EUROPEAN UNION

Structural Instruments 2014-2020

Extreme Light Infrastructure-Nuclear Physics (ELI-NP) - Phase II

IFIN-HH

Gamma-beam experiments at ELI-NP: The future is emerging

Dimiter L. Balabanski

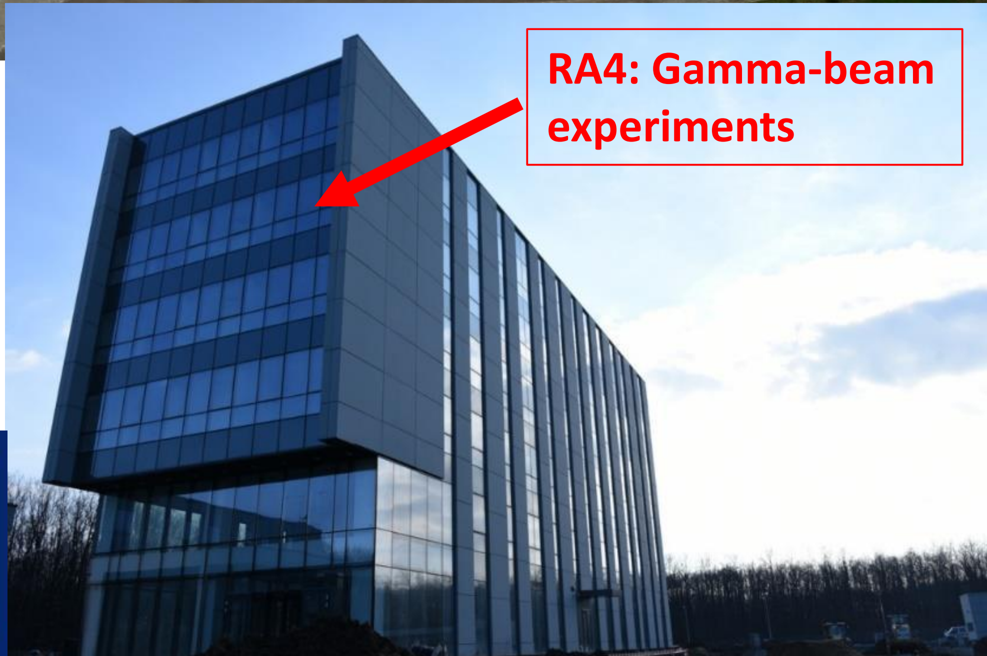
Optics & Photonics International Congress
LNPC'17: Light-driven nuclear-particle physics and cosmology,
Yokohama, April 18th-21st, 2017

Project co-financed by the European Regional Development Fund through the Competitiveness Operational Programme
"Investing in Sustainable Development"

Nuclear Physics

Extreme Light Infrastructure – Nuclear Physics (ELI-NP)

<u>Mission:</u> Nuclear Physics studies with high-intensity lasers and brilliant γ beams



- **Nuclear Physics experiments to characterize laser – target interaction**

- **Photonuclear Physics**

- **Exotic Nuclear Physics and astrophysics**

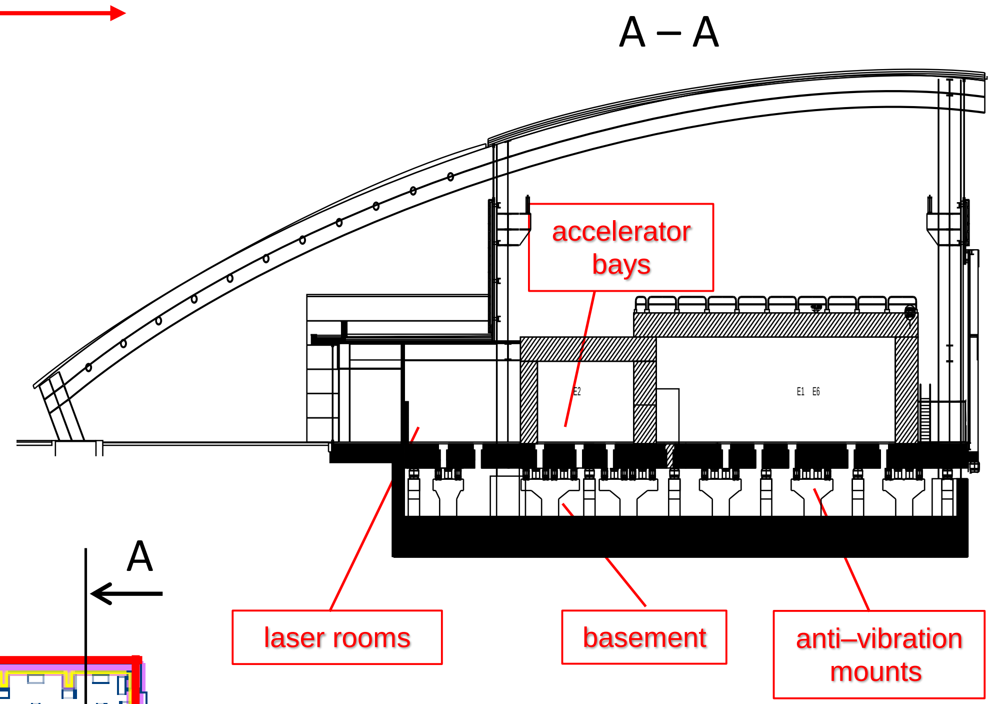
  complementary to other ESFRI Large Scale Physics Facilities (FAIR- Germany, SPIRAL2- France)

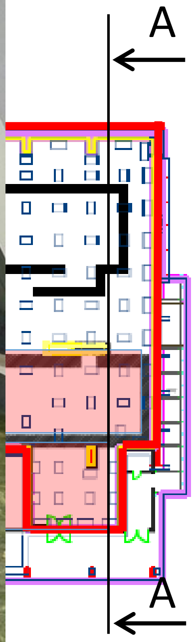
- **Applications based on high intensity laser and very brilliant γ beams**

ELI-NP in ‘**Nuclear Physics Long Range Plan in Europe**’ as a major facility

NP laboratory building

140 m





civil construction was commissioned in September 2016

Platform supported on dampers

Anti–vibration platform
±1 μm @ < 10 Hz

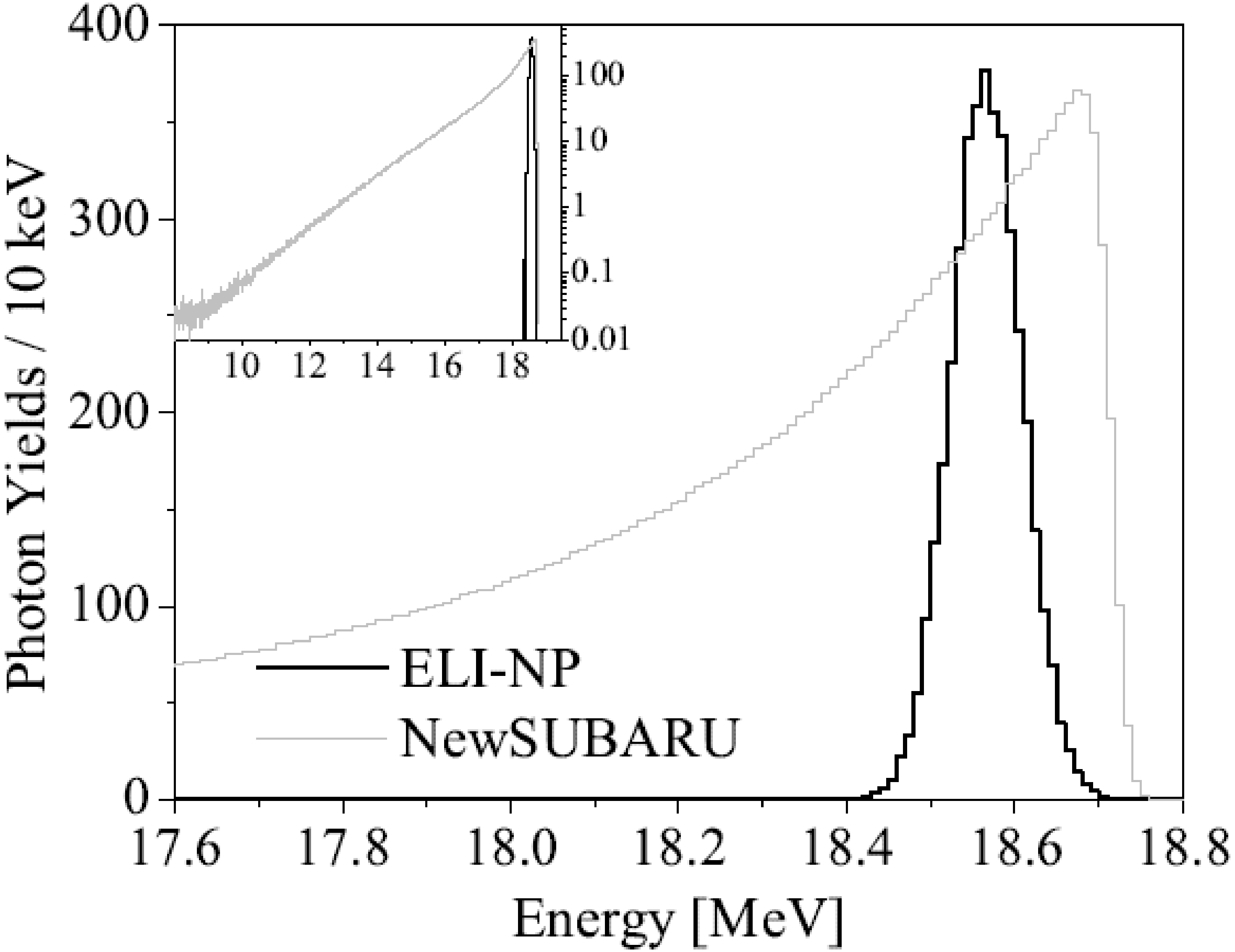
Thermalized building
22º ± 0.5º

Clean rooms

ELI-NP Gamma Beam System (GBS)

$$E_\gamma = 2\gamma_e^2 \cdot \frac{}{1+(\gamma_e}$$

E_e **e**

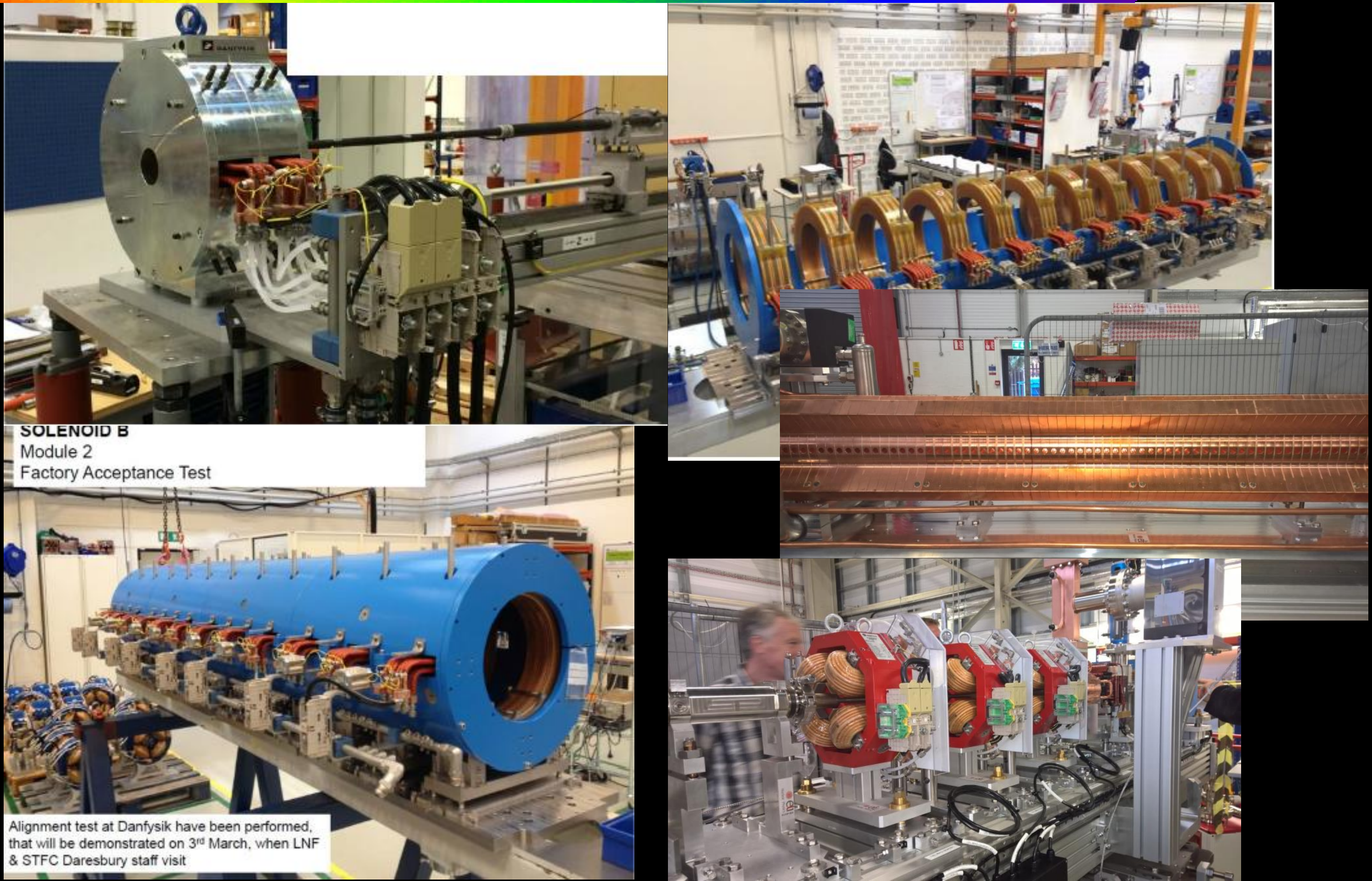


Narrow ba

Gamma Beam System

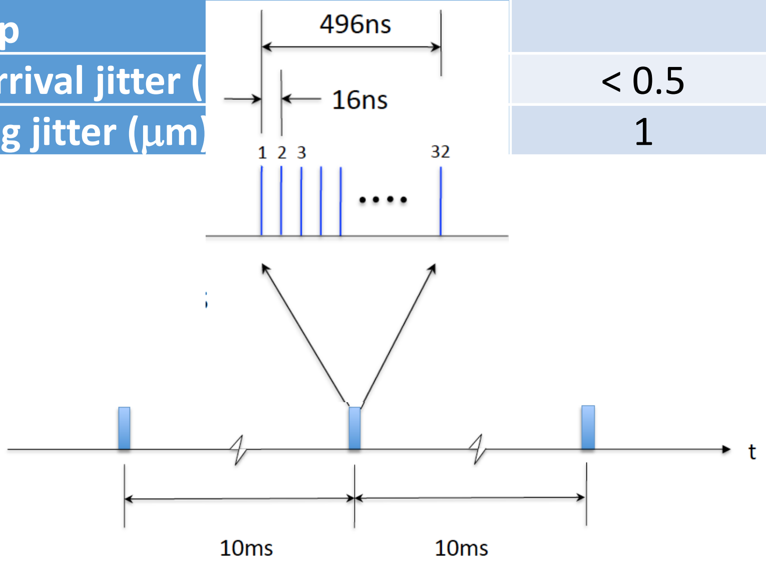
low-energy accelerator section:
0.2-3.5 MeV
factory acceptance in Dec. 2015

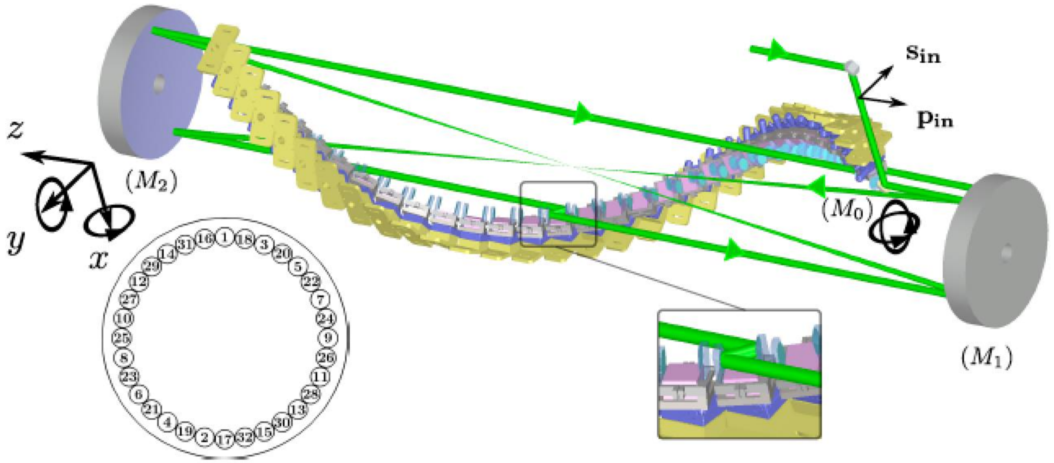
high-energy accelerator section:
3.0-19.5 MeV



A r.t. RF linac *vs* pulsed laser source

Electron beam parameter at IP	
Energy (MeV)	180-750
Bunch charge (pC)	25-400
Bunch length (µm)	100-400
$\varepsilon_{n-x,y}$ (mm-mrad)	0.2-0.6
Bunch Energy spread (%)	0.04-0.1
Focal spot size (µm)	15-30
# bunches in the train	> 31
Bunch separation (nsec)	16
energy variation along the train	0.1 %
Energy jitter shot-to-shot	0.1 %
Emittance dilution due to beam breakup	< 10%
Time arrival jitter (	< 0.5
Pointing jitter (µm	1

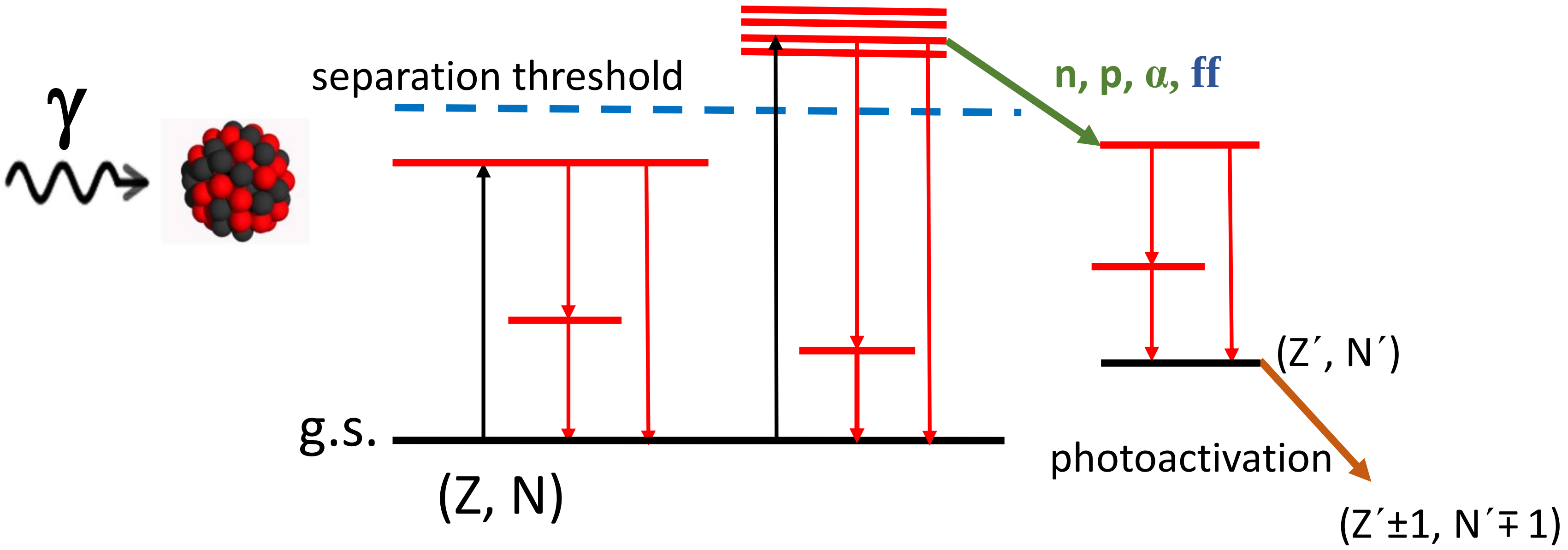




	intera	
Pulse energy (J)	0.2	0.5
Wavelength (eV)	2.4	2.4
FWHM pulse length (ps)	2-4	2-4
Repetition Rate (Hz)	100	100
M^2	≥ 1.2	≥ 1.2
Focal spot size w_0 (µm)	> 25	25
Bandwidth (rms)	0.05 %	0.05 %
Pointing Stability (µrad)	1	1
Sinchronization to an ext. clock	< 1 psec	< 1 psec
Pulse energy stability	1 %	1 %

