Update on the progress of the E-320 SFQED experiment

A. Knetsch on behalf of the E-320 Collaboration

SLAC National Accelerator Laboratory

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Stanford University | U.S. DEPARTMENT OF ENERGY

The collaboration

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Technical University (TU) of Darmstadt	Stephan Kuschel, Christian Rödel
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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

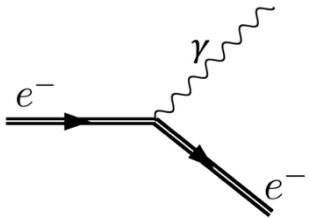
Strong-field QED: The physics we study

Dirac equation in the vicinity of a EM field

$$(i\hbar\gamma^{\mu}\partial_{\mu} - e\gamma^{\mu}A_{\mu}^{\mathrm{ext}} - mc)\psi = 0$$

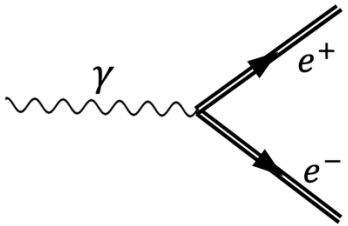
Non-linear inverse Compton scattering :

$$e^- + n\omega \rightarrow e^- + \gamma$$



Non linear Breit-Wheeler pair creation :

$$\gamma + n\omega \rightarrow e^- + e^+$$



Critical field of QED $E_s = \dfrac{m^2c^3}{e\hbar} \sim 1.32 \times 10^{18}\,\dfrac{V}{m}$ $\chi = \gamma\dfrac{E}{E_s}$ $\chi > 1$ marks onset of QED effects

Laser-beam collisions $a_0 = \dfrac{e\,E}{m\,\omega}$ $a_0 > 1$ marks onset of strong-field effects

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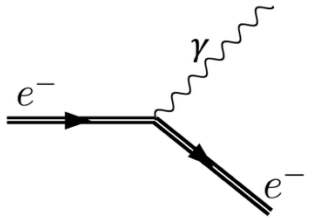
Strong-field QED: The questions we are addressing

Non-linear inverse Compton scattering :

$$e^- + n\omega \rightarrow e^- + \gamma$$

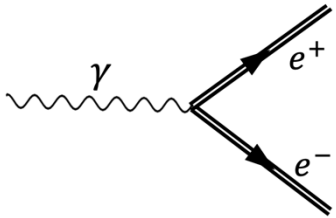


We investigate:

- Relativistic red shift of electron mass
- Quantum radiation reaction

Non linear Breit-Wheeler pair creation :

$$\gamma + n\omega \rightarrow e^- + e^+$$

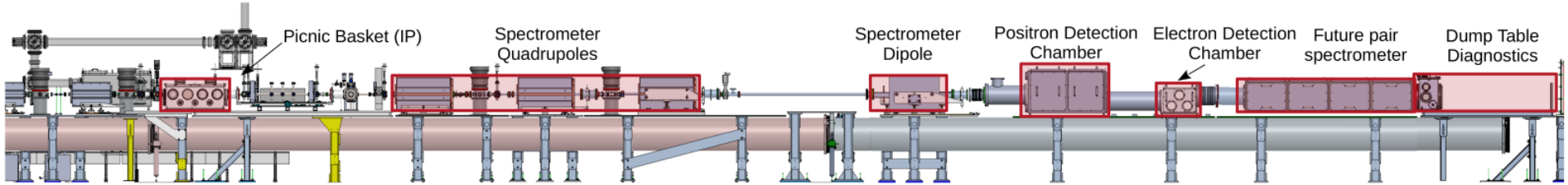


We investigate:

- Pair production from NLBW
- Tunneling regime of pair creation

How do we measure: The electron beam

FACET-II Facility for Advanced Accelerator Experimental Tests



FACET-II electron beam parameters

- Up to 2 nC bunch charge
- 10 GeV beam energy
- Energy spread 0.1 %
- Bunch length (rms) < 100 µm

IP capabilities

- Final Focusing to typically ~ 20 µm rms
- Control over waist location
- Quadrupole triplet for electrons or positron imaging
- Diagnostics for main-beam, scattered electrons, positrons, and Gamma rays
- Gamma ray spectrometer under development

