Technical Advancements at FRENA: India's *first* Nuclear Astrophysics Accelerator

FRENA: Facility for Research in Experimental Nuclear Astrophysics

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Postdoc: GSI, Germany (DESPEC)
Postdoc: FRIB, USA

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Presentation Layout

- Nuclear Astrophysics: the subject
- FRENA: introduction
- Some results
- Upcoming experiments
- Technical requirements and progress
- Collaboration!

Nuclear Astrophysics: the subject

- Nuclear reactions are important for energy generation in stars, stellar evolution and in nucleosynthesis.
- Most important quantity characterising these nuclear reactions: thermonuclear reaction rate at a given stellar temperature.
- This determines the rate of energy generation and the number of nuclear species created or destroyed in an astrophysical process.
- Thermonuclear reaction rate is related to the reaction cross section.
- Hence, cross section measurement is of critical importance.
- Accelerator-driven experiments try to measure reaction cross-sections.

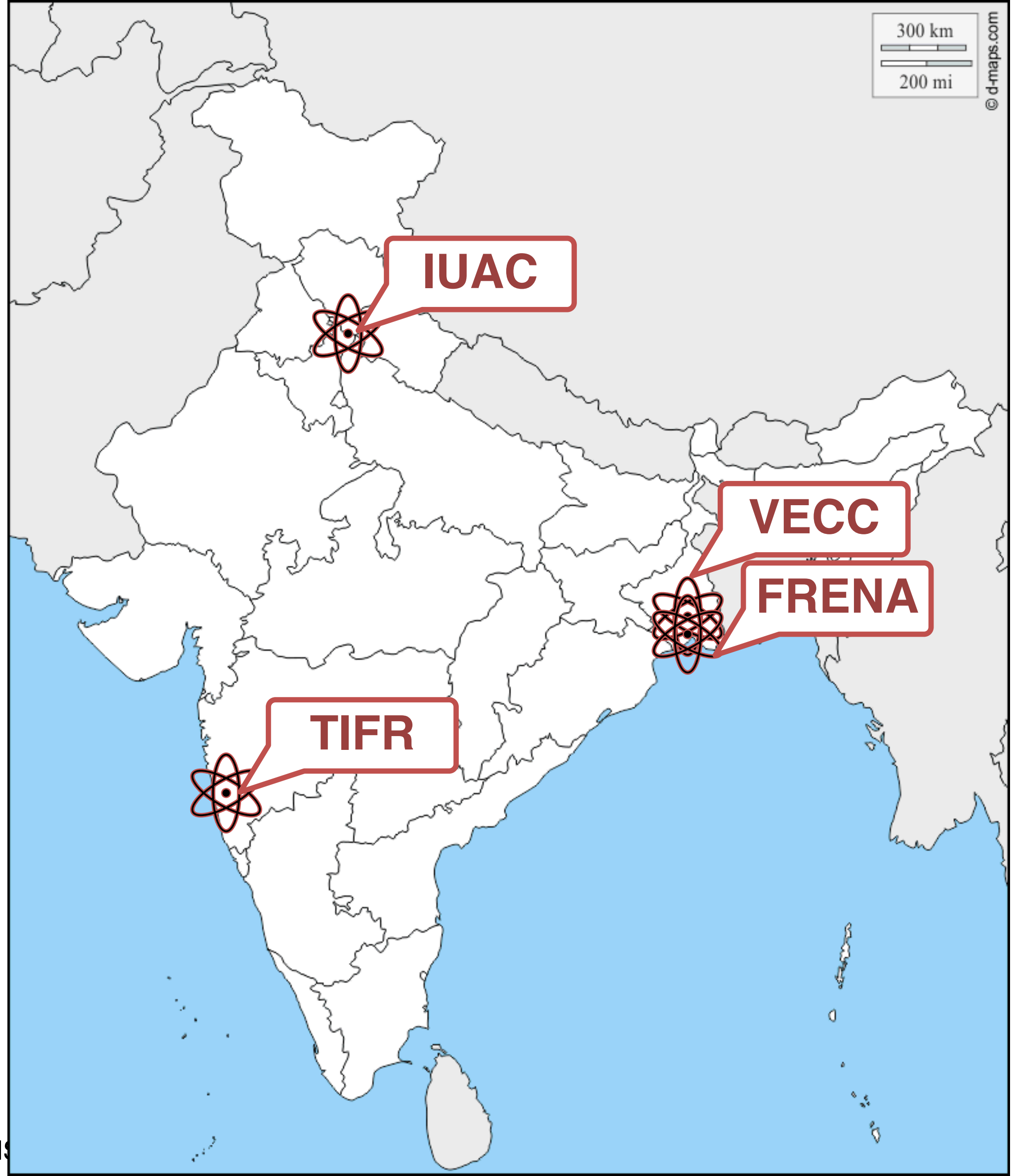
Prof. M.N. Saha (1893-1956)

$$\frac{N_{II}}{N_I} = \frac{2Z_{II}}{n_e Z_I}\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} e^{-\chi/kT}$$