Experiments with high-brilliance gamma beams at ELI-NP

S. Gales et al., Phys. Scr. 91, 093004 (2016)



Nuclear Resonance Fluorescence (NRF) – **Rom. Rep. Phys. 68, S483 (2016)**

Giant/Pigmy Resonances (GANT) – **Rom. Rep. Phys. 68, S539 (2016)**

Photodisintegration (γ,n), (γ,p), (γ,α) – **Rom. Rep. Phys. 68, S699 (2016)**

Photofission (γ,ff) – **Rom. Rep. Phys. 68, S621 (2016)**

Applications – **Rom. Rep. Phys. 68, S735 (2016), *ibid* 68, S799 (2016), *ibid* 68, S847 (2016)**

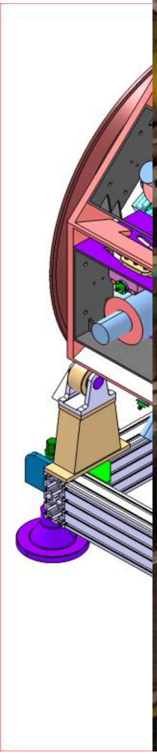
Nuclear

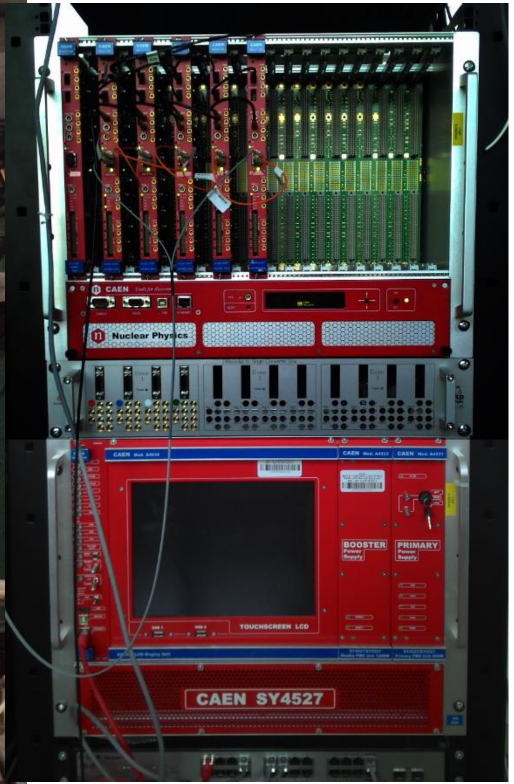
ep. Phys. 68, S483 (2016)

g

tage

under discussion





Dec. 12-18, 2016

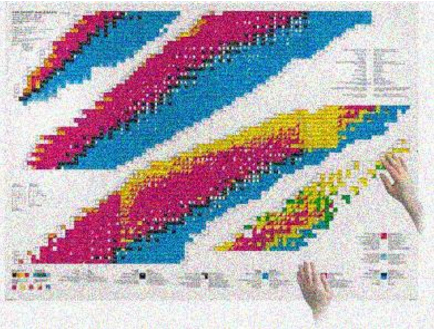
Rom. Rep. Phys. 68, S483 (2016)

ELI-NP NRF physics cases

- Self-absorption measurements (Γ_0/Γ_i)
- Low-energy dipole response (e.g. Actinides)
- Dipole response and parity measurements for weakly-bound nuclei
- Investigation of the Pigmy Dipole Resonance
- Rotational 2^+ states of the scissor mode
- Constraints on the 0νββ-decay matrix elements of the scissors mode decay channel: ^{150}Sm

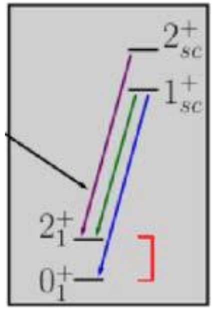
Availability frontier

***p*-nuclei and actinides**



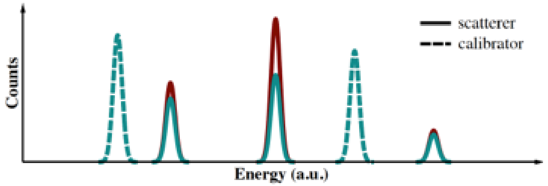
Sensitivity frontier

week channels



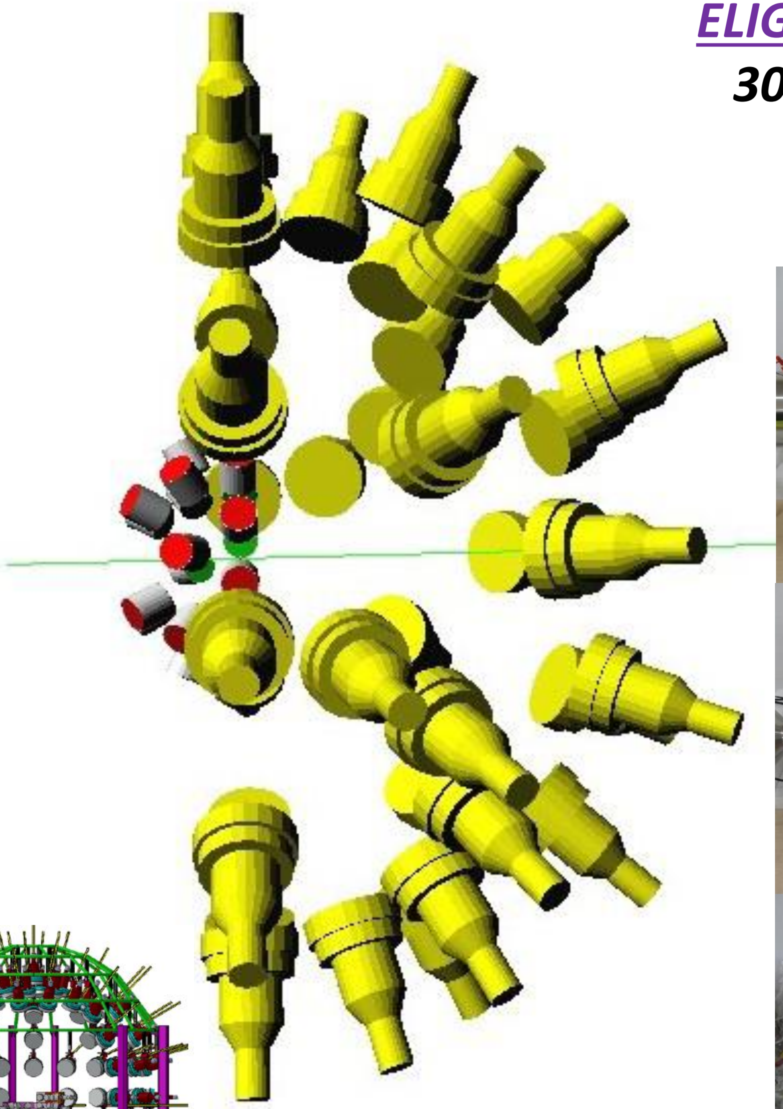
Precision frontier

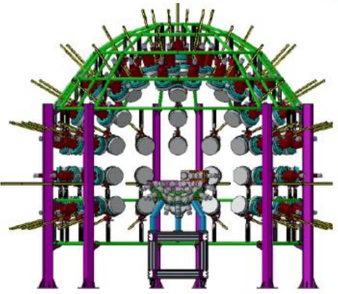
high statistics



Rom. Rep. Phys. 68, S539 (2016)

GANT experiment at ELI-NP





ELIGANT-GN array

30 $LaBr_3$ or $CeBr_3$

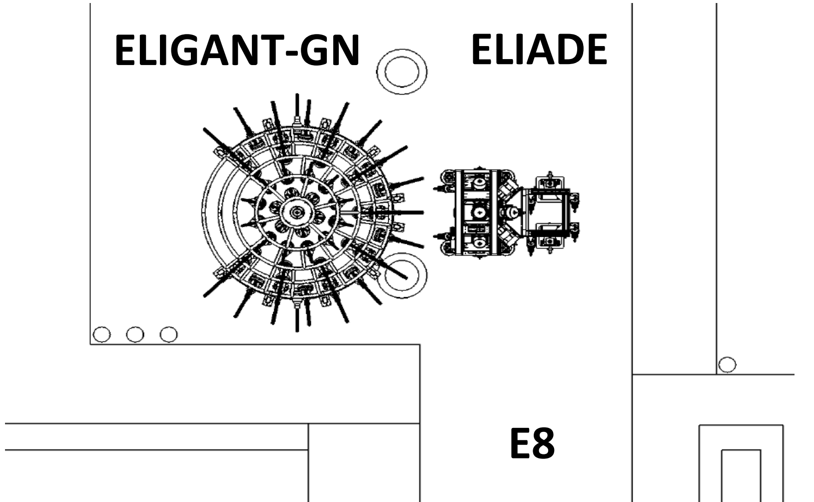
20 ^{7}Li glasses

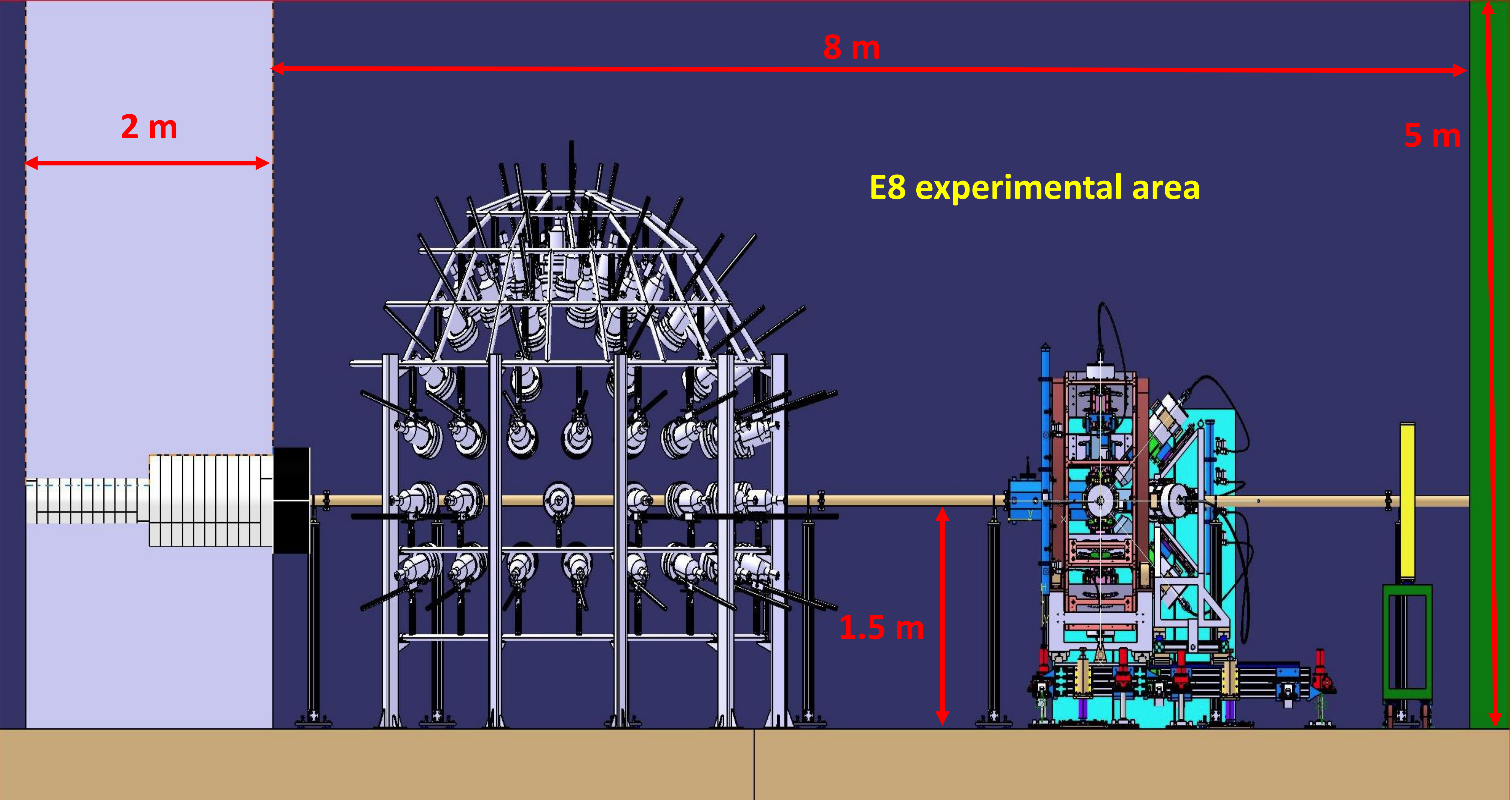
30 Lq. Scint.

Day ONE:

studies of GDR and PDR decay (^{90}Zr, ^{208}Pb)

- combine with information from (γ,n) experiments
- combine with information from (γ,γ’) experiments (*e.g.* polarization)
- γ-decay to gs and excited states as a function of excitation energy





8 m
2 m
5 m
E8 experimental area
1.5 m

Neutron stars, equation of state and dipole polarizability @ELI-NP

-Neutron stars (NS) properties depend sensitively on the equation of state (EOS) of nuclear matter
-EOS can affect many NS properties: mass-radius relationship, moment of inertia, cooling rates, Urca process, …
-It has been suggested that the slope (L) of the symmetry energy term of the EOS is closely related to the dipole polarizability α_D through the neutron skin thickness [1,2,3]

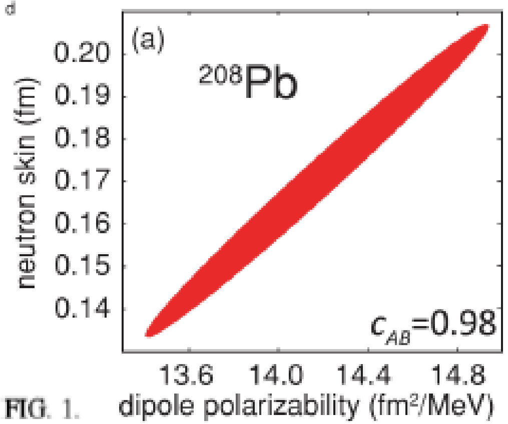


FIG. 1.

PHYSICAL REVIEW C **81**, 051303(R) (2010)

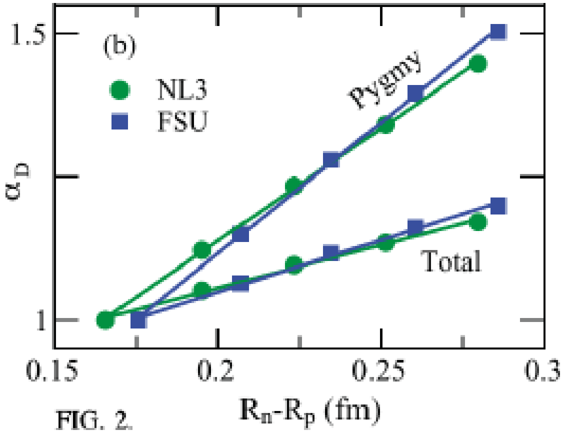


FIG. 2.

PHYSICAL REVIEW C **83**, 034319 (2011)

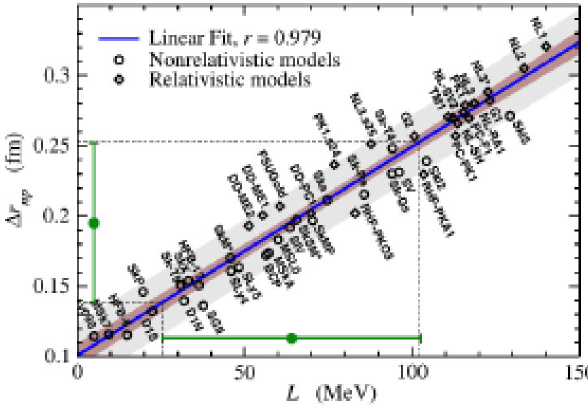


FIG. 3 (color online). Neutron skin of ^{208}Pb against slope of the symmetry energy. The linear fit is $\Delta r_{np} = 0.101 + 0.00147L$.

PRL **106**, 252501 (2011)

Nuclear Physics

ELI-NP: experimental photo-nuclear reaction facility

- The dipole polarizability is obtained from the photo-absorption cross section

$$\alpha_D = \frac{\hbar c}{2\pi^2}\int_0^\infty \frac{\sigma_{abs}}{\omega}\, d\omega = \frac{8\pi}{9}\int_0^\infty \frac{dB(E1)}{\omega}$$

-Strongly dependent on the low-energy strength, e.g. Pygmy resonance (see also FIG. 2)
-ELI-NP will provide (accurate and unambiguous) measures of E1 strength below and above the neutron-threshold
-Model independent results: pure electromagnetic excitation process

[1]P.-G. Reinhard and W. Nazarewicz, Phys. Rev. C81, 051303® (2010) [2] J. Piekarewicz, Phys. Rev. C83, 034319 (2011) [3] X. Roca-Maza et al., Phys. Rev. Lett.106,252501 (2011)

RCNP Osaka vs. ELI-NP experiments

RCNP

High-resolution (p,p') measurement at 0^{o} and forward angles

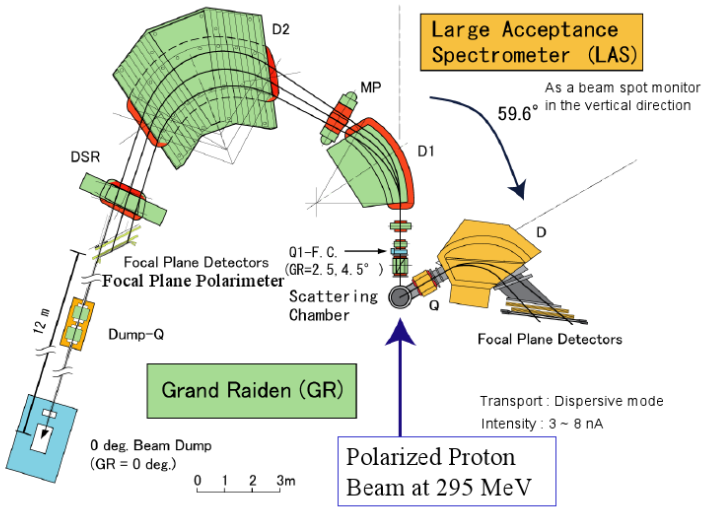
A. Tamii, NIM A605, 326 (2009)

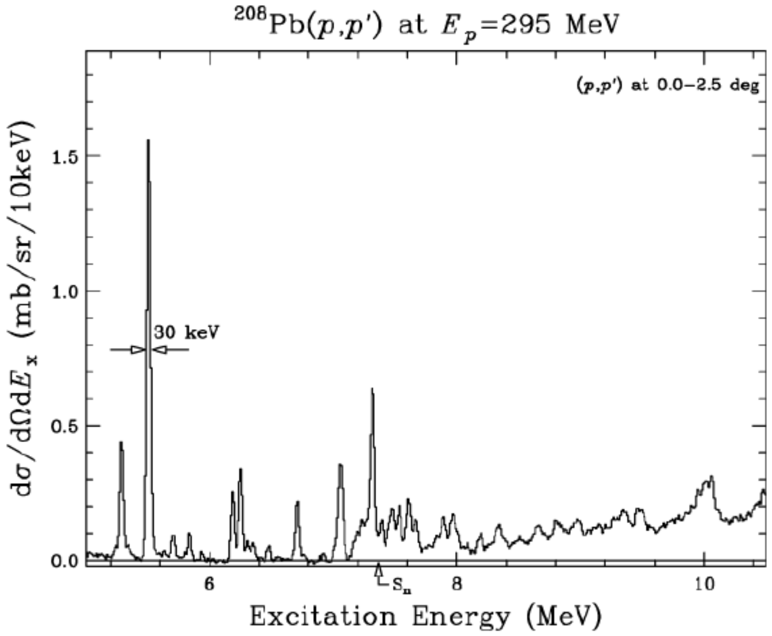
ELI-NP

High-resolution (γ,γ') + (γ,n) measurement

advantages: polarized (>99%) γ beam
simultaneous (γ,γ') + (γ,n) measurement

Spectrometers in the 0-deg. experiment setup

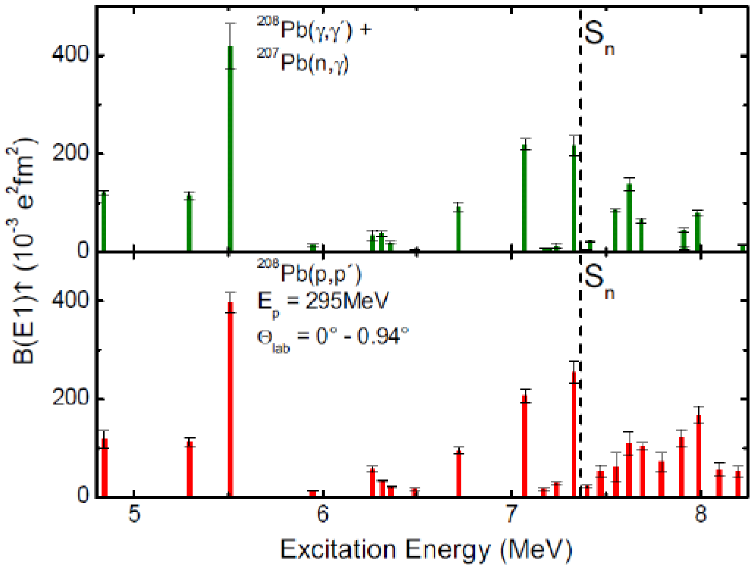




$$\alpha_D \equiv \frac{\sigma_{-2}}{2\pi^2} \cdot \frac{\hbar c}{e^2} = \sum \frac{\sigma_{abs}(E_x)}{E_x^2} \cdot \frac{\hbar c}{2\pi^2 e^2} = 20.1 \pm 0.6\ \mathrm{fm}^3/\mathrm{e}^2$$

