A collimation system for ELI-NP Gamma Beam System – design and simulation of performance

G. Paternò[1] , P. Cardarelli [1] , M. Marziani[1] , E. Bagli[1] , F. Evangelisti [1] , M. Andreotti[1] , M. Gambaccini[1] ,
V. Petrillo [2] , I. Debrot[2] , A. Bacci[2] ,
C. Vaccarezza [3] , A. Variola[3],
L. Palumbo[4]

[1] INFN - Ferrara, [2] INFN - Milano, [3] INFN - LNF, [4] Università La Sapienza - Roma

Channeling 2016, Desenzano del Garda, 29 September 2016

EuroGammaS

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

The Extreme Light Infrastructure – ELI Project

ELI is a **European Project**, involving nearly 40 research and academic institutions from 13 EU Members Countries, forming a pan-European facility, that aims to host frontier **high-power lasers**, as well as various **radiation beamlines** (electrons, protons, X-rays and gamma rays) for different applications.

- **ELI-Nuclear Physics** (Bucharest, Romania): dedicated to the development of PW laser beams and the generation of **intense gamma beams** for frontier research in nuclear physics.
- **ELI-Beamlines** (Prague, Czech Republic) highly competitive source of extremely short pulse X-rays, accelerated electrons, or protons for applications (also biomedical).
- **ELI-Attosecond** (Szeged, Hungary) ultrafast light sources (coherent XUV and X-ray radiation) including single attosecond pulses, to investigate electron dynamics in atoms, molecules, plasmas and solids.

EuroGammaS for ELI-NP Gamma Beam System

One of the goals of the ELI-NP infrastructure is the production of a gamma beam (ELI-NP-GBS) using **Inverse Compton Scattering** of laser light from an accelerated electron beam for nuclear physics experiments.

- **The produced gamma beam is expected to have:**

- Energy tunable in the interval between **0.2 MeV and 20 MeV**,
- Energy bandwidth **$\Delta E/E < 0.5\%$**,
- About **10^8 photons per second within FWHM.**

- EuroGammaS association is composed by INFN, as leader, the Università degli Studi di Roma "La Sapienza", CNRS, ACP S.A.S., Alsyom S.A.S., Comeb Srl, ScandiNova Systems AB.

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

EuroGammaS

http://www.e-gammas.com

ELI-NP Gamma Beam System parameter list

Table 63. Gamma-ray beam for 3 selected collision examples (from Start-to-end simulations)

all quantities are rms	Low Energy Interaction	Low Energy Interaction	High Energy Interaction	High Energy Interaction
Energy (MeV)	2.00	3.45	9.87	19.5
Spectral Density (ph/sec.eV)	39,760	21,840	16,860	8,400
Bandwidth (%)	0.5	0.5	0.5	0.5
# photons per shot within FWHM	$1.2 \cdot 10^5$	$1.1 \cdot 10^5$	$2.6 \cdot 10^5$	$2.5 \cdot 10^5$
# photons/sec within FWHM	$4.0 \cdot 10^8$	$3.7 \cdot 10^8$	$8.3 \cdot 10^8$	$8.1 \cdot 10^8$
Source rms size (μm)	12	11	11	10
Source rms divergence (μrad)	140	100	50	40
Peak Brilliance (N_{ph}/sec·mm^{2}mrad^2·0.1%)	$9.1 \cdot 10^{21}$	$1.9 \cdot 10^{22}$	$1.8 \cdot 10^{23}$	$3.3 \cdot 10^{23}$
Average Brilliance (N_{ph}/sec·mm^{2}mrad^2·0.1%)	$2.9 \cdot 10^{13}$	$6.2 \cdot 10^{13}$	$5.9 \cdot 10^{14}$	$1.1 \cdot 10^{15}$
Rad. pulse length (rms, psec)	0.92	0.91	0.95	0.9
Linear Polarization (%)	> 99.8	> 99.8	> 99.8	> 99.8
Macro rep. rate (Hz)	100	100	100	100
# of pulses per macropulse	32	32	32	32
Pulse-to-pulse sep. (nsec)	16	16	16	16
Contrast ratio 1st / 2nd harmonic	$1.5 \cdot 10^5$	$8.5 \cdot 10^4$	$7.0 \cdot 10^4$	$4.4 \cdot 10^4$
Luminosity @ (1,0.5) psec delay	(94,99) %	(92,98) %	(91,98) %	(85,96) %
Lumin. @ (5,2) μm misalignment	(98,99) %	(96,99) %	(90,97) %	(87,95) %

Gamma beam specifications

Photon energy	0.2-19.5 *MeV*
Spectral Density	$0.8\text{-}4 \cdot 10^4$ *ph/sec.eV*
Bandwidth (rms)	≤ 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·mm^{2}mrad^2·0.1%)	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*

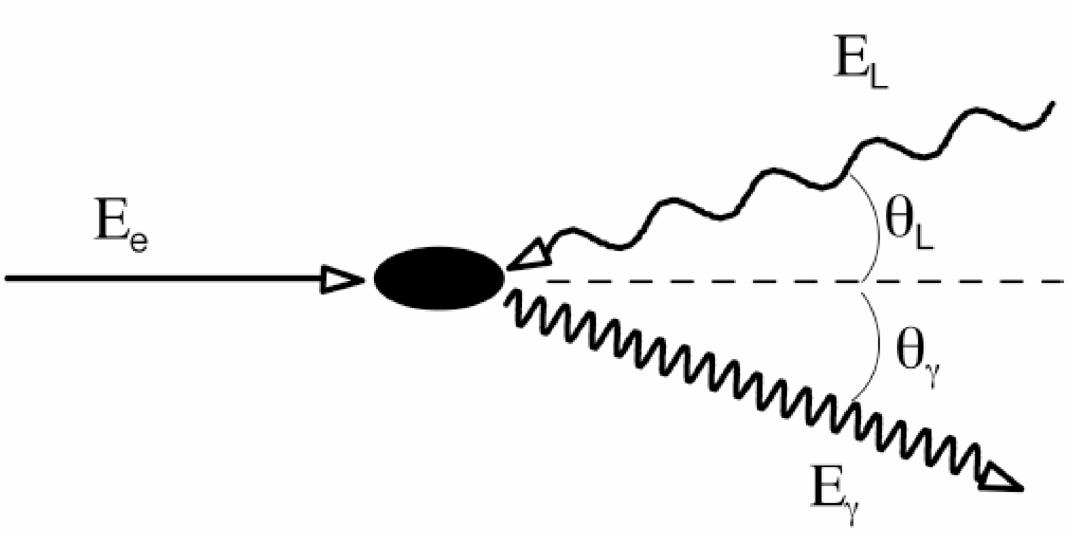
Technical Design Report

EuroGammaS proposal for the ELI-NP Gamma beam System

With 73 tables and 230 figures

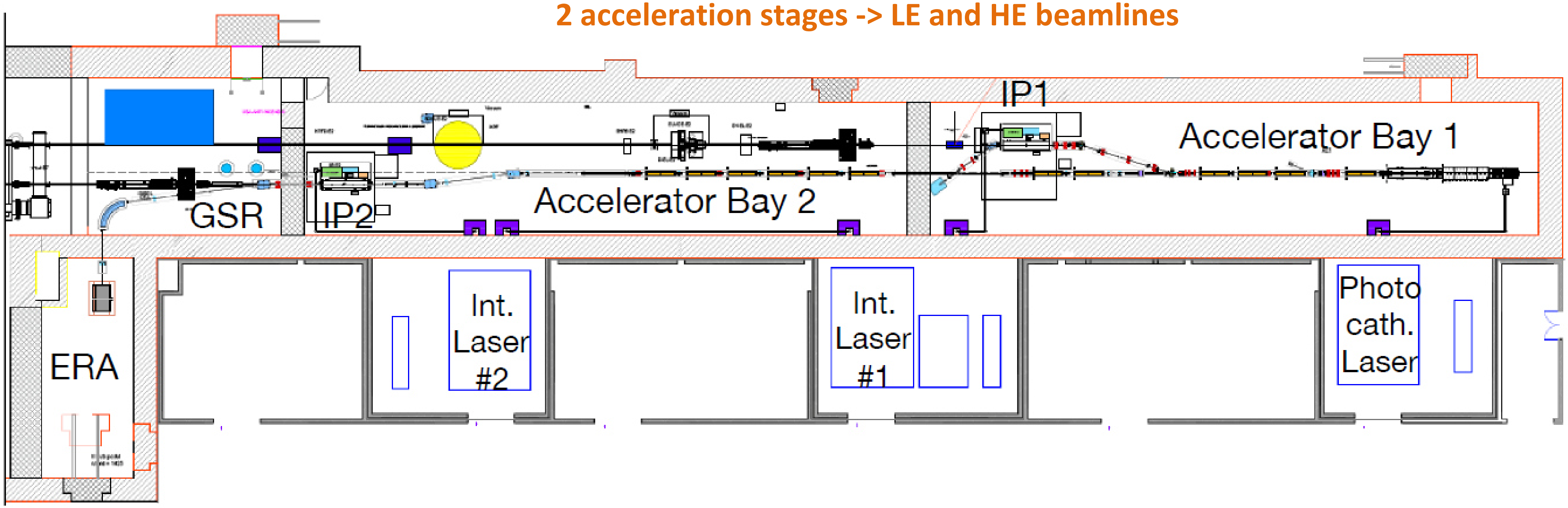
O. Adriani, S. Albergo, D. Alesini, M. Anania, D. Angal-Kalinin, P. Antici, A. Bacci, R. Bedogni, M. Bellaveglia, C. Biscari, N. Bliss, R. Boni, M. Boscolo, F. Broggi, P. Cardarelli, K. Cassou, M. Castellano, L. Catani, I. Chaikovska, E. Chiadroni, R. Chiche, A. Cianchi, J. Clarke, A. Clozza, M. Coppola, A. Courjaud, C. Curatolo, O. Dadoun, N. Delerue, C. De Martinis, G. Di Domenico, E. Di Pasquale, G. Di Pirro, A. Drago, F. Druon, K. Dupraz, F. Egal, A. Esposito, F. Falcoz, B. Fell, M. Ferrario, L. Ficcadenti, P. Fichot, A. Gallo, M. Gambaccini, G. Gatti, P. Georges, A. Ghigo, A. Goulden, G. Graziani, D. Guibout, O. Guilbaud, M. Hanna, J. Herbert, T. Hovsepian, E. Iarocci, P. Iorio, S. Jamison, S. Kazamias, F. Labaye, L. Lancia, F. Marcellini, A. Martens, C. Maroli, B. Martlew, M. Marziani, G. Mazzitelli, P. McIntosh, M. Migliorati, A. Mostacci, A. Mueller, V. Nardone, E. Pace, D.T. Palmer, L. Palumbo, A. Pelorosso, F.X. Perin, G. Passaleva, L. Pellegrino, V. Petrillo, M. Pittman, G. Riboulet, R. Ricci, C. Ronsivalle, D. Ros, A. Rossi, L. Serafini, M. Serio, F. Sgamma, R. Smith, S. Smith, V. Soskov, B. Spataro, M. Statera, A. Stecchi, A. Stella, A. Stocchi, S. Tocci, P. Tomassini, S. Tomassini, A. Tricomi, C. Vaccarezza, A. Variola, M. Veltri, S. Vescovi, F. Villa, F. Wang, E. Yildiz, F. Zomer

Inverse Compton Scattering

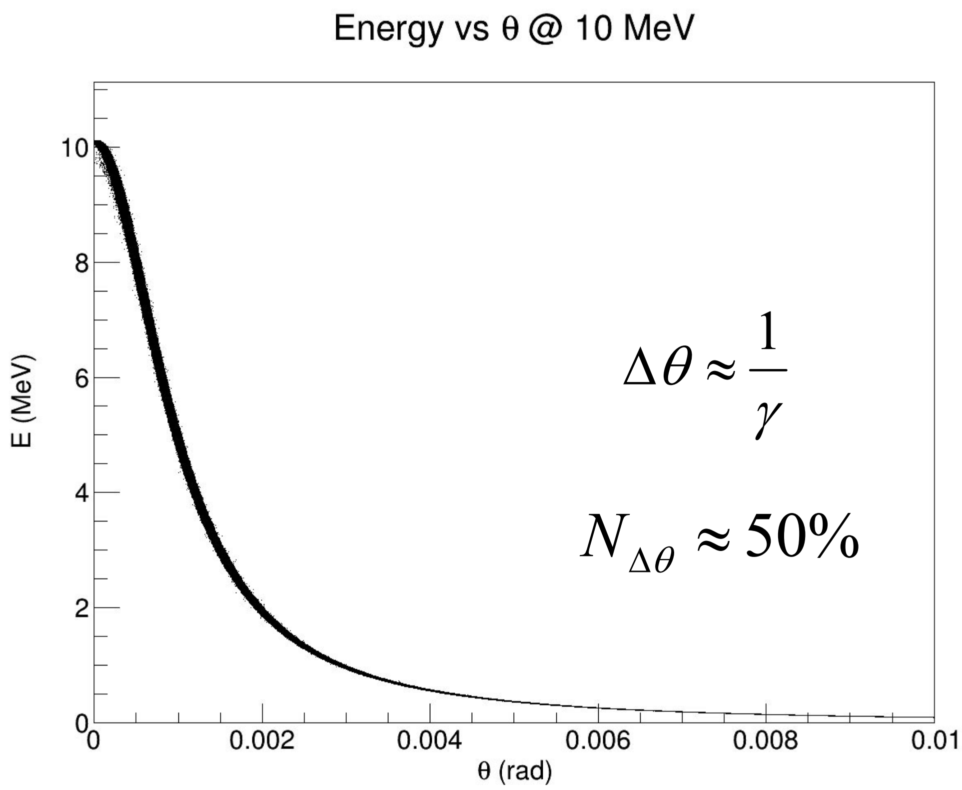


$$E_\gamma = \frac{2\gamma_e^2(1+\cos\theta_L)}{1+(\gamma_e\theta_\gamma)^2 + a_0^2 + \frac{4\gamma_e E_L}{m_e c^2}} E_L$$

