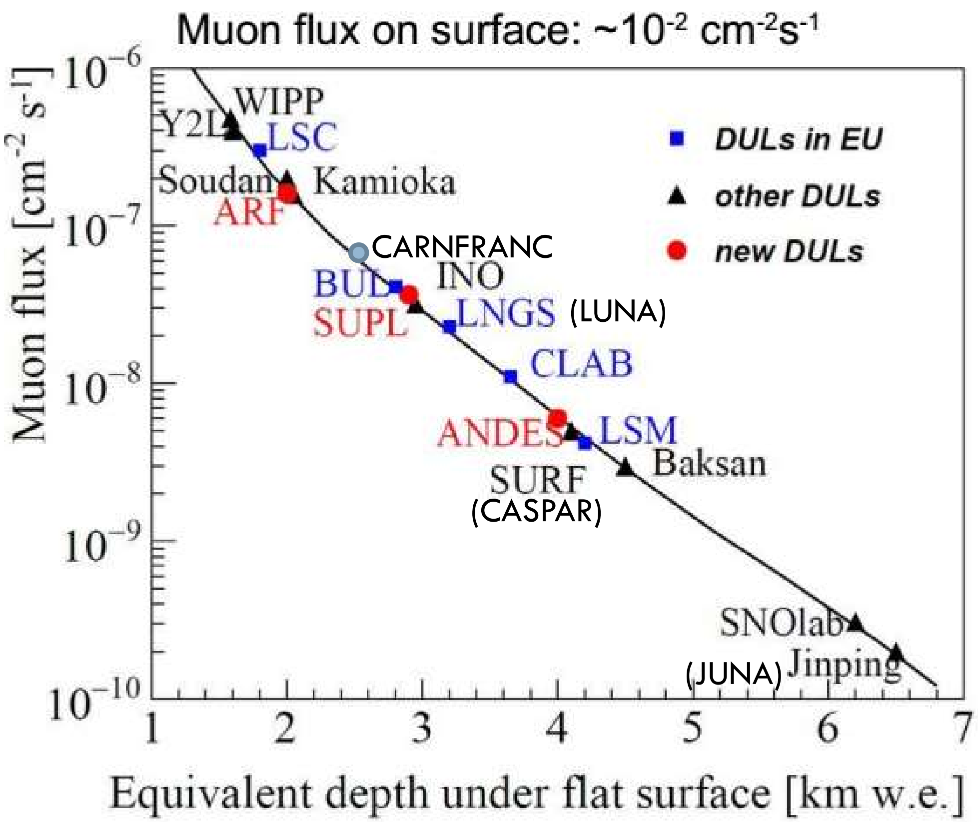
SURF:Sanford underground Research Facility, South Dakota

CASPAR:Compact Accelerator System for Performing Astrophysical Research

6 Major facilities:

5 of them are very recent (within last 5 years)

Flux attenuation at different underground labs



Facility	Depth	**Flux attenuation**		
		Muon	Neutron	Gamma
LUNA, Italy	1.4 km, 3.1 kmwe	10^{-6}	10^{-3}	10^{-3}
JUNA, China	2.4 km, 6.72 kmwe	10^{-8}	10^{-5}	10^{-5}
CASPER, USA	1.49 km, 4.3 kmwe	10^{-6}	10^{-3}	10^{-3}
Felsenkeller, Germany	50 m, 140 mwe	4×10^{-1}		4×10^{-1}
CANFRANC (Spain)	0.85 km, 2.5 kmwe	5×10^{-7}		
ANDES (S America)	1.75 km, 4.5 kmwe	10^{-6}		

Reactions of interest - 1

SL no.	Reactions	Physics	Gammow peak (keV)	X-section (barn)	Labs interested	Existing error	Reference
1	$^{14}N(p,\gamma)^{15}O$	CNO	148	10^{-13}	LUNA, CASPER		
2	$^{12}C+^{12,13}C$	C burning	820	10^{-13} (2.4 MeV)	LUNA		
3	$^{13}C(\alpha,n)^{16}O$	Heavy Ion synthesis, AGB	300	10^{-16}	LUNA, JUNA, CUNA, CASPER	60%	Astrophys. J., 414 (1993) 735
4	$^{22}Ne(\alpha,n)^{25}Mg$	Heavy Ion synthesis, AGB			LUNA, CUNA, CASPER		
5	$^{22}Ne(p,\gamma)^{23}Na$	Synthesis in AGB stars	190	2.4×10^{-3} (290 keV)	LUNA	Up to 3 orders	

Same reaction is addressed by multiple labs → to reduce uncertainties using different techniques