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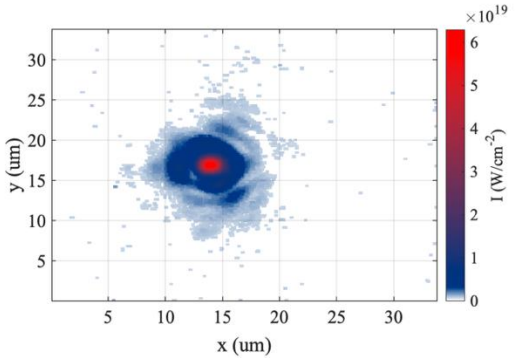
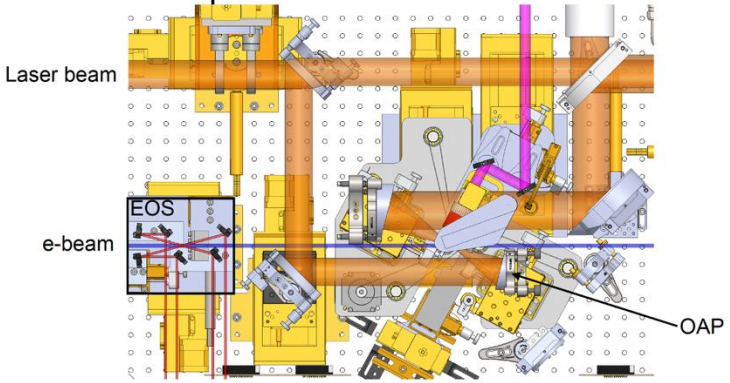
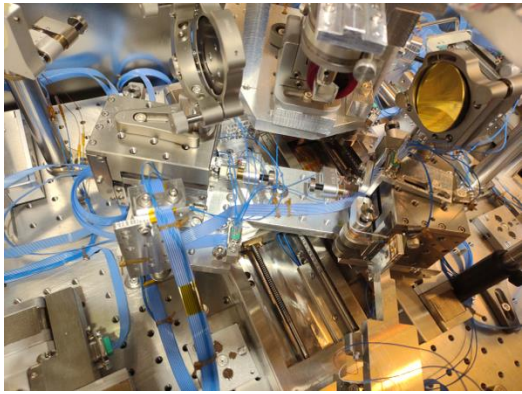
How do we measure: The laser pulse

Intensity distribution in focus

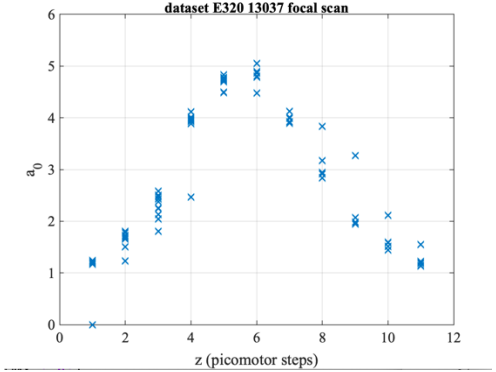


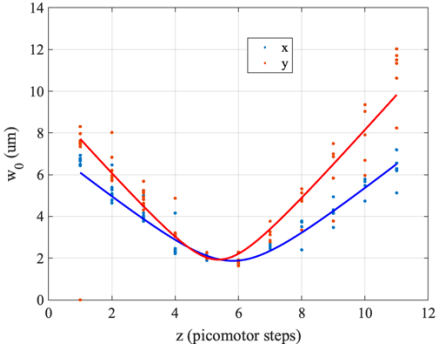
Setup to-view





Longitudinal max. a0 distribution





FACET-II laser parameters

- ~ 300 mJ on target
- 48 fs pulse length FWHM
- $w_{0,min}$ = 1.87 x 1.92 um
- Collision angle 28.1 deg
- $a_0 \leqq 5$
- $\chi \sim 0.3$

