EUROPEAN UNION

Structural Instruments 2014-2020

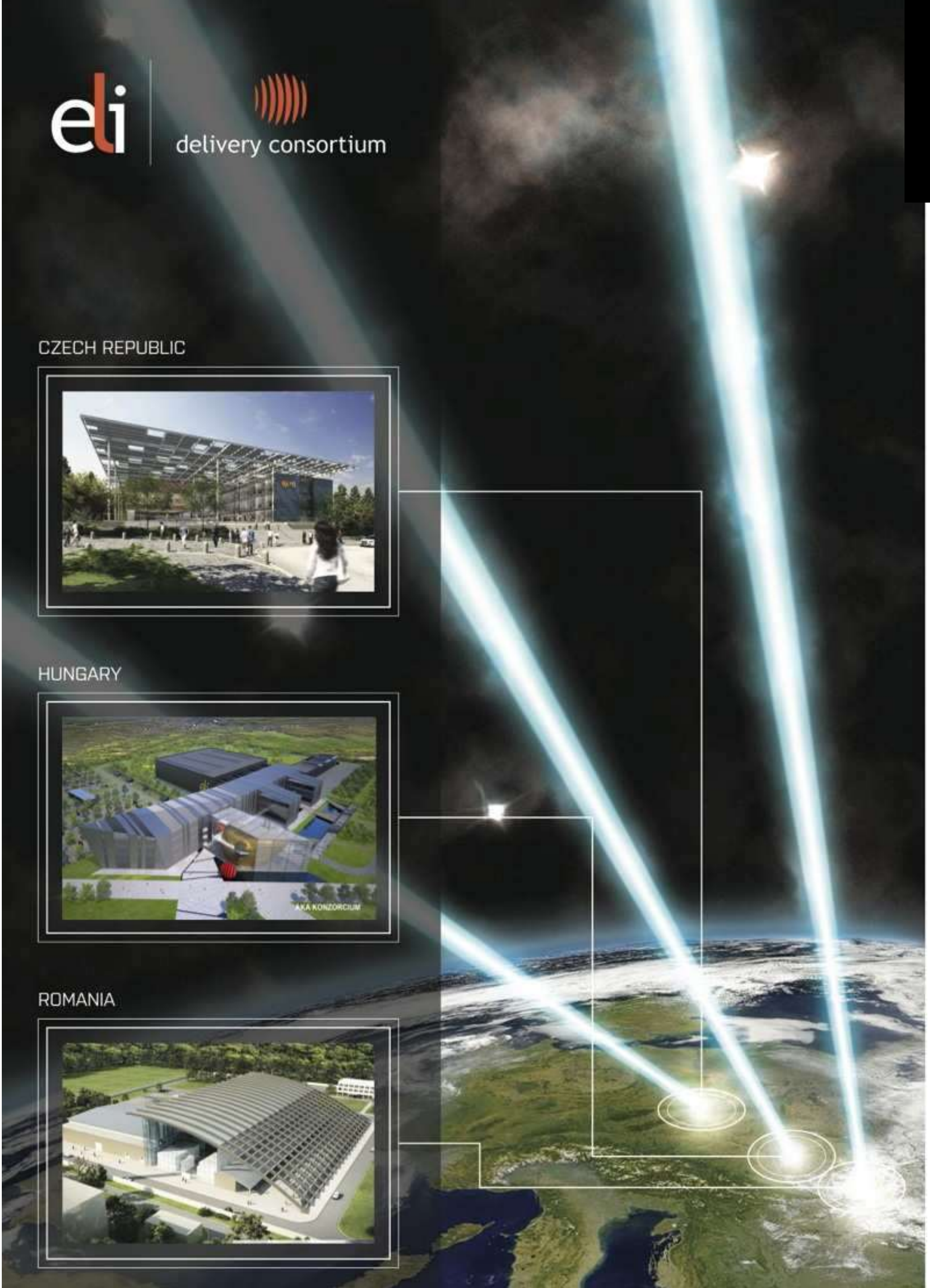
Extreme Light Infrastructure-Nuclear Physics (ELI-NP) - Phase II

Progress of ELI-NP and photofission

Dimiter L. Balabanski

NUSTAR meeting, GSI Darmstadt
February 26th- March 2nd, 2018

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



Extreme Light Infrastructure

the world’s first international laser research infrastructure

“The CERN of Laser Research”

a distributed research infrastructure based initially on 3 facilities in CZ, HU and RO

Total budget: 1 B€, e.g. 350 M€ for ELI-RO

ELI–ALPS, Szeged, HU

Attosecond Laser Science

new regimes of time resolution

ELI–Beamlines, Prague, CZ

High–Energy Beam Facility

development and application of ultra–short pulses of high–energy particles and radiation

ELI–NP, Magurele, RO

Nuclear Physics Facility with ultra–intense laser and brilliant gamma beams (up to 19 MeV)

novel photonuclear studies

ELI 4 , to be decided

Ultra–High–Field Science

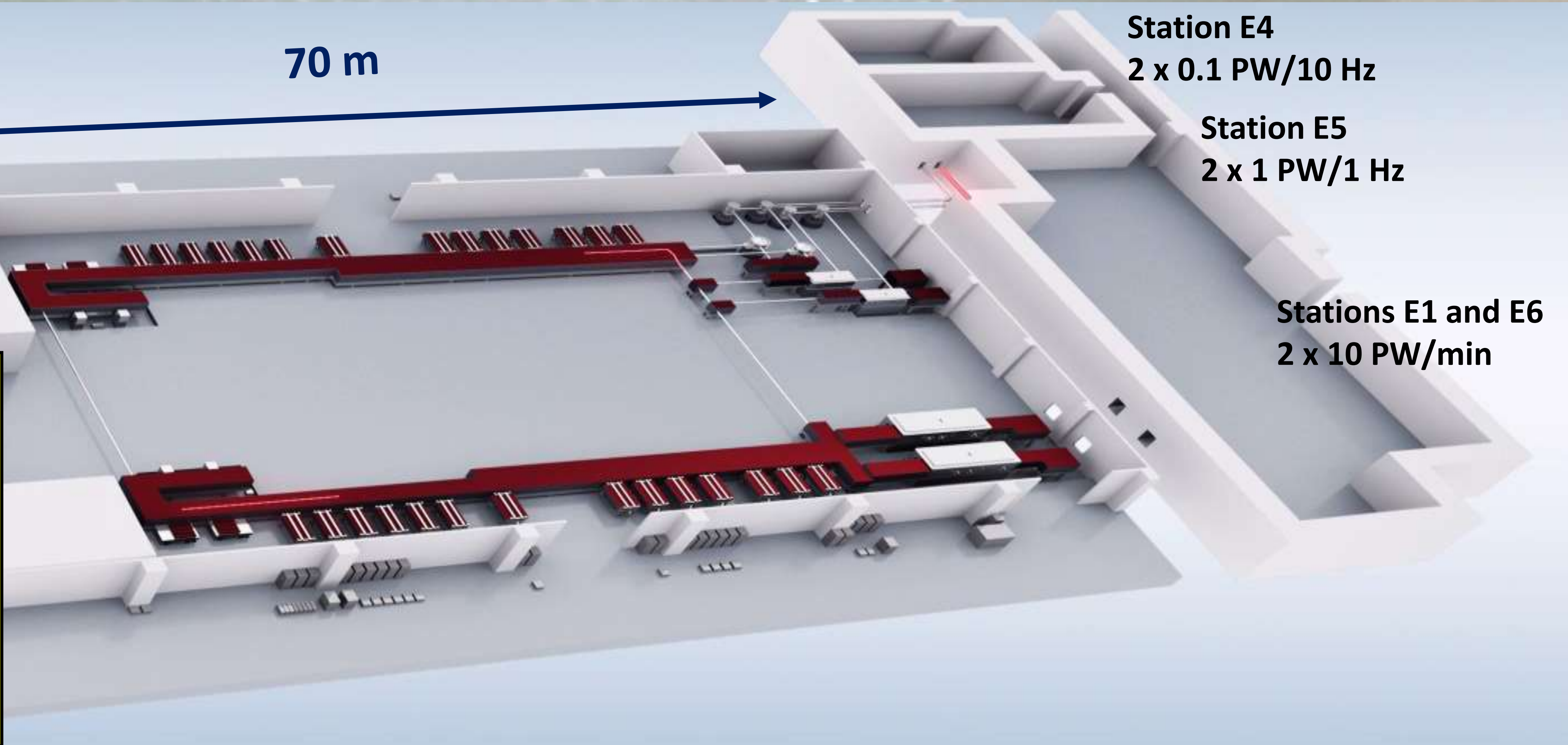
direct physics of the unprecedeted laser field strength

June 7th, 2013

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

- ***2 x 10 PW synchronizable lasers***
- ***0.2 – 20 MeV 0.5% bw 95% polarized γ beam***

1.5m thick, 150,000 ton “optical table”



250 J in 25fs

1 pulse/min

Contrast
$1:10^7$ @ 5ps
$1:10^9$ @ 10ps
$1:10^{14}$ @ 100ps

10 PW lasers will enable unique experiments from Day-1

Strong-field QED | ***Nuclear Physics with Lasers***

Extreme light intensity (10^{23} W/cm^2)

- Extreme electric fields (10^{15} V/m)
  - 10 PW laser + solid target
    - Ultra-intense PW γ-source
    - *"Day-0"*
  - 10 PW laser + 10 GeV LWFA electron beam
    - Radiation reaction, Breit-Wheeler pairs
- Extreme light pressures (Tbar)
  - Radiation Pressure Acceleration of dense 10 MeV/A ion beams
    - Neutron-rich nuclei
    - Ultra-intense neutron source
    - Nuclear reactions in plasmas

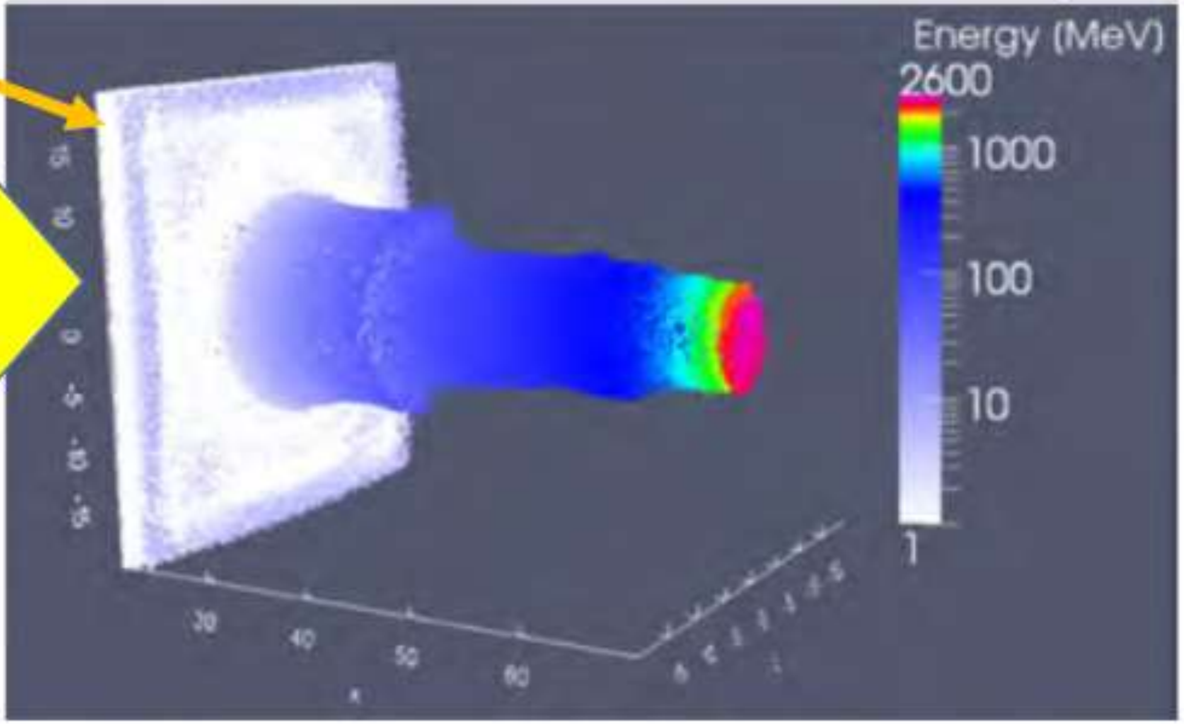
❑ Day-1 experiments reviewed by ELI-NP International Scientific Advisory Board

Extreme light pressure will be used at ELI-NP to accelerate solid density ion bunches to GeV energies

Radiation Pressure Acceleration (RPA)

10s of nm thick foil

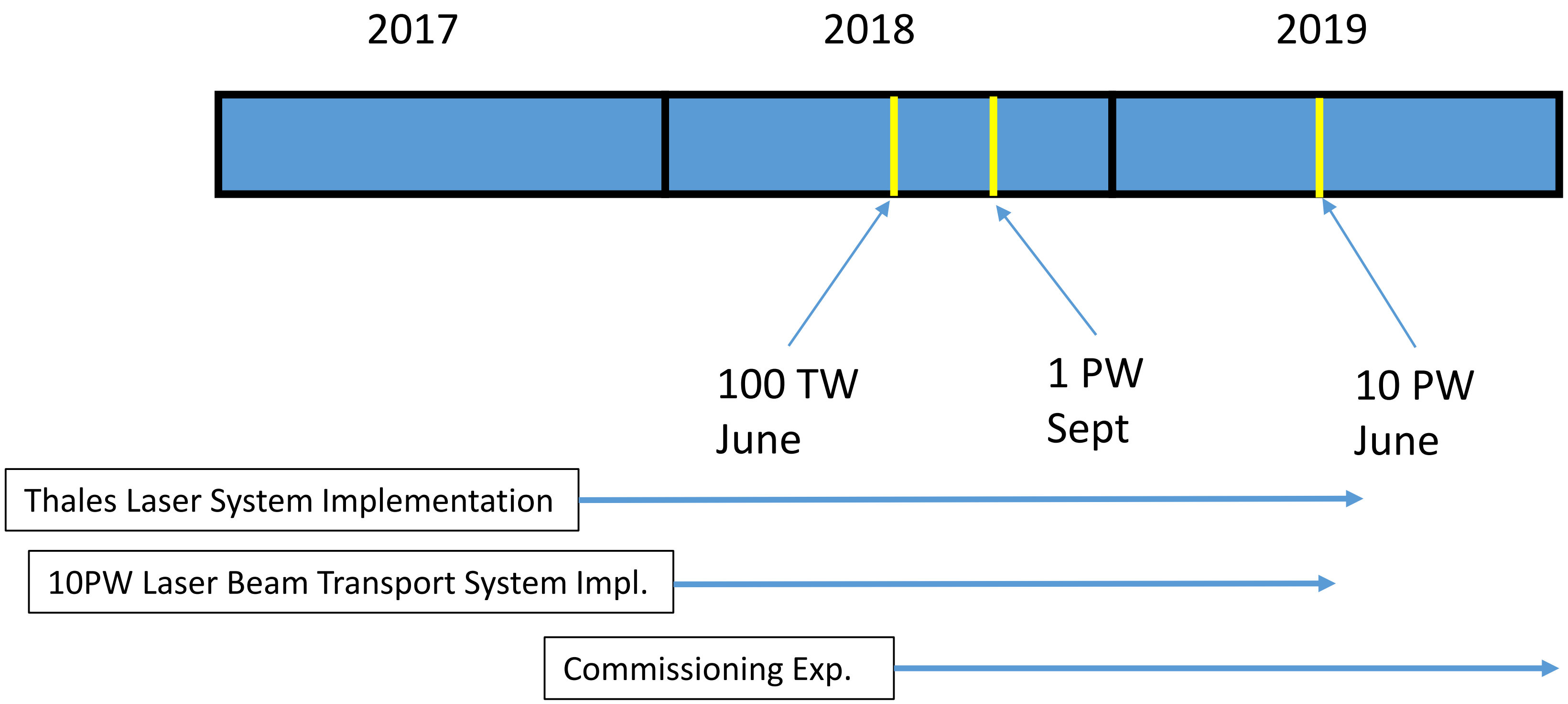
10 PW laser



Macchi et al 2013

- Light pressure >10^{13} atm for 5×10^{22} W/cm^2 intensity
- Pressure accelerates ultrathin solid foil as a whole ("light-sail")
- Good fraction of laser energy can be converted to GeV ions

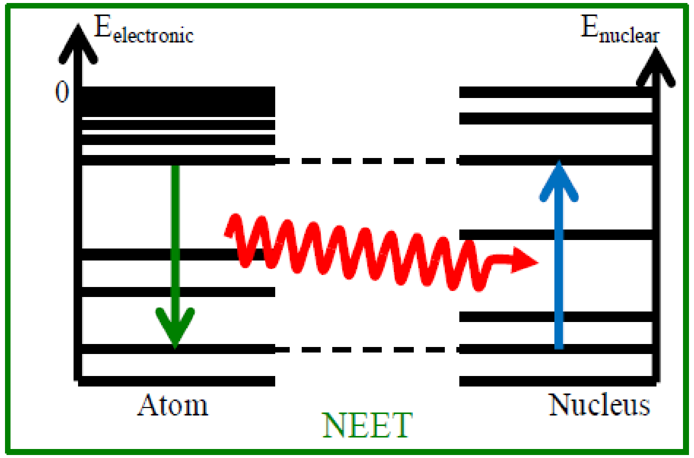
Laser System Implementation Schedule

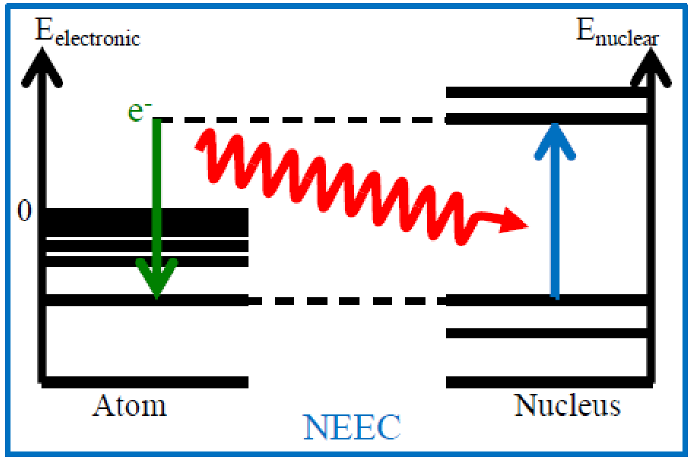


Nuclear processes in plasmas

Nuclear (de-)excitations in plasmas

observed in cold targets at 10^{-8} rates in ^{197}Au, ^{189}Os, and ^{193}Ir; never observed in plasmas

