

FACET-II Long Term Planning July 25, 2025

Sebastian Meuren (E-320)



Shifts in spring 2025: first high-quality data taken

- **2025, May 10-12:**

```
05/10/2025 23:59 E320 running log (current)
ACR zoom: https://stanford.zoom.us/j/97779786664?pwd=WmpwdVlOMXREK3pLc0RWK2d6SnRhOT09
13:00 Laser energy meter had stalled, fixed now. Laser energy at low: 595 +/-13.75 mJ
13:45 Beam config: http://physics-ellog.slac.stanford.edu/facetelog/show.jsp?dir=/2025/19/10_05&pos=2025-05-10T23:59:00
Spot sizes from 12:47, Bunch length from 07:42 AM
14:00 Calibration tests by Weizmann Team
14:40 Weizmann tests done for now. We continue with bunch length measurement
```

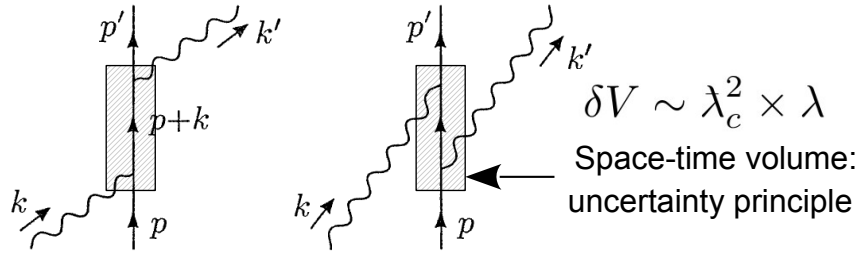
- **2023, May. 17-19:**

```
05/17/2025 23:59 E320 running log
ACR zoom: https://stanford.zoom.us/j/97779786664?pwd=WmpwdVlOMXREK3pLc0RWK2d6SnRhOT09
Procedure: https://docs.google.com/document/d/1V3C24HcgPRJRi05BVeVjuD1ZKTvsu4aIuWUISsbZ-o/edit?usp=sharing
Google DOC running log: https://docs.google.com/document/d/1ZTLJ0ARxxKz22v9Th_ZyG4BDc0XFZtfoRTBufHEd2oE/edit?usp=sharing
```

- Collided at the highest achievable laser intensities for the first time (online timing stabilization)
- Significantly reduced the background / noise (Be window retractable + LBG_LFOV upgrade)
- Attempted to detect positrons for the first time (WIS tracking detector successfully commissioned)
- Thanks for all the hard work in the FACET tunnel (J. Wang, A. Knetsch, S. Corde, S. Rego, ...)
- Thanks for all the improvements implemented (D. Storey, I. Rajkovic, B. O'Shea, S. Gessner, ...)

Major goals for E-320

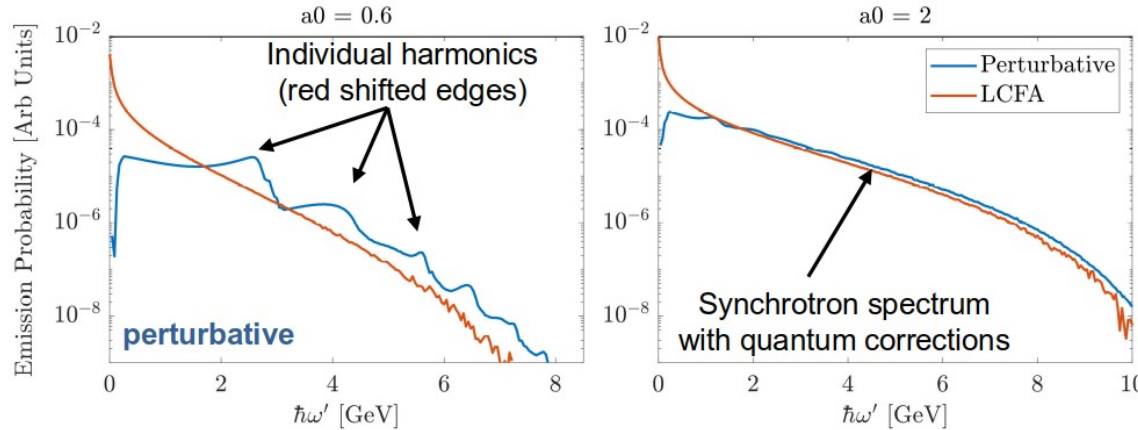
Goal 1: first measurement of the transition to nonperturbative scattering



Electron-photon (Compton) scattering
Klein & Nishina (1929)

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

Smallness of $\alpha \approx 1/137$ can be compensated by the laser photon density $\rho \Rightarrow$ nonperturbative interaction

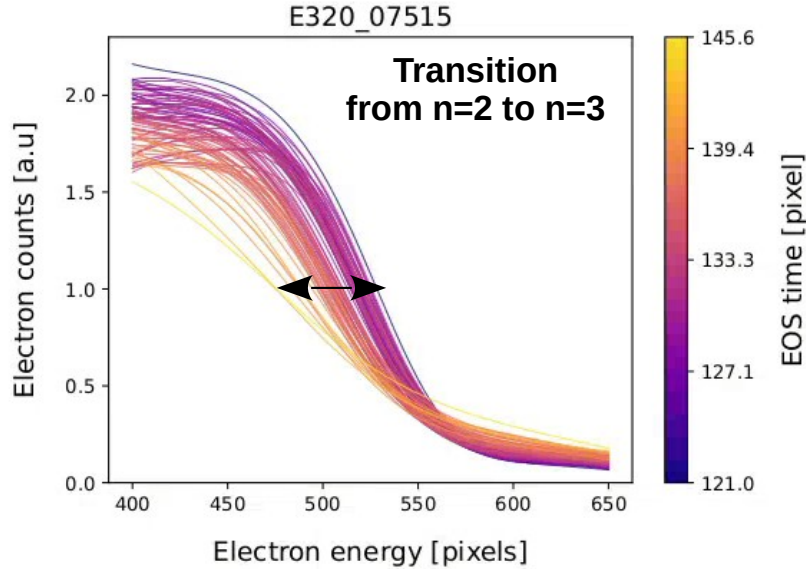


Transition from perturbative to nonperturbative interaction

Simulations: C. Nielsen (Aarhus)

Nikishov & Ritus, JETP 19, 1191 (1964); Brown & Kibble, Phys. Rev. 133, A705 (1964); etc.

High-impact result: edge shift due to ponderomotive mass dressing



Inside a laser field the electron mass increases, which shifts the position of the Compton edges

Analogous to the Higgs mechanism

symmetry magazine.org

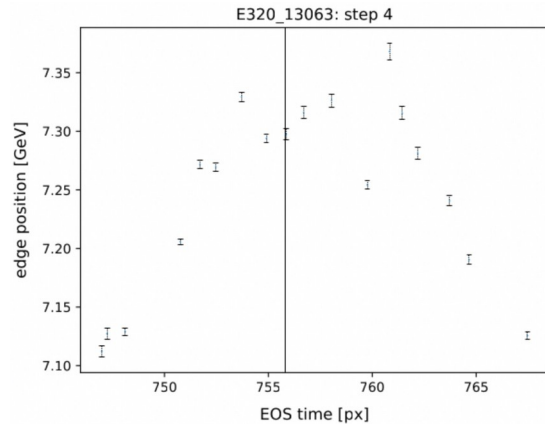
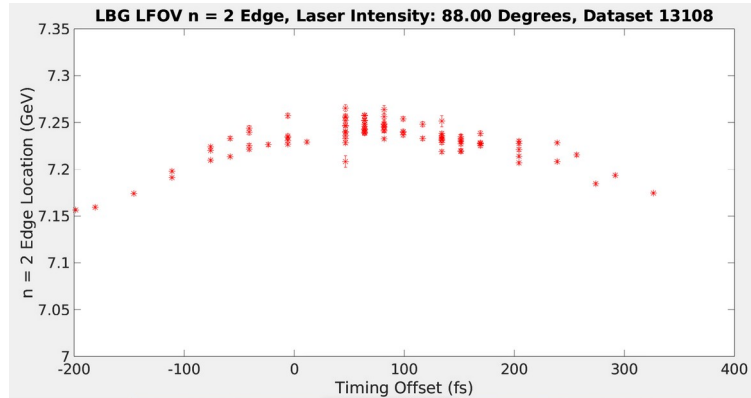


In the standard model, mass originates from interactions with the Higgs field

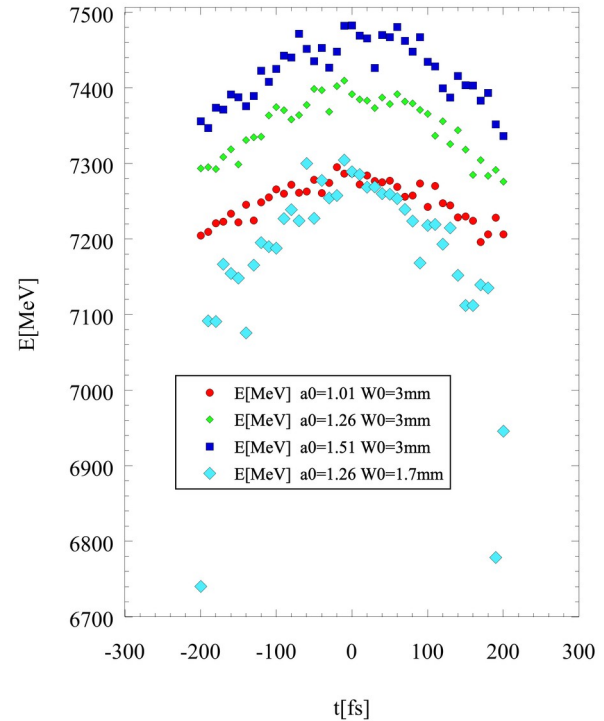
$$q^2 = m_*^2, \quad m^* = m\sqrt{1 + a_0^2/2}$$

where m_* acts as an “effective mass” of the electron in the field.

Shift of the 2nd Compton edge: matching with simulations ongoing



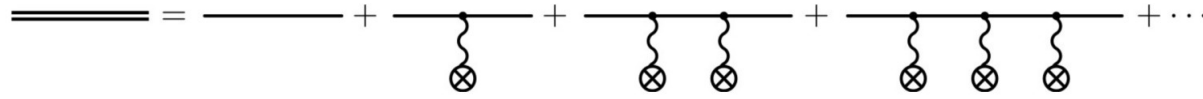
Simulation of Kinematic Edge $n=2 \times x_{\text{offset}}=0\mu\text{m}$ 10fs steps



R. Hessami / T. Smorodnikova / R. Holtzapple

Sebastian Meuren

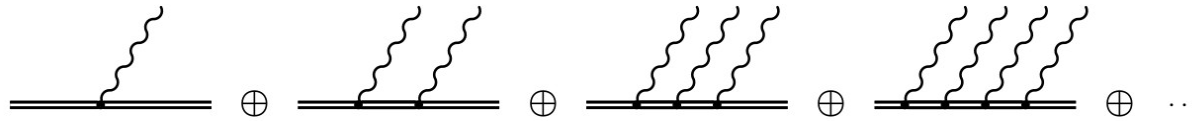
Goal 2: first unambiguous observation of quantum radiation reaction



Interaction with $\sim a_0^3/\chi \sim 100$ laser photons

$$a_0 = \frac{eE}{\omega_L mc} \approx 0.6 \frac{\lambda_L}{1 \mu\text{m}} \sqrt{\frac{2I}{10^{18} \text{ W/cm}^2}}$$

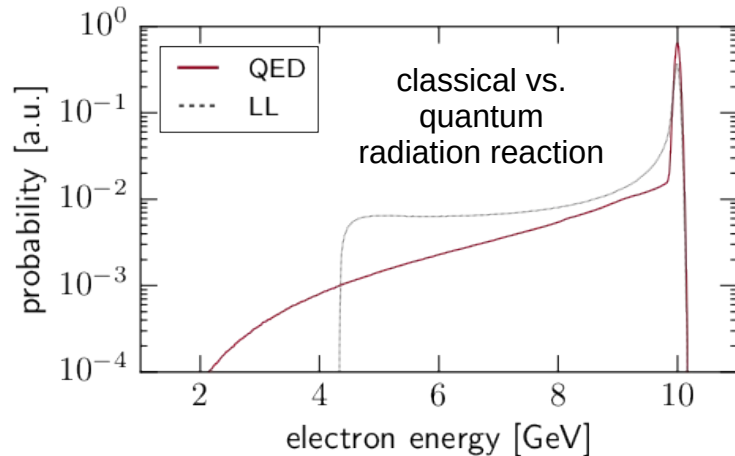
$a_0 \geq 1$: laser-electron interaction becomes non-perturbative



