Nuclear Photonics 2025
October 6 - 10, 2025 in Darmstadt, Germany

Broadband MeV to multi GeV 10 PW laser-driven gamma-rays generation, characterization and possible applications

Vincent Lelasseux on behalf of the ELI-NP team and collaborators

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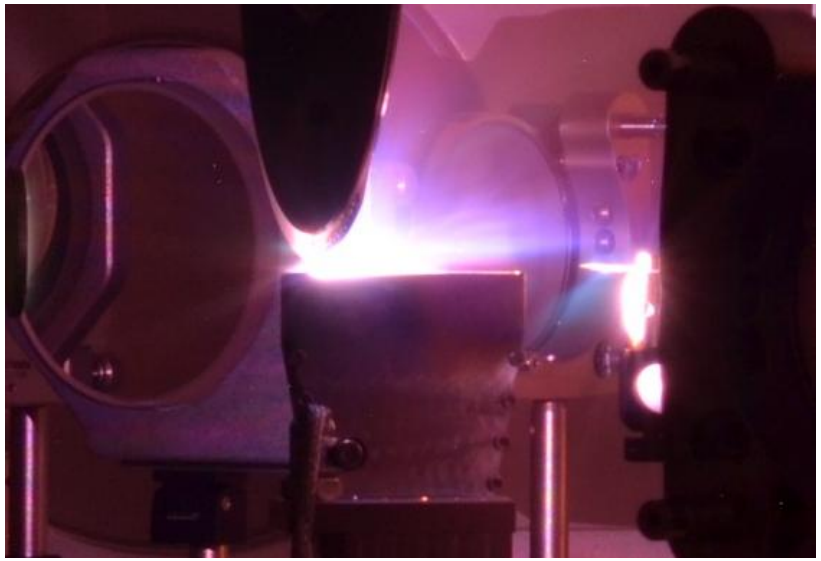
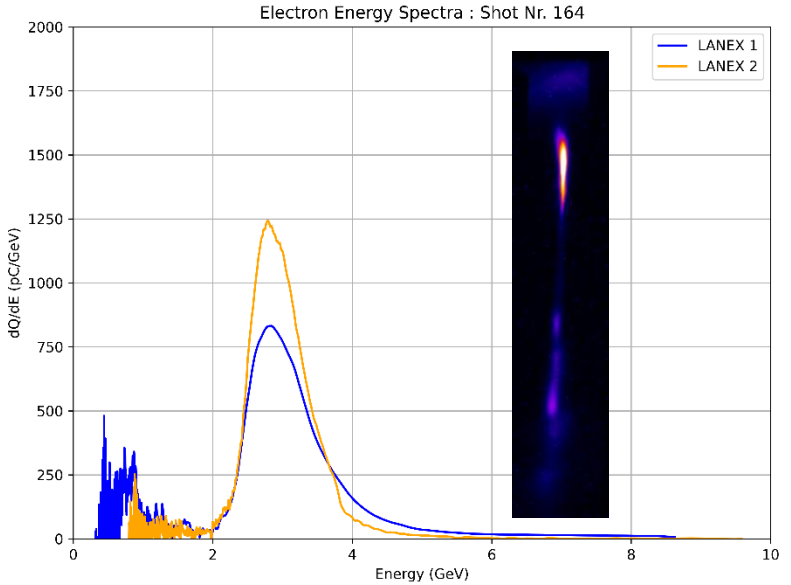
H. Ahmed

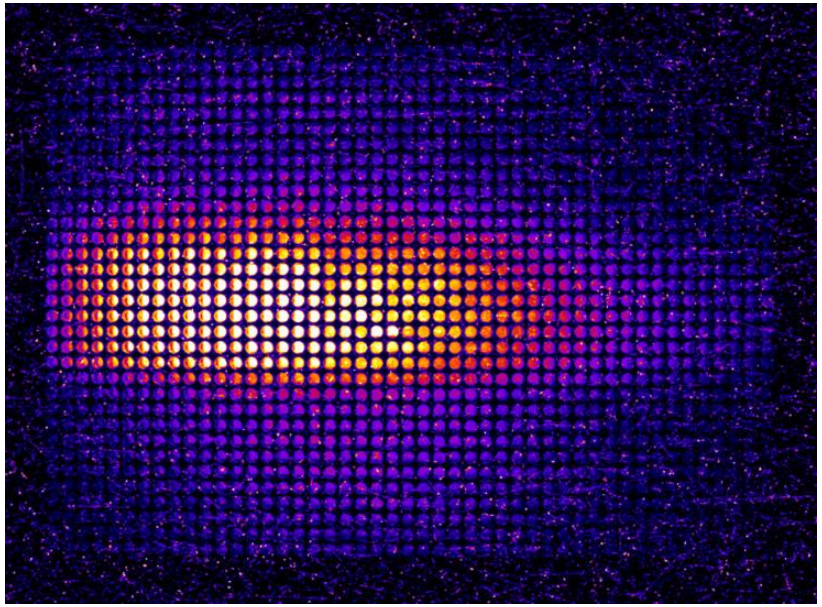
D. Choudhury

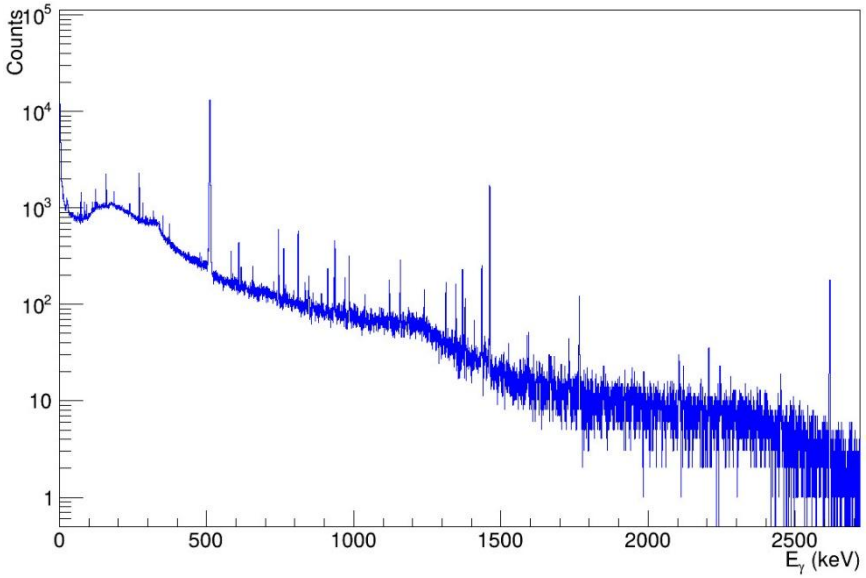
Outlook

- ❑ The 10 PW E6 experimental area
- ❑ Multi-GeV electron beam
- ❑ Gamma generation
  - Bremsstrahlung
  - Nonlinear reverse Compton
- ❑ Characterization (LYSO/CsI stack)
- ❑ Possible applications
  - QED investigation
  - Photonuclear reactions





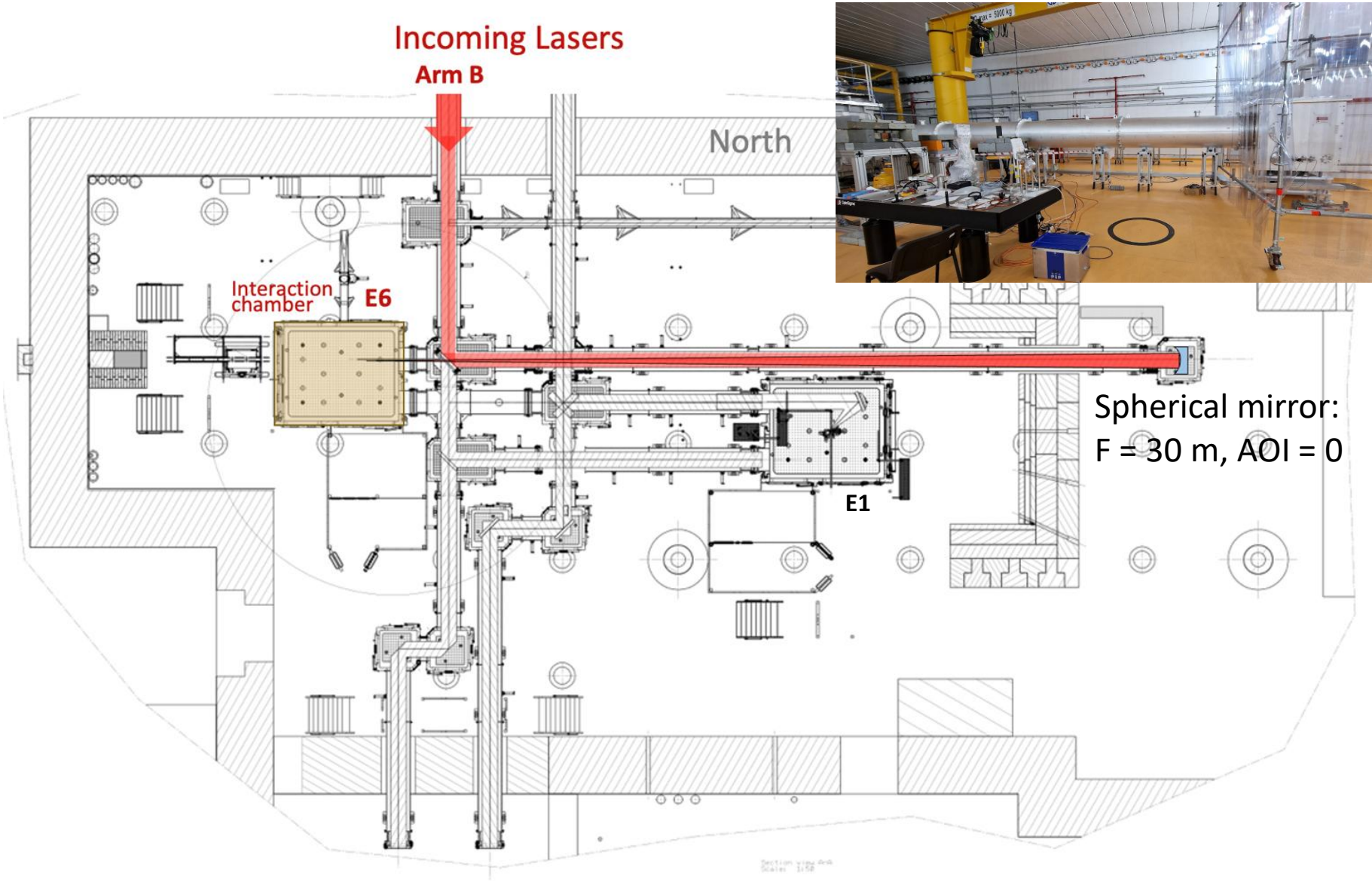




The 10 PW E6 experimental area

Laser specification (on target):

- 1 shot/min
- 240 J (max 10 PW)
- 23±1 fs

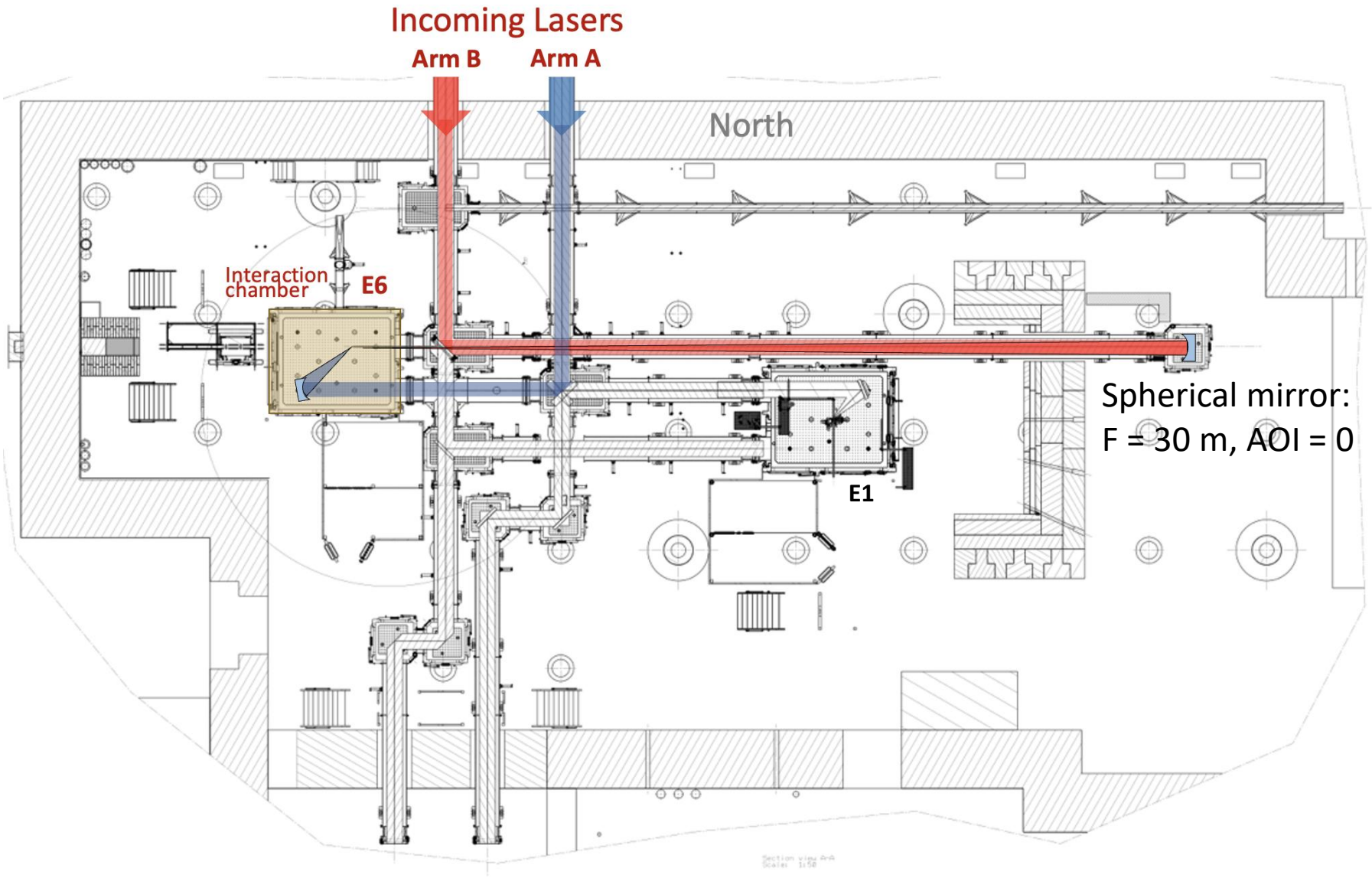


The 10 PW E6 experimental area

Laser specification (on target):

- 1 shot/min
- 240 J (max 10 PW)
- 23±1 fs

2x10 PW arms available

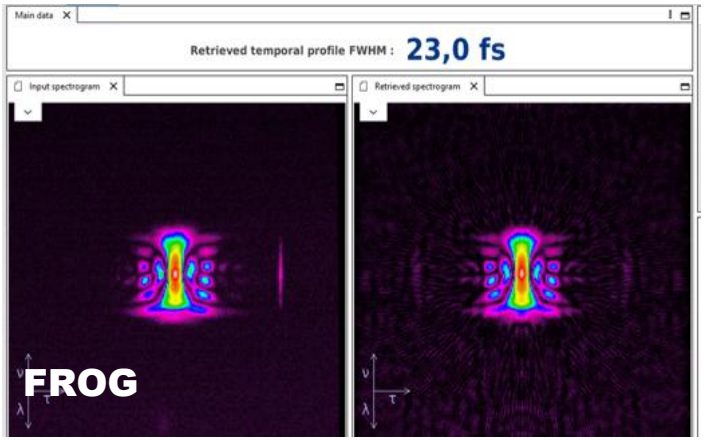


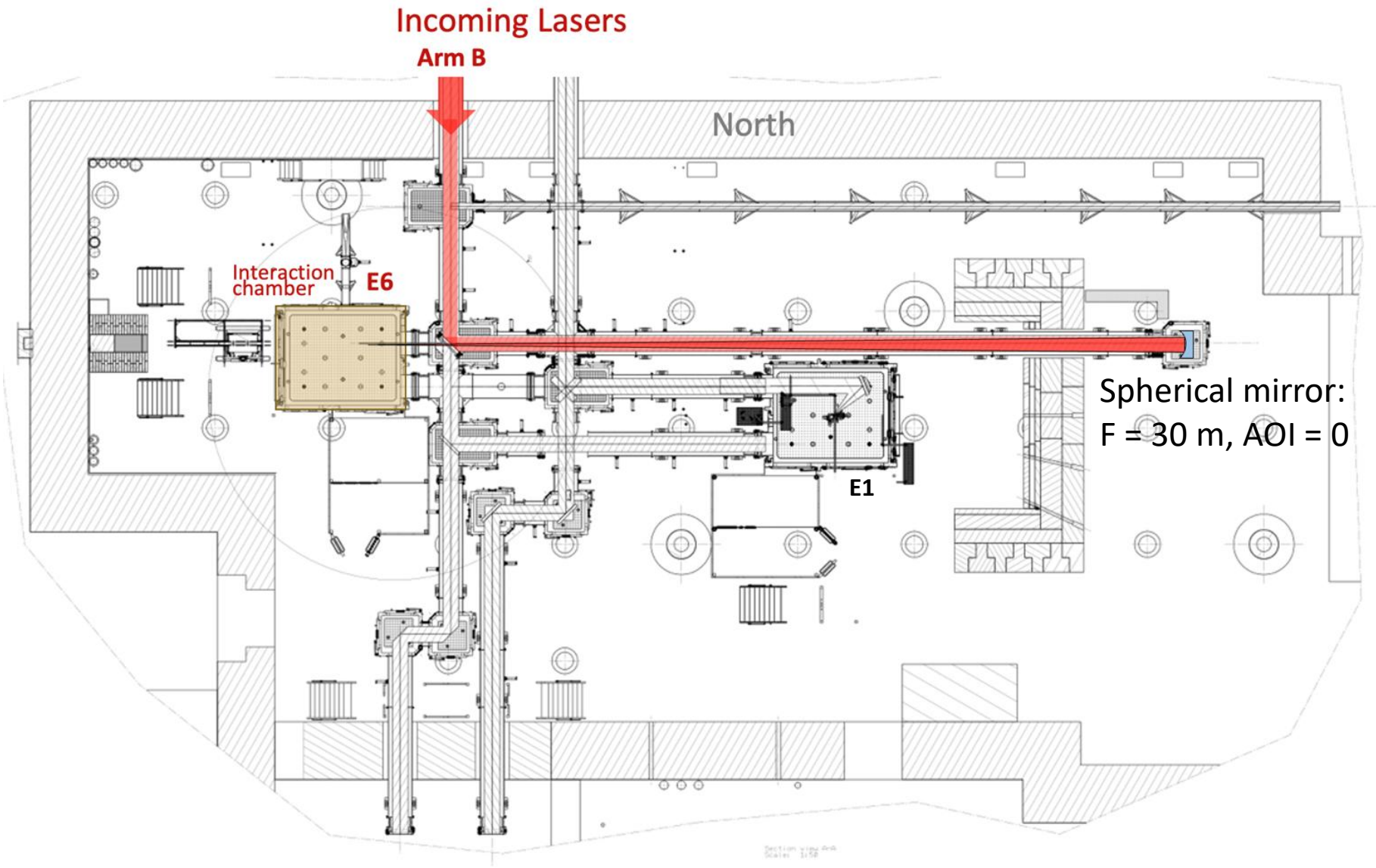
The 10 PW E6 experimental area

Laser specification (on target):

