FACET-II Long Term Planning July 10, 2026

Sebastian Meuren
(for the E-320 collaboration)

E-320 collaboration: apologies to everyone who is missing

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Aarhus University, Aarhus, Denmark	Ulrik Uggerhøj
École Polytechnique, Paris, France	Sébastien Corde, Mickael Grech, Sebastian Meuren (PI), Sheldon Rego, Caterina Riconda
Technical University (TU) of Darmstadt	Stephan Kuschel, Sarah Grimm
MPI für Kernphysik, Heidelberg, Germany	Christoph H. Keitel, Matteo Tamburini
University of Rochester, USA	Antonino Di Piazza
HI Jena and University of Jena, Germany	Harsh, Aimé Matheron, Felipe Salgado, Jannes Wulff, Matt Zepf
Universidade de Lisboa, Portugal	Frederico Fiuza, Thomas Grismayer, Pablo San Miguel Clavel, Luis Silva, Marija Vranic
Heinrich Heine Universität, Düsseldorf	Edgar Hartmann, Natascha Thomas
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Queen’s University Belfast, UK	Niall Cavanagh, Elias Gerstmayr, Gianluca Sarri, Matthew Streeter
California Polytechnic State University, CA USA	Robert Holtzapple and students
Lawrence Livermore National Laboratory, CA USA	Félicie Albert
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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	Elena Ros, Michael Litos

Goal of E-320: probe strong-field quantum electrodynamics (SFQED)

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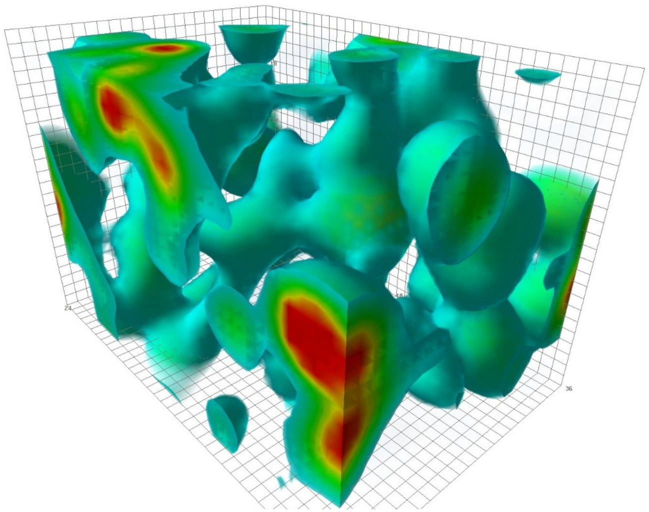
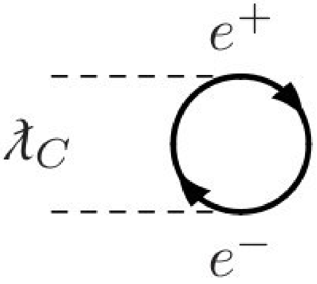


QED vacuum breakdown:

strong-field ionization of virtual electron-positron pairs

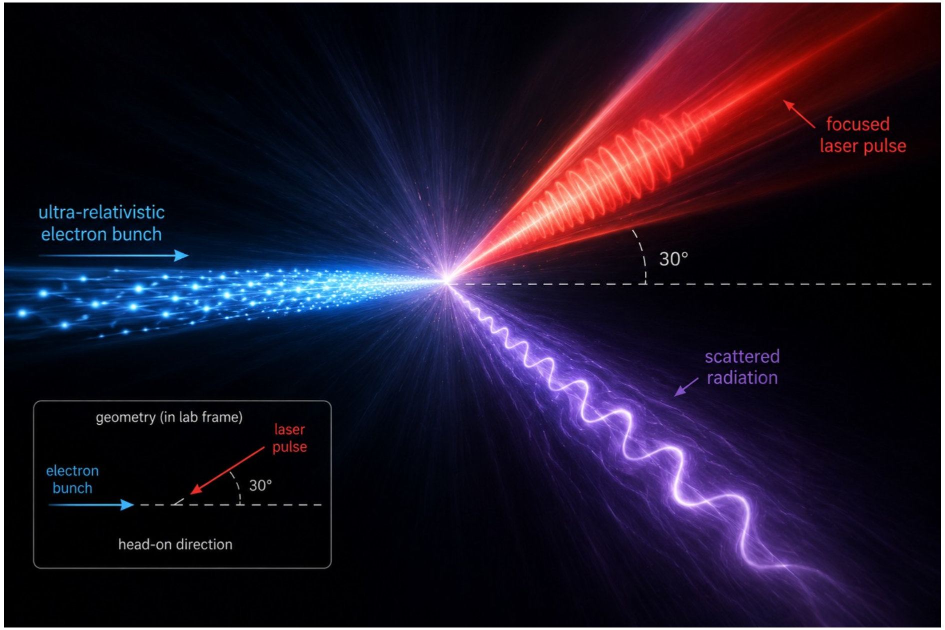


- Missing energy: $2mc^2 \sim 1$ MeV
- Life time: $\lambda\!\!\!^{-}_C/c = \hbar/(mc^2) \sim 10^{-21}$ s

Schwinger field: $E_{cr} = mc^2/(e\lambda\!\!\!^{-}_C) \sim 10^{18}$ V/m

Schwinger intensity: $I_{cr} = c\varepsilon_0 E_{cr}^2 \sim 10^{29}$ W/cm²

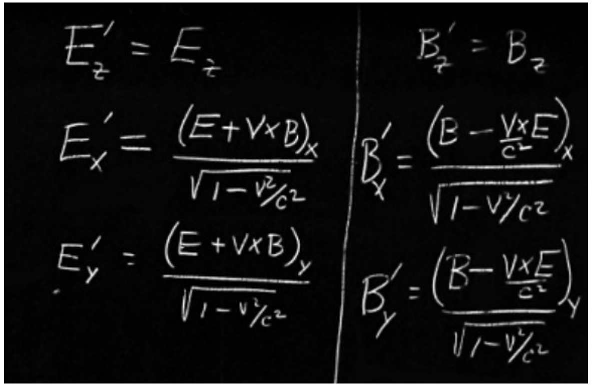
How to reach the Schwinger field?



Artistic impression (*generated with the assistance of OpenAI*)

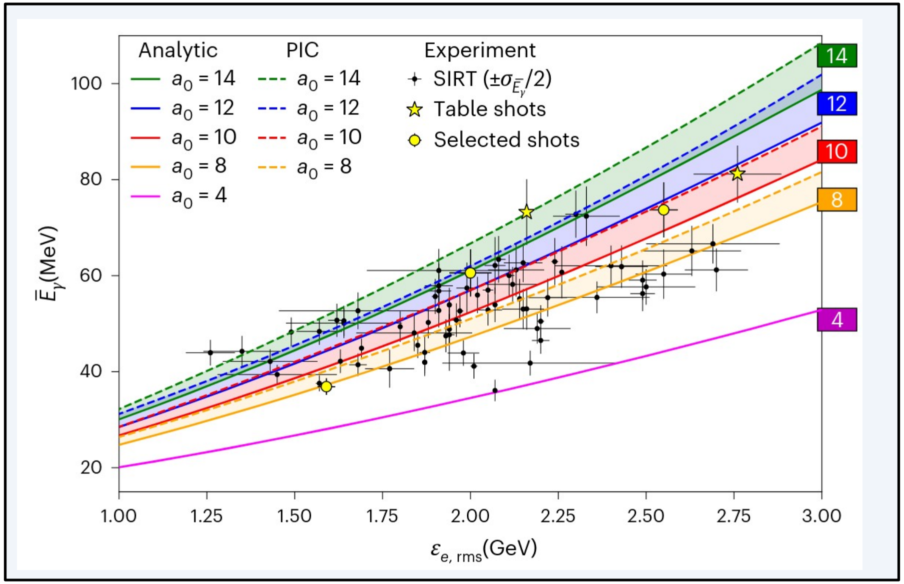
Critical intensity: $I_{cr} = c\varepsilon_0 E_{cr}^2/2 \approx 2.3 \times 10^{29}$ W/cm^2

Lorentz boost: $I_{rest} \approx I_{lab}\, 4\gamma^2$

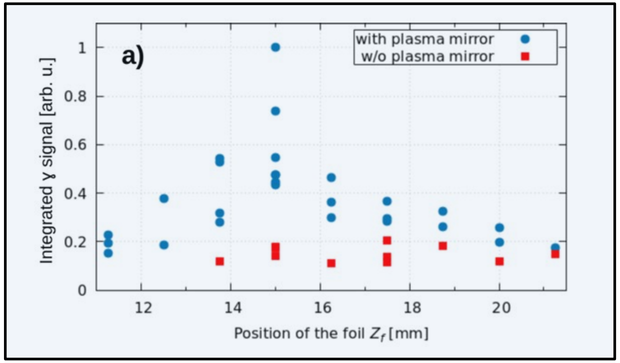


feynmanlectures.caltech.edu

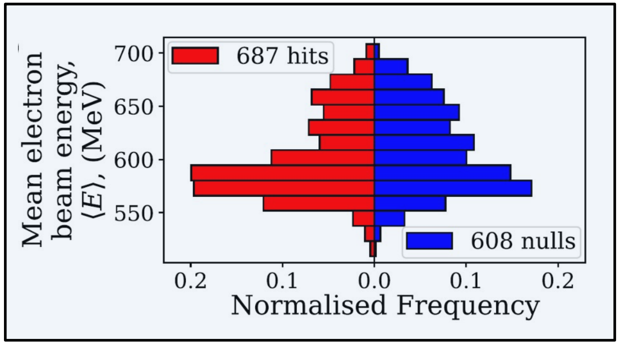
Advantages of E-320: stable, 10 Hz, 10 GeV electron beam



