EUROPEAN UNION

GOVERNMENT OF ROMANIA

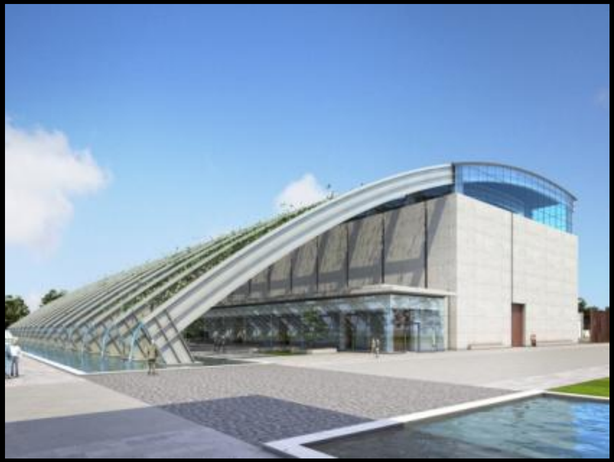
Structural Instruments 2007-2013

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

Nuclear Physics at the ELI–NP Facility



Călin A. Ur

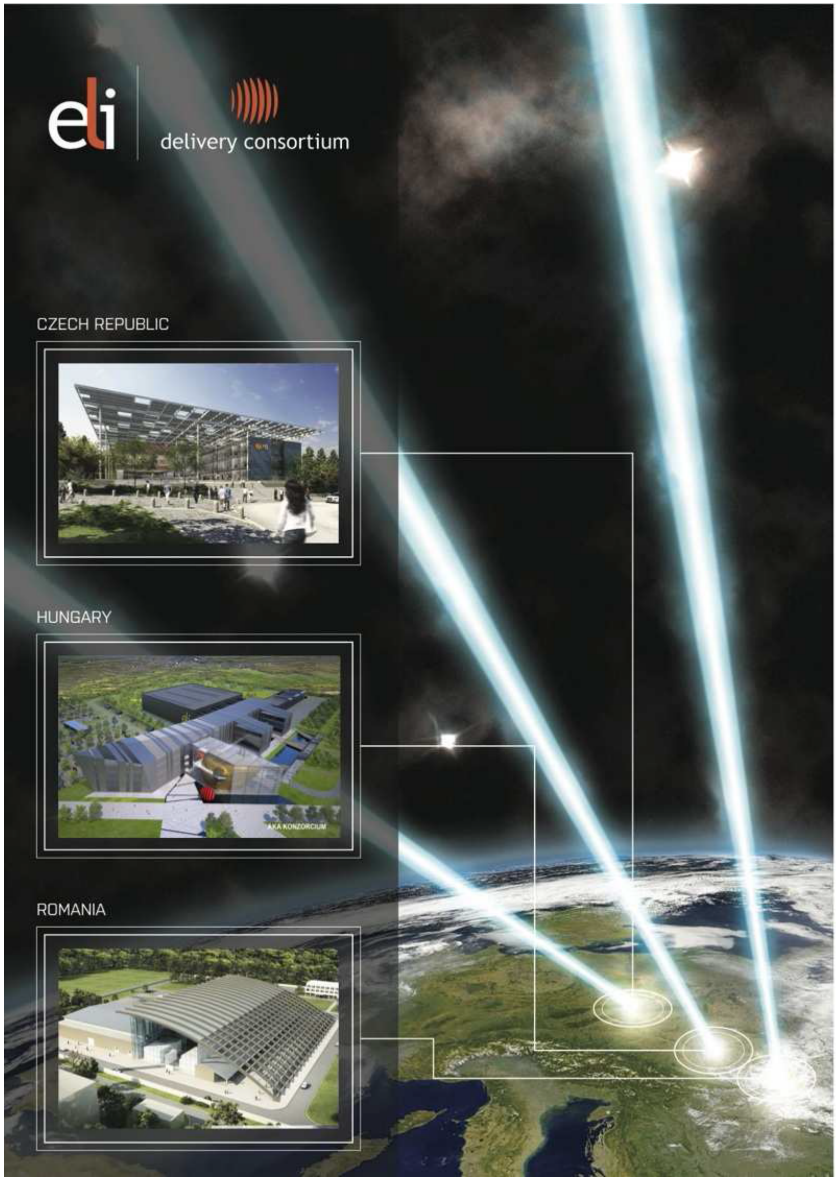
for the ELI–NP Team

European Gamma and Ancillary detectors Network, GSI, Darmstadt, June 23, 2014

Presentation Layout

- **General presentation of ELI–NP project**
  milestones
  location
  the facility
  status
  general physics case
- **High Power Laser System**
  layout
  laser driven nuclear physics
- **Gamma Beam System**
  the concept
  layout and implementation
  experimental setups
- **Concluding remarks**

Extreme Light Infrastructure (ELI)



the world's first international laser research infrastructure

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

ELI–ALPS, Szeged, HU
Attosecond Laser Science
new regimes of time resolution

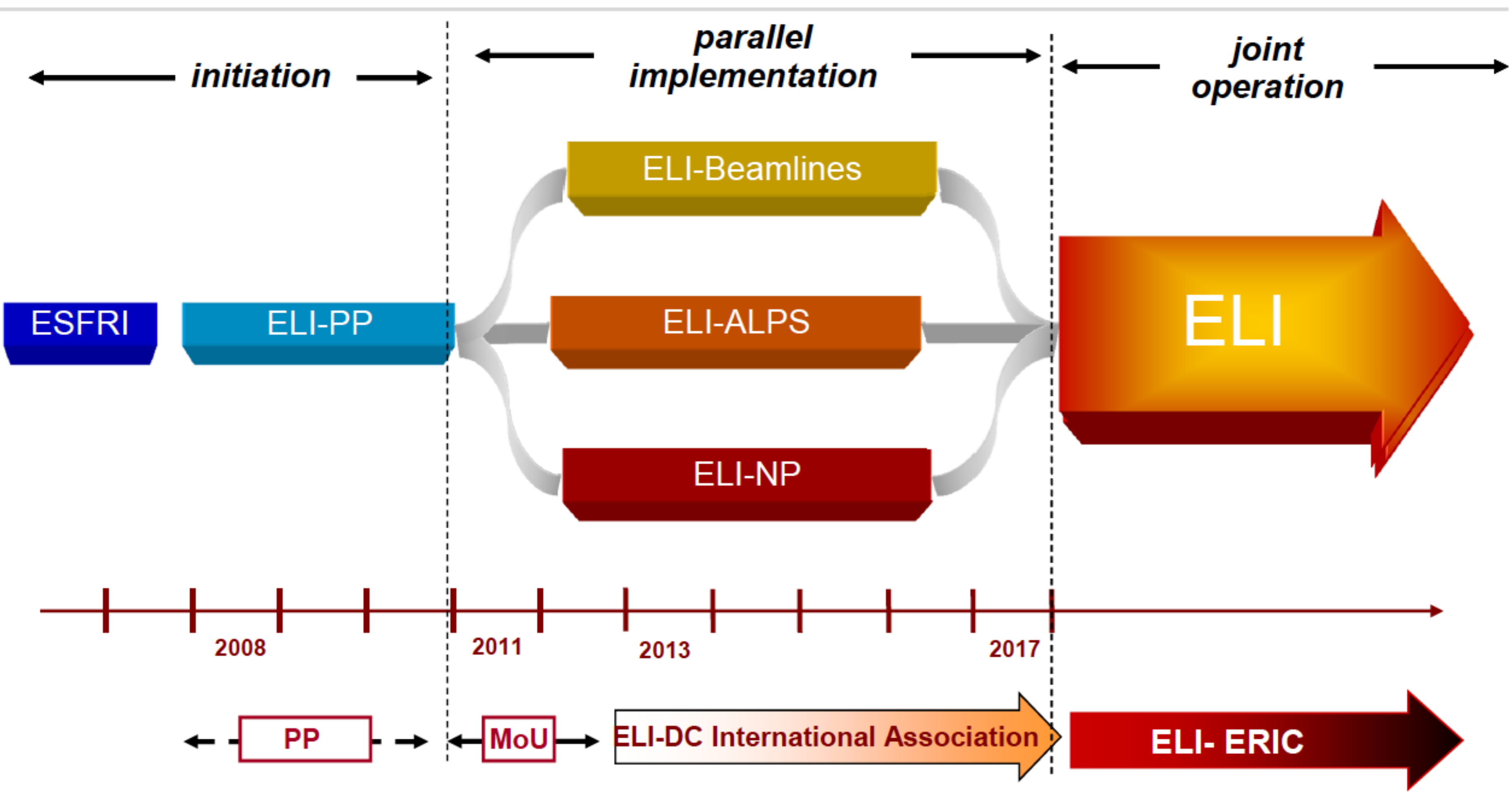
ELI–Beamlines, Prague, CZ

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 20 MeV)
novel photonuclear studies

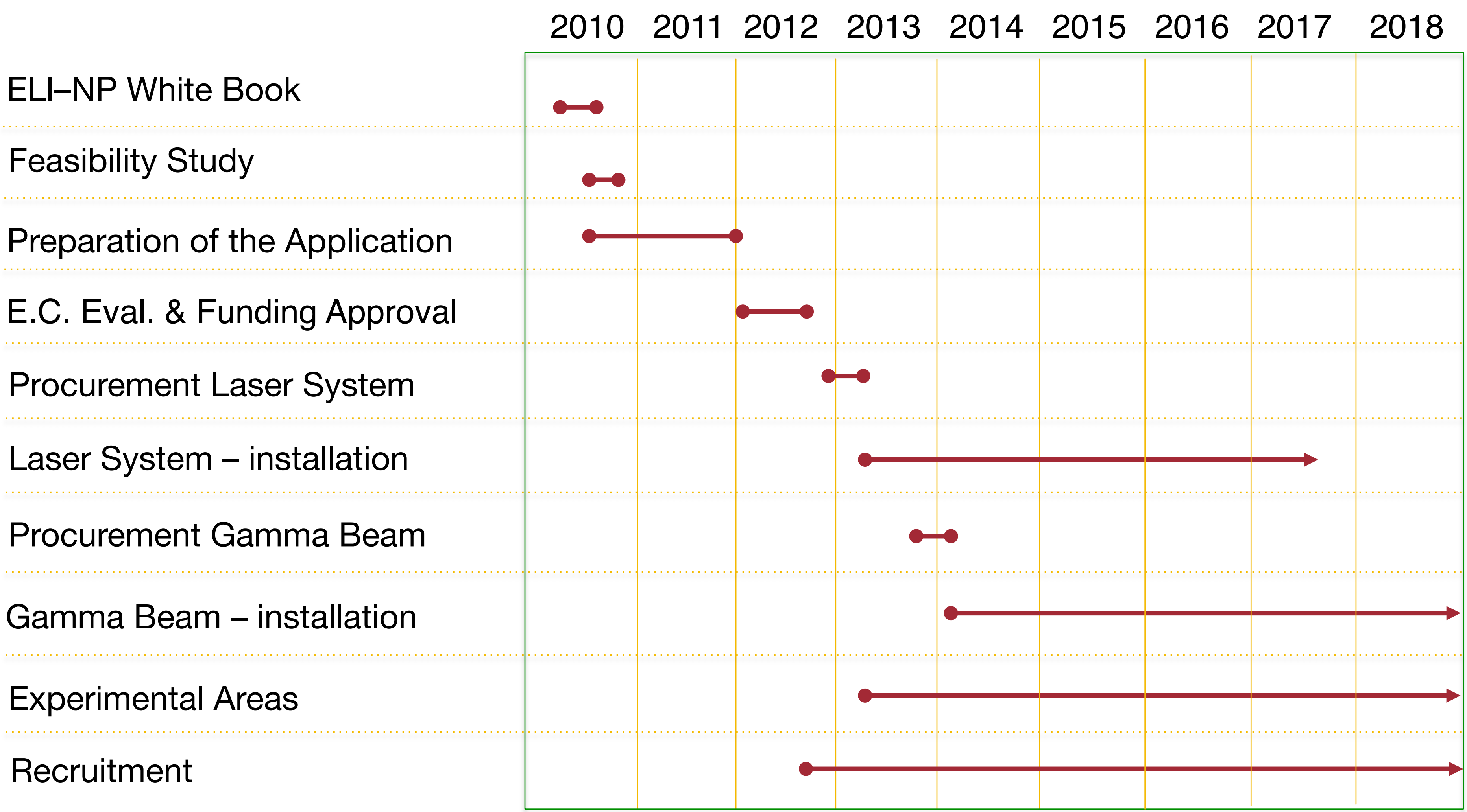
ELI 4 , to be decided
Ultra–High–Field Science
direct physics of the unprecedented laser field strength

