EUROPEAN UNION

GOVERNMENT OF ROMANIA

Structural Instruments 2007-2013

IFIN-HH

eli Nuclear Physics

# Perspectives in Nuclear Physics at ELI–NP

NUSPIN 2016 Workshop
June 27 – July 1, 2016
San Servolo, Venice

Călin A. Ur
for the ELI–NP Team

# Extreme Light Infrastructure – Nuclear Physics

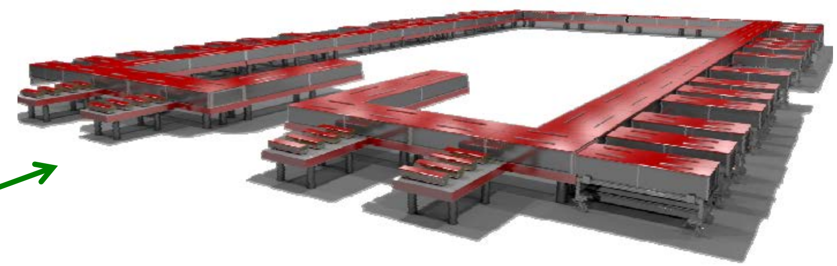
**Nuclear Physics research with extreme electromagnetic fields**

**Part of the Extreme Light Infrastructure pan–European Research Center**

**Based on the National Physics Platform in Magurele (Bucharest)**

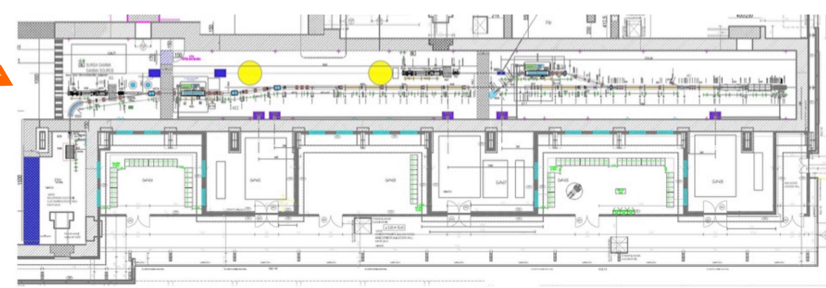
**Host for two major systems**

**2 x 10 PW High–Power Lasers System**



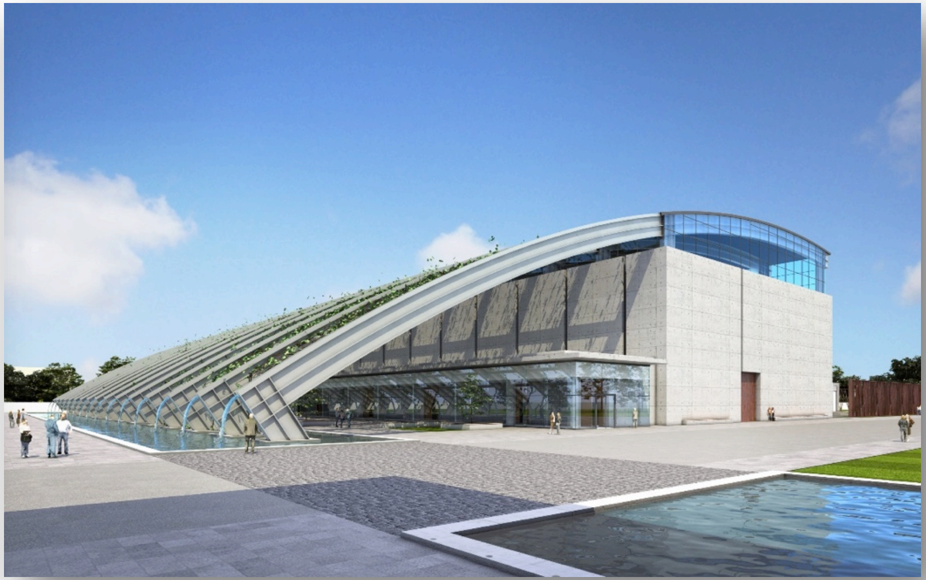
*Thales Optronique*

**High Brilliance Gamma Beam System**



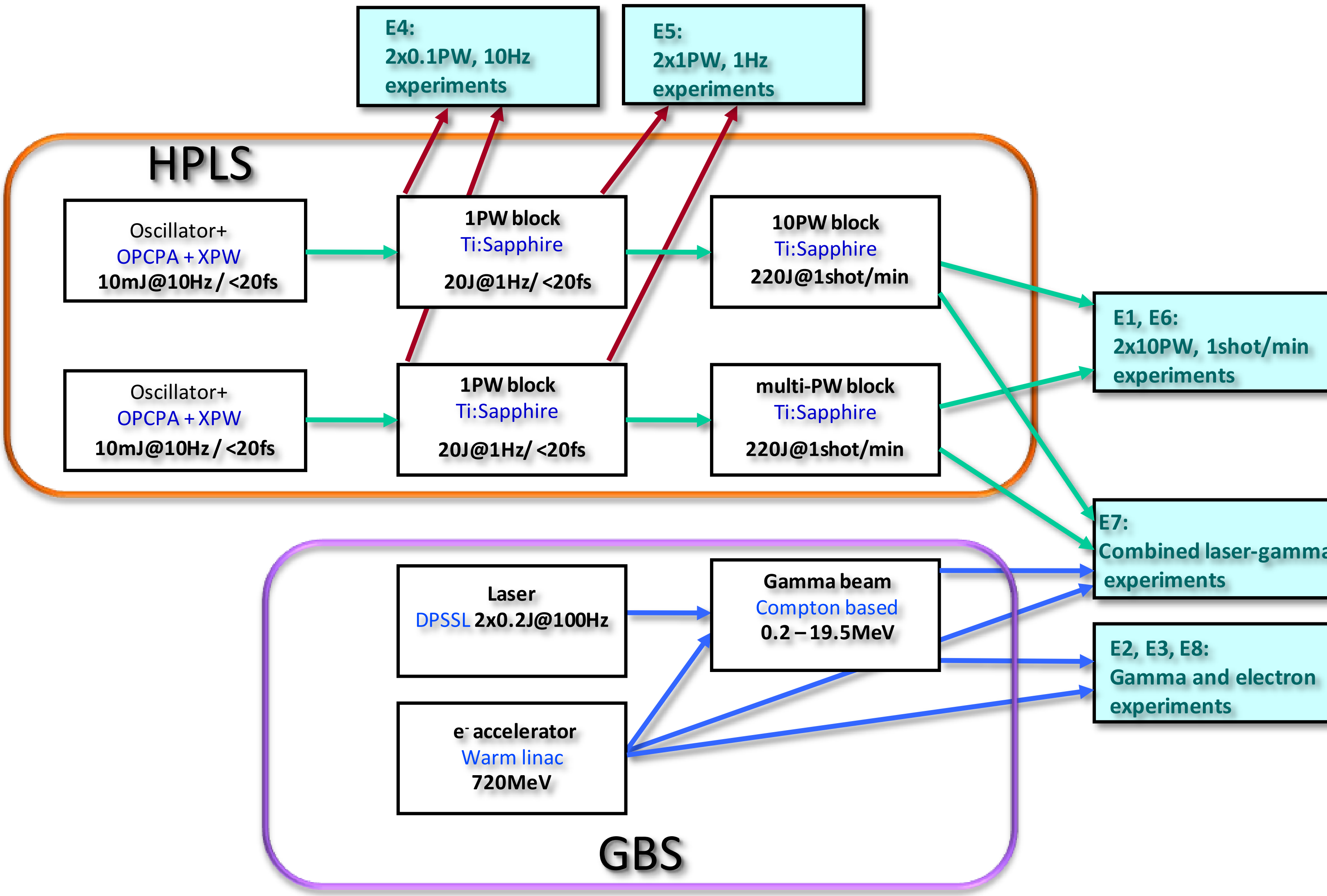
*EuroGammaS Association*

# ELI–NP –Building Status

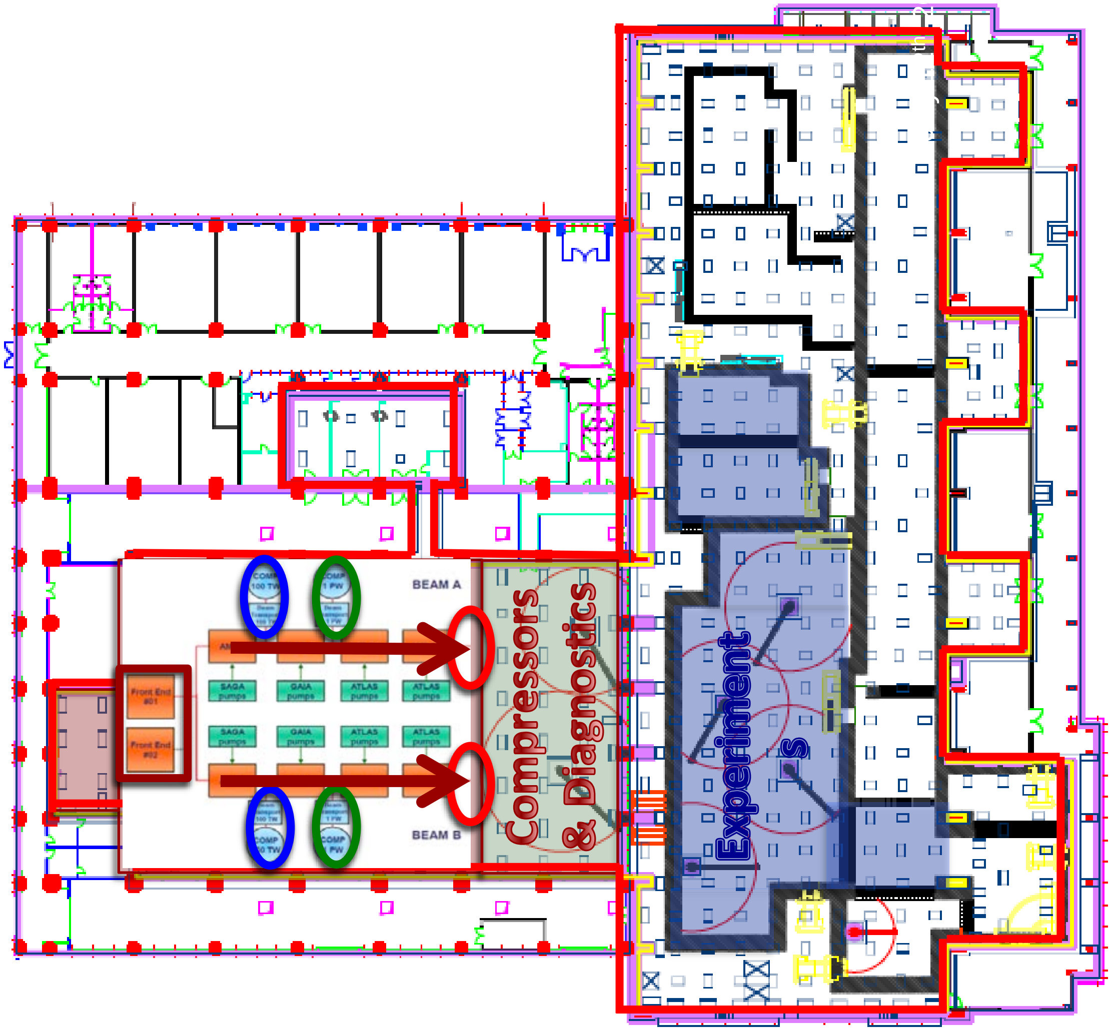


# ELI–NP –Building Status – April 2016

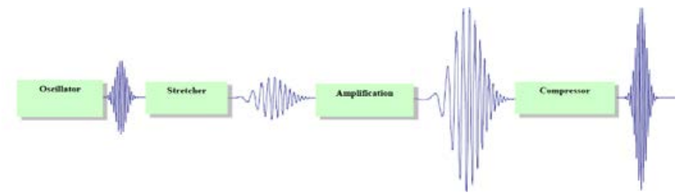
# Extreme Light Infrastructure – Nuclear Physics