- 1 shot/min
- 185±1 J (nominal 8 PW)
- 23±1 fs

Measured on shot

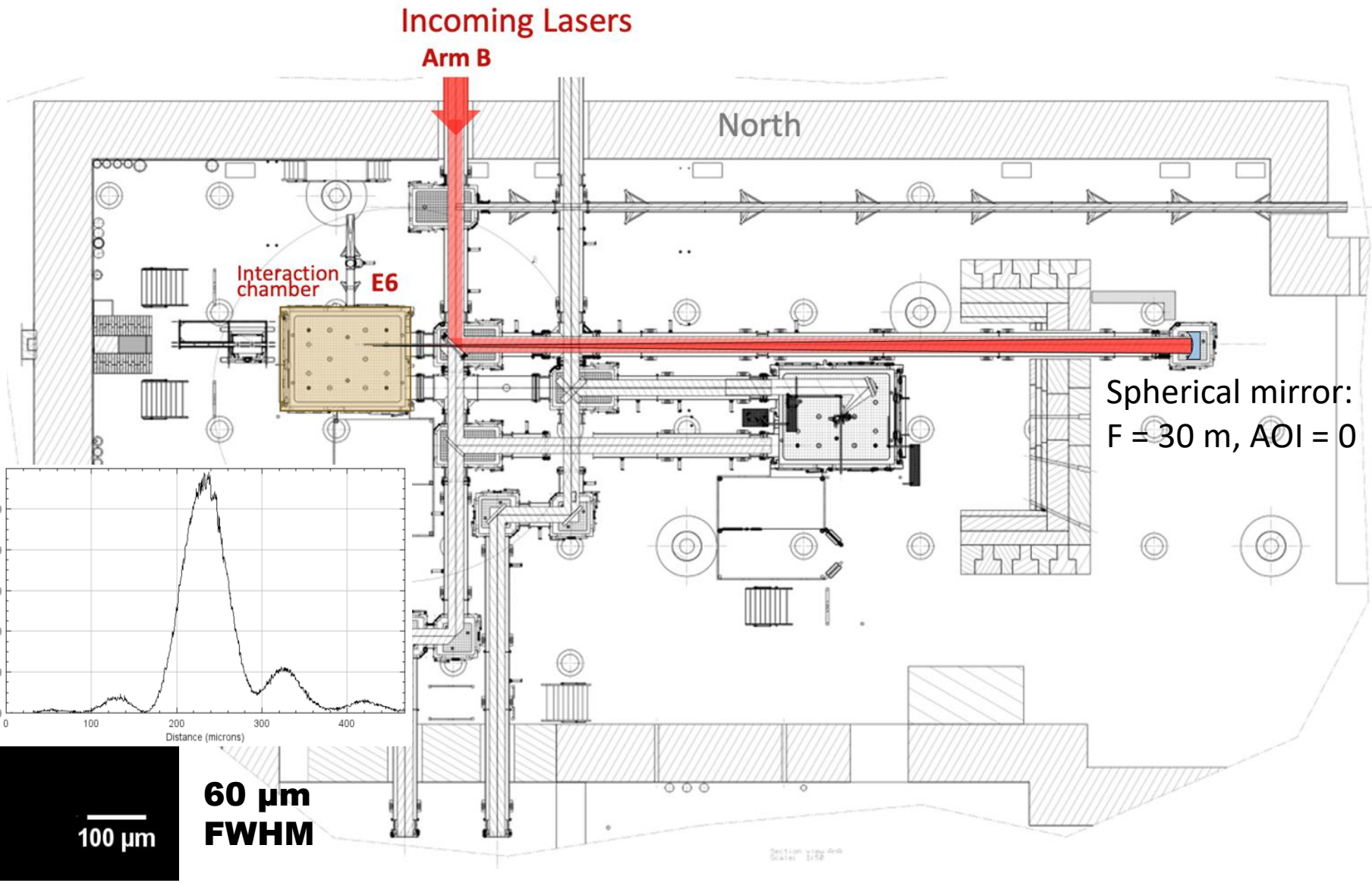




The 10 PW E6 experimental area

Laser specification (on target):

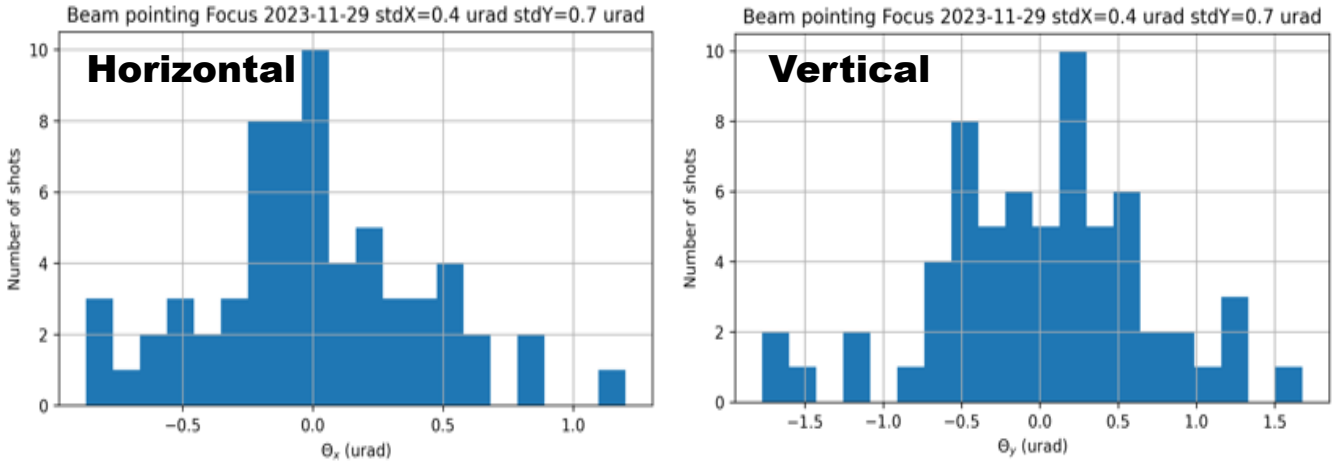
- 1 shot/min
- 185±1 J (nominal 8 PW)
- 23±1 fs
- 60±2 µm FWHM focal spot



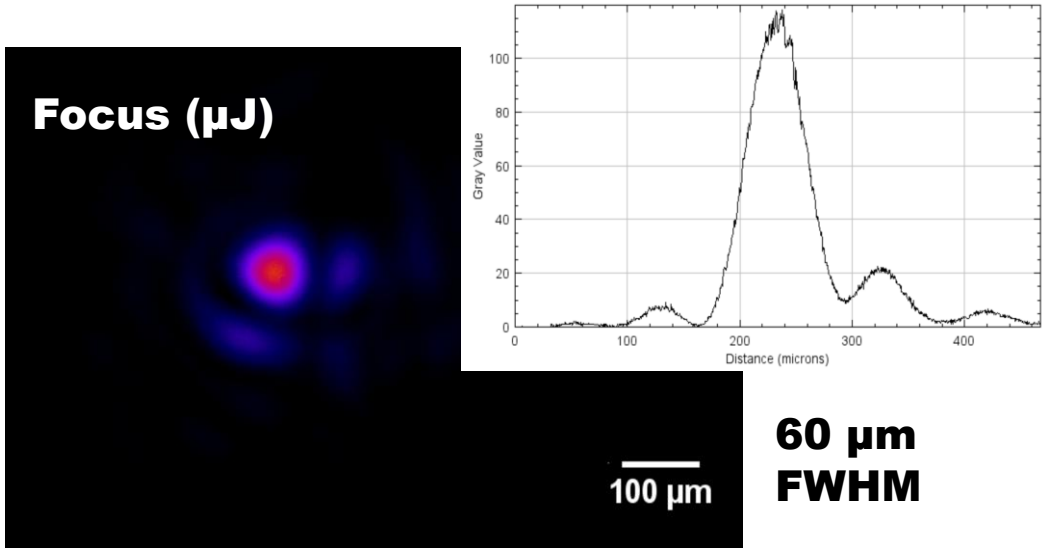
The 10 PW E6 experimental area

Laser specification (on target):

- 1 shot/min
- 185±1 J (nominal 8 PW)
- 23±1 fs
- 60±2 µm FWHM focal spot
- Encircled energy: ~40% @ $1/e^2$
- Energy stability at full power: ±2%
- Pointing stability: < 1 µrad

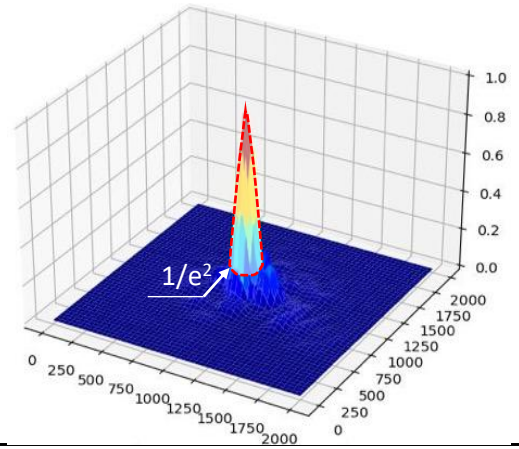


Approx 1 µrad FWHM focus pointing (0.5 - 1 focal spot)



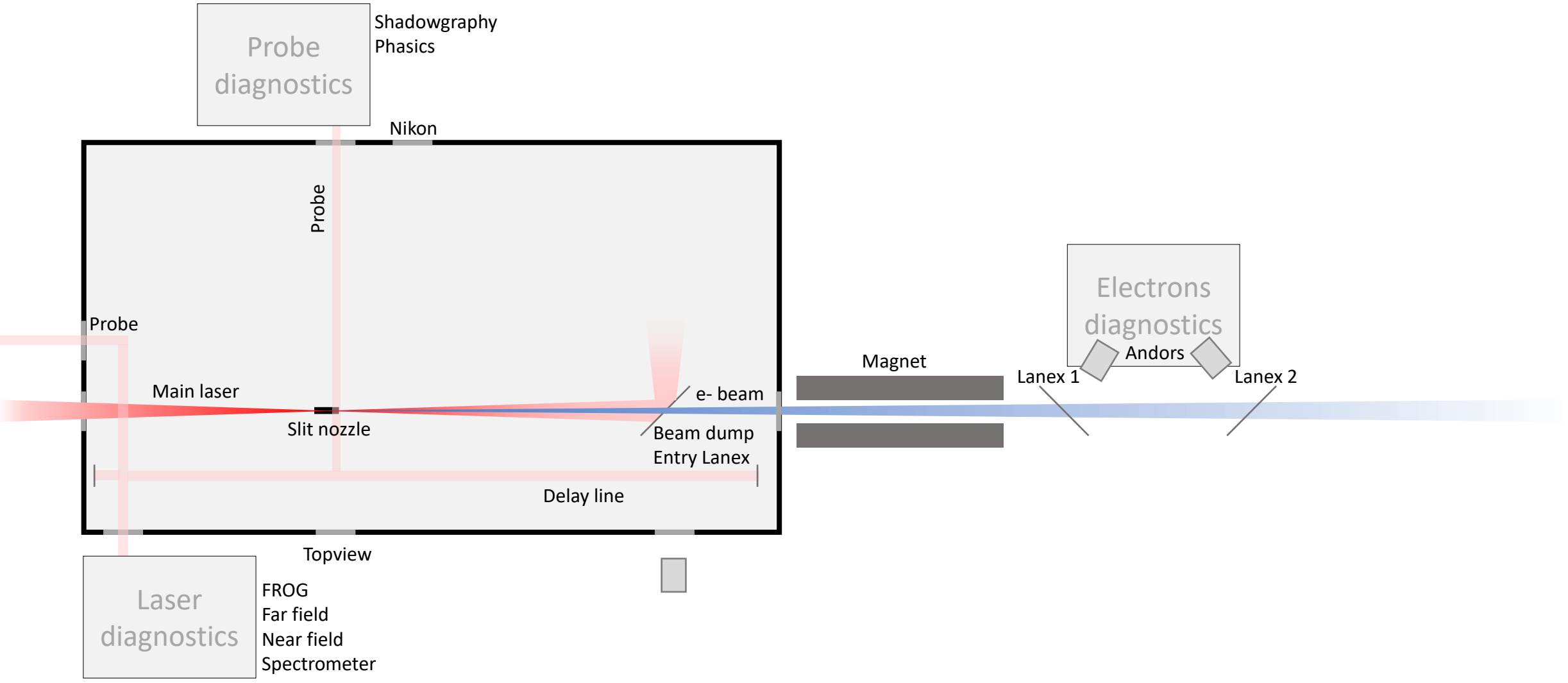
60 µm FWHM

Estimated encircled energy ~40%



Multi-GeV electron beam

Commissioning experimental campaign 2023/2024:



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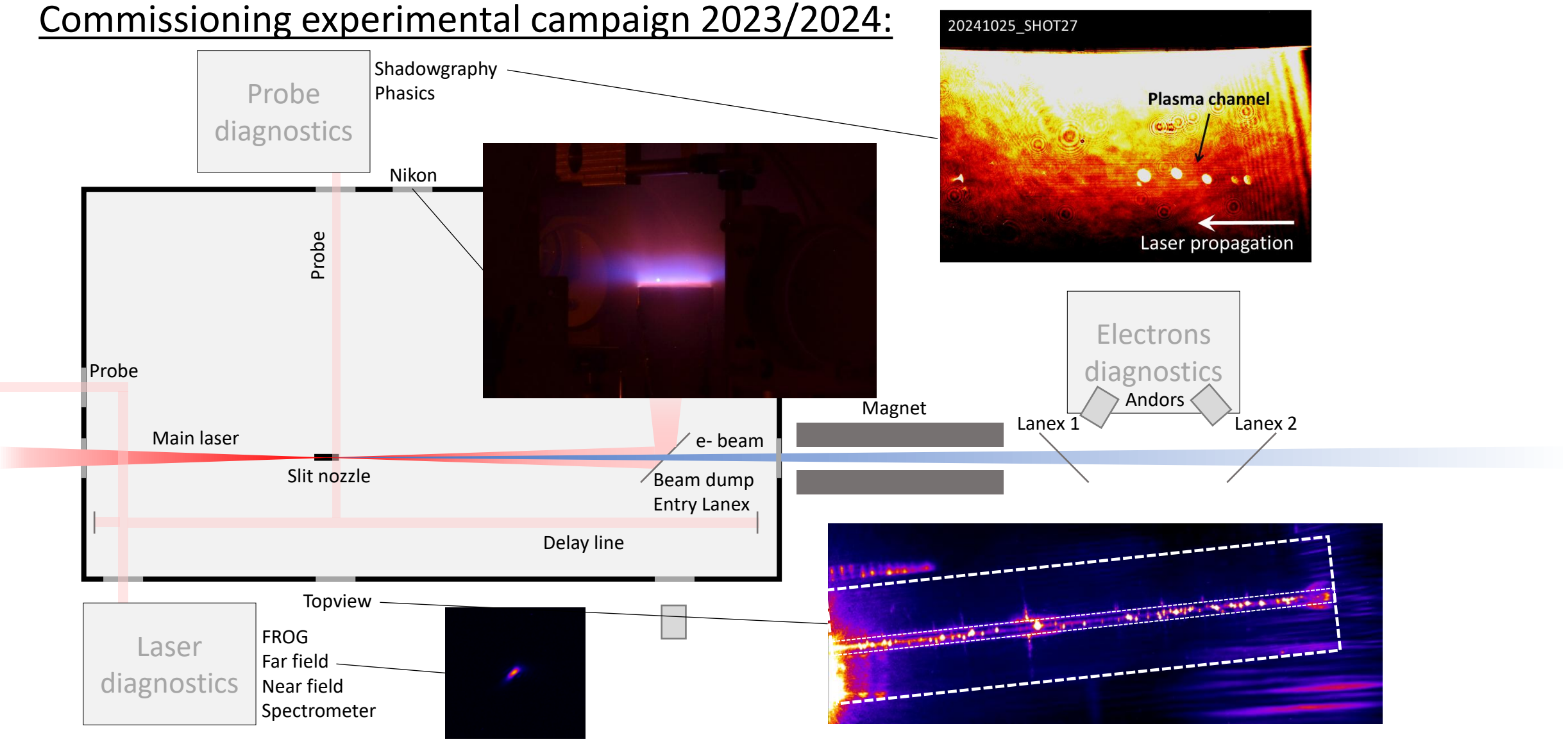

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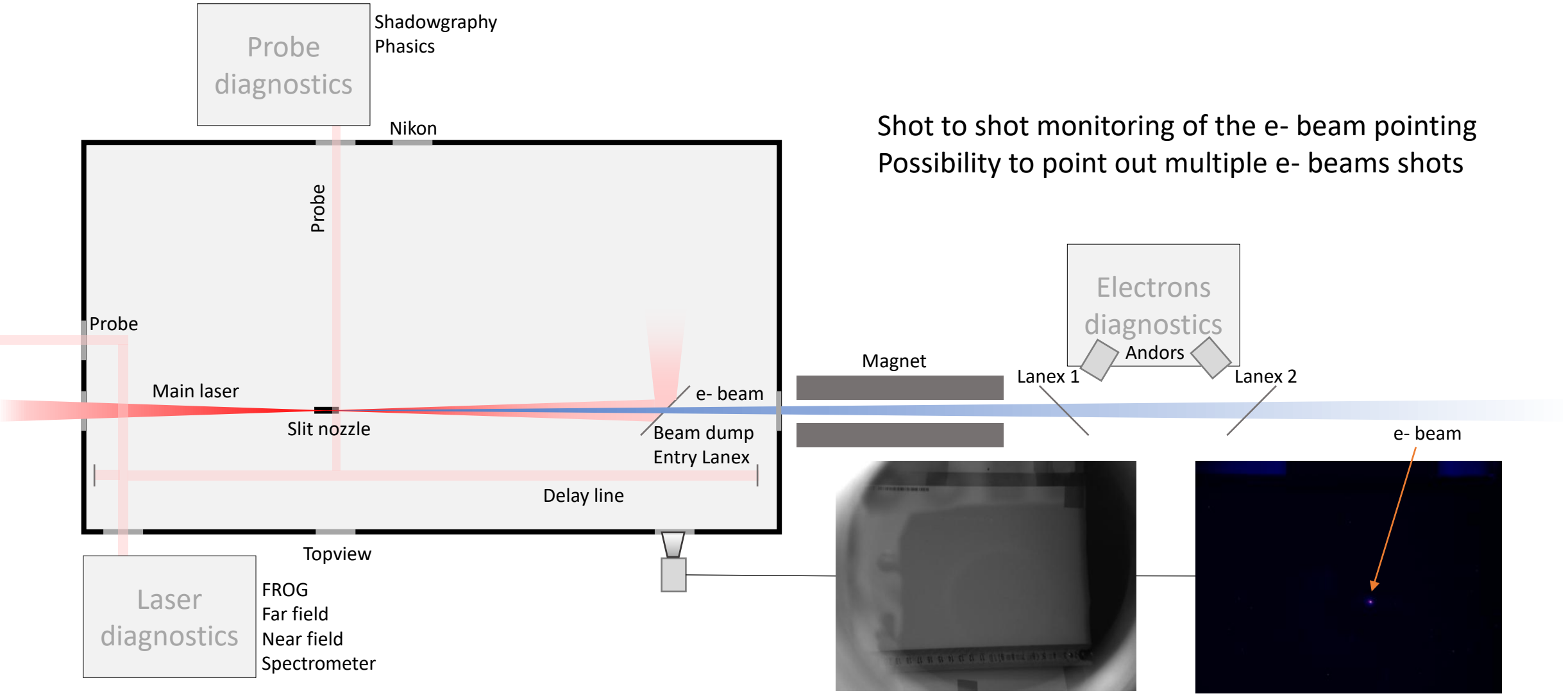

Shot to shot monitoring of the e- beam pointing
Possibility to point out multiple e- beams shots

