Collimation and Characterization of ELI-NP Gamma Beam

Crete conference on Applications of Nuclear Techniques

Gigi Cappello

INFN sezione Catania, EuroGammaS collaboration

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The ELI-np facility

The Extreme Light Infrastructure

ELI is a pan-European project involving over 40 institution from 13 EU countries that aims to host high-power lasers and extremely intense radiation beam lines devoted to scientific applications spacing from fundamental nuclear and molecular studies to applied biological and environmental researches.

Distributed into three specialized sites, currently in final phase of implementation:

- ELI-Attosecond (Szeged, Hungary
- ELI-Beamlines (Prague, Czech Republic)
- ELI-Nuclear Physics (Bucharest, Romania)

Eli-NP research activities

- Research Activity 1: High-Power Laser System
- Research Activity 2: High-Brilliance Gamma Beam

The design, manufacturing, delivery, installation, testing, commissioning and maintenance of the **Gamma Beam System (GBS)** is provided by the **EuroGammaS** association.

- Research Activity 3: Nuclear Physics with High-Power Lasers
- Research Activity 4: Nuclear Physics and Applications with high-brilliance gamma-beams
- Research Activity 5: Fundamental Physics with combined laser and gamma beams

Eli-NP research activities

- Research Activity 1: High-Power Laser System
- Research Activity 2: High-Brilliance Gamma Beam
- Research Activity 3: Nuclear Physics with High-Power Lasers
- Research Activity 4: Nuclear Physics and Applications with high-brilliance gamma-beams
  - Nuclear Resonance Fluorescence (NRF) studies;
  - Measurements of σ of photonuclear processes;
  - Studies on photo-fission;
  - Nuclear collective excitation models...
- Research Activity 5: Fundamental Physics with combined laser and gamma beams

The Gamma Beam System (GBS)

Gamma Beam System (GBS)

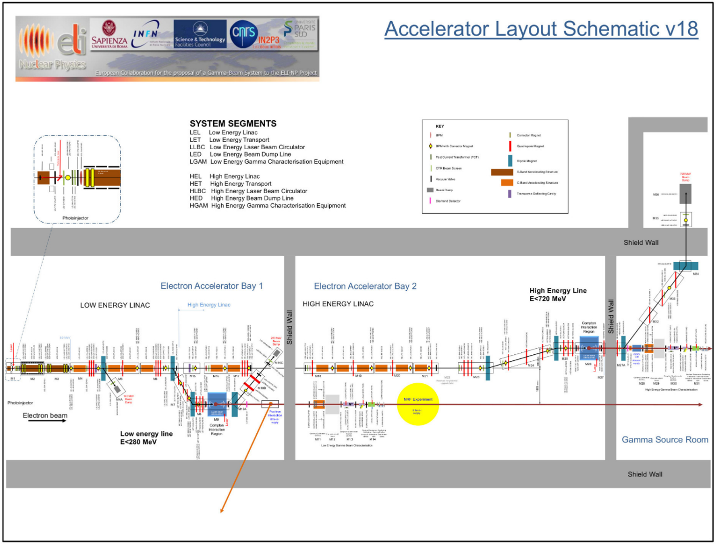
The Gamma Beam System (**ELI-NP-GBS**) will produce an intense $\gamma-$beam from **Compton inverse scattering** of pulsed laser light (at 550nm) from a (up to 720MeV) electron beam. The main goal is to make a jump w.r.t. the technology state of art to fulfill the physics requirements in terms of:

- energy
- tunability
- monochromaticity
- collimation
- brilliance
- polarizability

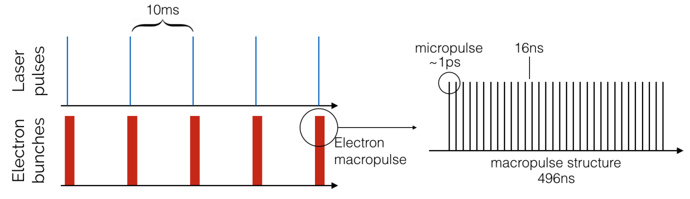
Photon energy	0.2-19.5 *MeV*
Spectral Density	$0.8\text{-}4 \cdot 10^4$ *ph/sec.eV*
Bandwidth (rms)	$\leq 0.5\%$
# photons per shot within FWHM bdw.	$\leq 2.6 \cdot 10^5$
# photons/sec within FWHM bdw.	$\leq 8.3 \cdot 10^8$
Source rms size	10 - 30 μm
Source rms divergence	25 - 200 μrad
Peak Brilliance ($N_{ph}/sec \cdot mm^2 mrad^2 \cdot 0.1\%$)	10^{20} - 10^{23}
Radiation pulse length (rms, *psec*)	0.7 - 1.5
Linear Polarization	> 99 %
Macro rep. rate	100 *Hz*
# of pulses per macropulse	≤ 32
Pulse-to-pulse separation	16 *nsec*

