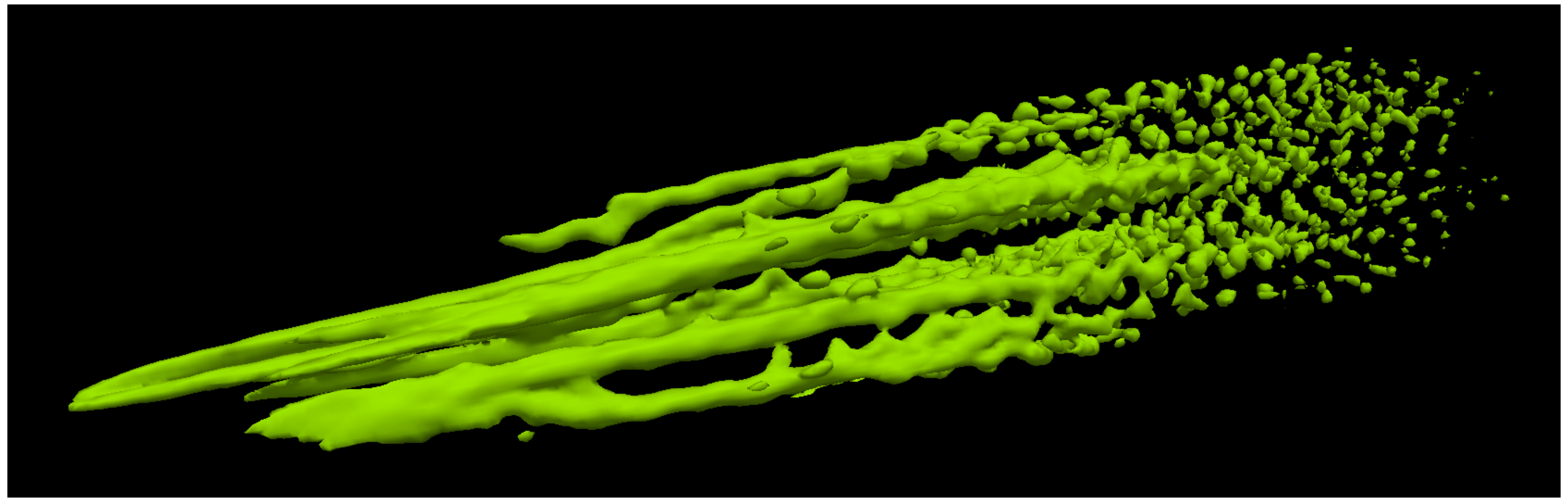
E-305: Beam filamentation and bright gamma-ray bursts

