E-320 FY22 Progress and Plans for FY23

FACET-II PAC Meeting, 25-27 October 2022

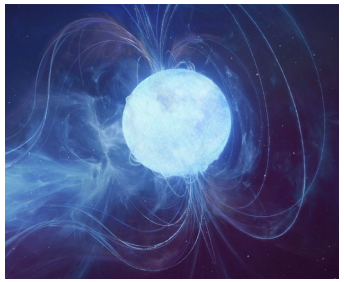
Sebastian Meuren (for the E-320 collaboration)

October 26, 2022

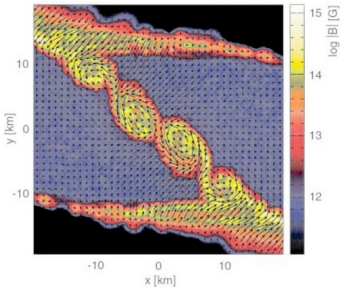
SLAC NATIONAL ACCELERATOR LABORATORY
Stanford PULSE Institute
Stanford University
U.S. DEPARTMENT OF ENERGY

Why do we care about reaching the QED critical field?

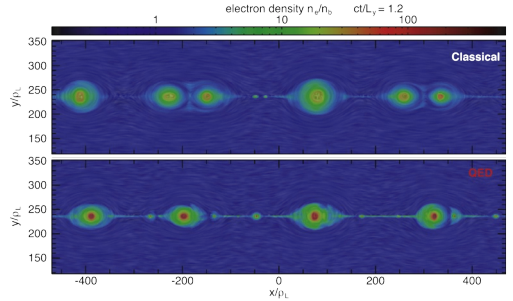
Extreme astrophysics: magnetars, FRBs
magnetic reconnection, neutron-star mergers



Bochenek et al.,
Nature 587, 59 (2020)



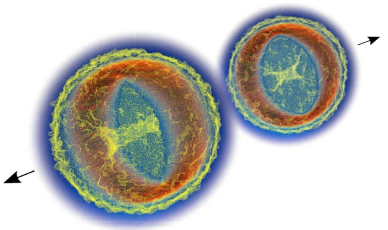
Price & Rosswog
Science 312 (2006)



Schoeffle et al., ApJ 870 (2019)

Fundamental questions in quantum field theory
Chiral Symmetry Breaking in QED induced
by an External Magnetic Field
Sinclair & Kogut, arXiv 2210.10863 (2022)

Beam-beam collisions: linear collider (CLIC, ILC);
probing the fully nonperturbative regime of QED



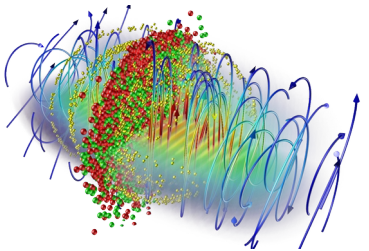
Shiltsev & Zimmermann,
RMP 93, 015006 (2021)

Yakimenko et al.,
PRL 122, 190404 (2019)

Esberg et al.,
PRSTAB 17, 051003 (2014)

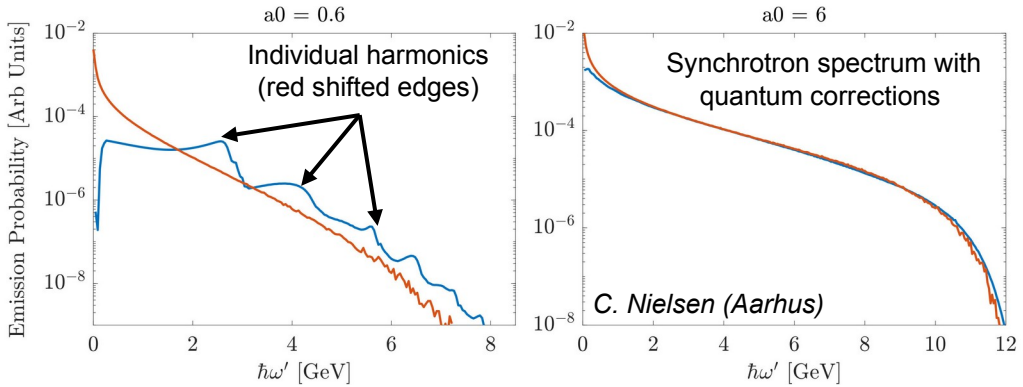
QED plasmas: beam-driven QED cascades
or seeded laser-laser collisions ($\gtrsim 10^{24}$ W/cm^2)