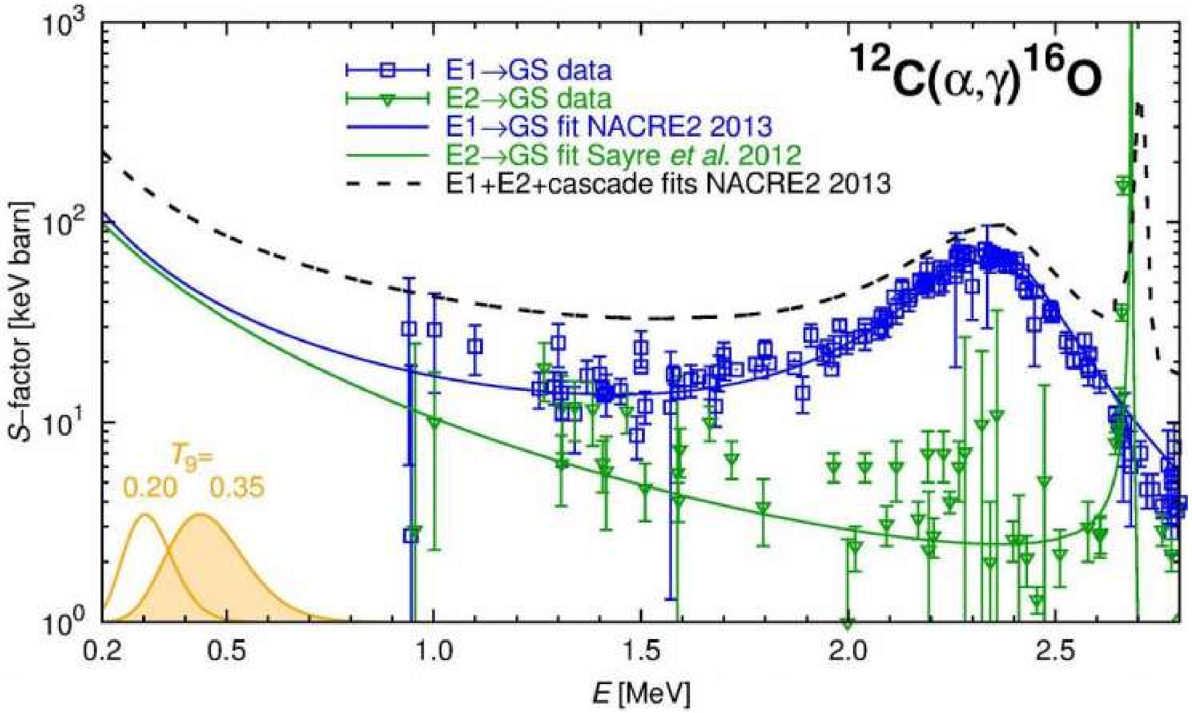
Reactions of interest - 2

SL no.	Reactions	Physics	Gammow peak (keV)	X-section (barn)	Labs interested	Existing error	Reference
6	$^{12}C(\alpha,\gamma)^{16}O$	Massive star	300	10^{-17}	LUNA, JUNA	60%	NPA, **758** (2005) 363
7	$^{18}O(p,\alpha)^{15}N$	CNO	160	3×10^{-5} (240 keV)	LUNA		
8	$^{19}F(p,\alpha)^{16}O$	F abundance	100	7×10^{-9}	JUNA	80%	PLB, **748** (2015) 178
9	$^{25}Mg(p,\gamma)^{26}Al$	Galaxy ^{26}Al	58 (reso)	2×10^{-13}	JUNA	20%	PLB **707** (2012) 60

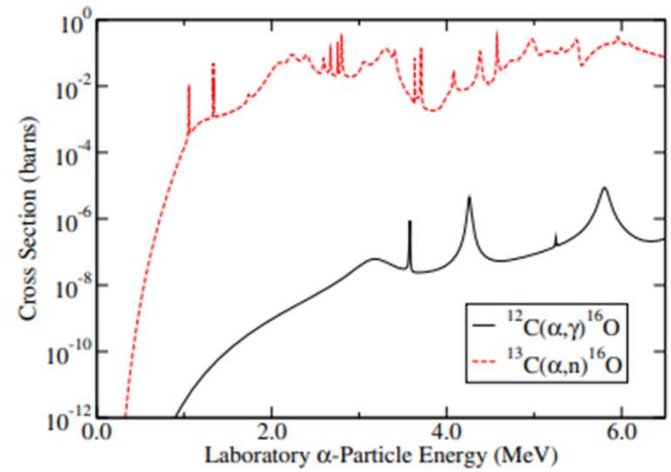
Gamow energies ~ a few keV to 100's of keV

Cross sections ~ as low as 10^{-17} barn → not possible to measure over ground due cosmic background

$^{12}C(\alpha,\gamma)^{16}O$, holy grail in Nuclear Astrophysics



- **Highly sought-after reaction data related to carbon/oxygen ratio in the Universe.**
- JUNA approach: high-intensity alpha beam on carbon target



Felsenkeller: Carbon beam on helium gas target, inverse kinematics ($^{13}C(\alpha,n)^{16}O$ x-section is 5 order more, tgt contamination is a problem)

Gamow energies for $^{12}C(\alpha,\gamma)^{16}O$ reaction at diff. sites

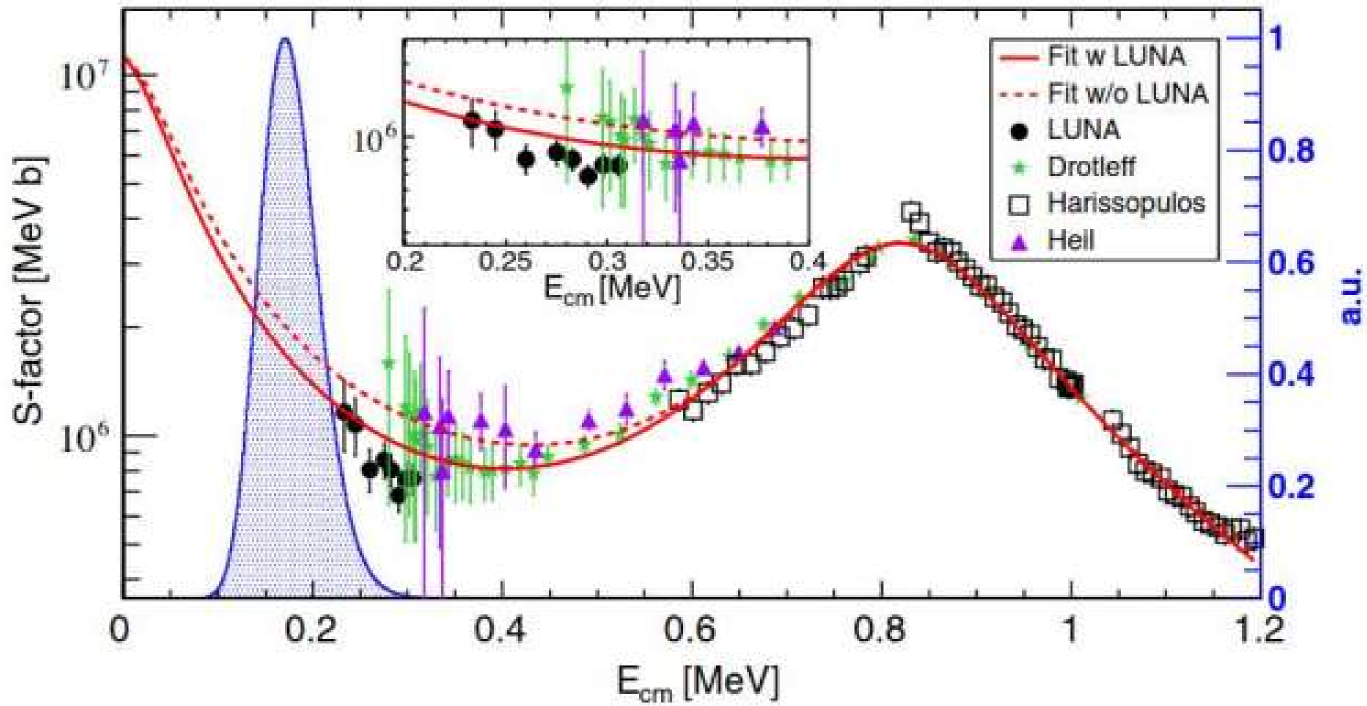
TABLE I. Astrophysical environments and burning stages where the $^{12}C(\alpha,\gamma)^{16}O$ reaction plays an important role. The temperatures of these environments dictate the energy ranges where the $^{12}C(\alpha,\gamma)^{16}O$ cross section must be well known for an accurate calculation of the reaction rate.

