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Gamma beam collimation and characterization system for ELI-NP-GBS

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ELI-Nuclear Physics (Magurele, Bucharest)

ELI-Nuclear Physics is a European research facility dedicated to the development of **laser** beams and the generation of **high-intensity gamma beams** for a broad range of science covering frontier fundamental physics, new nuclear physics and astrophysics, as well as applications in nuclear materials, radioactive waste management, material science and life sciences.

- High-power laser facility

- **Gamma beam source**
  - gamma beam **energy tunable between 0.2 MeV and 20 MeV**
  - energy resolution **$\Delta E/E < 0.5\%$**
  - 10^4 photons per pulse (1 ps) ~ **10^8 photons/s**

2013: International call for tenders for the realisation of the gamma source

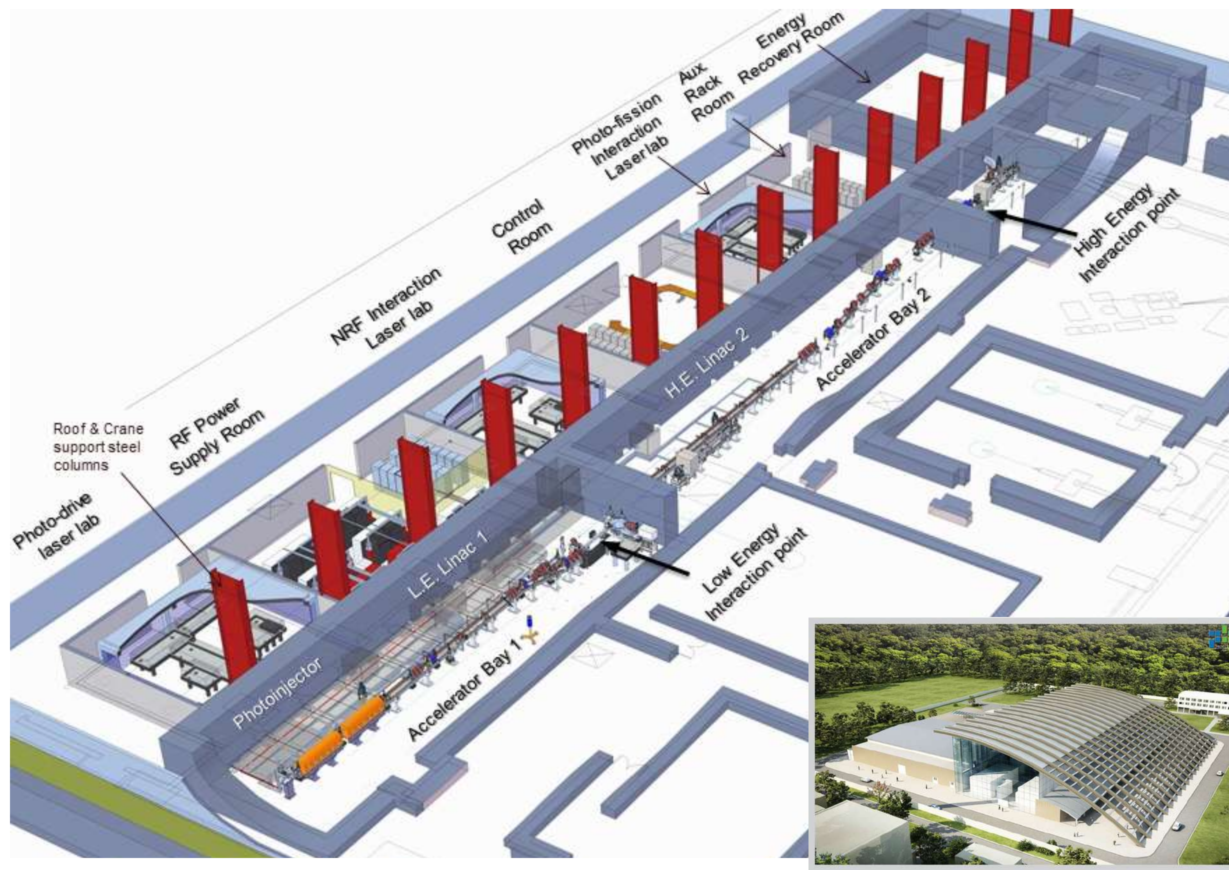
EuroGammas association

EuroGammaS Association is composed by:

- **Istituto Nazionale di Fisica Nucleare (leader)**
- Università degli Studi di Roma - La Sapienza
- Centre National de la Recherche Scientifique CNRS
- Industrial partners: ACP, Alsyom, Comeb, ScandiNova
- Subcontractors: STFC, M+W, Amplitude

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

EuroGammaS will provide the **design, manufacturing, delivery, installation, testing, commissioning and maintenance** of a Gamma Beam System (GBS) based on **inverse Compton** scattering, for the benefit of the ELI-NP project, managed by the Horia Hulubei National Institute for Physics and Nuclear Engineering Bucharest in Magurele, ROMANIA.



WP09 Gamma beam collimation and characterization

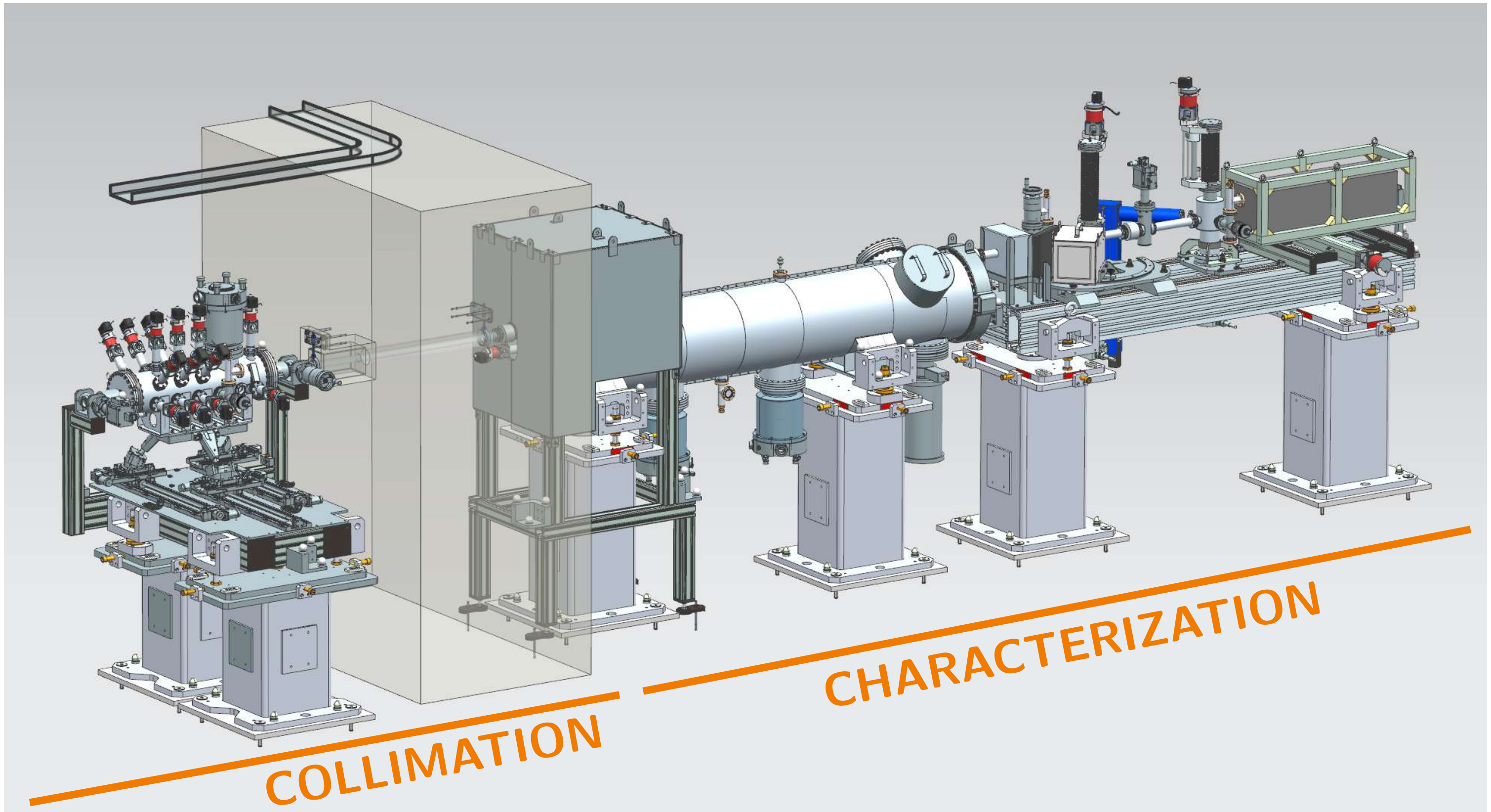
- **Collimation**

  → Provide the required energy bandwidth

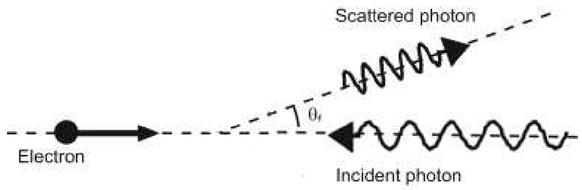
- **Characterisation**

  → Diagnostic for commissioning phase

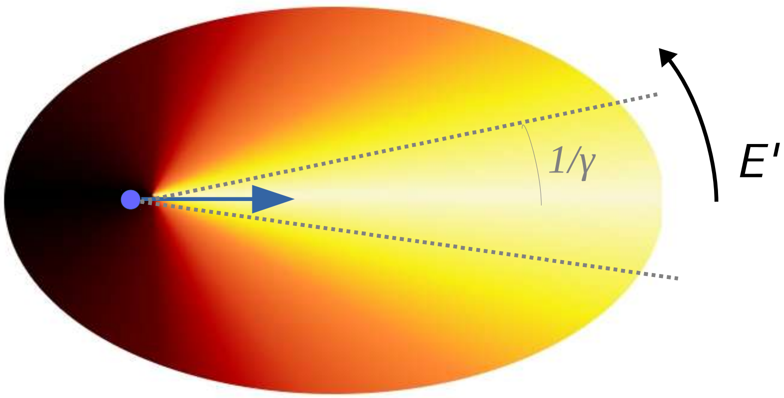
  → Evaluate and demonstrate the gamma beam performance.

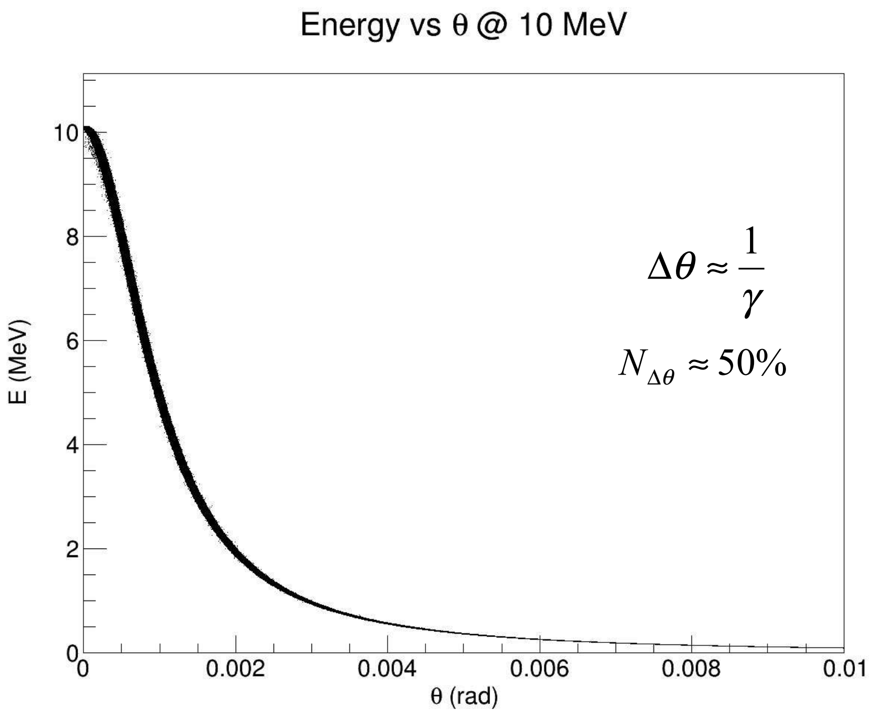


Inverse Compton



$$E'_\gamma = h\nu' \simeq E_\gamma \frac{4\gamma^2}{1+\gamma^2\theta^2}$$

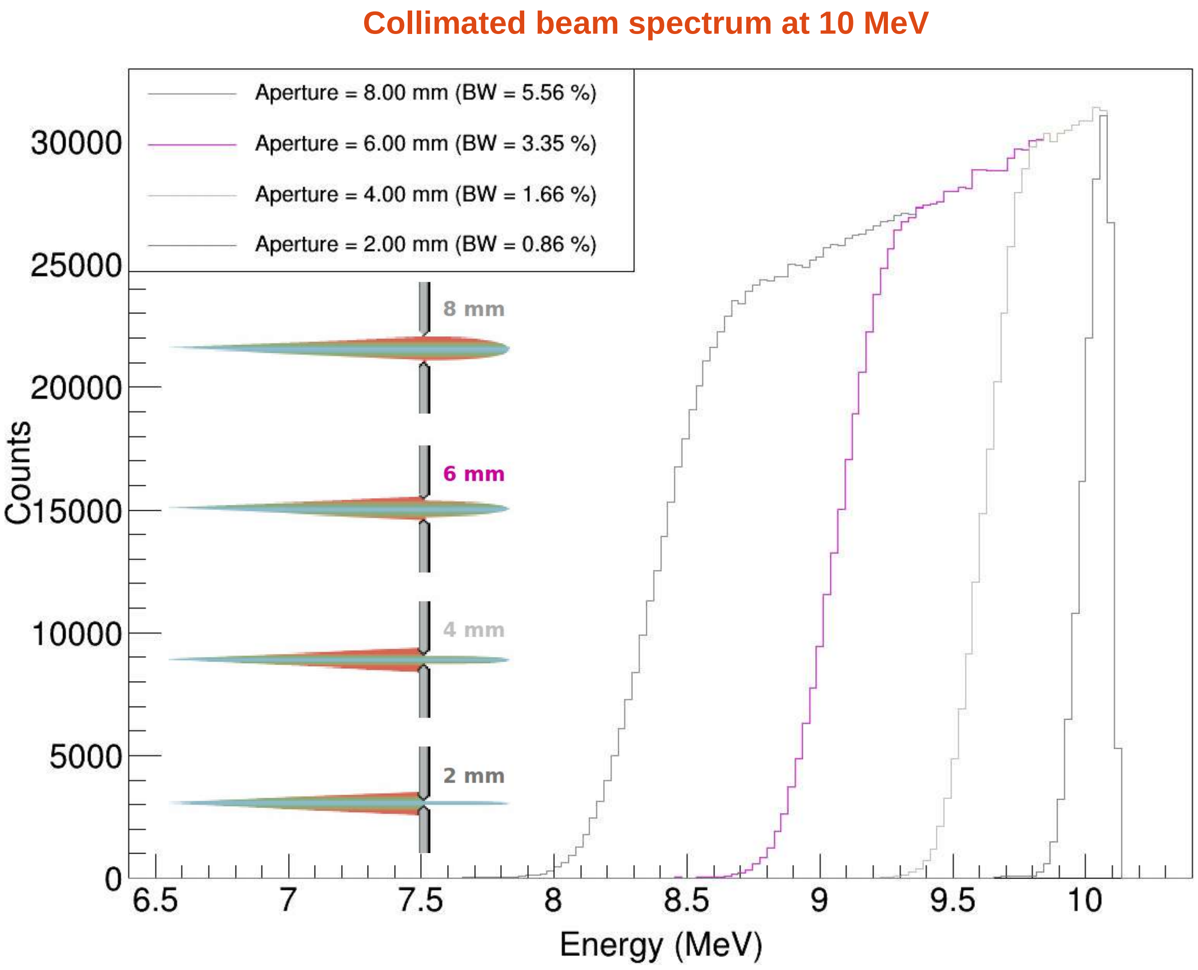


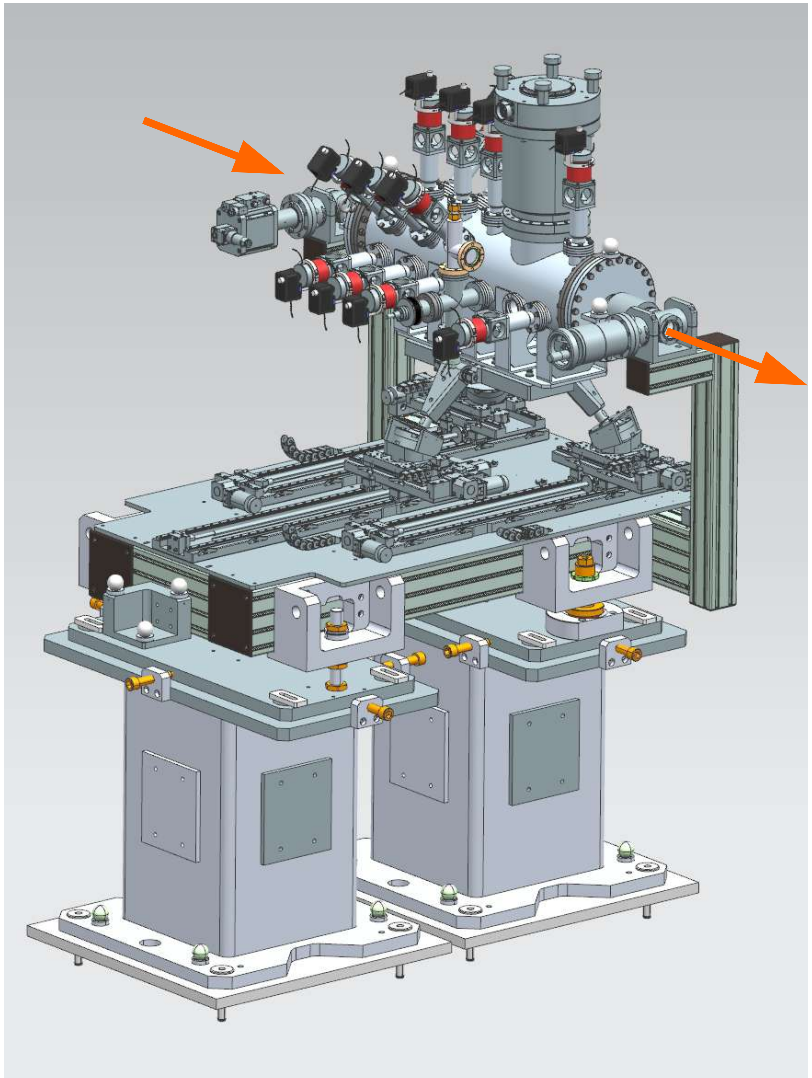


- Along the **backscatter** direction the **energy of incident photon** is multiplied by a **factor $4\gamma^2$**
- The angular distribution of e**mission is peaked on a cone** proportional to **$1/\gamma$**
- Energy decreases as the emission angle increases → **energy bandwidth determined by angular acceptance**

