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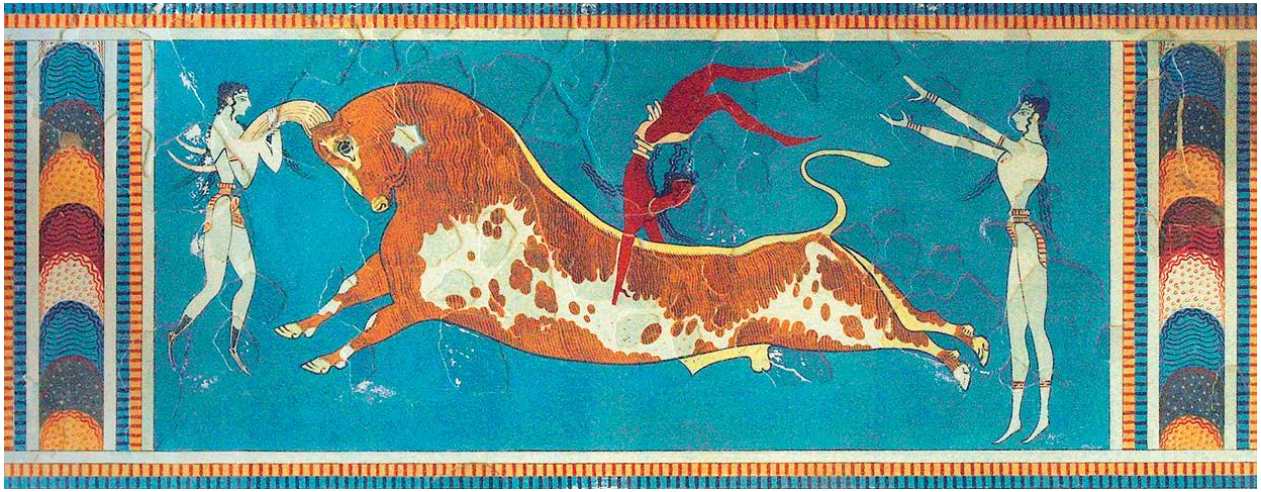
A characterization system for the monitoring of ELI-NP gamma beam

University of Florence and INFN

Rita Borgheresi

July 5, 2018



Outline

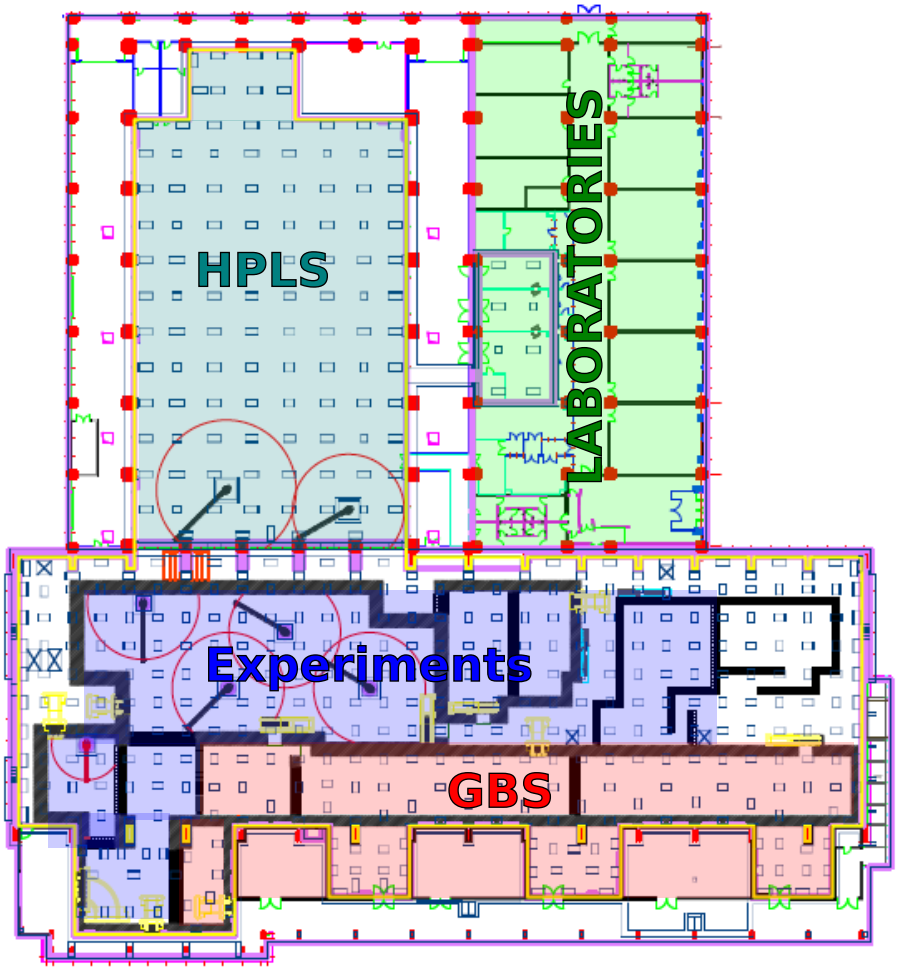
Next Section

ELI: Extreme Light Infrastructure

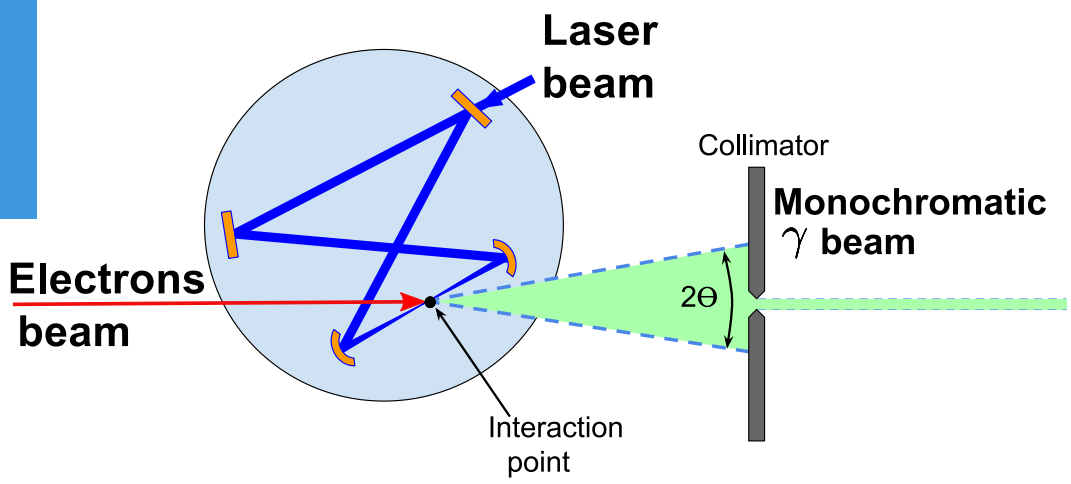
ELI-NP: Extreme Light Infrastructure - Nuclear Physics

ELI-NP will study a wide range of research topics in fundamental physics, nuclear physics and astrophysics, and also applied research.

1. **High Power Laser System: (HPLS)**
   - 2x10 PW Laser System
   - Focused laser intensity can reach 10^{23} W/cm^2
2. **High Intensity Gamma Beam System: (GBS)**
   - *Production method:* laser photons Compton inverse scattered on high energy electrons
   - Two energy lines



The source of ELI-NP γ beam



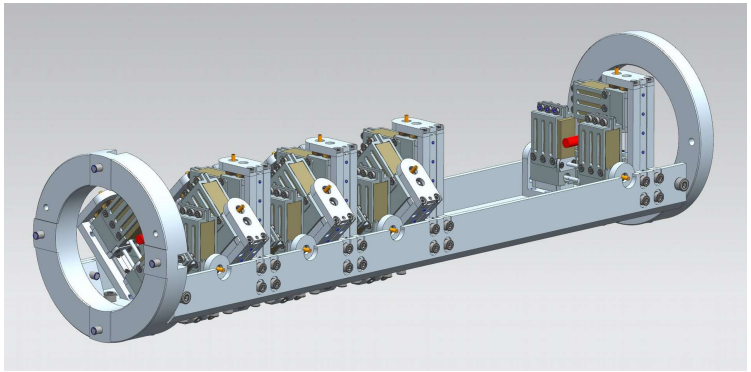
Inverse Compton radiation is not intrinsically monochromatic

$$E_\gamma \sim E_L \cdot \frac{4\gamma_e^2}{1 + a_0^2/2 + \gamma_e^2\theta^2} \cdot (1 - \Delta)$$

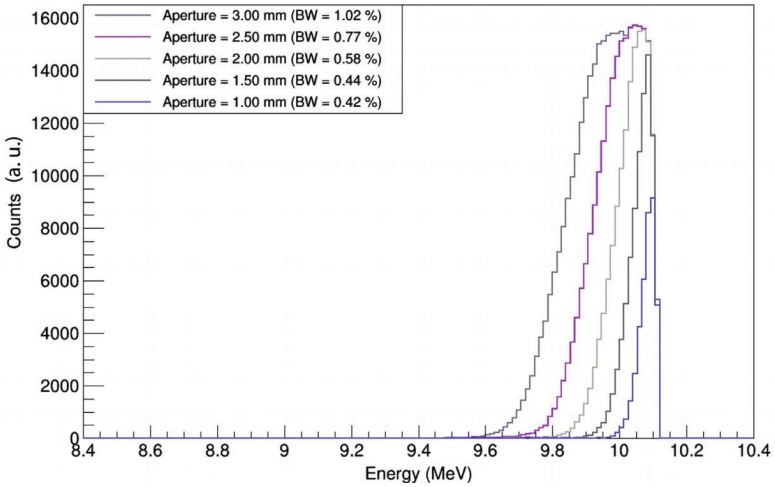
- a_0, laser parameter
- $\Delta \sim (4\gamma_e E_L)/mc^2$

Collimation system

- Stack of 14 slits with aperture independently adjustable (0-25 mm)
- Each slit composed of two 40×40×20mm Tungsten blocks.

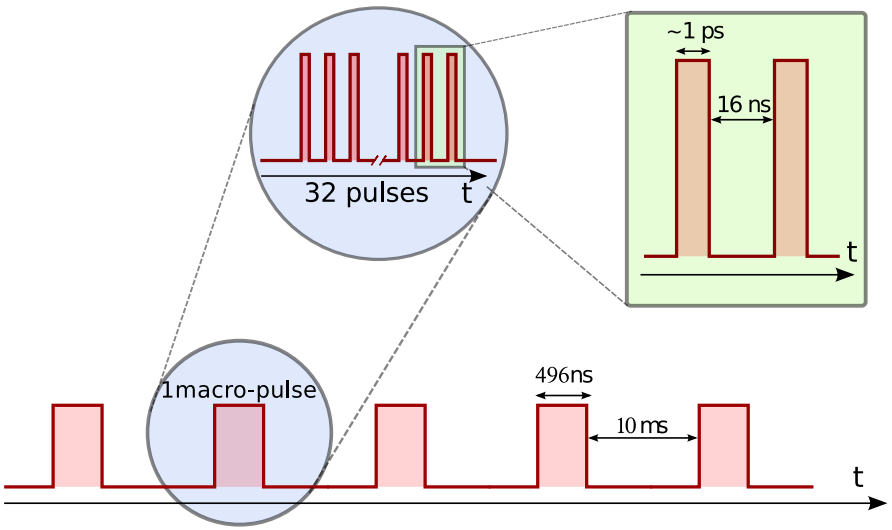


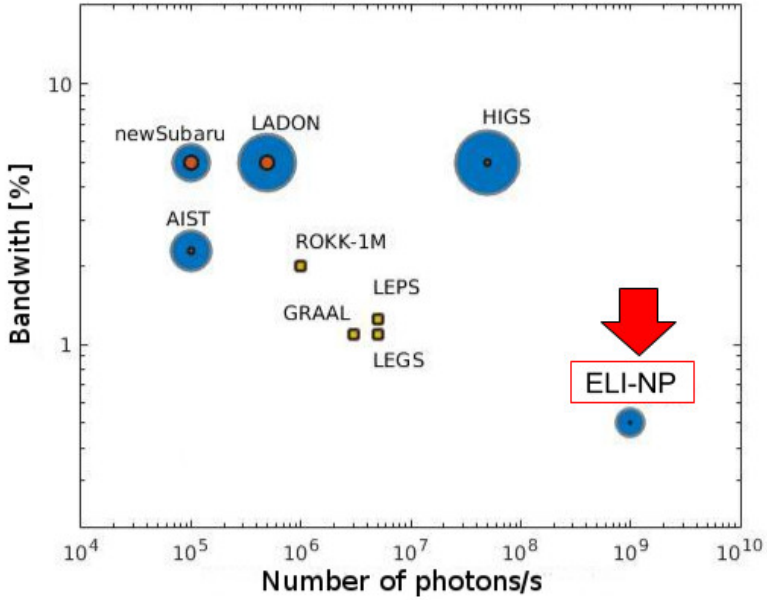
Gamma beam **energy distribution** vs collimator aperture



The requirements of ELI-NP γ beam

Photon energy [MeV]	0.2-19.5
Photon energy tunability	steplessy
Bandwidth	$\leq$ 0.5 %
# photons per shot within the FWHM	$\leq 2.6 \cdot 10^5$
Average diameter of beam spot	$\leq$ 1 mm
Peak brilliance [N_{ph}/s·mm^2·mrad^{2}0.1%]	$10^{22} - 10^{24}$
Linear polarization	$>$ 90 %





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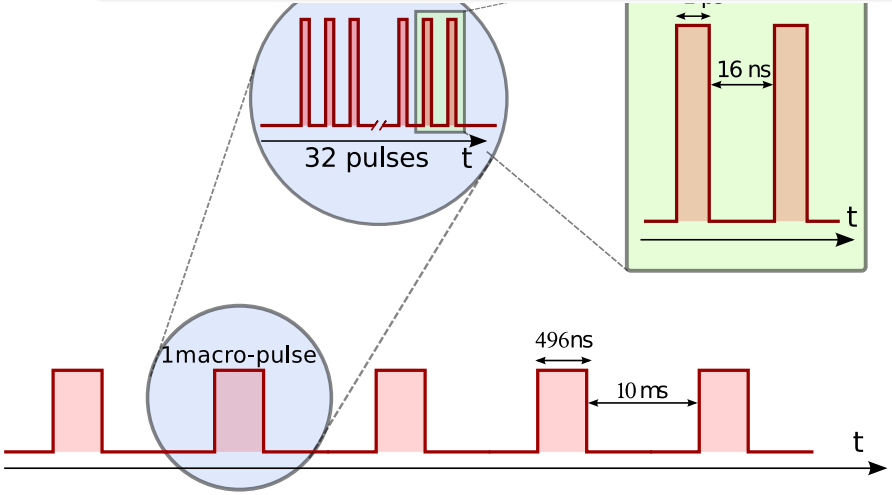
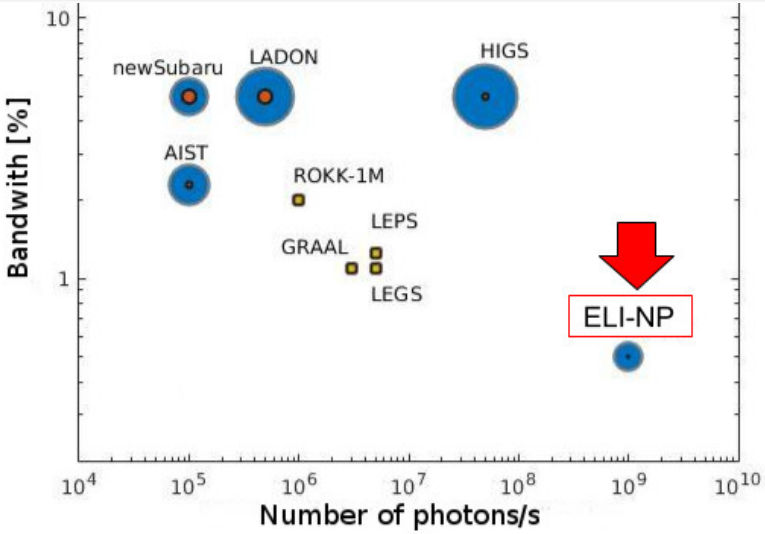
Gamma Beam Characterization System:

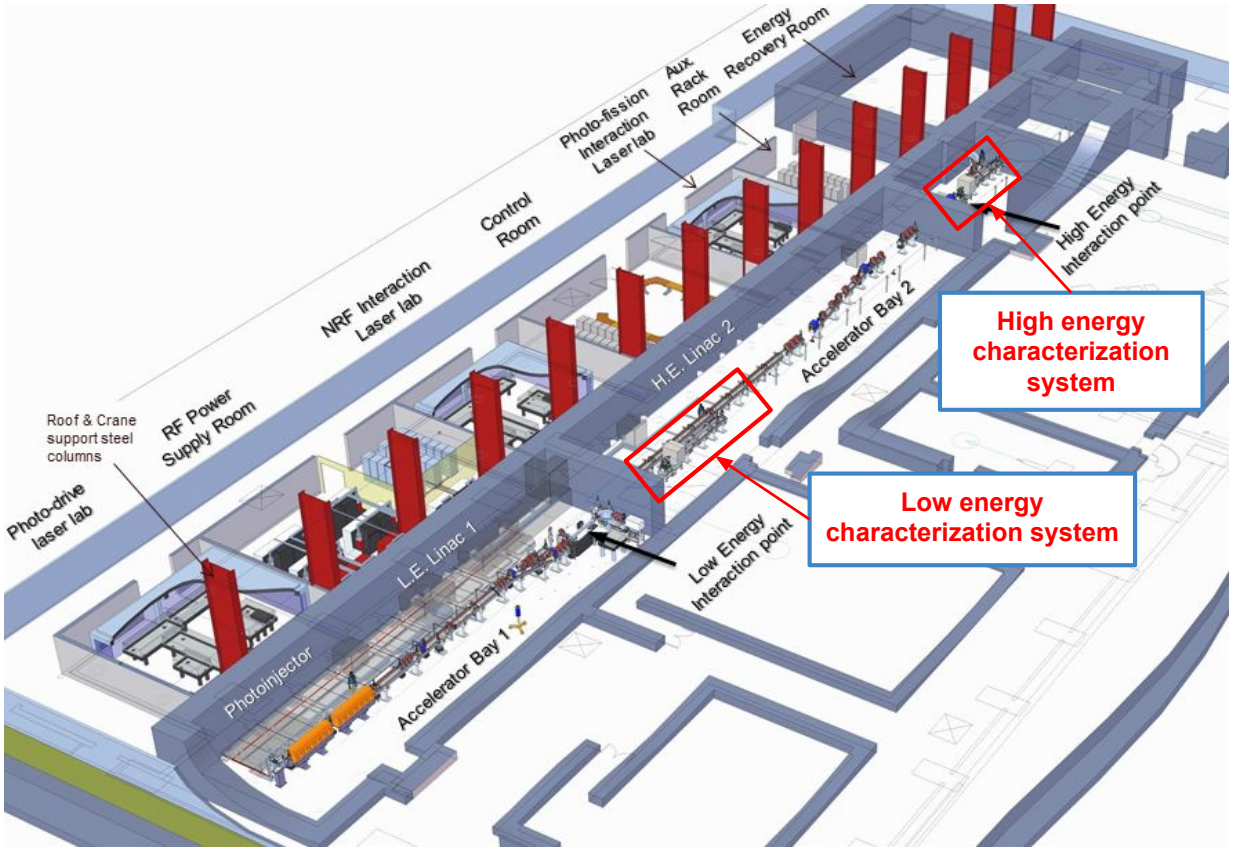
Give a measurement of the gamma beam **characteristics**.





Two Characterization System :

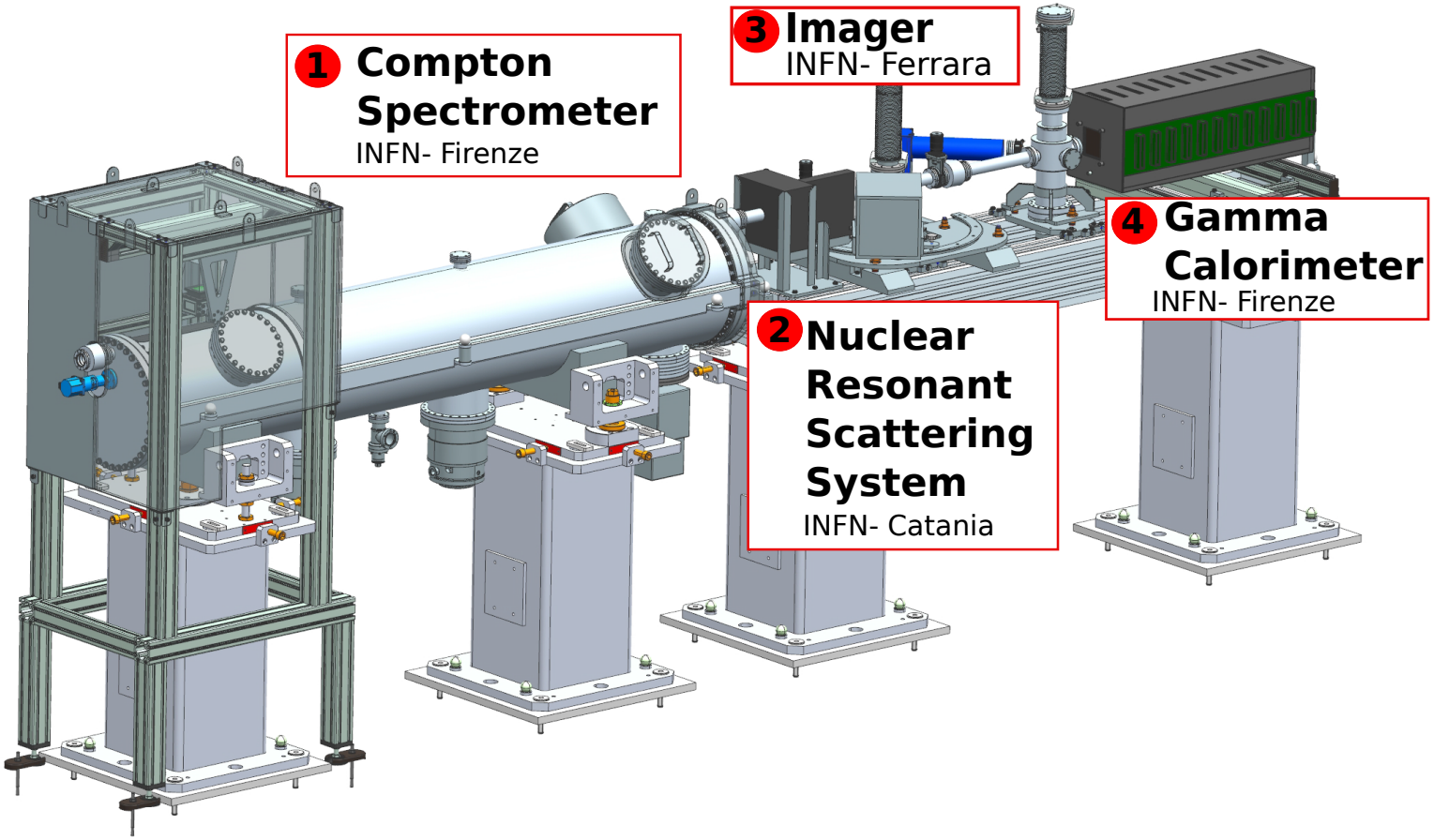
- low-energy line ($E_\gamma < 3.5$ MeV)
- high-energy line ($E_\gamma < 19.5$ MeV)



This talk is about the low energy line characterization system.

Gamma Beam Characterization System

A specific system equipped with **four detectors** has been developed to *measure* and *monitor* the beam parameters during the commissioning and the operational phase.



Next Section

Compton Spectrometer (CSPEC)

CSPEC is used for online energy spectrum monitor, using a *non-destructive* method.

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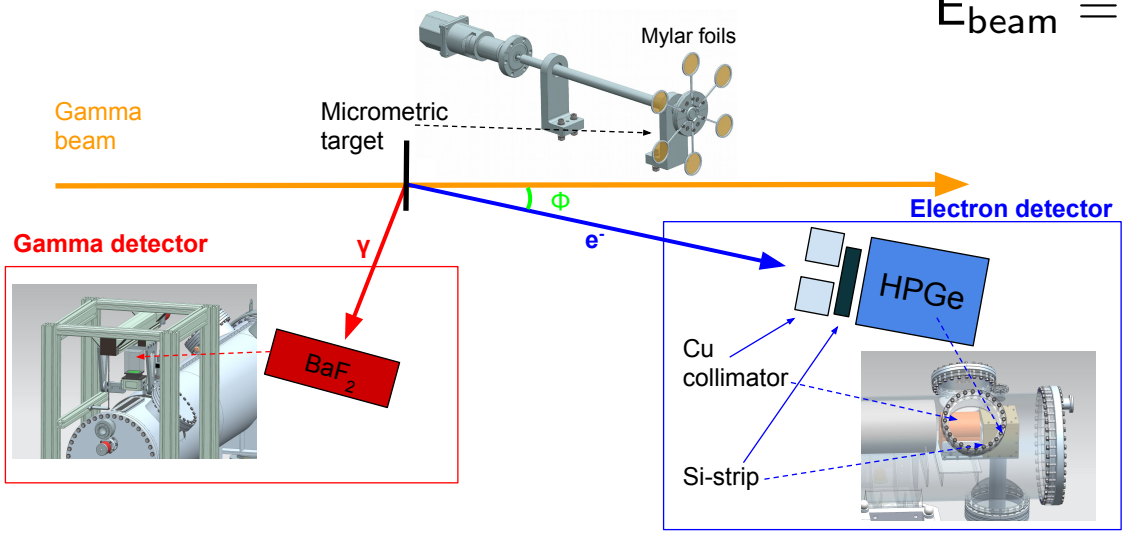
Working Principle

The basic idea is to measure the energy (T_e) and the scattering angle (ϕ) of electrons recoiling at small angles from Compton interaction of the beam on a micrometric target (1-100μm).



$$E_{beam} = \frac{m_e \cdot T_e}{\cos(\phi)\sqrt{T_e \cdot (T_e + 2m_e)} - T_e}$$

- T_e: measured with HPGe detector
- ϕ: determined by a double sided strip detector
- The scattered gamma is acquired for trigger purpose

Energy reconstruction: Expected performance

Peak energy

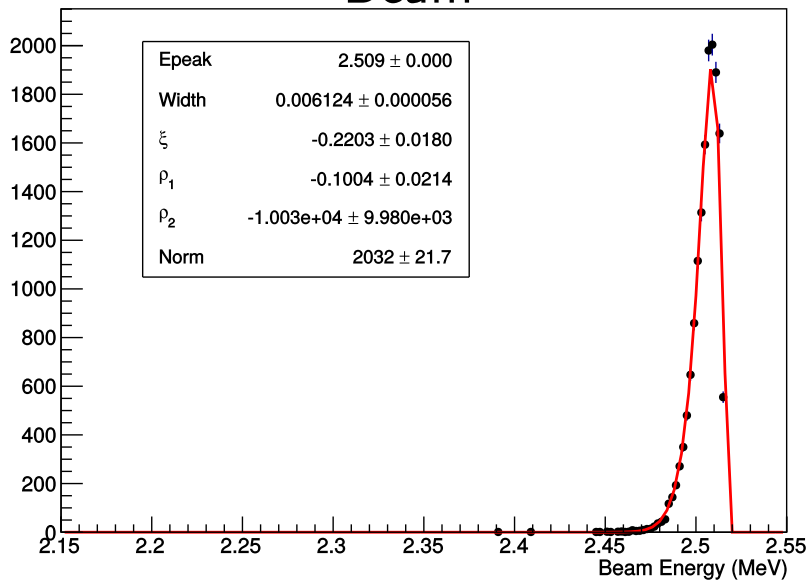
E_γ	2.5 [MeV]
$\frac{\sigma_{stat}(E_\gamma)}{E_\gamma}$ [%]	0.04
$\frac{\sigma_{syst}(E_\gamma)}{E_\gamma}$ [%]	0.11

Beam bandwith (BW)

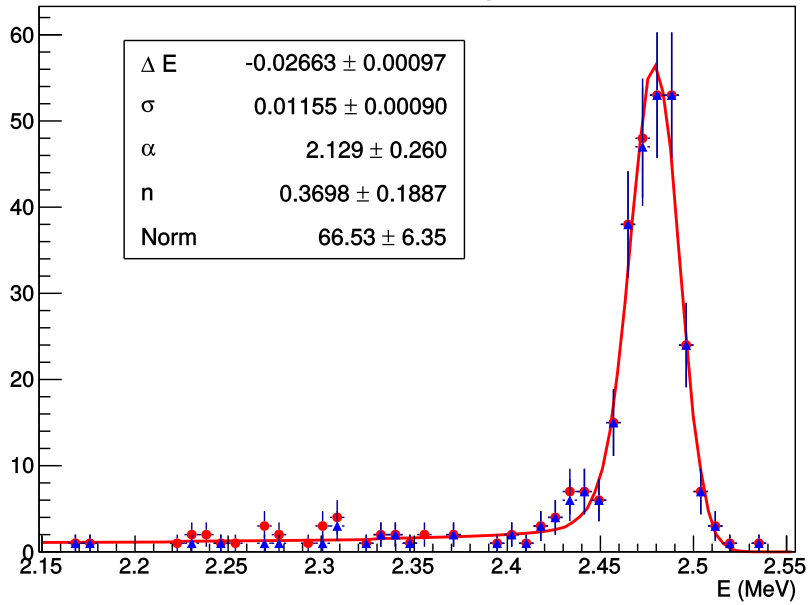
E_γ	2.5 [MeV]
Simulated BW [keV]	6
Detector σ [keV]	12

Detector resolution on measurement of peak energy and bandwith $\leq 0.5\%$, then **better than the beam bandwith**.