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



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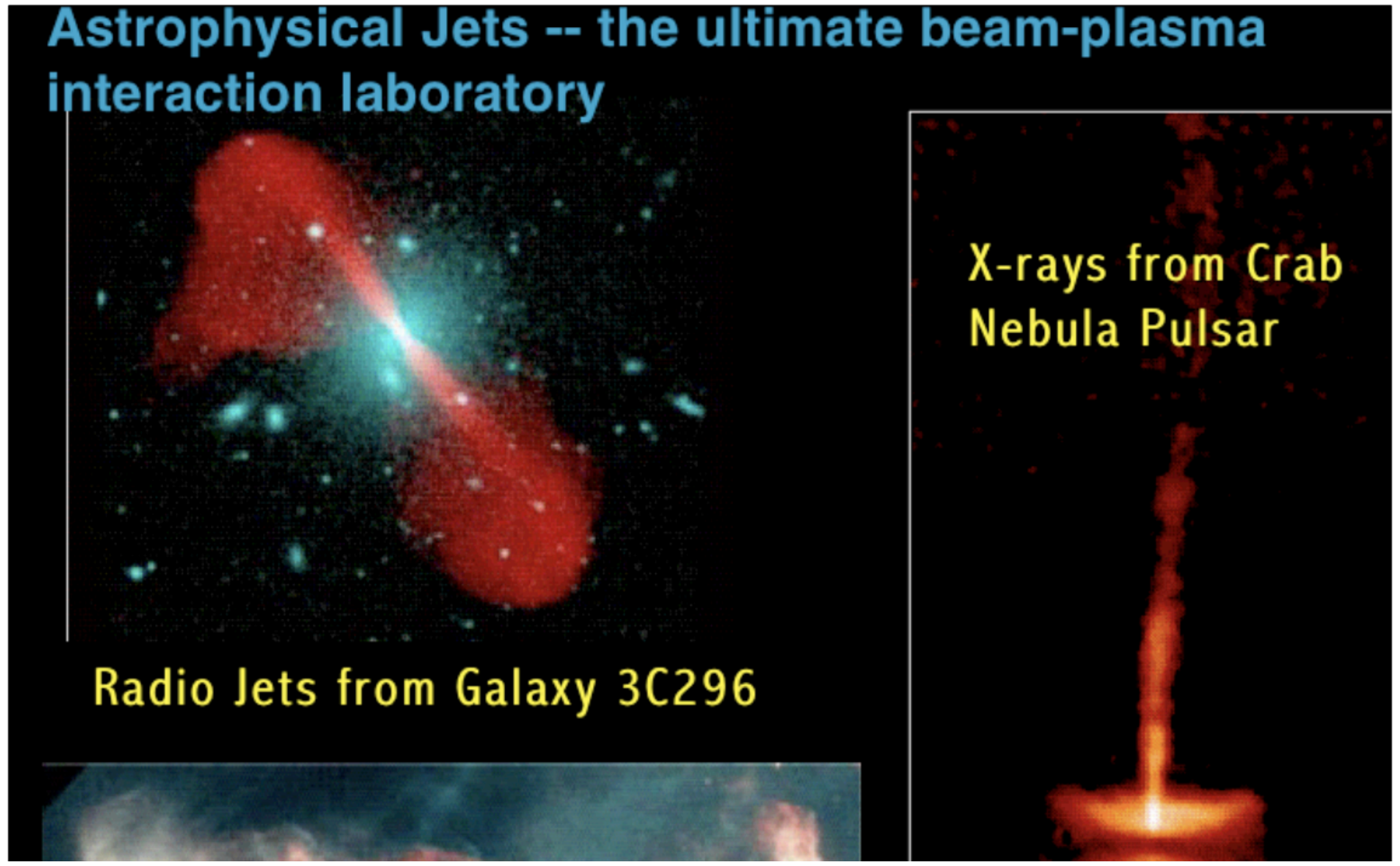
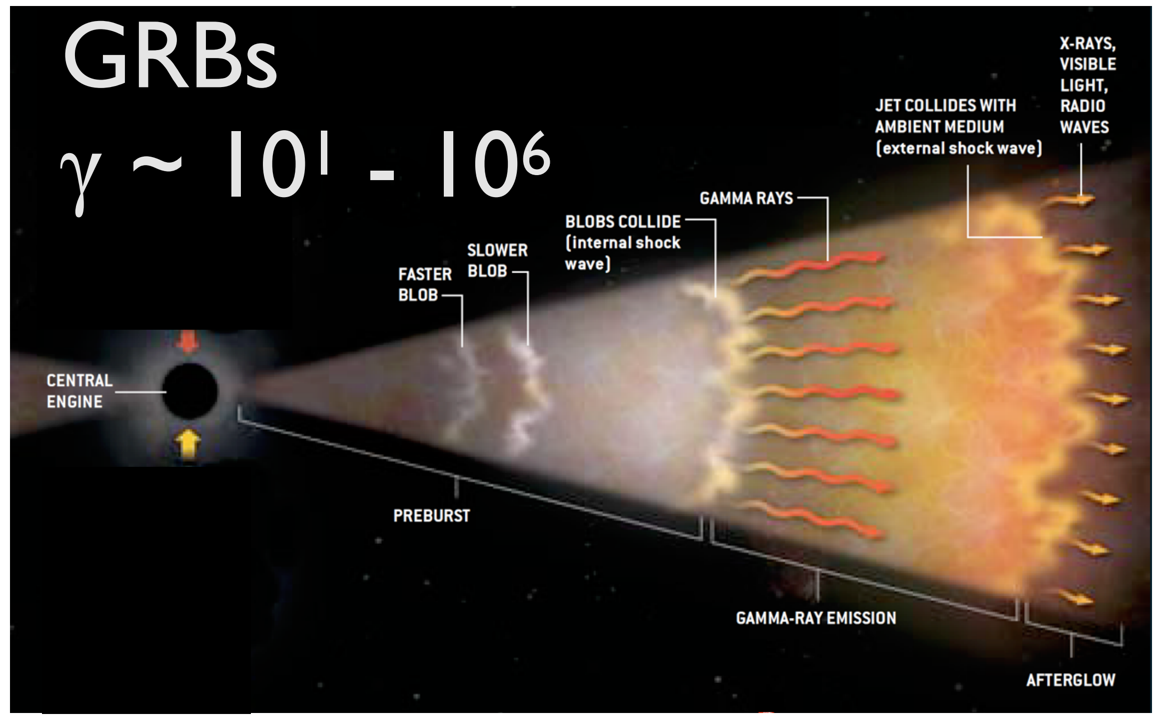
Collaborators: E-300 collaboration, CEA (France), MPIK (Germany)