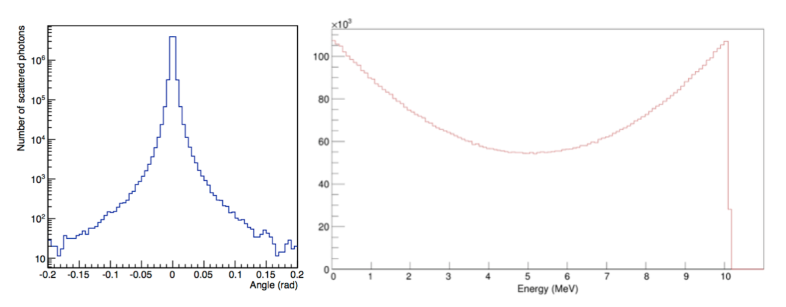
O. Adriani et al. arXiv:1407.3669 [physics.acc-ph] (2014)

Gamma Beam System (GBS)



Time and energy structure of the GB



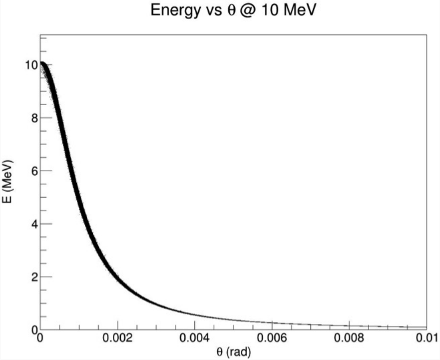


Left: Boosted angular distribution ($\Delta\theta \sim 1/\gamma_e$). Right: Energy spectrum of the γ

Time and energy structure of the GB

The ELI-NP gamma beam will be obtained by collimating the photons emerging from the Compton IP. This step is extremely critical to gain the required brilliance and monocromaticity.

A careful design of the collimation system is mandatory!



Collimation and Gamma Beam Characterization

The ELI-NP gamma beam will be obtained by collimating the photons emerging from the Compton IP. This step is extremely critical to gain the required brilliance and monocromaticity.

A careful design of the collimation system is mandatory!

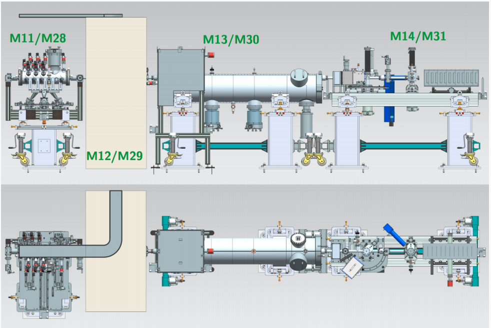
A precise energy calibration of the γ beam and a continuous monitoring of its parameters (peak energy, energy and space profile, intensity...) during operation are also necessary.

Given the unprecedented characteristics of the beam, these tasks are themselves an experimental challenge.

Collimation and Gamma Beam Characterization

The γ beam characterization (GBC) and collimation tasks are carried on by the Work Package 9 (WP09) of EuroGammaS collaboration.

Two complete beam characterization systems will be delivered for the two γ lines, almost identical but with optimized solutions.



- Collimator and concrete wall(GCOLL)

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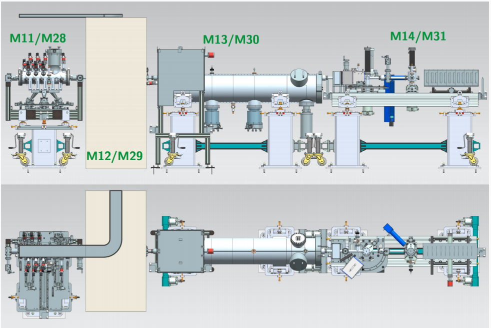

- Collimator and concrete wall(GCOLL)
- Compton spectrometer(CSPEC)

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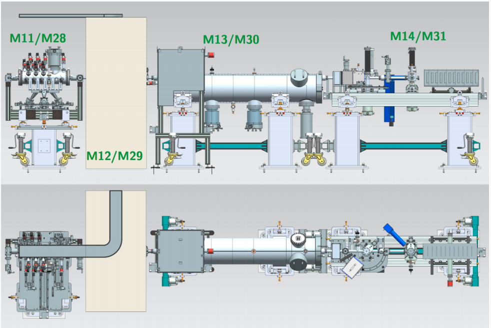

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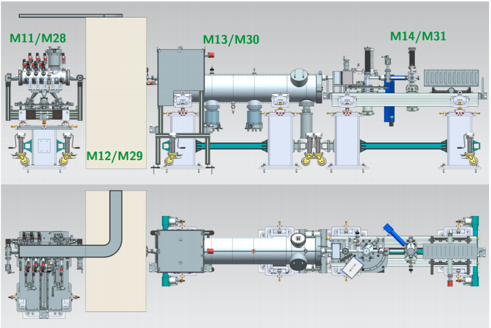