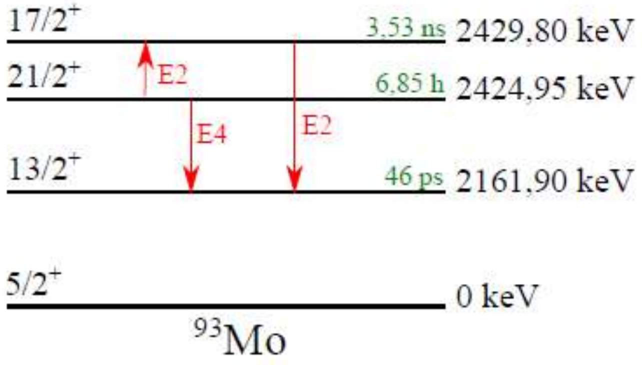


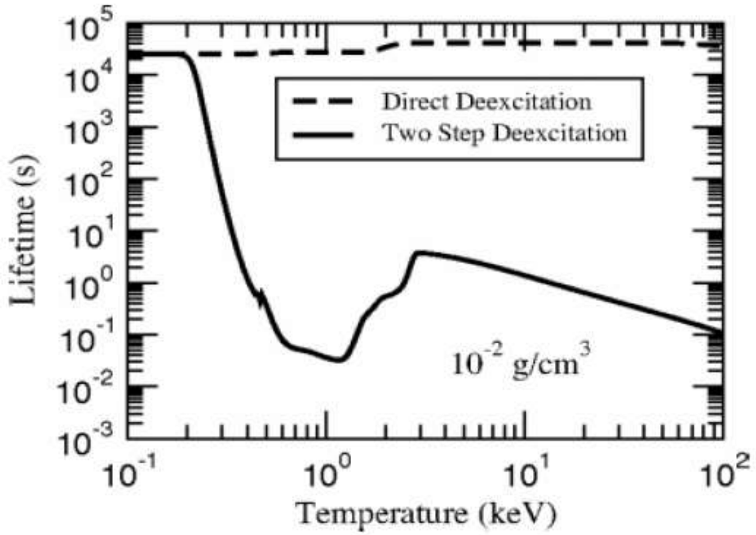


never observed

Nuclear lifetimes in plasmas

significant changes of nuclear lifetimes are predicted in hot and dense plasmas

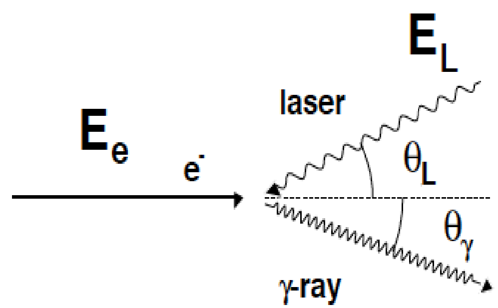




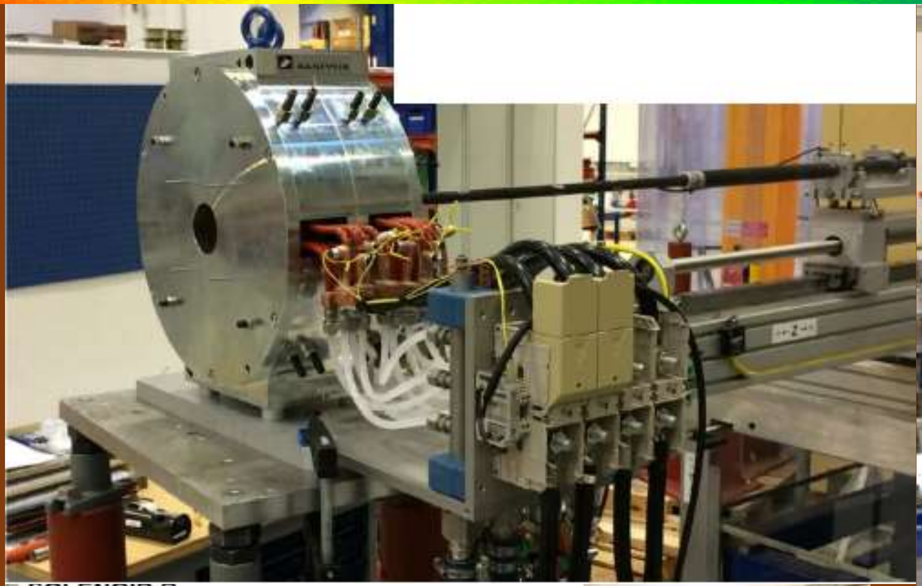
Gamma Beam System

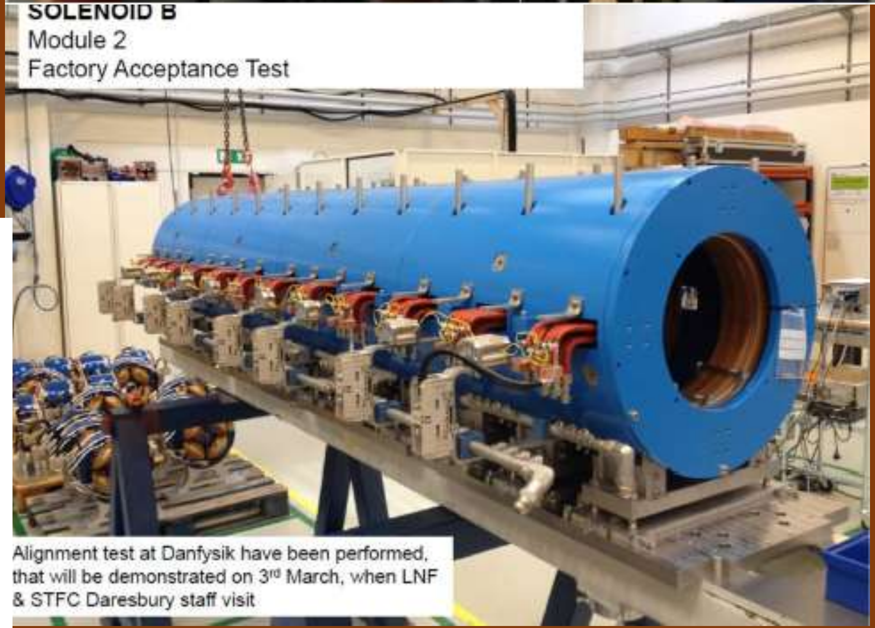
low-energy accelerator section:
0.2-3.5 MeV
factory acceptance in Dec. 2015

high-energy accelerator section:
3.0-19.5 MeV

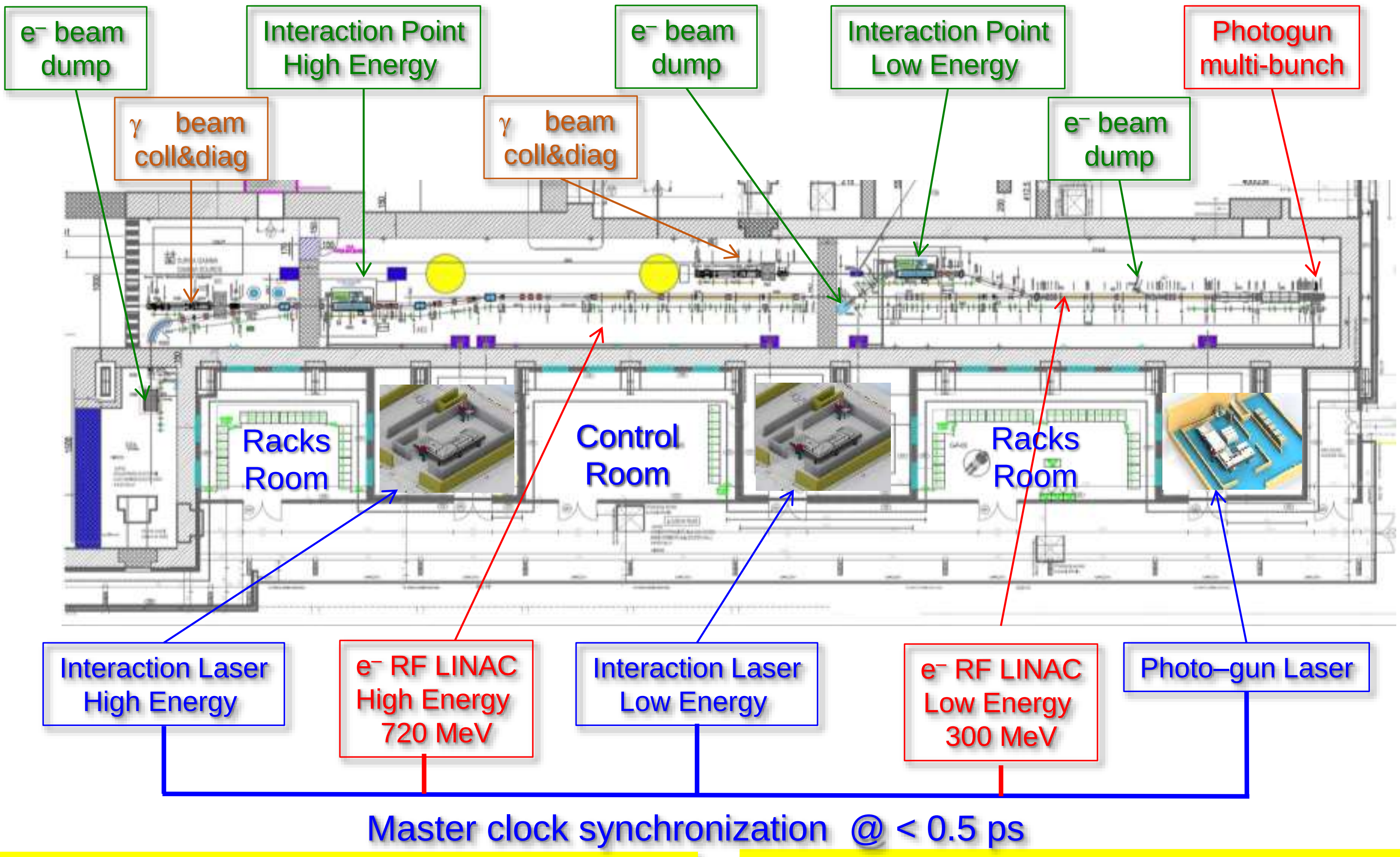


$E_\gamma \sim 4\gamma^2 \cdot E_L$





Gamma Beam System – Layout



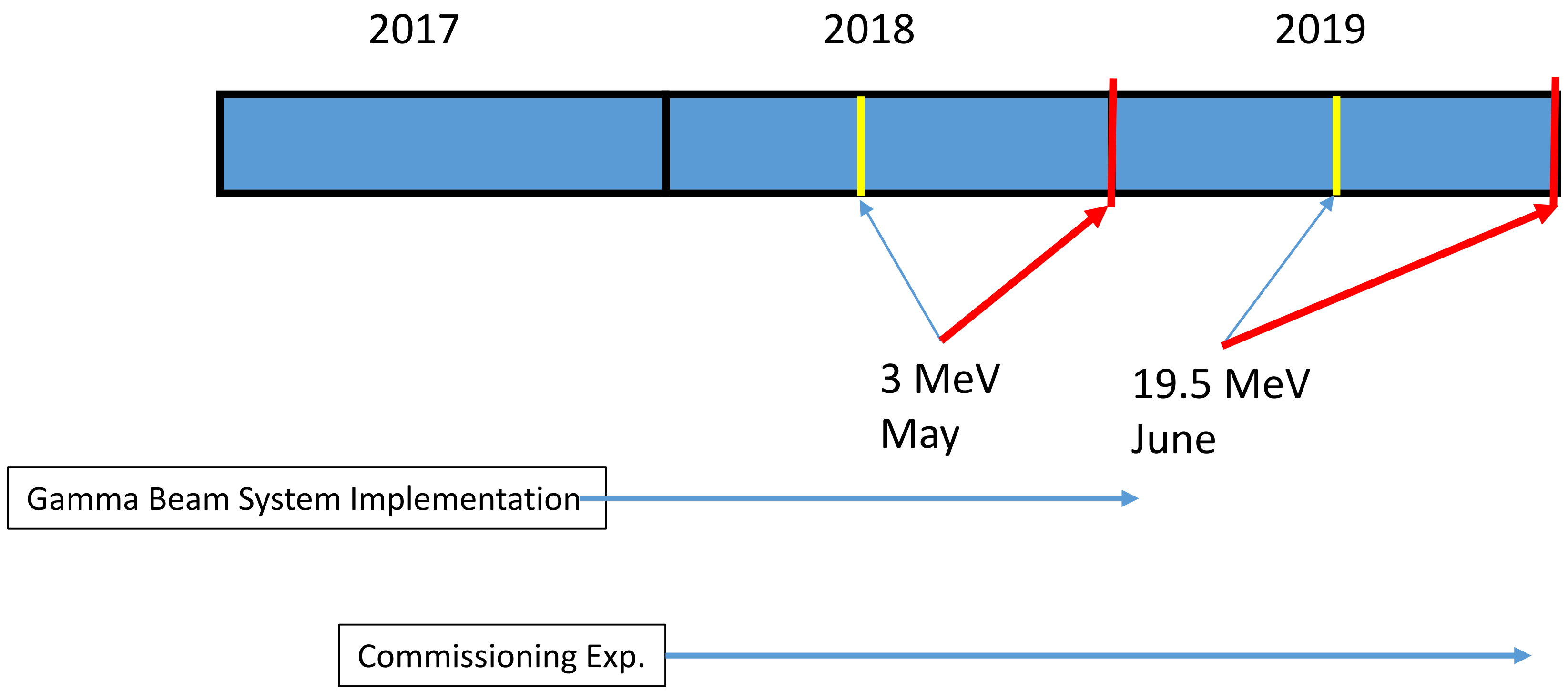
High-Energy Stage: γ rays up to 19.5 MeV

Low-Energy Stage: γ rays up to 3.5 MeV

what to remember

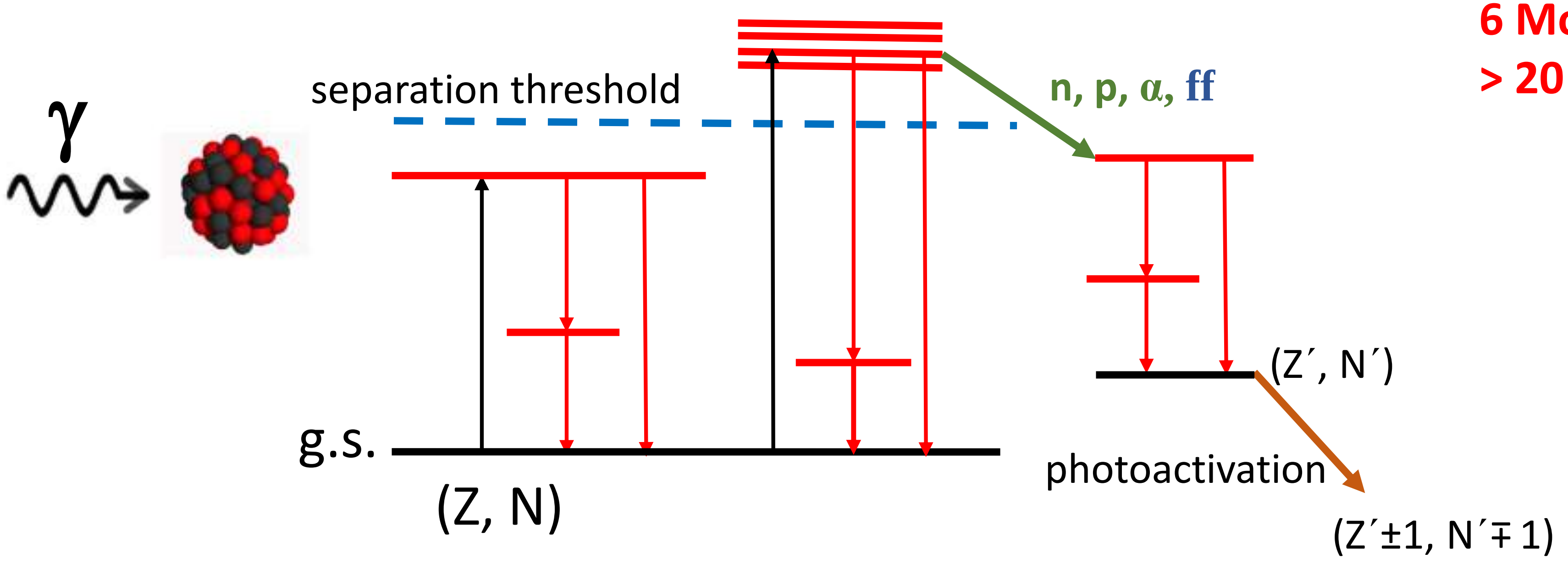
- beam size: 1 mm at 10 m away from collimator
- energy spread: 50 keV at E_γ=10 MeV
- time structure: micropulses at 16 ns
- photons/pulse: 10^5
- photons/macro-pulse: 32 x 10^5=3 x 10^6
- photons/s: 3 x 10^8

Gamma Beam System Implementation Schedule



Experiments with high-brilliance gamma beams at ELI-NP

TDRs: > 300 scientists involved
6 MoU with German institutes
> 20 German research groups
Rom. Rep. Phys. 68 (2016)



Nuclear Resonance Fluorescence (NRF) – **A. Zilges group, N. Pietralla group, D. Savran, W. Verner**

Giant/Pigmy Resonances (GANT) – **A. Zilges group, N. Pietralla group, D. Savran, R. Schwengner**

Photodisintegration (γ,n), (γ,p), (γ,α) – **N. Pietralla group, T. Aumann**

Photofission (γ,ff) – **J. Enders, P. Thirolf, Ch. Scheidenberger**

Applications (positron beams) – **Ch. Hugenschmidt**

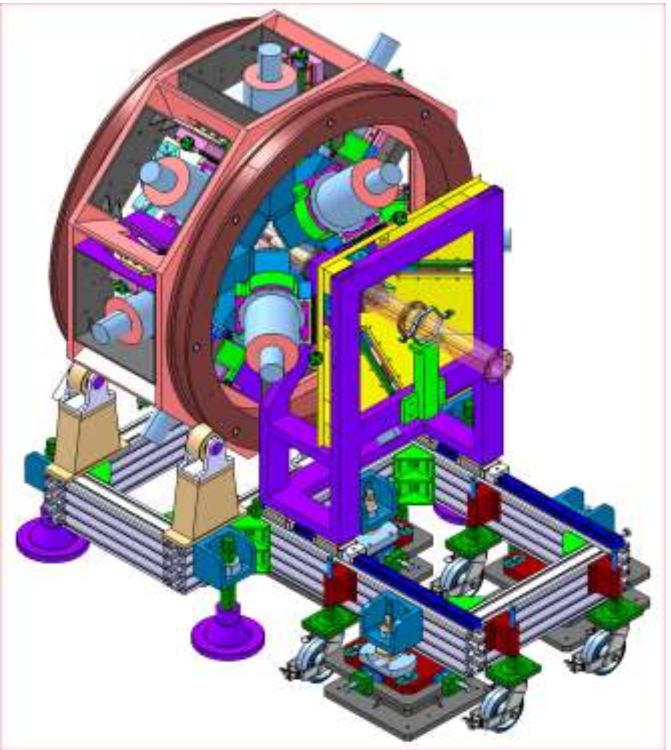
Rom. Rep. Phys. 68, S483 (2016)

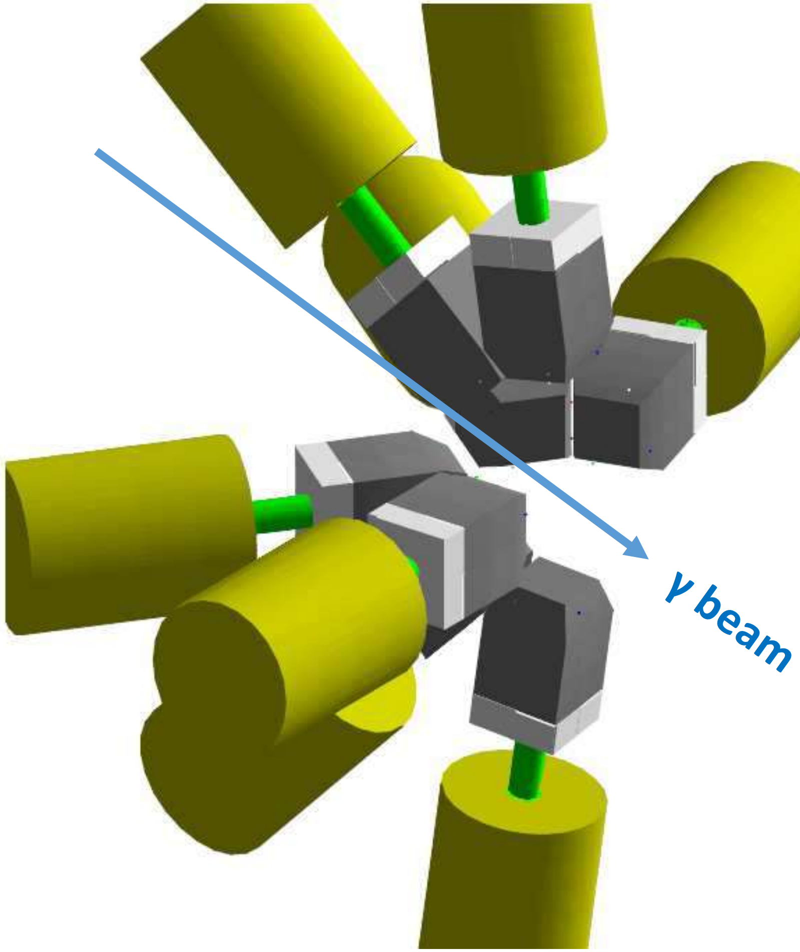
NRF experiment at ELI-NP

ELIADE array

in collaboration with U. Koeln
and TU Darmstadt

- detector tests are ongoing
- array design is at a final stage
- day-one experiments are under discussion





γγ coincidences
angular distributions
polarization measurements

First in-beam test: Dec. 12-18, 2016

ELI-NP NRF physics cases

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

Key contributions of several German research groups: N. Pietralla group, A. Zilges group, D. Savran, W. Verner…

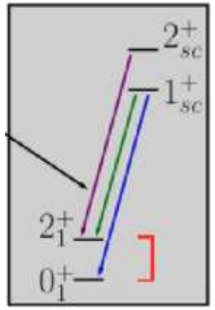
- Self-absorption measurements (Γ_0/Γ_i)
- Low-energy dipole response (e.g. Actinides)
- Dipole response and parity measurements for weakly-bound nuclei
- Investigation of the Pigmy Dipole Resonance
- Rotational 2^+ states of the scissor mode
- Constraints on the 0νββ-decay matrix elements of the scissors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

