E-305 and E-332: from beam filamentation, bright gamma rays to strong-field QED

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E305 & 332 motivations and concepts
Relativistic streaming instabilities are pervasive in astrophysics

Current filamentation instability and oblique instabilities are believed to:
- mediate slow down of energetic flows (e.g. in GRBs and blazars)
- mediate shock formation and cosmic-ray acceleration
- determine radiation signatures of energetic environments
- in solids, it has implications for ultrafast condensed matter physics
- in addition to its fundamental importance for astrophysics, it provides a mechanism for energy conversion from particles to EM fields, and to gamma-ray radiation: measurements of gamma rays provide a signature of beam-plasma instabilities
- gamma-ray source with applications to defence, industry, medicine, scientific research

\[ \gamma \sim 10^1 - 10^6 \]

Motivations for solid-density $e^-/\gamma$ beams and laserless SFQED

Dense gamma-ray beams open new opportunities for materials science, nuclear photonics, photo-fission, quark-gluon plasma, investigation of nuclear excited states, laboratory astrophysics, probing the quantum vacuum and photon-photon physics ($\gamma + \gamma \rightarrow \gamma + \gamma$, $\gamma + \gamma \rightarrow e^- + e^+$, $\gamma + \gamma \rightarrow X + \bar{X}$)

Solid-density electron beams open new opportunities in nonlinear material studies such as investigations of the relativistic plasma electron response at the surface and in the bulk, plasma channeling and generation of plasma wakefields in solid-density plasmas, probing SFQED without lasers in electron beam-solid-density plasma (quantum parameter $\chi = \gamma E/E_{cr} > 1$)

https://en.wikipedia.org/wiki/Quantum_fluctuation

CALDER 3D PIC simulation (Aimé Matheron)

$e^-$ beam-gold foil collision with $n_b = 0.7n_p$

A. Matheron et al., Communications Physics 6, 141 (2023)
E332 concept: near-field CTR

Smilei 3D PIC simulation, 2 nC beam, Gaussian spatial and momentum distribution with $\sigma_\parallel = \sigma_\perp = 0.55 \, \mu m$, 10 GeV mean energy, 212 MeV FWHM energy spread, 3 mm-mrad normalized emittance.

The beam collides with 20 consecutive aluminum foils with 0.5 $\mu m$ thickness, and 10 $\mu m$ interfoil distance.

Physics included in the simulation: initial self-consistent beam fields, field and collisional ionization, binary Coulomb collisions, synchrotron and bremsstrahlung emission, multiphoton Breit-Wheeler and Bethe-Heitler pair production.

E305 & 332 progress
E305 progress

- Commissioning of gas jet operation with He and H₂ and of PB pumping:
  - Numerous tests performed to evaluate the residual background pressure for different gas jet opening time, repetition rate, backing pressure and type of gas
  - Successfully operated gas jet at 5 Hz for backing pressure up to 200 psi
  - At high backing pressure of up to 1200 psi, gas jet operation limited to 1 Hz (with beam at 10 Hz); required DAQ development and tests
  - 5-mm round nozzle and 2-cm slit nozzle tested successfully

- Laser ionization:
  - Specific focusing optics for E305: diffractive axilens with 1-cm line focus for monochromatic light, stretched to 3-4 cm line focus by chromatic focusing with the real FACET-II laser
  - Successfully generated plasma in 5-mm nozzle, and in 2-cm slit nozzle up to 200 psi
  - Need to understand what’s limiting the plasma length at higher backing pressure

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</table>

- 5-mm nozzle, H₂ at 110 psi
- 2-cm nozzle, H₂ at 150 psi
- 2-cm nozzle, H₂ at 614 psi
E305 progress

- Electron and gamma diagnostics:
  - Instead of using a profile monitor downstream of IP for a measurement of the beam angular profile (compromised by coherent OTR light), we rely on DTOTR electron spectrometer at the dump table:
    - Large $M_{12}$ and $M_{34} = 0$ to measure horizontal momentum $p_x$
    - Gamma screens commissioned for E305
  - $M_{12} = M_{34} = 0$ for best energy measurement
  - GUI + DAQ functions
E305 progress

• Shadowgraphy:
  › Low resolution fully commissioned:
    - Conditions: H₂, 1010 psi and 1 Hz
    - Beam-ionized plasma trace
    - → residual background pressure in PB (~0.1 Torr)
    - → self-focused electron beam entering the gas jet
    - Conditions: H₂, 1010 psi and 5 Hz

  - First tests of high resolution, with microscope objective inserted and with laser ionization front identified:
    - Conditions: H₂, 500 psi
E305 progress

- Laser-ebeam overlap and beam-based characterisation of laser-produced plasma:
  - Timing: clear transition identified on most diags (shadowgraphy can be used for very high accuracy)
  - Approximate spatial overlap done on front view
  - More precise spatial overlap can be achieved from plasma traces on topview and shadow
  - Afterglow signal was found to be very powerful to quickly fine tune the laser-ebeam overlap
  - Laser raster scans give us a beam-based characterisation of laser-produced plasma:

![Graph](image)

- Sum of count on topview Afterglow signal
- Sum of count outside initial beam location on DTOTR2
E305 progress

First beam-plasma interactions in 2-cm H$_2$ gas jet:

- Expected from simulations: spanning regimes going from plasma lensing, PWFA, to beam filamentation when the pressure is increased from 1 to 1000 psi.
- Experimental observations: complex outcome that can be understood by a beam larger than the plasma along the horizontal axis, affecting only the central part of the beam.
E332 progress