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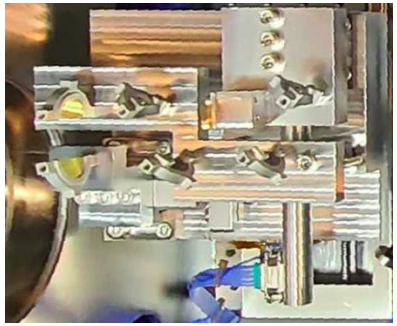
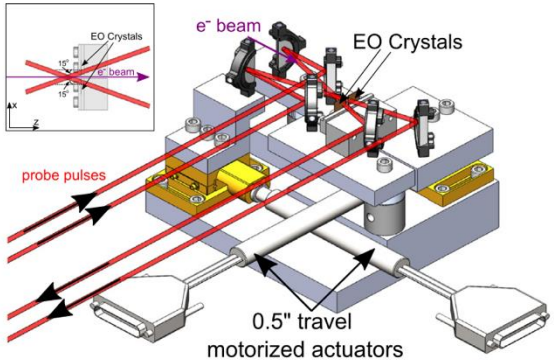
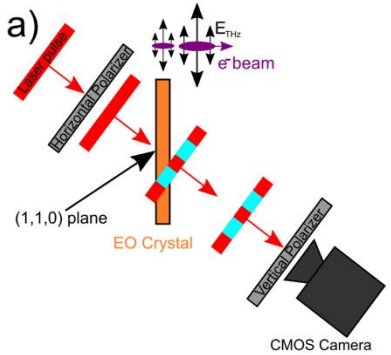
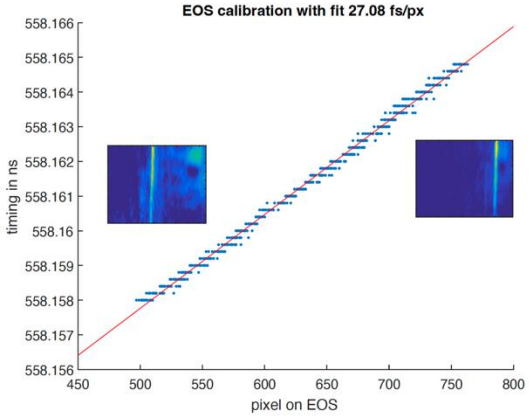
How do we measure: shot-to-shot time-stamping via EOS (UC Boulder)





EOS installed in the picnic basket





- electro-optical sampling (EOS) measures relative time-of-arrival between laser and e-beam
- Shot-to-shot non-invasive time-stamping
- Dial in collisions with EOS signal
- Typical calibration values 20 fs/px , resolution limit smaller

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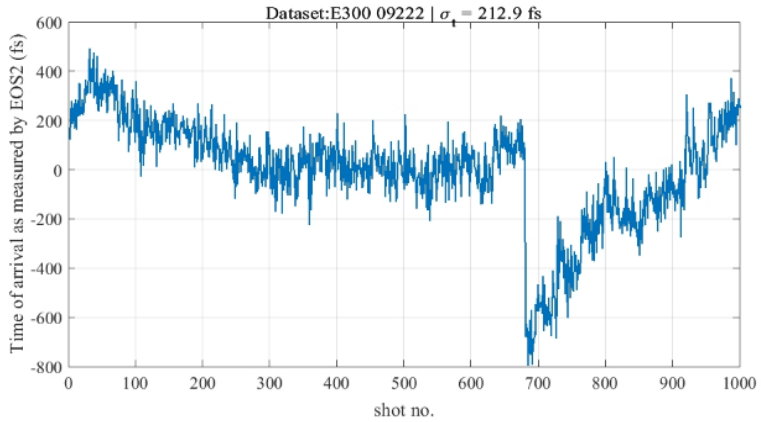
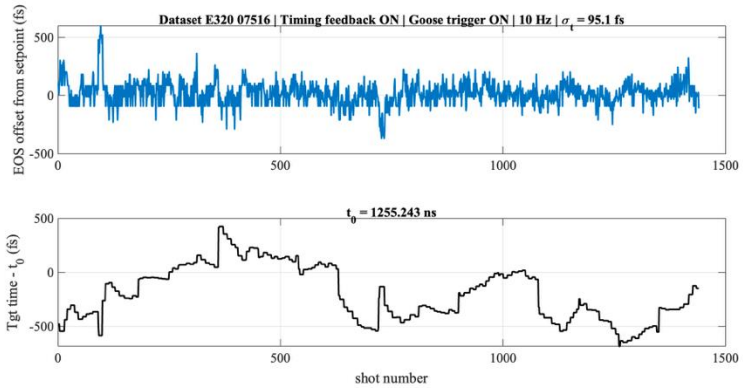
Hunt-Stone et al., NIMPRA 999, 165210 (2021)

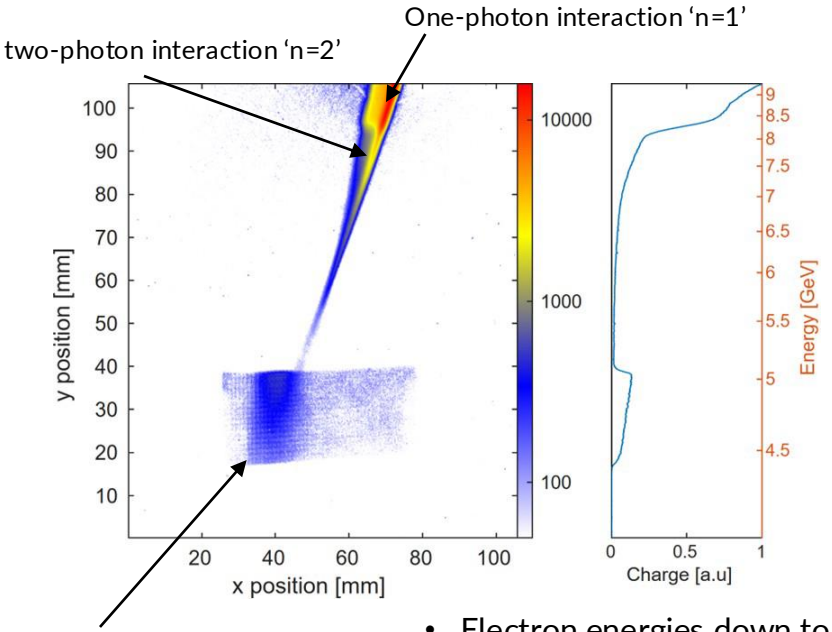
How do we control the experiment: Relative time-of-arrival stabilization

