E-320 Progress and Plans for FY24

2023 FACET-II User Meeting

David Reis

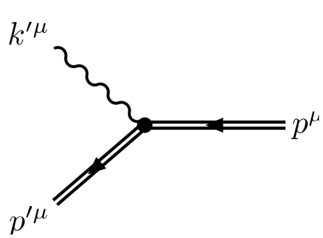
Sebastian Meuren

October 18, 2023

The collaboration

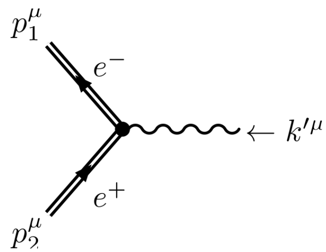
Carleton University, Ottawa, Ontario, Canada	Thomas Koffas
Aarhus University, Aarhus, Denmark	Christian Nielsen, Allan Sørensen, Ulrik Uggerhøj
École Polytechnique, Paris, France	Sébastien Corde, Pablo San Miguel Clave, Mickael Grech, Aimé Matheron, Sebastian Meuren (PI), Caterina Riconda
Technical University (TU) of Darmstadt	Stephan Kuschel, Christian Rödel
MPI für Kernphysik, Heidelberg, Germany	Antonino Di Piazza, Christoph H. Keitel, Matteo Tamburini
HI Jena and University of Jena, Germany	Harsh, Felipe Salgado, Jannes Wulff, Matt Zepf
Universidade de Lisboa, Portugal	Thomas Grismayer, Luis Silva, Marija Vranic
Imperial College London, UK	Stuart Mangles
Queen's University Belfast, UK	Niall Cavanagh, Elias Gerstmayr, Gianluca Sarri, Matthew Streeter
California Polytechnic State University, CA USA	Robert Holtzapple & students
Lawrence Livermore National Laboratory, CA USA	Félicie Albert
SLAC National Accelerator Laboratory and Stanford PULSE Institute, Menlo Park, CA USA	Robert Ariniello, Phil Bucksbaum, Christine Clarke, Angelo Dragone, Alan Fisher, Frederico Fiuza, Alan Fry, Spencer Gessner, Siegfried Glenzer, Carsten Hast, Mark Hogan, Chris Kenney, Alexander Knetsch (POC), Doug McCormick, Rafi Mir-Ali Hessami, Brendan O'Shea, David Reis, Tania Smorodnikova, Douglas Storey, Glen White, Vitaly Yakimenko
University of California Los Angeles, CA USA	Chan Joshi, Warren Mori, Brian Naranjo, James Rosenzweig, Oliver Williams, Monika Yadav
University of Colorado Boulder, CO USA	Chris Doss, Michael Litos
University of Nebraska - Lincoln, NE USA	Matthias Fuchs, Junzhi Wang
Former members	Zhijiang Chen, Henrik Ekerfelt, Erik Isele

High-level summary: fundamental SFQED processes we will study



Photon emission

Strong-Field Compton



Photon decay

Strong-Field Breit-Wheeler

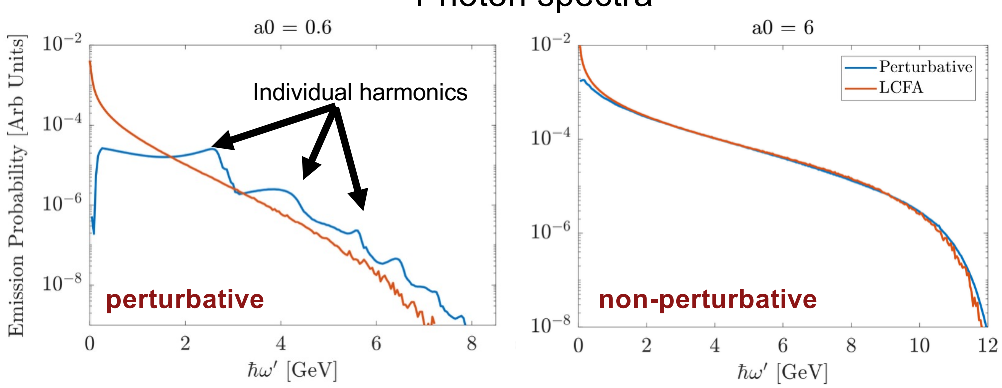
Current electron beam parameters	
Energy	10 GeV
Bunch charge	0.7 − 2 nC
Peak current	1 − 10 kA
Bunch radius (rms)	∼ 30 − 50 µm
Collision angle	150°
Quantum parameter χ	0.3–0.6

Current laser beam parameters	
Pulse energy (on OAP)	0.1–0.3 J
Pulse duration (FWHM)	∼ 50 fs
Photon energy	1.55 eV
Beam waist	2 µm
Peak intensity (Strehl: 0.5)	$2-6\times10^{19}$ W/cm^2
Classical intensity parameter a_0	3–5

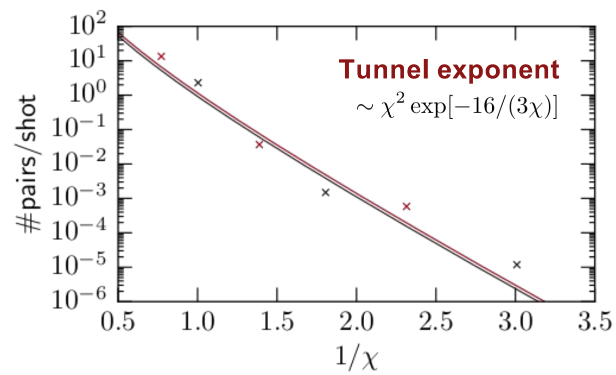
$$\chi = \frac{e\hbar[-(p\mathcal{F})^2]^{1/2}}{m^3c^3}$$

$$a_0 = \frac{e\sqrt{-A^2}}{mc}$$

Photon spectra



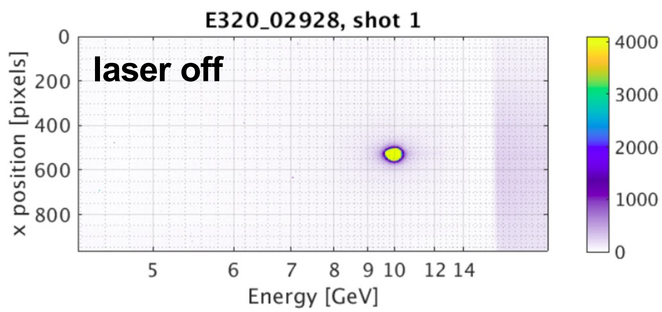
Pair production rate

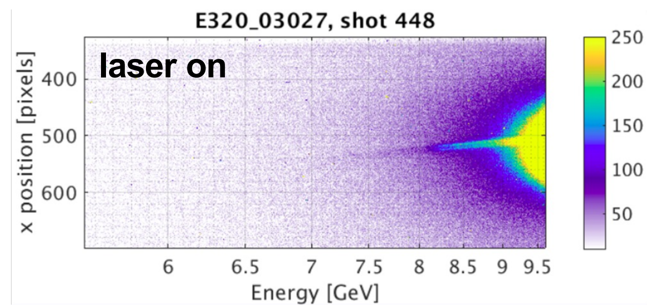


Simulations: C. Nielsen (Aarhus)