Beam



Detector response



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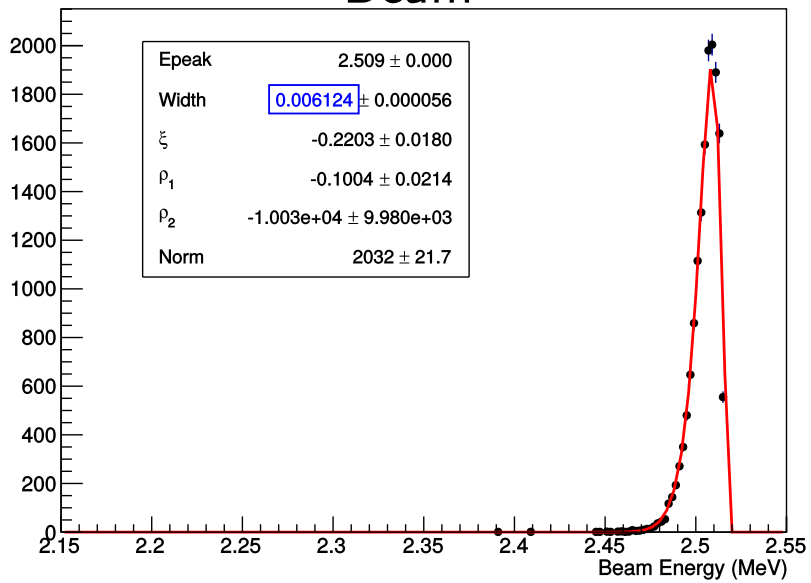
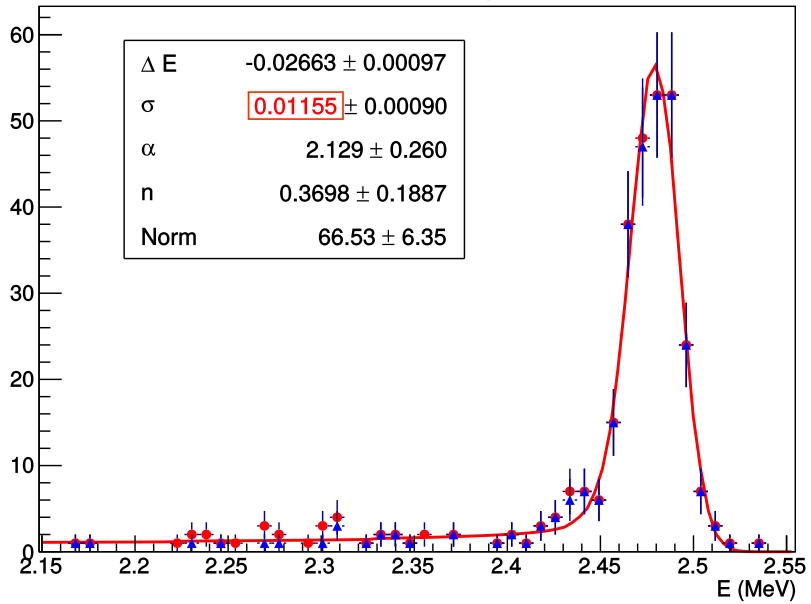
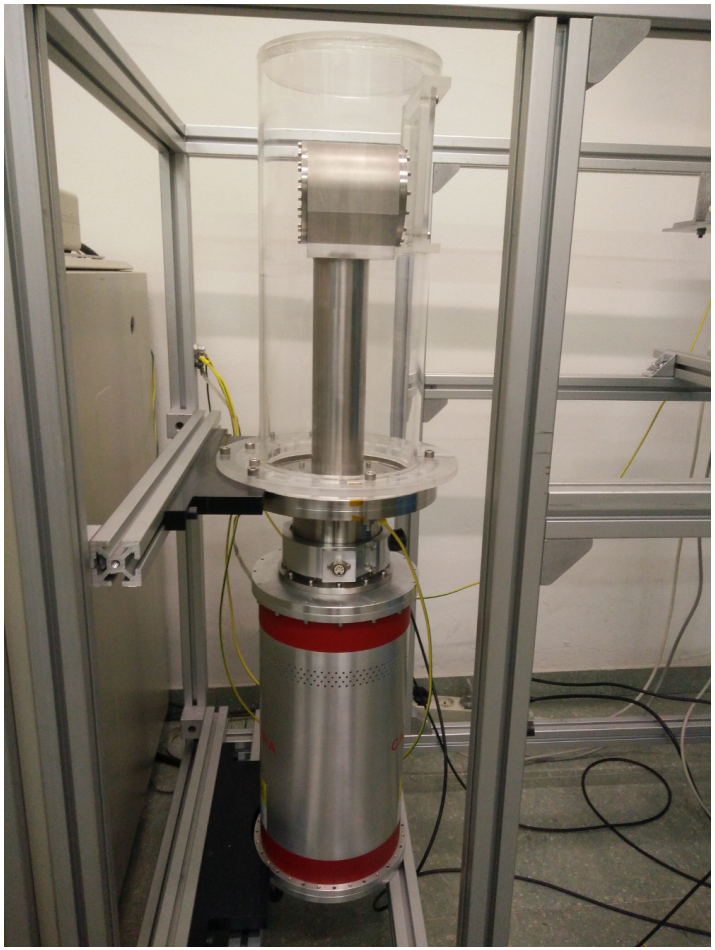


Detector response



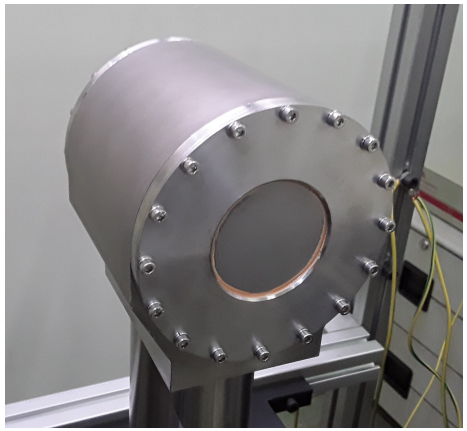
CSPEC: the HPGe detector

The **HPGe detector**, chosen for its excellent energy resolution, will measure the *energy* of the scattered electron.



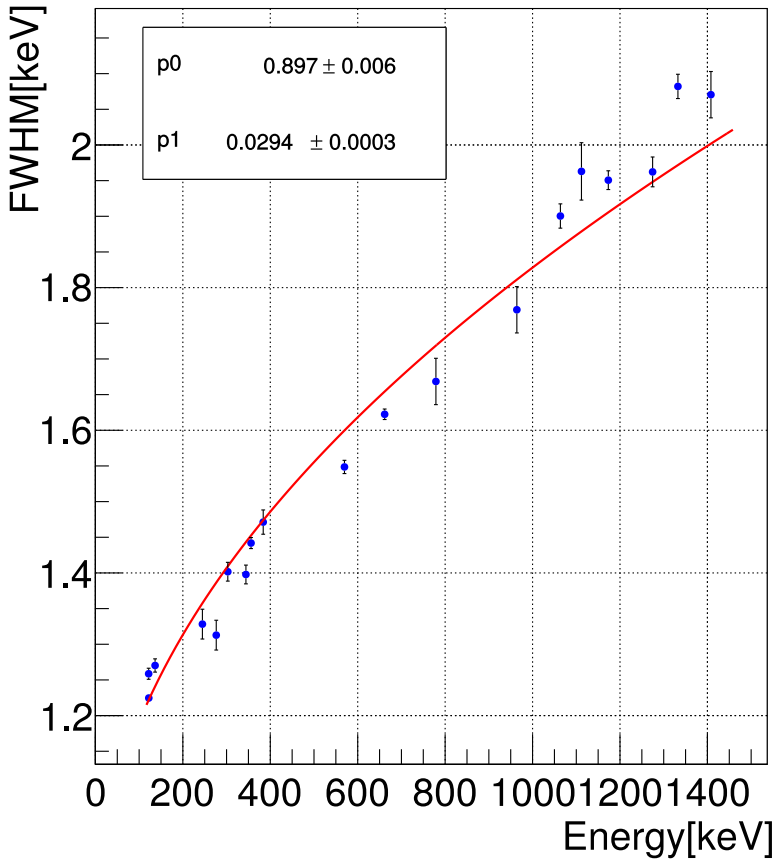
Detector design:

- The HPGe crystal is built in a planar custom configuration by CANBERRA:
  - 80 mm, diameter
  - 20 mm, thickness
  - electrically cooled
- To minimize the energy loss:
  - 100μm, cryostat Be-window thickness
  - $\leq$ 1μm, electrical contacts



HPGe detector tests

Energy resolution

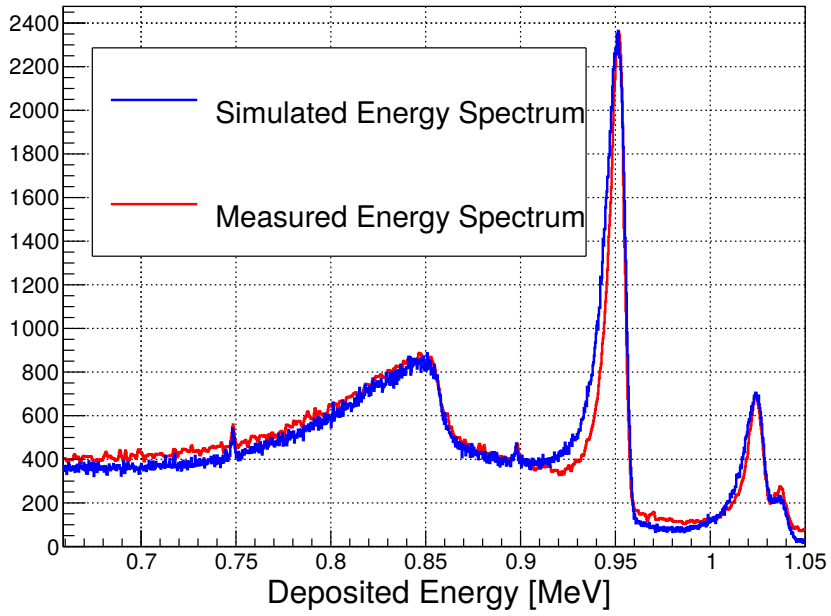


Energy resolution at 1332 keV:

$$R_E = \frac{FWHM}{E} = 0.157 \pm 0.002\ \%$$

Electron source test

Verified the accuracy of Monte Carlo simulation using electrons of definite energy emitted by ^{207}Bi source.



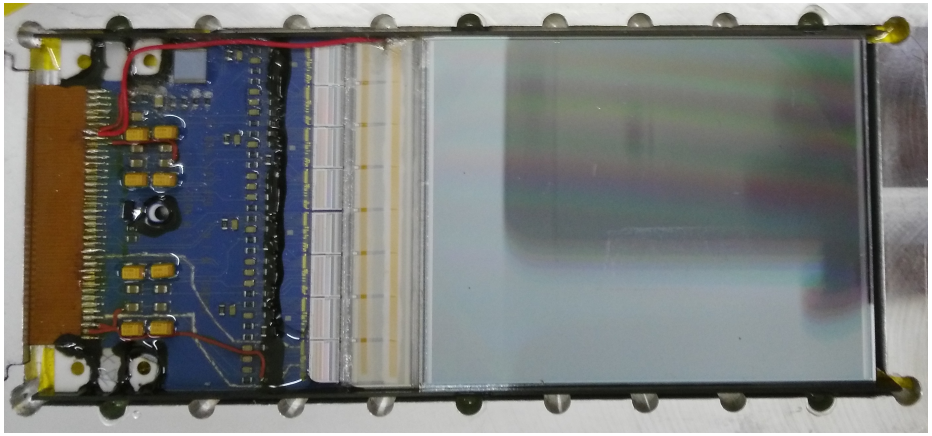
The measured peak positions are in agreement with the simulated ones with a **precision better than 1 keV**.

CSPEC: the Si-strip detector

The *angle* of the Compton scattered electron is determined by double-sided **silicon strip detector**.

Detector design:

- Silicon strip detector produced by Hamamatsu
  - 5.33×7 cm^2
  - 300 μm thickness

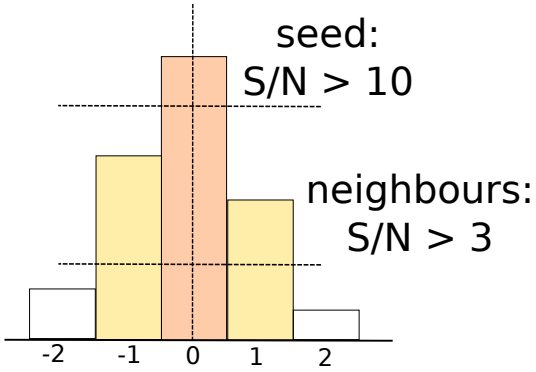


- 1024 strips for each view implanted along orthogonal directions
- readout by VA1 chip, with 128 charge sensitive amplifiers
- Impact point resolution:
  - 3 μm on the junction side (x-view)
  - 11 μm on the ohmic side (y-view)

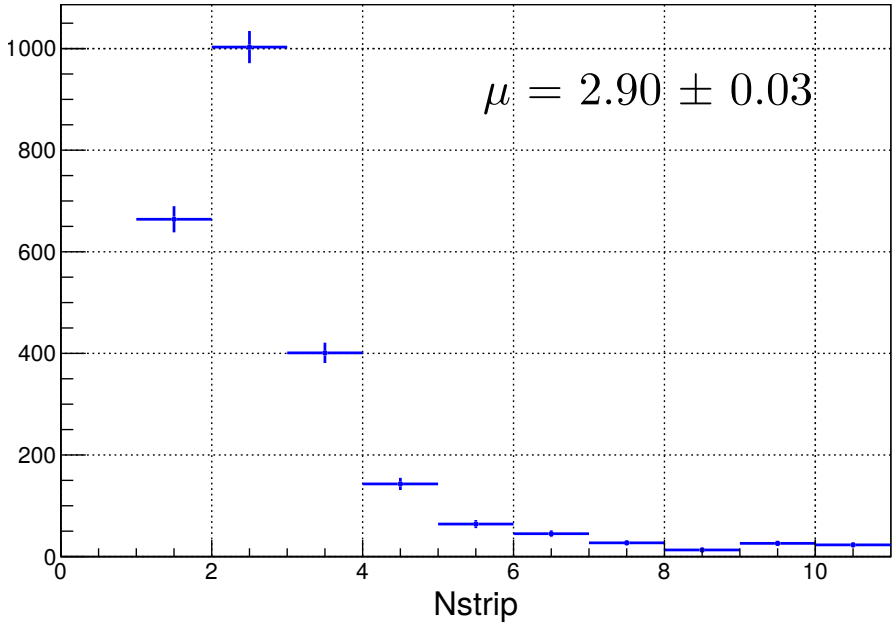
Si-strip preliminary test with cosmic rays

Cluster characteristic:

- Cluster inclusion cuts

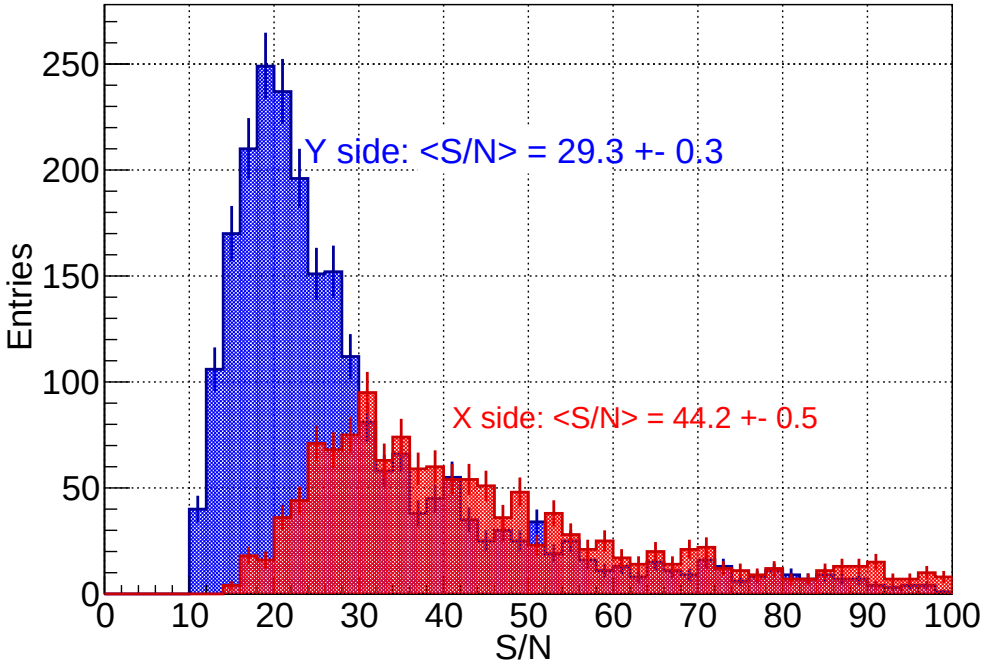


- Cluster Multiplicity - y view



Cluster Signal/Noise:

$$\left(\frac{S}{N}\right)_{\text{cluster}} = \sum_{i=1}^{m} \frac{S_i}{\sigma_i}$$