# The High–Power Laser System 2 x 10 PW




*APOLON–type HPL based on OPCPA*




HPLS architecture
- dual front–end
- two arms

→ 6 outputs

*2 x 0.1 PW 10Hz*

*2 x 1 PW 1Hz*

*2 x 10 PW 0.1Hz*

# The High–Power Laser System 2 x 10 PW

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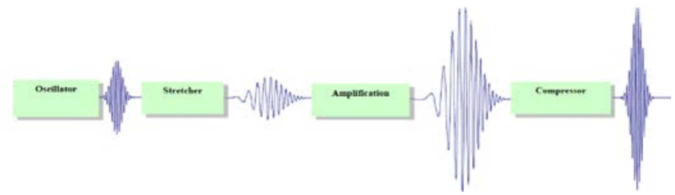
*based on OPCPA*

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- dual front–end
- two arms

→ 6 outputs

*2 x 0.1 PW 10Hz*

*2 x 1 PW 1Hz*

*2 x 10 PW 0.1Hz*

*Provided by THALES Optronique & Thales Romania*

# ELI–NP HPLS Parameters

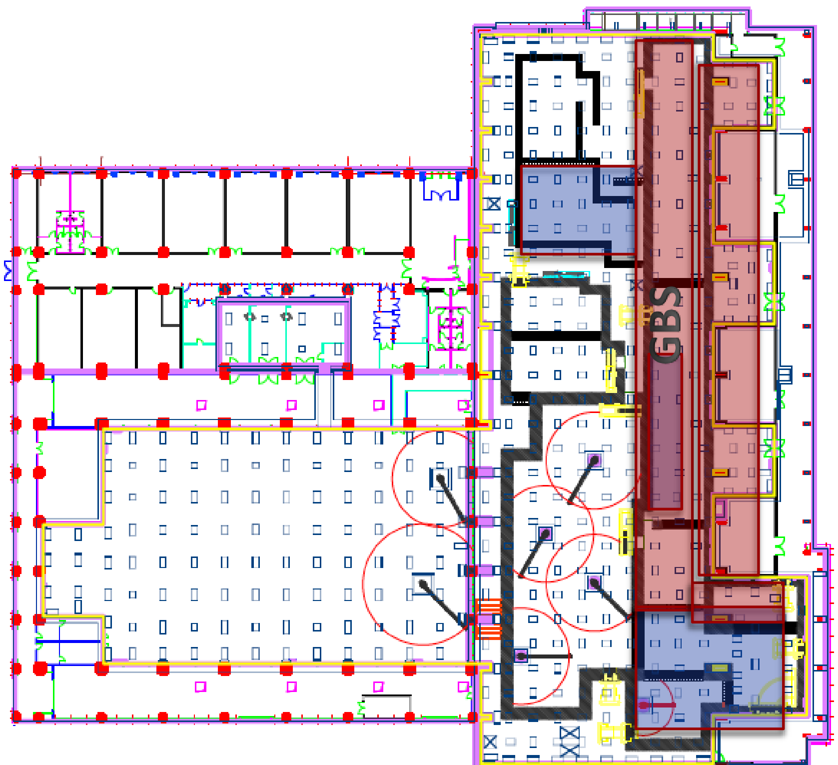
| | min | max | unit |
|---|---|---|---|
| Energy/pulse | 150 | 225 | J |
| Central wavelength | 814 | 825 | nm |
| Spectral bandwidth (FWHM) | 55 | 65 | nm |
| Spectral bandwidth (at nearly zero level of intensity) | 120 | 130 | nm |
| Pulse duration (FWHM) | 15 | 22.5 | fs |
| FWHM beam diameter/Full aperture beam diameter | 450/550 | | mm |
| Repetition rate | 1 | | pulse/min |
| Strehl ratio | 0.8 | 0.95 | |
| Pointing stability | 2 | 5 | µrad |
| Beam height to the floor | 1500 | 1510 | mm |

Intensity ~$10^{24}$ W/cm$^2$

# ELI–NP Gamma Beam System

## System with outstanding key features

**high peak brilliance** *(>$10^{21}$ ph/s · mm$^2$ · mrad$^2$ · 0.1%bwd)*, **high spectral density** *(> 0.5 · $10^4$ ph/s · eV)*, **tunable energy** *(0.2 – 19.5 MeV)*, **quasi–monochromatic** ***(relative bandwidth < 0.5%)***, **high degree of linear**




# ELI–NP Gamma Beam System

**Provider – EuroGammaS Association**

**Academic Institutions**
INFN (Italy), Sapienza University (Italy), CNRS (France)
**Industrial Partners**
ACP Systems (France), ALSYOM(France),
COMEB (Italy), ScandiNova Systems (Sweden)


**… and sub – contractors**

**Academic Institutions**
STFC (UK), ALBA Cell (Spain)

**Industrial Partners**
Amplitude Systems (France), Amplitude Technologies (France), Cosylab (Slovenia),
Danfysik (Denmark), Instrumentation Technologies (Slovenia), M&W Group (Italy),
Research Instruments (Germany), Toshiba (Japan)

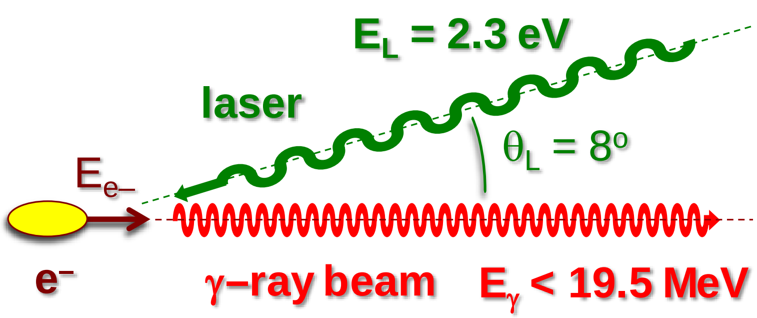
# E**L**I–NP Gamma Beam Features

| | |
|---|---|
| Energy (MeV) | 0.2 – 19.5 |
| Spectral Density (ph/s·eV) | > $0.5 \cdot 10^4$ |
| Bandwidth rms (%) | ≤ 0.5 |
| # photons per pulse within FWHM bdw. | ~$10^5$ |
| # photons/s within FWHM bdw. | $10^8$ – $10^9$ |
| Source rms size (μm) | 10 – 30 |
| Source rms divergence (μrad) | 25 – 200 |
| Peak brilliance ($N_{ph}$/sec·mm$^2$·mrad$^2$·0.1%) | $10^{20}$ – $10^{23}$ |
| Radiation pulse length rms (ps) | 0.7 – 1.5 |
| Linear polarization (%) | > 95 |
| Macro repetition rate (Hz) | 100 |
| # pulses per macropulse | 32 |
| Pulse–to–pulse separation (nsec) | 16 |

**Two stage system:**

**Low–energy stage: E$\gamma$ < 3.5 MeV**

**High–energy stage: E$\gamma$ < 19.5 MeV**



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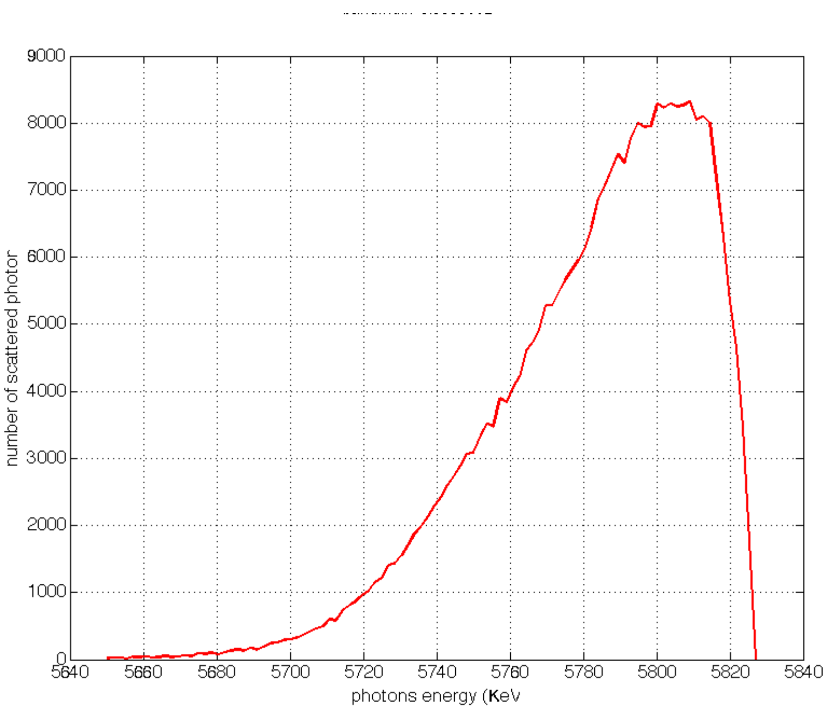

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**Two stage system:**

**Low–energy stage: Eγ < 3.5 MeV**

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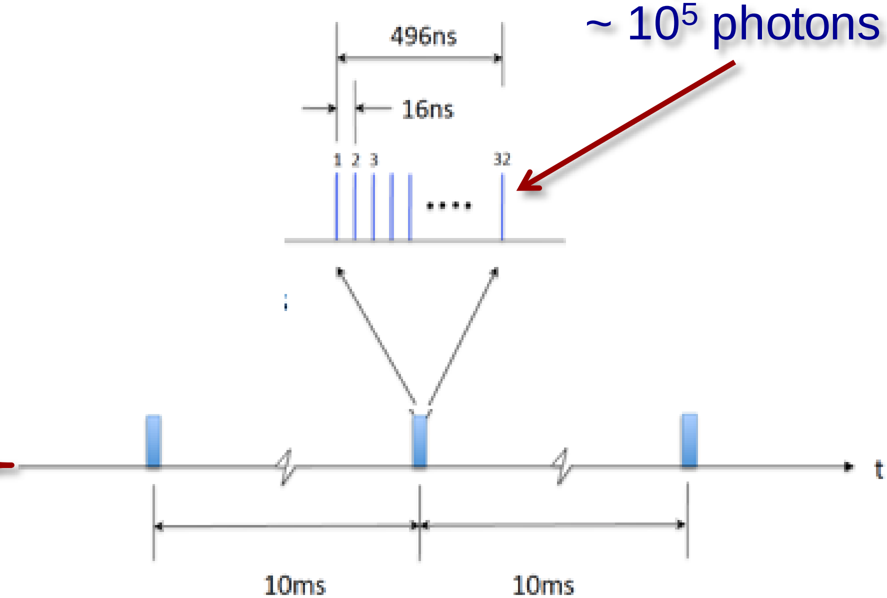
One pulse
~ 1 ps
~ $10^5$ photons



# ELI–NP Building the Experiments

## White Book ⟹ Day–1 Experiments

**Towards TDR of experiments with intense laser beams at ELI-NP**
**June 27-28, 2013 – Bucharest-Magurele (Romania)**

**Towards TDR of experiments with brilliant gamma-ray beams at ELI-NP**
**July 25-26, 2013 – Bucharest-Magurele (Romania)**

- *building the main working groups*
- *conveners and local liaisons*

**ELI-NP TDRs at Midway – High Power Laser March 16-17, 2014 – Bucharest-Magurele (Romania)**

**ELI-NP TDRs at Midway – SystemGamma Beam System**
**March 16-17, 2014 – Bucharest-Magurele (Romania)**

- *added new working groups*
- *applied physics*

**ELI-NP Science Program and Instruments: Technical Design Reports**
**February 18-20, 2015 – Bucharest-Magurele (Romania)**

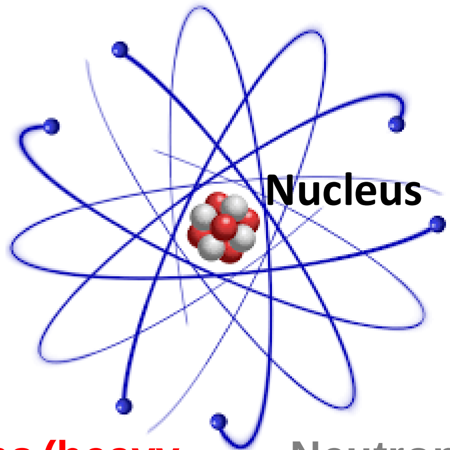
- *final TDRs*
- *definition of the experimental setups*