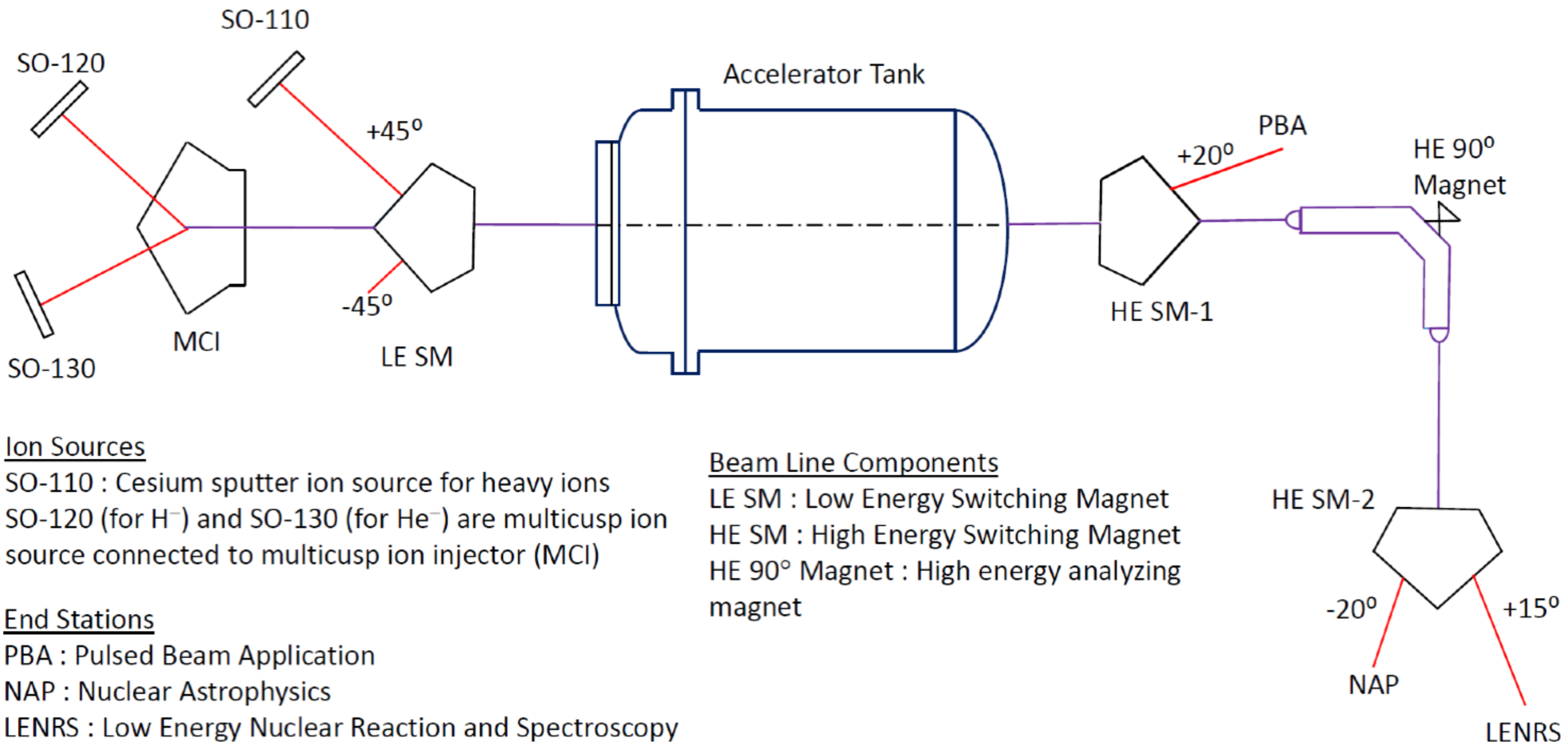
India: accelerators

- IUAC, New Delhi: 15-16 MV terminal voltage.
- BARC-TIFR Pelletron facility: 14-15 MV terminal voltage.
- VECC: room-temperature cyclotron (K-130) and super-conducting cyclotron (K-500).

- Nuclear Astrophysics energies require lower terminal voltages.
- High-current ion beams required.
- Exceptional terminal voltage stability necessary.
- FRENA: 3 MV tandem accelerator.



Schematic Layout of FRENA



<u>Ion Sources</u>

SO-110 : Cesium sputter ion source for heavy ions
SO-120 (for H^-) and SO-130 (for He^-) are multicusp ion source connected to multicusp ion injector (MCI)

<u>End Stations</u>

PBA : Pulsed Beam Application
NAP : Nuclear Astrophysics
LENRS : Low Energy Nuclear Reaction and Spectroscopy

<u>Beam Line Components</u>

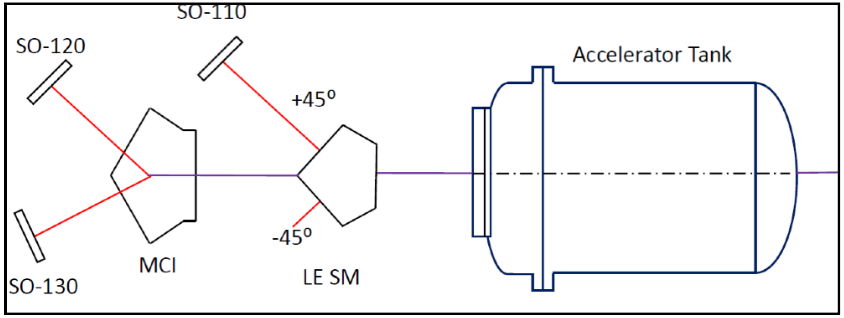
LE SM : Low Energy Switching Magnet
HE SM : High Energy Switching Magnet
HE 90° Magnet : High energy analyzing magnet

The FRENA 3 MV tandem accelerator, seen along with the ion source and high energy section

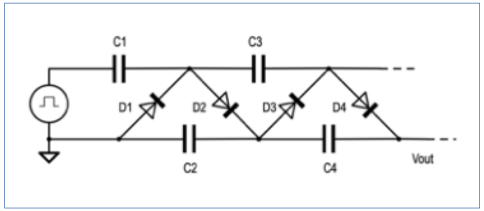

FRENA

FRENA: ion sources

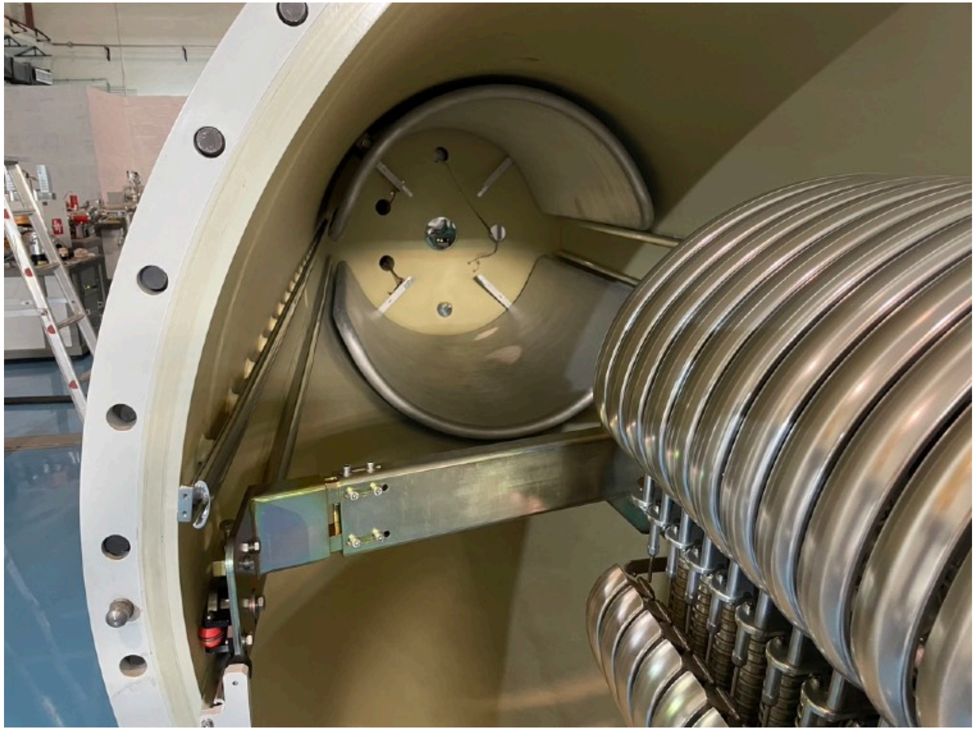
- Two ion injection systems- Cesium sputter source and multicusp ion injector (MCI).
- SO110: Cesium sputter source. Typically used for heavy elements.
- Programmable remotely-operable carousel with 50 cathode capacity.
- Positioned at 45^0 upstream of the low-energy switching magnet.
- SO120 and SO130: placed inside MCI cabinet at $\pm 30^0$. Tungsten-filament based gaseous source.
- Chopper-buncher system in light ion branch provides pulsed beams.