Collimation system - GCOLL

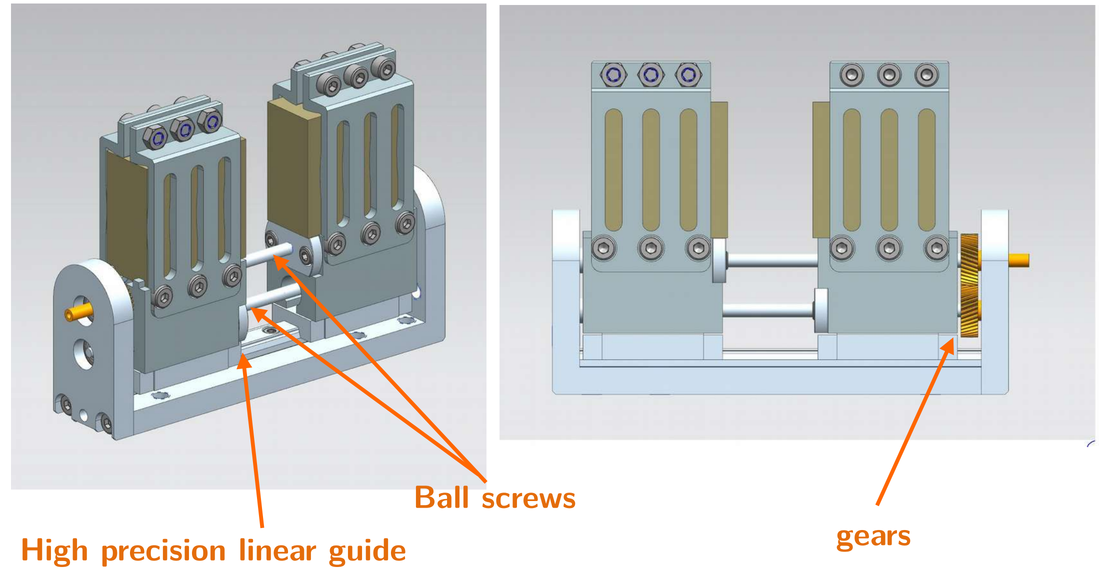
- Bandwidth < 0.5 % at 0.2-20 MeV → **700 – 70 µrad divergence** is needed → very challenging design.
- Collimation **apertures range** ∼ **1-10 mm**, depending on the beam energy **(continuously adjustable)**

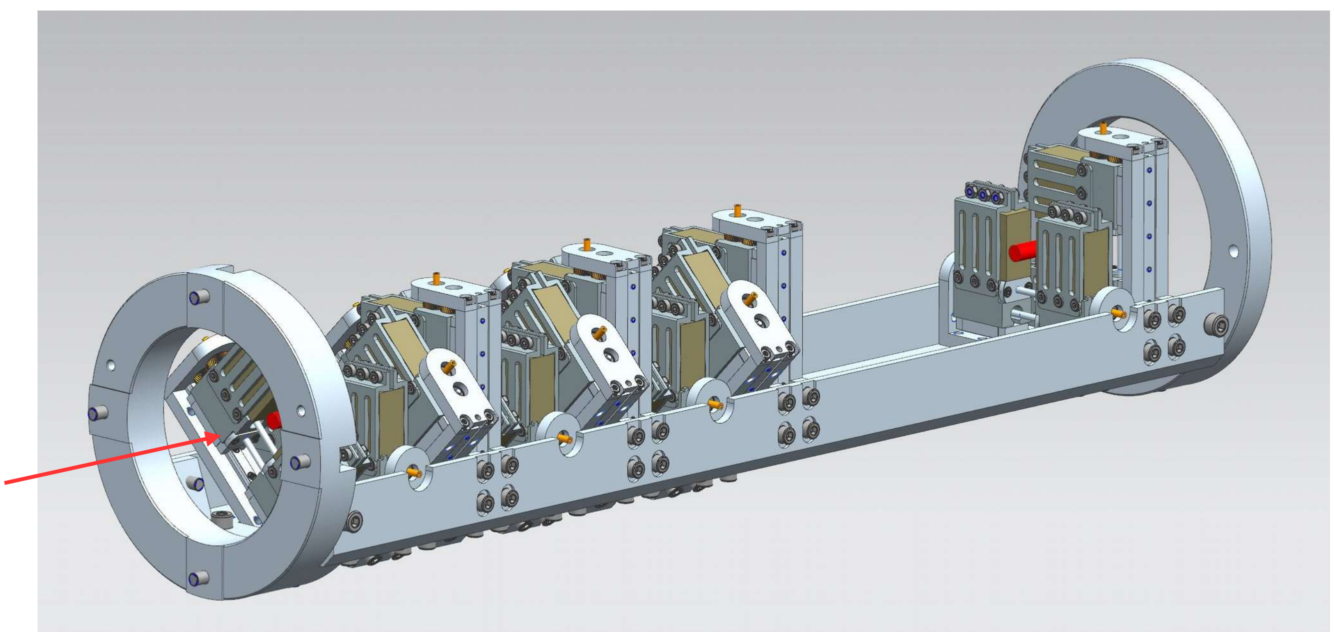


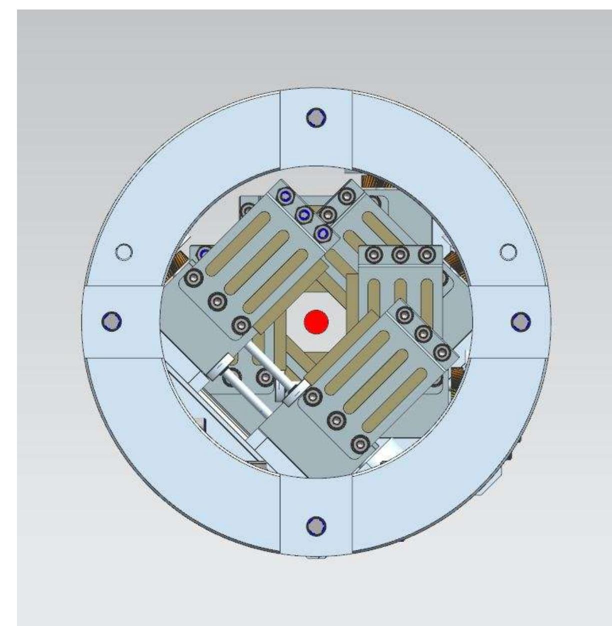


Collimation system – linear slits

- **Stack of 14 slits with aperture independently adjustable (0-25 mm)** mounted on a high precision frame.
- Each slit composed of 2 **blocks 40 x 40 x 20 mm made of a 97% W alloy** (2% Ni, 1% Fe) with surface roughness < 5 µm.
- **3 groups of** 4 slits each with a relative rotation of 45° around the beam axis.

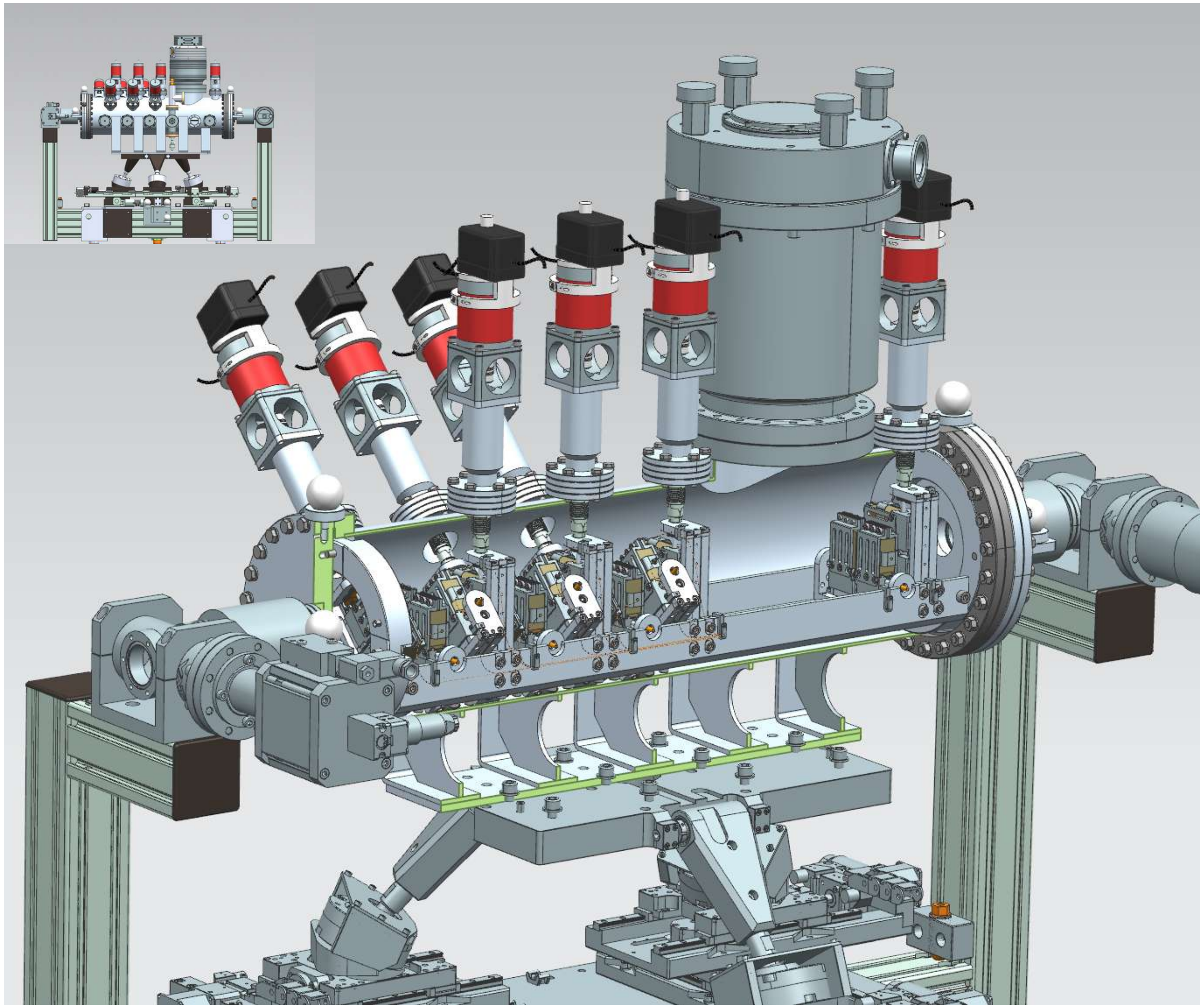


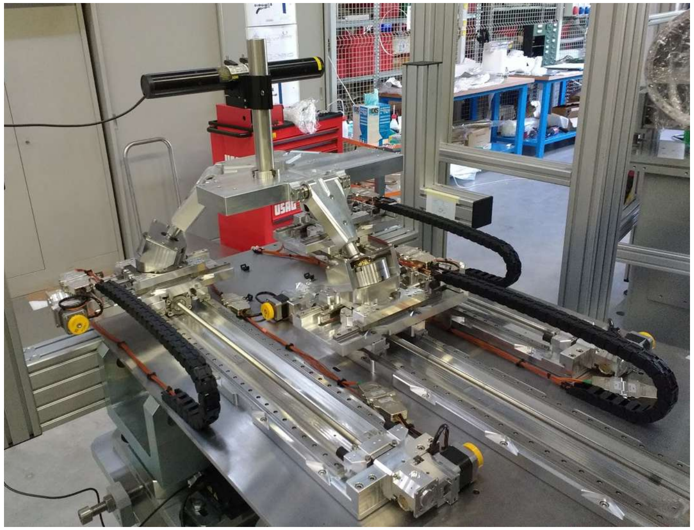




Collimation system – vacuum chamber and positioning system

The collimator frame is inserted in a **UHV vacuum chamber**, equipped with 14 rotative feed-through to transmit the rotation from the outside motors

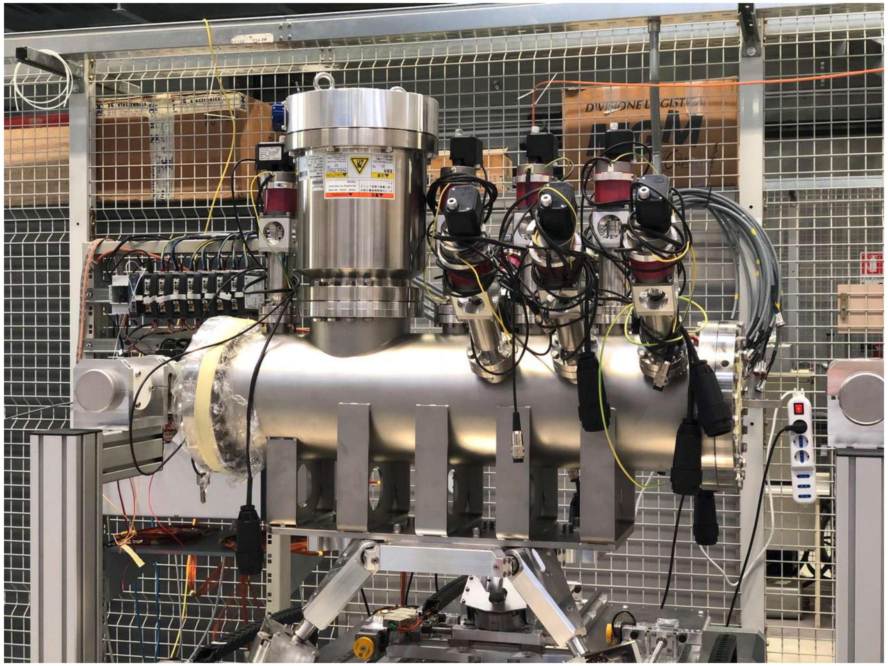




The entire system is mounted on top of a Spacefab (PI-MICOS) positioning system:

- High precision 6 degree of freedom
- Radiation-hard
- Position self-locking
- Low acceleration, jerk-free (even if malfunctioning)

Collimation system – Assembly at Ferrara laboratory



G.釀Paternò et al. A collimation system for ELI-NP Gamma Beam System – design and simulation of performance**,** Nucl. Instrum. Meth. B, 402, pp. 349-353 (2017)

Cardarelli, P. et al. Monte Carlo simulation of a collimation system for low-energy beamline of ELI-NP Gamma Beam System**,** Nucl. Instrum. Meth. B 355 (2015)

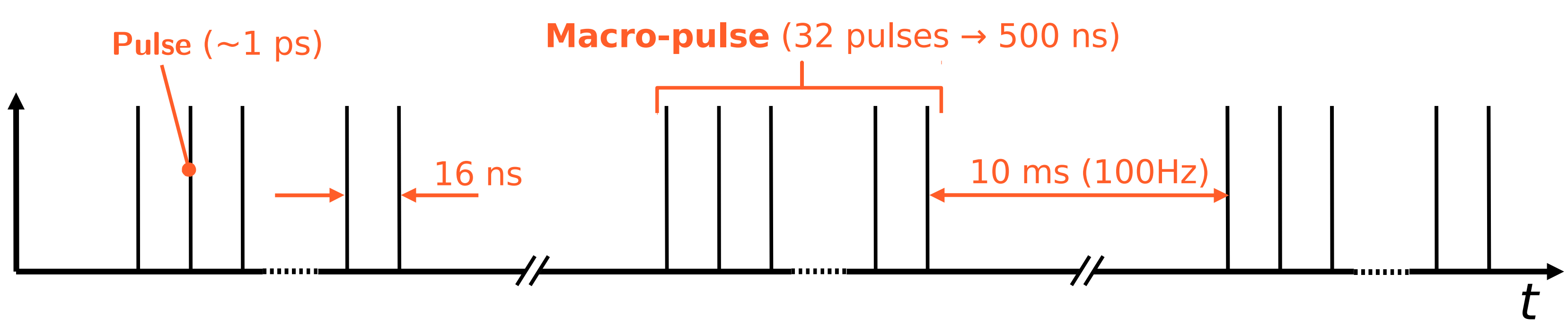
Gamma beam characterization

Characterization main goals:

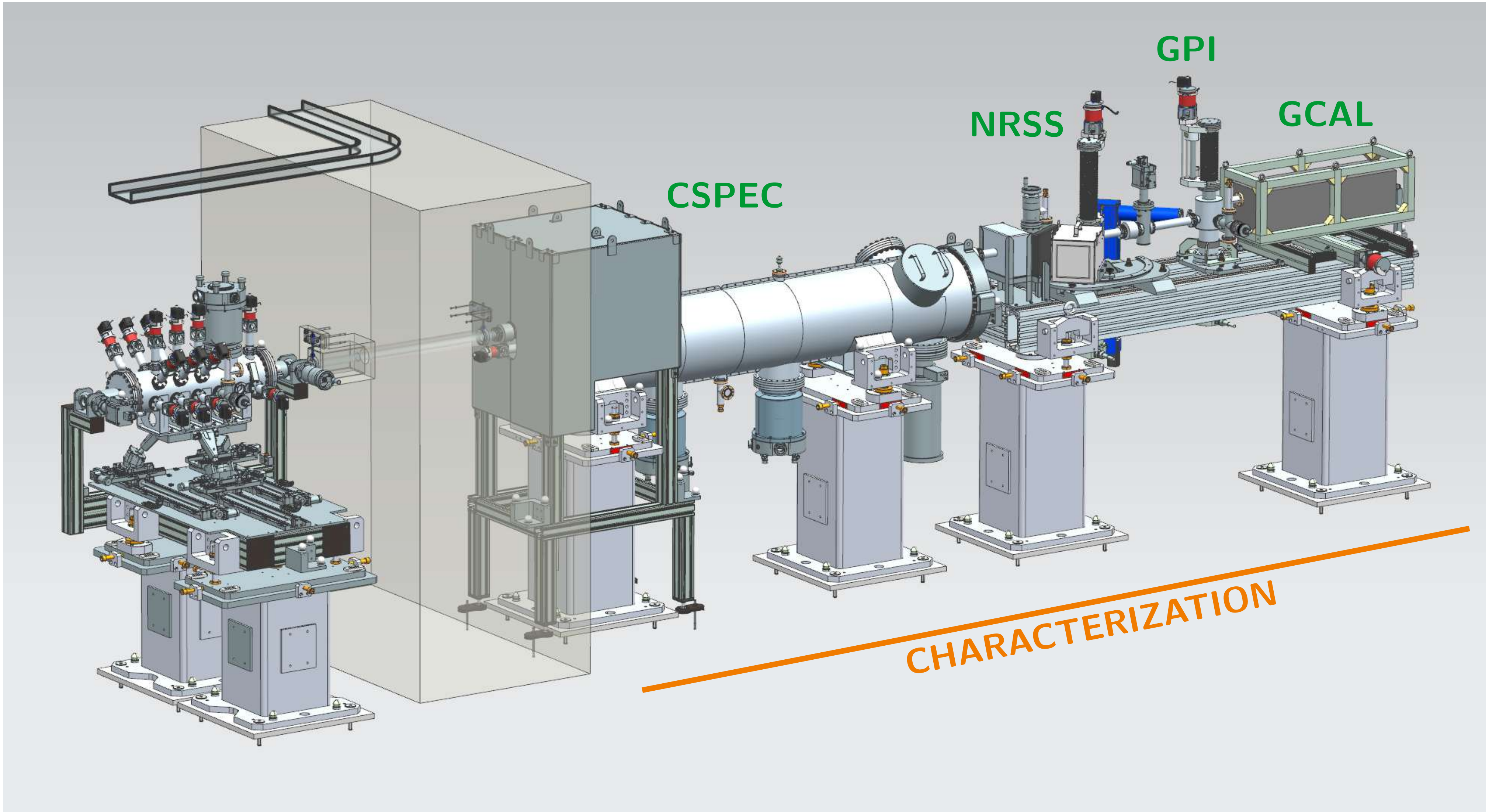
1) Measurement of the gamma beam **energy distribution (mean energy and bandwidth)**
2) Measurement of the **number of photons** per pulse
3) Measurement of the size and **spatial distribution** of the gamma beam

