EUROPEAN UNION

GOVERNMENT OF ROMANIA

Structural Instruments 2007-2013

Sectoral Operational Programme
„Increase of Economic Competitiveness"
"Investments for Your Future"

Extreme Light Infrastructure – Nuclear Physics (ELI–NP)
Phase I

Project co–financed by the European Regional Development Fund

eli Nuclear Physics

IFIN-HH

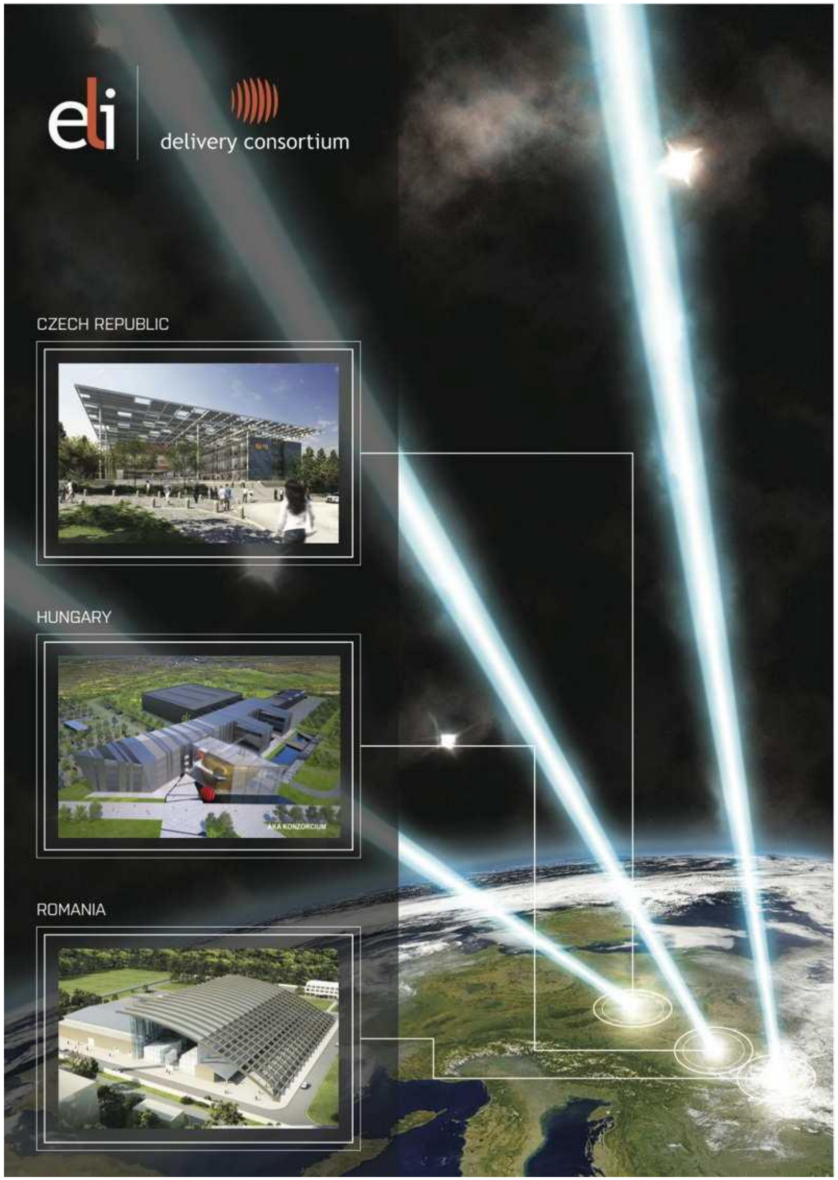
THE ELI –NP FACILITY FOR NUCLEAR PHYSICS RESEARCH

CĂLIN A. UR

FOR THE ELI–NP TEAM

6th International Conference on Charged & Neutral Particles Channeling Phenomena – Channeling 2014
October 5 – 10, 2014 Capri , Italy

Extreme Light Infrastructure (ELI)



the world's first international laser research infrastructure

pan–European distributed research infrastructure based initially on 3 facilities in CZ, HU and RO

ELI–Beamlines, Prague, CZ

High–Energy Beam Facility

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

ELI–ALPS, Szeged, HU

Attosecond Laser Science Facility

new regimes of time resolution

ELI–NP, Magurele, RO

Nuclear Physics Facility with ultra–intense laser and brilliant gamma beams (up to 20 MeV)

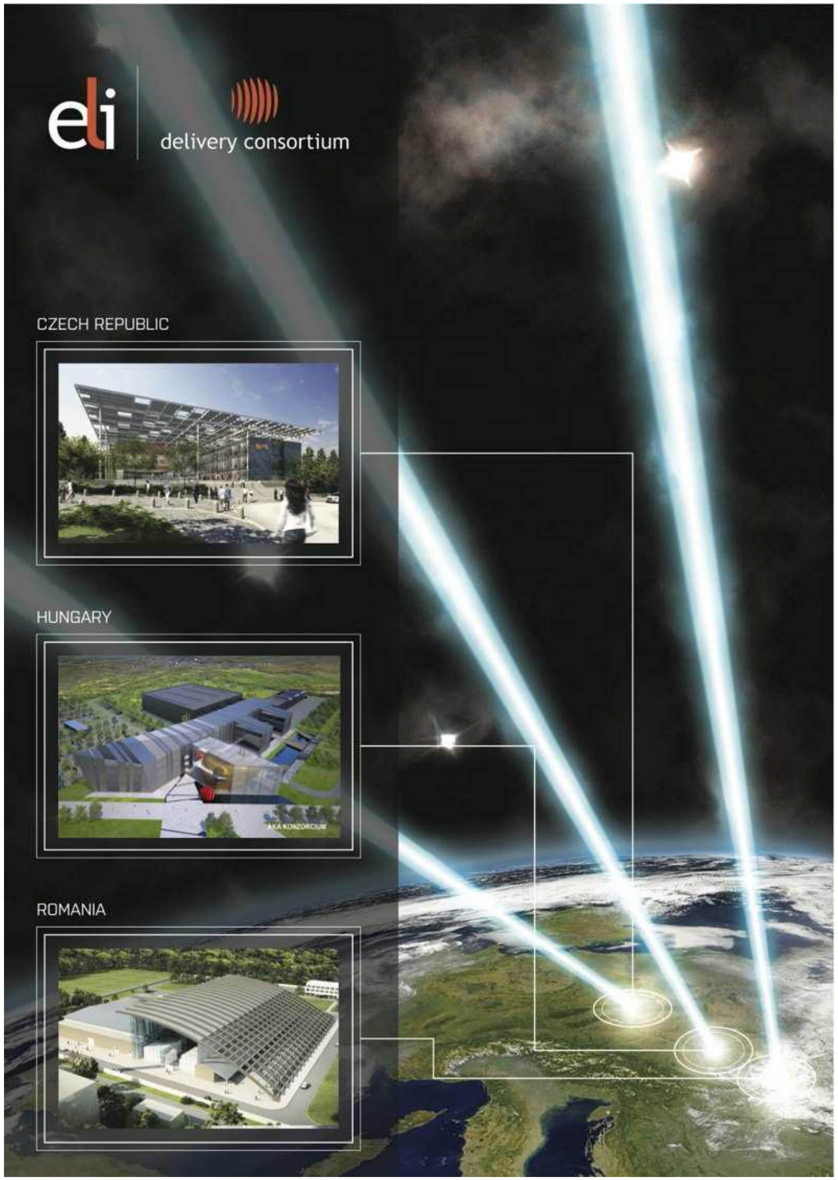
novel photonuclear studies

ELI 4 , to be decided

Ultra–High–Field Science

direct physics of the unprecedented laser field strength

Extreme Light Infrastructure (ELI)



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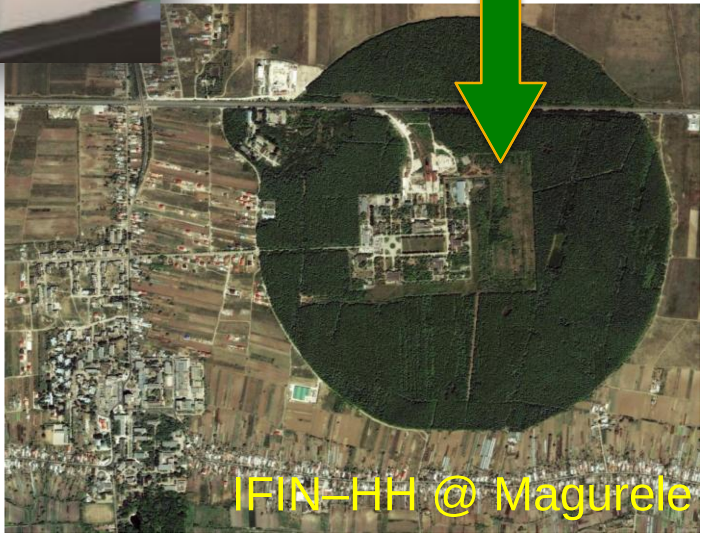
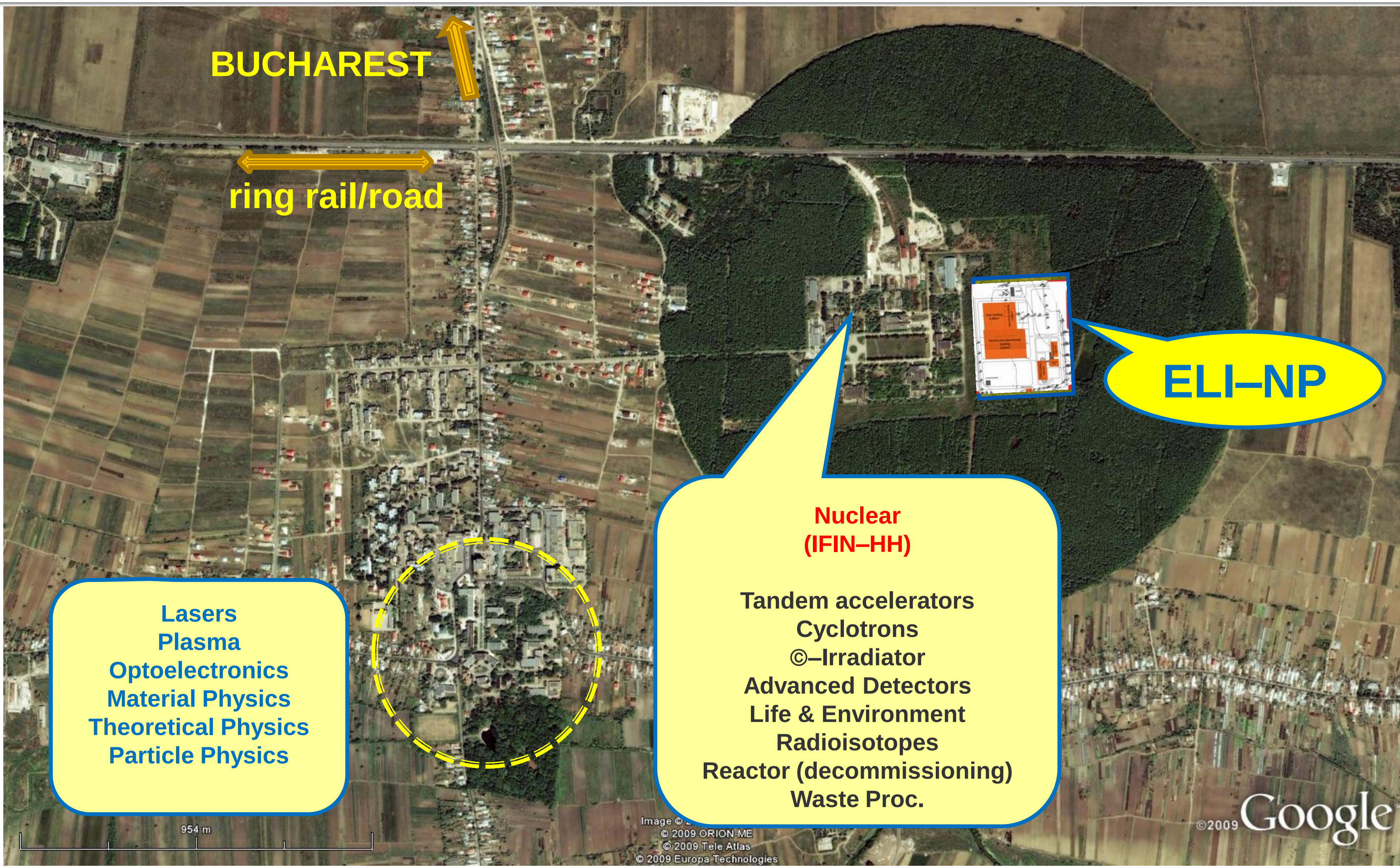
ELI–NP at Bucharest