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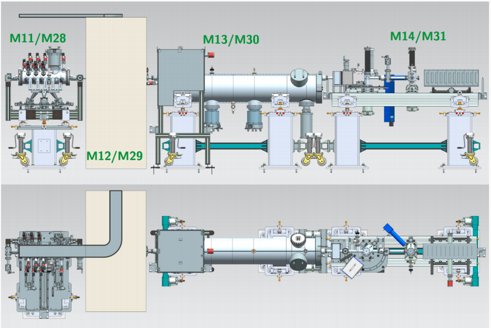
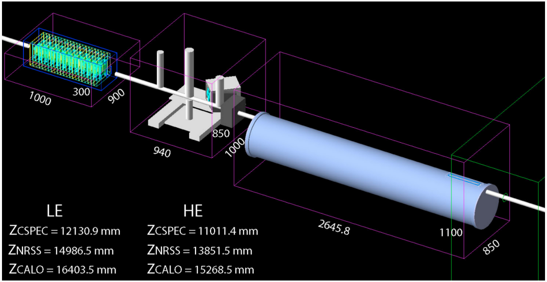


- Collimator and concrete wall(GCOLL)
- Compton spectrometer(CSPEC)
- Nuclear Resonant Scattering System (NRSS)
- Beam Profile Imager(GPI)
- Sampling Calorimeter(GCALL)

Collimation and GBC - Simulations

A detailed Geant4 model of the Collimation+GBC system has been developed in **Geant4** as well as models of the single sub-systems for local studies.



- Many realistic γ beams have been simulated for both low energy (**LE**: 0.2-3MeV) and High Energy (**HE**: 5-20MeV) studies.
- The beam is obtained running a transport model of electron beams to the Compton IP and then simulating the collision with the laser pulses, using the CAIN code (WP02).

Collimation

Requirements for collimation system

- Bandwidth $\leq 0.5\%$ in the whole energy range (0.2-20MeV)

  This requires a collimation at 700-70 μrad divergence, corresponding to slits apertures from 14mm to 1mm with the adopted design. A continuously adjustable aperture is also necessary.

- Low transmission of external photons

  Materials of high density and high atomic number are preferred (**Tungsten**)

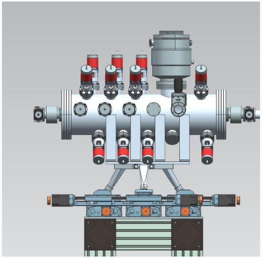
- Avoid production of secondary radiation that could contaminate the beam.

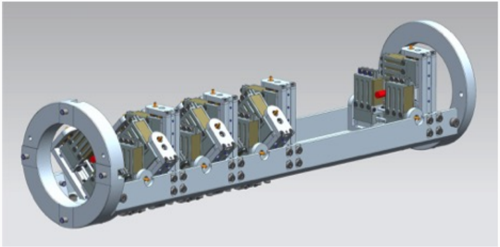
  Design and screeninig optimized via simulation of spurious deposits downstream the collimator.

Collimator design, building and simulations

The adopted design consists in a stack of 14 slits independently adjustable, each made of 40x40x20mm Tungsten blocks. The first 12 slits are arranged into 3 groups of 4 slits each, tilted by an angle $\phi = 45°$.

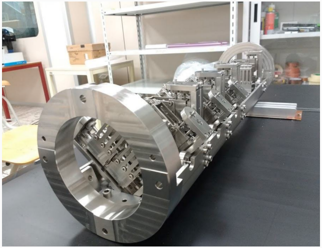
The system is hosted in a vacuum chamber and all movements are synchronized and servo-controlled.

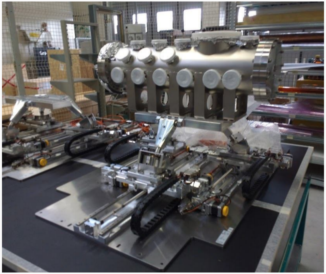




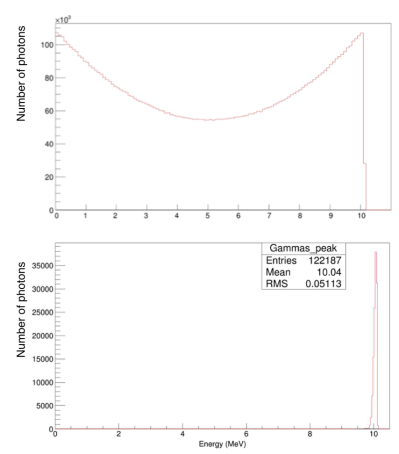
Collimator design, building and simulations

The system has been mounted in Ferrara (Italy) in these days for final tests.