Motivations for filamentation physics and bright gamma rays

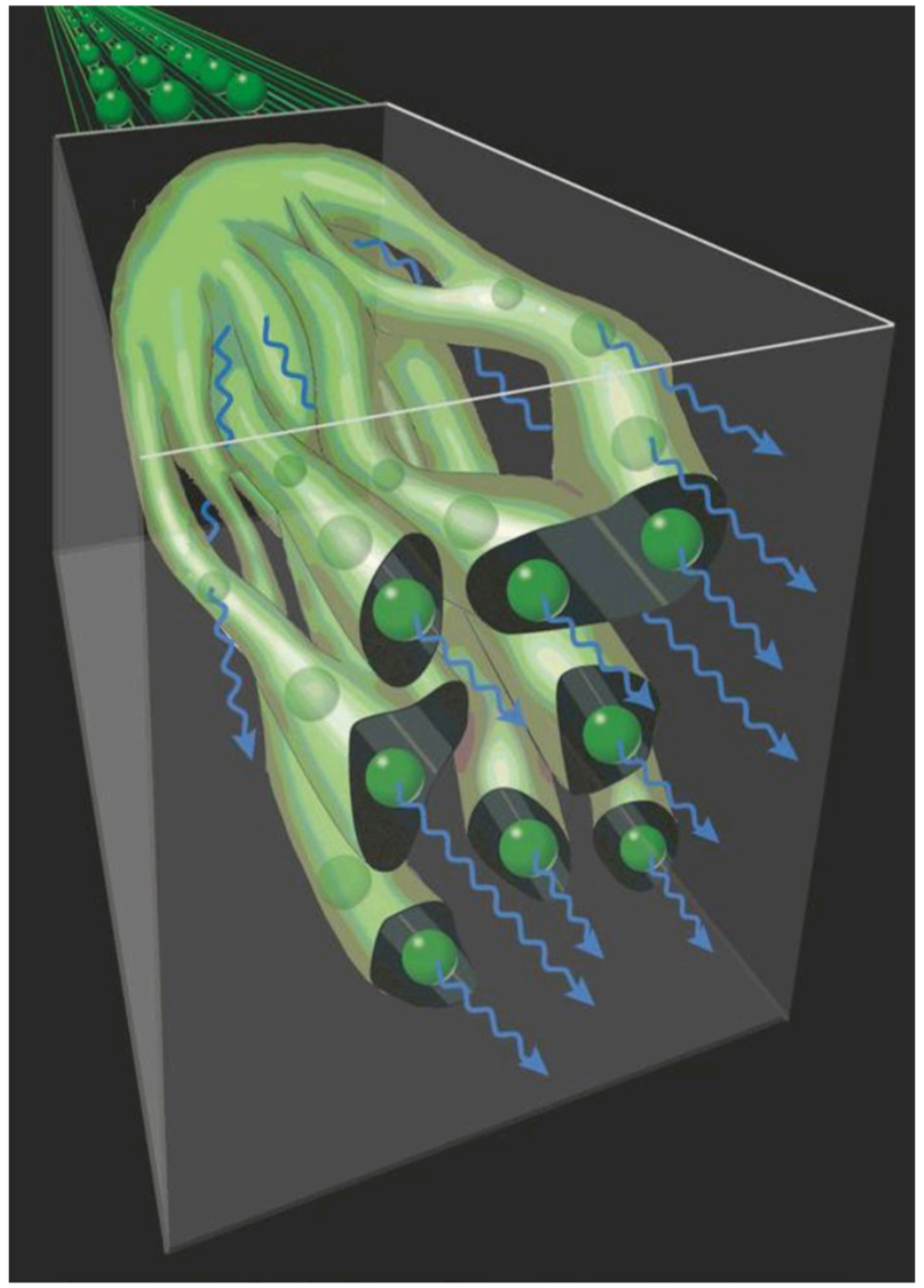
<u>Relativistic streaming instabilities are pervasive in astrophysics</u>