**June 2015 – Scientific evaluation of the TDRs by ISAB**

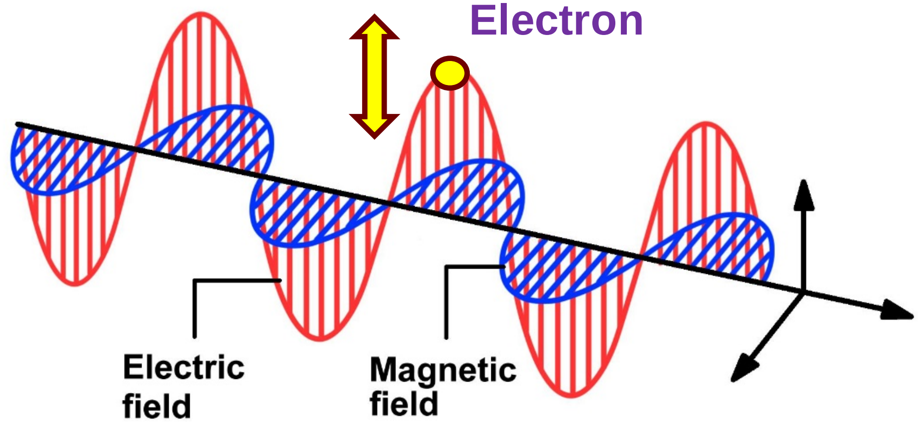
# Research with high–power lasers at ELI – NP

- **Nuclear physics experiments with Lasers:**
  - Nuclear physics requires particles accelerated at tens of millions of Volts
  - In conventional accelerators few particles accelerated over km distances
  - Extreme intensity lasers can accelerate trillions of particles over cm distances
- **Research:**
  - Nuclear reactions that happen only in stars
  - Nuclear reactions for energy storage ("nuclear batteries")
  - Nuclear beams and isotopes for radiotherapy
  - Ultra-bright X, gamma, and neutron beams for industrial and medical uses
- **High-Field Quantum Electrodynamics (QED) with Lasers:**
  - QED is quantum theory of interaction of light with matter
  - Verified in linear/weakly perturbative regimes
  - ELI-NP lasers will test non-linear/strongly-perturbative regimes
- **Research:**
  - Ultrahigh energy free electrons interacting with extreme intensity light
  - Extreme light interacting with electrons in dense plasmas
  - Extreme light interacting with itself and with quantum vacuum

# Extreme Intensity Light makes extreme electric fields



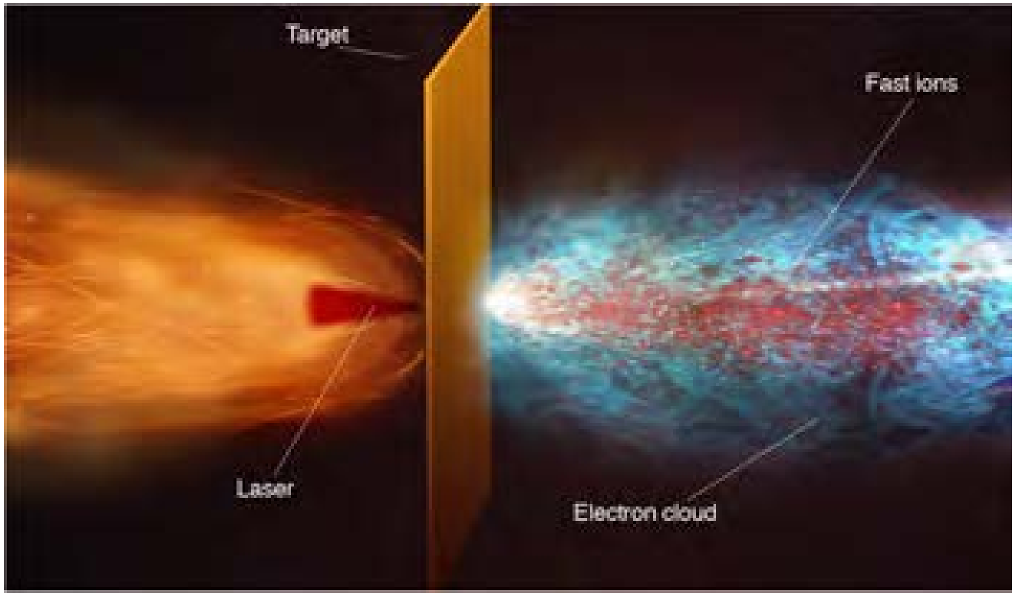

**Light is electromagnetic wave**
**Intensity = Power per unit area ($W/cm^2$)**
**Electric field proportional to Intensity$^{1/2}$**

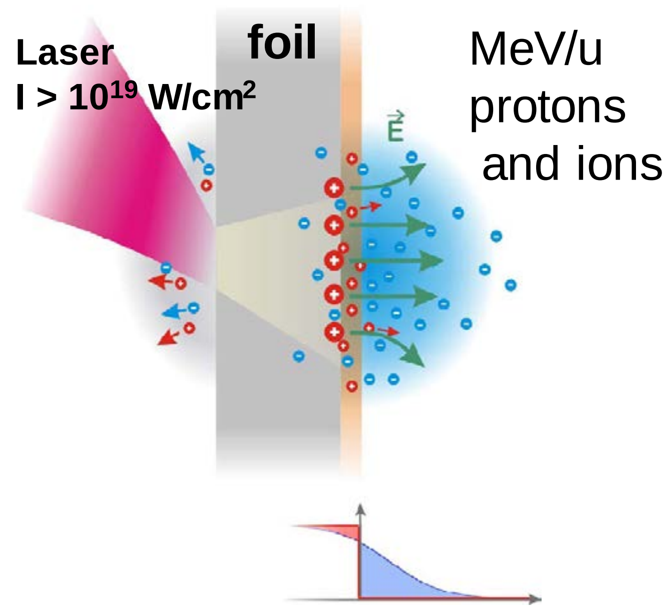



- **Electrons can be accelerated to high energy by extreme intensity light**
- **Ions follow electrons**
- **Use ultrahigh power lasers focused to μm area to produce extreme intensity light**

# Target Normal Sheath Acceleration of ions (TNSA)





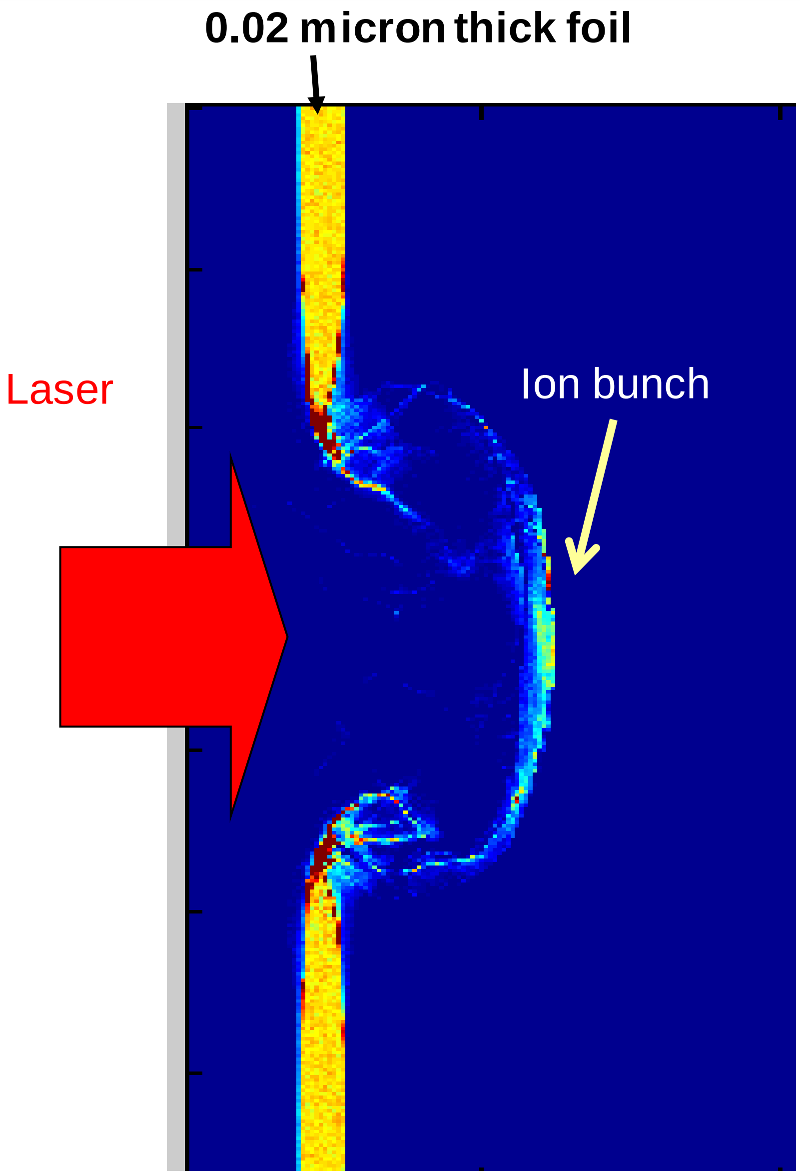

hot electron propagation
MeV energy, μC charge

**Laser pushes electrons => ions follow**

**Recent records:**

**85 MeV for protons (2016)**
**11.6 MeV/nucleonn for Al ions (2015)**

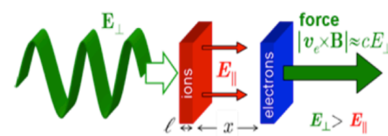
# Radiation Pressure Acceleration of ions (RPA)




- *Direct action of the ponderomotive force of the laser on the surface electrons*
- *Ultrathin targets (< 100–200 nm)*
- *Highly efficient energy conversion (> 60%)*
- *Ions and electrons accelerated as a neutral bunch → avoid Coulomb explosion*
- *Solid state beam density :*

  $10^{22} – 10^{23}$ *e/cm*$^3$

Stage 1



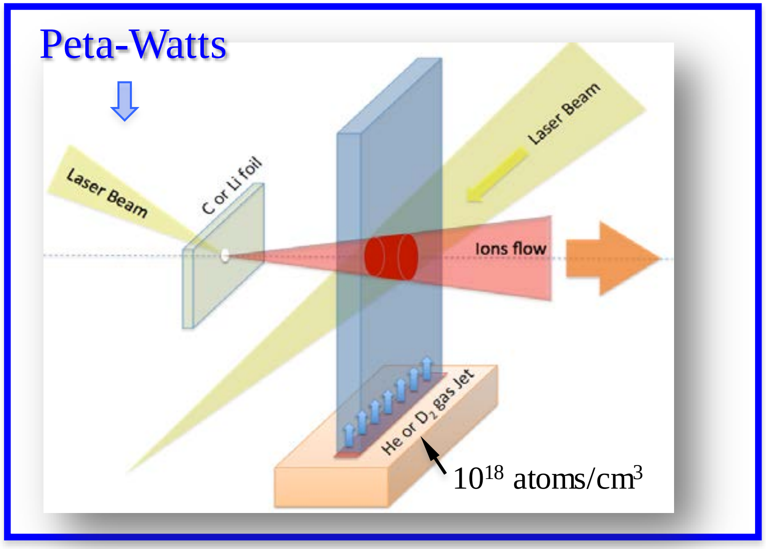

Laser field sweep away all electrons, forming an electrostatic field

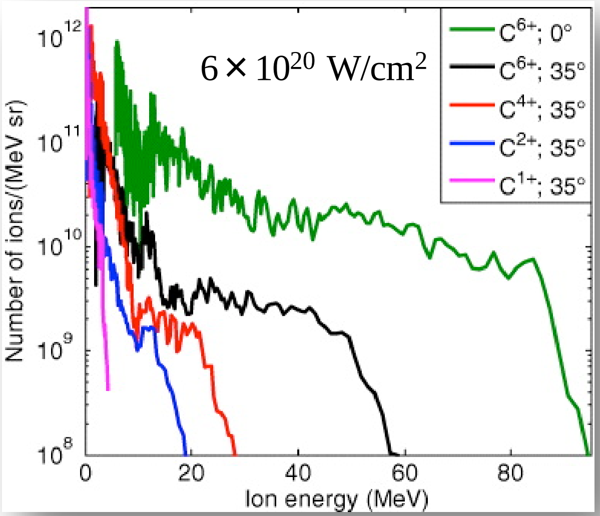
To produce 1 GeV protons in $\tau = 1$ laser period we need $I \sim 1.2\times10^{23}$ W/cm$^2$.
Ions pulled by the charge separation field move together with electrons.