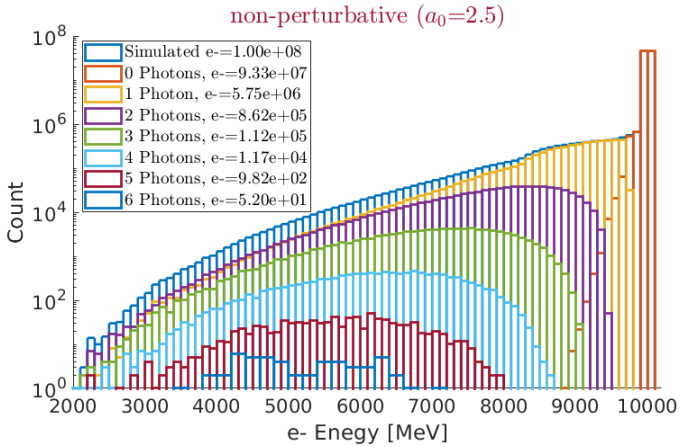




- Time-of-arrival jitter as low as 50 fs measured
- Time-of-arrival drift can vary up to ~1 ps
- **Drift compensation:** PID loop between EOS-measured TOA and laser target time

What do we measure: Measurement of scattered electrons

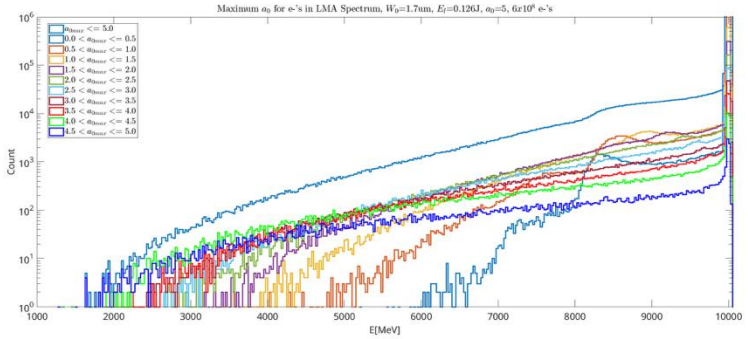


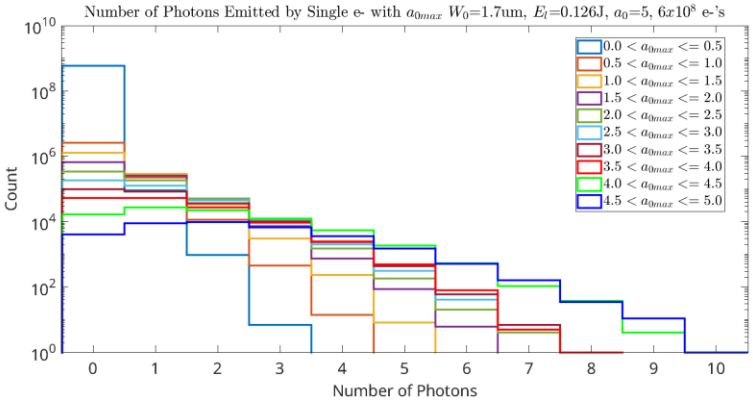


- Electron energies down to ~ 4 GeV measured,
- exponential spectrum indicator of non-perturbative interaction
- Regular background shots with laser timing offset (so called ‘goosed shots’)

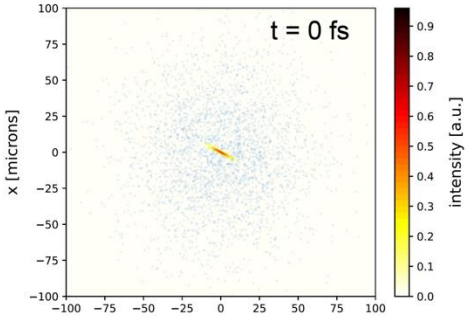
Analysis by S. Rego, Simulation by R. Holtzapple