ELI–NP will change the **LANDSCAPE** of Magurele (Bucharest)

ELI–NP at Bucharest



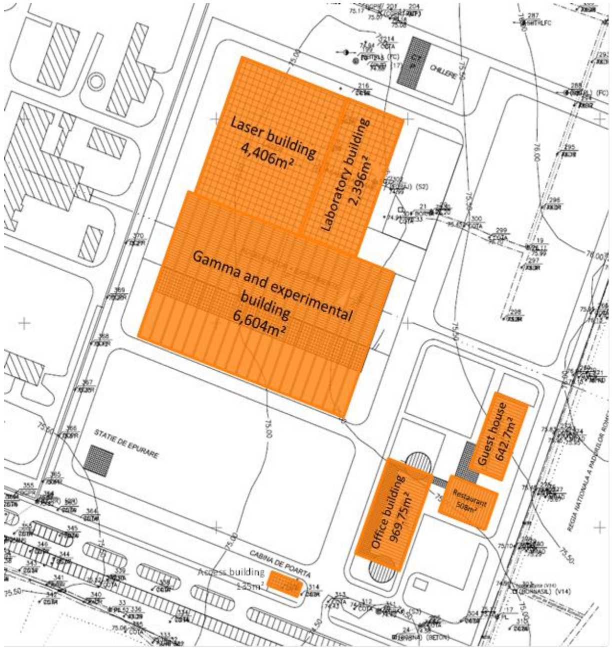
ELI–NP Facility Concept

Major research equipment : beyond present day state–of–the–art

- Ultra–short pulse high power laser system – 2 x 10 PW maximum power
- Gamma radiation beam, high intensity, tunable energy up to 20MeV, relative bandwidth ~10^{-3}

Buildings – one contractor, 33000 m^2 total

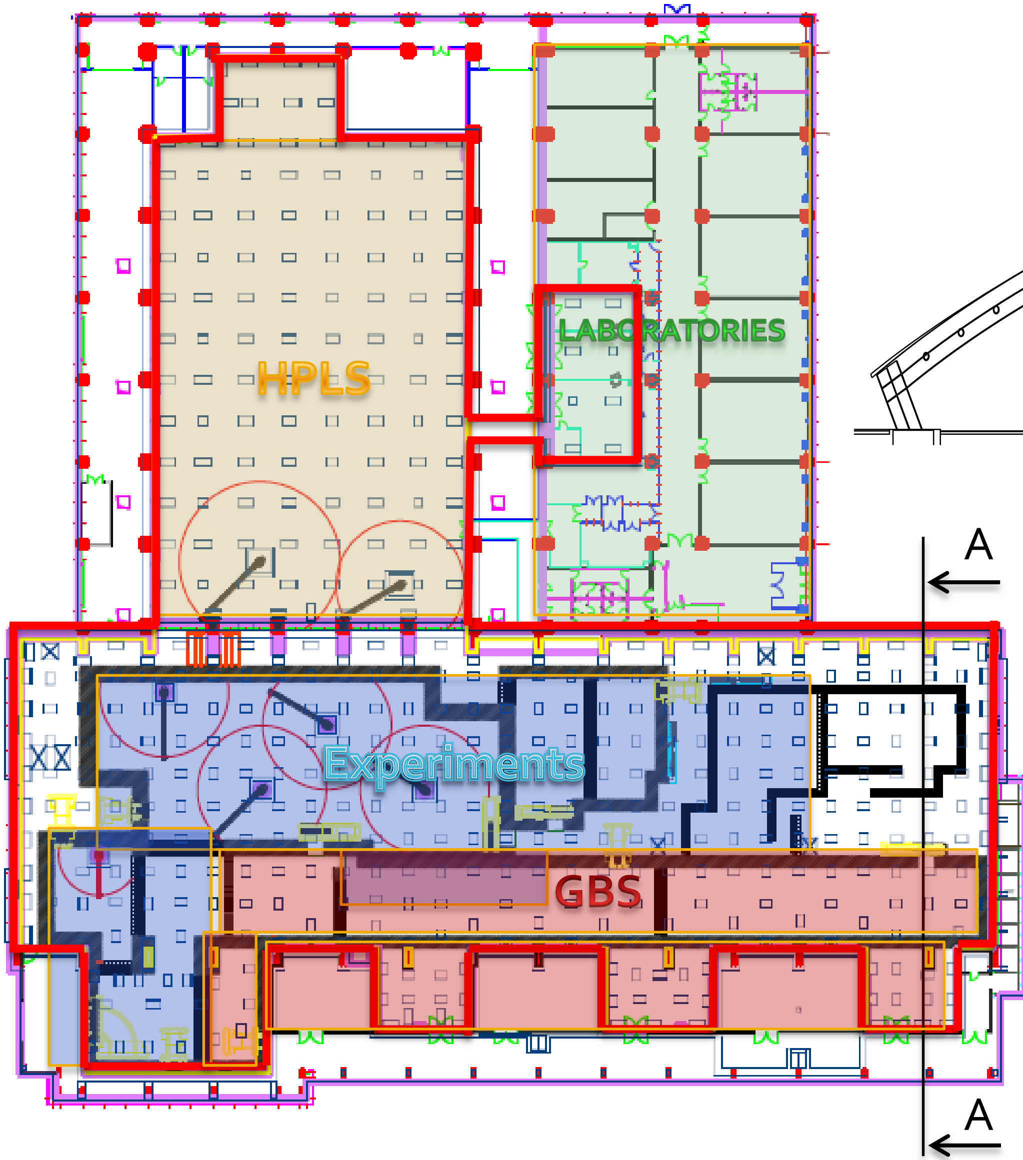
- Experimental area building
- Office building
- Guest house
- Canteen

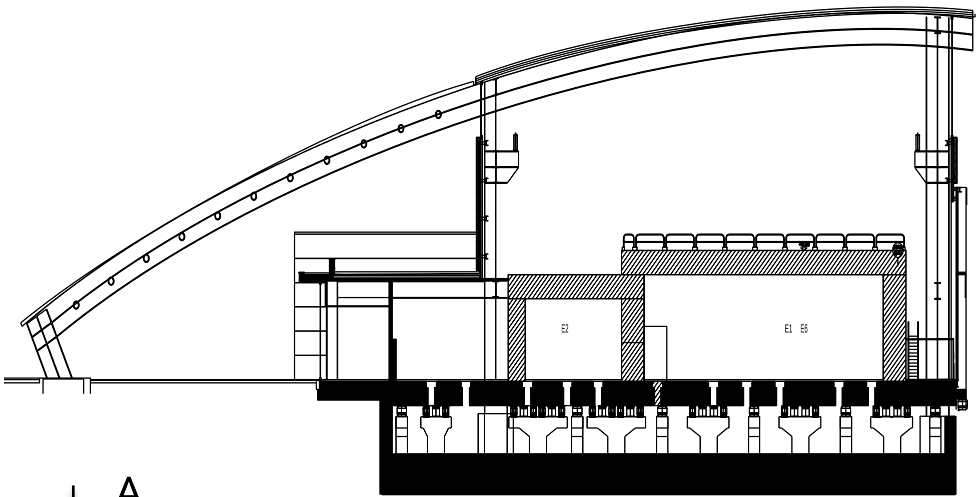


Experiments – 7000 m^2

- 8 experimental areas for gamma, laser, and combined gamma + laser research activities