ELI Roadmap

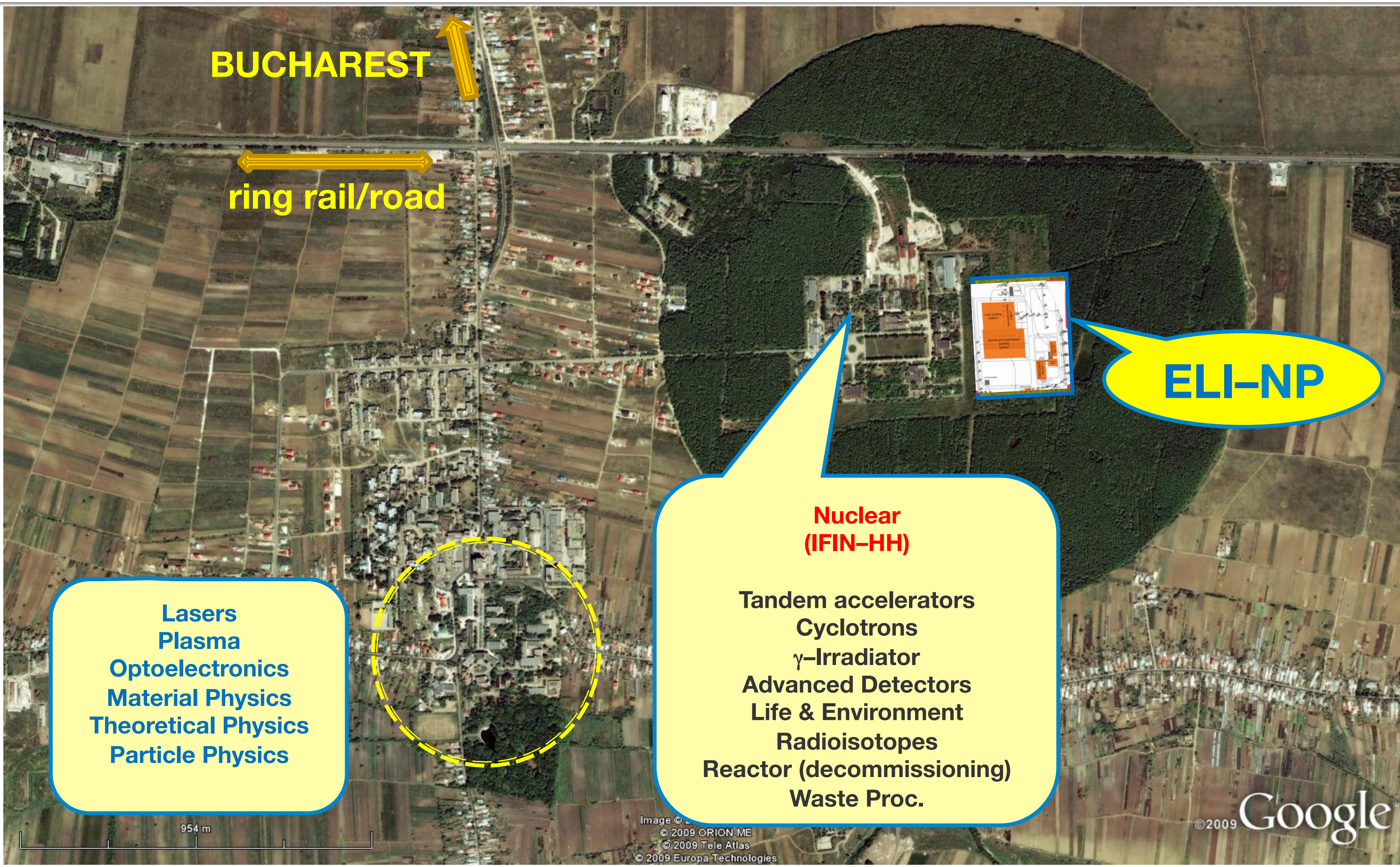


ELI Delivery Consortium

ELI–NP Implementation Timeline



Magurele–Bucharest Physics Platform



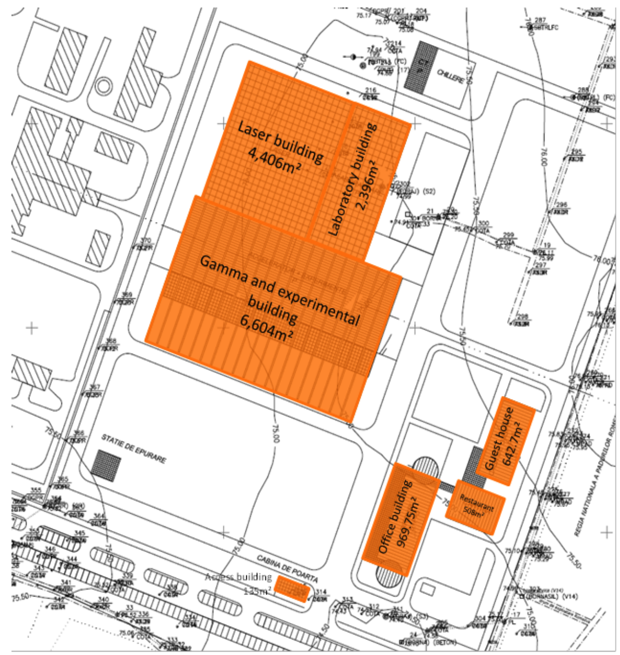
ELI–NP Facility Concept

Two major machines : 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 $\sim 10^{-3}$

Buildings – one contractor, 33000 m^2 total

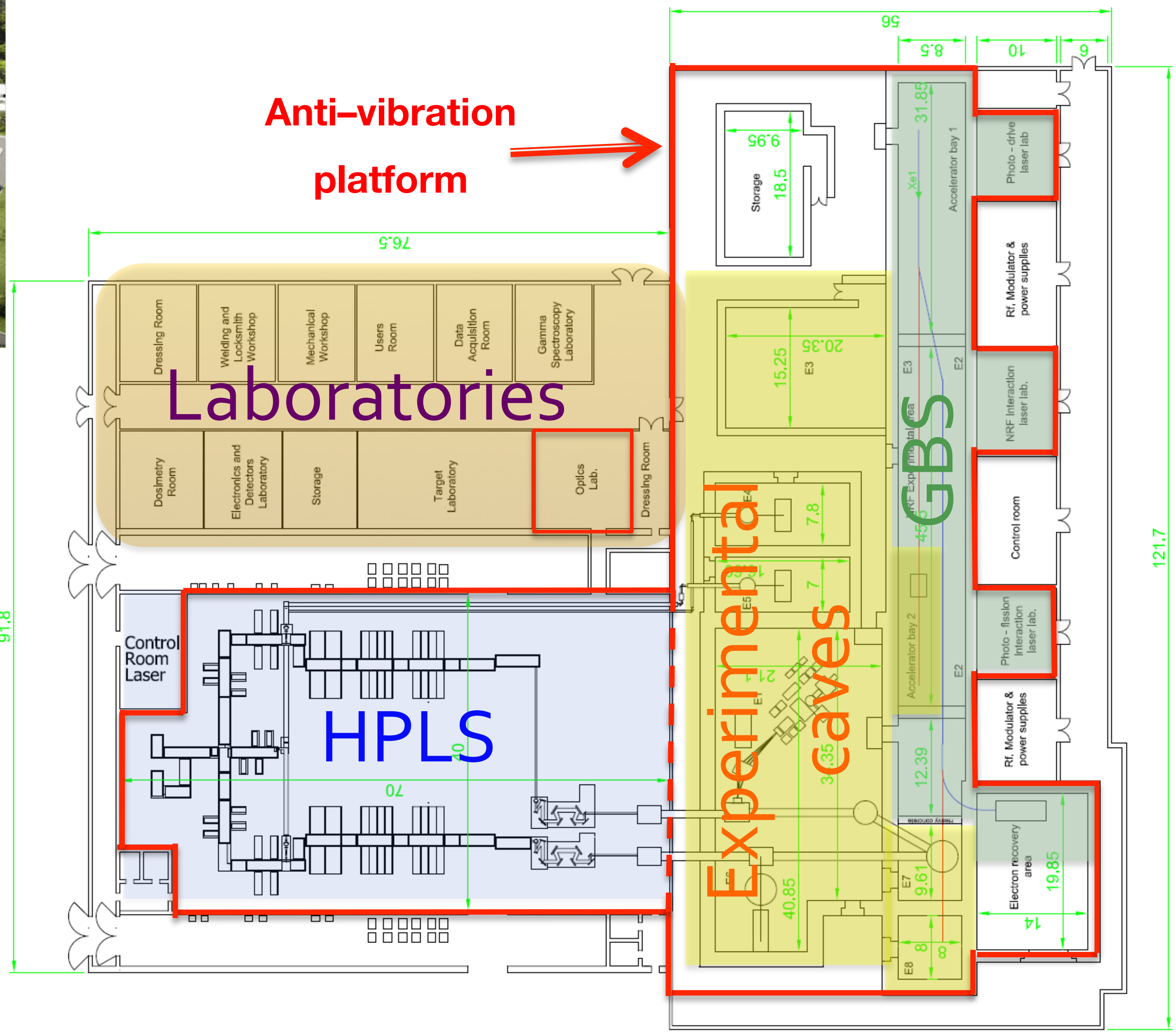
- Experimental area building
- Office building
- Guest house
- Canteen