FRENA: voltage generation

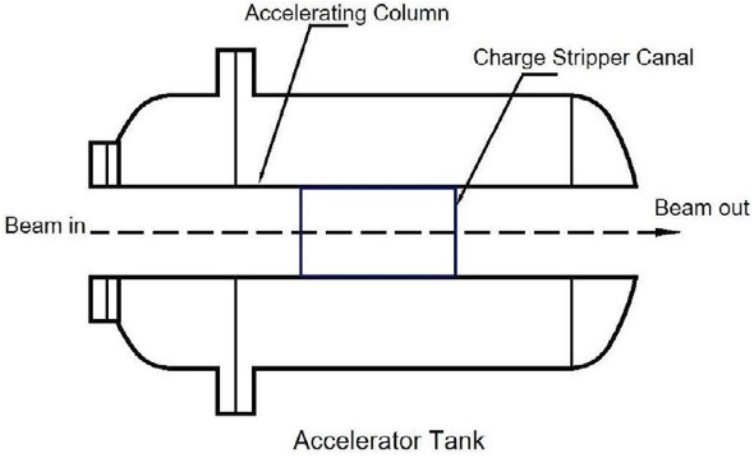


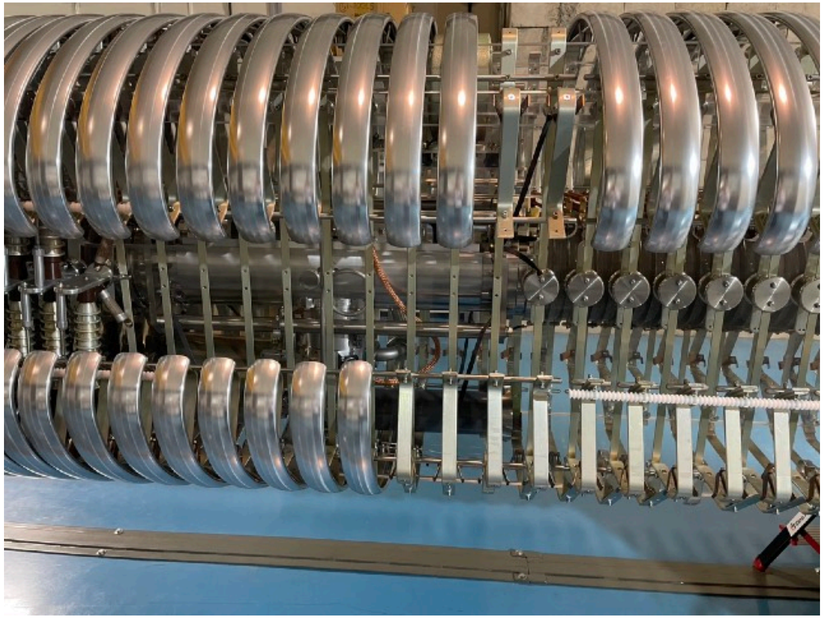
- Parallel-fed Cockcroft-Walton principle (no moving parts).
- Oscillating signal- generated by a driver positioned outside the accelerator tank.
- Driver- transforms three-phase 440V AC supply into RF voltage.
- RF Voltage- fed into a circuit containing RF resonance coils and the dynodes which are brought into oscillation at the circuit resonance frequency.
- Oscillating potential is applied to two dynodes capacitive-coupled to the Corona rings, resulting in the generation of DC high voltage.



FRENA: charge stripping

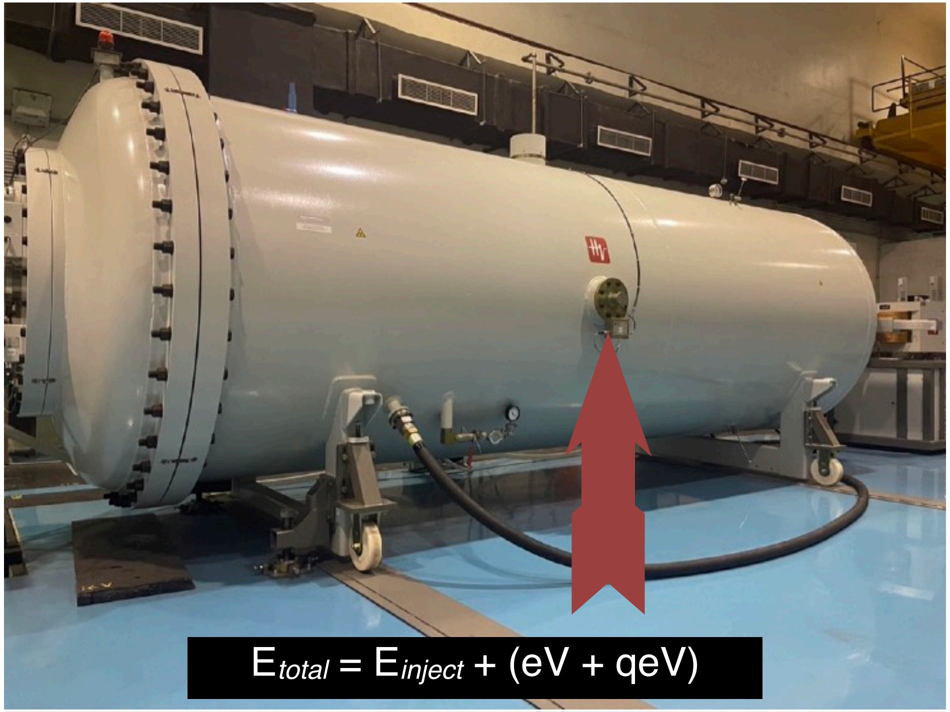
- Electrostatic lens (Q-snout)- focuses incoming ions into the accelerator's charge stripping canal.
- Stripper canal is located in the middle of the accelerating column.
- Stripper canal is filled with Nitrogen gas.
- Nitrogen pressure of 10^{-2} to 10^{-1} mbar is maintained within the canal.
- Accelerator is filled with SF_6 gas- typical pressure of 6 bar.
- SF_6: prevents sparking and acts as a heat sink for stripper canal's turbo molecular pump.





FRENA: the accelerator

- Terminal voltage range: **200 kV to 3 MV**.
- Typical beam currents
  - Proton: 300 eμA
  - Alpha: 70 eμA
  - C: 20-50 eμA
- Pulsed beams of Proton, Alpha possible (125-4000 kHz; 1-2 ns FWHM).
- Beam energy can be varied in steps of few keV. (Useful for resonance hunting.)



$E_{total} = E_{inject} + (eV + qeV)$

FRENA: voltage stabilisation

- GVM stabilisation and Slit stabilisation modes available.
- 90^0 magnet (0.67 T, 1.5 m) with upstream slits to further select energy.
- 2 switching magnets (before and after 90^0 magnet) with 4 ports each (15^0, 30^0, 0^0, 20^0).
- Terminal voltage stability: 30 V/hour at T_{max}; voltage ripple: ~30 V_{RMS} at T_{max}.
- Max beam power- 3 kW. Minimum transmission over entire energy range: 60%.

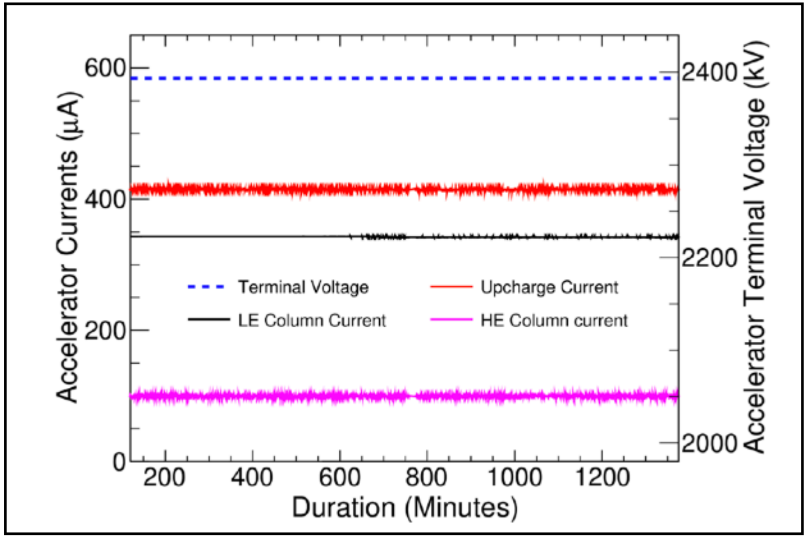
*Akashrup Banerjee et al., Eur. Phys. J. Spec. Top. (2024) **233**: 2859-2865*