ELI–NP Building Structure





Platform supported on dampers

Anti–vibration platform

±1 μm @ < 10 Hz

ELI–NP Building Progress

ELI–NP Building Progress

ELI–NP Implementation Timeline

Nuclear Physics

ELI–NP White Book

Feasibility Study
Cost estimate 293M€

Preparation of the Application

E.C. Eval. & Funding Approval

Procurement Laser System

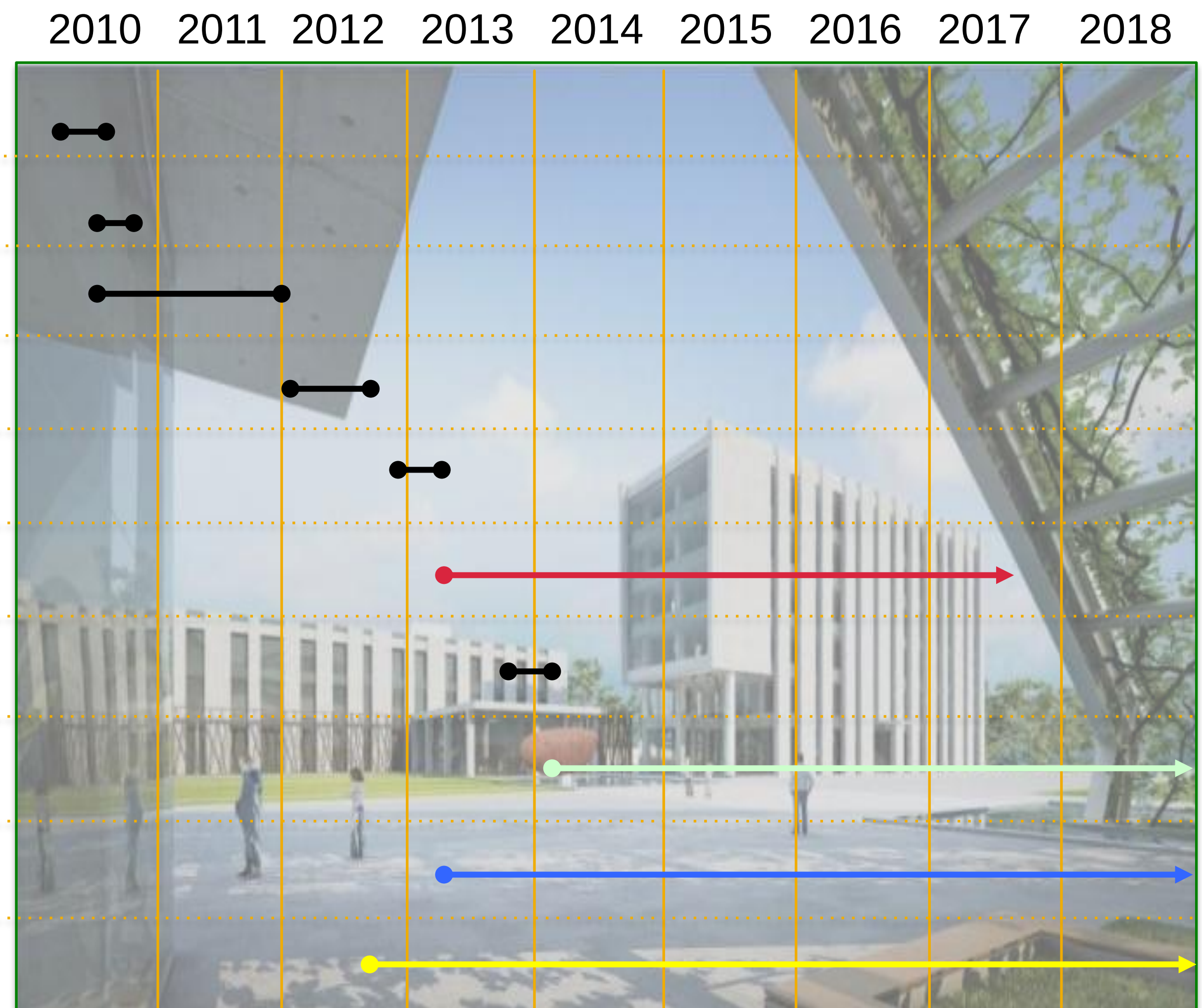
Laser System – installation

Procurement Gamma Beam

Gamma Beam – installation

Experimental Areas TDR

Recruitment

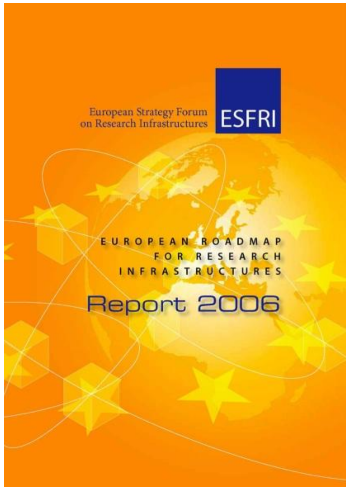


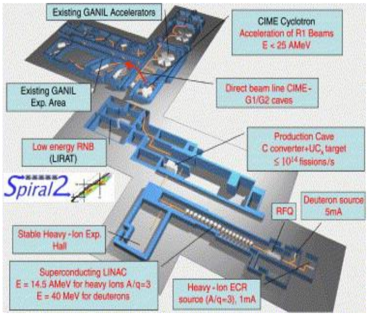
ELI–NP Nuclear Physics Research

- **Nuclear Physics experiments**
    - **Nuclear Photonics**
        - Nuclear Resonance Fluorescence
        - Photo–fission & Exotic Nuclei
        - Photo–disintegration and Nuclear Astrophysics

          complementary to other ESFRI Large Scale Physics Facilities (FAIR, SPIRAL2)
    - **Nuclear Physics diagnostics**
        - Laser–Target interaction characteristics
    - **Laser Driven Nuclear physics**
        - Fission - fusion
- **Applications** based on high intensity laser and very brilliant © beams complementary to the other ELI pillars

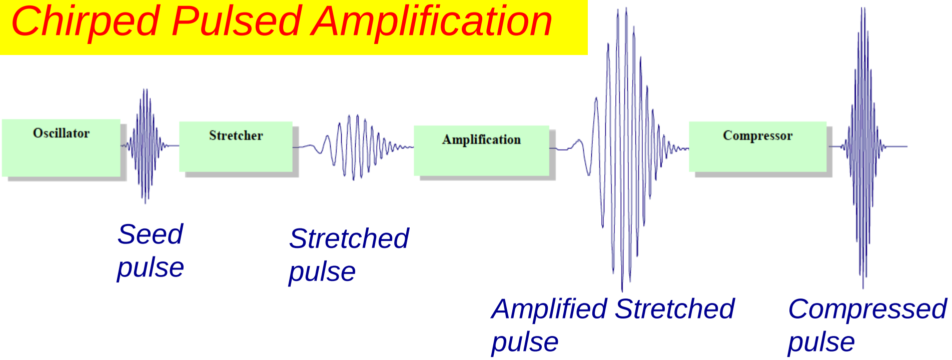
*ELI–NP in Romania selected by the most important science committees in Europe – ESFRI and NuPECC, in the '**Nuclear Physics Long Range Plan in Europe'** as a major facility*





ELI–NP HPLS

Chirped Pulsed Amplification



ELI–NP → 2 x HPL up to 10 PW
~ 300 J / 30 fs & 10^{23}–10^{24} W/cm^2

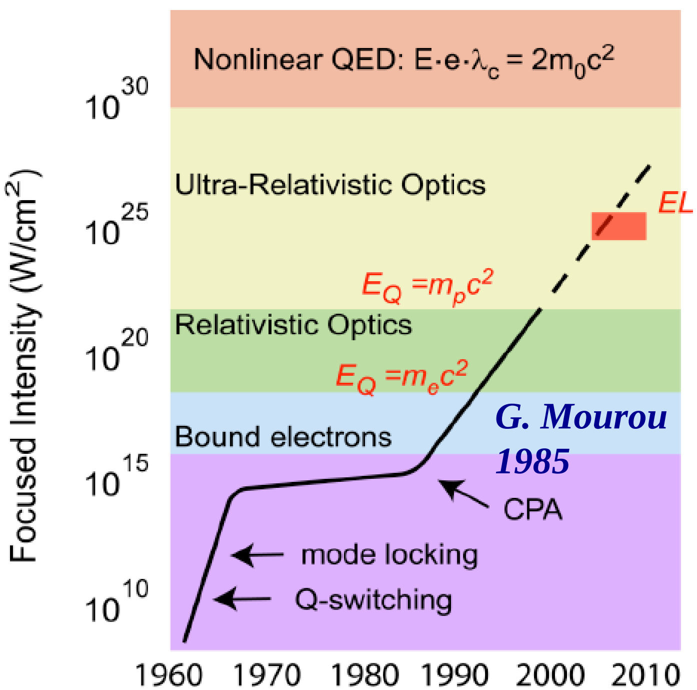
Provided by THALES Optronique – France

6 output lines → *2 x 0.1 PW*, *2 x 1 PW*, *2 x 10 PW*

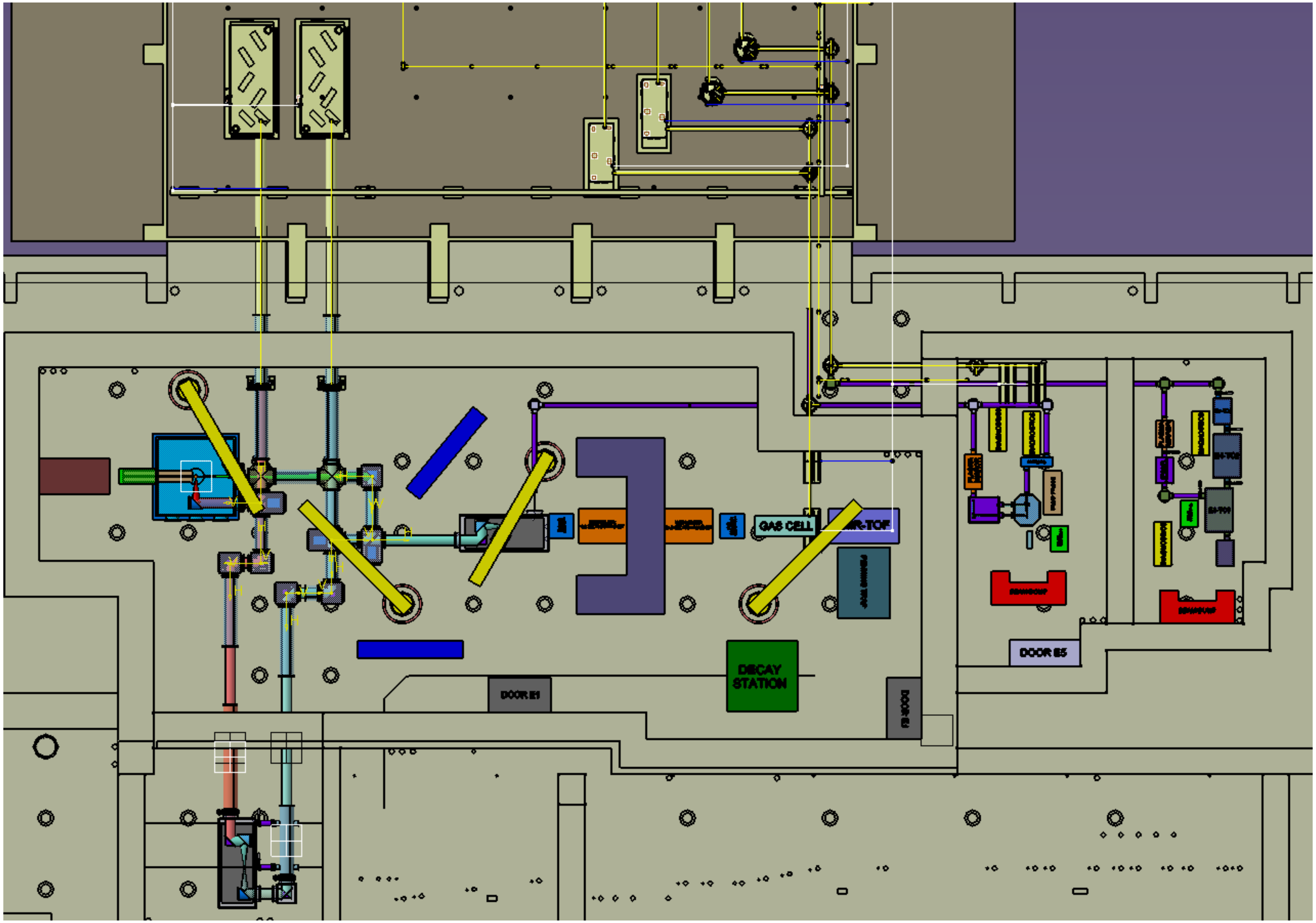
any combination of 2 lines can be operated in parallel

10^{25}W ~ 10% of The Sun's total power

10^{9}W ~ Power of a nuclear reactor



Laser Beam Delivery

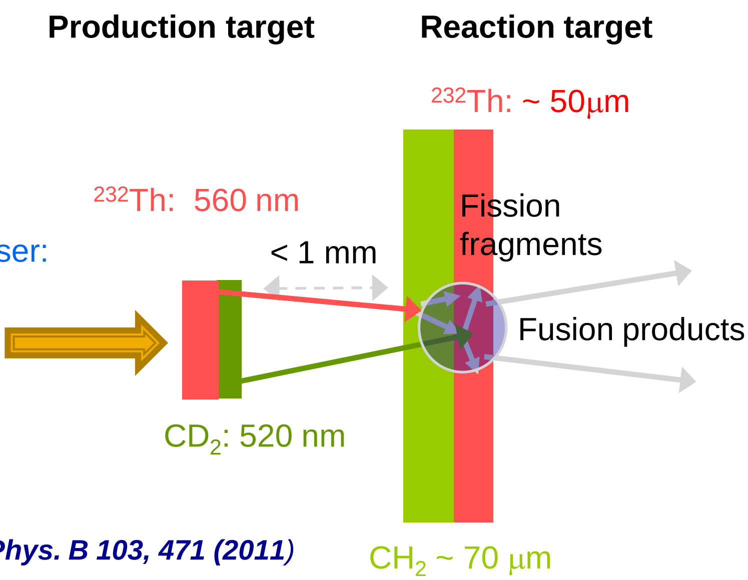


Laser Driven NP at ELI–NP

- Study of exotic nuclei of astrophysical interest produced using high density ion bunches : **fission–fusion reactions.** n–rich nuclei around N = 126 waiting point

high-power, high-contrast laser:

- 300 J, ~30 fs (10 PW)
- ~$\cdot 10^{23}$ W/cm^2
- focal diam. ~ 3 μm



D.Habs, P.Thirolf et al., Appl. Phys. B 103, 471 (2011)