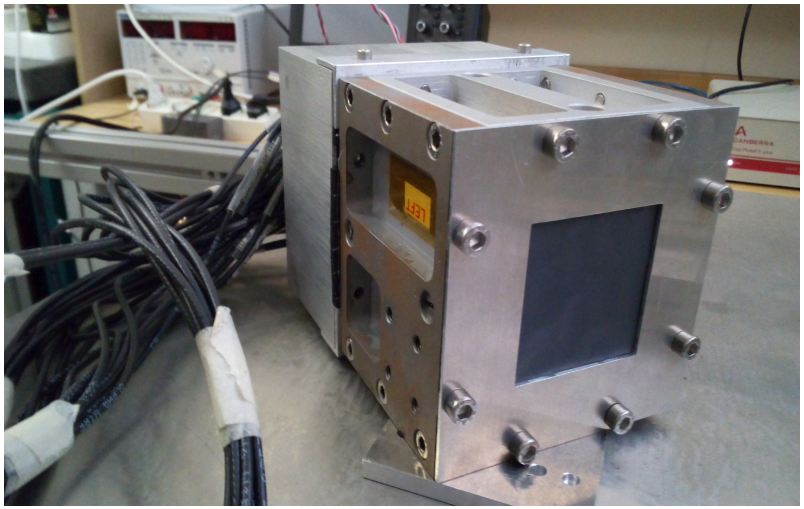


- Y-view: larger noise, due to a greater capacitance

CSPEC: the BaF_2 detectors

The scattered **photon** is detected, in coincidence with the electron, by **BaF_2** crystals to provide a **trigger** for the CSPEC data acquisition. This coincidence is very effective in suppressing the background.

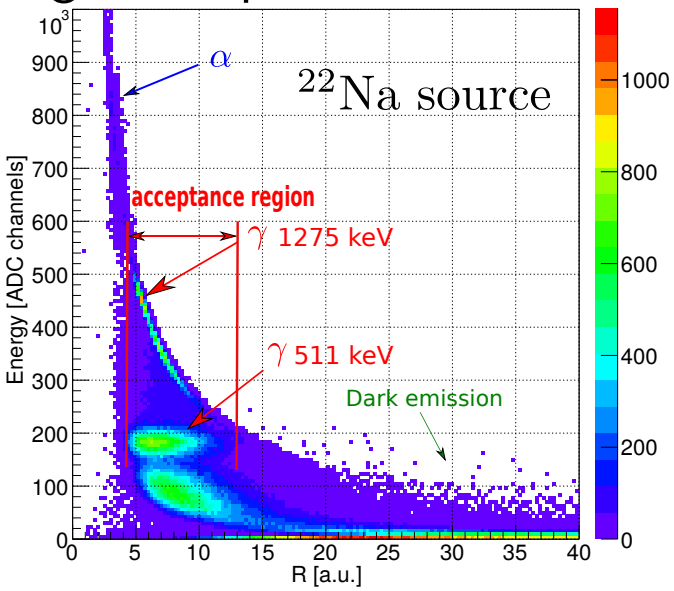
Detector design:



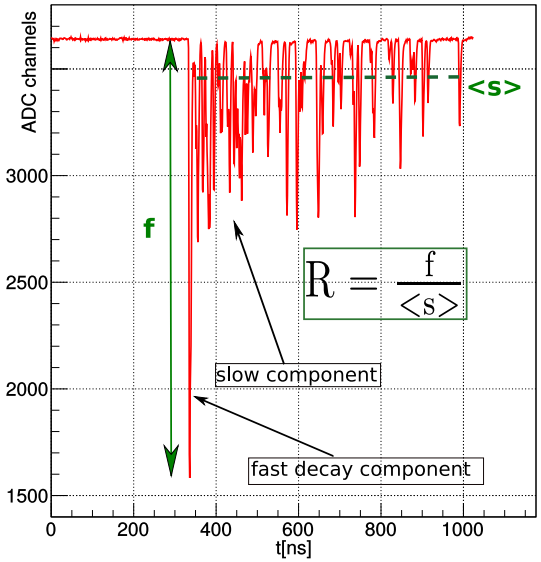
- Small calorimeter made of a matrix of 4×4 BaF_2 crystals (1.2×1.2×5 cm^3)
- Read out by a multianode PMT manufactured by HAMAMATSU (H12700 model)
- BaF_2 has two scintillation components:
  - fast: $\tau = 0.6 - 0.8$ns
  - slow: $\tau = 630$ ns

The BaF_2 detectors tests

- Signal shape identification



- Typical detector signal



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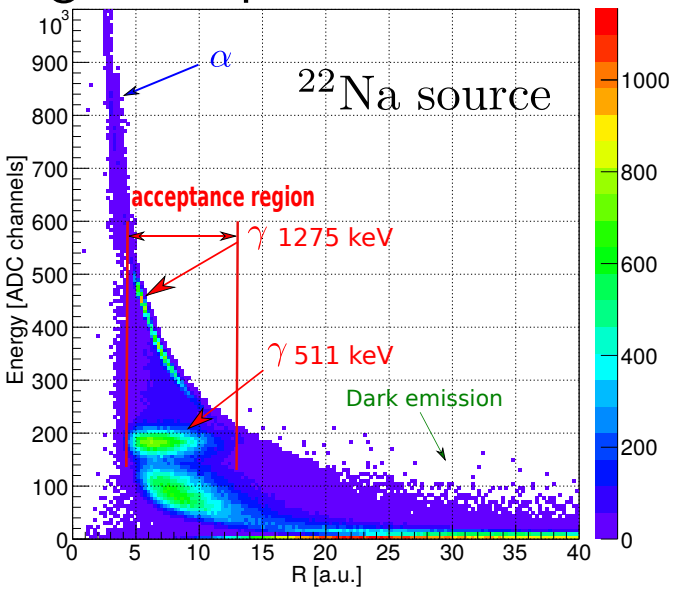

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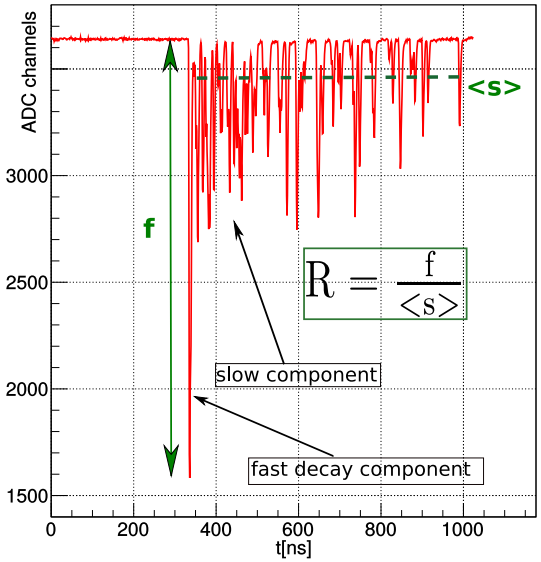
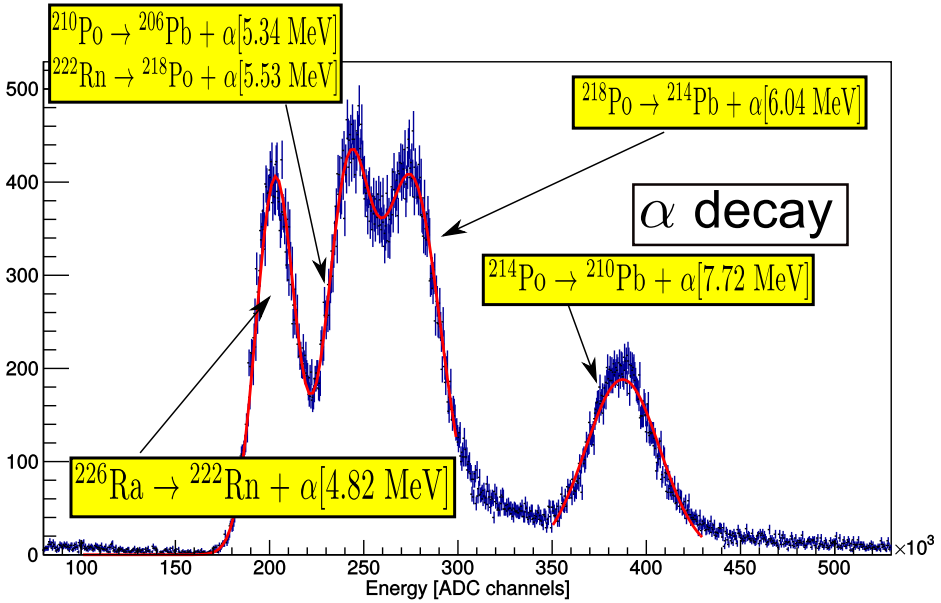


Detector self-calibration



The intrinsic radioactivity of BaF_2, originated from natural ^{226}Ra impurities, can be used to self-calibrate the detector.

Next Section

Nuclear Resonant Scattering System (NRSS)

NRSS has to provide an absolute energy calibration for GCAL and CSPEC.

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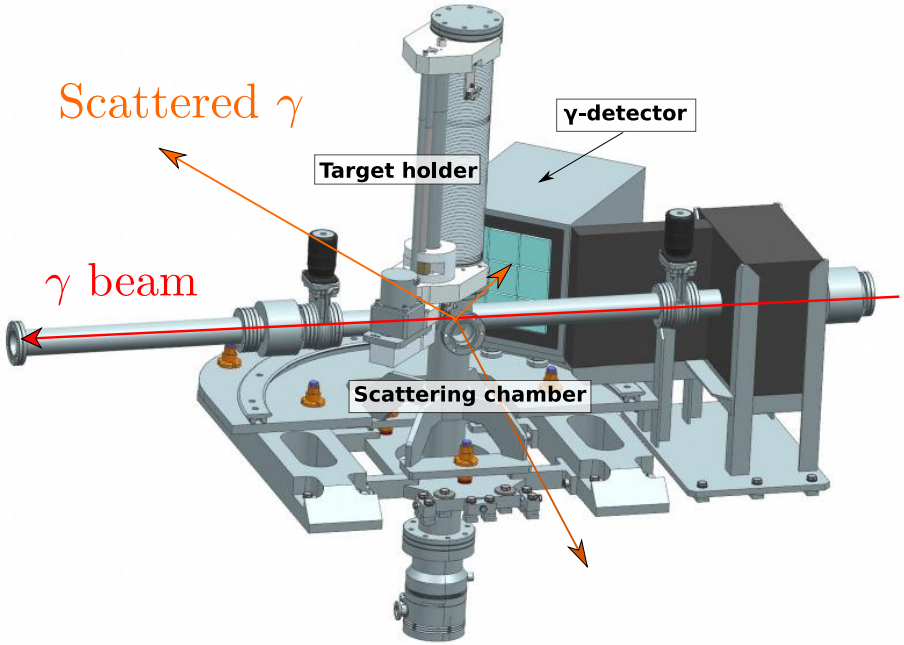
NRSS has to provide an absolute energy calibration for GCAL and CSPEC.

Working Principle

Detect the resonant γ decays of properly chosen nuclear levels when the beam energy spectrum overlaps the selected level.

Detector design



Target nuclear levels

^{A}X	E_r(MeV)	ΔE_r(MeV)
^{6}Li	3.56288	$1.0 \cdot 10^{-4}$
^{11}B	2.124693	$2.7 \cdot 10^{-5}$
^{12}C	4.43891	$3.1 \cdot 10^{-4}$
^{27}Al	2.21201	$10 \cdot 10^{-5}$
^{27}Al	2.98200	$5 \cdot 10^{-5}$

NRSS: The γ detector

The NRSS γ detector is made of a screened array of four **BaF_2** crystals ($5\times5\times8$ cm^3) surroundings a **LYSO** crystal ($3\times3\times6$ cm^3).

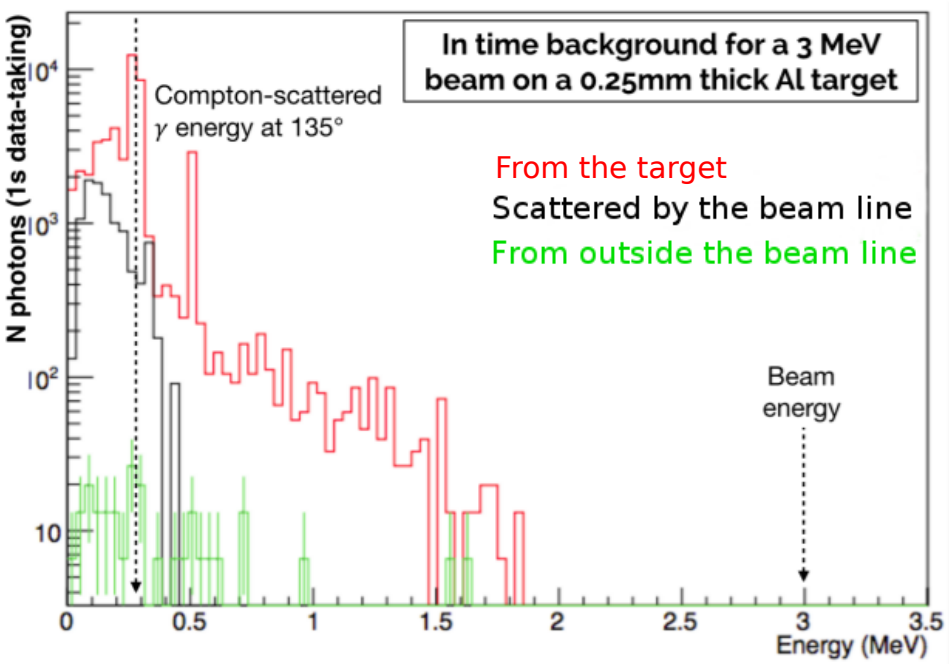
Two operation modes

- Fast Counting mode: Use the BaF_2 fast response to provide a prompt information on the established resonant condition.
- Energy mode: Use LYSO crystal to perform a energy spectrum measurement. In this configuration the BaF_2 act as Compton shield.

Background rejection

- Photons with energy comparable with the signal → come out of time.

- NRSS at $\theta = 135°$ to move away from signal energy region.
  Main problem: pile-up of low-energy photons back-scattered from the target.