Mirzaie et al., Nat. Photonics (2024) **~ 80 signal shots**

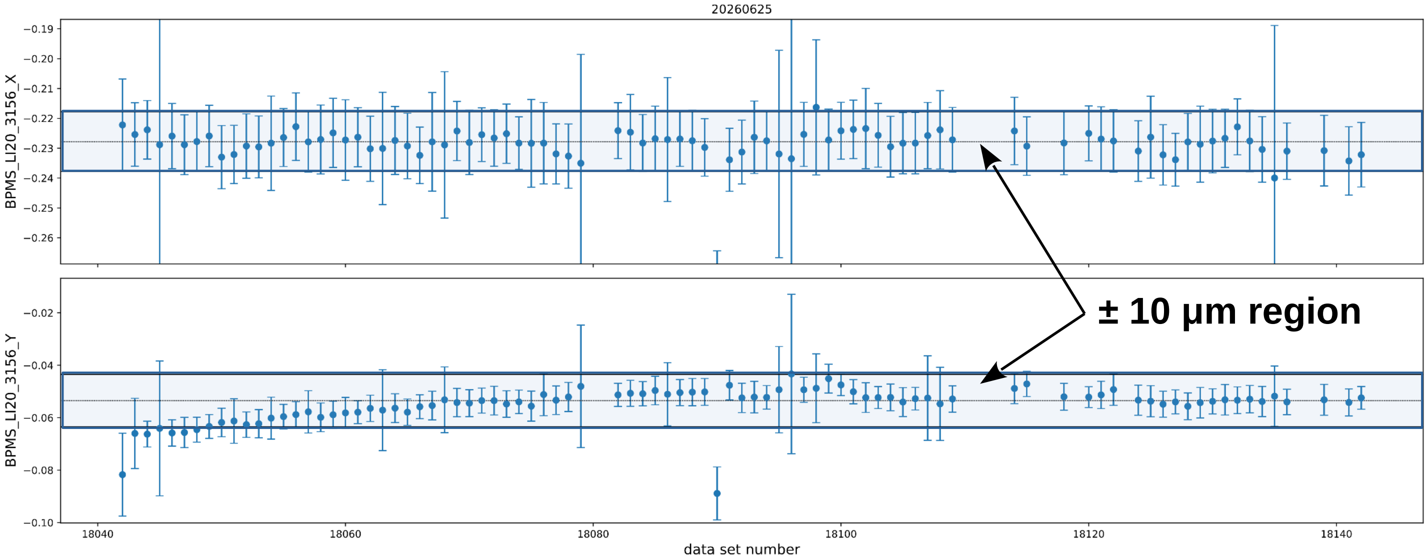


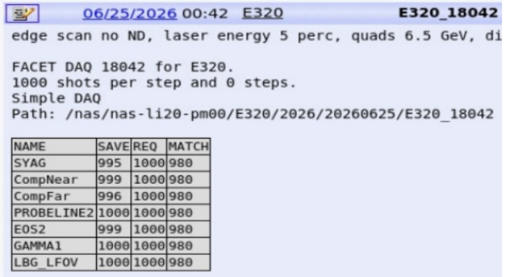
Matheron et al., arXiv:2412.19337 (2024)
~ 30 signal shots



Los et al., Nat. Commun. 17, 1157 (2026)
~ 700 signal shots

Advantages of E-320: FACET-II's stable, 10 Hz, 10 GeV electron beam



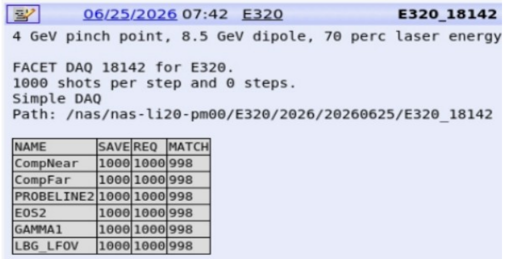


06/25/2026 00:42 E320 **E320_18042**

```
edge scan no ND, laser energy 5 perc, quads 6.5 GeV, di

FACET DAQ 18042 for E320.
1000 shots per step and 0 steps.
Simple DAQ
Path: /nas/nas-li20-pm00/E320/2026/20260625/E320_18042
```

NAME	SAVE	REQ	MATCH
SYAG	995	1000	980
CompNear	999	1000	980
CompFar	996	1000	980
PROBELINE2	1000	1000	980
EOS2	999	1000	980
GAMMA1	1000	1000	980
LBG_LFOV	1000	1000	980



06/25/2026 07:42 E320 **E320_18142**

```
4 GeV pinch point, 8.5 GeV dipole, 70 perc laser energy

FACET DAQ 18142 for E320.
1000 shots per step and 0 steps.
Simple DAQ
Path: /nas/nas-li20-pm00/E320/2026/20260625/E320_18142
```

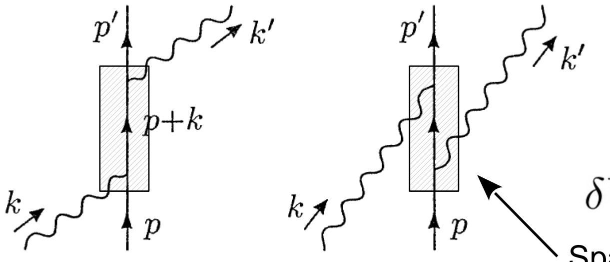
NAME	SAVE	REQ	MATCH
CompNear	1000	1000	998
CompFar	1000	1000	998
PROBELINE2	1000	1000	998
EOS2	1000	1000	998
GAMMA1	1000	1000	998
LBG_LFOV	1000	1000	998

- **7 hours of data taking** ➛ ~ **100k shots** (50% signal, 50% background)
- Efficiency: 100k / (7 x 3.6k x 10) = 40% (down time: mainly for data saving)

> The FACET-II LINAC was great (especially during the nights):
>
> we are **grateful to Jerry, Marcellus, Ryan, Zack**,**and everyone else involved** for making this possible

Main objectives of E-320

From perturbative to non-linear QED: E-144



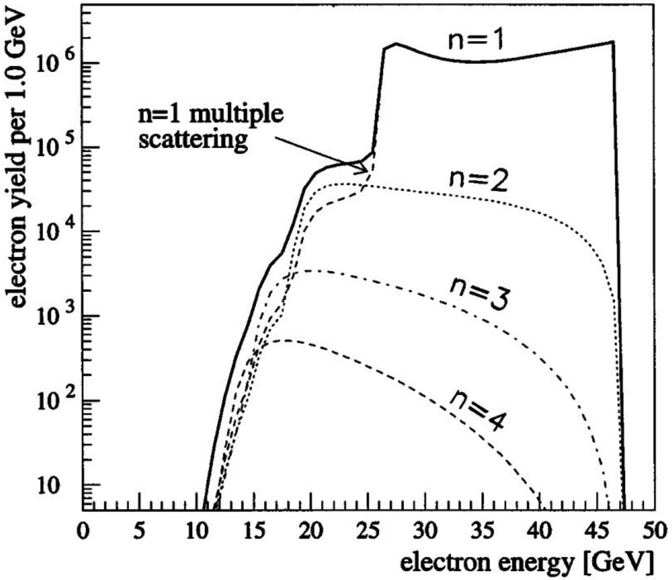
$$\delta V \sim \lambda_c^2 \times \lambda$$

Space-time volume:
uncertainty principle

Linear Compton scattering
Compton (1923, Nobel prize 1927),
Klein & Nishina (1929, theory)

$$\rho \sim \frac{I_0}{\hbar\omega c} \qquad \rho\,\delta V \gtrsim \frac{1}{\alpha} \qquad a_0^2 = \left(\frac{eE}{mc\omega}\right)^2 \gtrsim 1$$

Smallness of α ≈ 1/137 can be compensated by the photon density of the laser ρ ➛ harmonics in the spectrum



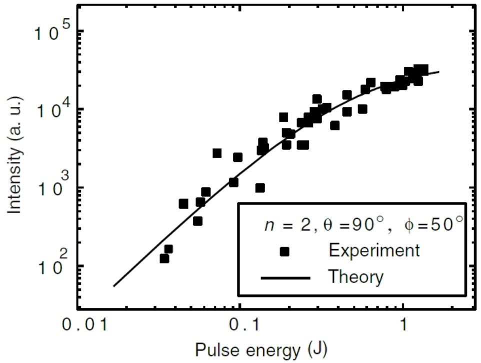
SLAC E-144 (simulation)

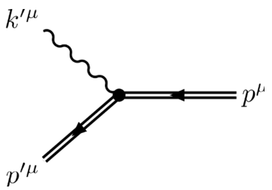
$$E' = \frac{E}{1+x} \qquad x = \frac{2En\omega}{m^2}[1+cos(\alpha)]$$

position of the n^th Compton edge

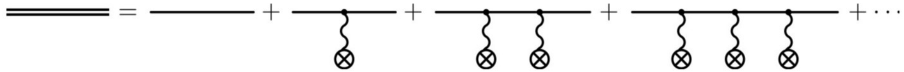
Non-linear Compton scattering
SLAC E-144: *Bula et al., PRL 76 (1996), Bamber et al., PRD 60 (1999)*
Nikishov & Ritus, JETP 19, Brown & Kibble, Phys. Rev. 133, A705, 1191 (1964, theory)

Mass dressing in the quantum regime: E-320

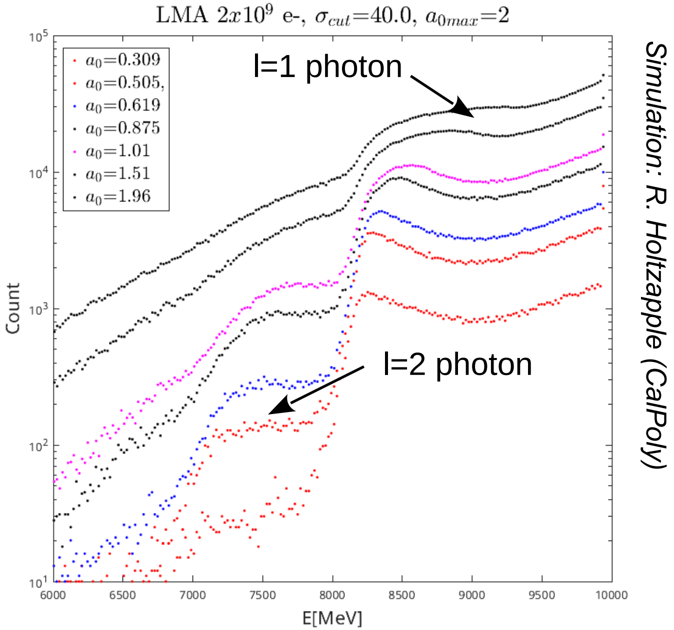




Nonlinear Thomson scattering (<u>classical ED</u>)
Meyerhofer, Knauer, McNaught, & Moore, JOSA (1996)
Chen, Maksimchuk, & Umstadter, Nature 396 (1998)