High-level summary: first collisions, and some competition

- We observed electron-laser collisions during two beam times in 2022
- 6 days ago (October 12/13, 2023) we re-established collisions





Electron spectrum (2022):
net absorption of 1&more laser photons

Presentation

20 July 2023

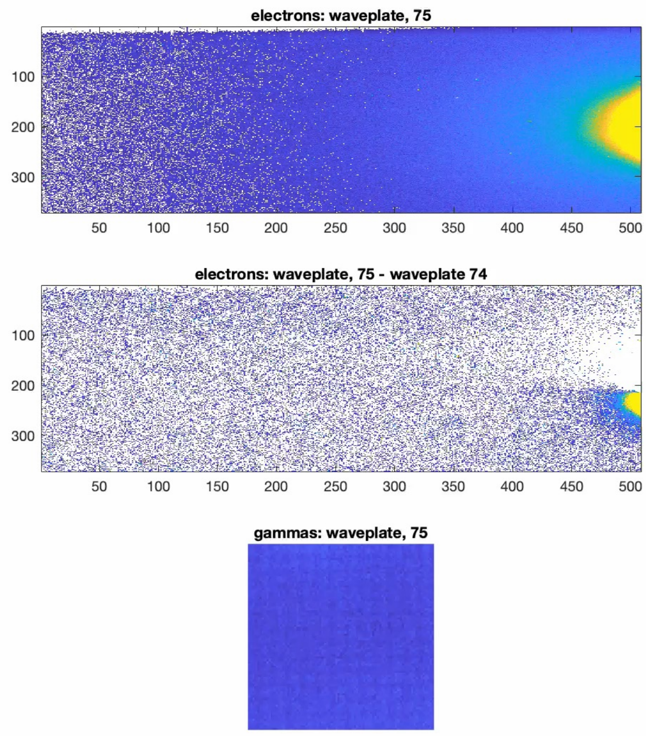
Demonstration of all optical nonlinear Compton scattering between a multi-GeV electron beam and an ultrahigh intensity laser

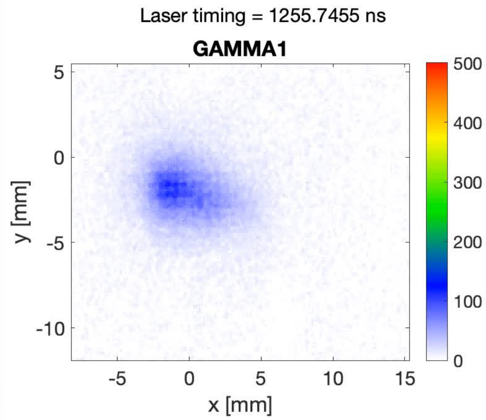
Chang Hee Nam

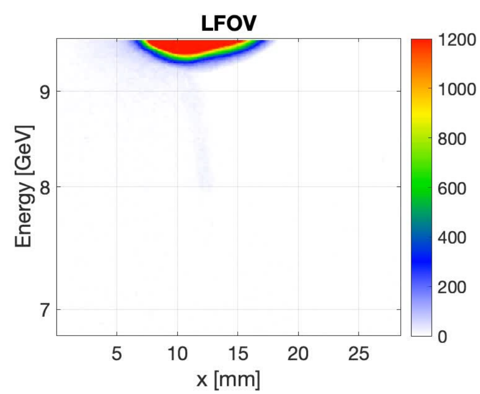
Multi-PW laser facilities have first result

It is timely to harvest low-hanging fruits

Scattered electron data (2022): laser wire-type beam diagnostic





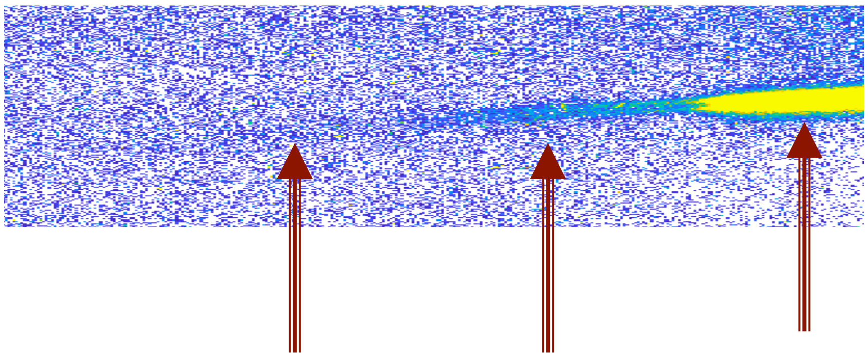


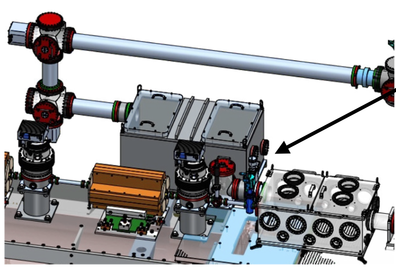
<u>right</u>: laser timing scan:
Compton scattered gammas and position/momentum correlation of scattered e-beam

San Miguel Claveria
http://arxiv.org/abs/2310.05535

<u>left</u>: Laser intensity scan
Scattered electrons position/momentum with low-intensity image is subtracted as "background" and gammas
desired: "goose" trigger

Estimation of the (peak) laser intensity (2022 beamtimes)



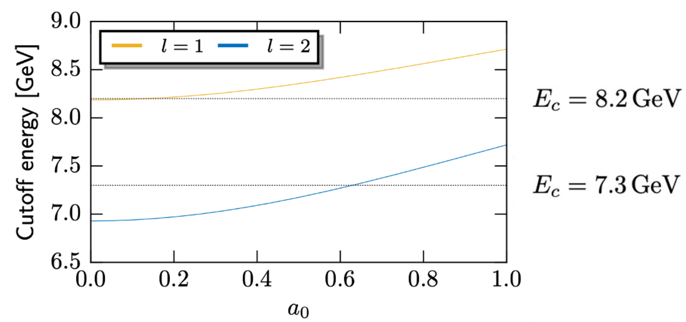


$$a_0 = 0.6 \pm 0.1$$
$$I_0 = 8 \times 10^{17}\,\mathrm{W/cm^2}$$

Conservation of quasi-momentum
(linear polarization)

$$k'^{\mu} = lk^{\mu} + q^{\mu} - q'^{\mu},$$

$$q^{\mu} = p^{\mu} + \frac{m^2 a_0^2}{4pk} k^{\mu}, \quad q'^{\mu} = p'^{\mu} + \frac{m^2 a_0^2}{4p'k} k^{\mu}$$