Qu et al., PRL 127 (2021)
Grismayer et al., PoP 23 (2016)
Bell & Kirk, PRL 101 (2008)

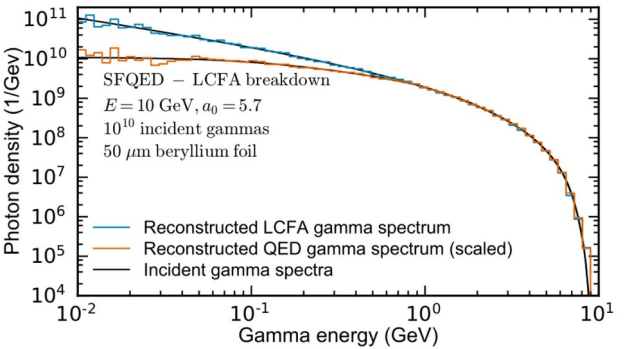


E-320: major near-term science goals

2023: Transition from perturbative to non-perturbative regime

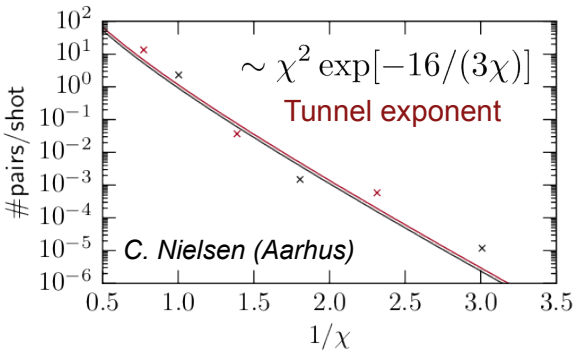


2024: measure formation length



UCLA group: Naranjo et al., THPAB270, JACoW, IPAC (2021)

2024: QED vacuum breakdown (tunneling pair production)



- Electron measurements require detector upgrades
- Pair production requires more laser intensity and a cleaner electron beam (less background)
- Local constant field approximation (LCFA) breakdown and detailed investigations of radiation reaction require the installation of the UCLA pair spectrometer

Experimental timeline

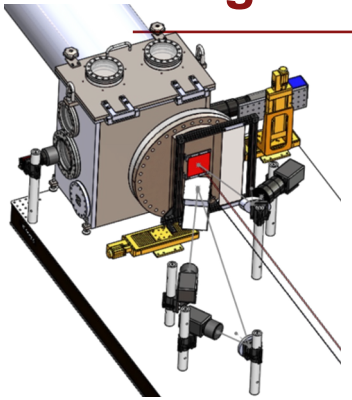
Short & mid-term goals:

Increase laser intensity	Improve electron detectors	Improve positron detectors	Install pair spectrometer (gamma photons)
reach $a_0 \gtrsim 5$, eventually $a_0 \gtrsim 10$	better optical readout direct detection (ePix)	silicon tracker (ePix) radiation-hard calorimeter	design is 90% ready, carried out by UCLA
2023/06	**2023/06**	**2023/12**	**2024/12**

Long-term goals:

- Propose a 100-500 TW laser upgrade for FACET-II (conceptual/technical design report)
- Introduce a 2nd IP for multi-GeV gamma production: light-by-light scattering experiments
- Install polarization-sensitive detectors: vacuum birefringence, radiative spin polarization
- Observe signatures of high-energy electron-positron recollisions

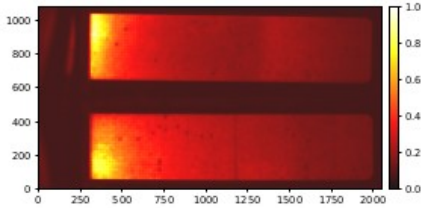
Diagnostics and Observables



Nonlinear Compton scattering
detection of 5-10 GeV electrons
using dump-table diagnostics

- Currently: DRZ + LFOV camera
- Increase light collection: new imaging system, high-QE camera + x/y-mover
- Use silicon-pixel detector (ePix)