Multi-GeV electron beam

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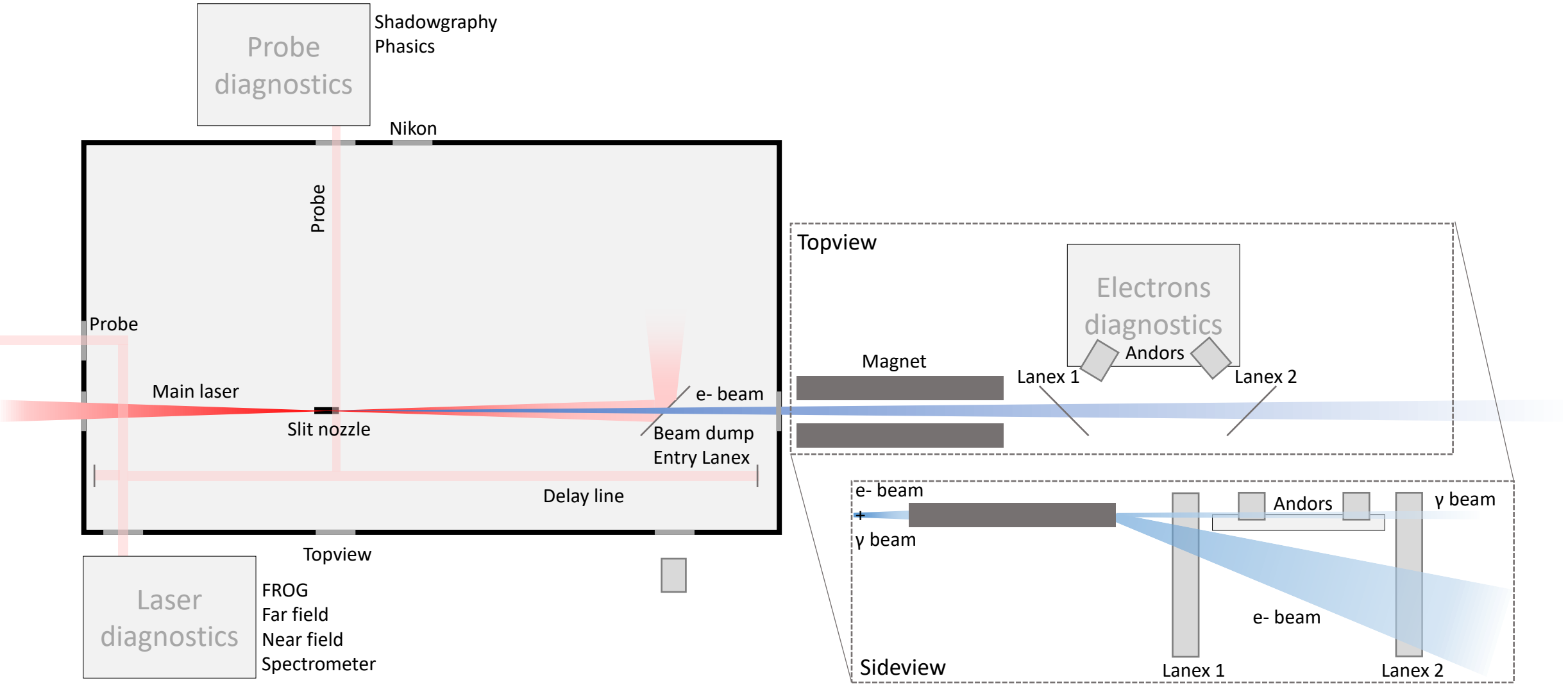

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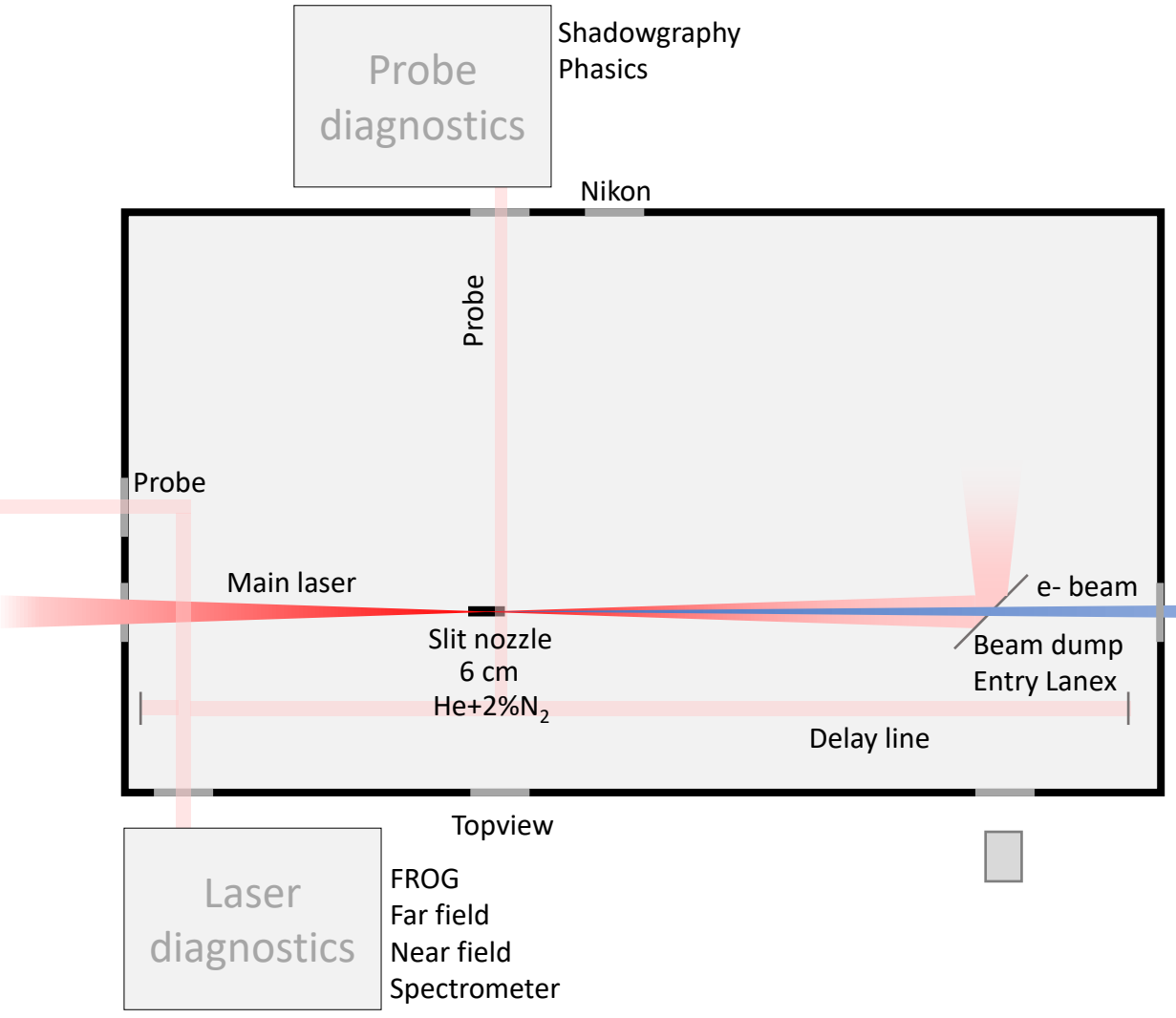

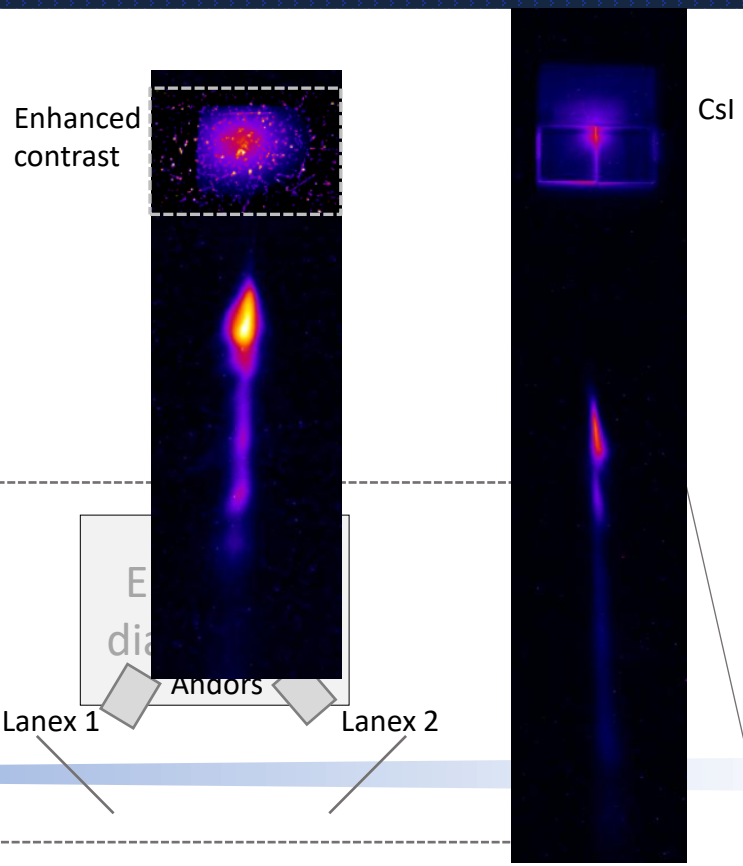

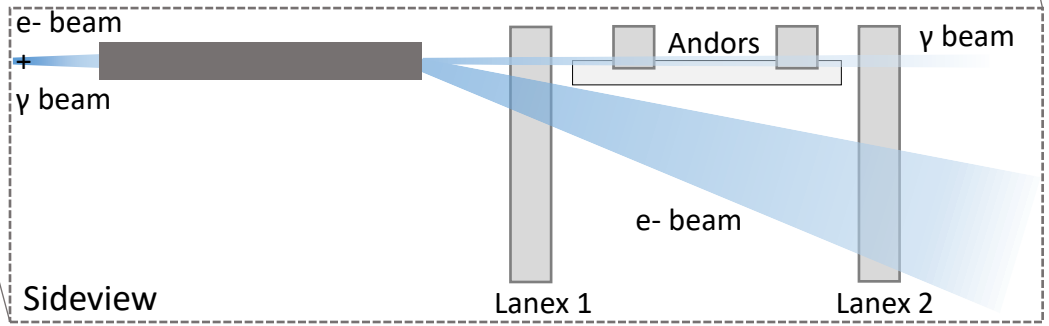

Multi-GeV electron beam

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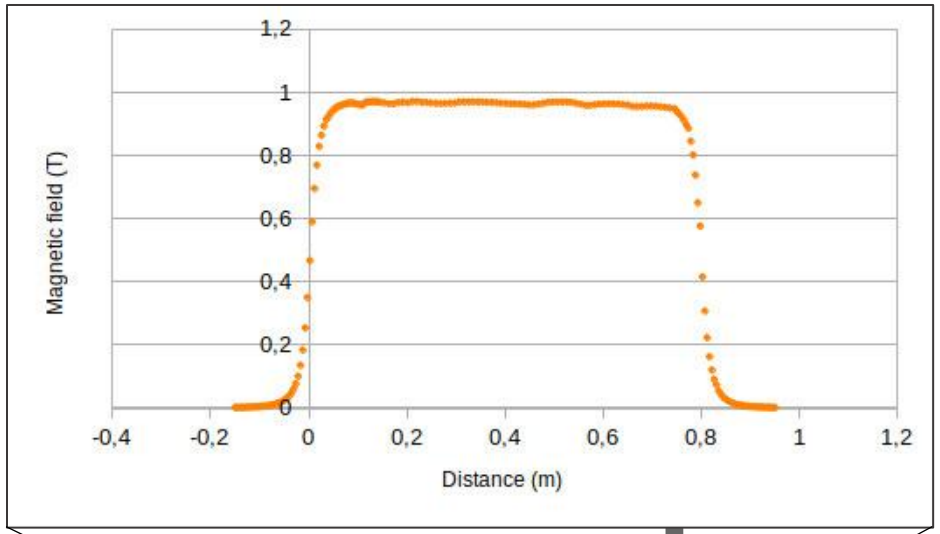
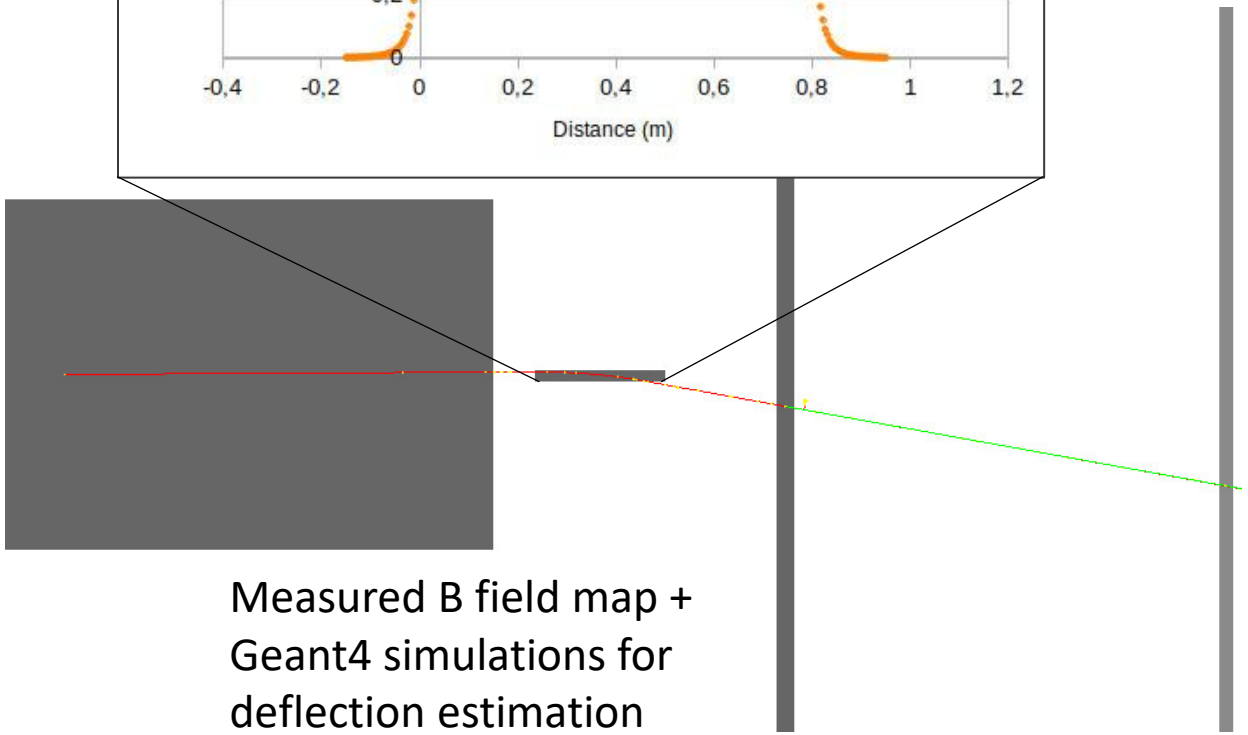
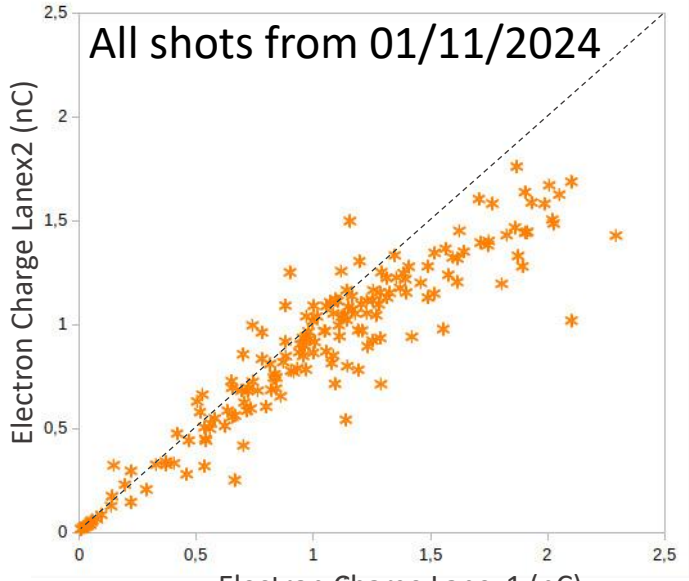
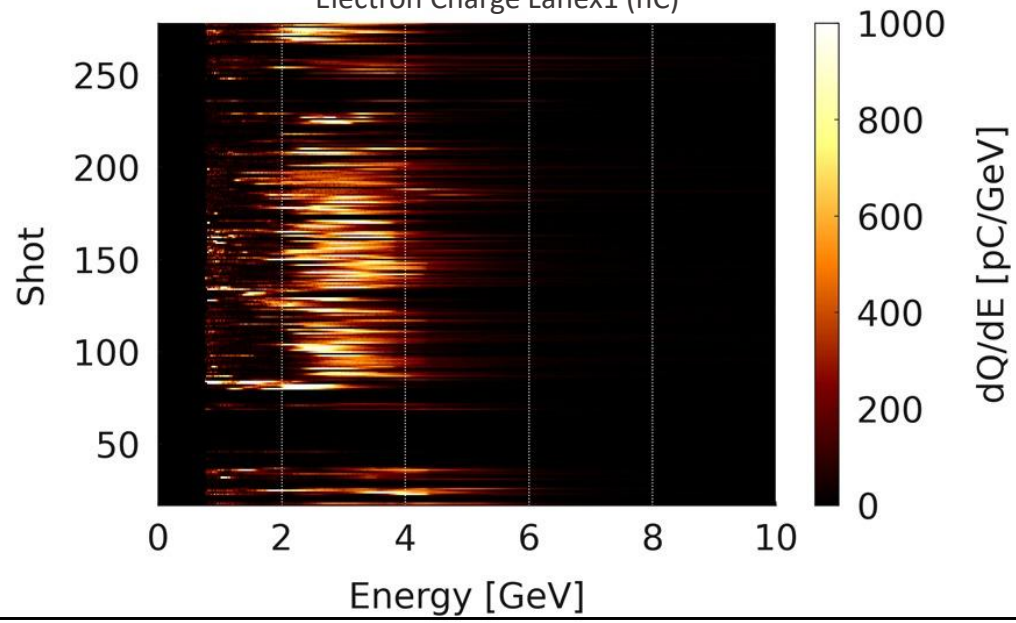




Measured B field map + Geant4 simulations for deflection estimation



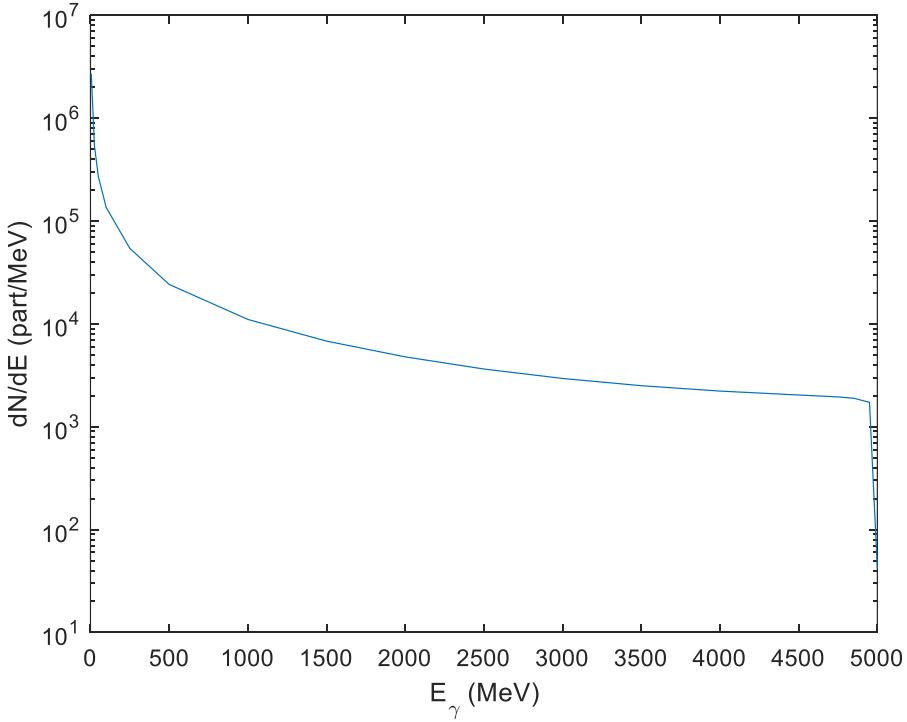


Gamma generation : Bremsstrahlung

Result of Coulomb interactions of electrons going through matter

$$\frac{d\sigma}{dk} = \frac{d\sigma_n}{dk} + Z\frac{d\sigma_e}{dk} \xrightarrow{*\rho l I/e} \frac{dN}{dE}$$