**Laser pressure pushes electrons and ions as one**

# Laser Driven Nuclear Physics

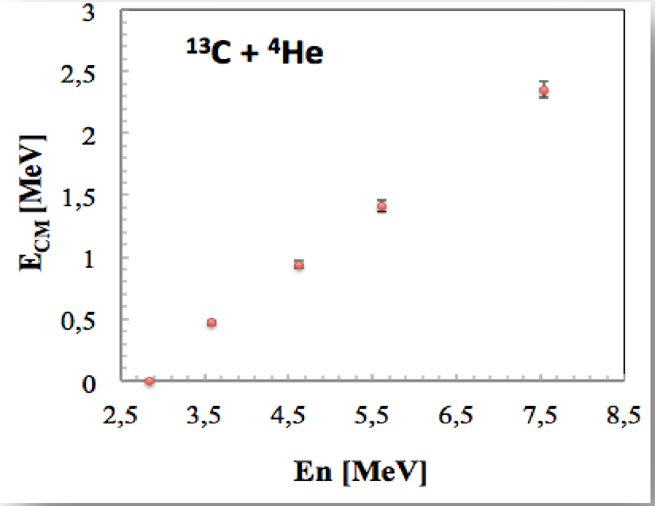
## Study of screening factor – The method and cases

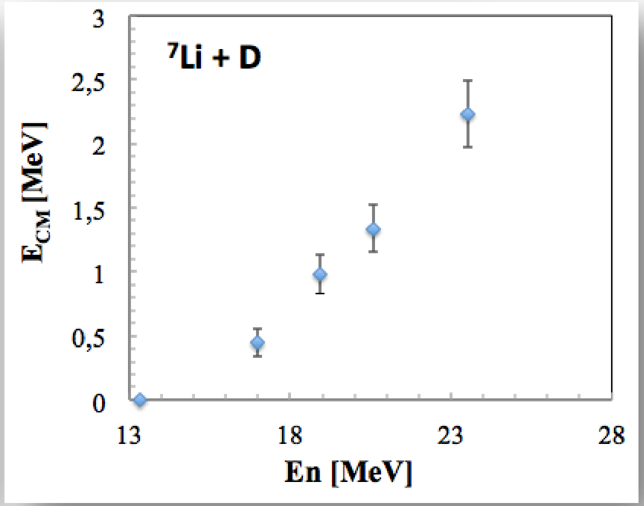



*D.C. Carrol et al., New J. of Phys. 12 (2010) 045020*

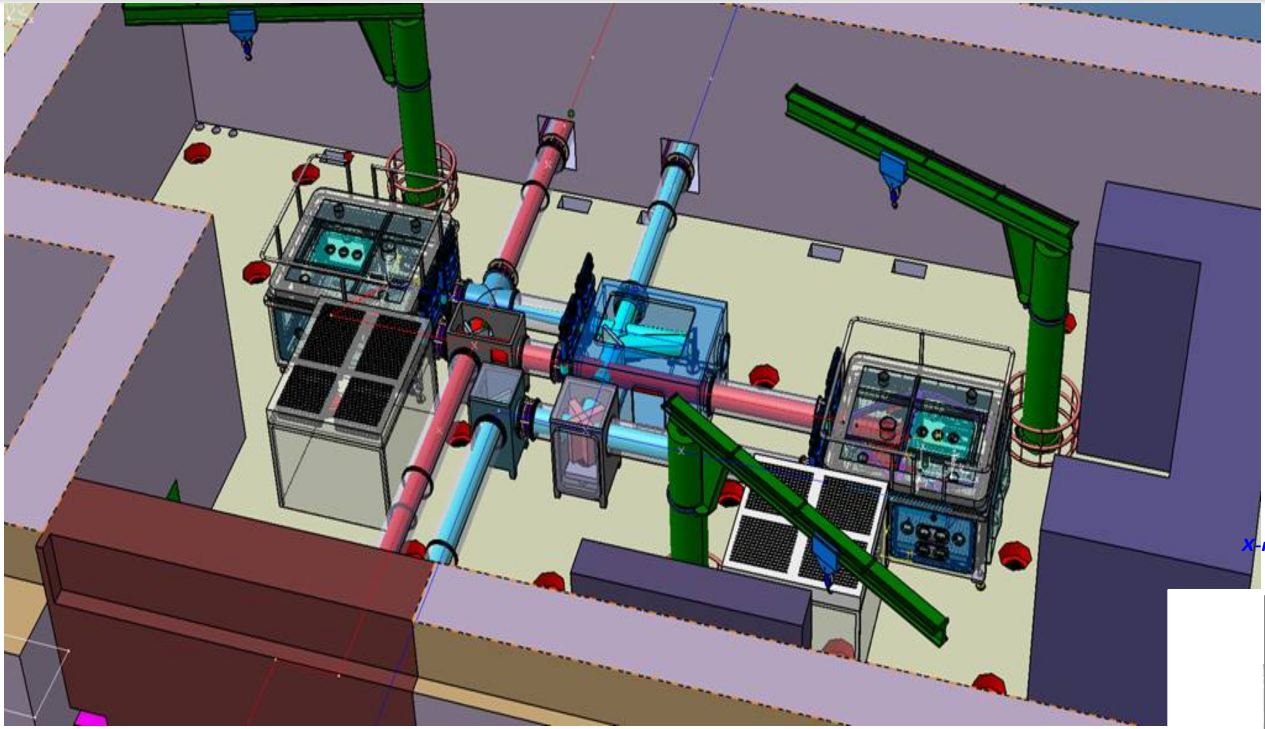
**Nuclear reaction is hot plasma created by laser beams simulating in laboratory stellar environments**



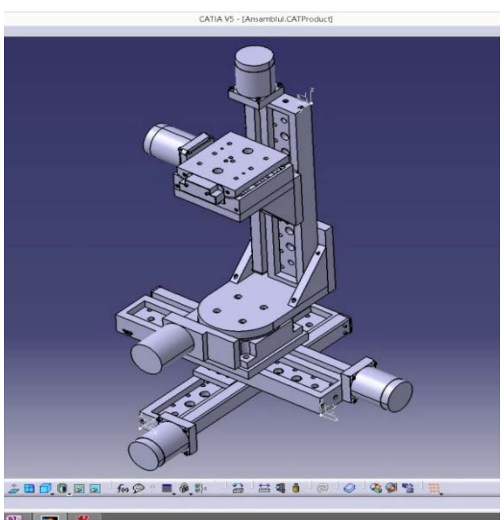




*S. Tudisco (LNS/INFN) et al.*

# Complex instrumentation

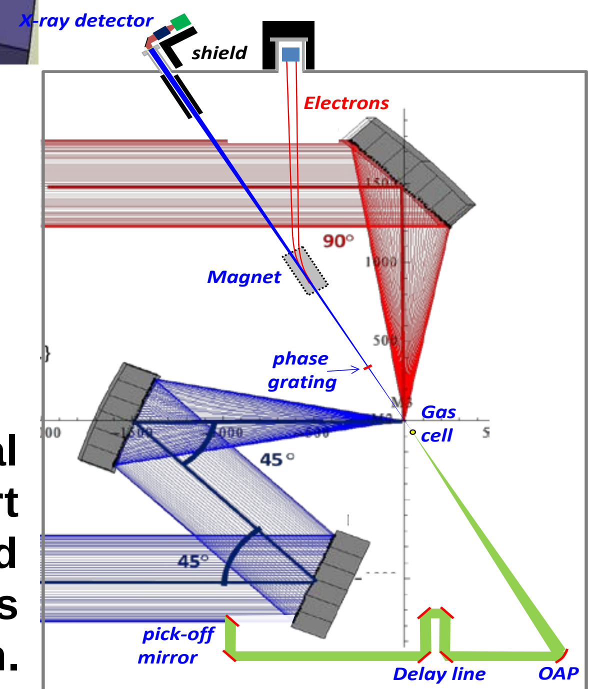


Laser transport lines and two interaction chambers each with 25 m$^3$ volume.

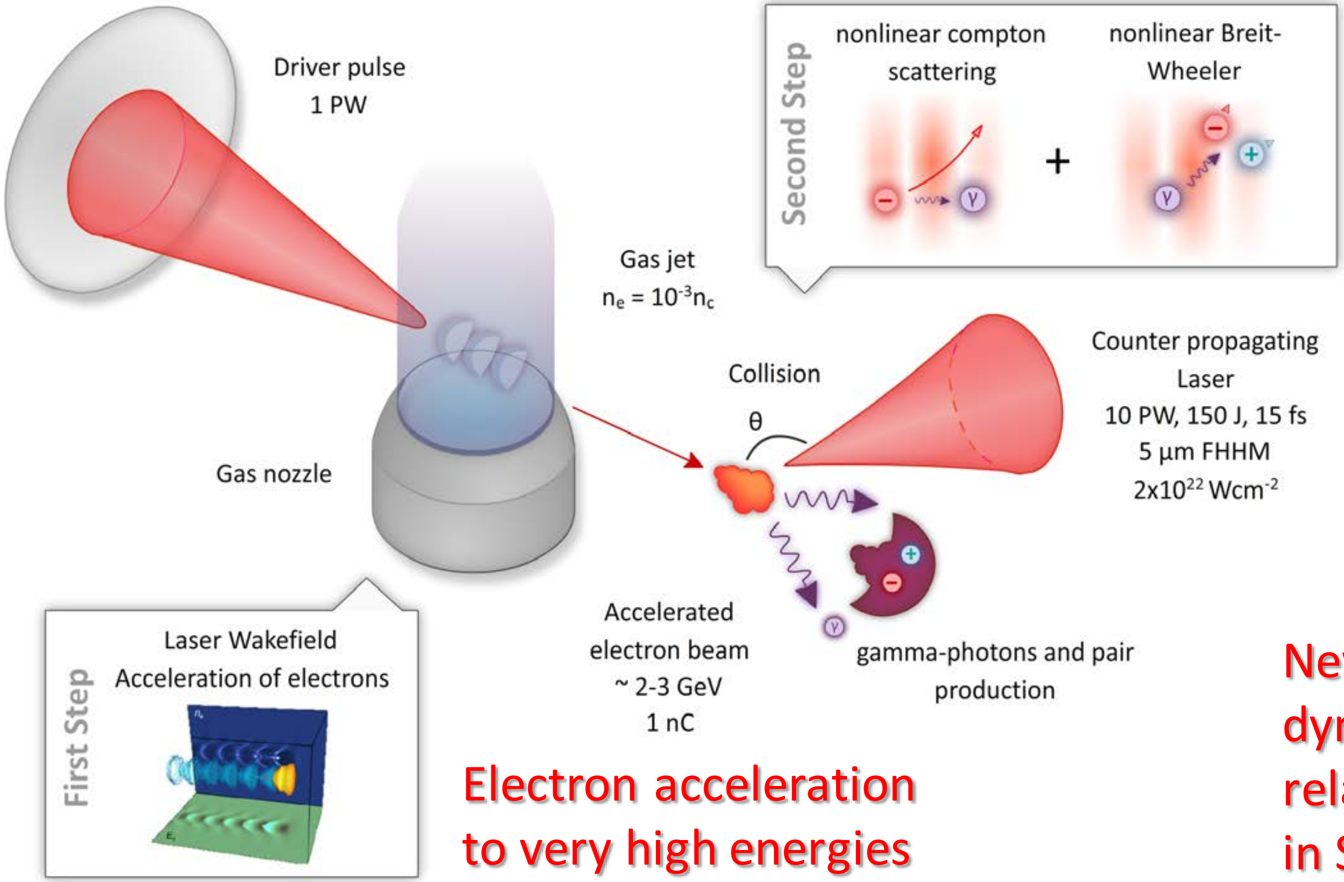


Target position system with micrometric precision.

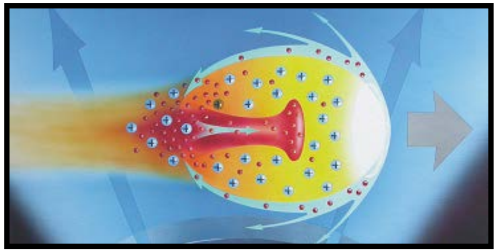
Complex experimental arrangement with short pulse, long pulse and probe beams combination.



