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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

Photoneutron cross section measurements on Sm isotopes

15th International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics, Dresden - 2014

Dan Mihai FILIPESCU

Outline

- Why measure (γ, n) cross sections?
- Laser Compton Scattering (LCS) gamma ray sources
- Experimental facility NewSUBARU – GACKO
  - Important parameters: Laser photon and Electron beam energies
  - Energy calibration of NewSUBARU electron storage ring
- Simulation of Laser photon – relativistic electron interaction
- Experimental setup
  - LCS energy profile measurement
  - Neutron counting
  - Incident LCS γ-ray beam flux measurement
- Results
  - Experimental results compared with existing experimental data
  - Comparison with theoretical calculations
- Status and feature plans of Gamma Source at ELI-NP
- Conclusions

Why measure (γ, n) cross sections?

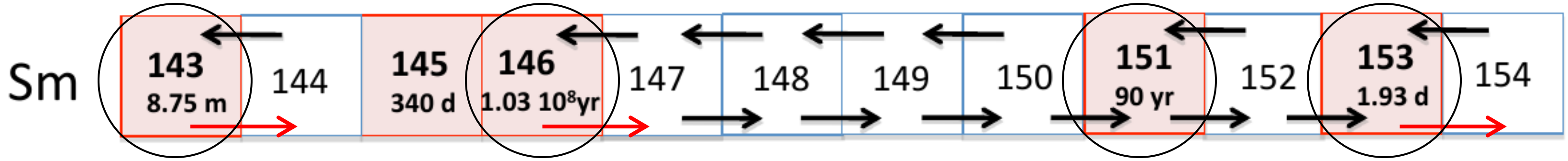
- (γ,n) c.s. measurement required by nuclear astrophysics in order to explain the nucleosynthesis of elements;
- (γ,n) reactions a very powerful tool for:
  - Study and parameterization of the γ-ray strength functions;
  - Level densities studies.
- (γ,n) reactions can be used to obtain (n,γ) c.s. using detailed balance theorem, useful for applications, IV-th generation of reactors, ADS etc.

$\sigma_{(n,\gamma)}$ for radioactive nuclei along the line of β stability in the medium-to heavy-mass region

→ Nuclear astrophysics - determine the *s*-process path at the *(n,γ) / β* decay branching points

→ Nuclear engineering - nuclear transmutation of long-lived fission products

Neutron capture



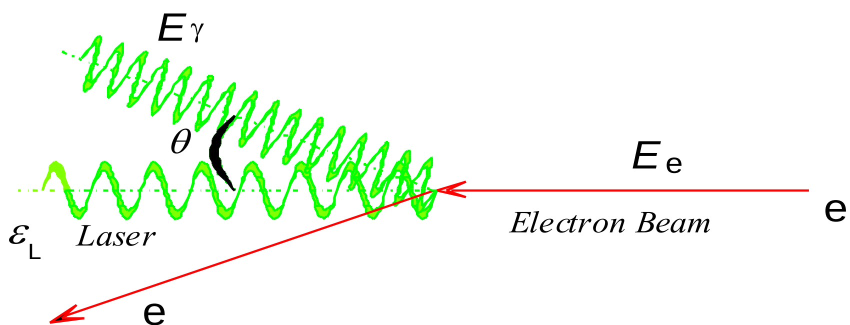
We performed a systematic measurement of photoneutron cross sections for stable Sm isotopes in the vicinity of four radioactive Sm nuclei. The radioactive Sm nuclei belong to the second peak of fission products centered around A $\sim$ 140 in the fission of nuclear fuels, ^{235}U and ^{239}Pu. ^{151}Sm is a *(n,γ) / β* decay branching point in the *s*-process nucleosynthesis.

The photoneutron emissions studied constitute a part of the reaction network of the p-process nucleosynthesis in which photodisintegration plays a primary role in re-processing the preexisting nuclei produced by the *s*-process and *r*-process.

Photoneutron cross sections for two odd-N nuclei, ^{147}Sm and ^{149}Sm, are measured for the first time. Those for ^{144}Sm represent the destruction cross section for the *p*-process nucleus.

Laser Compton Scattering (LCS) gamma ray sources

The γ ray beams are produced by the inverse Compton scattering of laser photons from relativistic electrons.



E_γ = energy of scattered photon
ε_L = energy of laser photon
E_e= total electron energy
θ = scattering angle of a laser photon with respect to the electron incident direction
mc^2 = rest energy of an electron

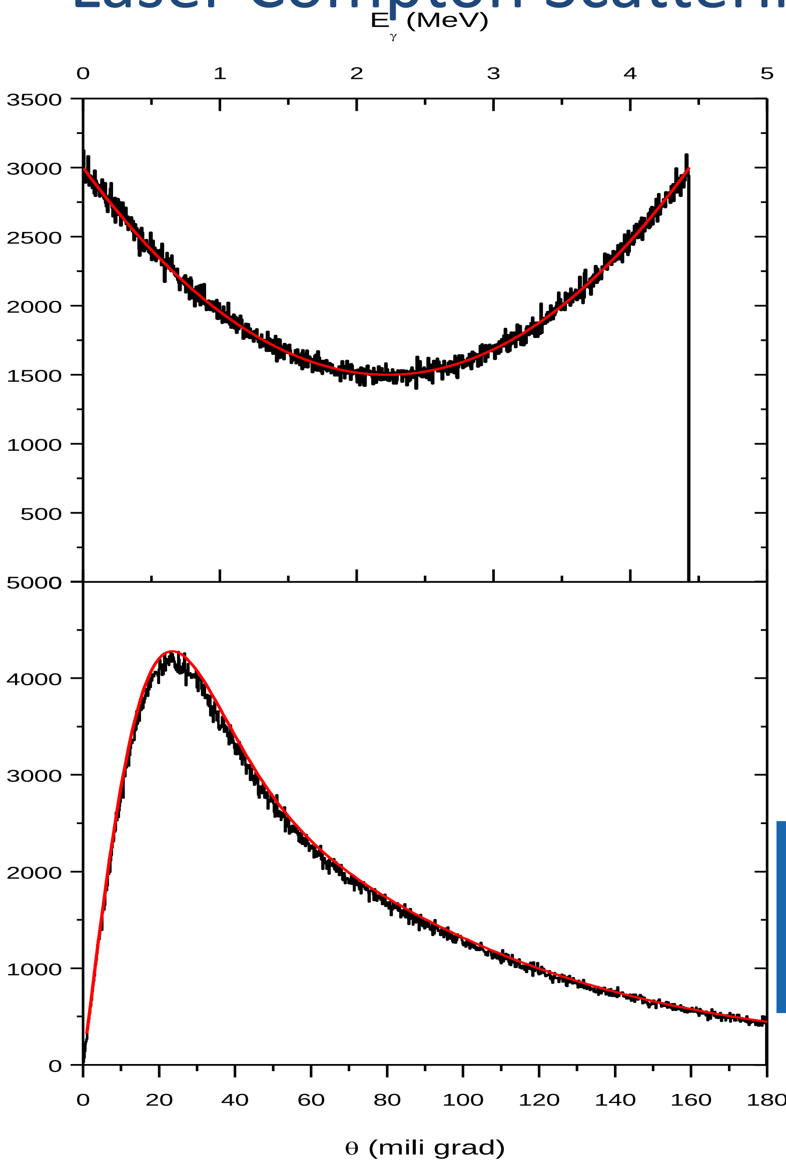
$$E_\gamma = \frac{\varepsilon_L(1+\beta)}{1+\varepsilon_L/E_e-(\beta-\varepsilon_L/E_e)\cdot\cos\theta}$$

$$(small\ \theta) \approx \frac{4\gamma^2\varepsilon_L}{1+(\gamma\theta)^2+4\gamma^2\varepsilon_L/(mc^2)}$$

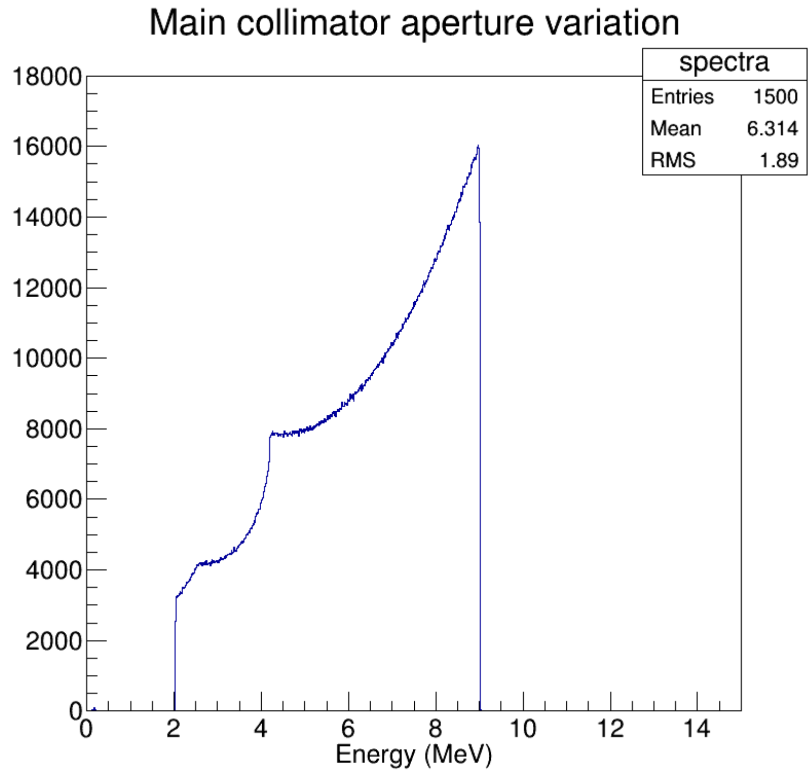
$$\boldsymbol{E_\gamma \sim 4\gamma^2\varepsilon_L} \qquad \gamma = E_e/mc^2$$

Continuous spectrum!