For 5 GeV e-, 1.5 nC, 200 µm C



Theoretical model (Bethe-Heitler formula + corrections)

$$\frac{d\sigma_n}{dk} = \frac{4\alpha r_e^2 Z^2}{k}\left(\chi_{Born}^{unscr} + \delta_{screen} + \delta_{Coul}\right)$$

$$\frac{d\sigma_e}{dk} = \frac{4\alpha r_e^2 Z^2}{k}\left(f_{e-e}\chi^{Haug} + \delta_{screen}^{e}\right)$$

From tabulated values

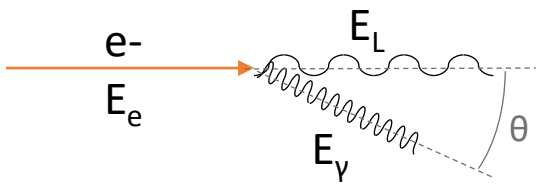
S.M. Seltzer & M.J. Berger (1986)

Gamma generation : Nonlinear reverse Compton

Linear reverse Compton :

$$E_\gamma = \frac{(1+\beta_e)E_L}{(1-\beta_e cos\theta) + \frac{(1+cos\theta)E_L}{E_e}}$$

$$E_\gamma^{max} = \frac{1}{1+\frac{(m_e c^2)^2}{4E_e E_L}} E_e$$



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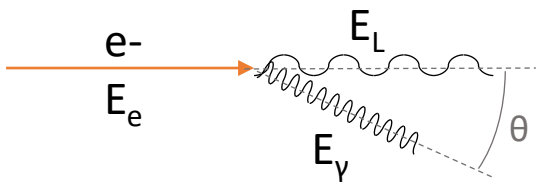
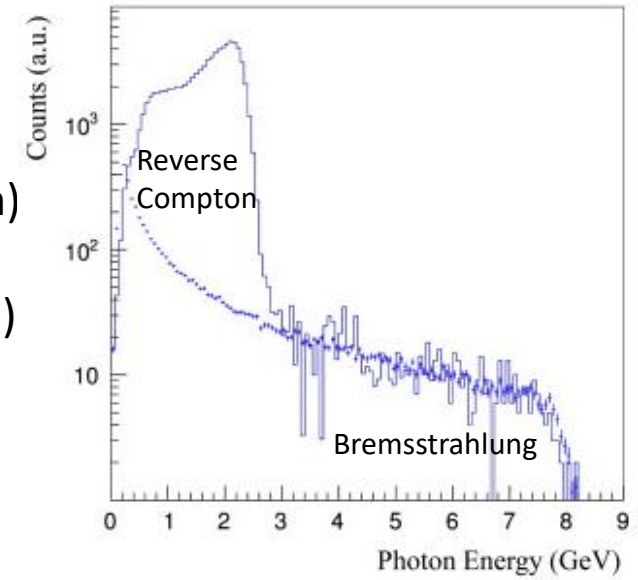


LEPS2 beamline
(Spring8 synchrotron)
E_e = 8 GeV
E_L = 4.66 eV (266 nm)

$E_{\gamma max}$ = 2.89 GeV



N. Muramatsu et al

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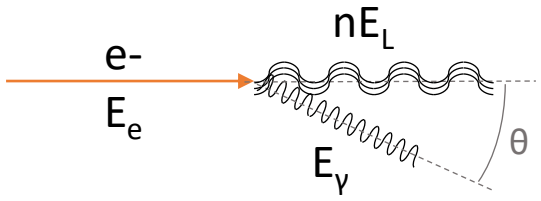

Nonlinear reverse Compton :

Need integration over a range of n depending on laser intensity

$$a_0 \sim 1$$

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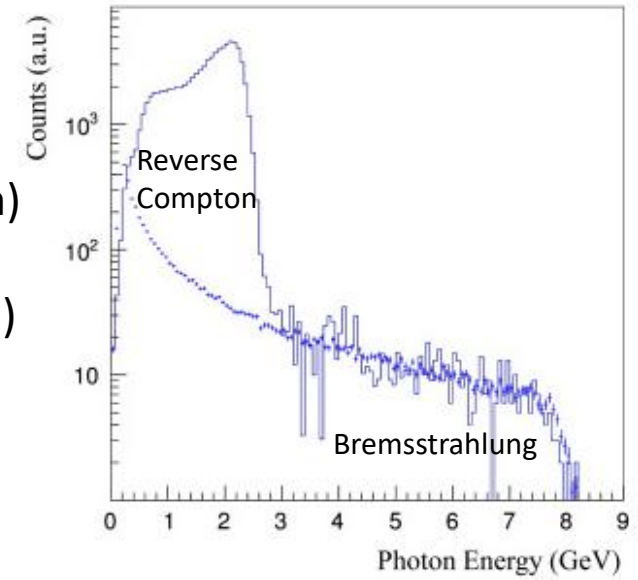
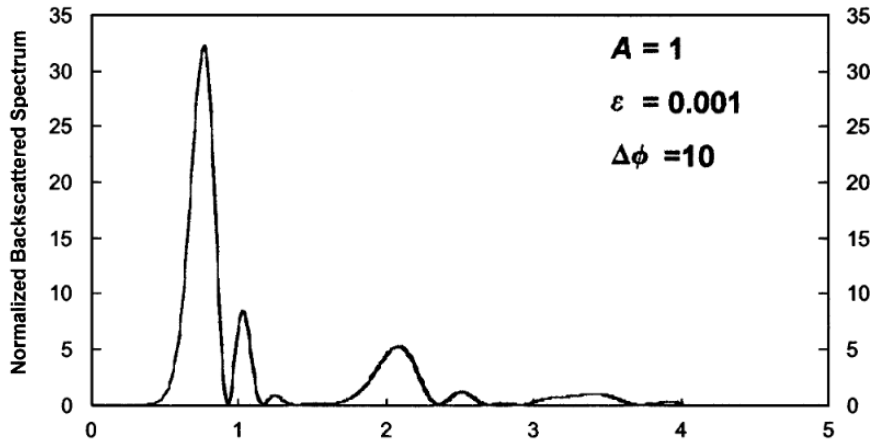


N. Muramatsu et al (2022)



F.V. Hartemann & A.K. Kerman (1995)

Gamma generation : Nonlinear reverse Compton

Linear reverse Compton :

$$E_\gamma = \frac{(1+\beta_e)E_L}{(1-\beta_e cos\theta)+\frac{(1+cos\theta)E_L}{E_e}}$$

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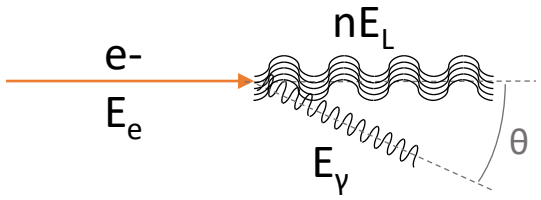

Fully nonlinear reverse Compton :

Need integration over a range of n depending on laser intensity

$$\frac{dN}{dE} \propto \int_{\frac{E}{E_c}}^{\infty} K_{5/3}(x)dx$$

Critical energy: $E_c \propto \gamma_e^2 a_0$

LEPS2 beamline
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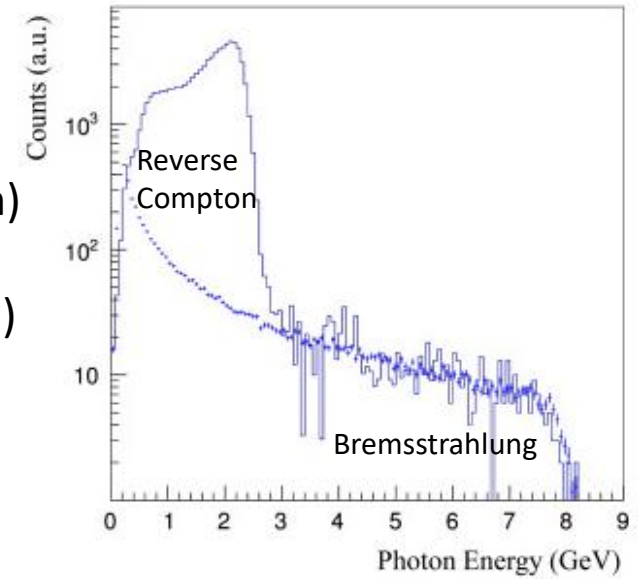

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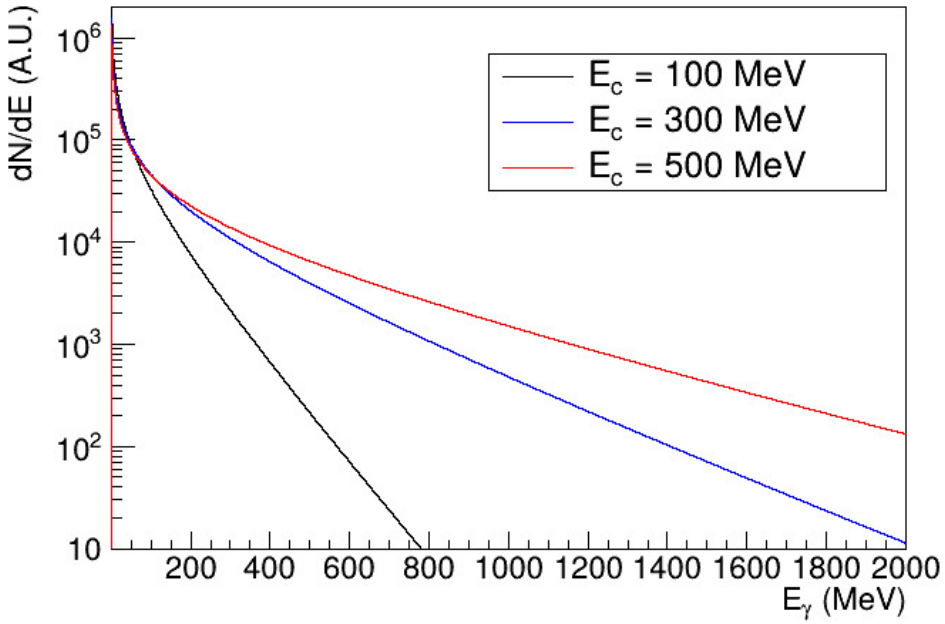
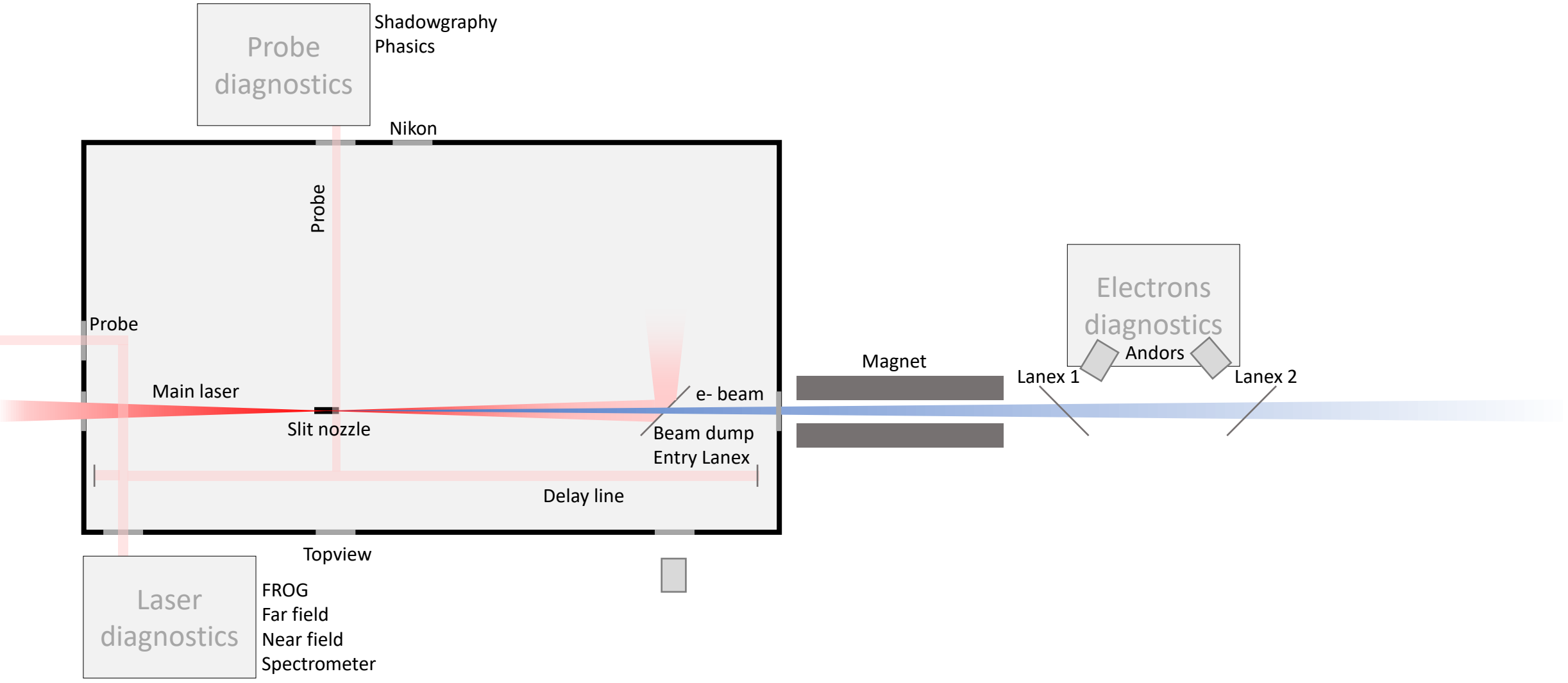


Gamma generation : Nonlinear reverse Compton

Commissioning experimental campaign 2023/2024:



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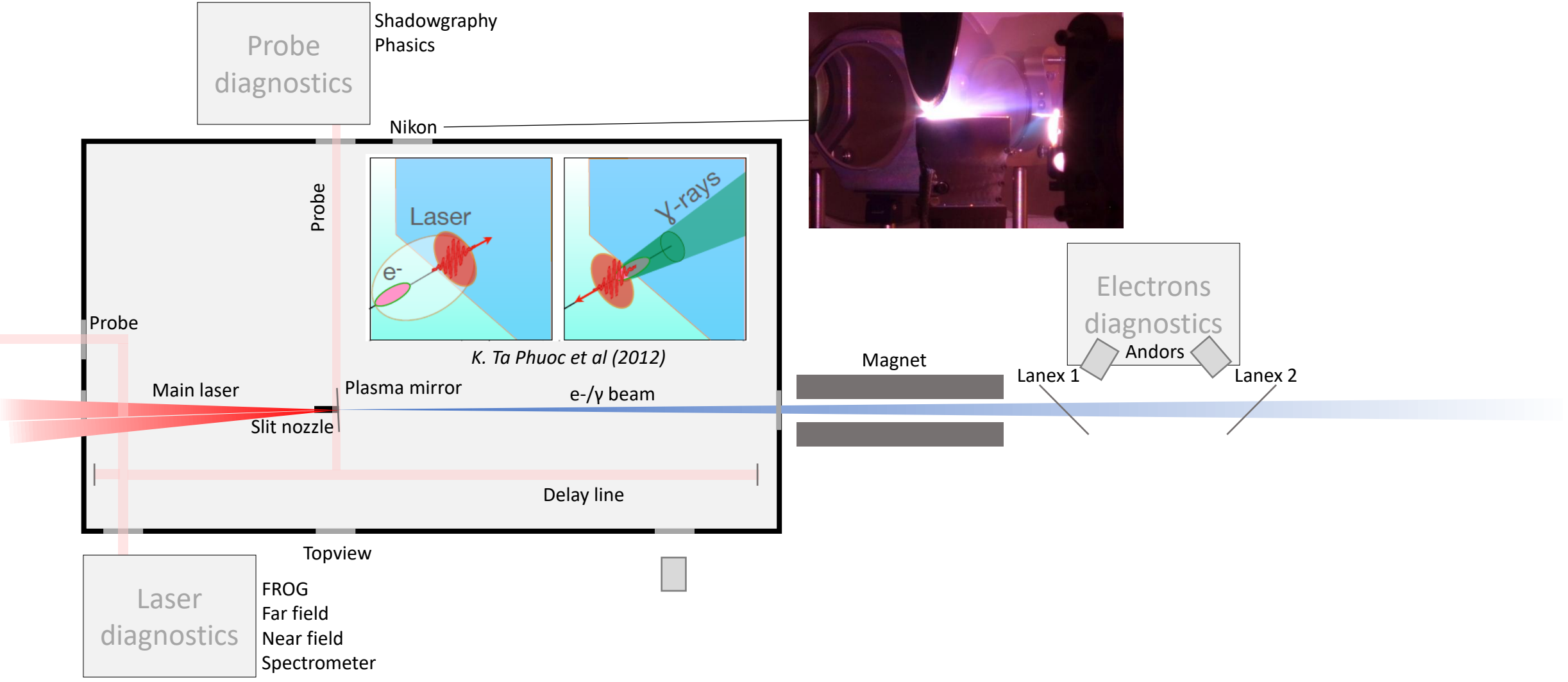

Characterization (LYSO/CsI stack)

Challenges:

MeV to GeV photons

Sub-ns bunches

Harsh environment (EMP, x-ray flash, …)

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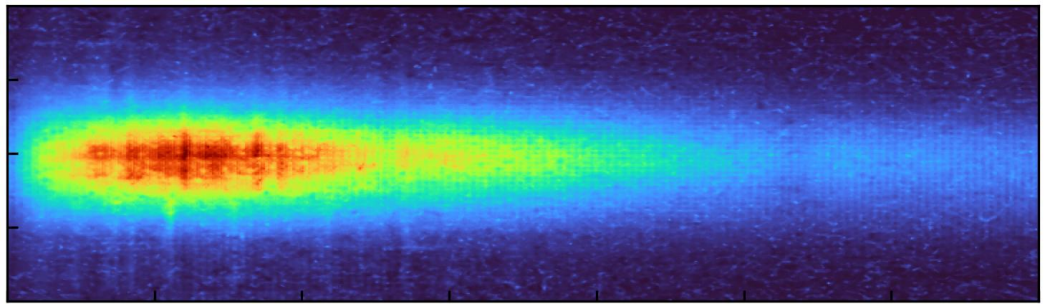
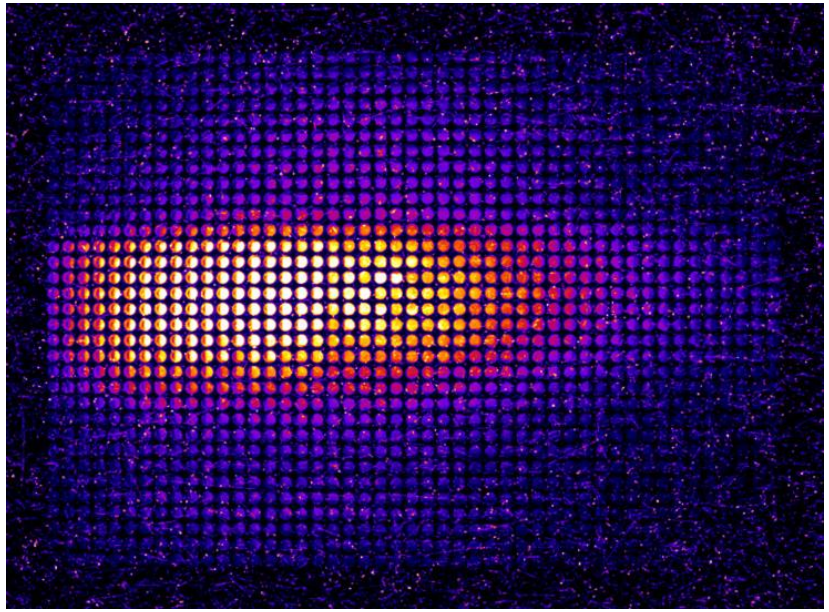
Challenges:
MeV to GeV photons
Sub-ns bunches
Harsh environment (EMP, x-ray flash, …)