# High Field QED

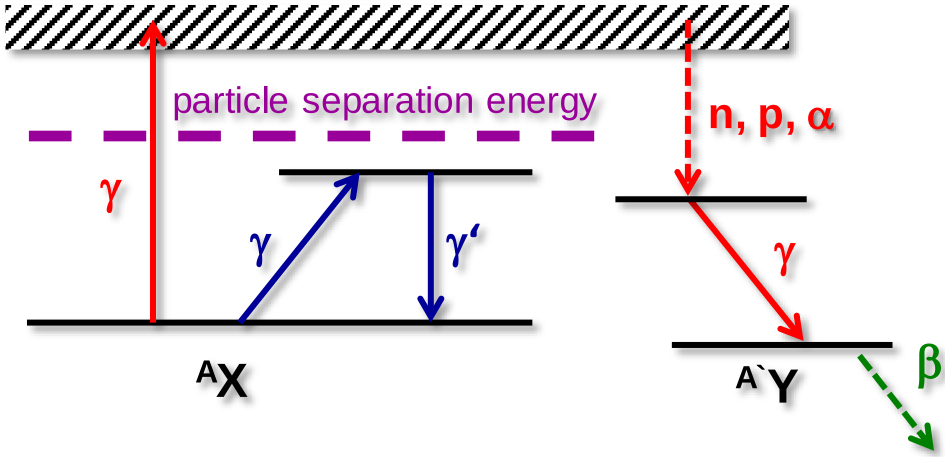



Electron acceleration
to very high energies
in few centimeters of gas



New QED effects:
dynamics of
relativistic electrons
in Strong Fields
produced by
a tightly focused
counter propagating
10 PW laser pulse

# Gamma Beam Experiments




## Photonuclear Reactions

- Nuclear Resonance Fluorescence
- Photodisintegration, Photofission
- Photoactivation

***Fundamental Research***

- Nuclear Resonance Fluorescence $(\gamma,\gamma')$
- Nuclear Astrophysics $(\gamma,p)$ $(\gamma,\alpha)$
- Photonuclear Reactions $(\gamma,n)$
- Photofission&Studies of Exotic Nuclei

***Applications***

- Gamma Imaging
- Material S
- Medical P

***R&D Gamm… …stics Detectors***

- Gamma Bea… …ivery and Diagnostics

**Broad International Collaboration**
**Germany, France, Italy, USA, Japan, Hungary, Poland, Vietnam,**
**Switzerland, UK, Russia, Israel, India, Bulgaria, Turkey, Finland,**
**………**

# Photonuclear Reactions

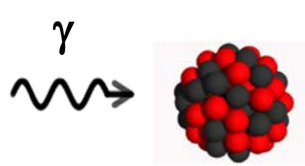
Pure EM interaction

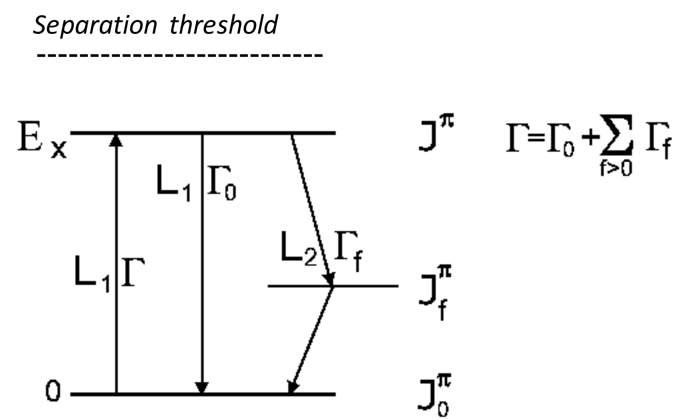
Spin selectivity (mainly E1, M1 and E2 transitions)

Strength selectivity

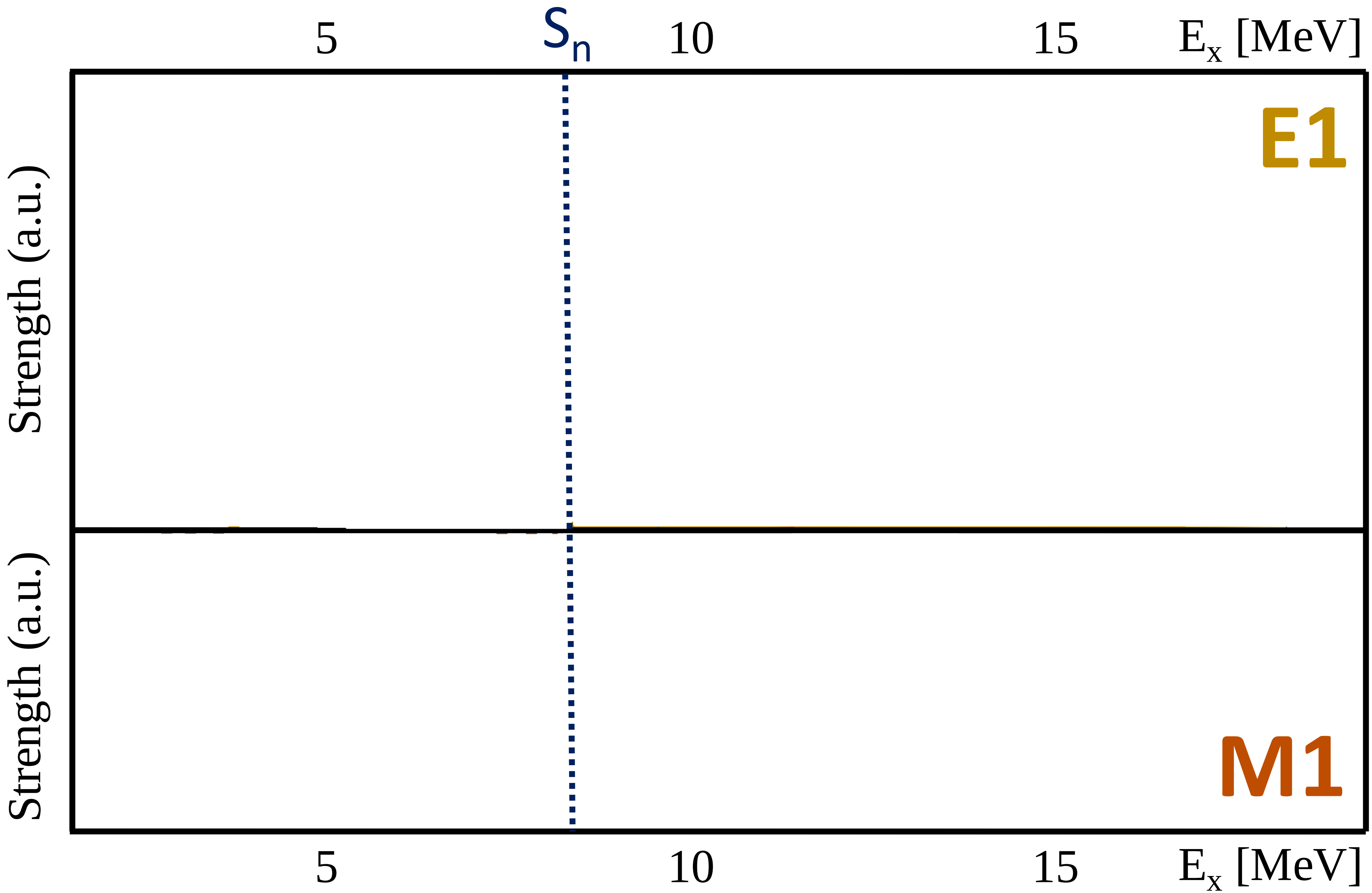
Access to nuclear observables – completely model independent

- Excitation Energy $E_r$
- Spin and parity $J, \pi$
- Decay Energies $E_\gamma$
- Partial Widths $\Gamma_i/\Gamma_0$
- Multipole Mixing $\delta$
- Decay Strengths $B(\pi\lambda)$
- Level Width $\Gamma$ (eV)



# Dipole Electromagnetic Response of Nuclei



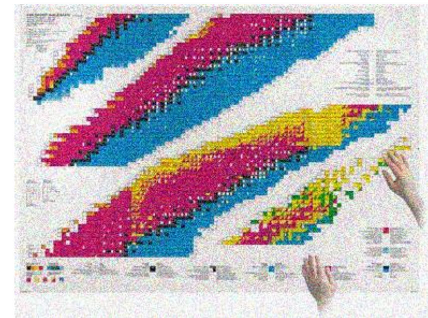
# New Discovery Frontiers for NRF at ELI–NP



## Availability frontier

access to rare isotopes

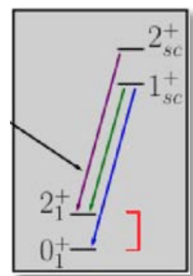
photoresponse of weakly abundant p–nuclei and actinides