T. Katsouleas, role of Weibel instability in astrophysics and cosmic jets



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



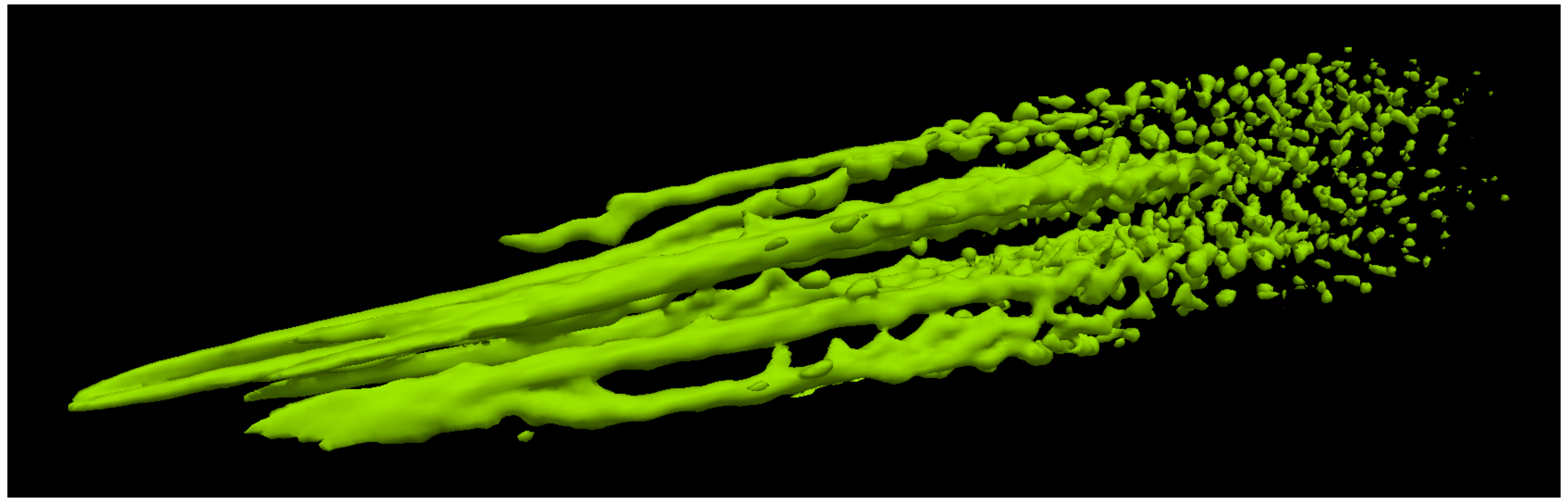
Nature Photon. 12, 314 (2018), Nature Photon. 12, 319 (2018)

- 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%

E305 - Experimental timeline

- 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 - 1st 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 - 2nd to 4th 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)