Availability frontier

p-nuclei and actinides

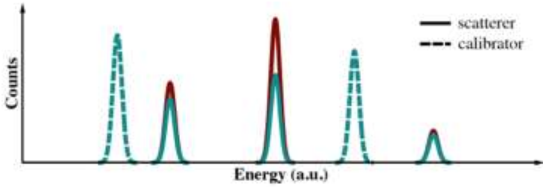
Sensitivity frontier

week channels

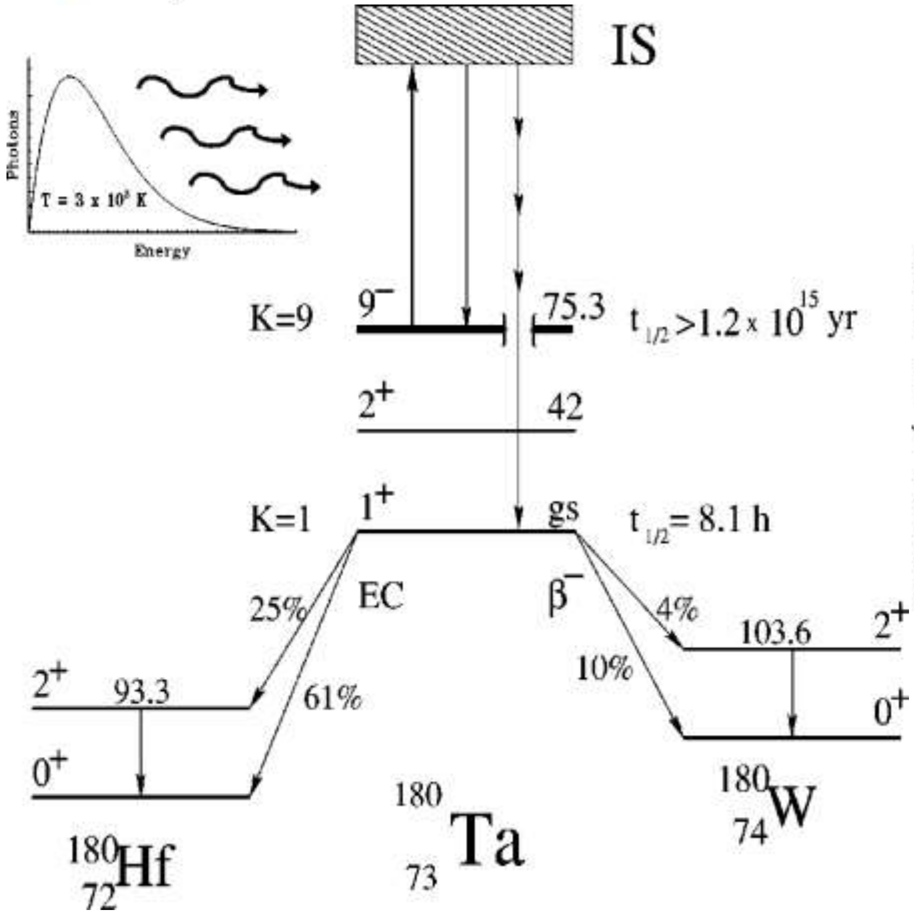


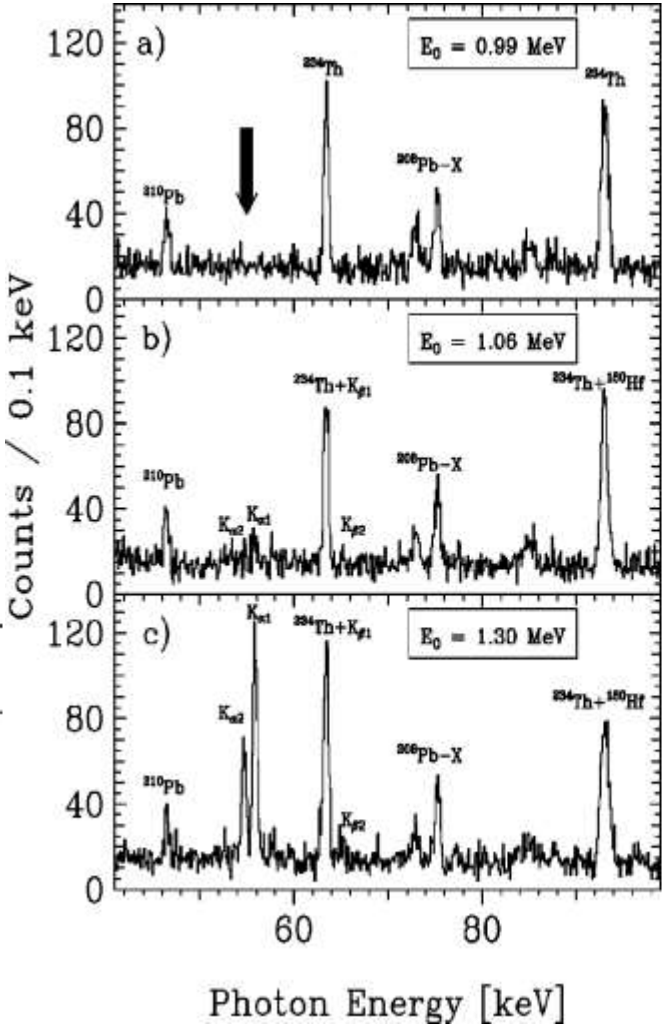
Precision frontier

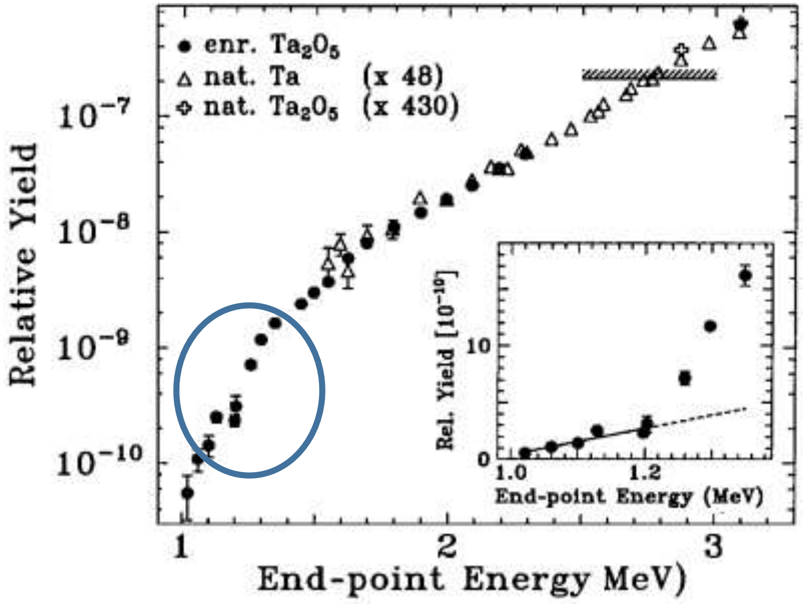
high statistics



Day-zero: Photoactivation of ^{180}Ta (ISAB recommendation)





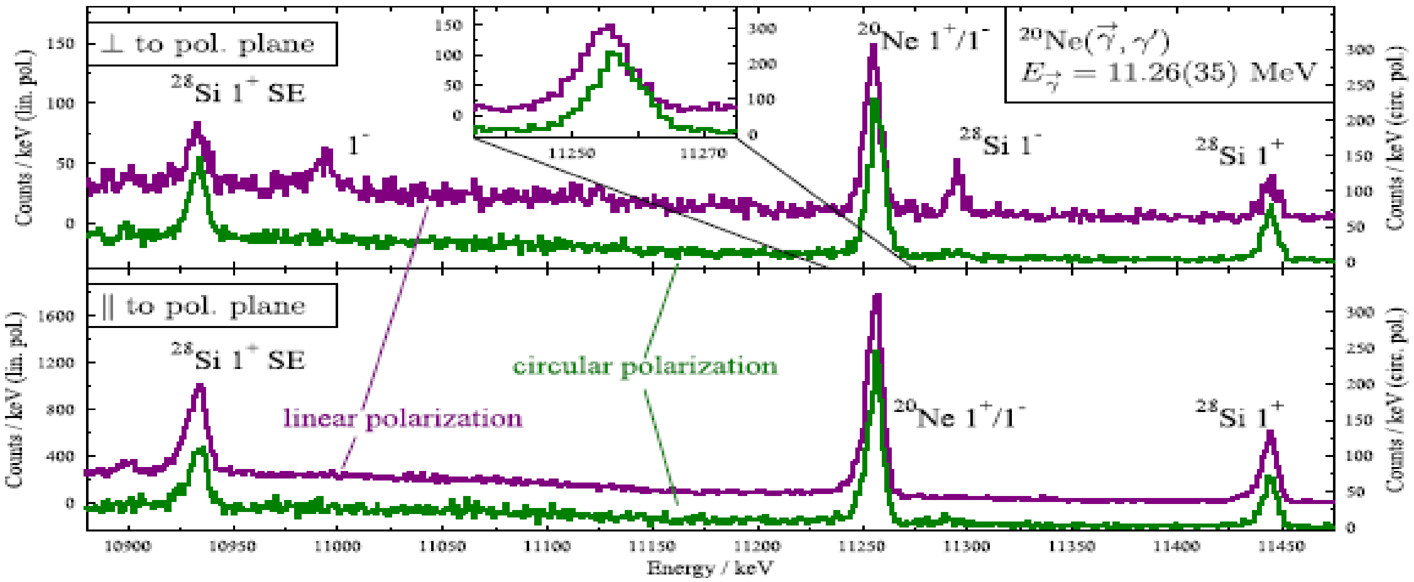


E_{IS} (MeV)	I_D (eV b)			$g_{IS} \cdot \Gamma_{ISO} \cdot \Gamma_{g.s.}/\Gamma$ (meV)		
1.01 [a]	0.057	±0.003	±0.015	0.015	±0.001	±0.004
1.22(2)	0.27	±0.02	±0.07	0.103	±0.008	±0.027
1.43(2)	0.24	±0.04	±0.06	0.126	±0.022	±0.033
1.55(3)	0.70	±0.09	±0.18	0.44	±0.06	±0.11
1.85(5)	1.11	±0.14	±0.29	1.0	±0.1	±0.3
2.16(2)	2.8	±0.3	±0.7	3.3	±0.3	±0.9
2.40(6)	3.5	±0.6	±0.9	5.2	±0.8	±1.4
2.64(3)	13	±1	±3	23	±2	±6
2.80(4)	36	±2	±9	73	±3	±19

[a]Fixed by the onset of the activation.

Belic D *et al*. 2002 *Phys. Rev. C* **65** 035801
Belic D *et al*. 1999 *Phys. Rev. Lett.* **83** 5242

Day-one: Separation of the parity doublet in ^{20}Ne (ISAB recommendation)



Beller J *et al*. 2015 *Phys. Lett. B* **741** 128

advantages at ELI-NP

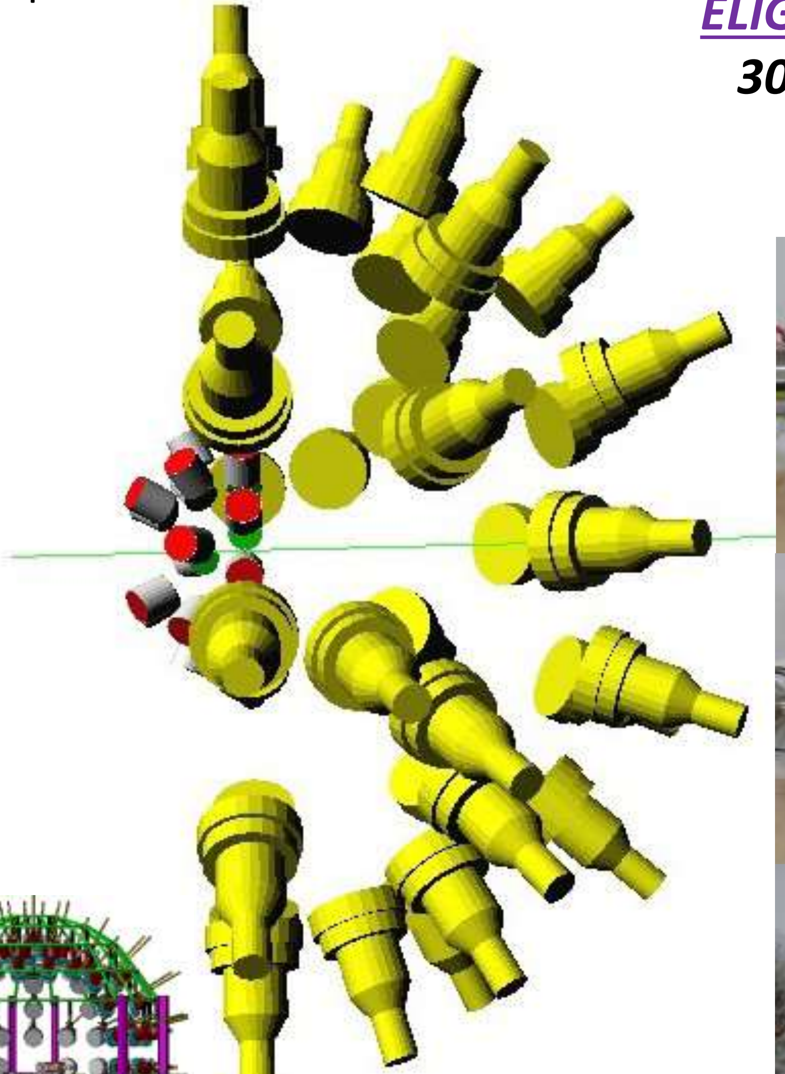
- Large volume Clover detector array
- Higher brilliance of the γ beam
- Narrow band-width: 0.3% vs 3% at HIγS
- Simultaneous measurement of polarization with ELIADE and within each Clover detector

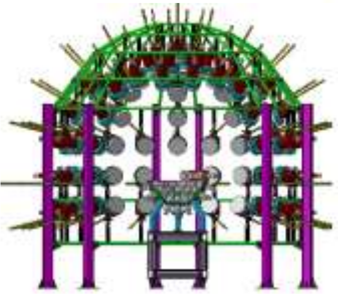
Observable	This work
$E(1^+)$ [keV]	11 258.6(2)[a]
$E(1^-)$ [keV]	11 255.4$(\pm 0.7)_{stat}(^{+1.2}_{-0.6})_{sys}$
ΔE [keV]	$-3.2(\pm 0.7)_{stat}(^{+0.6}_{-1.2})_{sys}$
$I^{(+)}_{s,0}/I^{(-)}_{s,0}$	$29(\pm 3)_{stat}(^{+14}_{-7})_{sys}$
$\mathfrak{F}_e$ [keV^{-1}]	$1.4(\pm 0.3)_{stat}(\pm 0.2)_{sys}$[b]

a Relative to 1^+ state of ^{28}Si.
b Correcting for the known decay ratios Γ_0/Γ [6].

GANT experiment at ELI-NP

key input U. Milano and Konan U.





ELIGANT-GN array

30 $LaBr_3$ or $CeBr_3$

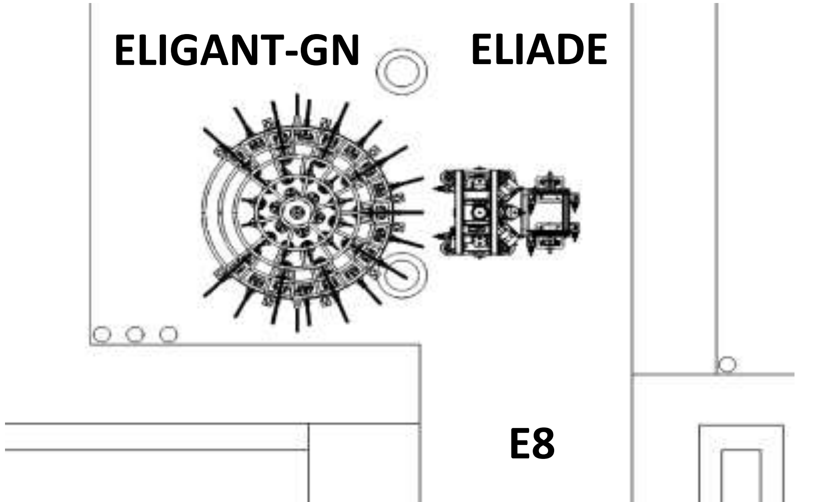
20 ^7Li glasses

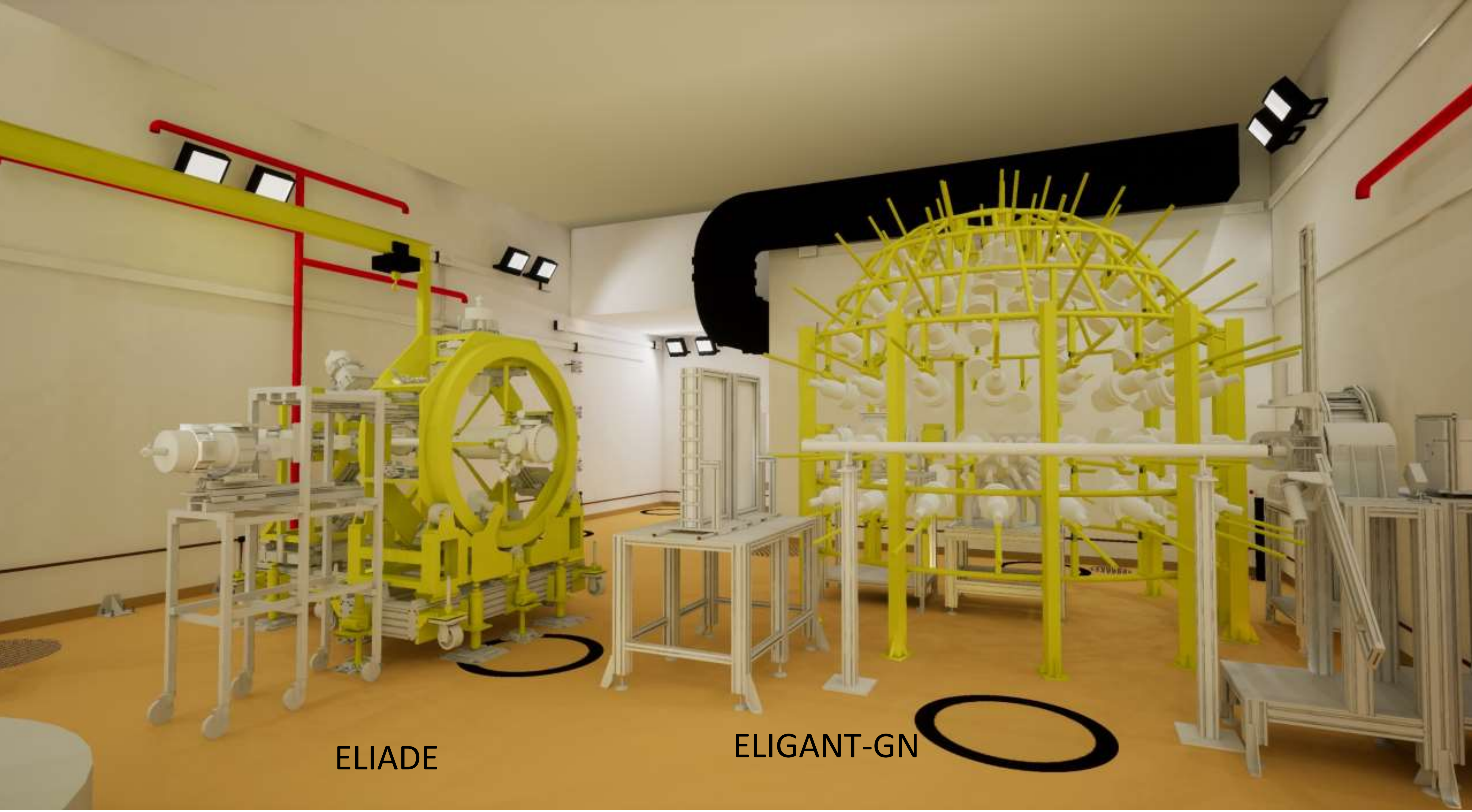
30 Lq. Scint.

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




ELIADE
ELIGANT-GN

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]

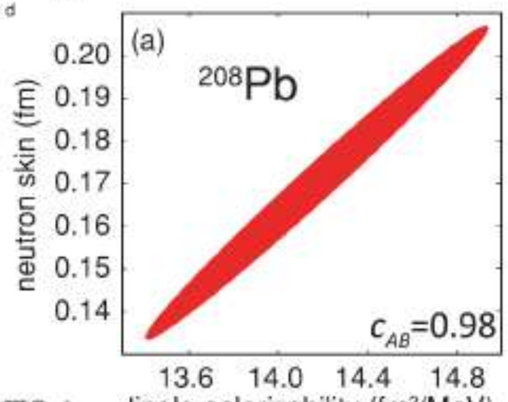


FIG. 1.

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

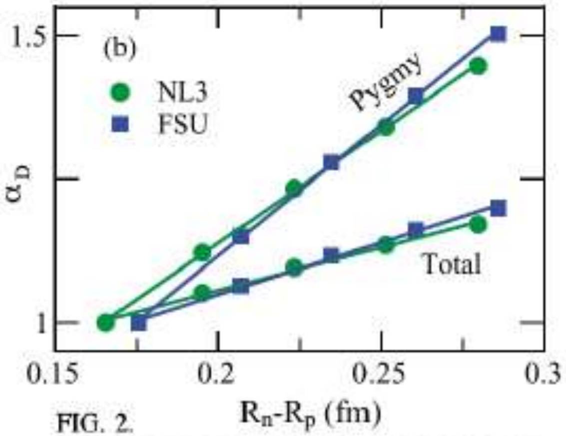


FIG. 2.