Emission of multiple hard photons: quantum radiation reaction

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

$\chi \geq 0.1$: quantum effects induce significant recoil



Simulation:
M. Tamburini

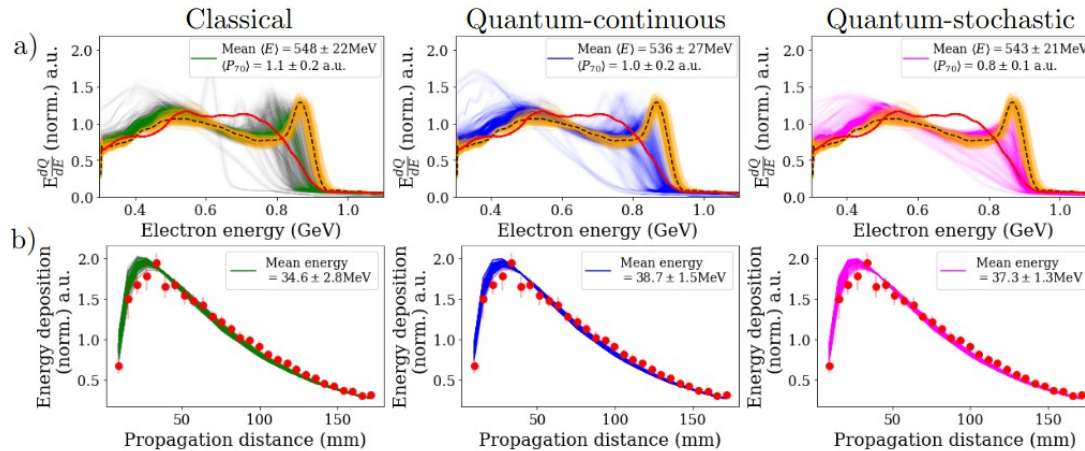
Fedotov et al., *Phys. Rep.* 1010, 1-138 (2023)
Gonoskov et al., *RMP* 94, 045001 (2022)
Di Piazza et al., *RMP* 84, 1177 (2012)

High-impact result: unambiguous observation of quantum effects

[Submitted on 16 Jul 2024]

Observation of quantum effects on radiation reaction in strong fields

E. E. Los, E. Gerstmayr, C. Arran, M. J. V. Streeter, C. Colgan, C. C. Cobo, B. Kettle, T. G. Blackburn, N. Bourgeois, L. Calvin, J. Carderelli, N. Cavanagh, S.J.D. Dann A. Di Piazza, R. Fitzgarrald, A. Ilderton, C. H. Keitel, M. Marklund, P. McKenna, C. D. Murphy, Z. Najmudin, P. Parsons, P. P. Rajeev, D. R. Symes, M. Tamburini, A. G. R. Thomas, J. C. Wood, M. Zepf, G. Sarri, C. P. Ridgers, S. P. D Mangles

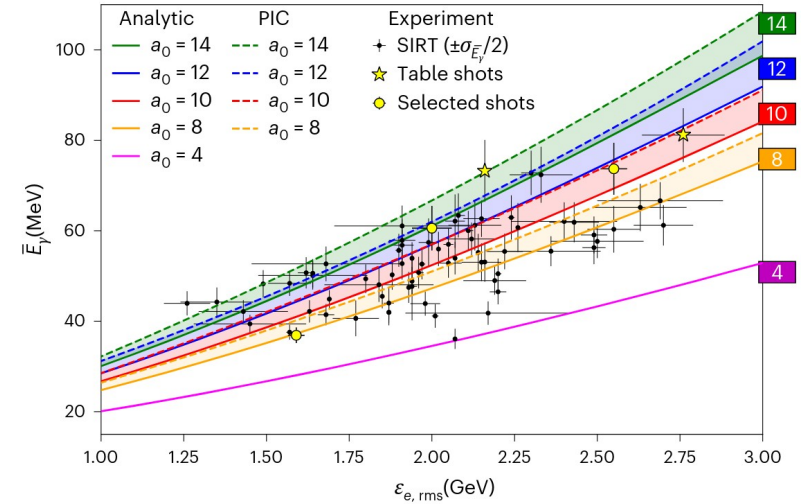


nature photonics

Article

<https://doi.org/10.1038/s41566-024-01550-8>

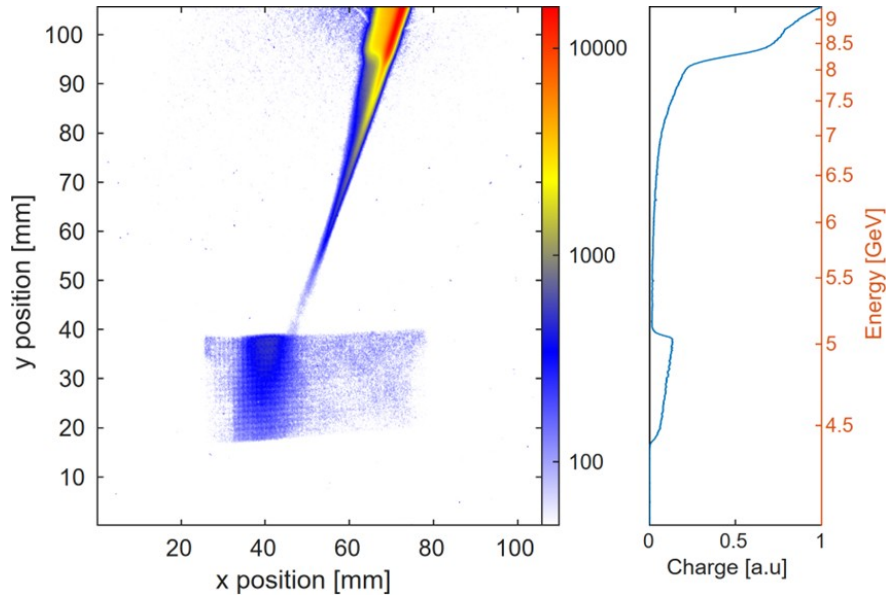
All-optical nonlinear Compton scattering performed with a multi-petawatt laser



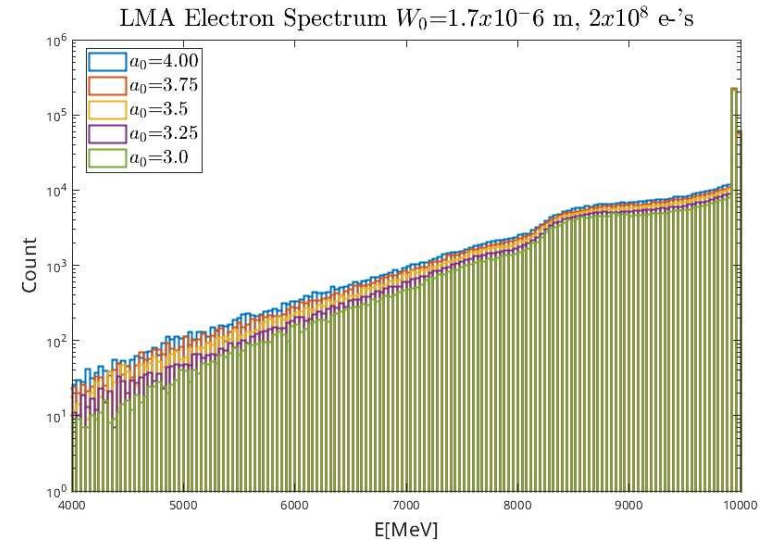
- Several campaigns planned at multi-PW lasers based on LWFA
- Our data have much higher quality, but we need to publish fast

Spring 2025 data: we observed scattering well below 5 GeV

High-intensity shot
(top: DRZ, bottom: GAGG)



Simulated electron spectra

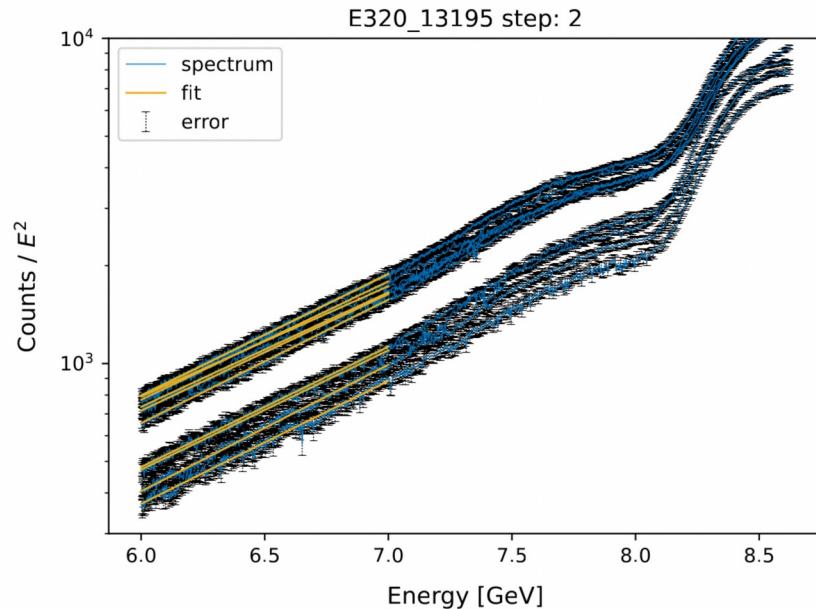


- We observe a quasi-continuous, exponential electron spectrum: QRR
- Linear Compton edge: electrons that interact outside the laser focus

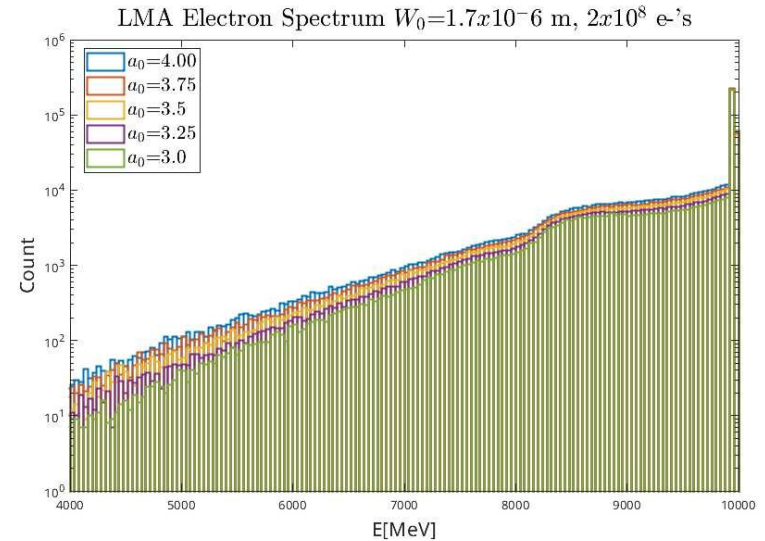
S. Rego / R. Holtzapfle

Spring 2025 data: we observed exponential spectra consistent with $a_0 \gtrsim 4$

Data with exponential fit
(DRZ without artifacts)



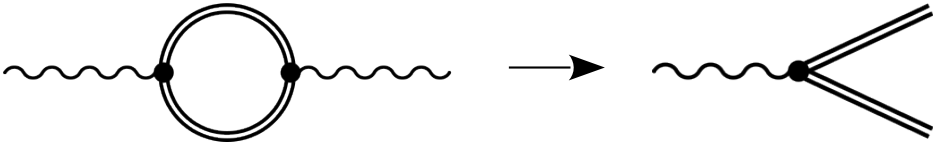
Simulated electron spectra



- We observe a quasi-continuous, exponential electron spectrum: QRR
- Linear Compton edge: electrons that interact outside the laser focus

T. Smorodnikova / R. Holtzapfle

Goal 3: observing tunneling electron-positron production for the 1st time

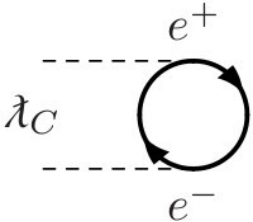


Vacuum polarization

photon transforms temporarily into an electron-positron pair

Pair production

virtual pair is “ionized” by laser at QED critical field

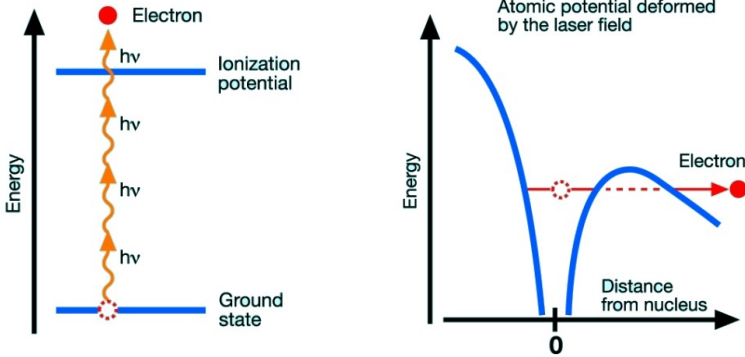


Length: $\lambda_C = \hbar/(mc)$
 Energy: $\mathcal{E} = mc^2$
 Critical field: $eE_{cr} = mc^2/\lambda_C$