Possible solution:
Pixelated scintillator stack associated with camera

LYSO



CsI



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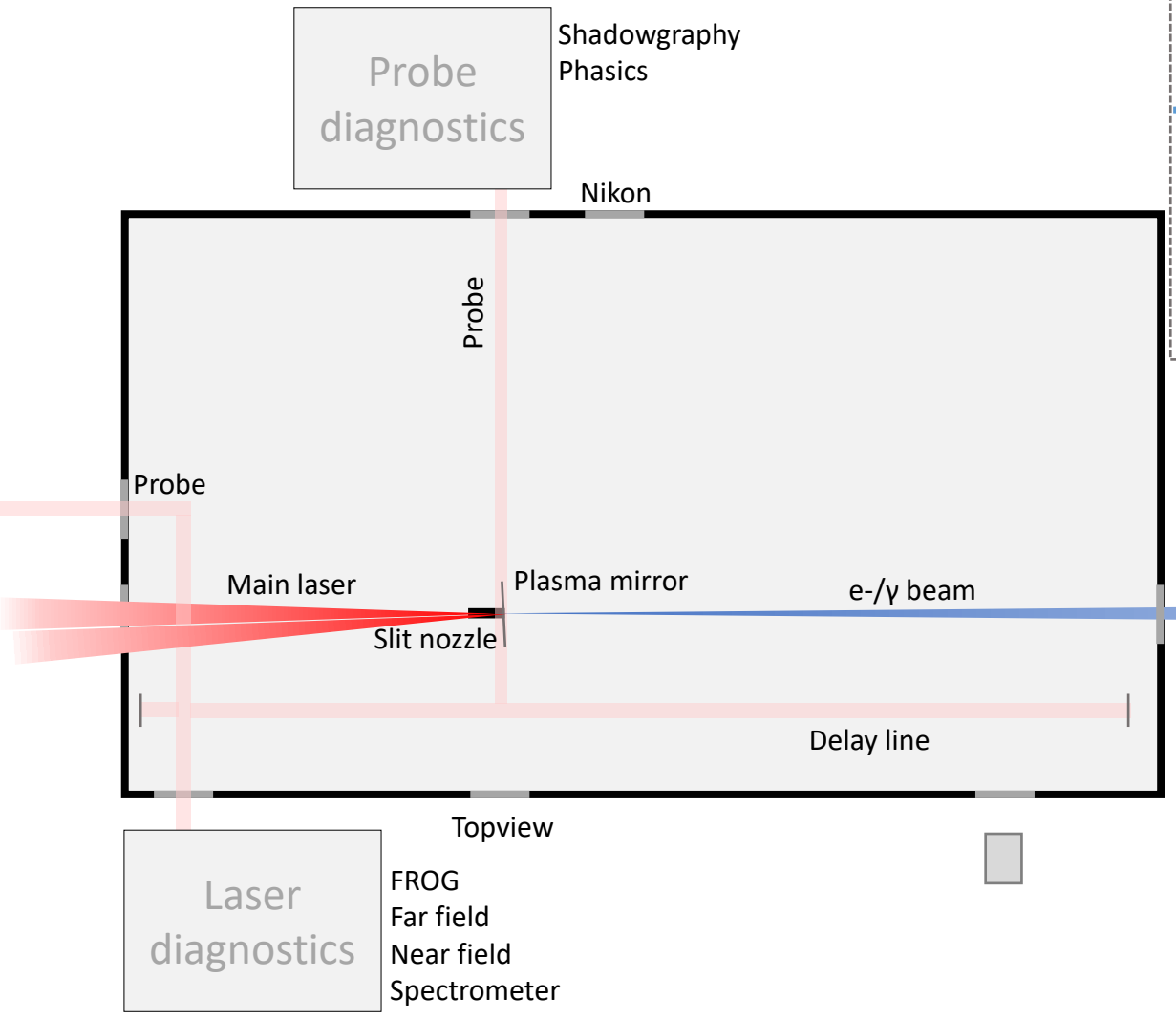
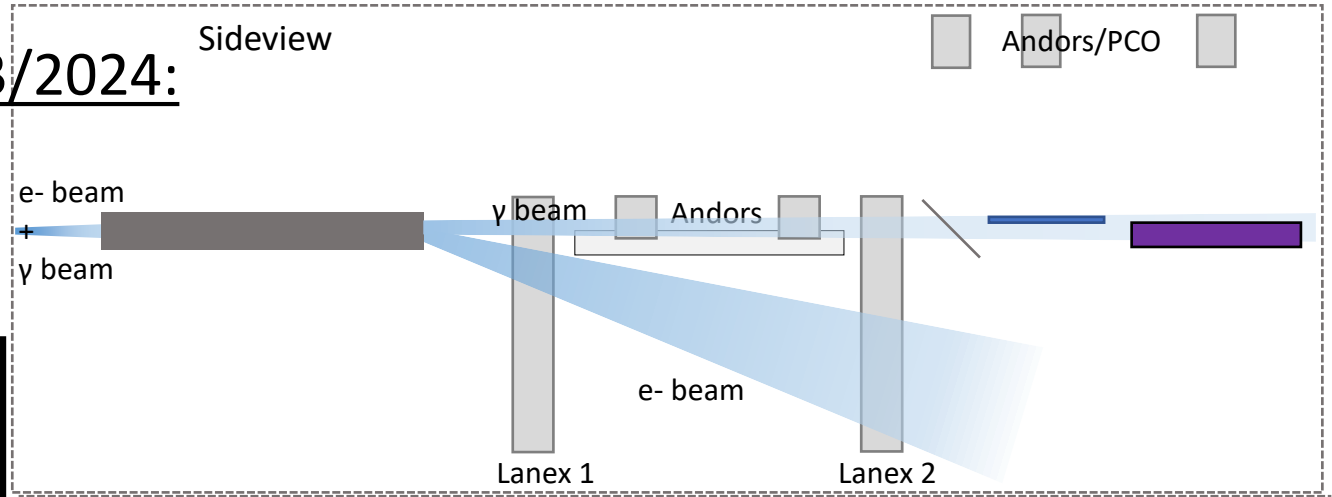
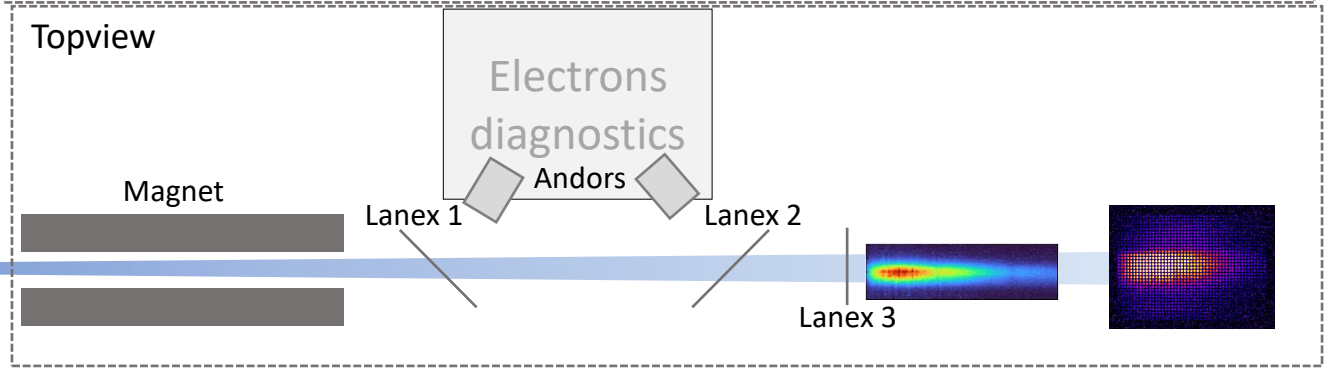
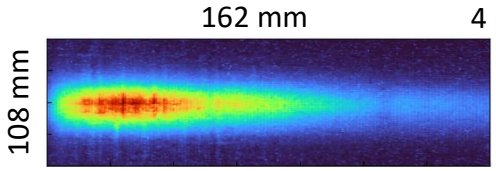
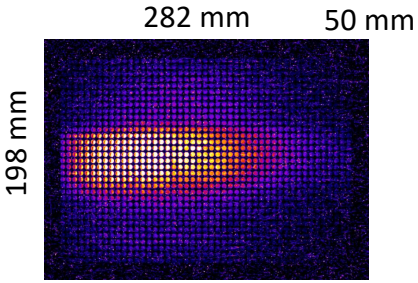








100x150 1x1x4 mm pixels



33x47 5x5x50 mm pixels

Characterization (LYSO/CsI stack)

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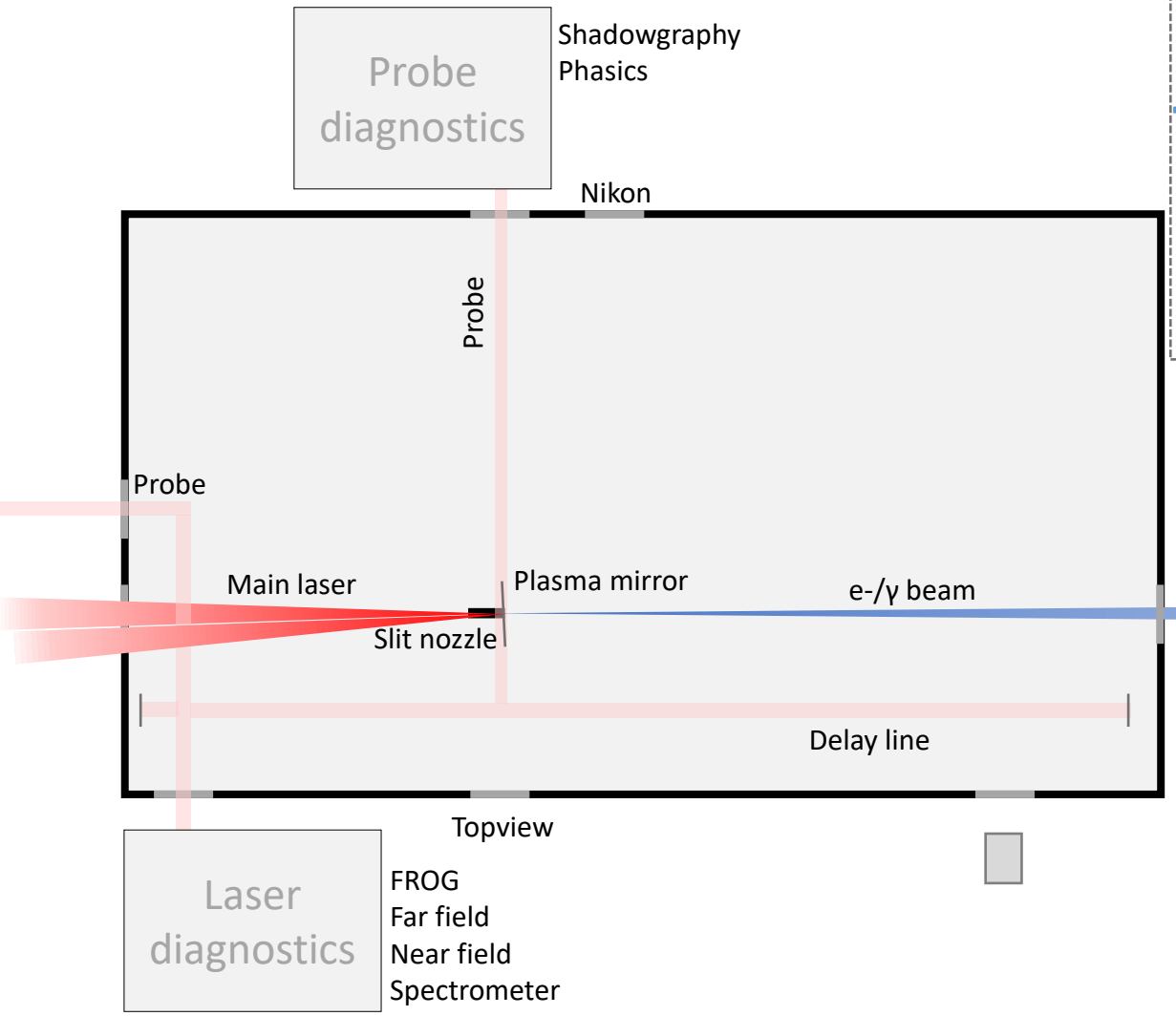

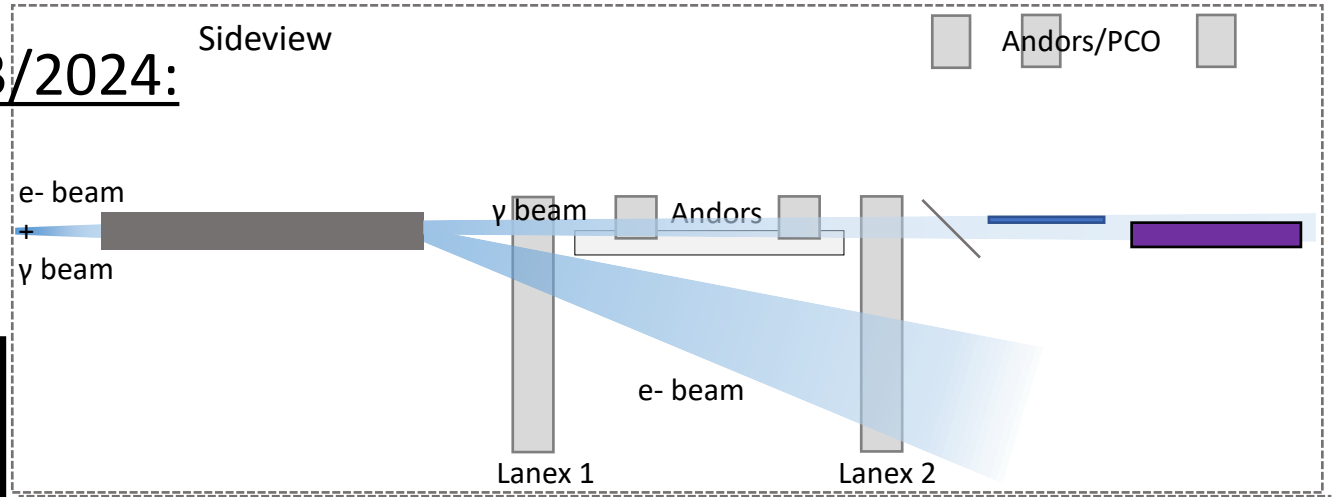

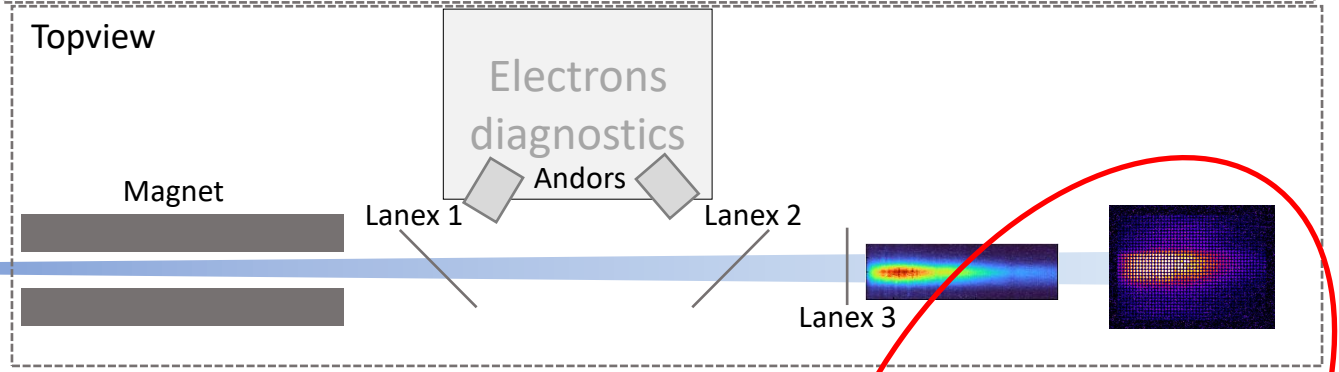

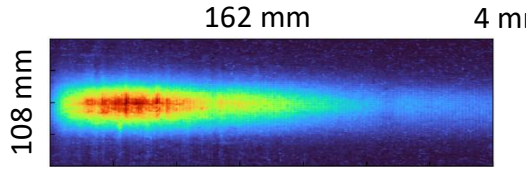

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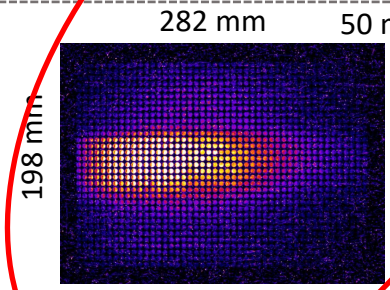
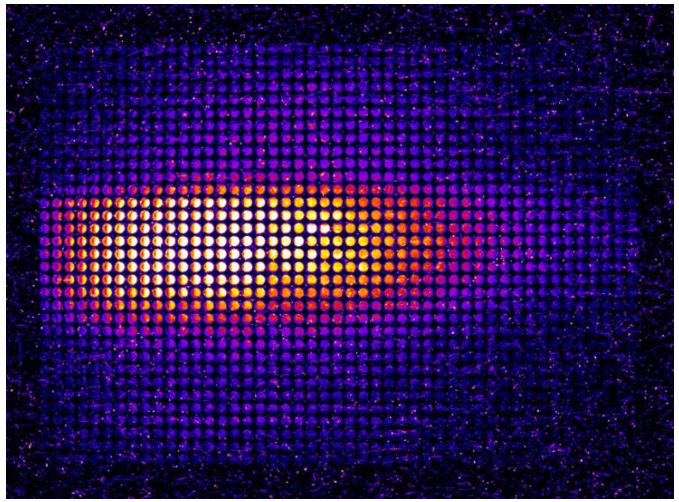
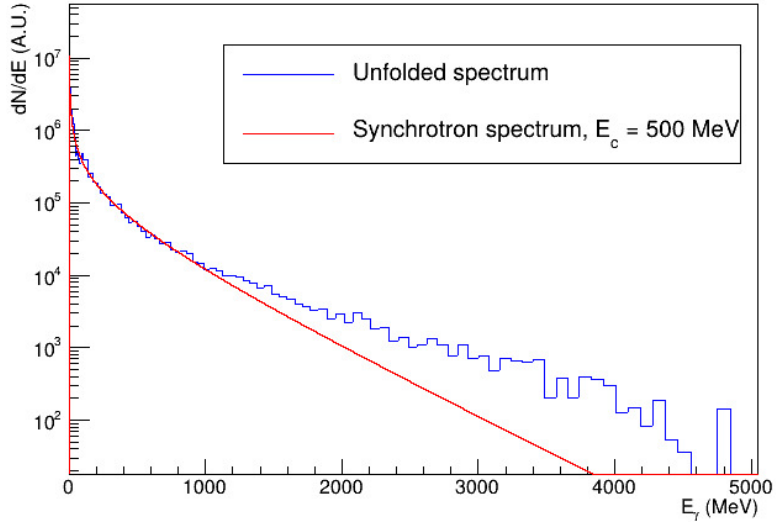


33x47 5x5x50 mm pixels

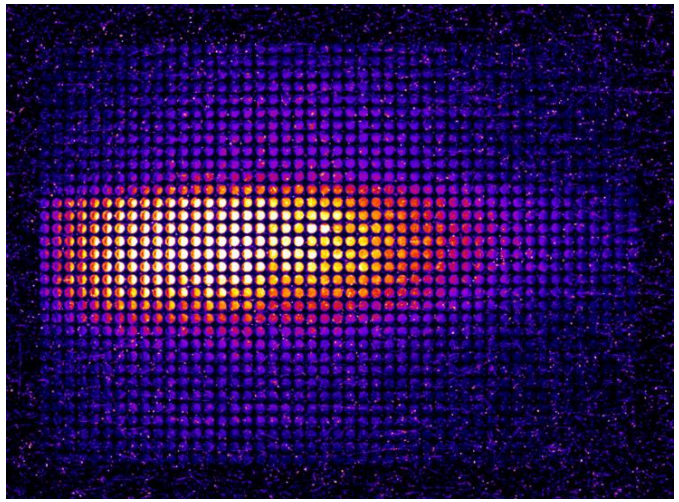
Characterization (CsI stack)



?