Burning stages	Astrophysical sites	Temperature range (GK)	Gamow energy range (MeV)
Core helium burning	AGB stars and massive stars	0.1–0.4	0.15–0.65
Core carbon and oxygen burning	Massive stars	0.6–2.7	0.44–2.5
Core silicon burning	Massive stars	2.8–4.1	1.1–3.4
Explosive helium burning	Supernovae and x-ray bursts	≈1	0.6–1.25
Explosive oxygen and silicon burning	Supernovae	> 5	> 1.45

- Nearly all models of different nucleosynthesis environments are affected by the production of carbon and oxygen
- Precise (within 10%) determination of the reaction rate of $^{12}C(\alpha,\gamma)^{16}O$ is a key ingredient
- Propose to use inverse kinematics i.e., Carbon beam on helium gas target and Recoil Mass Separator

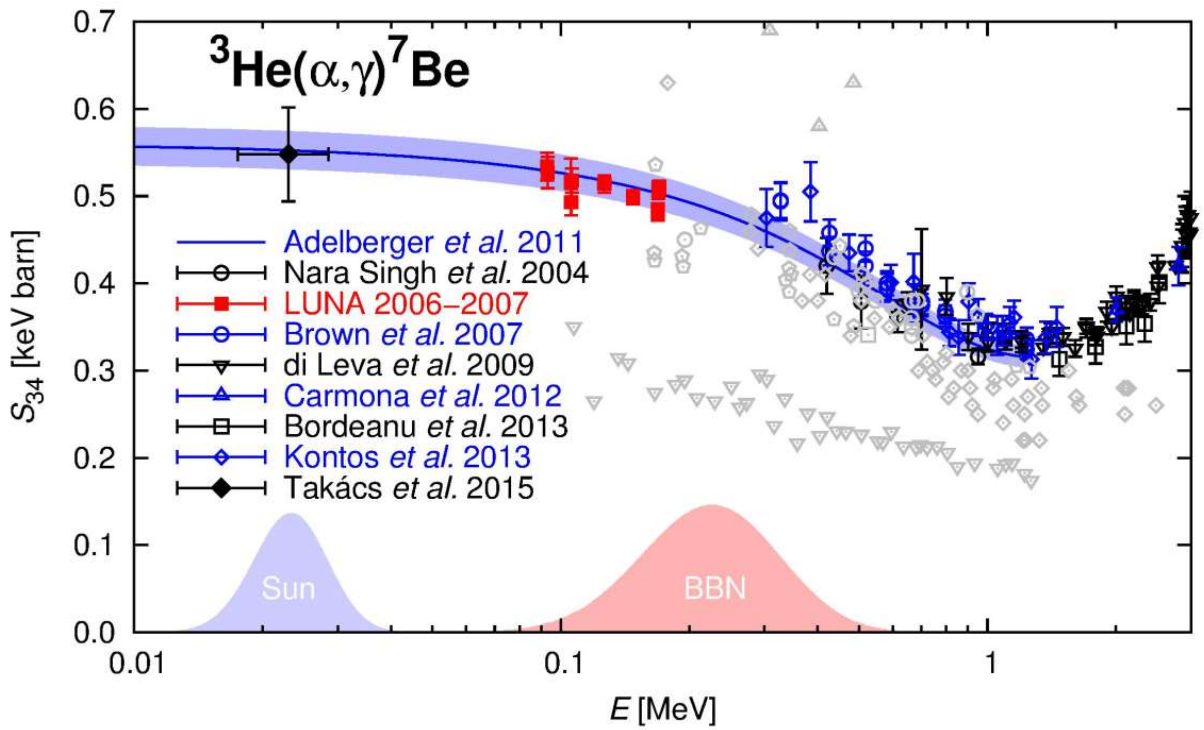
13C(α,n): S-process for Heavy Ion formation

- Normalization of data under debate
- Data unavailable in Gammow region
- Beam from MV machine with inverse kinematics can be used covering a wide range of energies
- RMS for background reduction