Qualitative changes between E-144 and E-320:
 (analogous to strong-field ionization of atoms)

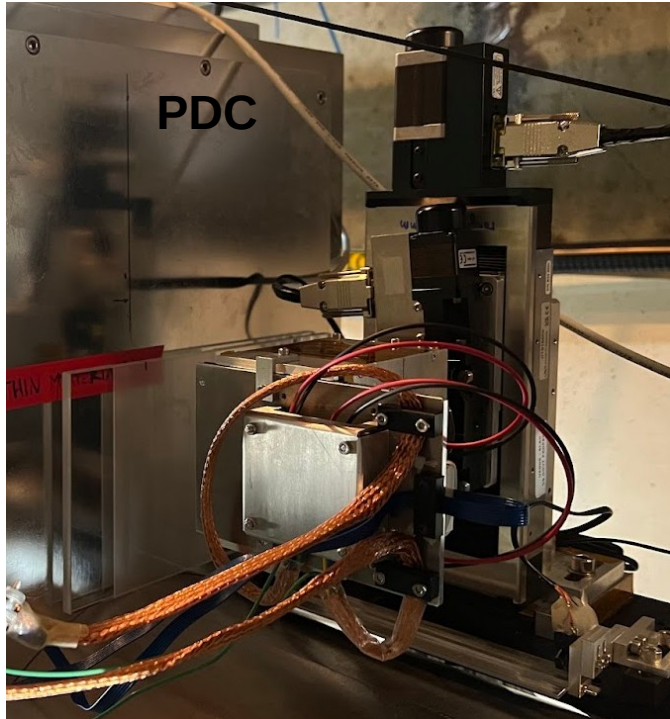
E-144 ($a_0 \lesssim 1$):
 multi-photon regime

E-320 ($a_0 \gg 1$):
 tunneling regime



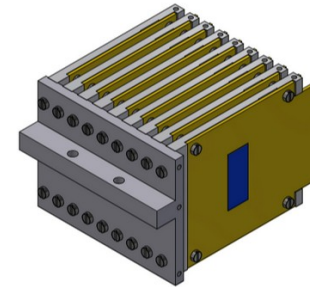
© Wikipedia

Positron tracker: Noam Tal Hod's group @ Weizmann, T-619



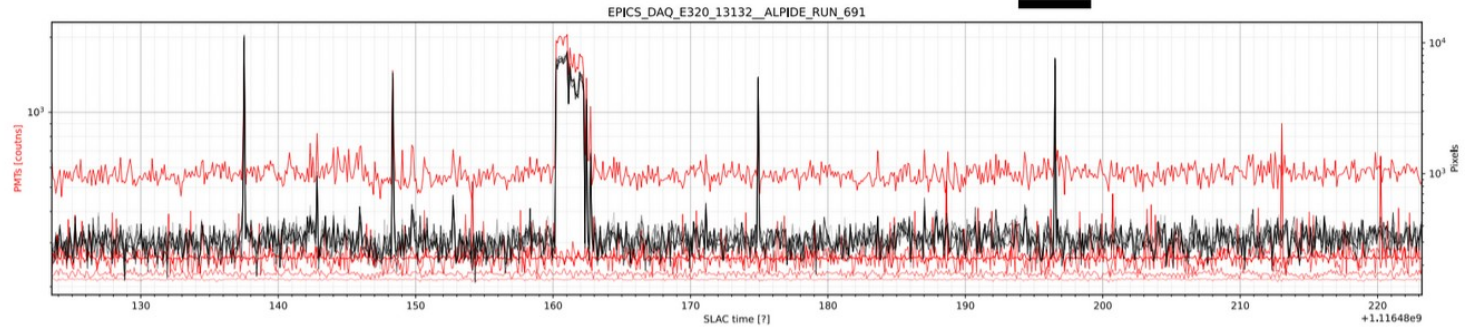
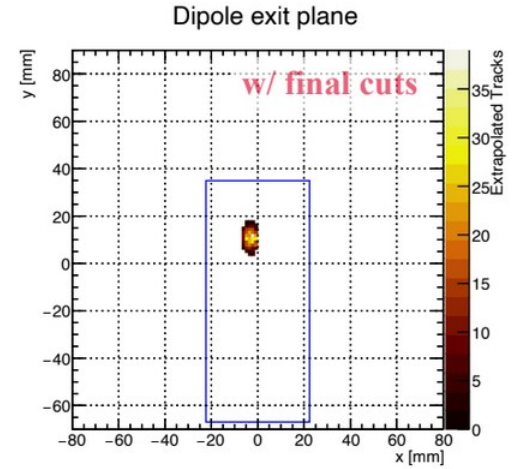
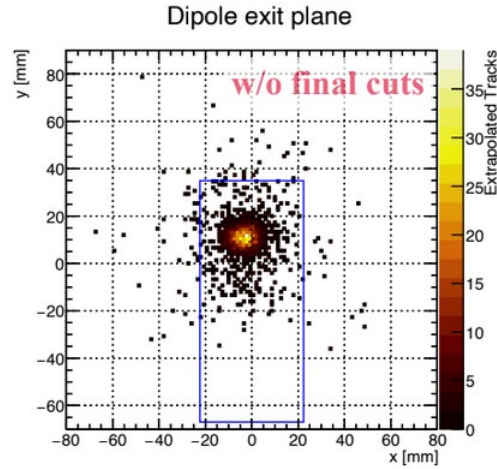
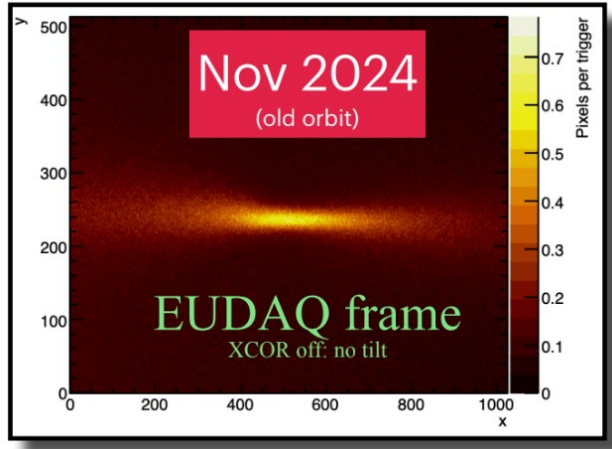
- Thin monolithic active pixel sensors (MAPS), dubbed “ALPIDEs” (ALice Pixel Detector)
- Produced by TowerJazz for the upgrade of the ALICE experiment at the LHC
- Radiation hardness: technology was selected for HL-LHC heavy ion collisions

Details: <https://arxiv.org/abs/2506.04992>



Tracker is critical for identifying laser-produced positrons and reducing backgrounds

WIS positron tracker: first successful shifts / measurements



Noam's presentation (URL)
<https://arxiv.org/abs/2506.04992>

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WIS positron tracker: first successful shifts / measurements

Summary

Assuming $p_{\text{EPICS}} = (((\text{scalar_PID} - 10)/36) \% 2)$

EUQAQ Run #	Duration [h]	Triggers				Pixels		Clusters		Non-synced tracks		Is in sync?	Synced tracks		Tracks rates		Rates ratio	
		All	Good	Good Even	Good Odd	Avg Pix Occ [1/Trig]	Avg Cls Occ [1/Trig]	HT Selected Tracks	Even	Odd	Even		Odd	Even	Odd	Even/Odd	Error	
690	0.47	17075	16323	8163	8160	278	277	84	84	5	6	✗	6	5	7.35E-04	6.13E-04	1.20	0.73
691	0.56	20056	19309	9655	9654	290	290	88	88	1	3	✗	3	1	3.11E-04	1.04E-04	3.00	3.46
692	0.60	21544	20889	10443	10446	320	319	97	97	3	4	✓	3	4	2.87E-04	3.83E-04	0.75	0.57
693	0.16	5921	5773	2885	2888	334	336	102	102	0	0	✗	0	0	0.00E+00	0.00E+00	0.00	0.00
694	0.56	20252	18958	9476	9482	289	289	87	87	2	2	✗	2	2	2.11E-04	2.11E-04	1.00	1.00
696	1.12	40318	36406	18204	18202	313	313	95	95	5	10	✗	10	5	5.49E-04	2.75E-04	2.00	1.10
701	0.99	35590	34124	17059	17065	290	291	88	88	2	17	✓	2	17	1.17E-04	9.96E-04	0.12	0.09
702	0.72	25742	23638	11825	11813	271	270	81	81	8	3	✗	3	8	2.54E-04	6.77E-04	0.37	0.25
Totals	5.18	186498	175420	87710	87710	298.125	298.125	90.25	90.25	26	45		29	42	3.31E-04	4.79E-04	0.69	0.17

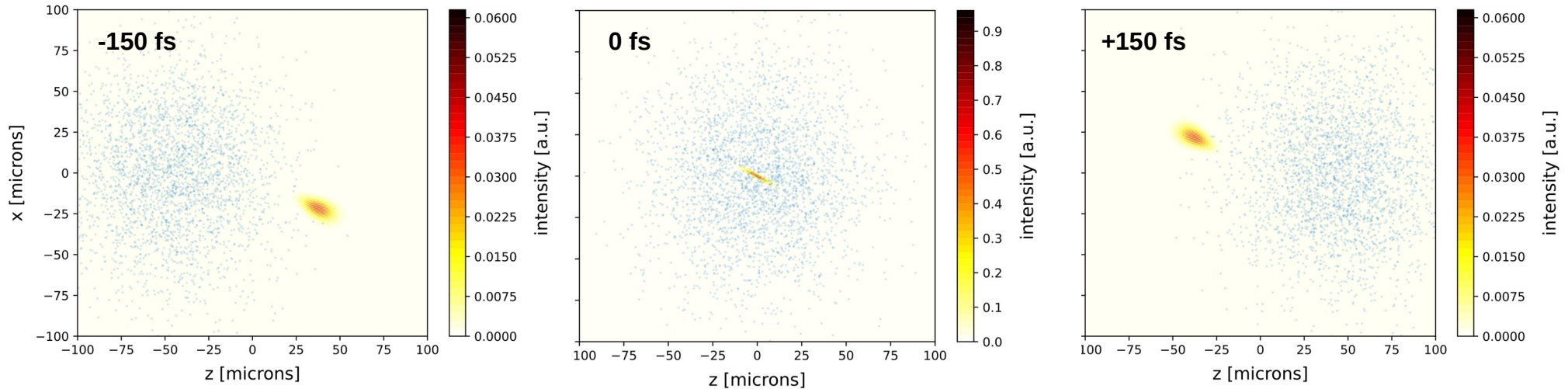
- The rate is $r^p = N_{\text{trk}}^p / N_{\text{trg}}^p$, where $p = \text{even, odd}$ and $R = r^{\text{even}} / r^{\text{odd}}$
- Naively $\Delta N = \sqrt{N}$ and hence $\Delta R = R \times \sqrt{1/N_{\text{trk}}^{\text{even}} + 1/N_{\text{trk}}^{\text{odd}} + 1/N_{\text{trg}}^{\text{even}} + 1/N_{\text{trg}}^{\text{odd}}}$
- In the limit of large stats if there's no parity dependence $R = 1$, however, we see that $R = 0.69 \pm 0.17$, which is $\sim 1.8\sigma$ away from 1.
- Even if the EPICS parity assumption is correct, we **cannot yet** claim that these are NBW positrons or background tracks from the collision.
- Next thing to do is to look at the even/odd momentum distributions and also try to do the same with the Saturday runs (noisier).