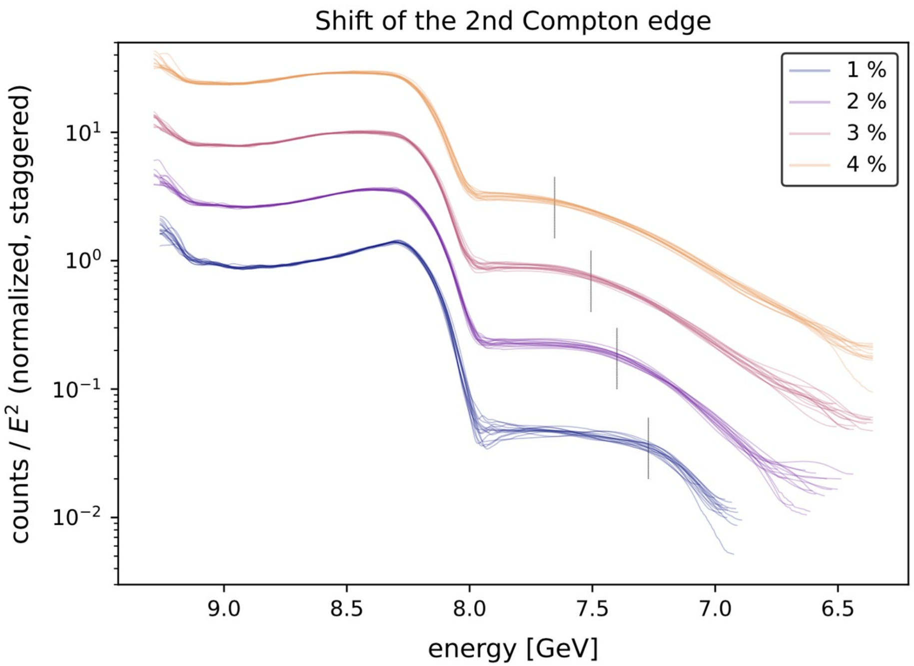
Dressed state / semiclassical picture in QFT
Volkov (1935), Furry (1951), Schwinger (1951), Glauber (1963),
Nikishov & Ritus (1964), Brown & Kibble (1964),
Baier, Katkov & Strakhovenko (1975)

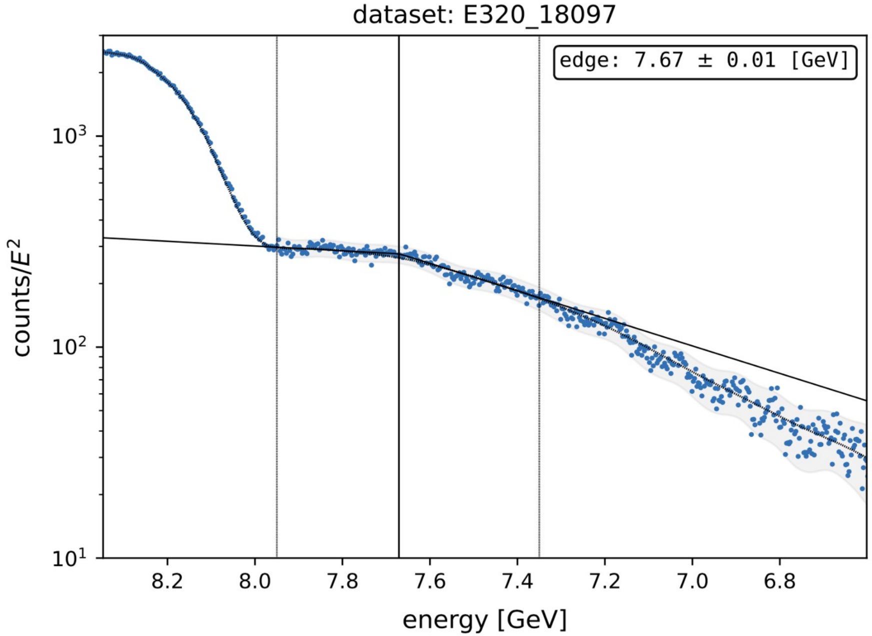


$$m^* = m\sqrt{1 + a_0^2/2} \qquad E' = \frac{E}{1+x} \qquad x = \frac{2El\omega}{m^{*2}}[1 + cos(\alpha)]$$

Before E-320 laser-induced dressed mass has only been observed in the classical regime

Experimental edge-shift observation: E-320 (2026)

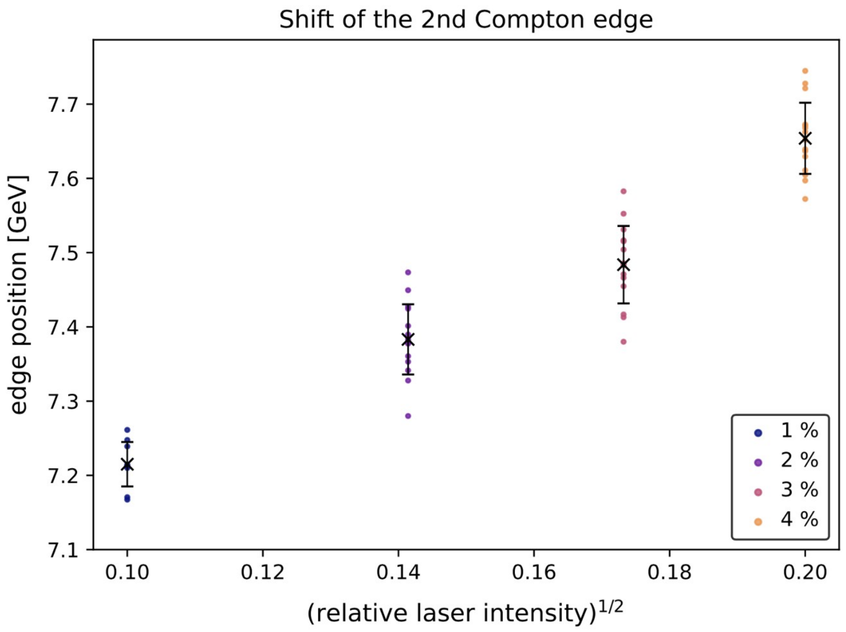




Analysis: T. Smorodnikova (Stanford)

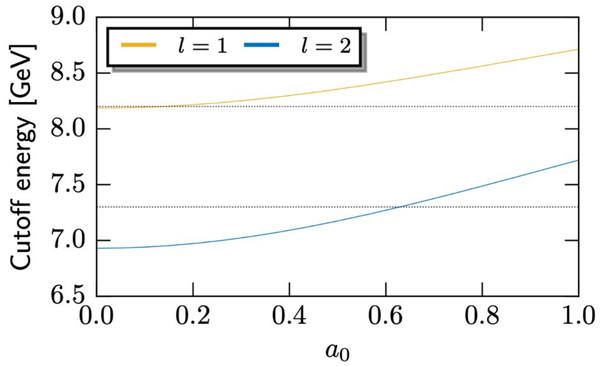
- For each intensity setting 1000 shots (from 5000 recorded) were evaluated
- 15 shots with best temporal (~80/500) and spatial overlap (~15/80) plotted
- <u>For the first time we see an edge shift as a function of intensity</u> (and not just indirectly via time)

Experimental edge-shift observation: E-320 (2026)



Analysis: T. Smorodnikova (Stanford)

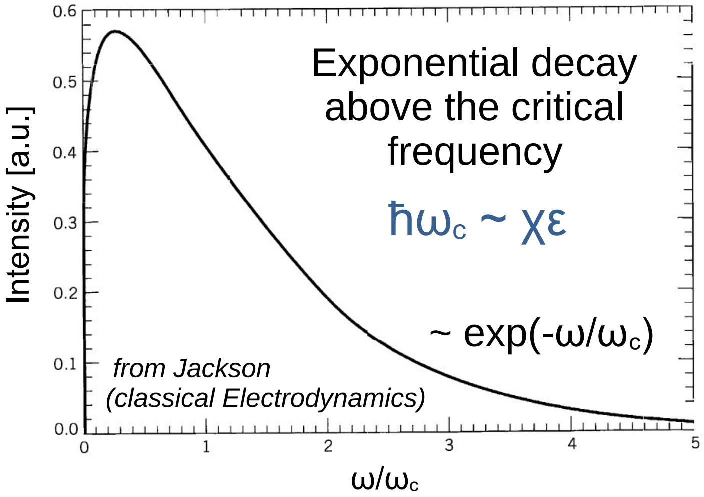
Edge shift / Dressed electron mass



$$m^* = m\sqrt{1 + a_0^2/2} \qquad E' = \frac{E}{1+x} \qquad x = \frac{2El\omega}{m^{*2}}[1 + cos(\alpha)]$$

- So far the analysis is very preliminary and requires proper calibration, etc.
- <u>Nevertheless, we clearly see a mass shift of about 0.5 GeV</u> (from ~ 7.2 to ~ 7.7 GeV)
- We conclude that a_0 ~ 0.4-0.5 for 1% laser intensity, implying a_0 ~ max(a_0) x sqrt(0.01) ➛ **max(a_0) ~ 4-5**

From classical to quantum radiation



Synchrotron spectrum
Schott (1912), Schwinger (1949)

Critical frequency $\omega_c \sim c\gamma^3/R$

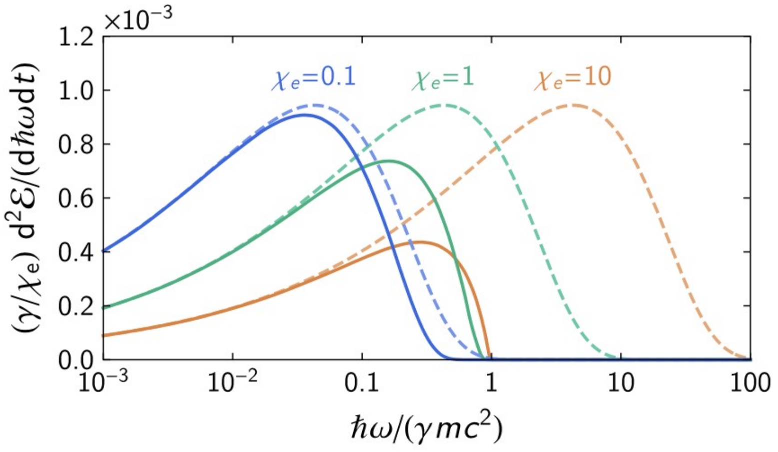
Gamma factor $\gamma = \varepsilon/(mc^2)$

$$\chi = \frac{E'}{E_{cr}} \approx 0.6 \frac{\mathcal{E}}{10\ GeV} \sqrt{\frac{2\,I}{10^{20}\ W/cm^2}}$$

Quantum parameter $\chi = \gamma B/B_{cr}$

- In classical electrodynamics photons are not quantized, therefore only the emitted power is meaningful
- Quantum mechanics: photon has energy $\hbar\omega$ (Einstein 1905) ➛ we find the Schwinger field in classical ED
- As soon as $\chi \gtrsim 0.1$: single-photon emission recoil ~ 10% of the electron energy ➛ quantum corrections