2 acceleration stages -> LE and HE beamlines

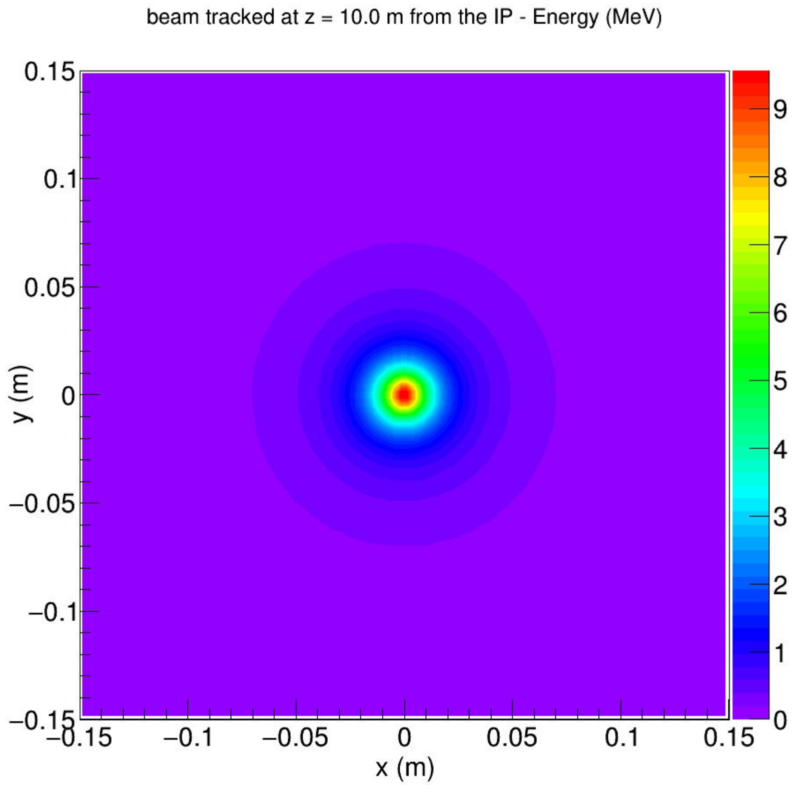


Inverse Compton Scattering

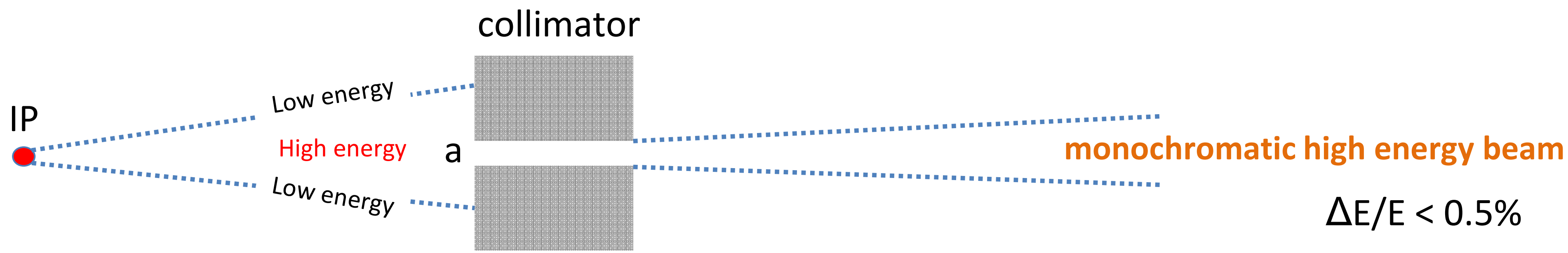


$$\Delta\theta \approx \frac{1}{\gamma}$$

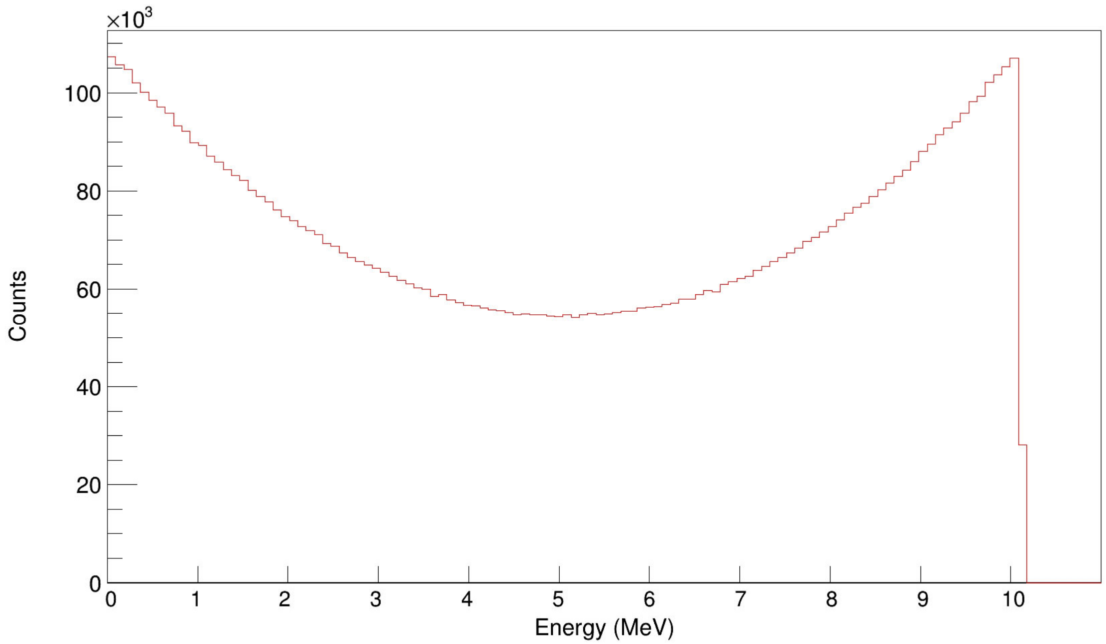
$$N_{\Delta\theta} \approx 50\%$$



- **Inverse Compton radiation is not intrinsically monochromatic**, the energy is related to the emission angle.
- The required **energy bandwidth** can be obtained by properly **collimating the gamma beam**.

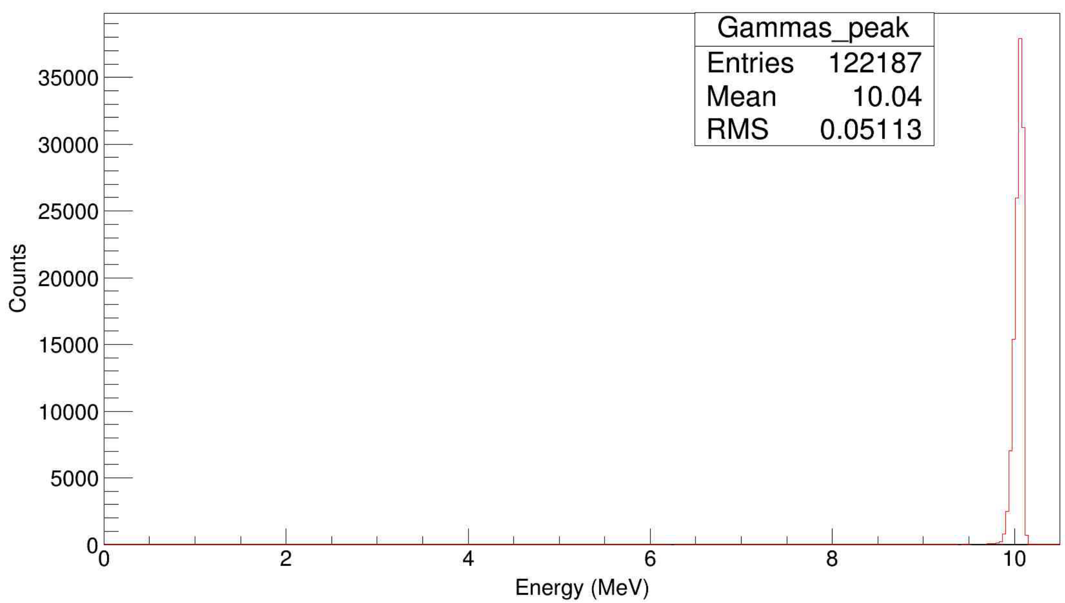


Effect of collimation



Beam spectrum at the IP

Collimated beam spectrum

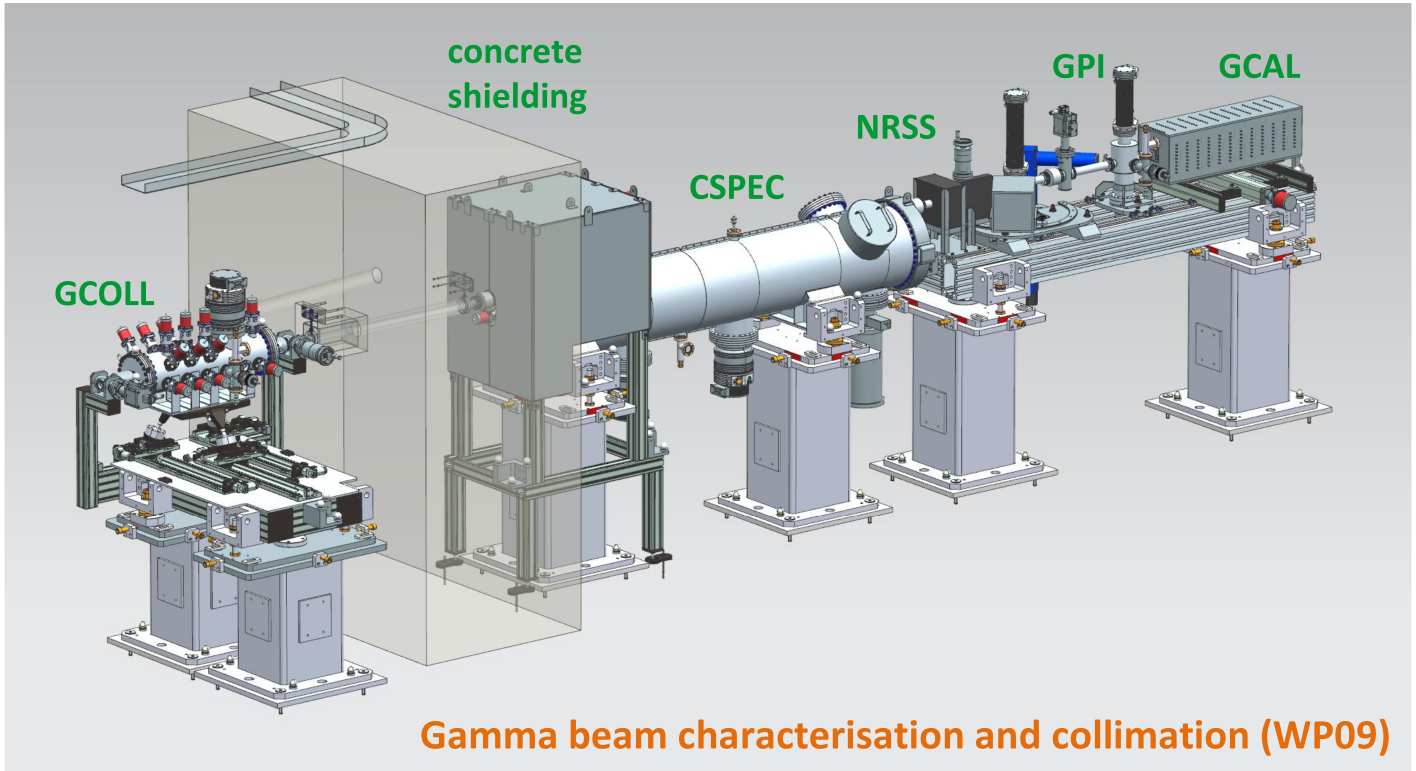


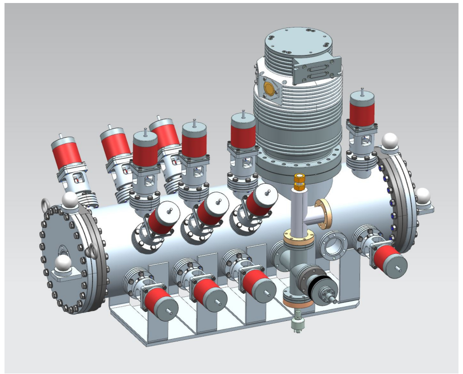
EuroGammas collimation system

- To obtain an **energy bandwidth < 0.5 % at 0.2 - 20 MeV** collimation apertures that varies from about **14 mm to 1 mm**, demanding a very challenging design.

Main requirements are:

- **Low transmission of gamma photons** (high density and atomic number material (vacuum compatible))
- **Continuously adjustable aperture** (to adjust the energy bandwidth in the entire energy range)
- **Avoid contamination of the primary beam** with production of secondary radiation



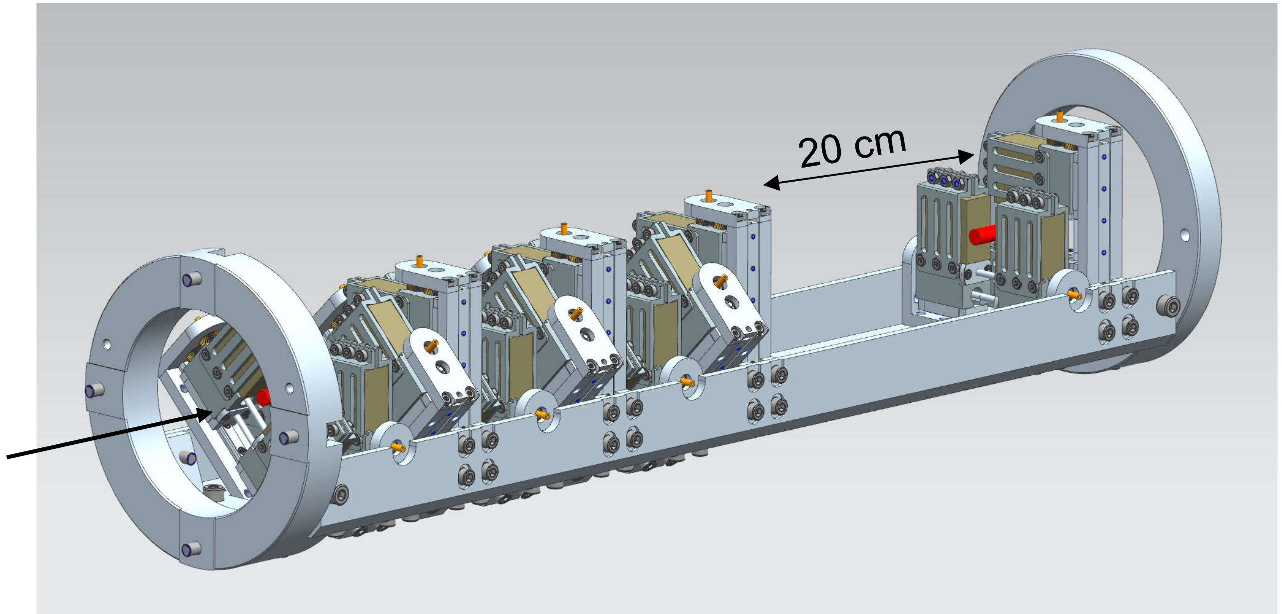


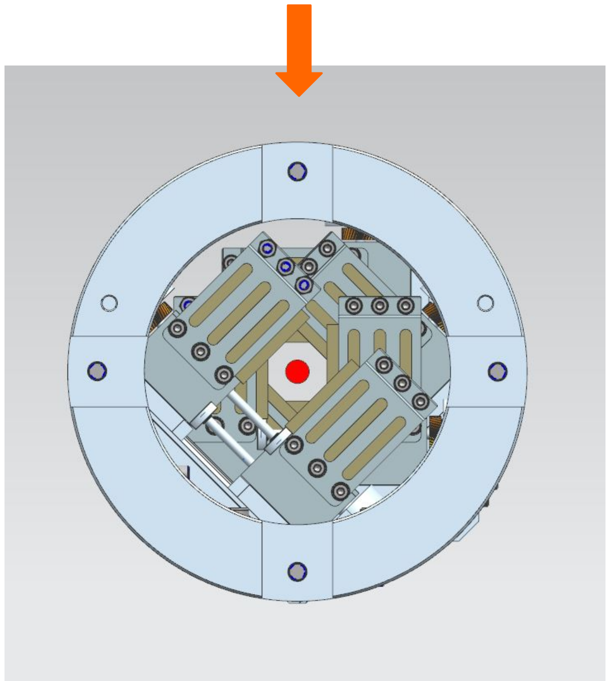
- Collimation system in a **vacuum chamber**.