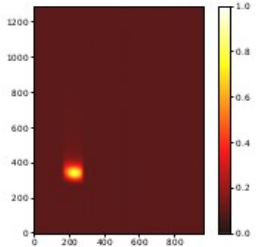
Vacuum breakdown
detection of (single)
multi-GeV positrons



Data: Aug 11, 2022 (234916)

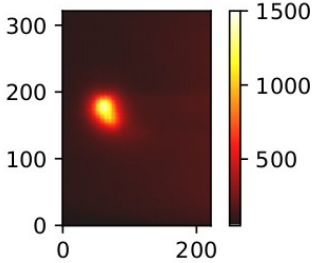
- Single-particle tracking (scintillator/SSD) + multi-channel calorimeter (readout: PMTs)
- Currently positron background is too high

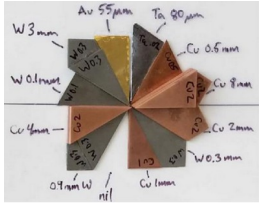
Quantum radiation reaction
low-energy electrons ($\lesssim 1$ GeV)



- Detection: EDC diagnostics
- Need to improve SNR
  Data: Aug 14, 2021 (024716)

Total gamma yield
(and angular distribution)

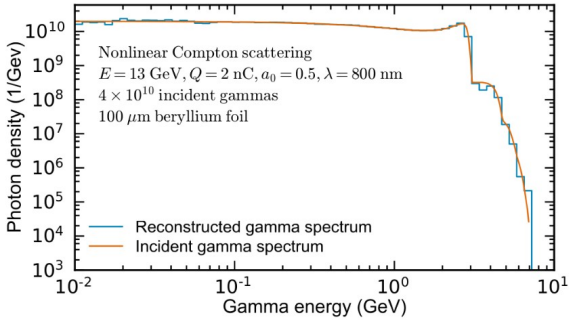




see talk by D. Storey

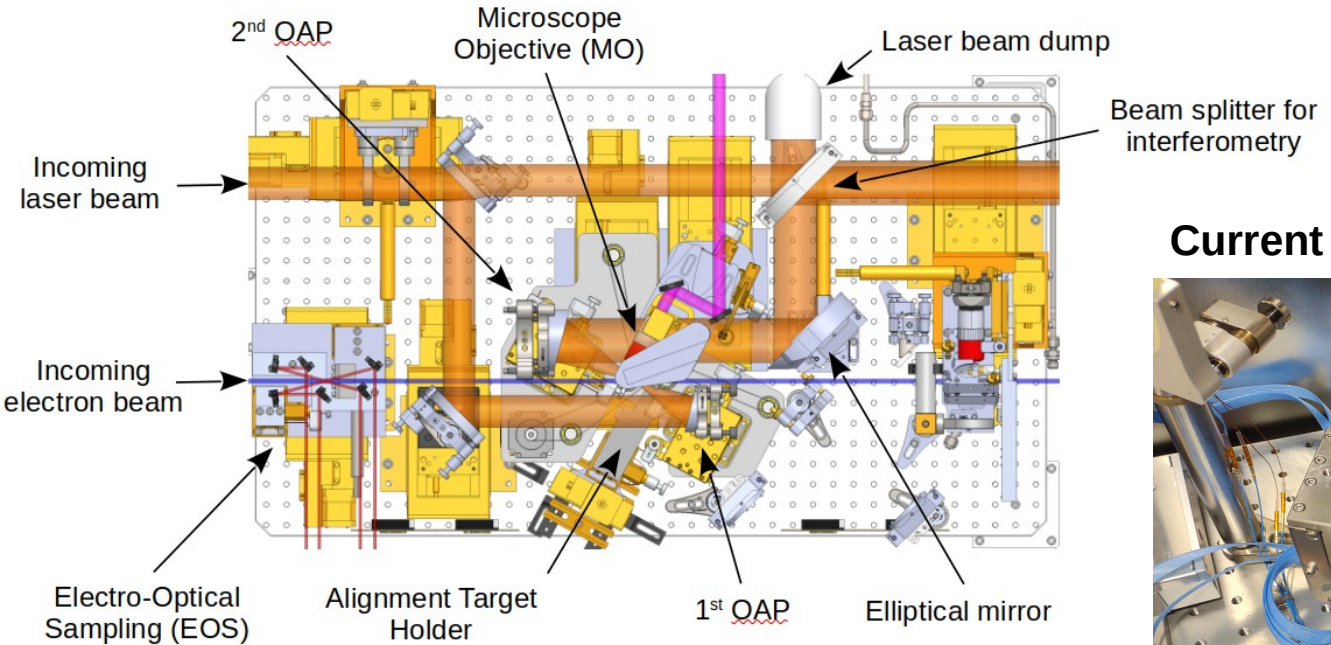
- Important for consistency checks
- Probably facilitates a_0 measurements
  Data: Aug 14, 2022 (dataset 2665)