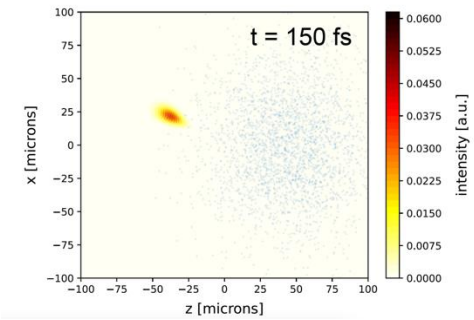
What do we measure: Focal averaging



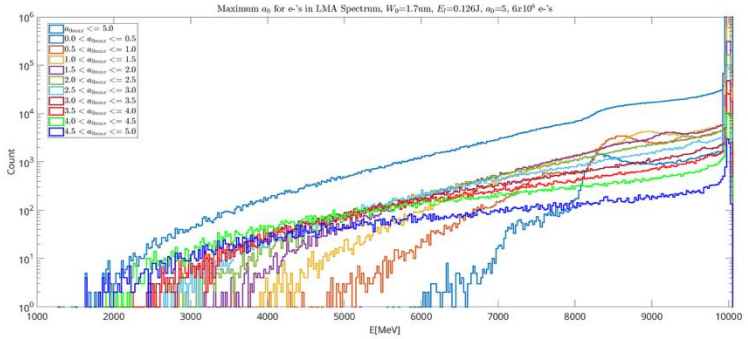


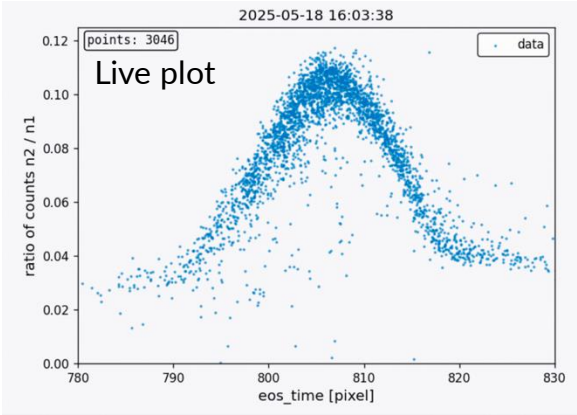
- Electrons interact with a distribution of a0 that is dependent of z,r and t
- Higher-energy scattered electrons can originate from different a0 interactions
- Low-energy scattered electrons are from high-a0 interaction