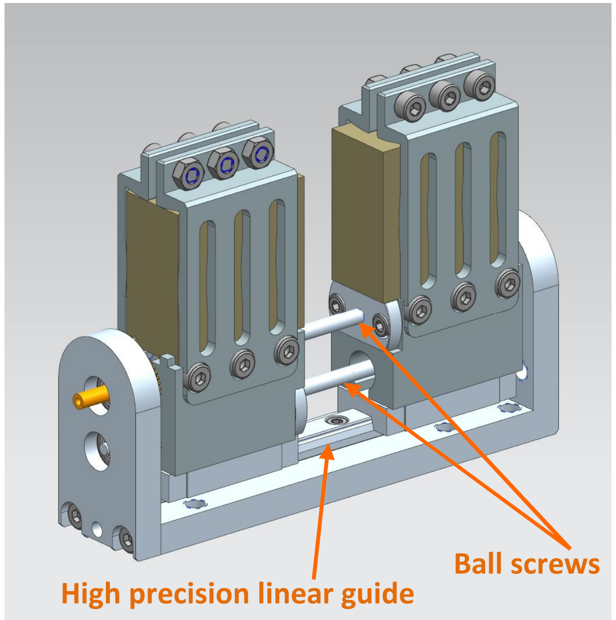
- A mechanical device provide **fine adjustment** in X , Y, θ (pitch) and Φ (yaw).

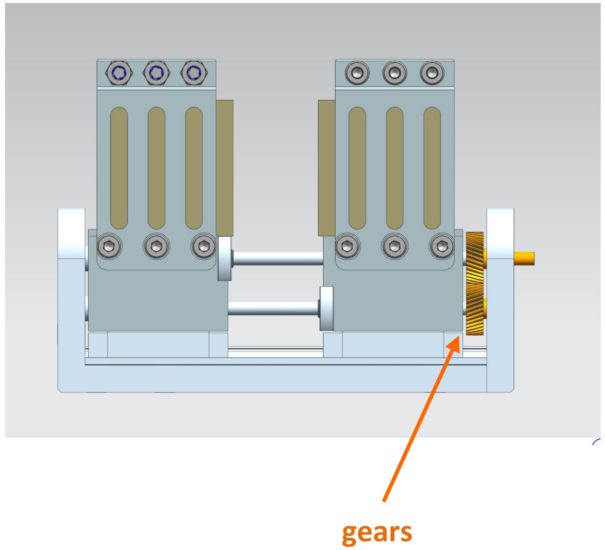
EuroGammas collimation system

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



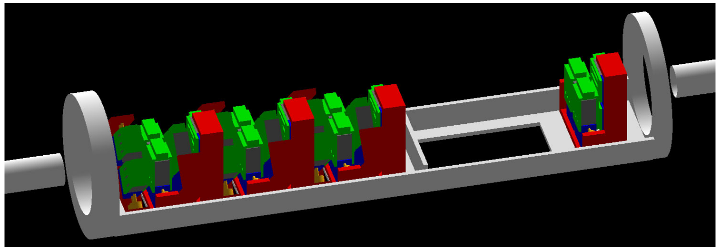


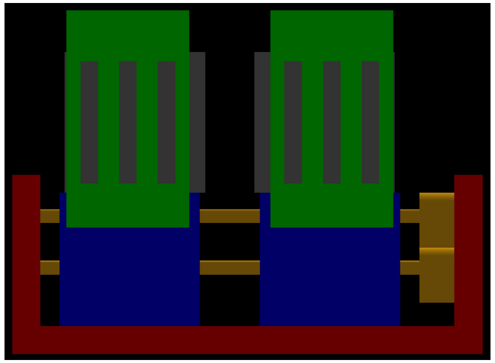




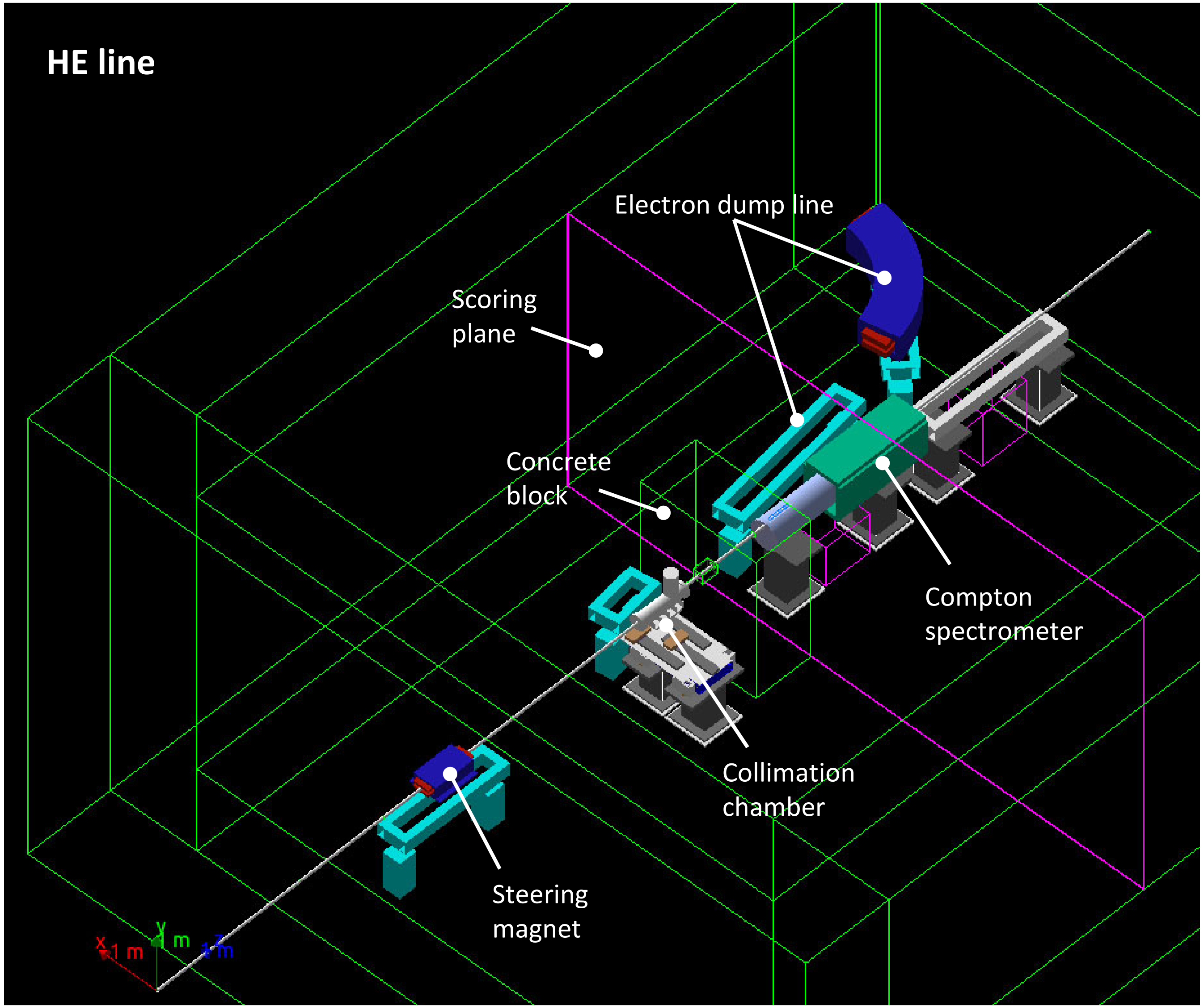
Collimation system - Monte Carlo simulations

- To evaluate the **collimation system performance** a set of Monte Carlo simulations has been carried out.
- A dedicated **Geant4 application** has been developed.





A complete geometry has been implemented. It includes:
- walls, floor and roof,
- girders, pedestals and magnets,
- pipe and shielding block,
- a **detailed model of the collimation chamber** and **Compton spectrometer**.



Collimation System - Monte Carlo Simulations

- The primary gamma radiation were obtained by transporting a realistic electron beam to the IP and then simulating(1), through the **CAIN** code, the collision with the laser (**EuroGammaS WP02 - Petrillo**).

- The radiation produced at the IP is then used as an input for **Geant4** simulations.

- **Gamma beams simulated:**
  - **LE**: 0.2, 1, 2, 2.5, 3, 3.5 MeV
  - **HE**: 5, 5.8, 10, 13, 18.6, 19.5 MeV

Implementation details:

- **Physics lists**:
  - G4EmStandardPhysics_option4
  - G4HadronPhysicsQGSP_BIC_HP and for G4HadronElasticPhysicsHP

- **Cuts** set to 1 μm for all the volumes

- **Scoring** performed by using:
  - Sensitive detectors
  - G4VPrimitiveScorers
  - UserAction classes

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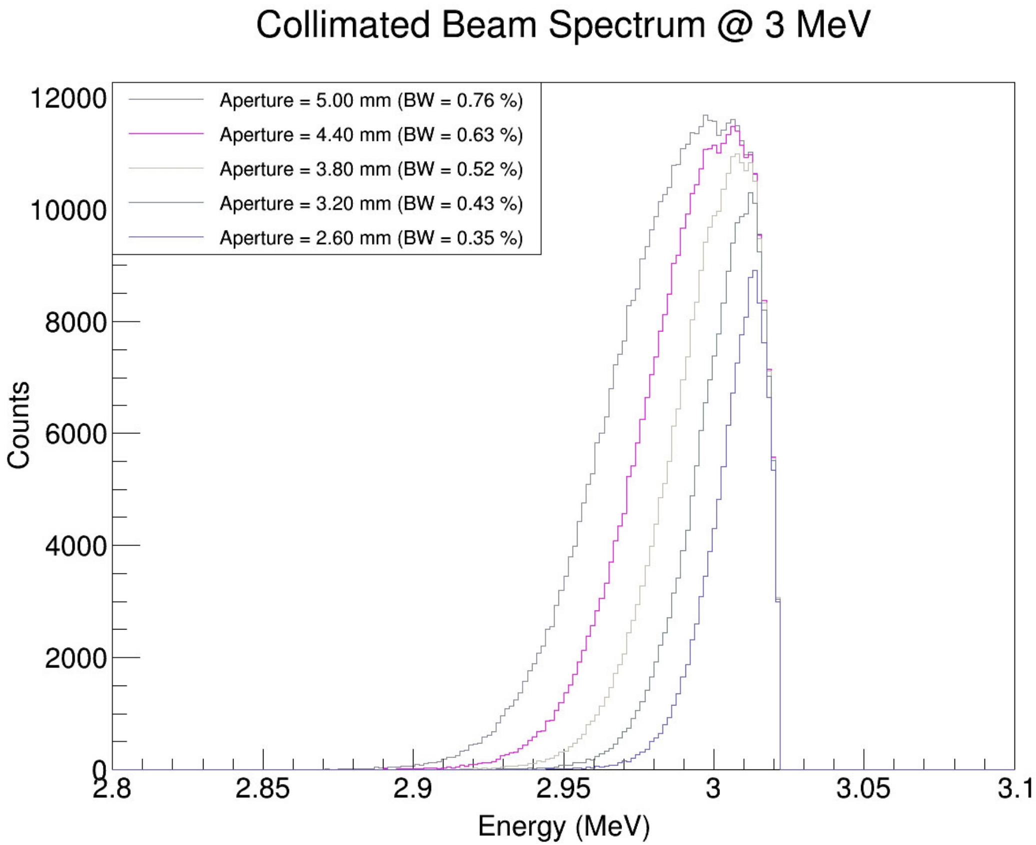
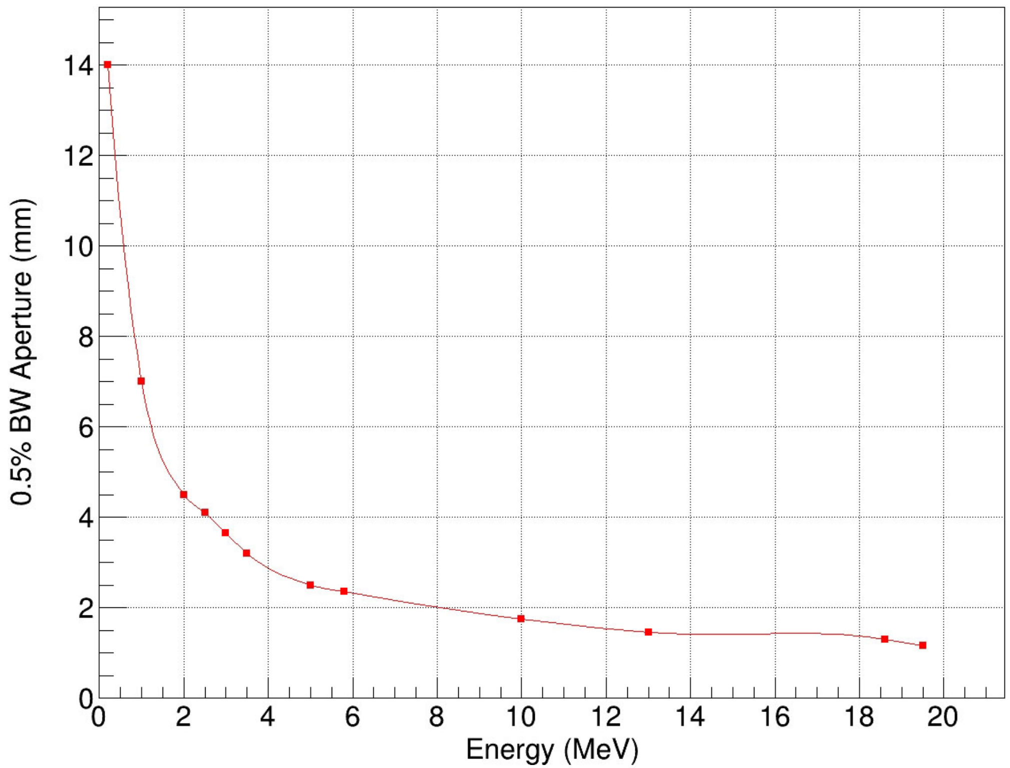
(1) Laser pulse energy 0.2 J for LE IP and 0.4 J for HE IP (Table 60 TDR).
For all simulations the electron charge per pulse is 250 pC.