Gamma energy distribution
requires pair spectrometer



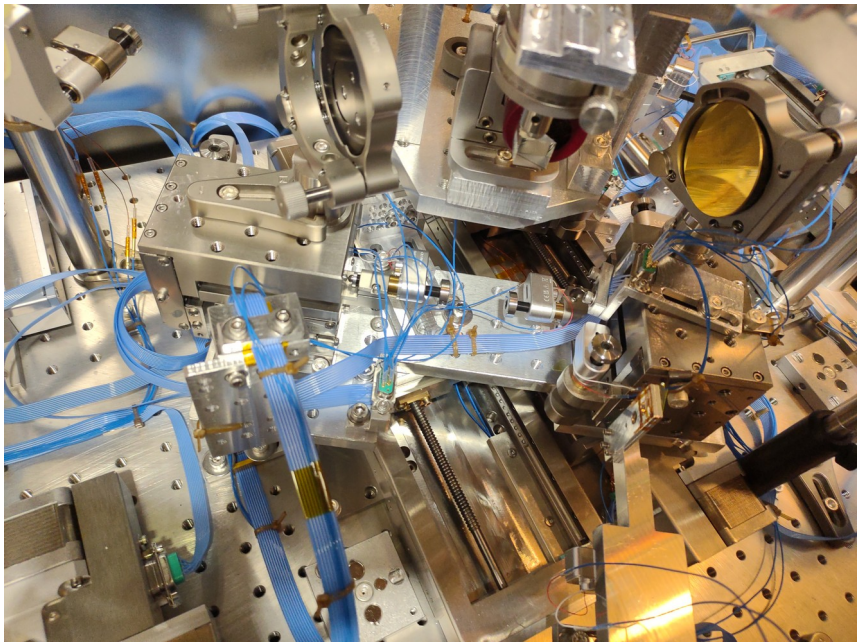
Naranjo et al., THPAB270, JACoW, IPAC (2021)