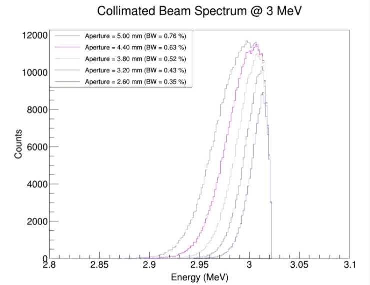


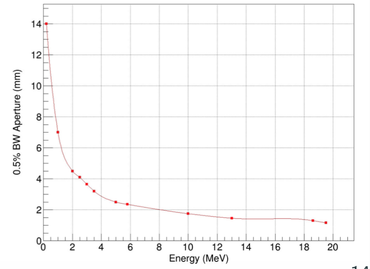


Simulation of the effects of the collimator on the beam bandwidth.



G.Paternò *et al.*: A collimation system for ELI-NP Gamma Beam System design and simulation of performance





The Gamma Beam Characterization System

Requirements for GBC

Energy calibration of the γ beam and monitoring of its parameters: Energy spectrum, Intensity, Space and Time profile.

Two complementary approaches are followed in parallel:

- Precise sampling of single photons interaction $\longrightarrow$ CSPEC

  Minimal interference with beam operation

  Slower response due to cut in statistics

- Measurement of the total beam energy $\longrightarrow$ GCAL

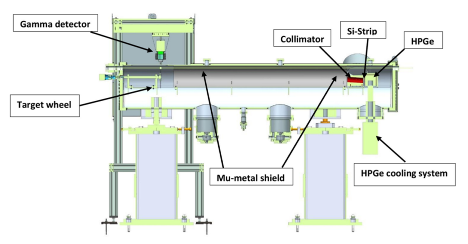
  Full gamma statistics

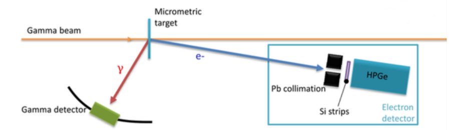
  Cannot be used during operations

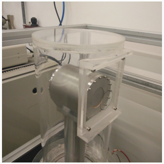
Interplay is fundamental! Moreover...

- Absolute energy calibration $\longrightarrow$ NRSS
- Determination of spatial profile $\longrightarrow$ GPI

CSPEC - Compton spectrometer







Measure γ energy from **electron recoil** at small angle from thin graphite absorber.

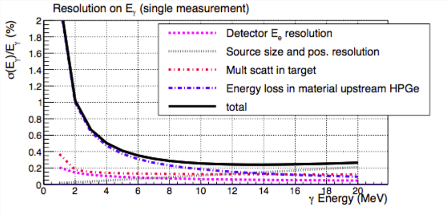
$$E_{\rm beam} = \frac{m_e T_e}{cos\Phi\sqrt{T_e(T_e+2m_e)} - m_e}$$

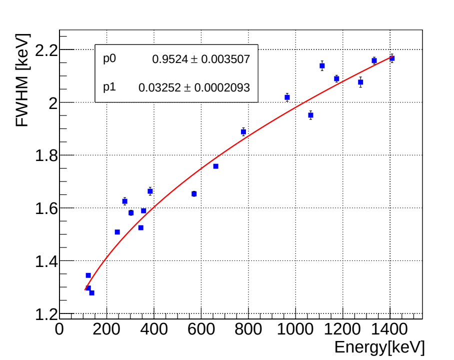
HPGe detector for electrons: high energy resolution *but* slow signal $\rightarrow$ reduce rate at $\sim$ $1e/Mpulse$ $\rightarrow$ Thin target ($\delta \sim 2-10\mu m$). **This is an advantage!**

Background suppression performed imposing coincidence with a BaF_2 gamma detector at right angle.

2-side SiStrips (res$\sim$ $50\mu m$) in front of HPGe for a precise measurement of the electron recoil angle.

CSPEC - Compton spectrometer





The expected performances have been evaluated simulating 100s data takings ($3.2 \cdot 10^8 \gamma$) at different energies.

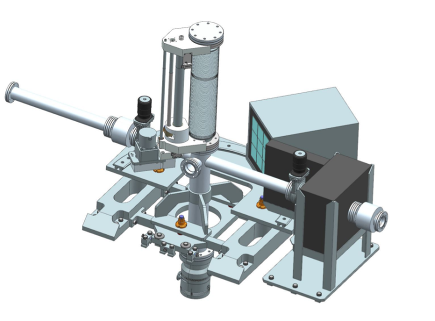
Beam Energy	**2.5 MeV**	**5 MeV**	**18.5 MeV**
$\sigma_{stat}(E_\gamma)/E_\gamma$	0.04%	0.02%	0.02%
$\sigma_{syst}(E_\gamma)/E_\gamma$	0.11%	0.06%	0.02%

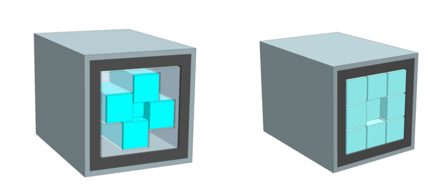
Beam Energy	**2.5 MeV**	**5 MeV**	**18.5 MeV**
Simulated BW (r.m.s.)	6	13	34
Experimental $\sigma(E_{\text{peak}})$	12	8	26
$\sigma_{stat}(BW)$	1.9	0.8	2.5
$\sigma_{syst}(BW)$	2.3	1.2	2.0

After 100s: Peak energy reconstructed within 0.1% and BW at 10 – 40%.