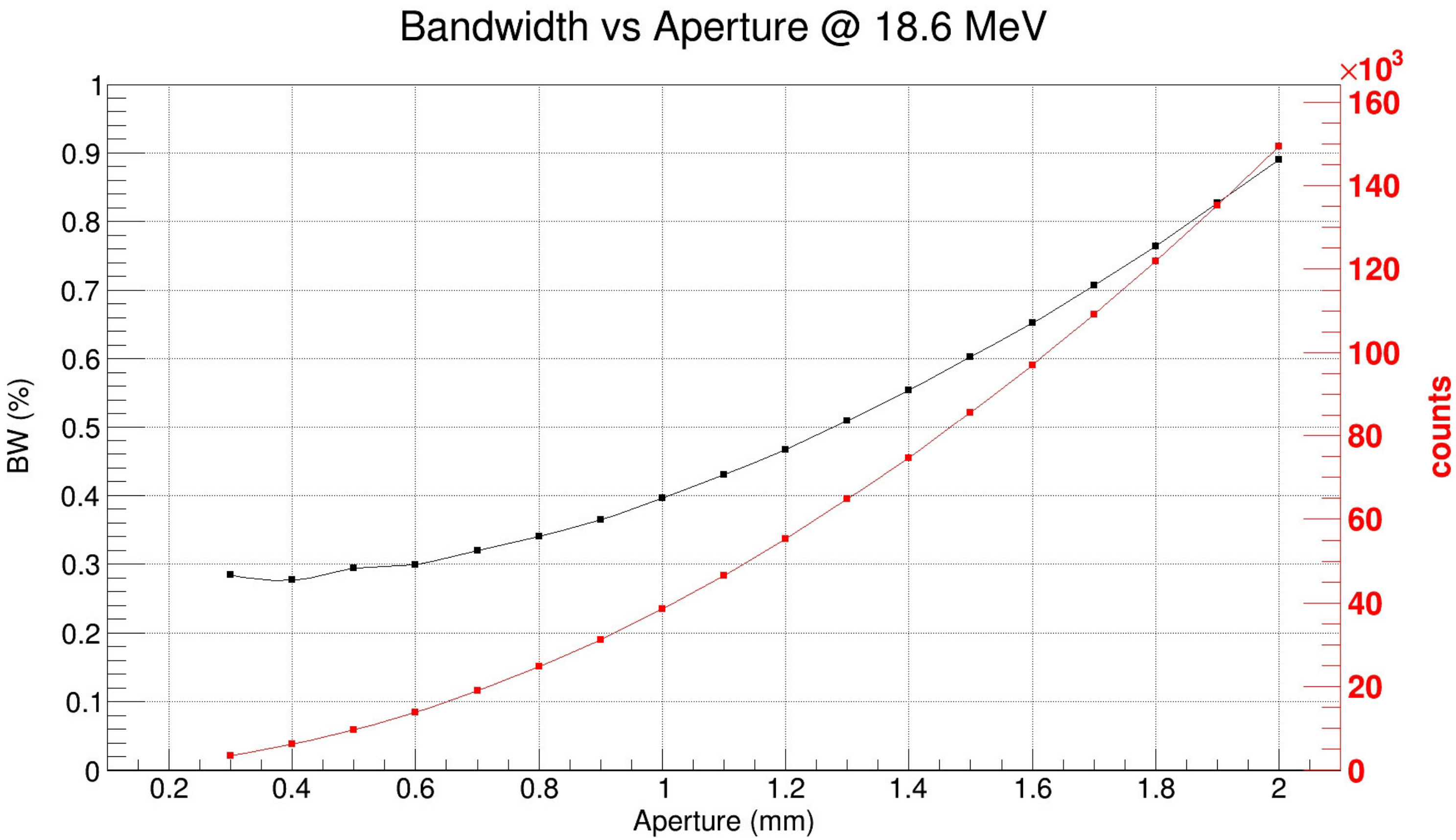
Collimation System - Expected performance

- A set of simulations to evaluate the **energy distribution as a function of the collimation aperture** was carried out for all the beams previously listed.
- The scoring was performed **inside the vacuum pipe at the exit of the concrete shielding block**.
- The results of simulations are compatible with the results of a **mathematical collimation** of the input beam ($\theta < \theta_{cut}$).





Collimation System - Expected performance



$$\frac{\Delta E}{E} = \sqrt{\Psi^4 + \left(\frac{\Delta\gamma_e}{\gamma_e}\right)^2 + \left(\frac{\Delta\varepsilon_n}{\sigma_x}\right)^2 + \left(\frac{\Delta\upsilon_L}{\upsilon_L}\right)^2 + \left(\frac{M^2\lambda_L}{2\pi w_0}\right)^4 + \left(\frac{a_0^2/3}{1+a_0^2/2}\right)^2}$$

acceptance

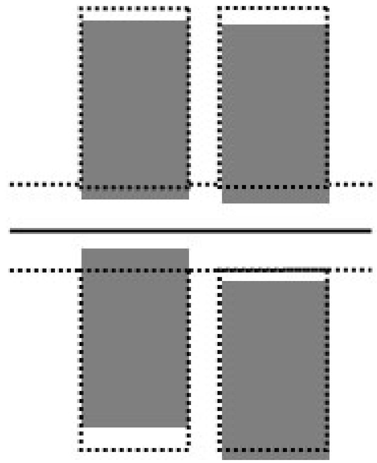
electrons

laser

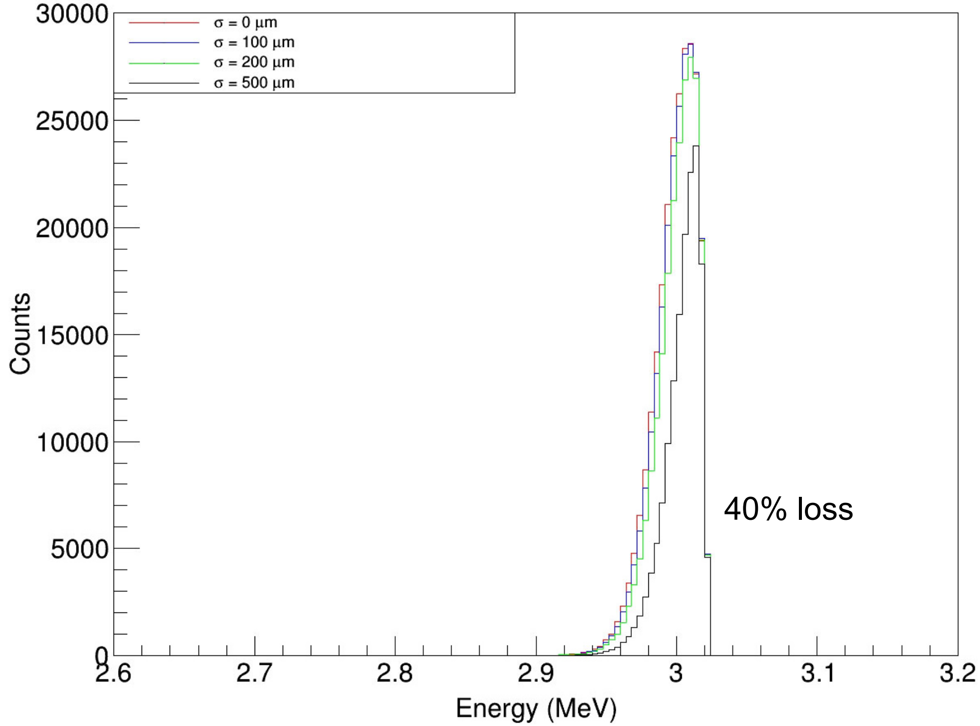
$$N = L\sigma_{th} = \frac{7.4\times10^9 U_L[J]Q[pC]\Psi^2 f}{h\upsilon_L[eV](w_0^2+2\sigma_X^2)\sqrt{1+(\sigma_z\delta/(4\sigma_x))^2}}$$

Collimation System - Slit misalignment

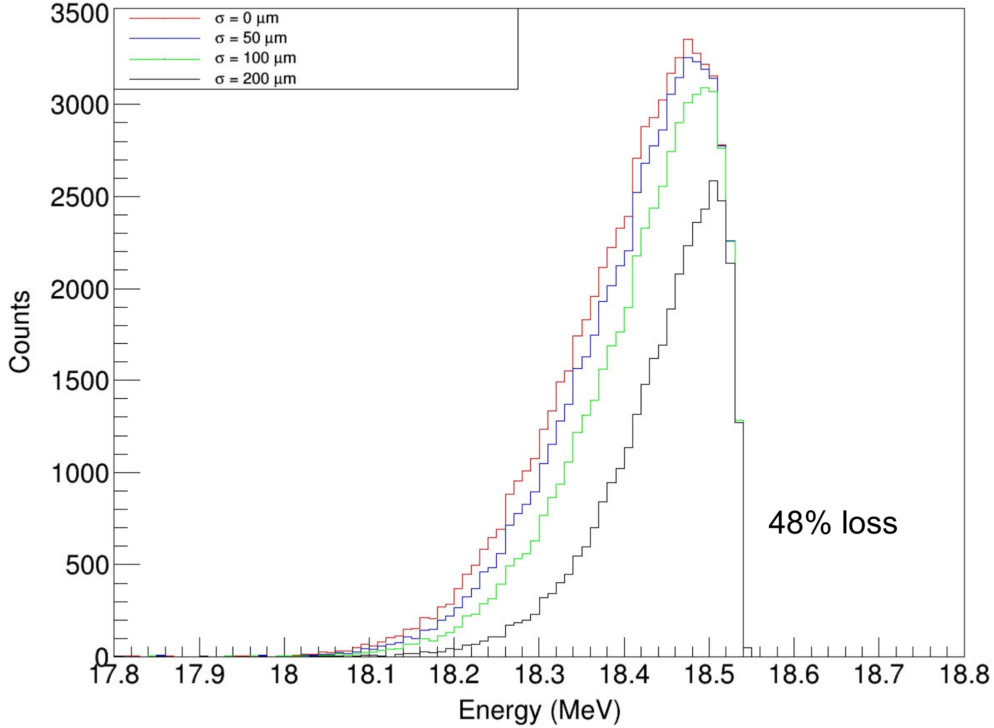
- The effect of slit misalignment with respect to the beam axis was evaluated.
- **A random misplacement** with Gaussian distribution of **increasing sigma** (50 µm -> 500 µm) was applied to each tungsten edge.
- The results show that the effect of this misplacement is **negligible up to 100 µm** (**expected 20 µm**) and in any case results in a flux and a slight bandwidth reduction. **No penumbra effects -> no bandwidth degradation emerges.**
- The effect is much **more relevant for HE** beams.