Laser Compton Scattering (LCS) gamma ray sources



Klein-Nishina C.S. theoretic vs. random generated



Collimation -> Quasi monochromatic spectrum

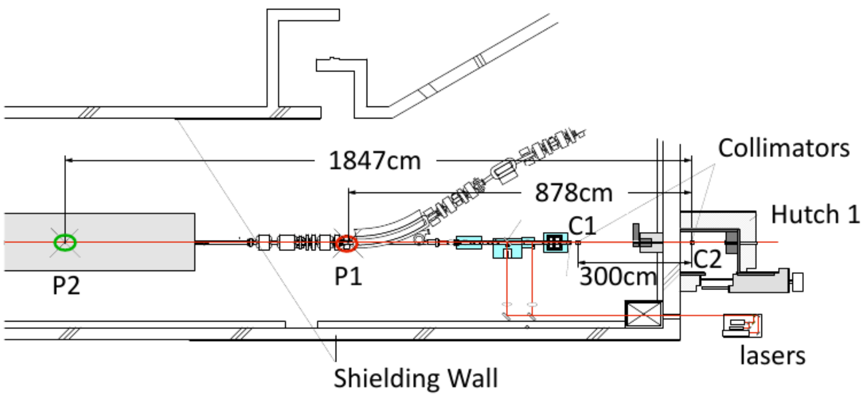
Continuous gamma spectrum
Forward focused

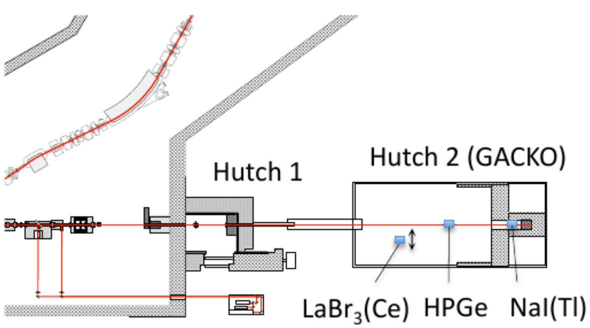
$E_e = 500 MeV \quad \lambda = 1064\, nm$

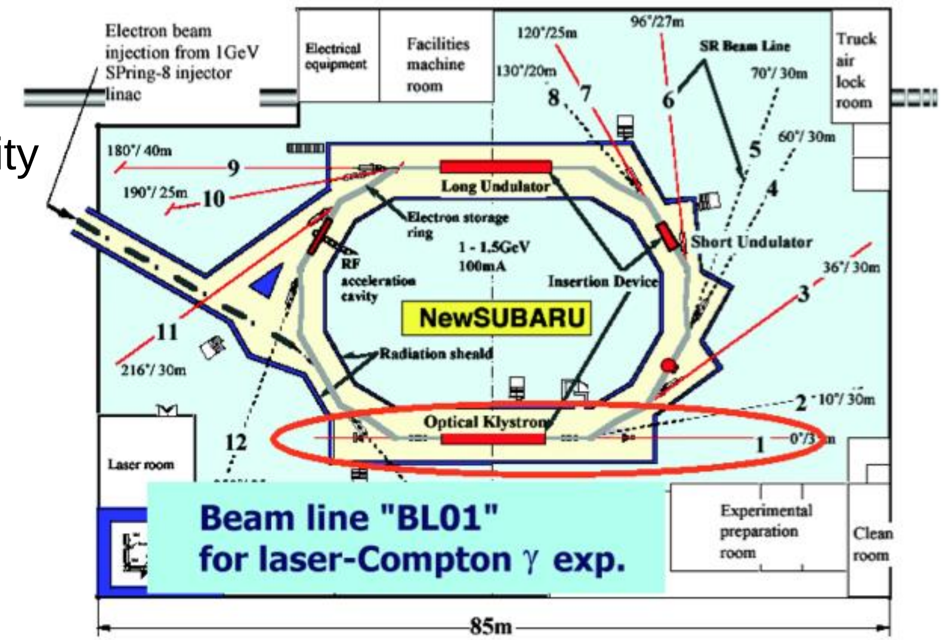
Experimental facility NewSUBARU – GACKO

Laser photons are scattered from relativistic electrons circulating inside the storage ring of the synchrotron radiation facility NewSUBARU.
A linear accelerator injects 974 MeV electrons into the storage ring.
$E_{electrons} = (0.5 – 1.5)\ GeV$.
Electron beam intensity – up to 500 mA

GAmma Collaboration Hutch of KOnan University







Laser photon energy:

CO_2 laser λ=10.59μm

Low-energy γ-ray beams:

1 – 4 MeV MeV

Nd:YVO_4 laser λ=1064nm

High-energy γ-ray beams:

7 – 34 MeV

Experimental facility NewSUBARU – GACKO

Electron energy:

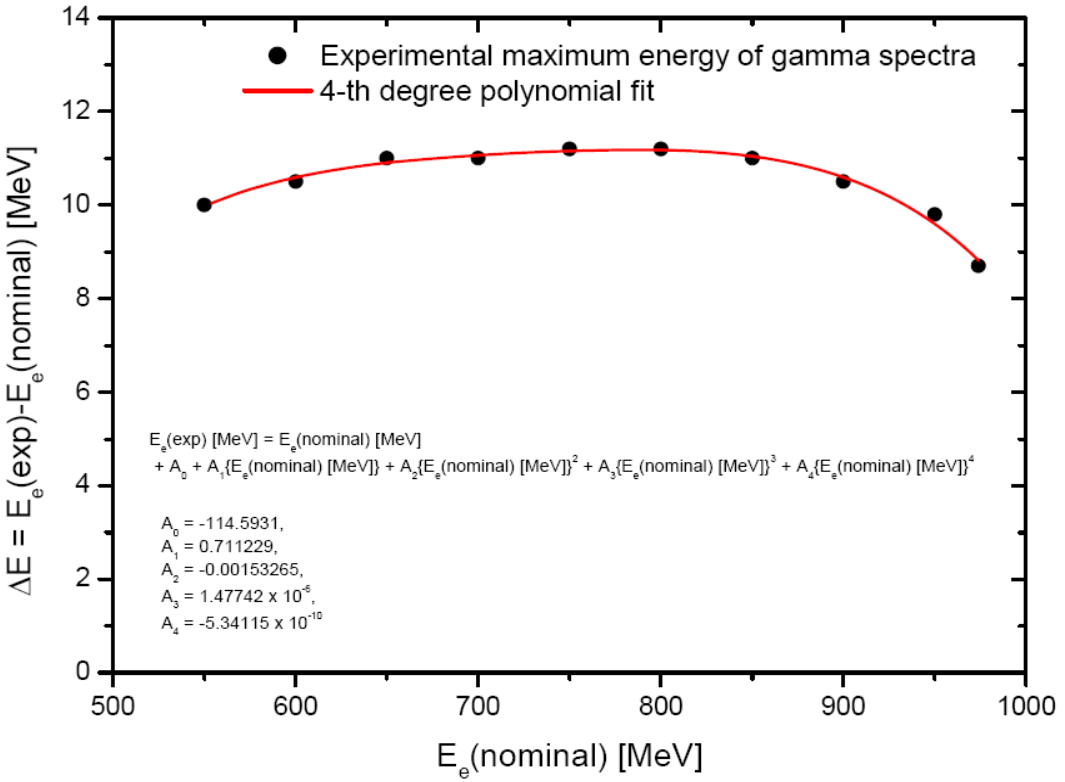
We performed an electron energy calibration experiment before the Sm(γ, n) measurements.

1. We produced low-energy (0.5 – 1.7 MeV) LCS γ-ray beams in collisions of CO_2 laser photons with electrons at ten nominal energies from 974 MeV to 550 MeV;

2. We measured the LCS γ-ray beams using a calibrated high-purity germanium (HPGe) detector;

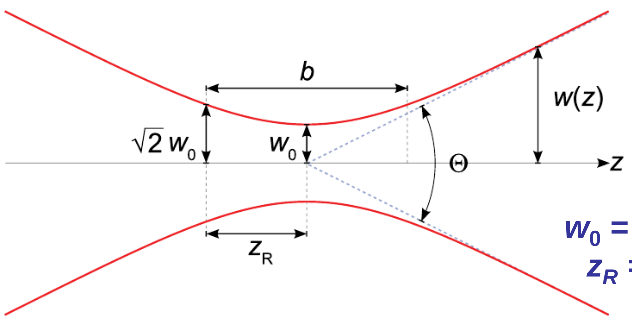
Calibration:
^{133}Ba, ^{137}Cs, ^{152} Eu, ^{60}Co + sum peak, ^{40}K;

3. We determined the electron beam energies by Monte Carlo simulations.



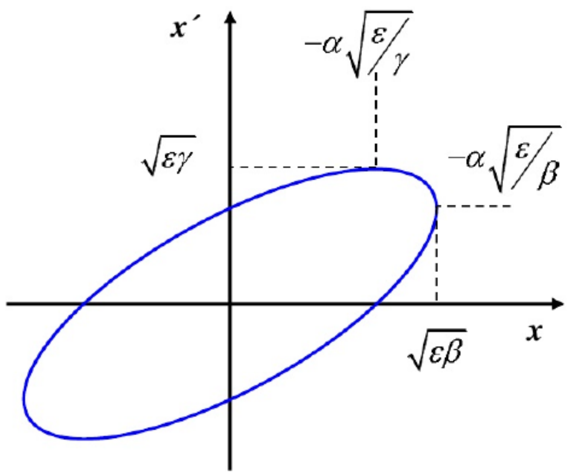
Unfortunately LCS gamma sources are produced by NOT-Ideal Electron & Laser beams

Laser modeling: hyperbolic dependence along the beam axis

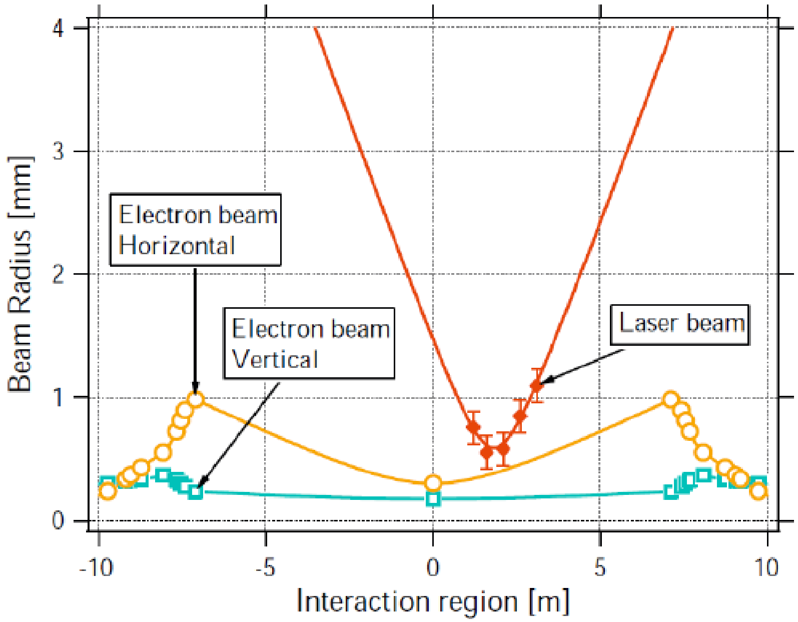


w_0 = beam size at focal point
z_R = b/2 = Rayleigh length

Drift space coordinates and Twiss parameters must be considered



Electron and laser beam shape in the interaction region along straight beamline in the NewSUBARU e⁻ storage ring

