E-315: Plasma Afterglow Attosecond Metrology

PIs: Bernhard Hidding, Andrew Sutherland

E-311: Plasma Torch Optical Density Downramp Injection

PIs: Bernhard Hidding, Heinemann/Habib/Sutherland

E-310: Trojan Horse-II

PIs: Bernhard Hidding, James Rosenzweig

Science Goals E-315 (slightly expanded from 2018/20)

Unbreakable diagnostics for extreme beams at IP

1. Spatiotemporal beam-laser coincidence at IP
   - ❑ Sub-10 fs, sub-5 µm accuracy (longer term)
   - ❑ Target time first full characterization: 3 months (Success: >E-210 precision)

2. Beam metrology at IP
   - ❑ Map beam duration, current, β^*…
   - ❑ Target time first full characterization: 3 months (Success: plasma pyro demo)

3. Gas target metrology (laser only mode)
   - ❑ Gas density profiling (jets, ramps, flows)
   - ❑ Target time first scans: 3 months

4. PWFA metrology
   - ❑ PWFA strength and dynamics along interaction
   - ❑ Target time: from first PWFA (either in PB or bypass line 2.0), using SideView and/or TopView

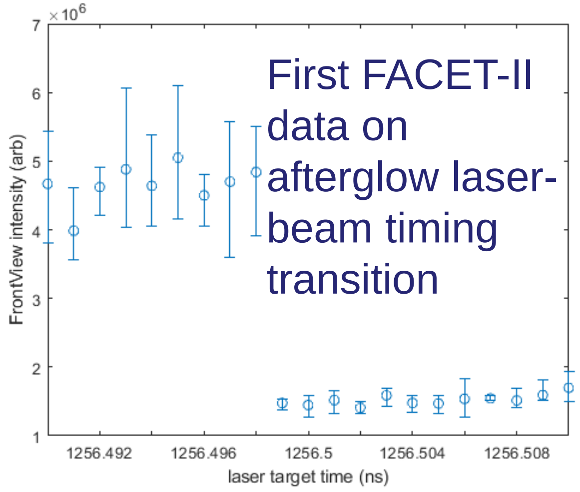
5. Development of plasma afterglow metrology to max. performance
   - ❑ Drive to precision limits: Dependent on incoming beam precision (will improve over lifetime and facility performance evolution), understand and exploit multi-parameter correlations
   - ❑ Further installations on beamline (pre- and post-PWFA)
   - ❑ Pathway into E-316 Icarus
   - ❑ Spectral/temporal resolution in addition to only spatial
   - ❑ Target time: continuously until end of program

Traditional diagnostics become consumables

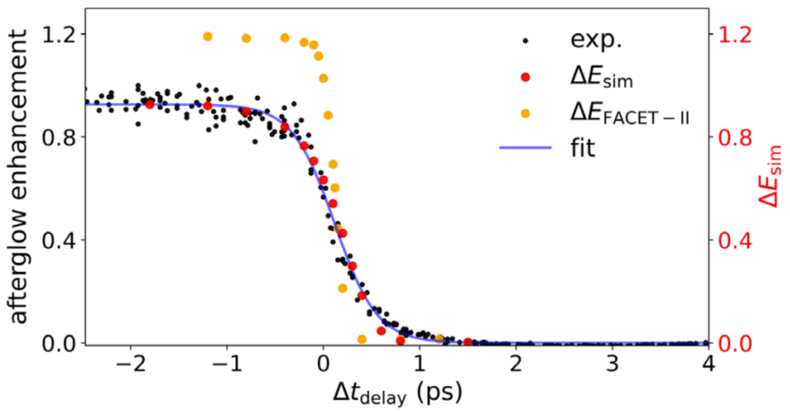
Experimental Timeline E-315

- Experimental design: 95% -- ionizing capability of laser to be recovered. Target: Autumn/winter 2022
- Installation: achieved during summer 2022, most recent addition SideView afterglow installation in 09/22
- Safety review: done (fully synergistic with E-308)
- Commissioning partially done (90%)
- First science: e-beam parameters more than sufficient (self field ionization observed), probe laser pulse ionization capability to be recovered

- Bottom line: ready to go with self-ionization scans, preionized plasma either collinear or 90°
- 2nd phase: exploit afterglow metrology for various experiments (already in good use during user-assisted commissioning for laser-beam timing overlap as in E-210, and gas jet metrology)



First FACET-II data on afterglow laser-beam timing transition



Compare Scherkl et al., PRAB 25, 052803 (2022)

Realization matrix so far

	Self-ionized	**Collinear pre-ionized**	**90° preionized**
Gas jet	Top view ✓ Front view ✓ Side view	Top view ✓ Front view Side view	Top view Front view Side view
Flooded chamber	Top view Front view Side view	Top view Front view Side view	Top view Front view Side view

Experimental layout for E-315

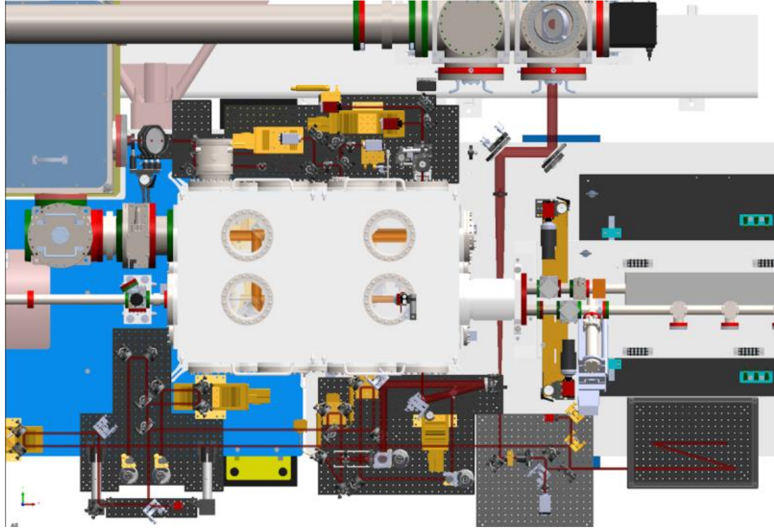
Shared setup
e.g. with E-308, E-305, for E-316

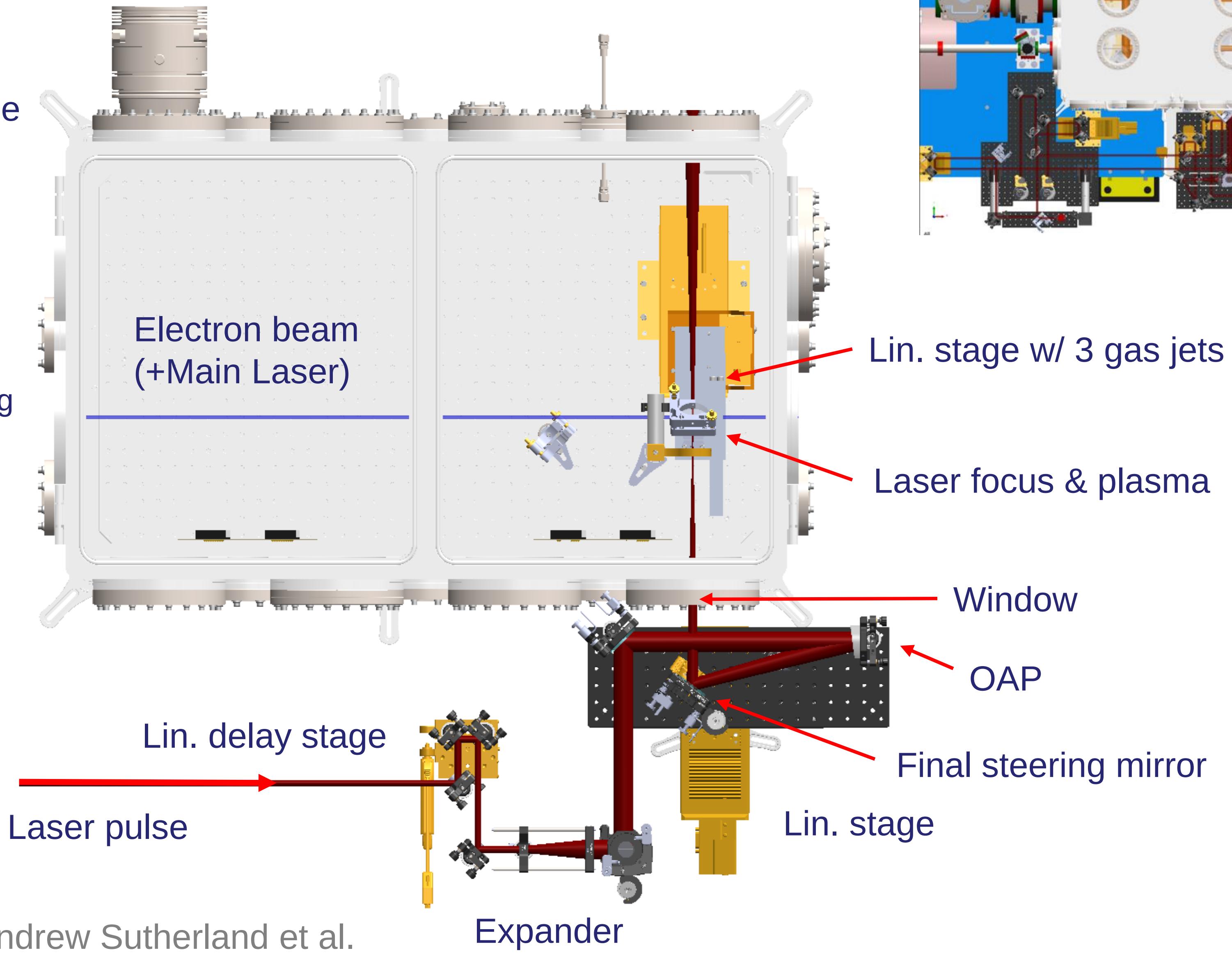
Current layout struggles to provide enough probe transmission to ionizer focus.

Proposed changes for FY23 include:

- ❑ Dedicated deformable mirror tuning for E315 or/and
- ❑ Independent wavefront correction hardware
- ❑ Softer beam expansion
- ❑ Motorised compressor grating
- ❑ Reduced B-Integral
    - ❑ Smaller dia. CaF2 window
    - ❑ Reflective beam expander
    - ❑ Replace OAP/optics

One piece of a complex probe network





Beamline setup Henrik Ekerfelt, Andrew Sutherland et al.