- **May 11** ($\sigma_x = \sigma_y = \text{?}$ μm): Operating the machine at 1Hz, DAQ commissioning.
- **June 13** ($\sigma_x = \sigma_y = \text{?}$ μm): Measuring beam on DTOTR/GAMMA1 cameras with and without Al 0.1 mm.
- **July 18** ($\sigma_x = 46 \mu m$, $\sigma_y = 48 \mu m$): **First holes**
  - First evidence of holes being drilled in foils (holes completely drilled in 2 minutes with Al 0.1 mm).
  - Data of GAMMA1 signal decreasing with time while shooting at a fixed foil position
- **July 25** ($\sigma_x = 47 \mu m$, $\sigma_y = 33 \mu m$):
  - We were able to use the new Quad-Scan functions of the DAQ and take comprehensive data.
  - Quad-scans of M12 performed and very clear data has been taken.
- **August 1** ($\sigma_x = 49 \mu m$, $\sigma_y = 39 \mu m$): **Compression optimisation**
  - Holes were drilled in the foils and an optimization of bunch compression was made using L2 phase (chirp scan).
  - Data of GAMMA1 signal for different foil thicknesses as a function of time.
- **August 4** ($\sigma_x = 40 \mu m$, $\sigma_y = 46 \mu m$): **First test of NF-CTR**
  - Data was taken for different compressions to search for a NFCTR effect.
  - Scans with and without foil were taken.
- **August 12** ($\sigma_x = 41 \mu m$, $\sigma_y = 46 \mu m$):
  - Object plane scan of the beam interacting with the Al 0.1 mm foil.
  - Data taken for different foil thicknesses.
  - Compare foil damage for different thicknesses with different repetition rates.
- **August 20** ($\sigma_x = 30 \mu m$, $\sigma_y = 51 \mu m$): **Small // function**
  - Scan of $\beta$ function from 50 cm to 5 cm: beam drilled holes faster at 5 cm.
  - Raster scan on the 0.1mm Al foil with $\beta = 5$ cm.
  - Foil damage analysis by looking at GAMMA cameras for different $\beta$.

*Note: $\sigma_x$, $\sigma_y$: from wire scanner before/after the shift.*
E332 progress

i. First evidence of holes being drilled in foils (holes completely drilled in 2 minutes with Al 0.1 mm).

ii. Data of GAMMA1 signal decreasing with time while shooting at a fixed foil position.

iii. Foil damage is proxy for strong near-field CTR (Ohmic heating by surface currents)

- GAMMA1 signal decreasing gradually after inserting the foil due to the hole being drilled.

- Drilled through Al 0.1mm with the e-beam over 1000 shots.

i. Damage is visible on Frontview camera

ii. Very clear signal on IP RADM that decreases by about 80% when hole is all the way through

- First time drilling a hole

- Many holes

IP RADM – 1mm Al
Size of damaged area

- Multi-shot burn through hole:
  - Max hole diameter \(~250\ \mu m\ \phi\)
  - Visible thermal damage \(~1\ \text{mm} \ \phi\)

- Single shot damage:
  - Diameter: \(100 - 250\ \mu m\ \phi\)

- Moving \(~0.5\text{mm/step}\) is enough to move to a fresh spot
  - This may change with smaller spot sizes
Effect of single foil (Al 0.1 mm) on the beam

$M_{12} = -20$ m ("large") to measure divergence at DTOTR2

Observed effect compatible with multiple scattering, no evidence of near-field CTR focusing
Multifoil installation (40 times Al 0.9 um, 100 um distance between foils)

We replaced the single foil by a 40 foils stack
E332 progress
Evidence of near-field CTR focusing in multifoil:

- Divergence doubles in multifoil (40x0.9 = 36 um of Al)
- Multiple scattering: well reproduced for Al 100 um
- Multiple scattering for Al 36 um: can only explain +20%

$M_{12} = +15 \text{ m and } M_{11} = 0$ (parallel-to-point optics) for perfect measurement of divergence at DTOTR2
Waist dependence of near-field CTR focusing in multifoil:

\[ \beta = 50 \text{ cm} \]

\[ \beta = 10 \text{ cm} \]

Credits C. Hansel
E305 & 332 plans
E305 plans for FY24

• Plans for E305 experimental set-up:
  ▶ Plasma generation at high pressure for length greater than 5 mm. Improved laser, leverage spatiotemporal couplings with a chirped laser.
  ▶ Produce clean and transversely-uniform plasma, larger than the beam
  ▶ Afterglow: dynamic range, consider using a lens to increase light collection, + filters on a flipper
  ▶ Shadowgraphy:
    - frequency-double shadowgraphy probe (designed and hardware ready)
    - assess the need to change pico by stepper motor for shadowgraphy MO
    - commission dark-field mode with mask for Fourier filtering (high-k shadowgraphy)

• Plans for E305 shifts:
  ▶ Repeat beam-plasma interaction with improved beam and plasma
  ▶ Carry out the experiment with a chirped beam (undercompressed with 100 um bunch length)
E332 plans for FY24

• Plans for E332 experimental set-up:
  - Change multifoil for 111 foils of Al 0.9 um: maximise near-field CTR focusing and provide clean comparison to single Al 100 um foil

• Plans for E332 shifts:
  - Take data with compressed beam and with bunch length characterised, to allow comparison to models and simulations
  - Demonstrate fully-resolved DTOTR1 beam size measurement
  - M_{12}/object plan scans to evidence the focused beam size and waist shift with respect to foil (can use 2 mm Al to calibrate “waist at foil” in M_{12} scans)
  - Clean waist scan data showing both increased divergence and decreased divergence
**E332 plans in the long run**

- Longer term:
  - With beam size of 5 um or less, current of 50 kA or more: **bright gamma-ray source**

- With 100 kA or more, couple **plasma lens (E308)** and **multifoil (E332)** for **laserless SFQED**.
Collaboration and institutions

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Thank you for your attention