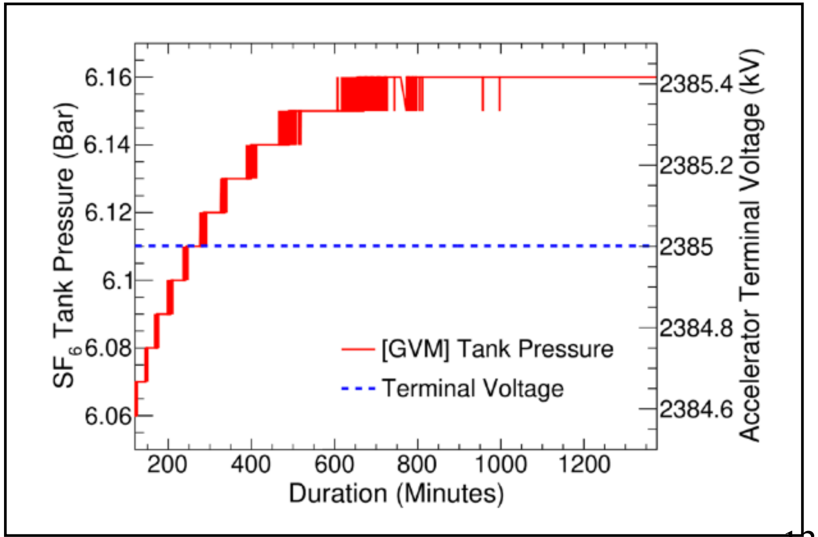
FRENA: terminal stability

- FRENA accelerator- tested for multiple parameters to check its suitability for nuclear astrophysics experiments.
- Stability of the terminal voltage was checked over a period of >24 hours.
- Any change in SF_6 pressure is compensated by the GVM read-back electronics-

$$GVM_{Output} = Measured\ Value \times (1 + Compensation\ Factor \times SF_6\ Pressure)$$

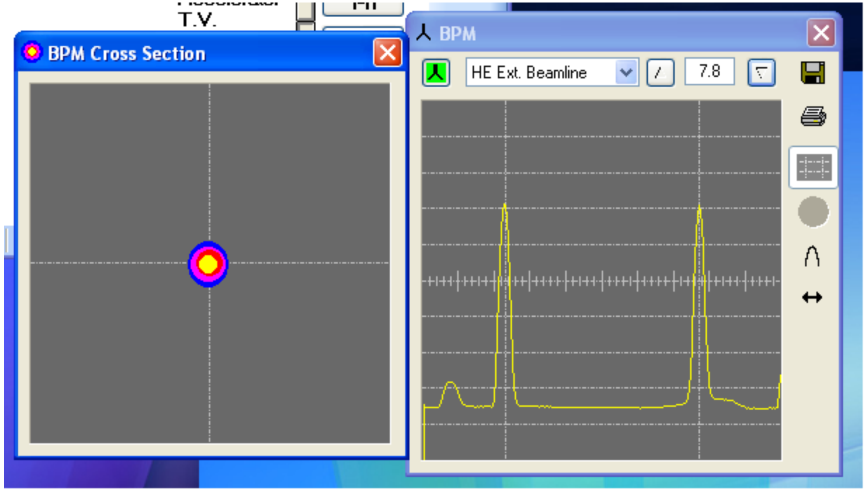
- Compensation factor: adjustable using a 25-turn trim potentiometer.





FRENA: calibration

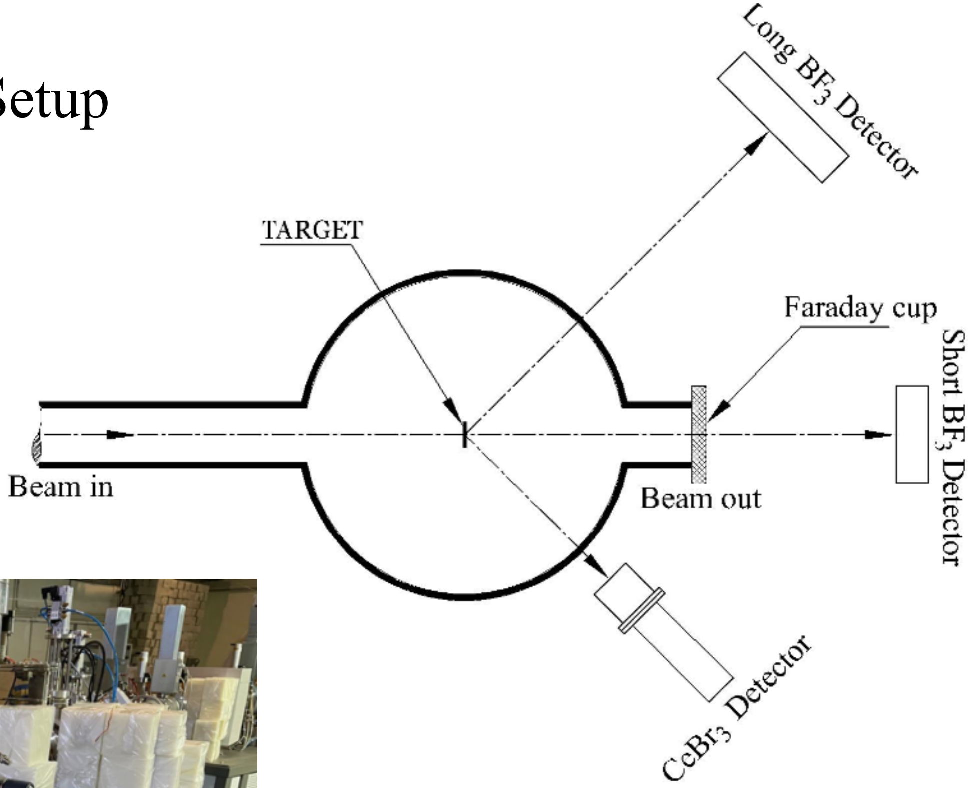
- A few standard experiments were carried out using DC proton beam (maximum current 100 enA).
- Neutron emission thresholds were measured.
- Gamma-resonances were studied.
- Different types of detectors were utilised: BF_3 and $CeBr_3$.
- Targets used: ^{7}Li, ^{19}F, ^{11}B, ^{24}Mg. Fabricated at FRENA and VECC.
- Reactions: ^{7}Li(p,n)^{7}Be, ^{19}F(p,n)^{19}Ne, ^{11}B(p,n)^{11}C, ^{19}F(p,αγ)^{16}O, ^{24}Mg(p, γ)^{25}Al .
- Major collaboration between FRENA and VECC.