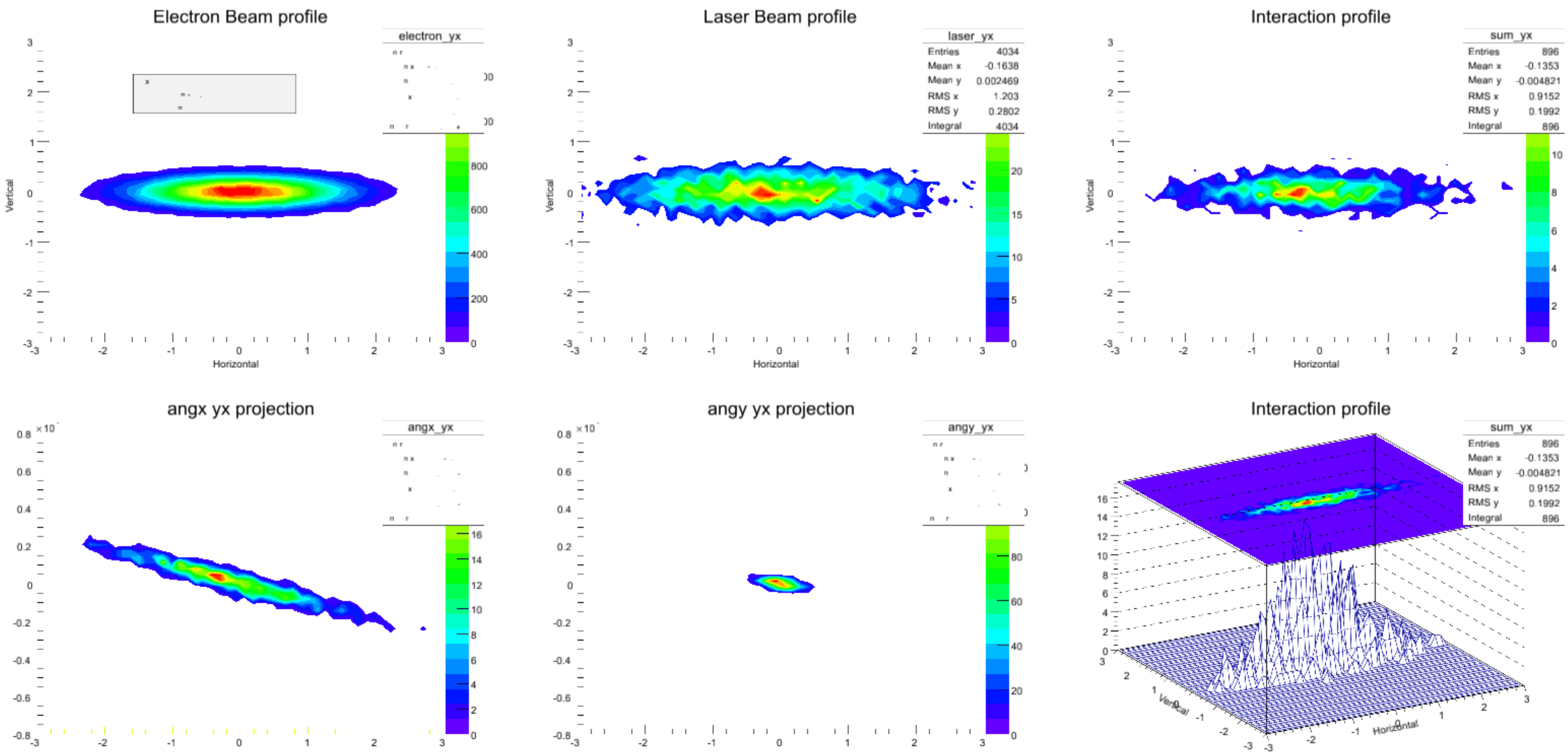


K Horikawa et. Al, NIM A 618 (2010)

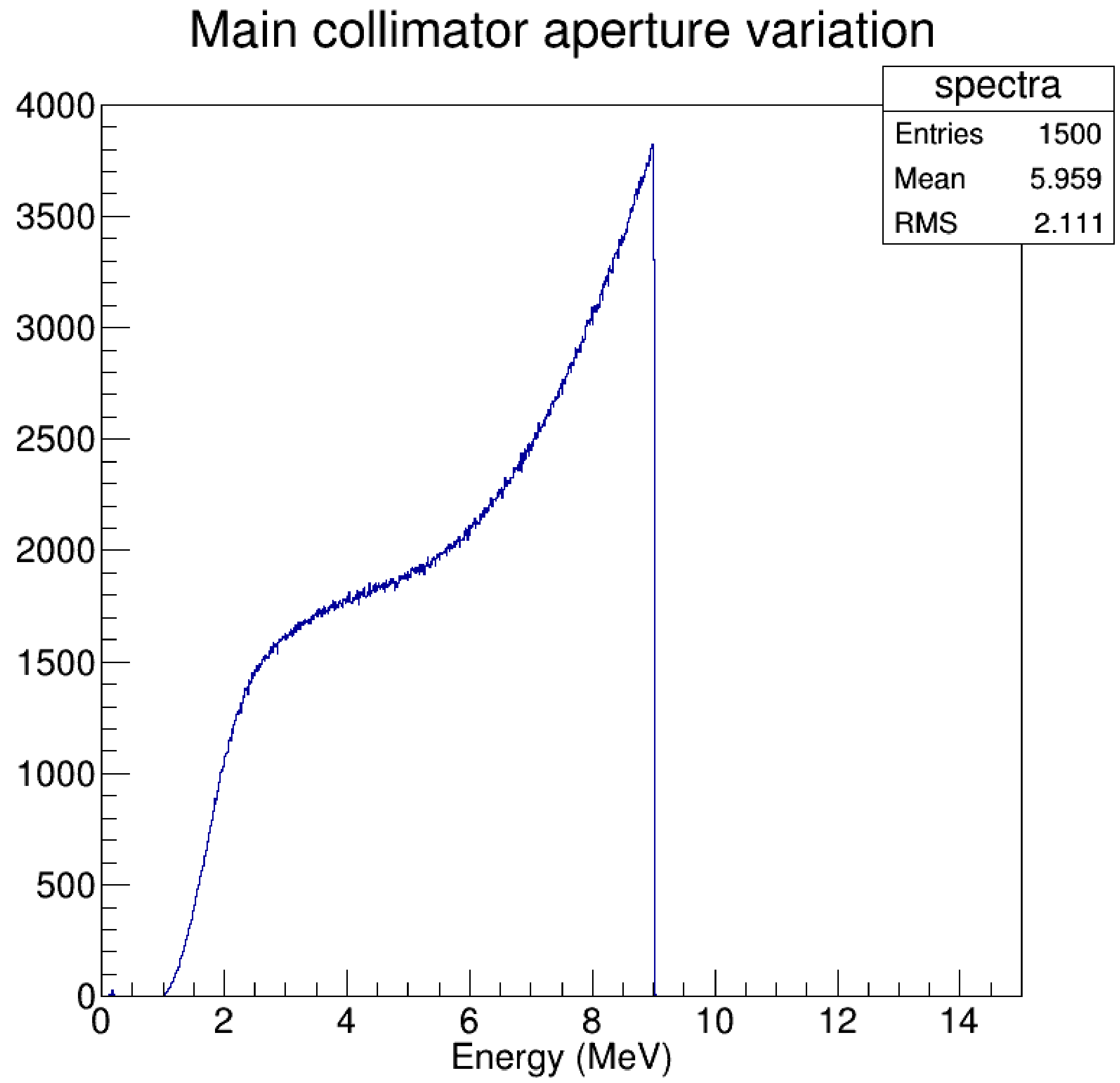
Electron beam emittance:

$$\varepsilon_x = \gamma_x(z)\cdot x^2(z) + 2\alpha_x(z)\cdot x(z)x'(z) + \beta_x(z)\cdot x'^2(z)$$

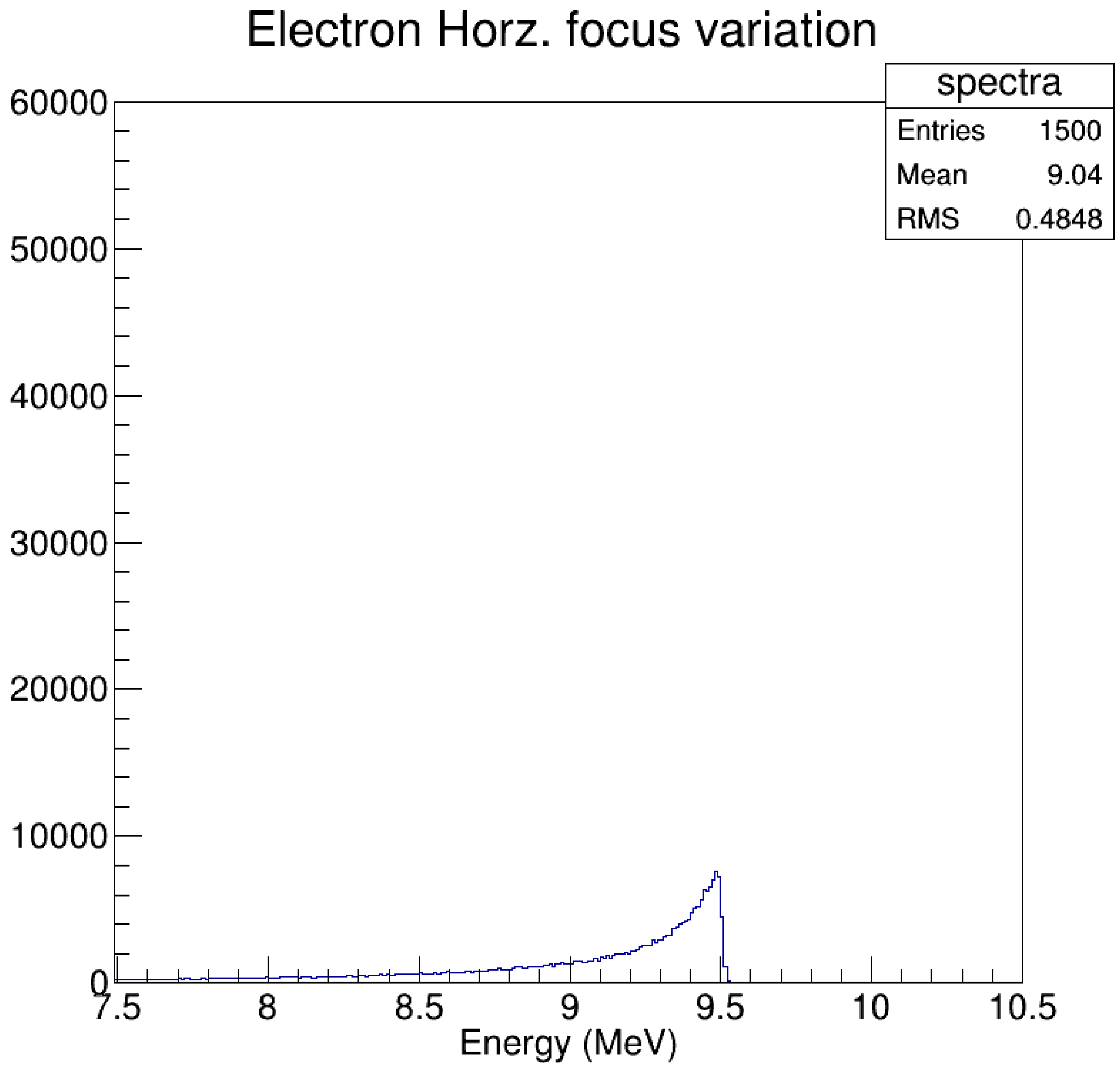
Dependence of Electron & Laser profile + space phase along the straight beamline of NewSUBARU e^- ring