From classical to quantum radiation



$$\chi = \frac{E'}{E_{cr}} \approx 0.6 \frac{\mathcal{E}}{10\ GeV} \sqrt{\frac{2\,I}{10^{20}\ W/cm^2}}$$

Quantum parameter

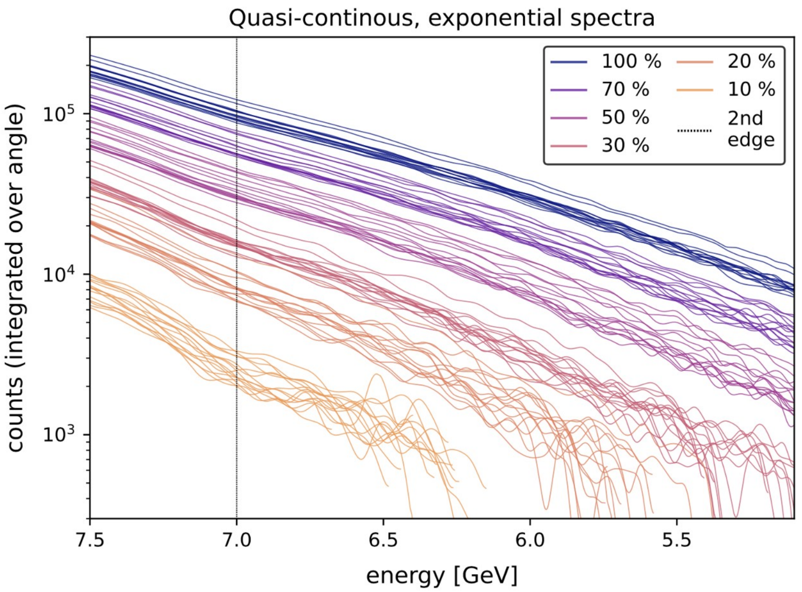
E-320: $a_0 \sim 4.5$ ➛ $\chi \sim 0.5$

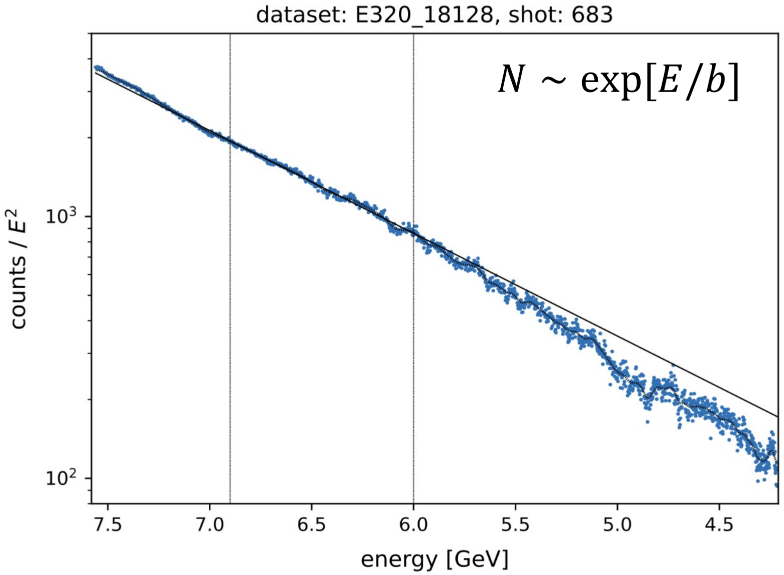
Quantum-corrected synchrotron spectrum
Sokolov, Klepikov, & Ternov (1952, 1968), Schwinger (1954)

- Strong-field quantum electrodynamics predicts significant corrections already for $\chi \sim 0.1$-1
- *This result is so well established theoretically that most physicists believe it has to be true*
- Nevertheless, E-320 is providing the first unambiguous experimental tests of these calculations

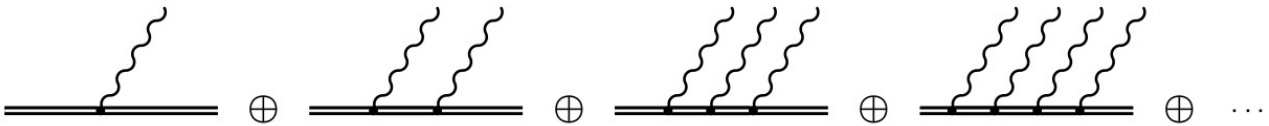
Gonoskov et al. (2022), Blackburn (2020), Di Piazza et al. (2012)

Observation of quantum synchrotron radiation



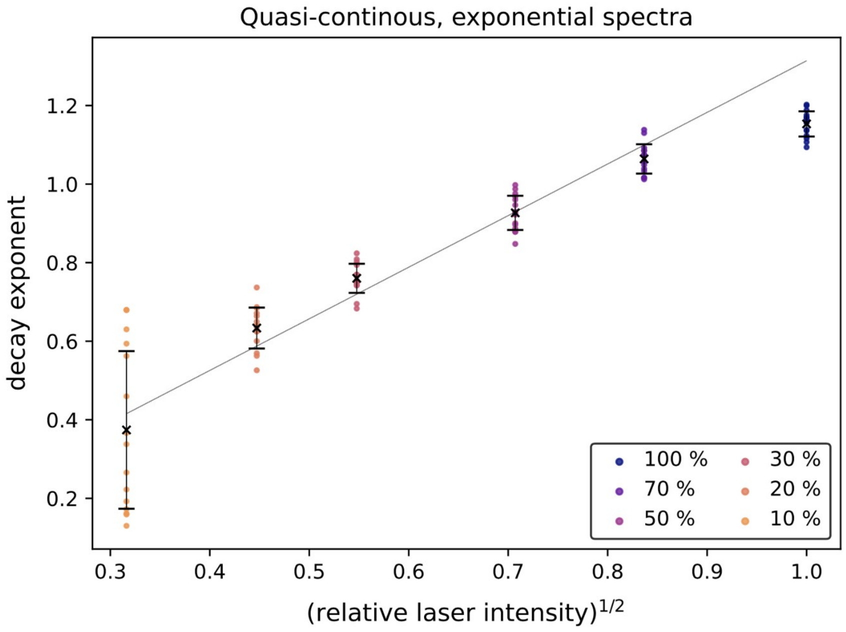


Analysis: T. Smorodnikova (Stanford)

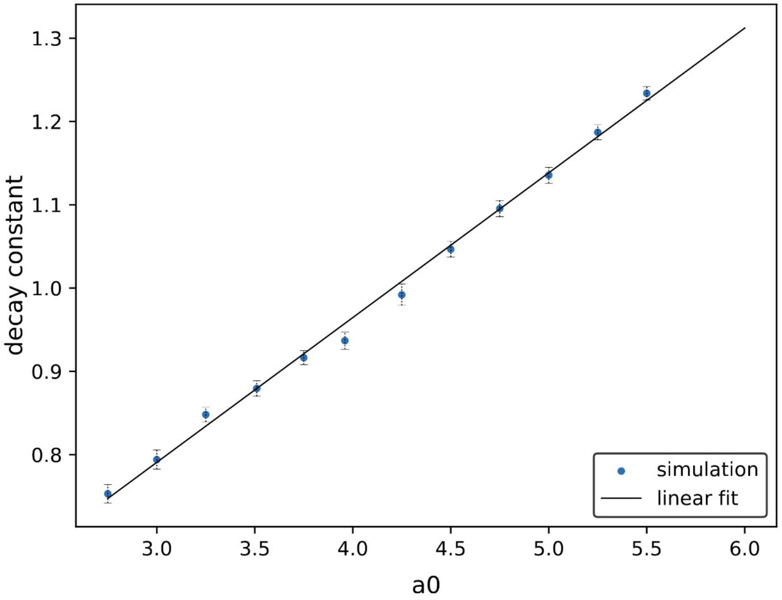


Multiple emissions: E-320 spectra are dominated by 1-3 emissions in the 9-6 GeV range

Observation of quantum synchrotron radiation



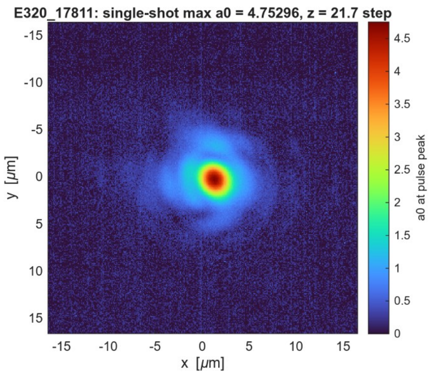
Analysis: T. Smorodnikova (Stanford)

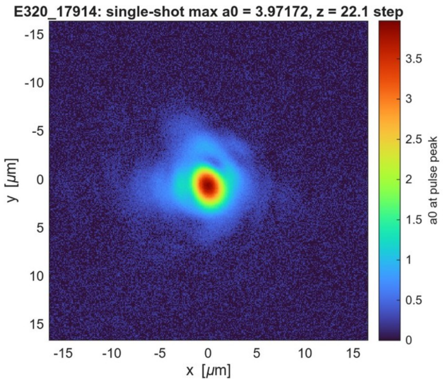


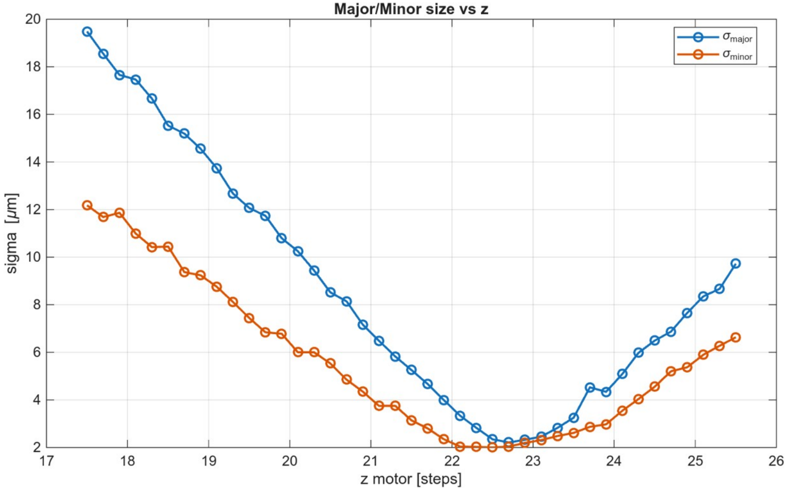
Simulation: R. Holtzapple (CalPoly)

- So far the analysis is very preliminary and requires proper calibration, etc.
- <u>Nevertheless, we see a linear change of the decay exponent as a function of a_0, as predicted by theory</u>
- We see that **max(a_0) ~ 4-5** is compatible with simulations (more refined simulations are ongoing)