Progress: E-320 IP installation in the FACET-II picnic basket



see talk by R. Ariniello

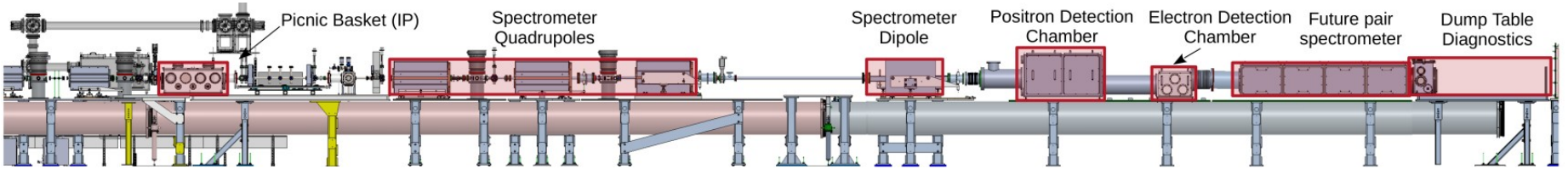
Current E-320 setup



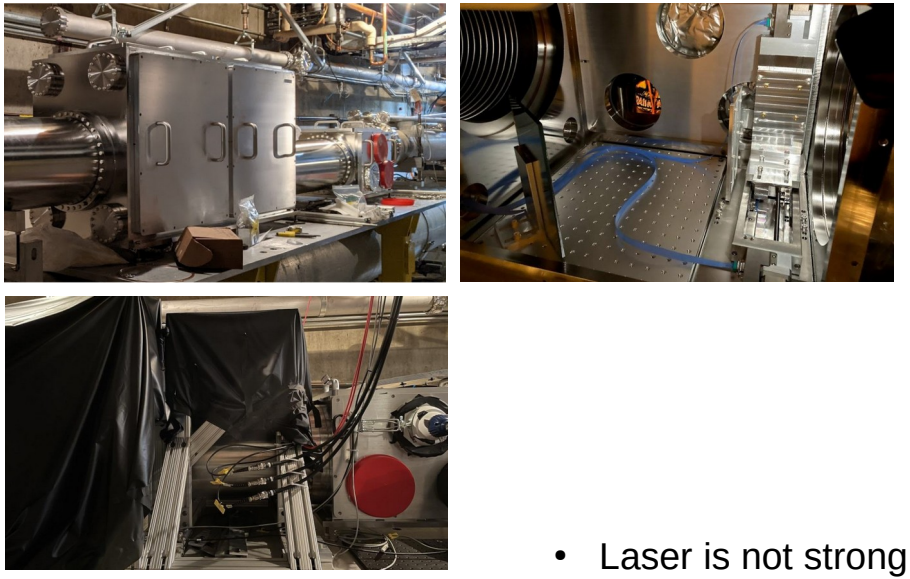
Setup fully functional, improvements envisioned

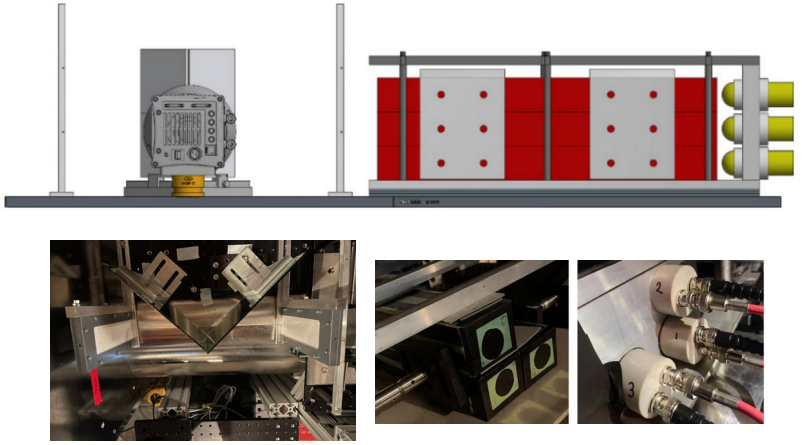
- Common baseplate needs further engineering & tests
- Dielectric OAPs require a safe environment
- Interferometer hasn't been used for alignment yet

Progress: PDC/EDC and positron diagnostics



Modifications to the FACET-II spectrometer beamline (see talk by D. Storey)



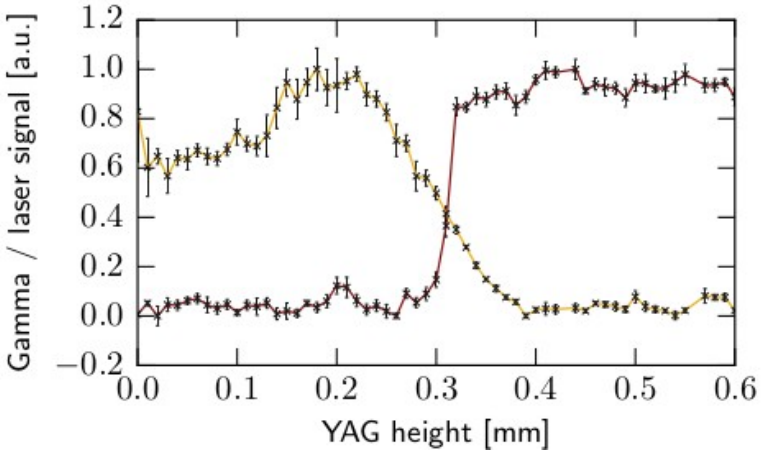


Salgado et al. NJP 24, 015002 (2021)

- Laser is not strong enough to create pairs or very low-energy electrons
- Electron beam has improved, but still large backgrounds of positrons