⟵ Linearity and resolution of the HPGe have been evaluated using radiactive sources.

NRSS - Nuclear Resonant Scattering System





To perform an absolute energy calibration of the CSPEC and the GCAL devices, the Nuclear Resonant Scattering method will be used. The **NRSS** will also be able to give a redundant measurement of energy (ES mode) and intensity (under study).

$$\sigma^0(E) = \pi\lambda^2 \frac{2J_1+1}{2(2J_0+1)} \frac{\Gamma^2}{(E-E_r)^2+\frac{1}{4}\Gamma^2}$$

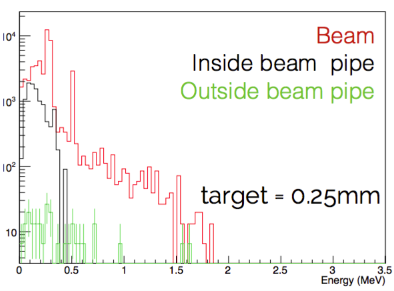
Resonance when $E_{\mathrm{beam}} = E_r$ ($\Gamma \ll \mathrm{BW}$).

Designed in two different setups (for LE and HE lines) to work in two modes:

- FC mode: Use the fast BaF_2 response (<1ns) to count photons in resonance region;
- ES mode: Use LYSO (slower but high resolution) and the BaF_2s as Compton shields to perform a energy measurement.

NRSS - Nuclear Resonant Scattering System

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



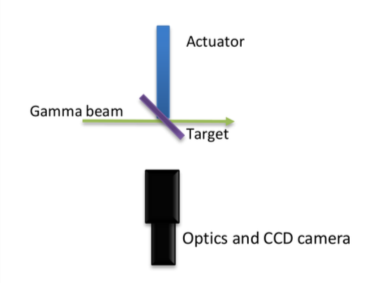
Simulated background at 3MeV

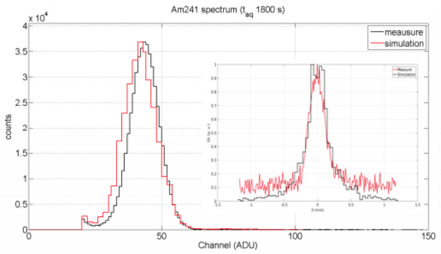
Main bkg source: Compton scattered beam γ at the NRS target $\longrightarrow$ NRSS in backward region ($\theta = 135^\circ$) to move away from signal energy region.

Photons with energy comparable with signal showed from simulation to come out of time $\longrightarrow$ cut using fast BaF_2 response.

A dual readout of Chernkov and scintillation light is foreseen for some BaF_2 crystals and shows good capabilities in the reduction of fake signal and of effects due to possible background pile-up.

GPI - Profile Imager



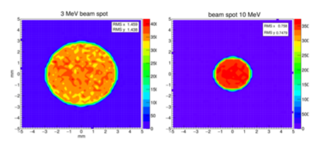


The **position and uniformity** of the beam outside the collimation system will be measured from the scintillating light collected by a CCD camera.

Placed at:

- 15.2m for High energy line;
- 16.3m for Low energy line

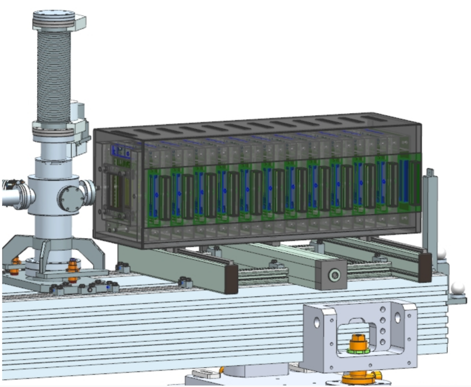
to get a beam spot size of 1-10mm.

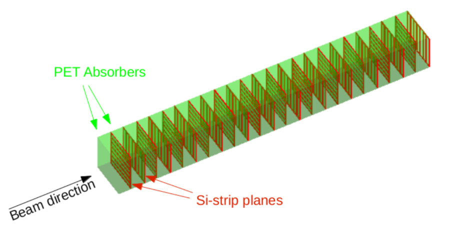


Many scintillating materials have been taken into account, and a LYSO has been finally chosen.

⟵ Tests of the LYSO+optics+CCD system have been performed using different sources together with MC checks.

GCAL - Absorption Calorimeter





The total energy carried by the beam will be measured using a sampling calorimeter.