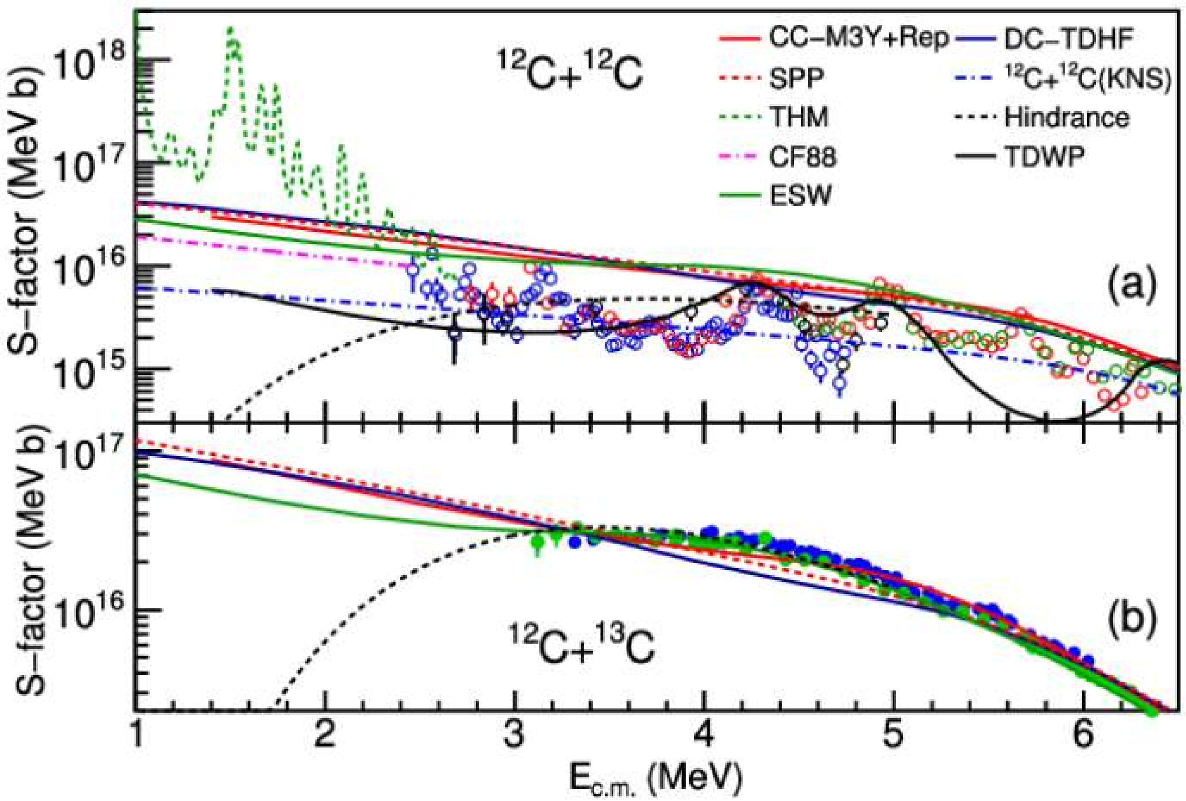
$^{3}He(\alpha,\gamma)^{7}Be$: PP chain & Li abundance

- Affects i) hydrogen burning in Sun and production of ii) 7Li in Big bang nucleosynthesis and iii) 7Be and 8B solar neutrino fluxes.
- Direct measurement data around Gamow peaks (25 and 250 keV) are sparse
- Proposed underground accelerator facility can cover the entire energy (20-500 keV) of interest and RMS for background reduction



$^{12}C+^{12,13}C$ fusion: $^{23}Na/^{20}Ne$

- Direct measurement data around Gamow peaks (<1 MeV) not available
- $^{12}C(^{12}C,p\gamma)^{23}Na$ and $^{12}C(^{12}C,\alpha\gamma)20Ne$. Ratio of ^{23}Na to ^{20}Ne important
- Proposed underground accelerator facilities can cover the entire energy of interest



Required terminal voltage for proposed experiments

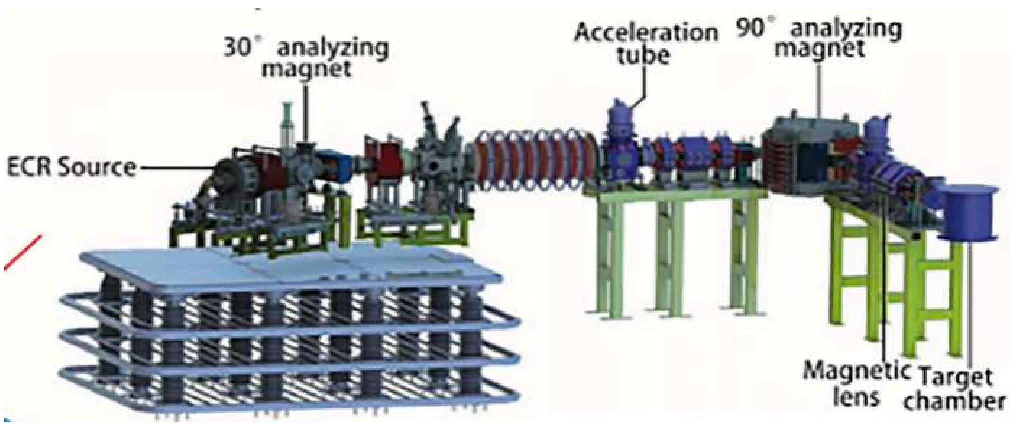
Maximum energy chosen to cover is 2 MeV, because

- High energy data required for S-factor normalization
- To avoid tail of resonances around 1 MeV for some reactions, normalization at higher energy required
- Inverse kinematics and RMS to be used to reduce background

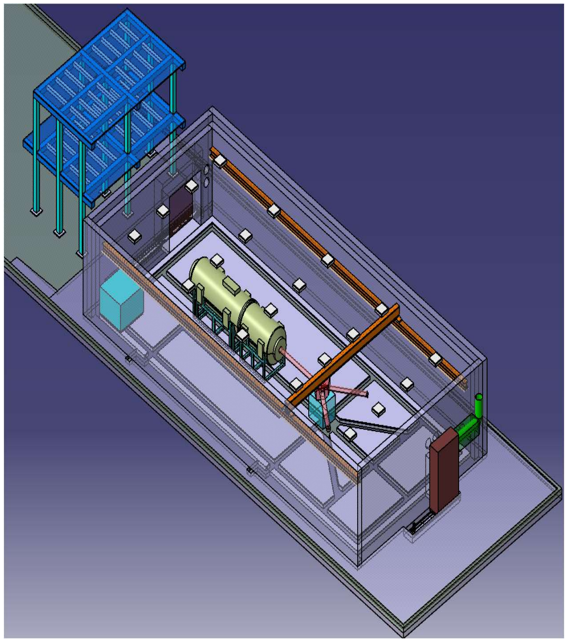
	Direct Kinematics)	Ecm=2 MeV, IKR	Q	TP
	LUNA- MV First 5 year			
A	$^{14}N(p,\gamma)^{15}O$	30	6	5
B	$^{12}C+^{12}C^*$	24	5	4.8
C	$^{13}C(\alpha,n)^{16}O$	10	3	3.5
D	$^{22}Ne(\alpha,n)^{25}Mg$	15	3	
E	$^{22}Ne(p,\gamma)^{23}Na$	46	9	5
	Dresden:			4
F	$^{12}C(\alpha,\gamma)^{16}O^*$	8	2	4
G	$^{18}O(p,\alpha)^{15}N$	38	8	4.8
	Monochromatic neutron source			
H	$^{7}Li(p,n)^{7}Be$	14.5	3	4.8

