E-305: Beam filamentation and bright gamma-ray bursts

Also E-303: Generation and Acceleration of Positrons at FACET II

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Collaborators: E-300 collaboration, CEA (France), MPIK (Germany)
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: potential for bright gamma-ray sources
- gamma-ray source with applications to defence, industry, medicine, scientific research
E305 - Science goals and definition of success

Two main configurations are considered for E305:

- High-density gas jets (plasma density from $10^{18}$ to $10^{20}$ cm$^{-3}$) - E305gas
- Solid targets (plasma density from $10^{23}$ to $10^{24}$ cm$^{-3}$) - E305solid

- Science goal 1 - push our understanding of relativistic kinetic plasma instabilities, including interplay of different modes, nonlinear stage, and ultrafast condensed matter physics in exotic states
  - Evidence of filamentation in E305gas (1 year)
  - Evidence of filamentation in E305solid (1 or 2 years)
  - Characterisation of growth and saturation/nonlinear stage as a function of beam and plasma parameters (2 years)
  - Benchmark against simulations, especially regarding collisional models for E305solid (2 years)
  - Distinguishing different modes of instability, showing how the interplay between oblique and CFI evolves with propagation, from front to rear of the bunch, and with bunch density (3 years)
  - Study instabilities with relativistic plasma response and/or with electron-positron fireball beams (4-5 years)

- Science goal 2 - generate bright gamma rays
  - First measurement of gamma-ray signal at a level distinguishable from the Bremsstrahlung background for E305solid (1 or 2 years)
  - Characterisation of the gamma-ray source as a function of beam and target parameters, comparison with blow-out for E305gas (2 years)
  - Demonstration of gamma-ray conversion efficiency exceeding the percent level (3 years), and possibly using a plasma lens to exceed 10%
• Experimental design (90%): Aug-Sep 2020.

• Installation plan:
  ‣ **target assembly** in B244: October 2020 *(mostly done)*, in tunnel: November-December 2020
  ‣ shadowgraphy diagnostics: hardware shipment ongoing, tests in B244 November 2020, in tunnel November 2020 to January 2021
  ‣ **dump table diagnostics** (electron and gamma): *mostly done*
  ‣ on-going at SLAC: gas delivery system (Keith Jobe) and pumping system for main experimental vacuum chamber
  ‣ ionising laser and E305 focusing optics: November 2020 to January 2021

• Ready for experimental **safety review**: yes; full documents sent + one iteration round in **August 2020**. Safety review in progress, no delay expected.

• **Full installation completion date**: aim for January 2021.
E305 - Experimental timeline

• Commissioning:
  ▸ December 2020: for targets (gas jets and solids), electron and gamma diagnostics, requires poor beam quality (1 nC, 30 micron beam size / bunch length, 30 micron emittance).
  ▸ January-February 2021: for laser ionisation and shadowgraphy in gas jet.

• First science: spring 2021, requirements: **Max compression configuration** (about 50-100 kA peak current, <50 x 10 micron beam size, 20-50 x 2-6 micron emittance)

• Science program:
  ▸ Phase 1 - 1\(^{st}\) Year: **First filamentation experimental tests, for both gas and solids.** Expect observation of filamentation and blowout in gas, and maybe some detectable gamma rays in solids. Diagnostics: high-resolution electron spectrometer, gamma-ray diagnostics, electron angular profile, high-k shadowgraphy.
  ▸ Phase 2 - 2\(^{nd}\) to 4\(^{th}\) Year: Improved beam parameters and upgraded/additional advanced diagnostics (e.g. CTR). **Full physics study and generation of bright gamma rays.** In solid: characterise positron generation influenced by instability, and integrate plasma lens with E308 to reach higher bunch densities.
  ▸ Phase 3: electron-positron fireball beams to reach high density ratio in 1e20/cc gas jets (astrophysically relevant, and avoid detrimental effect of gas ramps)
E303 (e+ PWFA) - Experimental timeline

• **Experimental design (90%): Aug-Sep 2020.**

• **Installation plan:**
  - **target assembly** in B244: October 2020 (mostly done), in tunnel: November-December 2020
  - W targets already available at SLAC, to be mounted on E305 target assembly
  - **dump table diagnostics** (electron/positron and gamma): mostly done
  - Other: SYAG, EOS, TCAV (same as E300).

• **Ready for experimental safety review:** done.

• **Full installation completion date:** aim for January 2021.

• **Commissioning:** can test W targets starting from December 2020 and check electron/positron and gamma diagnostics, requires poor beam quality (1 nC, 30 micron beam size / bunch length, 30 micron emittance).

• **Science program:**
  - Phase 1 - 1\textsuperscript{st} Year: characterise foil damage, drive beam energy loss/emittance growth, positron yield and angular spread in 0.5/1-mm-thick W from single bunch and from two-bunch configuration. Challenge: limited aperture for transport to dump.
  - Phase 2 - 1\textsuperscript{st} and 2\textsuperscript{nd} Year: E300 demonstrates beam-ionised lithium plasma, two bunch acceleration of trailing beam and significant energy loss of drive beam.
  - Phase 3 - 2\textsuperscript{nd} and 3\textsuperscript{rd} Year: Integrate W target in E300 plasma source and accelerate positrons in PWFA using a two-bunch configuration.

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E303 Phase 1 mostly ready and can be done can be done as part of the E-305.
Experimental layout

Beam direction

Experimental vacuum chamber (Picnic Basket)

3 gas jets and solid targets to be mounted on the E305 target mount:

X-Y stages for rastering and gas jet positioning and Out position, Z stage to be able to bring each gas jet to the nominal Z position. In-out motor for objective.
Diagnostics and observables

Main observables:
- Electrons
- Gamma rays
- High-k scattering in gas jet

Electrons:
- Beam profile monitor ~5 meters after target
- High-resolution in-vacuum OTR at the dump table (DTOTR)

Gammas:
- $\gamma$ screens at the dump table (incl. CsI to detect small gamma signals)
Possible evolution of the experiment (not exhaustive):

- Neutral beam filamentation: pair plasmas/beams are present in many extreme astrophysical environments (e.g. blazars, pulsars...); using electron-positron beams to study filamentation physics is the most natural evolution of E305. It will also allow to reach beam/plasma density ratio approaching with relativistic plasma response.

- Opening the way for the study of ultrafast solid state physics in exotic states (warm and out of equilibrium).

Desired facility upgrades:

E305 benefits from the highest bunch densities.

- In gas, the beam size cannot be too small (otherwise we enter blow-out regime), thus one needs high peak current, and an upgrade from 50-100 kA to 300 kA would be strongly beneficial.
- In solid, bunch densities in excess of $10^{20}$ cm$^{-3}$ are desired to uncover the full physics potential of E305solid. This requires focusability to beam size of $\lesssim 2 - 3 \mu$m and compression to bunch length of $\lesssim 2 - 3 \mu$m.
E-305 collaboration and institutions

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Thank you for your attention