Experiments

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

ELI–NP Experiment Building

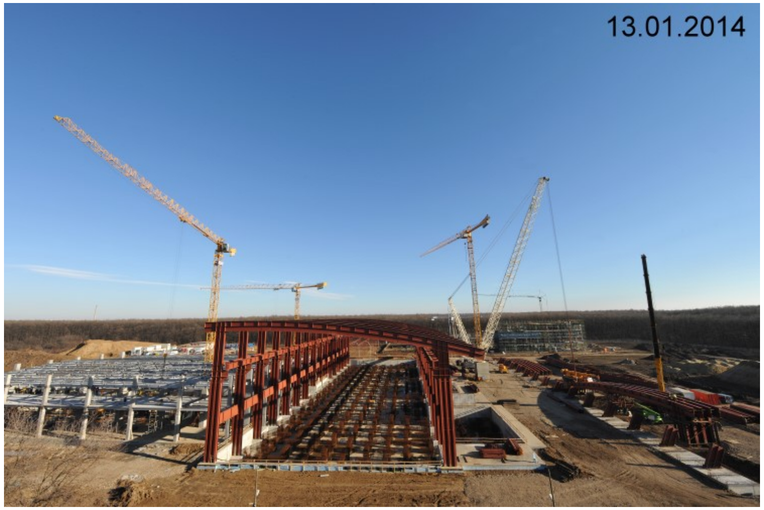


Platform vibrations

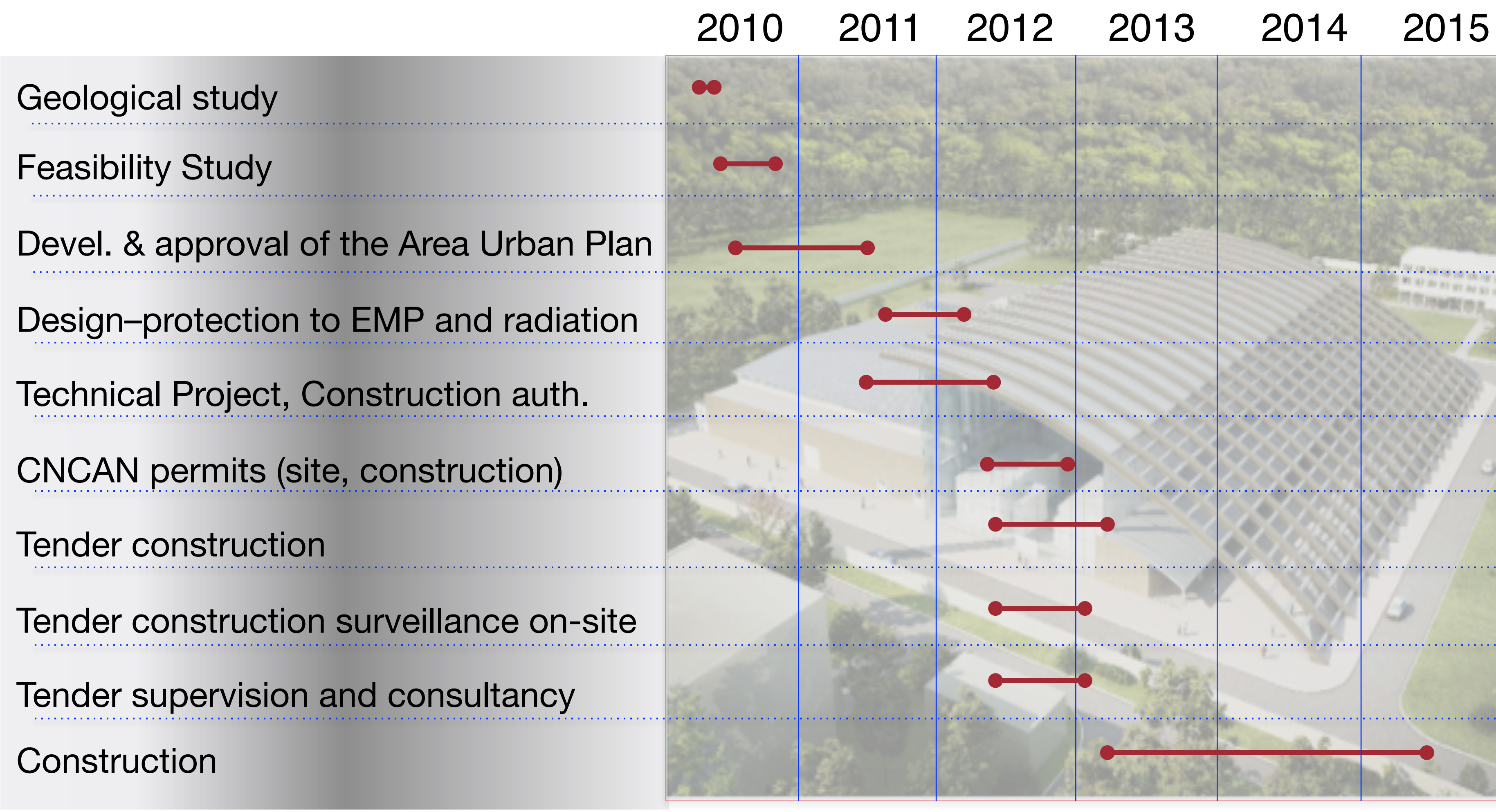
±1 μm @ < 10 Hz

- supported on dampers

ELI–NP Building Progress



ELI–NP Building Progress



ELI–NP Nuclear Physics Research

- Nuclear Physics experiments

  Photo–fission & Exotic Nuclei

  Nuclear Photonics (NRF)

  Photo–disintegration, Nuclear Astrophysics

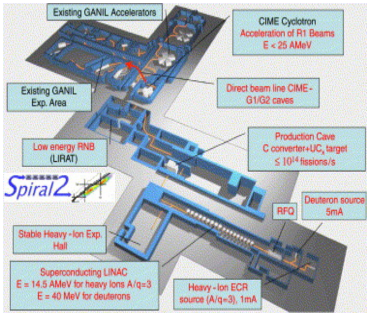
  complementary to other ESFRI Large Scale Physics Facilities (FAIR, SPIRAL2)

  Laser–Target interaction characteristics : NP diagnostics

  Laser Ion driven nuclear physics : fission–fusion

- Applications based on high intensity laser and very brilliant γ 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 Scientific Coordination

Research Activities

- HPLS
- GBS
- Experiments with HPLS
- Experiments with HPLS
- Combined experiments

Experiments with HPLS

1. Laser delivery and beam lines
2. Fission–fusion experiments
3. Strong field QED
4. Laser + Gamma interaction
5. Applications

Experiments with HPLS

1. Gamma Beam Delivery & Diagnostics
2. NRF Experiments
3. Photo–fission experiments
4. (γ,n) experiments
5. (γ,p) experiments
6. Positron source for material science
7. Applications

Combined experiments

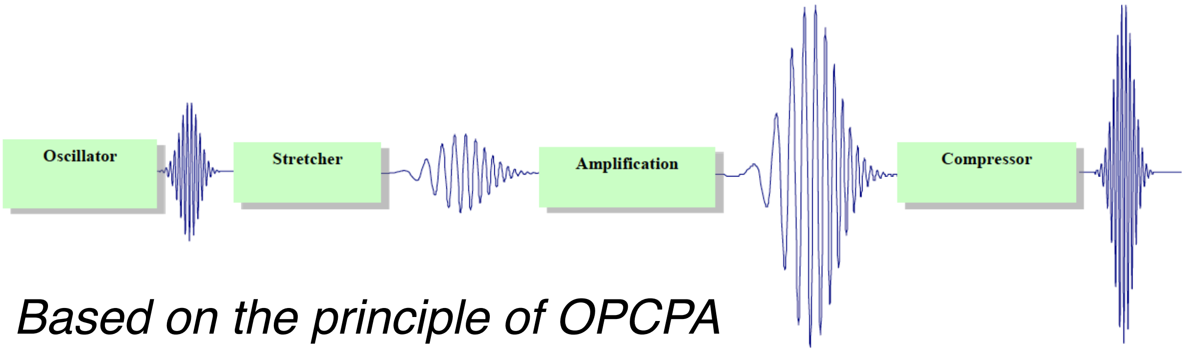
1. Laser delivery and beam lines
2. Fission–fusion experiments
3. Strong field QED
4. Laser + Gamma interaction
5. Applications

High Power Laser System

ELI–NP HPLS

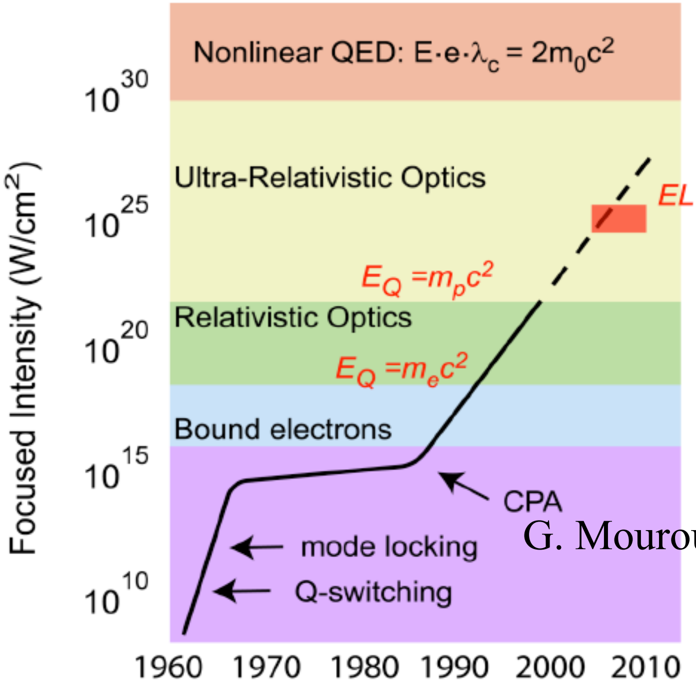
Provided by THALES - France

2 HPLS up to 10 PW – 6 output lines

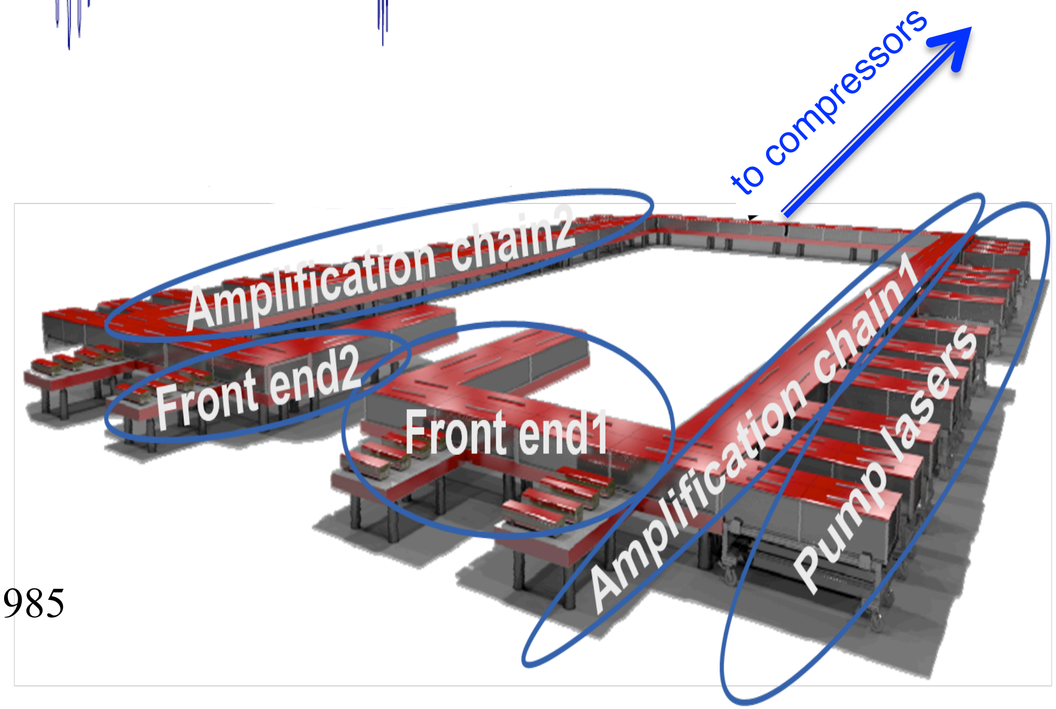


2 x 0.1 PW
2 x 1 PW
2 x 10 PW

Based on the principle of OPCPA



G. Mourou 1985

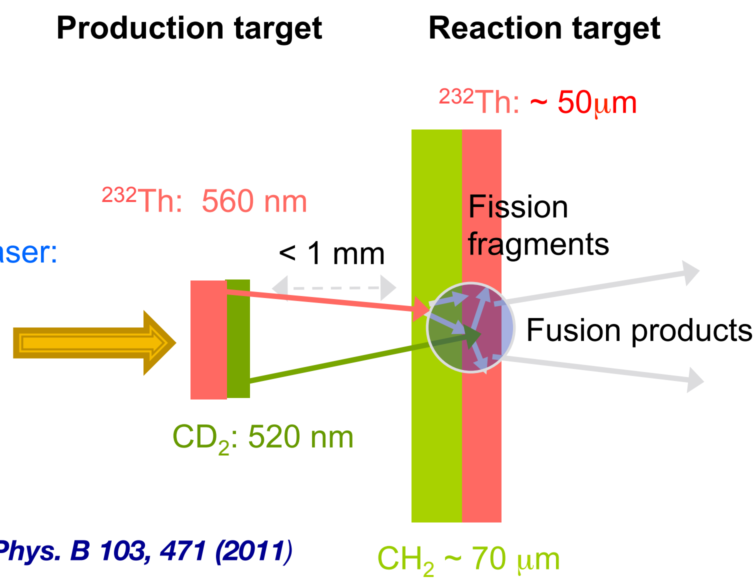


Laser Driven NP at ELI–NP

- 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:

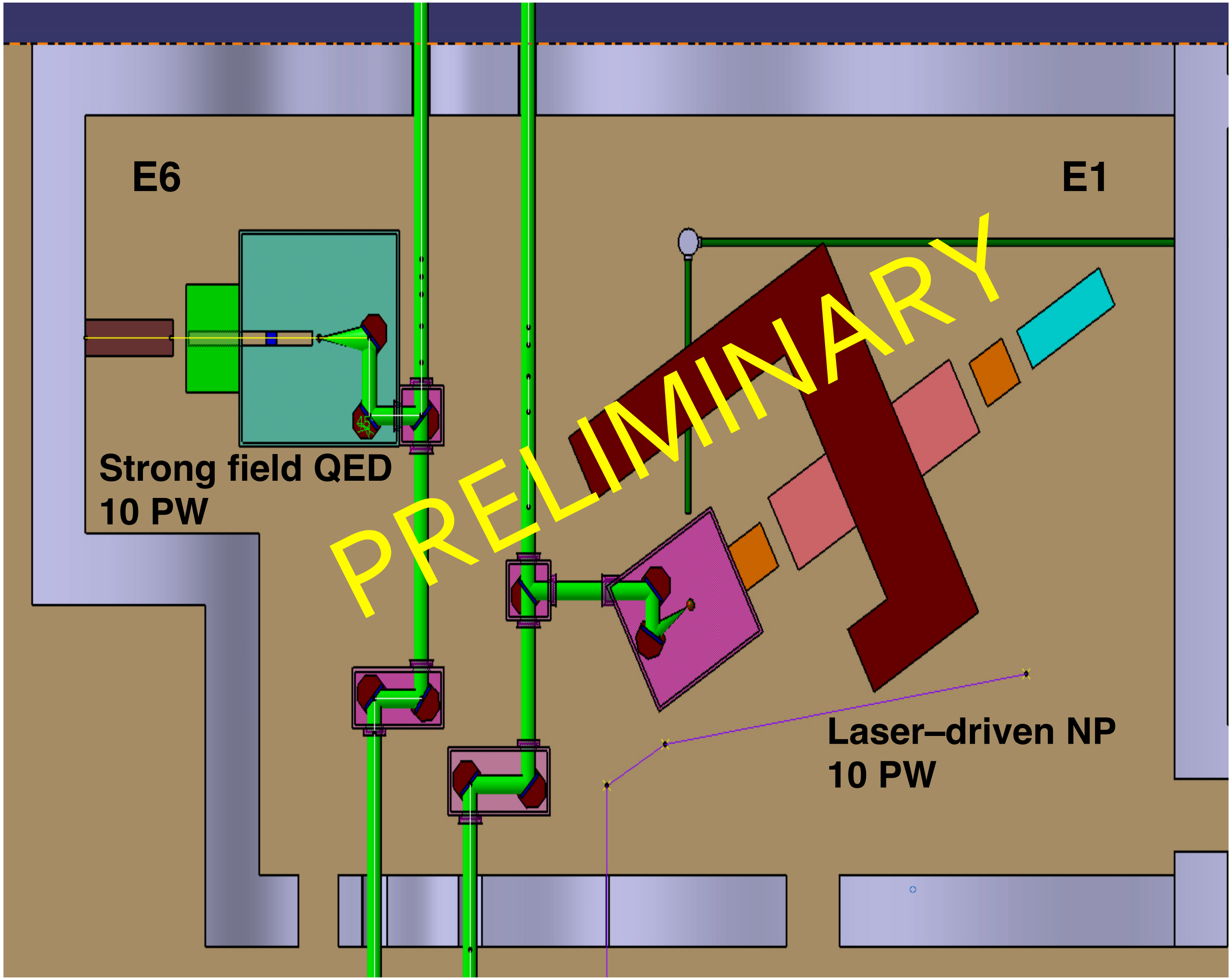
- 300 J, ~30 fs (10 PW)
- ~ 10^{23} W/cm^2
- focal diam. ~ 3 μm



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

HPLS Delivery



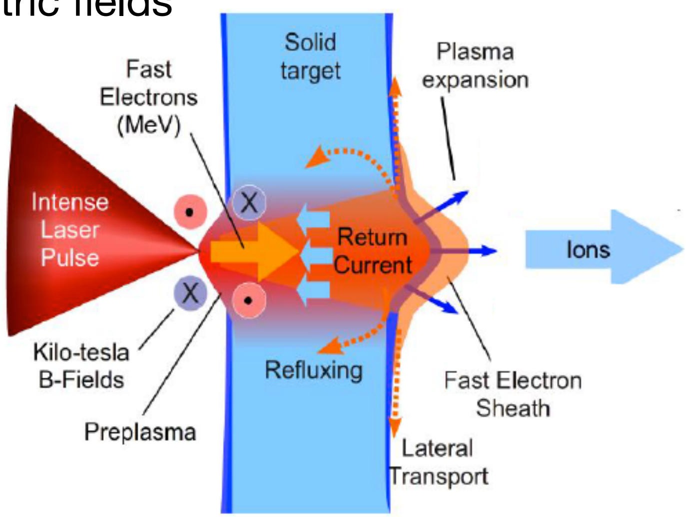
D. Ursescu, F. Negoita, E. Turcu

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

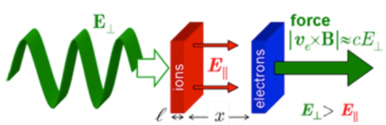


$E \sim (I_{laser})^{1/2}$ 300 – 400 MeV/u

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

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.

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

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

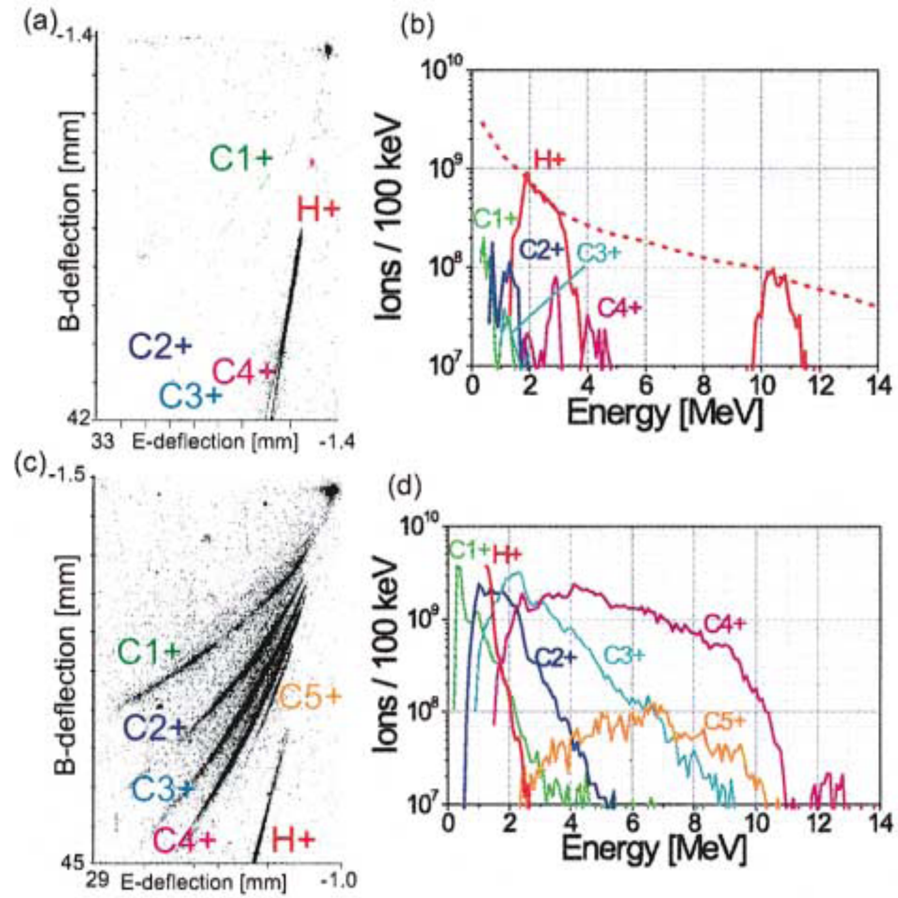
Protons & Heavy Ions

Heavy ion beams at LULI (France)

Laser pulses:
30 J, 300 fs, 1.05 mm => $5x10^{19}$ W/cm^2.

Target: 1 mm C
on rear side of 50 μm W foils

Detection: Thomson parabola spectrometers
+ CR-39 track detectors

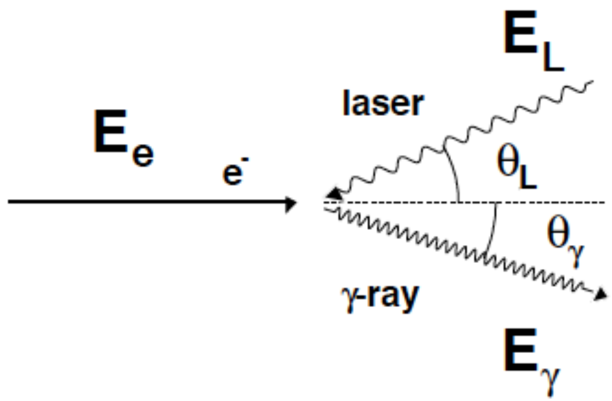


- Protons come from surface contamination
- Heating the target the protons are removed and heavy ions are better accelerated

O. Tesileanu, NN2012

The Gamma Beam System

The Gamma Beam System – Concept



Laser Compton Back–scattering (LCB)

- the most efficient frequency amplifier

'Photon accelerator'

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

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

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

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

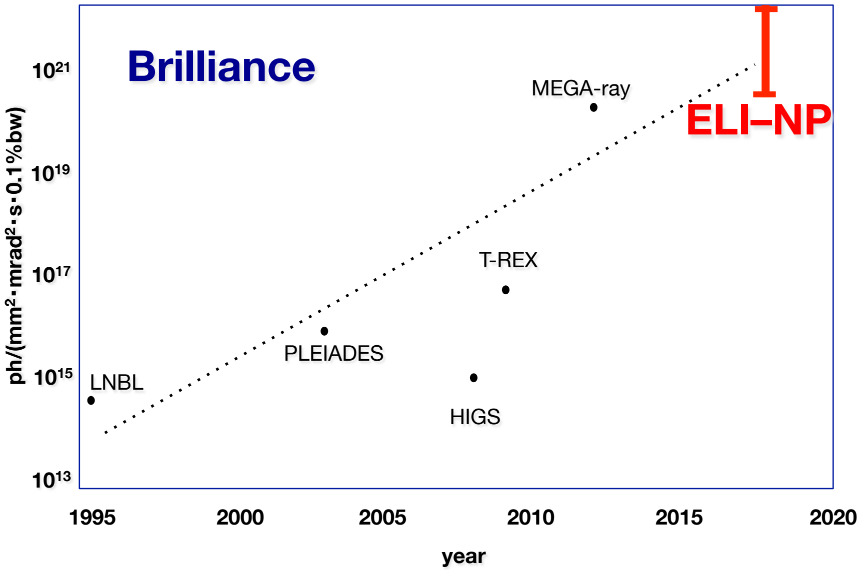
Low cross section (~10^{-25} cm^2) ➡ need of high photon and electron densities

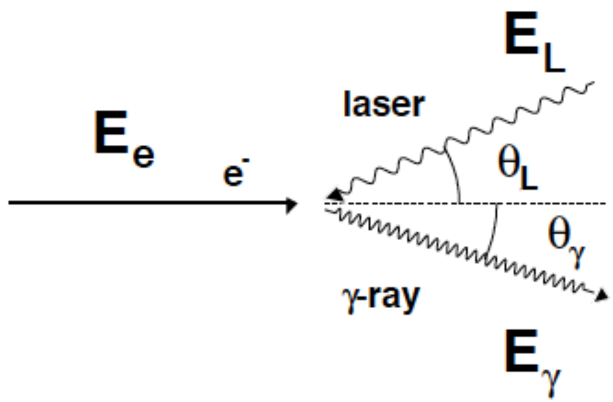
Maximum upshift

- head–on collision (θ_L=0) & backscattering (θ_γ=0) $E_\gamma \sim 4\gamma_e^2 \cdot E_L$

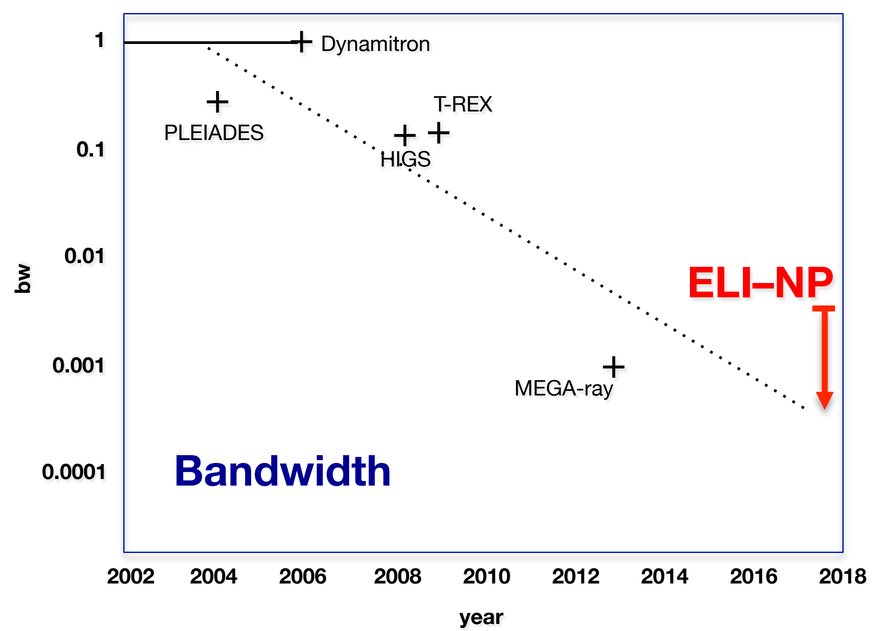
- E_L ~ 2.4 eV (green)
  - E_e ~ 300 MeV ➡ E_γ < 3.5 MeV
  - E_e ~ 720 MeV ➡ E_γ < 20 MeV