Slit random misalignment @ 3 MeV

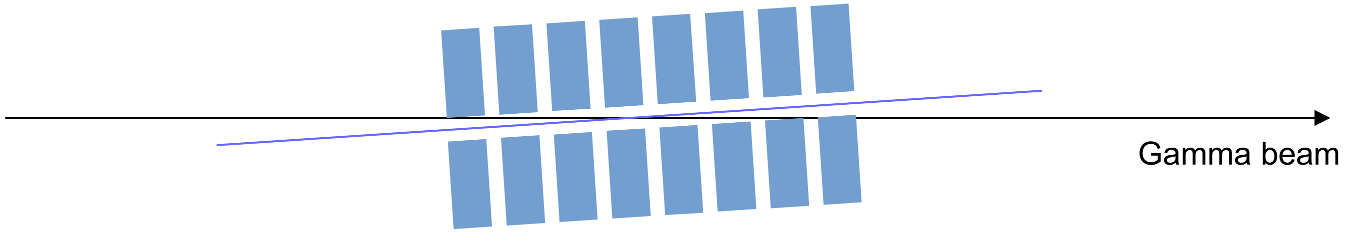


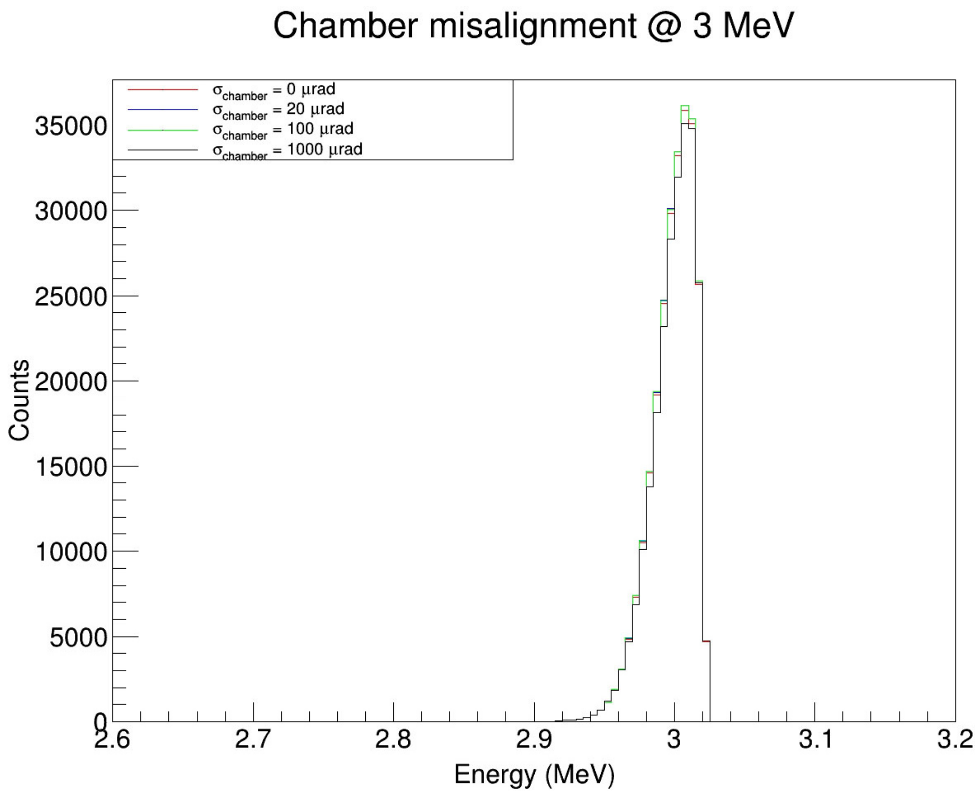
Slit random misalignment @ 18.6 MeV

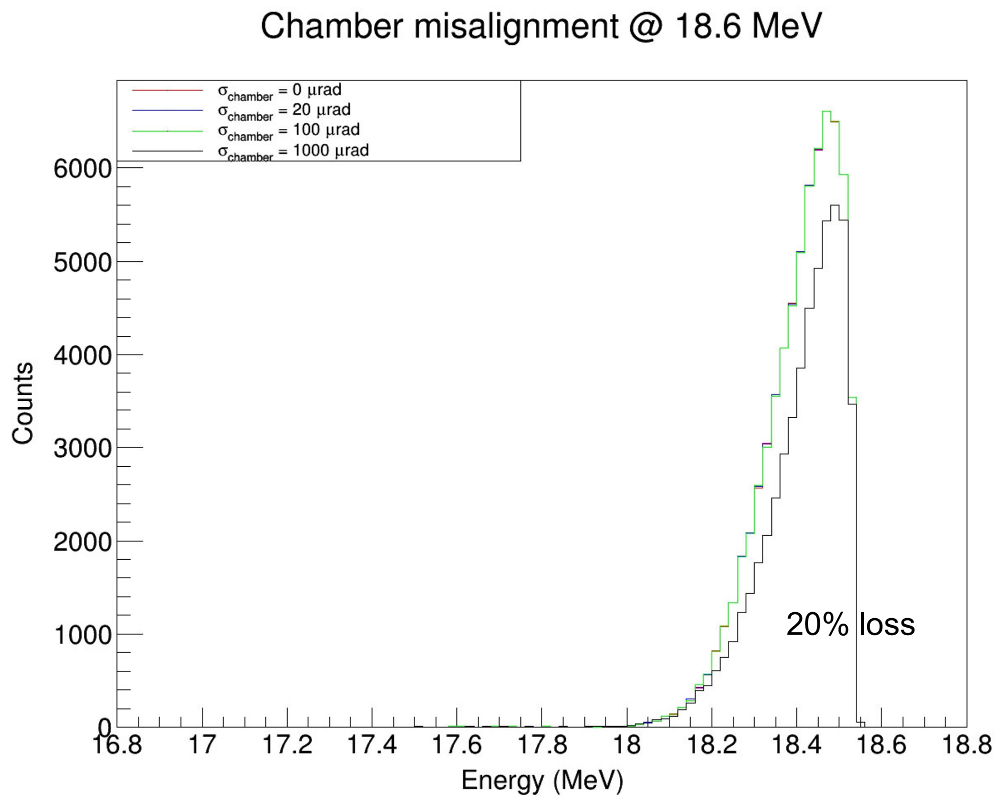


Collimation System - Chamber misalignment

- The effect the collimation chamber misalignment was also evaluated.
- The chamber was rotated on its center with respect to the beam axis by increasing angles, up to 1 mrad (**expected 0.1 mrad**).
- Misalignment causes a **reduction of the flux** and the effect is more relevant at **HE**.

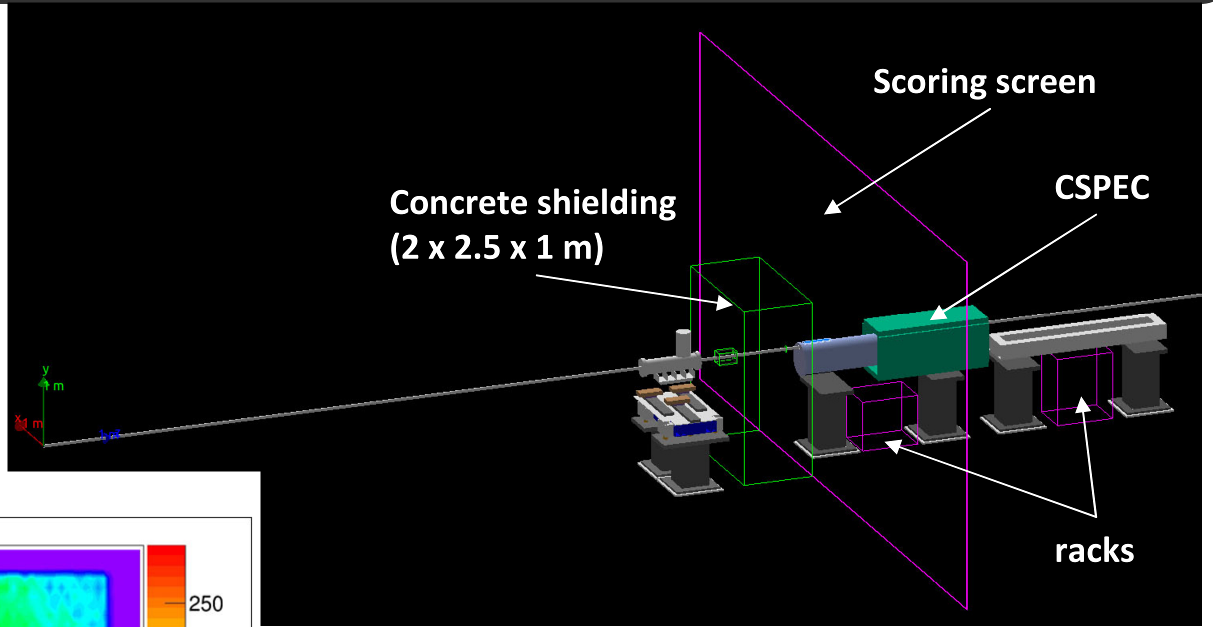


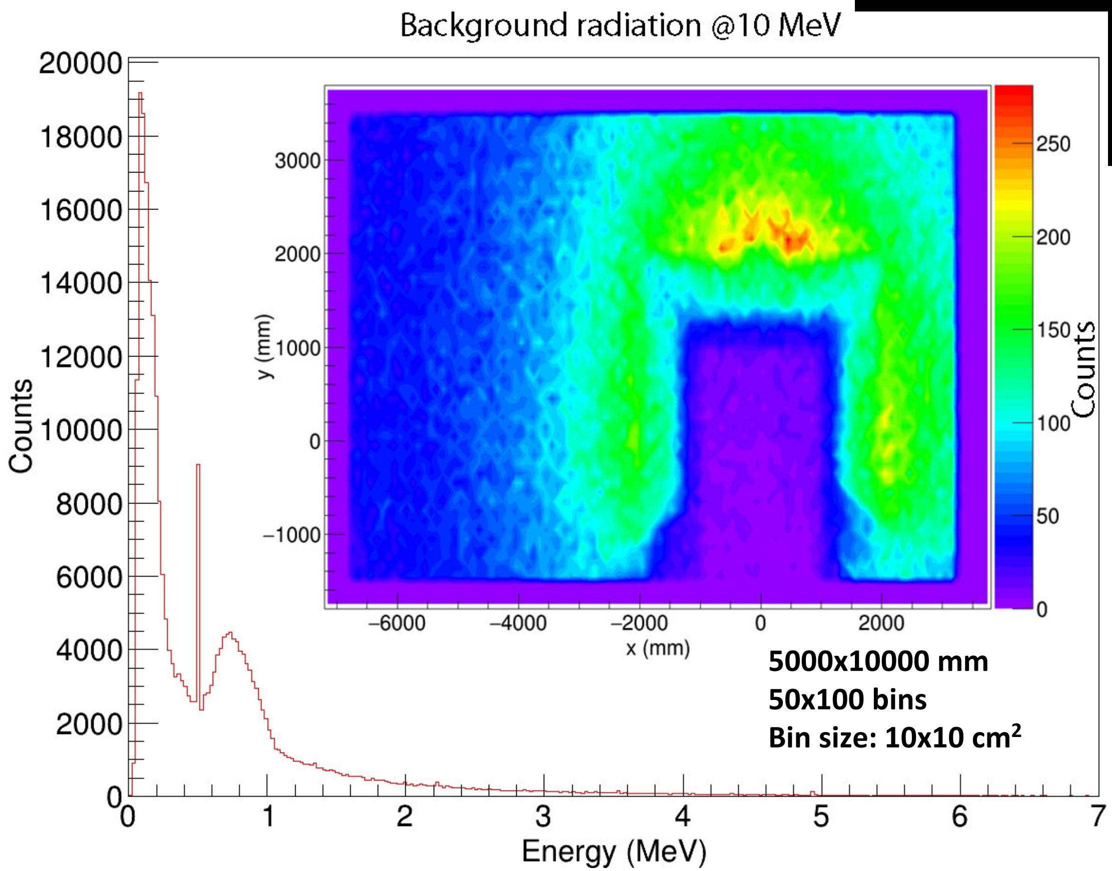




Background evaluation

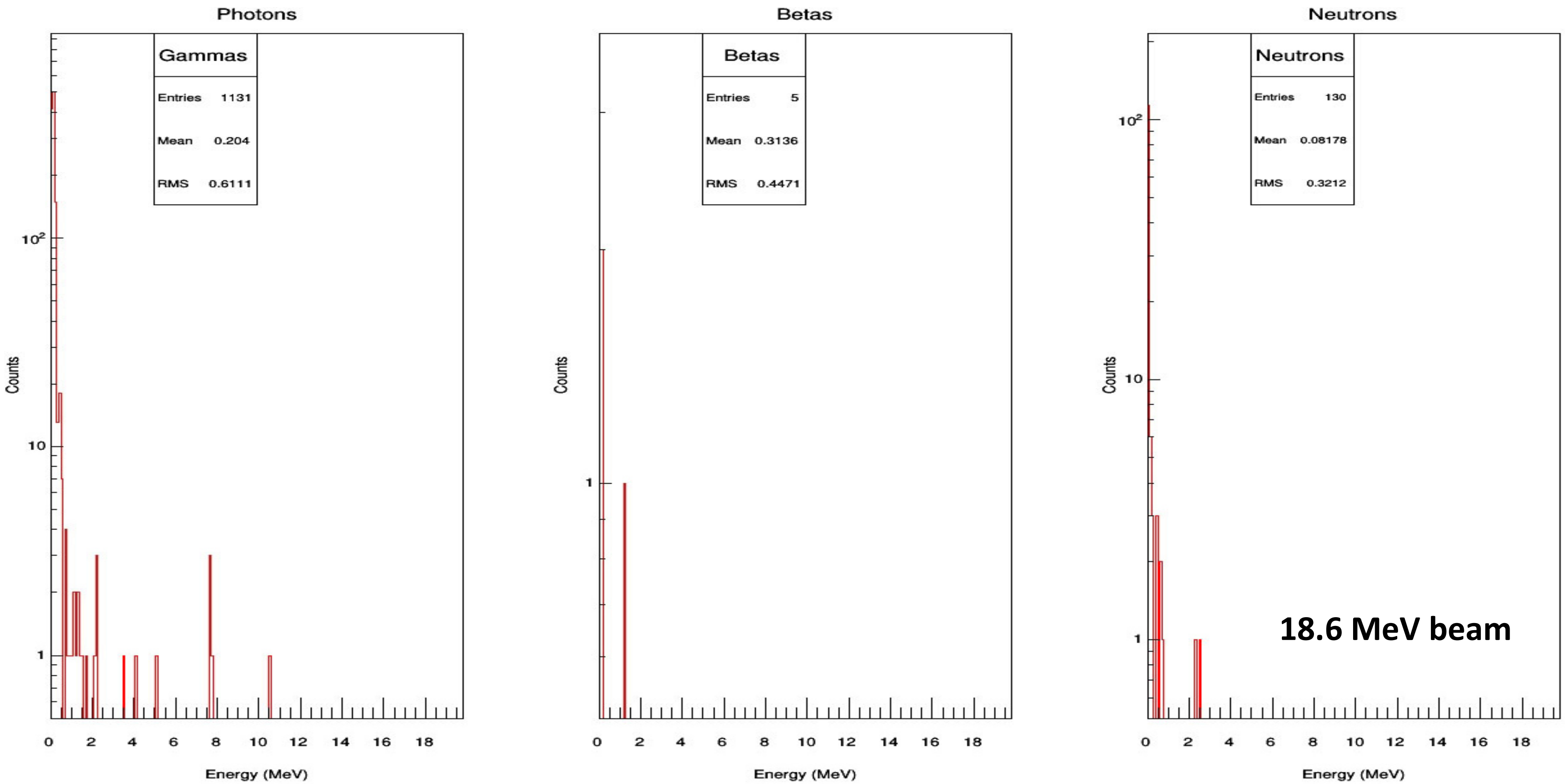
Flux of particles and **dose evaluated** in various **regions of interest**.





- Our simulations have been mainly aimed ad evaluating **the signal and the background on the detectors** downstream of the collimator.
- In the ideal case, there are **no particles in the region downstream of the concrete block** (outside of the pipe).
- Simulations of **high-statistic background** on the Ge detector of **CSPEC** as a function of misalignments **ongoing**.