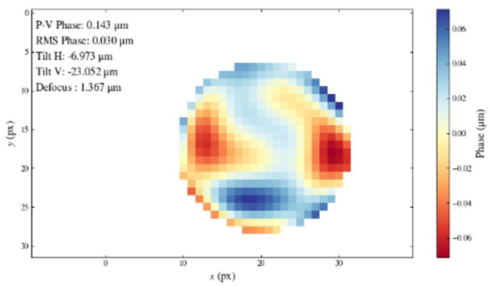


Analysis: Tatiana Smorodnikova
(see ExHILP 2023 talk)

New data taken last week

Laser quality improved significantly

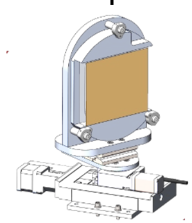
Phase-front /collimation improved



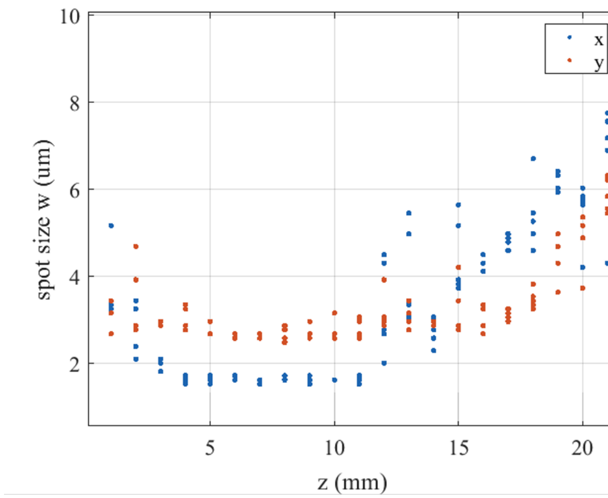
λ/6 wavefront in the tunnel, good focus on CompFar

General improvements

Grating motorization remove spatial chirp



E-320 focal scan: removed astigmatism



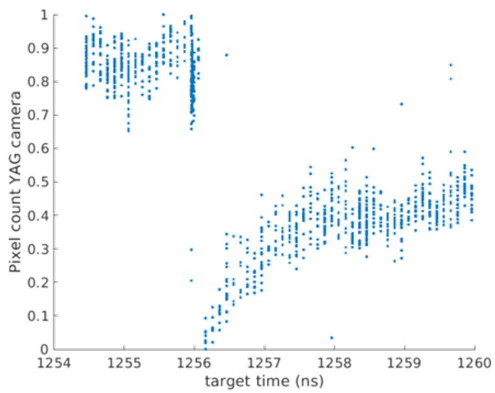
See talk by A. Knetsch: S20 laser and diagnostic probe lines

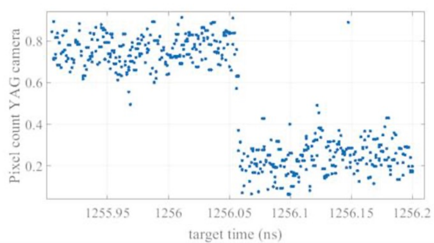
Great progress due to work by Junzhi / Alex / Robert et al.

See talk by R. Ariniello: S20 Laser High power performance and possible upgrades

Timing measurement: YAG tool very reliable

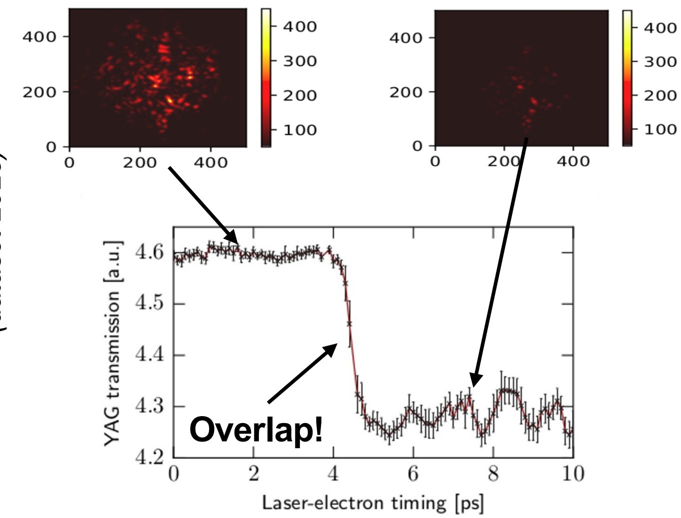
Electron-laser timing with YAG (2023)





Knetsch/Wang (datasets 3893-3895)

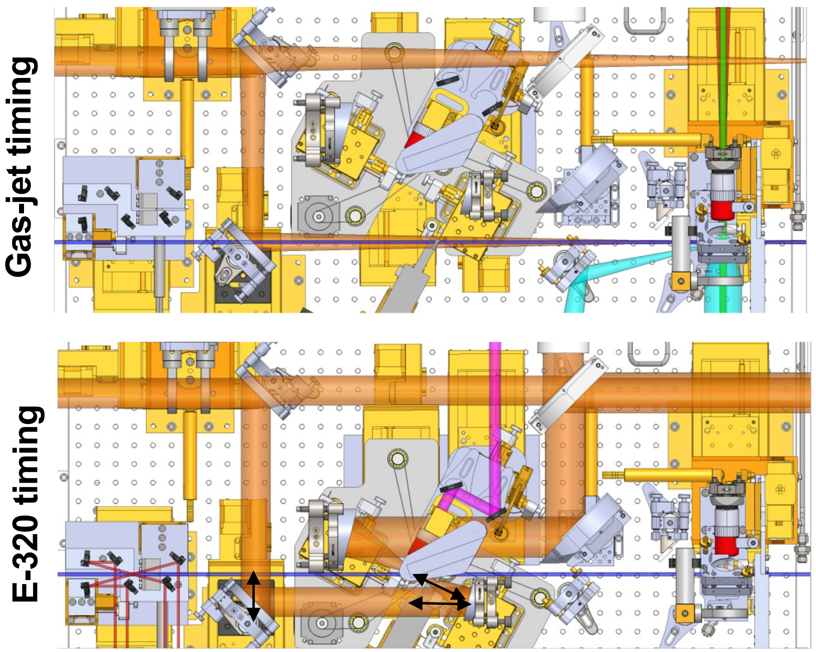
E-320 run on August 19, 2022
(dataset 2925)