- Time structure and high number of photons per pulse **do not allow to use traditional spectrometry techniques**
- It is not possible to disentangle the detector response to each single photon within a pulse

- **Alternative and new solutions for the energy distribution measurement** have been developed



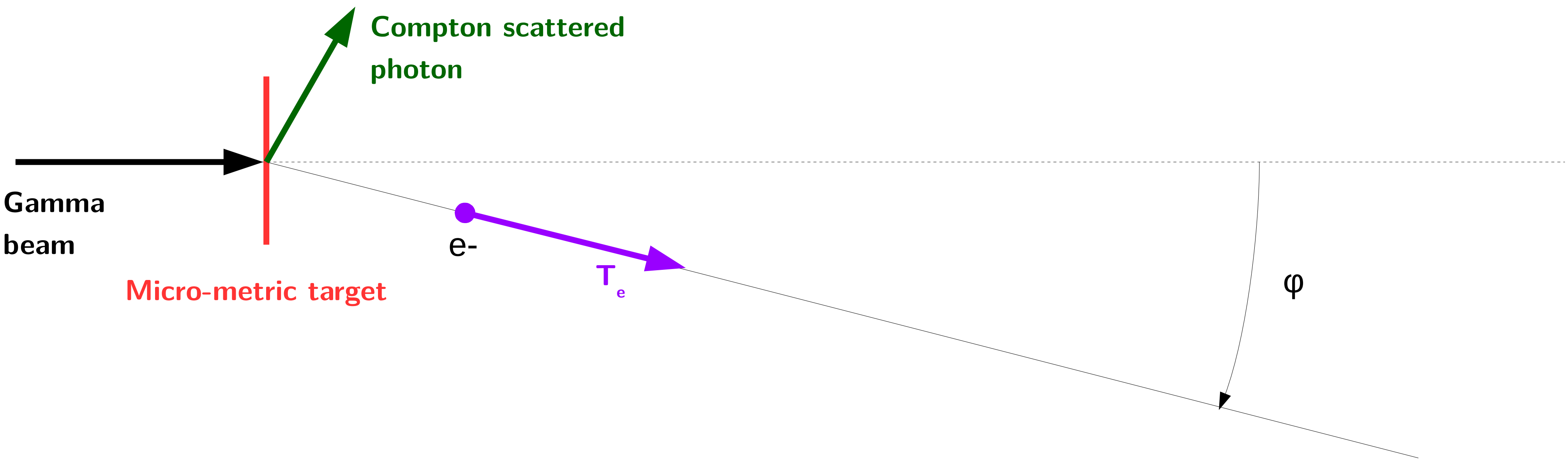
Characterization overview



Compton Spectrometer (INFN-Firenze)

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 micro-metric target (1-100 µm)

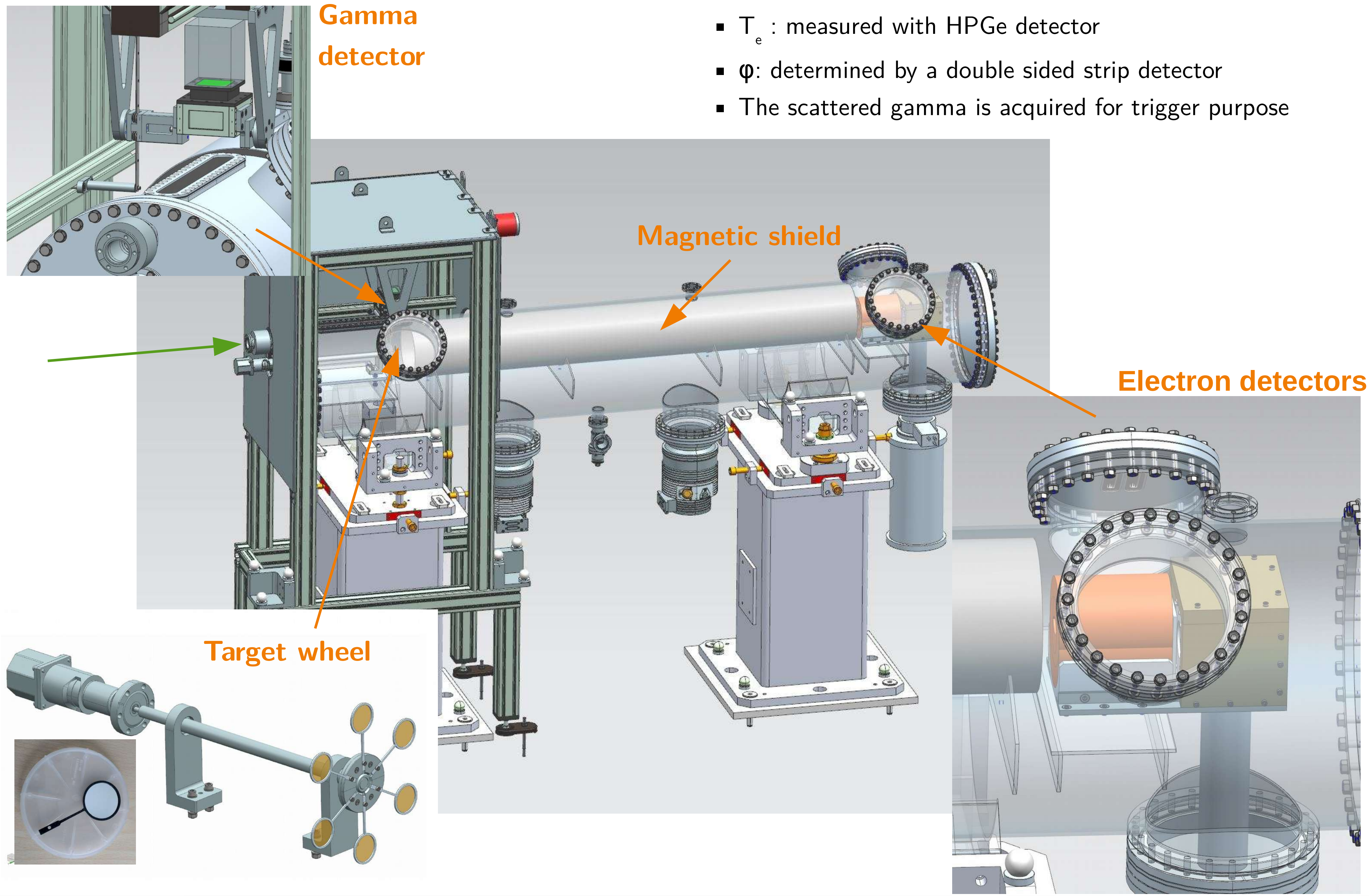
$$E_{beam} = \frac{m_e \cdot T_e}{\cos(\varphi)\sqrt{T_e \cdot (T_e + 2m_e)} - T_e}$$



- Non-destructive
- Spectrum over time integration of many macro-pulses (100 Hz)

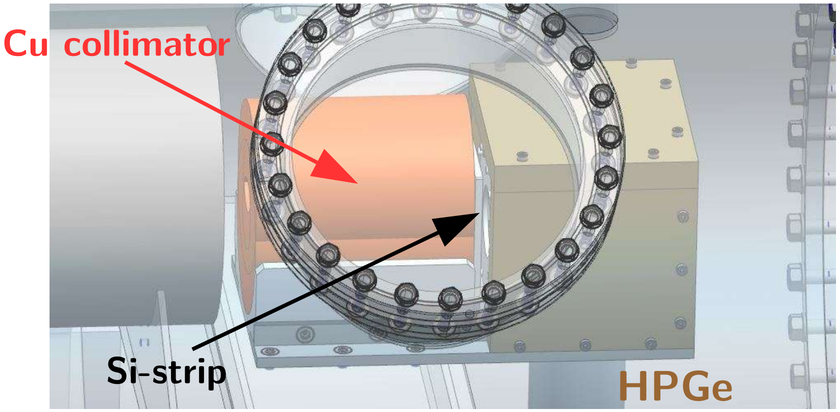
Compton spectrometer

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

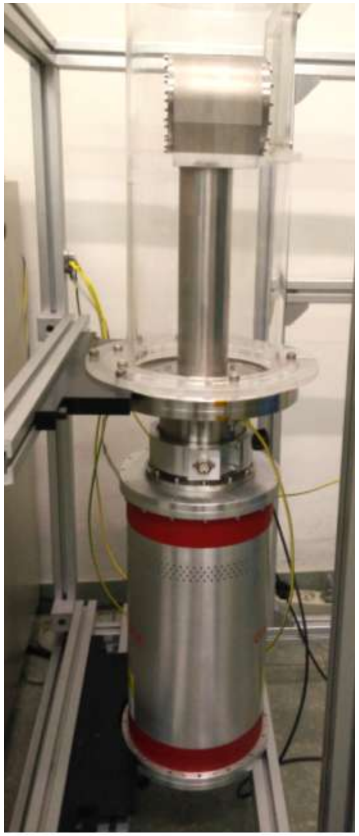


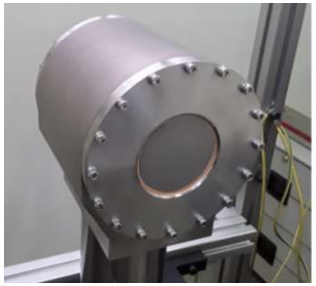
CSPEC – Electron detectors

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



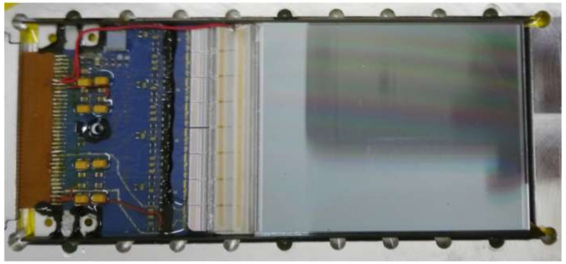
- HPGe planar custom configuration by CANBERRA:
  - 80 mm, diameter
  - 20 mm, thickness
  - electrically cooled
  - E res. 0.15% @ 1332 keV





- To minimize the energy-loss at entrance:
  - 100 µm, cryostat Be-window
  - ≤ 1µm, electrical contacts

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

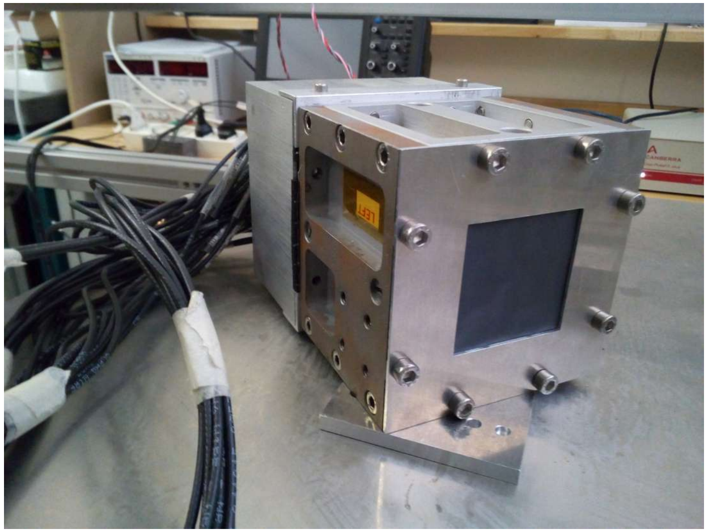


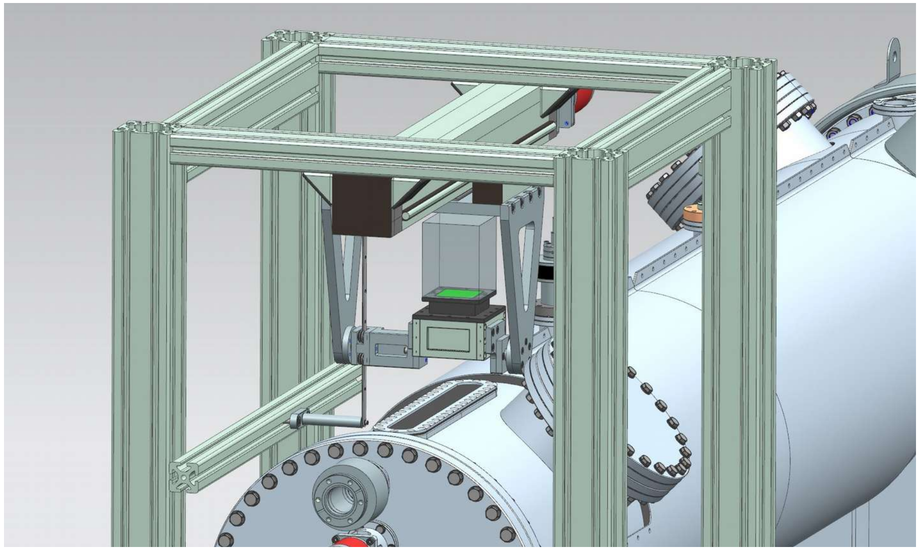
Silicon strip produced by Hamamatsu

- 5.33×7 cm^2
- 300 µm thickness
- 1024 strips for each side
- Impact point resolution: ~10 µm

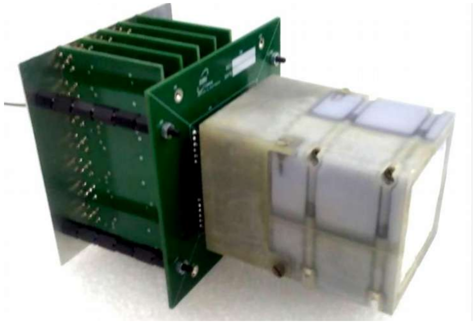
CSPEC – Gamma Detector

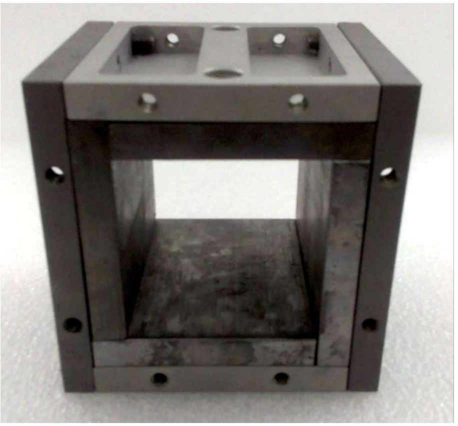
The scattered photon is detected, in coincidence with the electron, by BaF_2 crystals to provide a trigger for the CSPEC data acquisition. This coincidence is very effective in suppressing the background





- 4×4 BaF_2 crystals ($1.2 \times 1.2 \times 5$ cm^3)
- Read out by a multi-anode PMT HAMAMATSU (mod. H12700)
- BaF_2 has two scintillation components:
  - fast: $\tau = 0.6 - 0.8$ns
  - slow: $\tau = 630$ ns





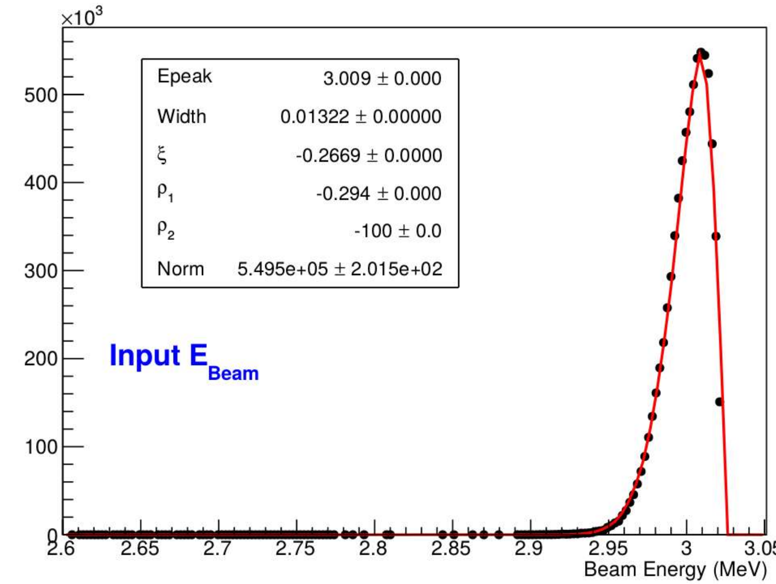
Compton spectrometer

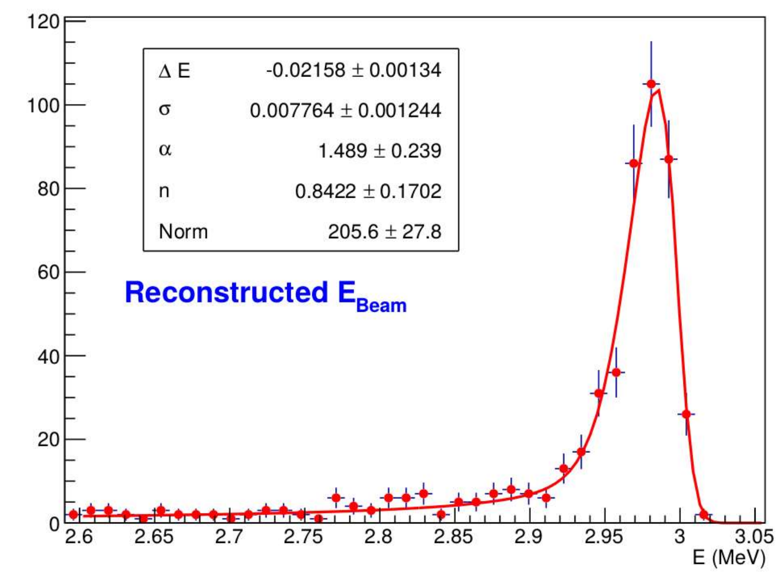
Reconstruction of spectrum from **detailed simulation of 100 s acquisition in the case of 3 MeV beam**

→ peak energy measured within 0.7%

(energy loss in Si-strip, Be window and HPGe dead layer)