Dose to racks



rack	E (MeV)	Dose rate in air (Gy/s)
1	3	4.95E-10
1	10	3.03E-11
1	18.6	3.61E-09
2	3	2.48E-10
2	10	1.46E-11
2	18.6	3.40E-09

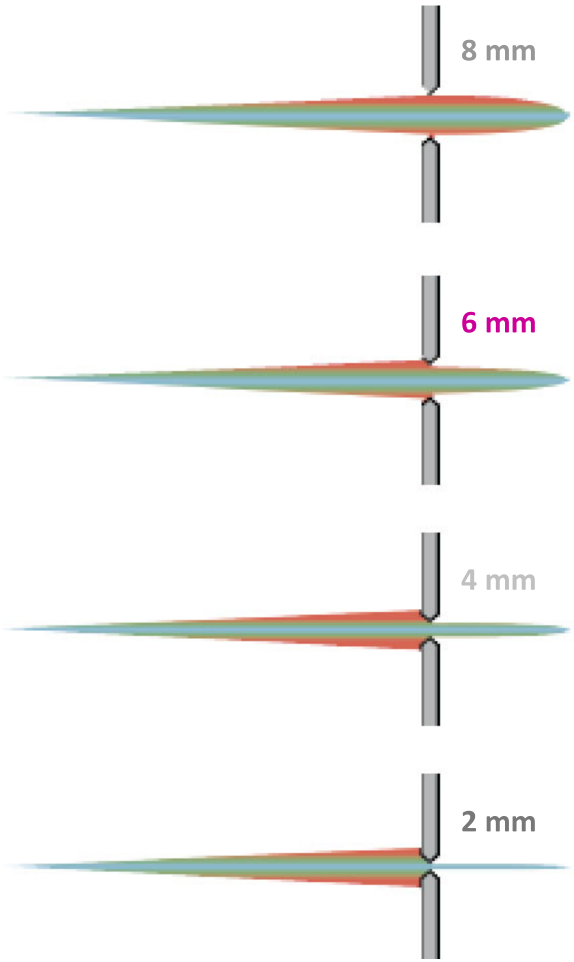
At higher energies, racks receive an higher irradiation, mainly due to low-energy scattered photons and neutrons ->
Evaluation of shielding requirement ongoing

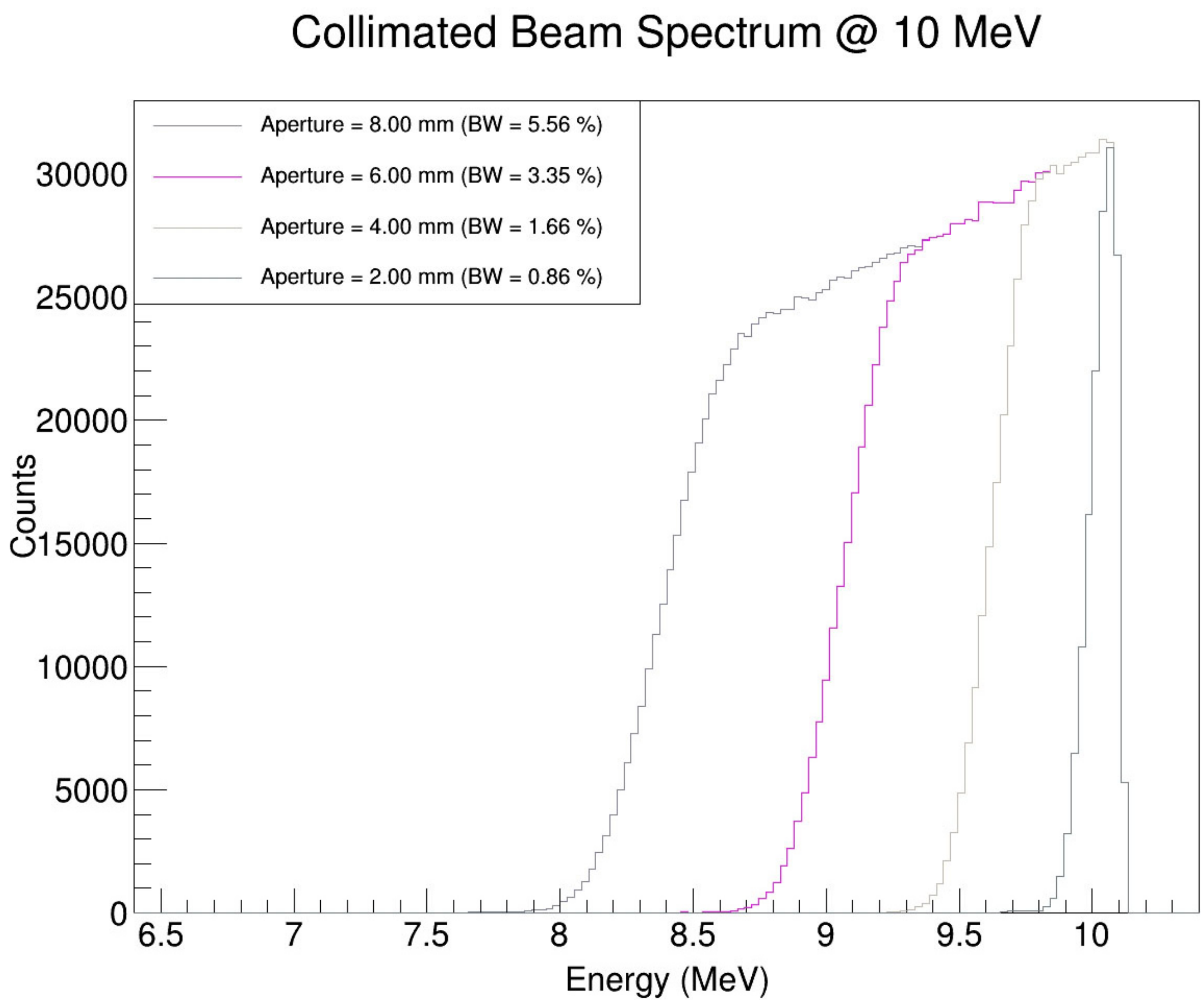
Conclusions

- An overview of the **design and simulation of the collimation system** for ELI-NP-GBS has been presented.
- The results of the simulations show that the **designed collimation system allows to obtain monochromatic beams** with an energy distribution compatible to the parameters required ($\Delta E/E < 0.5$ %).
- The study of the effect of misalignments was fundamental to **define the tolerances** required to finalize the mechanical engineering and realization of the system (**on going**).
- The **simulation of realistic collimated beams** was necessary to evaluate the expected **performance of the detectors** composing the characterization system downstream of the collimator and to finalize their design.

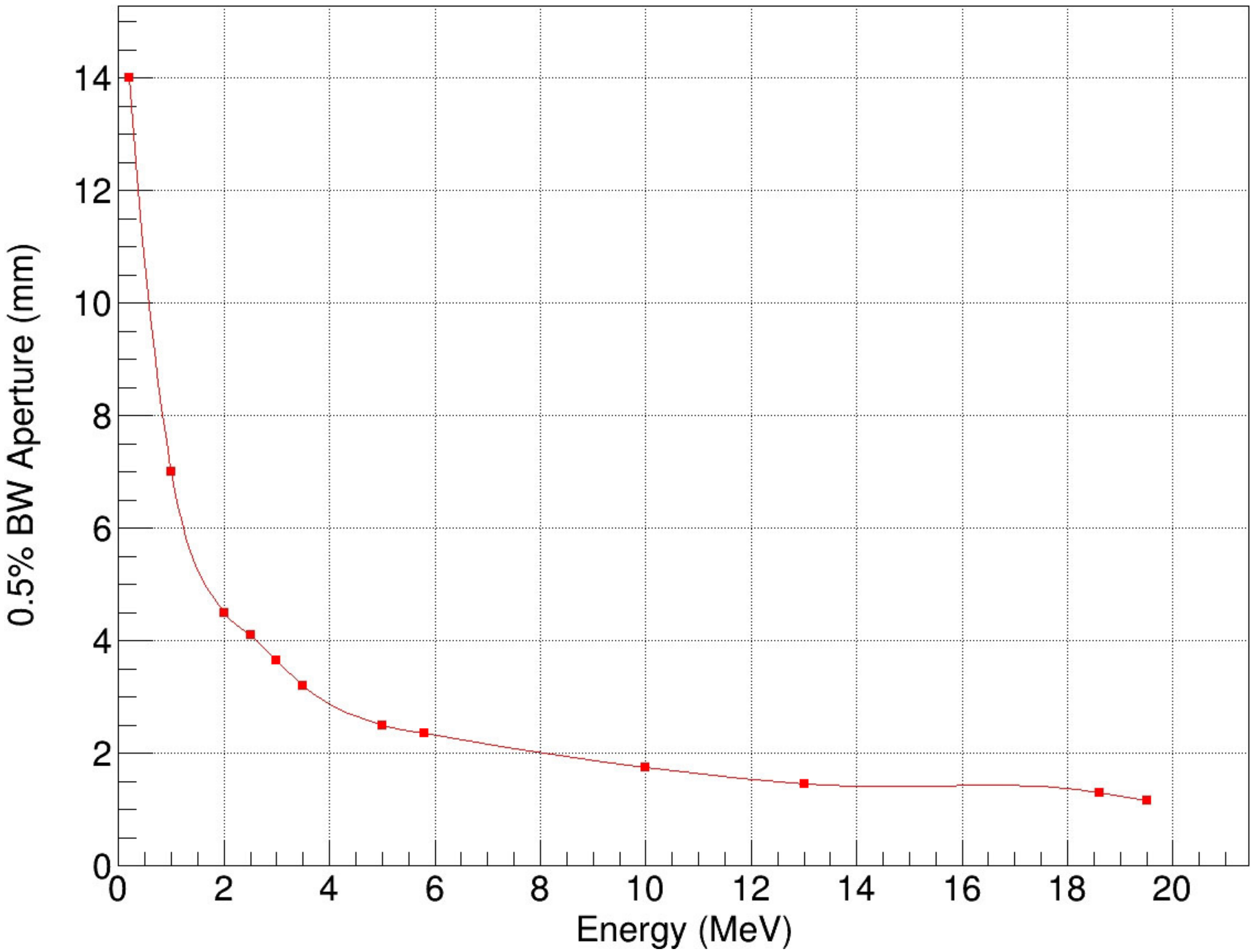
Backup slides

Collimation effect





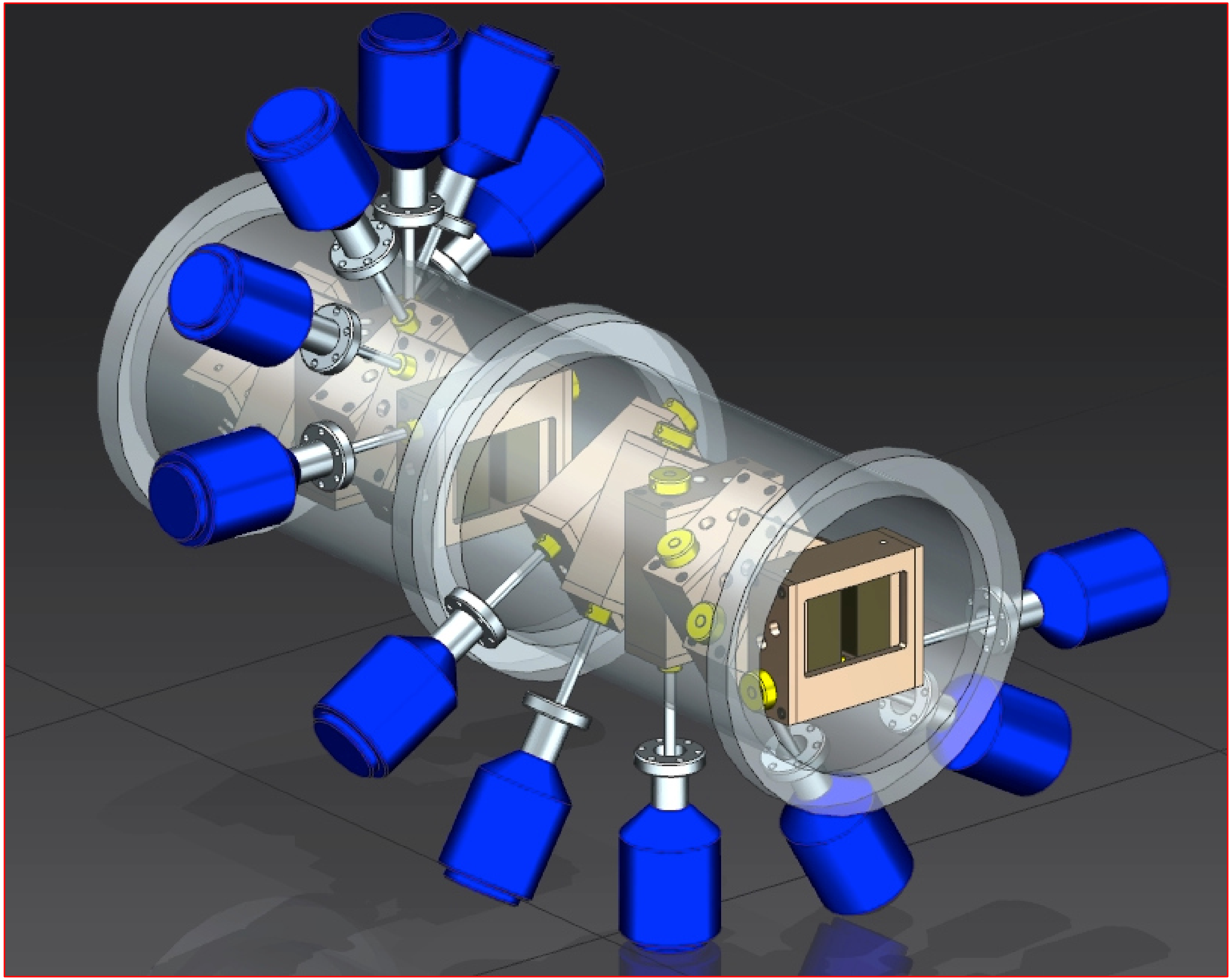
Collimation System - Expected performance