Analysis of the focal spot





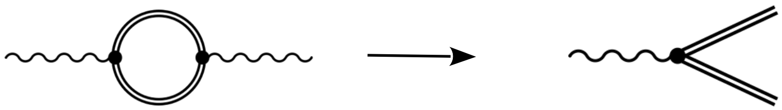


Analysis: Ching-En Lin (Stanford)

- So far the focal-spot optimization is still done by hand
- **FY27 upgrade**: finally install a wavefront sensor in the facet tunnel use ML & SDK for optimization
- Preliminary analysis of the focal spot supports that we reached a_0 ~ 4-5 during the 6-day run

Similar analysis also by Alex Knetsch & Sarah Grimm

Major goal FY27: observation of tunneling electron-positron pair production

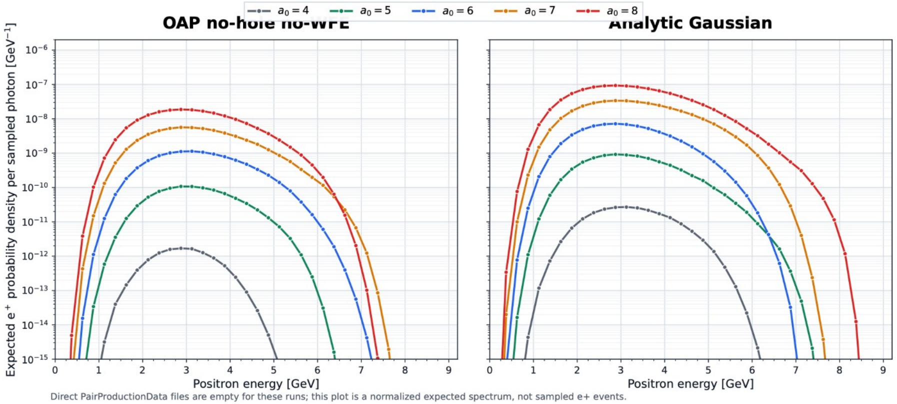


Vacuum polarization

photon transforms temporarily into an electron-positron pair

Pair production

virtual pair is “ionized” once the QED critical field is reached



Simulation: Robert Holtzappel (Cal Poly)

QED vacuum instability

Klein paradox (1929), Sauter (1931), Euler/Heisenberg (1936)
Schwinger (1951)

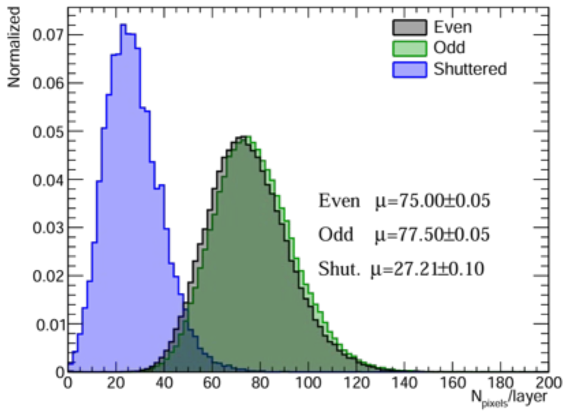
One of the oldest, unconfirmed predictions of the standard model of particle physics

(E-144 can be explained using perturbation theory)

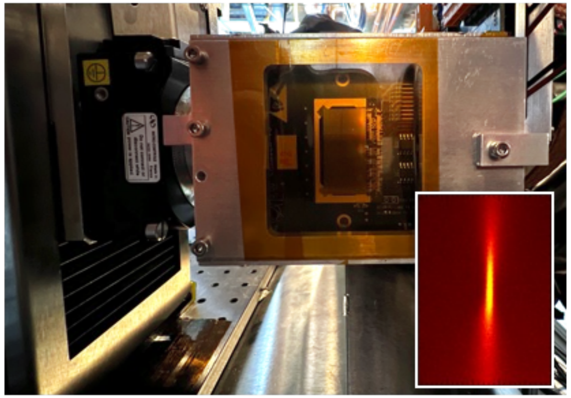
SFQED: an electron typically interacts with ~ a_0^3/χ ~ 100 laser photons:

E-320: clearly non-perturbative regime

Major goal FY27: observation of tunneling electron-positron pair production



Enhanced pixel activity for signal shots



Tracking detector in the FACET-II tunnel

Inset: solid-target positrons (calibration)

	Shots	Tracks	Rate	Error
background	123739	15	1.21E-04	3.13E-05
collisions	137388	21	1.53E-04	3.34E-05

Excellent background rejection demonstrated
(5e-5 feasible with Kalman filter)

Goal for FY27

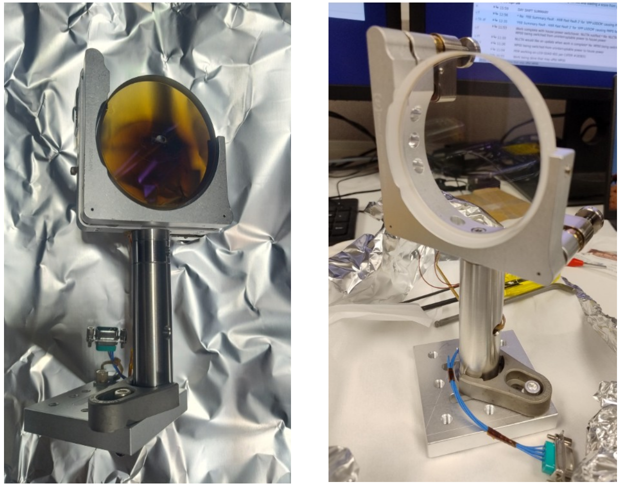
Laser intensity (current: a_0~4.5)	e+ /shot	Bg shots	Timed shots	Positrons	S/√B
$a_0 = 5.0$	0.01	50 %	10 %	6.1	14.3
$a_0 = 5.5$	0.05	50 %	10 %	**30**	71.6
$a_0 = 6.0$	0.2	50 %	10 %	120	286.4

detector acceptance: 30 %, tracking efficiency: 10 %; assumption: 10h run

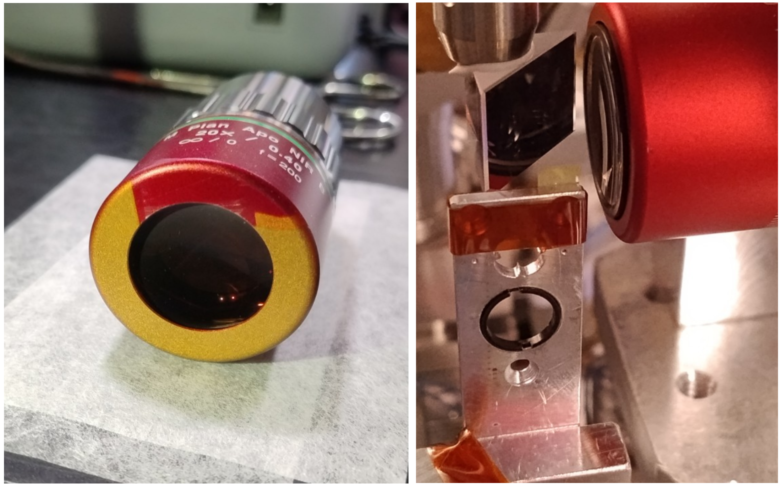
work led by the WIS team (more details from Noam)

Main improvements of E-320 in FY26

Re-aligned setup, replaced M2 & MO: major improvement w.r.t. May 2025



Old vs. new M2: mirror before OAP

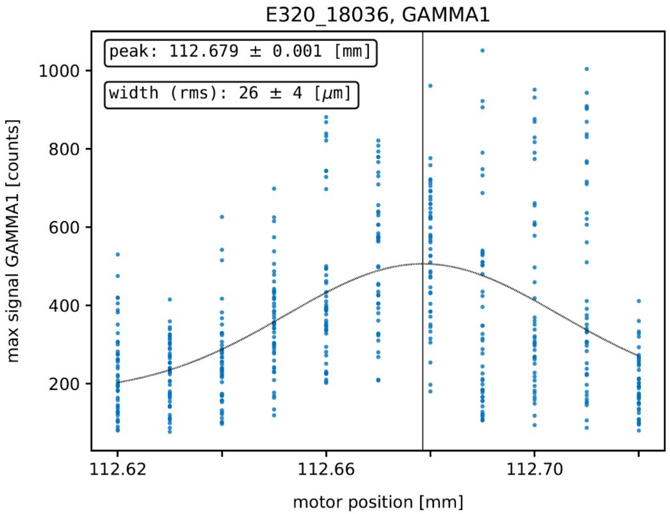


Old vs. new MO: MO/prism suffered from some kind of harassment

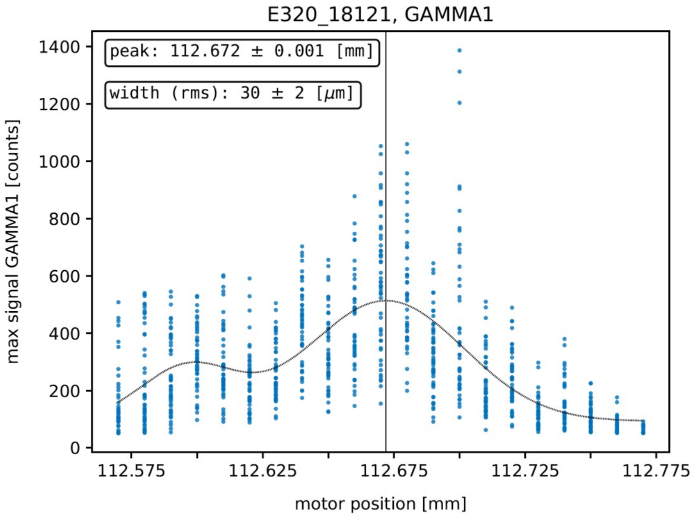
- M2 with a hole is significantly damaged by now (measured ~ 10 % losses)
- Prism was clipping periphery of the focal spot (laser is now centered on prism)
- Re-aligned Microscope objective and OAP