→ detector resolution on bandwidth ~ 0.25%

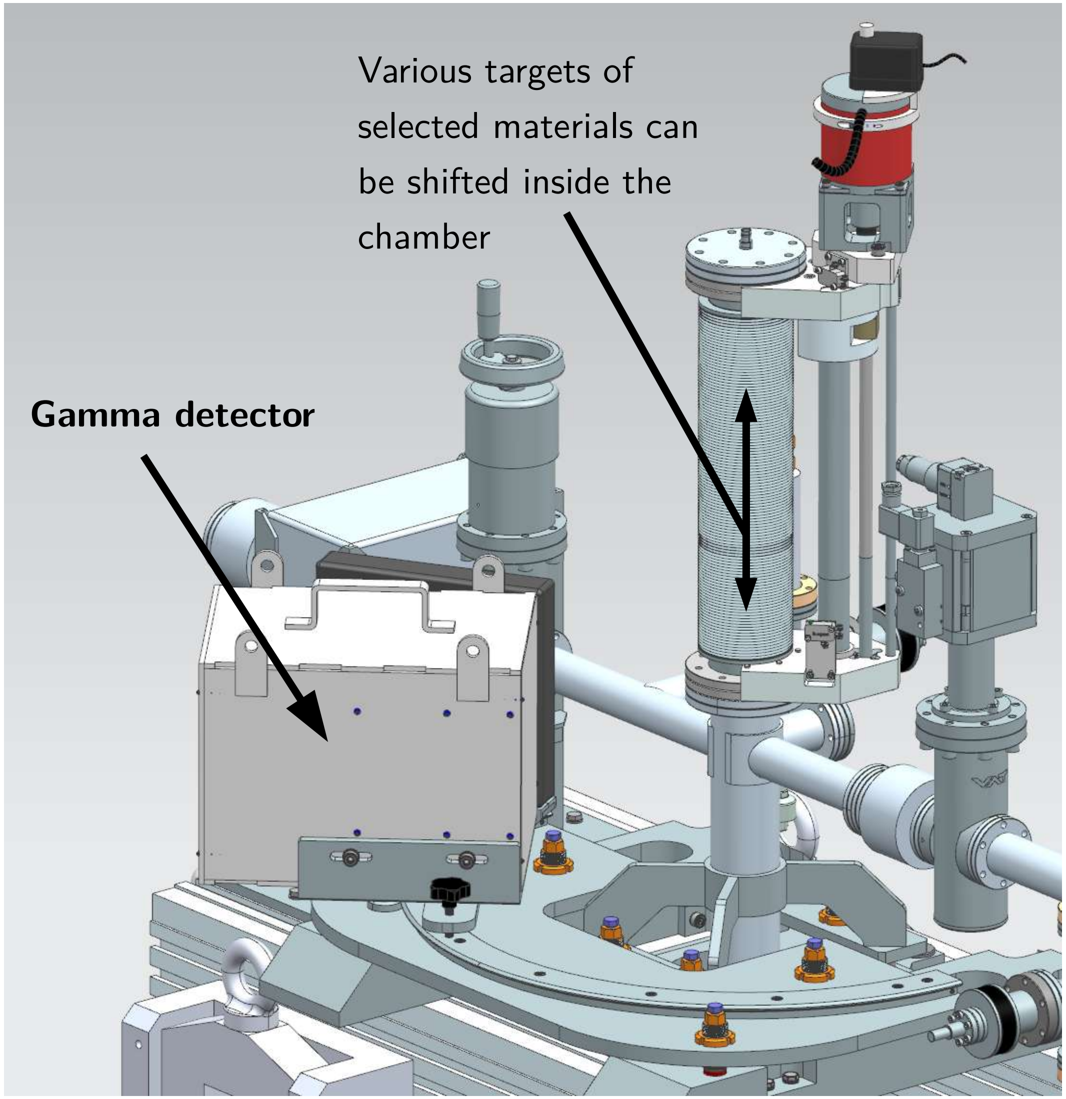


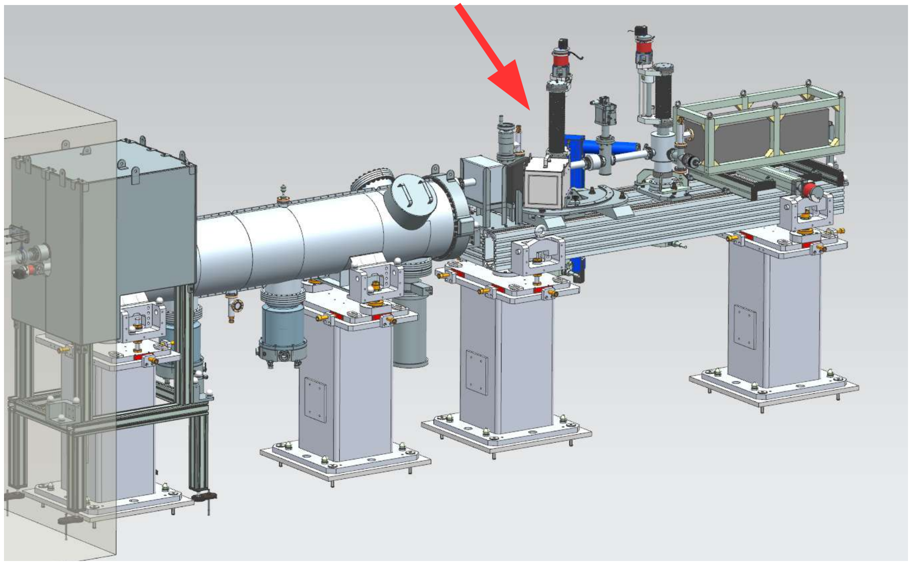


A Compton Spectrometer to monitor the ELI-NP beam energy R. Borgheresi et al. PM2018 -14th Pisa Meeting on Advanced Detectors,NIM-A proceedings (in review)

NRSS – Nuclear Resonance Scattering System

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





^{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	$5 \cdot 10^{-5}$

Many different resonance levels suitable for operation have been individuated and their signal has been simulated together with possible background sources from inside and outside the beam line.

NRSS – Gamma detector (INFN-Catania)

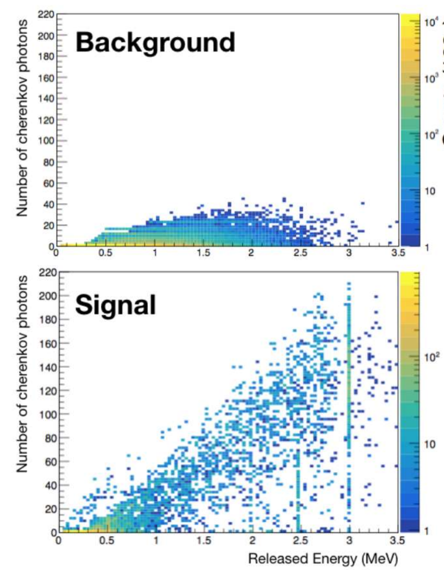
The NRSS gamma detector is made of a shielded array of four BaF_2 crystals ($5\times5\times8$ cm^3) surrounding a LYSO crystal ($3\times3\times6$ cm^3)

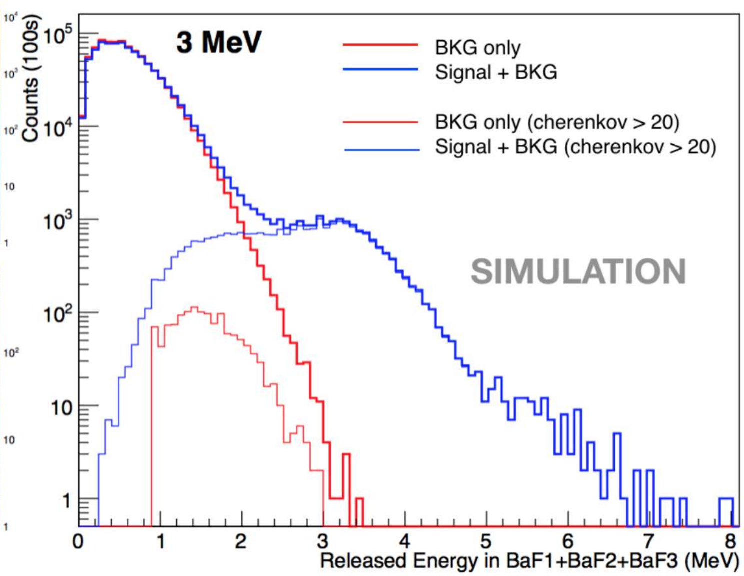
Two operation modes

- **Fast Counting mode**: 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_2act as Compton shield.

Main bkg source: Compton scattered beam γ at the NRS target → NRSS in backward region (θ = 135°) to move away from signal energy region.

A dual readout of Cherenkov (~300 keV threshold for emission by electrons) and scintillation light is foreseen for BaF_2 crystals and shows good capabilities in the reduction of fake signal and of effects due to possible background pile-up.





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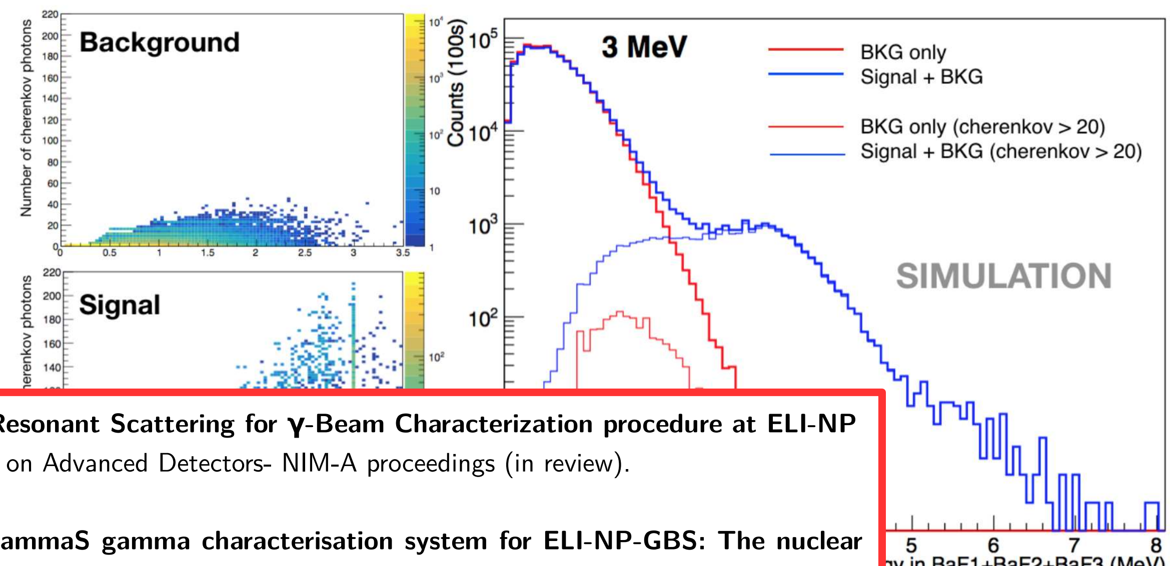


A dual readout of Cherenkov (~300 keV threshold for emission by electrons) and scintillation light is foreseen for BaF_2 crystals and shows go[...] reduction of fake signal and of [...] background pile-up.

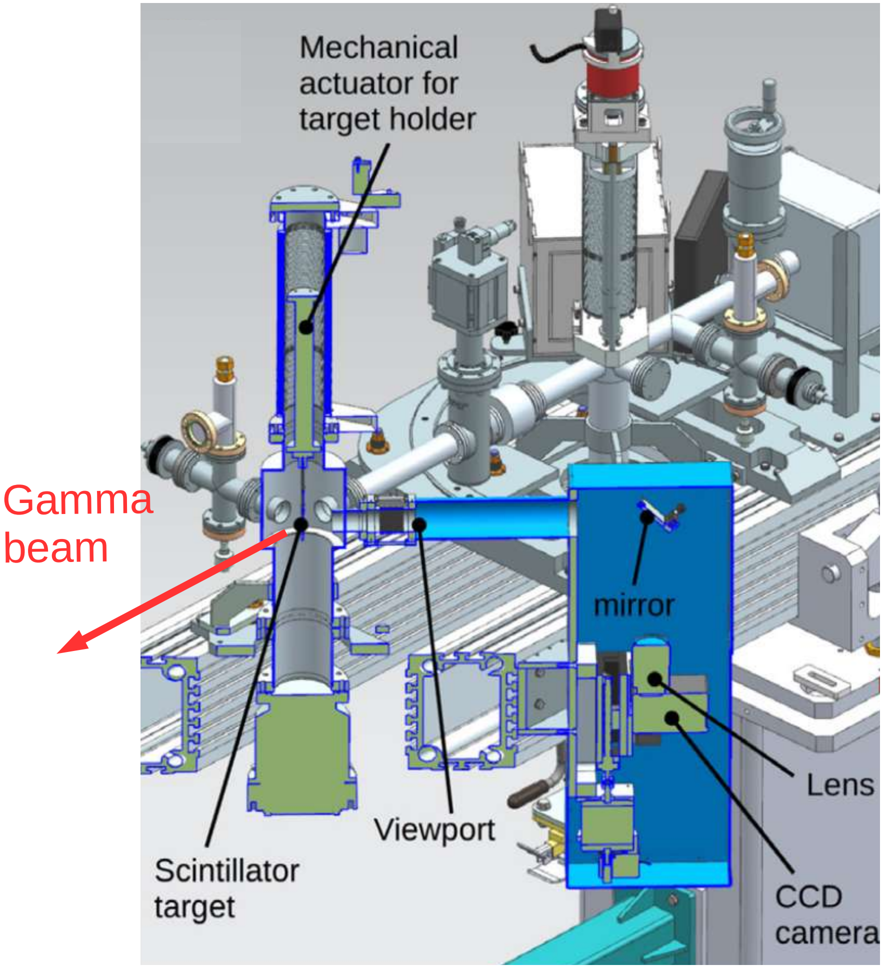
G. Cappello et al. **Nuclear Resonant Scattering for γ-Beam Characterization procedure at ELI-NP** PM2018 -14th Pisa Meeting on Advanced Detectors- NIM-A proceedings (in review).

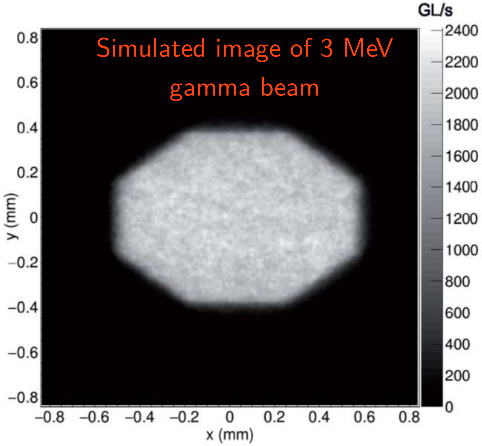
M.G. Pellegriti et al. **EuroGammaS gamma characterisation system for ELI-NP-GBS: The nuclear resonance scattering technique** Nucl. Instrum. Meth. A, 865, pp 60-62 (2017)

GPI Gamma Profile Imager

Gamma profile imager → image of the spatial distribution of the gamma beam

Thin scintillator target (LYSO) placed at 45° on beam → viewport and optics to focus the scintillation light onto a CCD





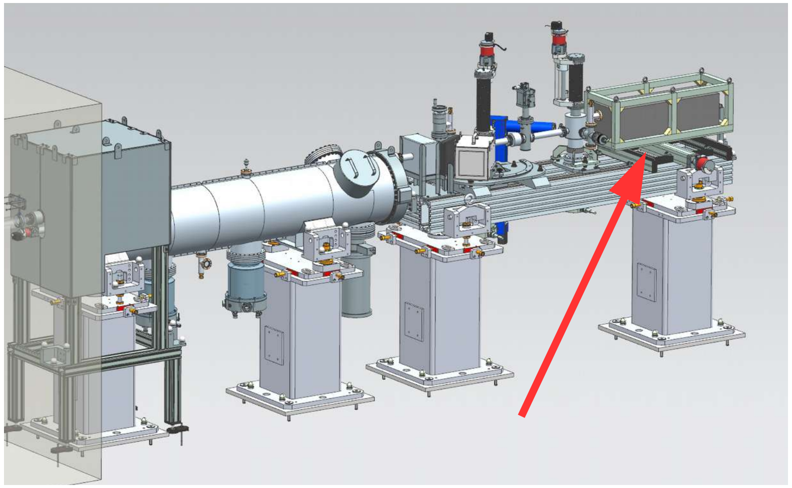
- To predict the **detector response a model was developed** using a combination of Monte Carlo and ray tracing
- **Detailed simulation** with realistic parameters **tuned by measurement** using x-ray tubes and gamma sources → **expected signal** on ELI-NP beam

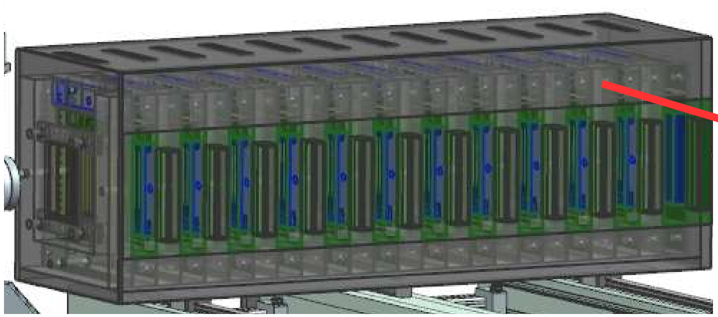
P. Cardarelli et al. **A gamma beam profile imager for ELI-NP Gamma Beam System**
Nucl. Instrum. Meth. A, 893, pp. 109-116 (2018)

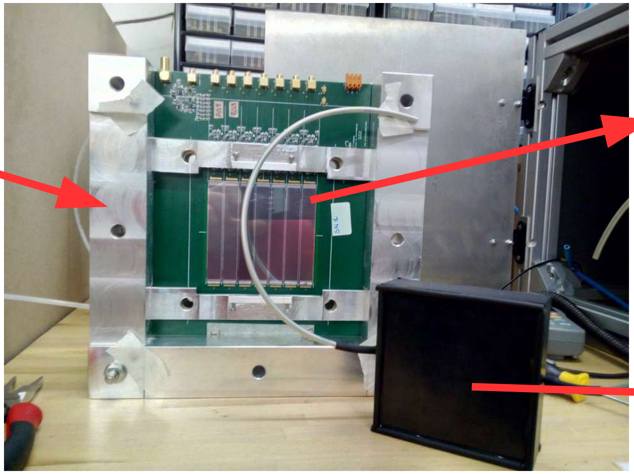
Calorimeter – GCAL (INFN-Firenze)

The calorimeter provides a fast destructive measurement of the beam average energy and intensity