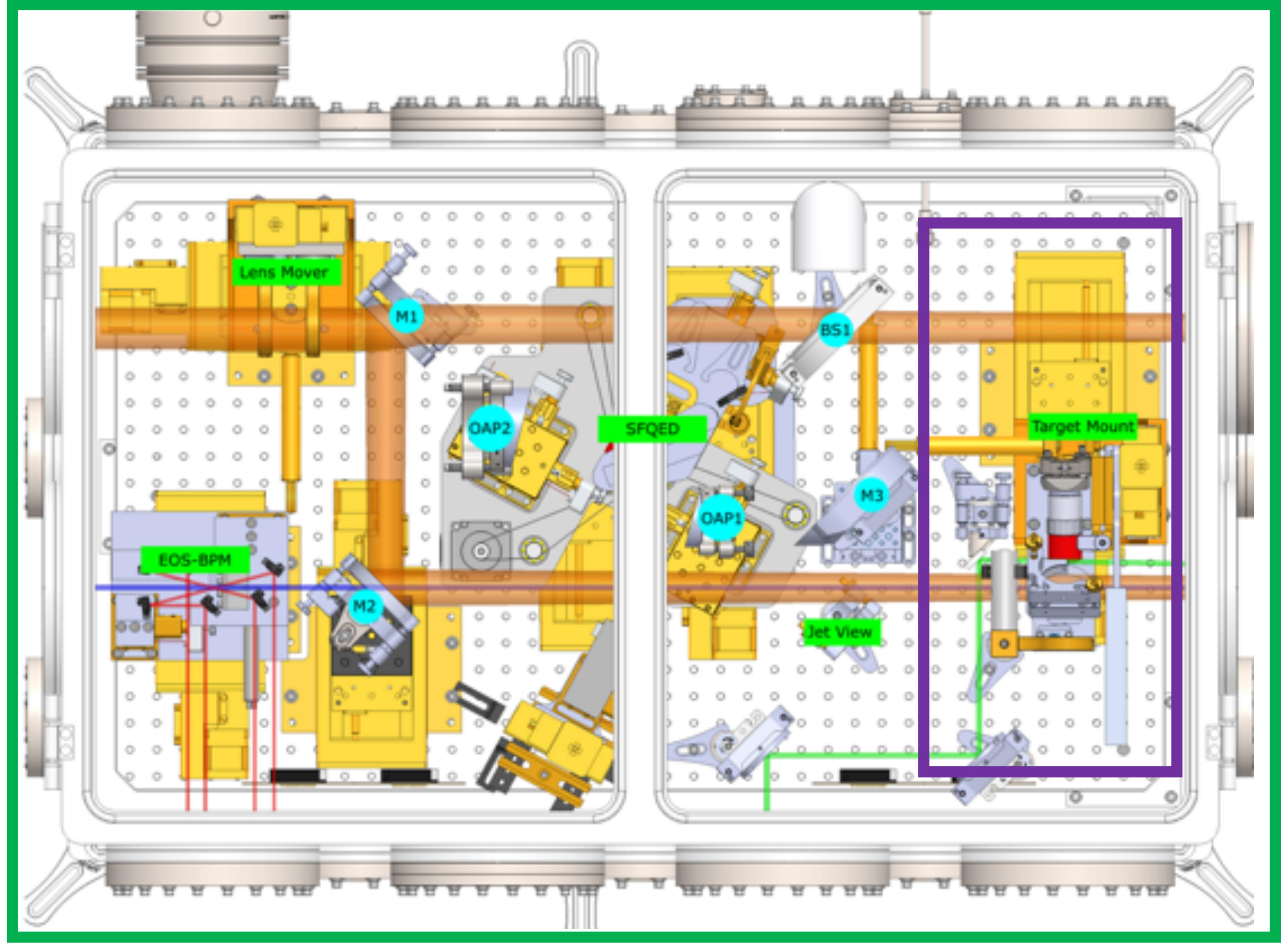
E303 (e+ PWFA) - Experimental timeline

- 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 - 1st 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 - 1st and 2nd Year: E300 demonstrates beam-ionised lithium plasma, two bunch acceleration of trailing beam and significant energy loss of drive beam.
  - Phase 3 - 2nd and 3rd Year: Integrate W target in E300 plasma source and accelerate positrons in PWFA using a two-bunch configuration.