Real Electron & Laser beam parameters (non-head on collision)

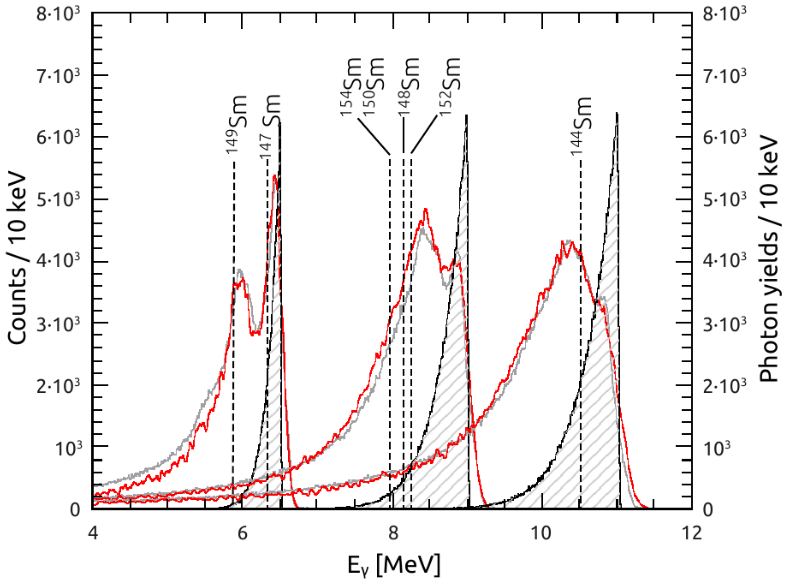


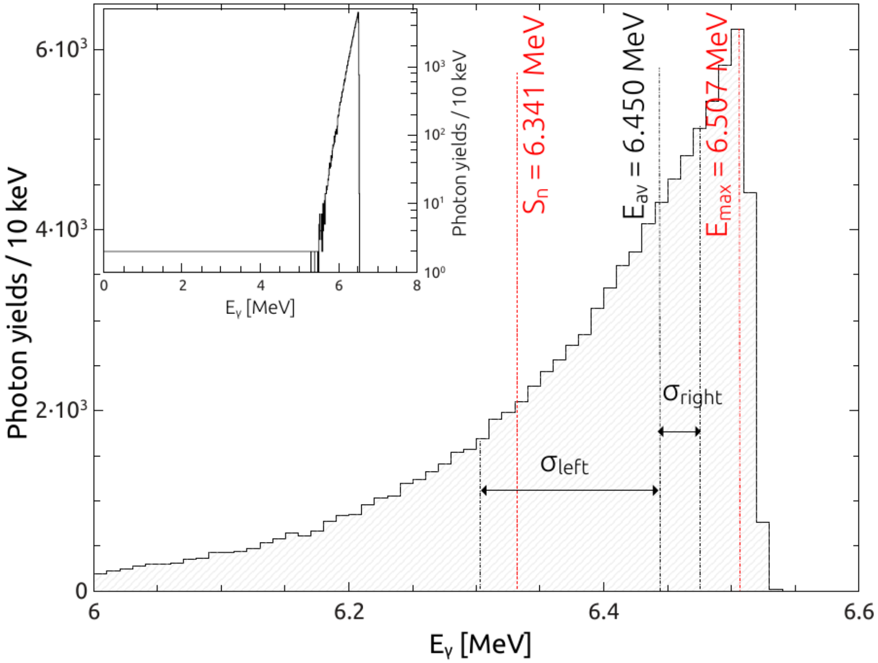
Real beam – dependence on the electron beam focus

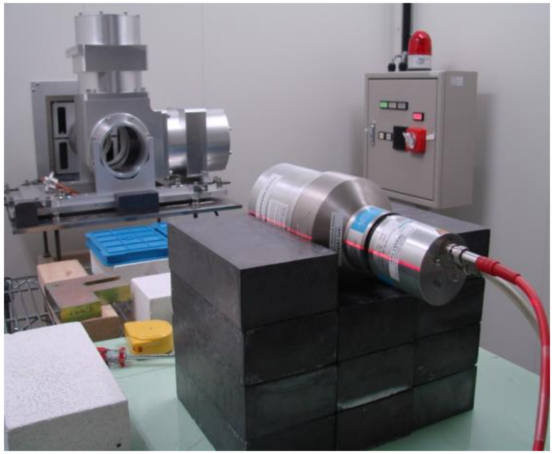


LCS γ–ray beam energy profile measurements

- Large volume LaBr3(Ce) detector 4 × 4 inch;
- Before and after each measurement single photon spectra was measured at low laser power;
- Incident LCS γ-ray spectra were obtained by reproducing with Geant4 simulations the $LaBr_3(Ce)$ spectra.

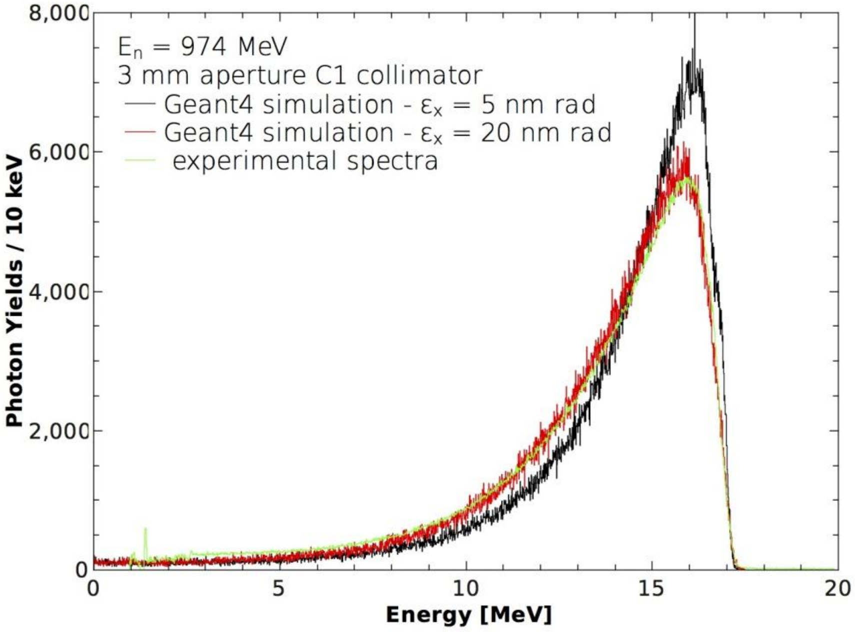


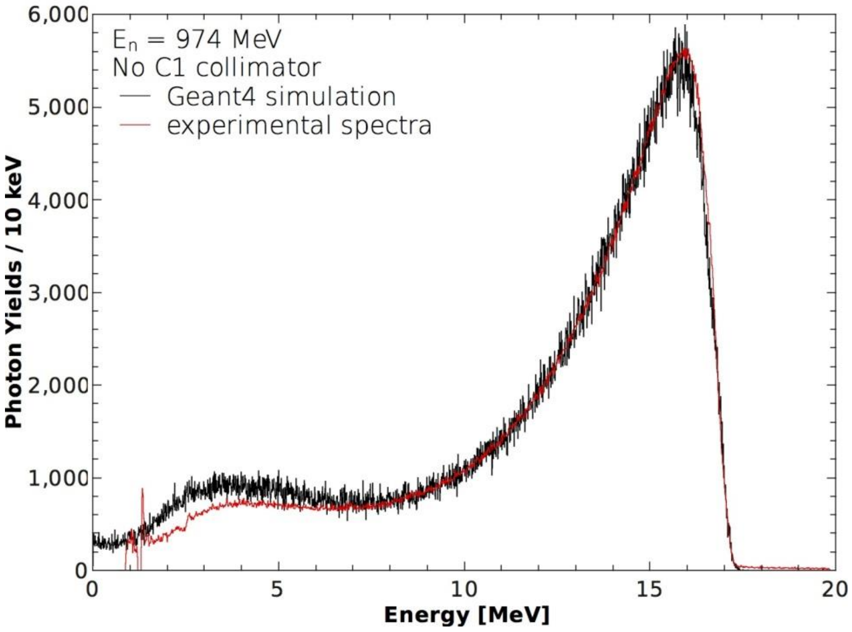




Simulation of Laser photon – relativistic electron interaction

- A complex simulation code of the interaction between the laser photons and the relativistic electrons was developed to analyze the energy spectra of the incident LCS γ-ray beam, which was measured with a $LaBr_3$ detector.
- Using Geant4, the simulations previously used to reproduce the $LaBr_3$ detector response were improved by generating the interaction between the laser photons and the relativistic electrons considering the electron beam size and emittance.
- The code was tested against experimental data produced at the NewSUBARU facility.