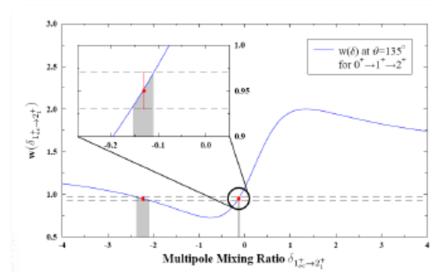


## Sensitivity frontier

weak channels

rotational 2+ states of the nuclear scissor modes

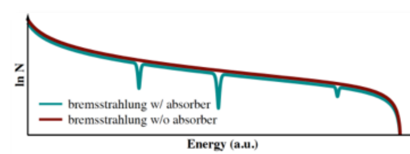


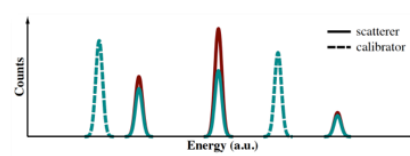




## Precision frontier

high statistics

$\Gamma_0$ and $\Gamma/\Gamma_0$ measurements

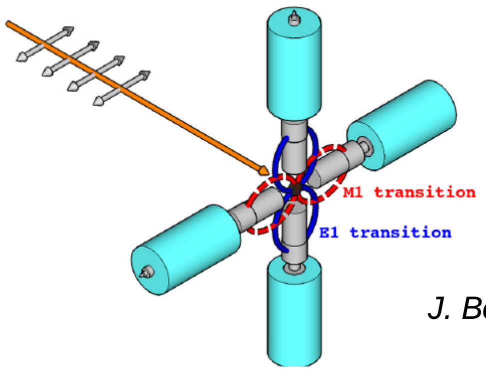


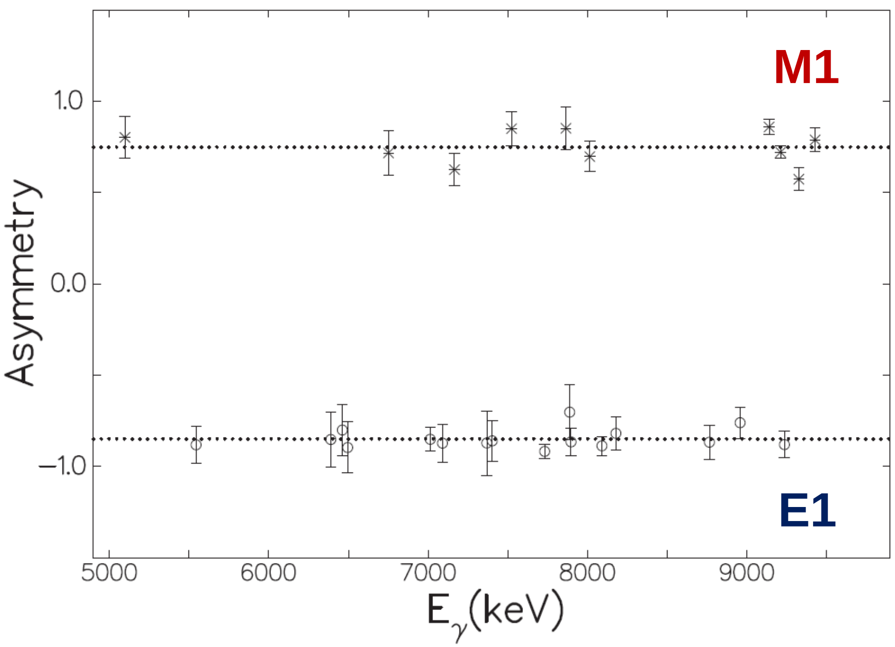
# NRF with Monochromatic Gamma Beams

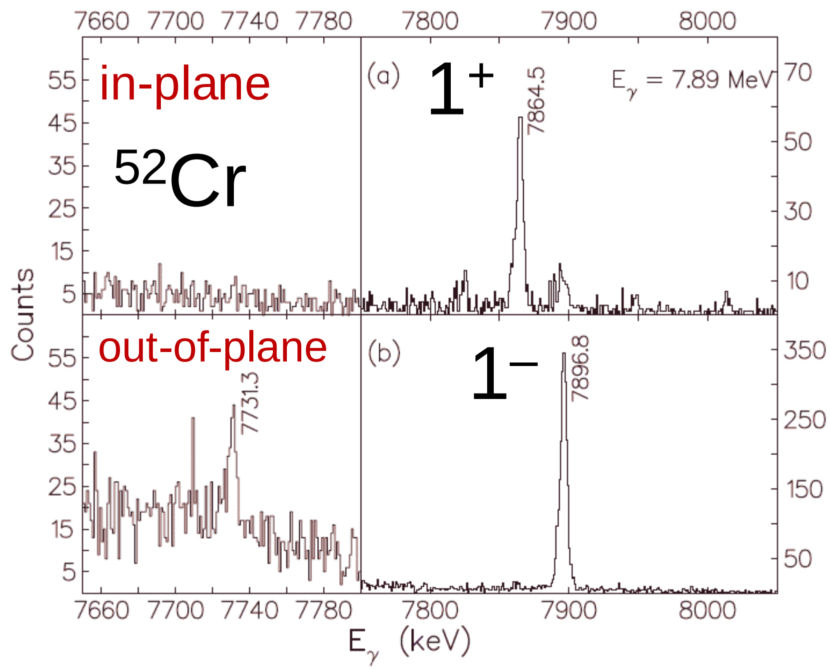


## Parity determination by measuring asymmetries




*J. Beller et al., PLB **741** (2015) 128*




*Krishichayan et al., PRC **91** (2015) 044328*

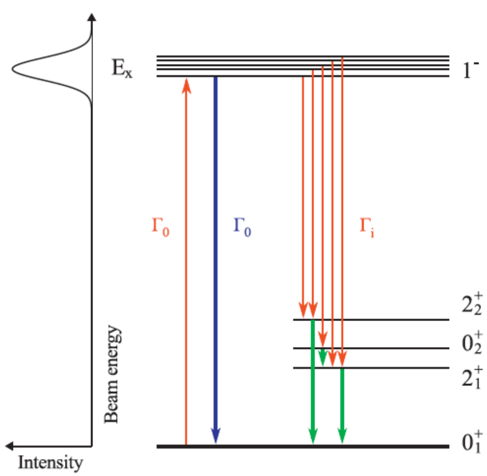
# NRF with Monochromatic Gamma Beams

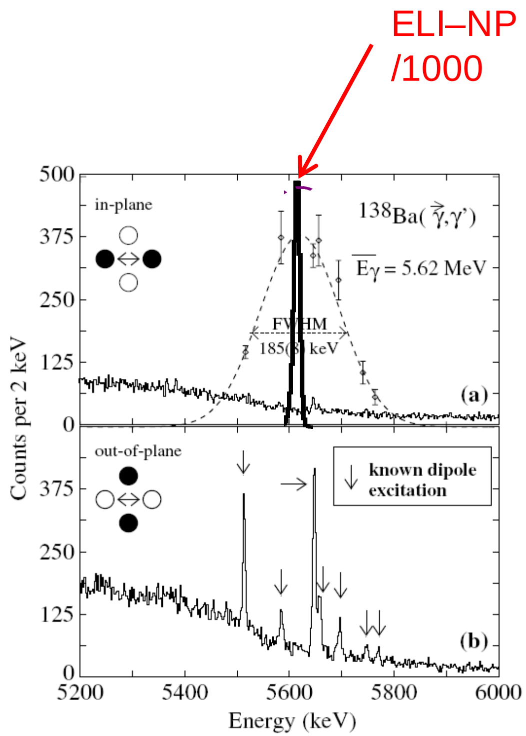
HIγS @ Duke U.

- Relative bandwidth ~ few percent
- Spectral density ~ $10^2$ ph/s/eV

ELI–NP @ Magurele

- Relative bandwidth ~ few per mille
- Spectral density ~ $10^4$ ph/s/eV




*N.Pietralla et al.*

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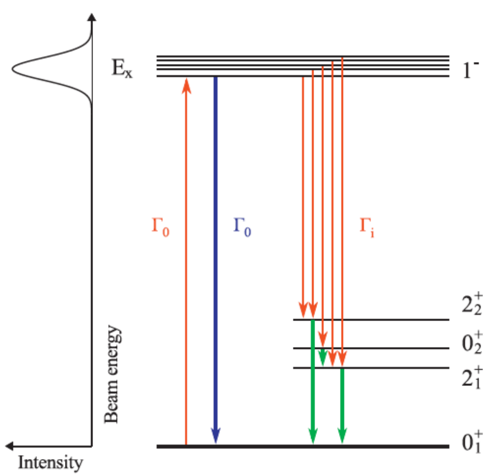


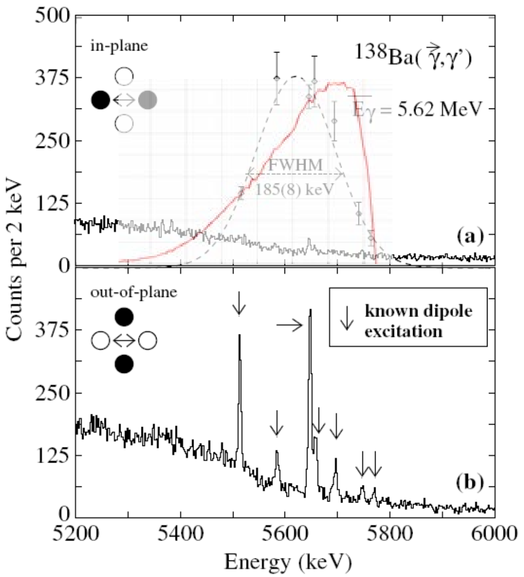


*N.Pietralla et al.*

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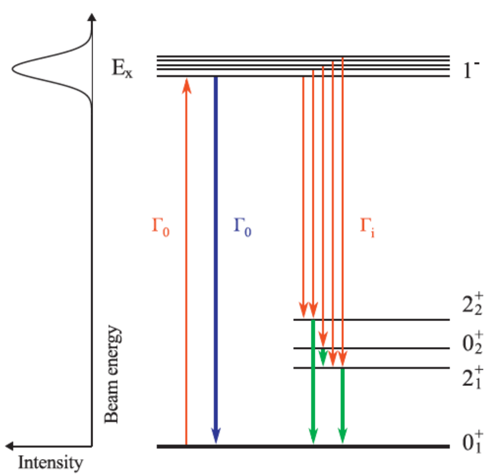
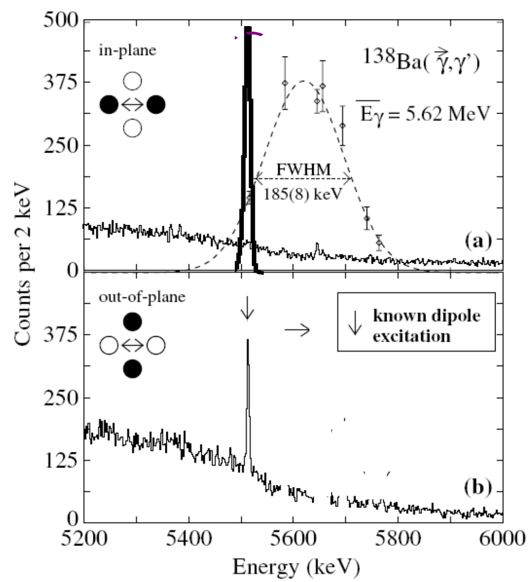



*N.Pietralla et al.*

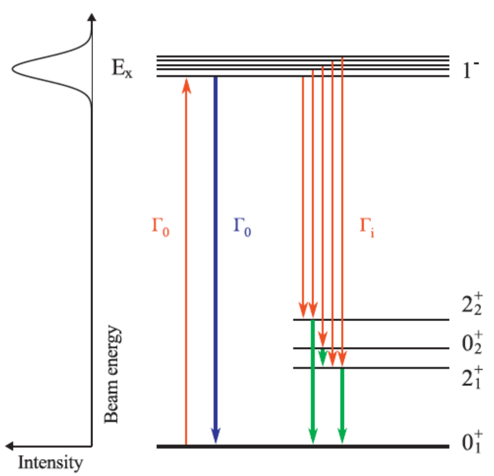
# NRF with Monochromatic Gamma Beams

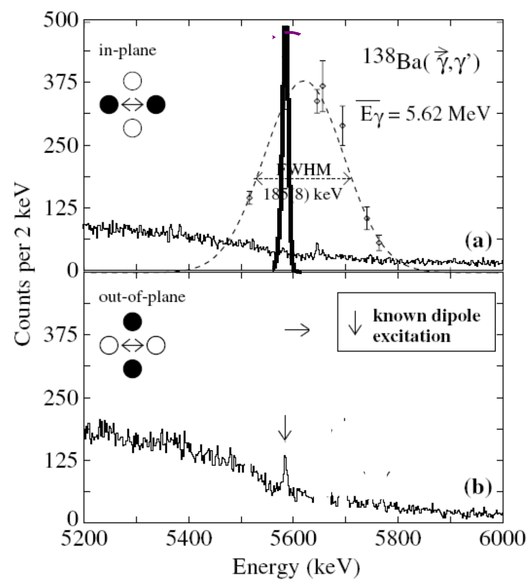
HI$\gamma$S @ Duke U.

- Relative bandwidth ~ few percent
- Spectral density ~ $10^2$ ph/s/eV

ELI–NP @ Magurele

- Relative bandwidth ~ few per mille
- Spectral density ~ $10^4$ ph/s/eV

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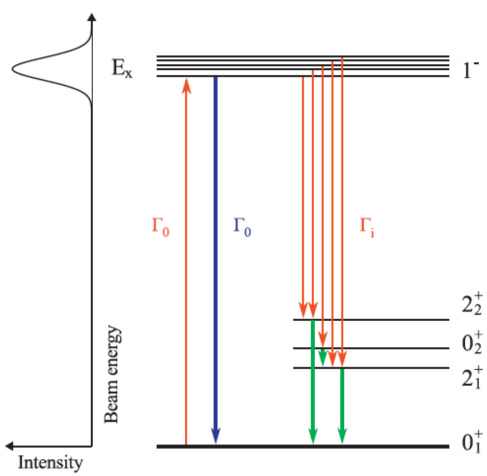


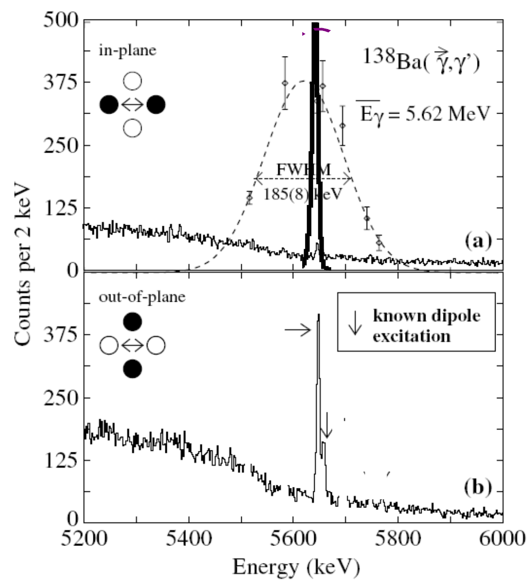


*N.Pietralla et al.*

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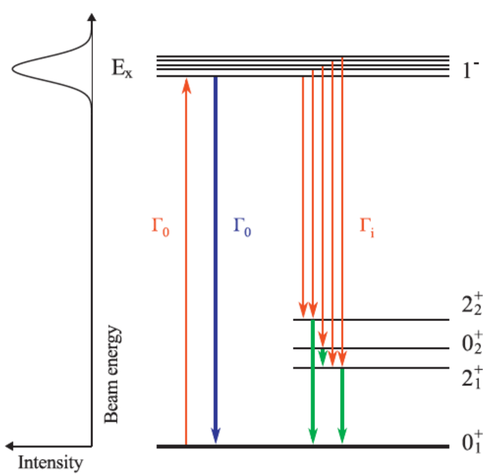