- e-beam arrives early: carriers excited → laser transmission is reduced
- rise time: $\lesssim$ 1ps, carrier lifetime: $\gtrsim$ 1 ns

Inspired by LCLS t0 finder: *Sato et al., J. Syn. Rad. 26, 647 (2019)*

Timing: E-320 vs. plasma experiments



Timing difference (theory)

(42.0mm + 70.73mm + 81.67mm) /
(speed of light) ≈ 648.45 ps

Gas jet t_0: 1256.7187 ns (previously: 1256.498 ns)

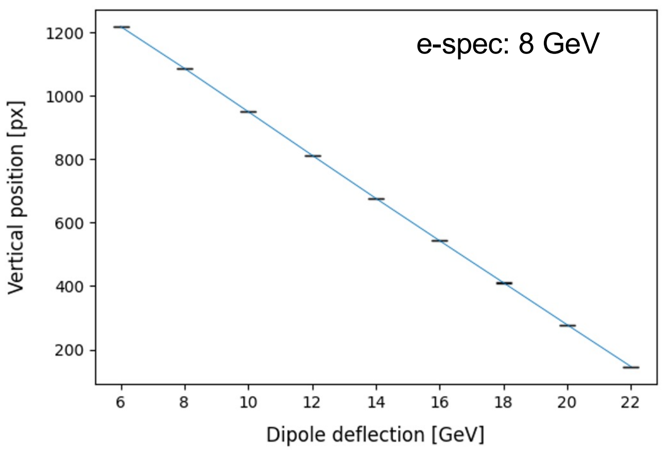
E-320 t_0: 1256.0676 ns (Δ≈651.1 ps)

Knetsch/Wang et al.

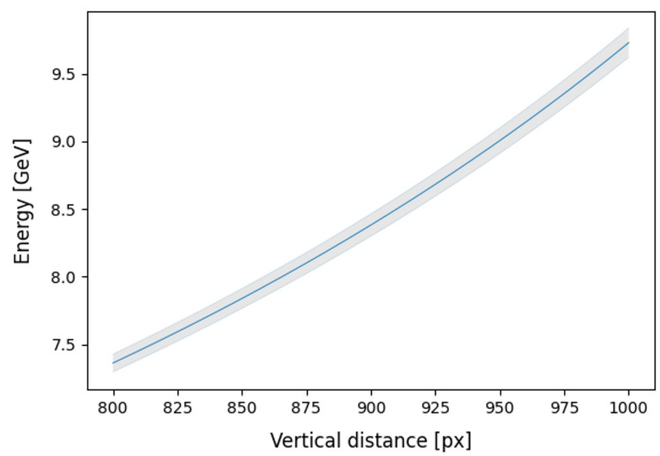
The 2x150 mm Master/EOS delay stage should be sufficient to have both the plasma experiments and E-320 compatible with EOS

Electron-spectrometer calibration

Dipole scan (beam-centroid fit)



Energy-calibration curve



- Calibration depends on quad settings: **BBA desirable!**
- Dipole steers also horizontally: **Improvable?**

Preliminary

from dataset 3876
(Oct 13, 2023)

Hessami/Smorodnikova

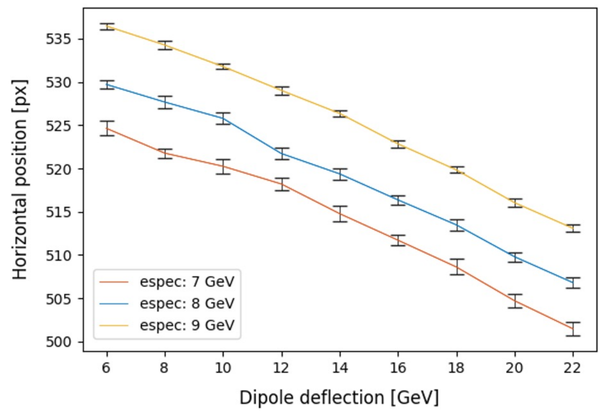
Electron-spectrometer calibration

Calibration dependence on quads

e-spec	7 GeV	8 GeV	9 GeV
Offset [px]	1615.9	1621.7	1629.7
Slope	-670.9	-672.2	-673.9

Electron energy [GeV] = slope x dipole setting [GeV] / (pixel position - offset)

Horizontal steering (not wanted)



- Calibration depends on quad settings: **BBA desirable!**
- Dipole steers also horizontally: **Improvable?**

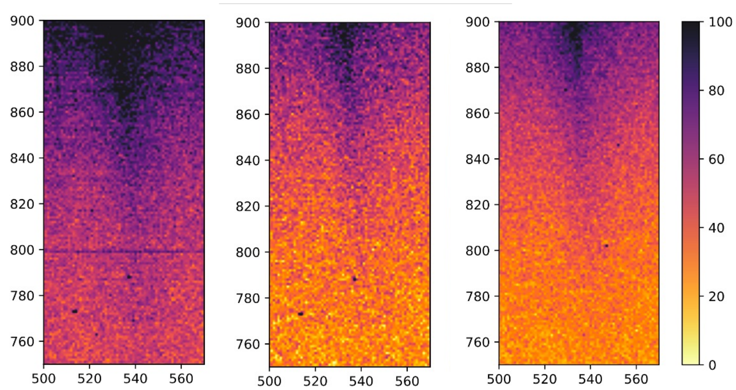
Hessami/Smorodnikova

Preliminary

from datasets 3875/3876/3877 (Oct 13, 2023)

Electron-laser scattering data: analysis

LFOV: scattered electrons (ROI: 6.9–8.3 GeV)



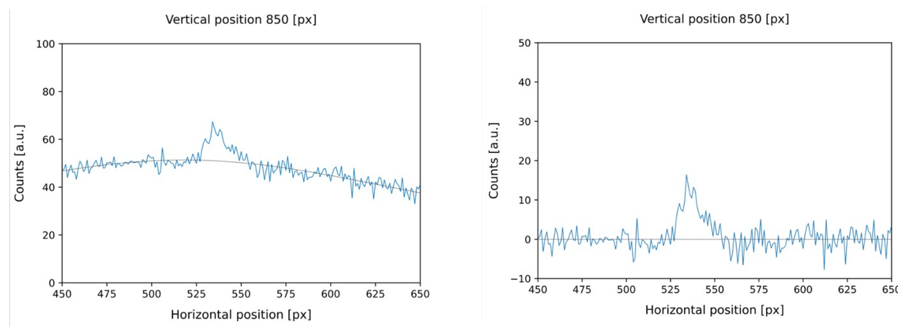
one shot (raw) | one shot (background subtracted) | average (30 shots)