<https://arxiv.org/abs/2506.04992> Noam's presentation (URL)

Major improvement:

real-time control of the scattering time

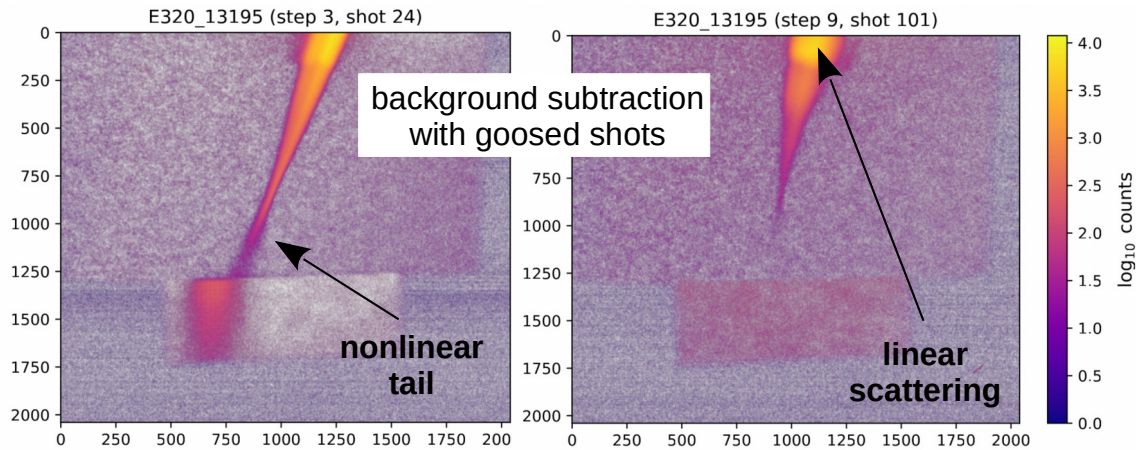
Relative timing: absolutely critical to probe the highest laser intensities



Laser-electron spatial-temporal alignment is critical on the scale of 10 fs ($\approx 3 \mu\text{m}$)

- Aligning “by hand” (optimize for maximum scattering signal) turns out to be very difficult
- Most previous data were taken with non-optimal timing: waste of beam time
- **We developed algorithms for real-time data analysis and optimization (major effort)**

Novel real-time analysis: background subtraction with Bayesian inference

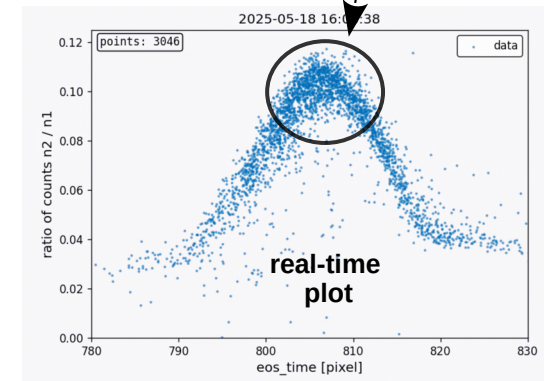
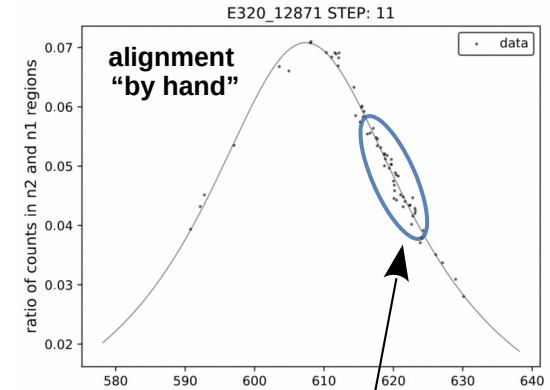


- **Ratio between non-linear & linear scattering:** to leading order independent of spatial impact parameters
- **Allows us to determine the achieved laser intensity:** largest ratio is obtained for optimal laser-electron timing

Critical for the success of the 2nd shift in May 2025

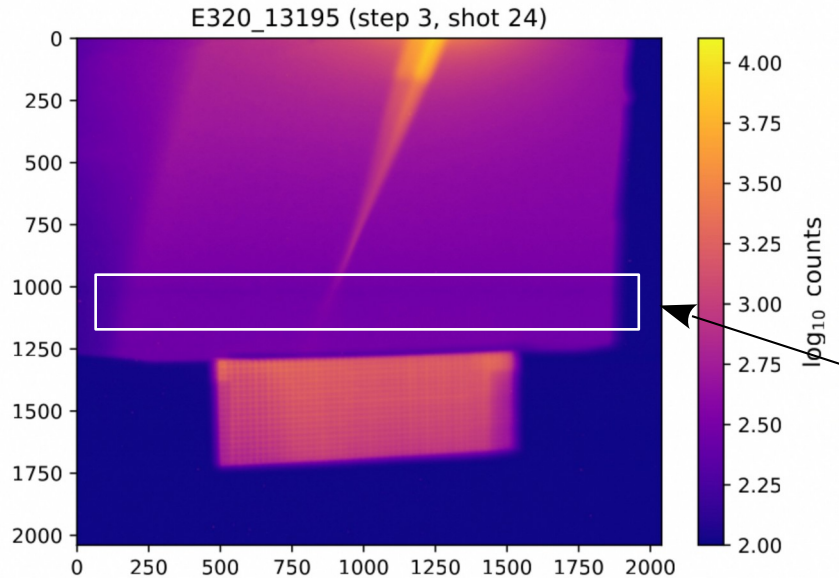
~6 months of development work (T. Smorodnikova)

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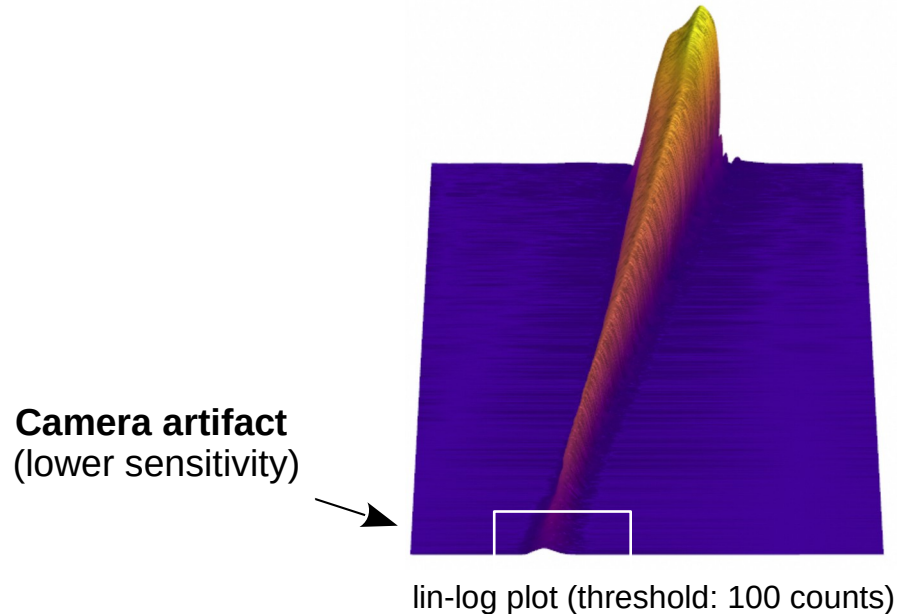


Novel real-time analysis: background subtraction with Bayesian inference

Low-background LFOV
(raw data, with background)



Reconstructed spectrum
(single-shot background subtraction)

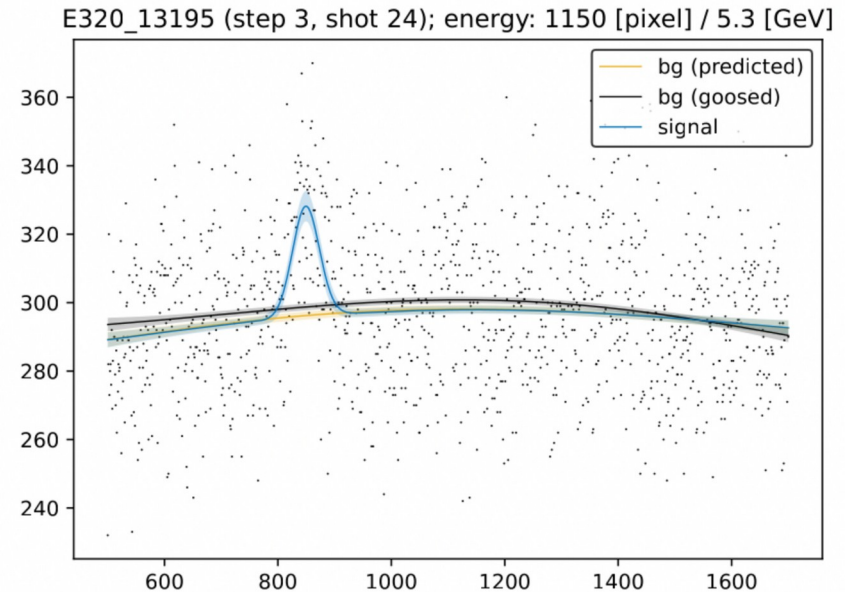
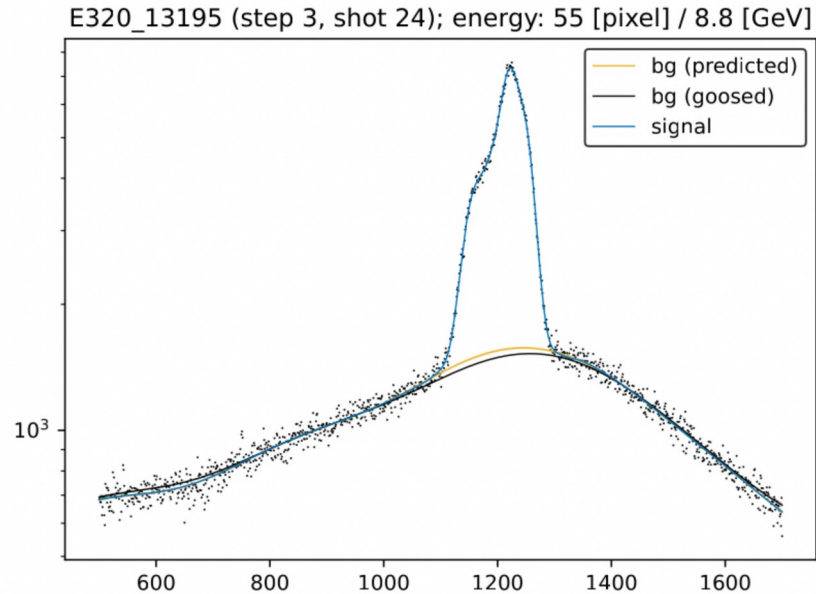


- Background is determined from the image itself via Bayesian inference: possible, as signal has much higher spatial frequencies than background
- Requires extensive computational resources: real-time online analysis on LULI cluster

T. Smorodnikova

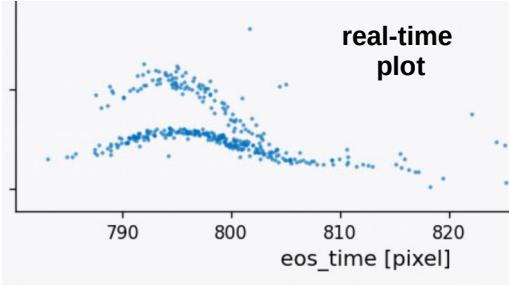
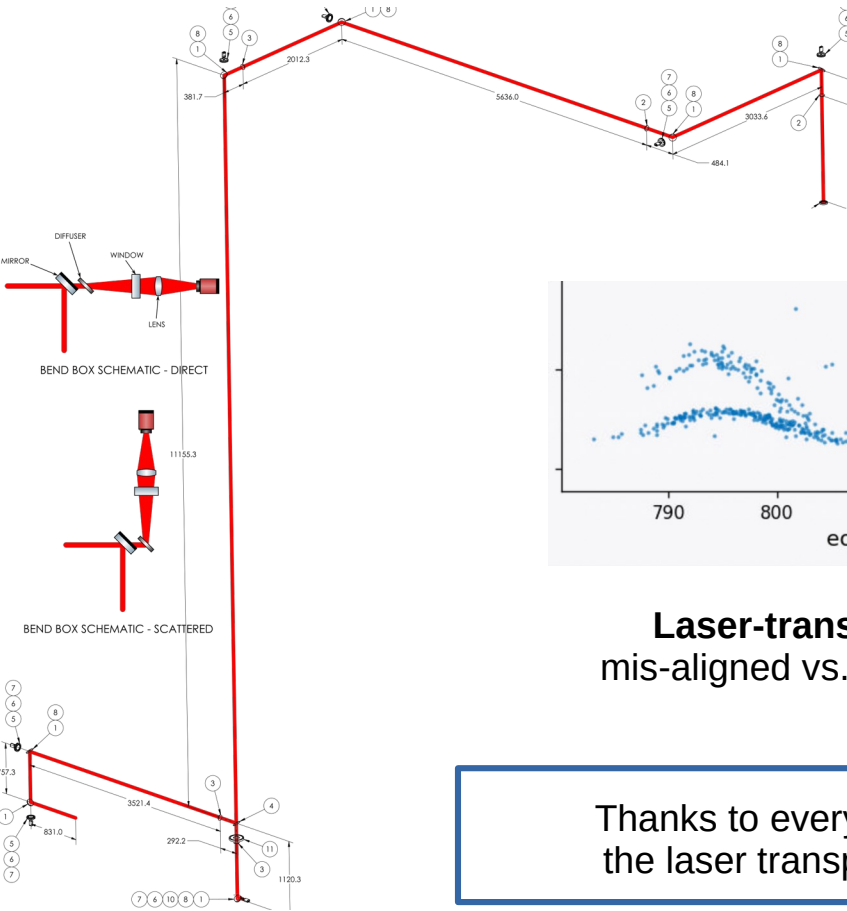
Performance: goosed vs. predicted backgrounds