work was led by Sarah Grimm

Laser wire: precise measurements of the e-beam spatial-temporal profile



July 24, 2026 23:30h →

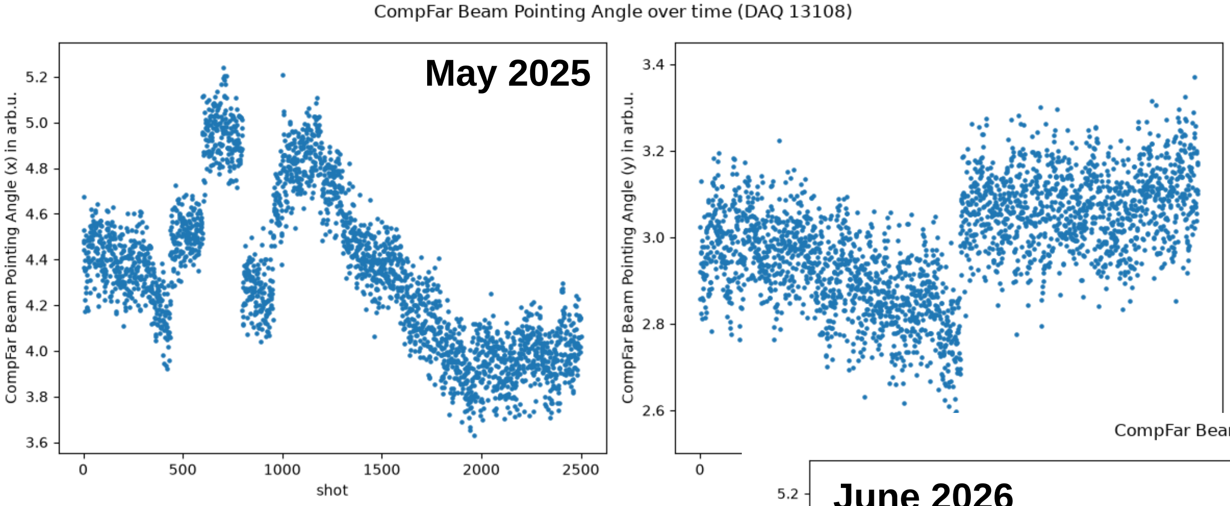


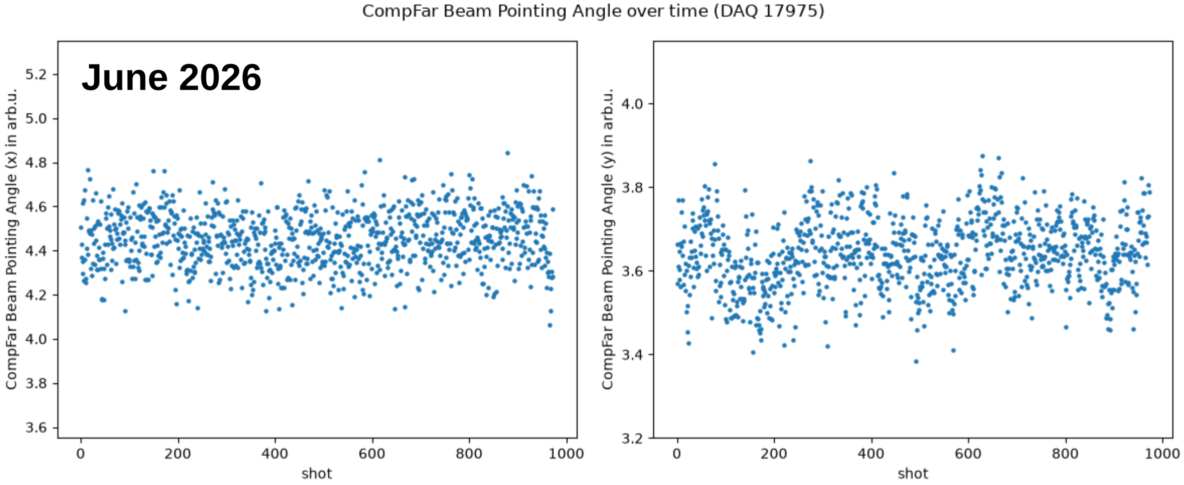
July 25, 2026 6:00h

- Analysis preliminary (likely better with LBG_LFOV instead of GAMMA1)
- We can <u>measure the transverse beam profile with ~ 5 micron precision</u>
- These scans prove the stability of the e-beam during night shifts
- By including timing/EOS cuts we likely will get the temporal profile as well

work was led by Junzhi Wang

Laser transport auto-alignment: major improvement from May 2025

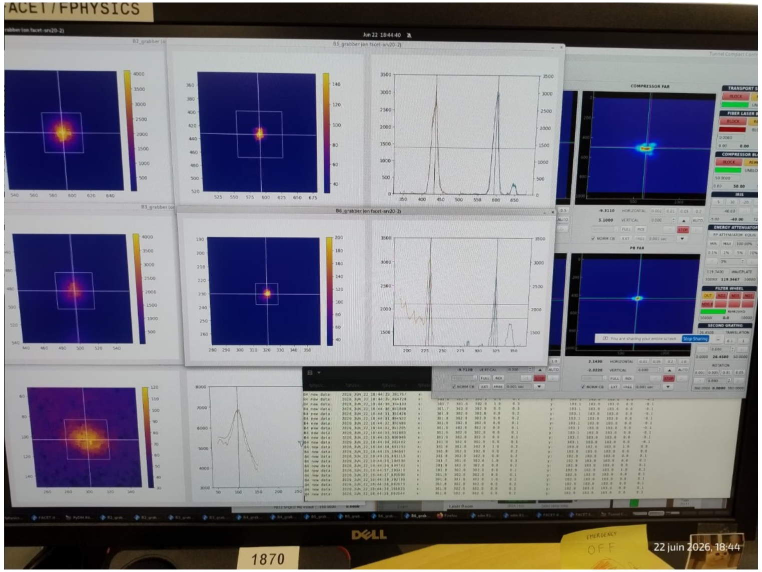




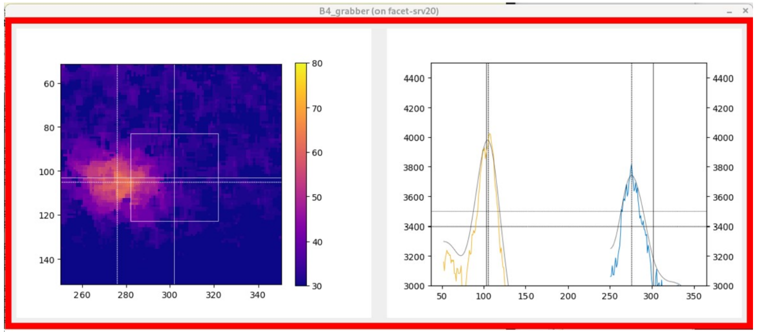
In 2025 our data quality suffered due to bad laser alignment into the PB

Analysis: Sarah Grimm (Tu Darmstadt)

Laser transport auto-alignment: major improvement w.r.t. May 2025



Unhappy laser transport watchdog

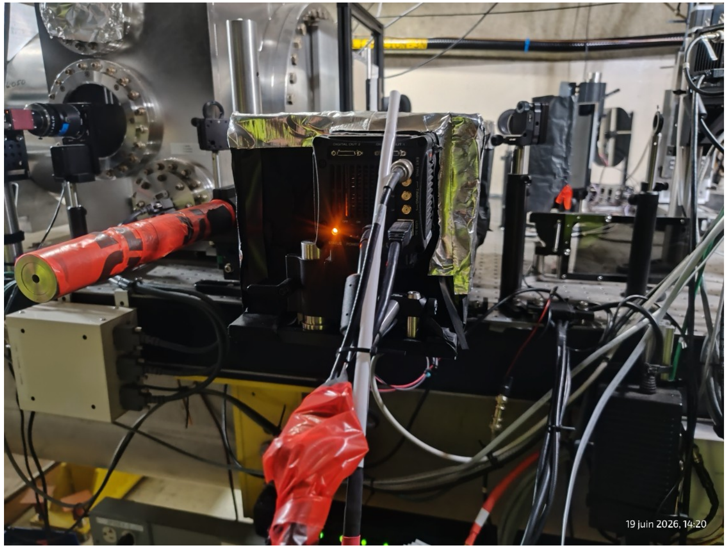


- Auto-aligner was re-written from scratch in python
- Better image hot-spot filtering: *reduced exposure time for B4 from 7.5 seconds to 0.3 seconds*
- Typical average over ~10 frames resulted in *alignment movements every few seconds* (if needed)
- Day 2 of the beam time: lost M4 horizontal motor; adapted aligner to compensate for this

Improvements of LBG_LFOV

(a bit of history)

Improved LBG_LFOV: changes before the June 2026 beamtime



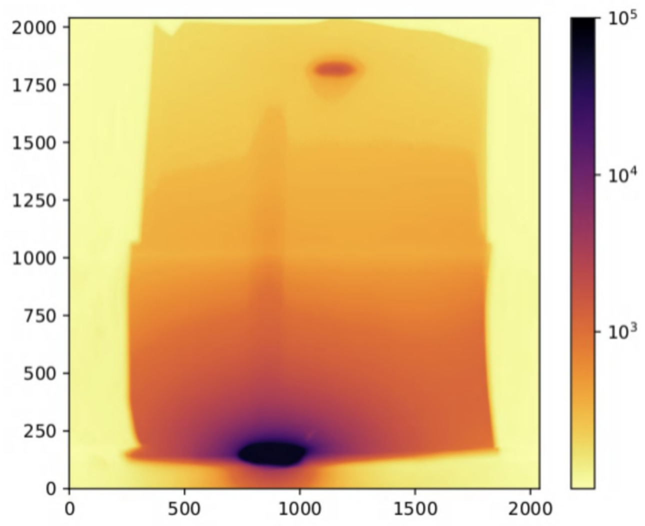
Improved light shielding & collection for LBG_LFOV

- May 2025 data had artifacts from 60 Hz light bulbs: further improved light shielding: Installed metal screen in front of DRZ, improved overall wrapping
- Improved focusing on DRZ/GAGG crystal: better image quality
- Re-optimized camera position & improved light collection

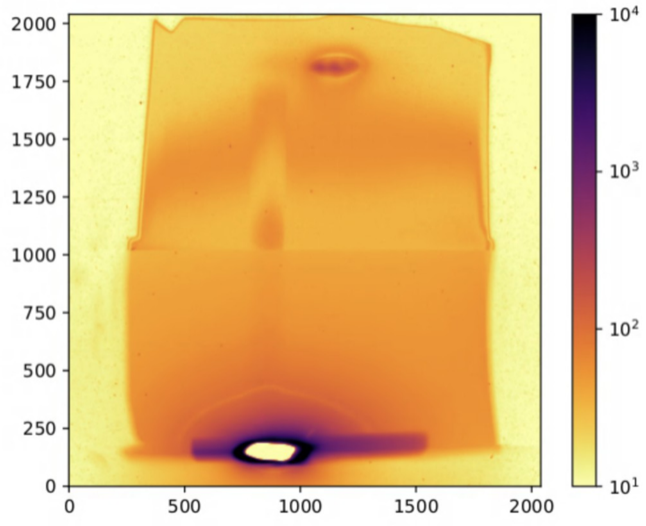
work was led by Alex Knetsch

Aug 2024: Be window induced very bad backgrouds

Goosed shots before Low-Background LFOV upgrade and with Be window in



(pixel-by-pixel mean)