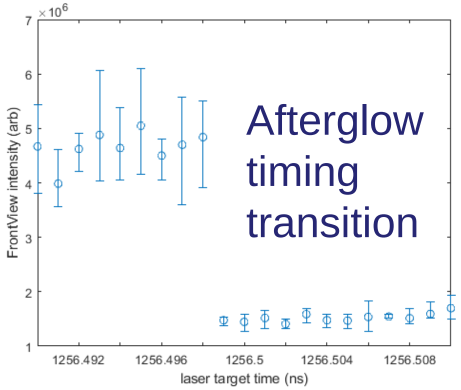
Observables and diagnostics for E-315

Three main diagnostics:
TopView, SideView, FrontView
CCDs for 3D imaging

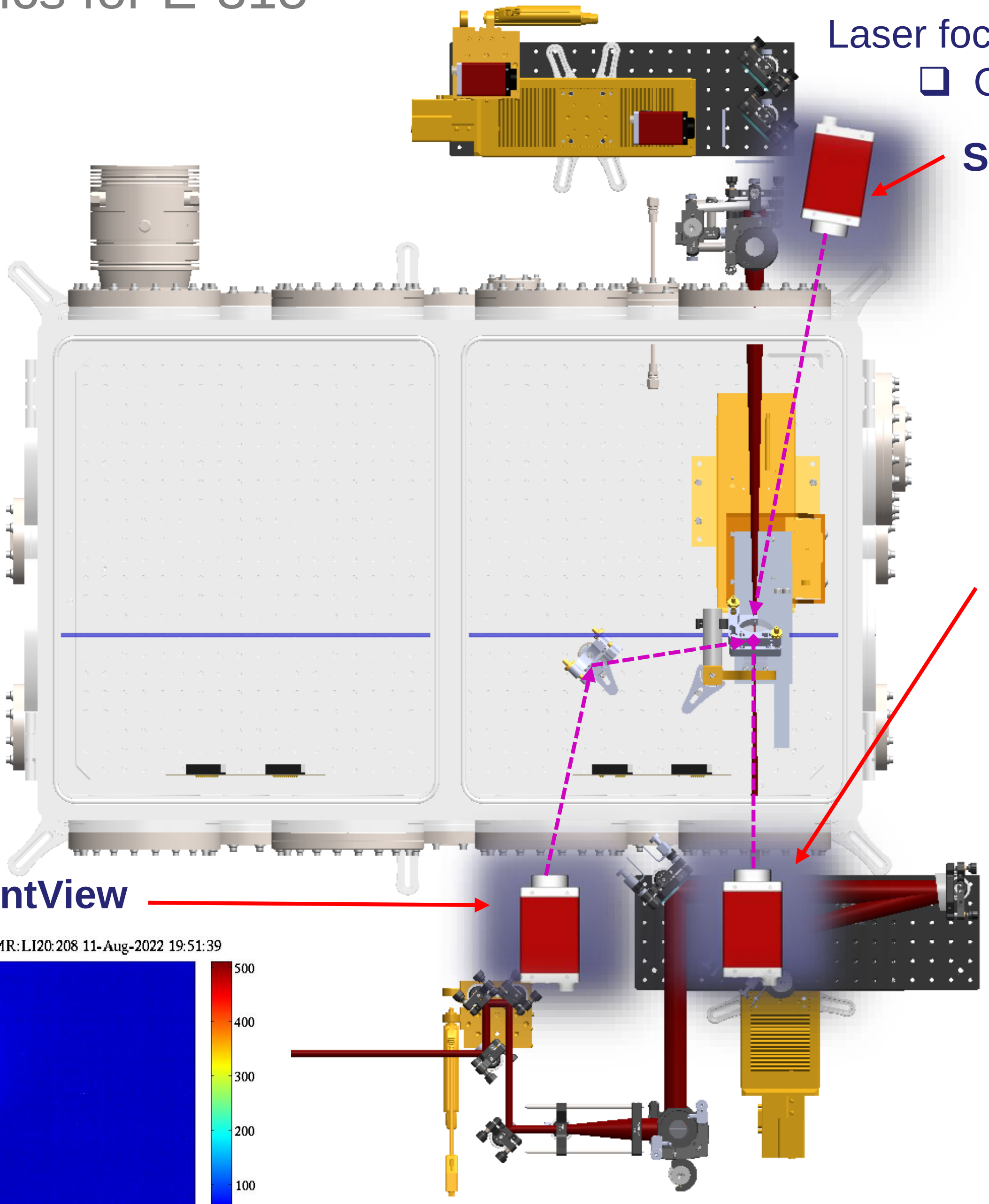
Composite measurements w/
EOS/EOS-BPM
- ❑ Time stamps
- ❑ Beam position

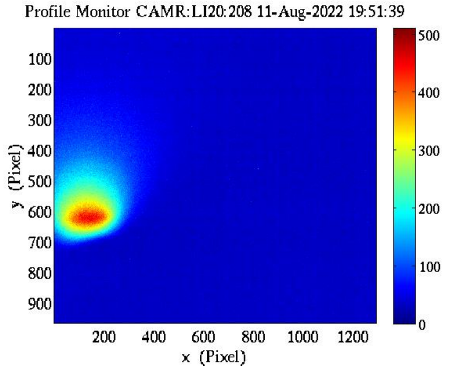
General Laser Diagnostics
- ❑ Alignment
- ❑ Transmission
- ❑ Deformable Mirror

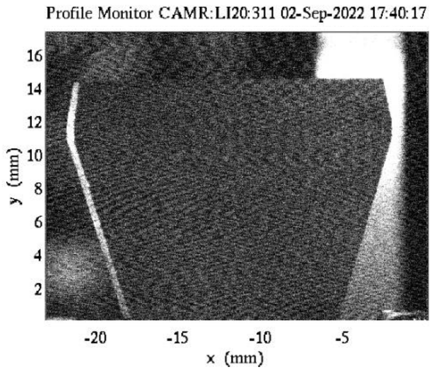
Beam spectrum & divergence
- ❑ Electron spectrometer

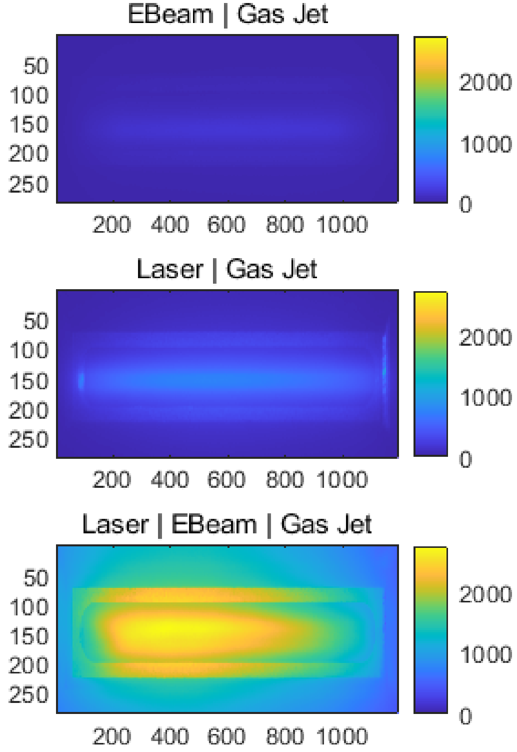


Laser focus, pointing and energy stability
- ❑ CCD imaging interaction region

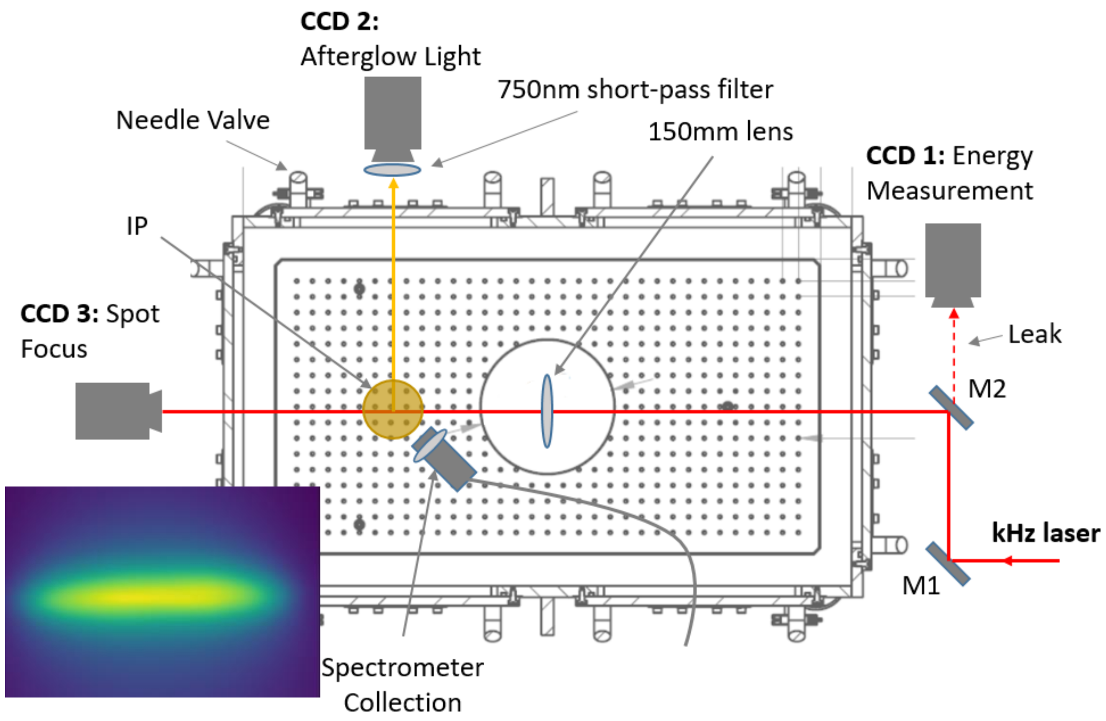


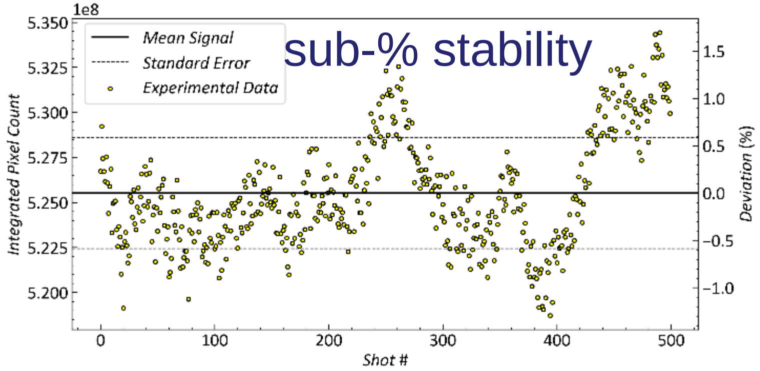


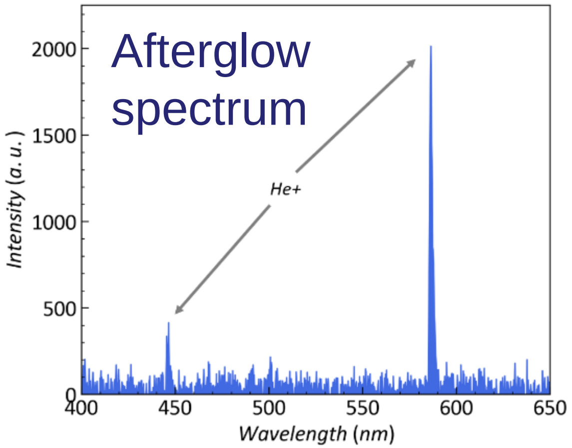




Plasma Afterglow @ SCAPA (laser only)