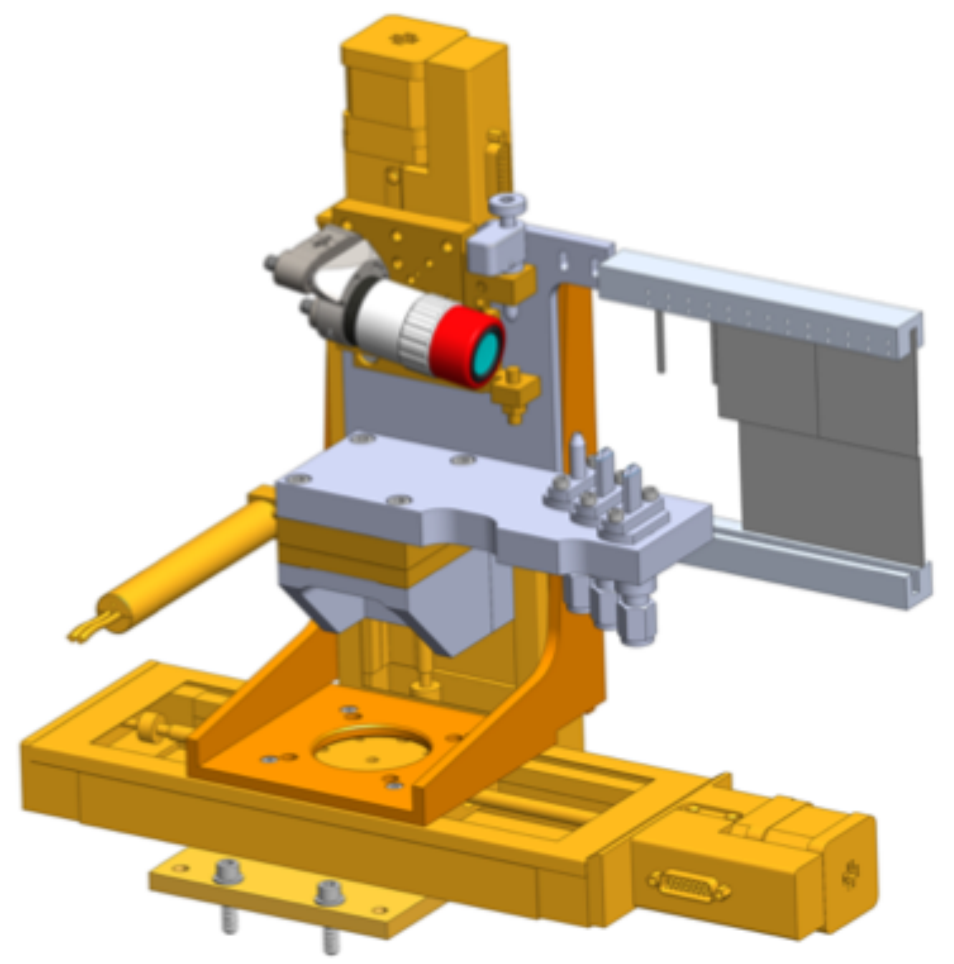
→ E303 Phase 1 mostly ready and can be done can be done as part of the E-305.

Experimental layout

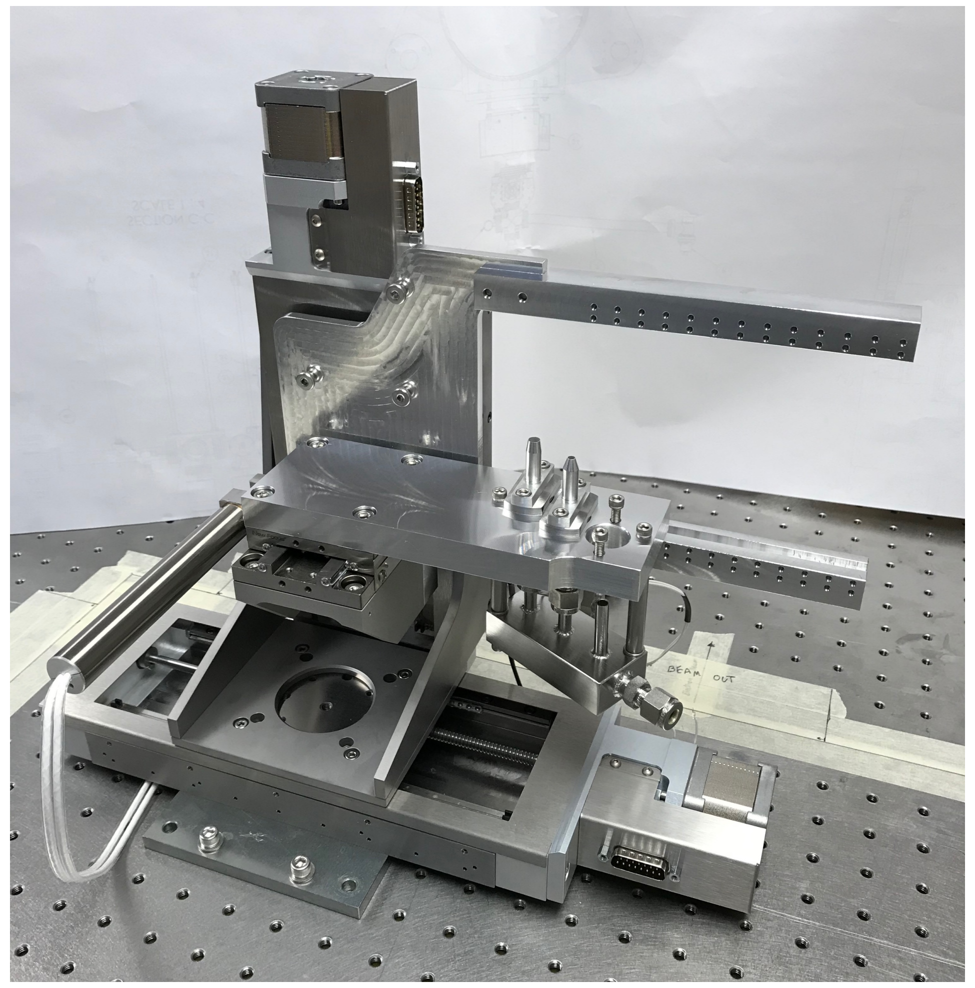
Experimental vacuum chamber (Picnic Basket)