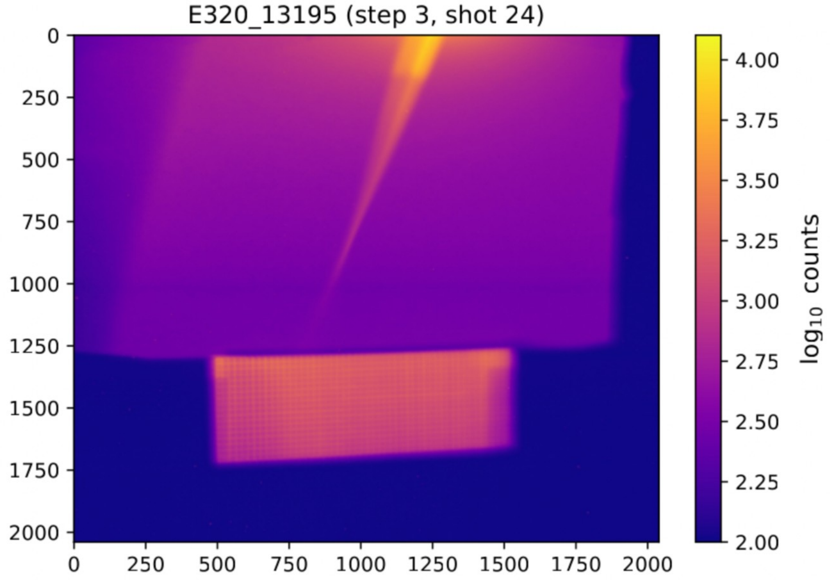


(pixel-by-pixel standard deviation)

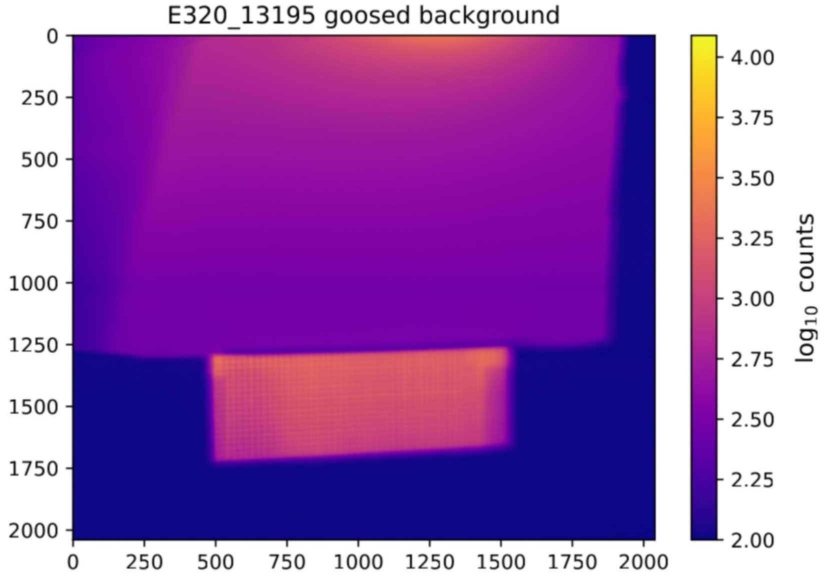
- Vertical stripe and other artifacts made the data analysis very difficult
- In addition, large shot-to-shot fluctuations (beam drifting on Be window)

May 2025 data: not perfectly in focus & light pollution

signal shot (raw data)



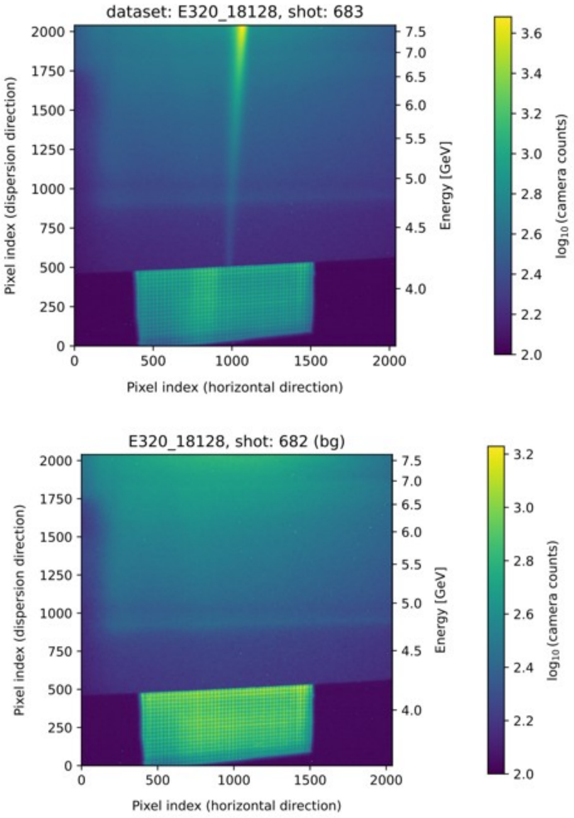
goosed shot (raw data)



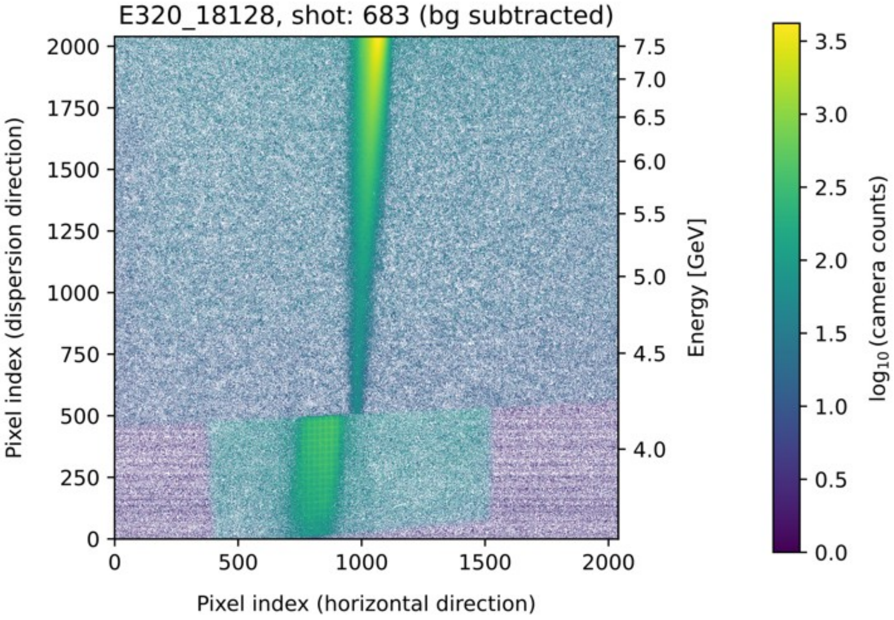
"Goosing" is critical for background subtraction, especially for the GAGG

- Currently: 50% on / 50% off: LCLS saw systematic errors in this mode
- The closer we get to pseudo-random goosing the better

June 2026 data: better light shielding/collection & DRZ/GAGG in focus



Signal and background shots



Signal shot with subtracted background

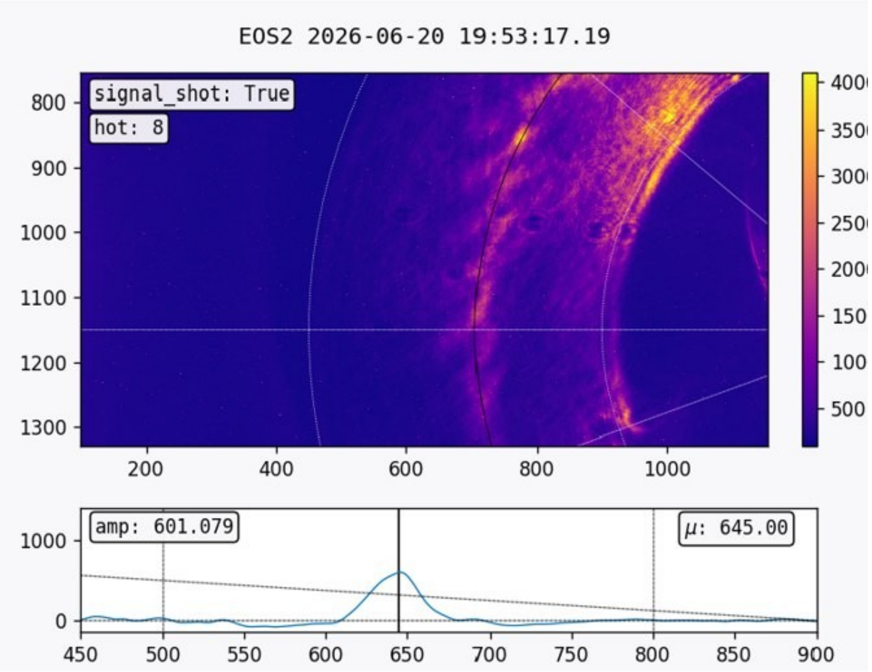
Main needs for FY27

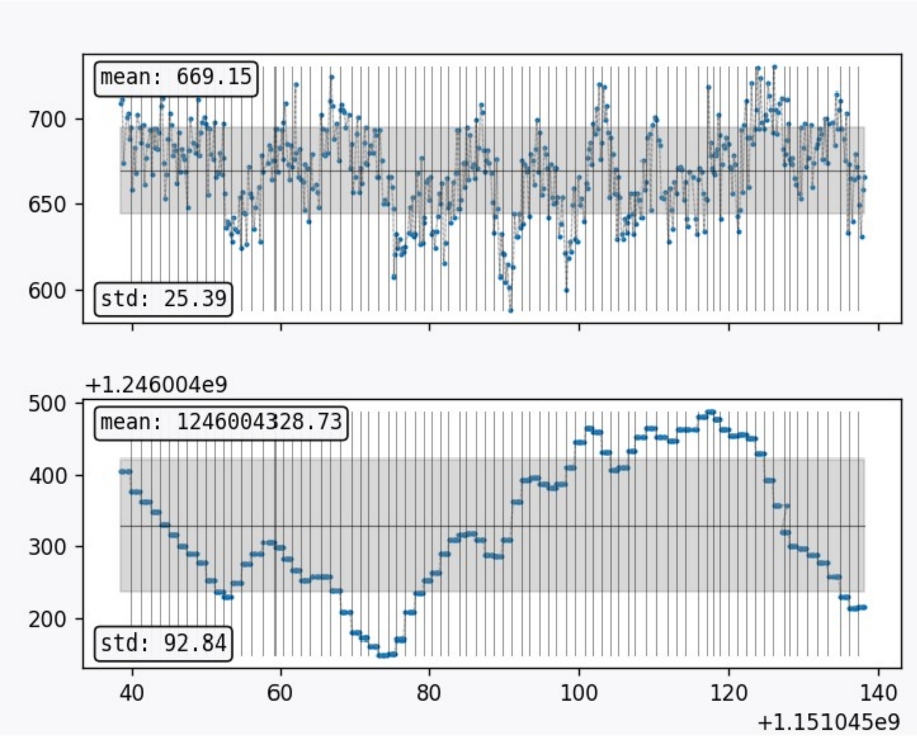
Laser intensity: how to get to $a_0 \sim 5\text{-}6$ and beyond