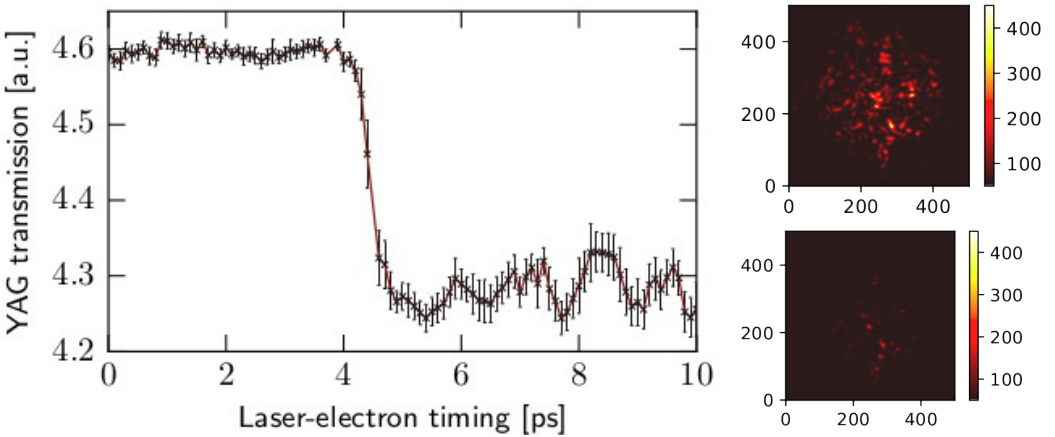
Progress: electron-beam – laser spatial & temporal overlap

Knife-edge scan: spatial overlap



E-320 run on August 19, 2022 (dataset 2918)

YAG timing tool: temporal overlap



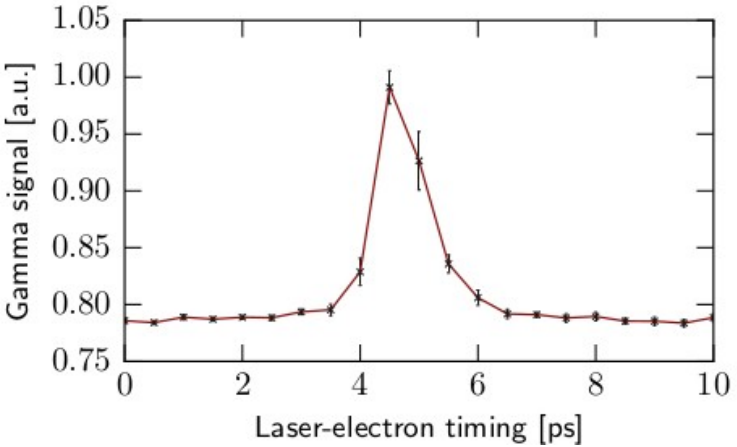
E-320 run on August 19, 2022 (dataset 2925)
Inspired by LCLS timing tool: *Sato et al., J. Syn. Rad. 26, 647 (2019)*

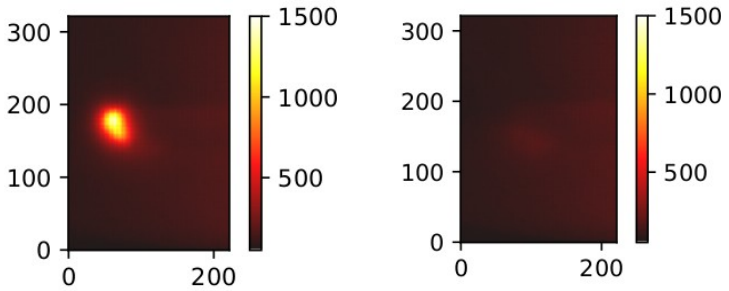
- Alignment target: 50 µm thick Ce:YAG screen, one side transparent, other side frosted (rough surface)
- A large laser spot is used (incoming laser has small diameter + YAG is placed behind/before focus)
- Frosted YAG surface is imaged with microscope objective (laser intensity must be below damaging threshold)

Spatial overlap (left): YAG is driven into the interaction point – laser attenuates, gamma signal increases
Temporal overlap (right): E-beam induces free carriers in YAG, attenuates laser if e-beam arrives early