Hessami/Smorodnikova

Preliminary

from dataset 3905 (Oct 13, 2023)
lowest laser energy (wave plate: 75)

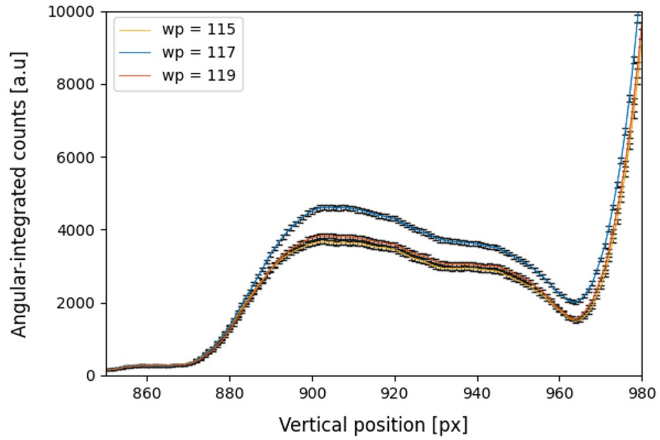
Horizontal lineout (7.8 GeV)



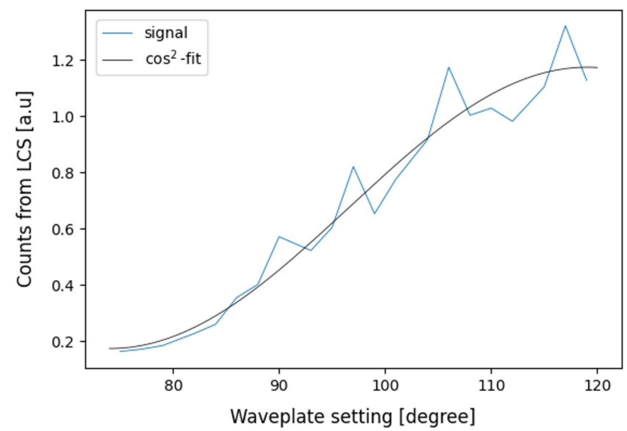
- Average over +/- 7 rows to reduce noise
- Gaussian background fit outside the signal region

Linear Compton Scattering (LCS)

Energy distribution
(angle-integrated signal)



Total LCS probability vs. laser intensity



Linear-Compton edge: 8.22 ± 0.08 GeV

- extracted from cosh-fit
- error: e-spec calibration Hessami/Smorodnikova

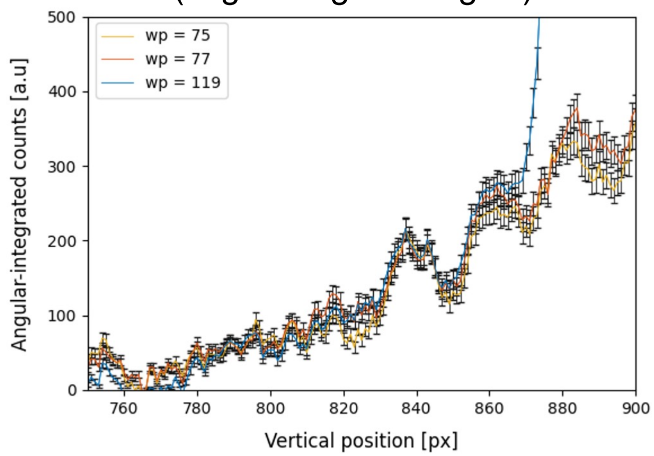
- Total LCS signal follows intensity scaling
- However: total change (factor 6.9) too low

Preliminary

from dataset 3905
(Oct 13, 2023)

Non-Linear Compton Scattering (NLCS): inconclusive

Energy distribution
(angle-integrated signal)



Needed to reach our near/mid-term goals

- Glass window after compressor should be removed
- (this requires RGA readings and maybe plasma cleaning)
- "Goose trigger" for pseudo-randomized laser on/off shots (game changer for subtracting beam-based background)
- Electron detector with much higher SNR (Orca, ePix, etc.)

- We see "signal" at energies below the 1st Compton edge (8.2 GeV)
- However: this signal doesn't scale with intensity, cannot be NLCS
- Need to improve signal to noise (and laser intensity)

Preliminary

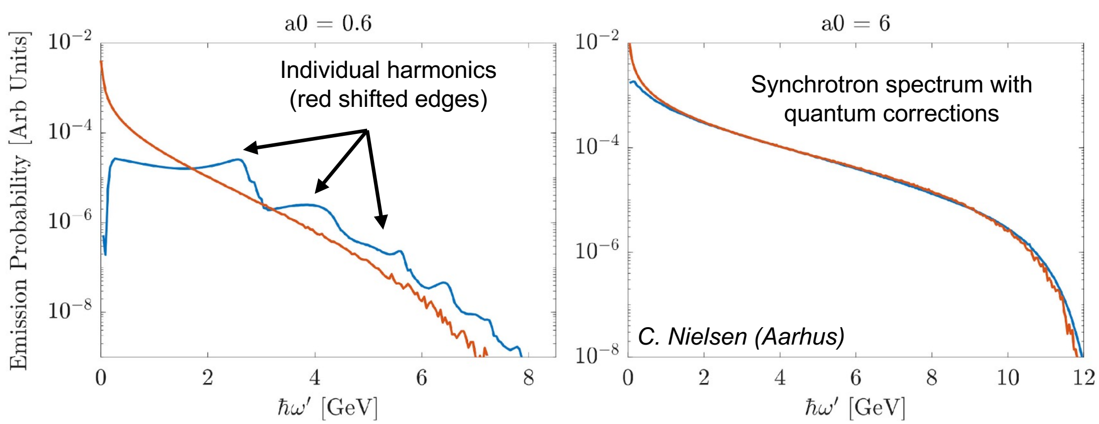
from dataset 3905
(Oct 13, 2023)

Hessami/Smorodnikova

E-320: objectives

Near-term goal

Transition from perturbative to non-perturbative regime

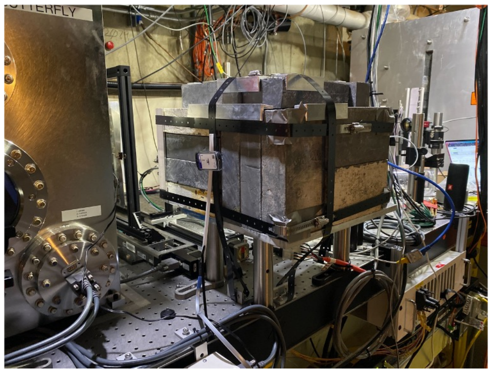


Beam diameter	40 mm
f#	~2
wavelength	0.8 µm
Spot size (FWHM)	2-3 µm
Pulse duration	~60 fs (→40fs?)
Gold OAP Strehl	~0.5
MPA output	0.6 J (→0.8 J?)
Transport/Comp. efficiency	37.5 %
Energy in PB	0.23-0.30 J
Intensity	**2.5×10^{19} W/cm^2 - 5×10^{19} W/cm^2**
a0	**3-5**