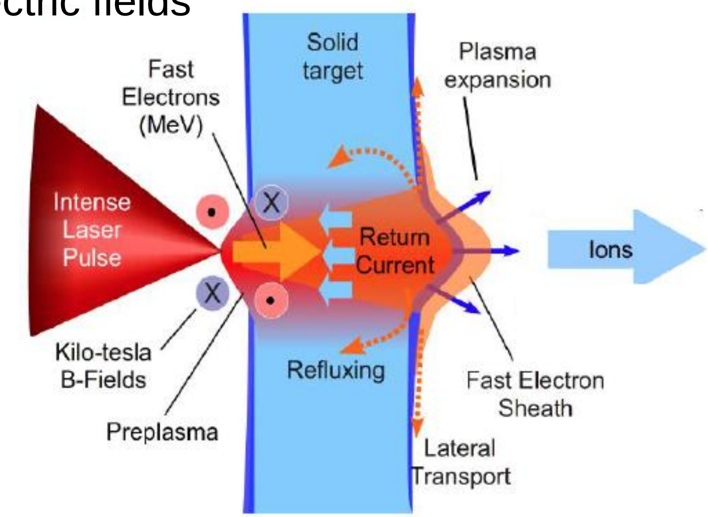
- Study of heavy ions acceleration mechanism at laser intensities > 10^{23} W/cm^2
- Deceleration of very dense electron and ion beams
- Understanding influence of screening effect on stellar reaction rates using laser plasma
- Nuclear techniques for characterization of laser–induced radiations

Laser Ion Acceleration

Short pulse high–power lasers → strong charge separation by laser–matter interaction → intense electric fields → ion acceleration

Target Normal Sheath Acceleration (TNSA)

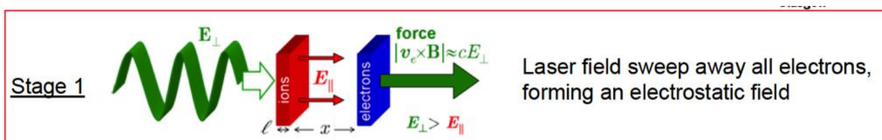
- Conversion of laser radiation into kinetic energy of relativistic electrons in μm thick targets
- Electrons move and recirculate through the solid target and appear at the surfaces where give rise to intense longitudinal electric fields



$E \sim (I_{laser})^{1/2}$ 300 – 400 MeV/u

Radiation Presure Acceleration (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



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.

$E \sim I_{laser}$ > GeV/u

P.McKenna, CETAL Workshop, Bucharest, Nov. 19, 2013

New Paradigm

In the 20th century Fundamental Research has been carried out and dominated by the Particle–based Paradigm: namely accelerator for Massive and Charged particles

The First example is the Extreme Light Infrastructure ELI

21st Century; the Photon Century Could basic research be driven by the massless and chargeless Photons??

Large Scale Lasers: Could they become the Next Large Scale Fundamental Research Infrastructures?

ELI–NP Gamma Beam System

EuroGammaS Association

Academic Institutions

INFN (Italy), Sapienza University (Italy), CNRS (France)

Industrial Partners

ACP Systems (France), ALSYOM(France),COMEB(Italy), ScandiNova Systems (Sweden)

and several Sub-Contractors:

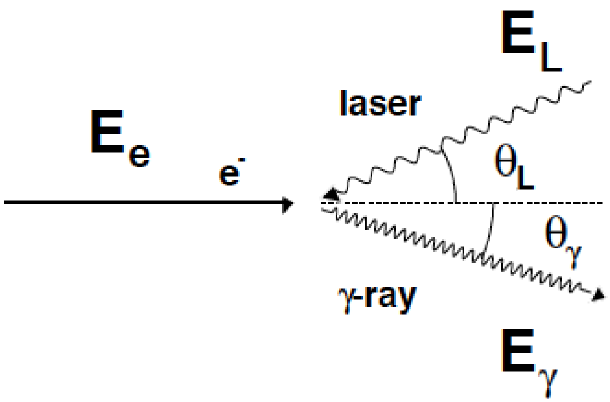
Alba (Spain), Cosylab (Slovenia), Danfysik (Denmark), IT (Slovenia), M+W Group (Italy), Menlo Systems (Germany), RI (Germany)

The Challenge : to design the *most advanced Compton* Gamma Beam Source based on *state–of–the–art* components, to be commissioned and delivered to users *by mid 2018 : an accelerator and a collider*

ELI-NP Gamma Beam Source: Bright, Monochromatic (bdw. 0.3%–0.5%), High Spectral Flux (10,000 ph/sec·eV), Tunable (0.2–20 MeV), Polarized (>95%)

TDR – arXiv:1407.3669 [physics.acc-ph]

Basic Concepts of the GBS



Gamma–rays from Inverse Compton Scattering

photon scattering on ultra relativistic electrons ($\gamma \gg 1$)

the most efficient frequency amplifier

'Photon accelerator'

The process is called inverse because the electrons lose energy rather than the photons

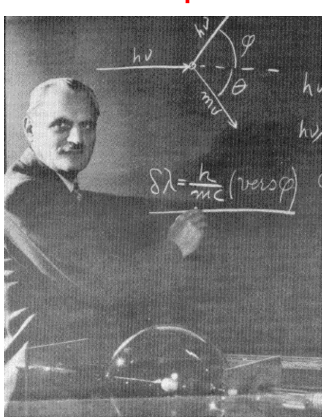
the opposite of the standard Compton effect

$$E_\gamma = 2\gamma_e^2 \times \frac{1+\cos\theta_L}{1+(\gamma_e\theta_\gamma)^2 + a_0^2 + \frac{4\gamma_e E_L}{mc^2}} \times E_L$$

$$\frac{4\gamma_e E_L}{mc^2} = \text{ recoil parameter ;}$$

$$a_L = \frac{eE}{m\omega_L c} = \text{normalized potential vector of the laser field;}$$

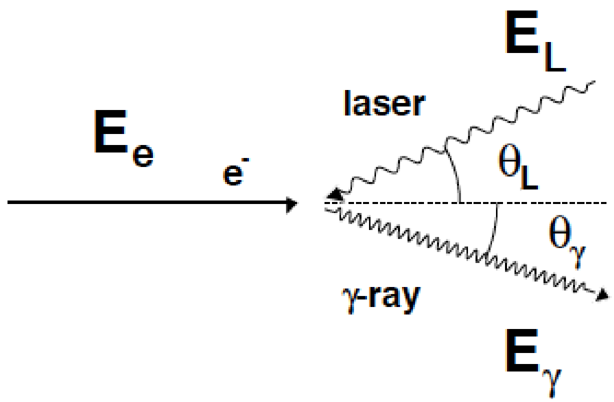
E = laser electric field strength; $E_L = \hbar\omega_L$



A.Compton 1923

Basic Concepts of the GBS

Gamma–rays from Inverse Compton Scattering



photon scattering on ultra relativistic electrons ($\gamma \gg 1$)

the most efficient frequency amplifier

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$$E_g = 2g_e^2 \times \frac{1+\cos q_L}{1+\left(g_e q_g\right)^2 + a_0^2 + \dfrac{4g_e E_L}{mc^2}} \times E_L$$

$$\frac{4\gamma_e E_L}{mc^2} = \text{recoil parameter ;}$$

$$a_L = \frac{eE}{m\omega_L c} = \text{normalized potential vector of the laser field;}$$

E = laser electric field strength; $E_L = \hbar\omega_L$

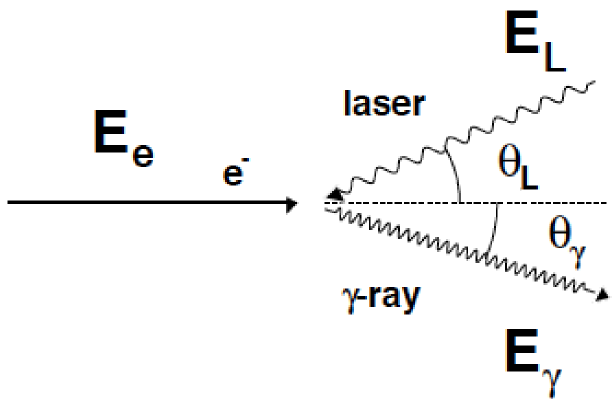
Maximum upshift

head–on collision (θ_L=0) &

backscattering (θ_γ=0)

$$E_g \sim 4g_e^2 \times E_L$$

Basic Concepts of the GBS



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$\gamma = 10^3 \rightarrow$

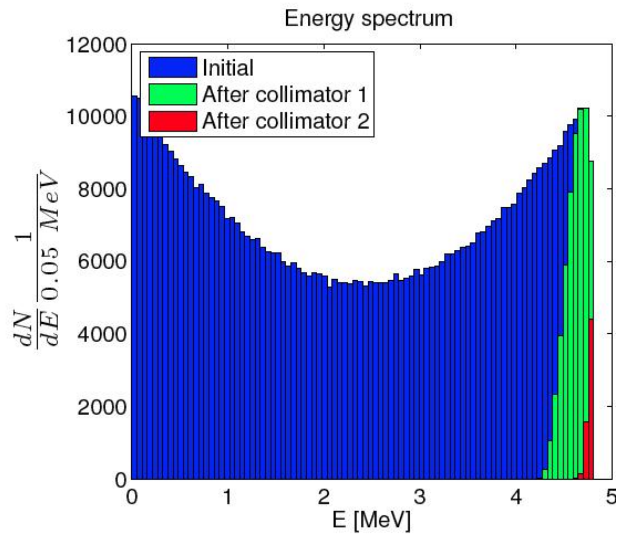
Waveband	Frequency (Hz)	Scattered Frequency (Hz) / Waveband
Radio	10^9	10^{15} / UV
Far–infrared	3×10^{12}	3×10^{18} / X–rays
Optical	4×10^{14}	4×10^{21} / γ–rays

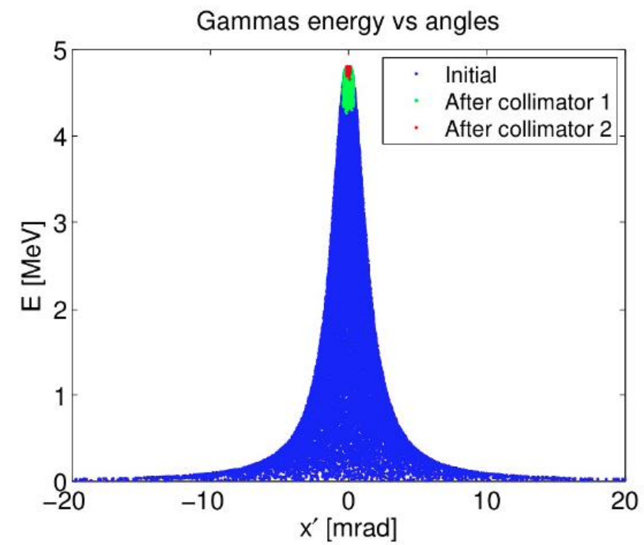
Basic Concepts of the GBS

Inverse Compton Scattering (ICS) – advantages

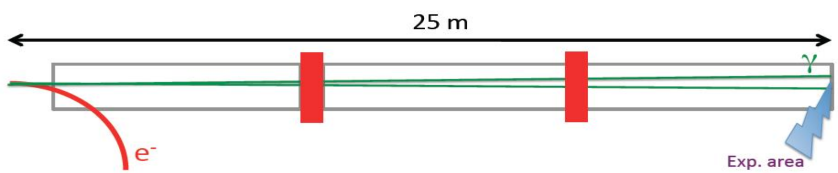
- strong correlation between scattering angle and gamma–ray energy
- strong forward focusing