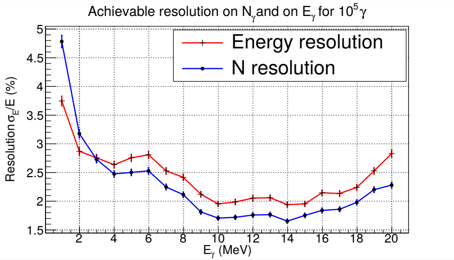
Energy range 1-20MeV → the longitudinal profile of the energy deposit is proportional to the average photon energy for **low Z** materials.
24 layers of inexpensive PE (3cm) and SiStrip (same technology of the CMS tracker).

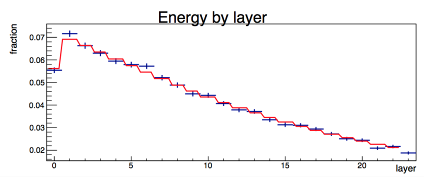
Average energy (profile) + total energy → **Intensity** (for absolute intensity measurements, an absolute energy cross-calibration with NRSS could be healthy).

In air (useful for PE and electronics and easier to move when beam will be operating). A 150μm thick Be window is placed at the end of the vacuum line.

GCAL - Absorption Calorimeter

The choice of longitudinal and transverse sizes have been driven by Monte Carlo studies of signal fluctuation. A per-layer profile parametrization has been obtained from simulation with the spectrum peak energy as only parameter.





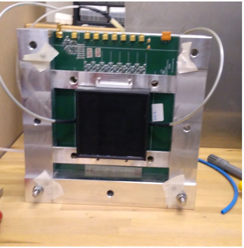
Example of energy reconstruction

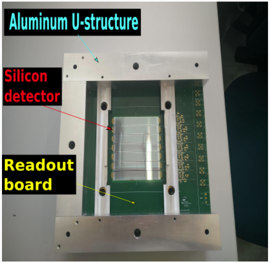
⟵ Simulation of a single beam micropulse ($10^5\gamma$): a few % resolution can be achieved in the whole energy spectrum.

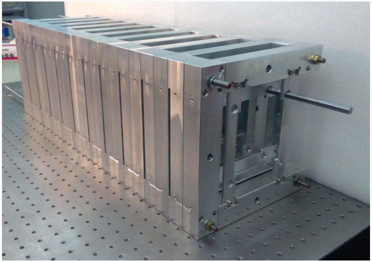
These uncertainties drop below 0.1% after collecting $\sim 10^3$ pulses (3 seconds data taking).

GCAL - Absorption Calorimeter

- Mechanical parts of the device layers are ready.
- Absolute energy calibration and linearity measurement of the silicon device has been performed in Florence.
- Front end electronics development is in the final stage.







Final outlook

Final outlook

- The collimation of the γ-beam of ELI-NP plays a key role in reaching the design BW leading to a quasi monoenergetic-highly polarized beam.

  The design adopted fulfills the requirements in terms of divergence, precision and background radiation control.

- The beam characherization and monitoring of the parameters is a challenghing tasks.

  Redundancy, cross-calibration and deep interplay between novel dec-tectors has been studied.

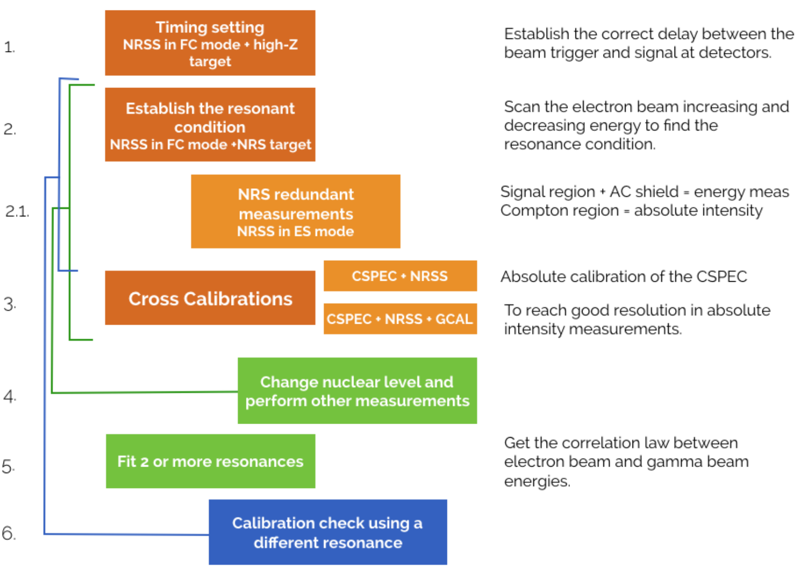
- All the sub-system have been designed and optimized from realistic simulations.
- Tests of the subsystems using sources are in final steges at Ferrara, Firenze and Catania.
- Next steps: Asembly the whole system for final tests in Ferrara. Ship to Bucharest.

Thanks for your attention!