ELI–NP Gamma Beam System

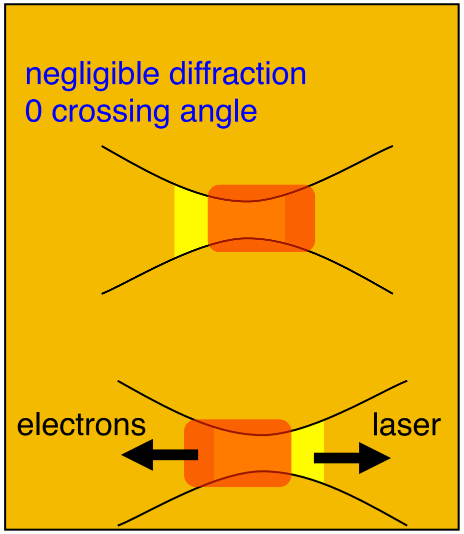


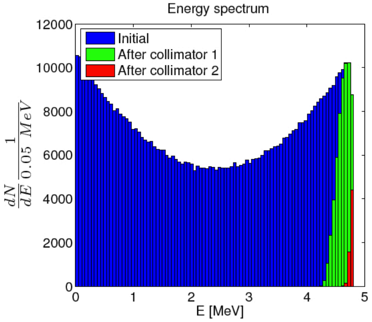


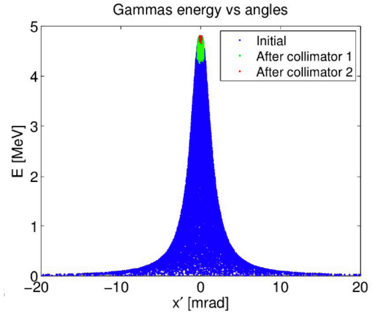
- high intensity / small emittance e⁻ beam from a warm LINAC
- very brillant high rep./rate int. laser
- small collision volume



ELI–NP Gamma Beam System







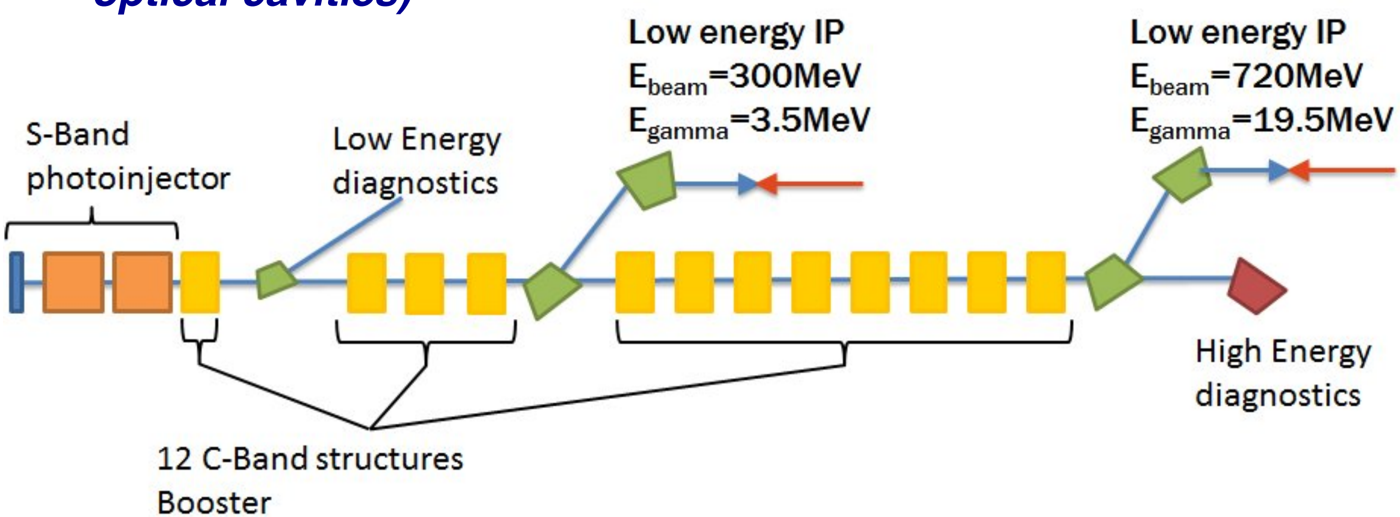
- **Build and run a Linear Collider (electron/photon), kind of photon accelerator promoting optical photons up to γ-ray energies**
- **Generate a secondary beam of gamma photons with unprecedented specs: Bright, Mono–chromatic (0.3%), High Spectral Flux (10^4 ph/sec·eV), Tunable (0.2–20 MeV),**
- **Highly Polarized**
- **In order to achieve this large step forward we need to improve the Spectral Luminosity of our Collider of about 2 orders of magnitude w.r.t. present state of the art**
- **Develop and implement innovative solutions for ultra-high phase space density electron beams (RF Linac mutuated from LC & FEL's) and ultra high quality recirculated lasers (mutuated from metrology / Fabry–Perot cavities)**

GBS – The EuroGammaS Project

Sapienza Università di Roma · INFN · Science & Technology Facilities Council · CNRS IN2P3 · Université Paris Sud

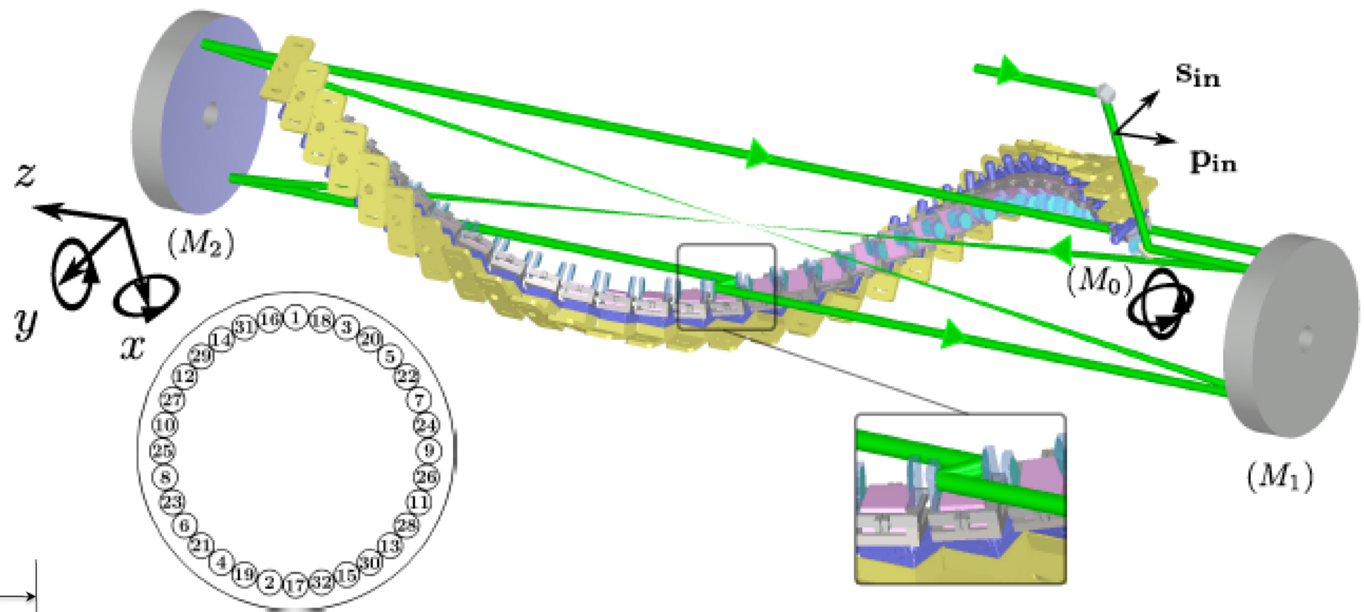
1) *RF Linac as per Linear Collider and FEL's machines (max rep rate, multi–bunch, max phase space density per average beam power)*
2) *High average power, high quality J–class 100 Hz psec Collision Laser (strategic investment in new Yb:Yag laser technology)*
3) *Laser recirculation with μm and μrad and sub–psec alignment/synchronization (metrology/interferometry optical cavities)*

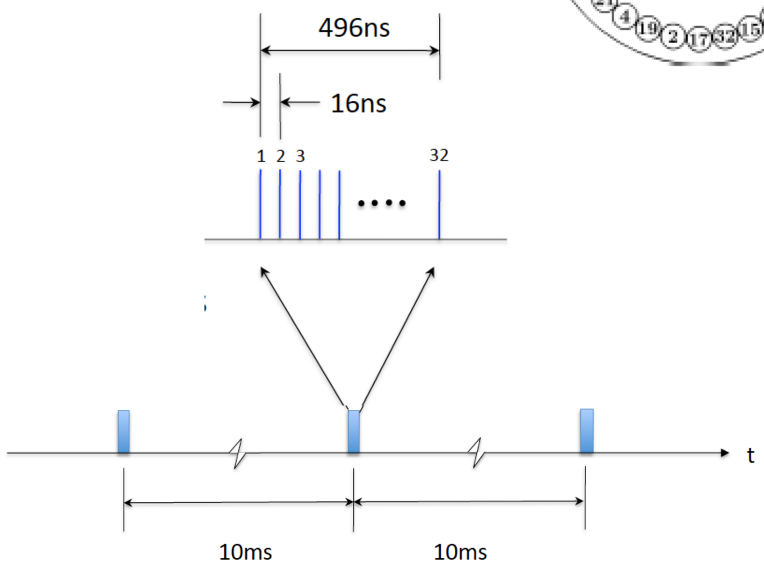
Bunch charge	250 pC
Number of bunches	32
Bunch distance	16 ns
C-band average accelerating gradient	33 MV/m
Norm. emittance	0.2-0.6 mm·mrad
Bunch length	<300 μm
RF rep Rate	100 Hz



EuroGammaS Technical Design Report

GBS – The EuroGammaS Project





'*Dragon–shaped*' Laser Recirculation

Electrons rep. rate –
macropulses 100 Hz
32 micropulses

Laser rep. rate – 100 Hz

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

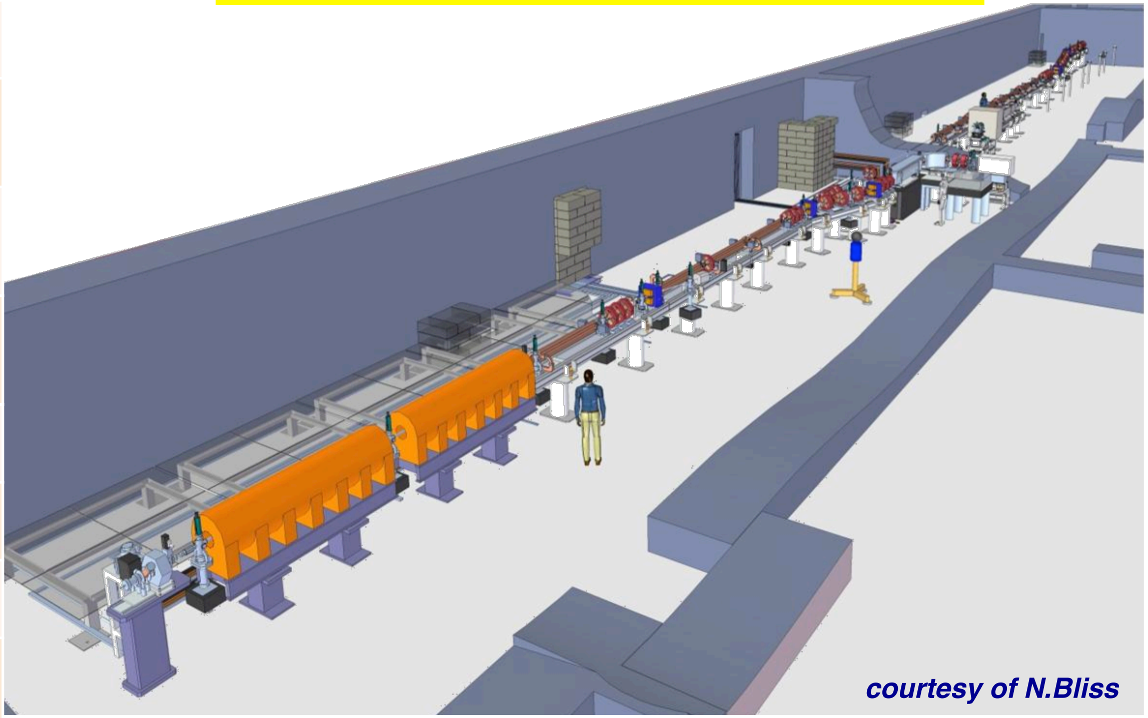
GBS – Beam Specifications

Energy (MeV)	0.2 – 19.5
Spectral Density (ph/s·eV)	0.8 – $4 \cdot 10^4$
Bandwidth rms (%)	≤ 0.3
# photons per shot within FWHM bdw.	≤ $2.6 \cdot 10^5$
# photons/sec within FWHM bdw.	≤ $8.3 \cdot 10^8$
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 (%)	> 99
Macro rep. rate (Hz)	100
# pulses per macropulse	32
Pulse–to–pulse separation (nsec)	16