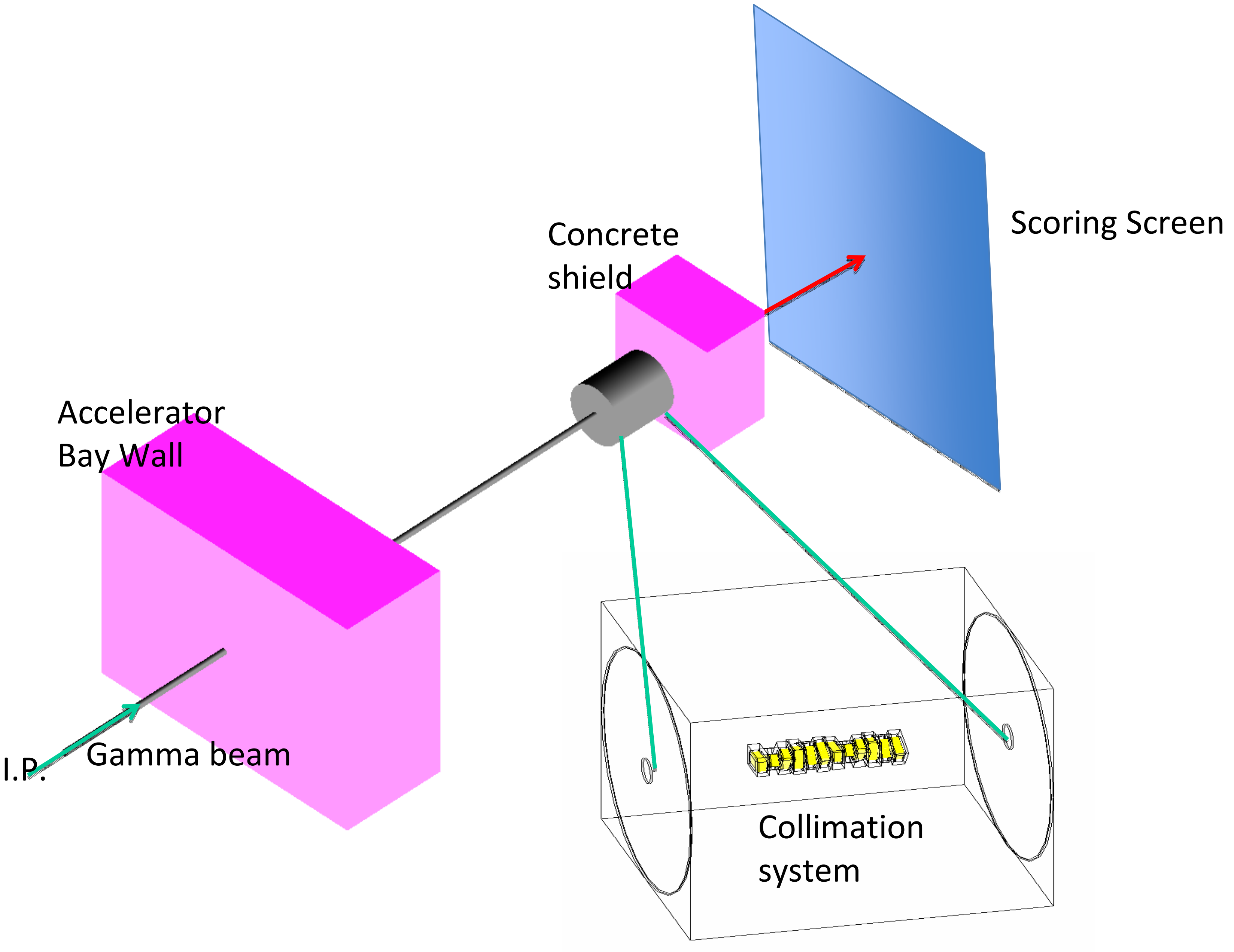
E (MeV)	A1-A4 (mm)	A5-A8 (mm)	A9-A12 (mm)	A13-A14 (mm)
3	3.53	3.53+0.022	3.53+0.044	3.53+0.100
10	1.69	1.69+0.012	1.69+0.024	1.69+0.100
18.6	1.25	1.25+0.009	1.25+0.018	1.25+0.100

Aperture of the slit at the collimator centre -> conical profile foreseen

EuroGammas collimation system – previous solution

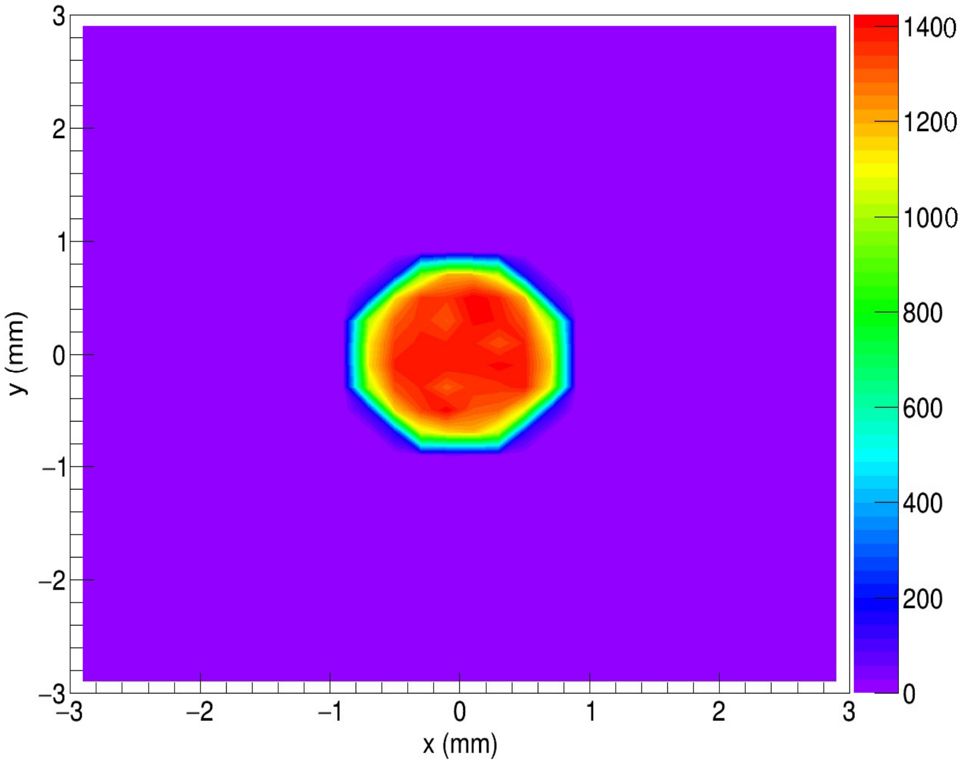


MC simulations – previous geometry (MCNPX)

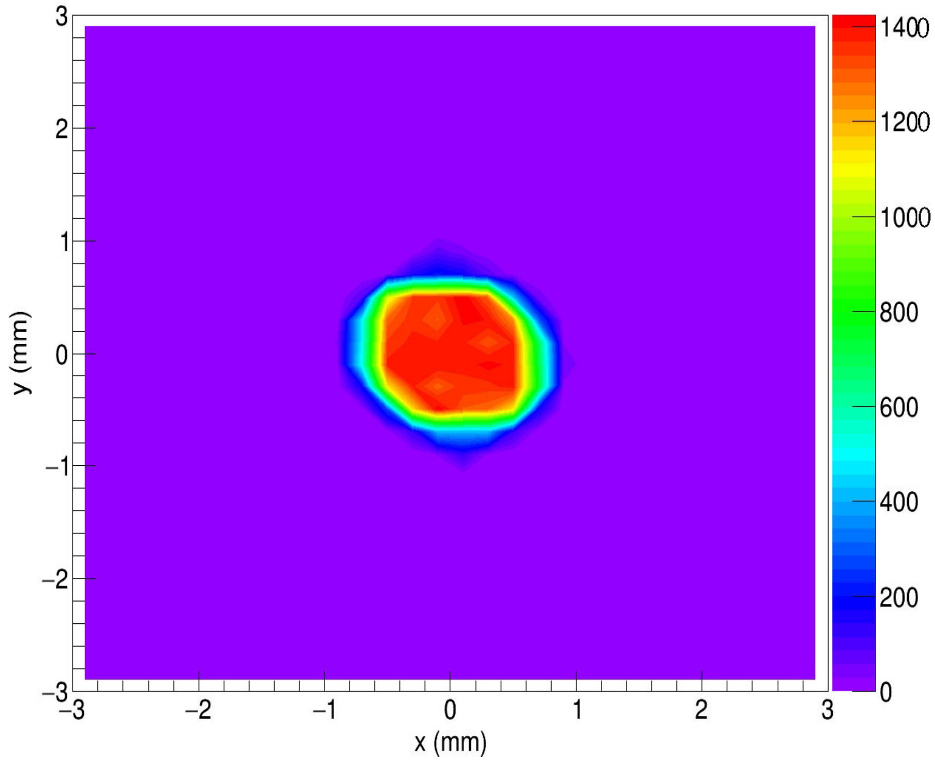


Slit misalignment

Collimated beam footprint @ 18.6 MeV



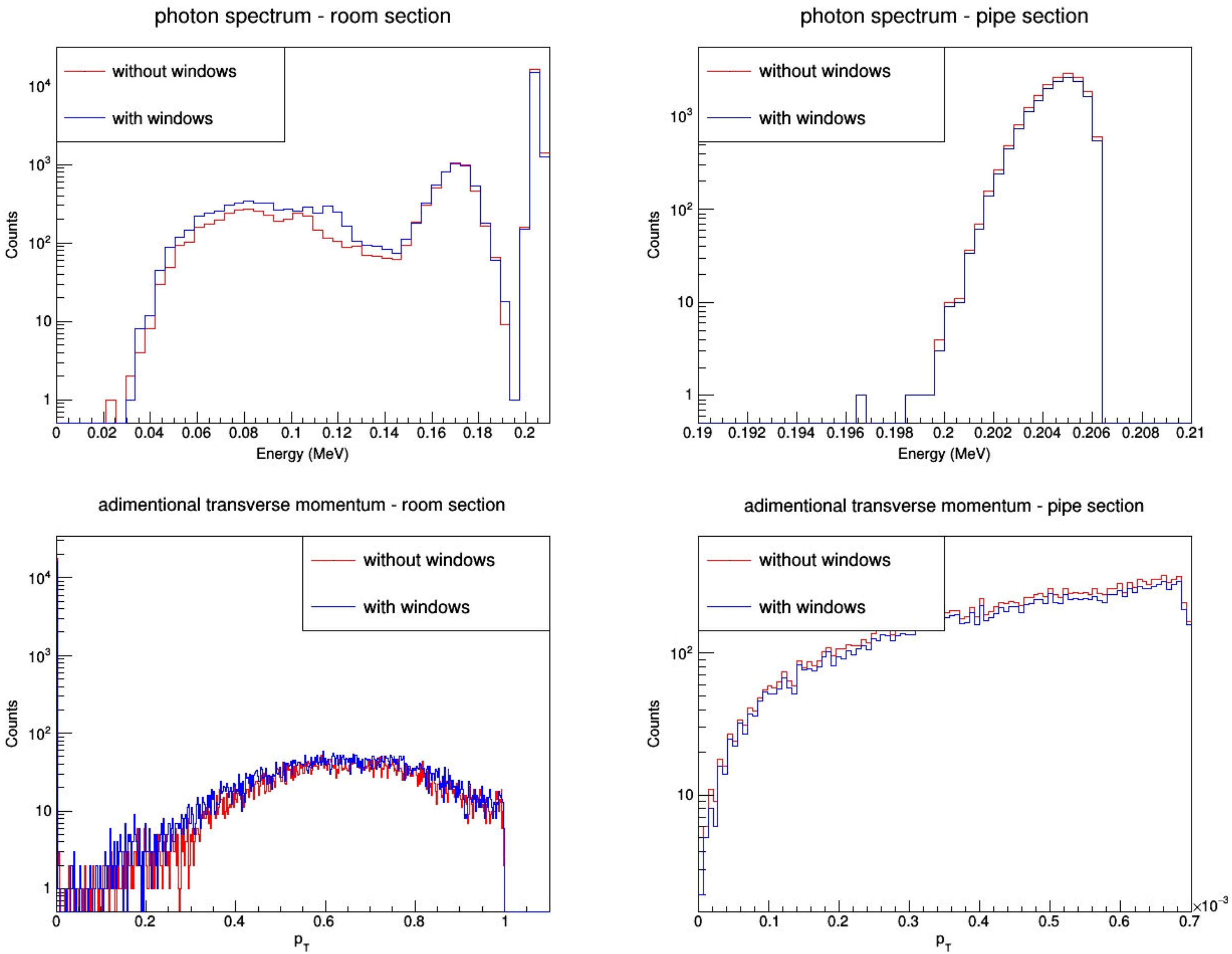
Perfectly aligned slits



Slits misaligned, σ = 100 μm

Effect of windows isolating our pipe vacuum

- **3 different material considered**: Al, Be and Kapton of **increasing thickness** (0.2 - 10 mm).
- the effect is an **attenuation of the collimated beam** (6% for 3 mm of Al windows) and an **increase of photons scattered at large angles**.