Background rejection

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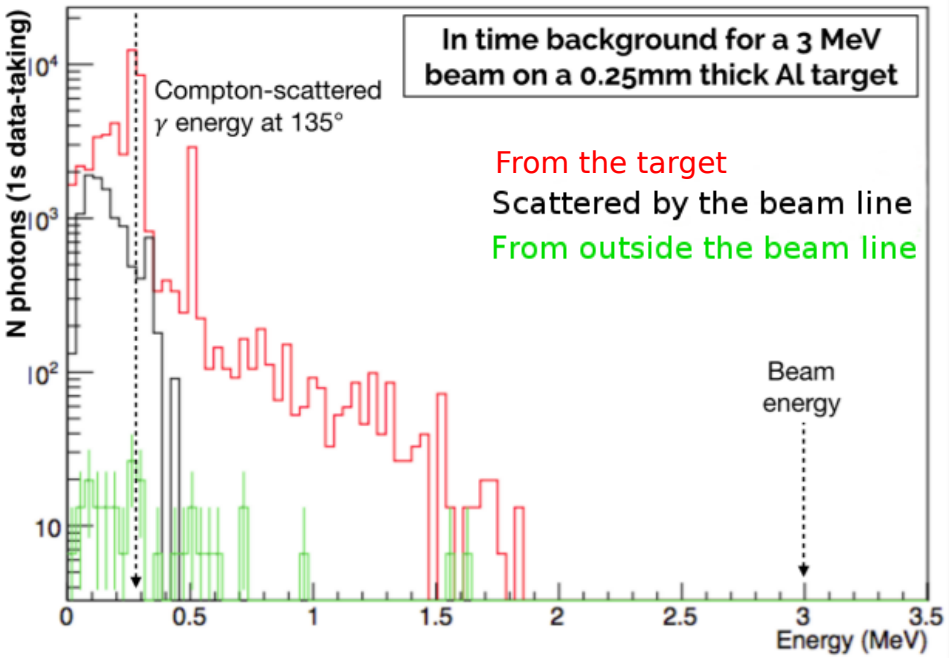
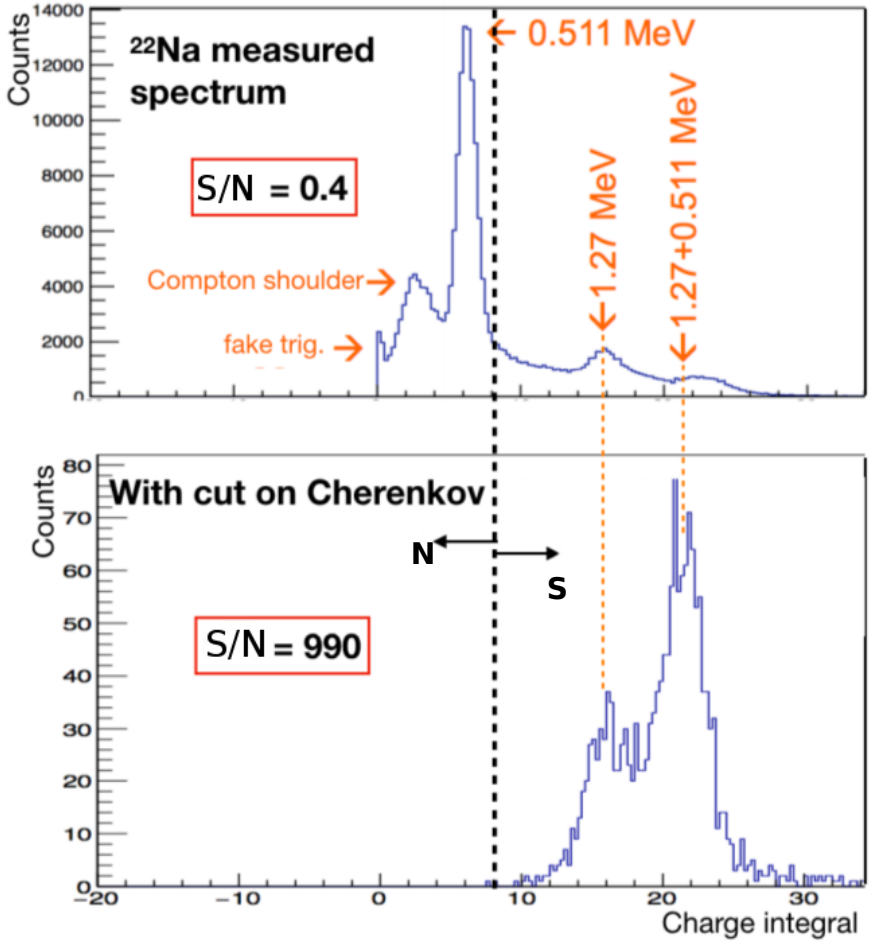
  Main problem: pile-up of low-energy photons back-scattered from the target.

A peculiar technique based on dual readout of *Cherenkov* and *scintillation light* has been developed. The basic idea is to use only the signal which have both the light components.

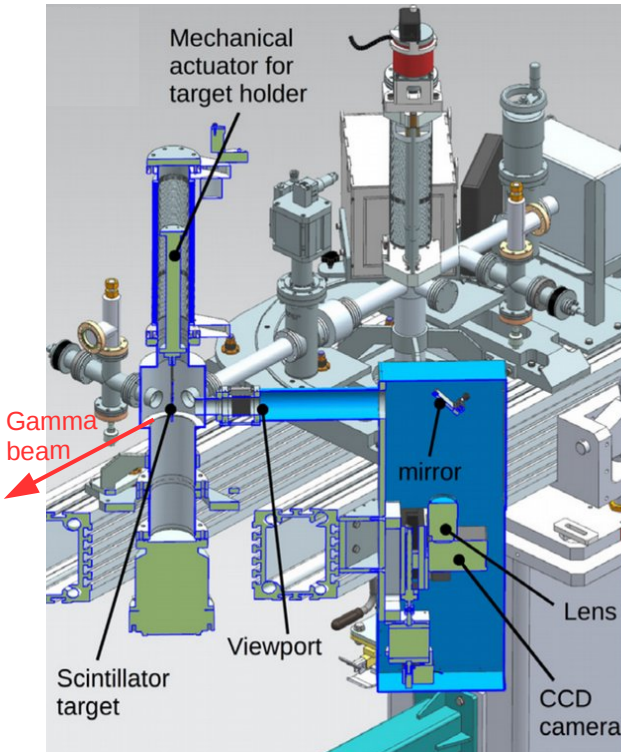


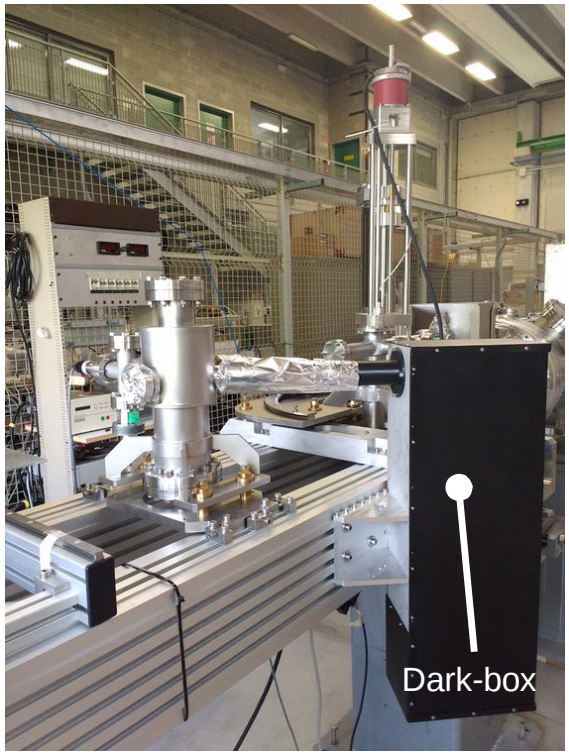


Next Section

Gamma Profile Imager (GPI)

GPI has to provide an image of the beam spatial distribution to display the *location* and the *uniformity* of the beam.



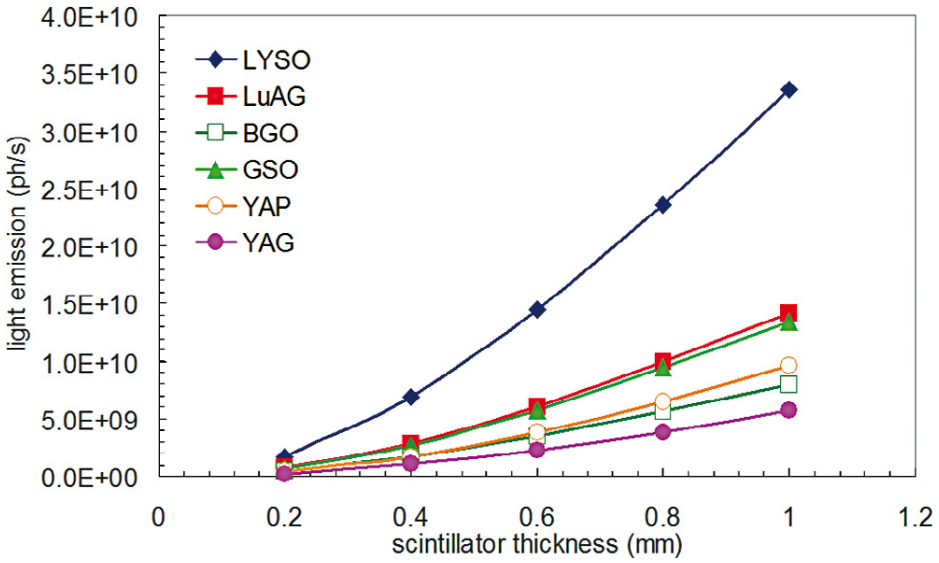


- **Scintillator target** material placed at 45° with respect to the beam axis and hosted in a target holder which support interchangeable materials.
- The scintillator light is focused onto a **CCD camera** with a mirror and a lens system.

GPI: the Scintillator target

1. **The target material**:

- good conversion efficiency (high density and thickness)
- high-Z
- good light yield



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LYSO scintillator crystal

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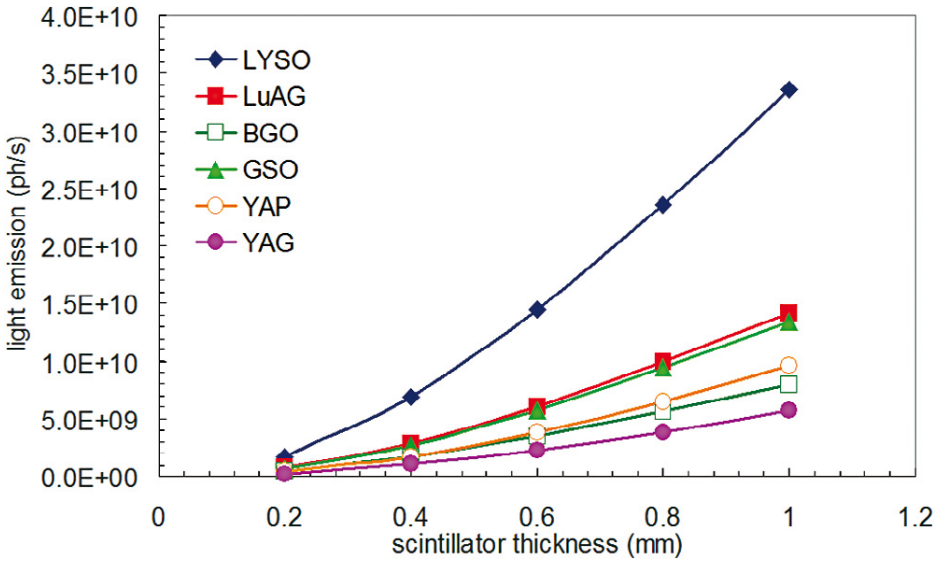

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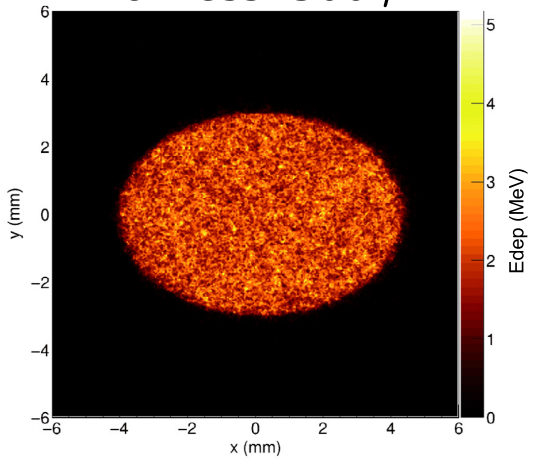
LYSO scintillator crystal

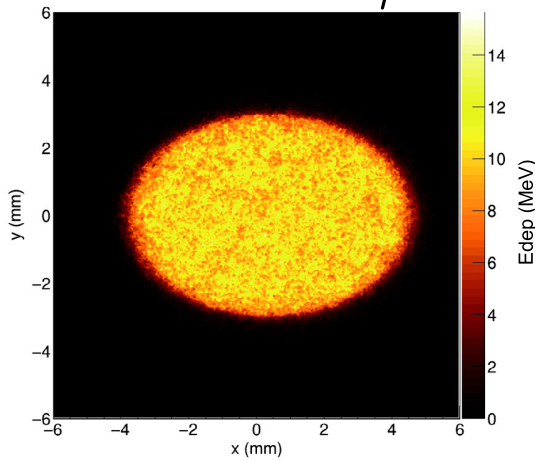
2. **The target thickness:**

cannot be increased without losing resolution.

Thickness: 300 μm

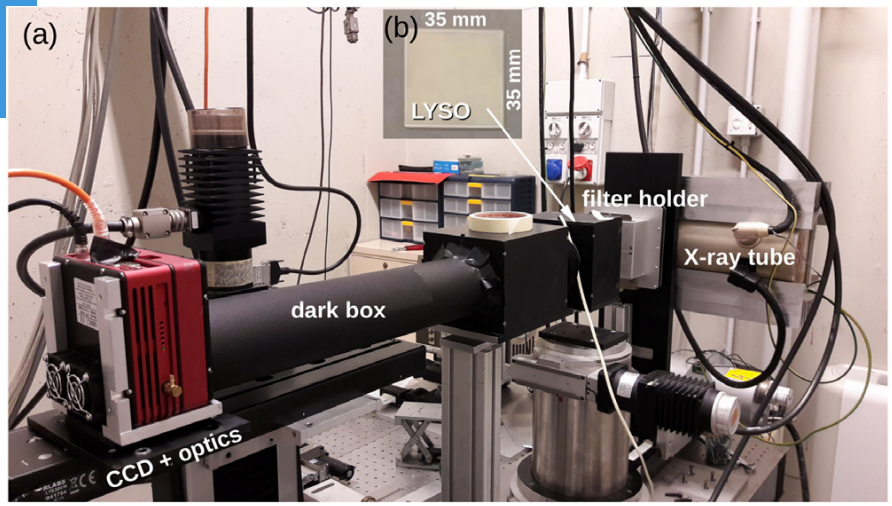


Thickness: 700 μm



Selected thickness: **100-500 μm**

GPI prototype testing and expected performances



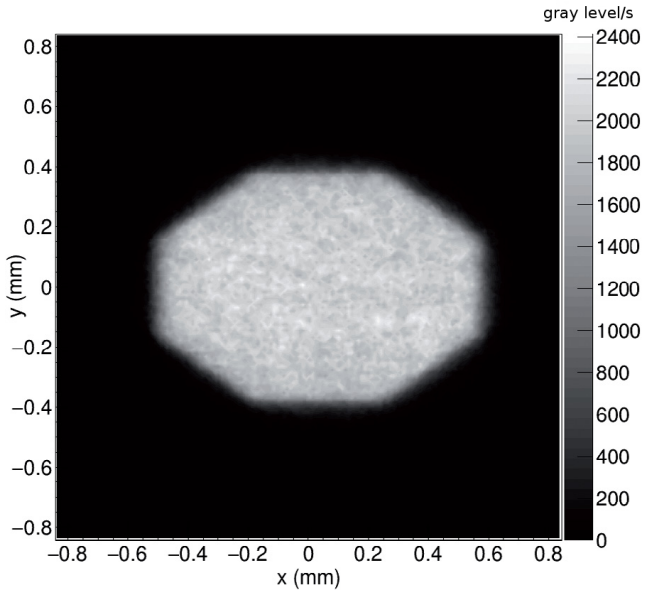
An **analytical model** has been developed to work out an expression for the signal expected on the CCD as a function of the system configuration.