Predicted signal / background vs. best-matched goosed measurement

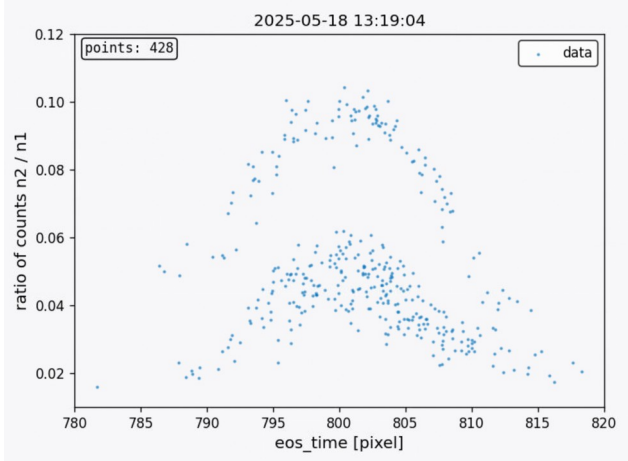


- Hints for small additional signal-induced backgrounds (scattering in the exit window?)
- Overall residual error ≈ 5 counts (difference between goosed and predicted background)

Laser-transport alignment: problems with the auto-aligner



Laser-transport
mis-aligned vs. aligned

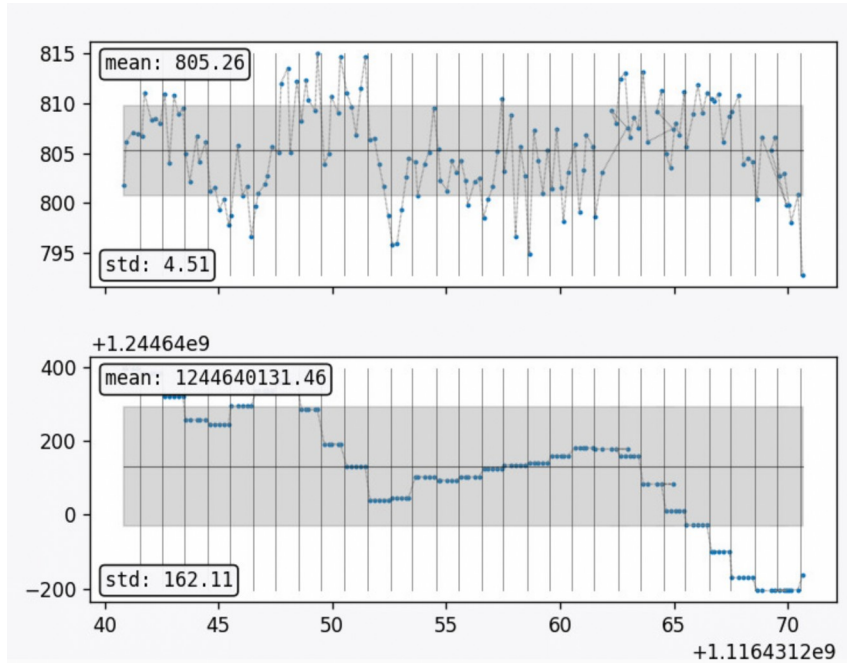


Laser-intensity scan
(changed on purpose)

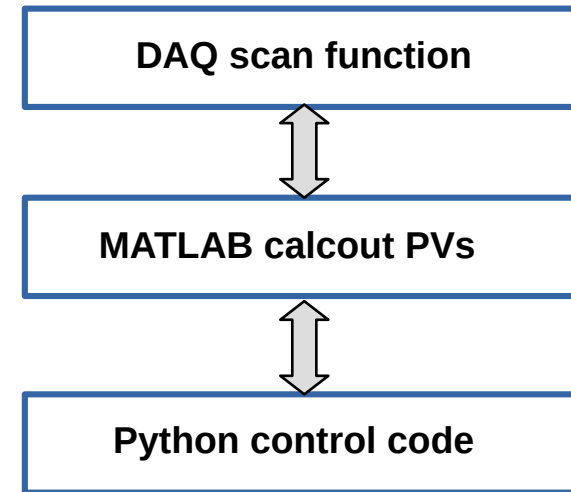
Thanks to everyone in the ACR for carefully monitoring & adjusting the laser transport in real time (J. Wang, A. Knetsch, S. Cord, etc.)

EOS critical for E-320: active stabilization of laser-electron timing

EOS signal (pixel) vs. Laser TGT (fs)



FACET DAQ: interfacing with Python



- Without active stabilization we can't take data: time drifts ~1ps
- **Implemented: long-range timing scans with active timing stabilization**

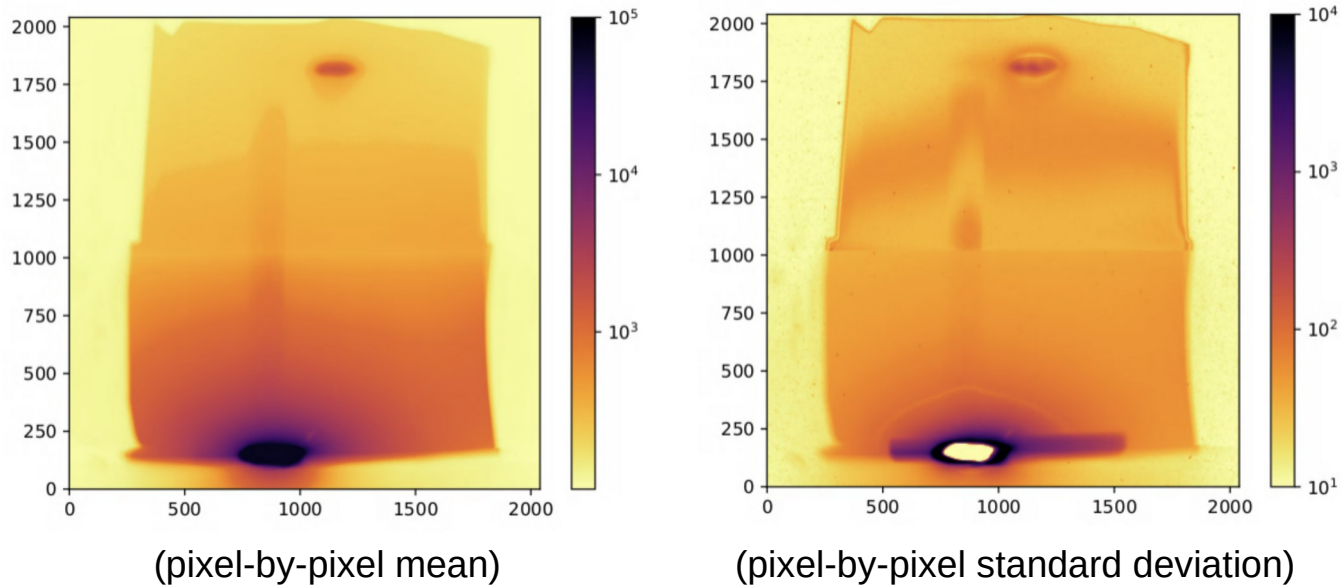
Knetsch/Smorodnikova

Major improvement:

new Low Background LFOV
&
retractable Beryllium window

Low-Background LFOV: situation before upgrades (Aug. 22, 2024 slides)

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



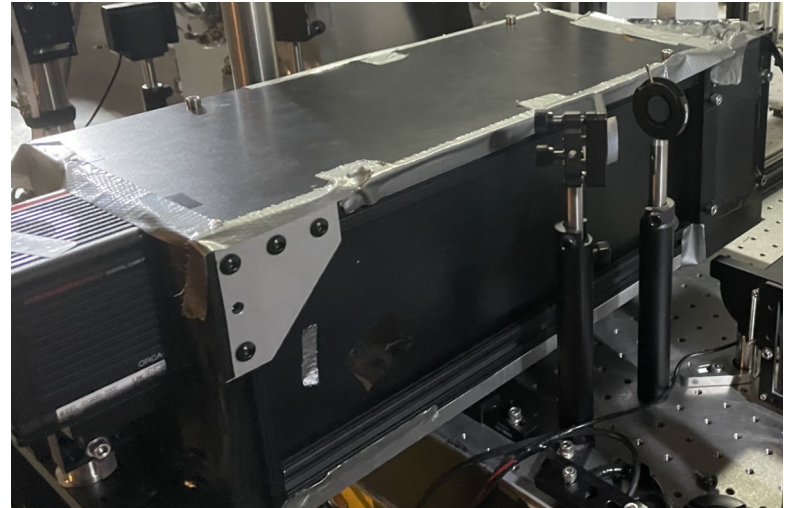
- Vertical stripe and other artifacts made the data analysis very difficult
- In addition, large shot-to-shot fluctuations (beam drifting on Be window)

Low-Background LFOV: improvements critical for data quality

1st version (2024 spring run)



2nd version (2025 spring run)



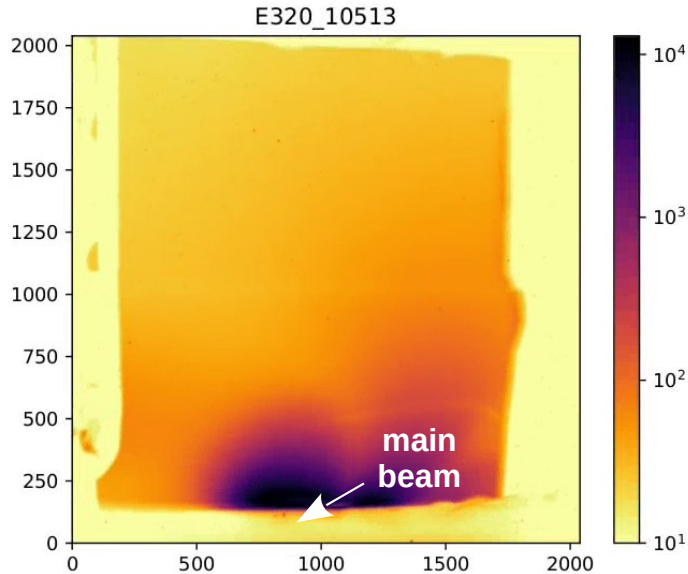
Currently the main diagnostic for scattered electron spectra (energy & angle)

- New design eliminated several artifacts from the images
- Critical for increasing the data quality (better light shielding, etc.)

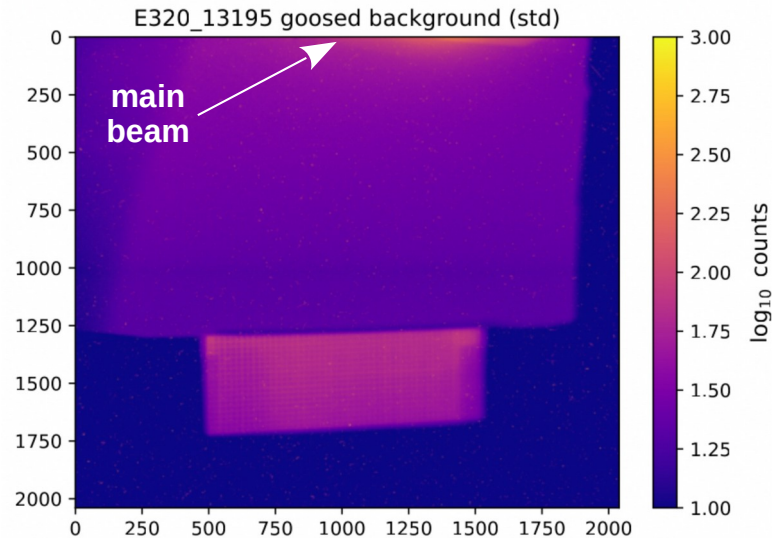
A. Knetsch et al.