Photoneutron cross sections

General formula:

$$\int_{S_n}^{E_{\text{Max}}} n_\gamma(E_\gamma)\sigma(E_\gamma)dE_\gamma = \frac{N_n}{N_t N_\gamma \xi \epsilon_n g}$$

First step:

Obtain monochromatic approximations.

$$\sigma^{\text{mono}}(E_{\text{o}}) = \frac{N_n}{N_t N_\gamma \xi \epsilon_n g}$$

Second step:

Take into account the measured energy distribution of the γ- ray beam. Apply an iterative fitting procedure using the Taylor expansion of the integral above to obtain the non-monochromatic cross sections.

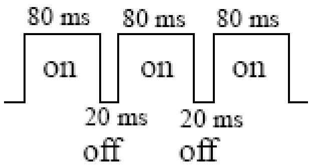
$$E_{\text{av}} = \int_{S_n}^{E_{\text{Max}}} E_\gamma n_\gamma(E_\gamma)dE_\gamma$$

$$\sigma_{(0)}(E) = \sigma_{\text{free}} \left(\frac{E_{\text{av}} - S_n}{S_n}\right)^p \frac{1}{1 + (E_{\text{av}}^2 - E_R^2)^2/(E_{\text{av}}^2 \Gamma^2)}$$

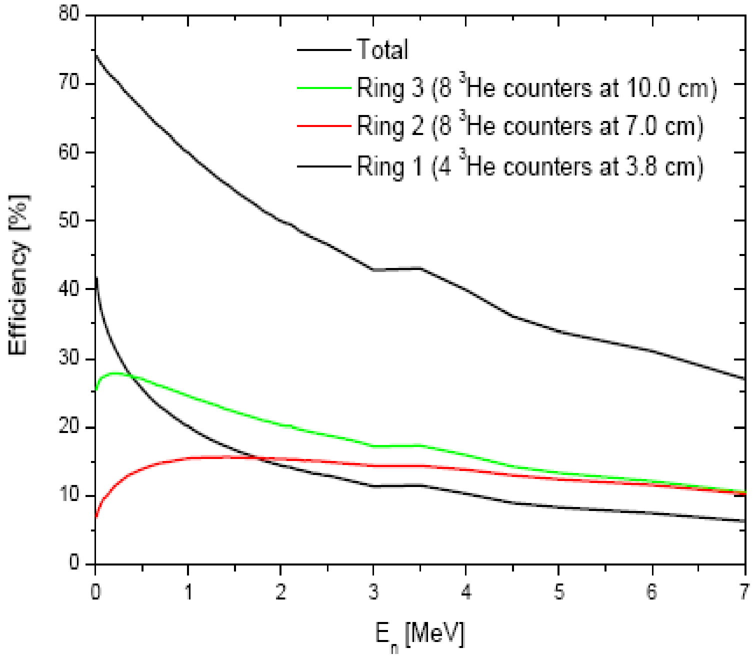
Neutron counting

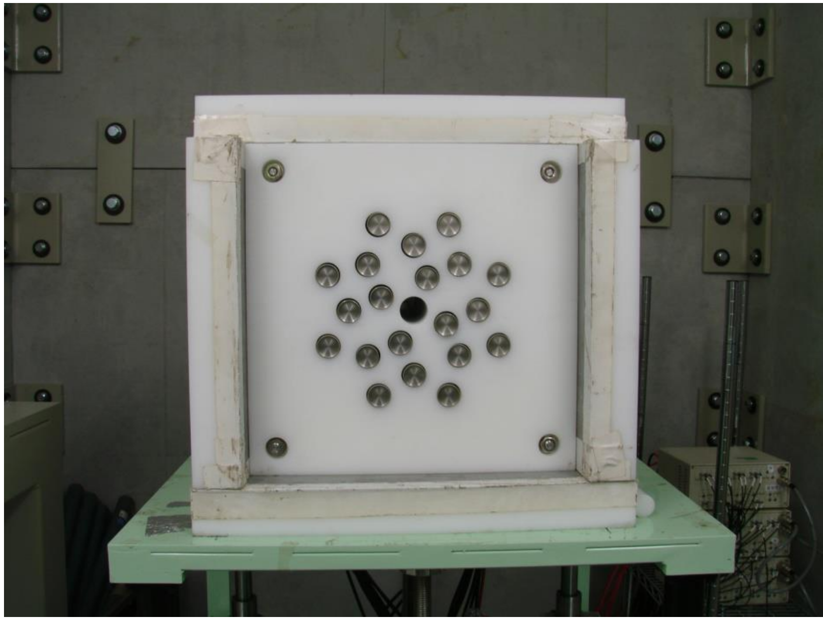
- 4π high efficiency neutron detector
- 20 ^{3}He proportional counters arranged in 3 concentric rings, embedded in a parallelepiped polyethylene moderator (36×36×50 cm) covered with polyethylene plates with cadmium sheets towards interior;
- Efficiency of neutron detector obtained with ring-ratio technique

Temporal macrostructure of γ beam used in order to measure neutron background



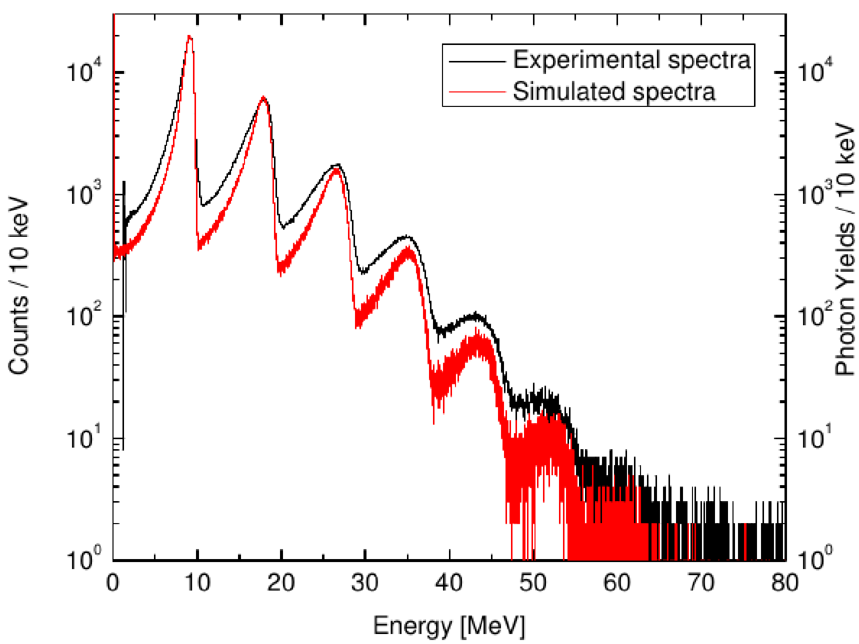
Neutron efficiency obtained with MCNP simulation

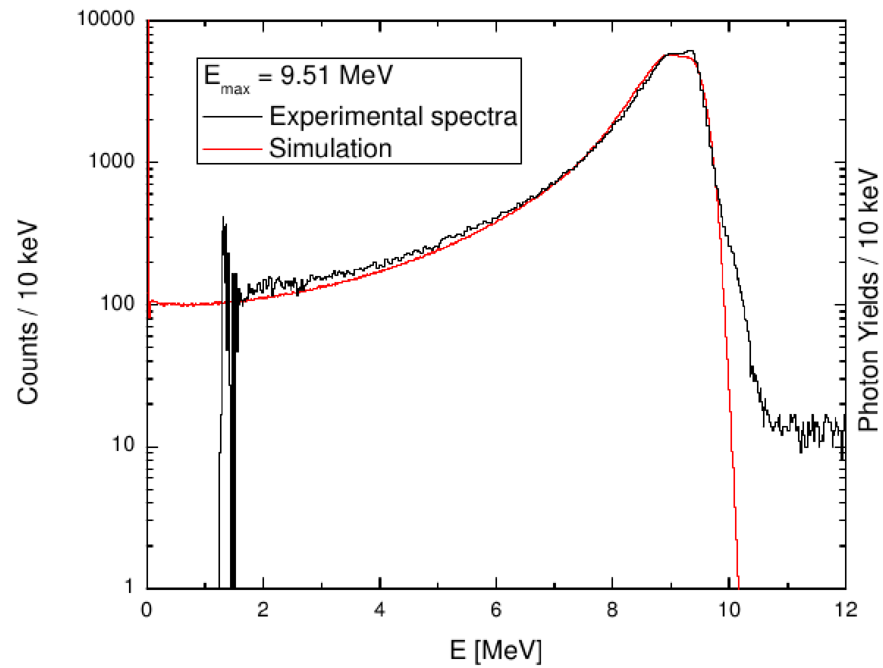




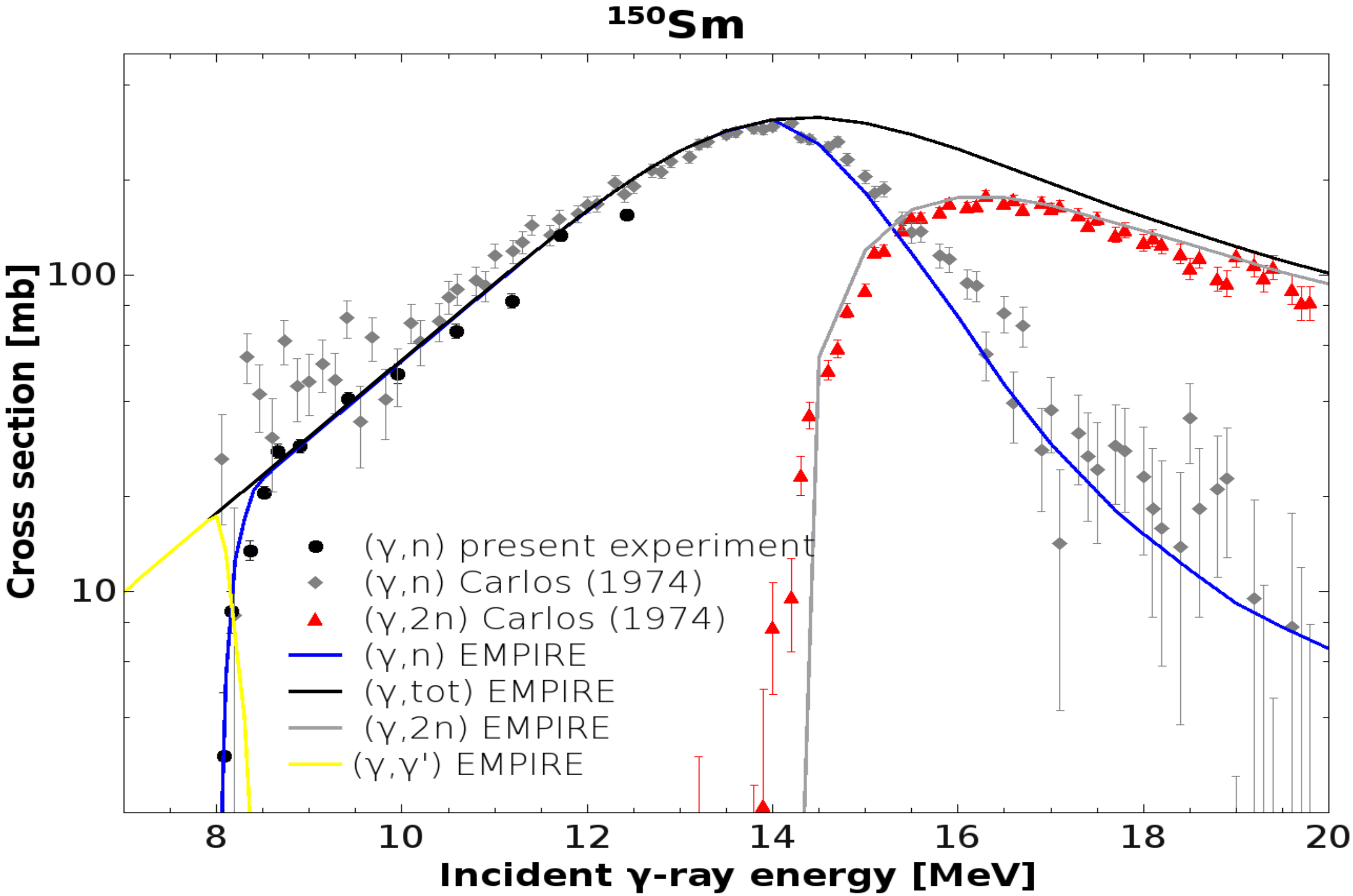
Incident LCS γ-ray beam flux measurement