Delivery contract signed on March 19, 2014

Low–energy stage: Eγ < 3.5 MeV
March 2017

High–energy stage: Eγ < 19.5 MeV
September 2018



courtesy of N.Bliss

GBS – Experimental Setups

E3: Positron spectroscopy

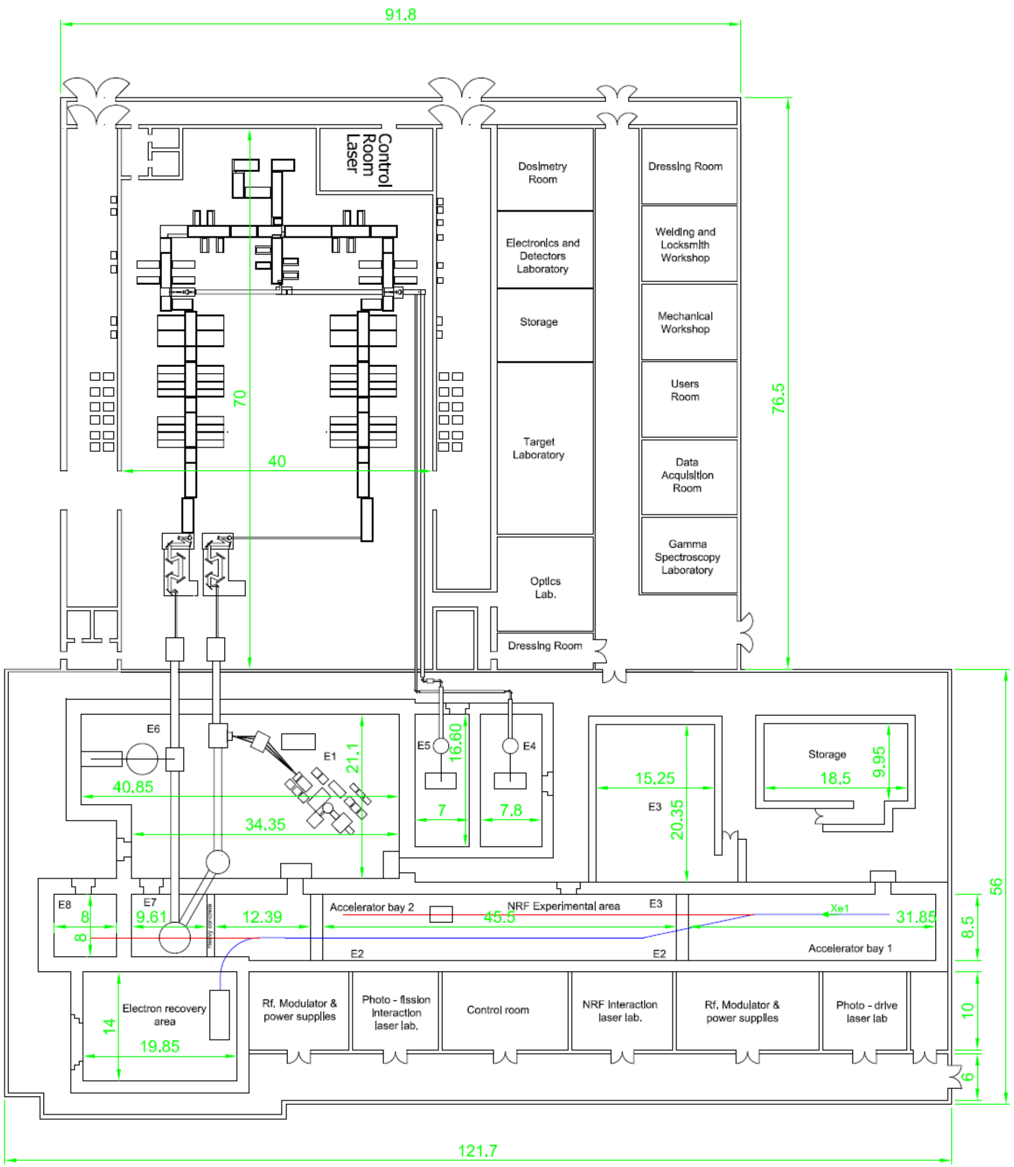
E2: Low energy gamma vault

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

E8: High energy gamma vault

- (γ,n) cross sections
- (γ,*charged particles*) astrophysics
- NRF
- Photofission

E7: Experiments with combined laser and gamma beams



GBS – Experimental Setups

E3: Positron spectroscopy

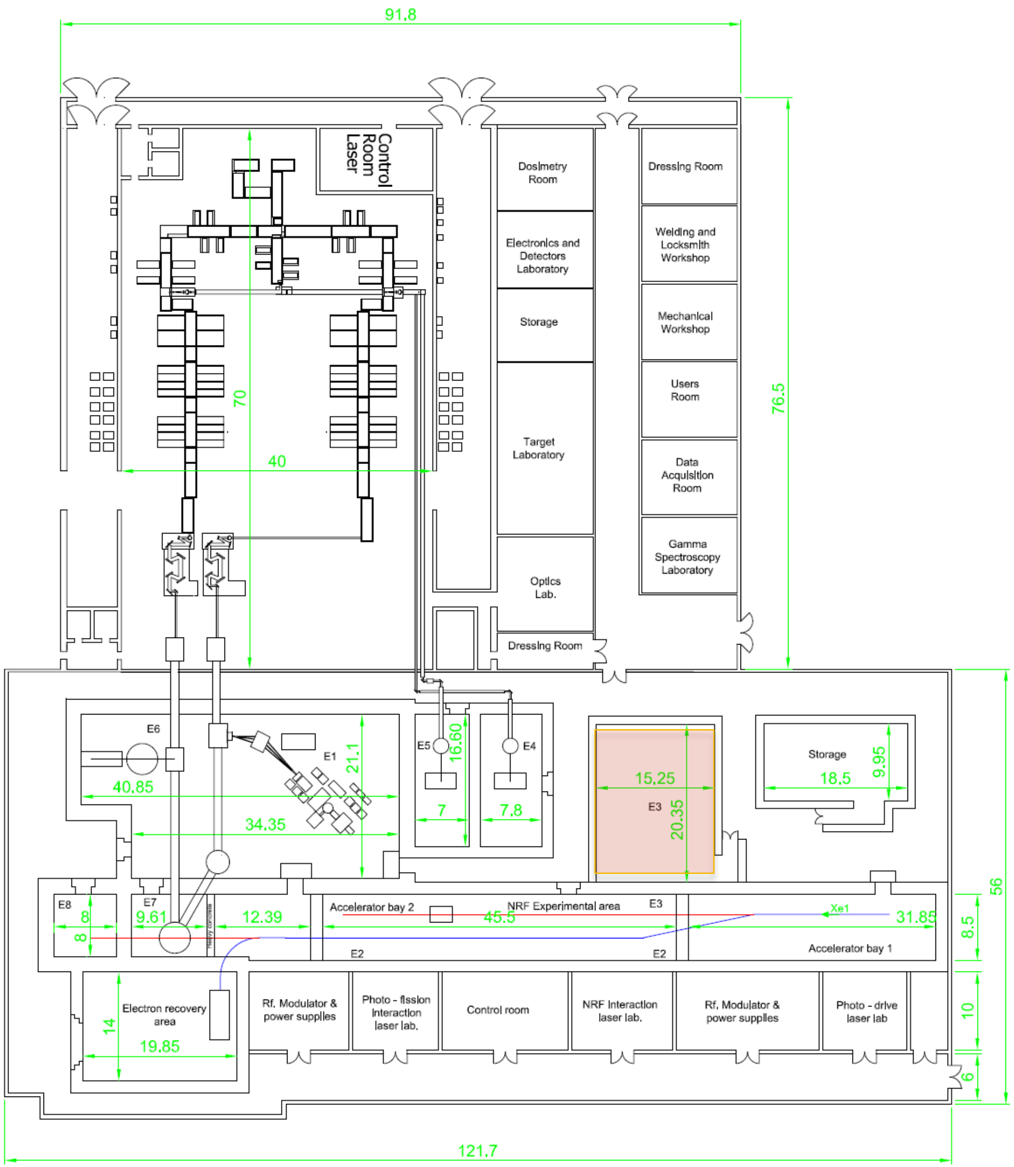
E2: Low energy gamma vault

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

E8: High energy gamma vault

- (γ,*n*) cross sections
- (γ,*charged particles*) astrophysics
- NRF
- Photofission

E7: Experiments with combined laser and gamma beams



GBS – Experimental Setups

E3: Positron spectroscopy

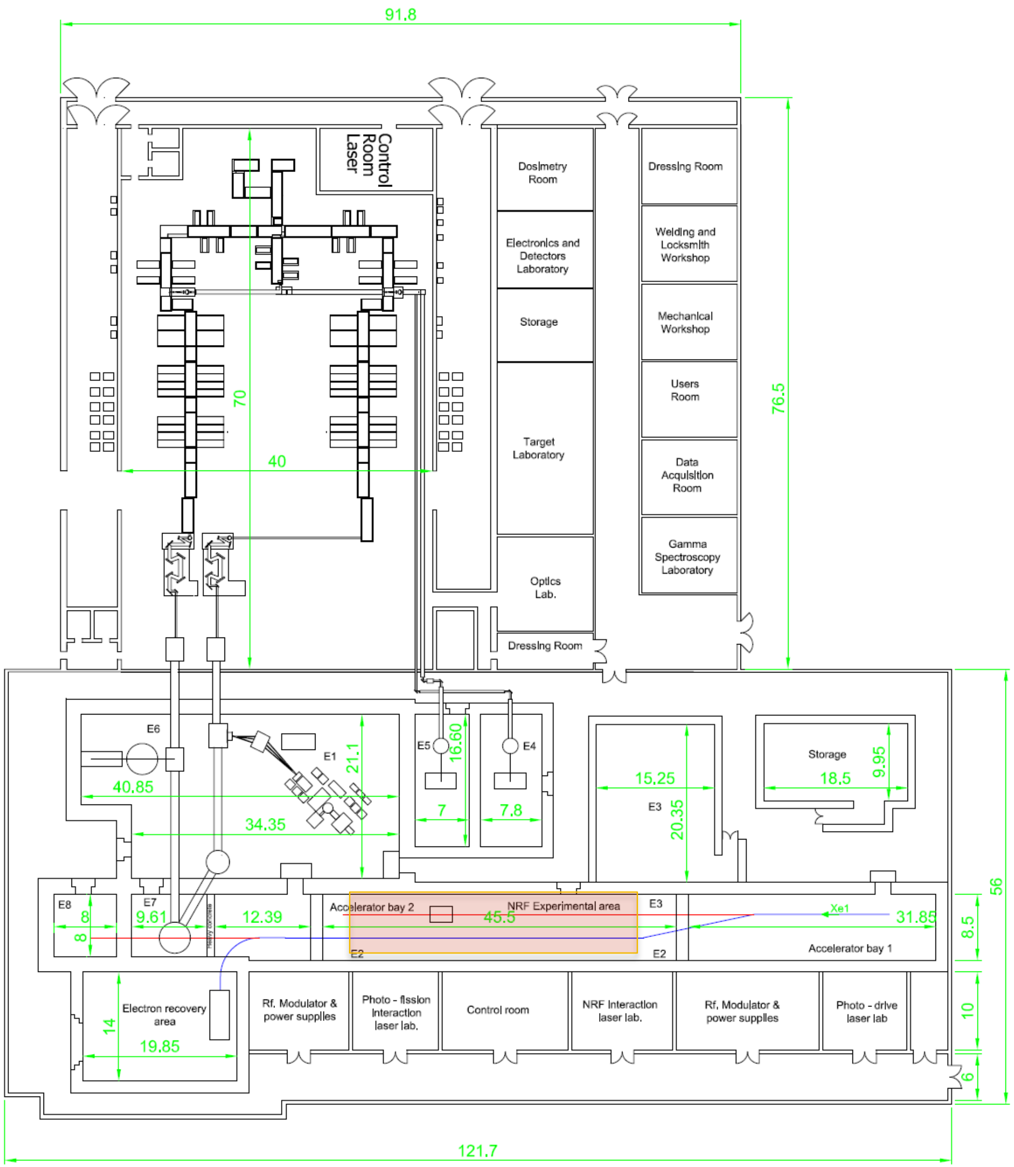
E2: Low energy gamma vault

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

E8: High energy gamma vault

- (γ,*n*) cross sections
- (γ,*charged particles*) astrophysics
- NRF
- Photofission