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

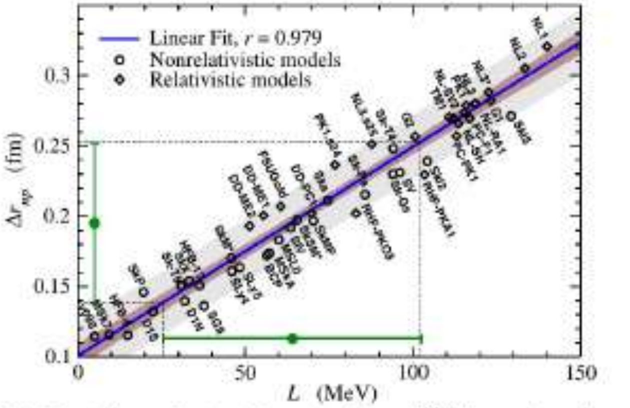


FIG. 3 (color online). Neutron skin of ^{208}Pb against slope of the symmetry energy. The linear fit is $\Delta r_{np} = 0.101 + 0.00147L$.

PRL **106,** 252501 (2011)

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° and forward angles

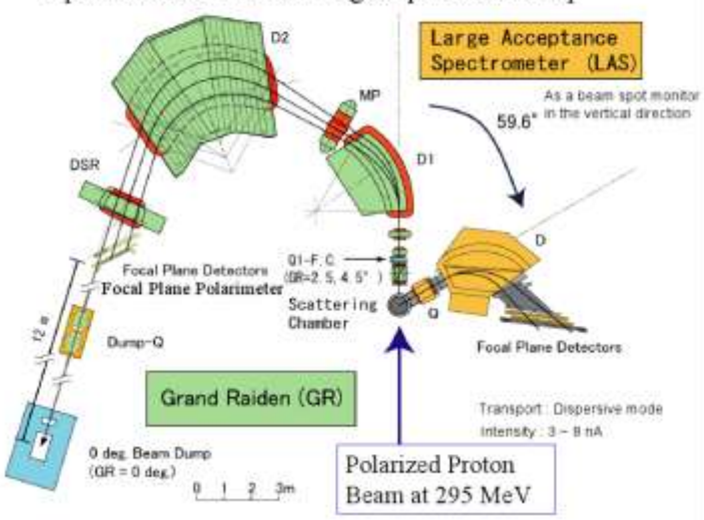
A. Tamii, NIM A605, 326 (2009)

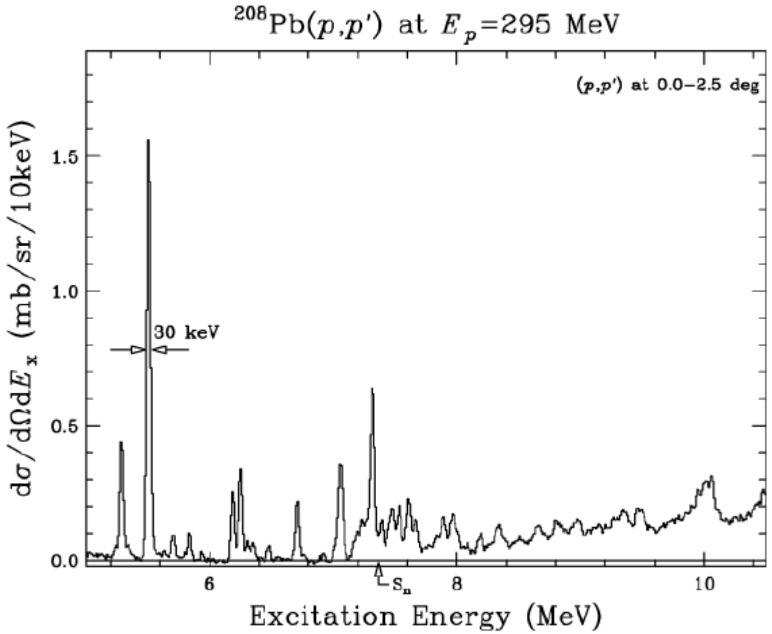
ELI-NP

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

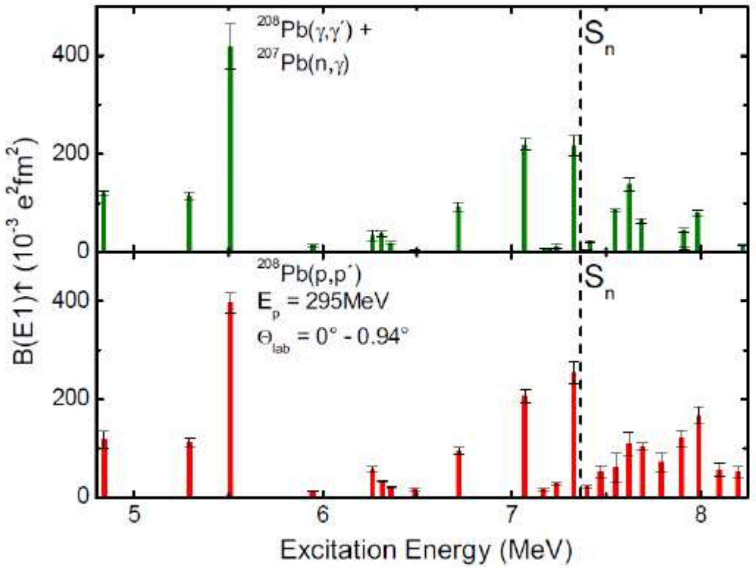
experiment: polarized (>99%) γ beam
simultaneous (γ,γ’) + (γ,n) measurement

Spectrometers in the 0-deg. experiment setup





B(E1) of discrete states



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

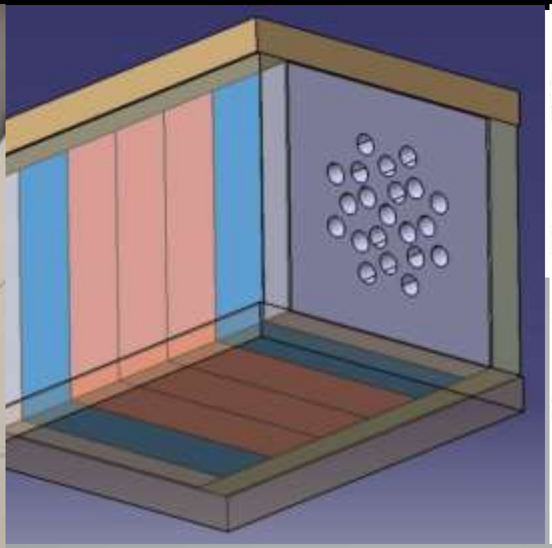
$$\alpha_D \equiv \frac{\sigma_{-2}}{2\pi^2} \cdot \frac{\hbar c}{e^2} = \sum \frac{\sigma_{abs}(E_x)}{E_x^2} \cdot \frac{\hbar c}{2\pi^2 e^2} = 20.1 \pm 0.6\ \mathrm{fm^3/e^2}$$

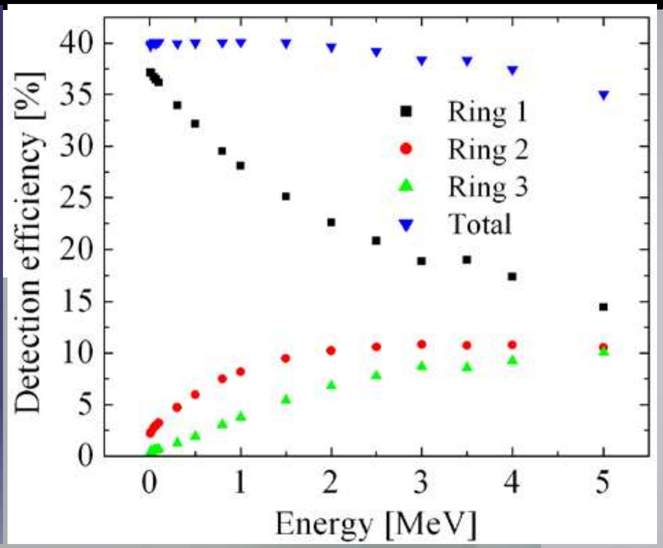
A. Tamii, PRL 107, 062502 (2011)

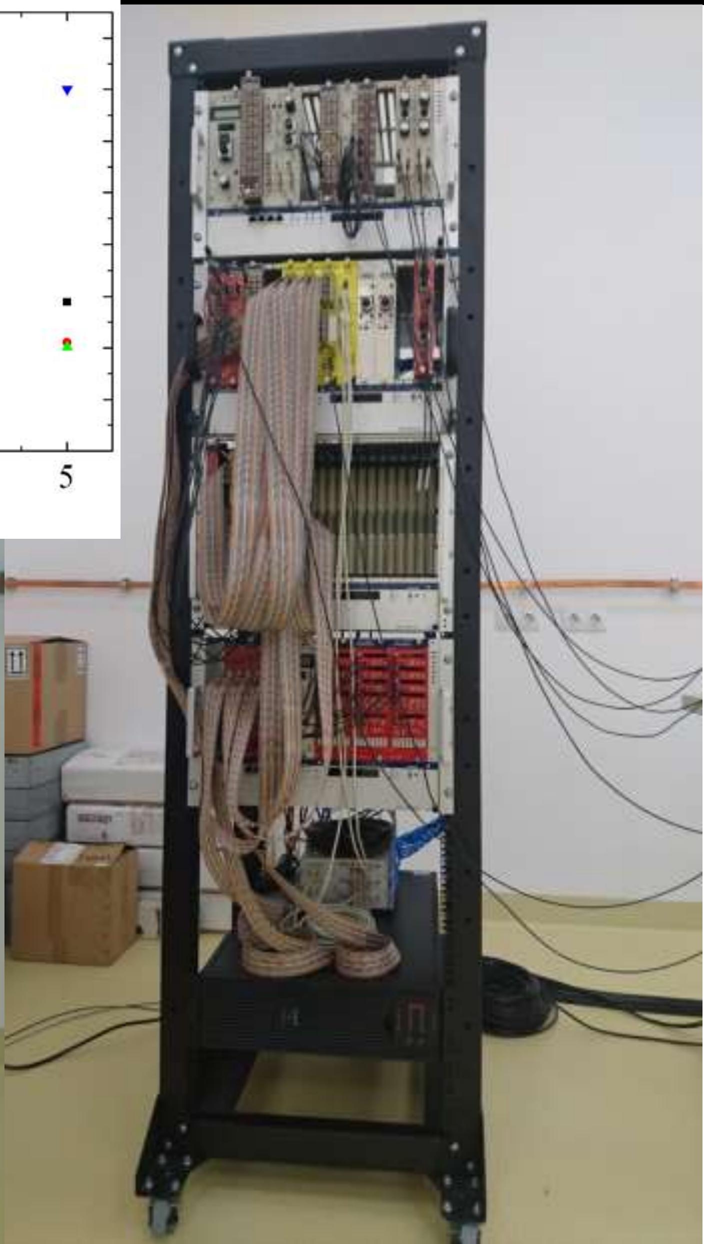
Rom. Rep. Phys. 68, S539 (2016)

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

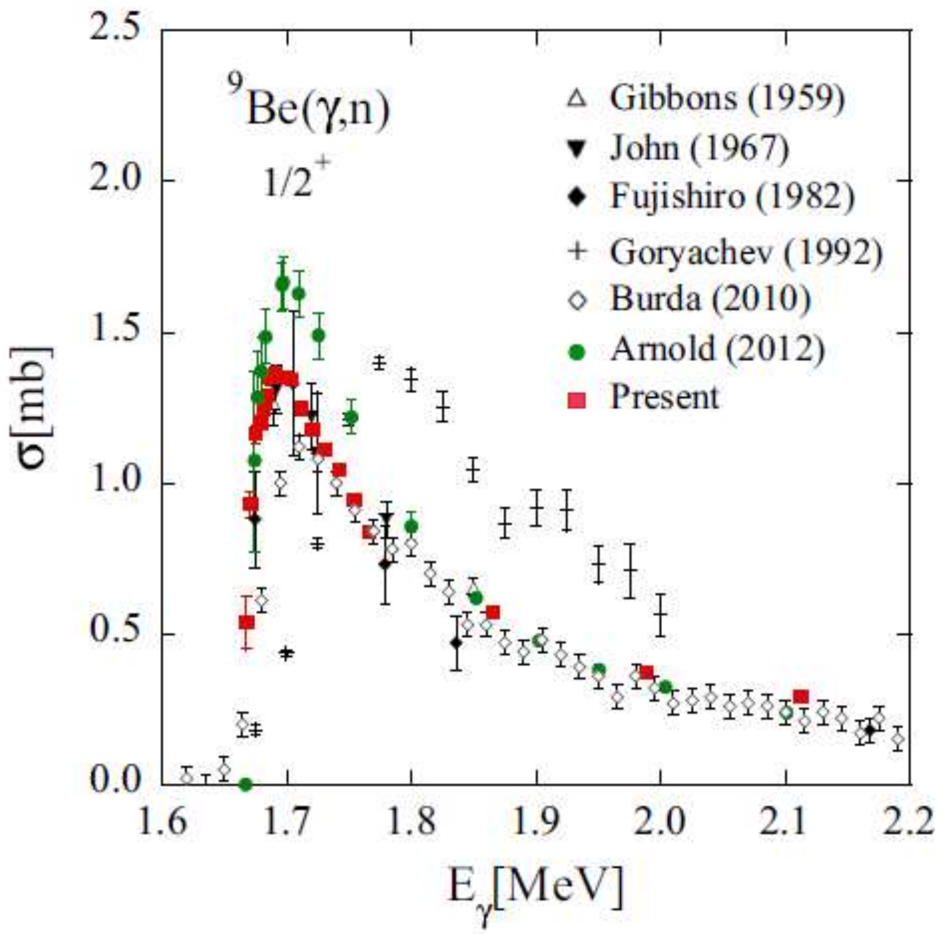
ELIGANT-TN





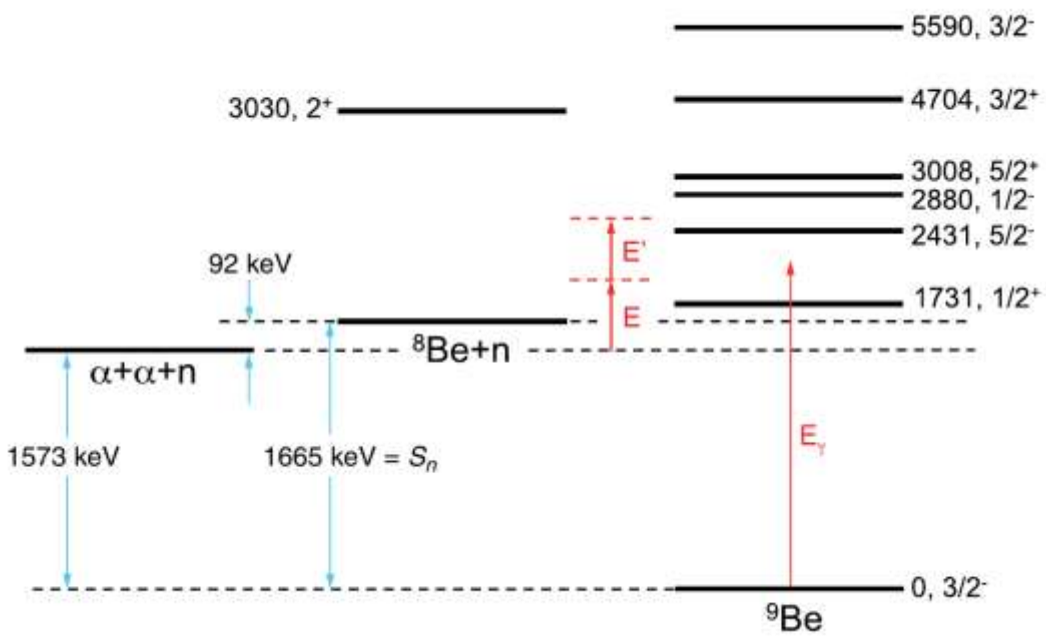


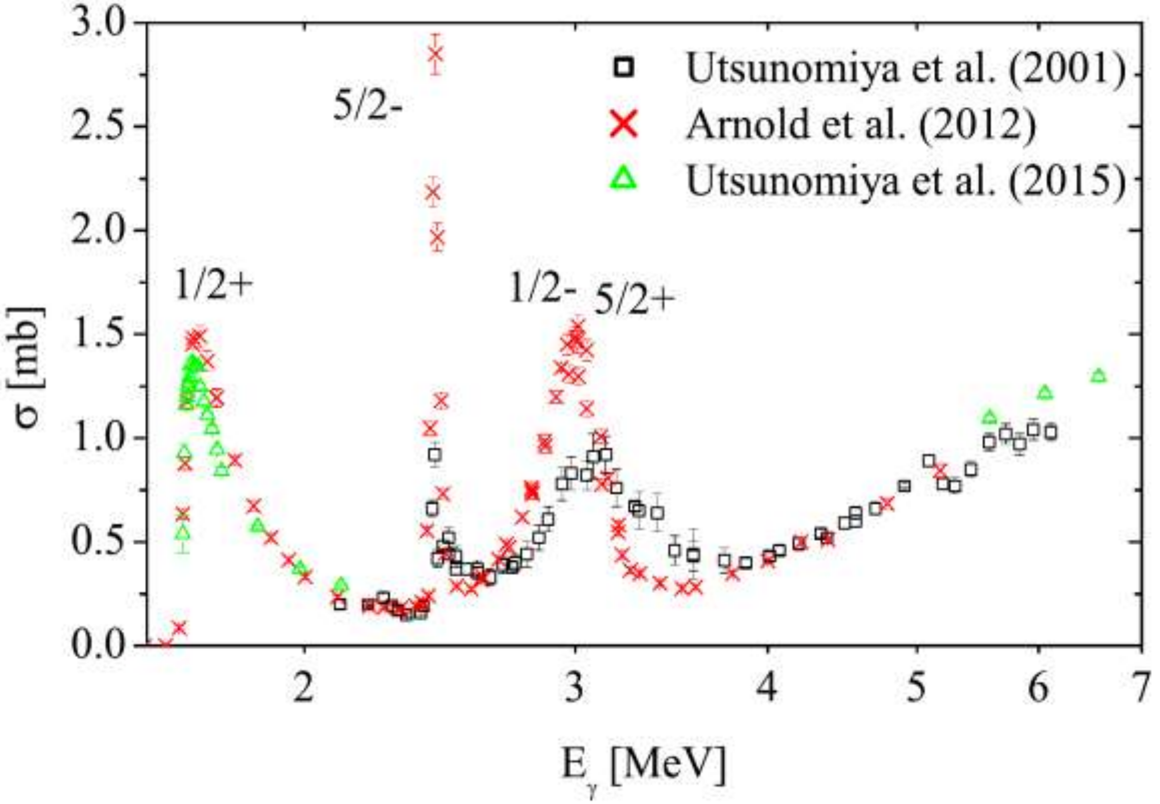
Day-zero: Measurement of the ^{9}Be(γ,n) cross section (ISAB recommendation)



$B(E1)\downarrow$ (e^2 fm^2)	Ref.
0.107 ± 0.007	Utsunomiya *et al.* [5]
0.104 ± 0.002	Sumiyoshi *et al.* [37]
0.136 ± 0.002	Arnold *et al.* [6]
0.111 ± 0.004	Present

- ■ Unsunomiya H *et al*. 2015 *Phys. Rev. C* **92** 064323
- ● Arnold C W *et al.* 2012 *Phys. Rev. C* **85** 044605

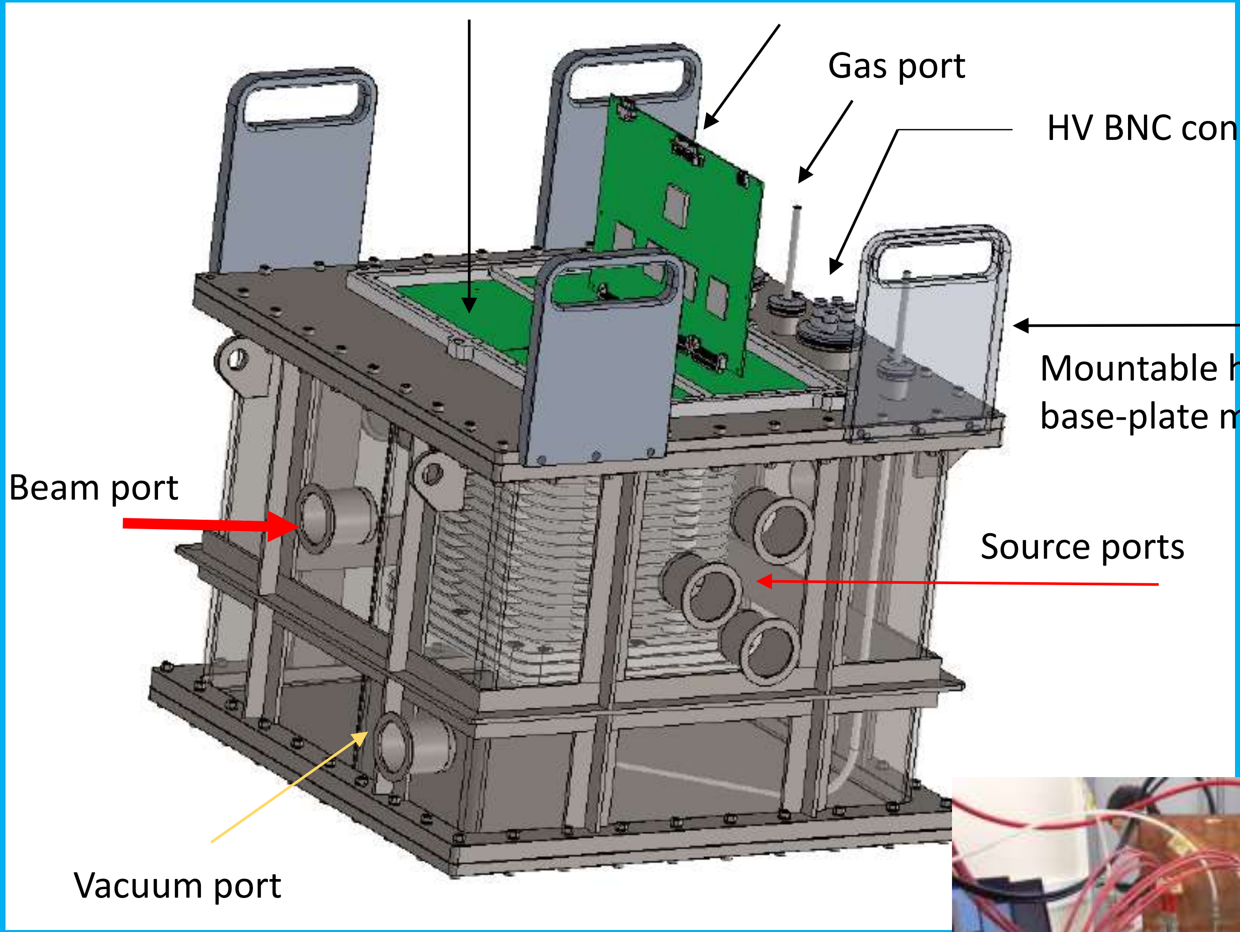




A case where ELI-NP will have a say at Day-Zero!