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





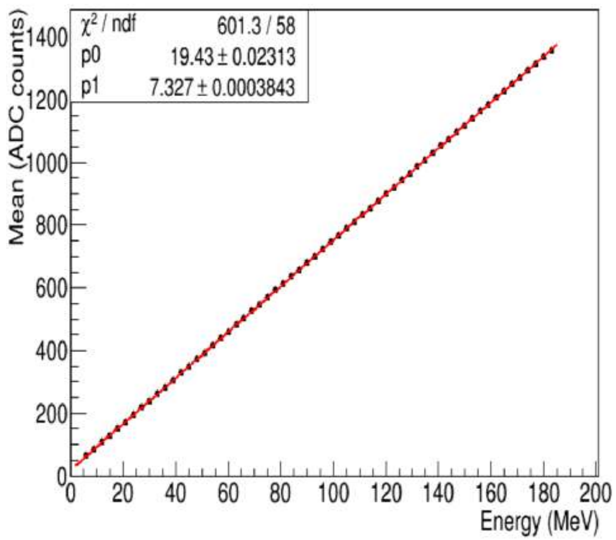


Si-strip
- test structure of the CMS tracker detectors, developed by Hamamatsu

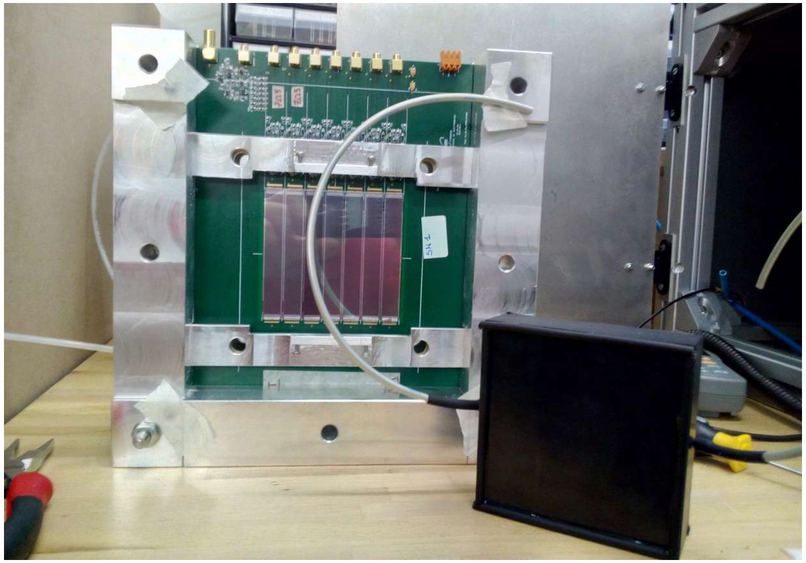
PE absorber
- 3 cm-thick
- 8.8×8.8 cm^2

Calorimeter – Si-strip detector

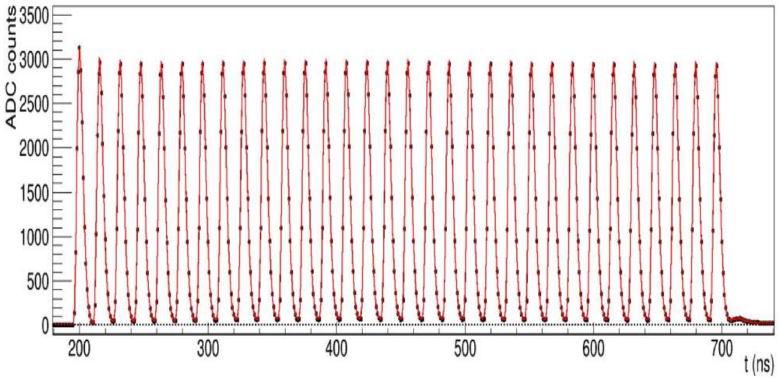
- Fast response
- Radiation hardness: can sustain up to 100 kGy irradiation
- Linearity
- 10.32×80.0 mm^2 active area
- 320 µm thickness
- Si-strip sensors bonded together.
- Custom electronics



- The **boards were tested** at the LABEC facility in Firenze
- The linearity of the system was tested up to 200 MeV of energy release using protons and up to 500 MeV using a pulsed laser.



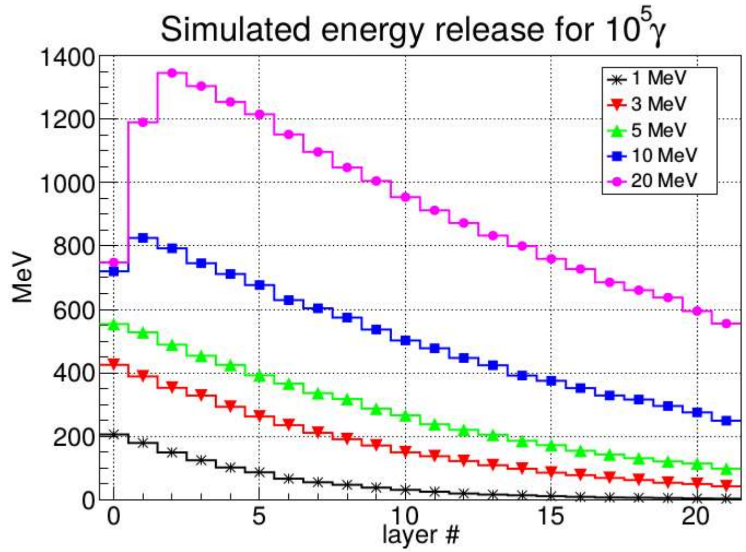
Detector response to a train of 32 pulses separated by 16 ns, which reproduces the temporal structure of the ELI-NP gamma beam.

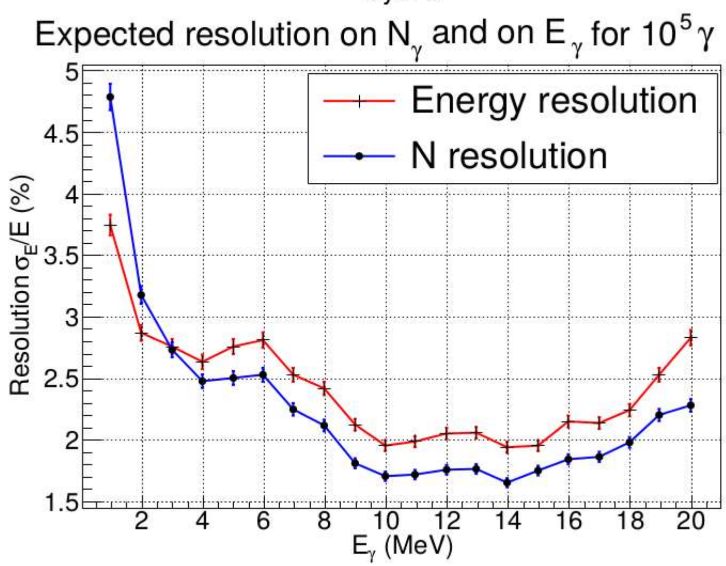


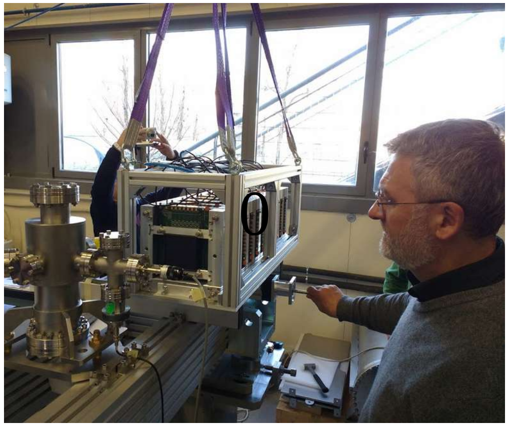
Calorimeter – expected results

Simulation of a single beam pulse ($10^5 \gamma$): a few percent resolution can be achieved in the whole energy spectrum.

These uncertainties drop below 0.1% after collecting 10^3 pulses (3 seconds data taking).



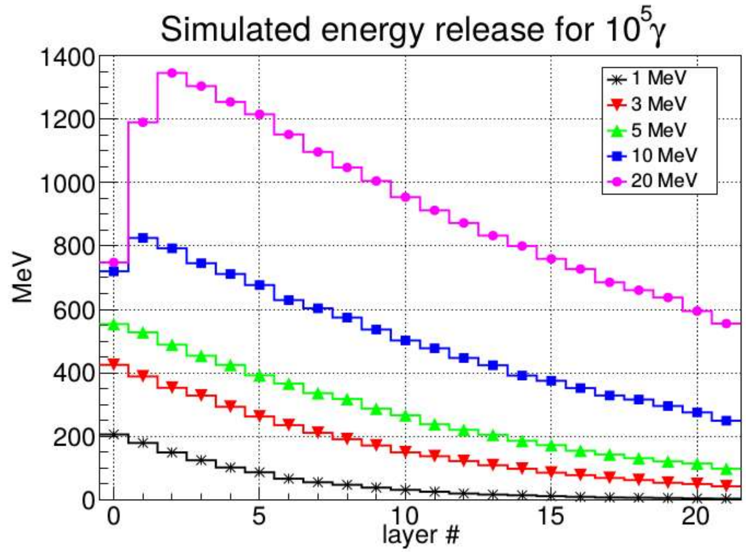


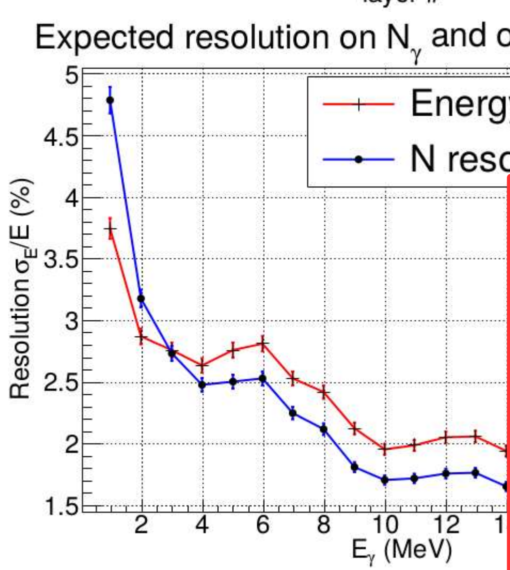


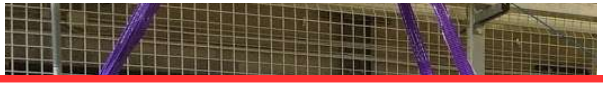
Calorimeter – expected results

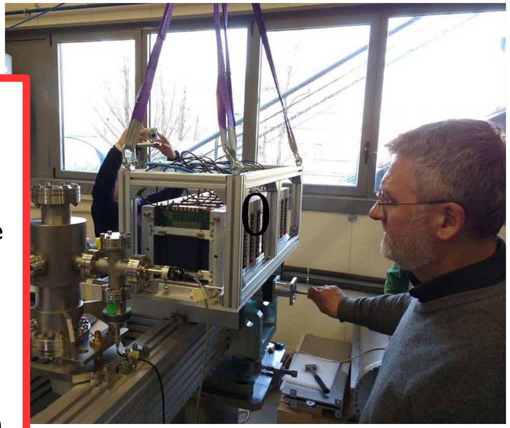
Simulation of a single beam micropulse ($10^{5}\gamma$): a few percent resolution can be achieved in the whole energy spectrum.

These uncertainties drop below 0.1% after collecting 10^3 pulses (3 seconds data taking).









M. Veltri et al. **A γ calorimeter for the monitoring of the ELI–NP beam**
PM2018 -14th Pisa Meeting on Advanced Detectors – NIM-A (in review)

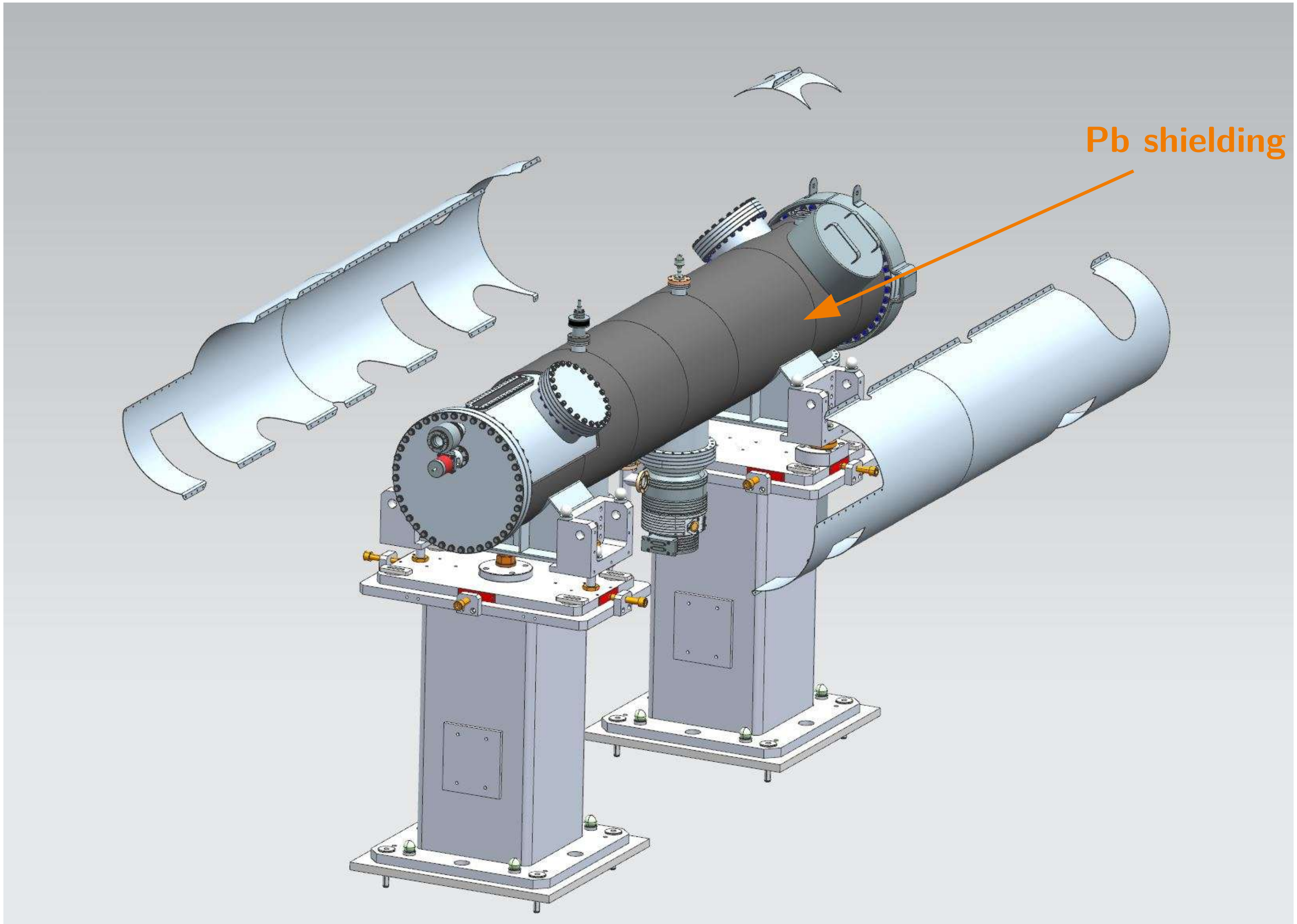
R Borgheresi et al. **Gamma beam characterization system for ELI-NP: The gamma absorption calorimeter**
2016 IEEE Nuclear Science Symposium, Strasbourg, pp. 1-4. (2016)

M. Lenzi et al. **A new-concept gamma calorimeter at ELI-NP**
14th Topical Seminar on Innovative Particle and Radiation Detectors (IPRD16)
J.Inst 12 CO2051 (2016)

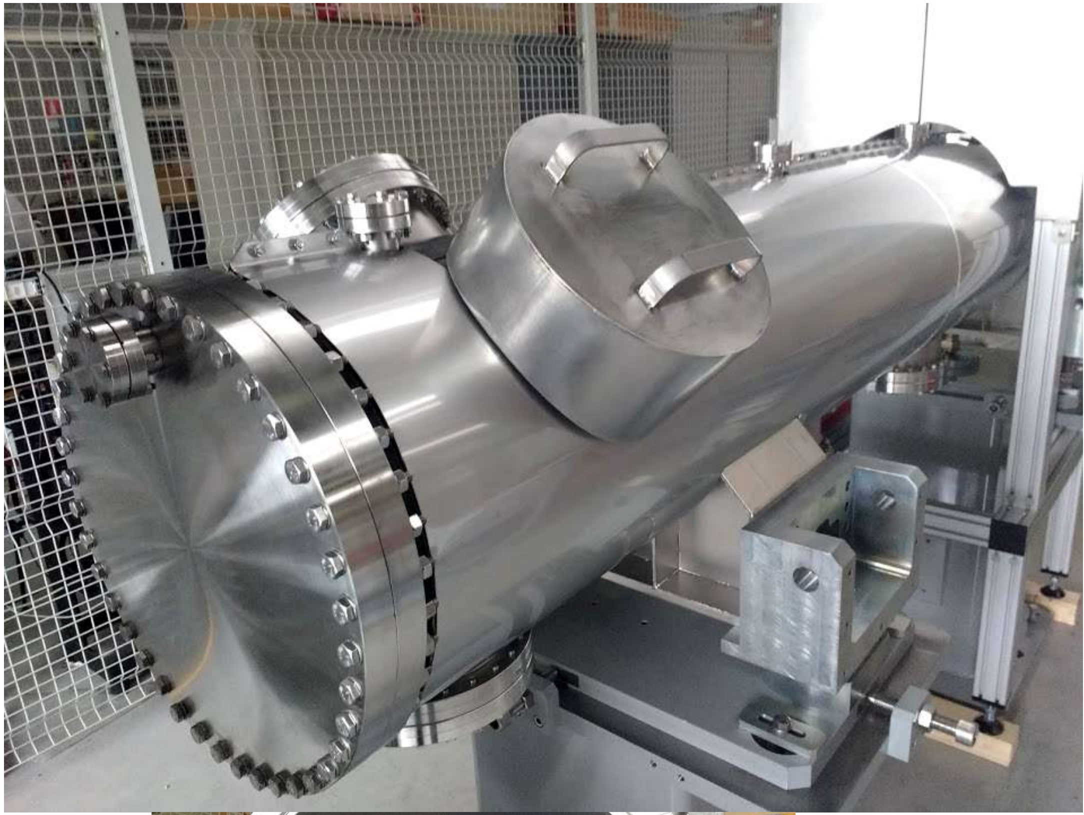
Summary

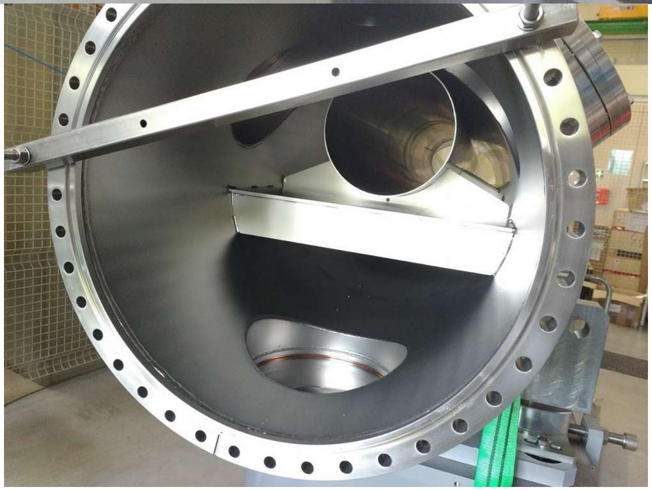
- The collimation of the gamma beam of ELI-NP plays a key role in reaching the required energy bandwidth
- The design adopted is the result of an extensive simulation activity and prototypes testing to fulfil the requirements in terms of divergence, assembly precision and background radiation control
- The beam characterization and monitoring of the parameters is a challenging task
- Several detectors have been designed and optimized performing realistic simulations and have been assembled at Ferrara, Firenze and Catania laboratories
- Tests and characterization of each subsystem using available sources have been carried out
- Final assembly and test of the low energy system ongoing in Ferrara