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



Current design

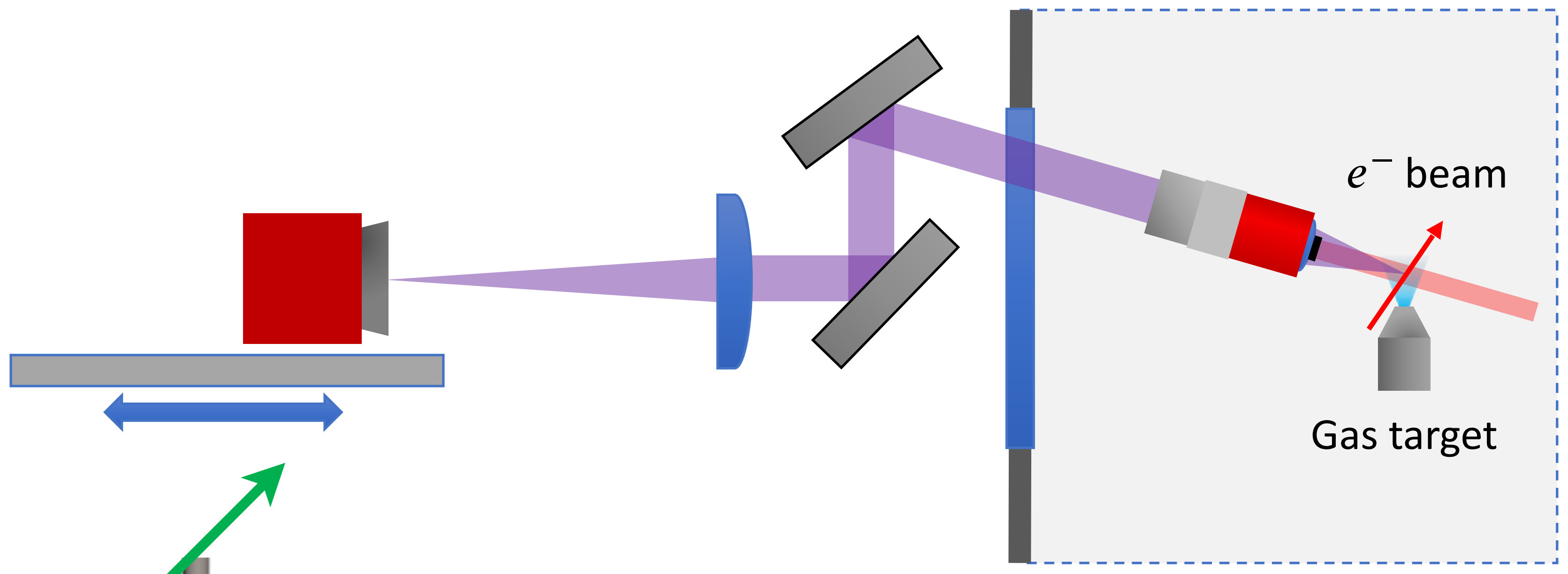


As built (as of Oct 16, 2020)

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.