A. Tamii, PRL 107, 062502 (2011)

B(E1) of discrete states



B(E1) strength distribution in ^{208}Pb below the GDR region

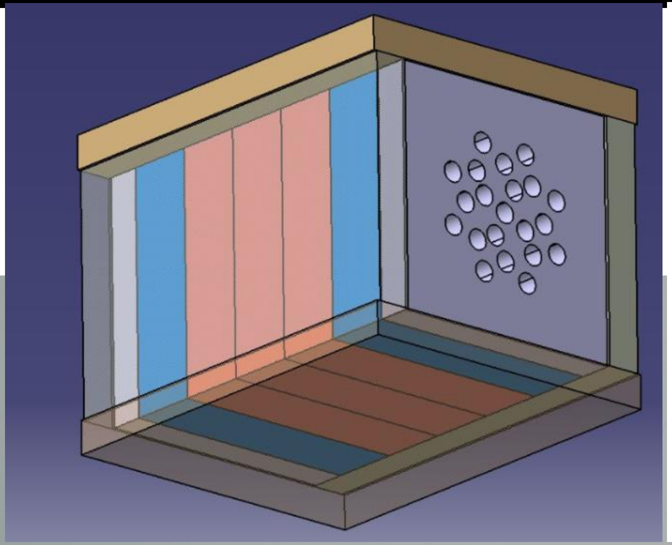
Rom. Rep. Phys. 68, S539 (2016)

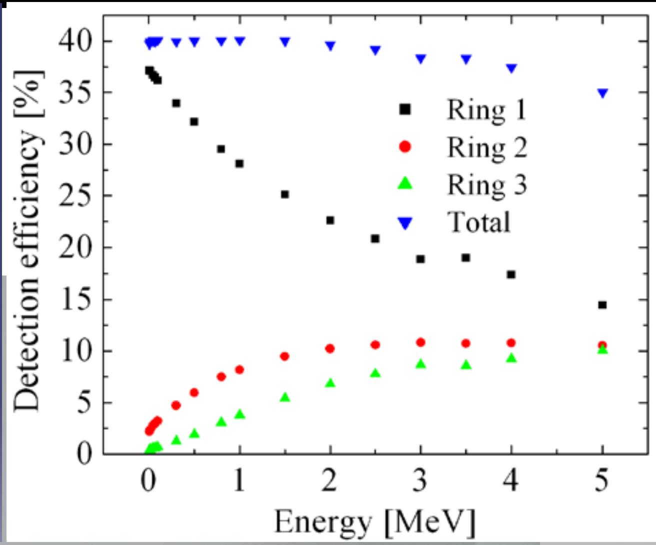
(γ,n) cross-section experiment at ELI-NP

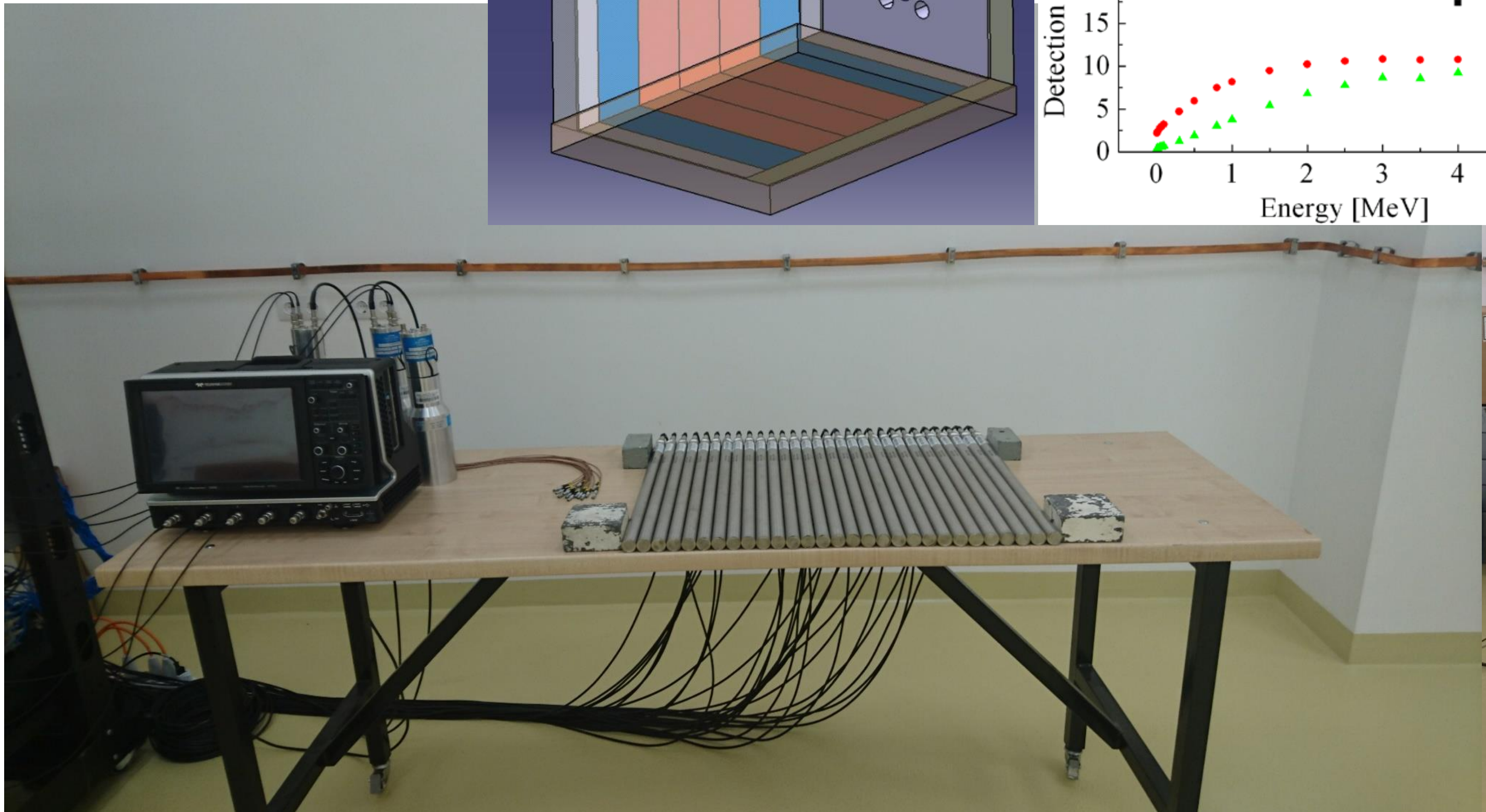
ELIGANT-THN array

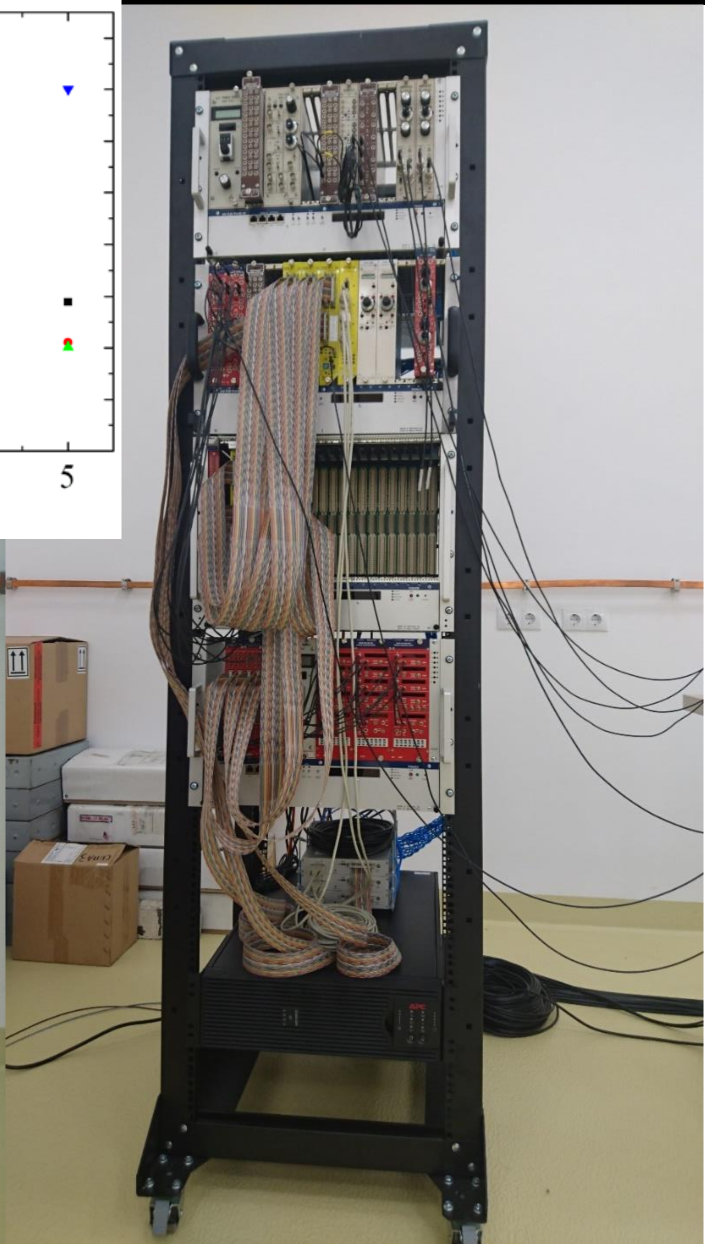
30 ^{3}He counters

40% detector efficiency







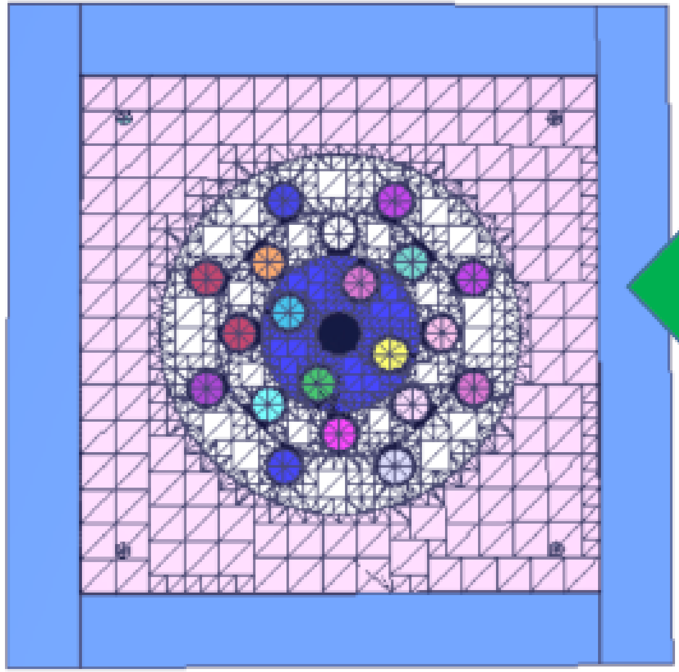


P-PROCESS NUCLEOSYNTHESIS FOR ^{180}Ta AND MEASUREMENTS OF THE PHOTO-NEUTRON CROSS SECTION

^{180}Ta characteristics

- Lowest natural abundancy (0.012%)
- Short-lived ($T_{1/2}$ = 8.15h) $J^{\pi} = 1^{+}$ ground state ($^{180}Ta^{g}$)
- Very long-lived ($T^{1/2} > 10^{15}$ yr) $J^{\pi} = 9^{-}$ isomeric state ($^{180}Ta^{m}$)
- ^{181}Ta(γ,n)^{180}Ta and ^{180}Ta(γ,n)^{179}Ta photo-disintegration reactions

- Correct prediction of the $^{180}Ta^{m}$ yield highly requires both ^{181}Ta(γ,n)^{180}Ta and ^{180}Ta(γ,n)^{179}Ta cross section measurements.
- The measurements for the (γ,n) cross sections related to the p-nuclides destruction requires gamma ray beam three orders of magnitude higher than the existing ones.
- Measurements of the ^{180}Ta(γ,n)^{179}Ta reaction are foreseen in the Day 1 experiment at ELI-NP facility by using the maximum available gamma ray energy of 19 MeV.



Transversal section of the ELIGANT - TNH High Efficiency 4π Thermal Neutron Detector

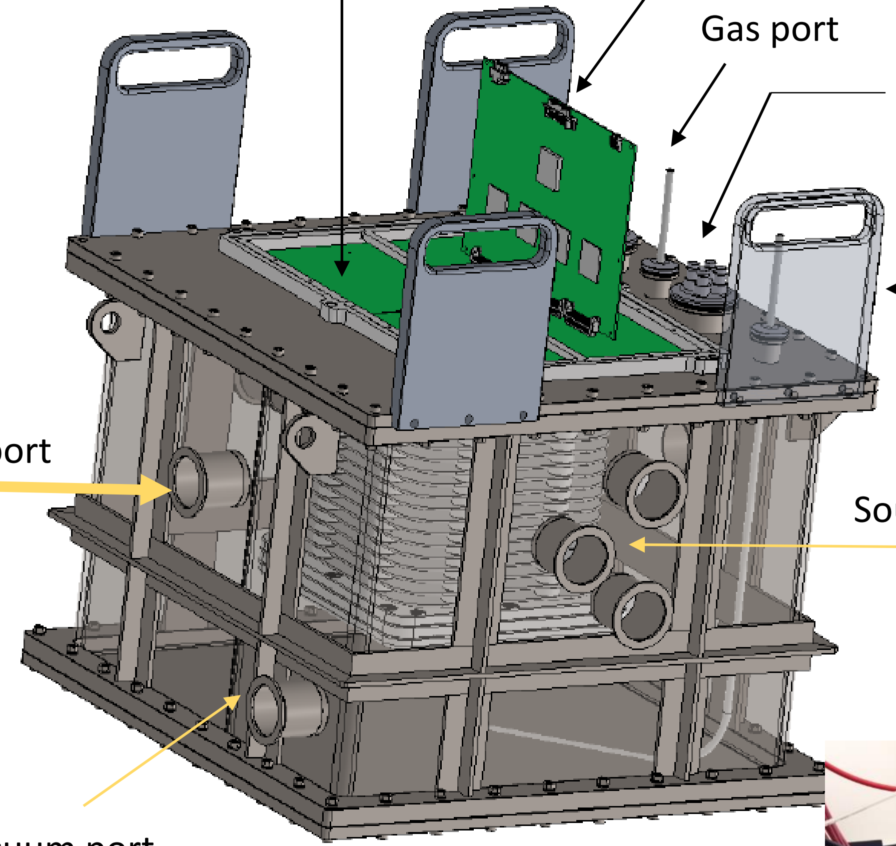
- ✓ 20 cylindrical ^{3}He proportional counters
- ✓ 60% detection efficiency
- ✓ low amount of ^{180}Ta target (1mg/cm^{2}) to be used.

eli Nuclear Physics

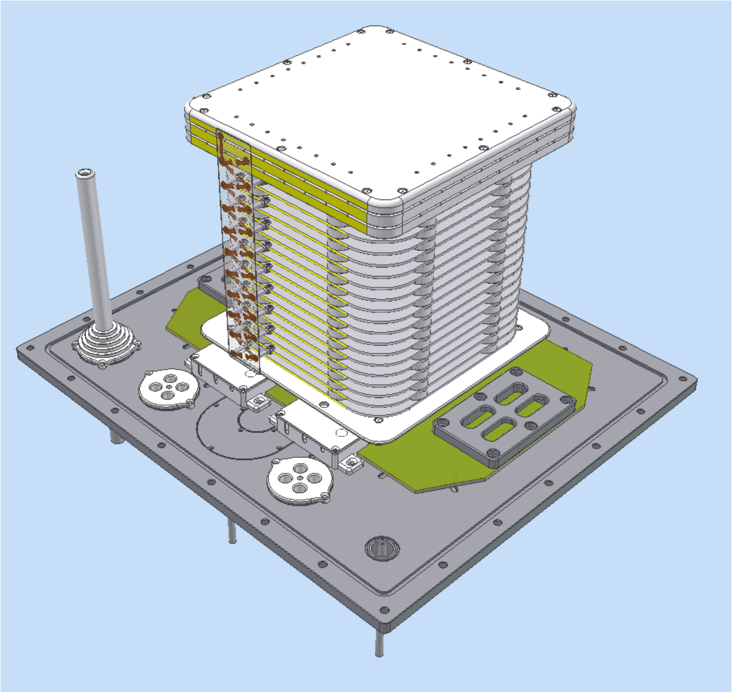
NuPECC LOng Range Plan 2016-2020 – Astrophysics

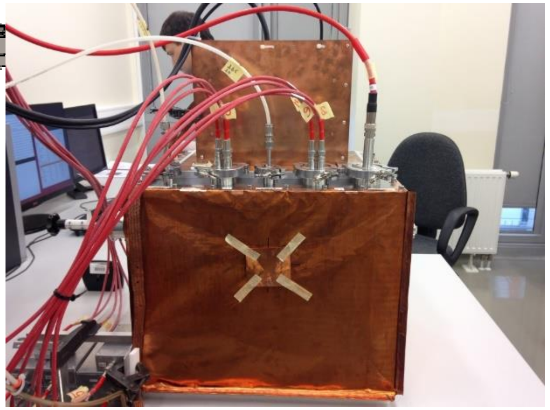
ELITPC

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



Detector upside-down view



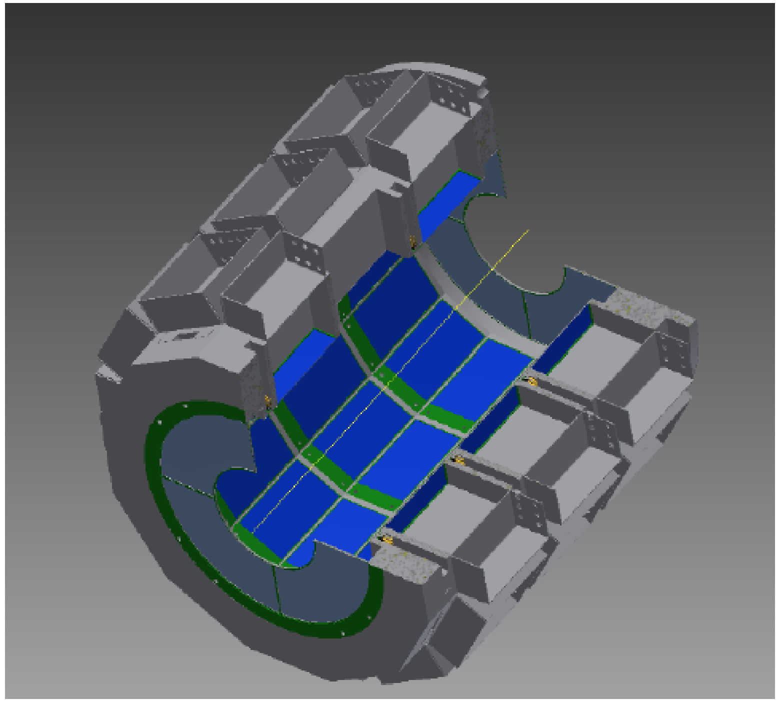


The mini-eTPC detector with 256-channel readout was built and successfully tested in-beam at the IFIN Tandem in 2016

U. Warsaw, ELI-NP, U. Connecticut

nuclear astrophysics with ELISSA

Nuclear Physics

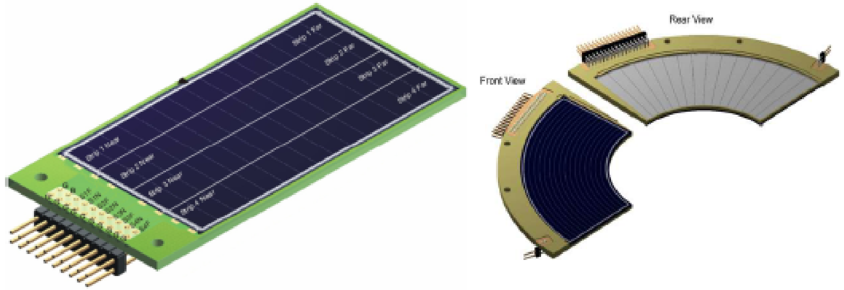


ELISSA:

- 3 rings of 12 position sensitive X3 silicon-strip detectors by Micron
- 2 end cap detectors from 4 QQQ3 segmented detectors by Micron
- 320 channels readout with GET electronics