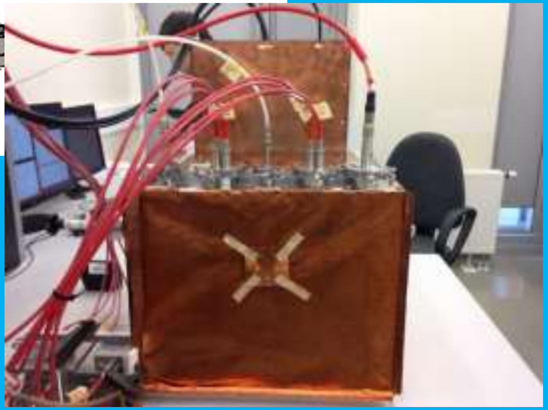
ELITPC

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



Detector upside-down view

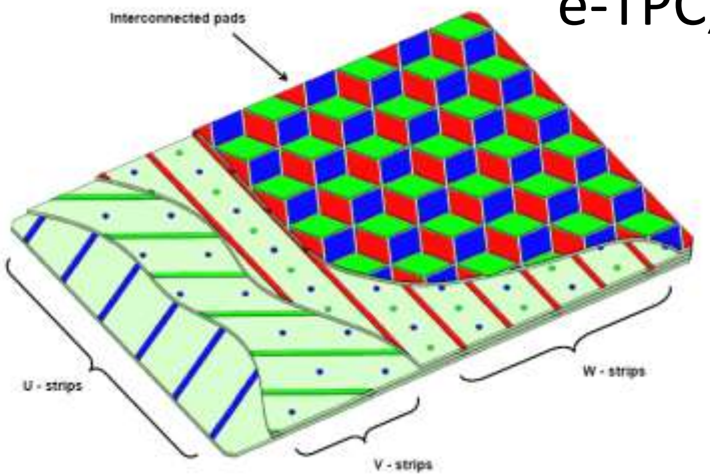
in collaboration with U. Warsaw

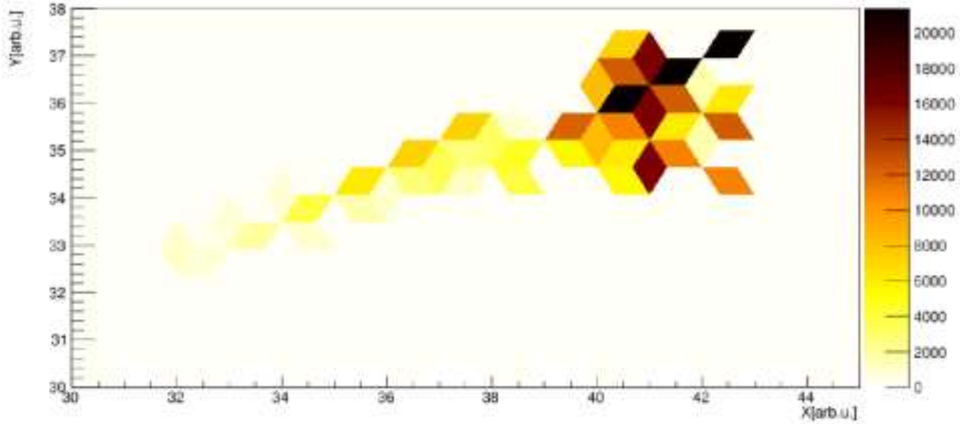


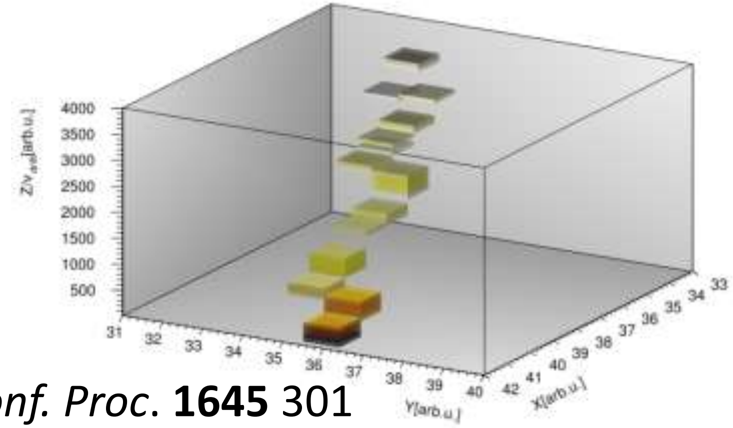
The mini-eTPC detector with 256-channel readout was built and successfully tested in-beam at the IFIN Tandem in 2016

mini-TPC event recognition

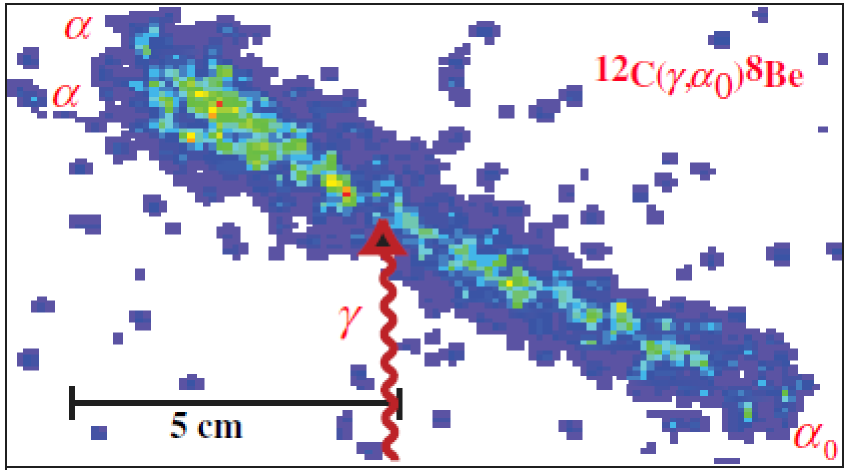
e-TPC, tests







o-TPC, HIγS



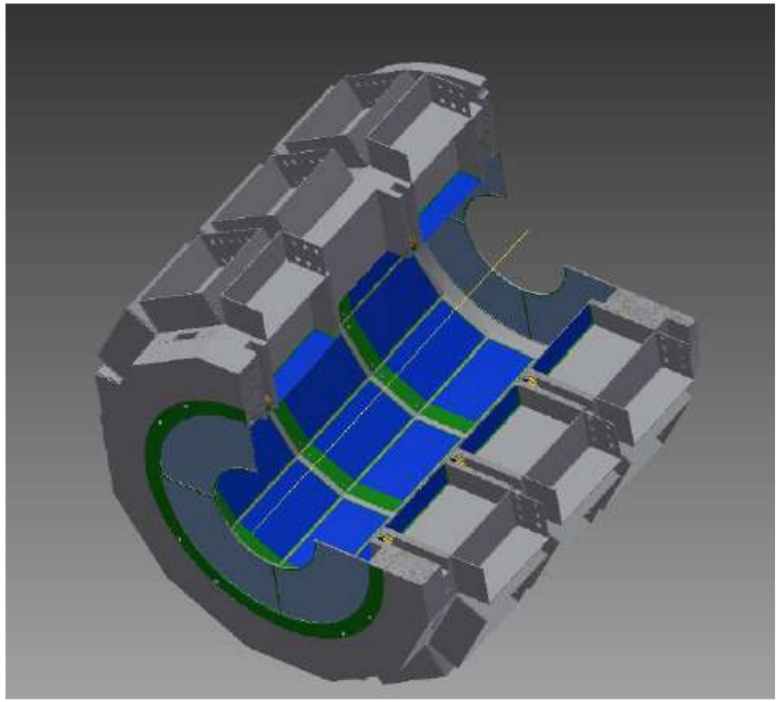
Zimmerman W R *et al*. 2012 *Phys. Rev. Lett*. **110** 152502

Bihałowicz J S 2015 *AIP Conf. Proc*. **1645** 301

nuclear astrophysics with ELISSA

ELISSA: **in collaboration with INFN LNS Catania**

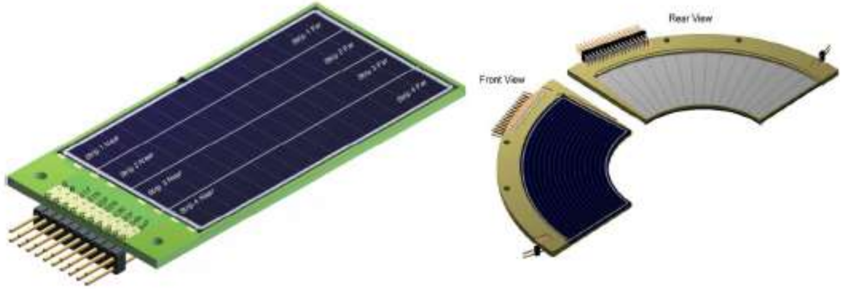
- 3 rings of 12 position sensitive X3 silicon-strip detectors by Micron
- 2 end cap detectors from 4 QQQ3 segmented detectors by Micron
- 320 channels readout with GET electronics



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

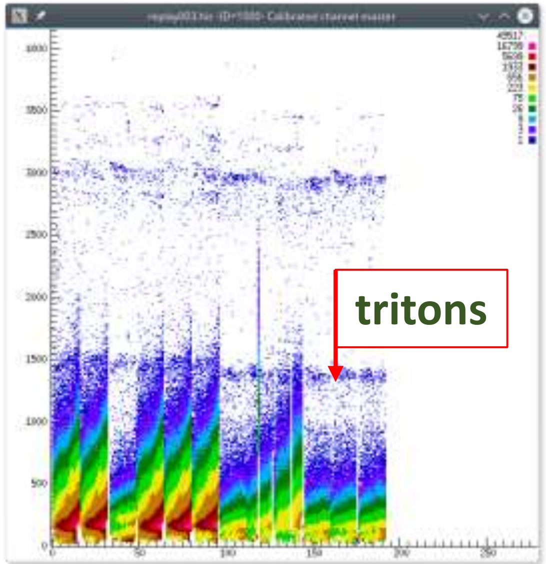
- reaction could still be a game changer in resolving the “Li problem”
- experimental measurements below 1.5 MeV are 30 yrs. old and disagree with theoretical predications
- higher energy measurements can restrict the extrapolation to astrophysically important energies

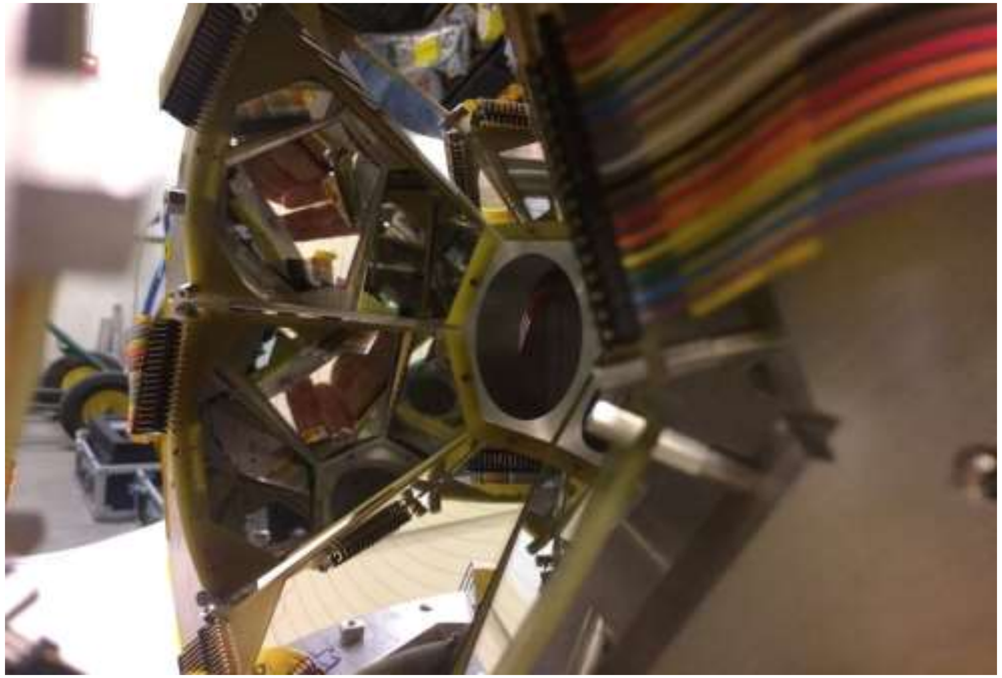
C. Matei et al., exp. at HIγS in March 2017

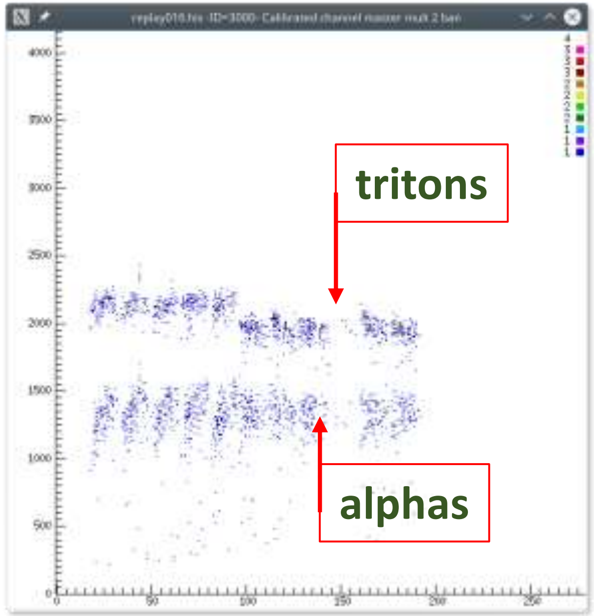


^{7}Li(γ,t)α w/ SIDAR at HIγS, March-April 2017

- addressing the Li-problem and theoretical aspects
- using SIDAR array from ORNL
- two lamp-shades of YY1: 300, 500, 1000 μm
- clean alpha-triton coincidence
- proposed by ELI-NP together w/: ORNL, Rutgers U, INFN-LNS, York U, Aarhus U, U Michigan