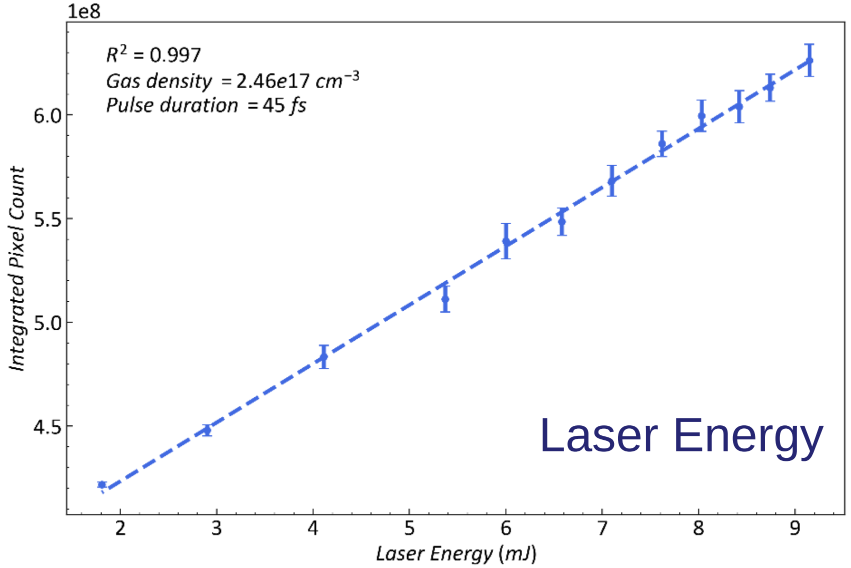


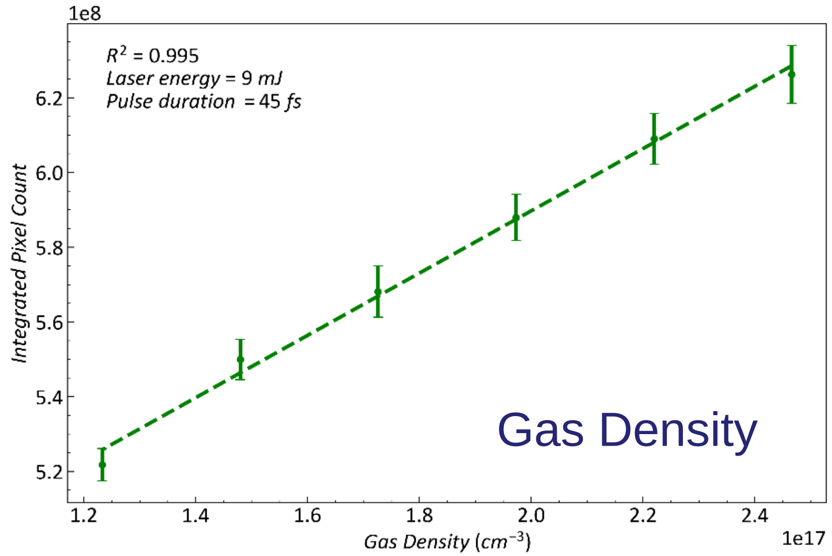


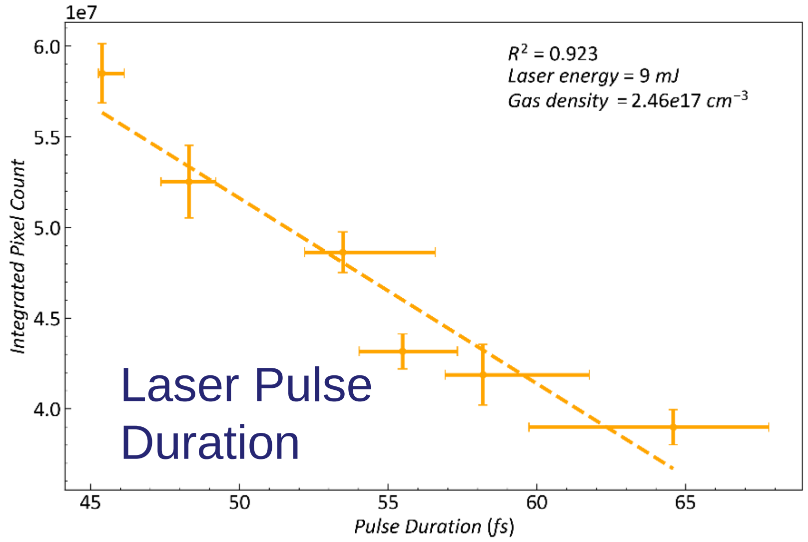
SCAPA kHz Laser has been a great test bed for

- ❑ Prototyping
- ❑ Equipment checkout
- ❑ Stability tests
- ❑ Parameter scaling
- ❑ Student training

Alex Dickson,
Grace Manahan,
Andrew Sutherland et al.



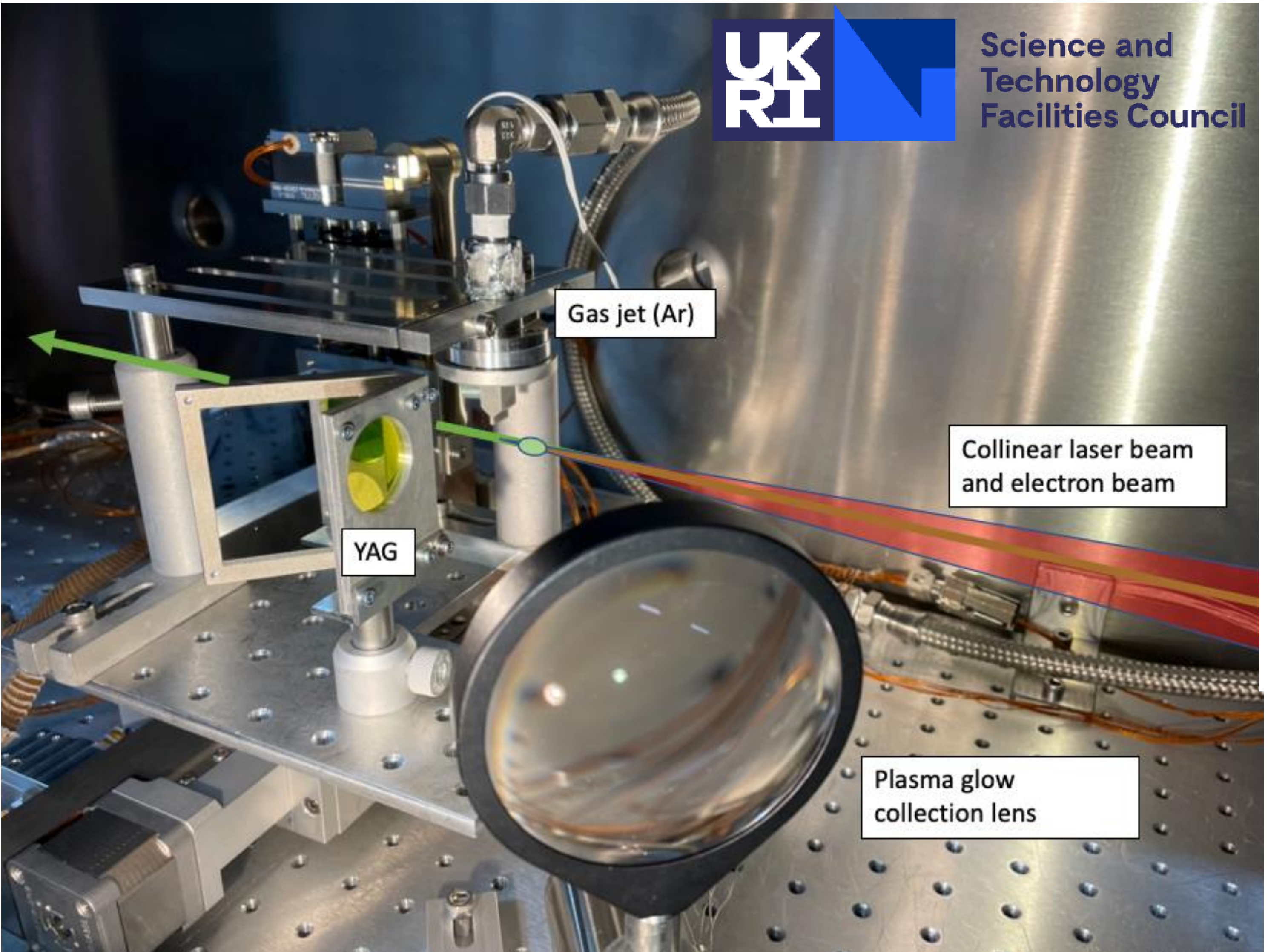


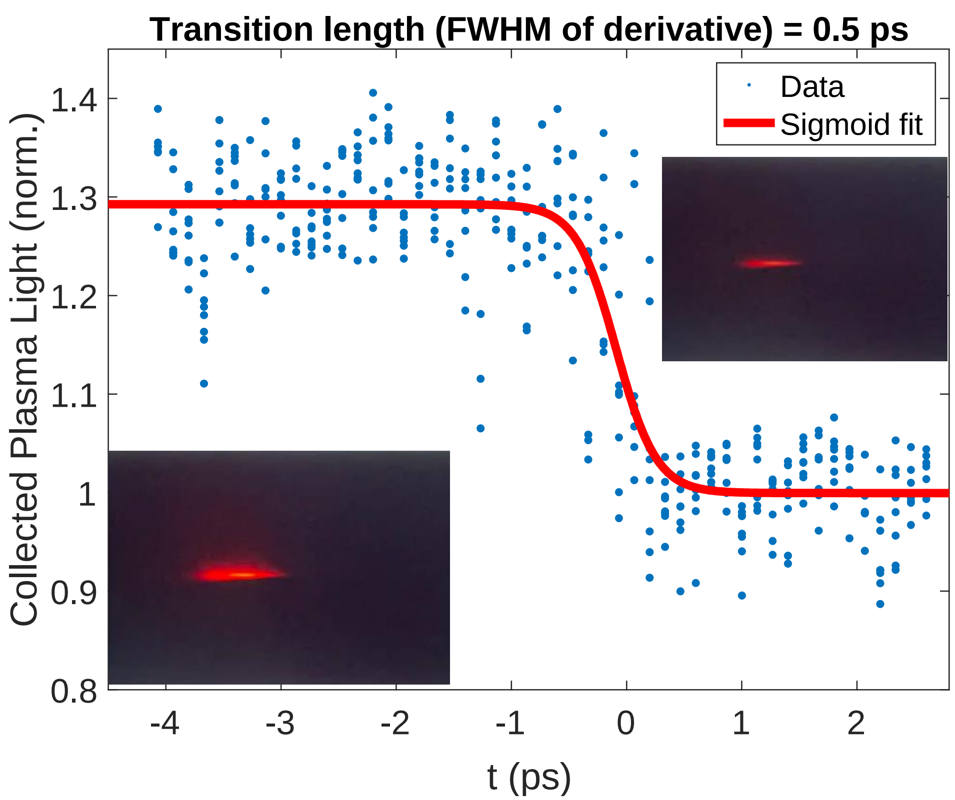


Plasma Afterglow @ CLARA 2021

- **Q1: does the method also work in collinear geometry?** ✔
- **Q2: does the method also work in a gas jet?** ✔
- Q3: does the method also work with sub-kA, ~100 MeV e-beams? ✔