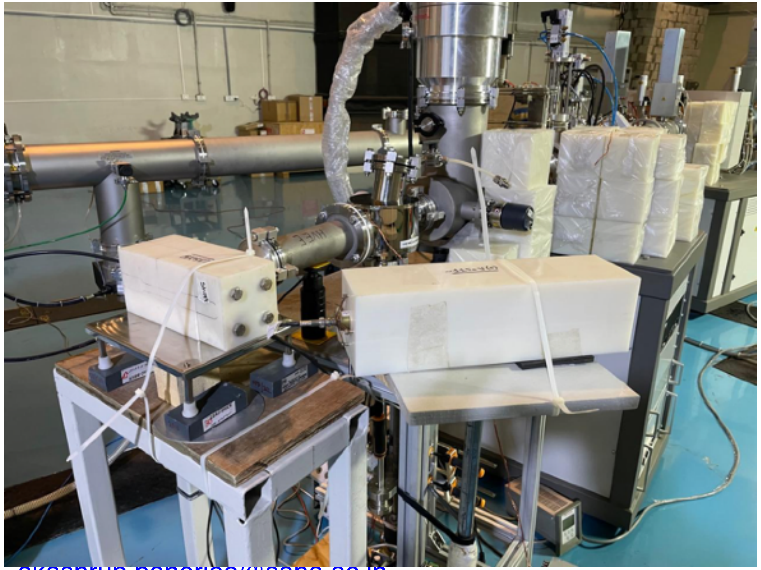


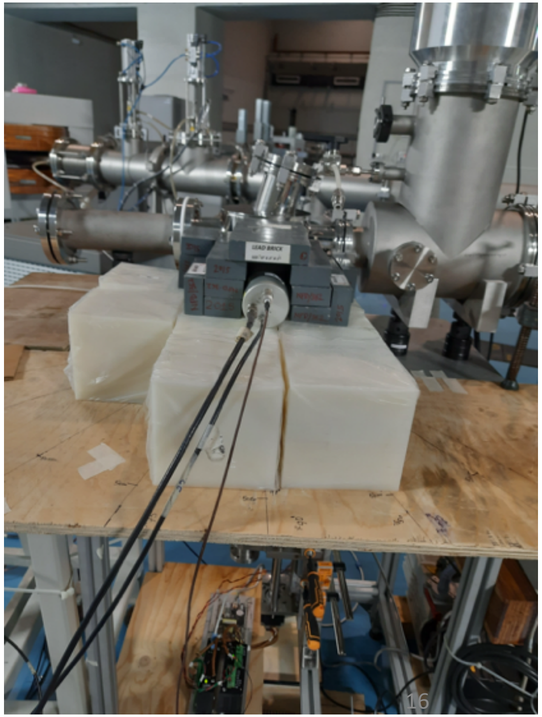
List of reactions used for calibration of the Terminal Voltage

Reaction studied	Resonance Energy/Reaction Threshold	Reference
$^{19}F(p,\gamma)^{16}O$	669.0	Rev. Modern Phys. 22 (1950) 291
$^{24}Mg(p,\gamma)^{25}Al$	823.0	Nucl. Phys. A 242 (1975) 519
$^{19}F(p,\gamma)^{16}O$	872.11 0.20	Phys. Lett. 21 (1966) 61, Rev. Modern Phys. 38 (1966) 660
$^{7}Li(p, n)^{7}Be$	1880.60 0.07	Phys. Lett. 21 (1966) 61, Rev. Modern Phys. 38 (1966) 660
$^{11}B(p, n)^{11}C$	3017.17 0.07	NNDC
$^{19}F(p, n)^{19}Ne$	4235.25 0.17	NNDC

Experimental Setup







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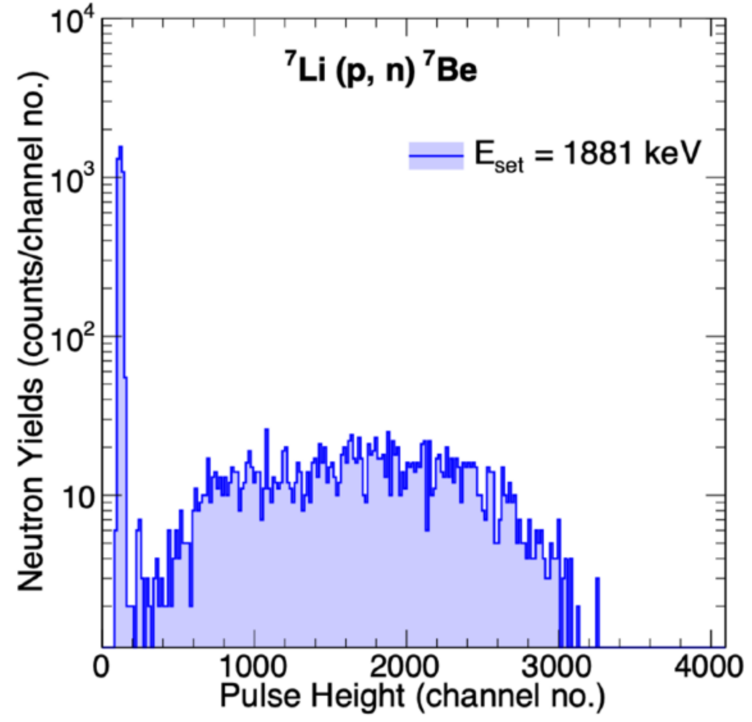
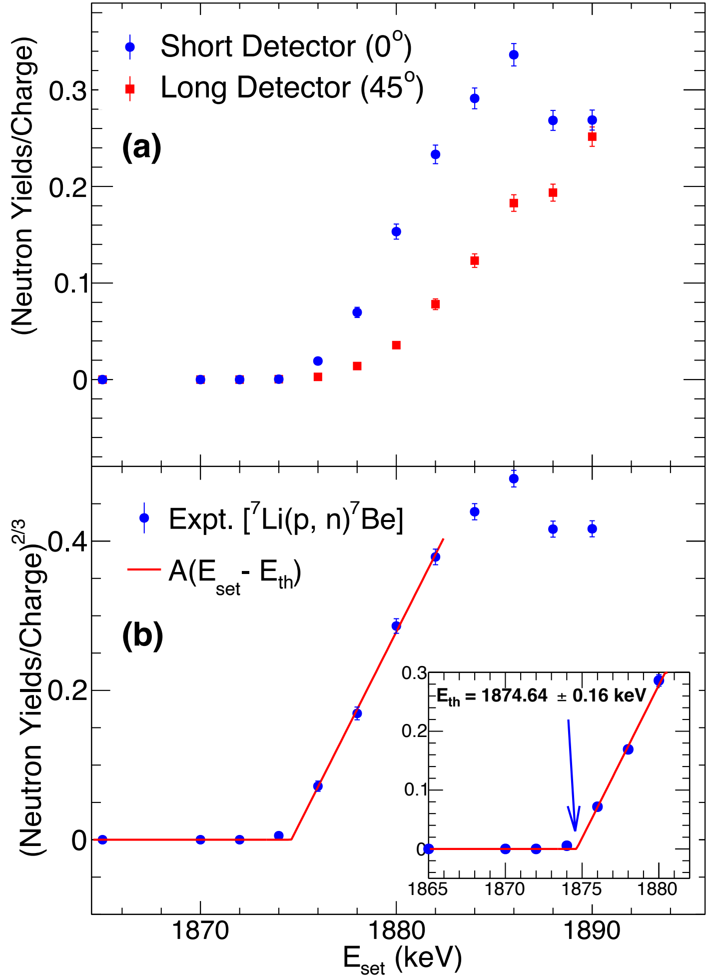
Measurement of reaction threshold in $^7Li(p, n)^7Be$