Needs to facilitate this measurement

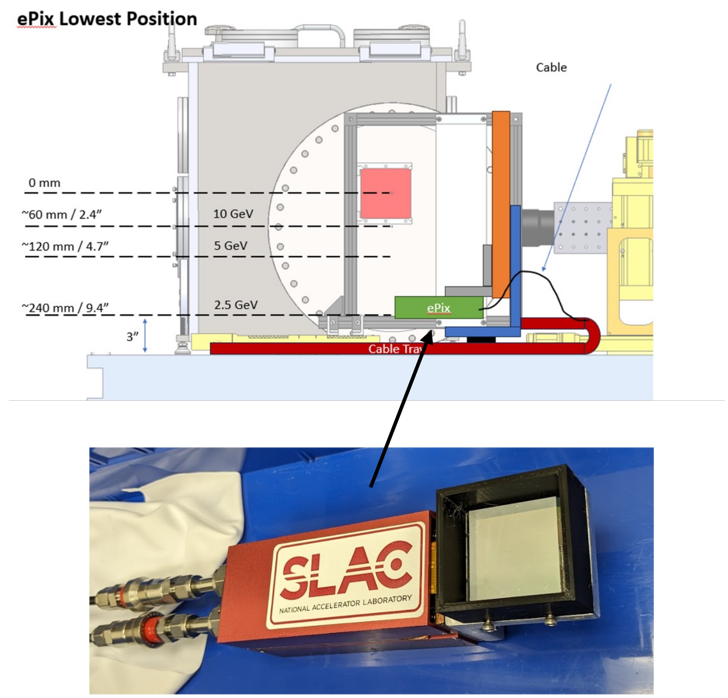
- Remove glass window after compressor (clean transmission)
- → requires RGA readings and maybe plasma cleaning
- "Goose trigger" for pseudo-randomized laser on/off shots
  → crucial to subtract beam-based background
- Electron detector with much higher SNR (Orca, ePix, etc.)

Goal: ePix installation at the dump table



shielding to keep ePix safe
during “high radiation times”

currently installed:
radiation sensor

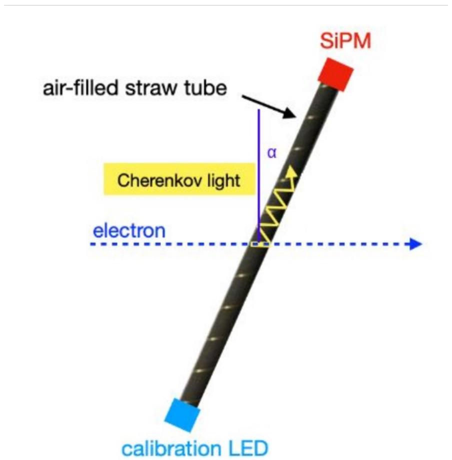


ePix module provided by the
SLAC detector group

Main contributors: Aimé Matheron, Sébastien Corde,
Robert Holtzapple, Adam Callman,Doug Storey, Chris Kenney

Goal: test DESY/LUXE straw Cherenkov detector

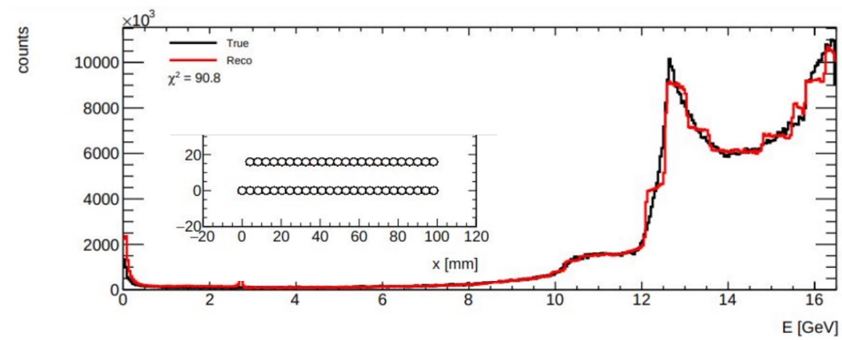
Basic idea



DESY team: A. Athanassiadis, L. Helary, R. Jacobs, J. List, E. Ranken, S. Schmitt

LUXE TDR: https://arxiv.org/pdf/2308.00515.pdf
EPS talk: https://indico.desy.de/event/34916/

Reconstruction algorithm (LUXE simulation)

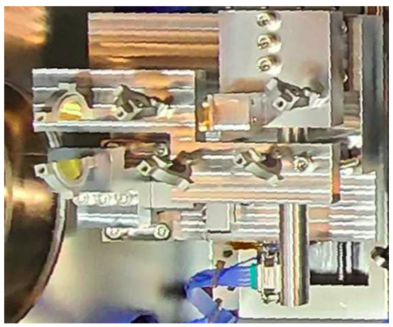


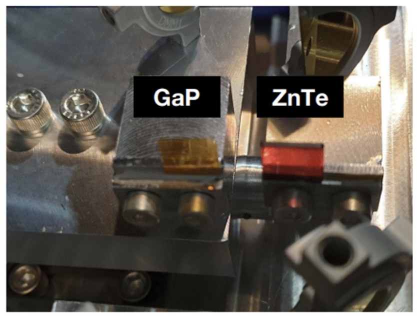
Proposal: start with proof-of-principle installation at FACET (~4 straws), full installation possible later

Benefits for E-320: radiation hardness of ePix not clear; this design is likely more robust / cheaper

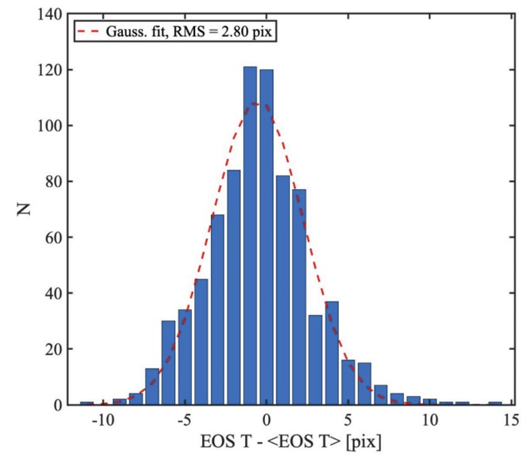
Goal: shot-to-shot timing (and position) information via EOS