VCAP03-21@CLARA Daresbury
PI Alexander Knetsch





e-beam 35 MeV, sub-kA, 80 pC, length 300 fs, 108 µm x 54 µm waist
Transition length 500 fs FWHM
$n_e \sim 10^{15}$/cc, pulsed subsonic gas jet

Potential future evolution beyond PAC

- ❑ Preparation for E-316 Icarus

- ❑ 2-bunch measurements
  - ❑ Linac- as well as plasma-injected driver/witnesses
    - ❑ Quantify individual contributions
    - ❑ Diagnose only second beam

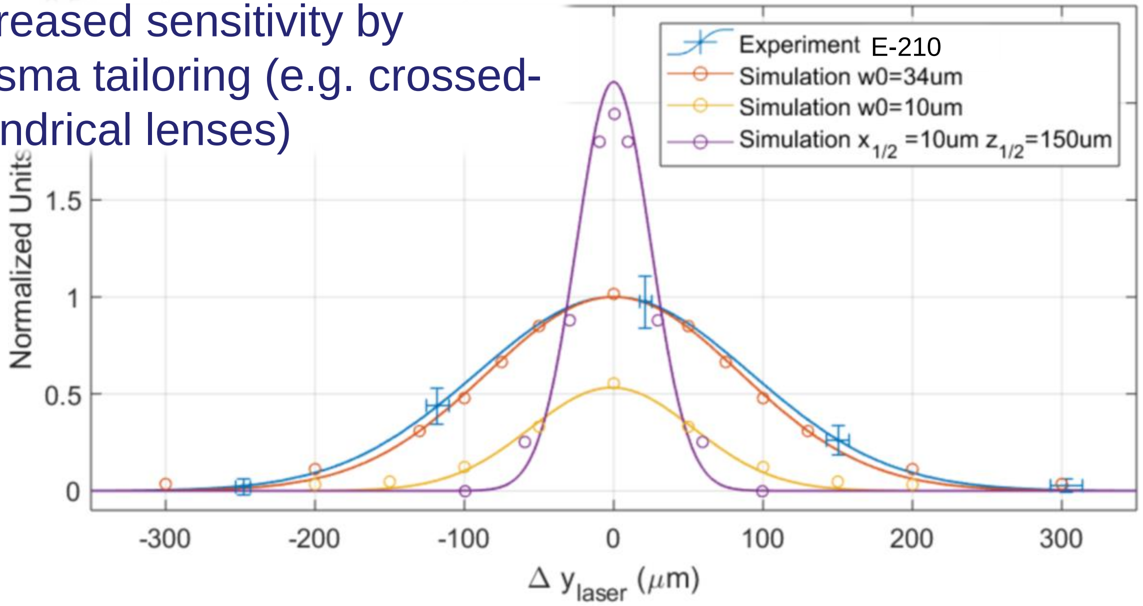
- ❑ Plasma clone as undisturbed reference
  - ❑ Explore potential for further jitter reduction

- ❑ Characterize compact/low-emittance beams (linac and plasma-based)
  - ❑ Test limits, also for calibrated single-shot

- ❑ Multiple implementation
  - ❑ Explore single-shot capabilities
  - ❑ Emittance measurement

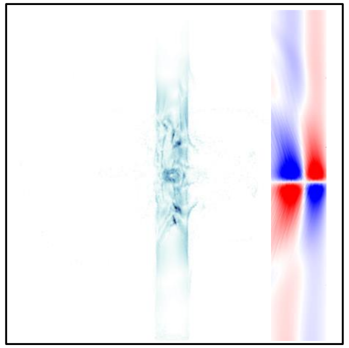
- ❑ Positrons
  - ❑ Demonstrate applicability of diagnostic
  - ❑ Positron-electron fireballs: use afterglow response to measure spatiotemporal overlap (space charge neutralization)

- ❑ Increased sensitivity by plasma tailoring (e.g. crossed-cylindrical lenses)

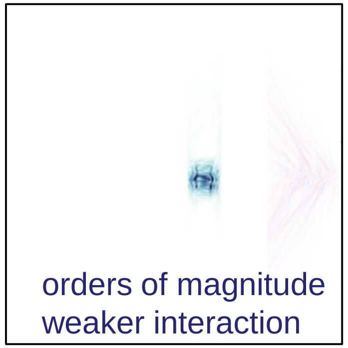


- ❑ e-/e+ fireball diagnostics

e^- - e^+ separated



e^- - e^+ overlapped



Desired facility upgrades

- ❑ Laser heater for more stable e-beam and enhanced tuning range
- ❑ e-beam diagnostics such as TCAV for benchmarking
- ❑ Further improved stability of ionizing laser pulses, diagnostics
- ❑ Windowless designs for laser (avoid focusing through window)
- ❑ Ultrafast (~ps level) cameras, spectrally and temporally resolved measurements
- ❑ More afterglow diagnostics stations for multi-modal composite measurements

Backup slides E-315

E-315 Collaboration

University of Strathclyde

TECH-X

radiasoft

radiabeam TECHNOLOGIES

hhu Heinrich Heine Universität Düsseldorf

UCLA

The Cockcroft Institute of Accelerator Science and Technology

l'X ÉCOLE POLYTECHNIQUE

SLAC

CU Boulder

erc NeXource

E-315 Publications, students

- **Oz et al. pre-FACET**: Optical Diagnostics for Plasma Wakefield Accelerators, 11th Advanced Accelerator Concepts, June 21-26 (2004), AIP Conference Proceedings 737, 708 (**2004**). First use of afterglow (aka ‘plasma light’) for PWFA energy transfer diagnostics

- Deng, Karger et al., Generation and acceleration of electron bunches from a plasma photocathode. Nature Physics 15, pages1156–1160 (2019). First proof-of-concept of Trojan Horse at FACET

- Scherkl et al., Plasma-photonic spatiotemporal synchronization of relativistic electron and laser beams, arXiv:1908.09263 (2019), Phys. Rev. AB 25, 052803 (2022). First dedicated seeded afterglow metrology at FACET

- Knetsch et al., Stable witness-beam formation in a beam-driven plasma cathode, Phys. Rev. AB 24, 101302 (2021). First exploitation of afterglow to find overlap for plasma torch at DESY

- Sutherland et al., FACET-II PRAB in prep. Outlining potential for enhanced afterglow metrology at FACET-II

- Boulton et al., Longitudinally resolved measurement of energy-transfer efficiency in a plasma-wakefield accelerator, https://arxiv.org/abs/2209.06690 Novel afterglow-based method for PWFA diagnostics

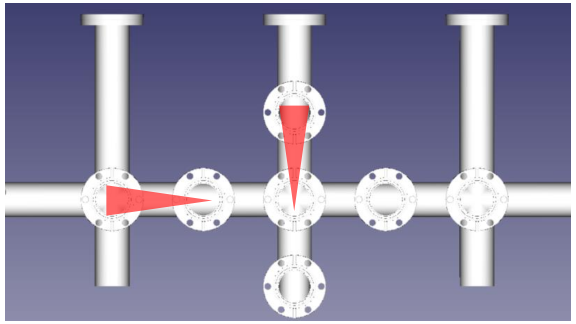
- Postdocs: Thomas Heinemann, Ahmad Habib, Andrew Sutherland*, Grace Manahan, Michael Stumpf* et al.
- Students: Adam Hewitt*, Lorne Rutherford, Lily Berman*, Alex Dickson et al.

* Indicates presence during commissioning at FACET-II and in remaining 2022

E-310 and E-311

Core Science Goals E-311/E-310 (unchanged from 2018)

1. Torch injection with 90° (as at FACET, but advanced)
   - ❑ Improved stability / quality / energy gain (Success > 1 GeV)
   - ❑ 4D fine structured beams and novel modes (e.g. counter-oscillating beamlets)
   - ❑ Target time first realization: 6-12 months



2. Trojan injection with 90° (as at FACET, but advanced)
   - ❑ Improved stability / quality / energy gain (Success > 1 GeV)
   - ❑ Target time first realization: 6-12 months

3. Trojan injection (near-)collinear
   - ❑ Full charge capture (Success 100 %)
   - ❑ Cold release (no driver kick)
   - ❑ Tens nm-rad norm. emittance
   - ❑ Target time first realization: ~12 months

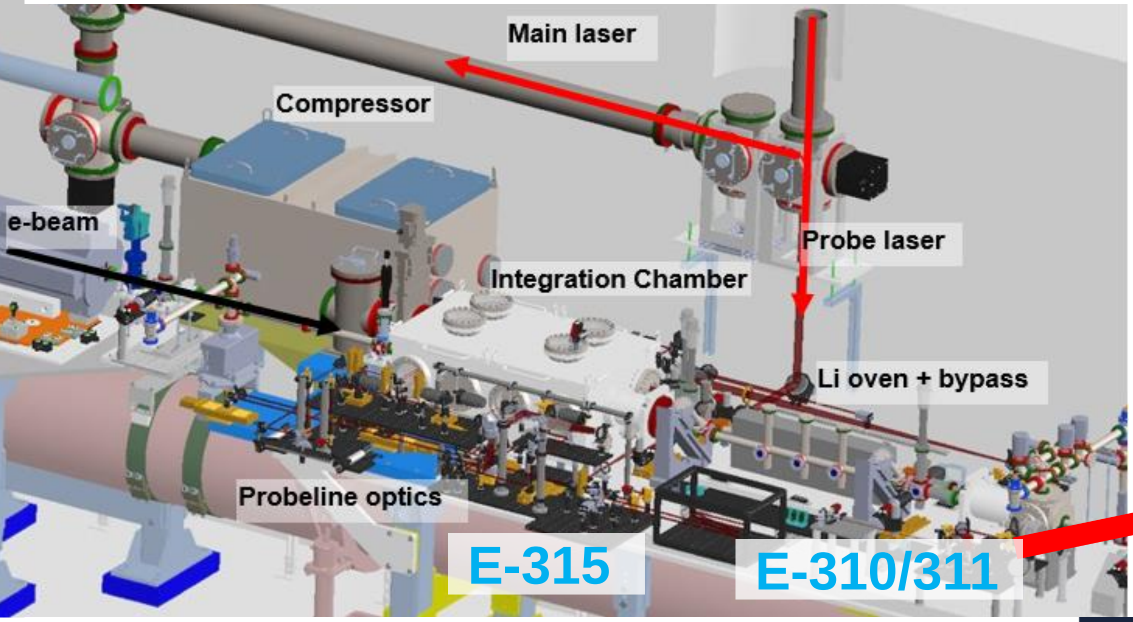
Other science goals: see 2018 proposals

- Overarching goal: expand science capabilities and enable novel experiments at FACET-II and beyond by provision of ultrabright beams