→ collimation : good bandwidth and large spectral density

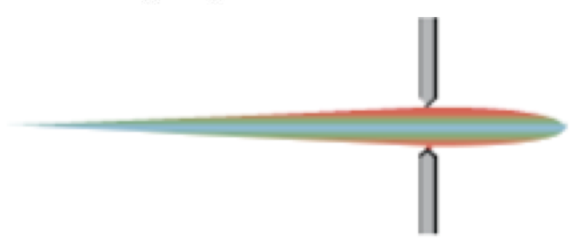




Photon extraction line

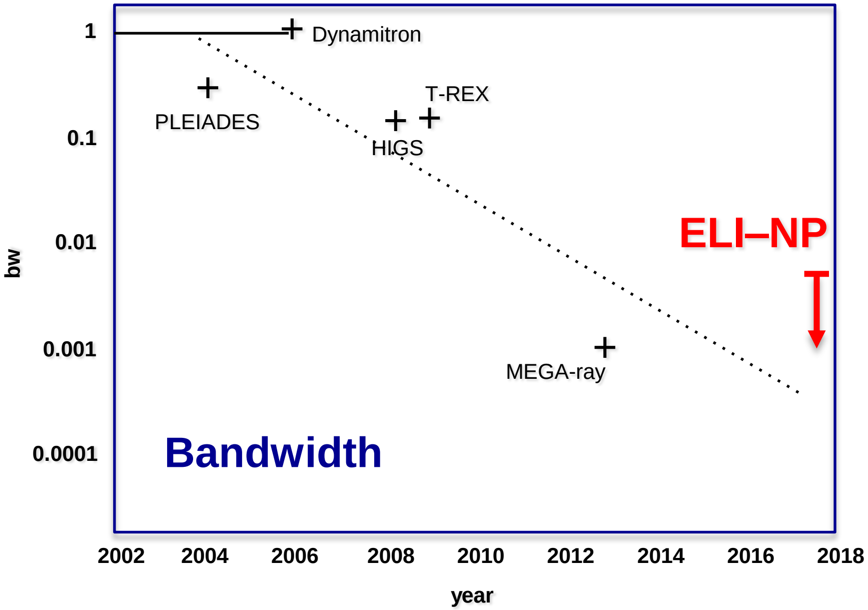


- Collimator 1 : d=11 m r= 0.3 cm , t= 5 cm (W)
- Collimator 2 : d=15 m r= 0.1 cm, t= 5 cm (W)



Courtesy of L.Serafini

ELI–NP Gamma Beam System

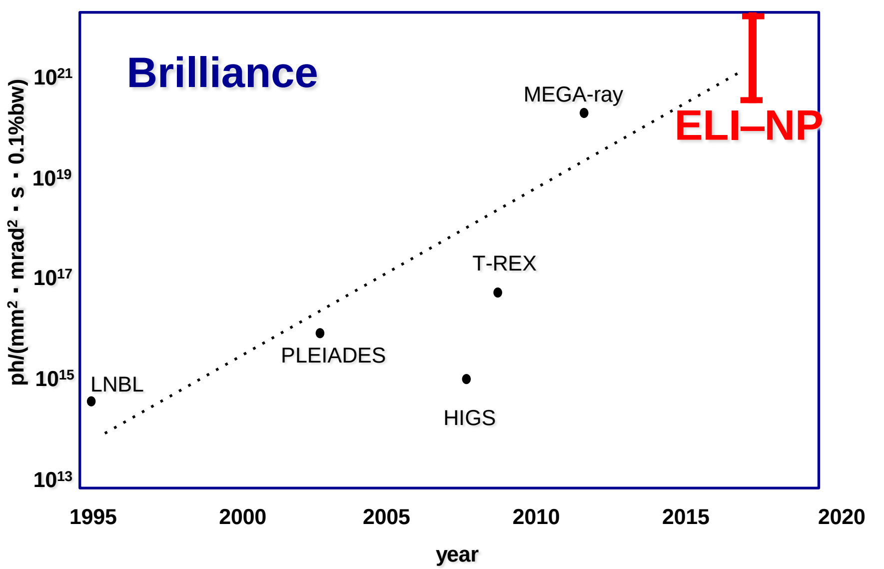


Inverse Compton scatering

- the most efficient frequency amplifier
- but very low–cross section ~ 10^{-25} cm^2

Requirements

- high–intensity electron beam
- very brilliant high rep. rate laser
- small collision volume



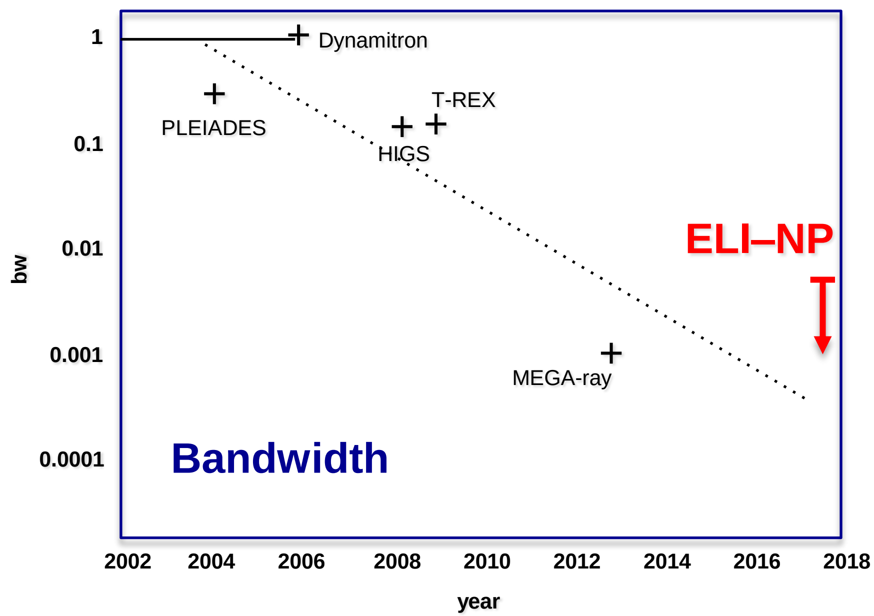
ELI–NP Gamma Beam System

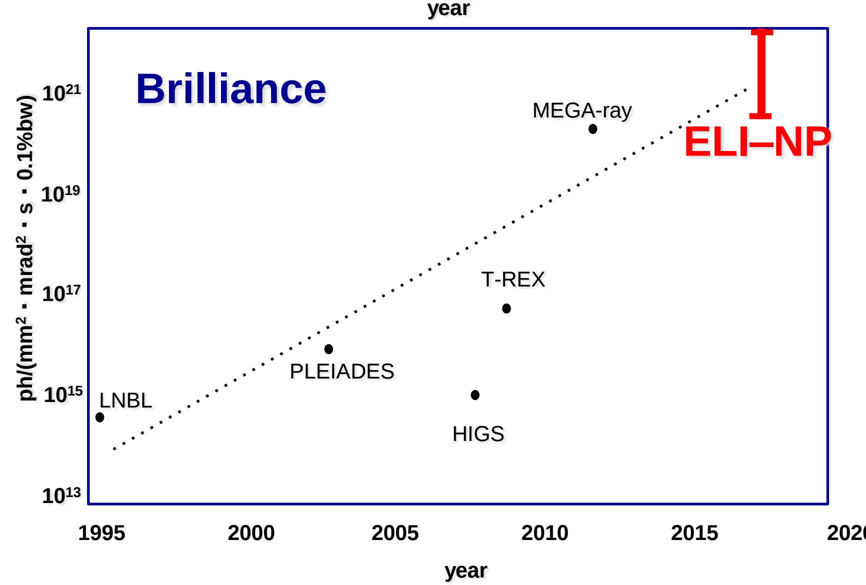
1) Warm electron RF Linac as for Linear Collider and FEL's machines
   - two acceleration stages (300 MeV and 720 MeV)

2) High average power, high quality J–class 100 Hz psec Collision Laser
   - two lasers (one for low–Eγ and both for high–Eγ)

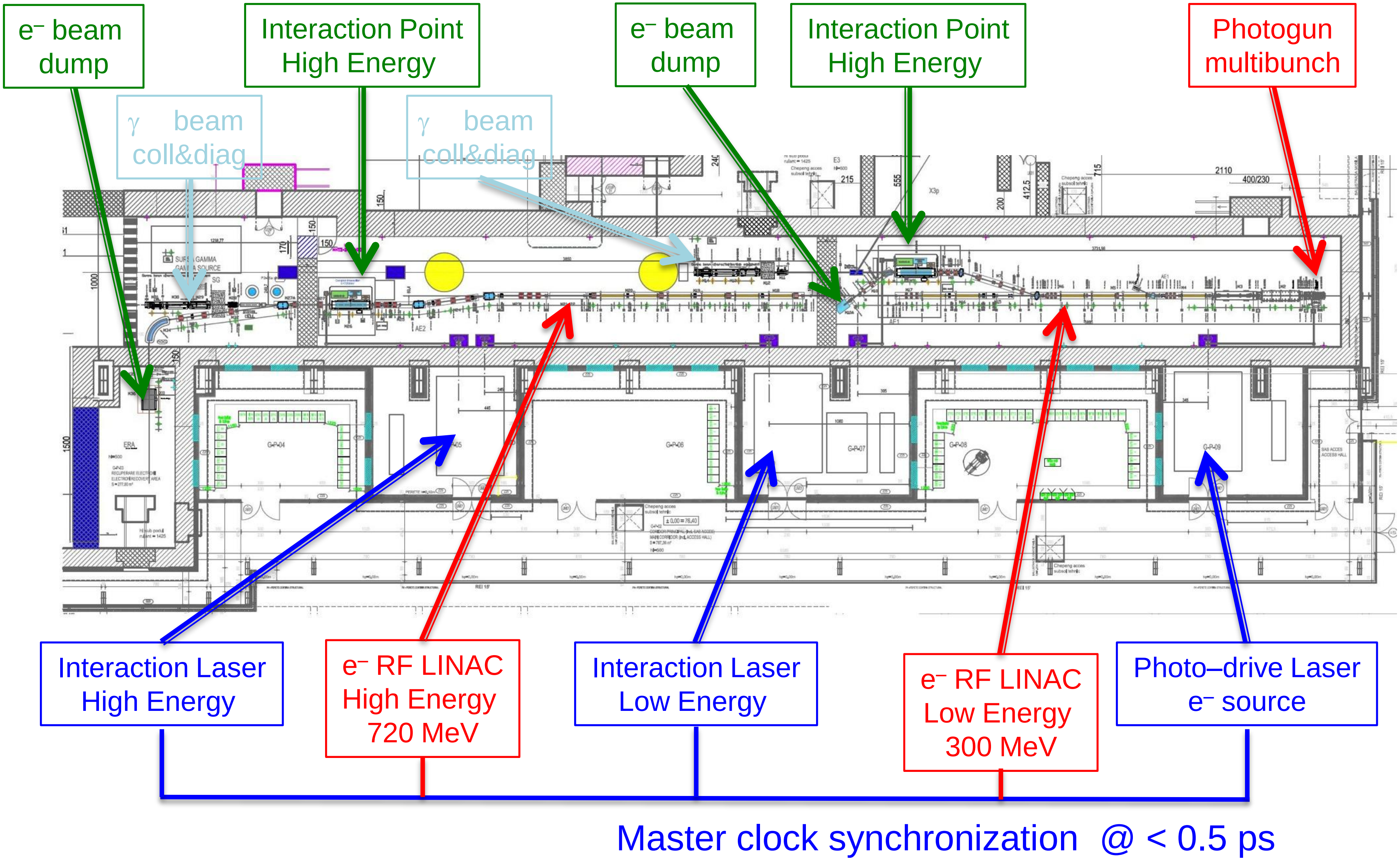
3) Laser recirculation with μm and μrad and sub–psec alignment/synchronization (metrology/interferometry optical cavities)
   - two interaction points – low–Eγ < 3.5 MeV and high–Eγ < 19.5 MeV