The *parameters* in the model were tuned with a set of **experimental tests** on a GPI prototype, using the radiation produced by an x-ray tube.

Expected signal with the **ELI-NP gamma** beam

Beam energy [MeV]	Signal (gray level/s)
0.2	305
3	2165

Far above the expected readout and thermal **noise of $\sim$ 45** gray level.



Next Section

Gamma Calorimeter (GCAL)

The calorimeter has to provide a fast destructive measurement of the beam average energy and intensity.

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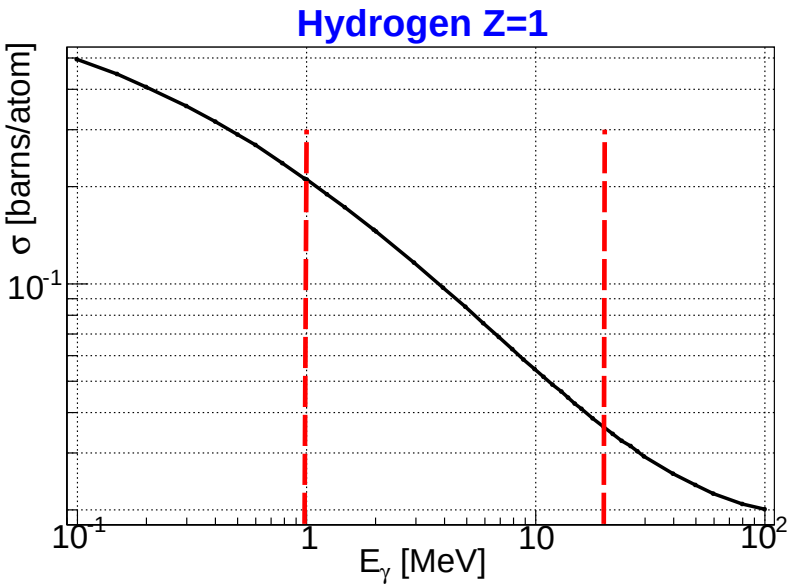
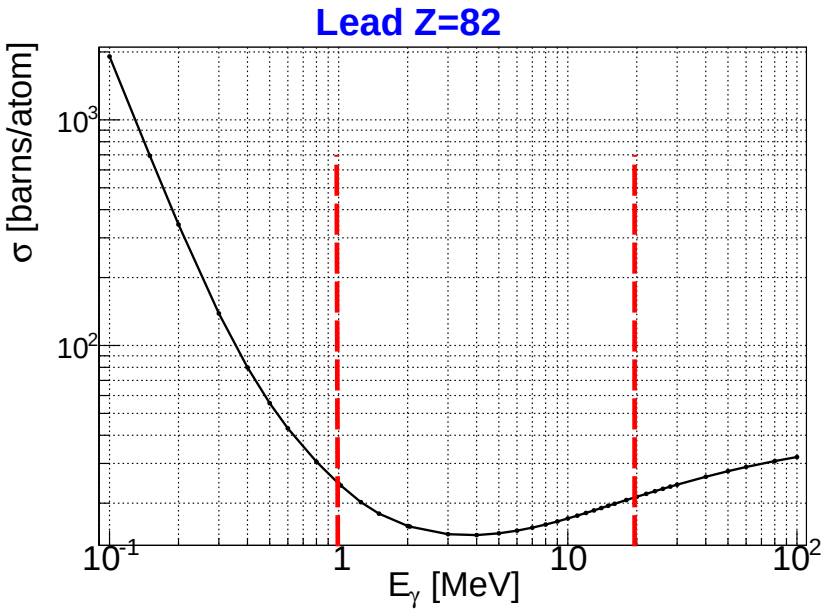
- **Problem:** the photon energy can not be derived simply from the total energy released.
- **Solution:** The beam energy can be estimated from the energy dependence of the γ absorption cross-section for low-Z materials.



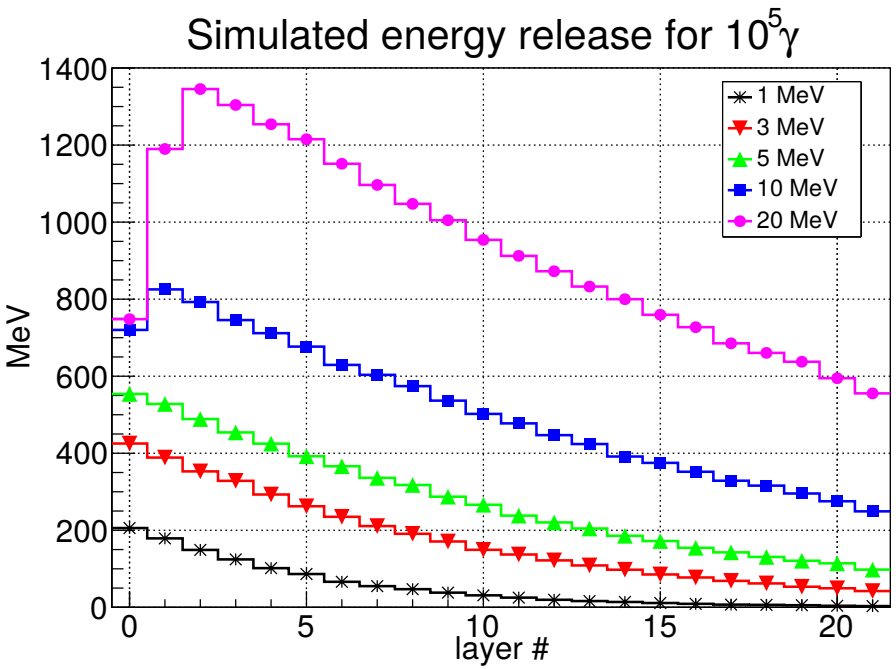


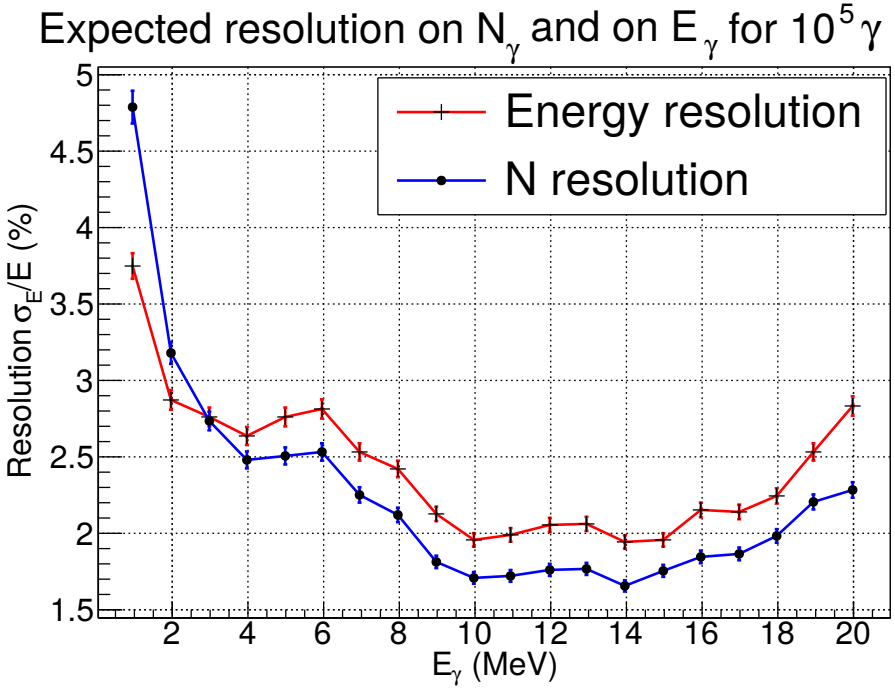
Gamma Calorimeter

Working principle

In a light calorimeter the average energy of the beam can be measured by fitting the measured longitudinal profile against parametrized distributions. Once the photon energy has been known, the intensity is obtained from the total energy released.

Expected Performances:

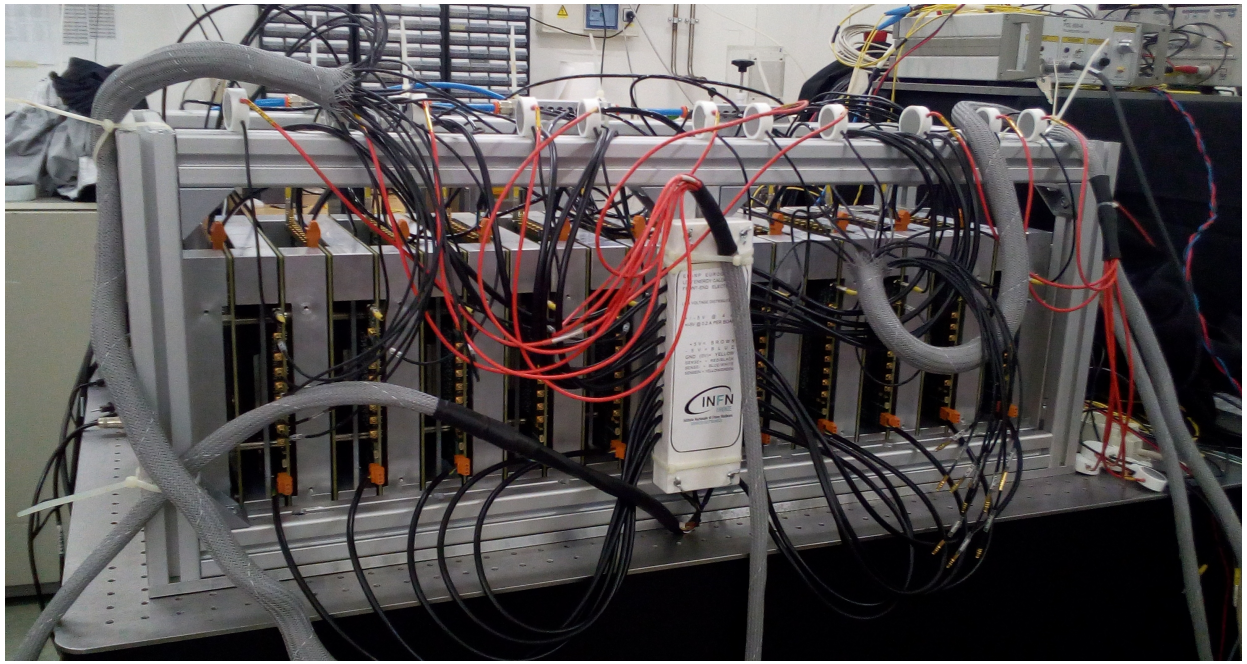




GCAL: Detector design

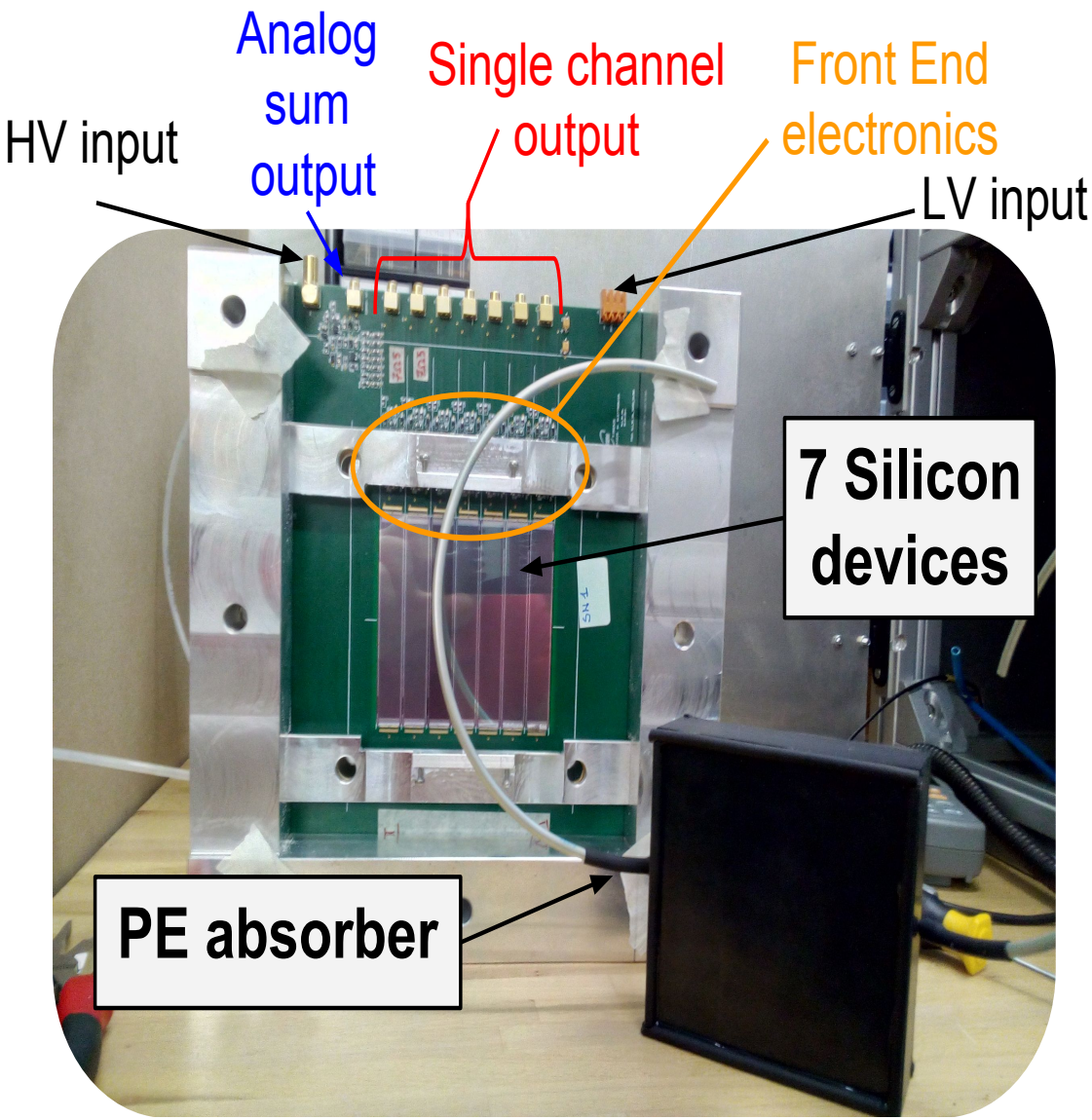
The sampling calorimeter is made by 22 identical layers of **Polyethylene (PE) absorber** interleaved with active **Si-strip detectors**.