- Large volume NaI(Tl) detector 20 cm diameter × 30 cm length was used;
- Pile-up spectra was acquired in beam at full laser power;
- Before and after each measurement single photon spectra was measured at low laser power;
- Total number of photons was obtained as weighting average of the pile-up spectra using single photon spectra as weighting function;
- Beam flux varied between 1×10^5 and 6×10^4 for electron current drop from 170 to 60 mA during 8 hours.

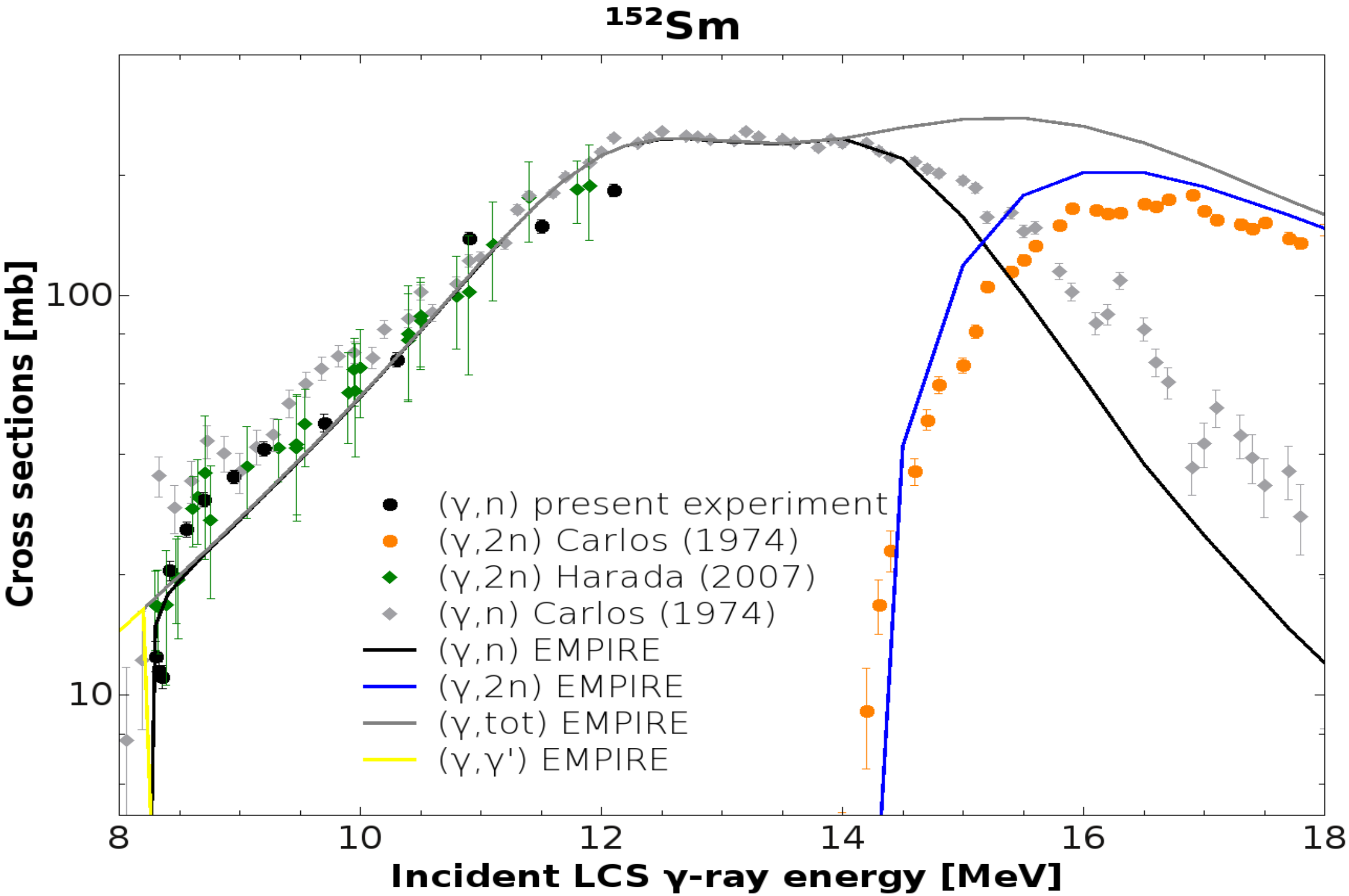




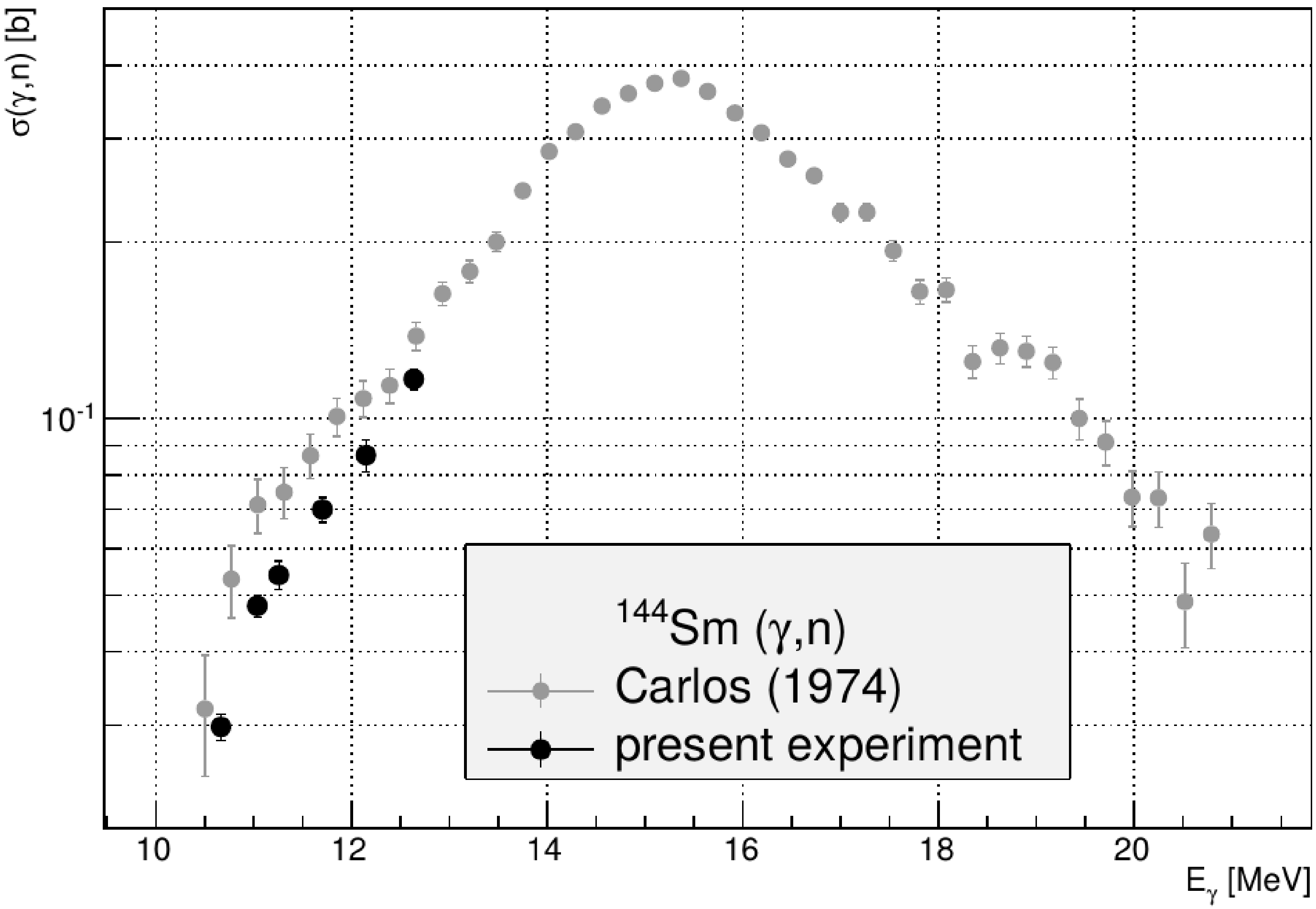
Preliminary results



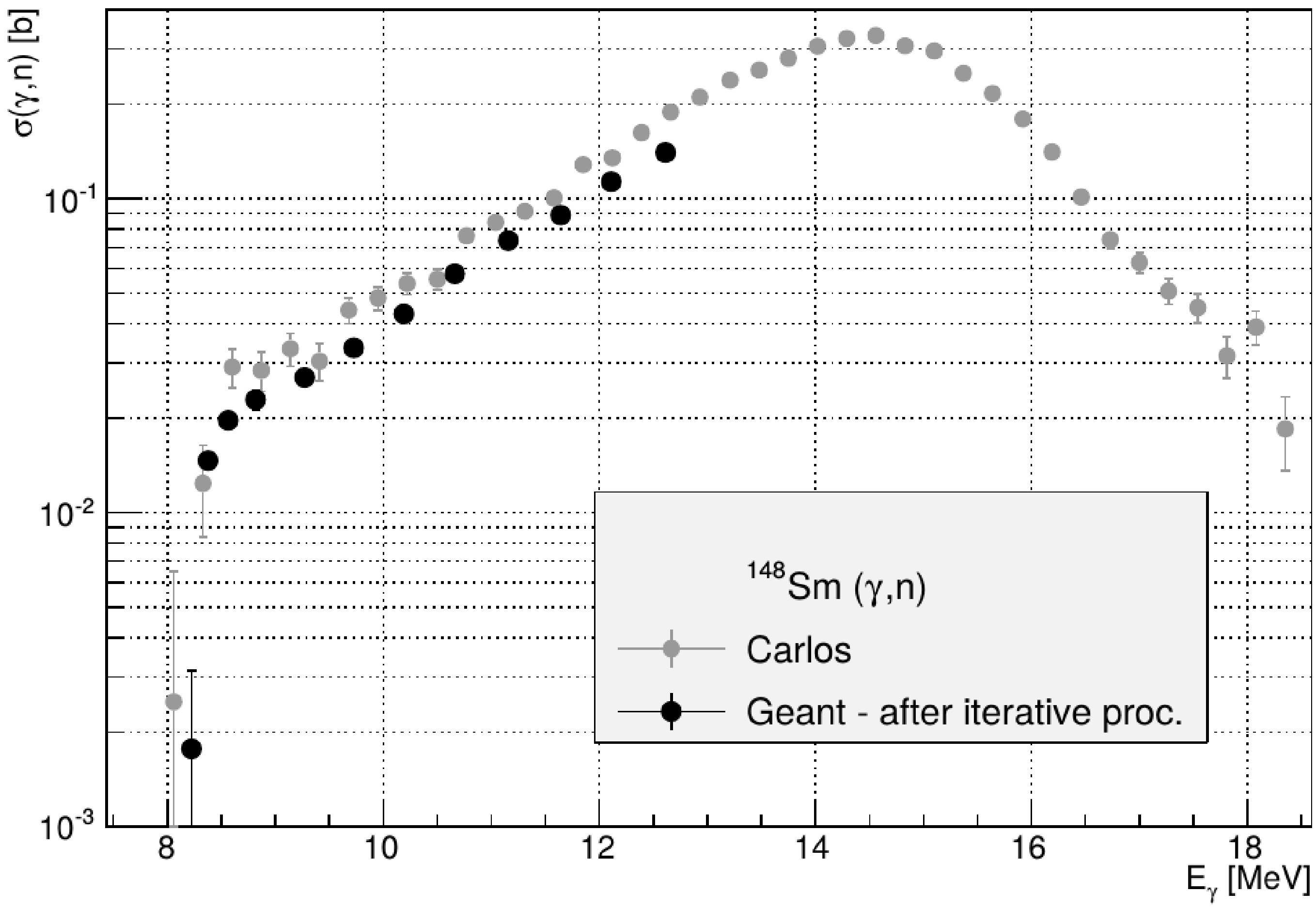
Preliminary results



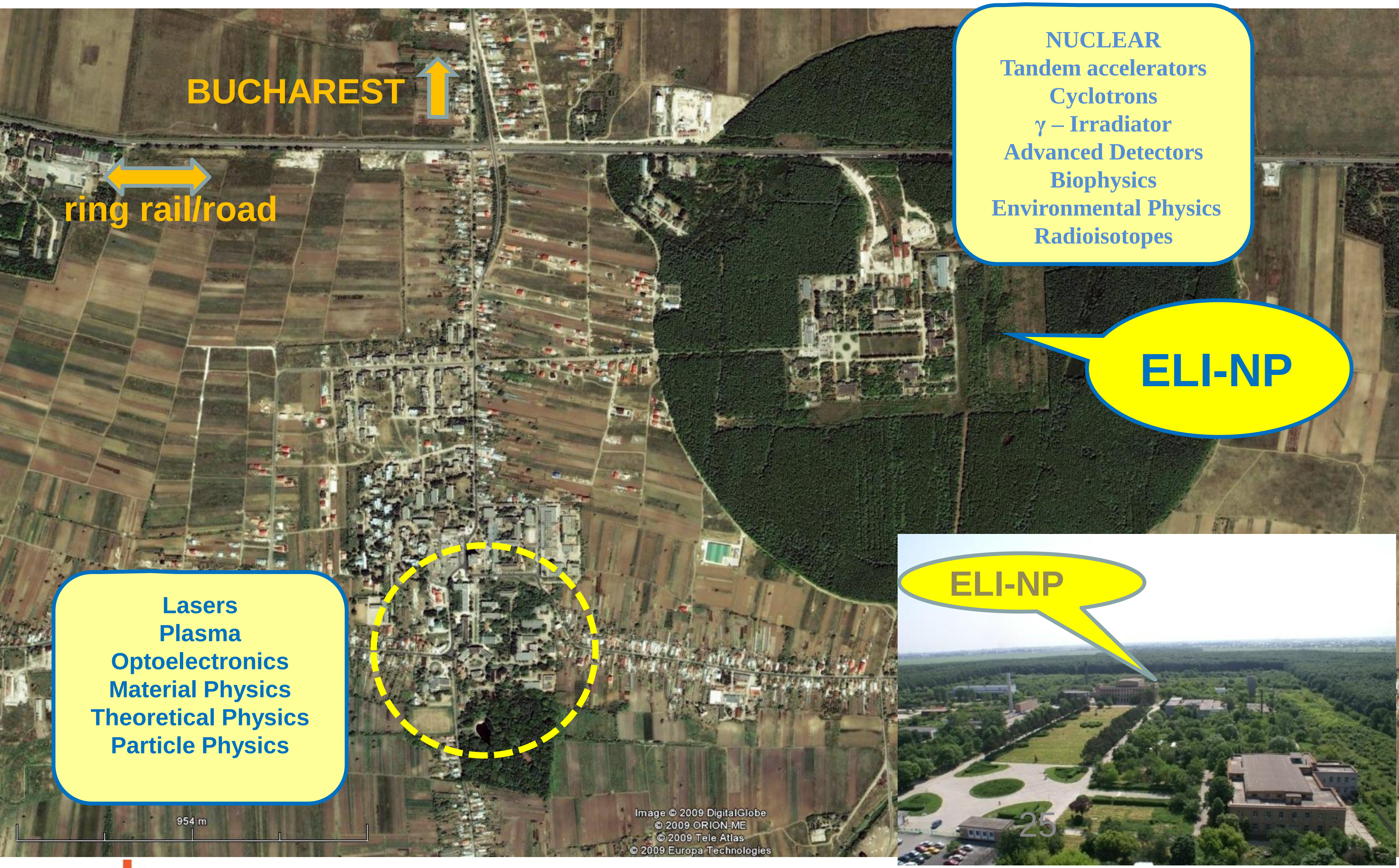
Preliminary results



Preliminary results



Bucharest-Magurele National Physics Institutes



Nuclear Physics

ELI-NP Status

December 2012: *Tenders for civil construction and major instrumentation*

May 2013: *Earth breaking*

Civil construction of the ELI-NP complex (2013 – 2015)