Experimental Timeline E-311/310

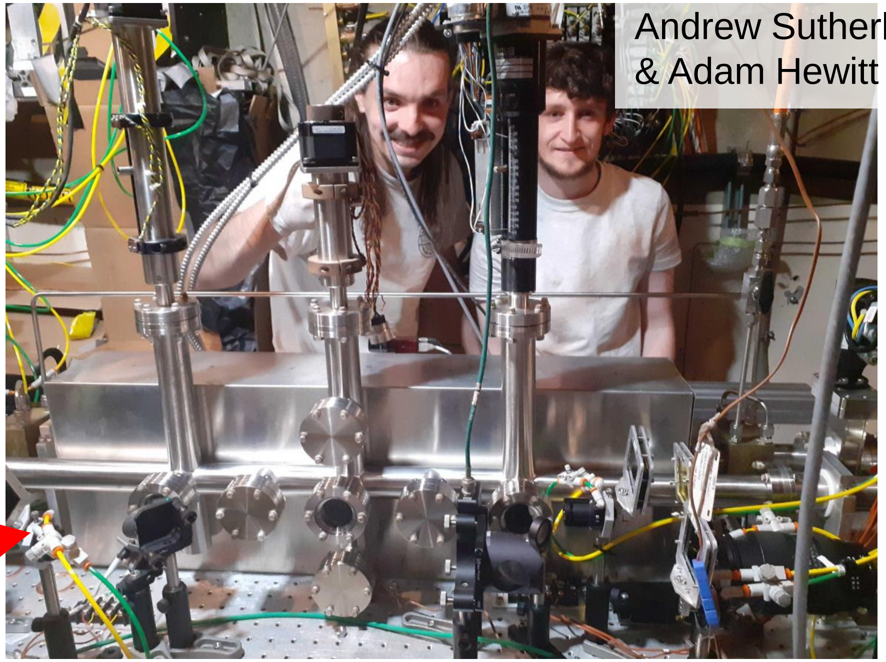
- ❑ Experimental design: 80%
- ❑ Bypassline 2.0 w/ 5 ports and ladders – installed (and: Doppelganger at Strathclyde). Optics to be integrated
- ❑ Optimized axilens set – arrived today (Doppelganger for Strathclyde)
- ❑ Experimental laser safety review: in progress, same as for E-315/E-308 (unproblematic)
- ❑ Experimental gas safety review: done
- ❑ 90° injection in picnic basket: possible
- ❑ E-beam requirements: already met (tailored linac mode desirable)
- ❑ Key task and path: recover Picnic Basket ionization, then complete beamline to downstream and bypass line 2.0. Timeline: required time dependent on access, ~weeks.
- ❑ Doppelgangers to speed up implementation at FACET-II and benchmarking

Experimental layout E-311/310



Duplicate E-315 injection at bypass line 2.0

Enable 90° and collinear injection w/ optics on ladders

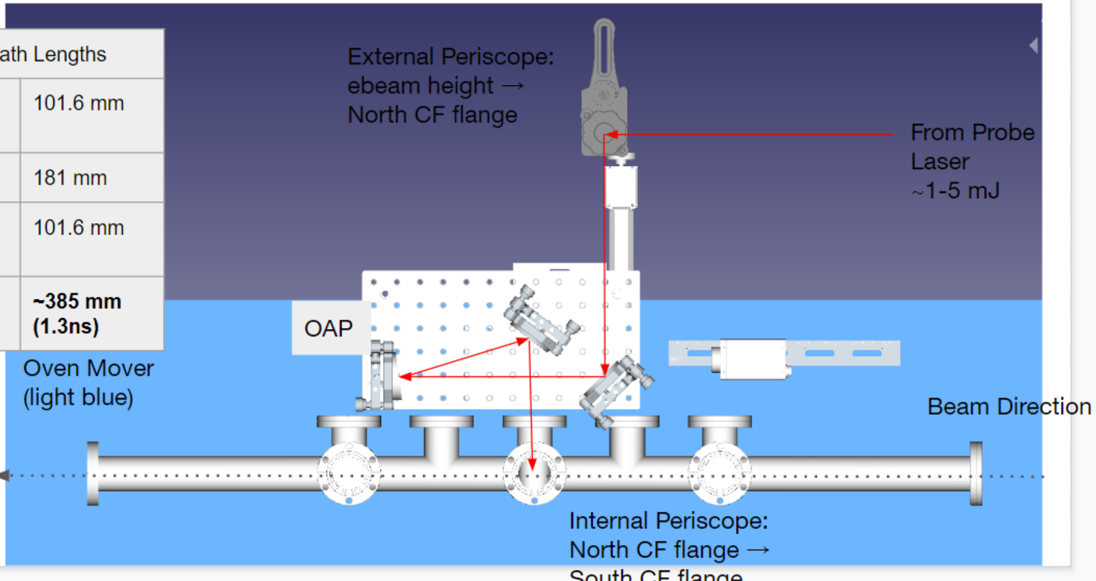


4. Downstream beamline for bypass line 2.0

Justification: E310 et al.

University of Strathclyde Glasgow

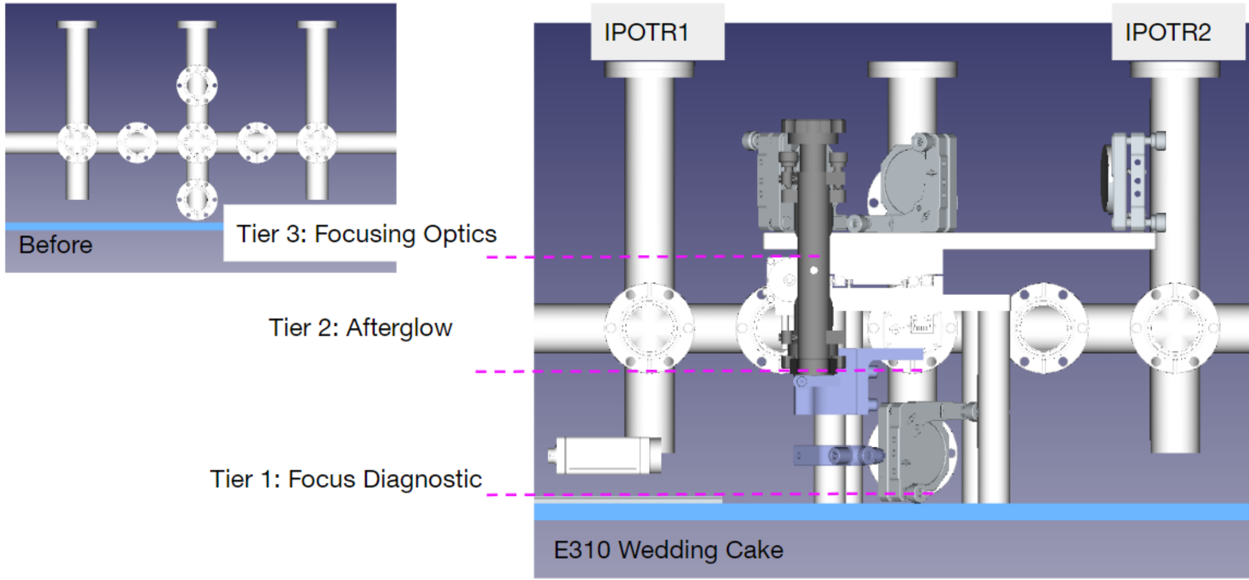
Additional Path Lengths	
External Periscope	101.6 mm
OAP	181 mm
Internal Periscope	101.6 mm
Total	**~385 mm (1.3ns)**



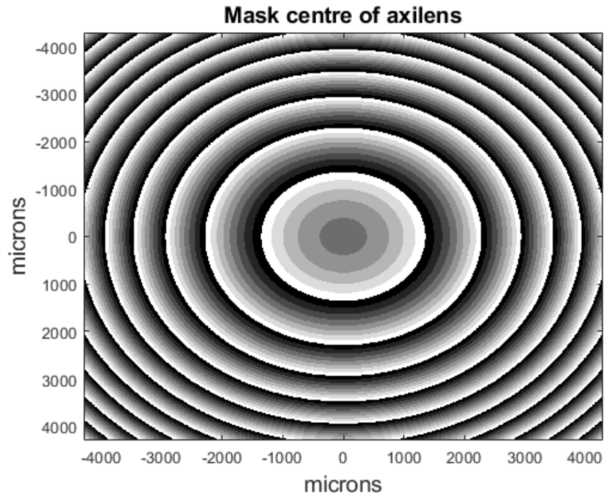
4. Downstream beamline for bypass line 2.0

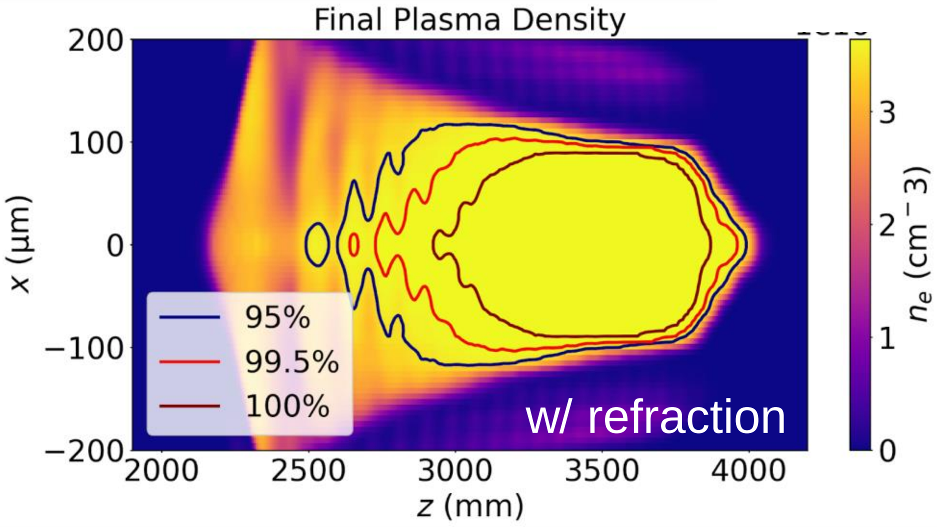
Justification: E310 et al.