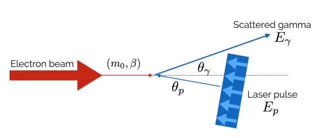
gigi.cappello@ct.infn.it

Backup

Inter-calibration procedure



Gamma Beam System (GBS)



$$E_\gamma = \frac{(1+\beta\cos\theta_p)E_p}{1-\beta\cos\theta_\gamma+(1-\cos\Delta\theta)\frac{E_p}{\gamma m_0 c^2}}$$

Electron beam parameters at Interaction Points

Energy (MeV)	80-720
Bunch charge (pC)	25-400
Bunch length (μm)	100-400
$\varepsilon_{n\_x,y}$ (mm-mrad)	0.2-0.6
Bunch Energy spread (%)	0.04-0.1
Focal spot size (μm)	> 15
# bunches in the train	≤ 32
Bunch separation (nsec)	16
energy variation along the train	0.1 %
Energy jitter shot-to-shot	0.1 %
Emittance dilution due to beam breakup	< 10%
Time arrival jitter (psec)	< 0.5
Pointing jitter (μm)	1

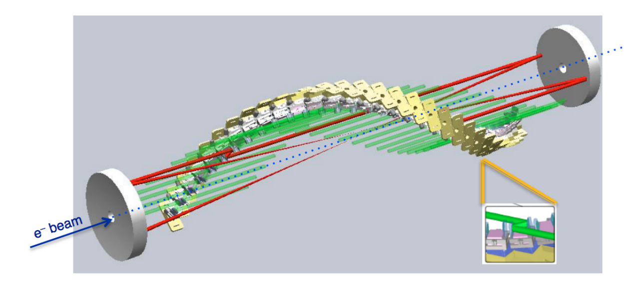
Laser beam Recirculator parameters

	Low Energy Interaction	High Energy Interaction
Distance between the two Parabolic Reflectors	2.38 *m*	2.38 *m*
Collision Angle	7.5°	7.5°
beam waist w_0	28 *μm*	28 *μm*
rotation at IP of linear laser polarization (along 32 passes)	≥ 1°	≤ 1°
integrated luminosity over 32 passes	> 90 %	> 90 %
Mirrors parallelism default	≤ 10 *μrad*	≤ 10 *μrad*
Mirrors alignment tolerance	≤ 10 *μm*	≤ 10 *μm*
Sinchronization to an ext. clock	< 1 *psec*	< 1 *psec*

Yb:Yag Collision Laser beam parameters

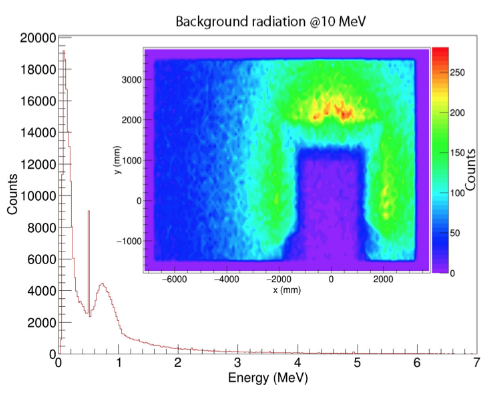
	Low Energy Interaction	High Energy Interaction
Pulse energy (*J*)	0.2	2x0.2
Wavelength (*eV,nm*)	2.3,515	2.3,515
FWHM pulse length (*ps*)	3.5	3.5
Repetition Rate (*Hz*)	100	100
M^2	≤ 1.2	≤ 1.2
Focal spot size w_0 (*μm*)	> 28	> 28
Bandwidth (*rms*)	0.1 %	0.1 %
Pointing Stability (*μrad*)	1	1
Sinchronization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

O. Adriani et al. arXiv:1407.3669 [physics.acc-ph] (2014)

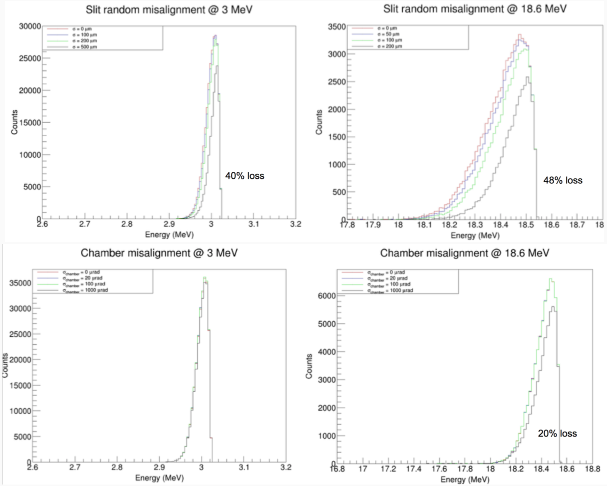


Collimator design, building and simulations

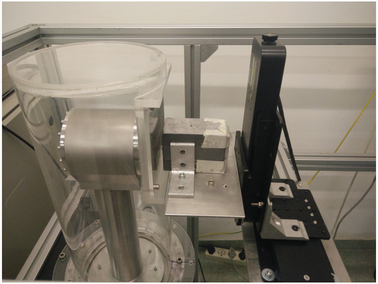
Transmission of external photons and secondary productions could have effects on the background evaluated in the detectors downstream the collimator ⟶ Spurious counts in the first GBC detector and flux beyond the concrete wall evaluated through simulation.