Noise improvements (Be window is finally retractable: major improvement)

New LBG_LFOV, Be-window in
(pixel-by-pixel standard deviation)



New LBG_LFOV, Be-window retracted
(pixel-by-pixel standard deviation)

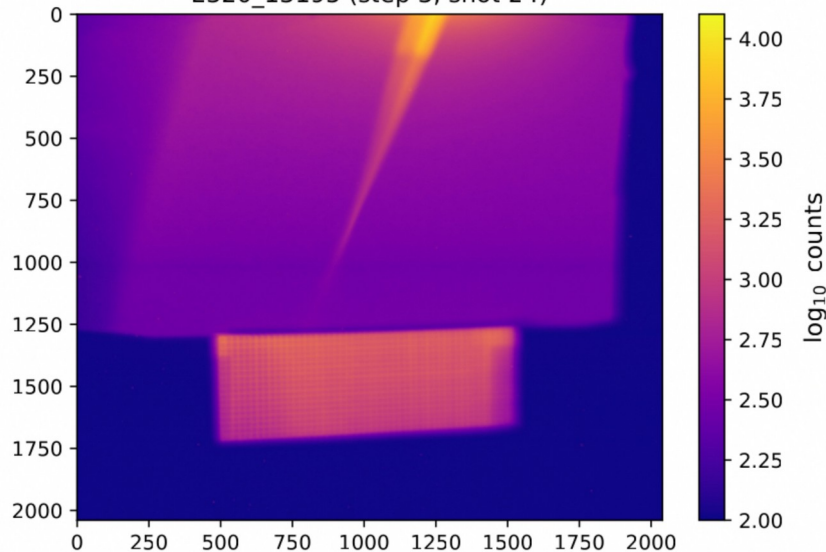


- The background is now very smooth (no beam-halo scattering in the Be window)
- Shot-to-shot fluctuations have significantly decreased after retracting the Be window

LBG_LFOV: signal vs. goosed shots

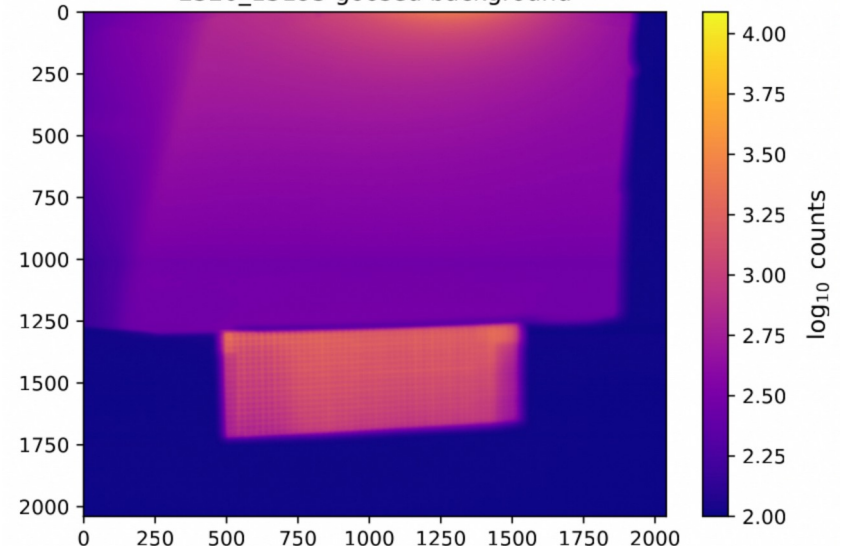
signal shot (raw data)

E320_13195 (step 3, shot 24)



goosed shot (raw data)

E320_13195 goosed background

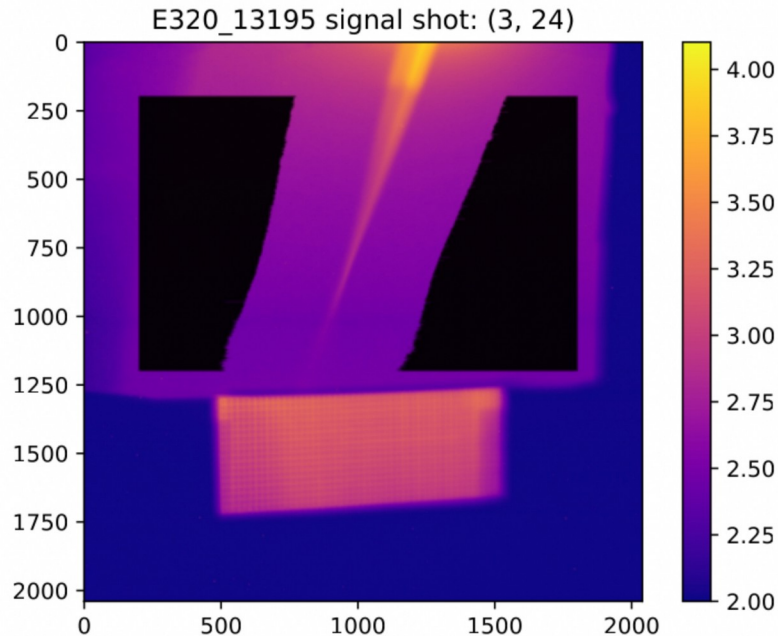


“Goosing” is critical for background subtraction, especially for the GAGG

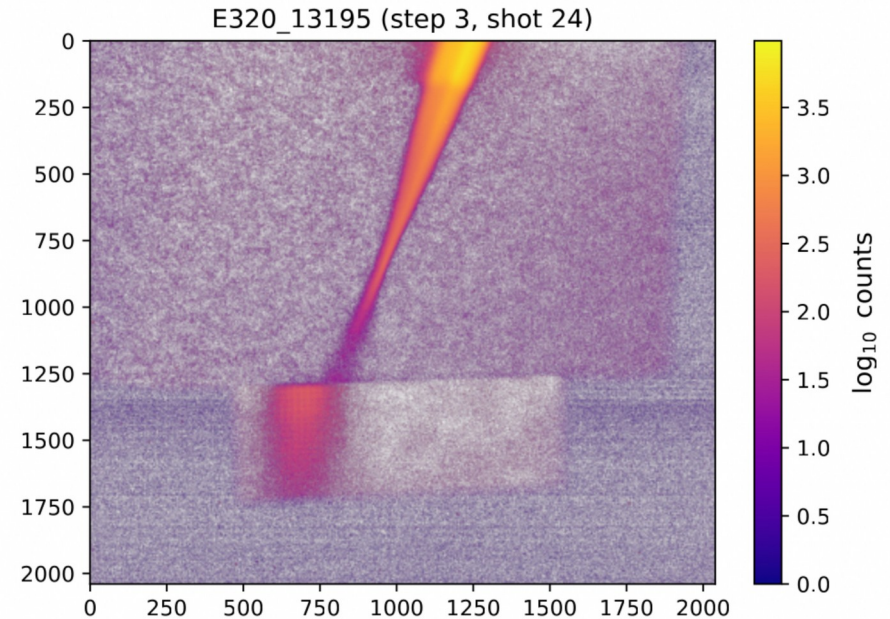
- Currently: 50% on / 50% off: LCLS saw systematic errors in this mode
- The closer we get to pseudo-random goosing the better

Background subtraction: matching region & final result

Matching goosed shots
(black: matching region)



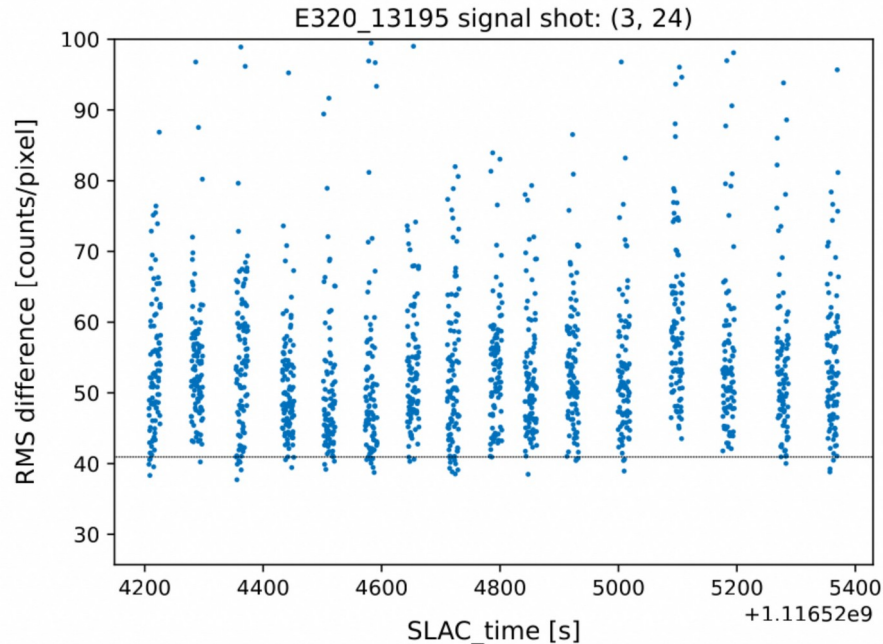
Background subtracted
(negative counts: white)



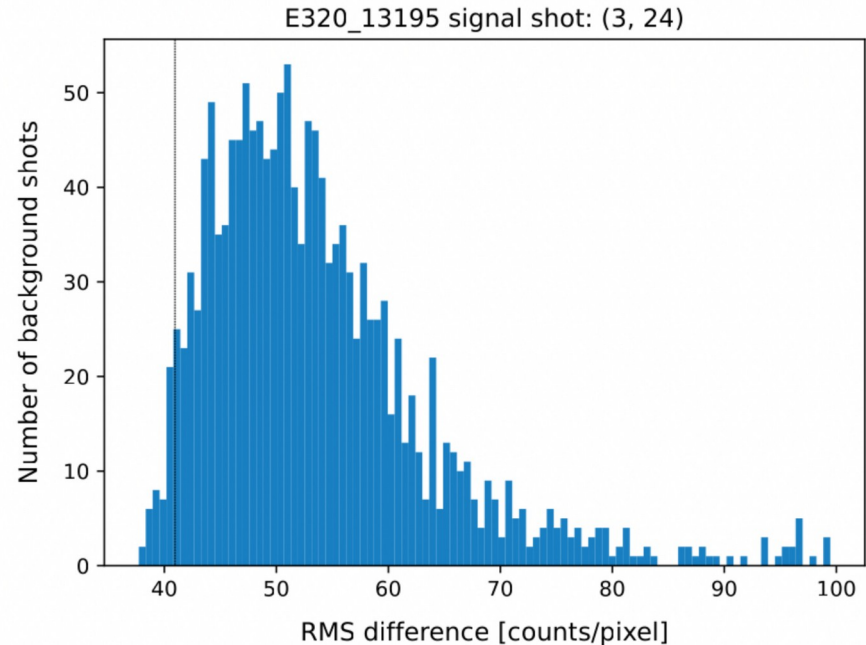
From ~ 1.5k goosed shots we find 50 shots that are closest to the signal in the matching region
Due to drifts in the accelerator this method is challenging to implement for online analysis

Background subtraction: distribution of goosed shots

Background matching
(temporal evolution)



Background matching
(shot distribution)



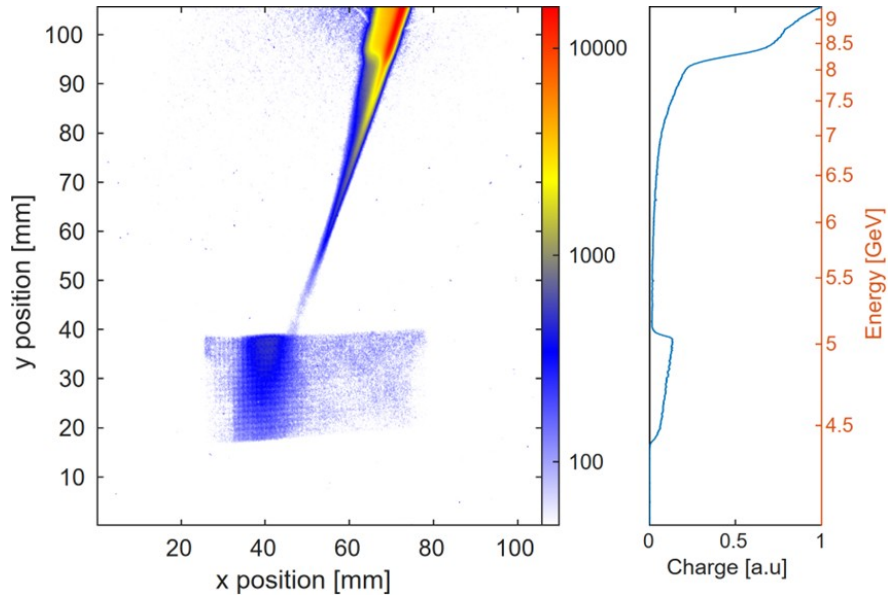
- Due to drifts / jitter, the best matches are distributed over the entire dataset
- Need to balance number of selected shots: better statistics vs. increasing error

Major improvement:

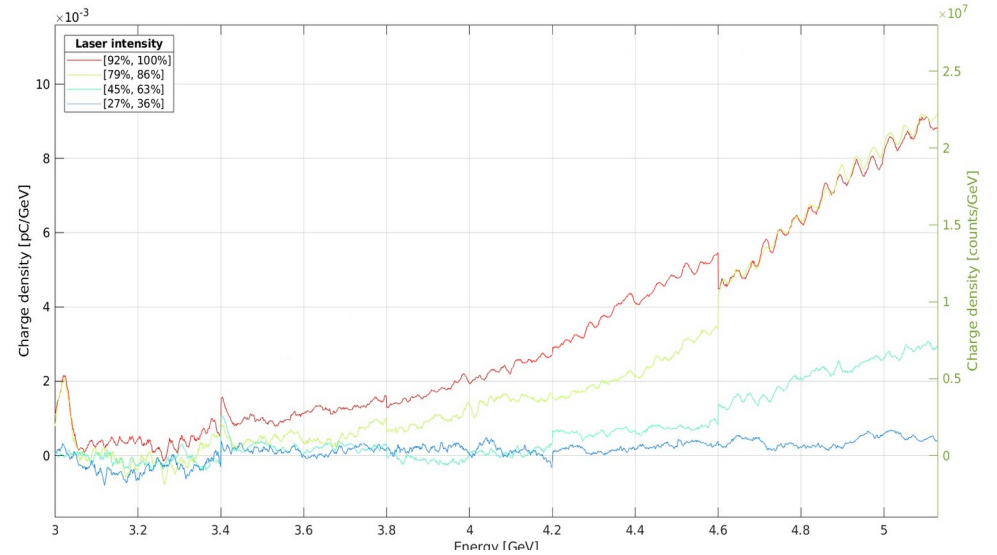
Gagg for low-energy scattered electrons

Low-energy scattered electrons: GAGG vs. DRZ

DRZ vs. GAGG
(sensitivity vs. spatial resolution)