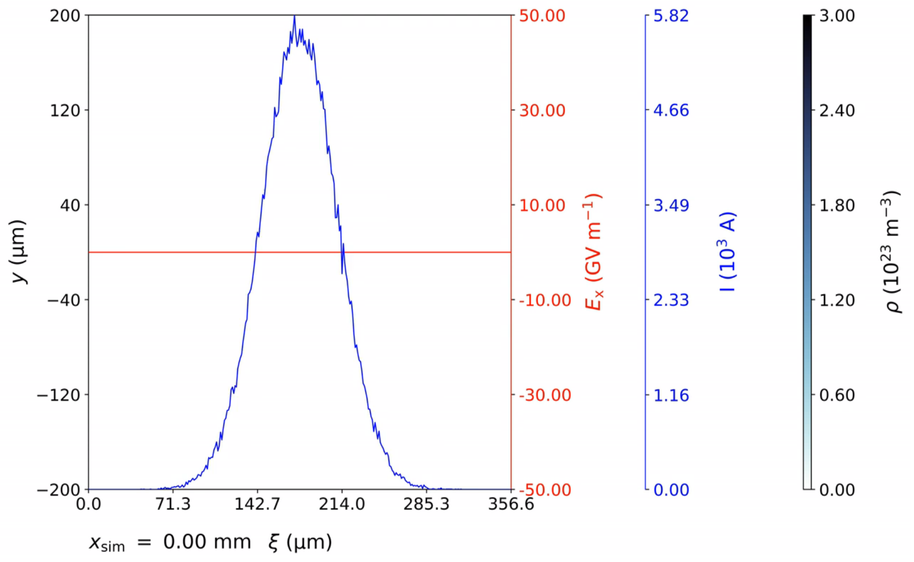
University of Strathclyde Glasgow



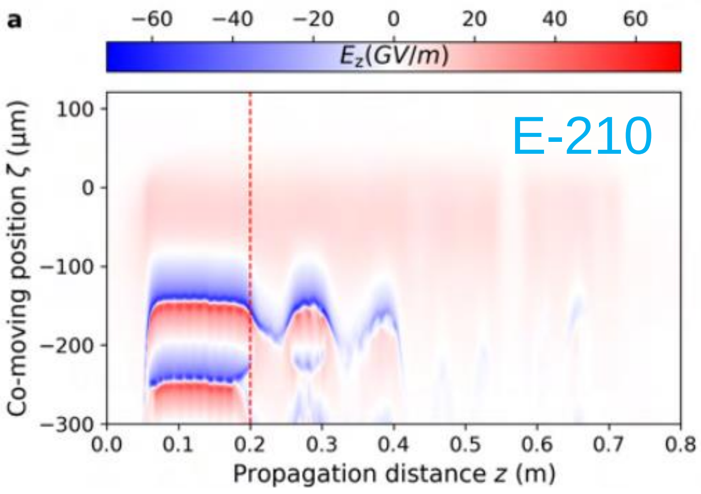
Realistic E-310 simulations for tailored axilens in bypassline 2.0

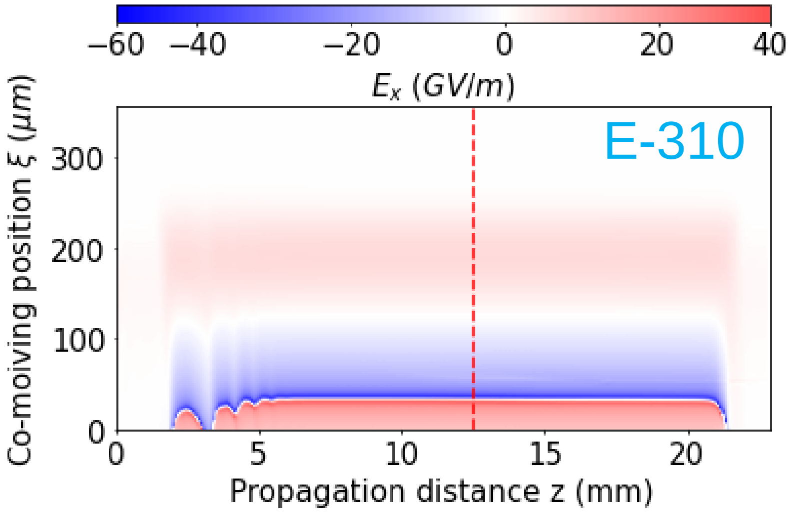






- E-210 bottleneck removed, much wider plasma → stable injection & acceleration





- To date most realistic PIC-simulations for exp. working point show full charge capture, multi-GeV (potentially 11-13 GeV) energy gains, 20 nm-rad normalized emittance (pC level), 200 nm-rad (10s to 100 of pC), ultrashort (depending on charge < fs) bunches

Adam Hewitt, Thomas Heinemann et al.

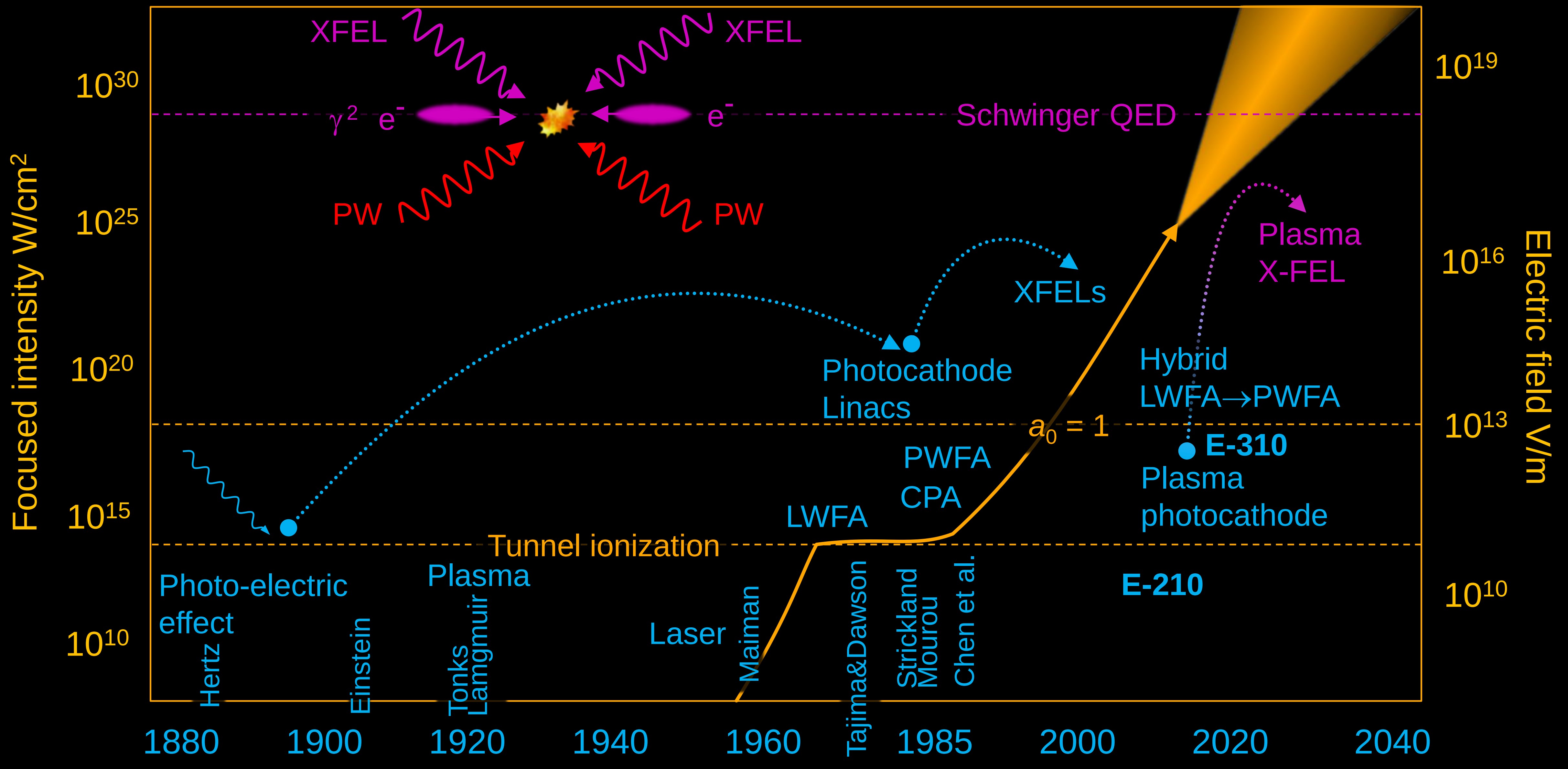
Diagnostics & Observables E-311/E310

- ❑ E-SPEC: BPMs: charge
- ❑ E-SPEC: energy
- ❑ Afterglow (various)
- ❑ Divergence, emittance (E-SPEC, quad scans) – for µm-rad scale
- ❑ TCAV
- ❑ Emittance: sub-100 nm-rad to 10s of nm-rad scale: future
- ❑ Various laser beam diagnostics
- ❑ EOS-BPM
- ❑ Shadowgraphy for PWFA visualization

Potential future evolution

- ❑ Preparation for E-313
- ❑ Preparation for nm-rad scale emittance preservation acid tests
- ❑ Preparation for Plasma-X-FEL
- ❑ Preparation for collider w/o damping ring and competitive luminosity

Strategic Vision: Co-located ultrabright beams for next generation experiments e.g. at FACET-III



Desired facility upgrades

- Space! Bypassline 2.0 designed to co-exist with oven. Ideal: dedicated PWFA chamber
- Laser heater for more stable e-beam and enhanced tuning range
- Tailored linac mode for E-31x: e.g. 1.5 nC, $\sigma_{x,y} \approx 4.5$ µm, $\sigma_{x,y} \approx 32$ µm, $\varepsilon_n \approx 50$ mm-mrad
- Further improved stability of ionizing laser pulses, diagnostics
- Laser polarization control
- Windowless designs for lasers (avoid focusing through window)
- Beam transport line / witness extraction
- Diagnostics for witness emittance / brightness characterization, TCAV for benchmarking