EOS-BPM installed in the picnic basket





Getting shot-to-shot timing and position information allows us to sort data based on collision quality. important for collecting high-quality E-320 data



Relative timing jitter: ≈ 50 fs

EOS timing resolution: 18.26 ± 0.38 fs/px

Hunt-Stone et al., NIMPRA 999, 165210 (2021)

see talk by: C. Hansel, A. Knetsch, V. Lee, M. Litos (this meeting)
and EOS analysis: S. Gessner, C. Emma, C. Doss, C. Hansel, H. Ekerfelt, A. Scheinker (Oct. 5, 2022)

Goal: shot-to-shot high-intensity diagnostic

MO focal imaging: only possible at low intensities

beam splitter
(≲1:≳99)

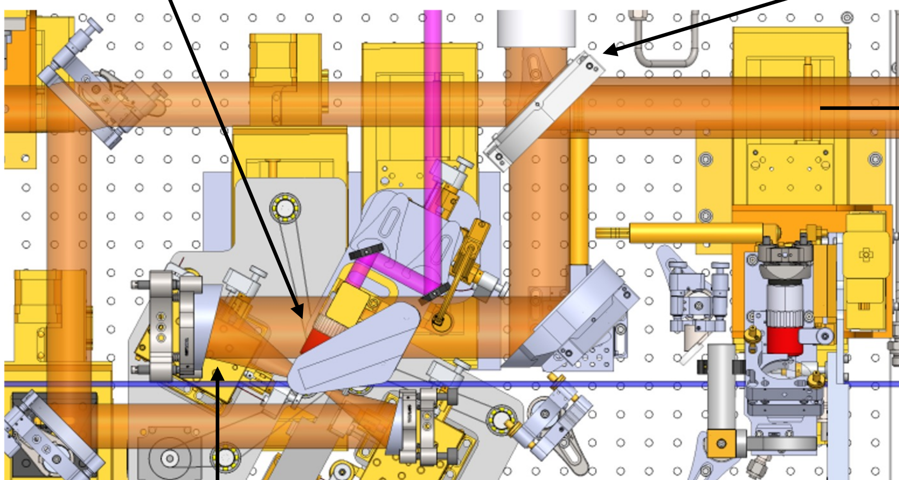


image of focal spot
is formed outside the
PB with a lens

- Aim: re-image focal spot for each shot
  → alignment of the 2nd OAP becomes critical

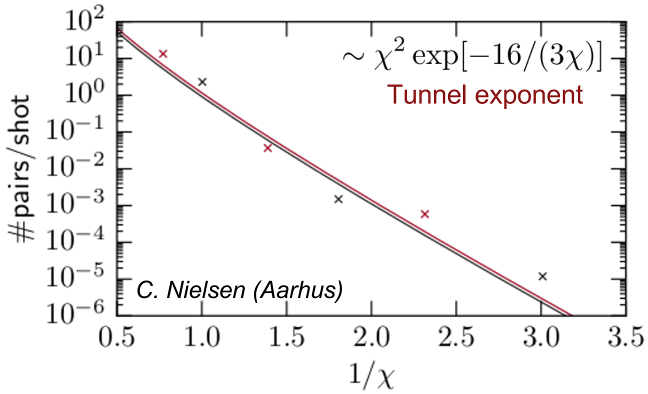
- Use interferometry to align OAP pair
  → we know that "errors" are due to the actual focus and not the mis-alignment of OAP2

High-intensity diagnostics: 2nd OAP re-images the focal spot

Interferometric alignment of the two OAPs

Mid-term goal

Electron-positron pair production



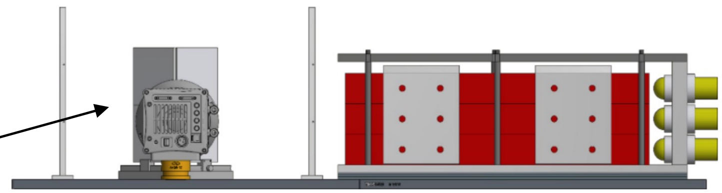
Needs to facilitate this measurement

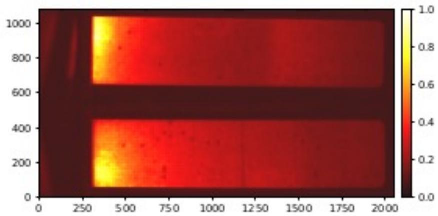
- Clean transmission of the electron beam to the dump
  → requires pencil beam with large beta function
- Highest possible laser intensities
  → improvements on all parameters to reach $a_0 > 7$
- Single-positron detection with good background rejection
  → required silicon-based tracker and calorimeter upgrade

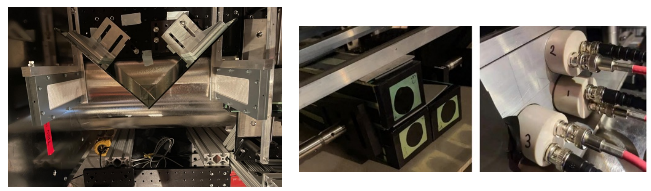
Beam diameter	40 mm
f#	~2
wavelength	0.8 µm
Spot size (FWHM)	2-3 µm
Pulse duration	~40 fs
Dielectric OAP Strehl	~0.8
Transport/Comp. efficiency	40 %
Energy in PB	0.40 J
Intensity	**$1\text{x}10^{20}$ W/cm^2**
a0	**6.8**

Mid-term goal: upgrade positron detector

Current single-positron detector







Salgado et al. NJP 24, 015002 (2021)

Lead glass is not radiation hard

Current tracking: two LYSO screens
(sensitivity not sufficient for single positrons)

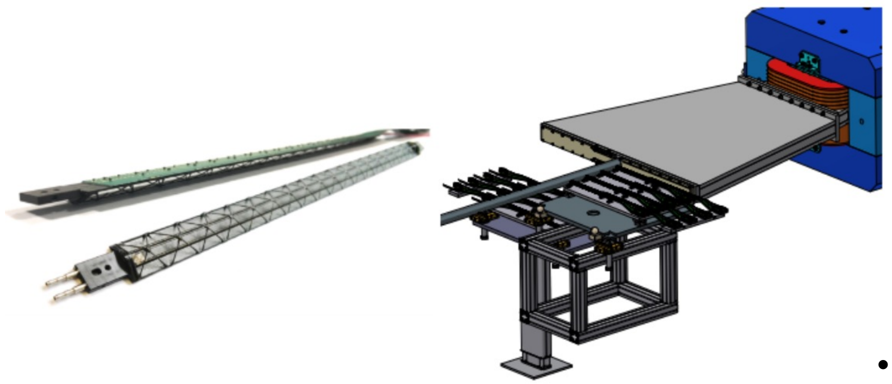
desired change: silicon-based tracker

Current Cherenkov radiator: is degrading too much
desired change: use radiation-hard material, e.g., lead fluoride