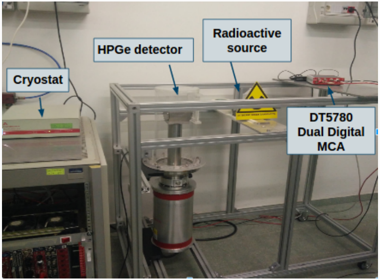


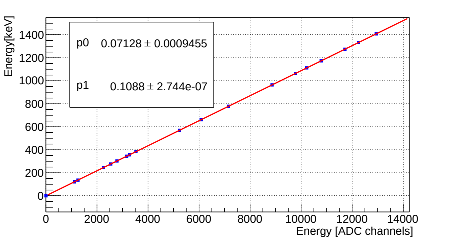
Collimator design, building and simulations

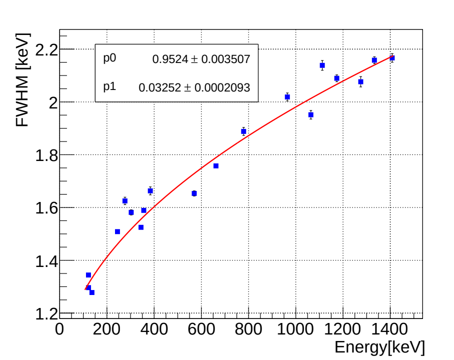


CSPEC - Compton spectrometer









Trigger and timing

Timing references:

1. 100 Hz Trigger - Macro-pulses – hardware signal
2. 62.08 MHz – Micro-pulses – hardware signal
3. Timestamp synchronized with 100 Hz – software

1. 100 Hz Trigger
   - AB2 (LGAM) - 3 NIM signals (TTL from GP08 to AB2 too long)
   - GSR (HGAM) - 1 TTL signal from GP04 (to be converted and replicated)
     (replicated NIM signal from AB2 to GSR too long)
   - TTL signals available in GP04/GP08

2. 62.08 MHz – sinusoidal tone distributed in AB2/GSR

3. 100 Hz Trigger-Timestamp
   - GPS sync
   - Distributed as EPICS variable
   - Readable with EPICS client

NRSS crystals

Crystal	$\rho(gr/cm^3)$	$\lambda(nm)$	$\tau(ns)$	$light_{output}(ph/MeV)$
BaF_2	4.88	220 310	0.88 600	12000
LYSO	7.2	420	45	32000

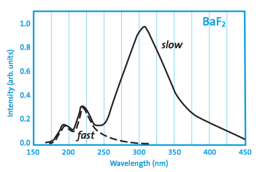
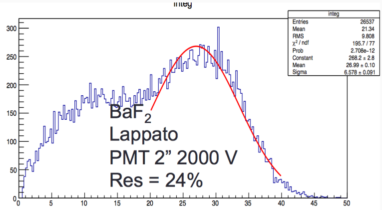
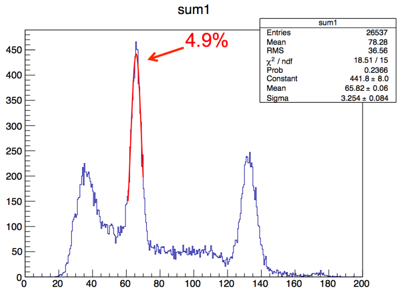


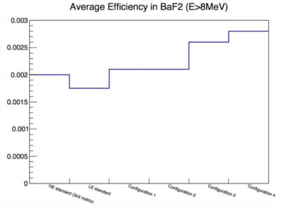
Figure 1. Scintillation emission spectrum of BaF_2





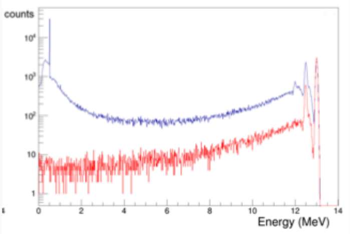
NRSS - Nuclear Resonant Scattering System

Dimension and arrangements of the crystal in both energy configurations have been optimized in simulation for collection and energy efficiency.



Crystal	PtT	$PtT_{anti-compton}$	Efficiency
BaF_2 5x5x8 cm^3	12%		0.27% (E>3MeV)
LYSO 3x3x6 cm^3	11%	45%	0.025% (peak eff.)

Crystal	PtT	$PtT_{anti-compton}$	Global Eff.
BaF_2 5x5x11 cm^3	3%		0.20% (E>8 MeV)
LYSO 5x5x9 cm^3	7%	51%	0.04% (peak eff.)



Simulation at 13MeV

Effects of the anti-Compton shielding in LYSO spectrum for ES operation mode.