Progress: first electron-laser collisions

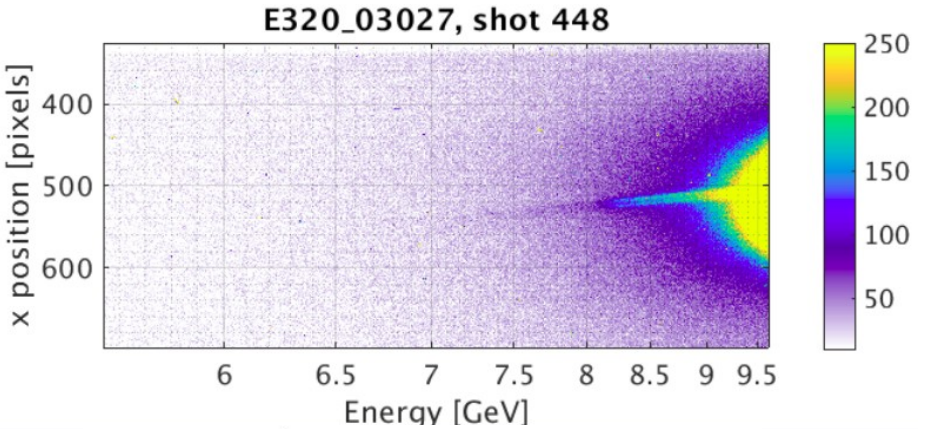
Electron-laser collisions: gamma signal

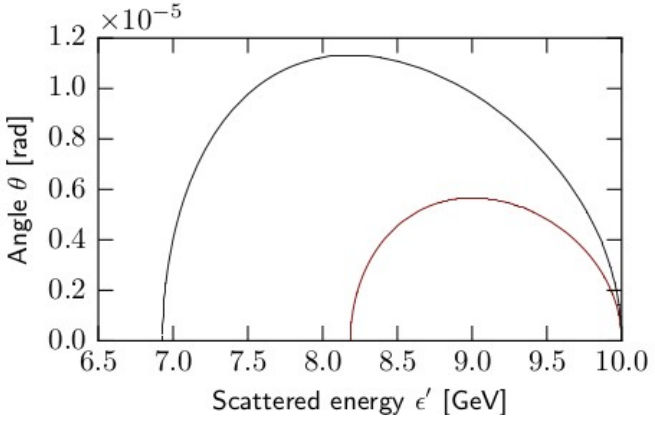




E-320 run on August 14, 2022 (dataset 2665)

Scattered electrons – 1st and 2nd harmonic

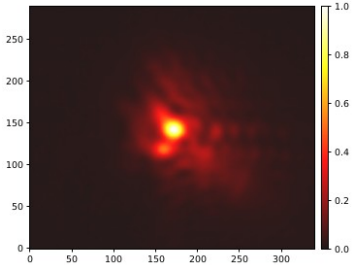




Tasks for 2023 (*aka future evolution of the experiment*)

Improve laser intensity and spot quality

MPA output	0.8 J
Transport efficiency	0.88 %
Probe splitter	0.8 %
Compressor	0.7 %
Compressor window	0.96 %
Energy in PB	**0.38 J**
Pulse duration	**60 fs**
Gold OAP Strehl	**0.3**
Spot size (FWHM)	**2 µm**



Currently possible:

I ≈ 4x10^{19} W/cm^2
a_0 ≈ 4.2

$$I_f \approx 0.8\frac{\mathcal{E}_L}{\mathrm{FWHM}^2\tau_0} \quad a_0 \approx 0.60\,\mu\mathrm{m}^{-1}\lambda\sqrt{2I_0/(10^{18}\,\mathrm{Wcm}^{-2})}$$

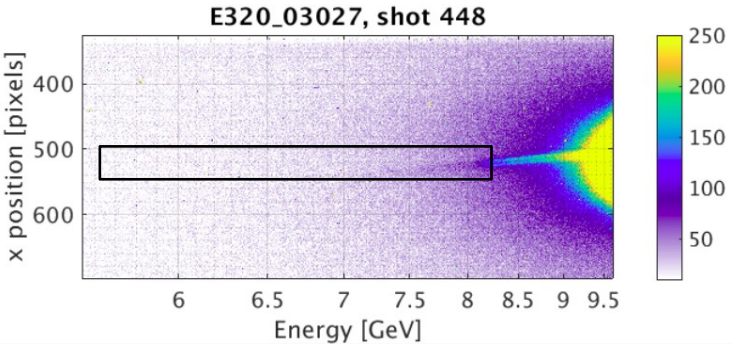
see talk by Brendan O'Shea; data: Aug 19, 2022 (223418)