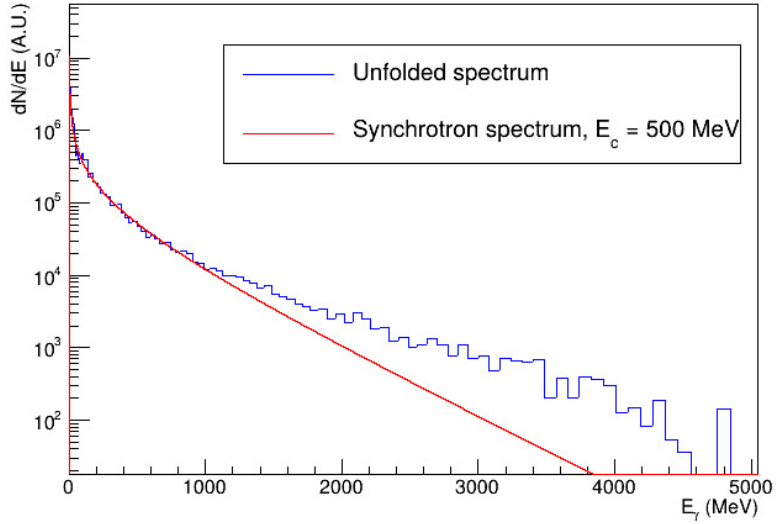


Characterization (CsI stack)



Unfolding procedure

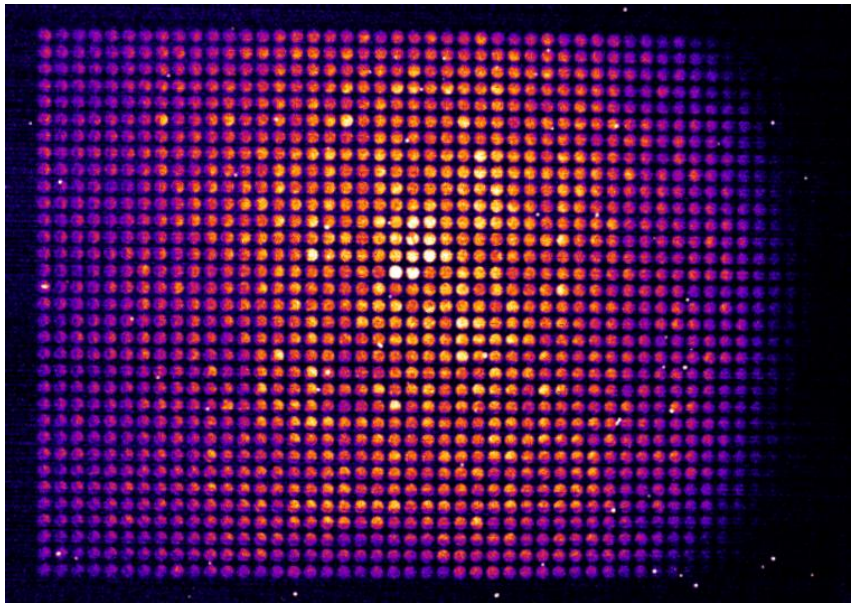
using response matrices



Characterization (CsI stack)

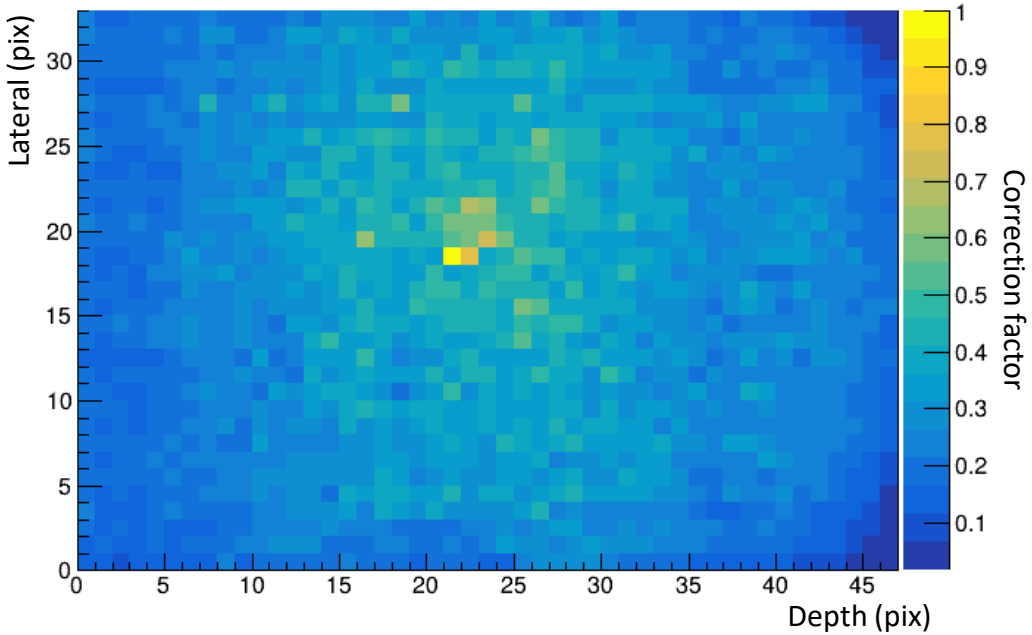
Optical response matrix:

Homogenous X-ray irradiation from the bottom



Regular size pixel integration

+ background subtraction (X-ray tube off)



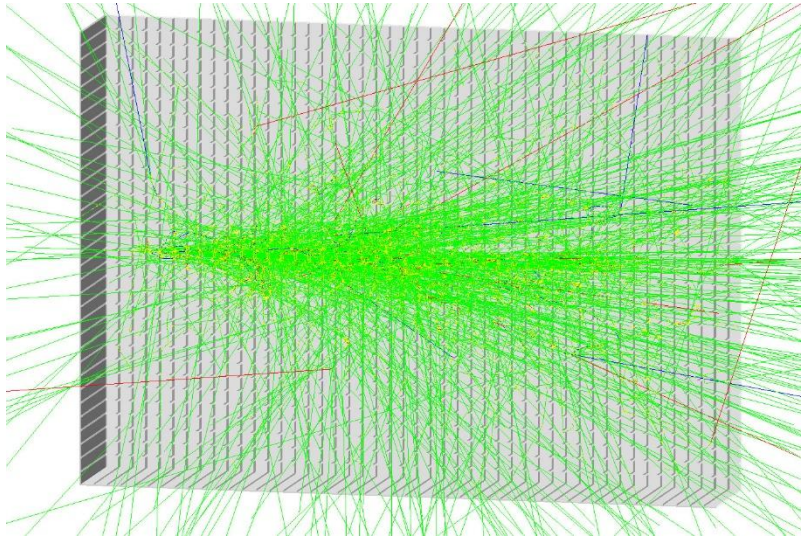
Correction factor to apply to each pixel signal

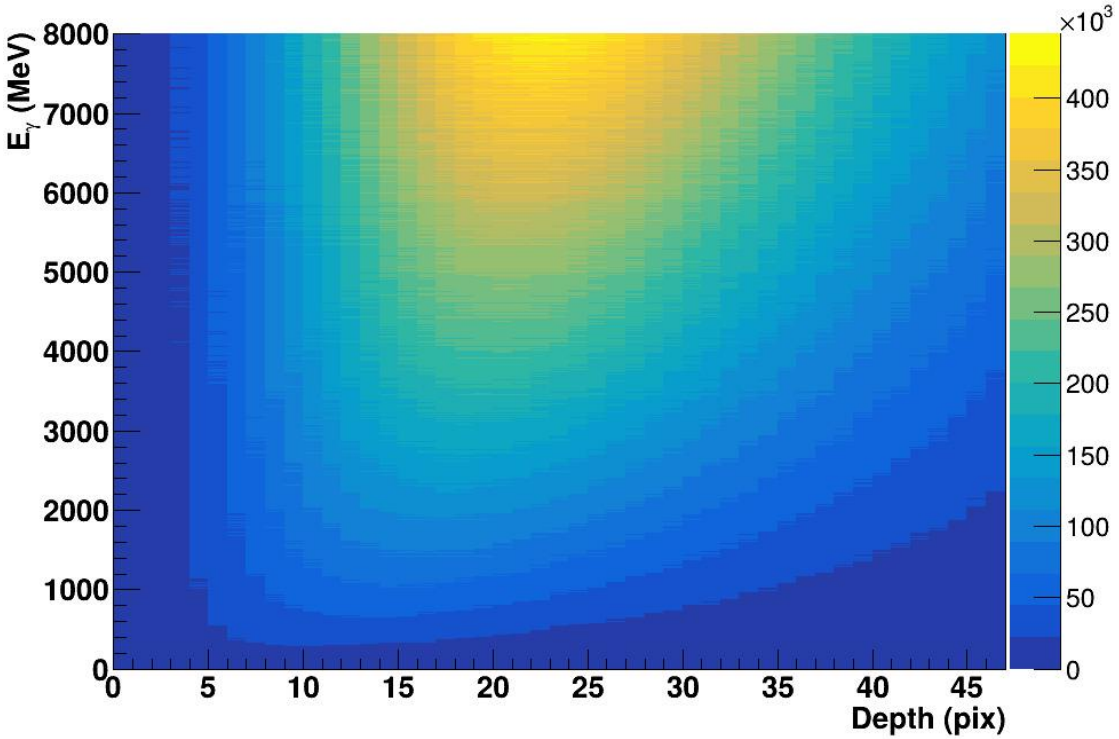
Characterization (CsI stack)

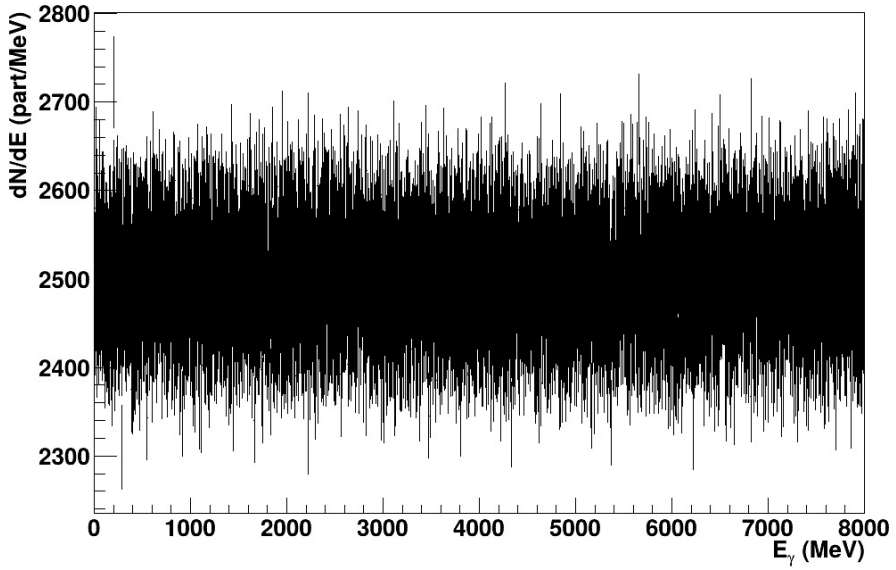
CsI stack response matrix:

Geant4 simulations to retrieve energy deposition in each pixel according to E_γ

One 3 GeV incoming γ-ray



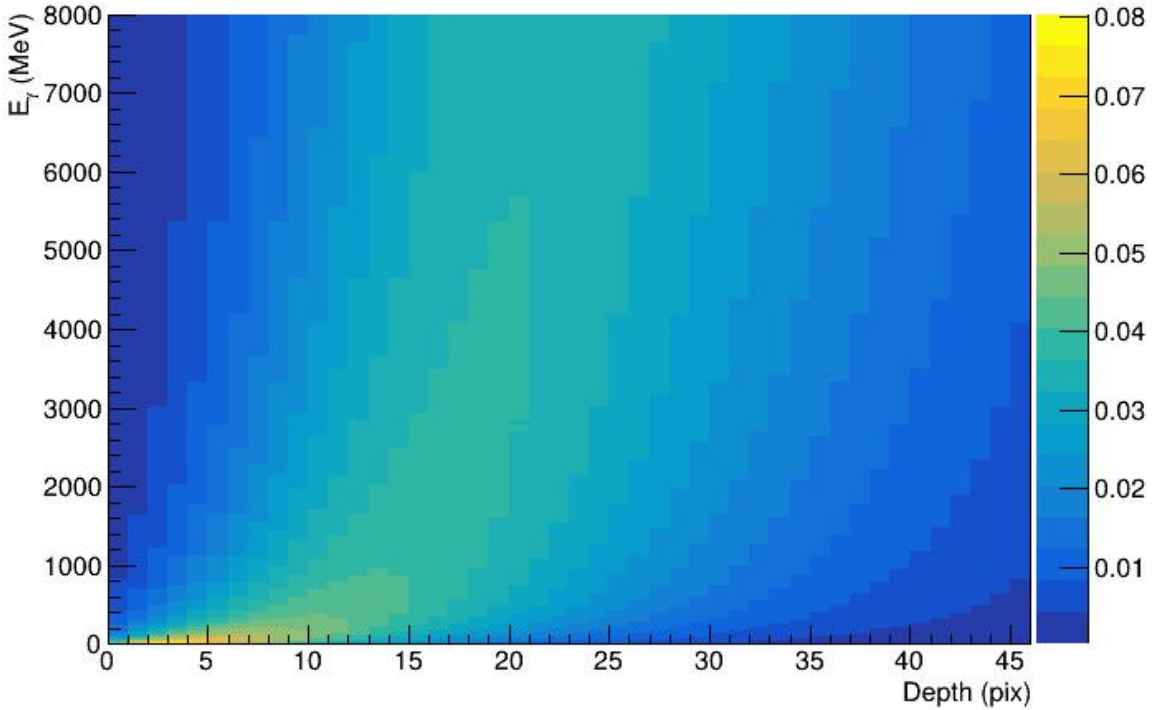




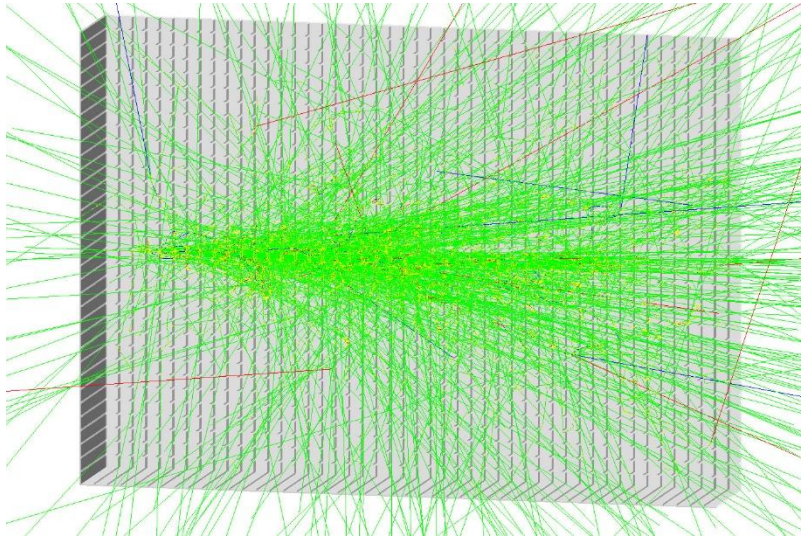
Characterization (CsI stack)

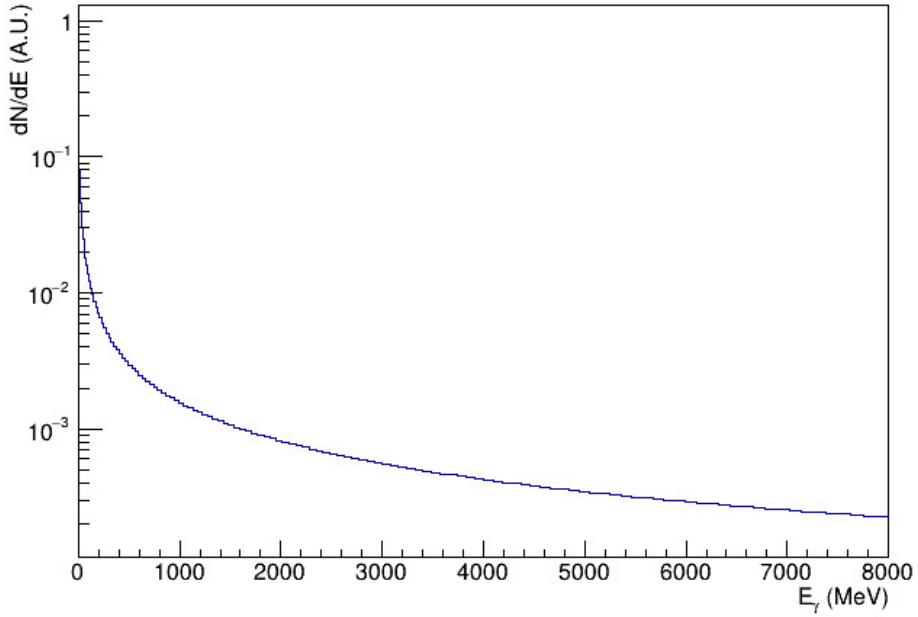
CsI stack response matrix:

Geant4 simulations to retrieve energy deposition in each pixel according to E_γ
With rebinning and normalization



One 3 GeV incoming γ-ray



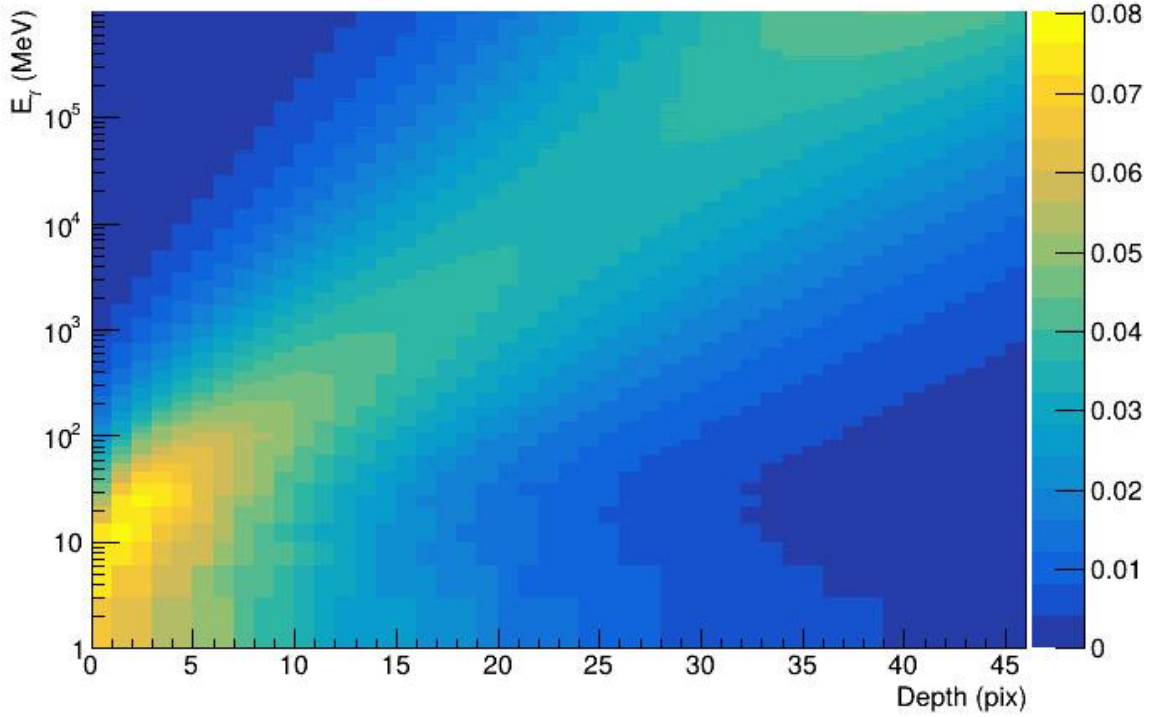


Characterization (CsI stack)