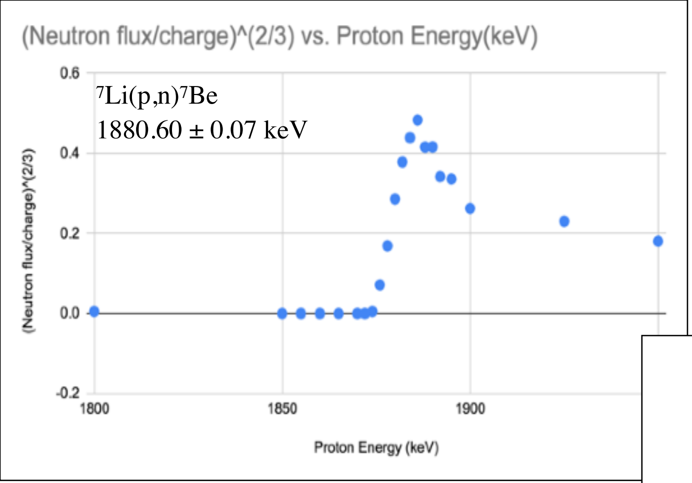
Pulse height distribution of the BF_3 detector used for the reaction threshold measurement

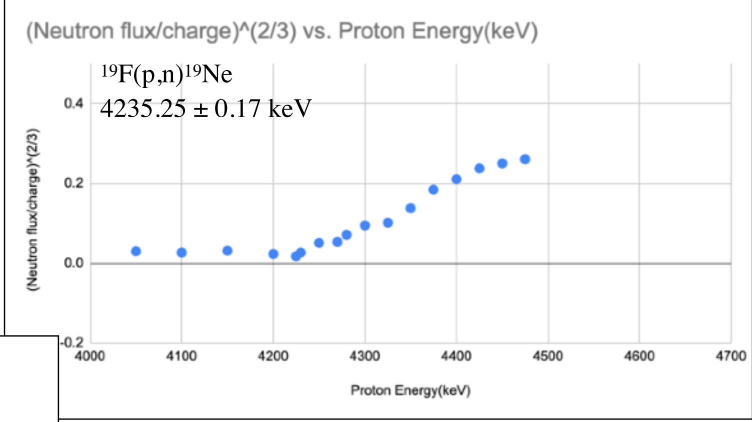
Total neutron cross section just above the threshold follow the variation of $(E_{set}-E_{th})^{3/2}$.

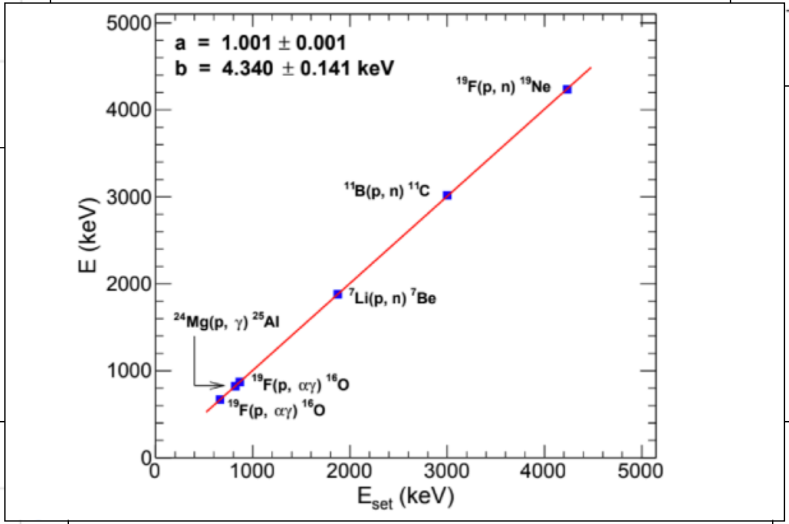
This distribution was fitted with $A(E_{set} - E_{th})$

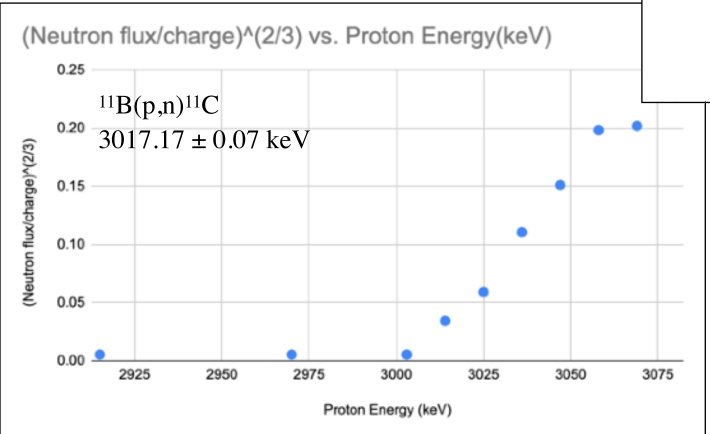


To make it linear 2/3rd power of the measured neutron yield/beam charge was plotted as a function of proton energy.

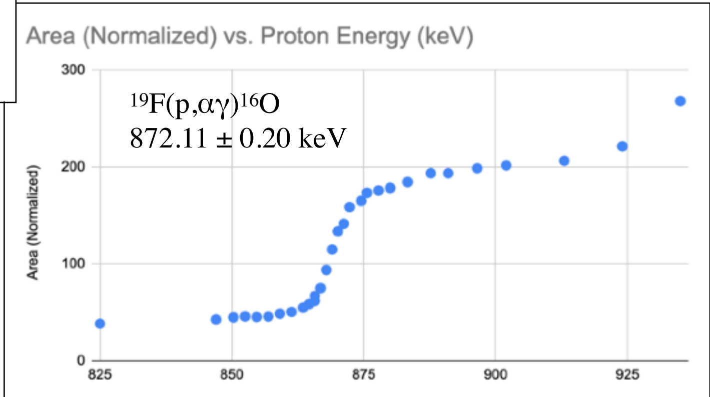








A. Banerjee, K. Banerjee et al., NIM A, 1072 (2025)



FRENA: different beams

N.C. Podaru et al. / Nuclear Instruments and Methods in Physics Research B 273 (2012) 231–233 233

Table 1
Summary of analyzed ion source beam currents and of H, He and C particle transmission through the 3 MV Tandetron™ accelerator.

Atomic species	E_{beam} (LE) (keV)	I_{beam} (analyzed) (eμA)	I_{beam} (Injected in Tandetron™) (eμA)	TV (kV)	Charge state (HE) (eC)	I_{beam} (HE) (eμA)	Particle transmission (%)
H	30	648	230	200	+1	165	71.7
		469	409	2000		252	61.6
		451	421	2000		323	76.7
		620	583	3000		361	61.9
		563	524			360	68.7
		618	576			375	65.1
He	20	63	53	2250	+2	69.5	65.6
		70	59	3000	+2	65.3	55.3
C	35	–	41.8	3000	+1	0.8	1.9
				3000	+2	15	17.9
				3000	+3	55	43.9
				3000	+4	34.6	20.7
				3000	+5	1.1	0.5
				3000	+6	0.1	0

Nuclear Inst. and Methods in Physics Research, A 903 (2018) 1–7

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The STELLA apparatus for particle-Gamma coincidence fusion measurements with nanosecond timing