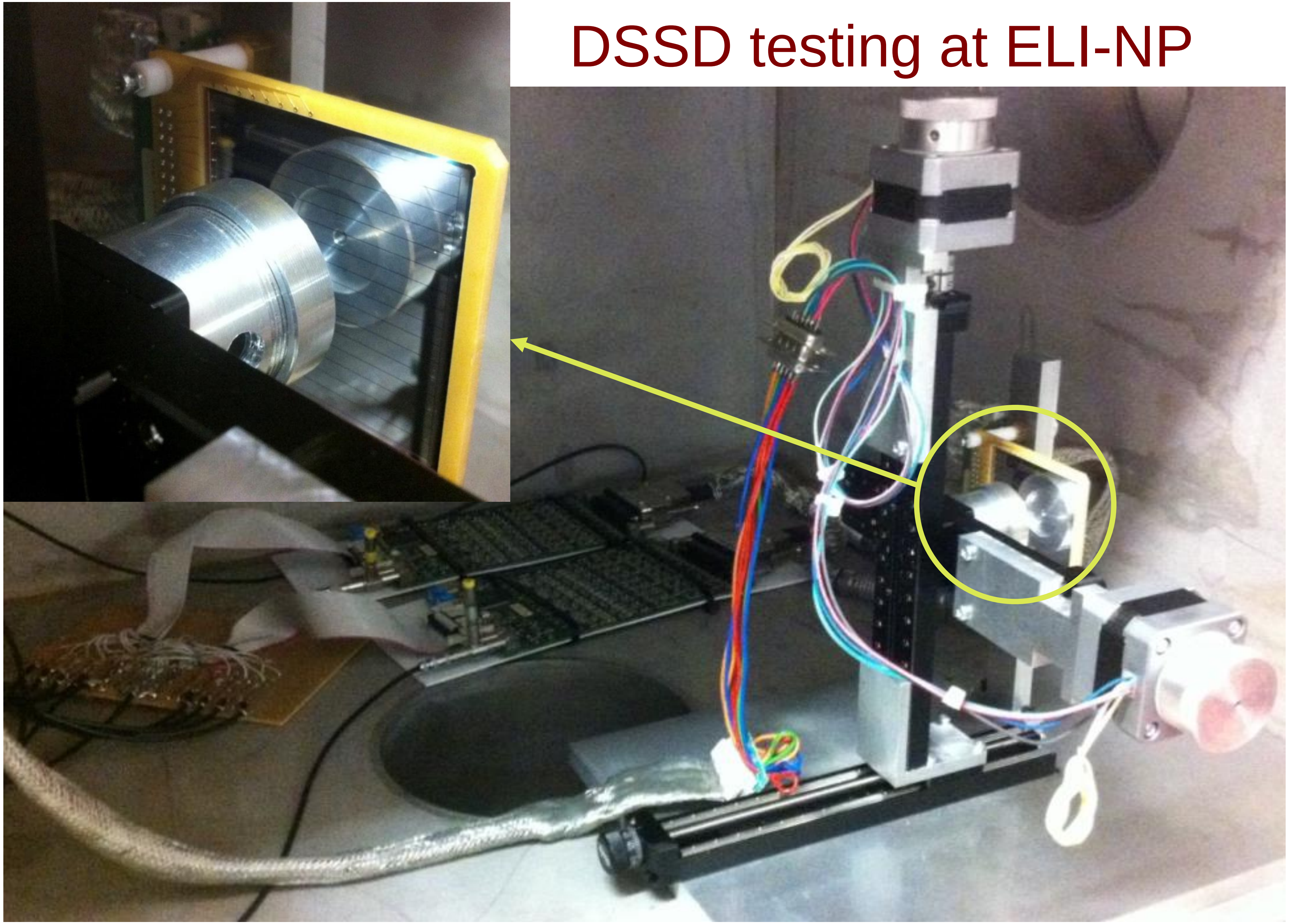
$^{7}Li(\gamma,t)\alpha$

- reaction could still be a game changer in resolving the "Li problem"
- experimental measurements below 1.5 MeV are 30 yrs. old and disagree with theoretical predications
- higher energy measurements can restrict the extrapolation to astrophysically important energies



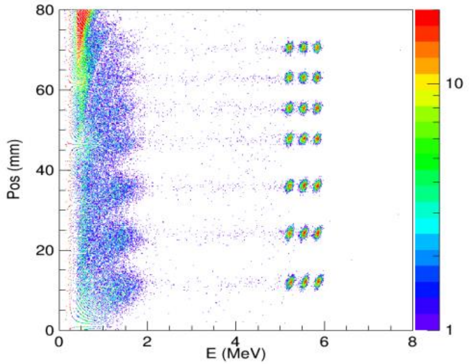
C. Matei et al., exp. at HIγS approved by the 2016 PAC

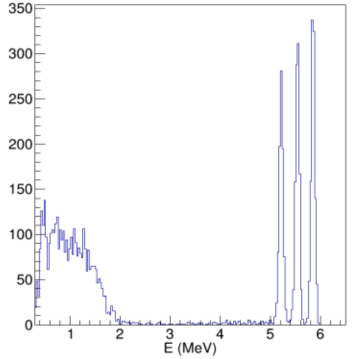
DSSD testing at ELI-NP



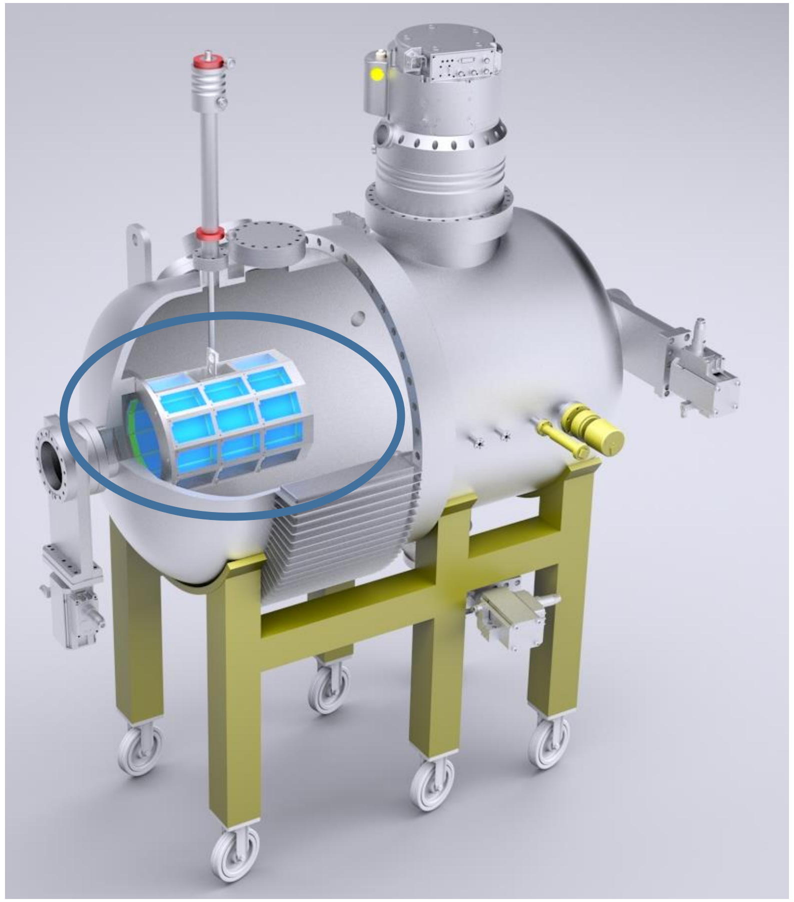
ELISSA (ELI-NP Si strip detector array)

- X3 detector tests at INFN-LNS in Feb 2016
- energy thresholds at 300 keV
- measured energy, position resolution
- responsible: INFN LNS and ELI-NP





- all 40 X3 detectors tested at IFIN 08-11/16
- analog DAQ developed at ELI-NP
- responsible: ELI-NP



- geometry updated in GEANT4 by INFN LNS
- GET electronics under development by INFN LNS

INFN LNS Catania and ELI-NP

Nuclear Physics

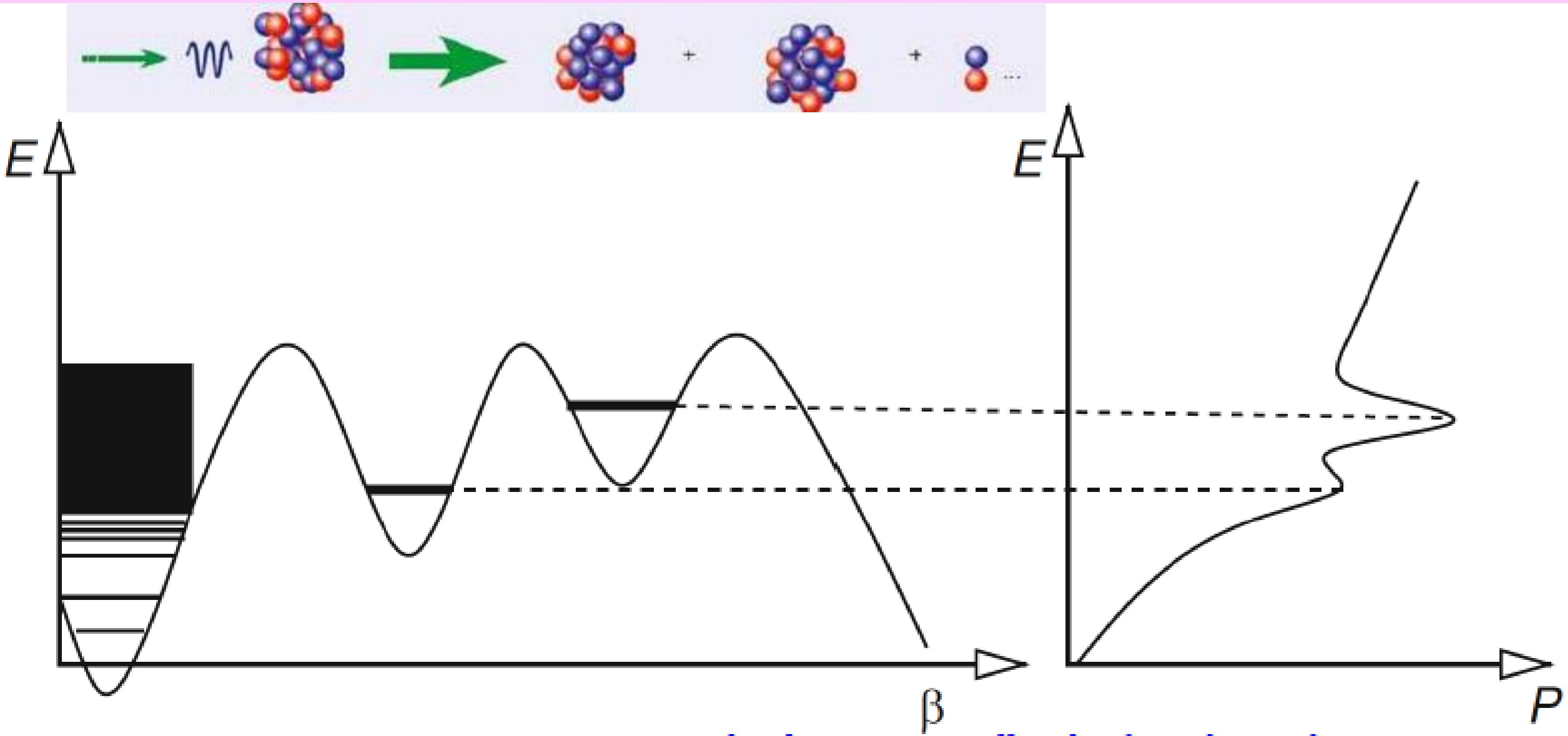
Rom. Rep. Phys. 68, S621 (2016)

Photofission: Physics goals

1. High-resolution photo-fission studies in actinides as a function of the photon energy → study of the fission resonances, investigation of 2^{nd}, 3^{rd} potential minima, mapping the fission barrier
2. Angular distribution measurements for the fission fragments. → Study of the J^{π} and K-values of the resonances
3. Mass and charge distribution measurements for the fission fragments → study of the clusterization before fission
4. Study of the ternary fission probability as a function of the photon energy → direct proof for highly deformed states
5. Study of the true ternary fission. → clusterization

Experimental approach for study of fission barrier

Observation and study of transmission resonanses



A. Krasznahorkay, in: Handbook of Nuclear Chemistry, p.281 (2011)

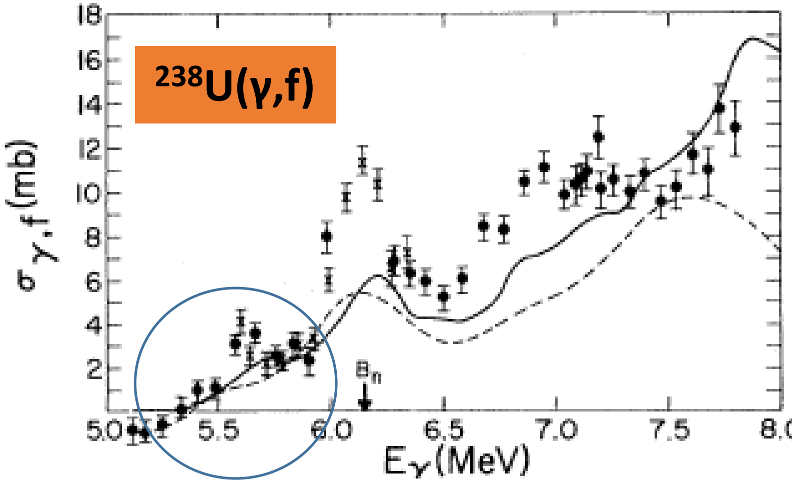
Note: Nuclear structure correlations influence the fission probability

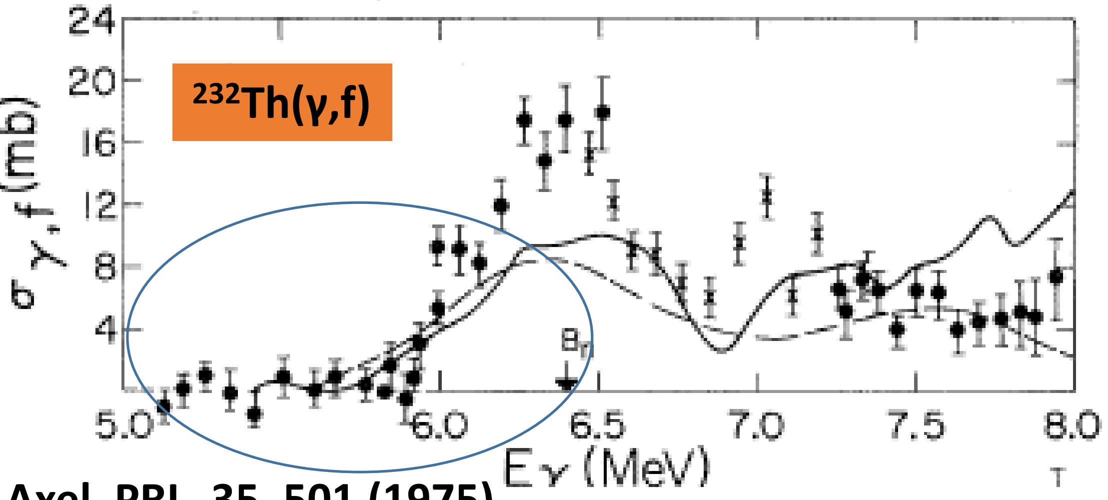
Investigation of Transmission Resonances as function of energy

- *mapping the fission barrier*
- *study of SD and HD states in these min*
- *fine str. in the isomeric shelf*

see also ELI-NP White Book: contributions of P. Thirolf and D. Habs

Transitional Resonances: Status

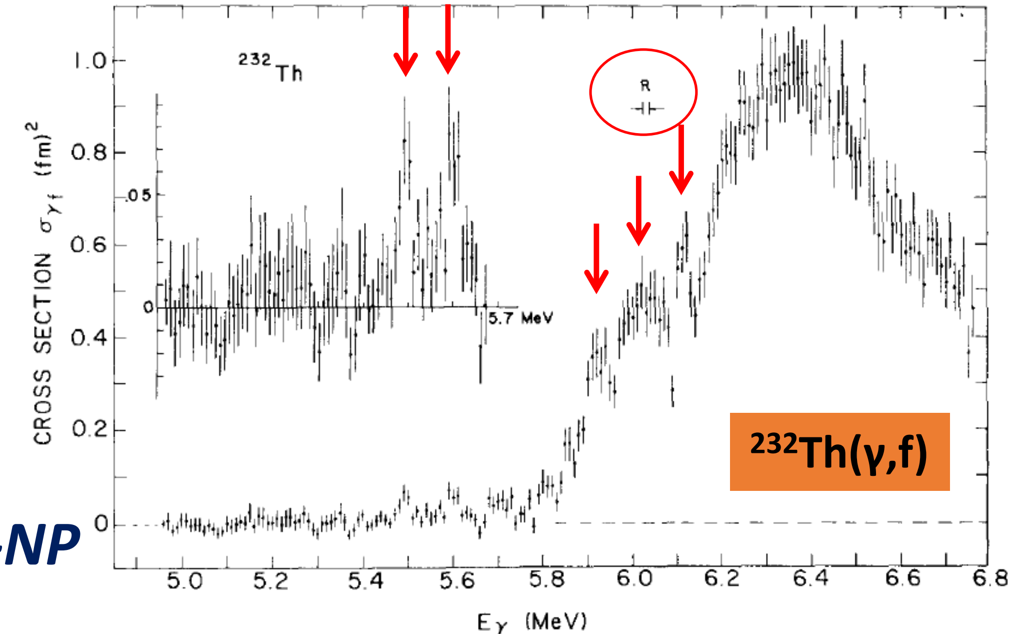




P. A. Dickey, P. Axel, PRL, 35, 501 (1975)

J. W. Knowles et al, PLB 116, 315 (1982)

bandwidth *R* = 12 – 14 keV

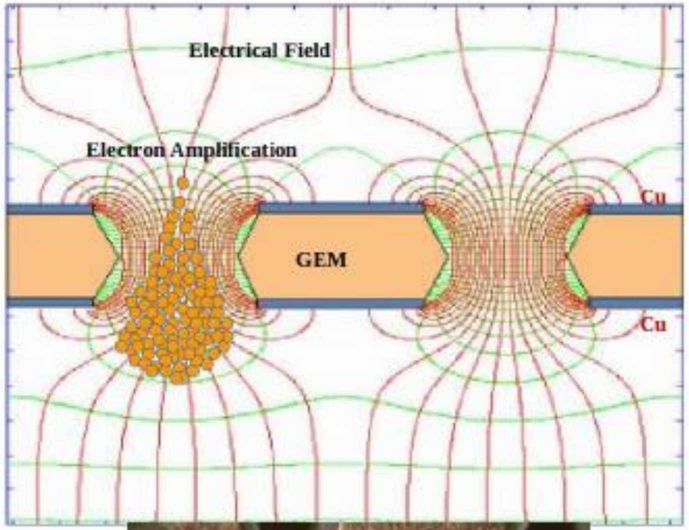


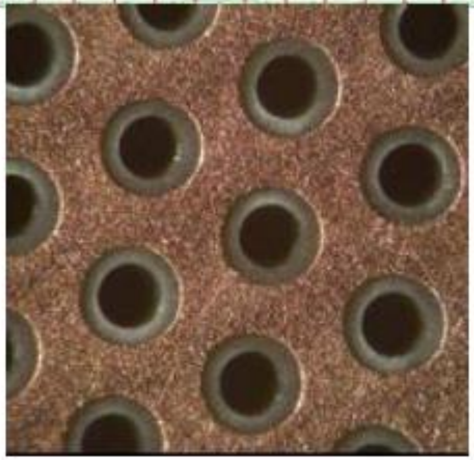
***NOTE*: this is the bandwidth expected at ELI-NP**

Setup-1 : ELITHGEM

- ✓ Measurement of fission cross section
- ✓ Measurement of angular distribution of fission fragments

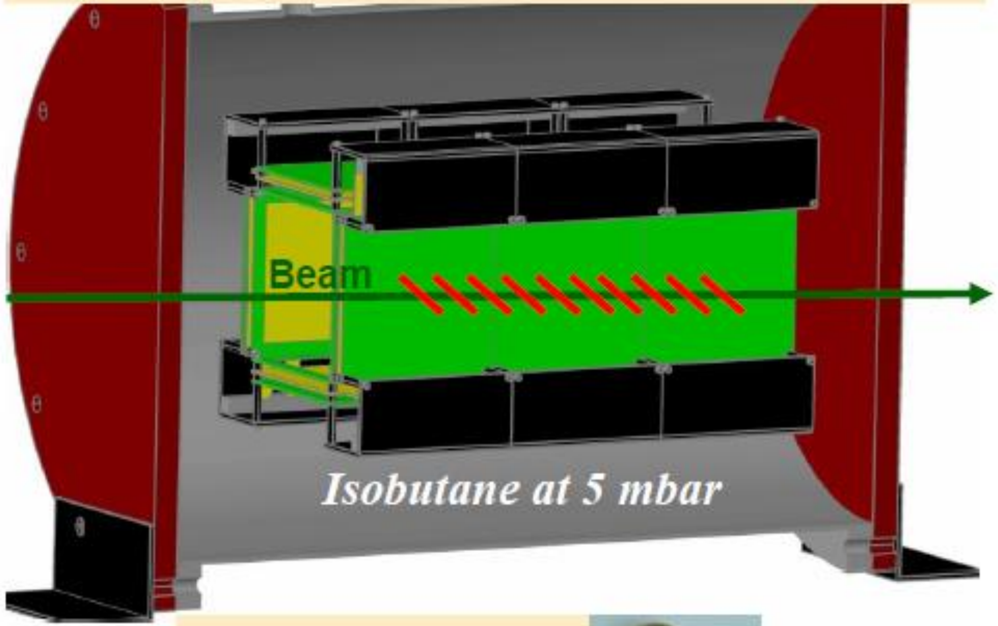
Multi-target detector array consisting of position sensitive gas detector modules based on the state-of-art THGEM technology