- PE absorber:
  - 3 cm thickness
  - 8.8×8.8 cm^2
- Si-strip:
  - test structure of the CMS tracker detectors, developed by Hamamatsu



GCAL: One layer design

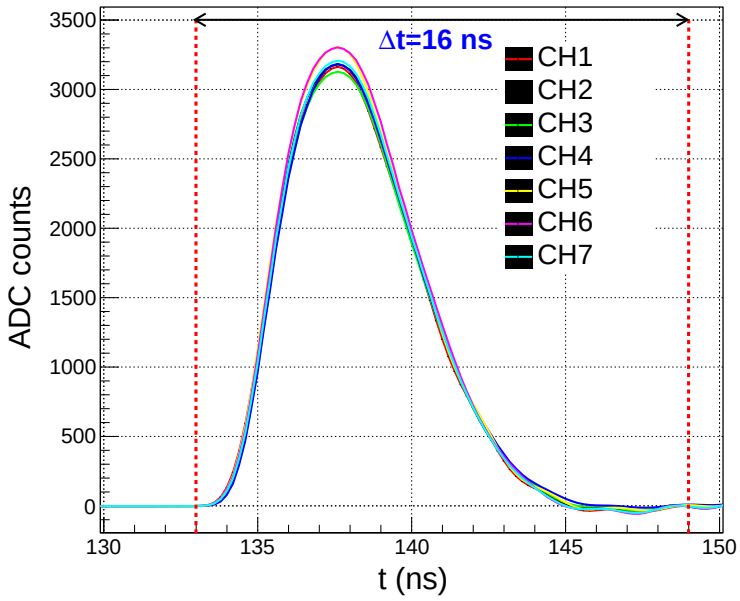
- Si-Strip technology:
  - **Fast response**
  - **Radiation hardness**: can sustain up to 100 kGy irradiation
  - Linearity
- Silicon detector:
  - 10.32×80.0 mm^2 active area
  - 320μm thickness
- Si-strip sensors bonded together.
- Custom electronics.



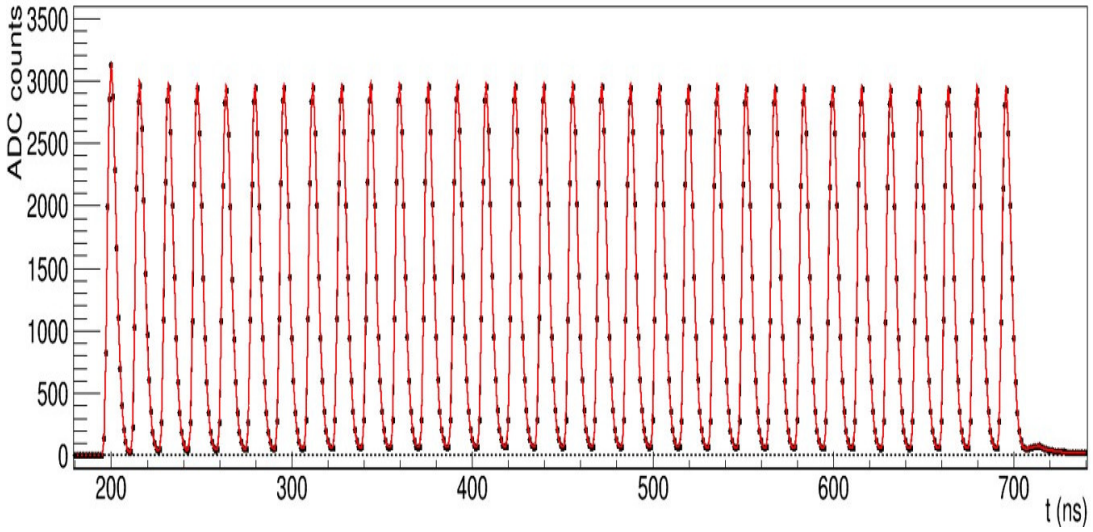
GCAL: Time response test

Very fast response of detector and custom readout electronics optimized and tested with *infrared laser*

7 Si-strip sensors response to single laser pulse



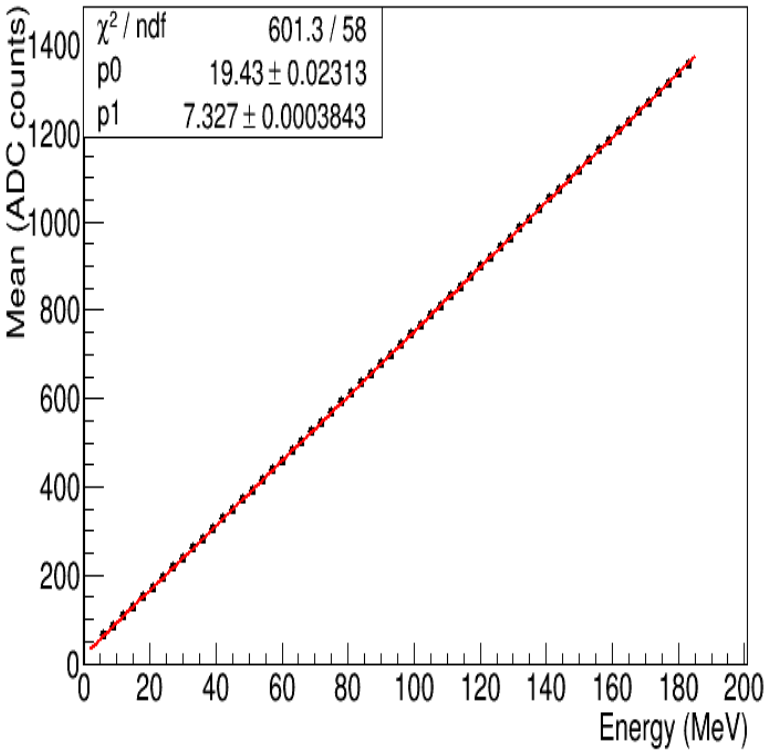
Detector response to a train of 32 pulses separated by 16 ns, which reproduces the temporal structure of the ELI-NP gamma beam.



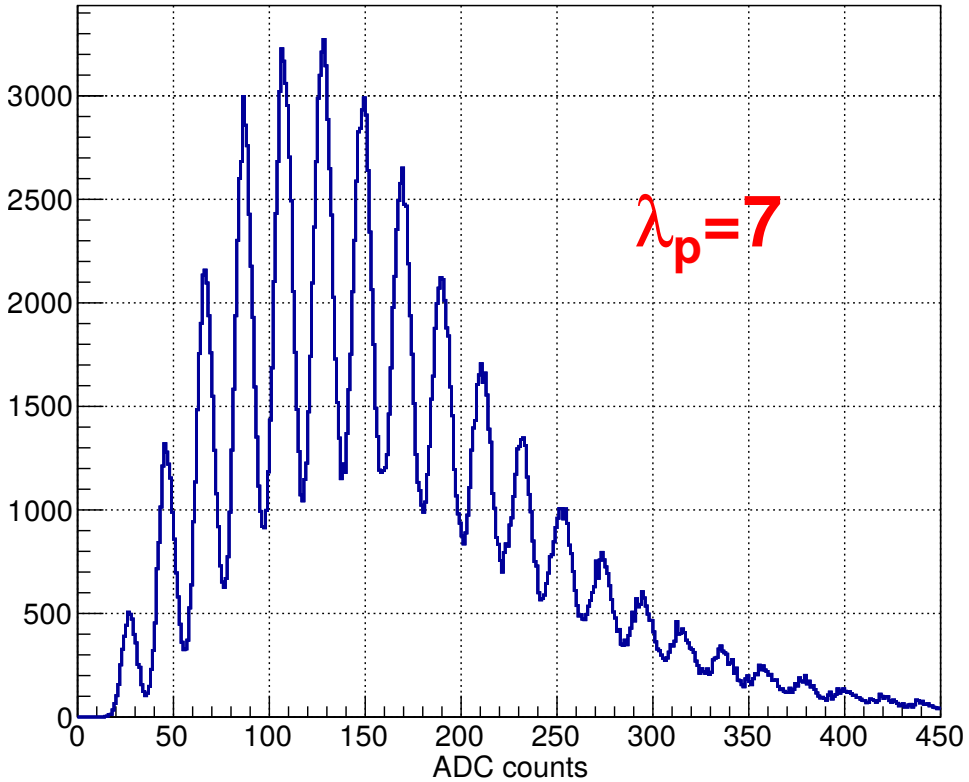
These tests prove the capability of our system to cope with the demanding time structure of the ELI-NP beam.

GCAL: Energy response

Test to verify silicon and electronics **linearity** has been performed at DEFEL facility at INFN-LABEC in Florence. A pulsed and intensity controlled **3 MeV proton** beam was used.



Spectra are fitted with Poisson distribution convoluted with a sum of Gaussian



Summary

- The beam characherization and monitoring of the ELI-NP γ beam parameters is a challenghing tasks.
- An overview of the four detectors composing the **characterisation system** has been presented:
  1. **Compton Scattering Spectrometer:** Energy distribution
  2. **Nuclear Resonant Scattering System:** Absolute energy calibration
  3. **Gamma Profile Imager:** Spatial distribution
  4. **Gamma Calorimeter:** Average energy and intensity
- All the sub-system have been designed and optimized from realistic simulations.
- Tests of each subsystem performed at INFN of Ferrara, Firenze and Catania have been reported.

Summary

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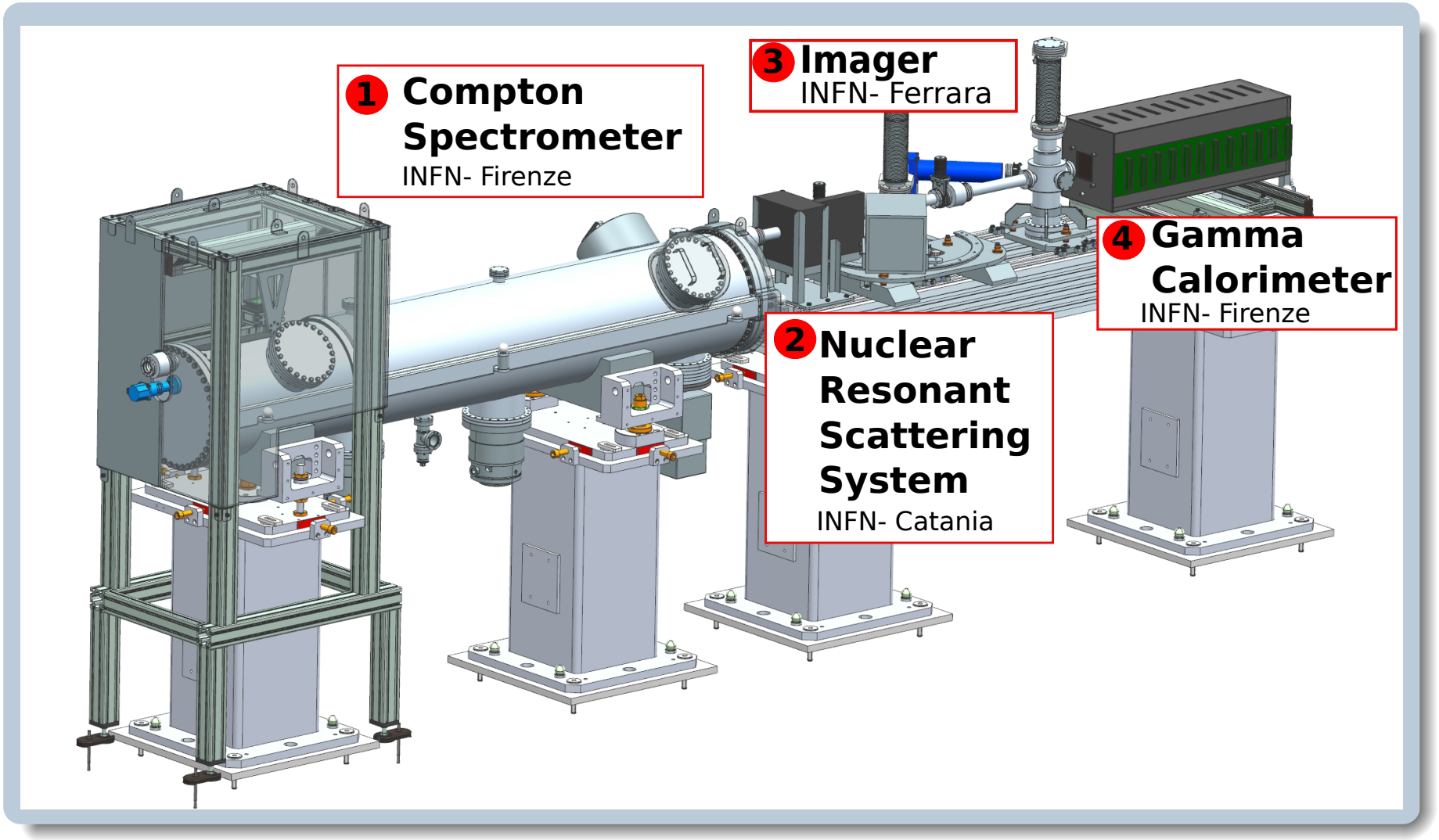
Next steps

Assembly the whole system for final tests in Ferrara.
Installation at ELI-NP Magurele, Bucharest.

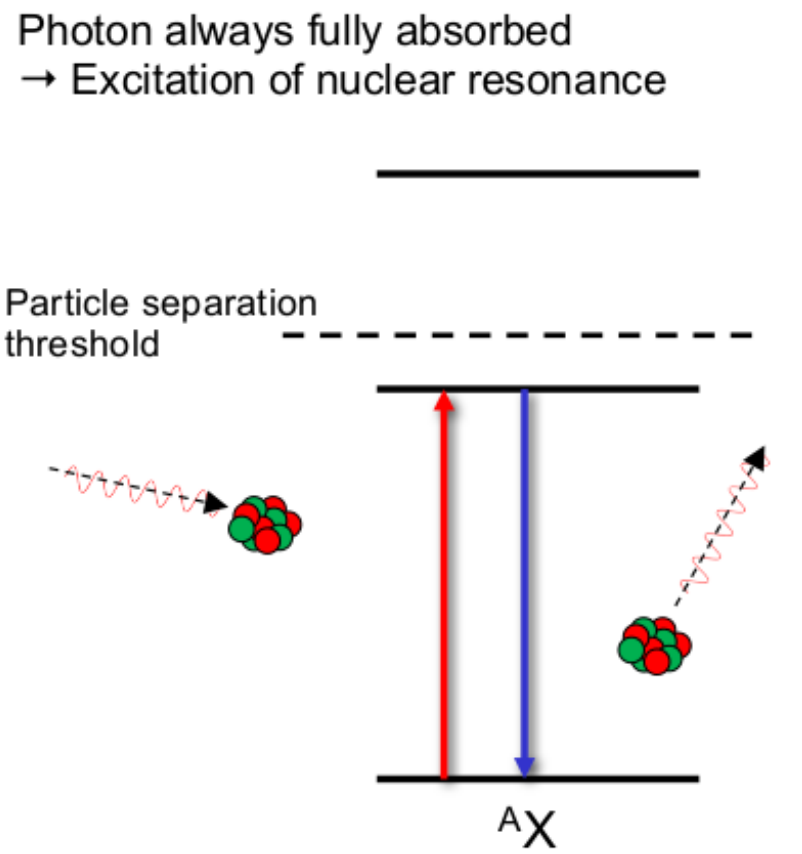

1 Compton Spectrometer
INFN- Firenze
3 Imager
INFN- Ferrara
4 Gamma Calorimeter
INFN- Firenze
2 Nuclear Resonant Scattering System
INFN- Catania

Why characterization of the γ beam is it important?

- A characterisation system providing the diagnostic of the γ beam is essential for the **commissioning and development** of the source.
- A precise energy calibration of the gamma beam and a continuous monitoring of its parameters (peak energy, energy and space profile, intensity...) during **operation** are also necessary.
- Given the unprecedented characteristics of the beam, these tasks are themselves an experimental challenge.