E7: Experiments with combined laser and gamma beams



GBS – Experimental Setups

E3: Positron spectroscopy

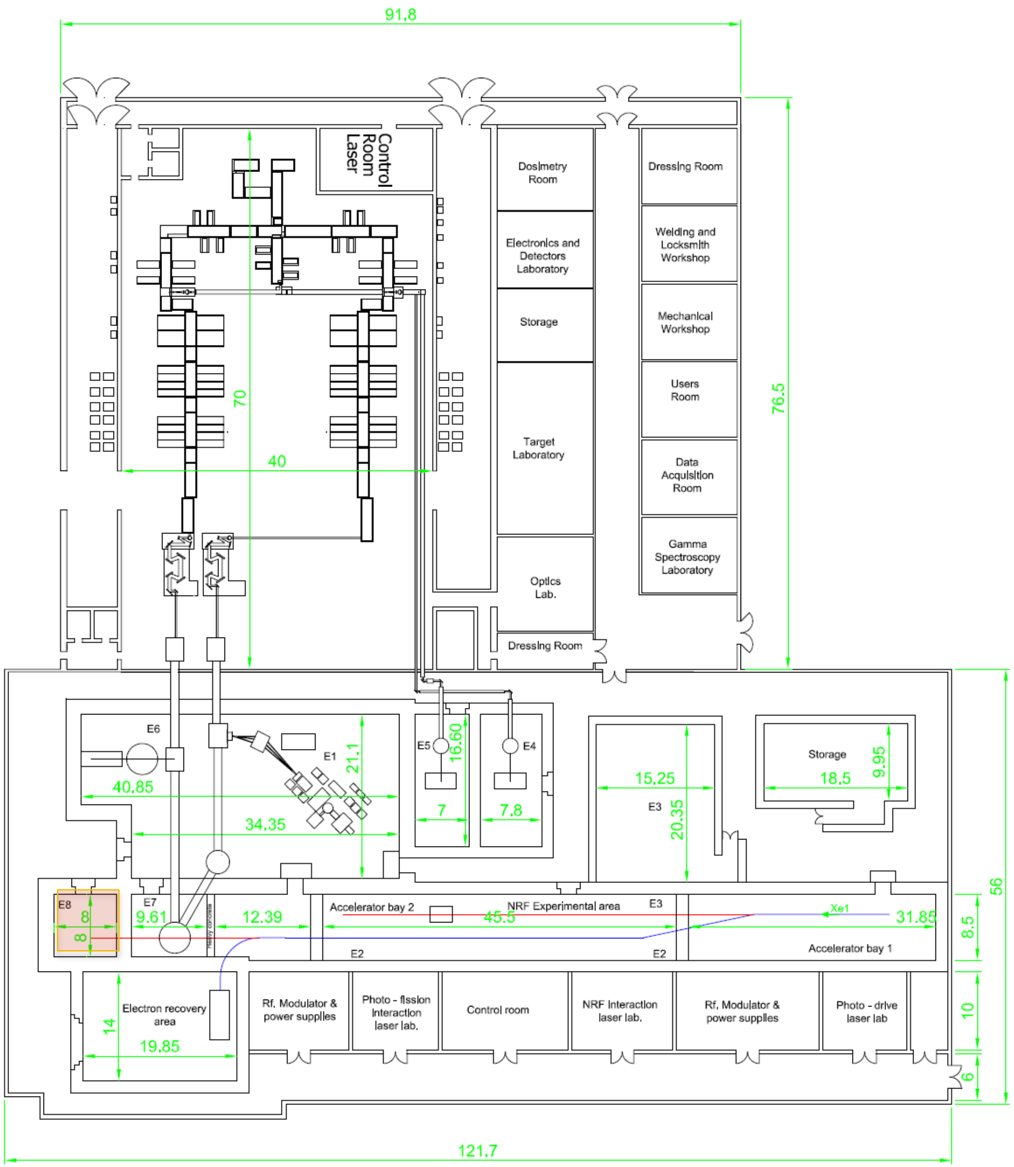
E2: Low energy gamma vault

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

E8: High energy gamma vault

- (γ,*n*) cross sections
- (γ,*charged particles*) astrophysics
- NRF
- Photofission

E7: Experiments with combined laser and gamma beams



GBS – Experimental Setups

E3: Positron spectroscopy

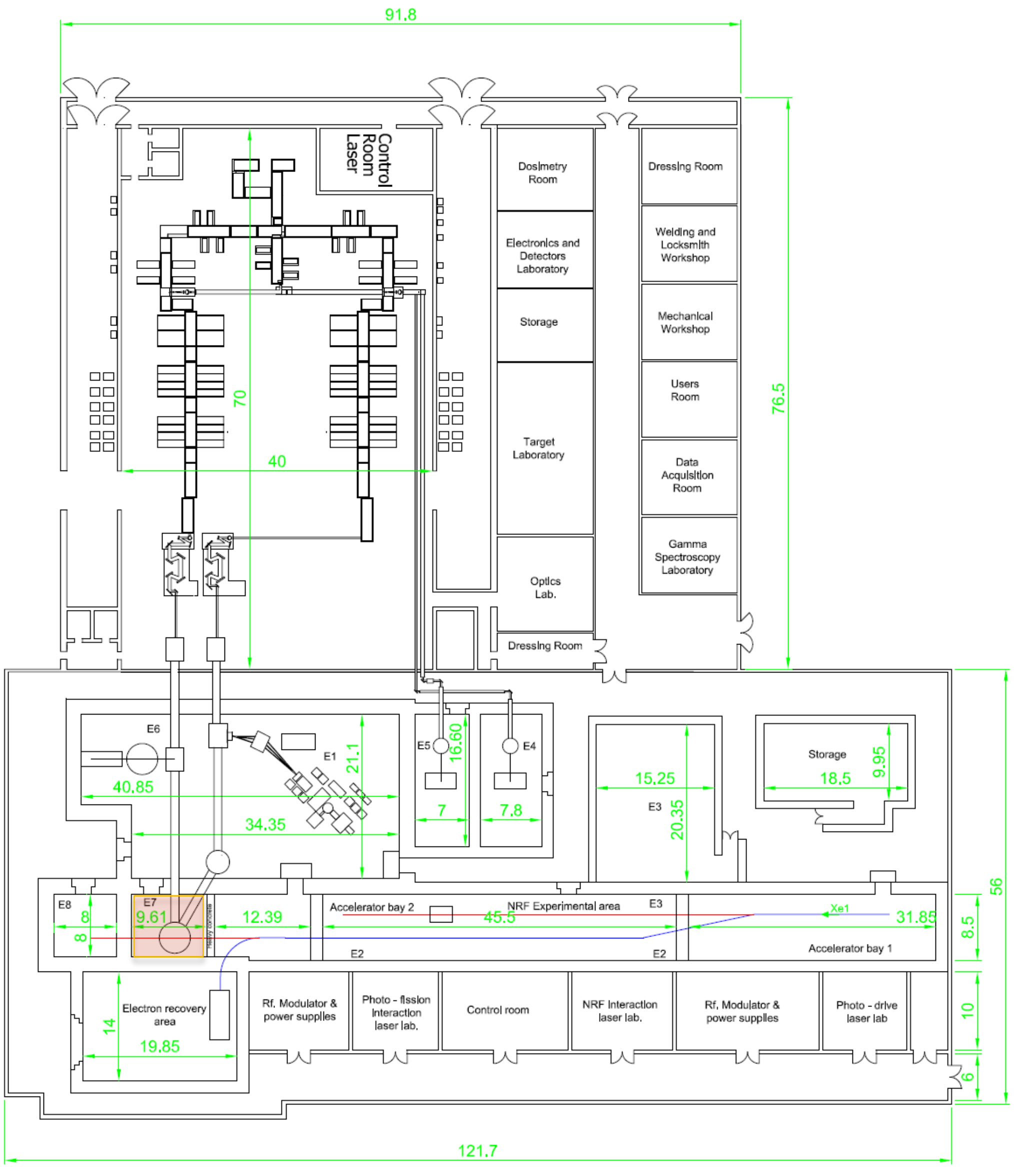
E2: Low energy gamma vault

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

E8: High energy gamma vault

- (γ,*n*) cross sections
- (γ,*charged particles*) astrophysics
- NRF
- Photofission

E7: Experiments with combined laser and gamma beams

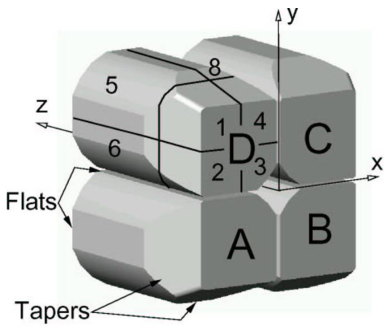


NRF – Physics case

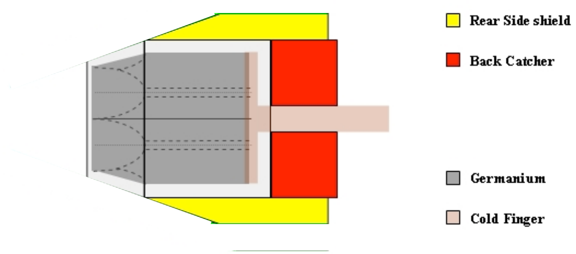
Electromagnetic dipole response of nuclei

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

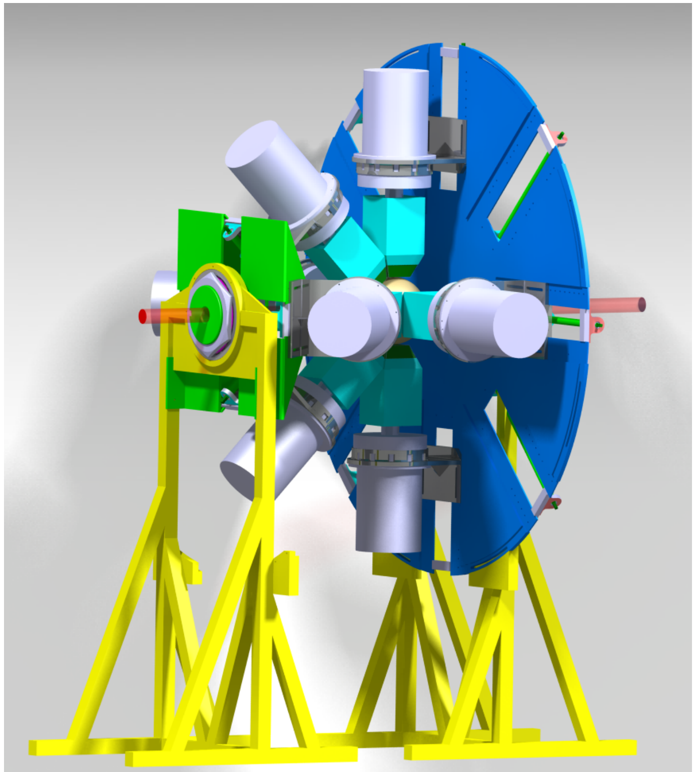
- use of composite Ge detectors
  HPGe → higher photopeak
  efficiency due to add–back



- EXOGAM–type Clover detector
  with AC shield : rear back and back–catcher



ELIADE – ELI–NP Array of DEtectors



4 Clovers @ 98° + 4 Clovers @ 135°

4 3”x3” $LaBr_3$ det. @ 90 deg.