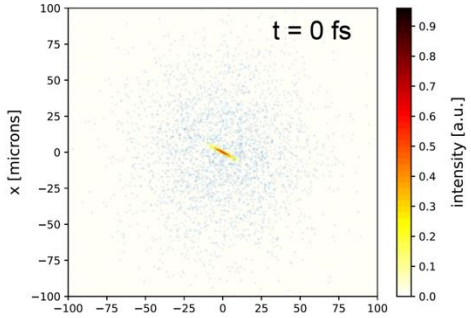


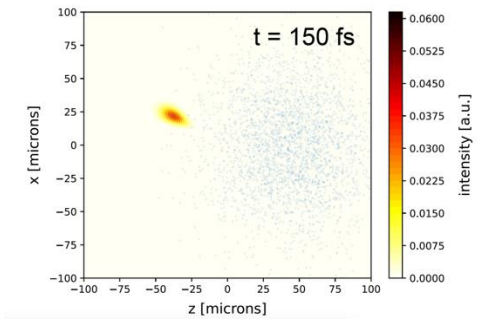
What do we measure: Focal averaging



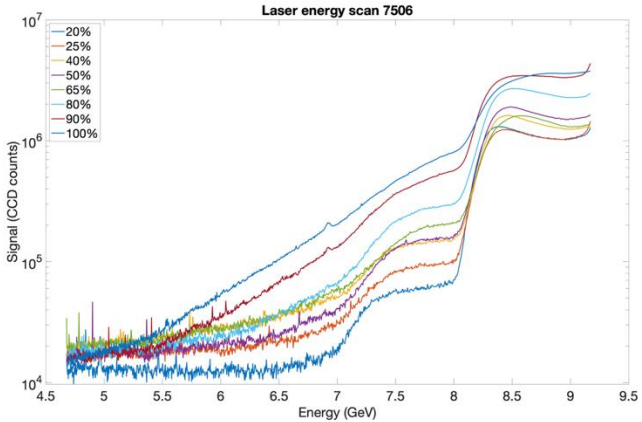


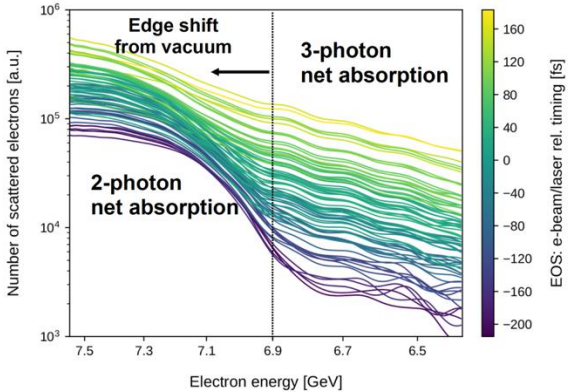
- Electrons interact with a distribution of a0 that is dependent of z,r and t
- Higher-energy scattered electrons can originate from different a0 interactions
- Low-energy scattered electrons are from high-a0 interaction
- Timing stabilization by evaluating Q(n=2) / Q (n=1)

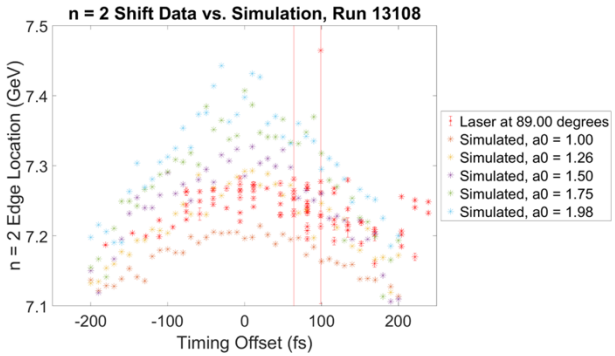




What do we measure: Relativistic red-shift of electron mass



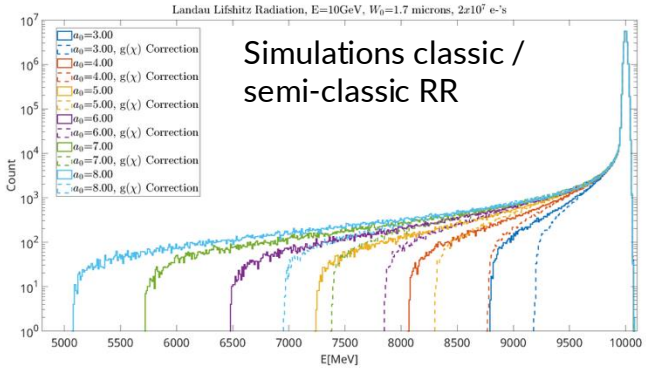


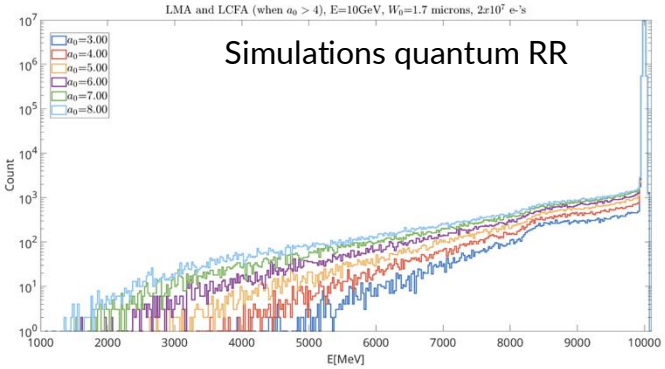


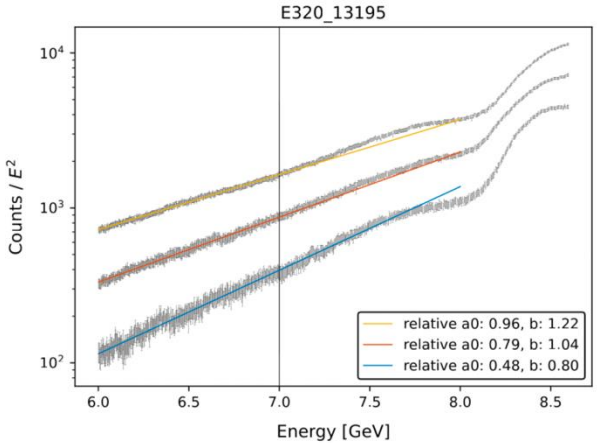
- Electron mass relativistically increased in laser field to $m^* = m\sqrt{1 + a_0^2/2}$
- Increased electron mass shifts Compton-edge to higher energies
- Data regime highly influenced by focal averaging and requires precise simulations of beam and laser geometry