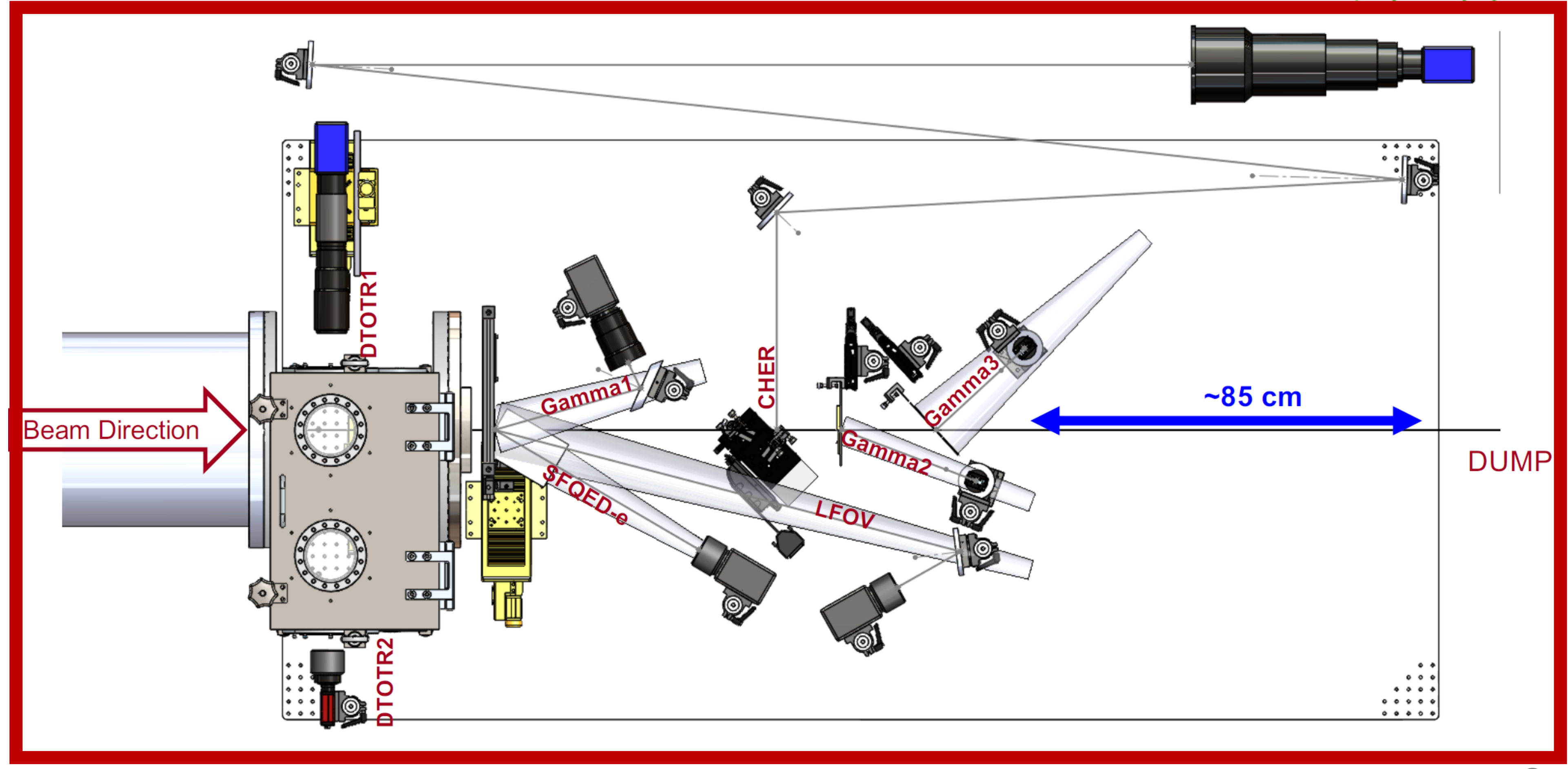
Diagnostics and observables

High-k shadowgraphy



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:
- γ screens at the dump table (incl. CsI to detect small gamma signals)

Potential evolution of the experiment and facility upgrades

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