M13 CSPEC – Vacuum chamber

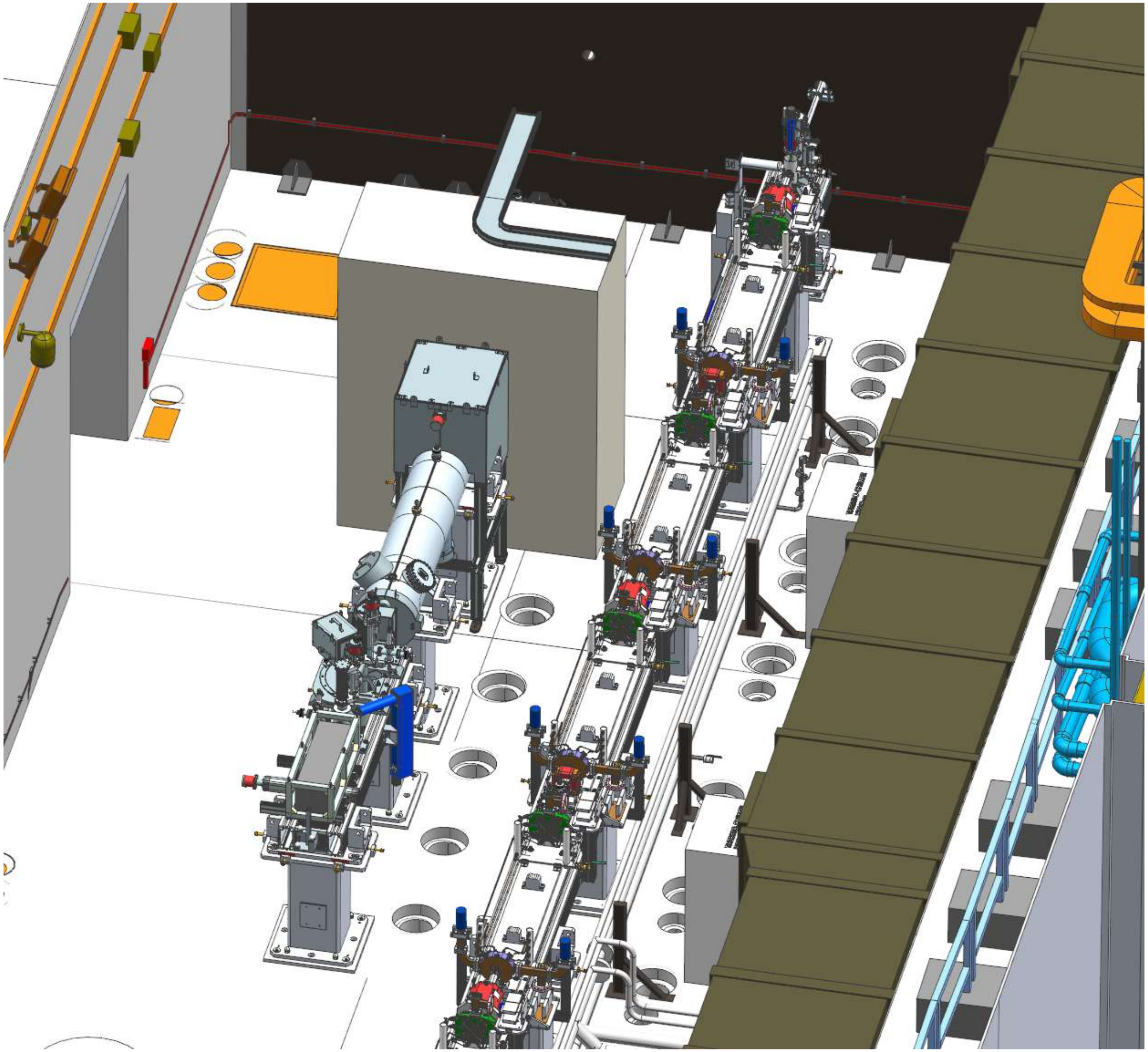


M13 – CSPEC

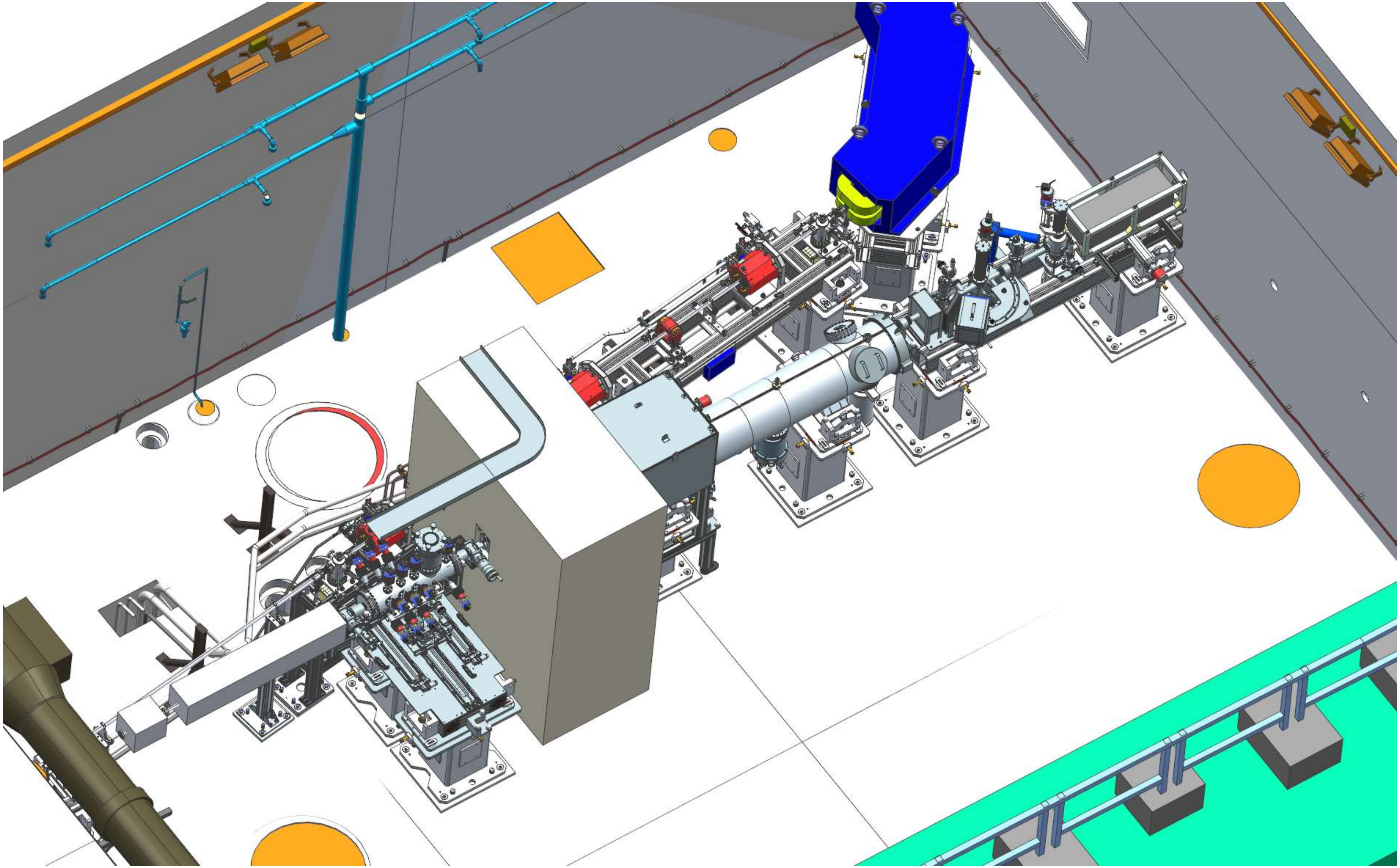




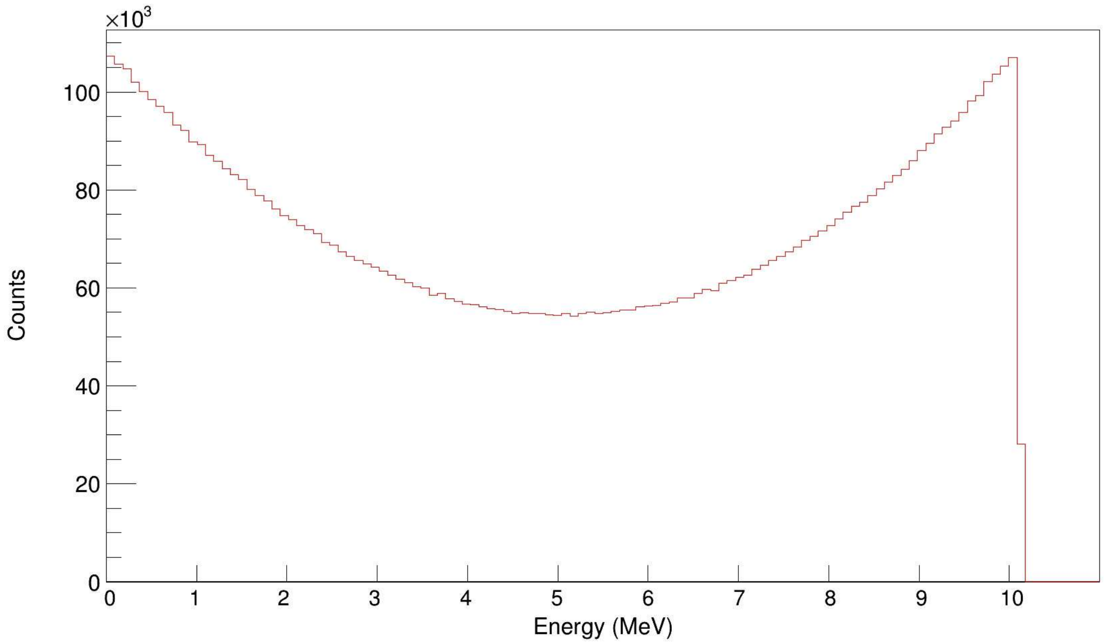
M11-M14 Low energy beamline



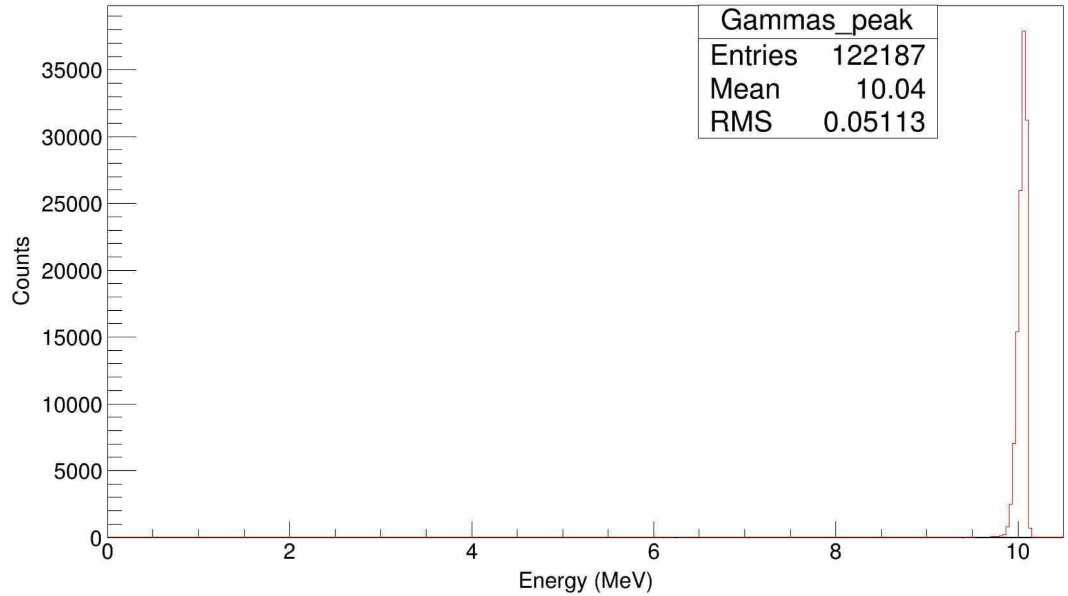
M28-31 High energy beamline



Effect of collimation



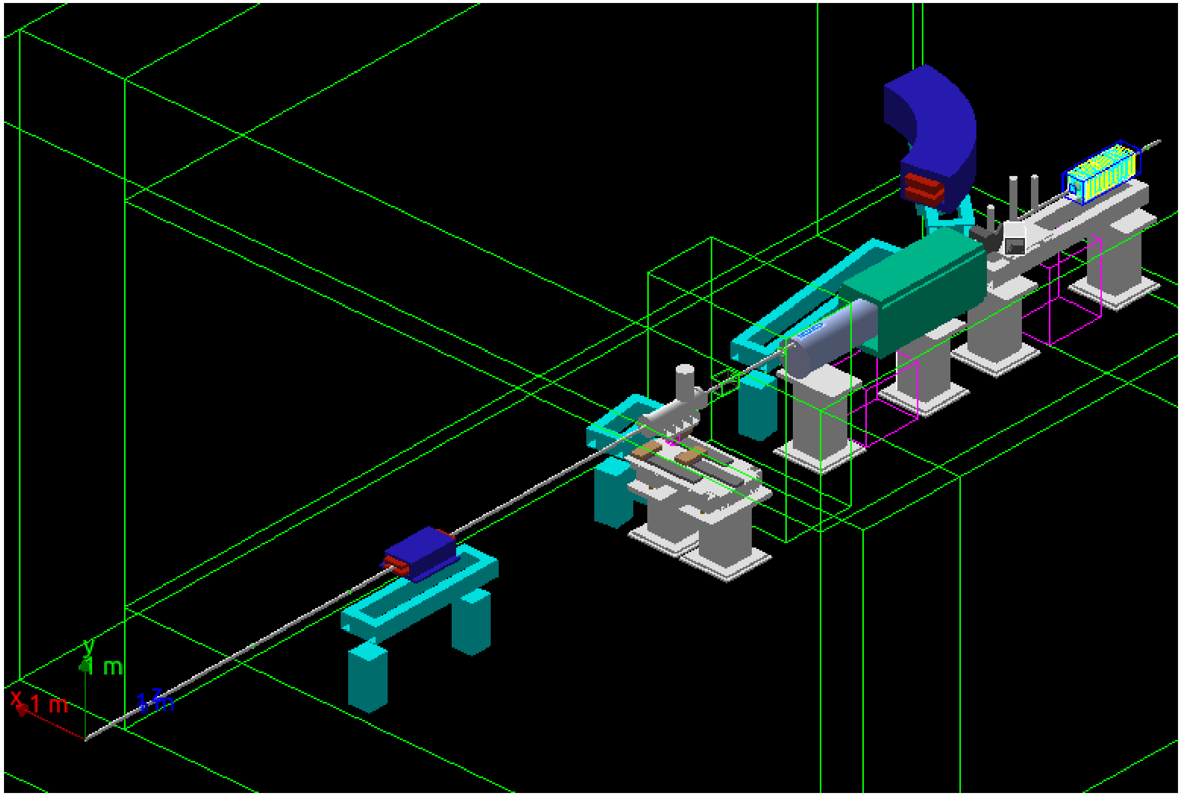
Beam spectrum at the IP

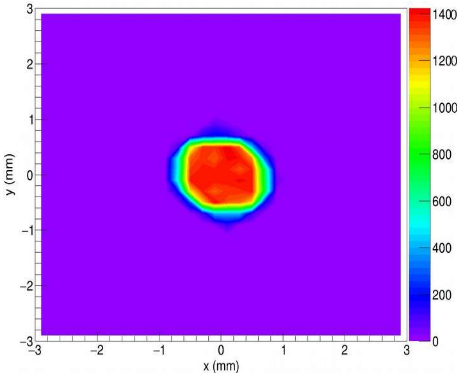


Collimated beam spectrum

Simulation activities

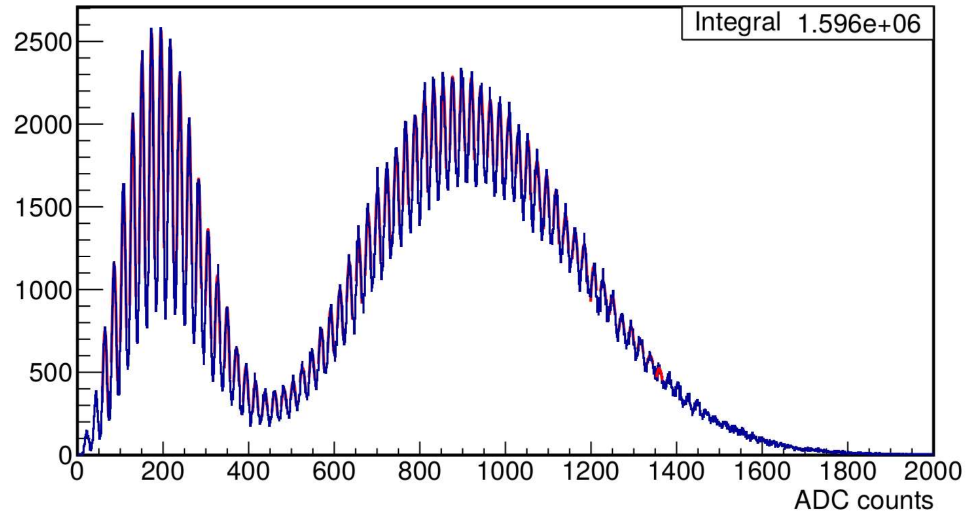
- A full **Monte Carlo simulation for radiation transport** (Geant4 has been implemented) allowed to optimise detector performance, design collimation system and shielding etc..