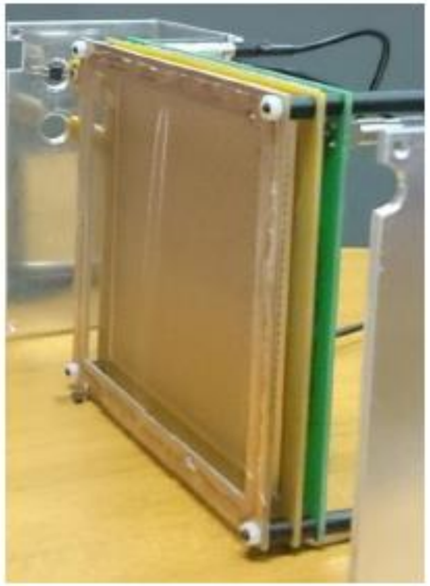




Setup-1 : ELITHGEM

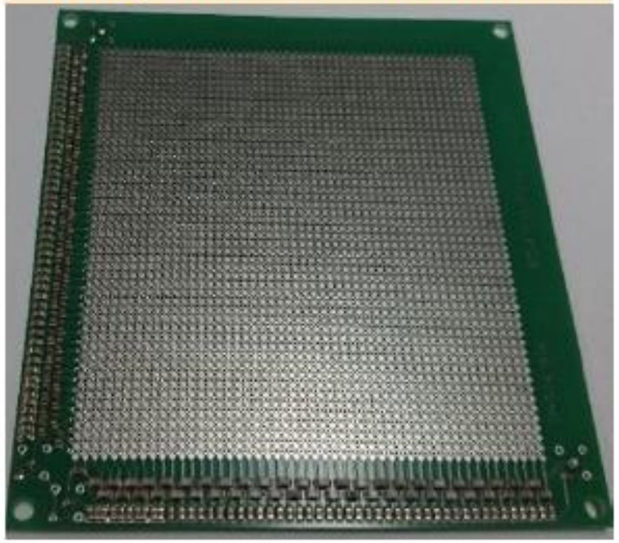
Entire setup : Array of 12 detectors





THGEM board

Delay-line readout anode



Set-up 2: The ELI-BIC array

- ***Bragg Ionization Chamber***:

–**Based on the design of a Frisch grid twin ionization chamber**

–**1 bar P10 gas mixture → 3.5 cm range for fission fragments (*SRIM*)**

–**Fissile sample in the center of the cathode**

–**Electrodes: d=8 cm metal disks and stainless steal mesh (Frisch grid)**

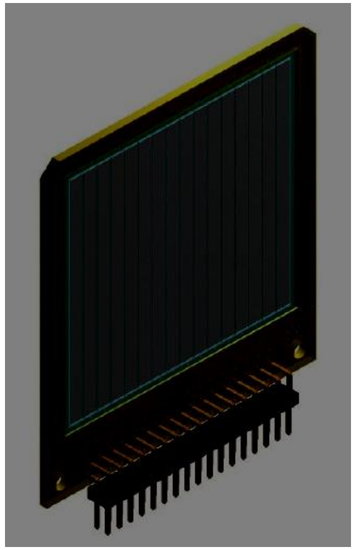
–**Field rings: stainless steal wires with a diameter of 0.5 mm**

- ***ΔE – E array***:

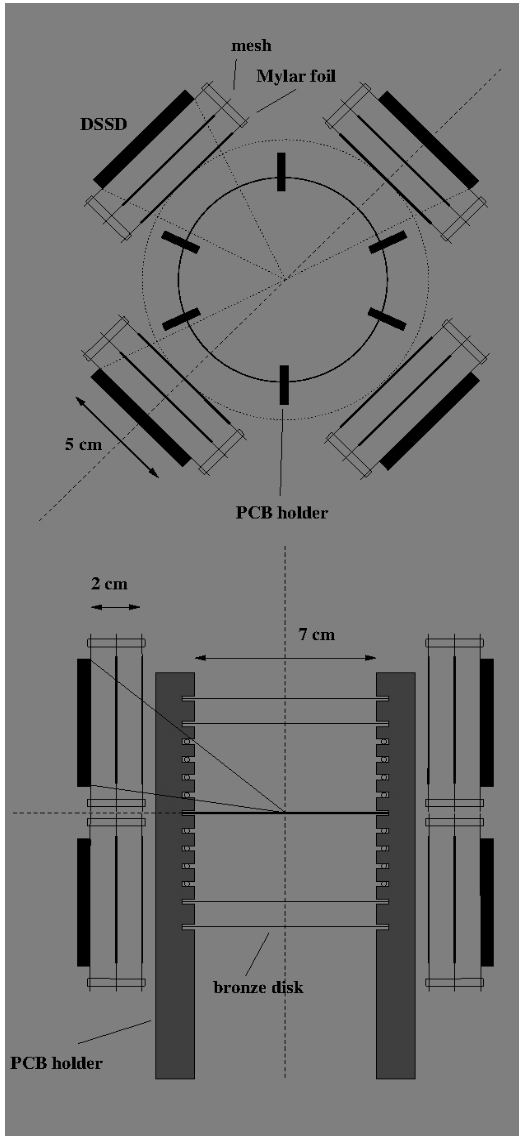
–**DSSD (MicronSemiconductor Design W1) + small ionization chamber**

–**Dimensions: 50x50 mm2**

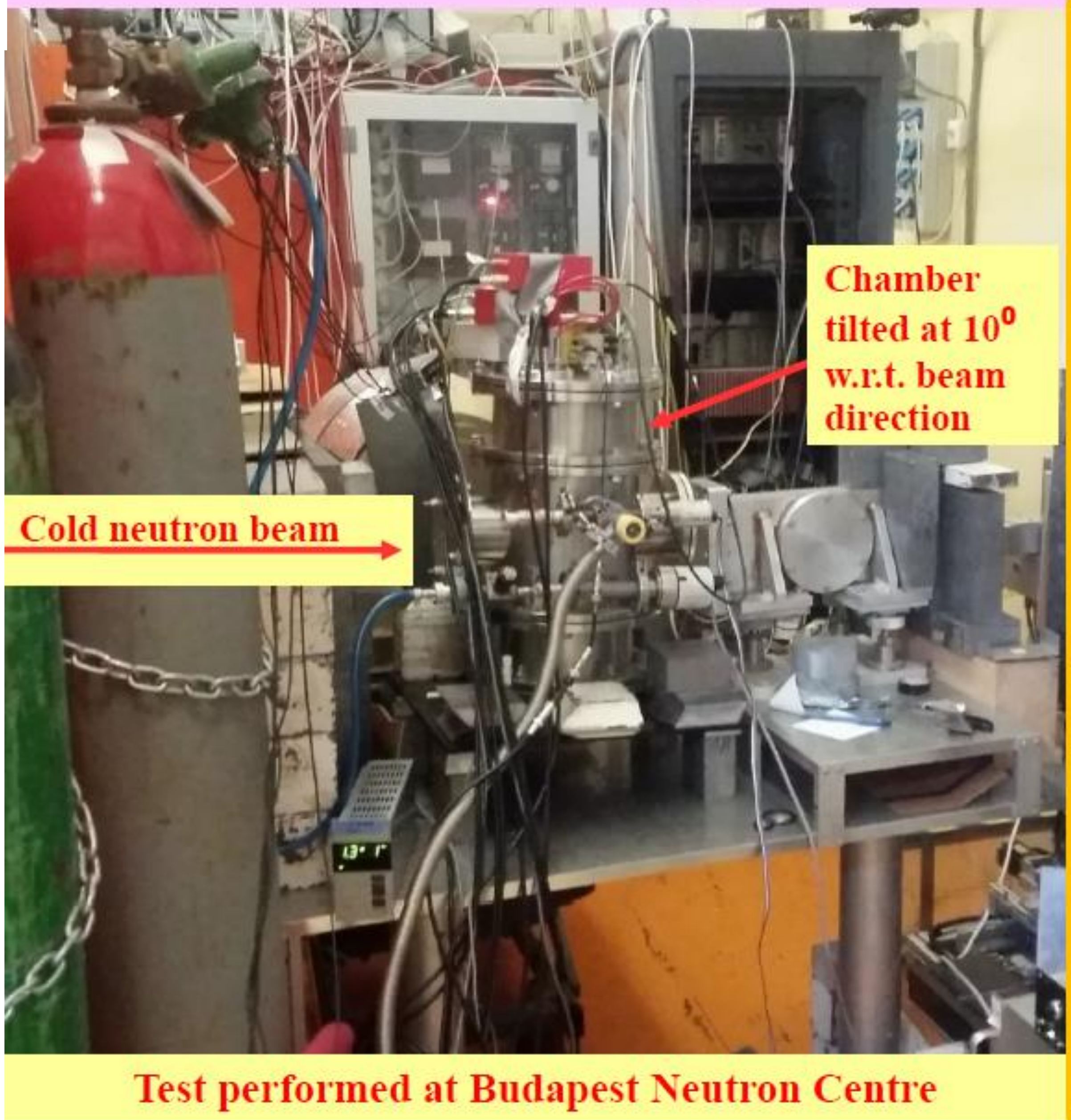
–**Ionization chamber**



DSSD W1

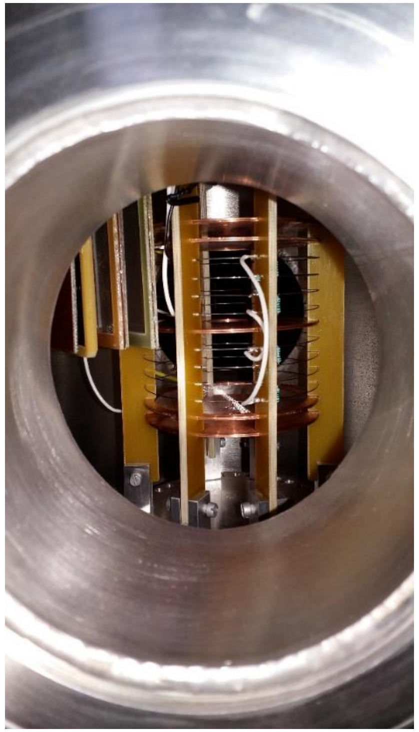


In-beam Test Experiment of one Ionization Chamber coupled with 1 dE-E detector array [cold neutron beam on ^{237}Np target]



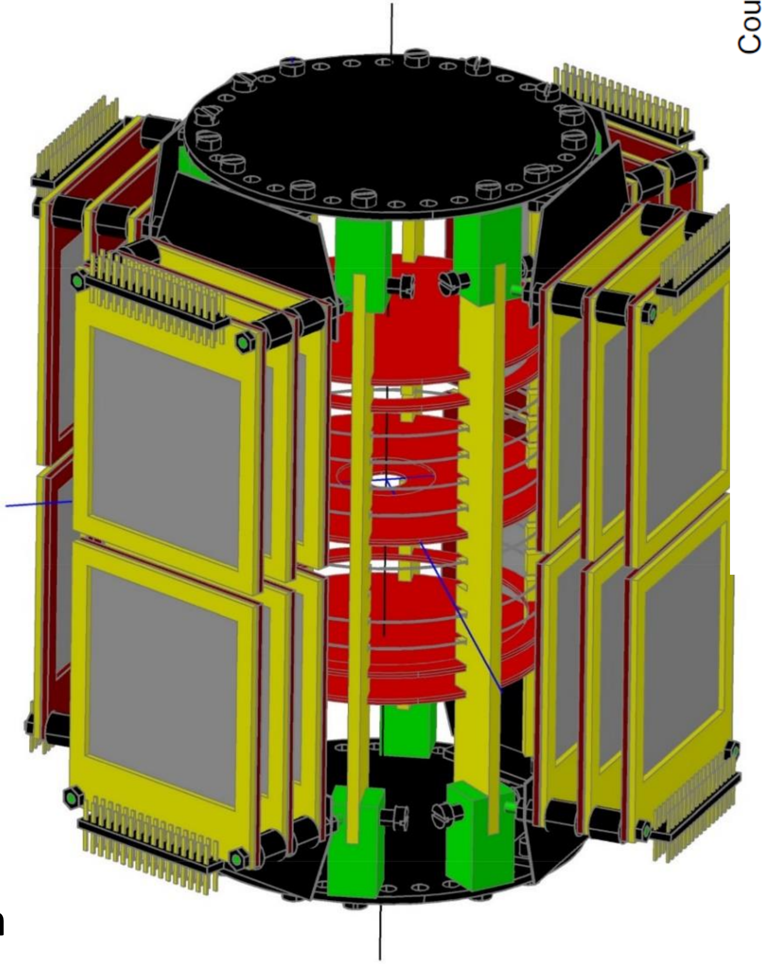
Rom. Rep. Phys. 68, S621 (2016)

Photofission experiments at ELI-NP

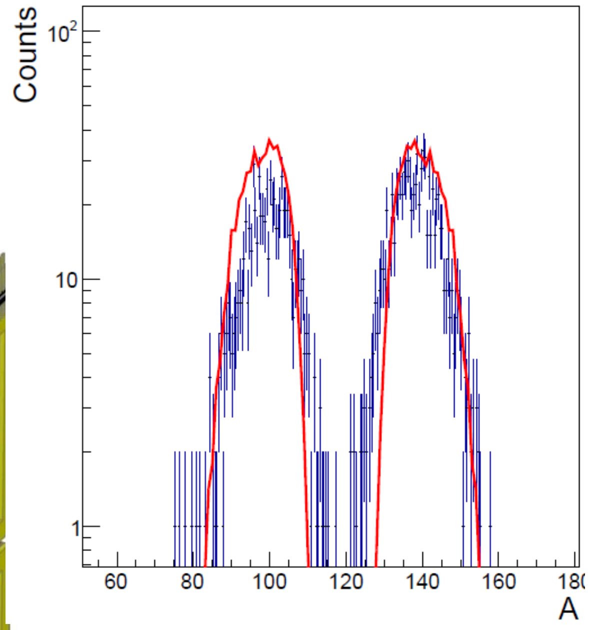


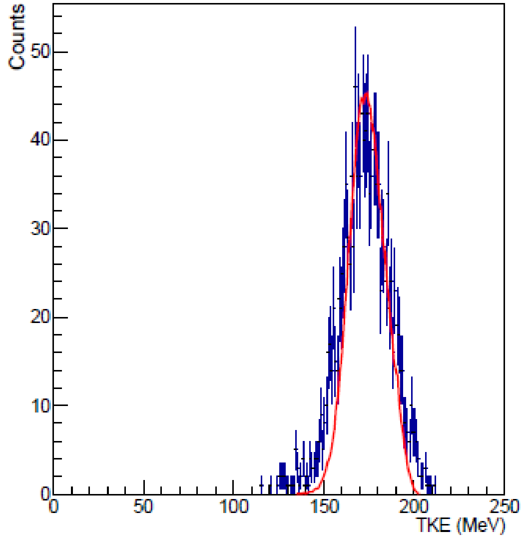
BIC prototype tested with sources and in-beam

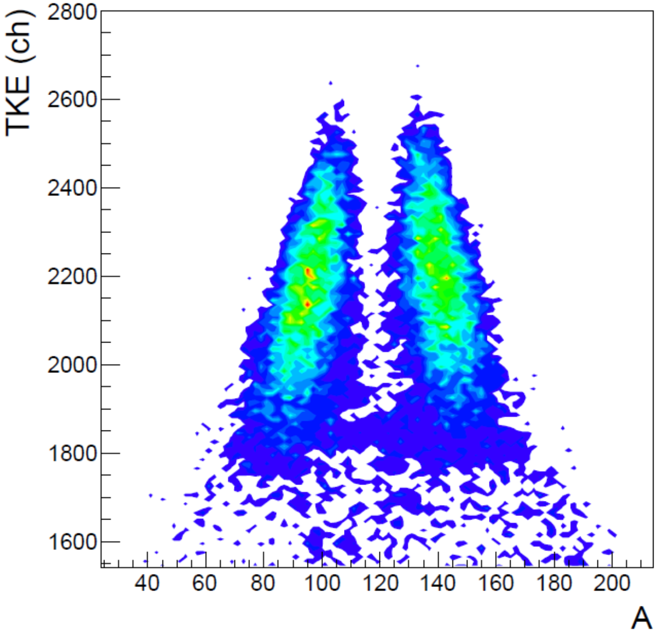
ELI-BIC



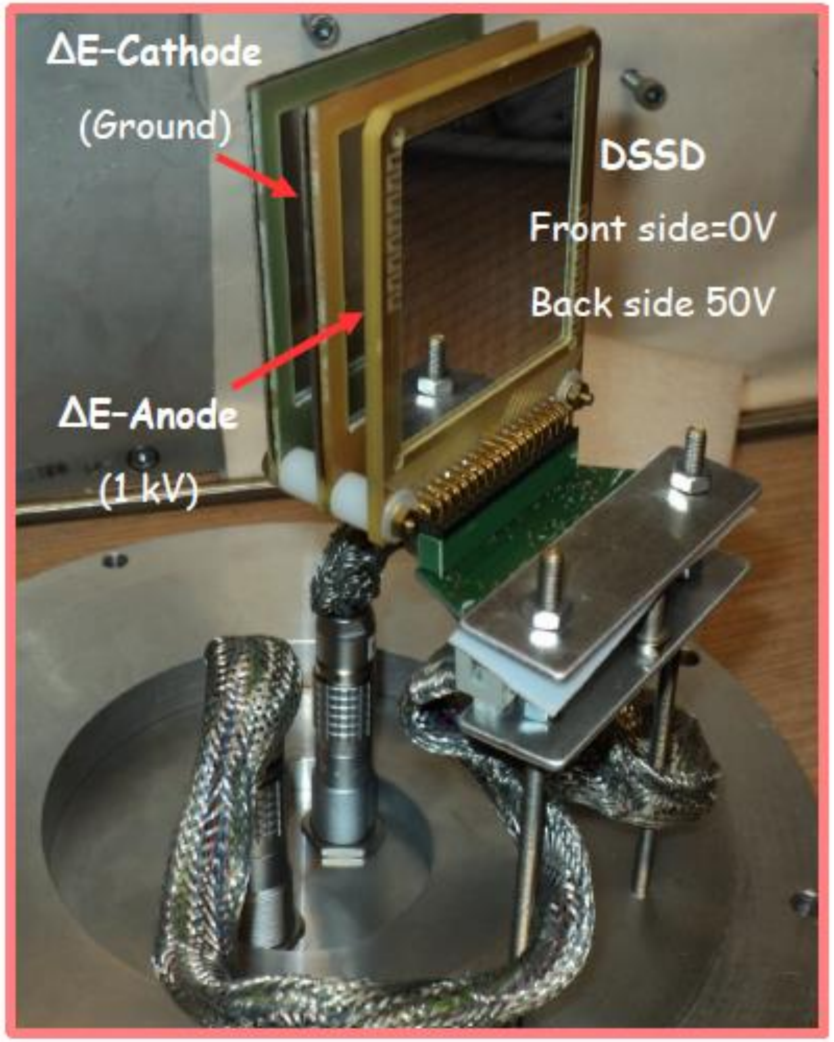
Array of Bragg ICs coupled to Si DSSD based ΔE-E detectors