Simulation plots by R. Holtzapple, analysis plots by T. Smorodnikova, and R. Mir-Ali Hessami and J Wang

What do we measure: Classical versus quantum radiation reaction



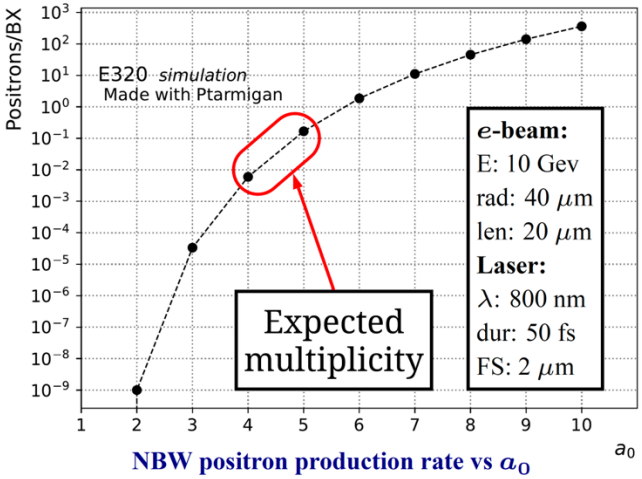




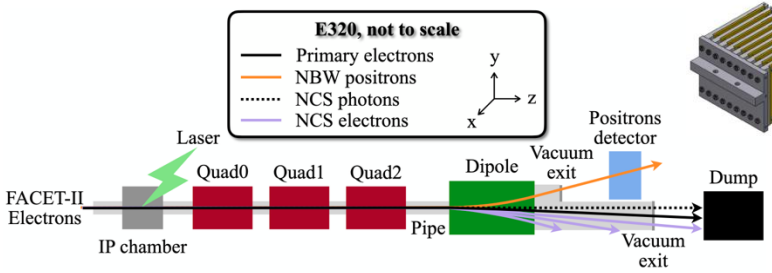
- Lower energies of scattered electrons much less effected by focal averaging
- → Pure high-a0 measurement
- Allows for precise distinction of RR regimes
- Experimental data favors quantum radiation reaction (analysis ongoing)

Simulation plots by R. Holtzapple, analysis by T. Smorodnikova

What do we measure: Nonlinear Breit-Wheeler pair creation



- 10^{-2} – 10^{-1} positrons expected per bunch
- 10^{4} – 10^{5} positrons for 8 h of continuous measurement
- Challenge: Identify NBW positrons from classical BW positron noise
- **Detector requirements:**
  - High spatial resolution
  - High efficiency
  - Insensitive to neutral particles
  - Radiation hard



5 ALPIDE tracker cards

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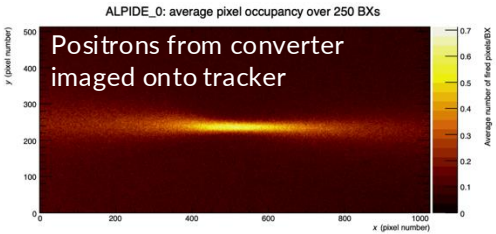
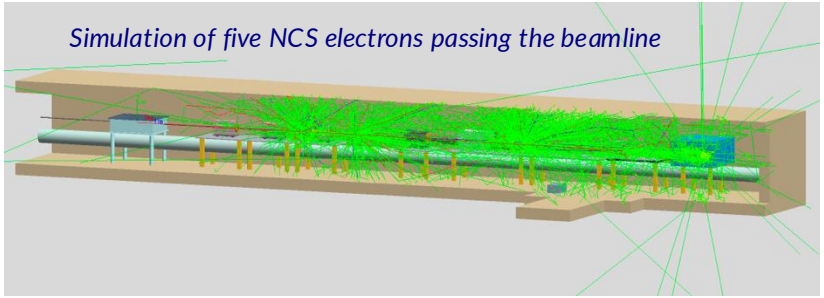
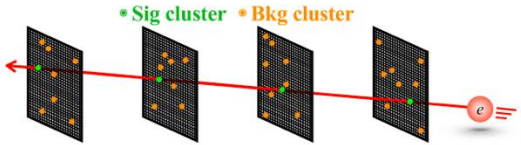
Borysov, Oleksandr, et al. *arXiv preprint arXiv:2506.04992* (2025).