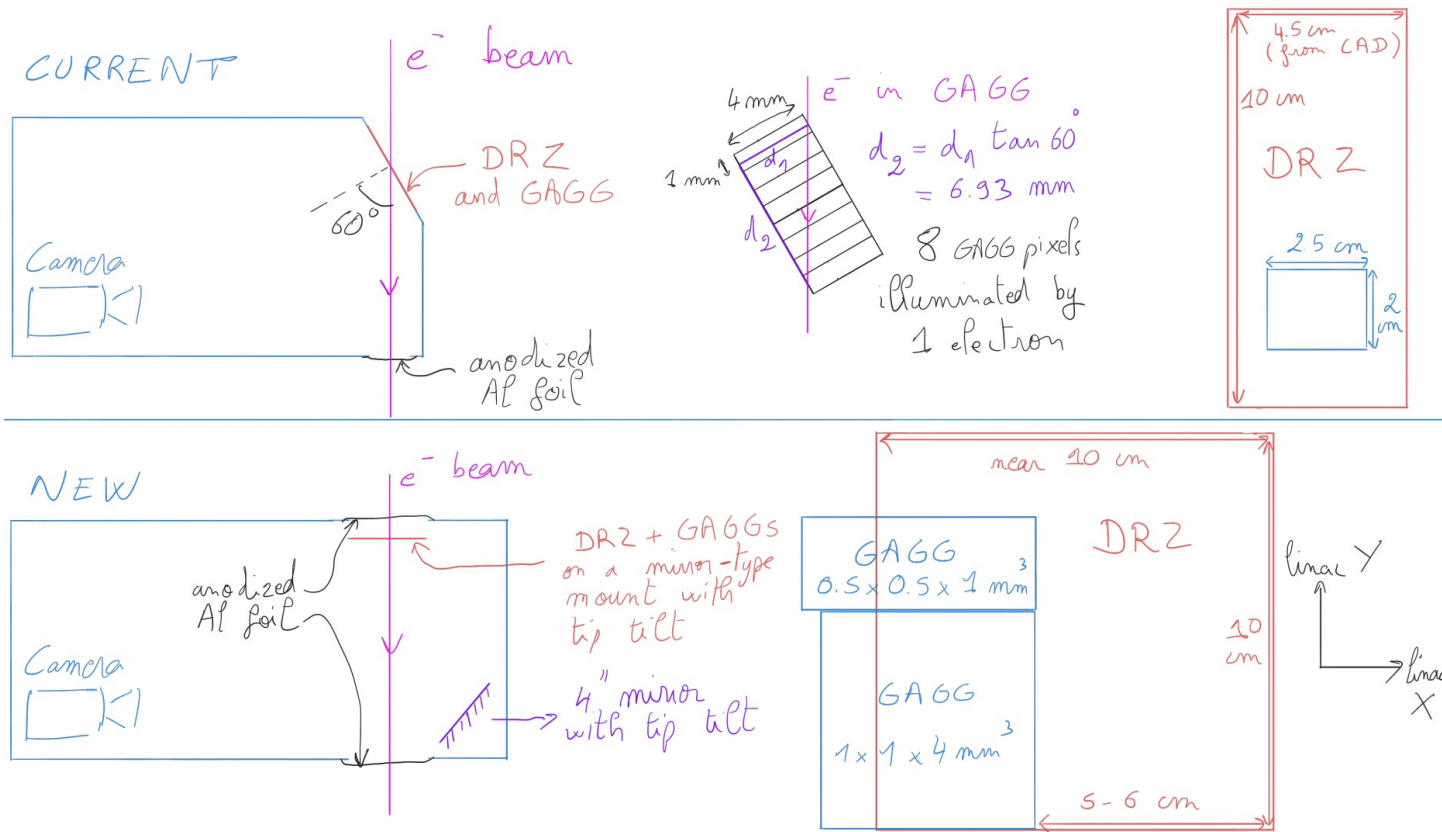
Low-energy spectrum
(stitched from multiple shots)



- At very low energies (≈ 5 GeV at full intensity) we need more sensitivity
- GAGG crystal: reduced spatial resolution for (much) higher light yield

S. Rego

Mid-term revision of Low-Background LFOV: first ideas



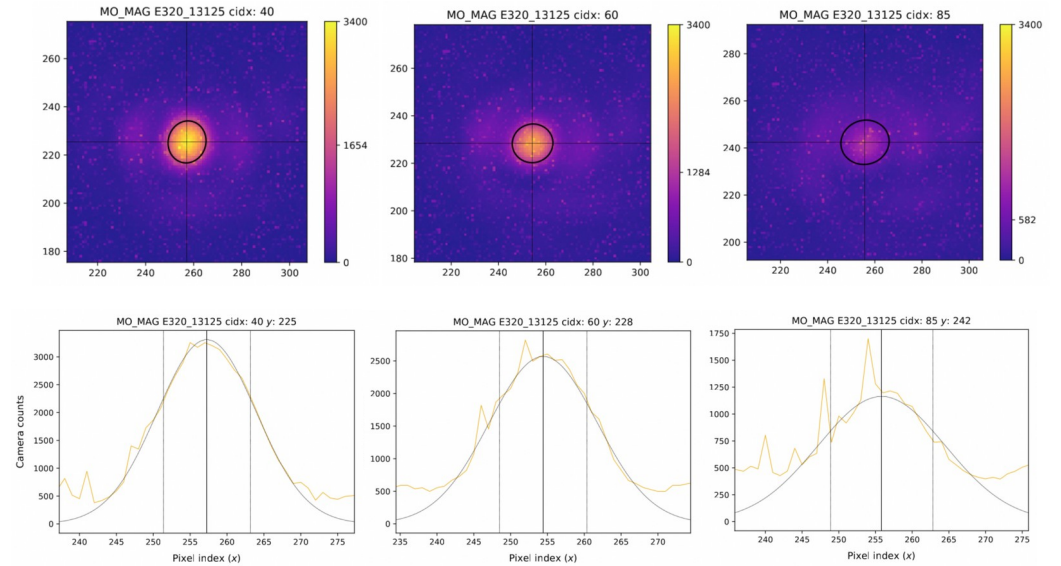
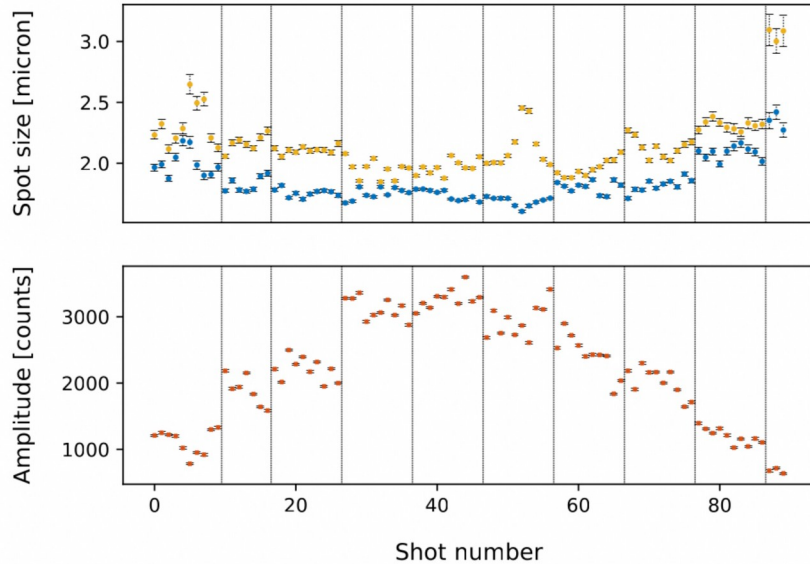
Ideal: vertical translation stage to move GAGG up/down

S. Corde

Major progress:

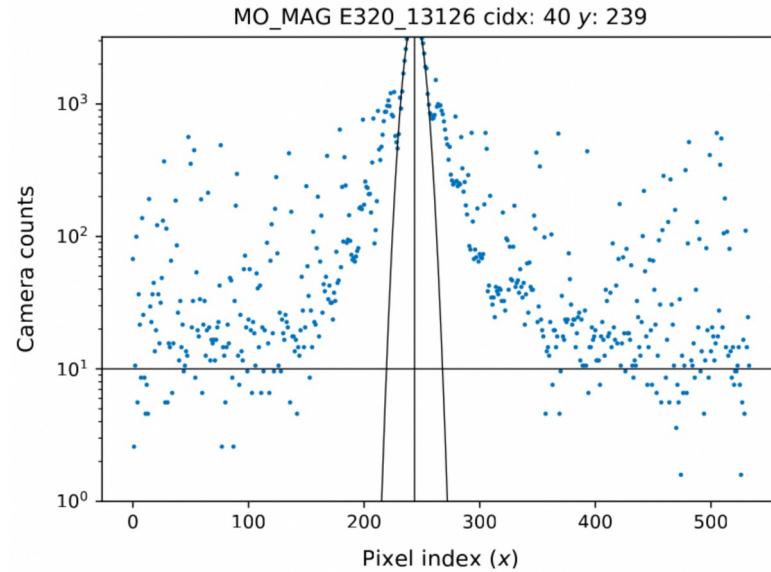
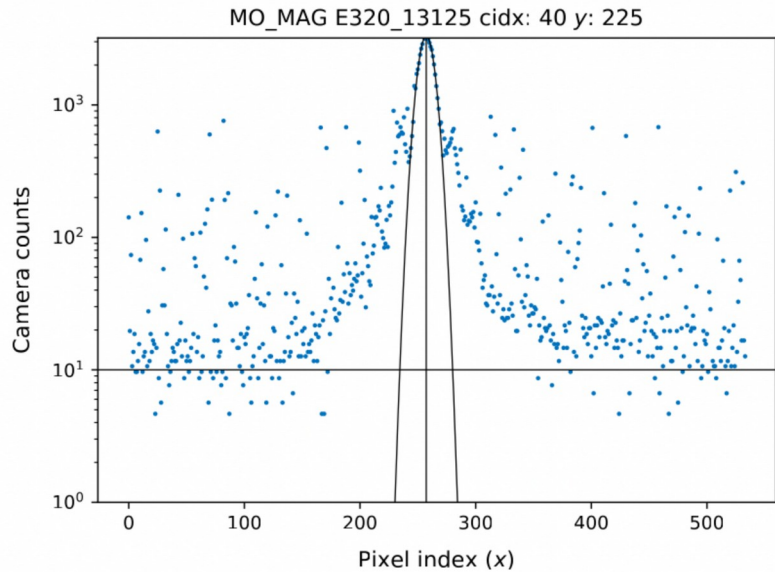
We seem to have consistent estimates for the laser intensity

Laser spot optimization: we achieved $\approx 2 \mu\text{m}$ with dielectric SORL OAP



J. Wang / A. Knetsch

Strehl ratio: estimation ongoing

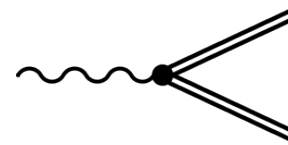
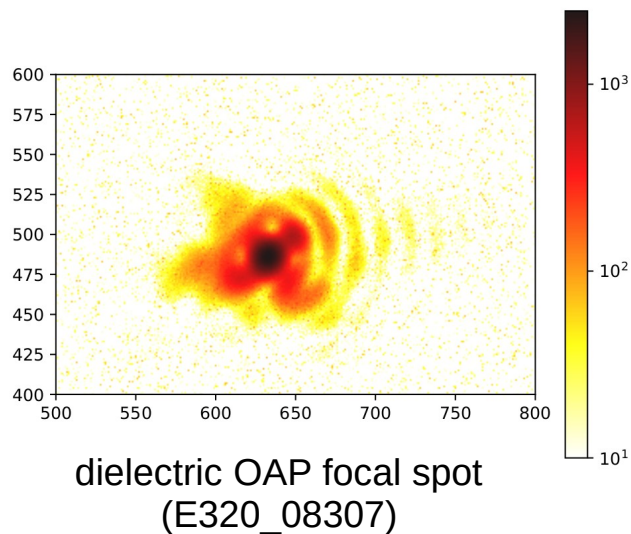