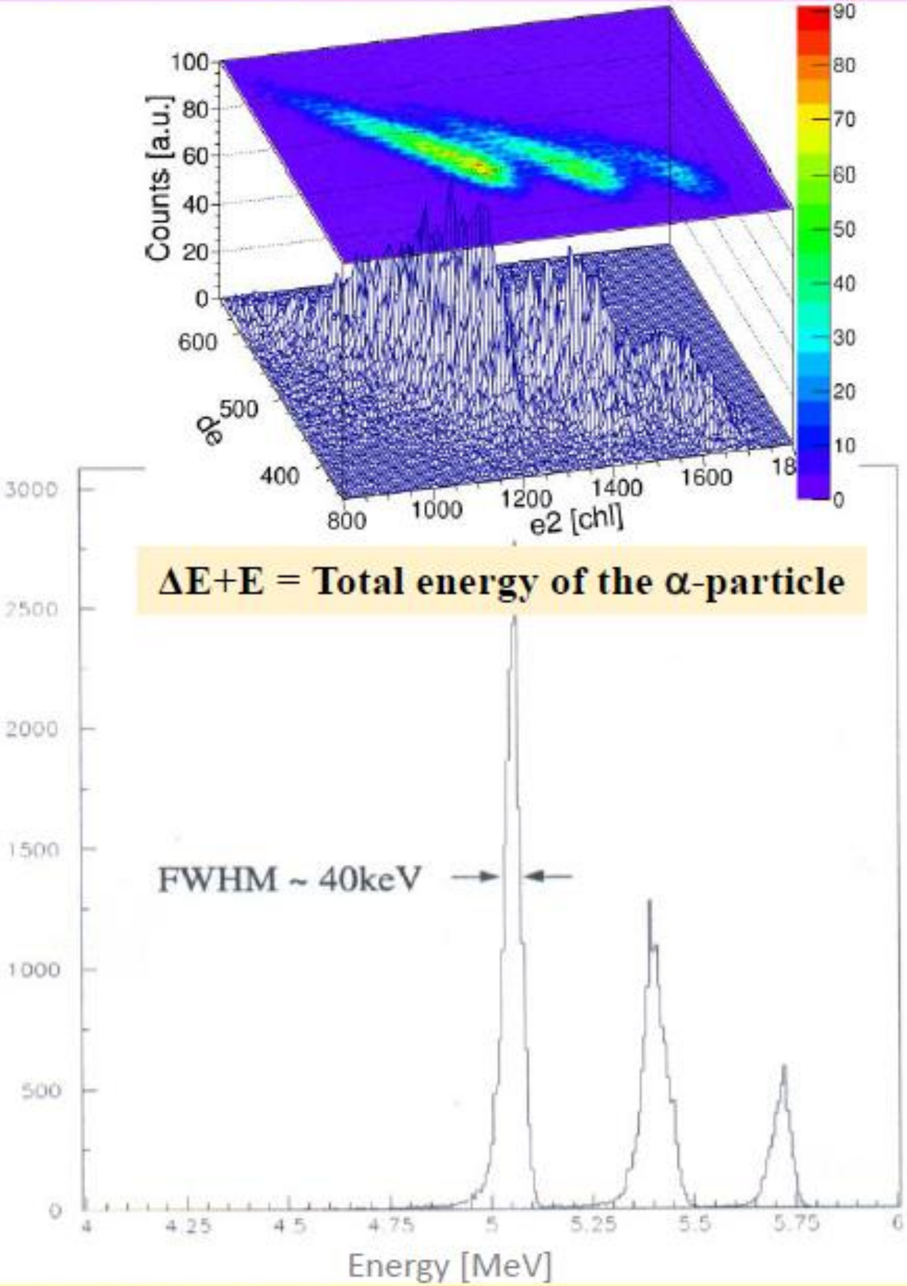






Feasibility test of dE-E detector with AMR-33 ($^{239}Pu + ^{241}Am + ^{244}Cm$)

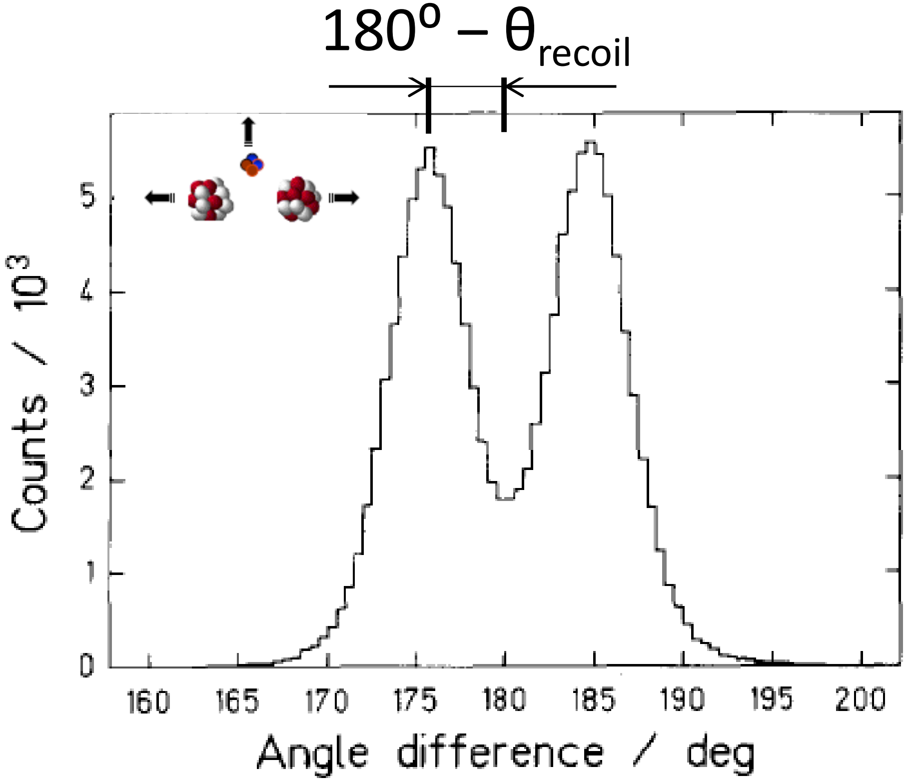


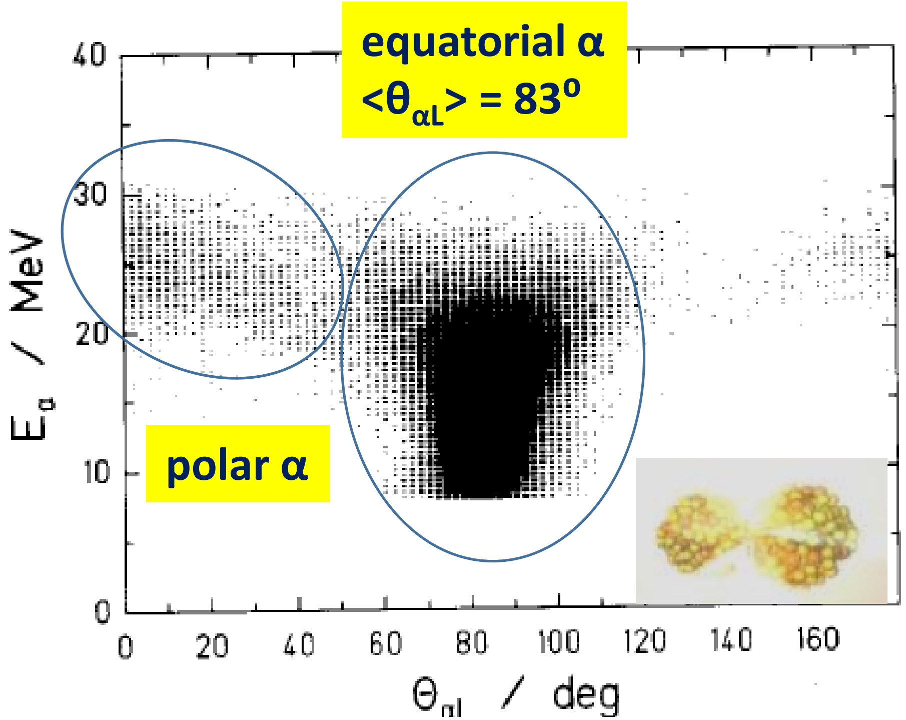


Conclusion: *The designed dE-E array is effective for the α detection*

Rare fission modes: Ternary fission

at ELI-NP detailed studies of rare fission modes will be possible



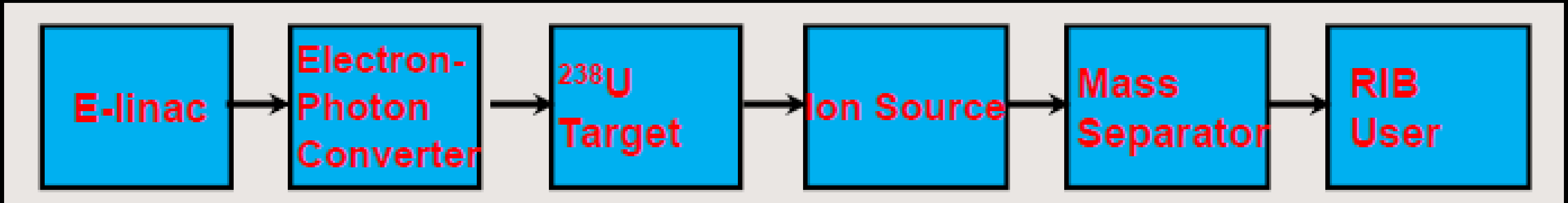


angular difference of fission fragments in ternary fission **α particle yield distribution**

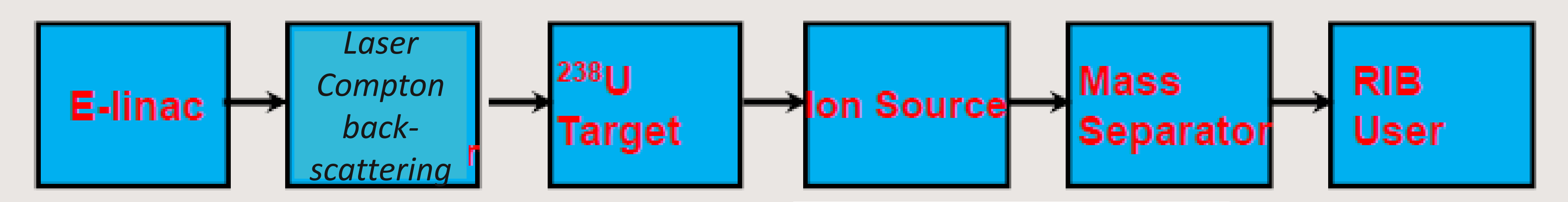
P. Heeg et al., NIM A 278, 452 (1989)

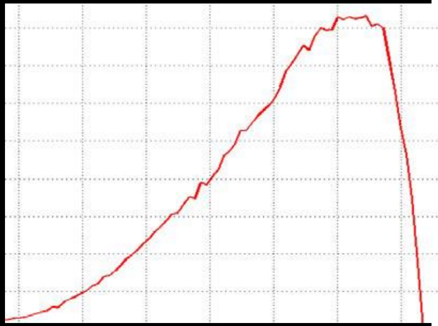
spontaneous fission of ^{252}Cf

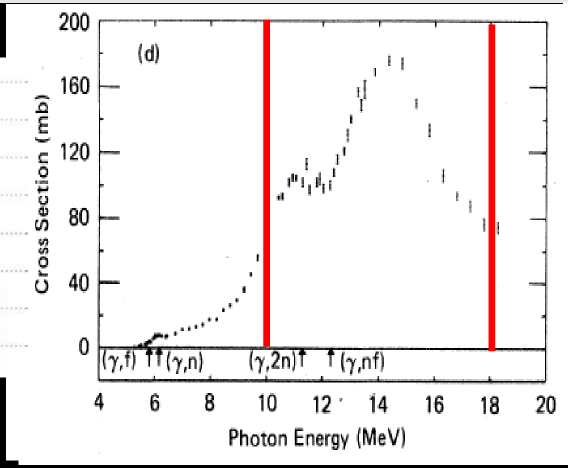
ALTO, ARIEL, etc

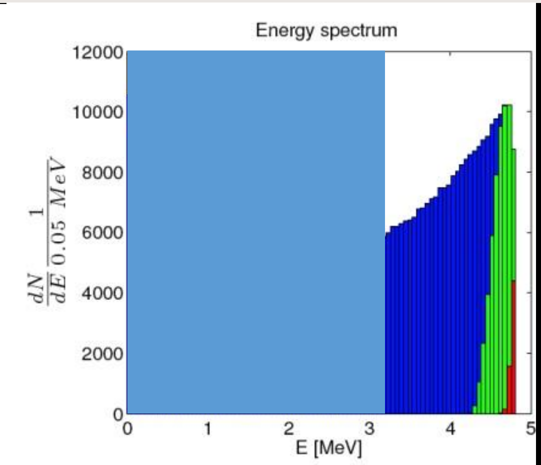


ELI-NP

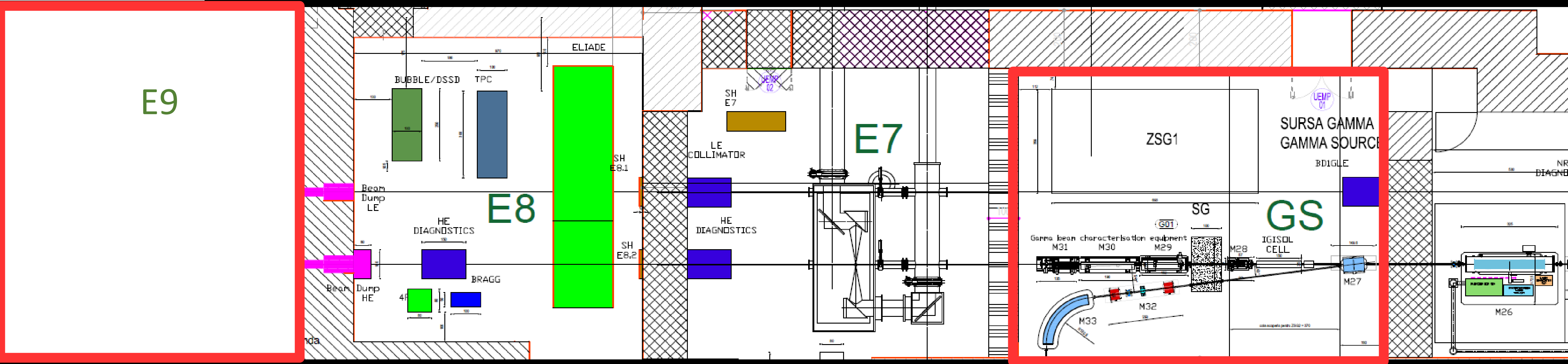






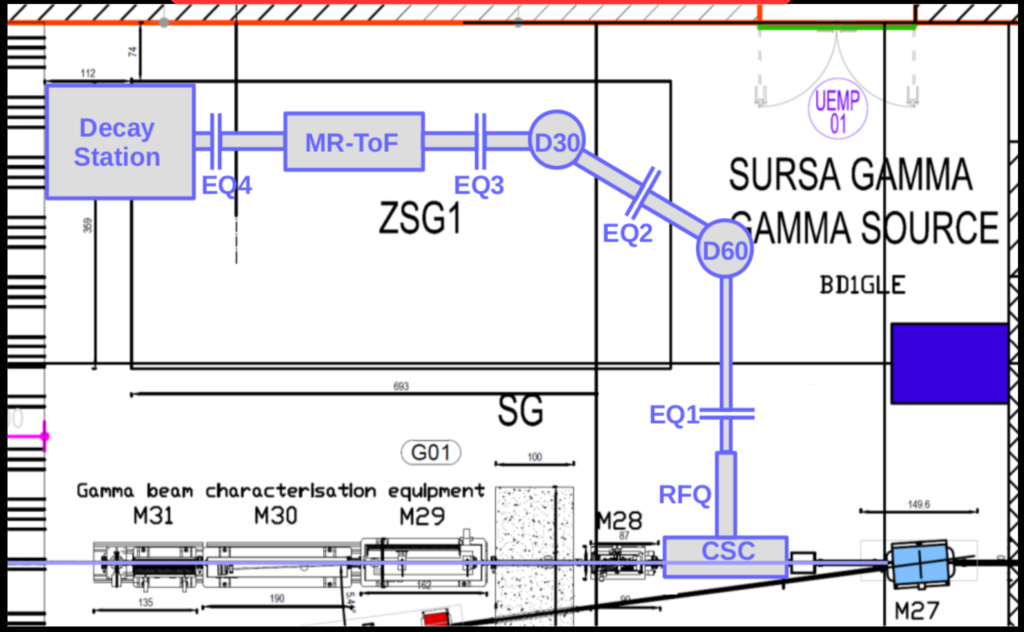


IGISOL beamline: Location

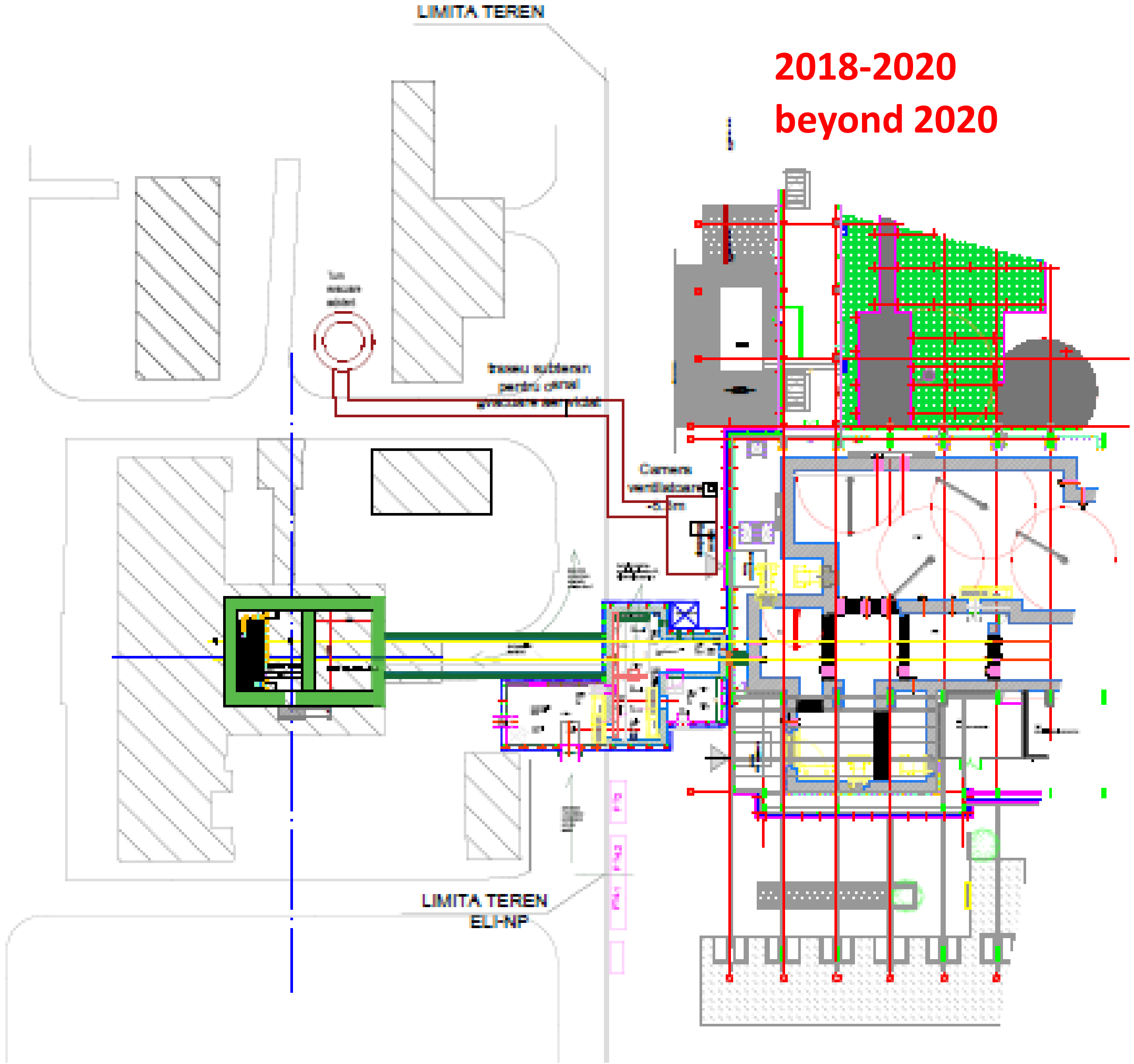


Location 1:
- CSC at 7m from IP →A ≈ 0.7cm
- maximum CSC length 1.5m
- crowded exp hall!

Location 2:
- CSC at 40m from IP → A ≈ 4cm
- plenty of space!