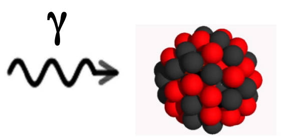
ε_{ph} ~ 5–7% at minimum distance of 15 cm from the target

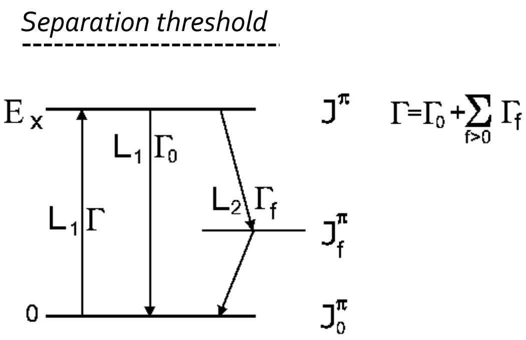
N. Pietralla, C.A. Ur

Nuclear Resonance Fluorescence

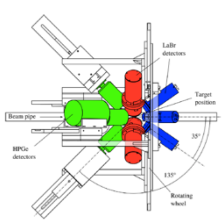
Observables

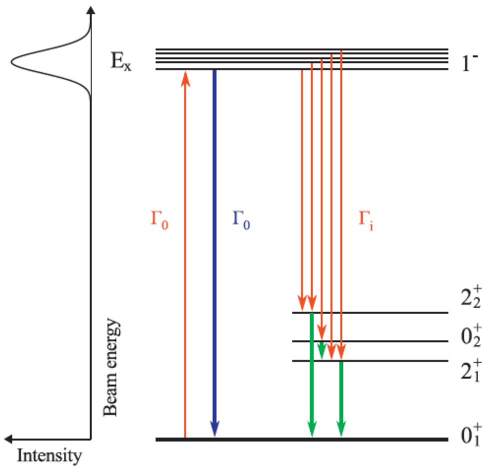
- Excitation Energy E_r
- Spin and parity J, π
- Decay Energies E_γ
- Partial Widths Γ_i/Γ_o
- Multipole Mixing δ
- Decay Strengths $B(\pi\lambda)$
- Level Width Γ (eV)
- Lifetime τ (ps – as)



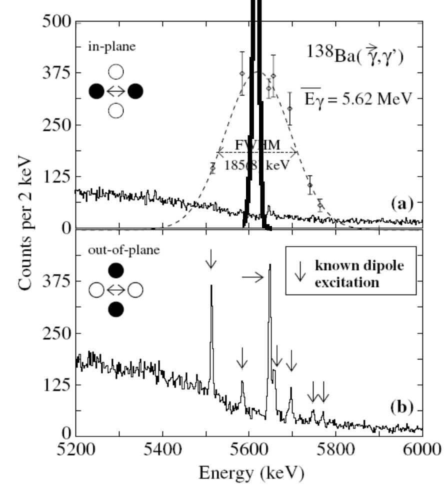


- γ–γ coincidences help reducing background/select decay paths
  - e.g., HIγS – γ^3
    @ TUNL/Duke University





ELI – NP : BW ~ 10^{-3}

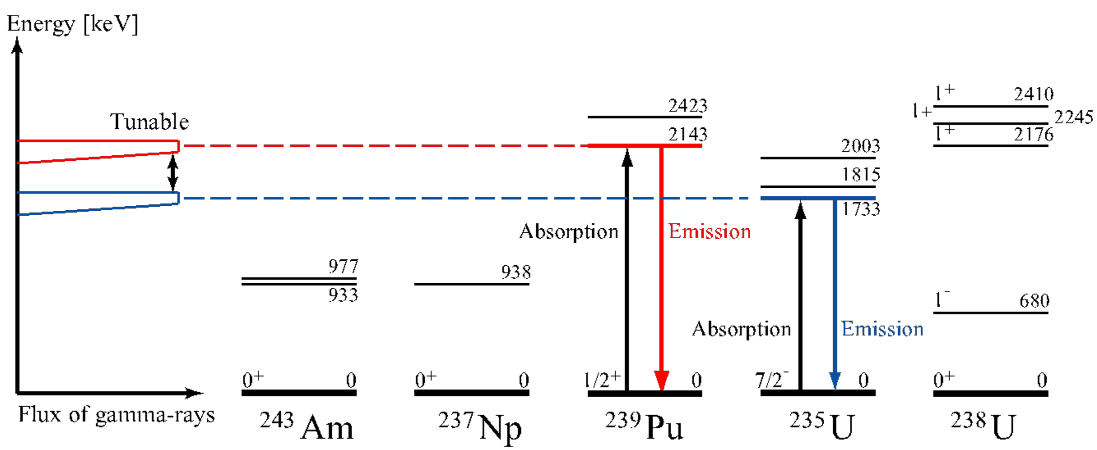


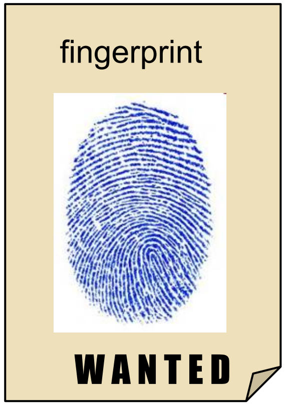
Applications of NRF

- Management of Sensitive Nuclear Materials and Radioactive waste
  - isotope–specific identification $^{238}U/^{235}U$, ^{239}Pu,
  - scan containers for nuclear material and explosives
- Burn–up of nuclear fuel rods , inspection of spent fuel
  - fuel elements are frequently changed in position to obtain a homogeneous burn–up
  - measuring the final ^{235}U, ^{238}U content may allow to use fuel elements 20% longer
- Radioisotopes production for medical applications
  - ^{195m}Pt for clinical scintigraphy of tumors
- Computerized Tomography with high–energy quasi–monochromatic gamma–ray beams
  - non–destructive inspection of objects
  - need of high beam intensity to shorten the scanning time

NRF – Applications

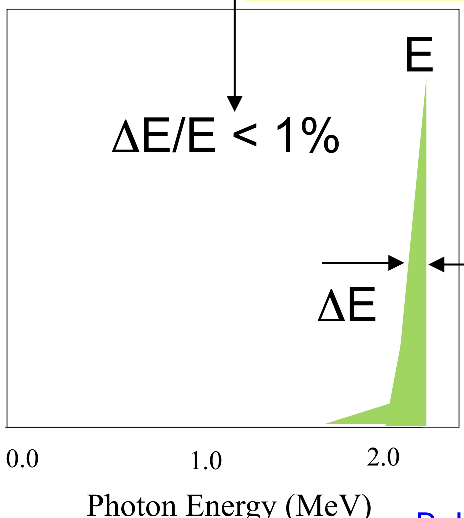
- **Non–distructive detection and assay of nuclear waste**

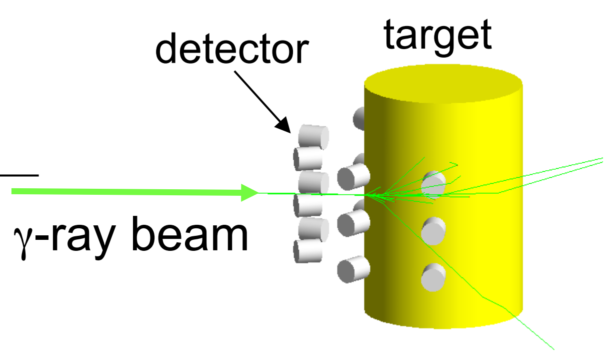


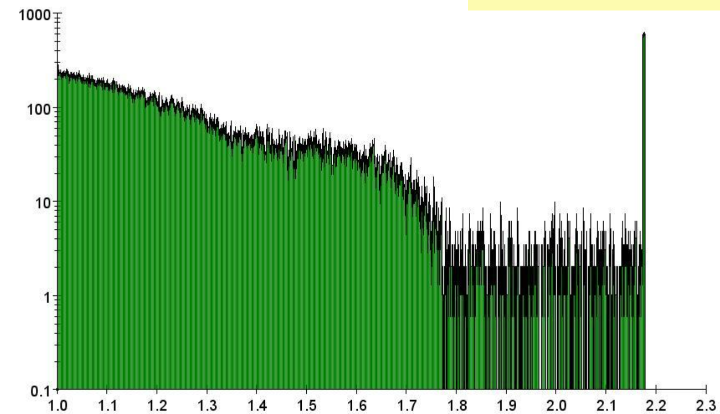


2.176 MeV for U–238

NRF signal
U–238
2.176 MeV



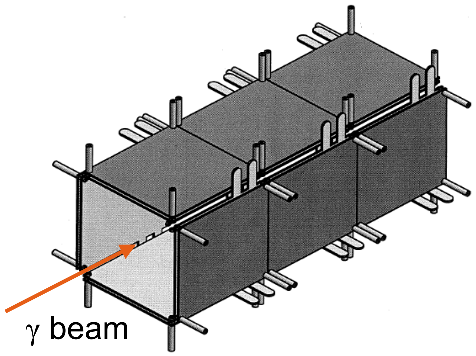




R. Hajima et al., J. Nucl. Sci. Tech. 45, 441-451 (2008)

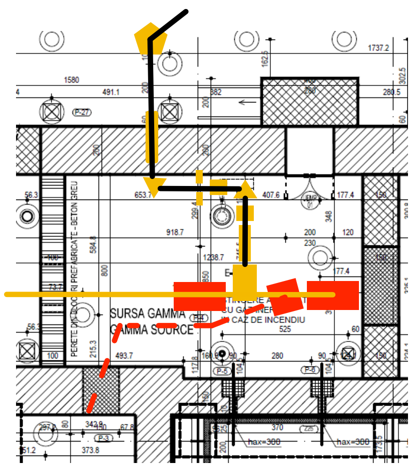
Photofission

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



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

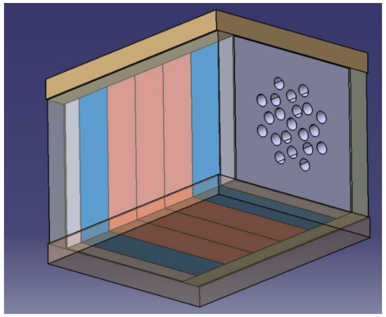
- In–beam gamma–ray spectroscopy of fission fragments
  - gamma–ray detectors (Clover, $LaBr_3$)
  - g–factors

F.Ibrahim, A.Krasznahorkay, D.Balabanski

Astrophysics Related Studies

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

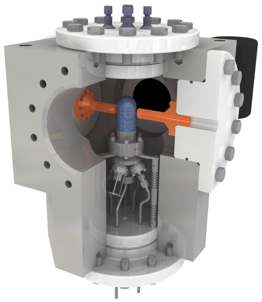
- Neutron capture cross section of s–process branching nuclei with inverse reactions
  - studies on long–lived branching points (e.g. ^{147}Pm, ^{151}Sm, ^{155}Eu) showed that the recommended values of neutron capture cross sections in the models differ by up to 50% from the experimentally determined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



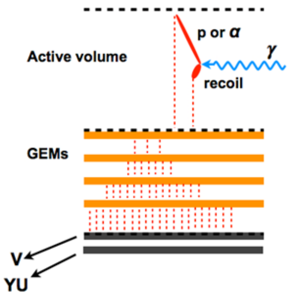
4PIN – neutron counter array

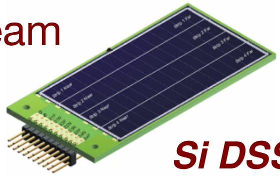
- Measurements of (γ,p) and (γ,α) reaction cross sections for p–process nucleosynthesis
  - determination of the reaction rates by an absolute cross section measurement is possible using mono–energetic photon beams produced at ELI–NP
  - tremendous advance to measure these rates directly
  - broad database of reactions – high intense γ beam needed

Bubble chamber



eTPC





Si DSSSD

M. Gai, O.Tesileanu
H. Utsunomiya, F. Camera, D.Filipescu

Concluding remarks

ELI–NP Next Steps

- Beginning 2015: TDRs for experiments
- Mid 2015: Completion of buildings
- June 30th, 2015: Lasers and Gamma Beam – end of Phase 1
- 2017: End of second Phase, Beginning operation

Perspectives

- a new research facility is being under construction at Bucharest
  - HPLS
  - GBS
- research opportunities
  - nuclear physics
    - nuclear photonics
    - HP laser driven
  - strong field QED
- young researchers are invited to join the fun !

Acknowledgements

Thanks are due to the ELI–NP Core Team

N.V. Zamfir
G. Cata–Danil
S. Gales
I. Ursu
C. Ivan
I. Morjan
D. Balabanski
O. Tesileanu
D. Filipescu
A. Oprisa
D. Ursescu
R. Dabu
F. Negoita
E. Turcu
I. Dancus
S. Balascuta
L. Neagu
T. Asavei
M. Toma
C. Petcu
M. Risca
M. Cernaianu

+ many collaborators from IFIN–HH Bucharest

Disclaimer

"The content of this document does not necessarily represent the official position of the European Union or of the Government of Romania"

For detailed information regarding the other programmes co-financed by the European Union please visit *www.fonduri-ue.ro, www.ancs.ro, http://amposcce.minind.ro*