Nuclear Physics with ELI-NP γ beam

- **Nuclear Resonance Fluorescence (NRF) studies**

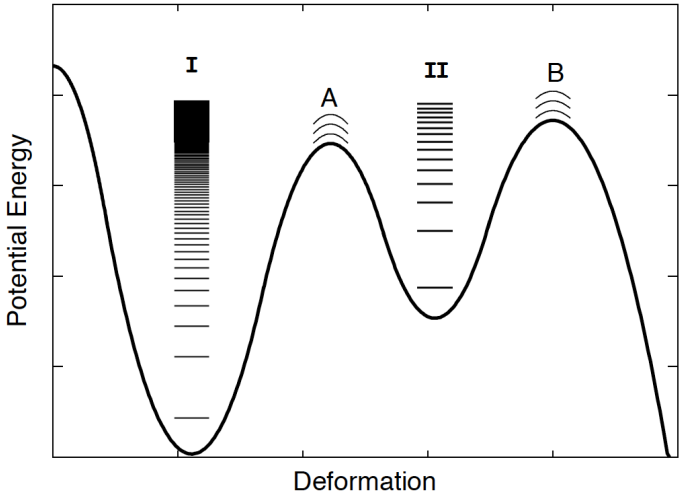


Nuclear Resonance Fluorescence
("Photon scattering")

- Connection of intrinsic level properties (width, spin, parity) to observables (cross section, angular distribution)
- By using electromagnetic probes to study nuclear structure the interaction is well-known and one can determine in a model indipenndent way the observables.
- The high brilliance of the gamma beam will provide an increase in sensitivity leading to a reduction of the material required for the target.

Nuclear Physics with ELI-NP γ beam

- **Studies of photo-fission**



- The ELI-NP γ beam provide a new-perspective for photofission research, as high-resolution studies become possible.
- In particular the investigations of the fission potential-barrier landscape in the actinide nuclei.
- Rare photofission events, such high-asymmetric fission or ternary fission will be investigated

- **Production of exotic nuclear beams in photofission**
  - Studies of neutron-rich nuclei, lying away from the valley of β stability, are the main topic of recent nuclear structure research.
  - Beams of such nuclei are produced with the isotope- separation on-line (ISOL) technique, or with the in- flight separation technique.
  - Photofission provides another possibility to create exotic nuclei in the laboratory.

Nuclear Physics with ELI-NP γ beam

- **Astrophysics studies**
  - Measuring capture reactions (astrophysical) by means of the inverse photodisintegration reactions (with the ELI-NP gamma beam), has the advantage of having different systematic uncertainties.
  - Nuclear astrophysics needs highly accurate measurements of small cross sections for nuclear reactions of the H and He burning processes in order to enhance the reliability of stellar evolution models and simulations.
  - Key reaction:$\gamma + {}^{16}\mathrm{O} \rightarrow {}^{12}\mathrm{C} + \alpha$
    The ratio between the abundances of carbon and oxygen (C/O) at the end of this stellar evolution stage has been identified remains today, as one of the main open questions in nuclear astrophysics.

Nuclear Physics with ELI-NP γ beam

- **Nuclear collective excitation modes**
  The brilliant ELI-NP γ-ray beam will open up new horizons for the investigation of the nuclear photo-response at and above the particle separation threshold.

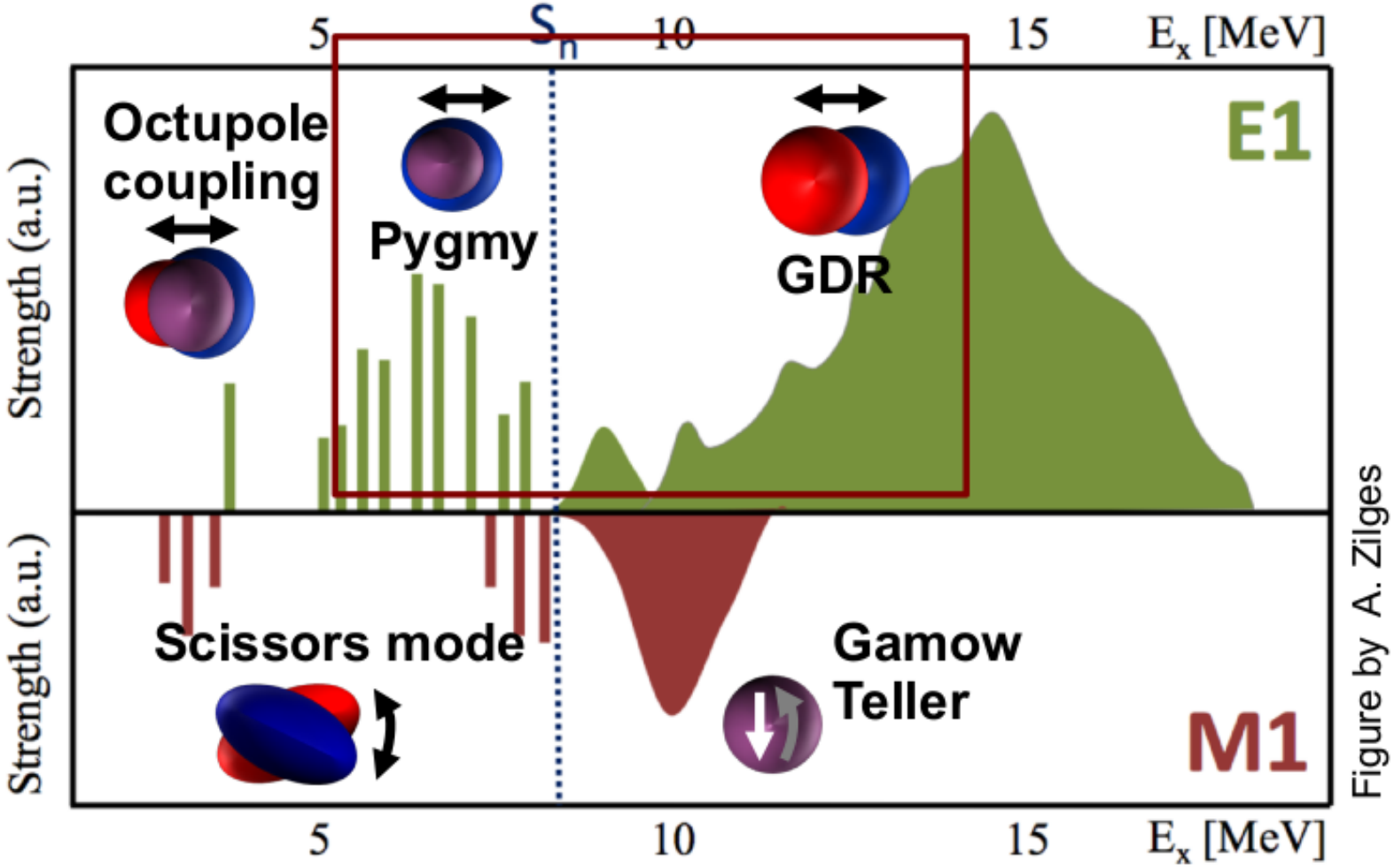
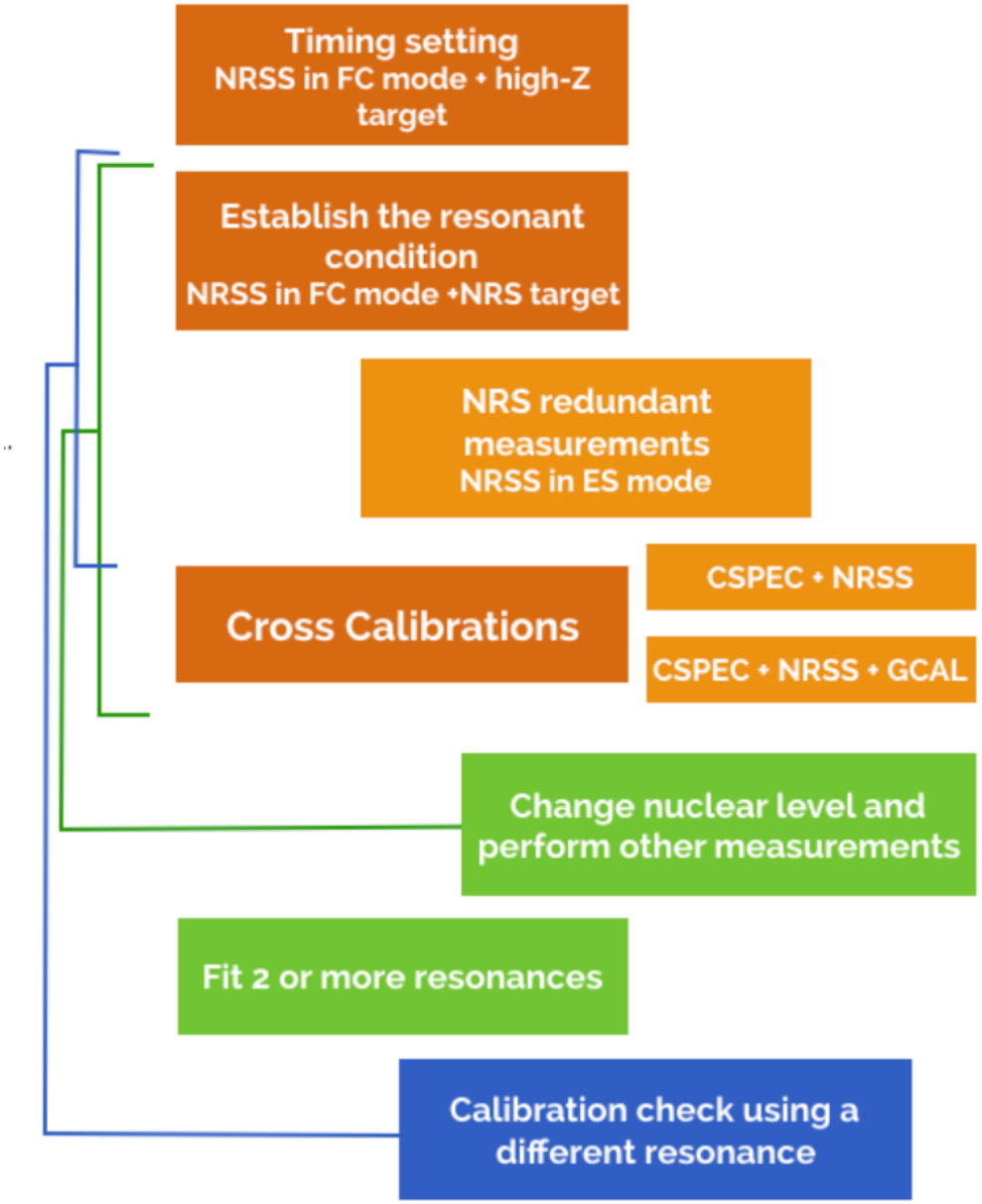


Figure by A. Zilges

Inter-calibration procedure



Establish the correct delay between the beam trigger and signal at detectors.

Scan the electron beam increasing and decreasing energy to find the resonance condition.

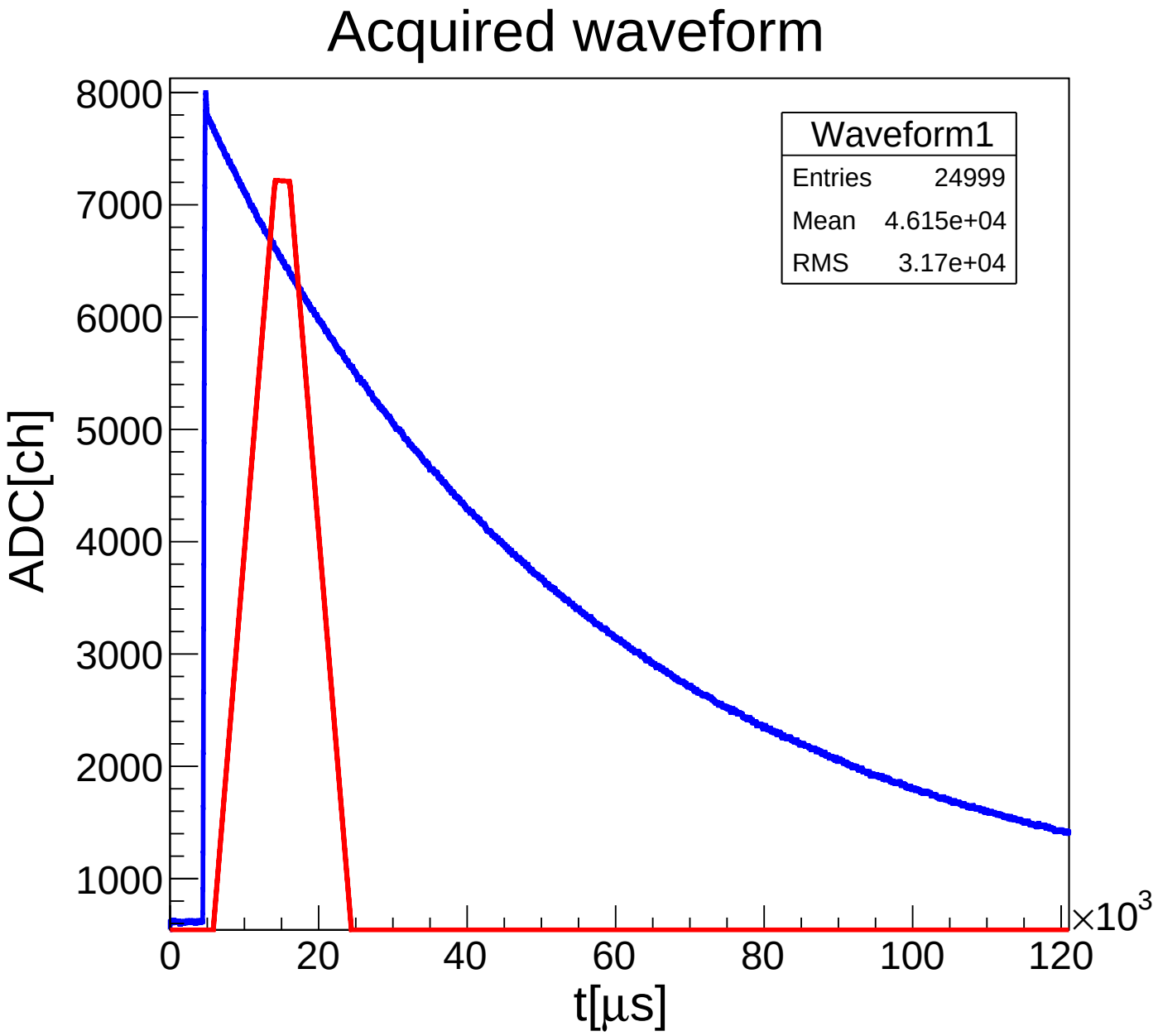
Signal region + AC shield = energy meas
Compton region = absolute intensity

Absolute calibration of the CSPEC

To reach good resolution in absolute intensity measurements.

Get the correlation law between electron beam and gamma beam energies.

HPGe Signal


Acquired waveform
Waveform1
Entries 24999
Mean 4.615e+04
RMS 3.17e+04
ADC[ch]
8000
7000
6000
5000
4000
3000
2000
1000
0
20
40
60
80
100
120
×10^3
t[μs]

Barium Fluoride

- The fast scintillation light is emitted in the UV in bands centered at 220 and 195nm. The decay time of the fast component varies between 600 and 800ps.
- The BaF_2 also emits a relatively slow scintillation component in a band centered at 310nm. The decay time of this component has an average value of 630ns.
- The ratio between the intensity of the fast and the slow scintillation components of BaF_2 depends on the ionizing power of the absorbed particle. That allows gamma discrimination and particle identification by pulse shape analysis.