What do we measure: Nonlinear Breit-Wheeler pair creation



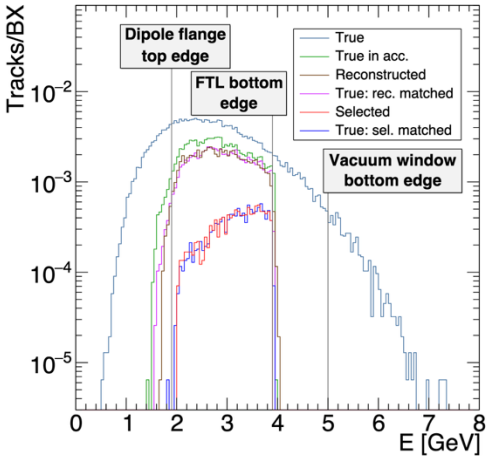


Track selection



Exclusion Algorithms

Spectrum reconstruction



- Challenge: Identify NBW positrons from background
- Quadrupole system can image onto tracker in different imaging modes
- Combination of long-term stability (a lot of data) and clever track detection algorithms

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Borysov, Oleksandr, et al. *arXiv preprint arXiv:2506.04992* (2025).

Summary

- E-320 performs precision strong-field QED studies in the transition regime from the perturbative to non-perturbative regime (a_0<1 – a_0 >>1)
- High stability and well-understood electron and laser parameters allows for long-term high-quality data acquisition
- Studies of radiation reaction theories
- Measurement of relativistic red-shift in dressed electron mass
- Investigation of positrons from Nonlinear Breit-Wheeler

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Thank you for your attention

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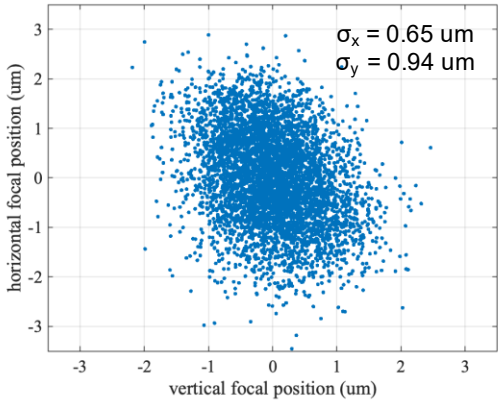
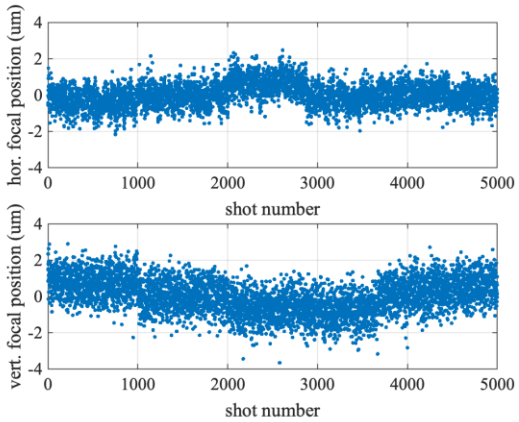
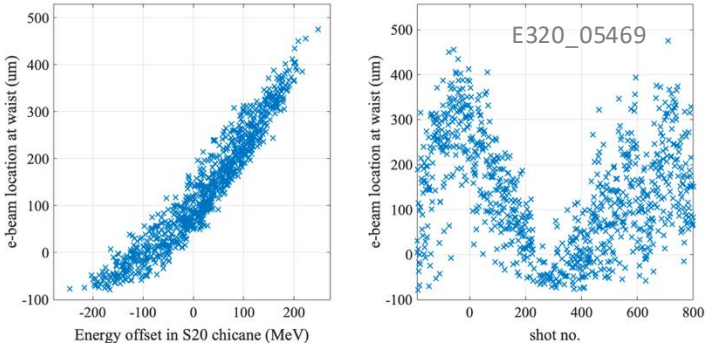
Laser focal stability



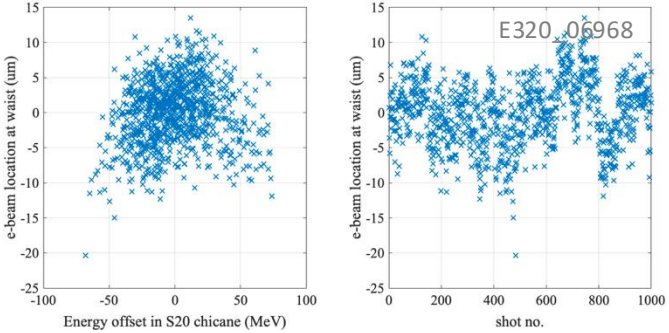


Beam waist stability

Dominated by drift and dispersion



Dominated by jitter only



- Sub-um position jitter for laser focus achievable
- Few-um position jitter for e-beam achievable