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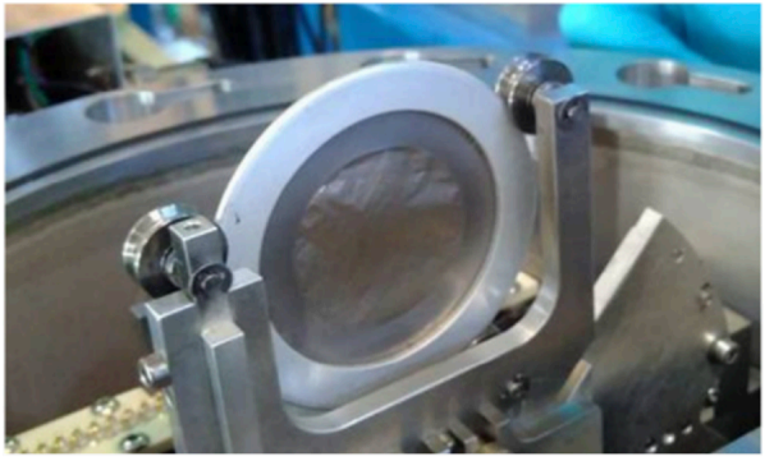
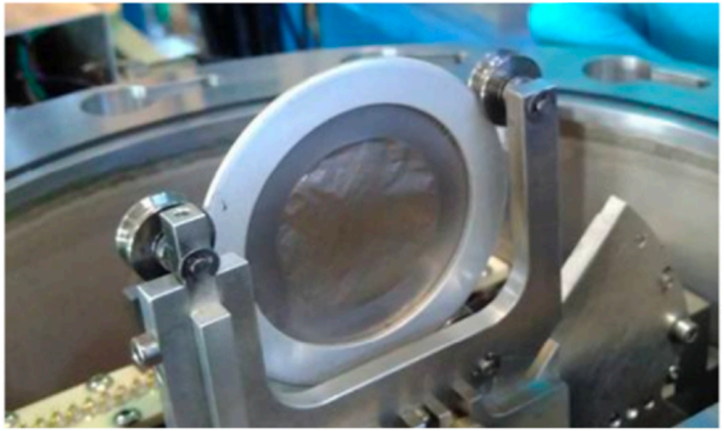
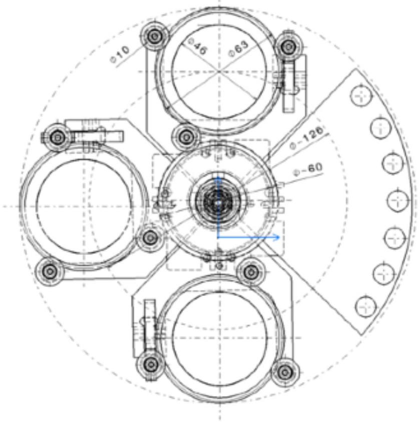
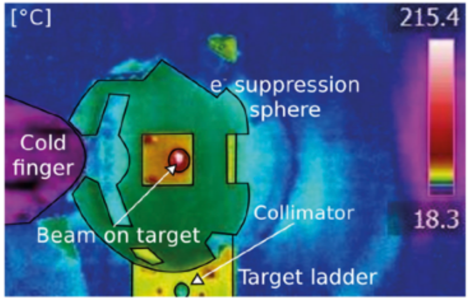


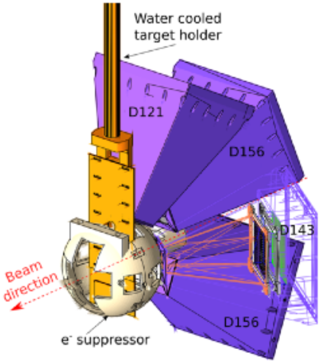
Fig. 4. [Color online] Photography of a 35 μg/cm^2 carbon target after 50 h of exposure to 2.5 pμA beam. The beam focus is at the upmost position so the beam spot forms a track along the outer area of the target foil close to the frame.