Proposal for an underground accelerator facility

Phase I: 400 kV high current accelerator with an ECR source
Timeline = 2024-2034; Cost~140 Cr (excluding tunnel works)



Phase-II : 5 MV single ended ECR based Pelletron accelerator
Timeline=2034-2039, Cost~150 Cr)



Space =50 m x 20 m   Project duration=15 years   Tentative cost=290 crore

Implementation/Delivery

Year	Implementation/Delivery
Phase-I	
1st – 3rd	Building of tunnels and caverns; design of laboratories, beam lines & experiments
4th to 7th	Procurement and commissioning of a 400 keV machine; setting up of experimental facilities including beam lines, detector array, target assembly and data acquisition system
7th – 10th	Phase-I activities including a few challenging experiments will be completed
Phase-II	
11th – 15th	Procurement and commissioning of 5 MV machine; setting up of experimental facilities; Experiments using MV machine

End of first presentation

Summary at the end of 2nd presentation

AJT coupled to an RMS for deep underground measurements - J J Das

Concept proposal: AJT coupled to an RMS for deep underground measurements at INO

Raktima Kalita, Nabajyoti Pandit, Mridul Deka, Dimpal Saikia, Sakera Khatun, A Barthakur, M Baro, J J Das, A MP Hussain, A K Nath, M Patgiri, D Sarma, G C Wary: Department of Phys., Cotton University, Guwahati, Assam
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D Kumar, Tumpa Bhattacharjee: VECC, Kolkata
B K Nayak: HBNI, Mumbai
V M Datar: IMSC, Chennai

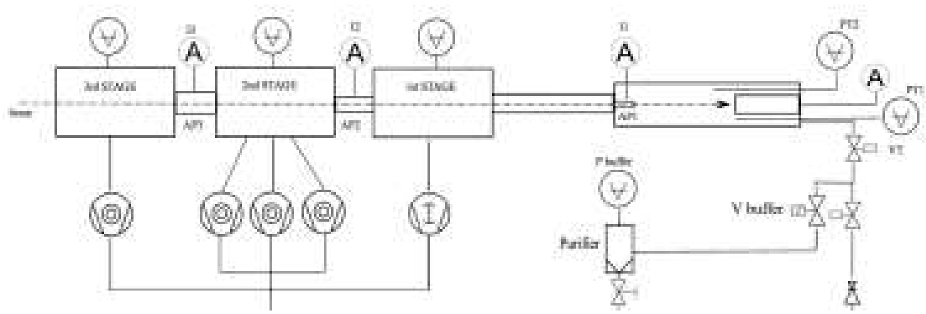
Nabajyoti Pandit
Dimpal Saikia

CUPAC-NE Proposal for Underground facility

•If the "accelerator system for nuclear astrophysics at INO site" is approved, then
•CUPAC-NE collaboration would like to participate in construction of some instrumentations of common interest:

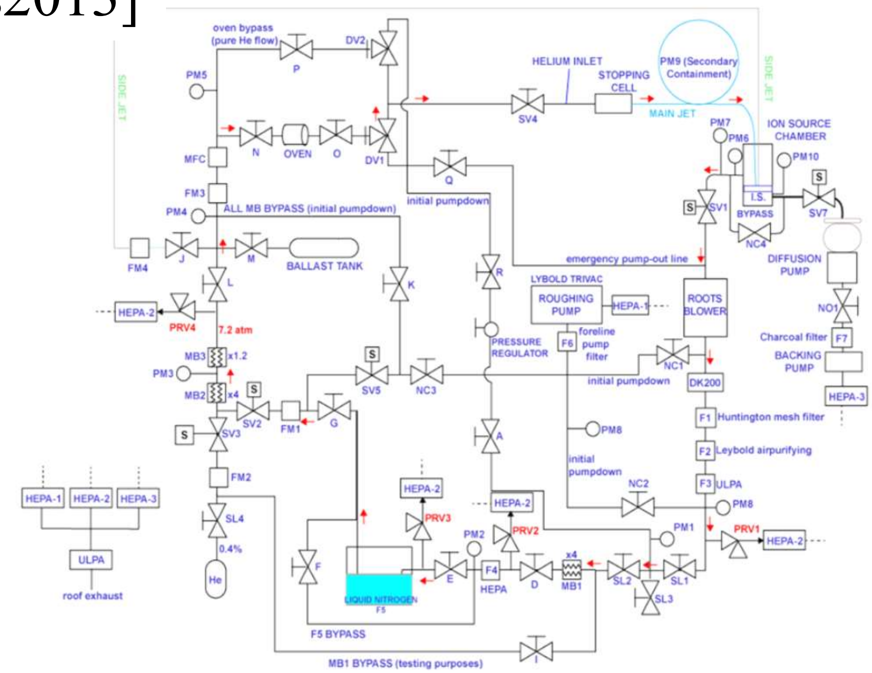
1. AJT (Advanced Jet Target) Close loop supersonic Jet target
2. An RMS of MD-ED-MD type (with rotation) with compact foot print
3. Strictly monochromatic neutron source for investigation of s-process in AGB stars
4. **Explore extracting beam in space charge limited domain**