4) Gamma beam collimation system
   - to obtain bandwidths < 5 x 10^{-3}



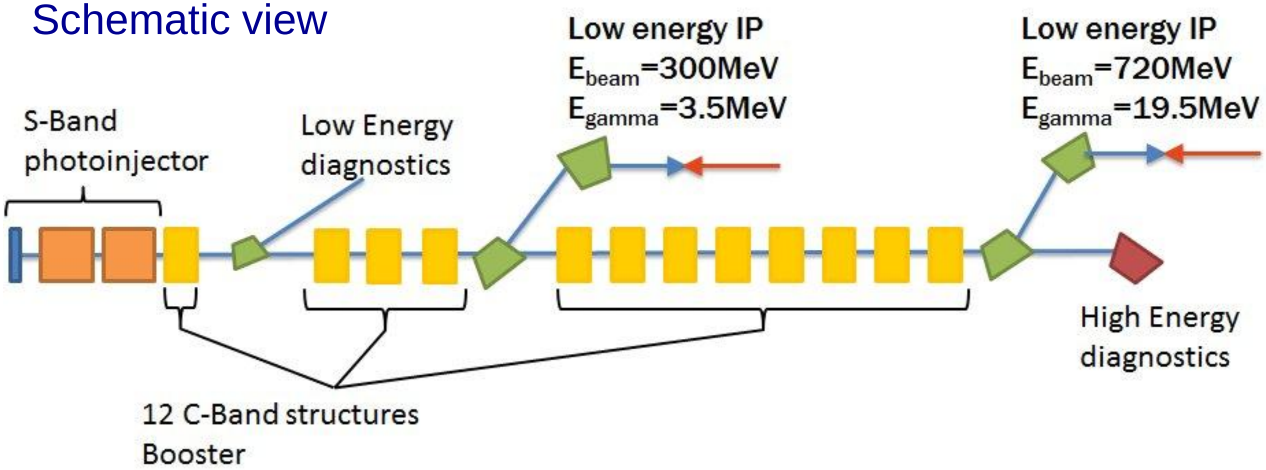


Gamma Beam System – Layout

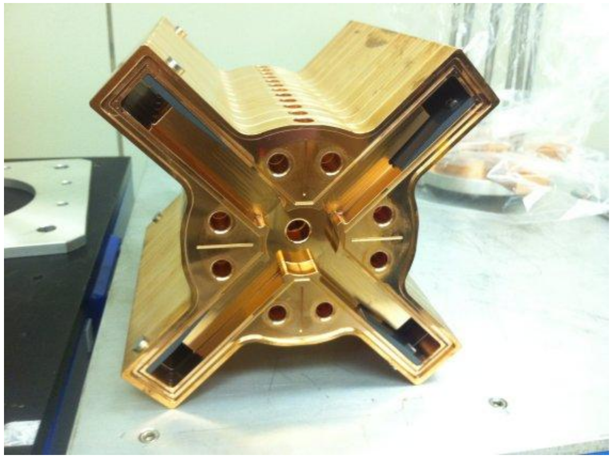


The Electron LINAC

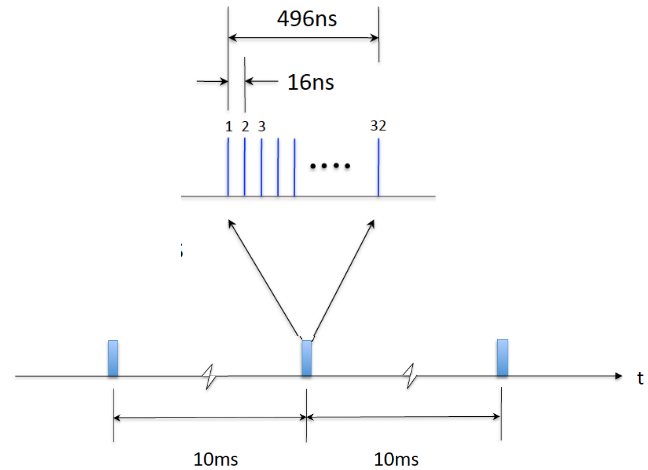
Schematic view



C–Band RF cavity



Time structure of the e⁻ beam



Energy	80 – 720 MeV
Bunch charge	25 – 500 pC
Number of bunches	32
Bunch distance	16 ns
C-band average accelerating gradient	33 MV/m
Norm. emittance	0.2-0.6 mm·mrad
Bunch length	100 – 400 μm
RF rep Rate	100 Hz
Focal spot size	> 15 μm
Bunch energy spread	0.04 – 0.1 %
Pointing jitter	1 μm

The IP Lasers

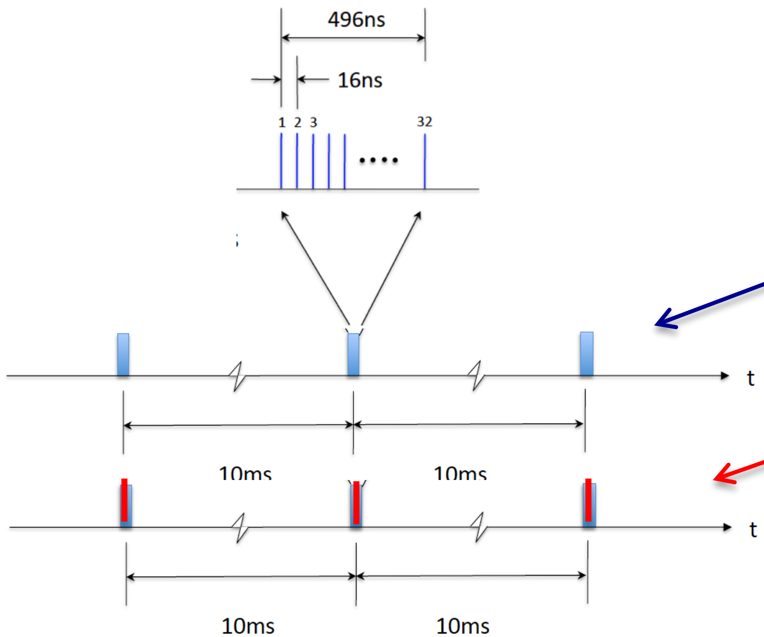
Interaction Lasers: cryo–cooled Yb:YAG

	Low Energy Interaction	High Energy Interaction
Pulse energy (*J*)	0.2	2x0.2
Wavelength (*eV,nm*)	2.3,515	2.3,515
FWHM pulse length (*ps*)	3.5	3.5
Repetition Rate (*Hz*)	100	100
M^2	≤ 1.2	≤ 1.2
Focal spot size w_0 (*μm*)	> 28	> 28
Bandwidth (*rms*)	0.1 %	0.1 %
Pointing Stability (*μrad*)	1	1
Sinchronization to an ext. clock	< 1 *psec*	< 1 *psec*
Pulse energy stability	1 %	1 %

provider – Amplitude Systemes (France)

Laser Recirculation at IP

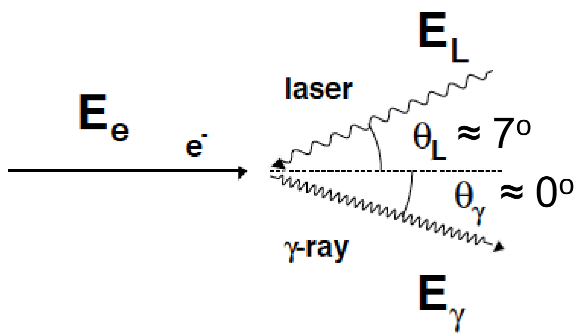
Designed by

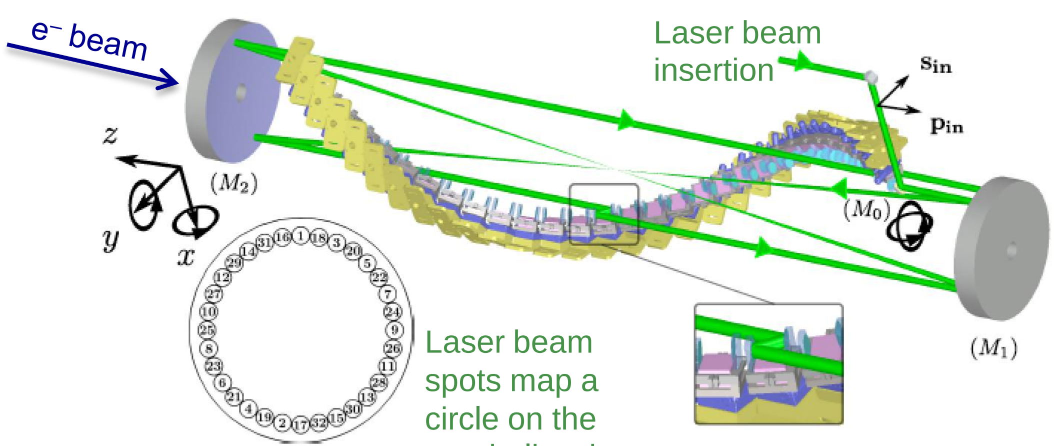


Electrons rep. rate –macropulses 100 Hz
32 micropulses @ 16 ns

Laser rep. rate – 100 Hz → ***laser recirculation***

'*Dragon–shaped*' Laser Recirculation



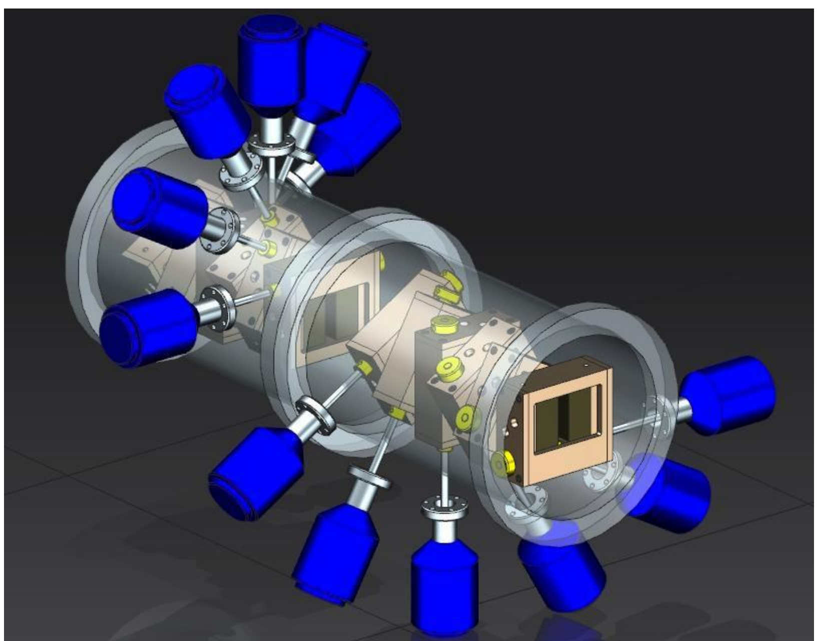


K.Dupraz et al., Phys.Rev. STAB 17 (2014) 033501

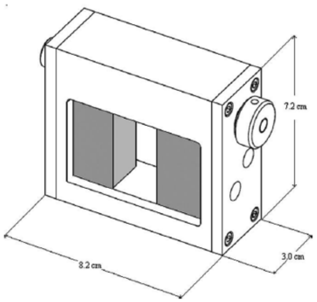
Gamma Beam Collimation

Main requirements are:

- **Low transmission of gamma photons** (high density and atomic number)
- **Continuously adjustable aperture** (to adjust the energy bandwidth in the entire energy range)
- **Avoid contamination of the primary beam** with production of secondary radiation