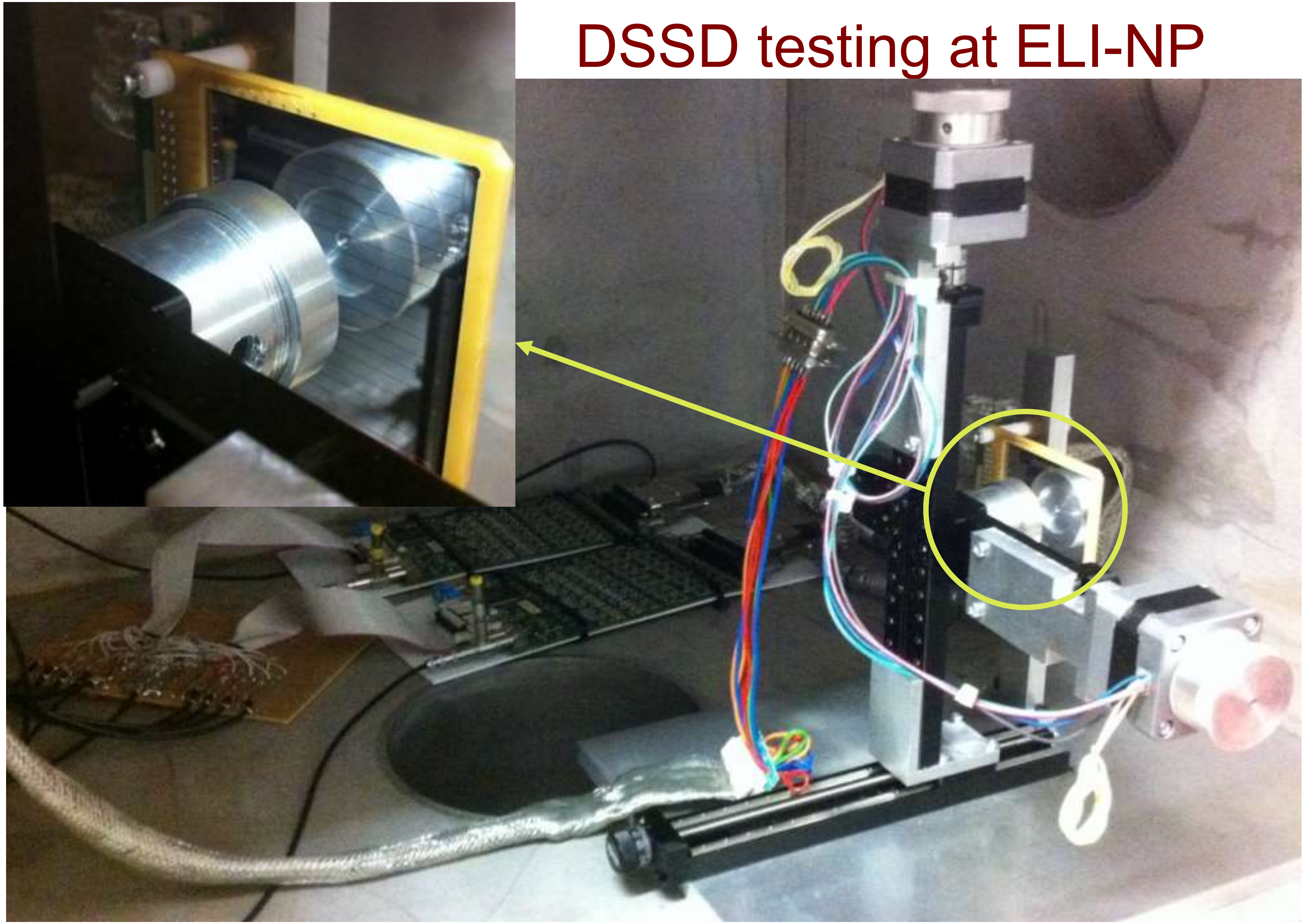






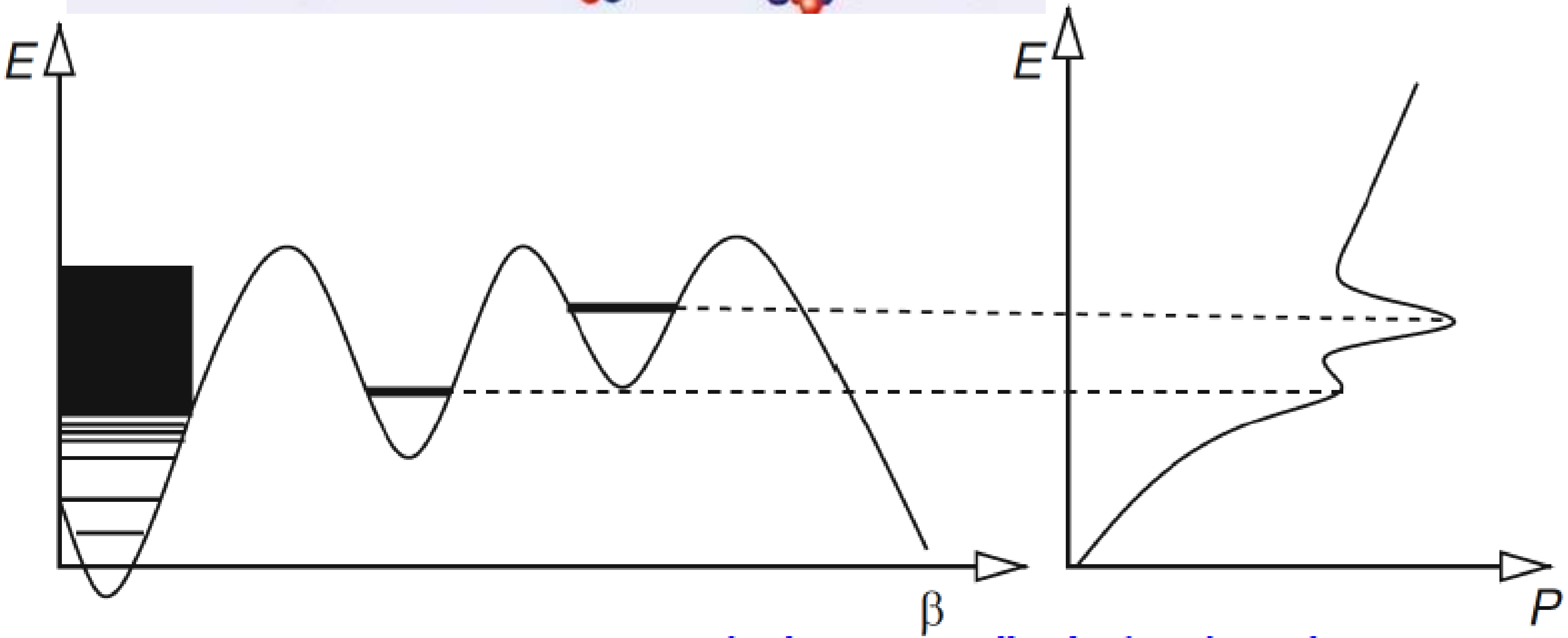
eli Nuclear Physics

DSSD testing at ELI-NP



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

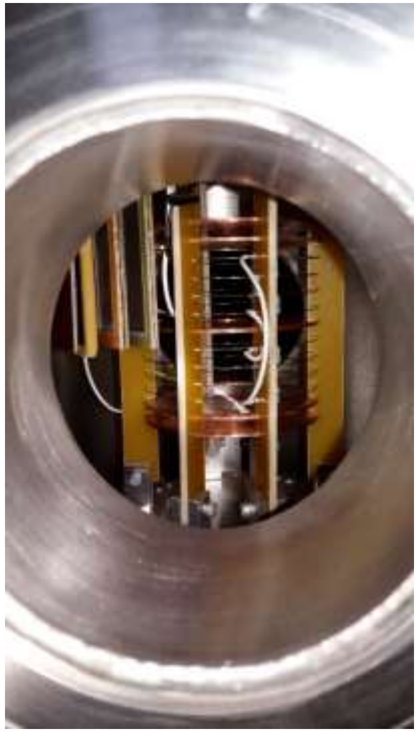
Investigation of Transmission Resonances as function of energy

- *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

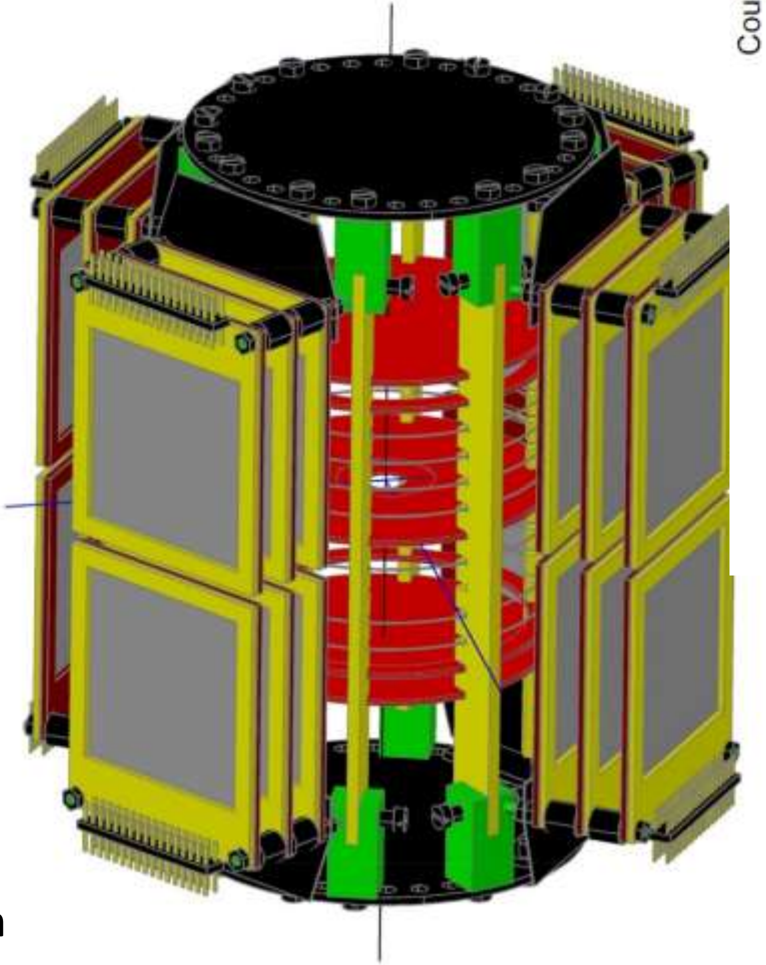
Rom. Rep. Phys. 68, S621 (2016)

Photofission experiments at ELI-NP

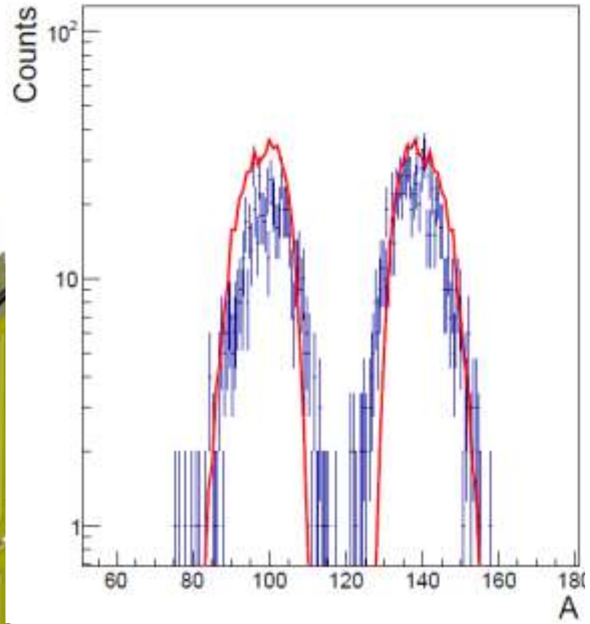


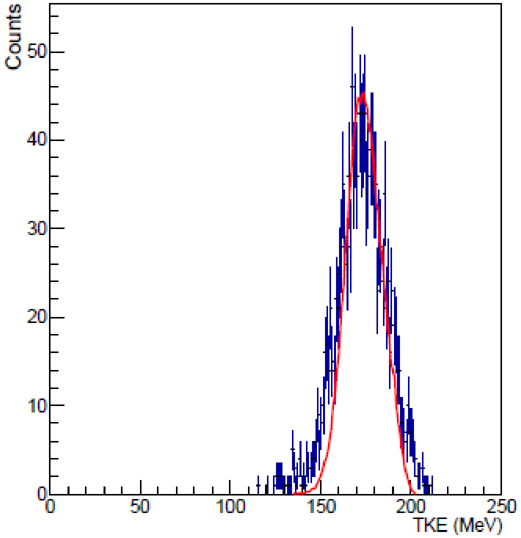
BIC prototype tested with sources and in-beam

ELI-BIC

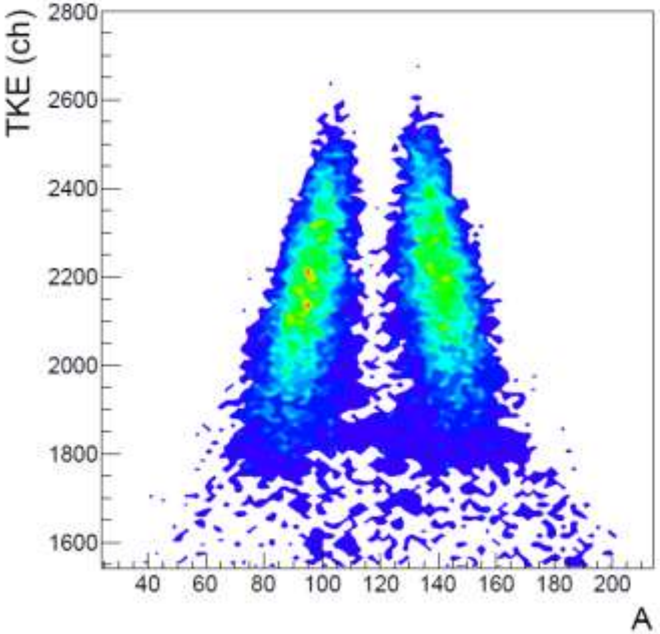


Array of Bragg ICs coupled to Si DSSD based ΔE-E detectors

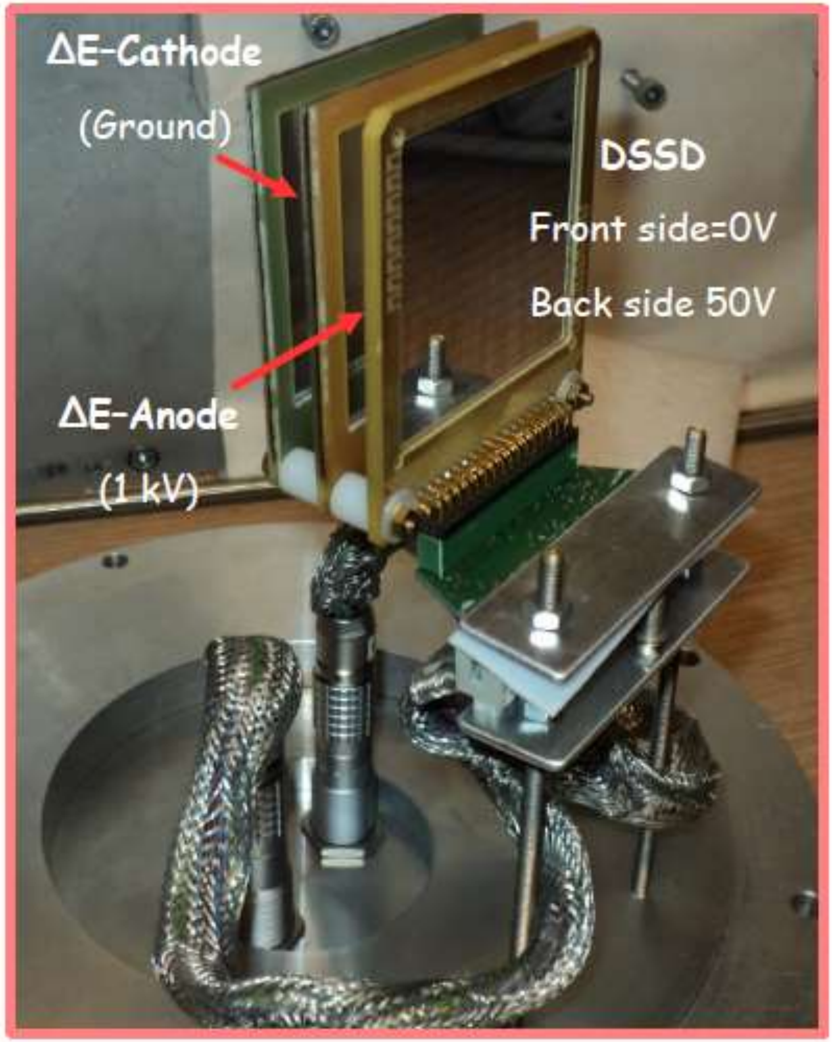


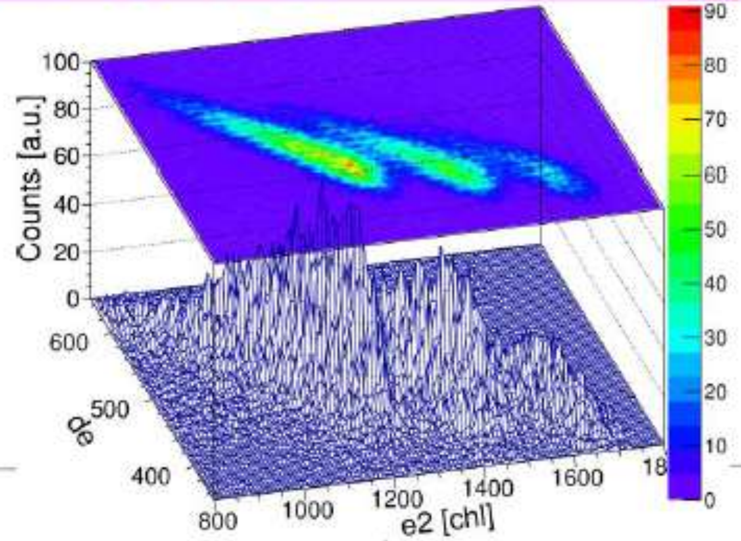


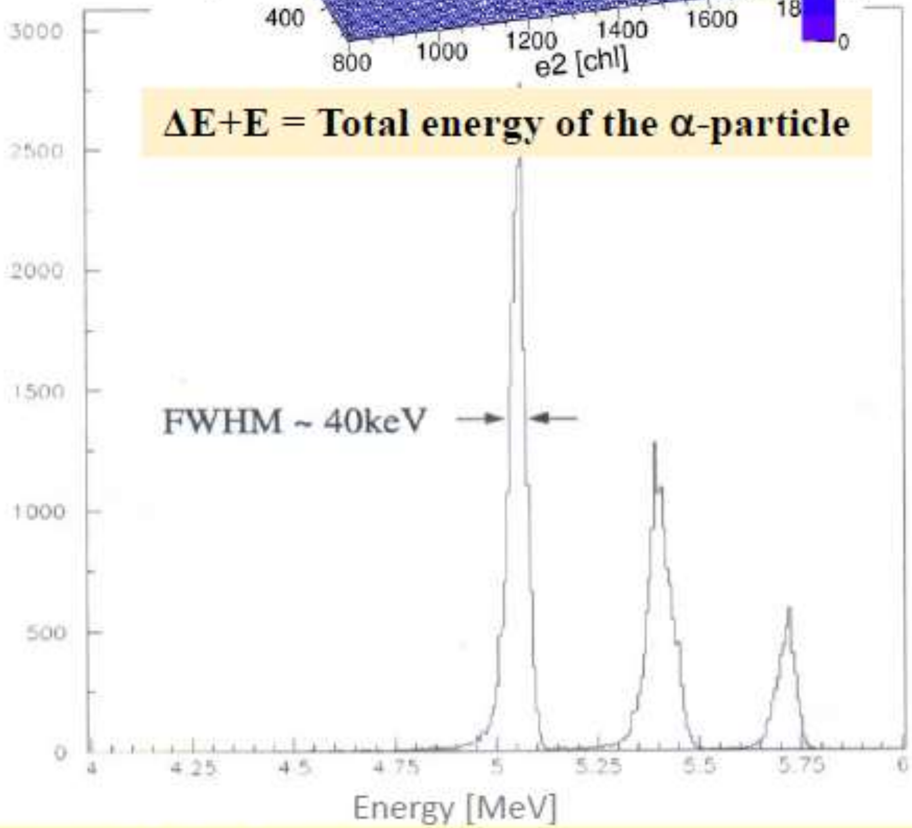
in collaboration with ATOMKI



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







<u>Conclusion</u>: *The designed dE-E array is effective for the α detection*

RA4 Timeline of Instrument Implementation

Gamma Beam Delivery & Diagnostics

Item	2017	2018	2019
Beam pipes/vacuum			
Beam Dumps/Mobile shielding			
Attenuator system for beam energy			
Detectors & electronics for d(g,n)			
CCD cameras, optics			
Detector & electronics for Compton			
Integration & testing			

ELIADE

Item	2017	2018	2019
LaBr3 detectors			
Single-to-differential conversion & transport			
Electronics for single-diff conversion			
Mechanical structure			

ELIGANT

Item	2017	2018	2019
Gamma Mechanical Structure			
Neutron Mechanical Structure			

Positron production

Item	2017	2018	2019
Pipes and Chambers			
HPGe detectors			
Na-22 source			
DAQ electronics			
Vacuum and Control			
Power Supplies (e^+ transport)			
PAES			

Industrial applications

Item	2017	2018	2019
Positioning systems for S&L objects			
Detectors & collimators			
Integration & tests			

ELITHGEM

Item	2017	2018	2019
THGEM detectors			
Vacuum system			
Gas system			
Integration & tests			

ELISSA

Item	2017	2018	2019
QQQ3 end-cap detectors			
Front-end electronics & cables			
SSD testing station			
Experimental reaction chamber			
Integration & tests			

ELITPC

Item	2017	2018	2019
Gas-flow system			
ELITPC drift cage (internal structure)			
ELITPC vacuum chamber			
GEM detectors			
Integration & tests			

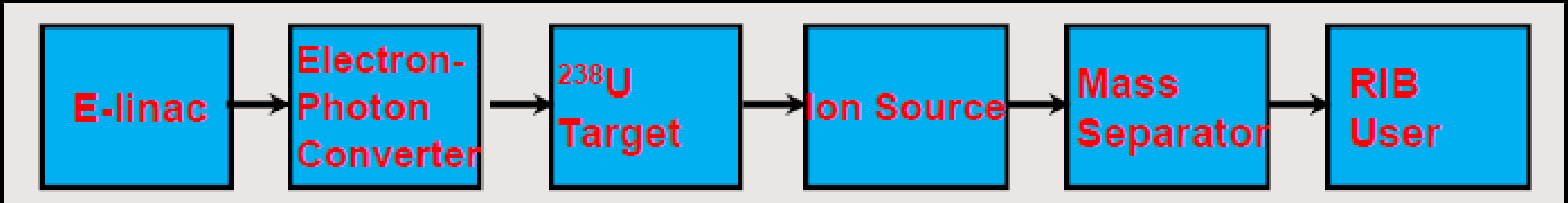
ELIBIC

Item	2017	2018	2019
Front-end electronics			
Gas system			
Vacuum system			
Digitizers			
Integration & tests			

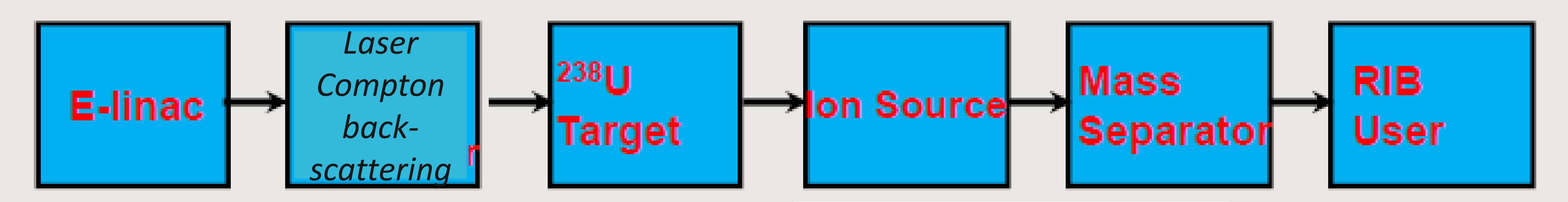
Medical applications

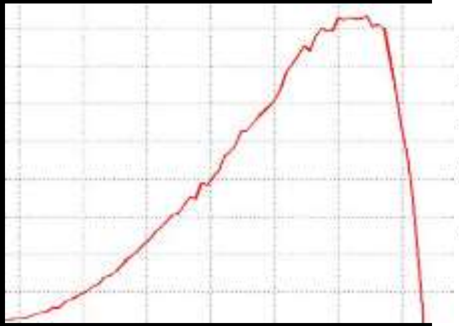
Item	2017	2018	2019
Solid target gamma beam irradiation system			
Measurement station (HPGe detector)			
Target Body and Target Materials			
Integration & tests			