Advanced Jet Target system



Simplified scheme of the **LUNA** recirculation gas target

ORNL [Das2013]

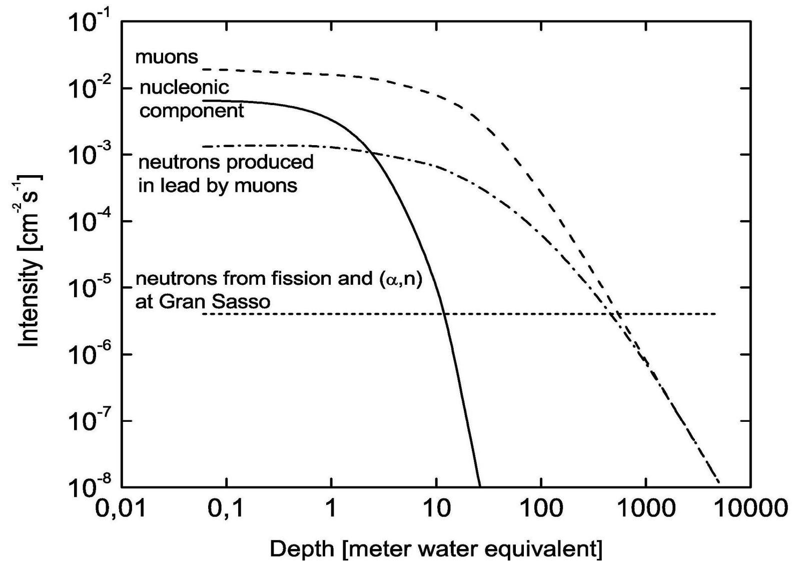


Recirculation gas target >99% gases: 8 Roots blower, 10 1000l/s turbo pumps, compressors, filters and purifiers, exhaust system

Design of windowless gas target

Recoil mass separator at Underground: first time

•**LUNA Data** precision limited by backgrounds: natural, beam induced and target
→RMS can provide a solution: NOT used underground so far
Inverse kinematics→interchange target & projectile
→ improves accuracy: reduces systematic errors



CUPAC-NE-BARC Concepts: AJT+RMS

•**AJT:** Reduce systematic errors (**use ^{3}He,^{3}H** gas target with recirculation target)
•**RMS:** **Eliminate** beam and natural background and target impurity
•**Novel RMS design: very compact** PIMS + HIRA ED1 slot+ RIB optics for IKR

Recoil mass separator at Underground: first time

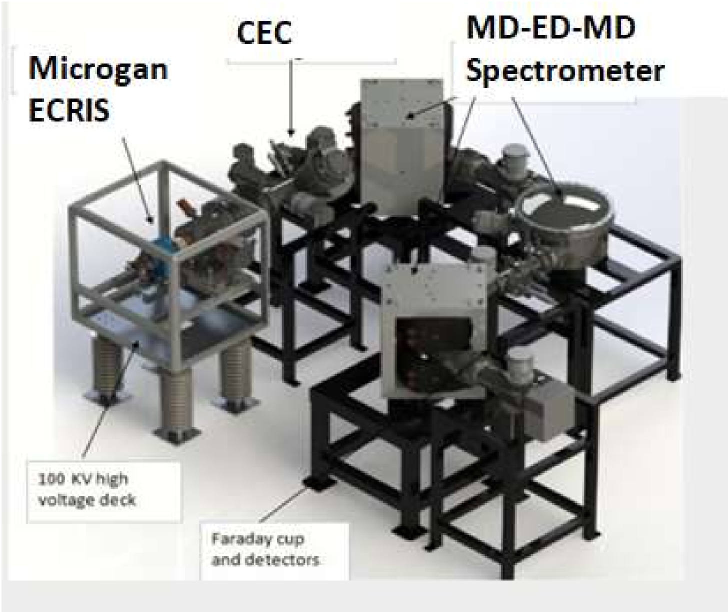
Propose: A Rotatable PIMS spectrometer: MD-ED-MD

Doubly focusing spherical ED, No quadrapoles

Novelty of the concept: MD-ED-MD similar to HIRA (ED-MD-ED)

1. Compact foot print, no quadrapoles, hardware corrections of aberrations
2. Spherical doubly focusing ESA (Electrostatic Analyzer) [Das 1997]
3. Anode slot like HIRA for High current operation [Sinha 1997]

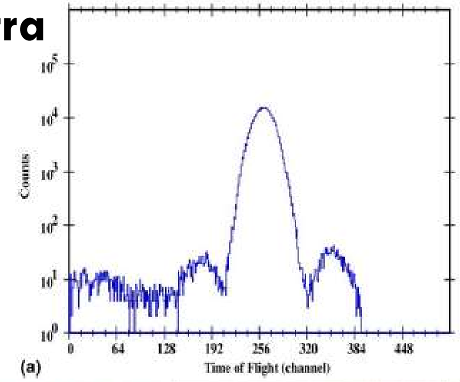
Experience in ion optics: GIOS, GICOZY for inverse kinematic reactions IKR [Das 2005], SIMION 8.2