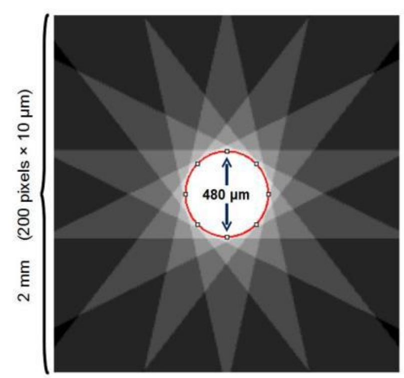
Collimation aperture varies from 20 mm to less than 1 mm, depending on the beam energy



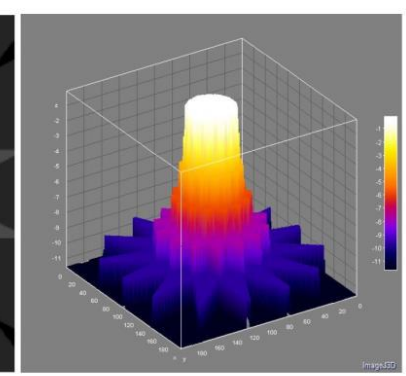
Tungsten slits – 20 mm thick

Low–energy configuration:
12 independent slits with 30º relative angle

High – energy configuration:
14 independent slits with 25.7º relative angle



Simulated radiography of the collimator assembly ($\log_{10}$ pixel values)



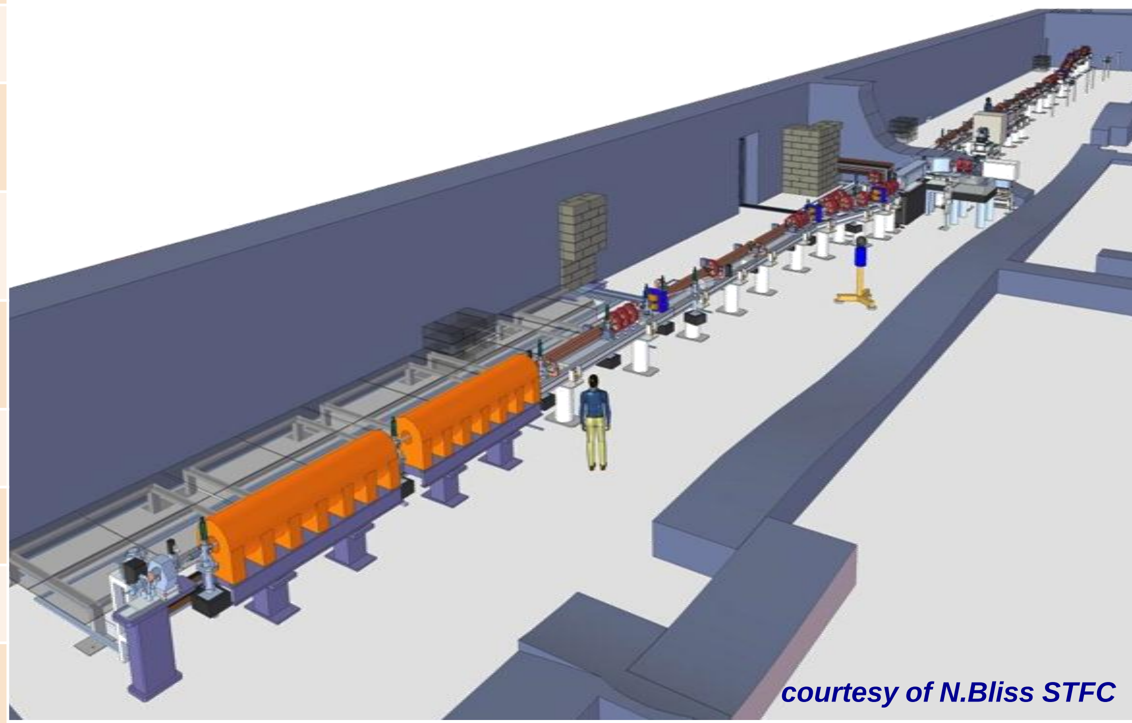
3D plot

GBS – Beam Specifications

Energy (MeV)	0.2 – 19.5
Spectral Density (ph/s·eV)	$0.8 - 4\cdot10^4$
Bandwidth rms (%)	≤ 0.5
# photons per shot within FWHM bdw.	$\leq 2.6\cdot10^5$
# photons/sec within FWHM bdw.	$\leq 8.3\cdot10^8$
Source rms size (μm)	10 – 30
Source rms divergence (μrad)	25 – 200
Peak brilliance (N_{ph}/sec·mm²·mrad²·0.1%)	$10^{20} - 10^{23}$
Radiation pulse length rms (ps)	0.7 – 1.5
Linear polarization (%)	> 99
Macro rep. rate (Hz)	100
# pulses per macropulse	32
Pulse–to–pulse separation (nsec)	16

Low–energy stage: Eγ < 3.5 MeV
March 2017

High–energy stage: Eγ < 19.5 MeV
September 2018



courtesy of N.Bliss STFC

GBS – Experimental Setups

E2: Low energy gamma vault

- Nuclear Resonance Fluorescence
- Isotope-specific material detection, assay and imaging
- Medical isotopes

E3: Positron spectroscopy vault

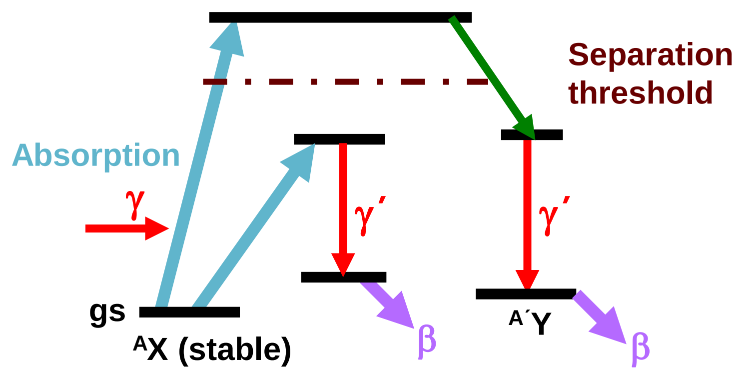
GSR: Photofission – exotic nuclei

- production of exotic nuclei

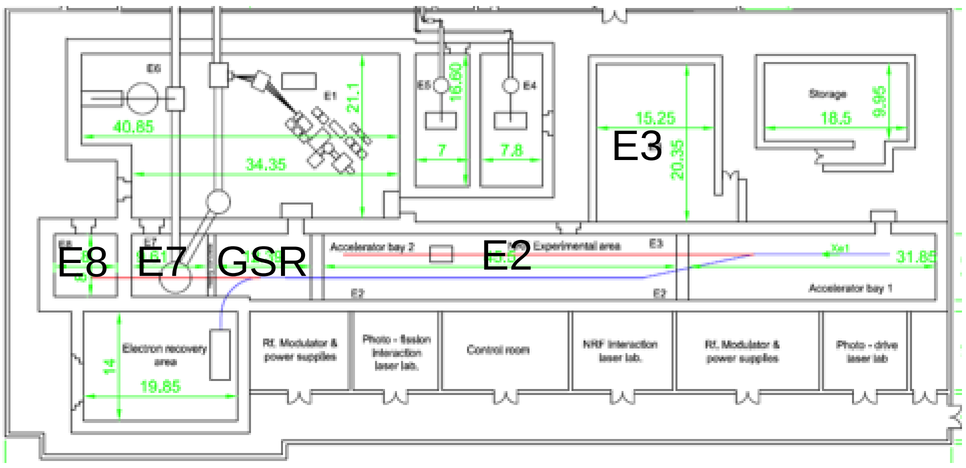
E7: Experiments with combined laser and gamma beams

E8: High energy gamma vault

- (γ,n) cross sections
- (γ,*charged part.*) astrophysics
- Nuclear Resonance Fluorescence
- Photofission
- Medical isotopes



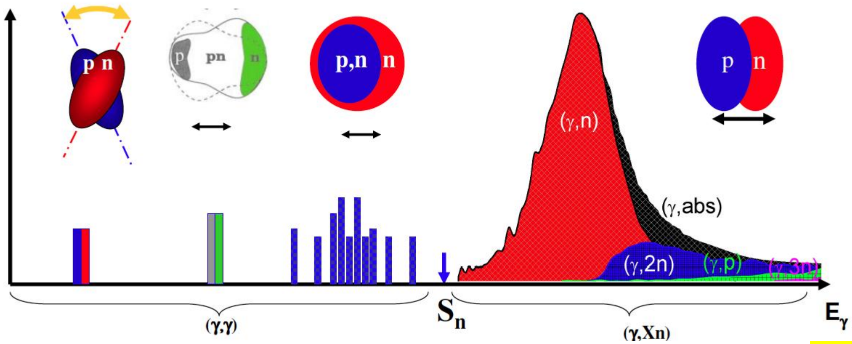
Nuclear Resonance Fluorescence (NRF)
Photoactivation
Photodisintegration (–activation)
Photofission



Nuclear Resonance Fluorescence

Electromagnetic dipole response of nuclei

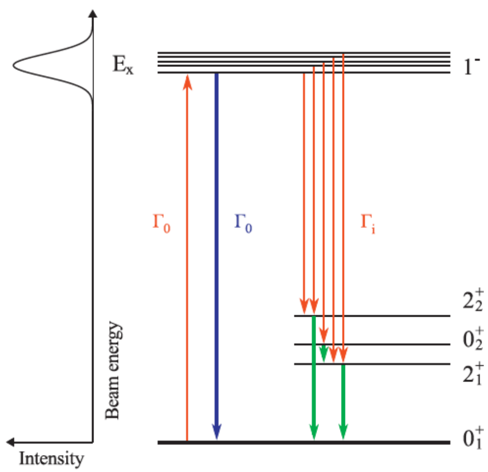
- p–nuclei, actinides
- scissor modes
- Pygmy Dipole Resonances
- Γ_0 and Γ/Γ_0 measurements

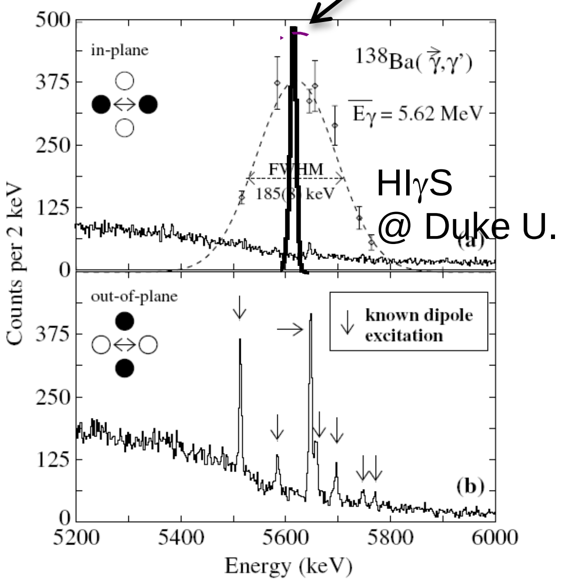


ELI–NP
/ 1000

Observables

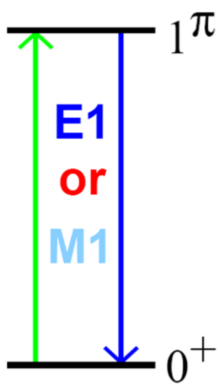
- Excitation Energy E_r
- Spin and parity $J,\ \pi$
- Decay Energies E_γ
- Partial Widths Γ_i/Γ_o
- Multipole Mixing δ
- Decay Strengths $B(\pi\lambda)$
- Level Width Γ (eV)
- Lifetime τ (ps – as)