Backup slides E-310 and E-311

E-310/311 Collaboration

University of Strathclyde

TECH-X

radiasoft

radiabeam TECHNOLOGIES

hhu Heinrich Heine Universität Düsseldorf

UCLA

The Cockcroft Institute of Accelerator Science and Technology

l'X ÉCOLE POLYTECHNIQUE

SLAC

CU Boulder

erc NeXource

E-310/311 Publications, postdocs, students

- ❑ Deng, Karger et al., Generation and acceleration of electron bunches from a plasma photocathode. *Nature Physics* 15, pages1156–1160 (2019). First proof-of-concept of Trojan Horse at FACET

- ❑ Ullmann et al., All-optical density downramp injection in electron-driven plasma wakefield accelerators, https://arxiv.org/abs/2007.12634 (2020), Phys. Rev. Res. 3, 043163 (2021). In-depth investigation of Plasma Torch capabilities, such as fine-structured beams

- ❑ Knetsch et al., Stable witness-beam formation in a beam-driven plasma cathode, Phys. Rev. AB 24, 101302 (2021). First demonstration of Plasma Torch at DESY

- ❑ Couperus Cabadağ et al., Gas-dynamic density downramp injection in a beam-driven plasma wakefield accelerator, *Phys. Rev. Research* 3, L042005 (2021). First demonstration of gas-dynamic downramp injection at HZDR

- ❑ Foerster et al., Stable and high quality electron beams from staged laser and plasma wakefield accelerators, https://arxiv.org/pdf/2206.00507, accepted at PRX. First Plasma Torch demonstration with hybrid LWFA$\rightarrow$PWFA at LMU

- ❑ **Habib, Heinemann et al., Ultrahigh brightness beams from plasma photoguns, arXiv:2111.01502 (2021). In-depth investigation of performance and stability potential of plasma photoguns** E-310 parameter scans

- ❑ Postdocs: Thomas Heinemann, Ahmad Habib, Andrew Sutherland*, Grace Manahan, Michael Stumpf* et al.
- ❑ Students: Adam Hewitt*, Lorne Rutherford, Lily Berman*, Alex Dickson et al.

* Indicates presence during commissioning at FACET-II and in remaining 2022

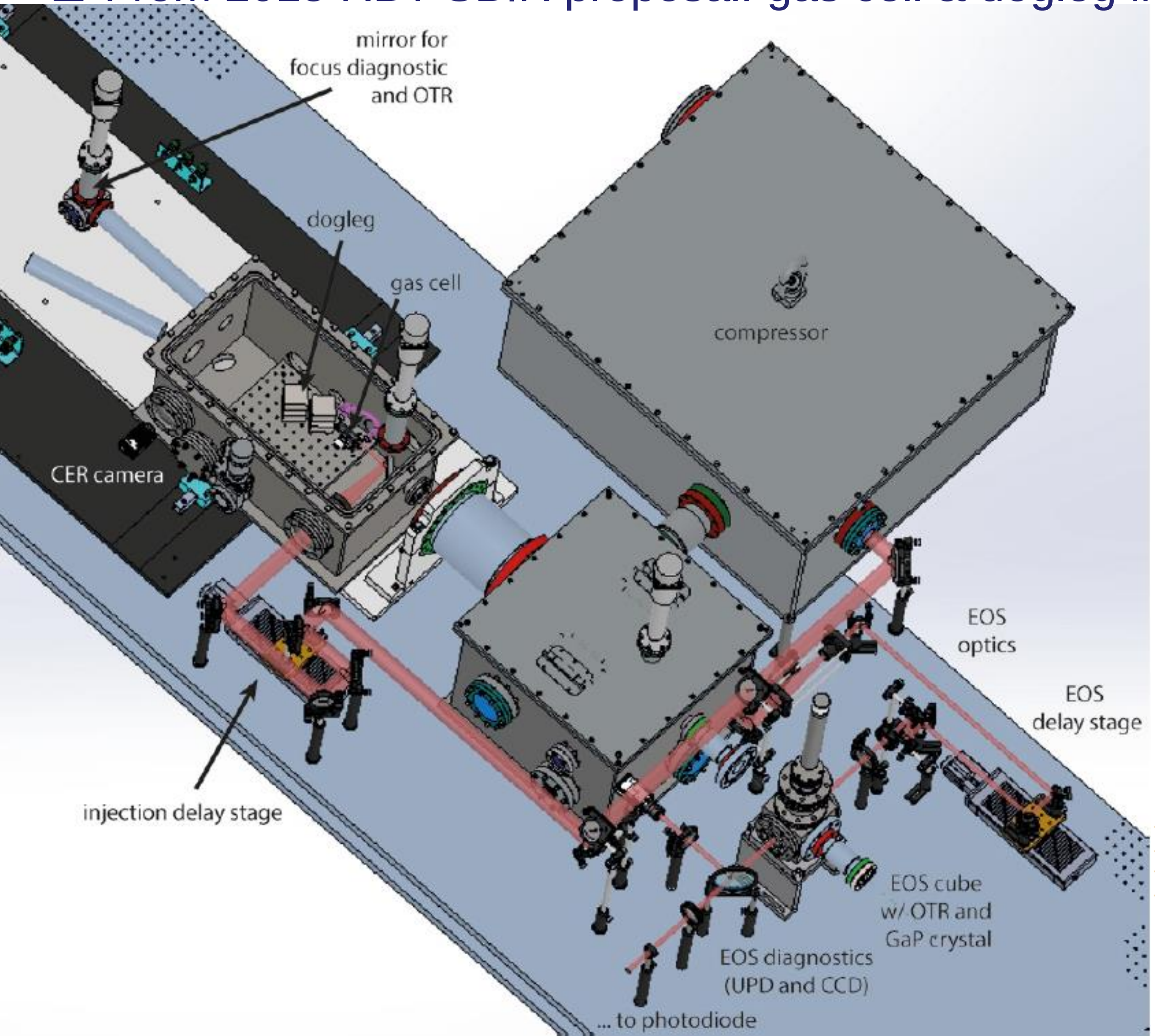
General Backup

Gas cell in picnic basket

❑ From 2018 E-310 proposal:

- Any other aspect of Importance: The above setup can be realized with various gas reservoir, either chamber completely flooded as in E210, or gas cells, or simply gas jets. The gas reservoir needs optical access for preionization and torch laser. Plasma torch laser shaping is required to shape the plasma torch.

❑ From 2015 RBT SBIR proposal: gas cell & dogleg in PB



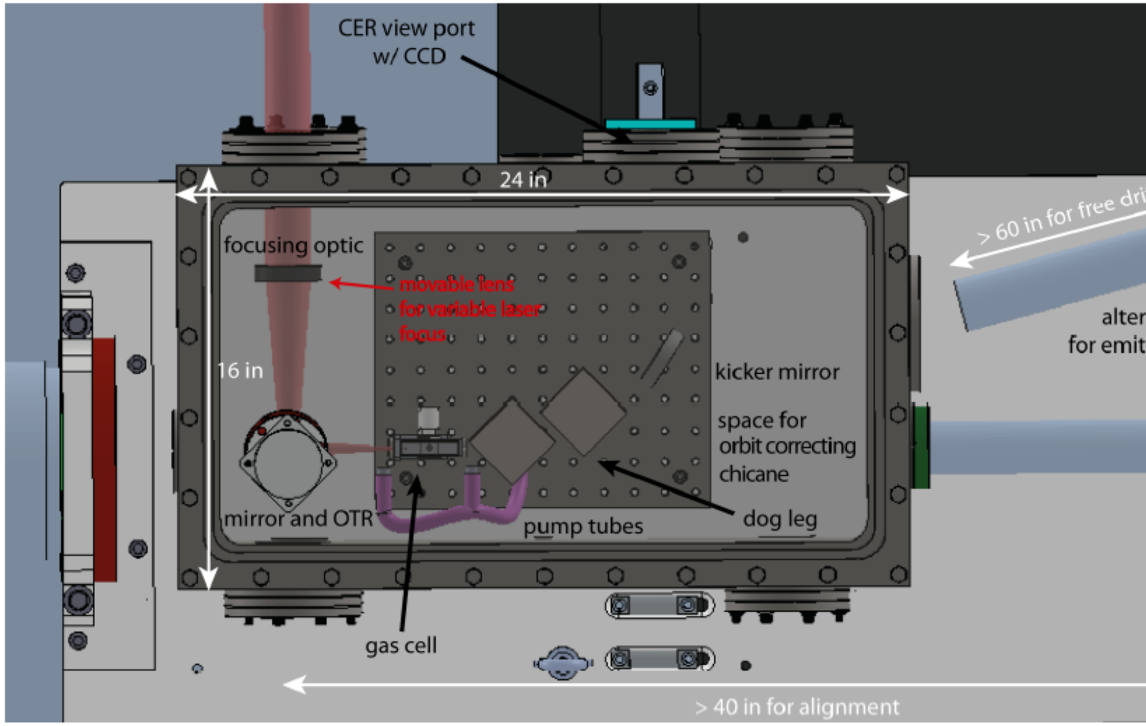
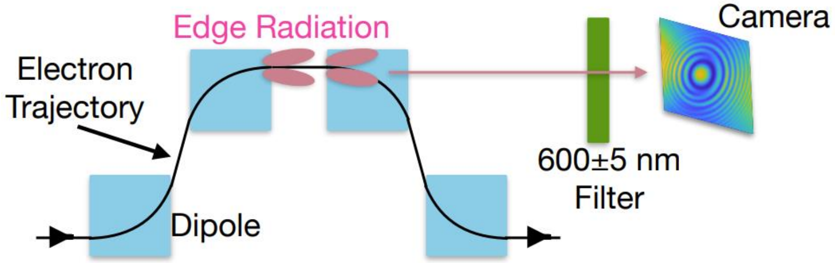
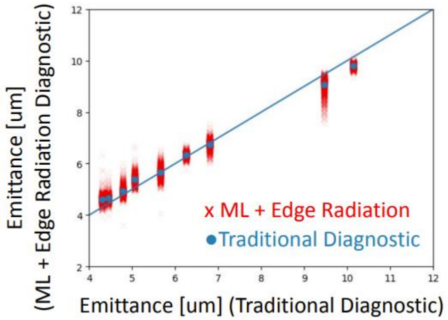


Figure 9: Rendering of proposed diagnostic section for beam characterizat FACET line with available locations was provided by SLAC.