Next phases of ELI-NP



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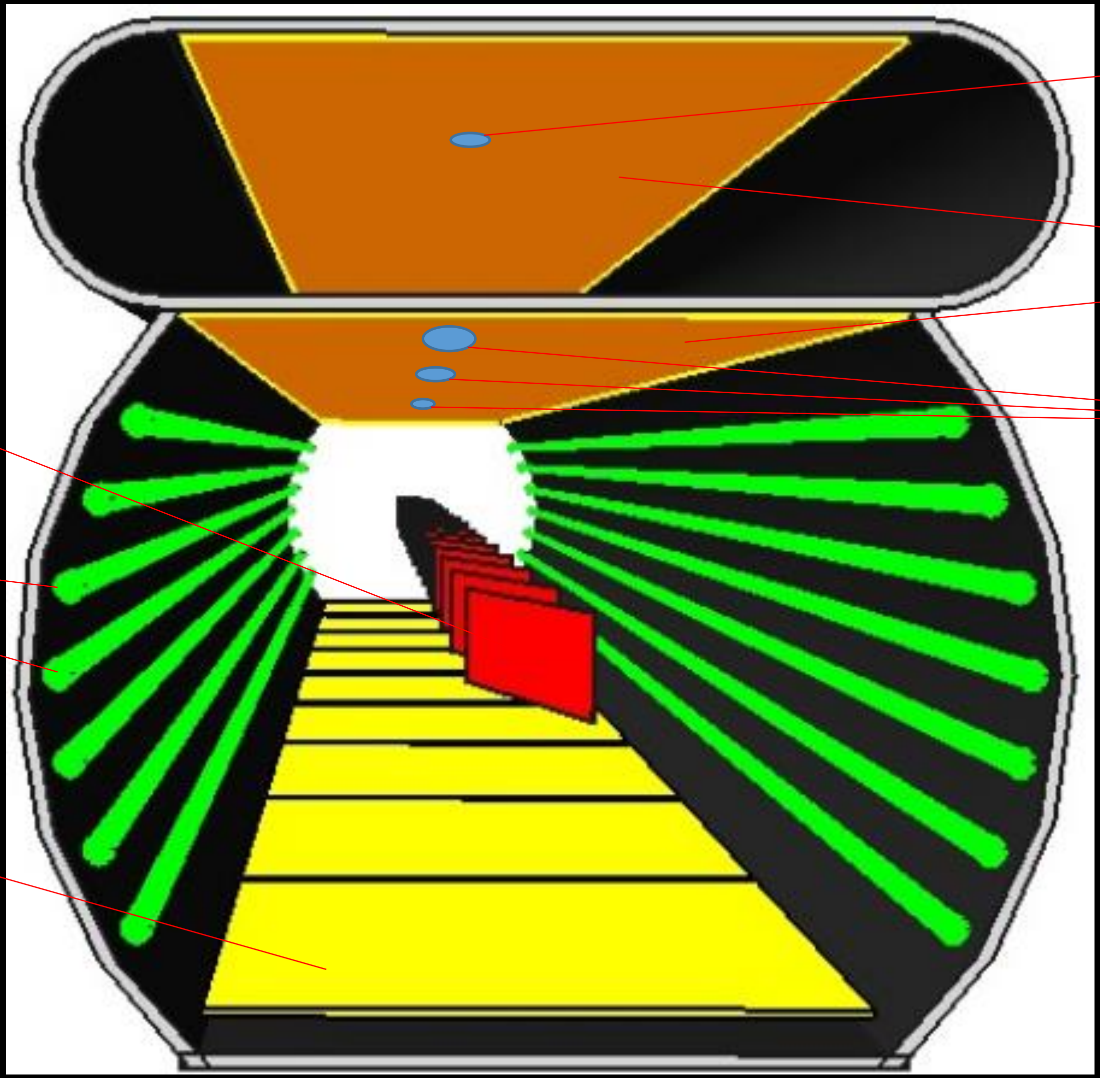
IGISOL facility at ELI-NP

double-chamber CSC



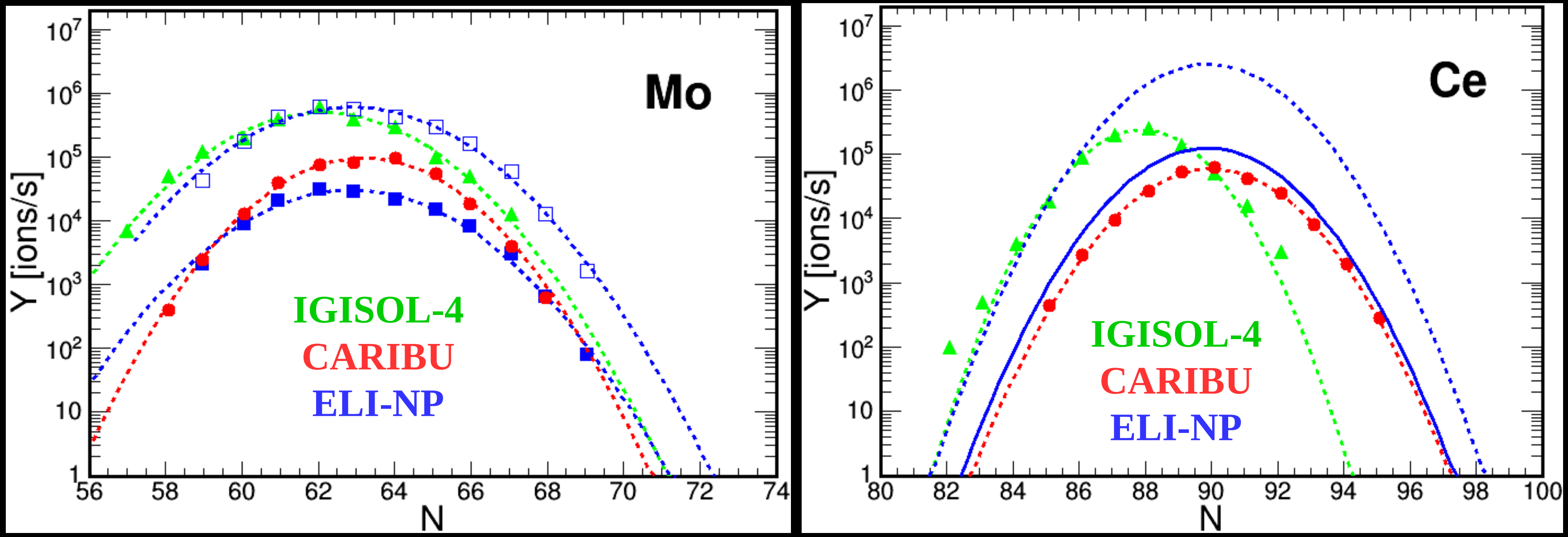
Work in collaboration with GSI, Darmstadt and University of Giessen

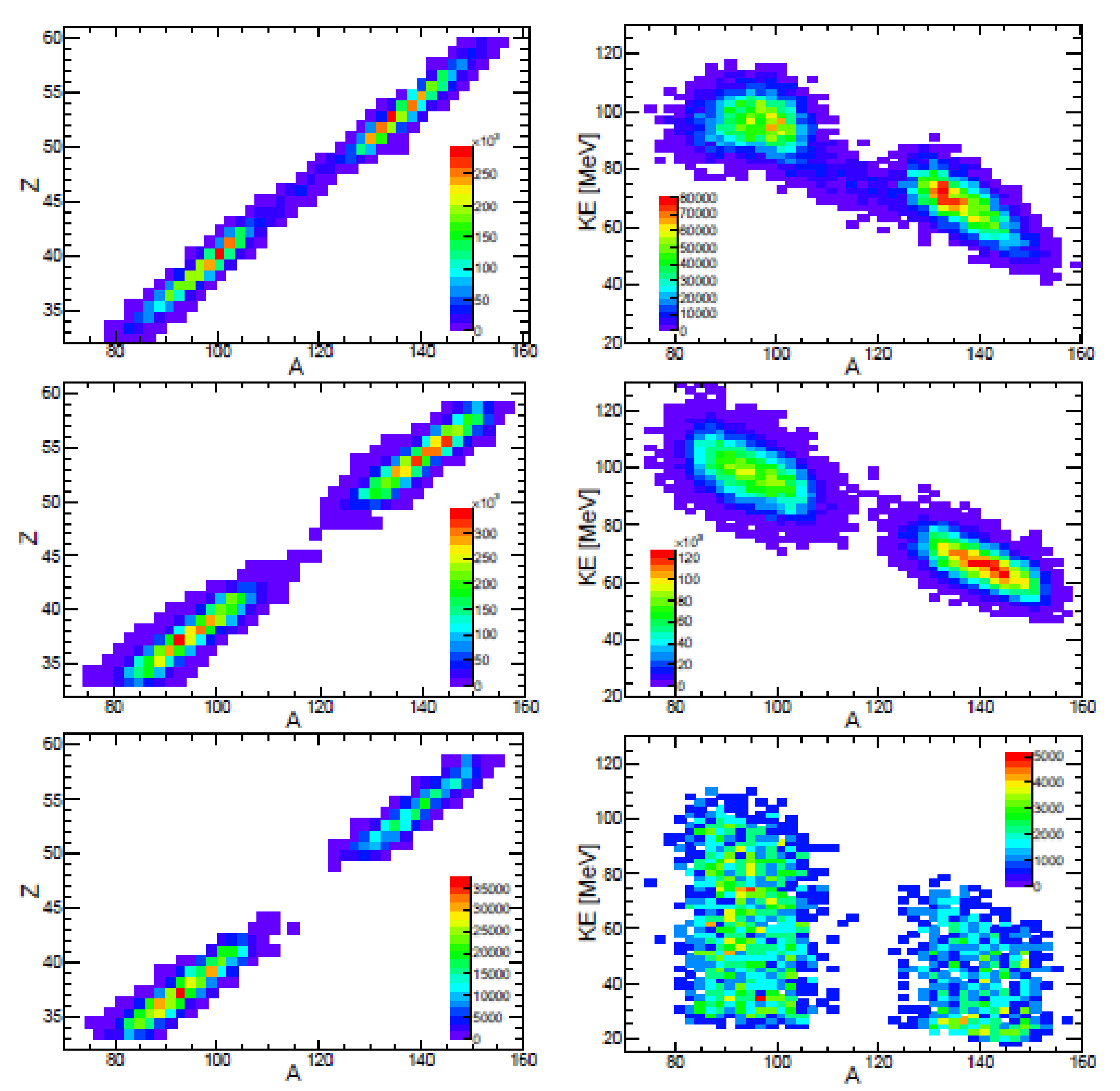
Expected Rates

Rom. Rep. Phys. 68, S699 (2016)

Conservative "day-one": beam $5 \cdot 10^{10}$ γ/s, target release eff. 25% , CSC extraction eff. 50%
→ ~10^7 photofissions/s and ~ $(0.8\text{-}2) \cdot 10^6$ extracted ions/s

Optimal estimate: beam 10^{12} γ/s, twice CSC extraction eff.
→ expect ~2 orders of magnitude more!

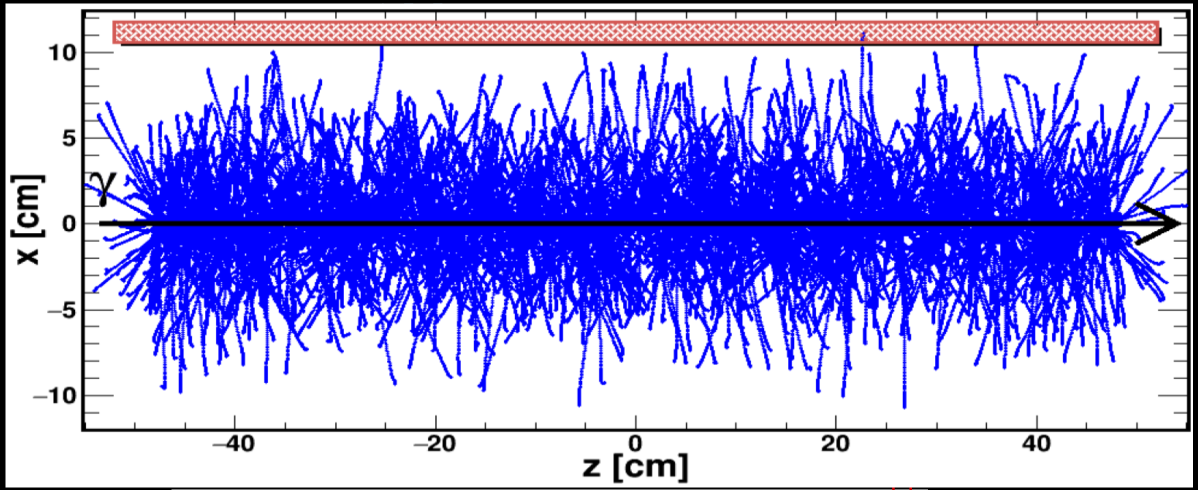


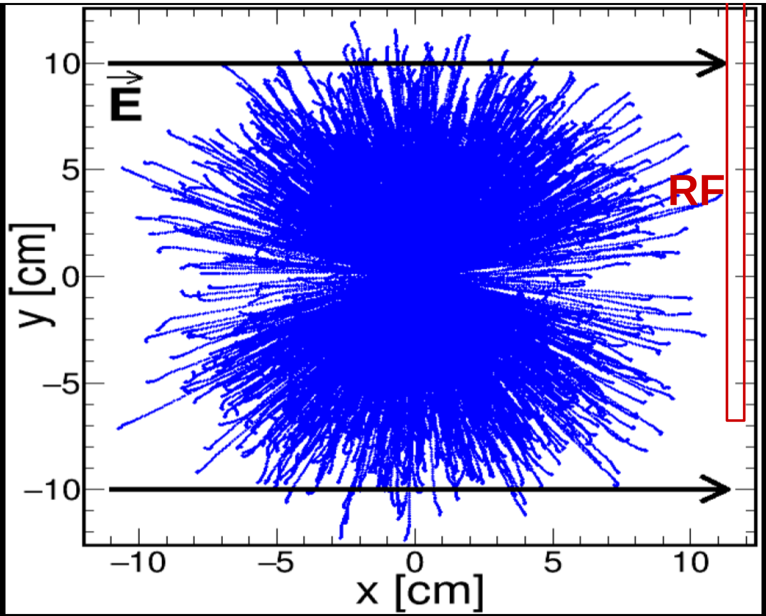


P. Constantin et al, NIM B 378, 78 (2016), ibid (2016) submitted

CSC Simulations:
Fragment Slowing Down in the Gas Cell

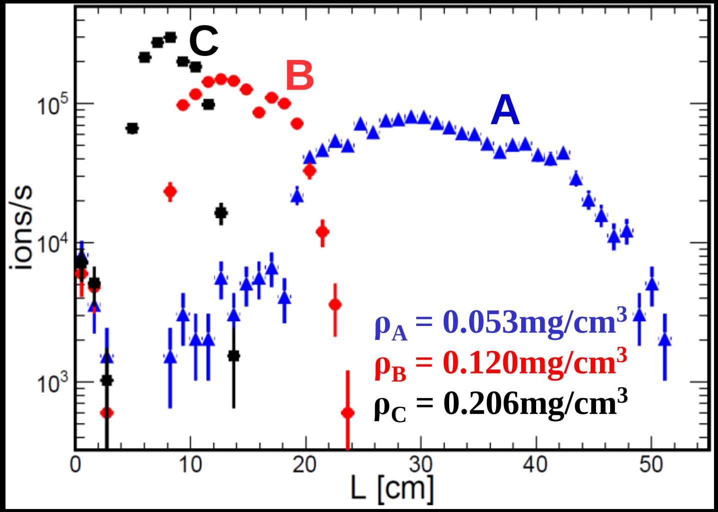
Geant4: He, T=70K, p=300mbar (ρ=0.206mg/cm^3) → >95% of fragments stop in





	A	B	C
ρ [mg/cm^3]	0.053	0.120	0.206
p [mbar]	100	200	300
T [K]	90	80	70
L_{max} [cm]	43.7	19.4	11.3

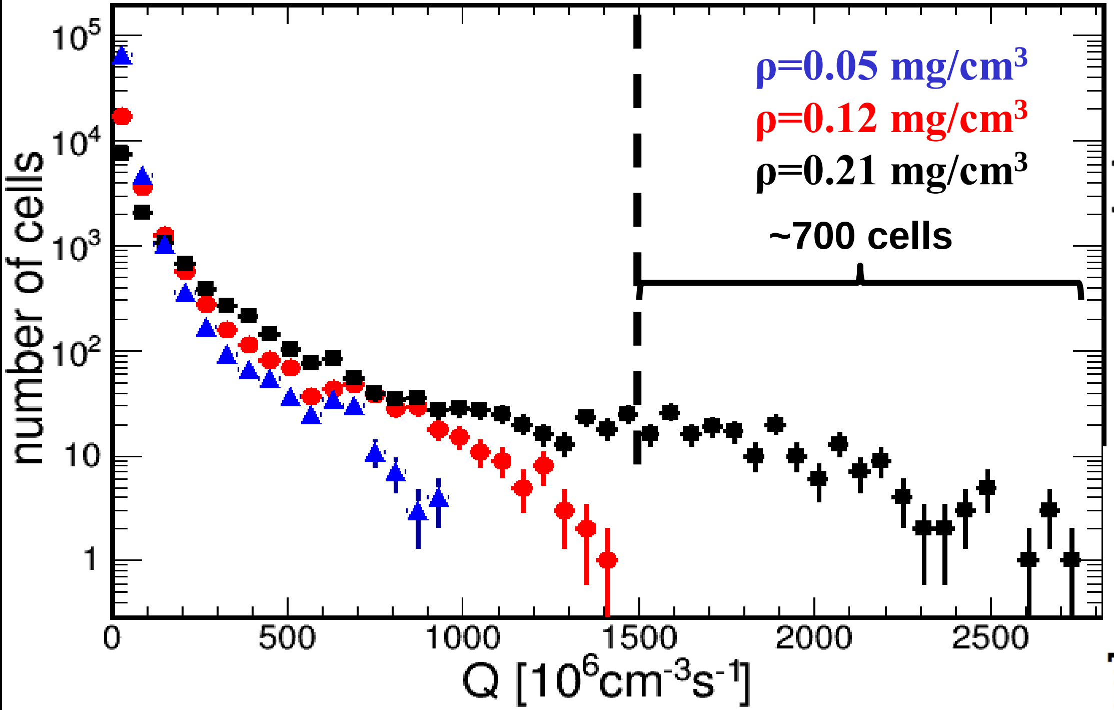
CSC width [cm]: 90 40 24

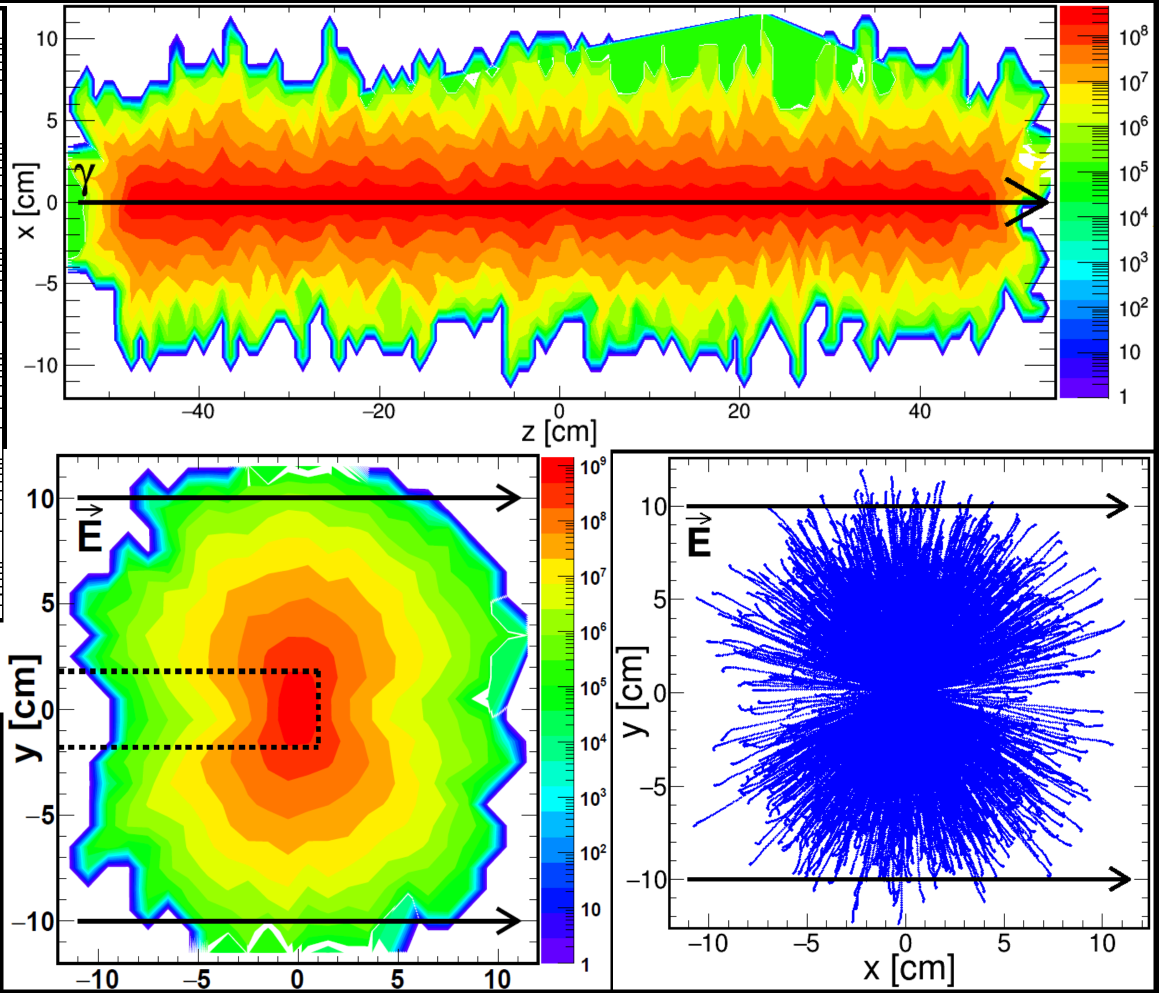


$$\rho \cdot L_{max} = 2.33\ mg/cm^2$$

CSC Simulations: Space Charge (I)

Divide CSC in 1x1x1 cm^3 cells: 24x24x100 for ρ=0.21 mg/cm^3, 40x40x100 for ρ=0.12 mg/cm^3, 90x90x100 for ρ=0.05 mg/cm^3;
Cummulate dE/dx deposited in 1s of beam and divide by W_i=41 eV.