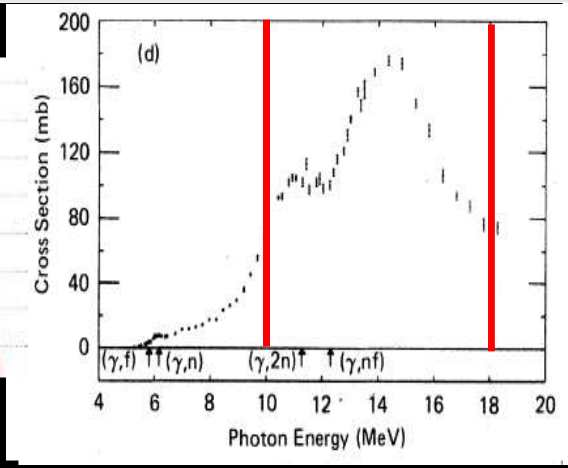
ALTO, ARIEL, etc

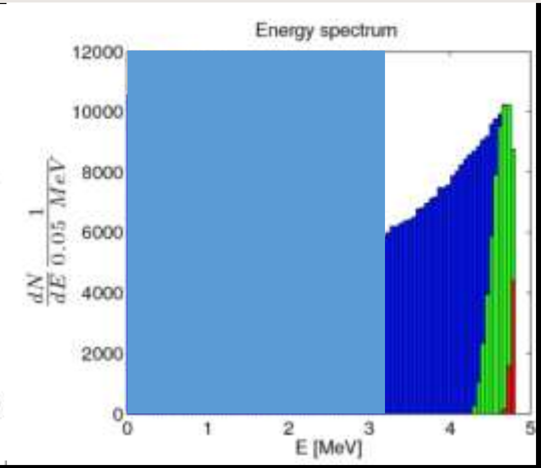


ELI-NP



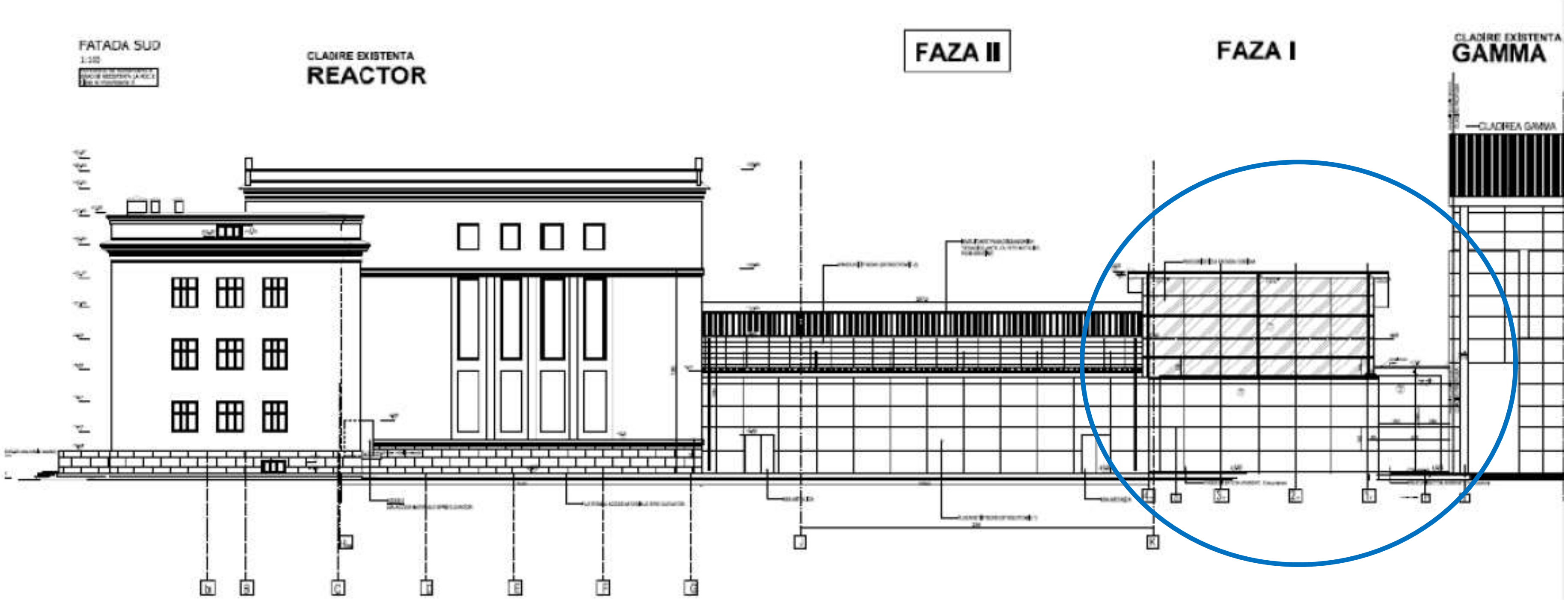






ELI IGISOL

- Simulations related to the cryogenic stopping cell (CSC) are finalized.
- Gas flow simulations to study the properties of the supersonic jets through the nozzles are ongoing.
- An extension (E9) along the high-energy gamma beamline is under construction.
- A project to connect the ELI experimental building with the Reactor hall has been prepared.

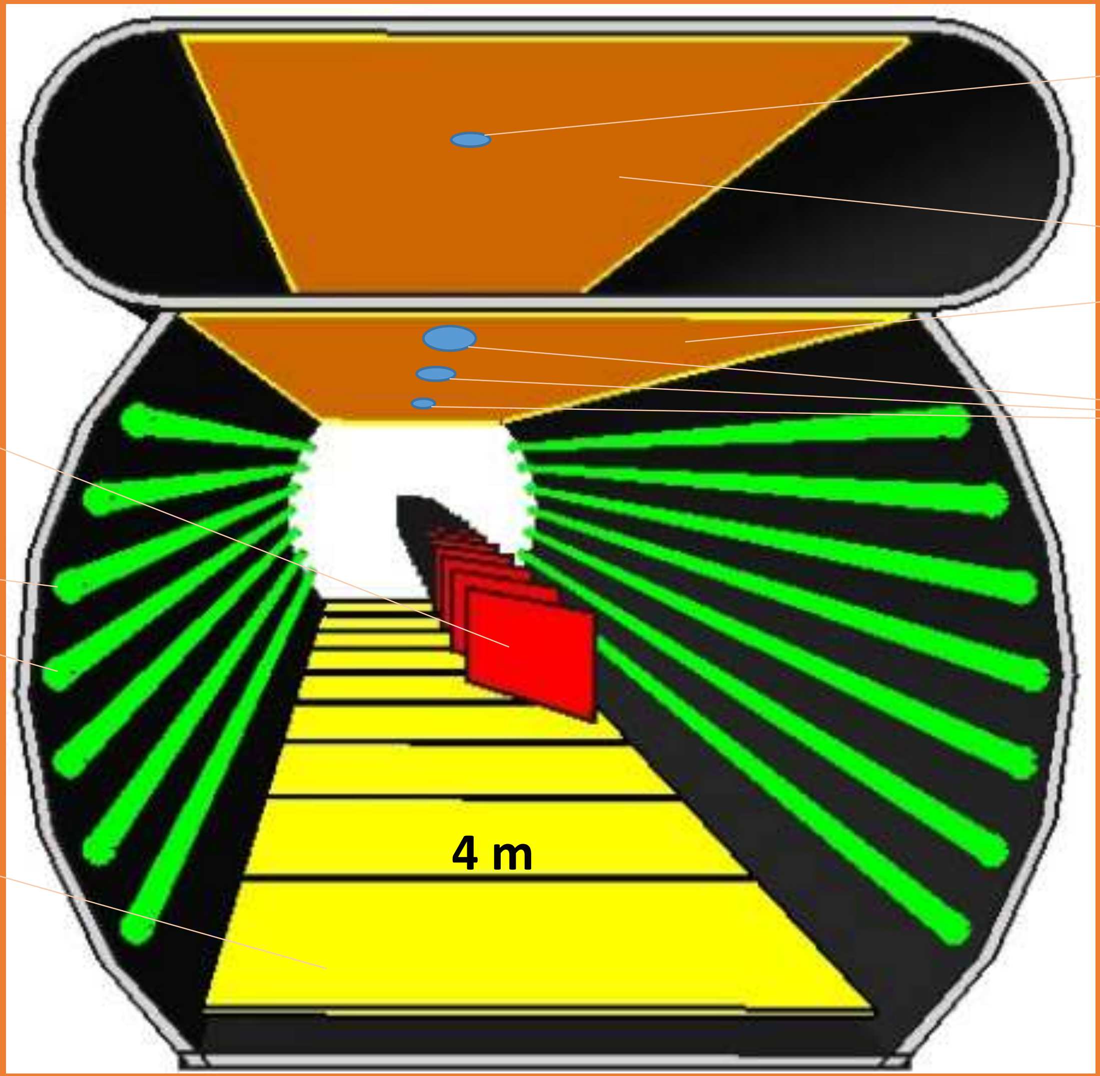


Rom. Rep. Phys. 68, S621 (2016)

IGISOL facility at ELI-NP

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

double-chamber CSC



Studies of gas-flow dynamics funded by the Romanian Science Agency

Work in collaboration with GSI, Darmstadt and University of Giessen

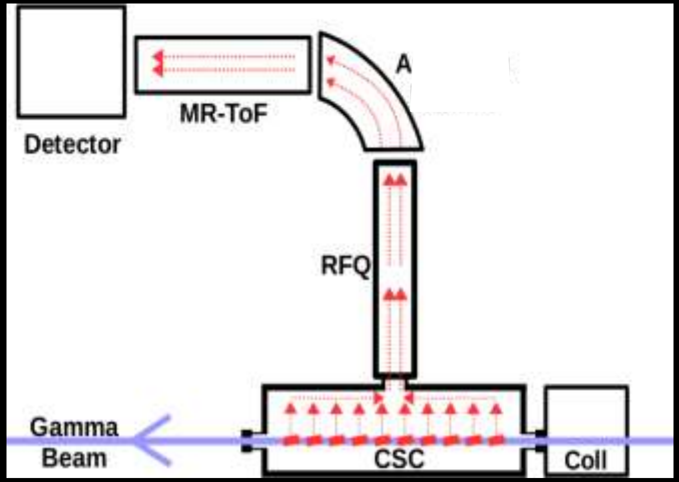
IGISOL beamline:
Exotic Neutron-Rich Isotopes

- **Energy range up to 19.5MeV covers the GDR:**
- **RIB via photofission in a actinide thick target**
- **Production of exotic neutron-rich fission fragments**
- **Refractory elements: light region Zr-Mo-Rh and heavy rare-earths region around Ce**

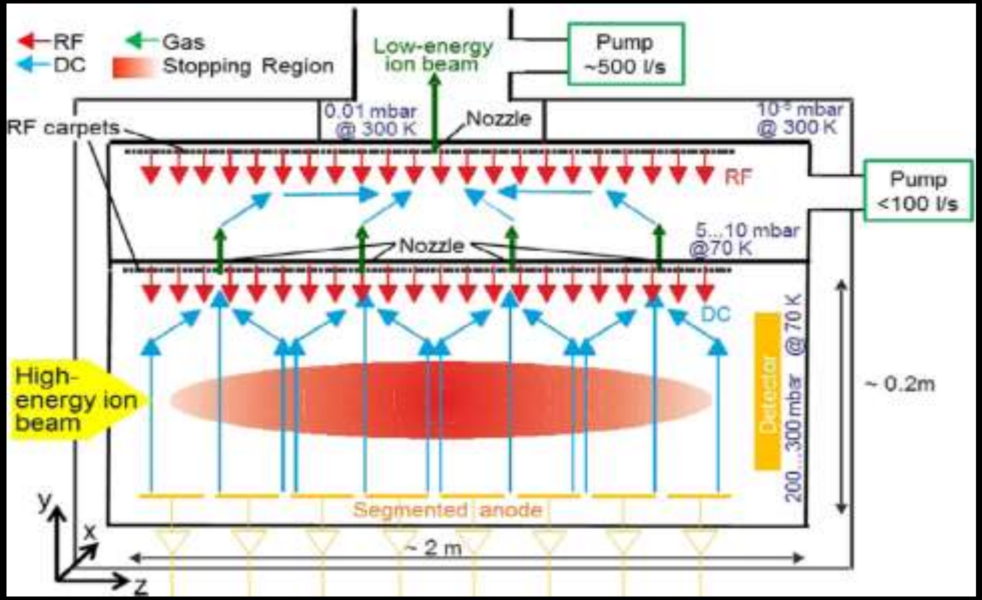
U-238 target:
- thick because σ(γ,f)~1b
- sliced in many thin foils: refractory, fast extraction
- tilted foils:
  (1) avoid hitting neighboring foils
  (2) increase γ pathlength w/o increasing thickness

IGISOL beam line:
(collaboration with GSI/Giessen)
1. Cryogenic Stopping Cell (orthogonal extraction)
2. RFQ
3. MR-ToF mass spectrometer

A β-decay measurement station:
(collaboration with IPN Orsay)
tape station, HPGe detectors

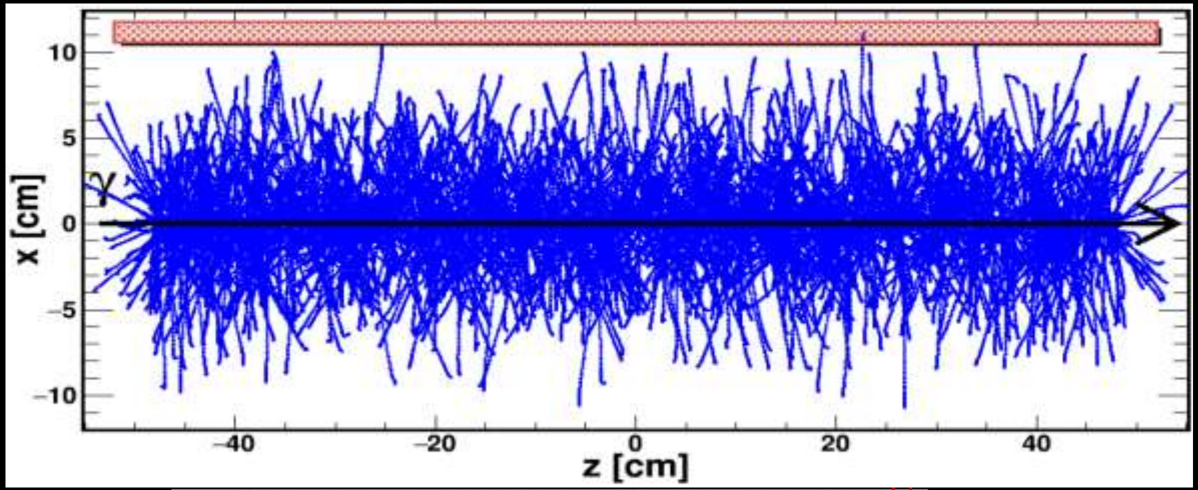


T. Dickel et al., NIM B 376 (2016) 216

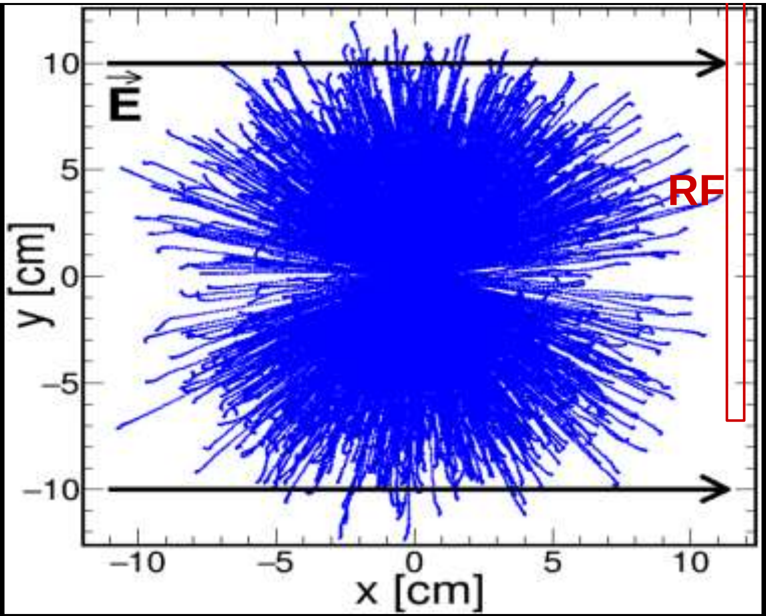


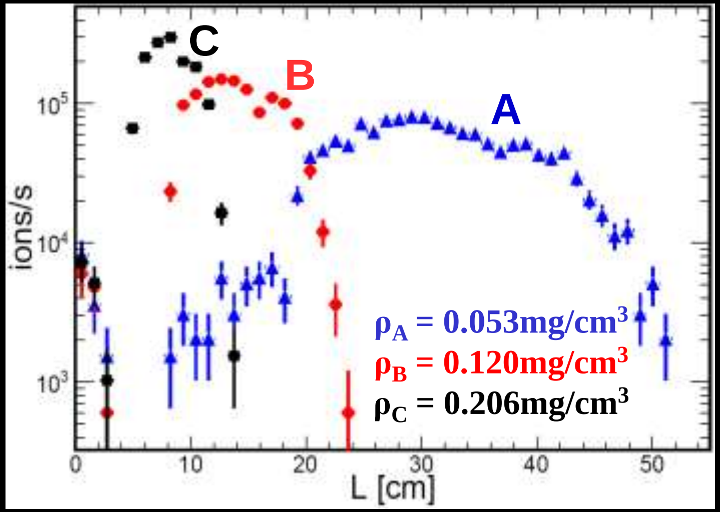
CSC Simulations: Fragment Slowing Down in the Gas Cell