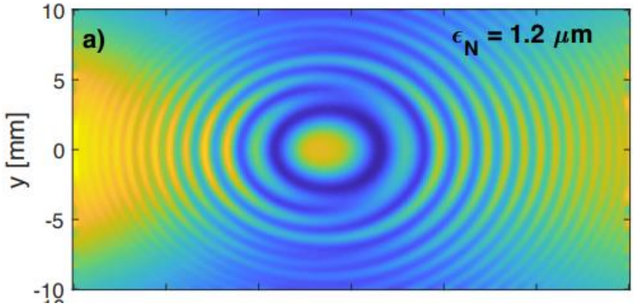
Emittance measurement options

- Multi µm-rad scale: Use existing butterfly method and test TH scalings, then trust sub-threshold trends

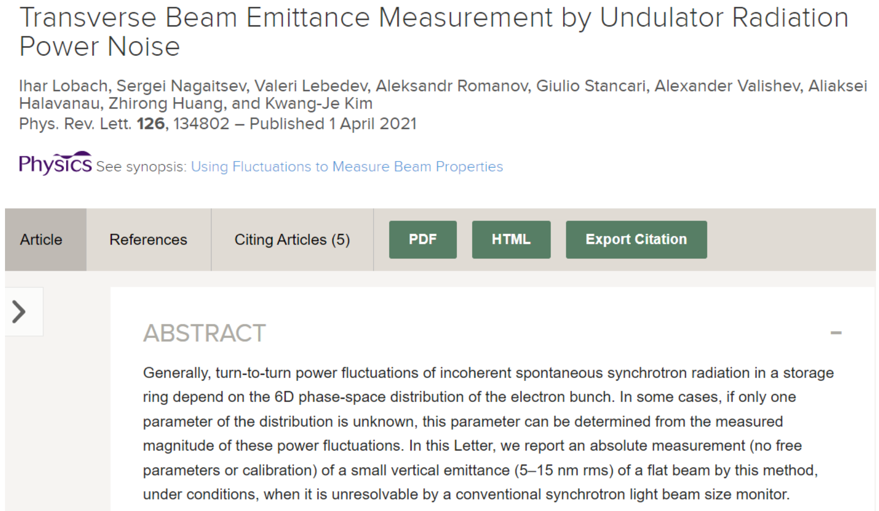




- µm-rad scale:



- Sub µm-rad scale: undulator radiation?


Transverse Beam Emittance Measurement by Undulator Radiation Power Noise

Ihar Lobach, Sergei Nagaitsev, Valeri Lebedev, Aleksandr Romanov, Giulio Stancari, Alexander Valishev, Aliaksei Halavanau, Zhirong Huang, and Kwang-Je Kim
Phys. Rev. Lett. **126**, 134802 – Published 1 April 2021

Physics See synopsis: Using Fluctuations to Measure Beam Properties

Article | References | Citing Articles (5) | PDF | HTML | Export Citation

ABSTRACT

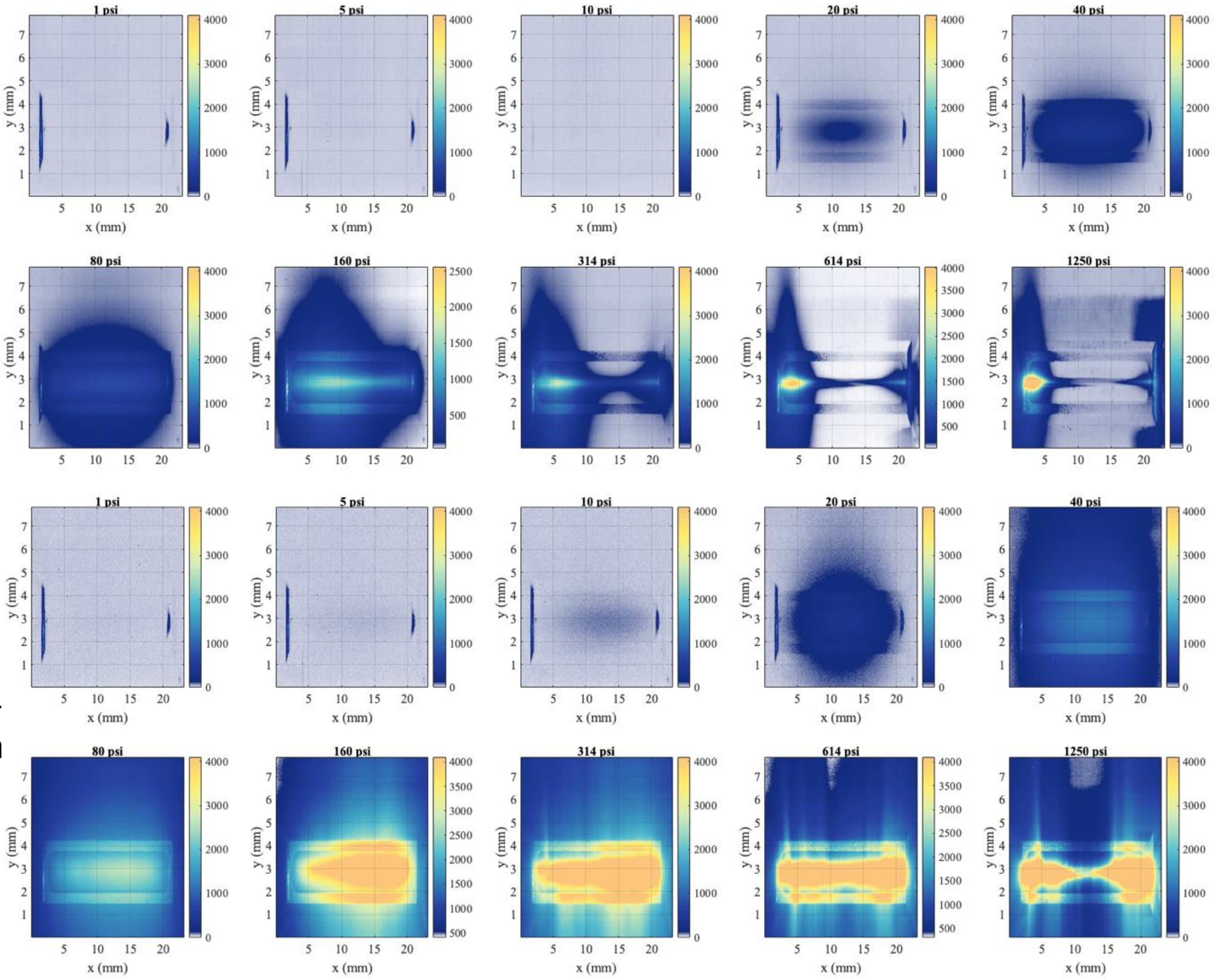
Generally, turn-to-turn power fluctuations of incoherent spontaneous synchrotron radiation in a storage ring depend on the 6D phase-space distribution of the electron bunch. In some cases, if only one parameter of the distribution is unknown, this parameter can be determined from the measured magnitude of these power fluctuations. In this Letter, we report an absolute measurement (no free parameters or calibration) of a small vertical emittance (5–15 nm rms) of a flat beam by this method, under conditions, when it is unresolvable by a conventional synchrotron light beam size monitor.

General Backup

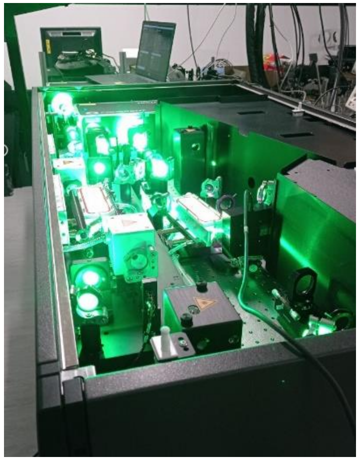
- 2 cm nozzle TopView afterglow scan from E-305 beamtime:

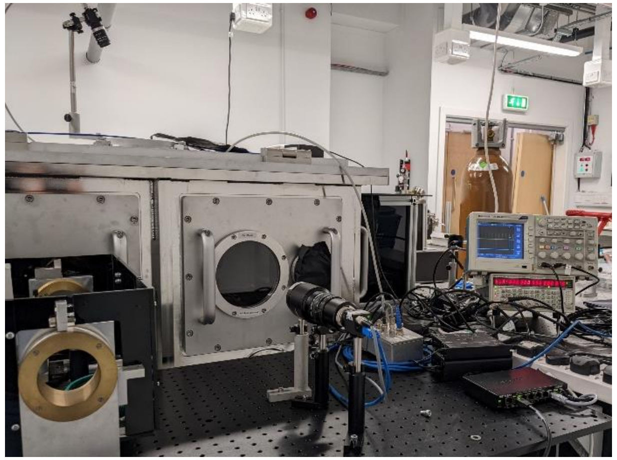
Laser only

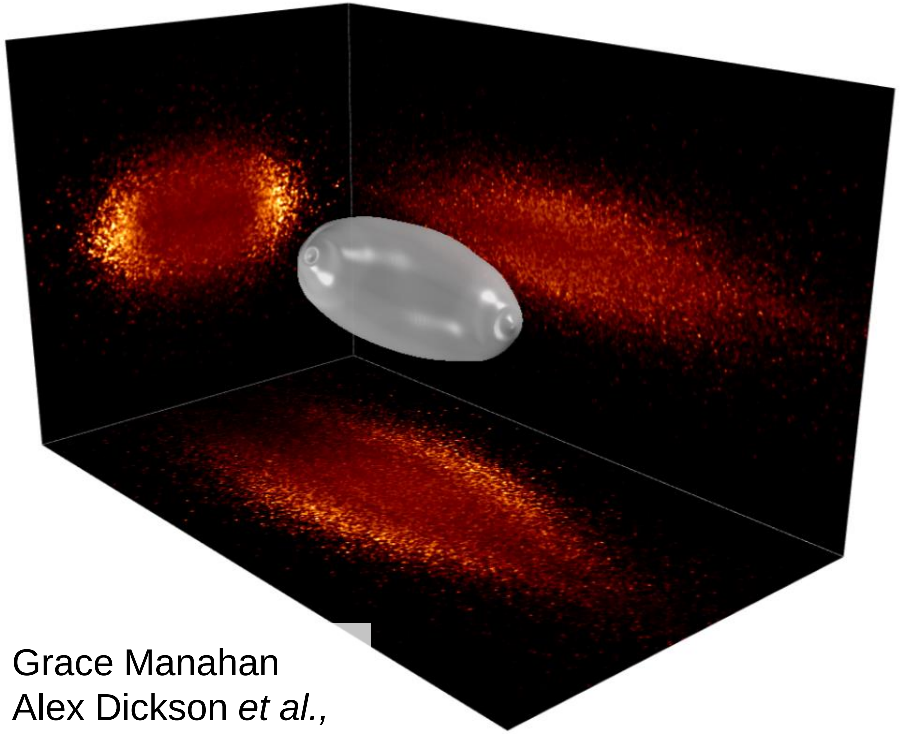
Laser + e-beam



kHz-laser @ SCAPA exploited for plasma photocathode prototypes, afterglow and doppelganger bypassline 2.0 tests







Grace Manahan
Alex Dickson *et al.*,

kHz plasma Trojan/afterglow high precision studies