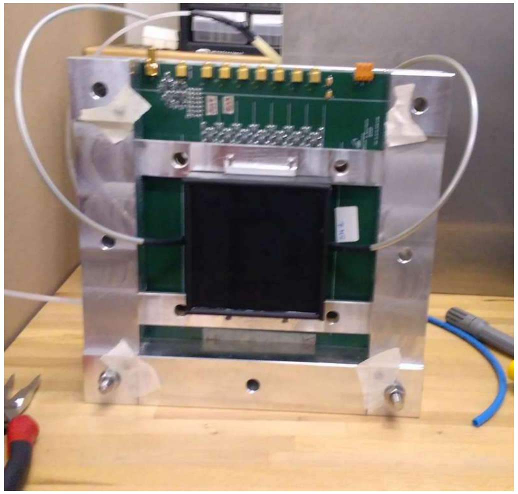


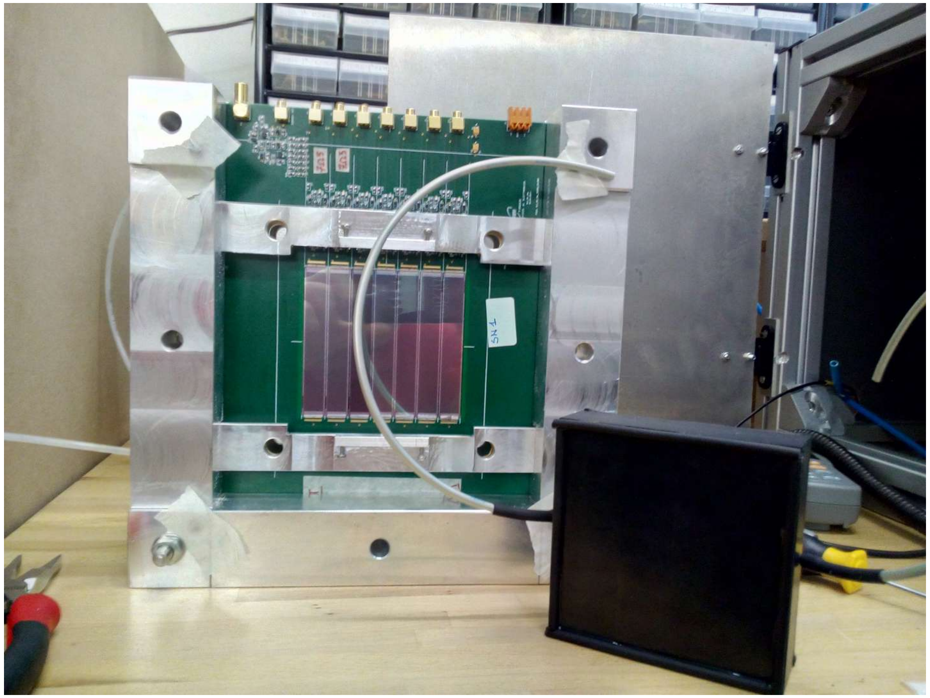
GCAL

- All the **Si-Strip detectors have been characterized**



- The **prototype boards were tested** at the LABEC facility in Firenze
- The linearity of the system was tested up to 200 MeV of energy release





GCOLL – M11 SpaceFab testing results

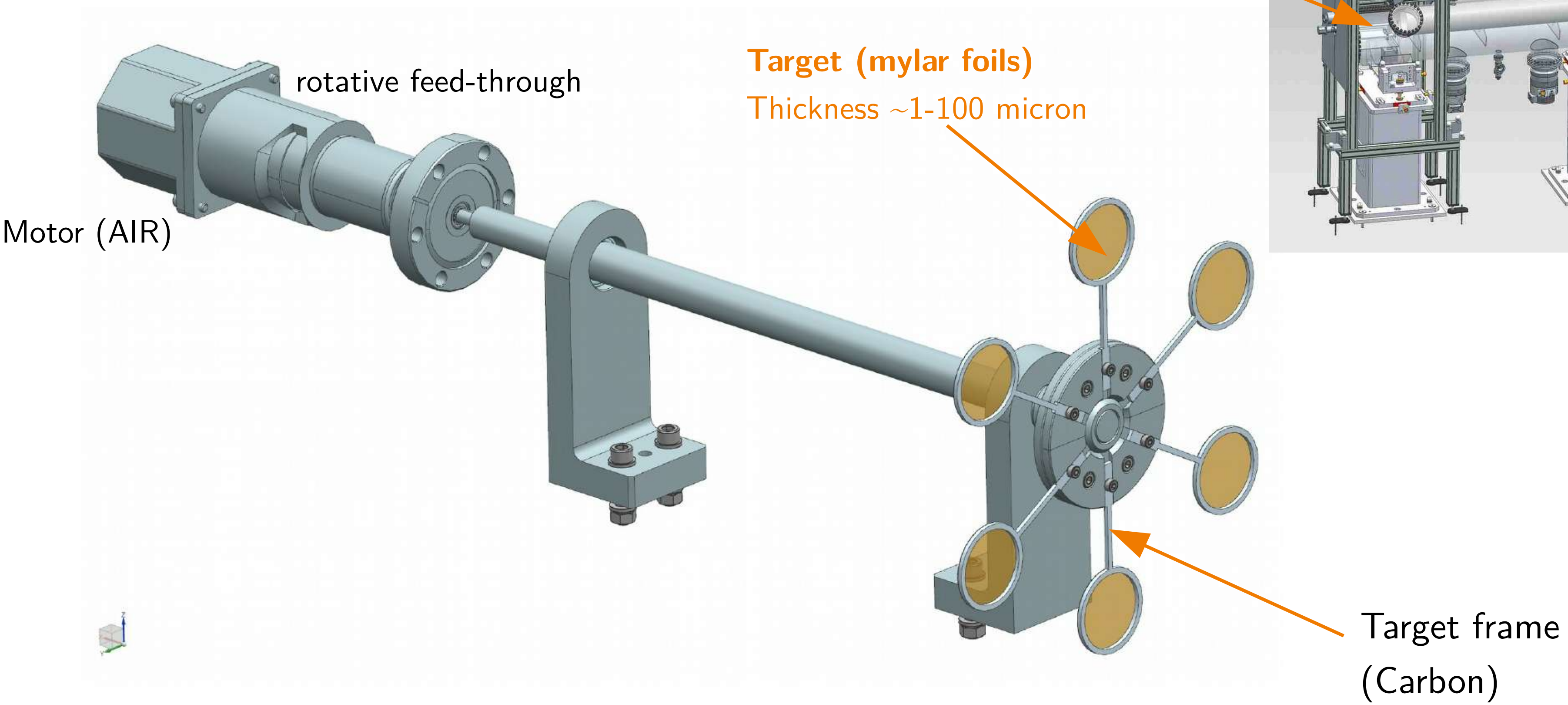
- FAT Factory acceptance test
- SAT Acceptance test repeated here in Ferrara (October 2016)
- Control GUI completed (developed in Ferrara)

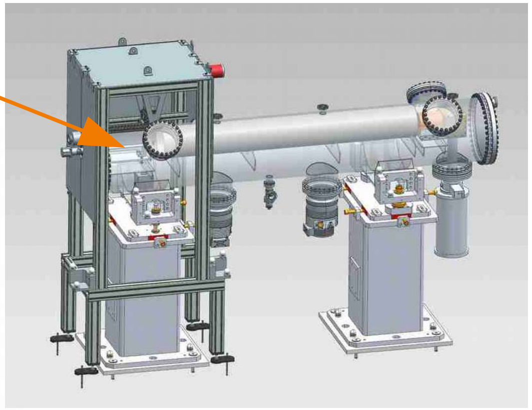
SpaceFAB #1 (SN: 416003375)

Overview of the results:

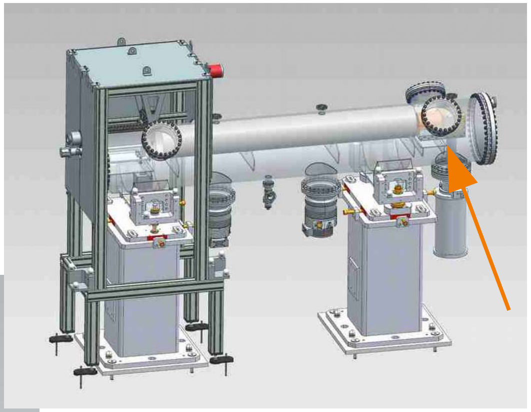
Parameter	**Result (max. value)**
Linear Bi-directional Repeatability X	0.500 µm
Linear Bi-directional Repeatability Y	3.604 µm
Linear Bi-directional Repeatability Z	4.216 µm
Angular Bi-directional Repeatability Rx	0.00205°
Angular Bi-directional Repeatability Ry	0.00068°
Angular Bi-directional Repeatability Rz	0.00230°

M13 – CSPEC Target Wheel



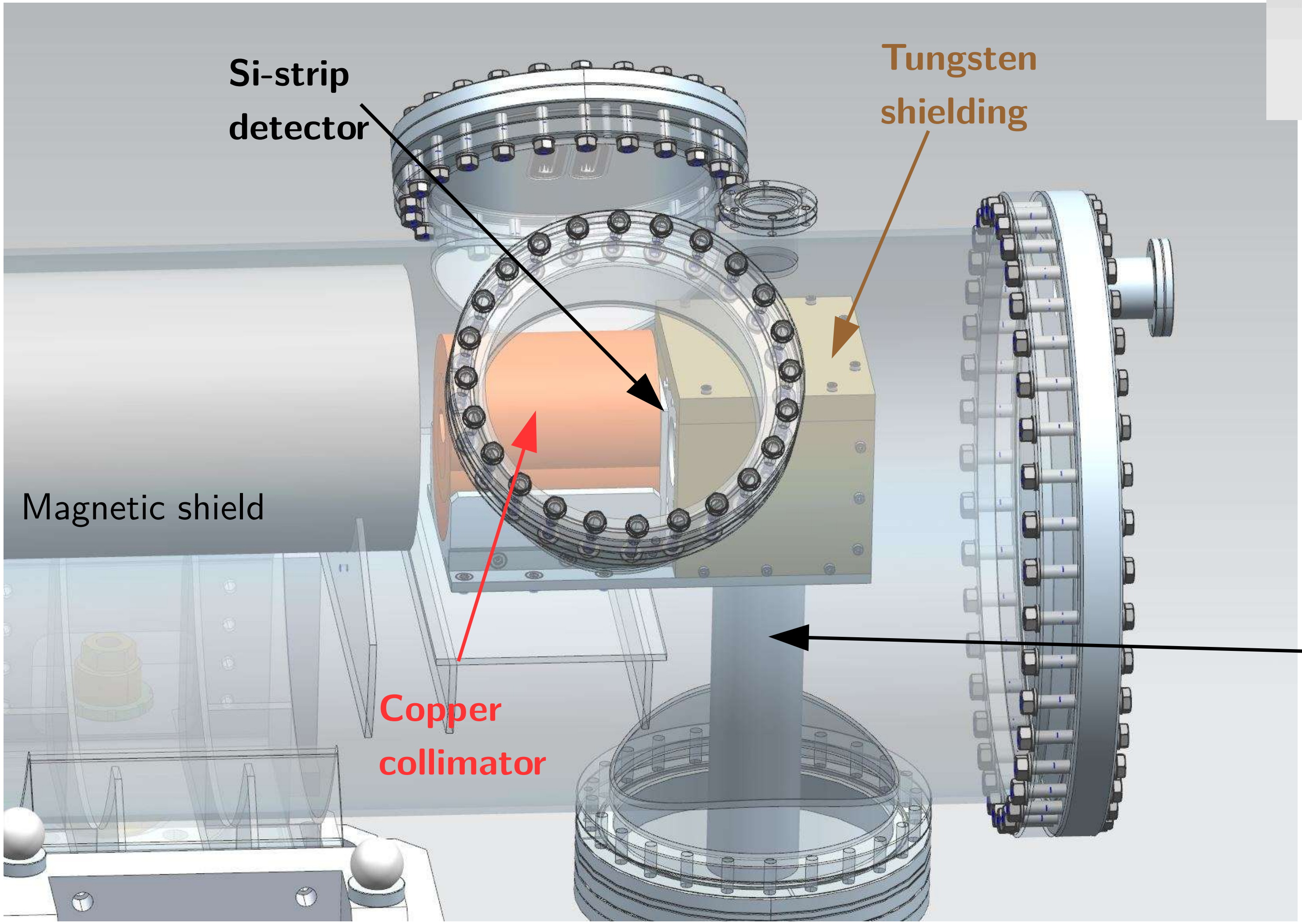


M13 – CSPEC Electron Detection



Electron detectors:

- High Purity Germanium **HPGe** (Energy)
- **Si-strip** detector (position)



GPI – Gamma Profile Imager

- Prototype testing done (scintillator, optics and camera in air)
- The results of experimental test have been used tune and check the simulation parameters of the system
- Resolution better than 0.1 mm (depends on target and geometry)

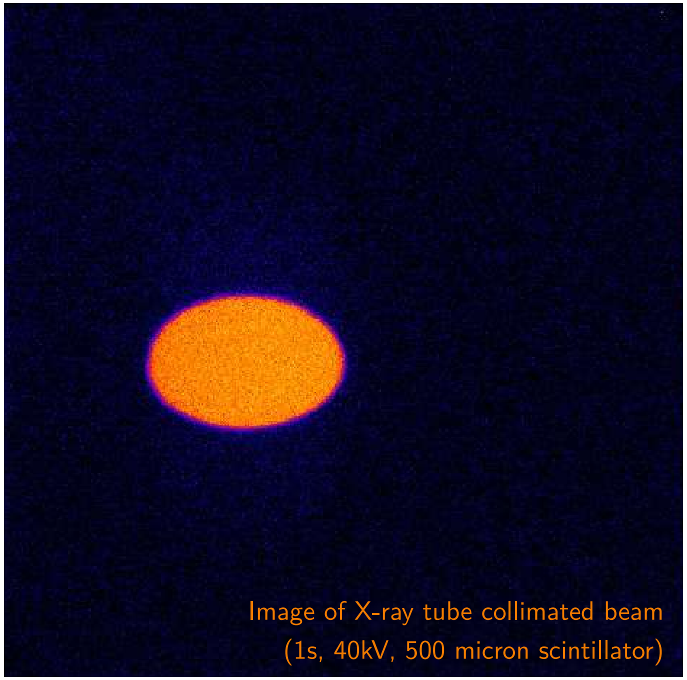
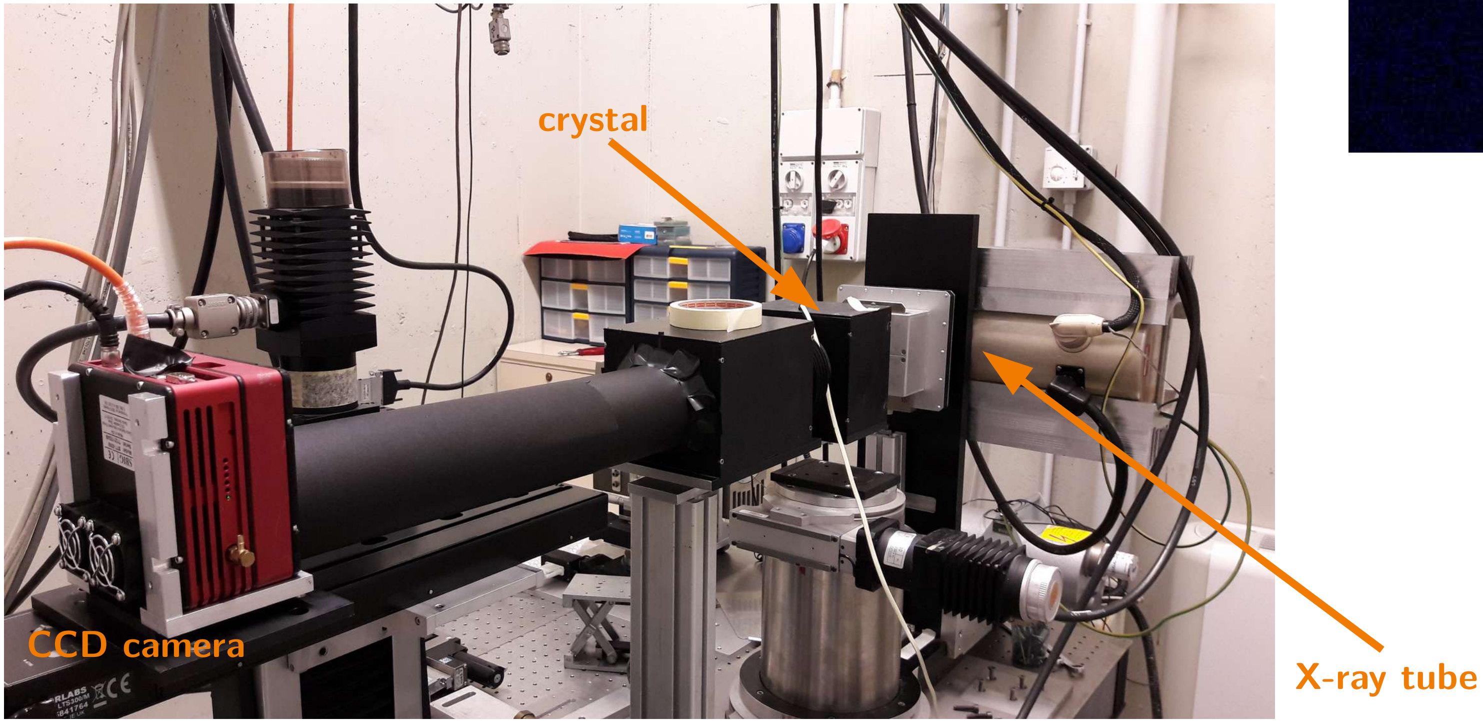
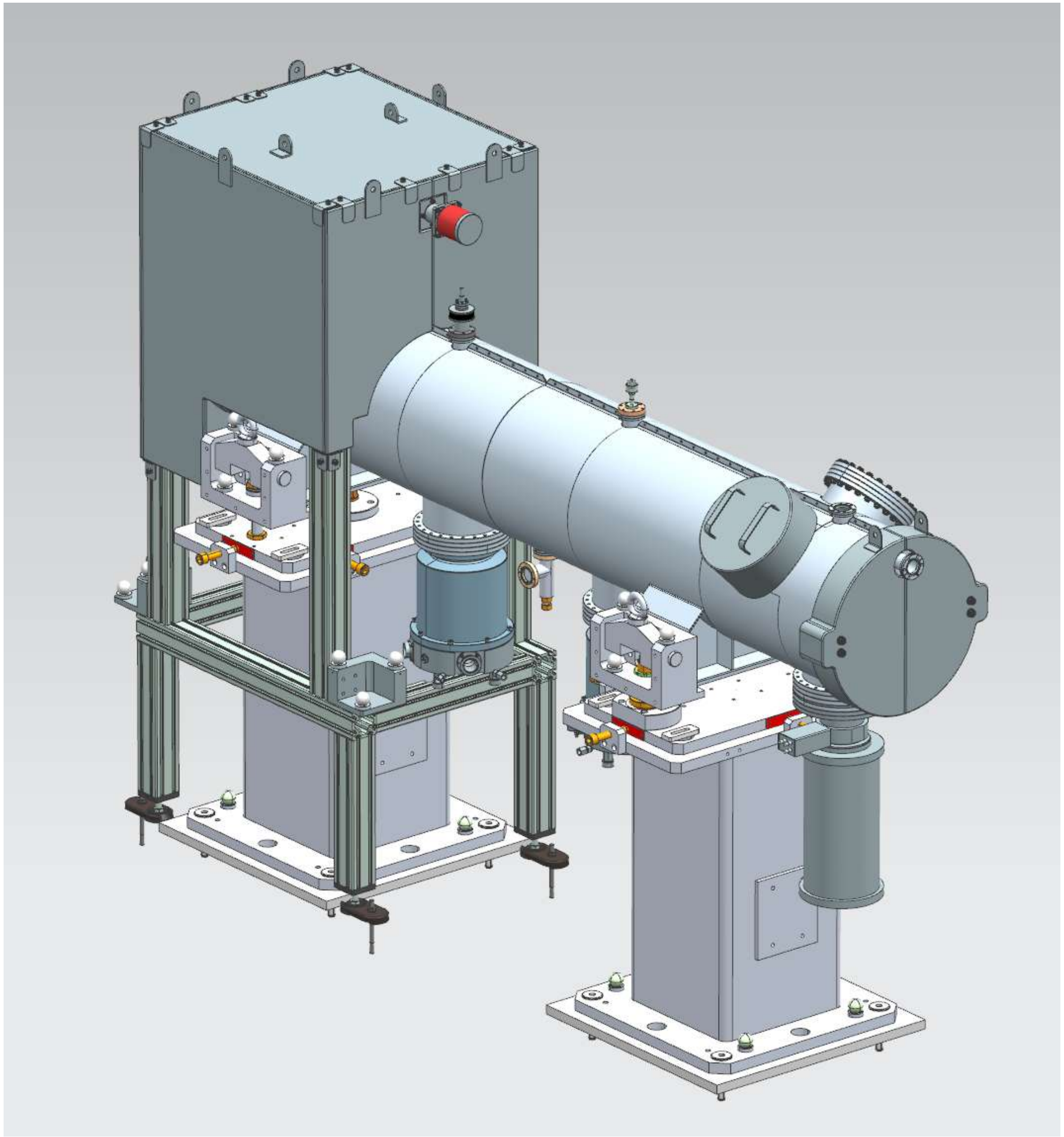