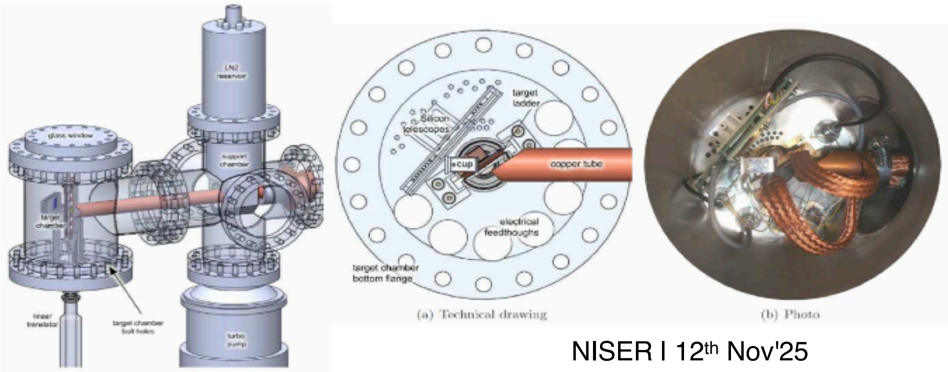


STELLA-ANDROMEDE, IJC Labs, Orsay





CASERTA, Italy



MLL, TU München

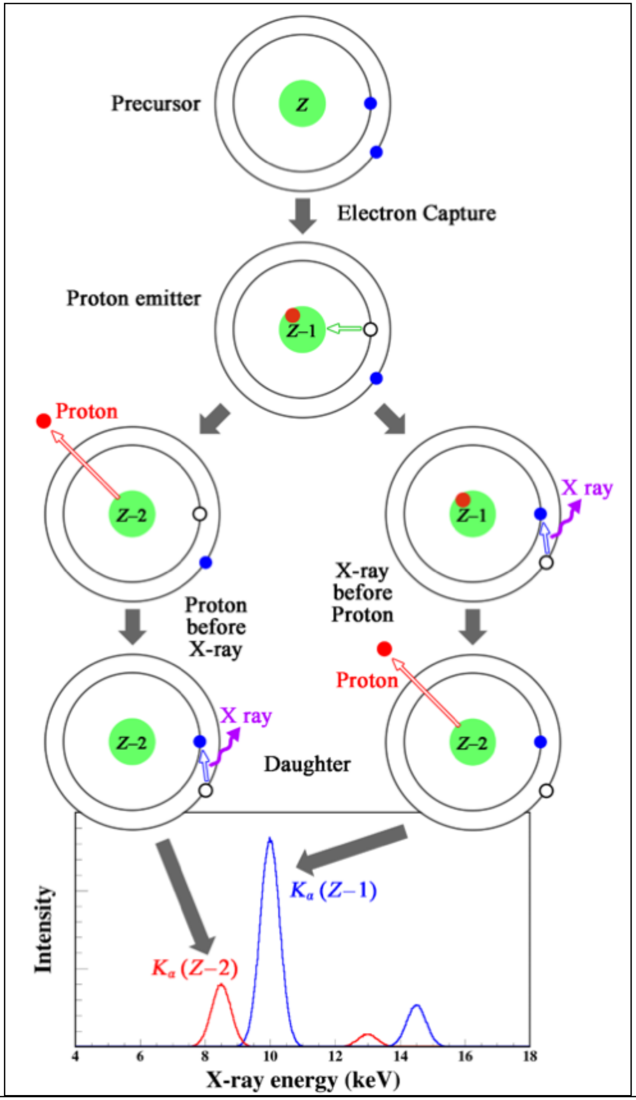


Figure: Demonstration of the technique to be exploited with PERCS

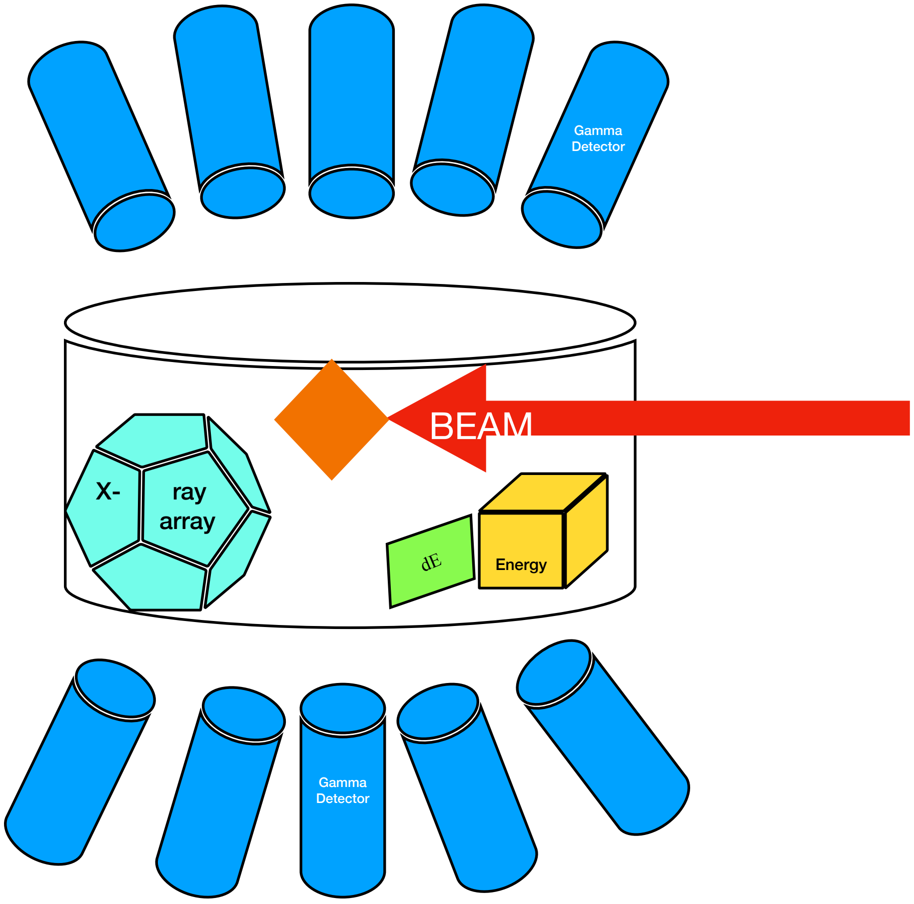
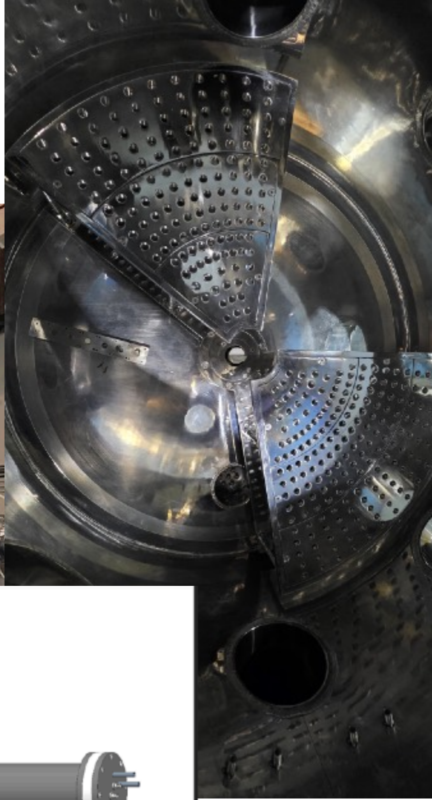


Figure: A cartoon representation of the PERCS active-chamber. The beam and target are off-centred to protect in-situ sensors during irradiation time. The target ladder would move towards the detector cluster during counting, with the beam off.

FRENA: the possibilities

- 1-metre diameter scattering chamber commissioned, with provisions for installing detectors inside on movable arms.
- Some charged particle emitting reactions like ^{19}F(p,α), ^{15}N(p,α), ^{12}C(^{12}C,p), ^{12}C(^{12}C,α) etc. occurring in the CNO cycle or carbon burning phase will be measured using the scattering chamber facility.
- Charged particle detection does not suffer due to cosmic background.
- Provision for particle-gated gamma spectroscopy is possible with the chamber, with a gamma cup.



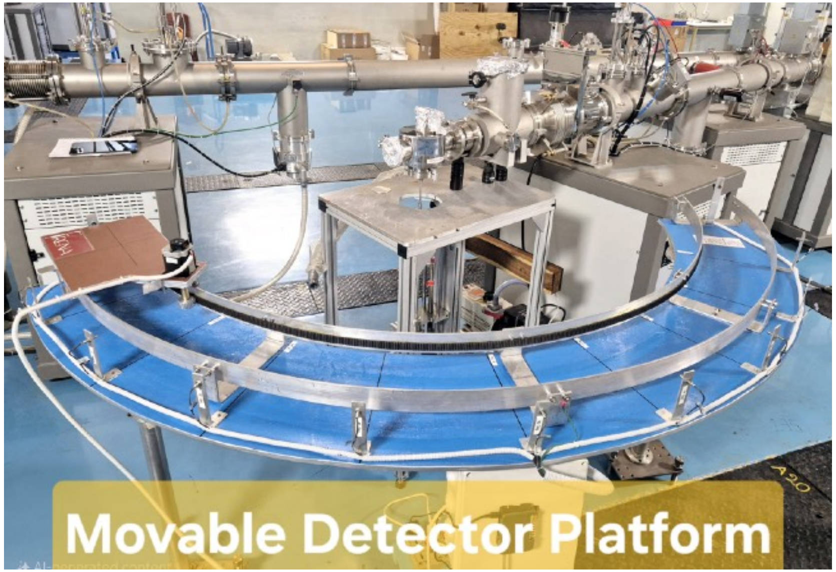
FRENA: upcoming experiments

Beam	Target	Channels of Interest
p	^{7}Li	n,γ
p	^{10}B	n
p	^{11}B	n,γ
p	^{12}C	γ
p	^{13}C	n,γ
p	^{14}N	γ
p	^{19}F	n,γ,α,αγ
p	^{27}Al	n,γ
p	^{85}Rb	n
p	^{106,108}Cd	γ
p	^{144}Sm	γ
α	^{12}C	α,γ
α	^{16}O	γ
α	^{113}In	α
^{7}Li	^{12}C	t
^{12}C	^{12}C	various
^{16}O	^{16}O	various

Our Stockpile: SINP + Collaborators

Detectors

- HPGe CLOVER array (INGA)
- n-type HPGe detectors (mechanically cooled and LN_2 cooled)
- $CeBr_3$ detector array
- $LaBr_3$ detectors (different dimensions)
- NaI detector array
- Silicon detectors (various thickness)
- Scintillators- liquid, plastic
- BF_3 detectors
- …



FRENA: developments

- Target setup suitable for high-current experiments
  - Cooled wheel for conductive targets,
  - Peltier-cooling and cryogenic-finger for radiative targets.
- Specialised target chamber for electronic veto of cosmic muons.
- Fully-automated liquid nitrogen filling system to support gamma spectroscopy campaigns at FRENA.
- Setup to support angular distribution measurement of neutron flux.
- …

Beam Hall: 22m x 15m x 9m

Next BIG plan = RMS?

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