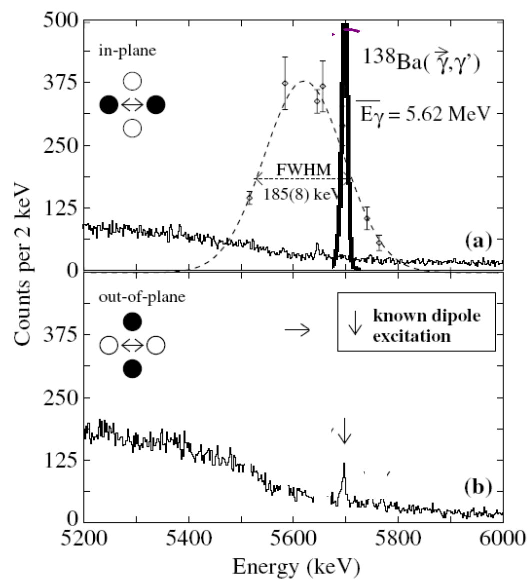


*N.Pietralla et al.*

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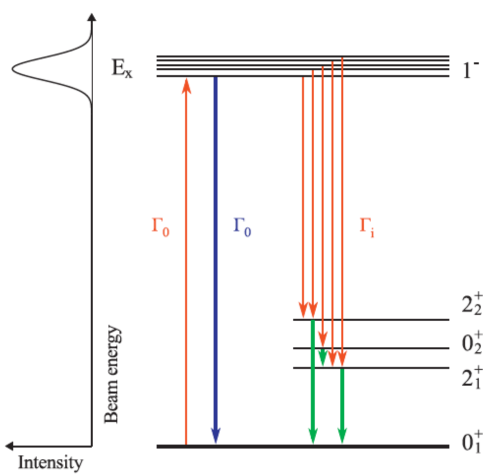
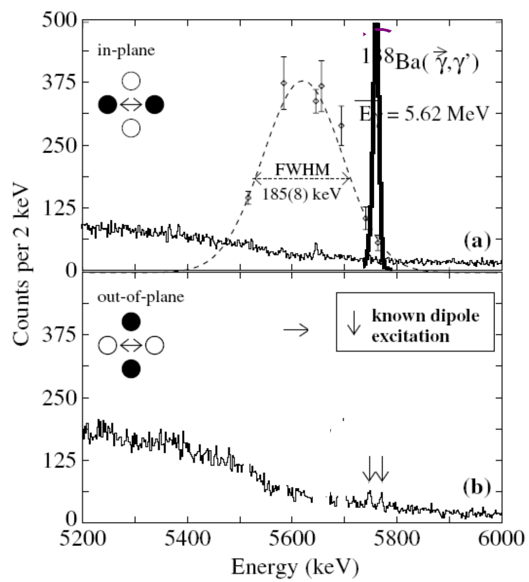


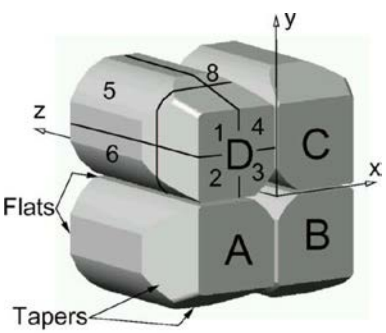

*N.Pietralla et al.*

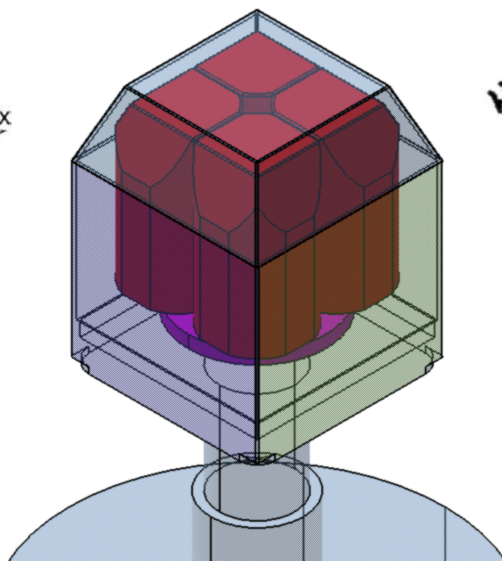
# Nuclear Resonance Fluorescence

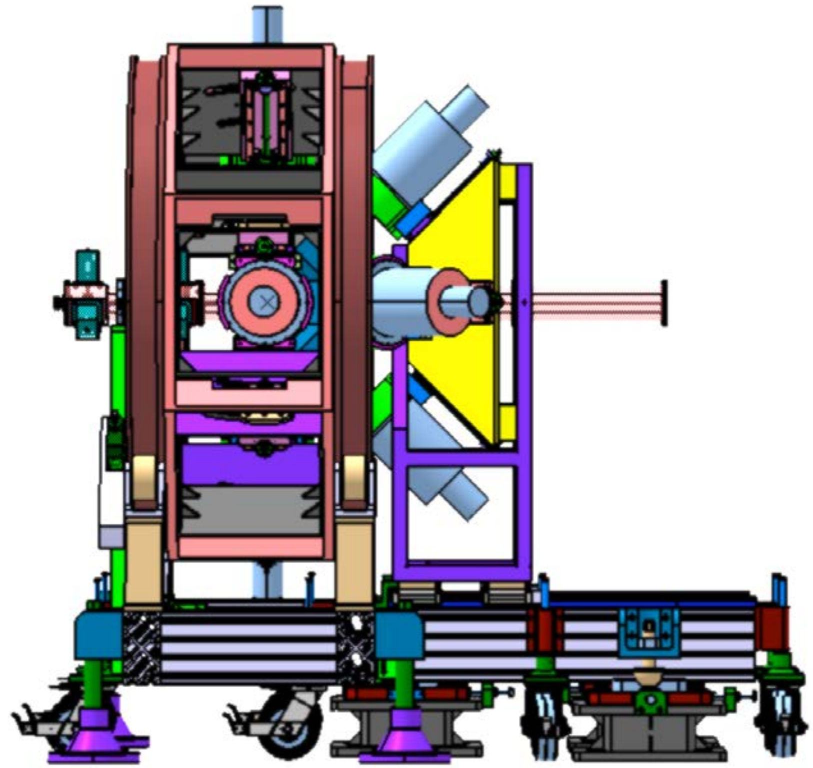
<u>Instrumentation:</u>

***ELIADE*** = **ELI**–NP **A**rray of **DE**tectors

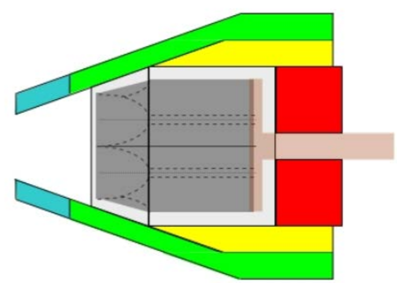
- 8 x TIGRESS – type Clover detector (*segmented*) with back–catcher ($\varepsilon_{ph}$ ~ 6%)
- 4 x 3”x3” $LaBr_3(Ce)$ detectors
- Digital DAQ





*CAD : C.Petcu and E.Udup*



back–catcher

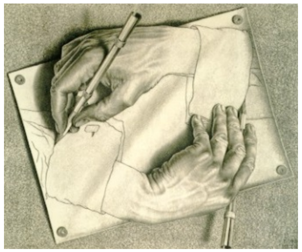
passive shield

passive shield

# NRF Physics Cases

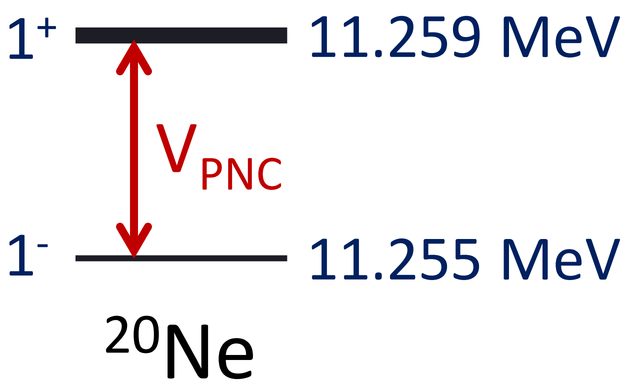
- constraints on **neutrinoless double-beta decay** matrix elements: A novel decay channel of the scissors mode
- **parity violation** in nuclear excitations: The case of $^{20}Ne$
- an access to the **equation of state** and to neutron-rich matter: Investigation of the Pygmy Dipole Resonance
- proton-neutron **symmetry breaking**: Rotational $2^+$ states of the nuclear scissors mode
- the **origin of matter**: Studies of the photoresponse of low-abundant *p* nuclei
- photons and **radioactive isotopes**: Electric and magnetic dipole response of unstable nuclei

# Parity Violation in Nuclear Excitations



Study level mixing in $1^+/1^-$ parity doublets

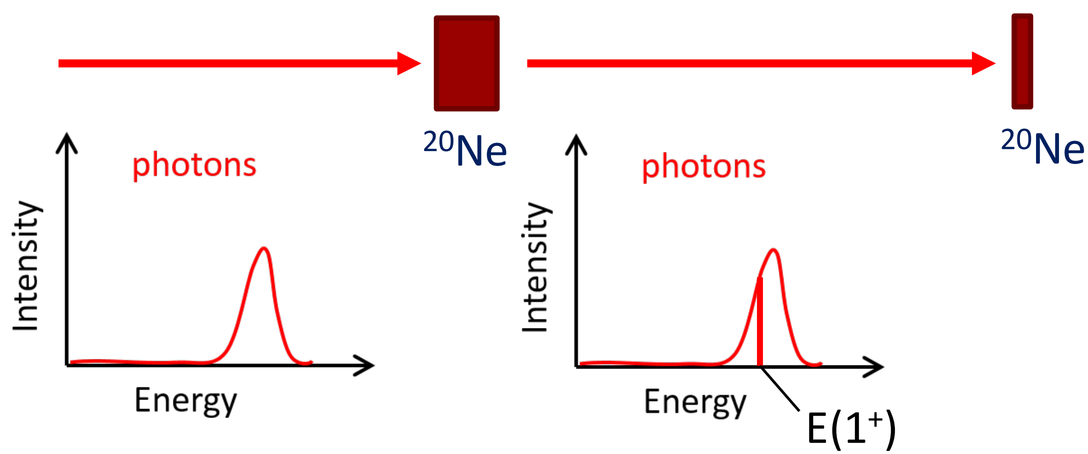
$\rightarrow$ constrain weak meson-nucleon coupling

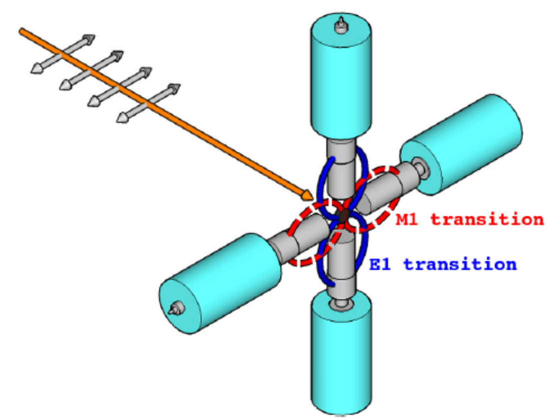



$V_{PNC} \equiv$ parity non-conserving interaction (about 1 eV)

# Parity Violation in Nuclear Excitations

- nearly 100% polarized $\gamma$ beam
- thick $^{20}$Ne absorber in front of target removes photons to excite broad $1^+$ state, because $\sigma(1^+) \approx 30 \cdot \sigma(1^-)$
- only $1^-$ state of doublet is excited by remaining photons
- measure M1 admixture to E1 excitation by analyzing NRF events in detector perpendicular to beam axis