Need to reduce camera exposure time next run to reduce noise

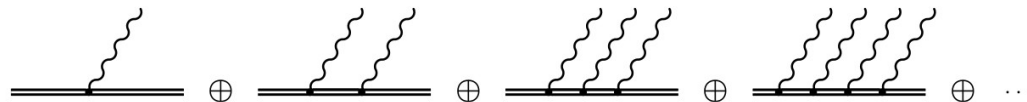
J. Wang / A. Knetsch

Other desired improvements

Increase the peak laser intensity



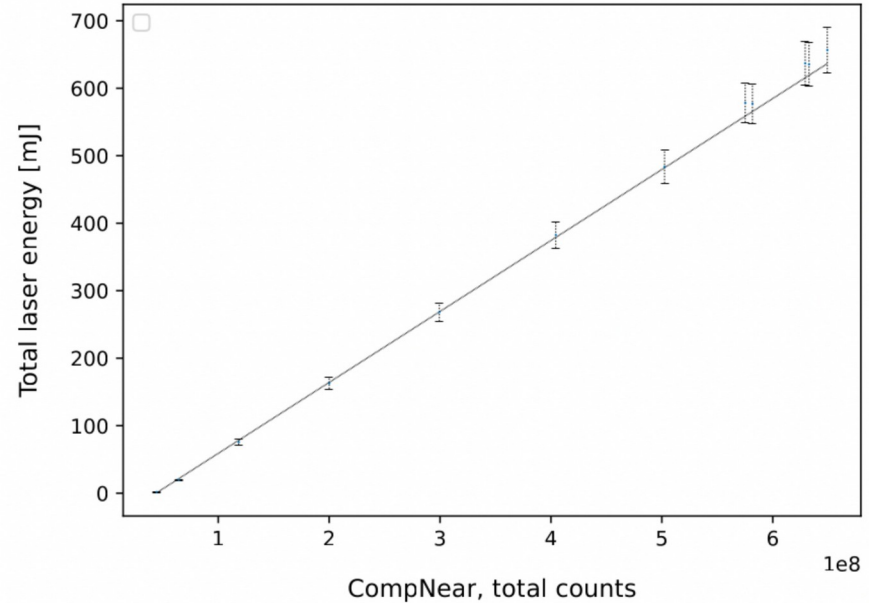
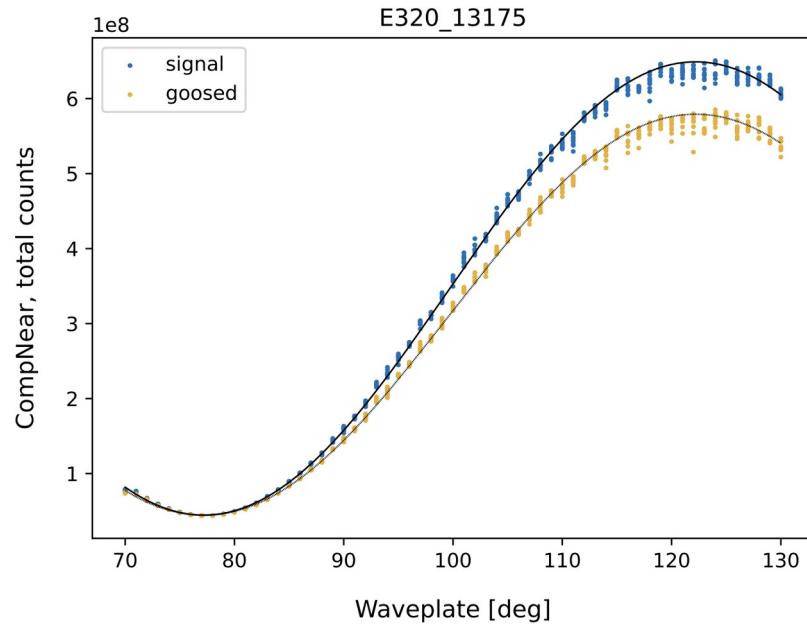
Tunneling electron-positron pair production
(high-impact publication)



Clear dominance of higher-order emissions
(high-impact publication)

- Can we send: ≥ 1 J to the tunnel
- Transport splitting: can we reduce to $\leq 10\%$?
- Improve Strehl ratio: wave-front sensing in tunnel?

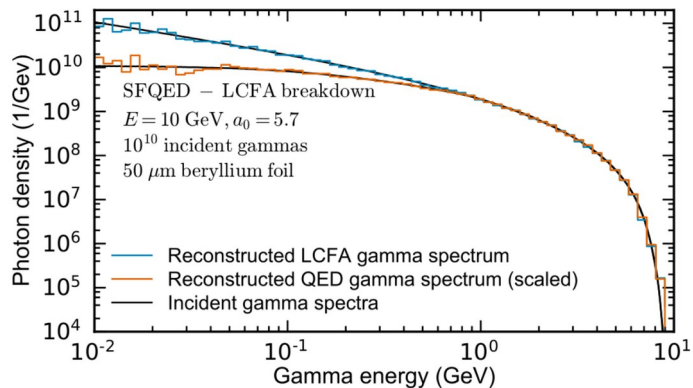
Goose trigger: get as close as possible to pseudo-randomness



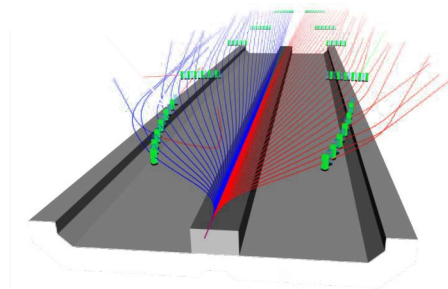
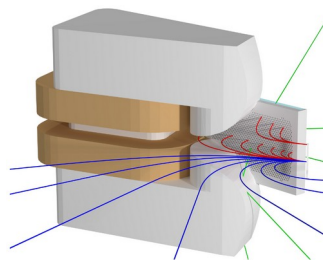
Systematic difference between goosed / non-goosed shots

Gamma-ray spectrometer (UCLA)

Measure photon formation length

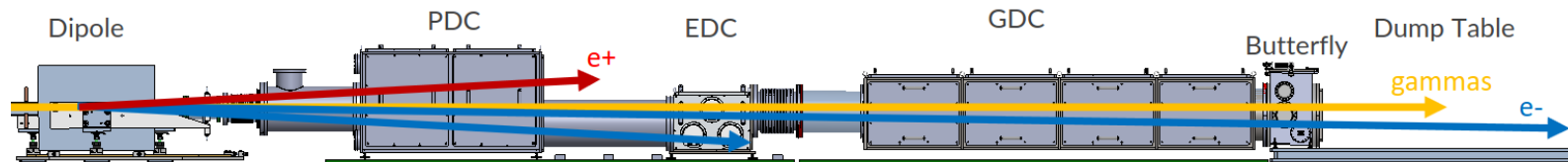


UCLA group



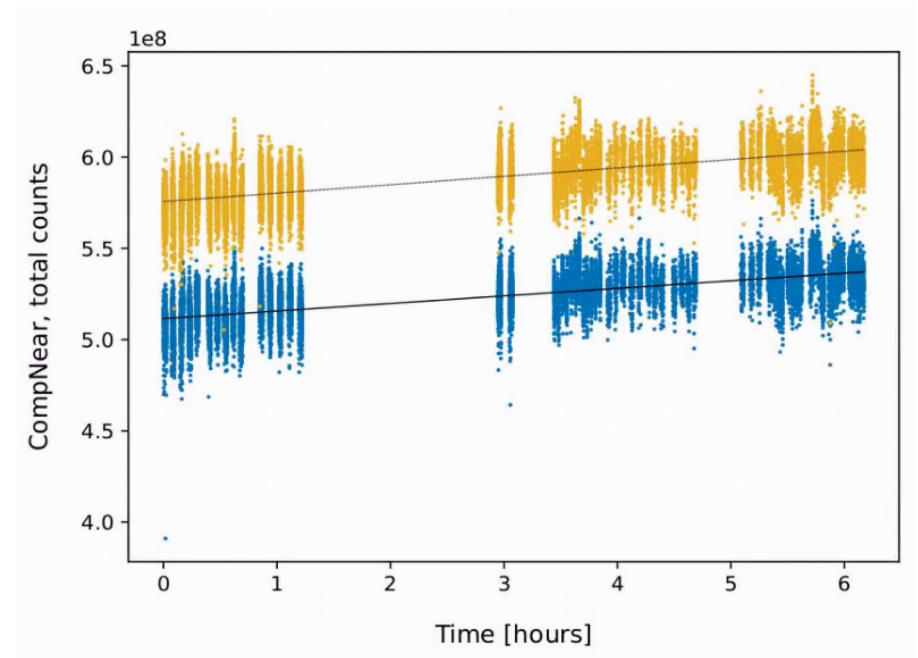
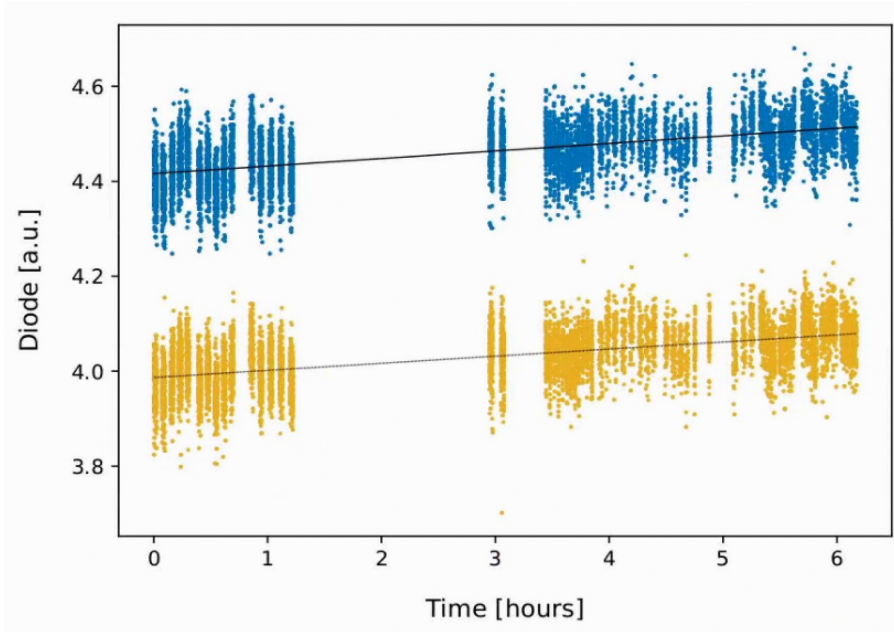
Compton (MeV) + gamma pair spectrometer (GeV)

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



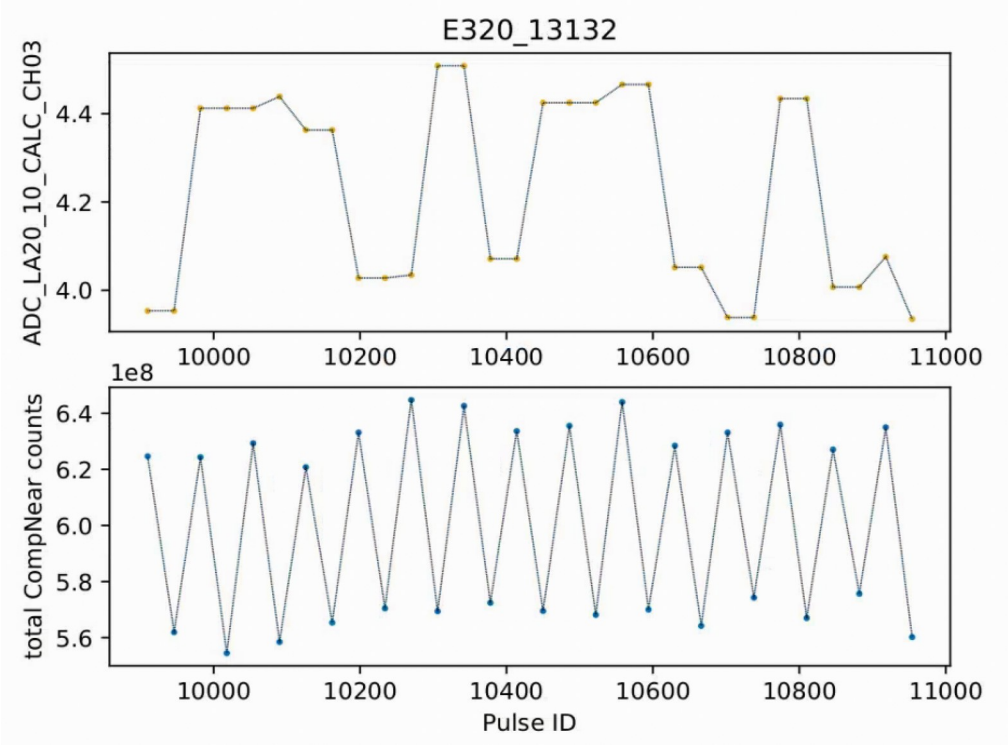
High priority: LCFA breakdown (nature-scale publication)

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