July 2013: *Laser-Beam System (LBS) contract signed*

Construction of the 2 x 10 PW Lasers (2013 – 2017)

March 2014: *Gamma-Beam System (GBS) contract signed*

Construction of 200 keV – 20 MeV gamma-beam system (2104 – 2018)

April 2013: *Science Division of ELI-NP was established*

Definition and preparation of experimental TDRs (due in early 2015)

2015: *Tenders for experimental instrumentation*

2017: *Commissioning experiments*

Nuclear Physics

Buildings – one contractor, 33000 m^2 total

12.05.2014

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

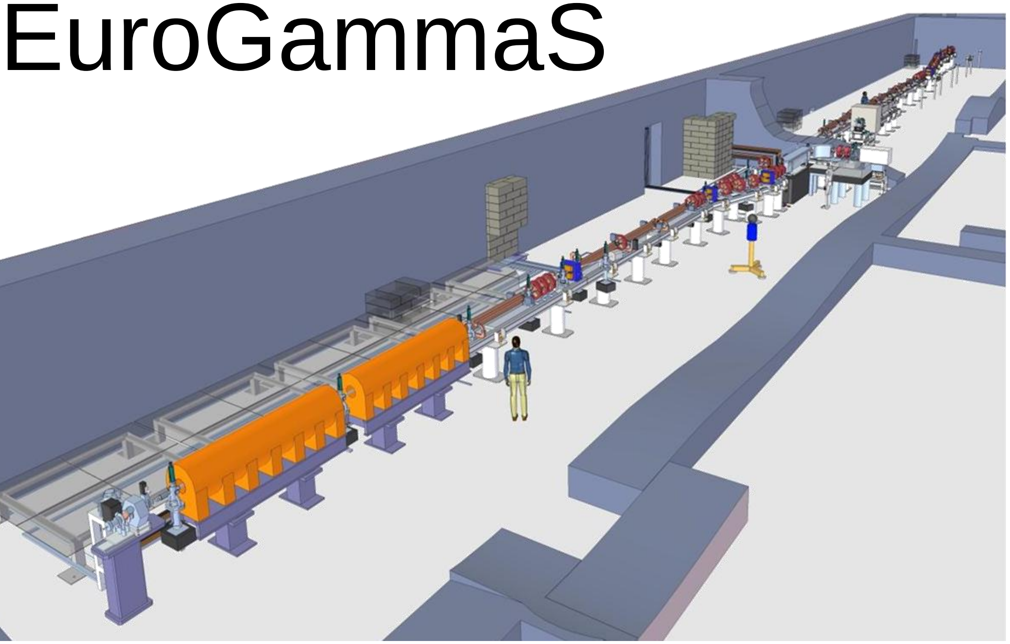
ELI-NP Gamma Beam System: the Italy-France-United Kingdom proposal

Nuclear Physics

SAPIENZA UNIVERSITÀ DI ROMA — INFN Istituto Nazionale di Fisica Nucleare — Science & Technology Facilities Council — cnrs IN2P3 Les deux infinis — UNIVERSITE PARIS SUD Comprendre le monde construire l'avenir

European Collaboration for the proposal of a Gamma-Beam System to the ELI-NP Project