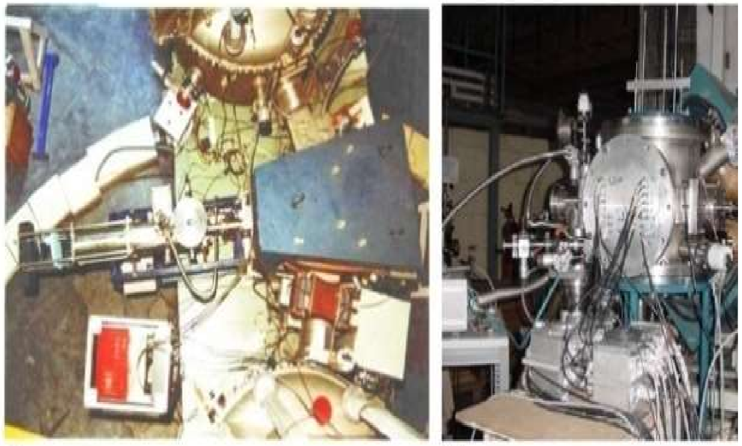


PIMS spectrometer

HIRA spectrometer layout and optics

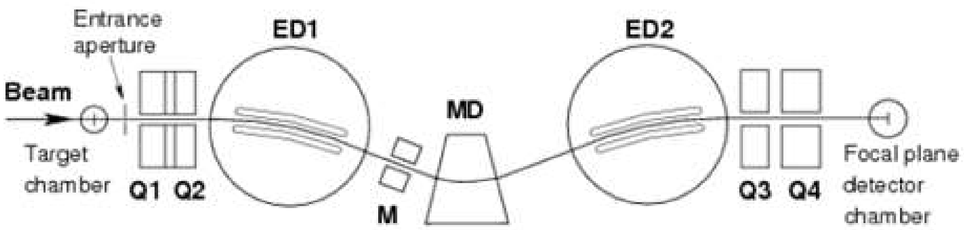
^{7}Be ToF spectra

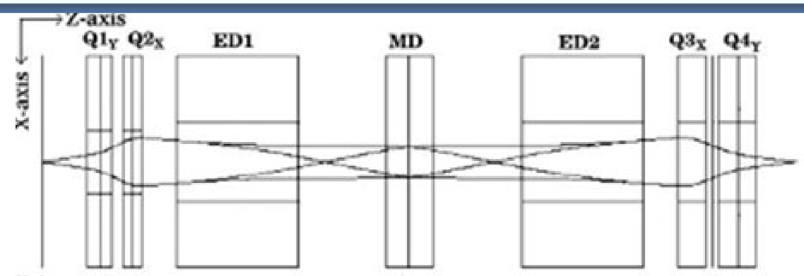




Momentum filter slits

RTS

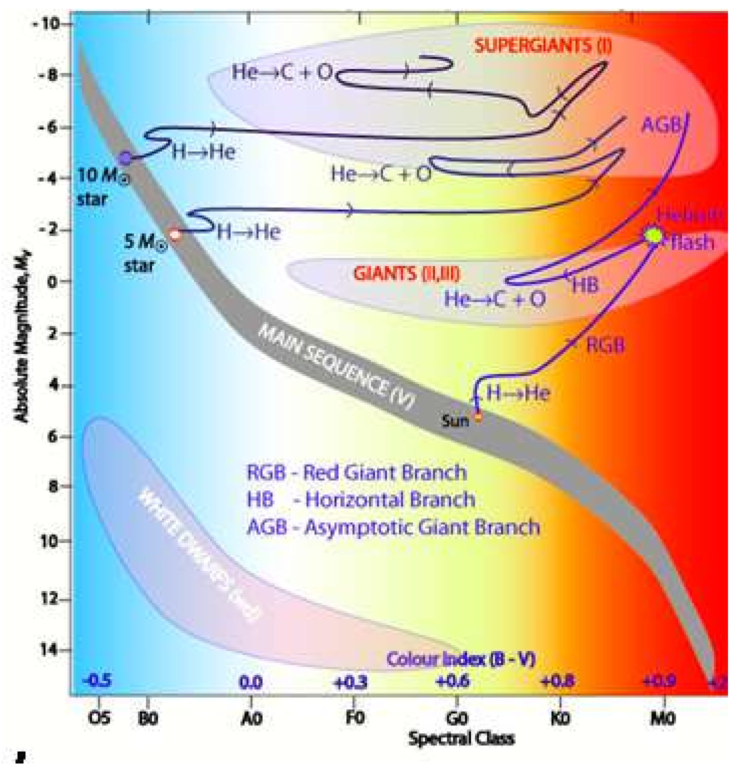




Investigation of s-process for neutron sources in AGB stars using monochromatic neutron source

Novelty of the concept:

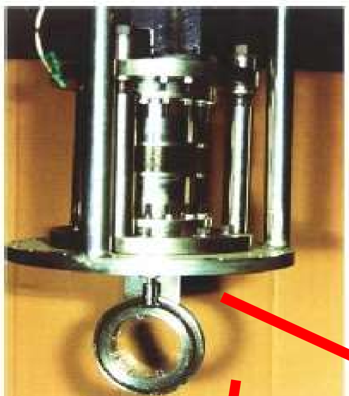
1. Strictly monochromatic neutron beam, kinematic reconstruction
2. p(^{7}Li,^{7}Be)n at 14.5 MeV with ^{7}Be kinematic coincidence
3. Normalization of neutron flux using counting of ^{7}Be in PPAC
4. Neutrons produced in <1Sr forward solid angle due to IKR, so >90% contamination caused by backward scattered neutrons vastly eliminated.
5. Reconstruction of neutron energy from Be angle using kinematics