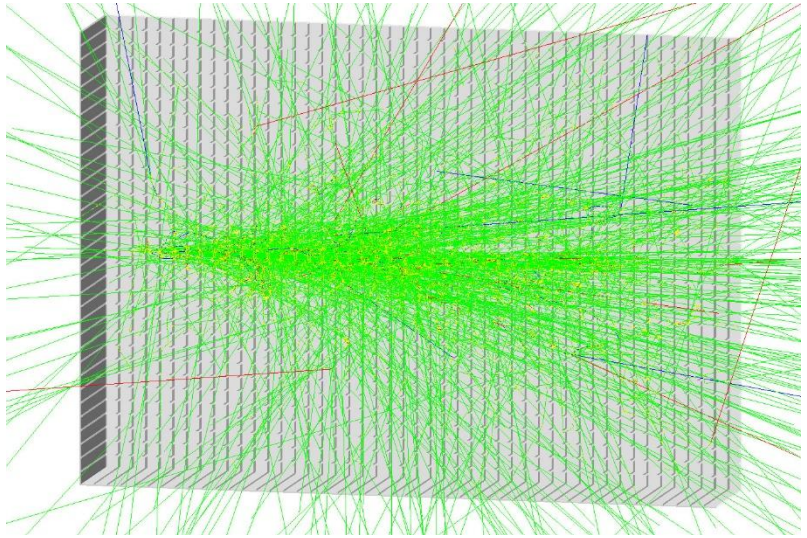
CsI stack response matrix:

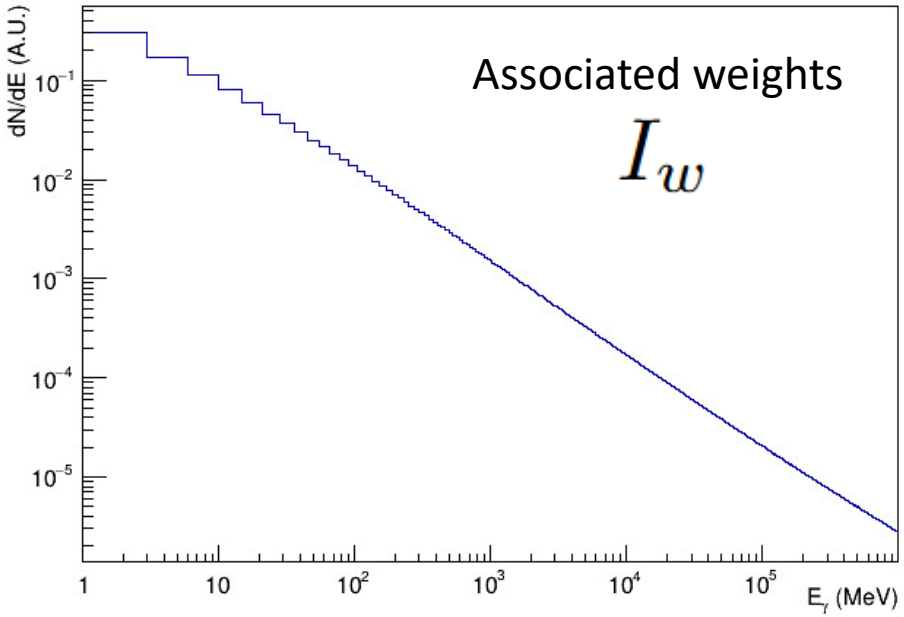
Geant4 simulations to retrieve energy deposition in each pixel according to E_γ
With rebinning and normalization

Response matrix R



One 3 GeV incoming γ-ray

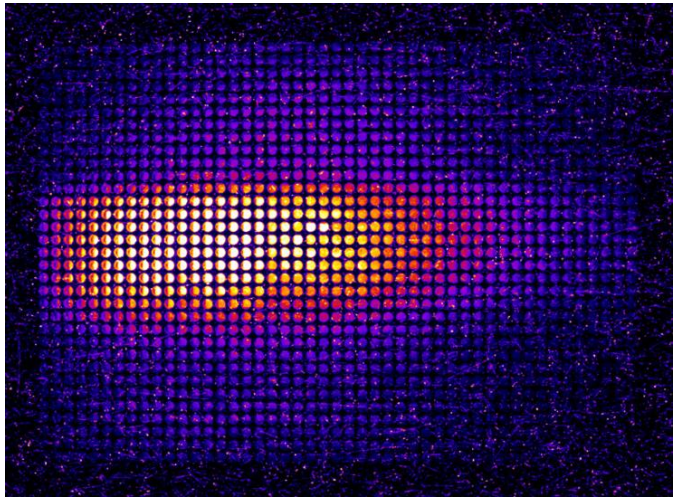




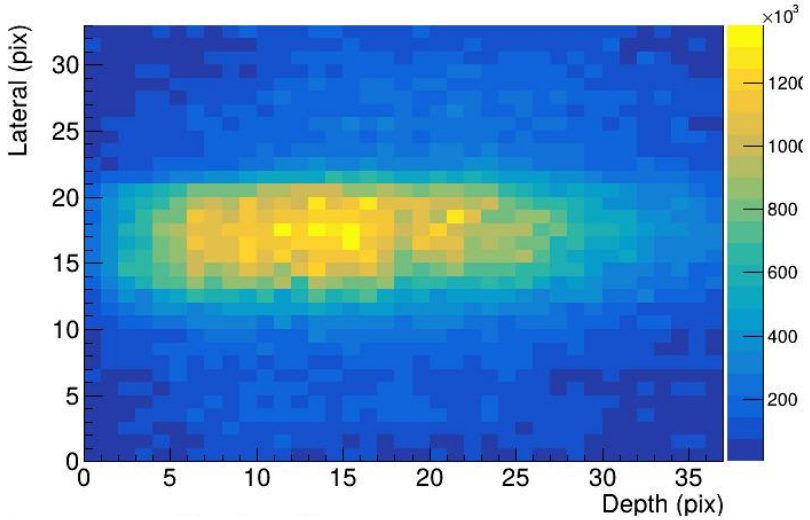
Characterization (CsI stack)

Unfolding procedure:

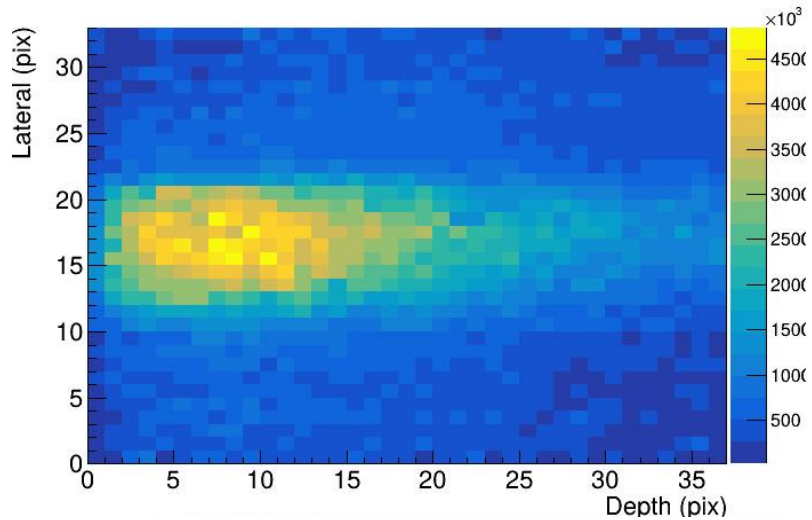
Original image



Pixel counts



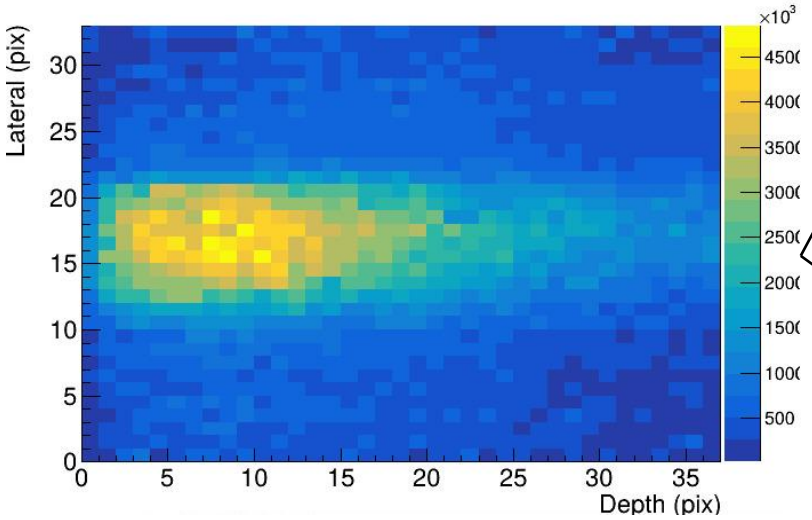
After optical response correction

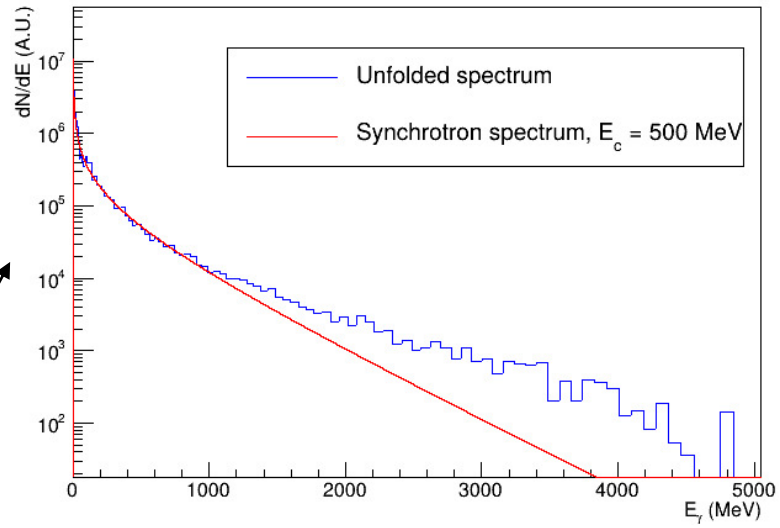


Characterization (CsI stack)

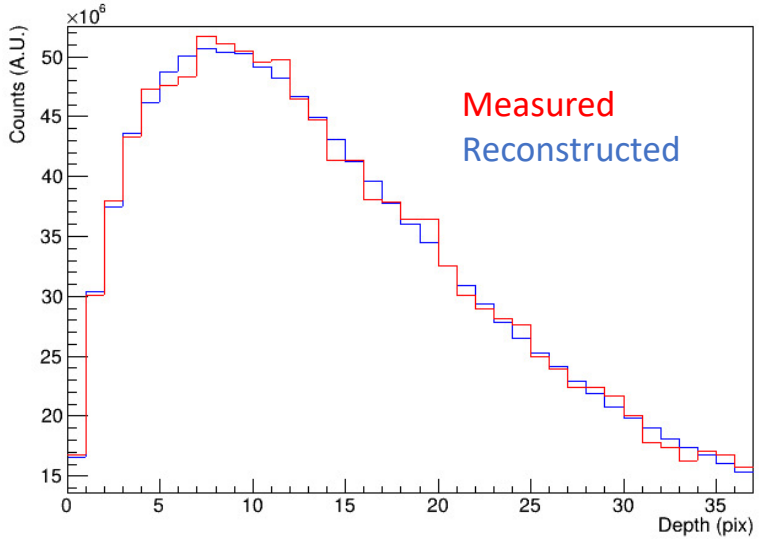
Unfolding procedure:

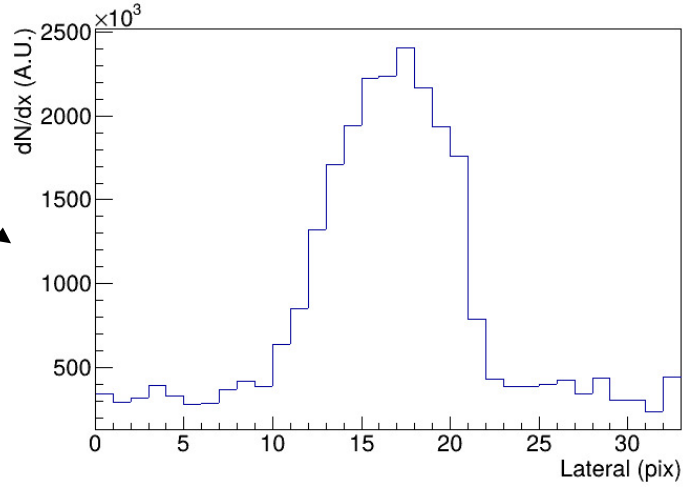
$$\vec{t} = I_w (R^T R + \tau I)^{-1} R^T \vec{m}$$





Projected pixel counts according to depth



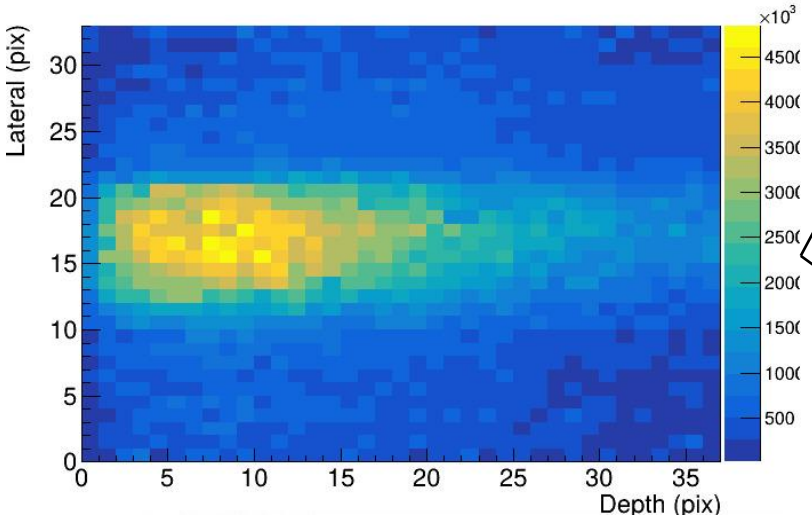


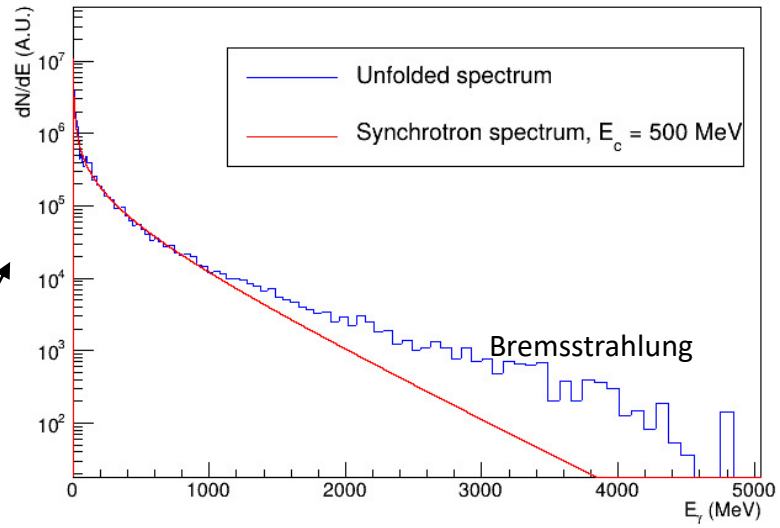
Another unfolding procedure for lateral dispersion

Characterization (CsI stack)

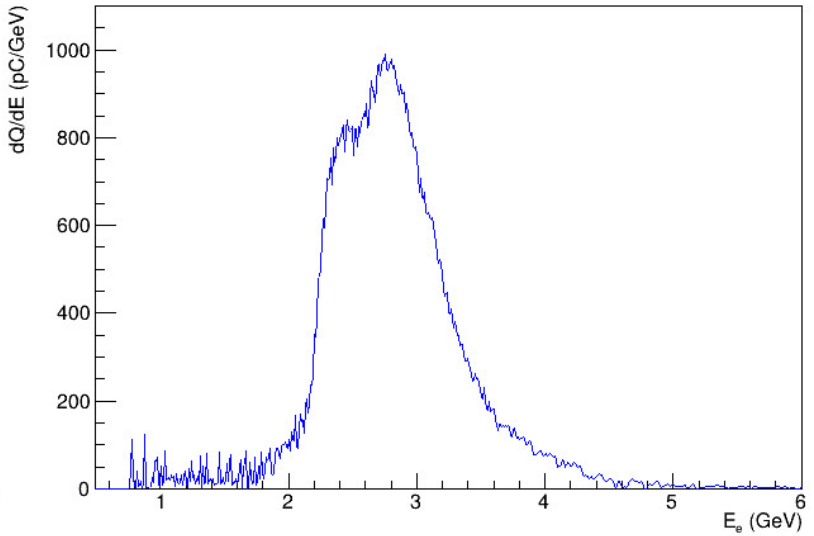
Unfolding procedure:

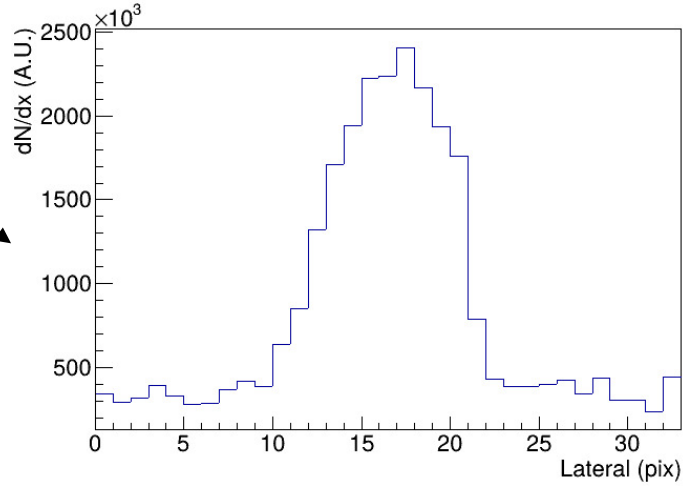
$$\vec{t} = I_w (R^T R + \tau I)^{-1} R^T \vec{m}$$





e- spectrum





Another unfolding procedure for lateral dispersion

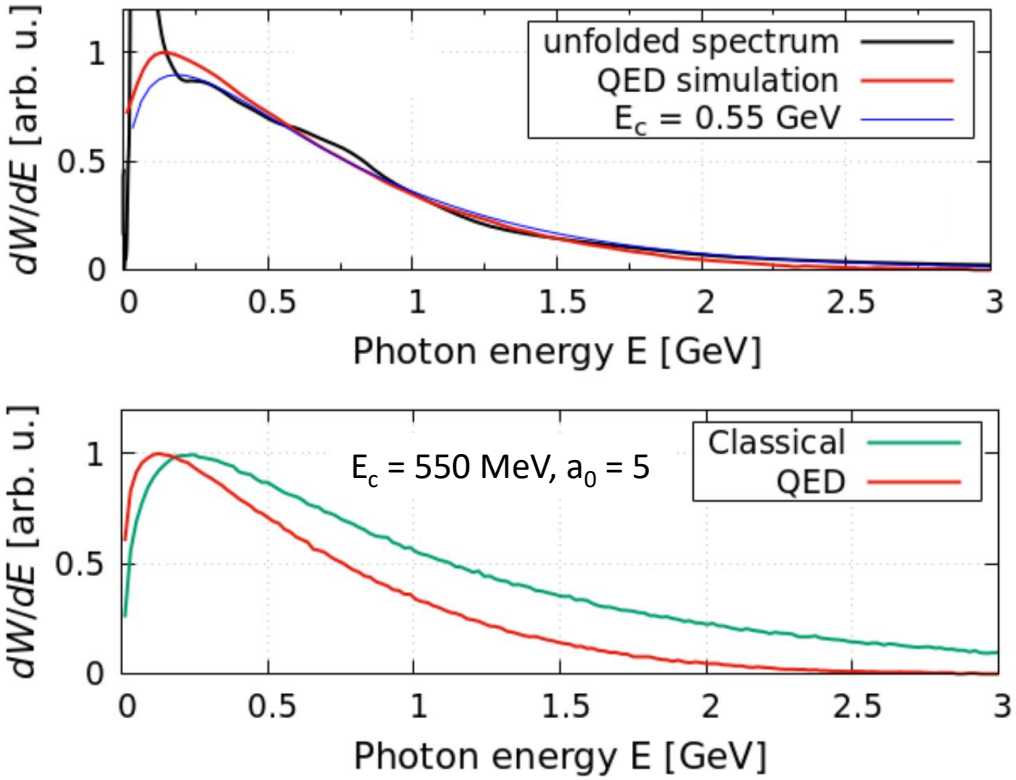
Possible applications: QED investigation