EuroGammaS



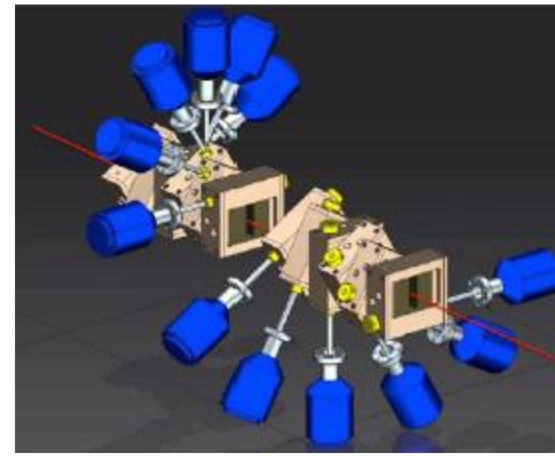
European Collaboration for the proposal of the gamma-ray source:

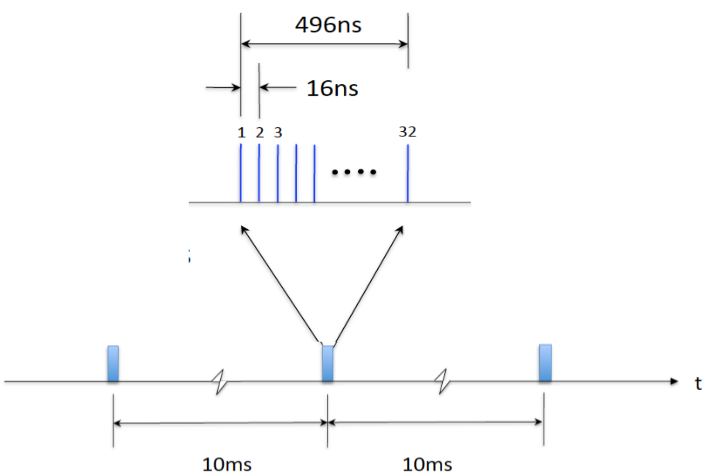
- ✓Italy: INFN,Sapienza
- ✓France: IN2P3, Univ. Paris Sud
- ✓UK: ASTeC/STFC

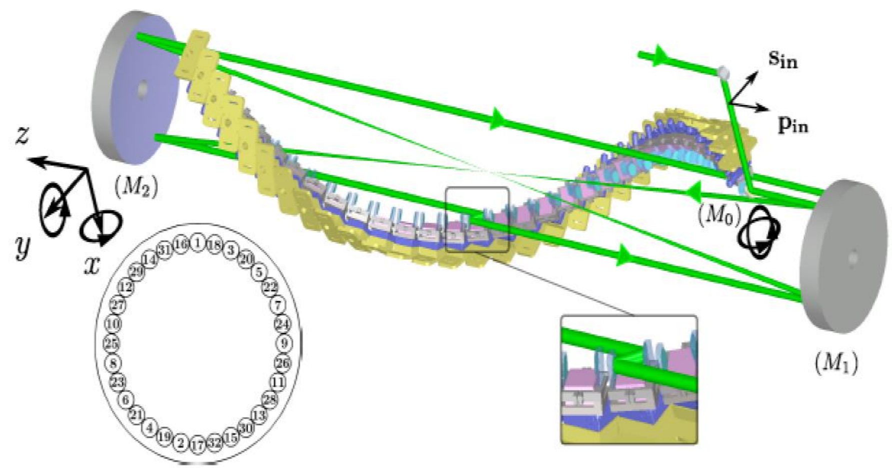
~ 80 collaborators elaborating the CDR/TDR

GBS – Gamma beam parameters

Photon energy	1-20 *MeV*
Spectral Density	> 10^4 *ph/sec.eV*
Bandwidth (rms)	<0.3%
# photons per shot within FWHM bdw.	$1.0\text{-}4.0 \cdot 10^5$
# photons/sec within FWHM bdw.	$2.0\text{-}8.0 \cdot 10^8$
Source rms size	10 - 30 μm
Source rms divergence	25-250 μrad
Peak Brilliance ($N_{ph}/sec \cdot mm^2 mrad^2 \cdot 0.1\%$)	10^{22} - 10^{24}
Radiation pulse length (rms, *psec*)	0.7-1.5
Linear Polarization	> 99 %
Macro rep. rate	100 *Hz*
# of pulses per macropulse	>31
Pulse-to-pulse separation	16 *nsec*

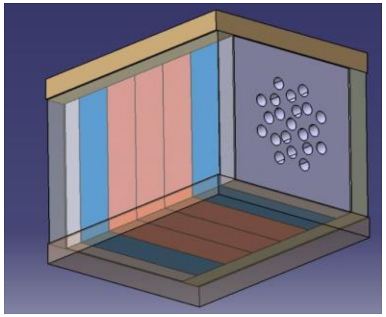




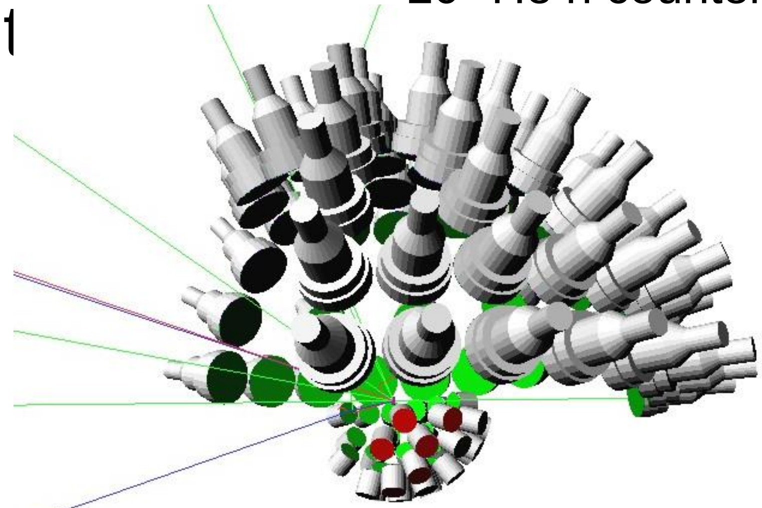


TDR on physics above the neutron threshold

- Studies of GDR and PDR decay
- Studies of spin-flip M1 resonances
- (γ, n) cross section measurements, *e.g.* p process related measurement
  - the ^{138}La(γ,*n*) ^{137}La reaction,
  - the ^{180m}Ta(γ,n)^{179}Ta reaction.



20 ^{3}He n counters



62 n det. (20cm x 5cm) +
34 (x2) $LaBr_3$ det. (3 x 3 inch)

<u>Instrumentation:</u>

(i) $LaBr_3$(Ce) array,

(ii) Fast-neutron detector array

(iii) NE213 liquid scintillator array

Nuclear eli Physics

Conclusions

- ✓ Photoneutron cross section measurements were performed for all the stable Sm isotopes using γ-ray beams produced by the inverse Compton scattering of laser photons on relativistic electrons.
  - Due to the high energy resolution of this new gamma ray source, we investigated the cross sections of (γ,n) reactions with a lower degree of uncertainty and also at energies much closer to the neutron emission threshold compared to the previous experiments.
- ➢ Data reduction
  - ✓ Obtain the monochromatic cross sections.
  - ➢ Obtain the incident LCS γ-ray spectra for each measurement point.
    - ➢ We have developed a new Geant4 simulation code of the interaction between the laser photons and the relativistic electrons. The collision parameters are generated considering the emittance of the electron beam and the spacial distribution of the laser beam with physical constraints between these two input parameters.
  - ➢ Obtain the non-monochromatic cross sections.
- ○ Perform photoneutron cross section calculations for all stable Sm isotopes and use the experimental values to constrain the γSF.
- ○ Test the adopted γSF by reproducing experimentally known reverse (n, γ) cross sections, both for the stable Sm isotopes and for the unstable ^{151}Sm.
- ○ Predict (n, γ) cross sections for the radioactive ^{143,146,153}Sm isotopes.

Collaborators

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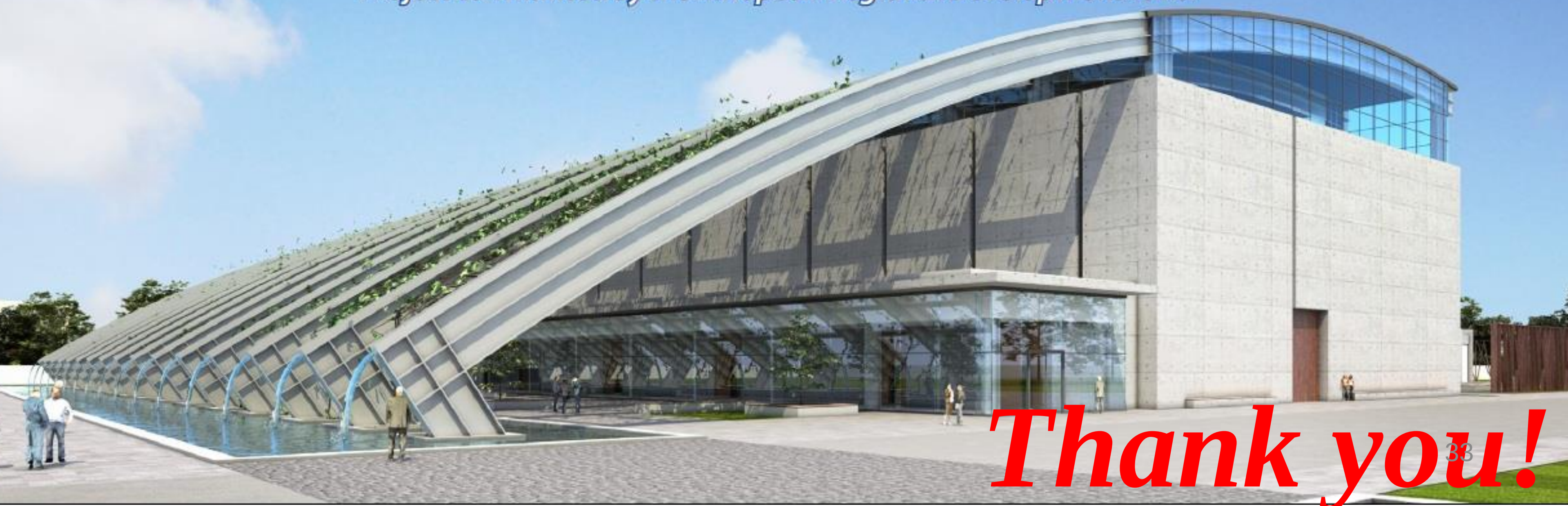

Thank you!