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

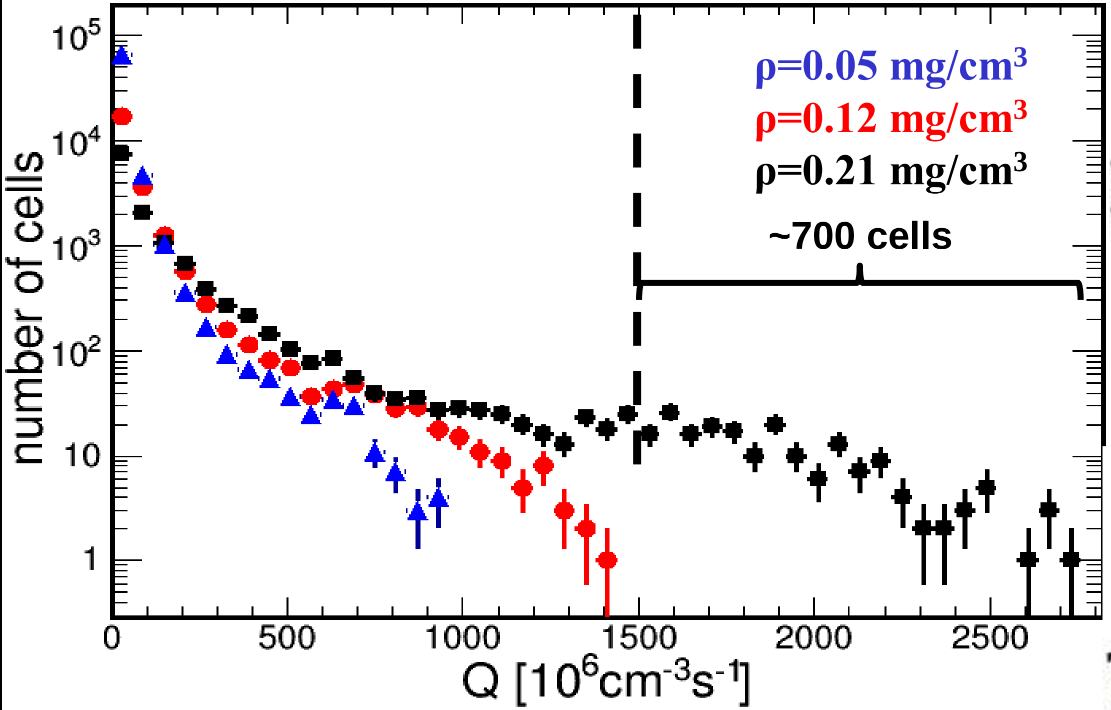


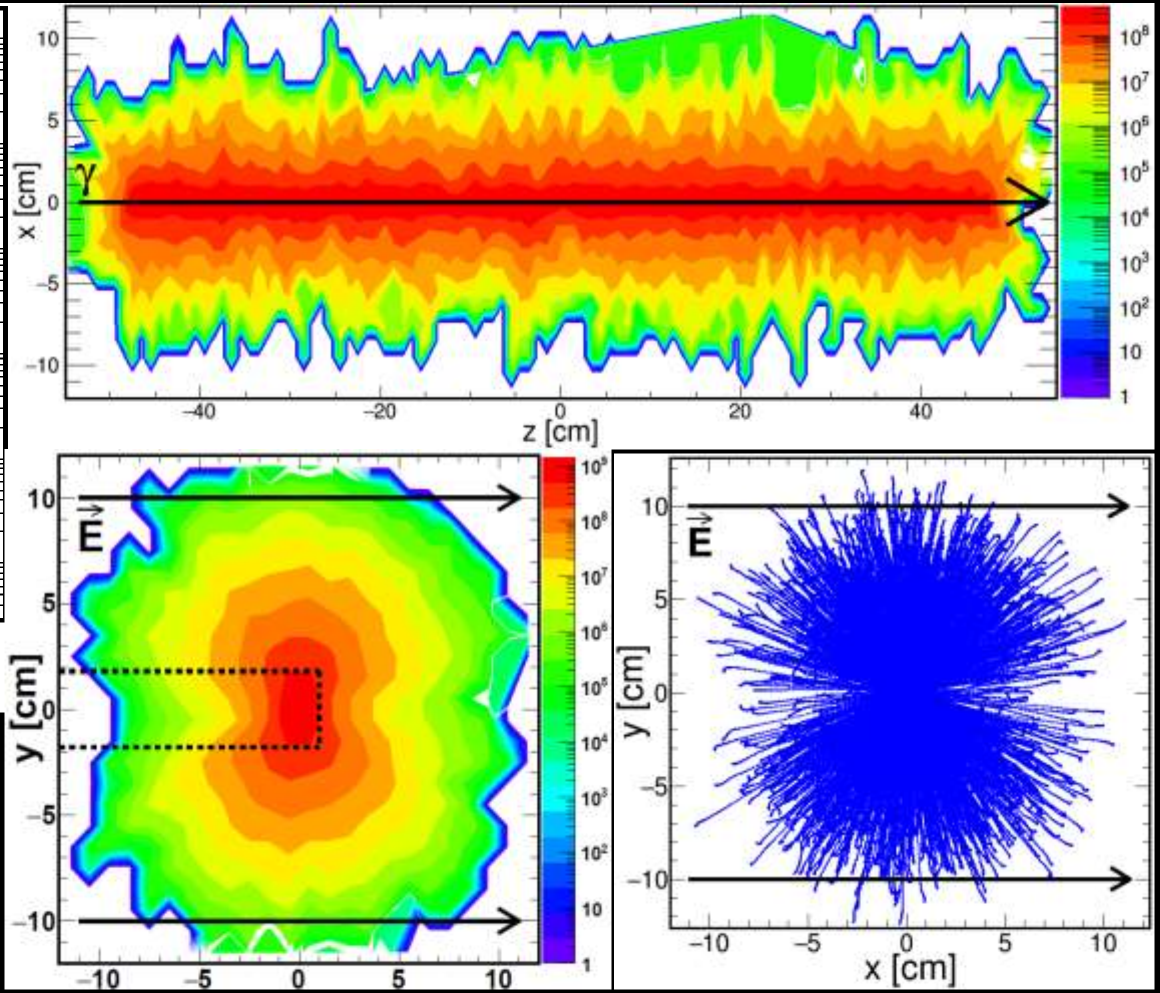


$$\rho \cdot L_{max} = 2.33\ mg/cm^2$$

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%

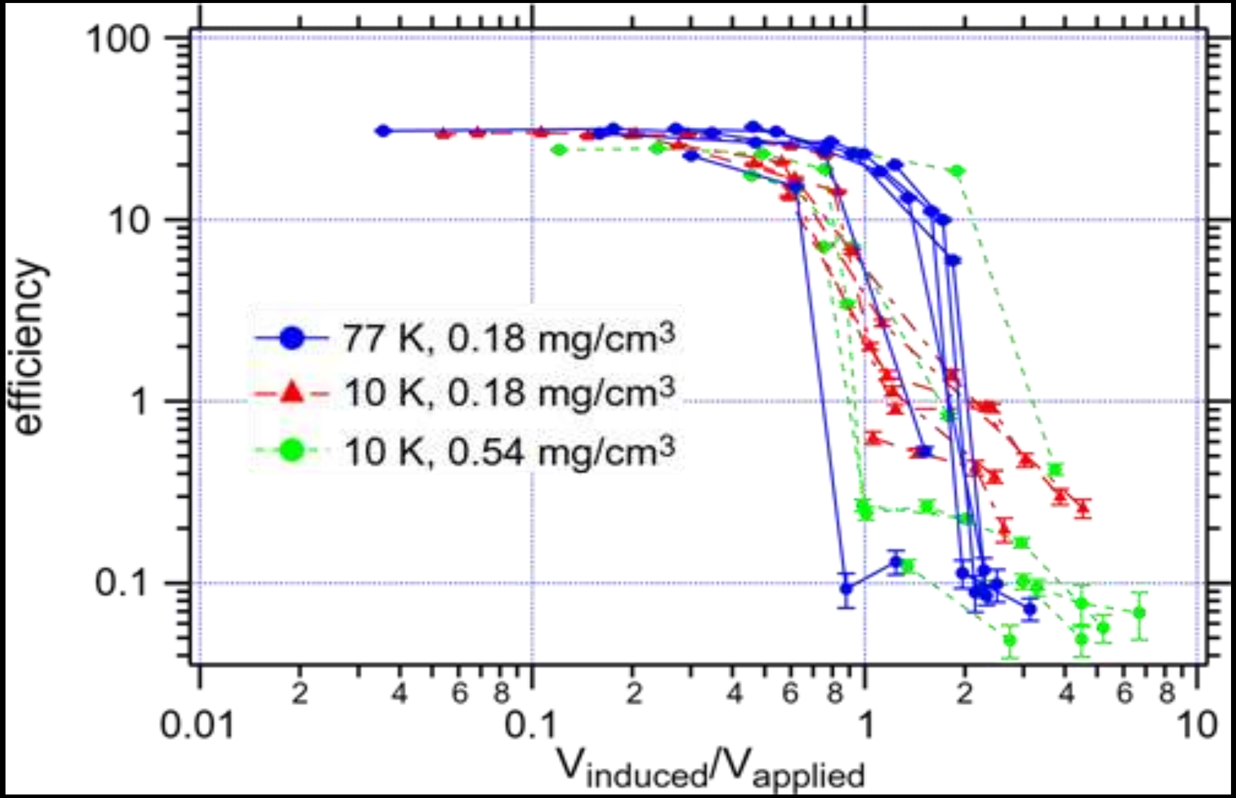
CSC Simulations: Space Charge (II)

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 $V_{ind}/V \approx 1\text{-}2$.
Field saturation sets in for $V_{ind}/V > 1$.

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



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

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

CSC Simulations: Space Charge (III)

Heavy ions trajectory: (1) stopping segment: ultra-fast (~50 ns), high KE (>20 MeV), high charge (>30$^+$)
(2) electric drift segment: slow (~several ms), low KE (~2 keV), low charge (1-2$^+$)

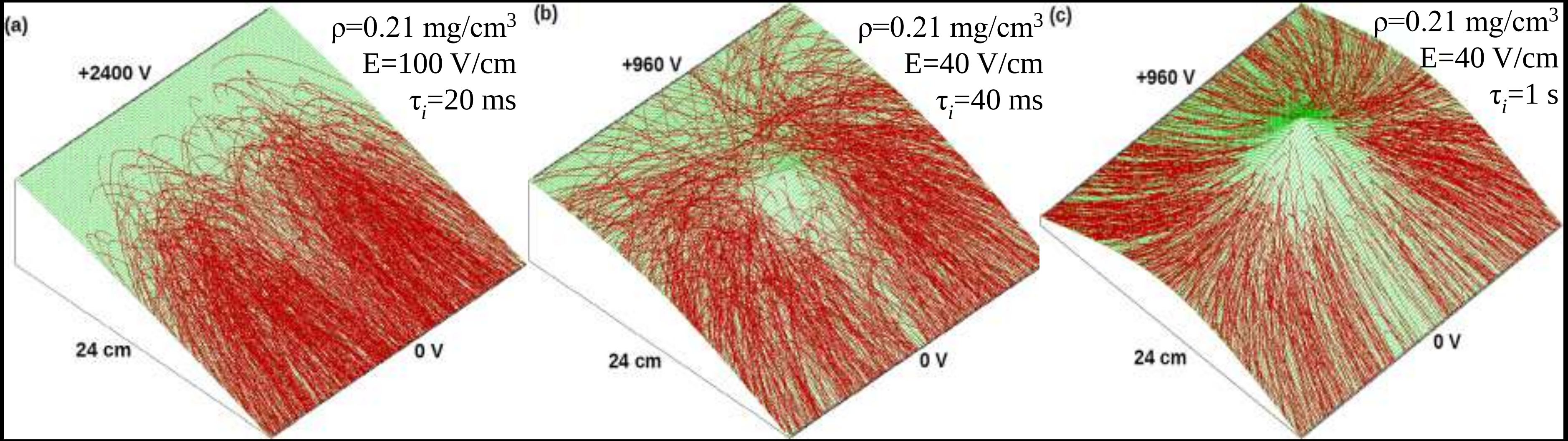
SIMION 8.1 simulation in 3 steps:

1) solves the Poisson equation: $$\epsilon \nabla^2 \Phi(x,y) = -e\tau Q(x_i, y)$$

with Q(x,y) from Geant4 and DC extraction time: $\boldsymbol{\tau_i = 1.32/E}$ (+7ms along carpet)

2) drifts 4000 photofission fragments from Geant4 thru Φ(x,y)

3) obtain extraction efficiency ε and time τ. Reiterate until <10% variation: **ε = 50-85%, τ ~ 10ms**



ε=86% **<τ>=6ms**	**ε=50%** **<τ>=15ms**	**ε=29%** **<τ>=1ms**

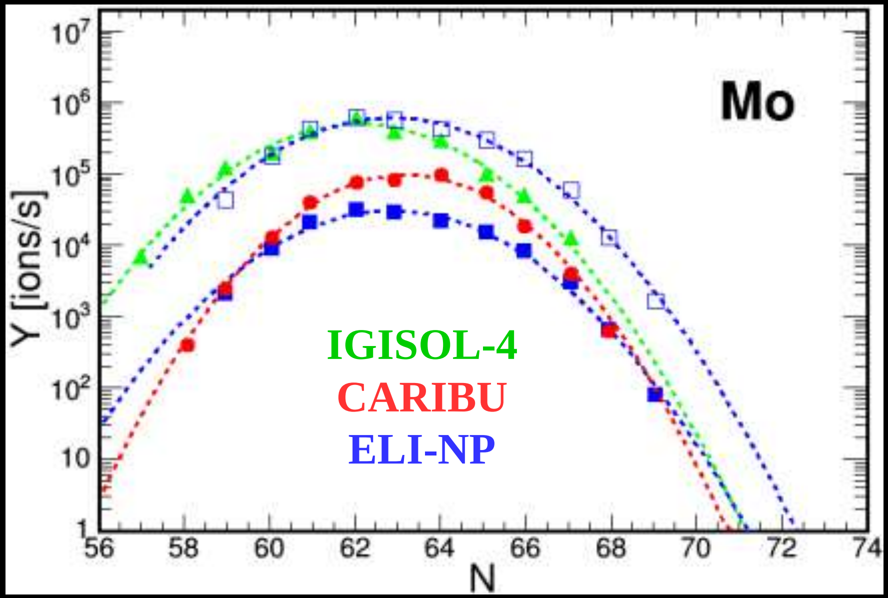
NB! IF τ<9.5ms: PULSED REGIME!

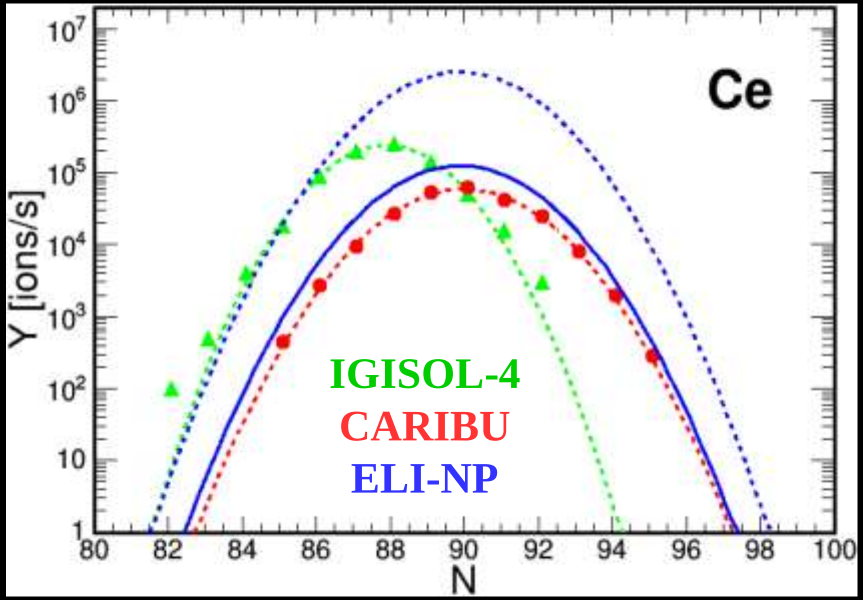
Expected Rates

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!

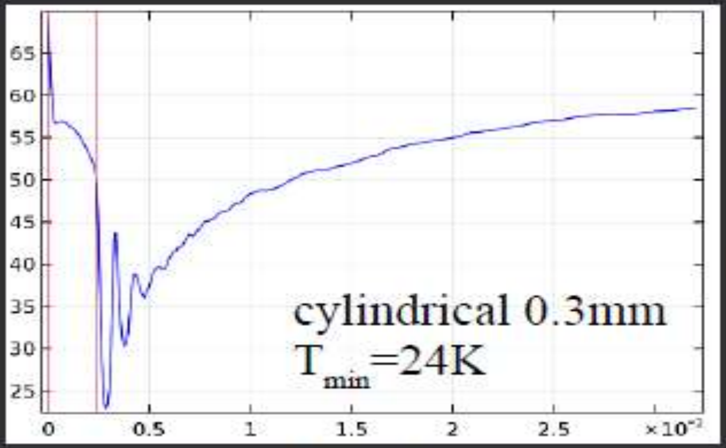




Gas jet properties and gas system design with COMSOL

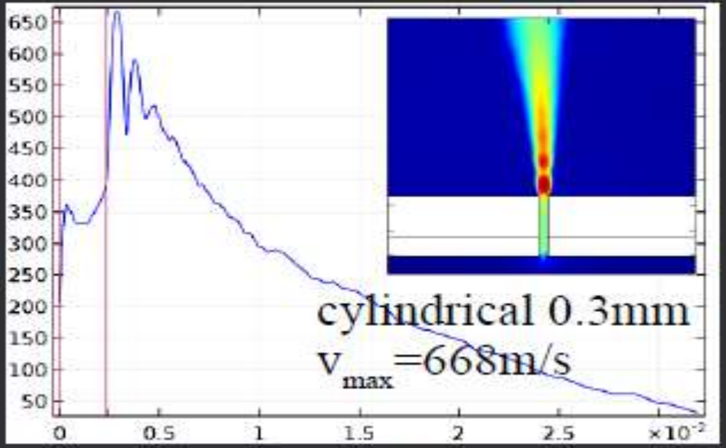
Nozzles (number, diameter, length), gas recirculation system (outlet number, diameter, location, mass flow) and cryogenic system (power) study w.r.t. the properties of the supersonic gas jets.
COMSOL modules: Computational Fluid Dynamics, Heat Transfer, Particle Tracing

T [K]



x [mm]

v [m/s]

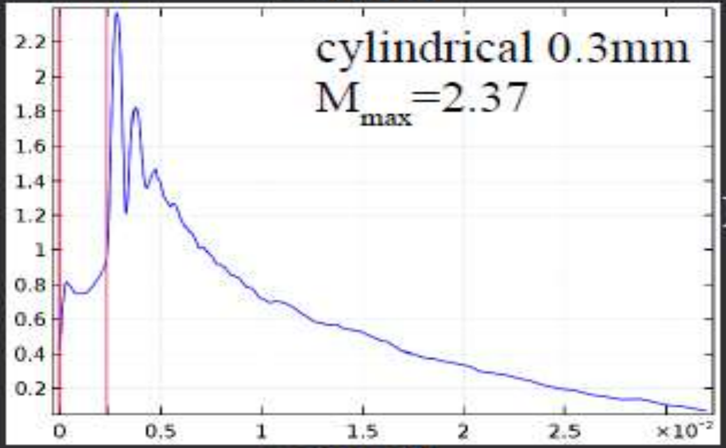


x [mm]

results from Alex & Mihai

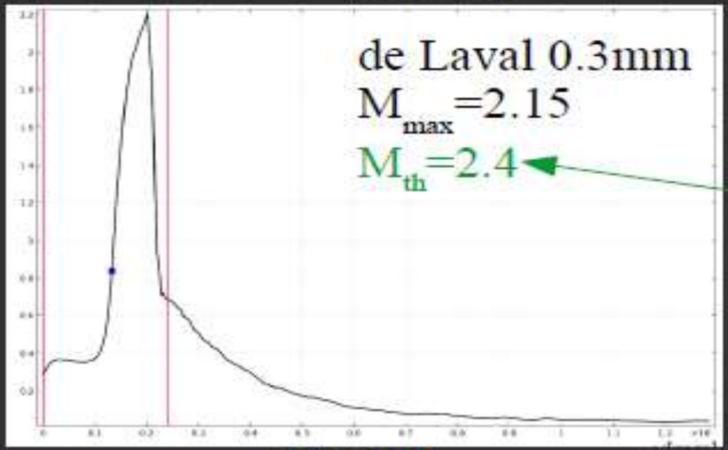
$$M = \frac{v}{\sqrt{\gamma R T}}$$

M

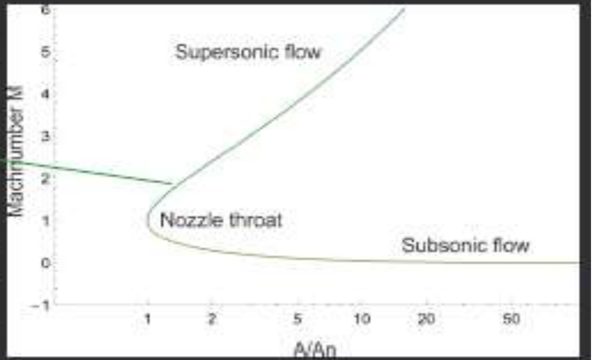


x [mm]

M



x [mm]

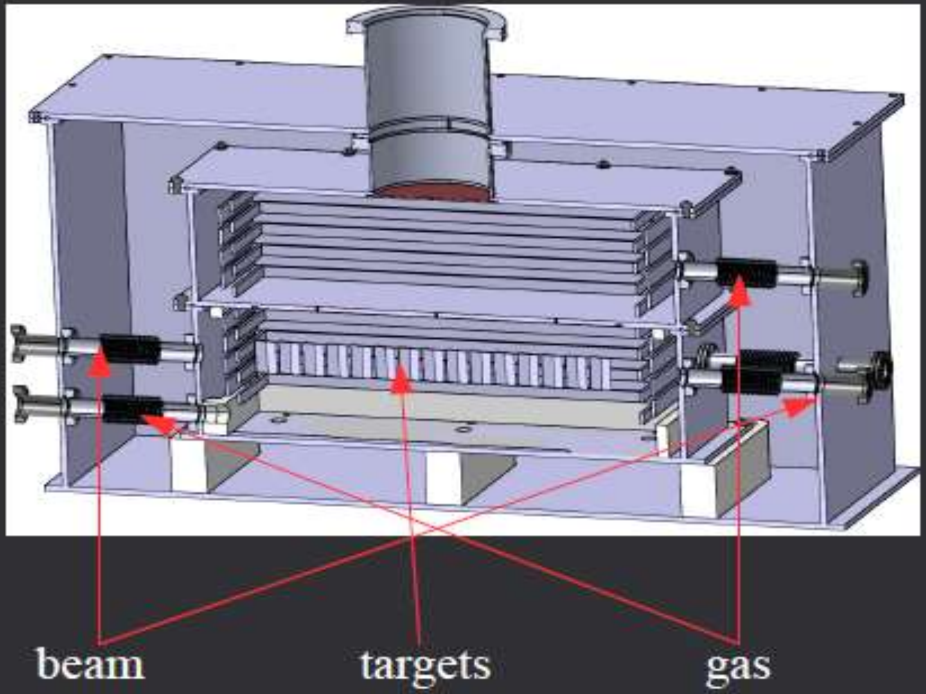


Current developments

Design of the main CSC components:
– target system
– gas recirculation and purification system
– cryogenic system
– electrode system (RF carpets) for ion drift

A CSC demonstrator to test these systems:
– visualize and optimize gas flow
– test offline & online ion extraction

CAD by Adrian



Summary

- the instrumentation of the ELI-NP GBS experimental program is been implemented according to the project timeline;
- the physics cases, which will be addressed, have been prepared within a broad scientific community;
- commissioning and day-one experiments are currently under discussion;
- the ELI-NP GBS is expected to provide beam to the users in 2020.

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

www.eli-np.ro

Project co-financed by the European Regional Development Fund

Thank you!