Image of X-ray tube collimated beam (1s, 40kV, 500 micron scintillator)



Compton Spectrometer



- **Compton spectrometer to measure energy distribution**

- Main components:
  - **Micrometric target**
  - **Gamma detector**
  - **Electron detector**

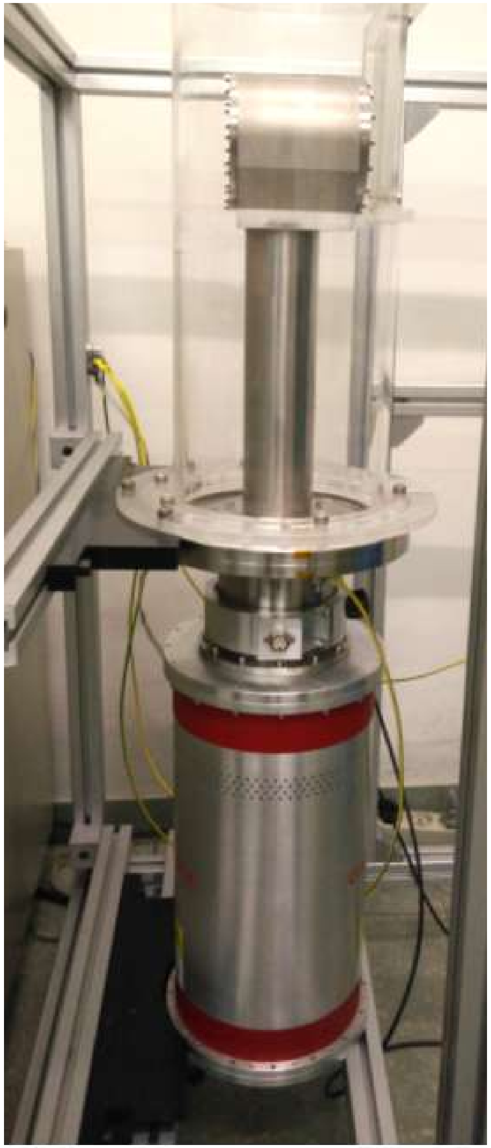
- Developed by INFN – Firenze

- **Mechanic** design and assembly mainly in **Ferrara**

- **Target and detectors study, design and test in Firenze**

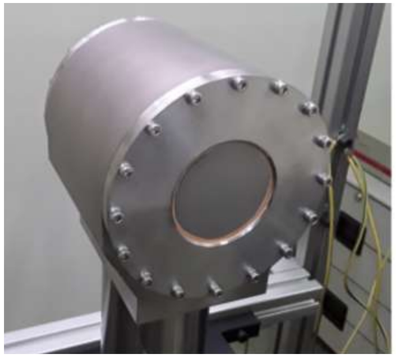
CSPEC - HPGe

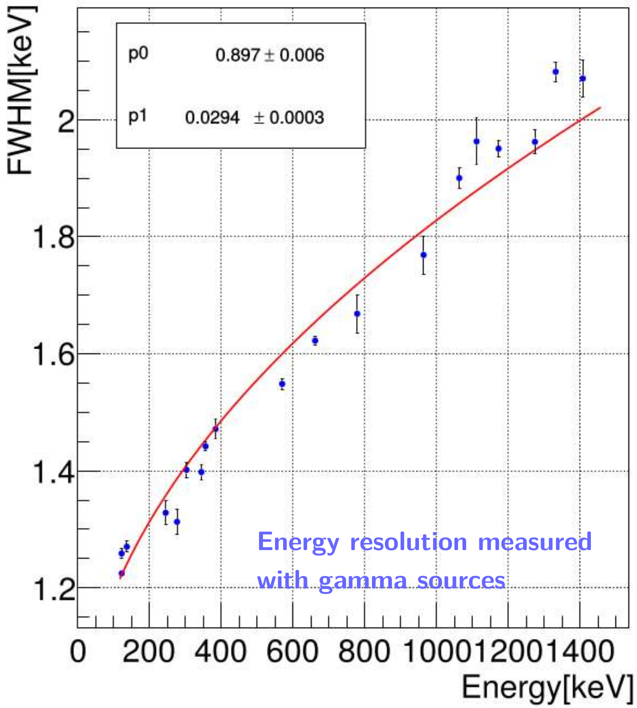
The HPGe detector, chosen for its excellent energy resolution, will measure the energy of the scattered electron.

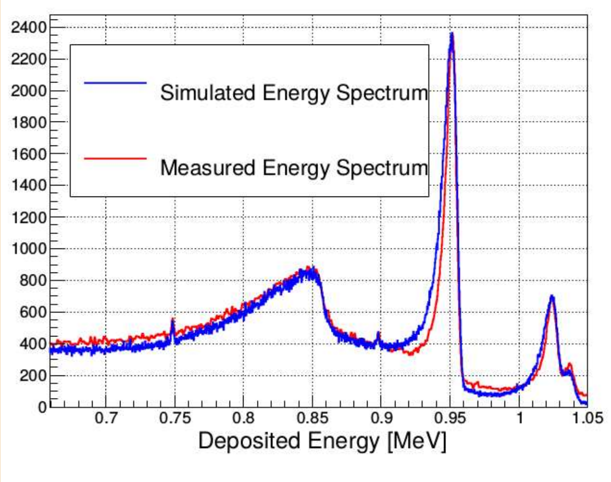


- HPGe planar custom configuration by CANBERRA:
  - 80 mm, diameter
  - 20 mm, thickness
  - electrically cooled

- To minimize the energy loss:
  - 100 µm, cryostat Be-window thickness
  - ≤ 1µm, electrical contacts



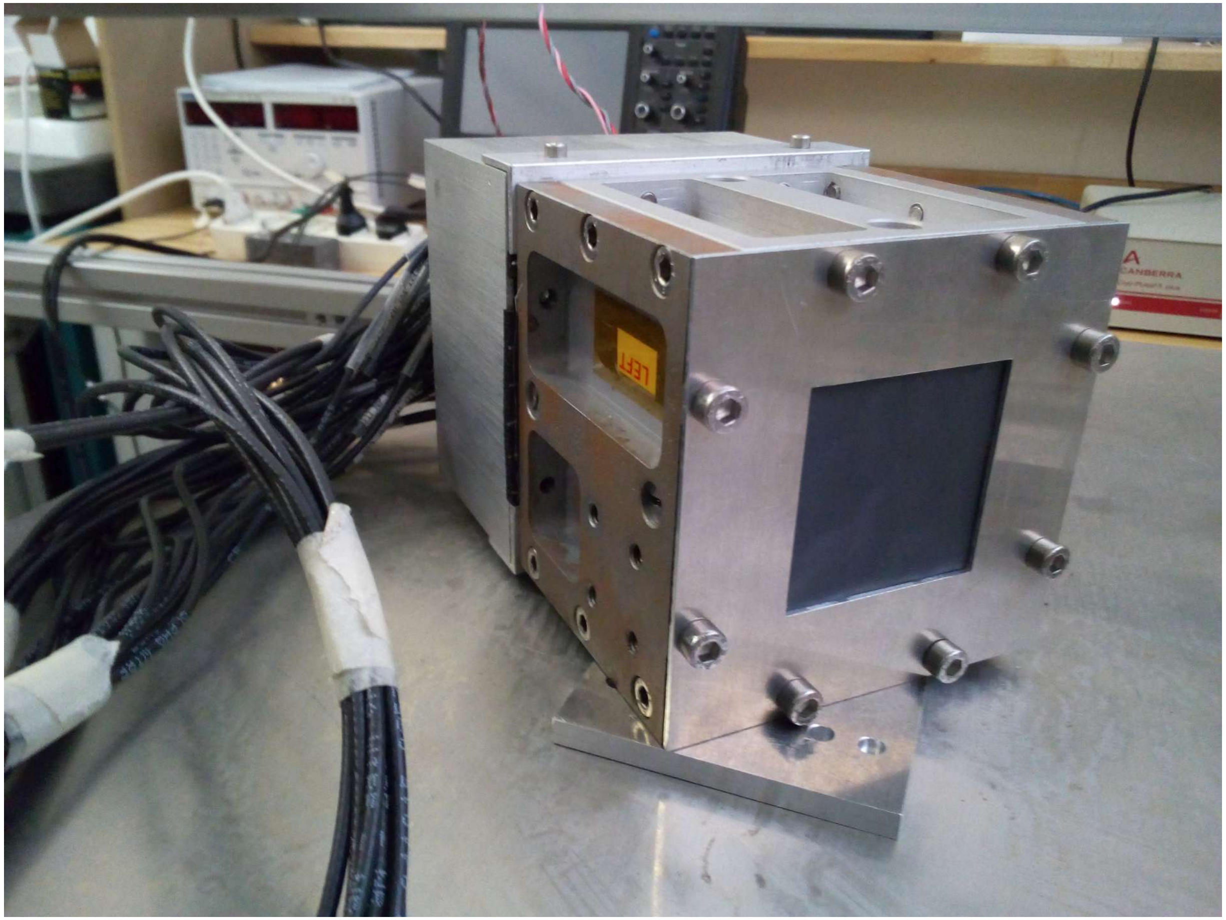


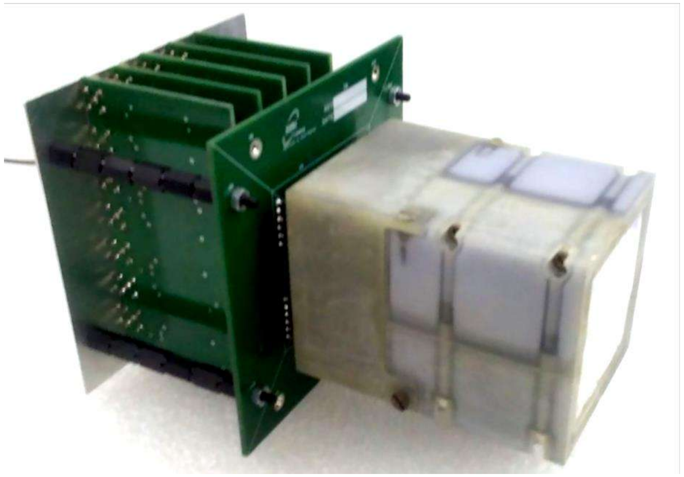


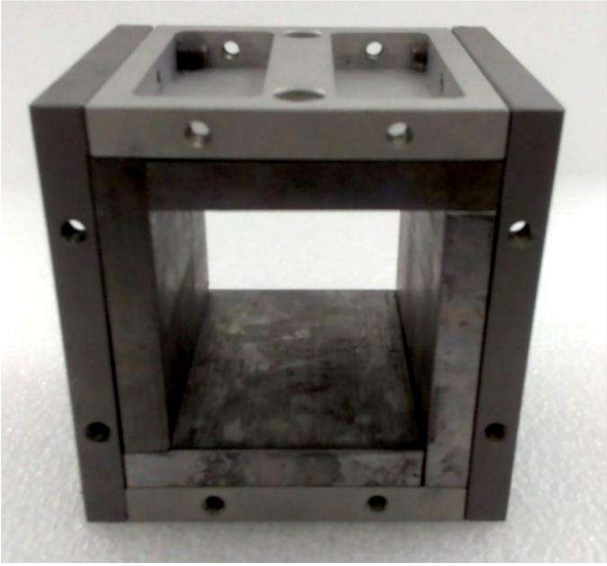
Verified the accuracy of Monte Carlo simulation using electrons of definite energy emitted by 207 Bi source. The measured peak positions are in agreement with the simulated ones with a precision better than 1 keV

CSPEC – M13 Gamma Detector

- Gamma detector assembled and tested in Firenze
- BaF_2 Crystal and PMT

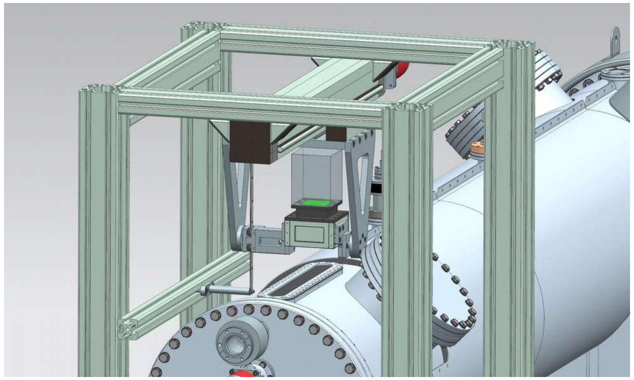


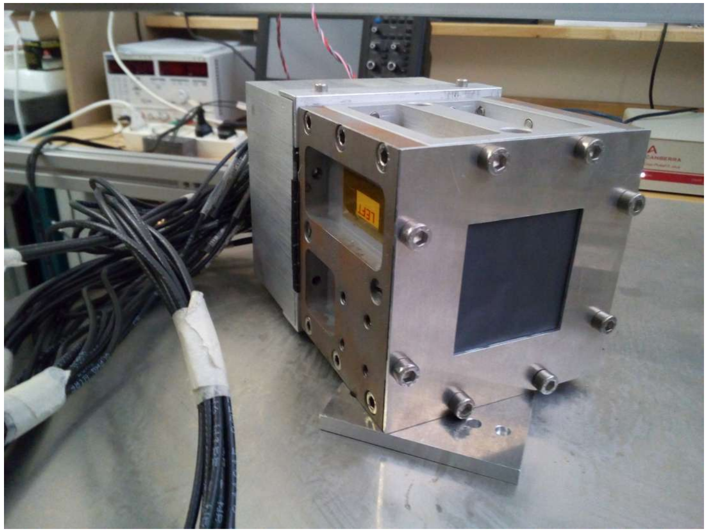




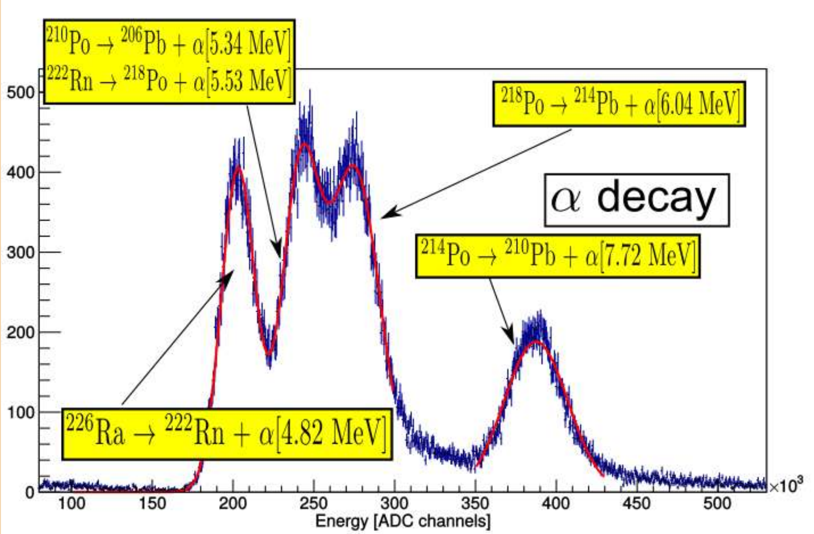
CSPEC – Gamma Detector

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





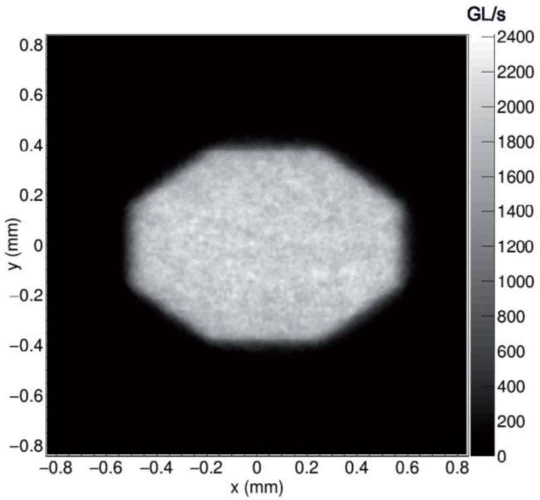
- 4×4 BaF_2 crystals (1.2×1.2×5 cm^3)
- Read out by a multianode PMT manufactured by HAMAMATSU (mod. H12700)
- BaF_2 has two scintillation components:
  - fast: $\tau = 0.6 - 0.8$ns
  - slow: $\tau = 630$ ns



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

GPI – Gamma Profile Imager

- To predict the **detector response a model was developed** based on two components:
  - Monte Carlo simulation, to evaluate energy deposition in the scintillator
  - custom-made paraxial ray-tracing code, to simulate the light propagation up to the CCD camera.
- **Comparison of simulations and measurement** using x-ray tube and Am-241 source → simulation parameters tuning
- Detailed simulation with realistic parameters → expected performances on ELI-NP beam



Simulated image on the CCD of the 3 MeV gamma beam

E_{beam} (MeV)	GL_p/s
0.2	305
3	2165
10	24321
19.5	51400

Background signal ~30 GL/s