~2% stop in saturated region
~10% stop in "dead region"
~5% ions not stopped
extraction efficiency < 85%

CSC Simulations: Space Charge (II)

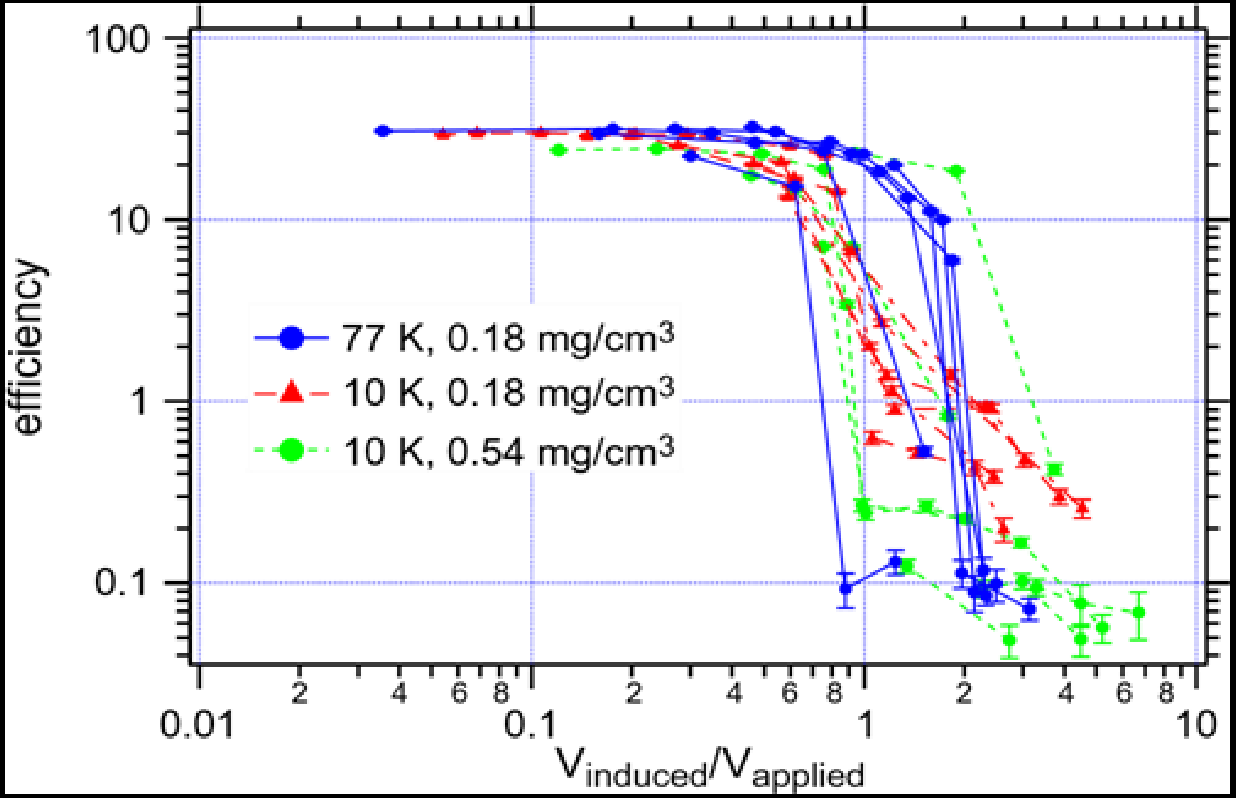
Q is not the best parameter.

$$V_{ind} = d^2\sqrt{\frac{eQ}{4\varepsilon\mu}}$$

d = distance between parallel electrodes
ε = electrical permitivity
μ(T,p) = ion mobility
Universal threshold at $V_{ind}/V \approx 1$-2.
Field saturation sets in for $V_{ind}/V > 1$.

Supported by theoretical calculations:
S. Palestini et al., NIM A 421 (1999) 75

S. Purushothaman et al., NIM B 266 (2008) 4488



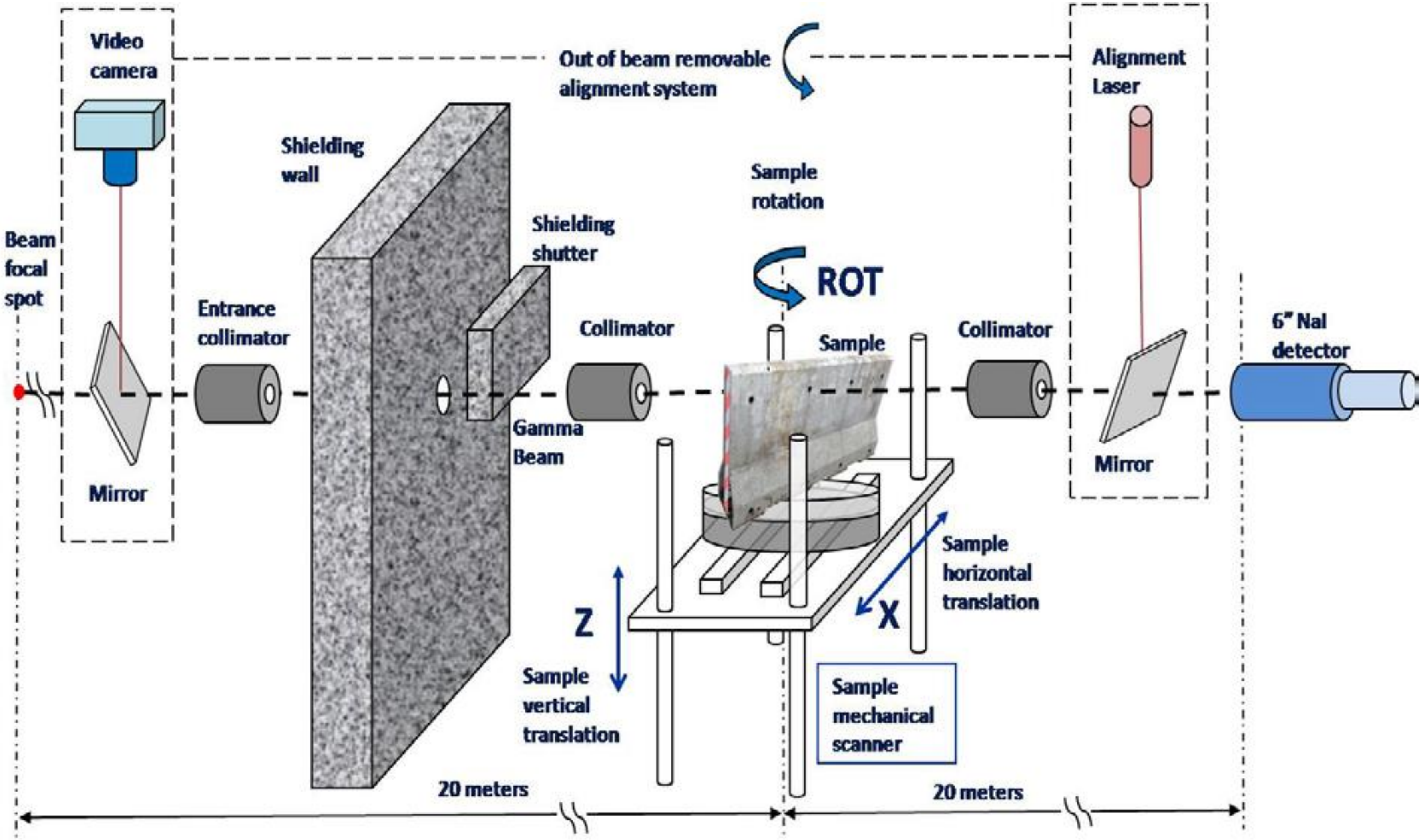
However, for our CSC: **Q(r,φ,z) inhomogeneous!** → moving to **SIMION!**

NRF applications at ELI-NP

Industrial Radiography and Tomography

Two tomography tables with biaxial movement and rotation
Various collimators with collimation holes between 0.2 mm and 5 mm.

High volume detector for pencil-beam
2D detector for cone-beam: CCD based gamma-ray camera or 2D flat panel



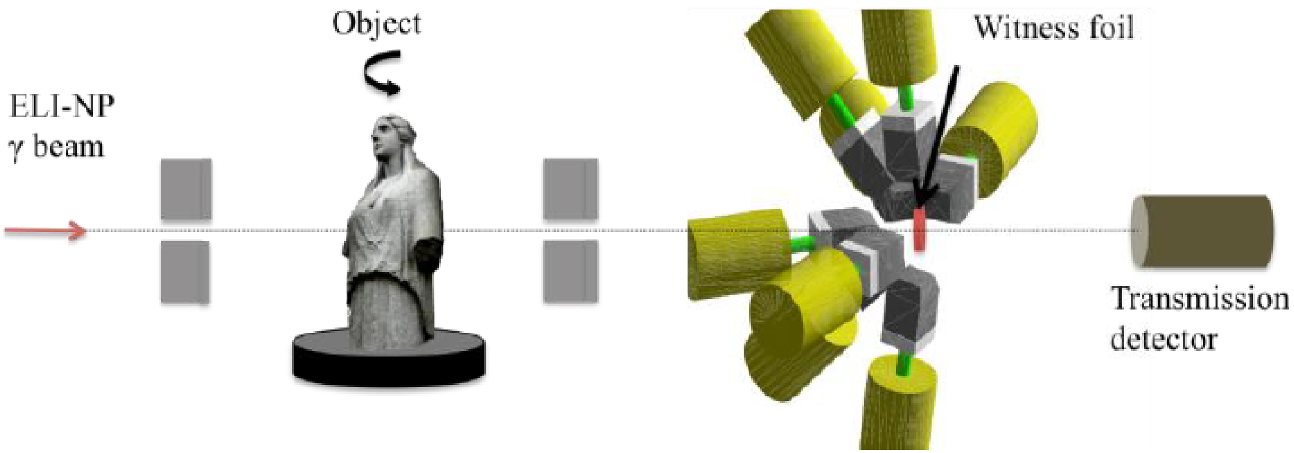
Nuclear Physics

EPS Topical Paper on Cultural Heritage

NUCLEAR PHYSICS FOR CULTURAL HERITAGE

Nuclear Physics Division

- The European initiative for Extreme Light Infrastructure laboratories in Romania (ELI-NP), will shortly provide tunable energy γ-rays from inverse Compton scattering of laser light on a high-energy electron beam. This will allow Nuclear Resonance Fluorescence studies of isotope-specific trace element distributions to be performed with unprecedented sensitivity. It is planned to use this powerful tool for cultural heritage object studies.

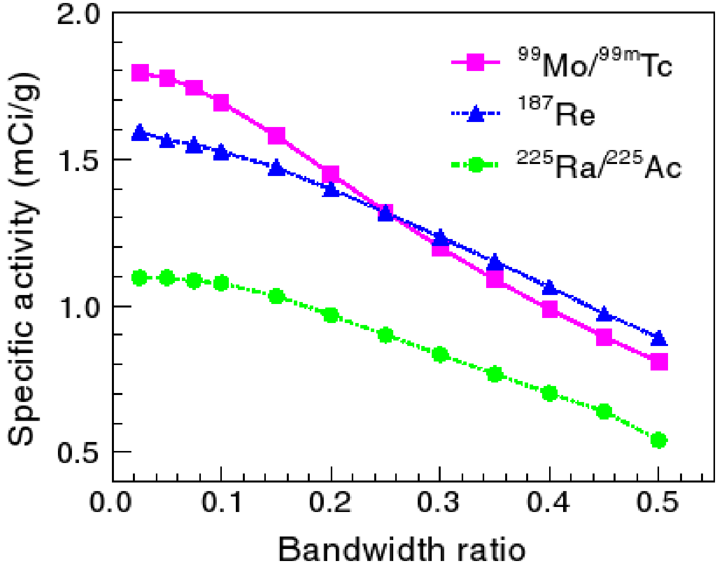


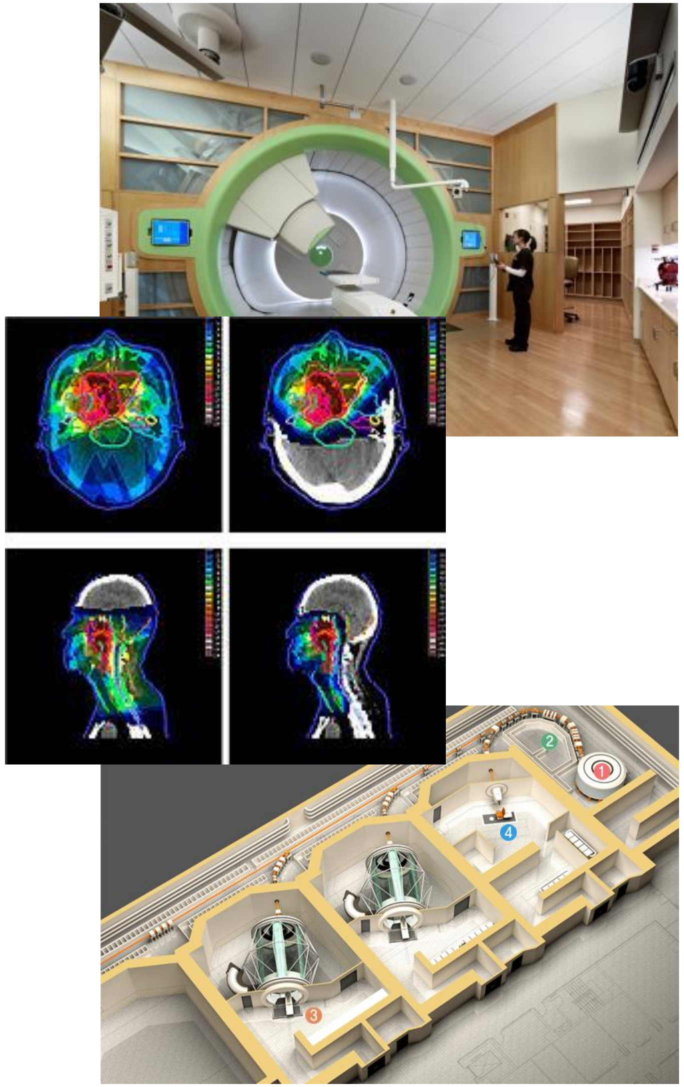
Rom. Rep. Phys. 68, S849 (2016)

Medical radioisotopes at ELI-NP

test case

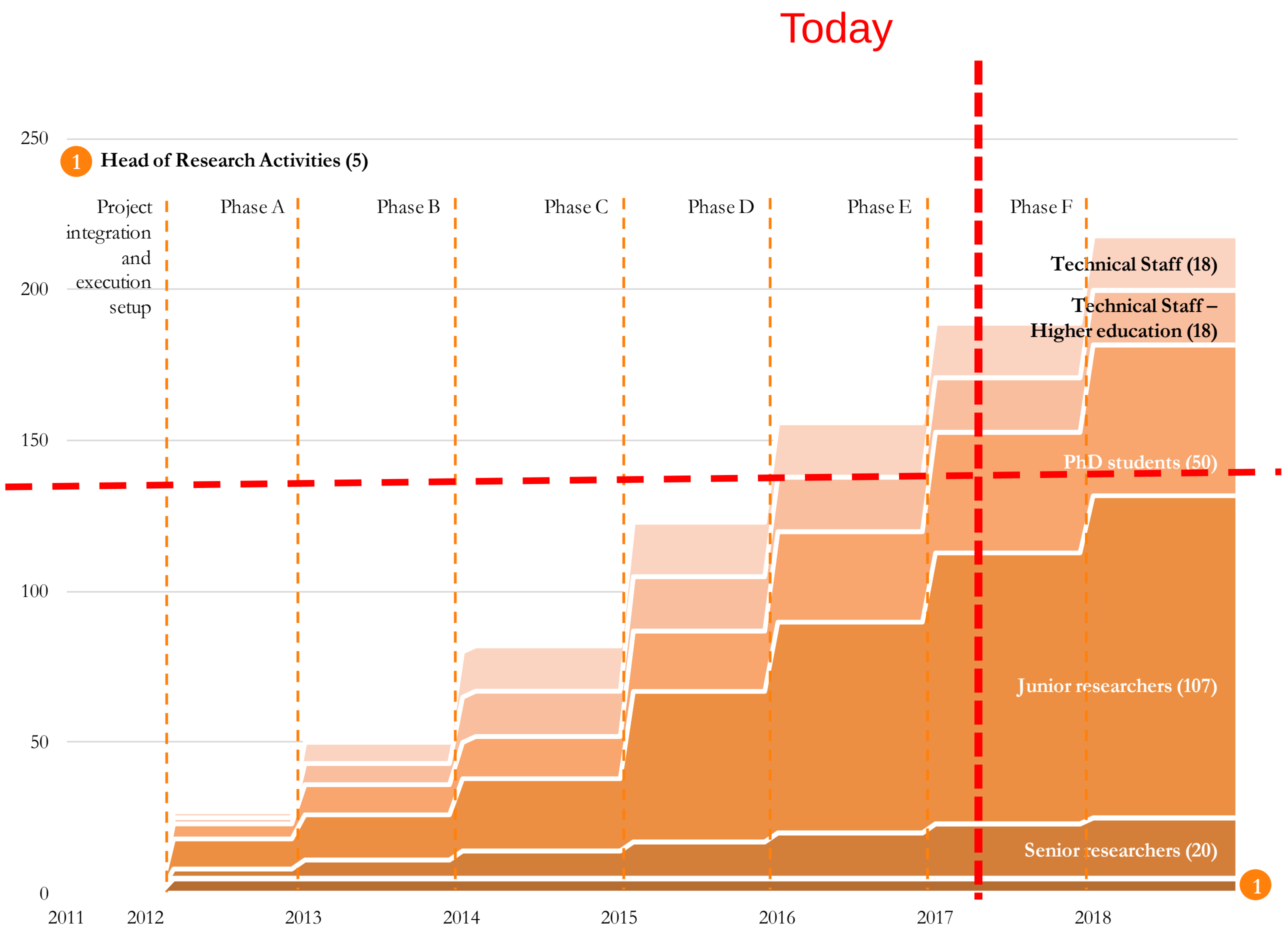
• ^{195m}**Pt**: In chemotherapy of tumors it can be used to exclude ”non responding” patients from unnecessary chemotherapy and optimizing the dose of all chemotherapy





feasibility study: **Wen Luo et al., Appl. Phys. B 122, 8 (2016)**

Human Resources



http://www.eli-np.ro/jobs.php

EUROPEAN UNION

GOVERNMENT OF ROMANIA

Structural Instruments 2007-2013

Sectoral Operational Programme “Increase of Economic Competitiveness”

“Investments for Your Future!”

IFIN-HH

Extreme Light Infrastructure - Nuclear Physics (ELI-NP) - Phase II

eli Nuclear Physics

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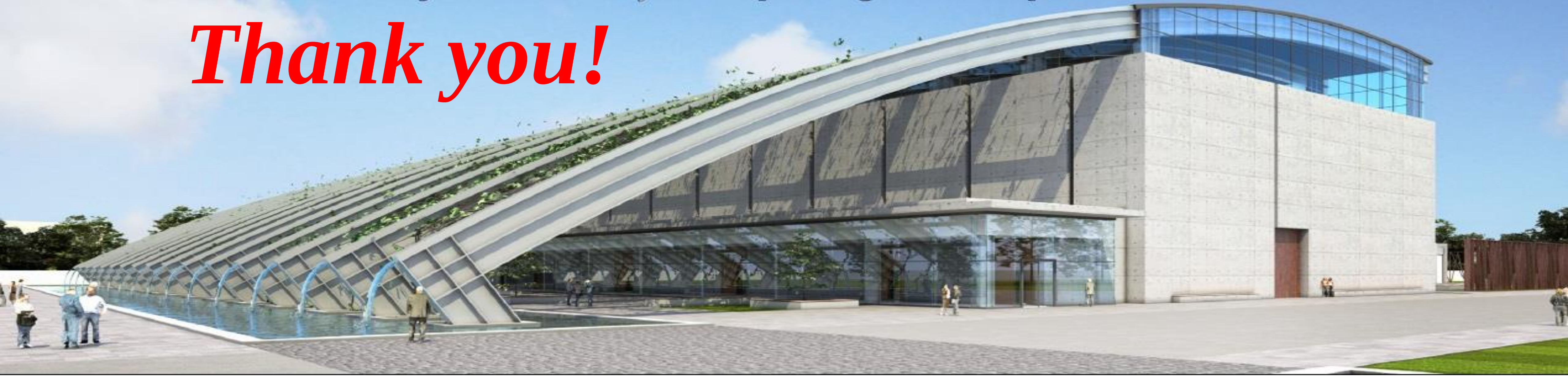
Project co-financed by the European Regional Development Fund



Thank you!