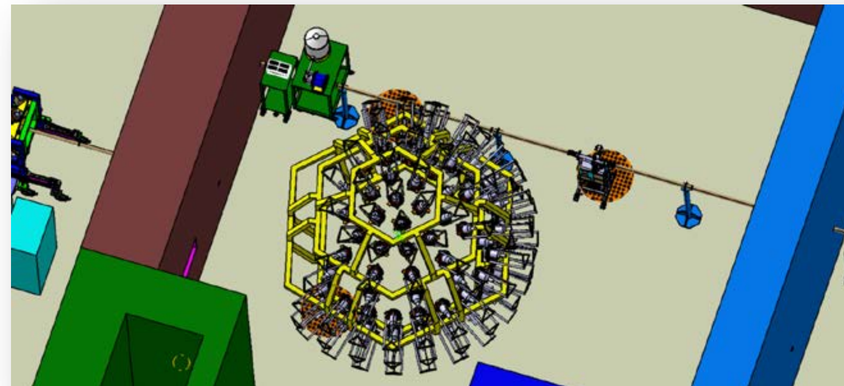



*A.Zilges et al.*

# Gamma Above n Threshold

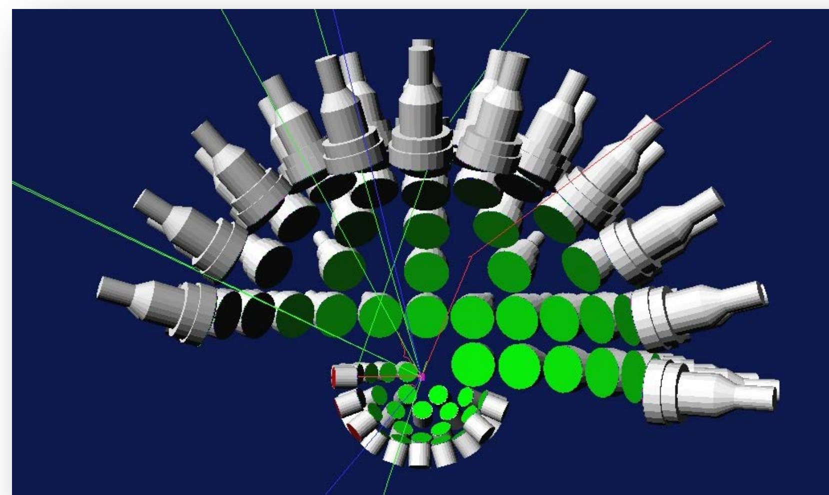
- Studies of GDR and PDR decay ($^{90}Zr$, $^{208}Pb$)
- Studies of spin–flip M1 resonances
  - combine with information from (γ, γ□) (*e.g.* polarization)
  - γ decay to g.s and ex. states as a function of excitation energy



***ELIGANT–GN*** = **ELI**–NP **G**amma **A**bove **n** Threshold

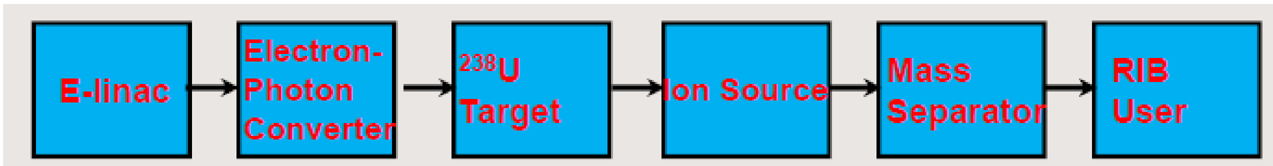
<u>Instrumentation:</u>

- $LaBr_3(Ce)$ / $CeBr_3$ array (34)
  – high–energy gamma rays
- GS10 $^6Li$–glass detectors (29)
  – neutrons $E_n < 1$ MeV
- BC501A liquid scintillator array (33)
  – neutrons $E_n > 1$ MeV



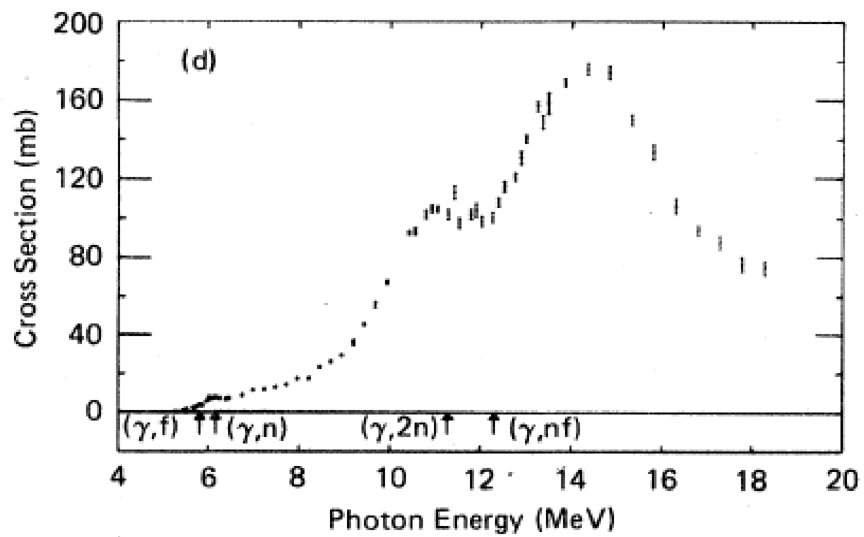
# Photofission and Exotic Nuclei

ALTO, ARIEL, etc.




## Photofission cross section for $^{238}$U

*Caldwell et al., Phys. Rev. C 21 (1980) 1215*



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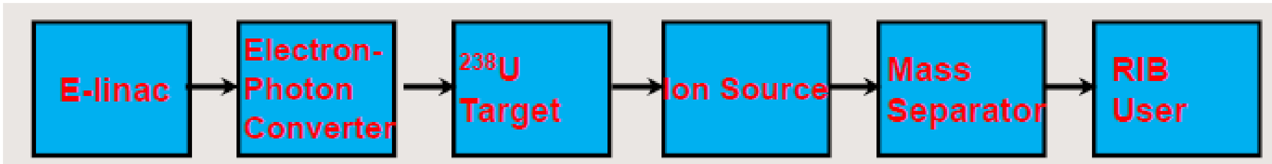
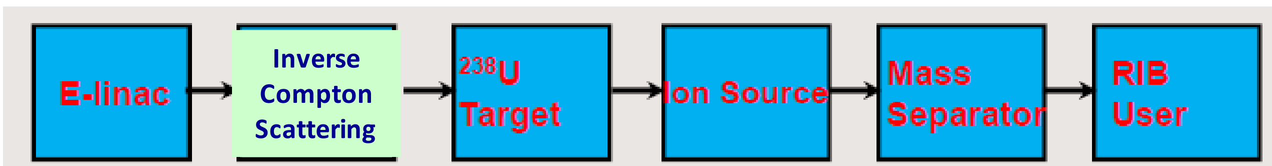



ELI-NP

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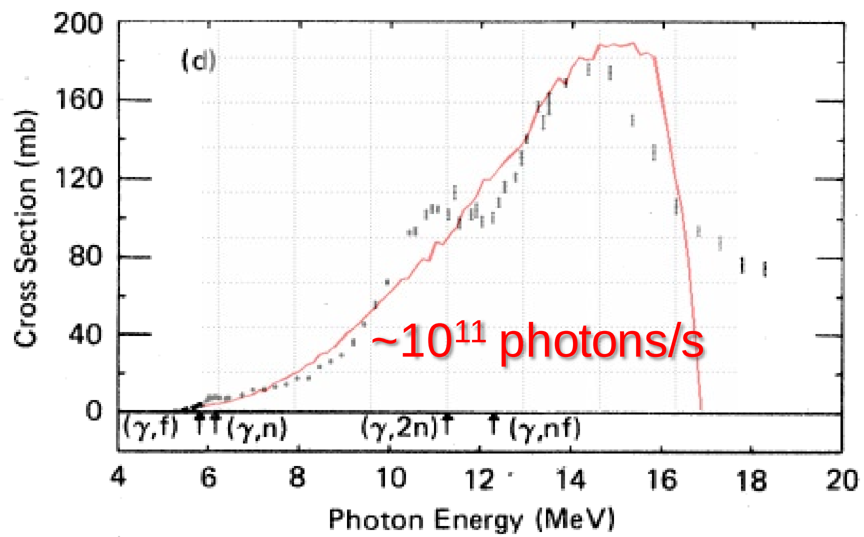
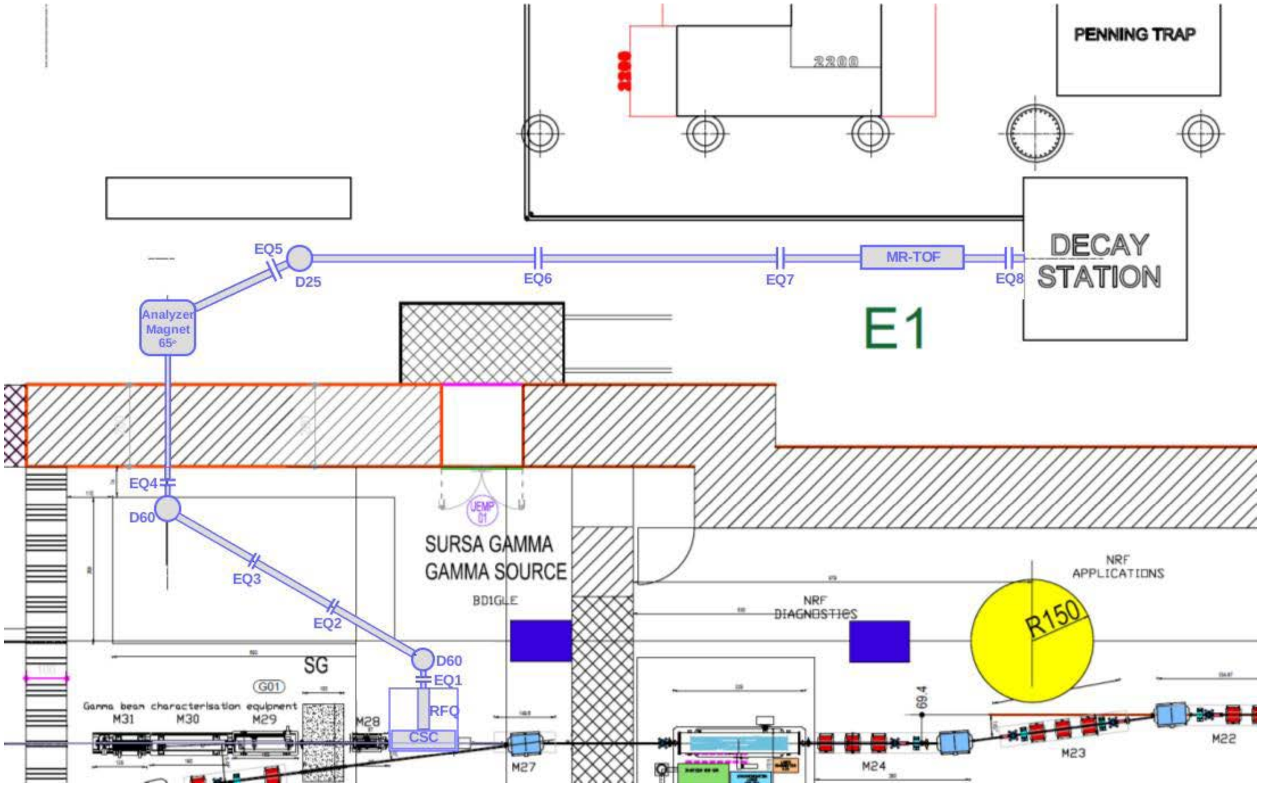


# IGISOL Setup




**β-decay studies at the IGISOL beam line :**

- Test of the SM around the doubly-magic $^{132}$Sn;
- Studies of the onset and fading away of deformation in the A = 100 Sr–Zr region;
- Studies of collective excitations in the A = 150 deformed region;
- Studies of octupole excitations in Sm-Nd nuclei.

# Summary

- the new research facility ELI–NP under construction at Bucharest entered the second Phase of implementation
  - systems with features beyond state–of–the–art : **HPLS and GBS**

→ many new research opportunities and challenges

  - **Nuclear Physics**
    - Laser Driven Nuclear Physics, combined laser–gamma
    - NRF, photofission, photodissociation
  - QED
    - High field QED

→ implementation of the experimental setups

EUROPEAN UNION

GOVERNMENT OF ROMANIA

Structural Instruments 2007-2013

# Extreme Light Infrastructure - Nuclear Physics (ELI-NP) - Phase I

eli Nuclear Physics

**Project co-financed by the European Regional Development Fund**

# ELI–NP Implementation Timeline