Divergence from classical scaling:

Classically : $E_c \propto \gamma_e^2 a_0$

Wrong if the electric field seen by the electron is non negligeable compared to the Schwinger field

a_0 estimated using simulations (Ptarmigan code) to reproduce measured e- and γ spectra

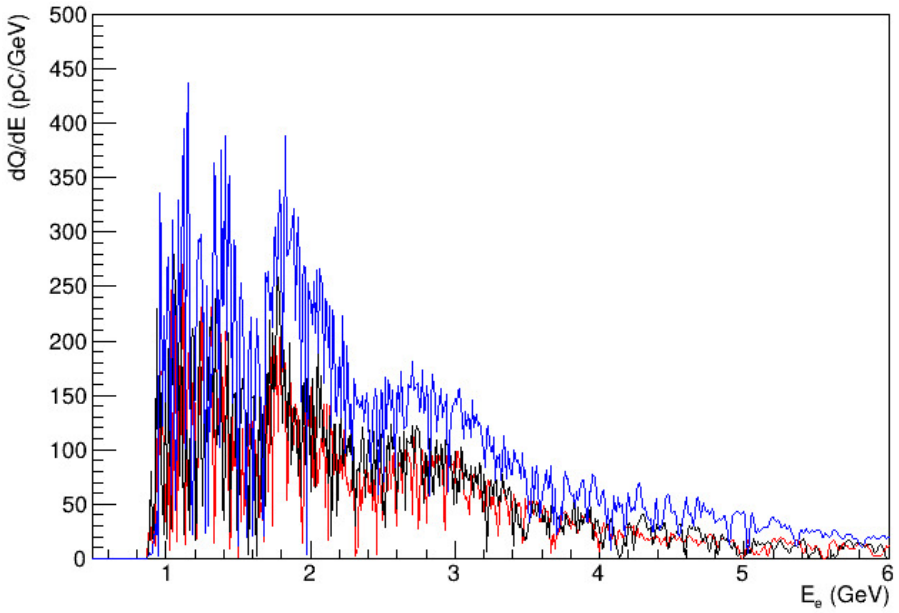


A. Matheron et al, arxiv (2024)

Possible applications: photonuclear reactions

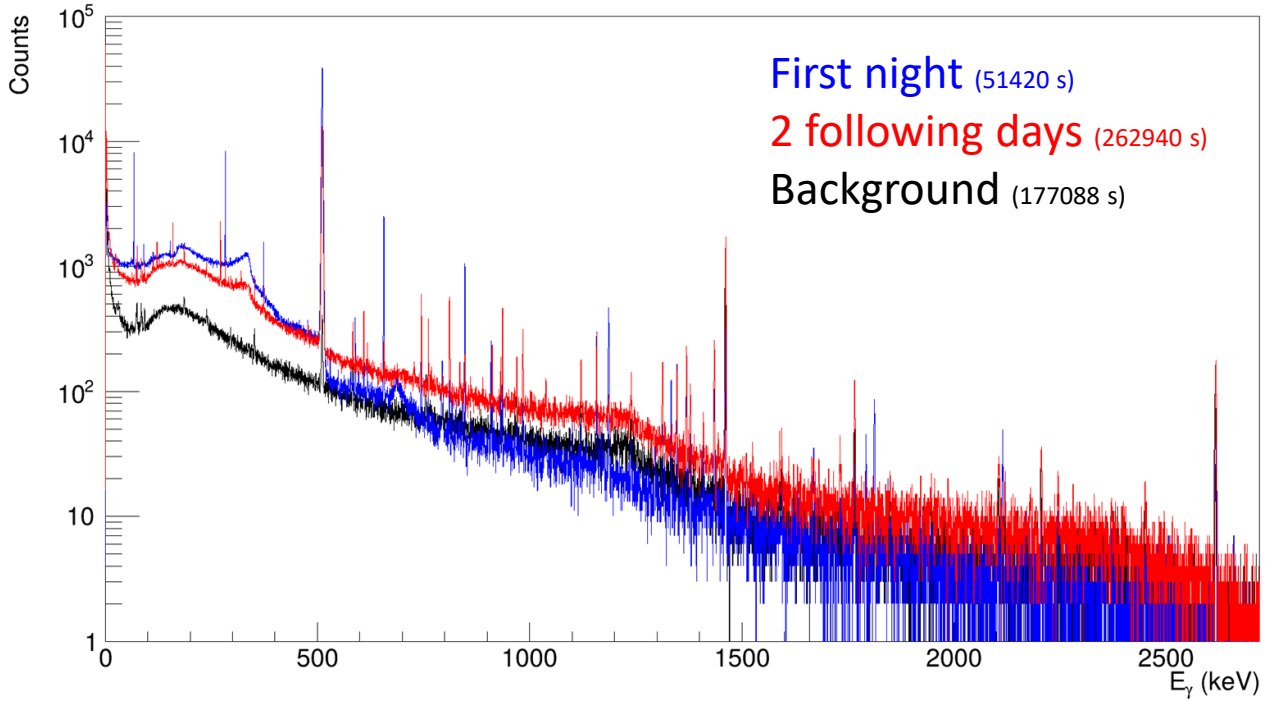
Reproduction of known yields on activation targets (June 2025):

Multi-GeV e- beam + Bremsstrahlung converter (lead)
^{nat}Cu & Al activation measured with HPGe station



e- spectra recorded after the converter
40 shots overall with similar spectra

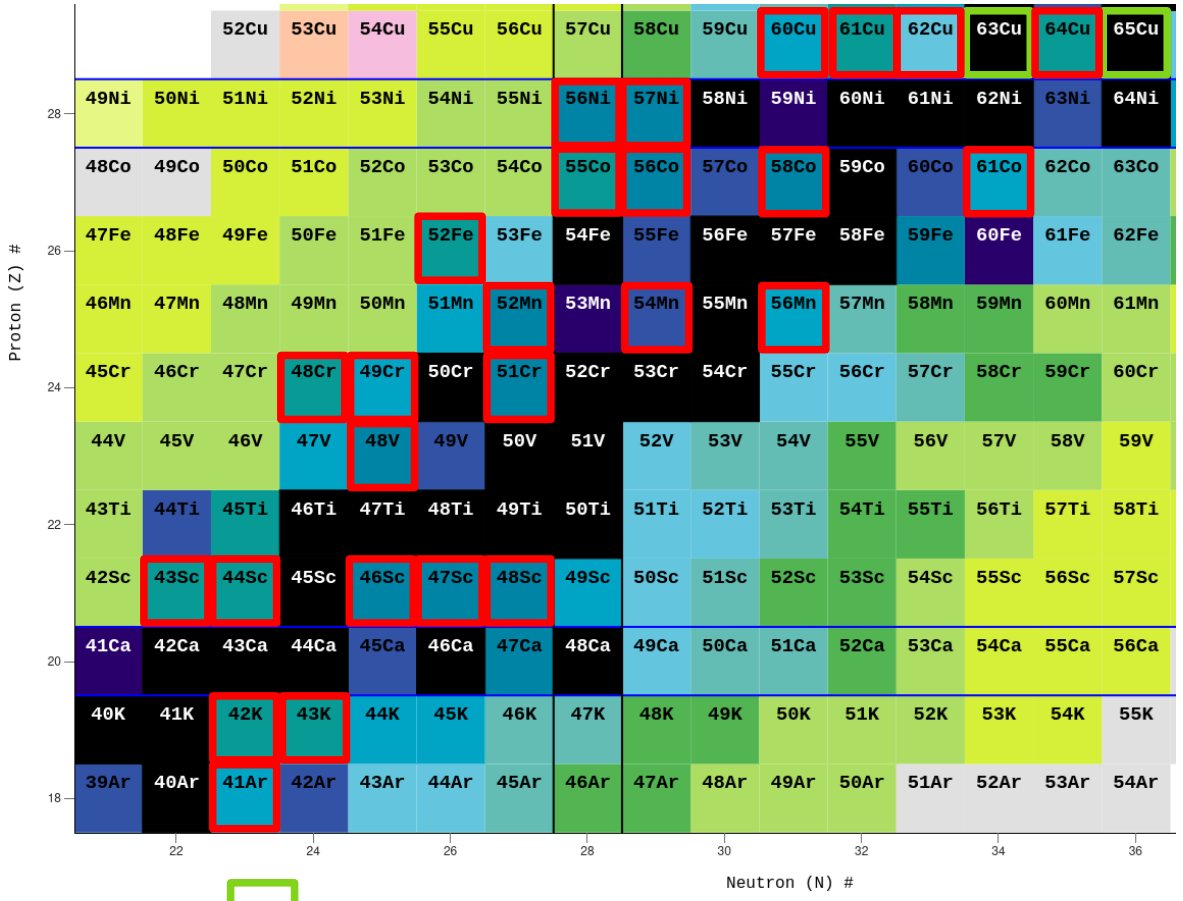
^{nat}Cu & Al activation measured with HPGe station
4 + 1 mm



γ spectra recorded after the irradiation

Possible applications: photonuclear reactions

Reproduction of known yields on activation targets (June 2025):



Target nuclei

Isotope with identified deexcitation gamma lines

^{24}Na used for γ beam quantitative estimation

Alternatively ^{nat}Cu(γ,xn)^{64,62,61,60}Cu

Goal : reproducing yields measured by Shibata (1986)

Analysis still undergoing

Conclusions & perspectives

Work done:

- Multi-GeV e-/γ beams available for experiments at ELI-NP
- Characterization of such beams available on a shot-to-shot basis
- First attempt to use such beams conducted during commissioning experiments

Perspective:

- User experiments (call for proposal open)
- Extra γ beams diagnostics (Compton/pair production) are envisioned
- Improvement of unfolding stability
- Quantitative calibration of the scintillators stack should be done

Thank you for your attention !

Questions ?

Title

Compton vs Bremsstrahlung

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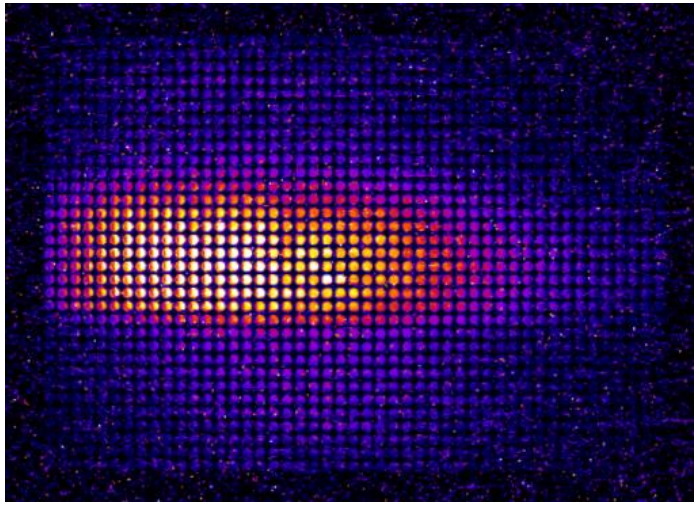
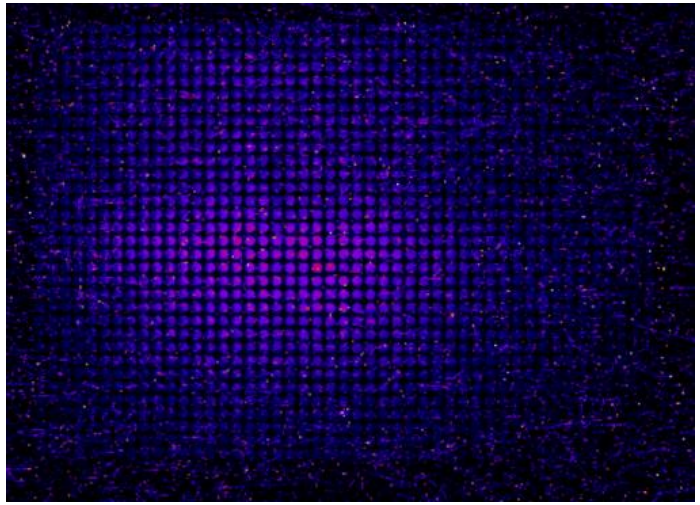


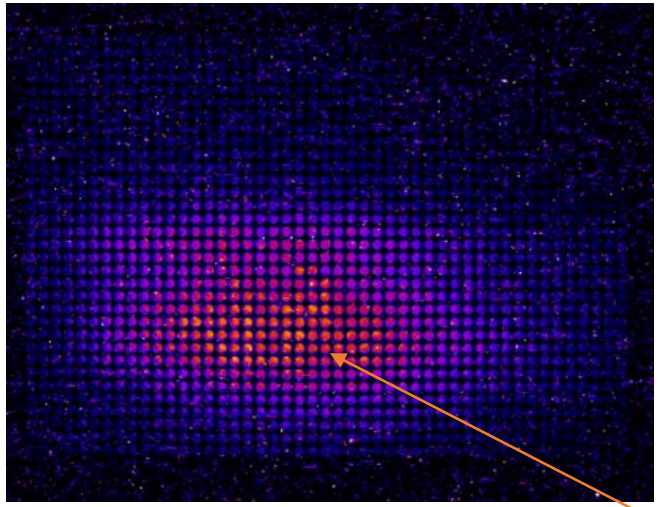
Plasma mirror

104



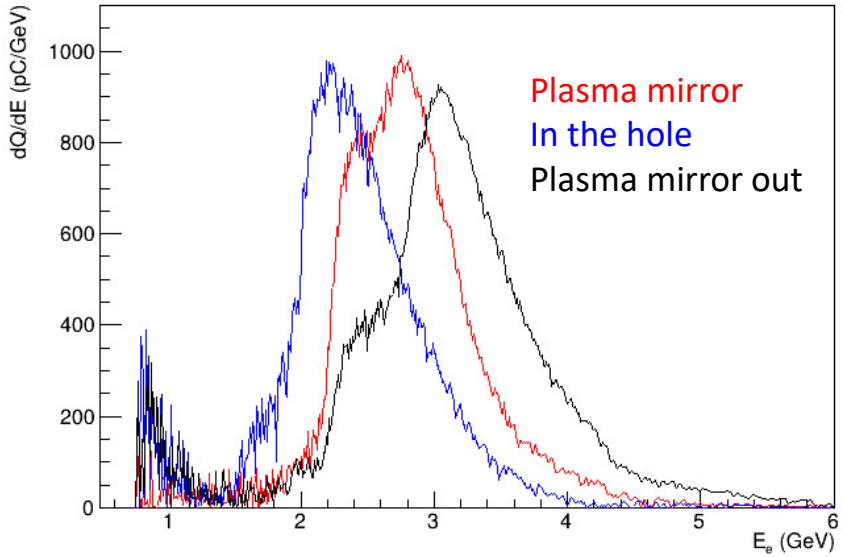
In the hole

105



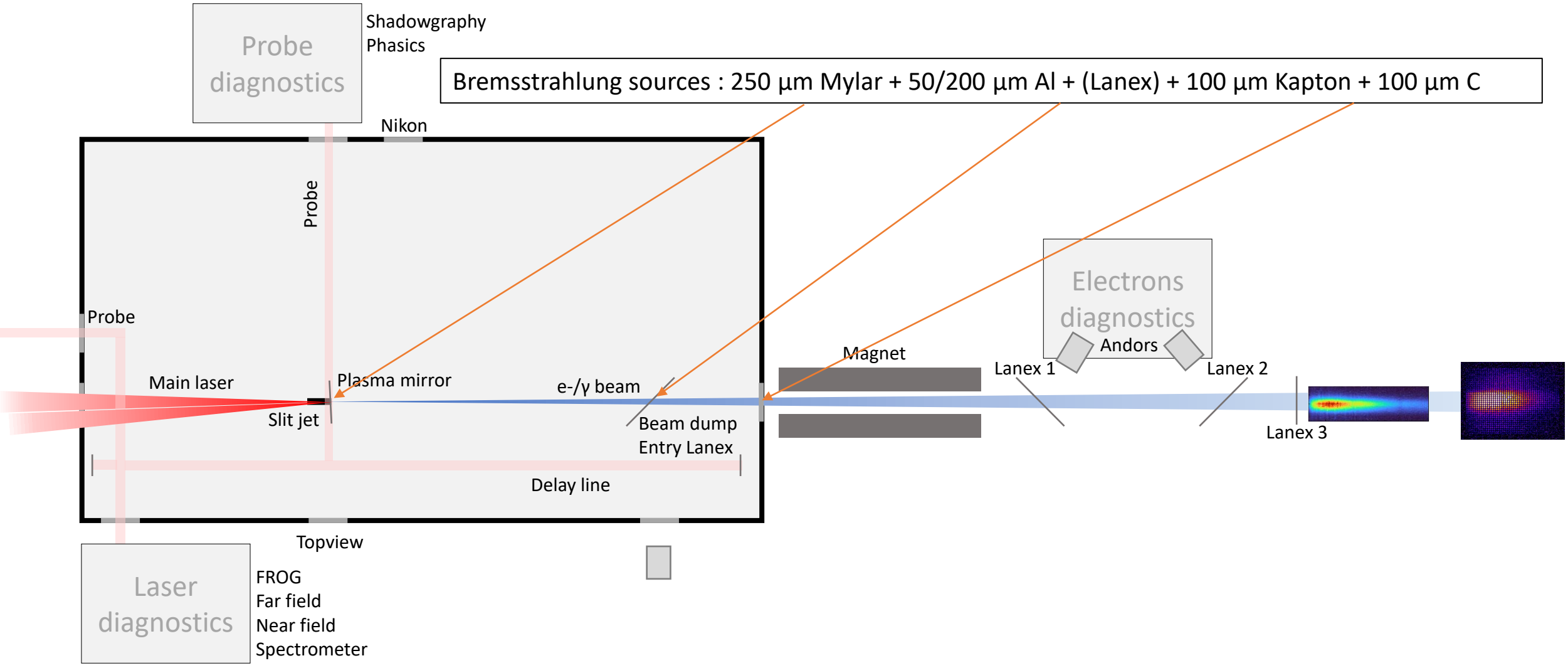
Plasma mirror out

Surely e-



Compton vs Bremsstrahlung

Commissioning experimental campaign 2023/2024:



Critical energy estimation

$$\frac{dW}{dE} \propto \frac{E}{E_c} \int_{\frac{E}{E_c}}^{\infty} K_{5/3}(x)dx$$