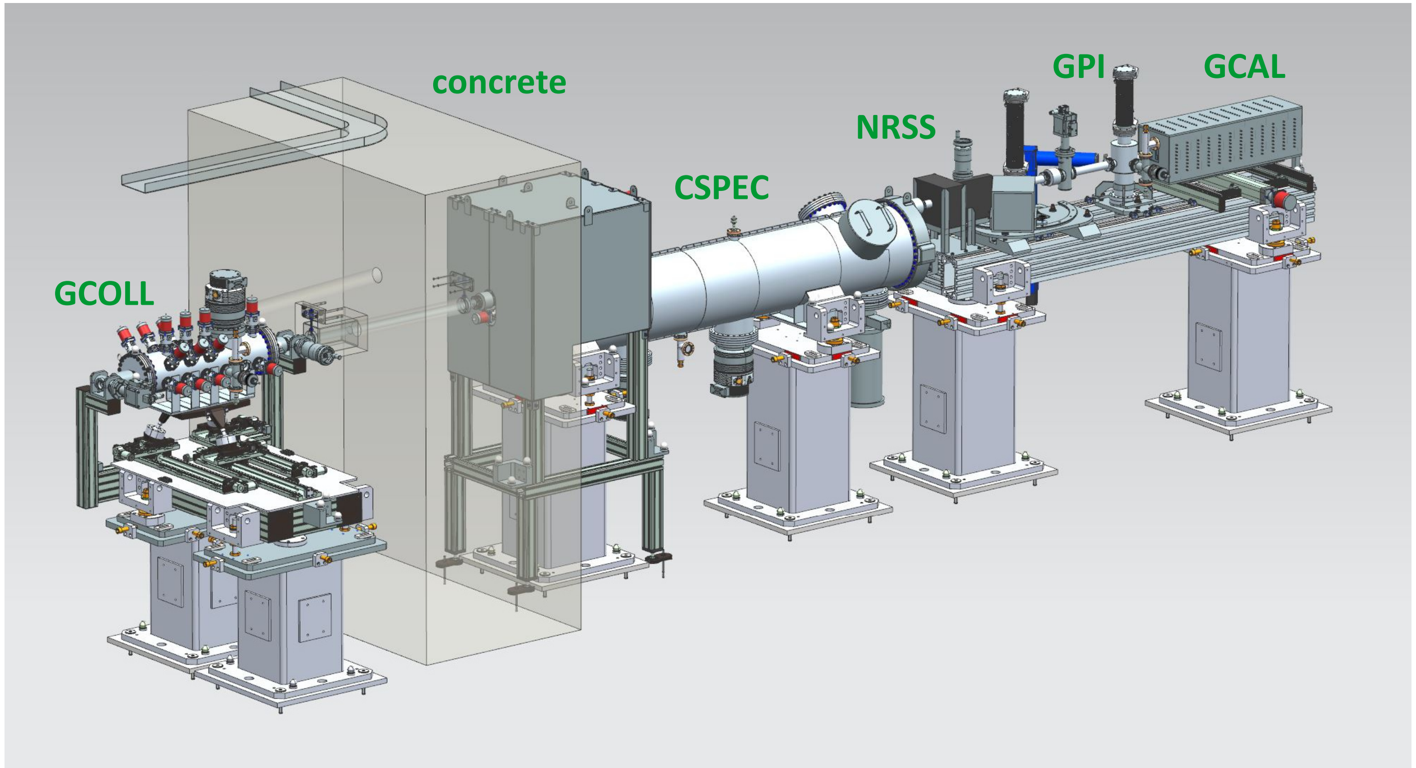


0.2 MeV beam, 3 mm Al windows

Gamma Beam Characterisation

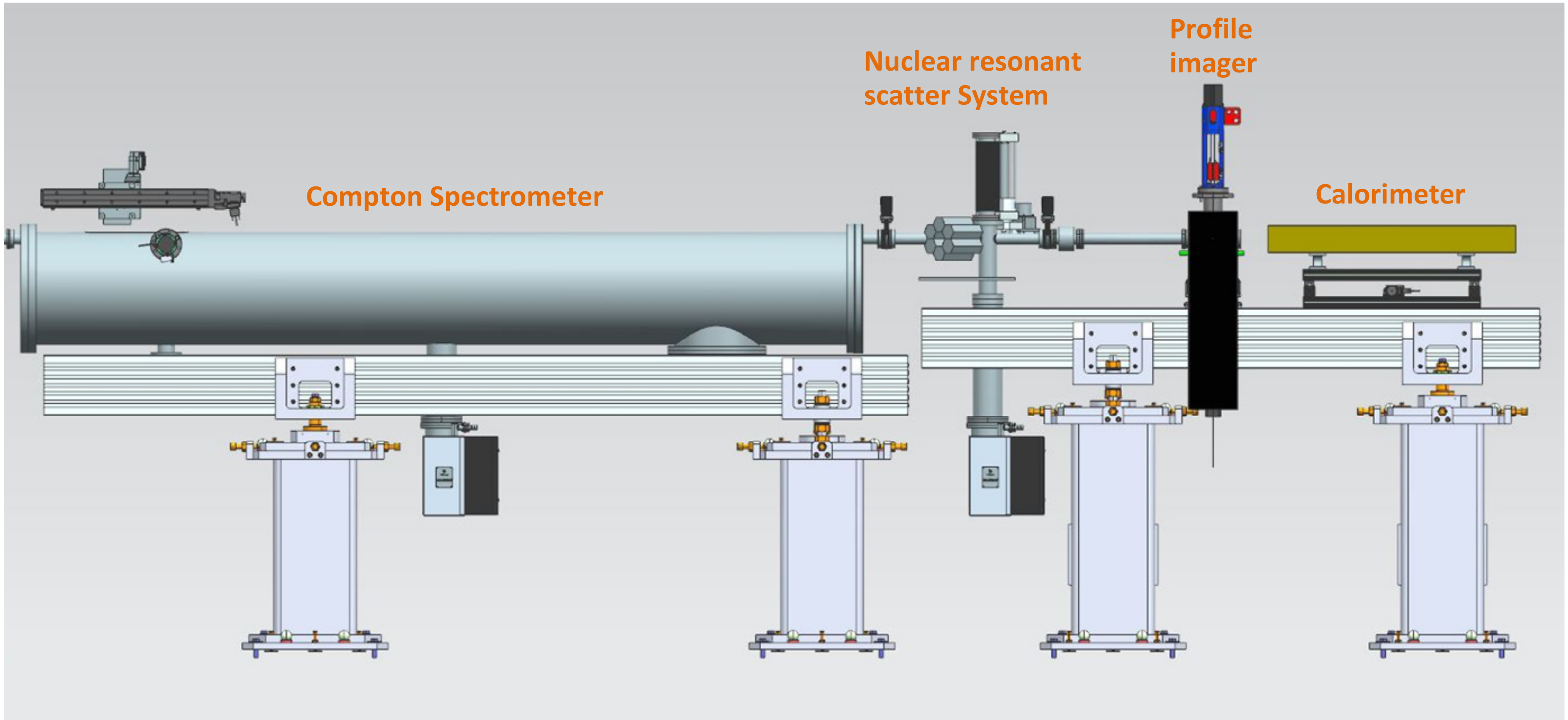
The characterization of the gamma beam includes **the measurement** of:

- Average energy oh the photons
- Energy distribution, energy bandwidth
- Beam intensity, number of produced photons
- Spatial distribution, profile shape



Gamma Beam Characterisation

- A set of various detectors is needed to perform a full characterization of the gamma beam
- The definition of the solutions and detectors is complete, the realization of the final design is currently ongoing



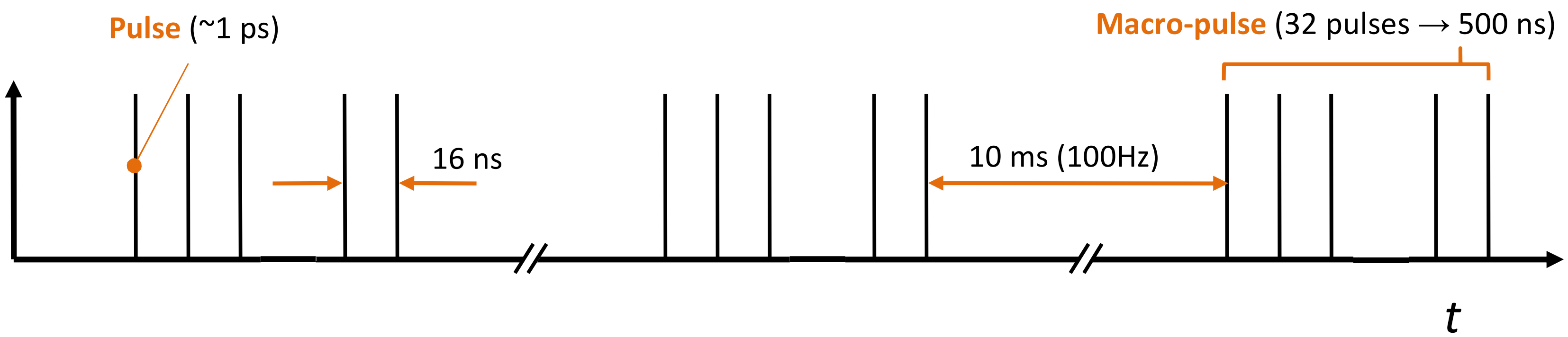
Energy Distribution Measurement

- Time structure and high number of photons per pulse (10^5 photons, 1 ps duration)

  -> do not allow to use traditional spectrometry techniques
- It is not possible to disentangle the detector response to each single photon within a pulse

<u>Two possible solutions:</u>

- **Measure the energy of 1 photon** in average per each Macro-pulse (**time-integrated** energy spectrum)
- Obtain average energy and number of photon by **measuring the total energy of all gamma** photons for each pulse



Energy Distribution Measurement

- **Compton Scattering Spectrometer**

  high-precision measurements of **single** Compton scattering from thin target,

  Integration over time (about 100 s) -> **energy distribution evaluation**

- **Absorption Calorimeter**

  calorimetric, **total absorption** technique

  Fast detectors, pulse-to-pulse detection -> **average flux and average energy**

- **Nuclear Resonant Scattering calibration system**

  high-precision energy measurement for selected energy values

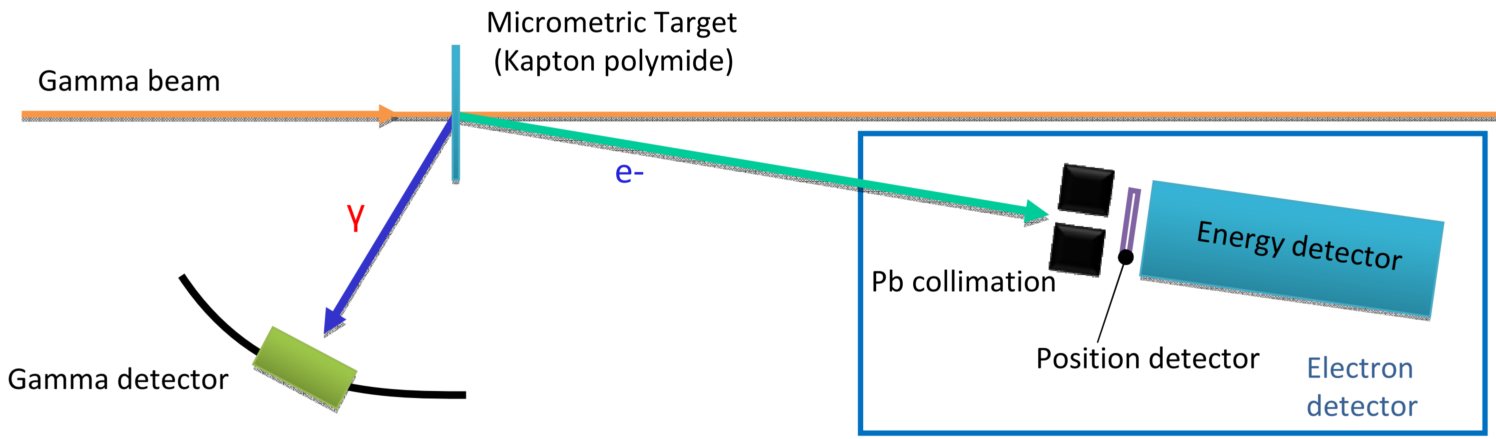
  (integration time about 100 s) -> **absolute energy calibration**

Compton Spectrometer - Concept

- Reconstruct the beam energy spectrum by sampling Compton interactions of single gamma in a ultra-thin target

- Measuring the **energy and position of the scattered electron**, is possible to reconstruct the energy of the interacting gamma photon:

$$E_{gamma} = \frac{m_e T_e}{cos\emptyset \sqrt{T_e(T_e + 2m_e)} - T_e}$$



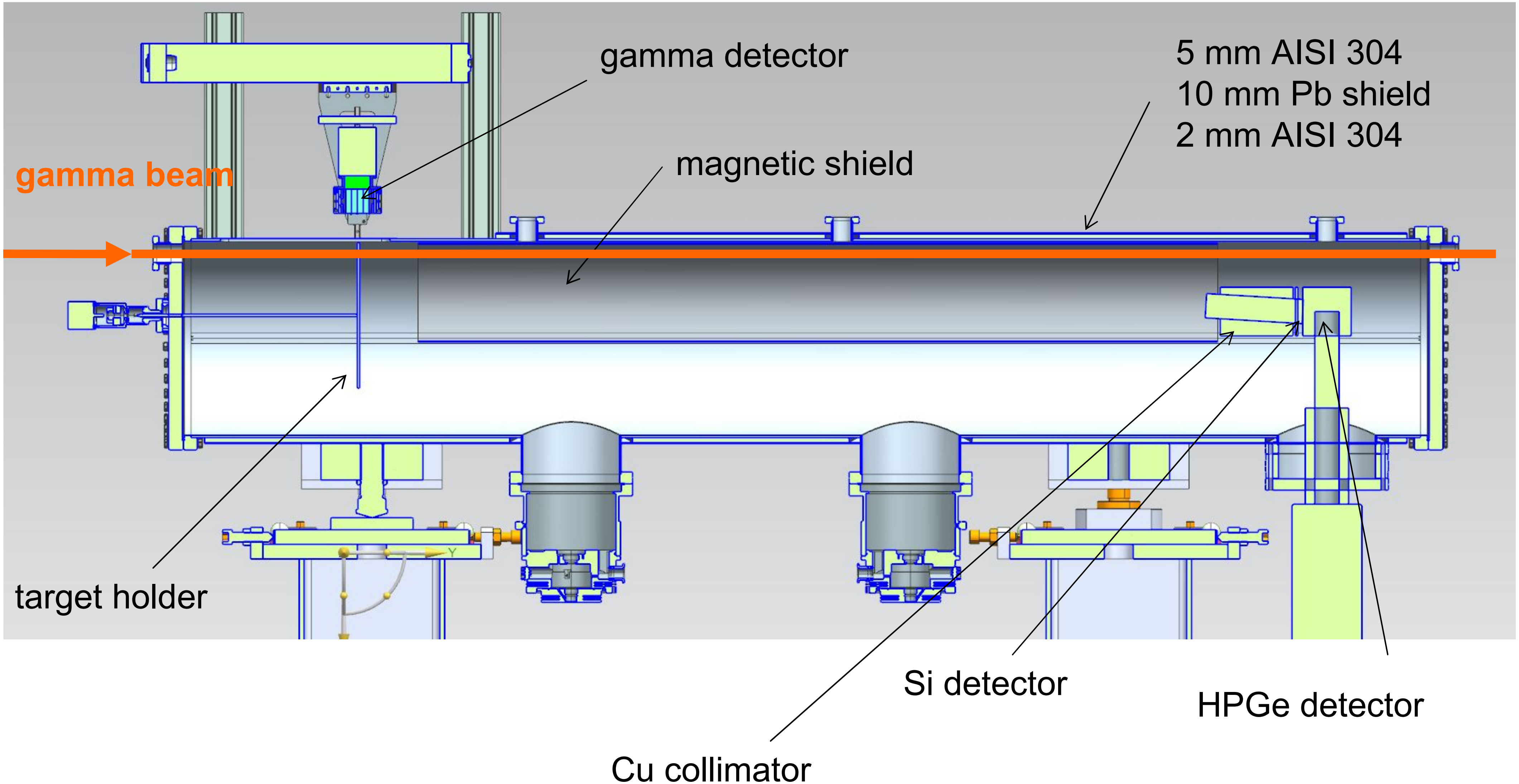
$$\phi = 60mrad$$

$$N_{\gamma MP} \approx 3.2\times10^{6} \quad \sigma_C \approx 150-30mb \quad \alpha \approx 1\%$$

$$N_{eMP} = N_{\gamma MP}\sigma_C \alpha \rho N_A \frac{Z}{A} t \approx 1$$

$$\rho N_A \frac{Z}{A} \approx 7\times10^{23} cm^{-3} \Rightarrow t \approx 2-10\mu m$$

M13/M30 - CSPEC



M13/M30 - CSPEC

Geant4 model of CSPEC

M13/M30 - CSPEC