Reaching the quantum regime (χ=1)

$$\chi \approx 0.057\,\mathrm{GeV}^{-1}\epsilon\sqrt{2I_0/(10^{20}\,\mathrm{Wcm}^{-2})}$$

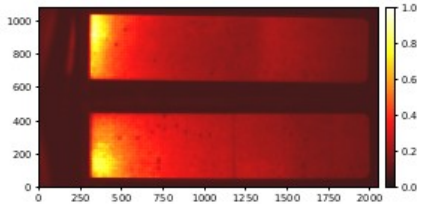
- Need: a_0 ≈ 8.5 (10 GeV) or a_0 ≈ 6.5 (13 GeV)
- Currently possible: χ ≈ 0.5 (10 GeV + a_0 ≈ 4.2)

Improve detector signal-to-noise ratio



- Current SNR of dump-table e$^-$-detectors is not sufficient
- Detector upgrades crucial for the E-320 science program

Establish high-quality beam mode



Parameter (units)	Value
Final beam energy E_f (GeV)	13.0
Bunch charge Q_b (nC)	2.0
rms bunch length σ_z (mm)	0.1
β^* (m)	10
Final rms energy spread, dE/E (%)	0.05

- Cleaner beam transmission crucial for positron detection
- Find optimum between compression, energy, & tails

see talks by J. Yocky & G. White

Desired facility upgrades

Solid-state detectors (ePix)

https://lcls.slac.stanford.edu/detectors/ePix10k

- Direct e^-/e^+ detection (100 µm pixel)
- Prototype ready for installation in the tunnel (Holtzapple & Callman, Kenney & Blaj)

High QE, low noise cameras

https://www.hamamatsu.com/

- Install ORCA-Fusion CMOS camera
- Requires new EPICS driver
- Prevent early death by radiation

Modify EOS delay line

see talk by C. Doss

- EOS and E-320 cannot be viewed simultaneously (delay too small)
- Needed for shot-to-shot timing

Deploy radiation-hard calorimeter

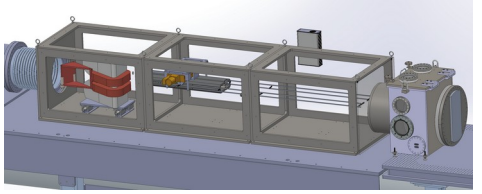
- Current radiator: lead glass, degrading
- Use different material, e.g., lead fluoride

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

Upgrades for the FACET-II laser

- Improve transport efficiency
- Remove hot spots, send more energy
- Prevent grating degradation
- Reduce pulse duration
- Implement ability for laser on/off shots
- EPICS interface for deformable mirror: facilitates machine-learning algorithms to improve spot quality

Pair spectrometer (UCLA)



- Will facilitate the measurement of MeV-GeV gamma-photon spectra
- *Naranjo et al., THPAB270, JACoW, IPAC (2021)*

Thank you for your attention

To be continued...

The E-320 collaboration

Additional support: Juan Cruz, Joe Frisch, Shambhu Ghimire, Carl Hudspeth, Cindy Patty, Nadya Smith, Takahiro Sato, the PULSE Team (in particular Ritu Khurana and Sheetal Singhal), and many more

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, Aimé Matheron
Technical University (TU) of Darmstadt	Christian Rödel
University of Hamburg	Tais Gorkhover, Stephan Kuschel
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,** Maison Singleton, Liam Frank, Jack Kloeckl, Adam Callman, Ben Knudson, Max Varerakis, and Sebastian Turkewitz
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, Doug McCormick, **Sebastian Meuren (PI)**, **Rafi Mir-Ali Hessami**, Brendan O'Shea, **David Reis**, **Tania Smorodnikova**, **Douglas Storey**, Glen White, **Vitaly Yakimenko**
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