Anderson et al., NIMPRS A290, 385 (1990)

Mid-term goal: test LUXE positron tracker/detector

Electron/positron tracker for LUXE@DESY



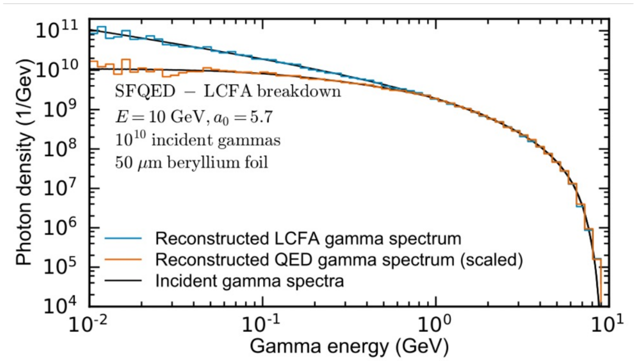
LUXE TDR: https://arxiv.org/pdf/2308.00515.pdf

- Thin monolithic active pixel sensors (MAPS), dubbed "ALPIDEs" (ALice PIxel Detector)
- Produced by TowerJazz for the upgrade of the ALICE experiment at the LHC
- Radiation hardness: technology was selected for HL-LHC heavy ion collisions

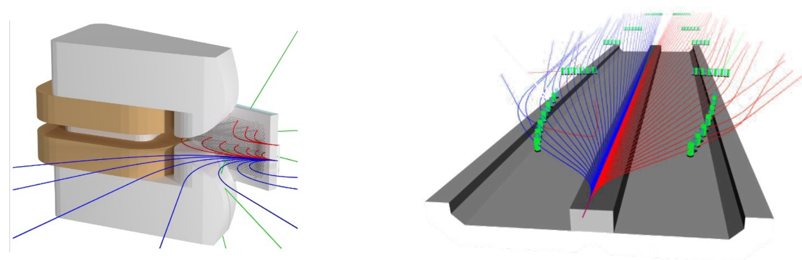
Noam's group (Weizmann institute) would like to test/provide their tracker for E-320

Mid-term goal: upgrade gamma diagnostics

Measure photon formation length

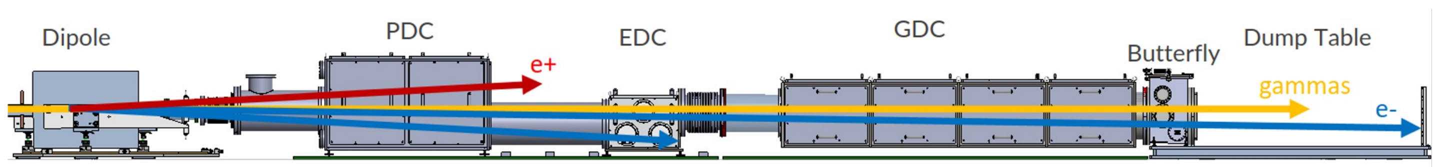


UCLA group



Compton (MeV) + gamma pair spectrometer (GeV)

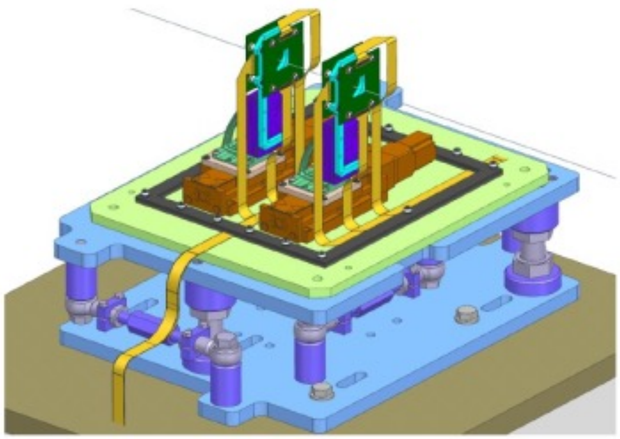
B. Naranjo et al., IPAC2021 THPAB269, THPAB270 (2021)



B. Naranjo: Gamma Detection: Compton and Pair Spectrometers
D. Storey: Experimental area (e- and gamma diagnostics, DPS, Li oven)

Mid-term goal: install gamma-ray profiler with higher resolution

Sapphire-strip detector

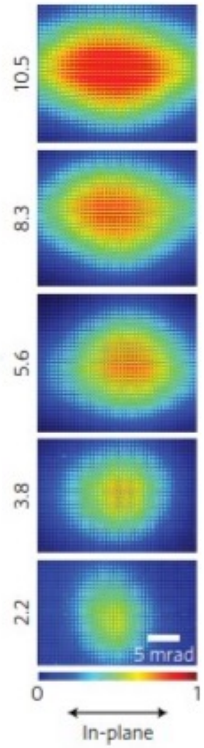


2x2cm² field of view, 5-10 µm resolution,
High radiation resistance (Sapphire)

The gamma-profile ellipticity is related to a_0 in the interaction region

High-order multiphoton Thomson scattering
Yan et al., Nature Photon. 11, 514 (2017)

Har-Shemesh & Di Piazza
Opt. Lett. 37, 1352–1354 (2012)



<u>INFN, U. Bologna, & U. Padova</u>: P. Grutta, M. Bruschi, M. Morandin, F. Lasagni, S. Vasiukov, U. Dossell
<u>QUB</u>: K. Fleck, N. Cavanagh, E. Gerstmayr, M. Streeter

Summary and timeline

Short & mid-term goals:

Increase laser intensity
reach $a_0 \gtrsim 5$,
eventually $a_0 \gtrsim 10$
Improve S:N
(automate laser-off)
2023/12

Improve electron detectors
better optical readout
direct detection (ePix)
2024/06

Improve positron detectors
silicon tracker (ePix)
radiation-hard calorimeter
LUXE detectors?
2024/12

Install pair spectrometer (gamma photons)
carried out by UCLA
Upgrade to 13 GeV?
2024/12

Long-term goals:

- 100-500 TW laser upgrade for FACET-II
- 2nd IP: light-by-light scattering experiments, (pair production & vacuum birefringence)
- Polarization-sensitive detectors: vacuum birefringence, radiative spin polarization
- Observe signatures of high-energy electron-positron coherent recollisions, waveform synthesis
- …