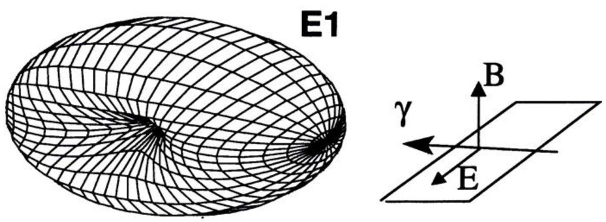




N.Pietralla

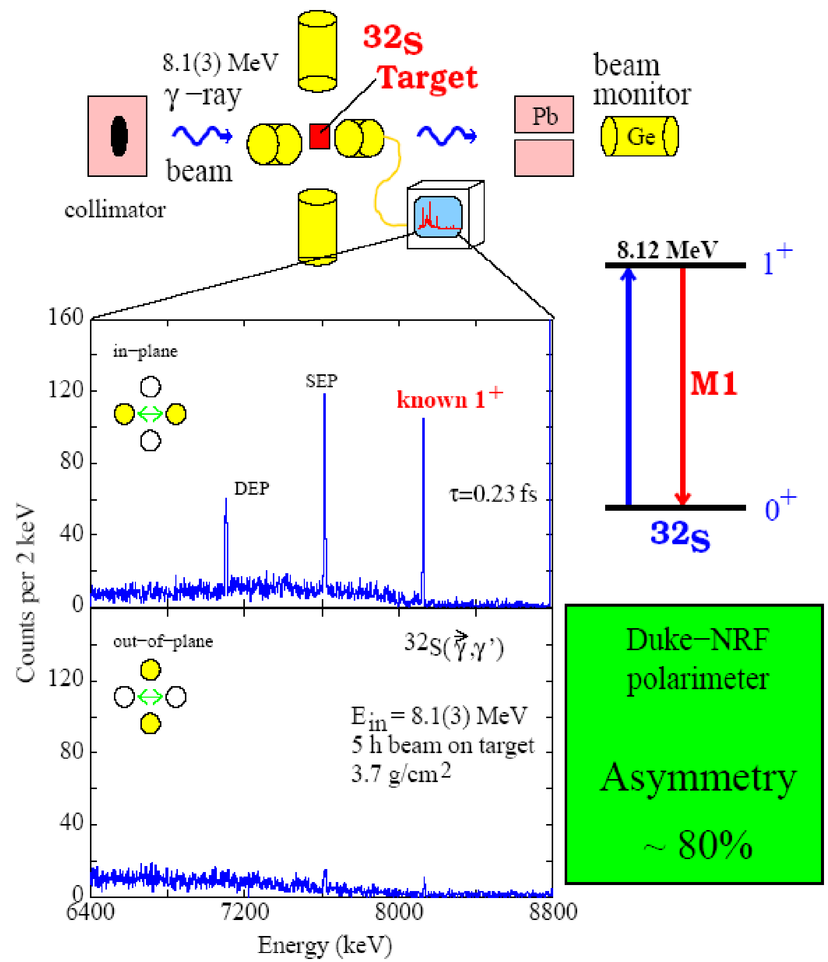
NRF – Polarization





$$W(\theta,\phi) = 1 + \tfrac{1}{2}[P_2(\cos\theta) + \tfrac{1}{2}\pi_1 \cos(2\phi) P_2^{(2)}(\cos\theta)]$$

- Elastic scattering distribution not isotropic about incident polarization plane.
- No intensity along oscillating dipole vector
- Azimuthal rotation by 90º for M1 and E1 distributions
- Observable only for linearly polarized beam

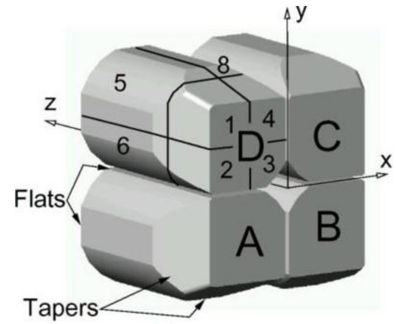


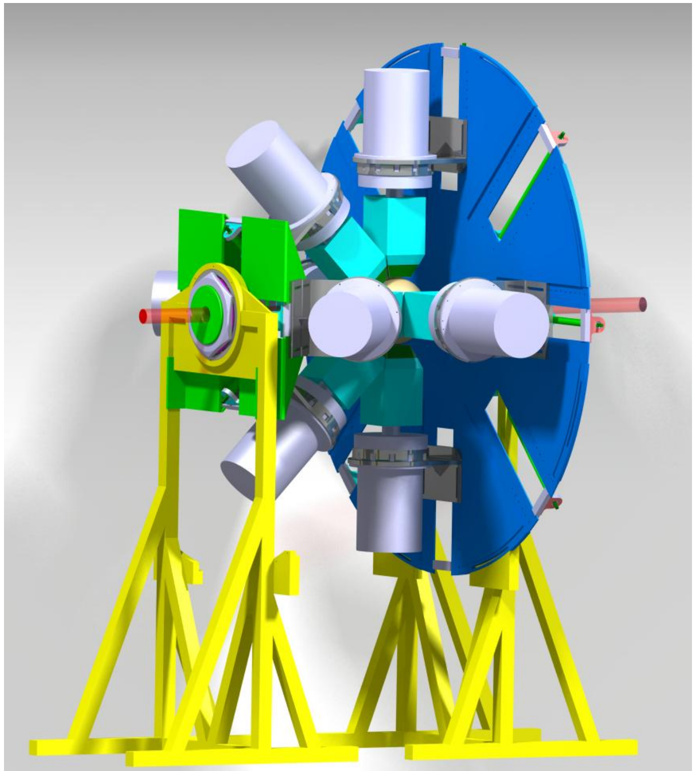
N.Pietralla, H.R. Weller et al., NIM A 483 (2002) 556.

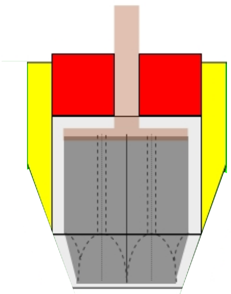
NRF – Setup

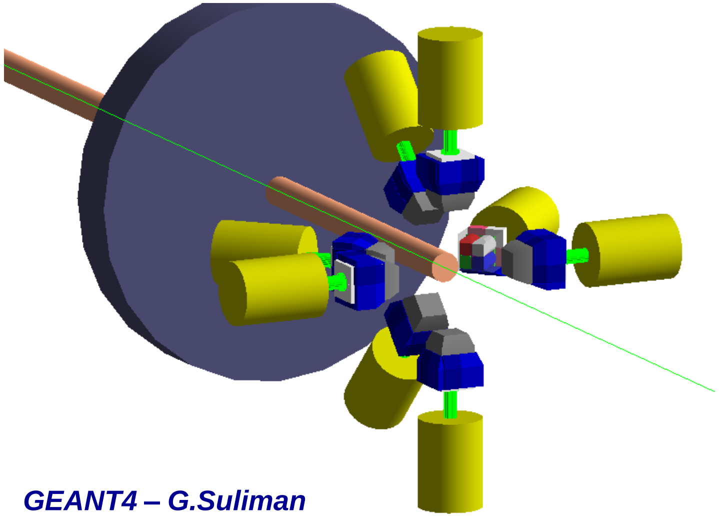
ELIADE – **ELI**–NP **A**rray of **DE**tectors

- use of composite HPGe detectors → higher photopeak efficiency due to add–back
- EXOGAM or TIGRESS – type Clover detector (*segmented*) with AC shield (rear back and back–catcher)









GEANT4 – G.Suliman

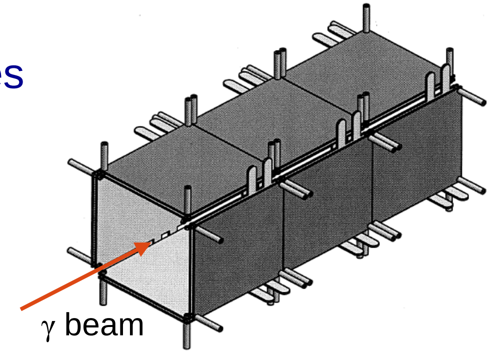
4 Clovers @ 90^o + 4 Clovers @ 135^o

4 3"x3" $LaBr_3$ det. @ 90 deg.

ε_{ph} ~ 10–12% at minimum distance of 11 cm from the target

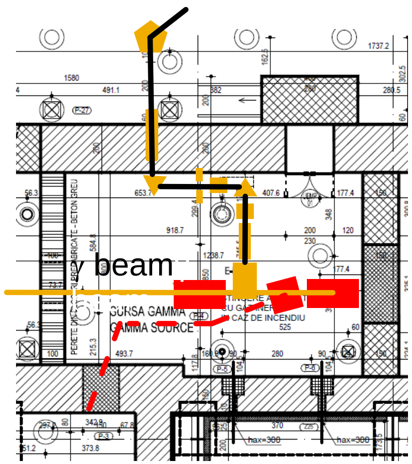
Photofission

- Study photofission barriers, cross sections and rare fission modes
  - High resolution photofission studies in actinides, 2nd and 3rd minimum, angular and mass distribution of the fragments
  - Ternary fission studies
  - Measurements of absolute photofission cross sections



THGEM
Bragg Chamber + Si DSSSD

- Separation, manipulation and experiments with fission fragments
  - Emphasis on the isotopes of refractory elements
  - IGISOL technique: gas catcher, RF ion guide, mass separator



IGISOL Setup

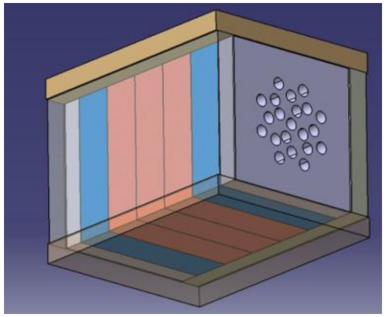
- In–beam gamma–ray spectroscopy of fission fragments
  - gamma–ray detectors (Clover, $LaBr_3$)
  - g–factors

F.Ibrahim, A.Krasznahorkay, D.Balabanski, G.Georgiev

Astrophysics Related Studies

Production of heavy elements in the Universe – a central question for Astrophysics

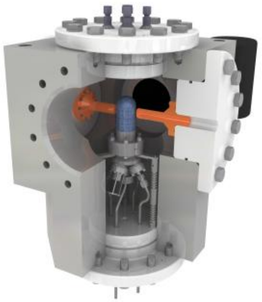
- Neutron capture cross section of s–process branching nuclei with inverse reactions
    - studies on long–lived branching points (e.g. ^{147}Pm, ^{151}Sm, ^{155}Eu) showed that the recommended values of neutron capture cross sections in the models differ by up to 50% from the experimentally determined values



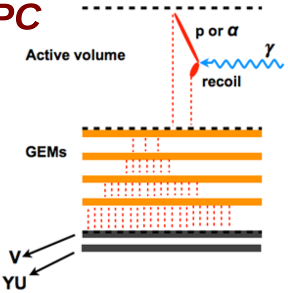
4PIN – neutron ^{3}He counter array

- Measurements of (©,p) and (©,〈) reaction cross sections
    - p–process nucleosynthesis
    - clustering phenomena in light nuclei
    - photodisintegration: ^{16}O(©,α)^{12}C, ^{22}Ne(©,α)^{18}O, ^{19}F(©,p)^{18}O, ^{24}Mg(©,α)^{20}Ne

Bubble chamber



eTPC



Si DSSSD

M. Gai, O.Tesileanu, C.Mazzochi, A.Anzalone
H. Utsunomiya, F. Camera, D.Filipescu

Perspectives

- a new research facility is being under construction at Bucharest
    - HPLS
    - GBS
- research opportunities
    - **nuclear physics**
        - nuclear photonics
        - HP laser driven
    - applications

- **young researchers are invited to join the fun !**
    - job opportunities: post–doc, junior and senior researchers, engineers
    - for details visit the website
      www.eli-np.ro/jobs.php

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