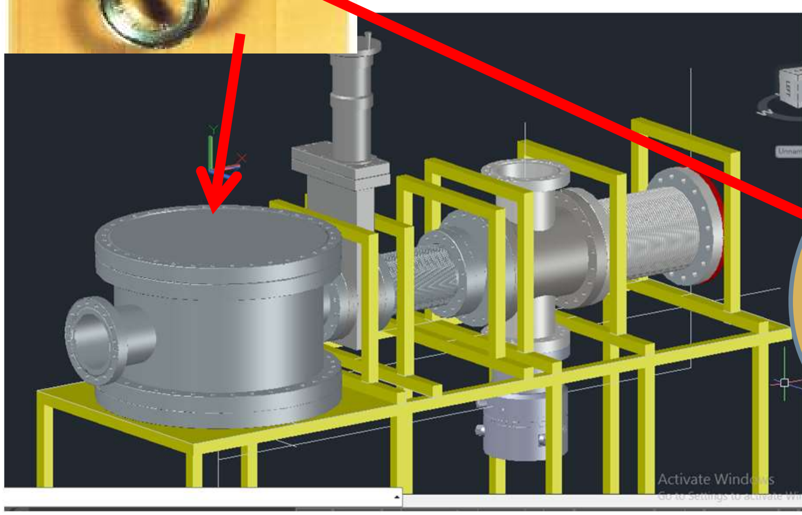


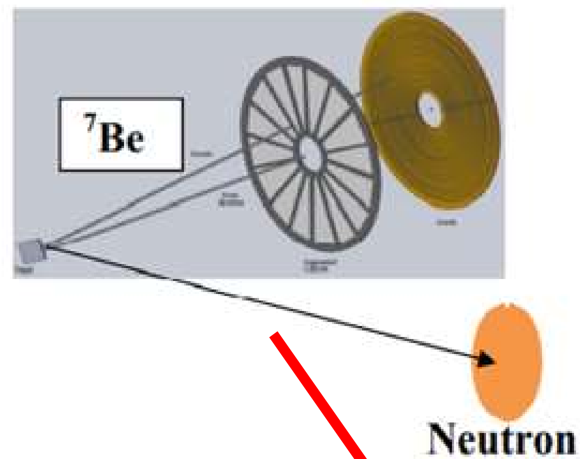
NOT done before

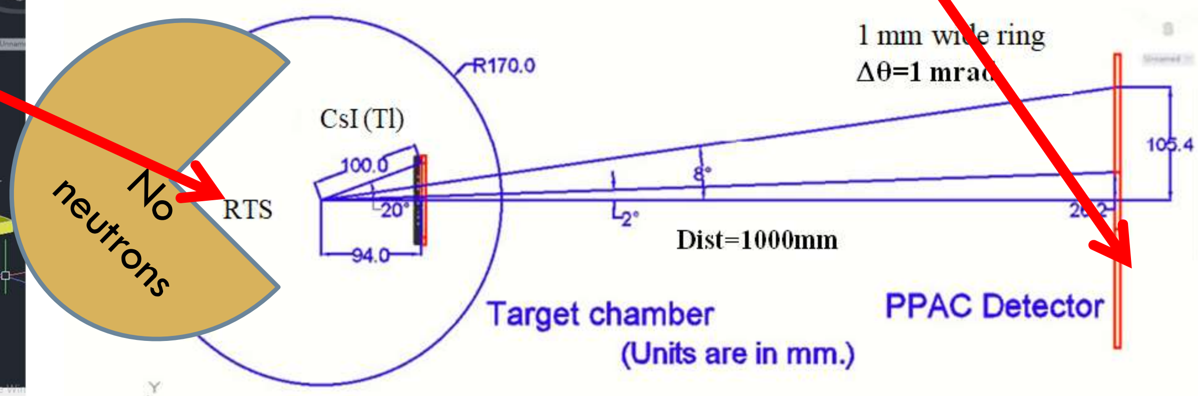
Potential CUPAC-NE-BARC contribution : monochromatic neutron source

$p(^7Li, ^7Be)n$ at 14.5 MeV with ^7Be in kinematic coincidence





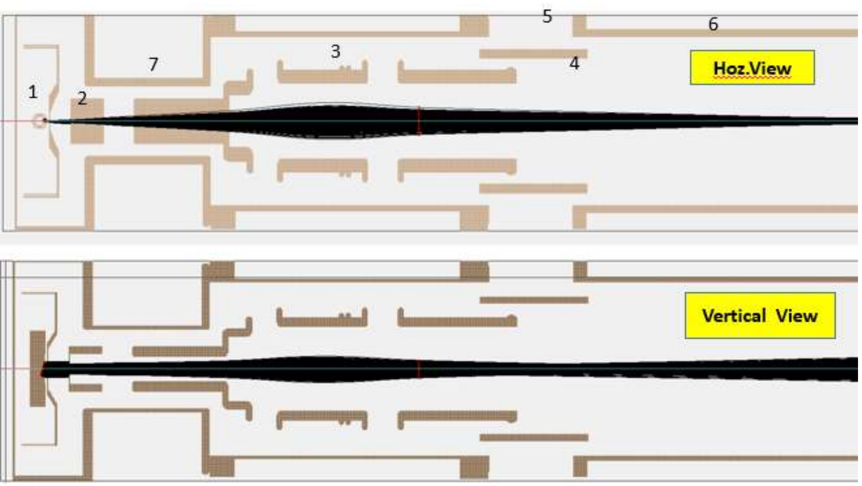




Potential CUPAC-NE contribution : Space charge limited beam extraction

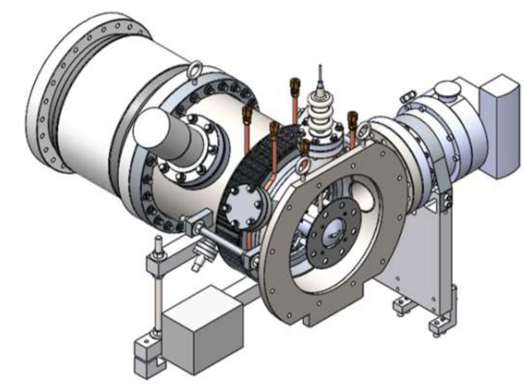
- Commercial accelerators don’t have space charge Compensation, current LIMIT <1 mA.
  - Some hands on experience at Cotton
  - Designed and implemented Space charge compensation at ISTF3, ORNL
- Would like to explore ~5 mA

SIMION 8.0: Space charge can be estimated.
Gerald Alton suggested following:
Trap electrons by a negative electrode. High +ve charge of Beam attracts electrons and exits as space charge balanced beam



Commissioning results of ISTF3, ORNL

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



Summary & conclusions

- A lot of opportunity exists to explore the reactions of interest to nuclear astrophysics, specially relevant to He and C, due to unavailability of data around the Gamow region and large uncertainties in experimental data
- To keep pace with the international community of nuclear astrophysics a deep (>1.5 km) underground accelerator facility is essential
- Proposed Accelerator facility, with 400 keV (phase-I) and 5 MV single ended (phase-II), will be able to cover the energy range of interest including inverse kinematics
- The above facility coupled with Recoil Mass Separator and windowless gas target will be a unique facility in the world

Thank you for your kind attention