We are open to everything that helps:

- probe splitter to 90:10
- laser room efficiency from 70% back to 85%
- more energy to the tunnel (we should be far from damage threshold)
- shorter pulses (Dazzler)
- Better focal spot (WFS + SDK + algorithms/ML)
- Re-alignment of the compressor (M. Litos, thank you)
- Your suggestion here

How to improve number of good shots: improve timing stabilization





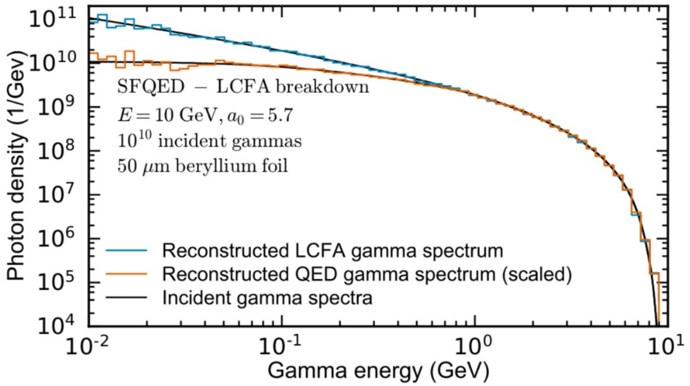
Todo FY27: replace PID with ML (reinforcement learning, etc.)

Other improvements

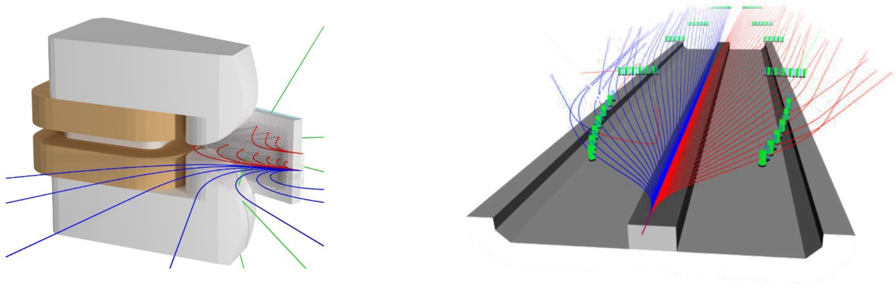
(still on the list from 2025)

Gamma-ray spectrometer (UCLA)

Measure photon formation length

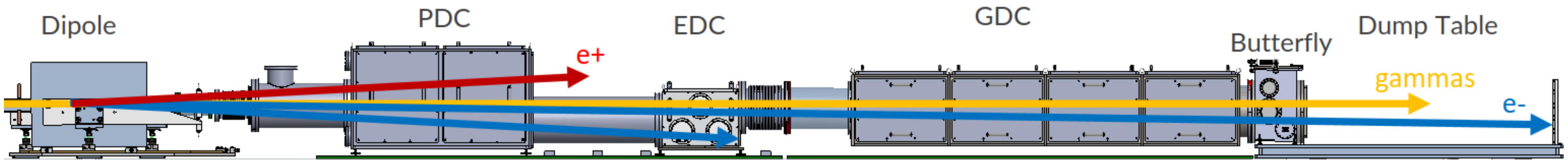


UCLA group



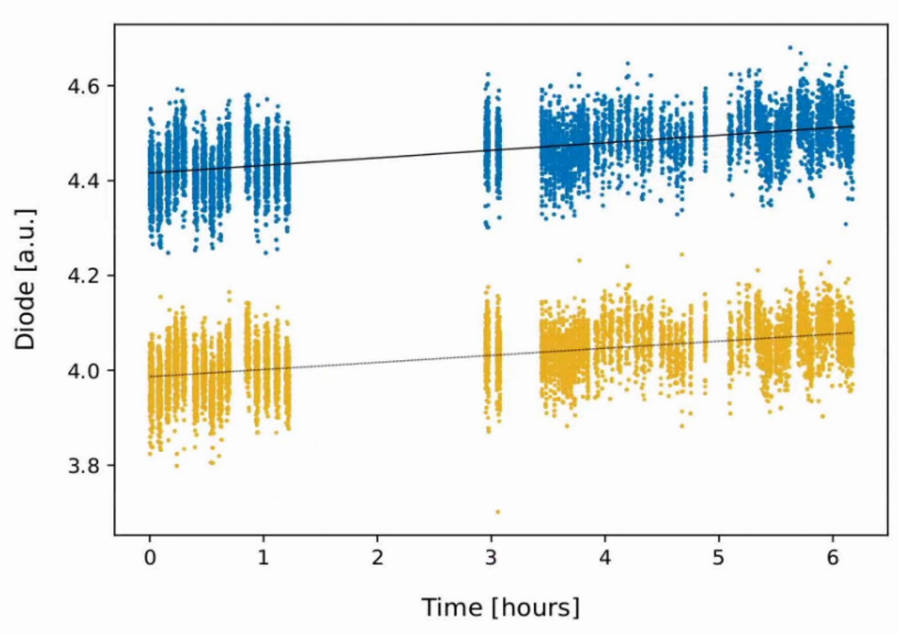
Compton (MeV) + gamma pair spectrometer (GeV)

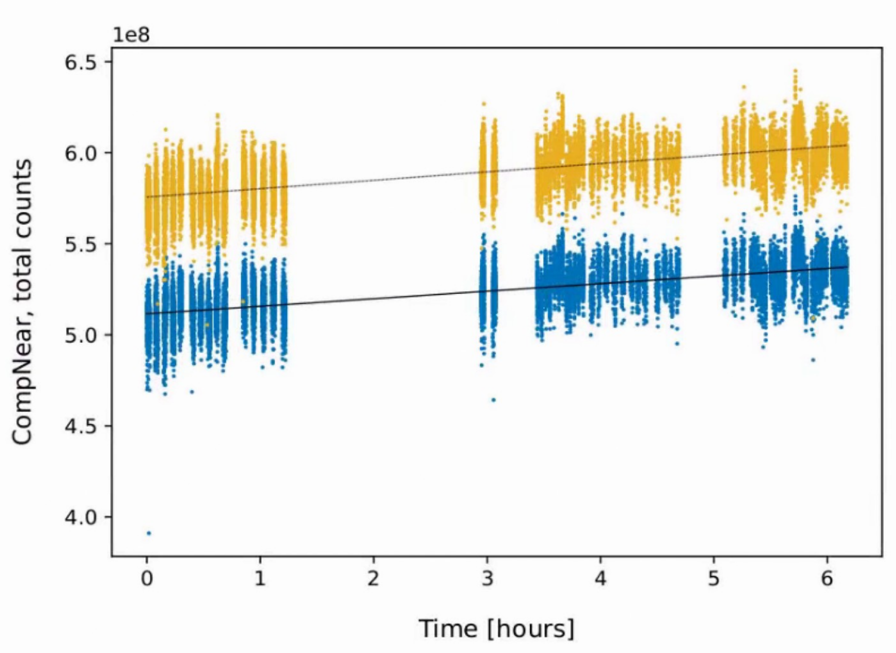
B. Naranjo et al., IPAC2021 THPAB269, THPAB270 (2021)



High priority: LCFA breakdown (nature-scale publication)

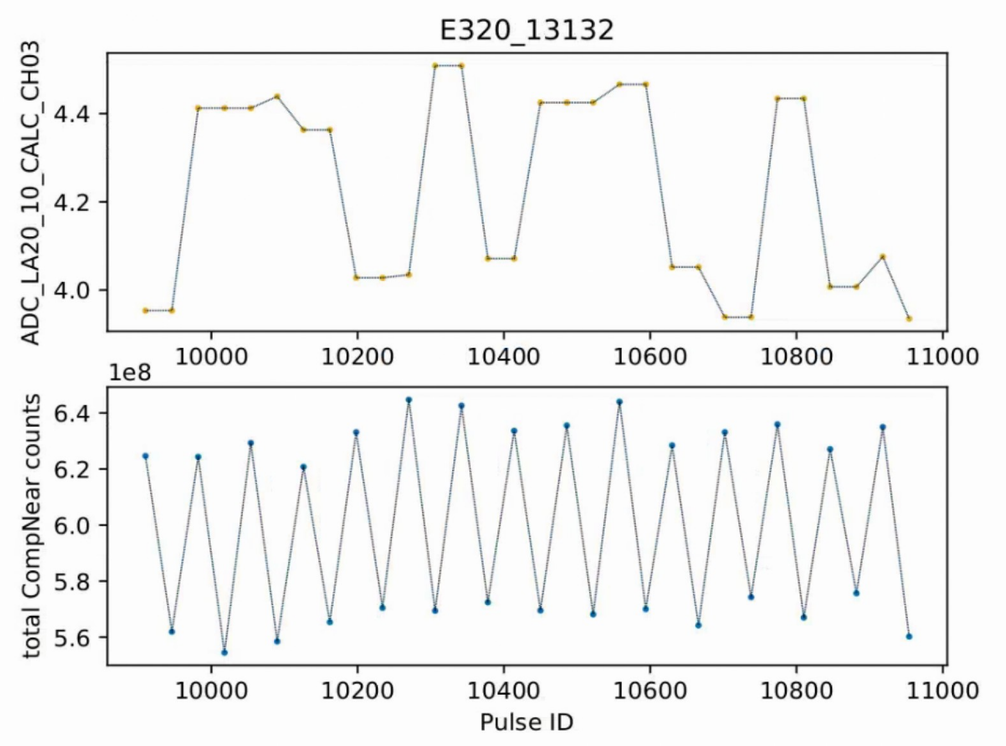
FACET DAQ: current up-time is only 50% (rest is used for data saving)





Requires that we save data outside the standard DAQ

Laser diode: data acquisition is currently non-BSA



Diode delays measurements / keeps same values at times

Thank you all for your support of E-320