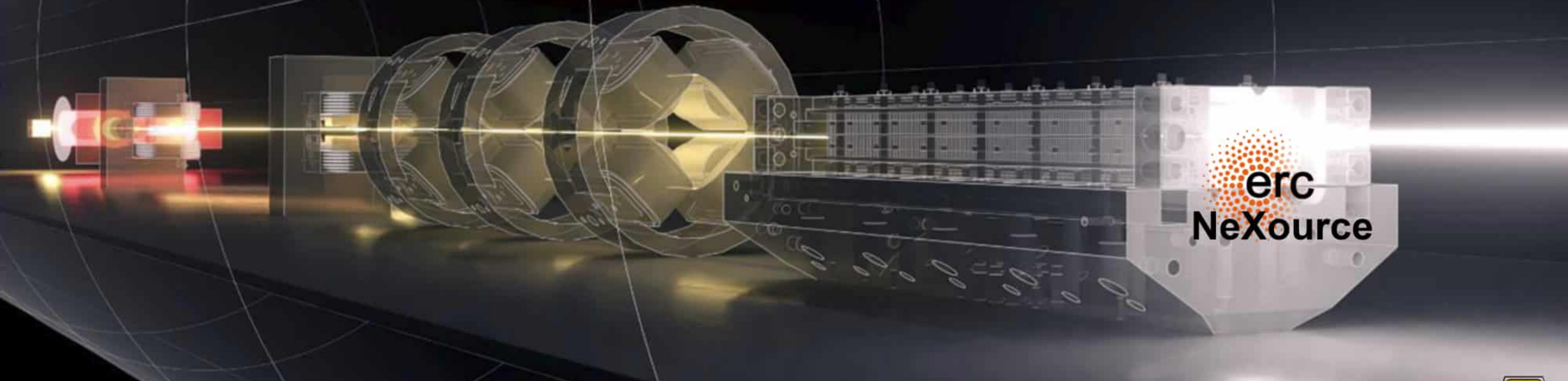
SLAC FACET-II
PAC 2023-10-18

FACET-II

hhu Heinrich Heine University Düsseldorf

E-310/311/315

Bernhard Hidding
Andrew Sutherland
Lily Berman *et al.*



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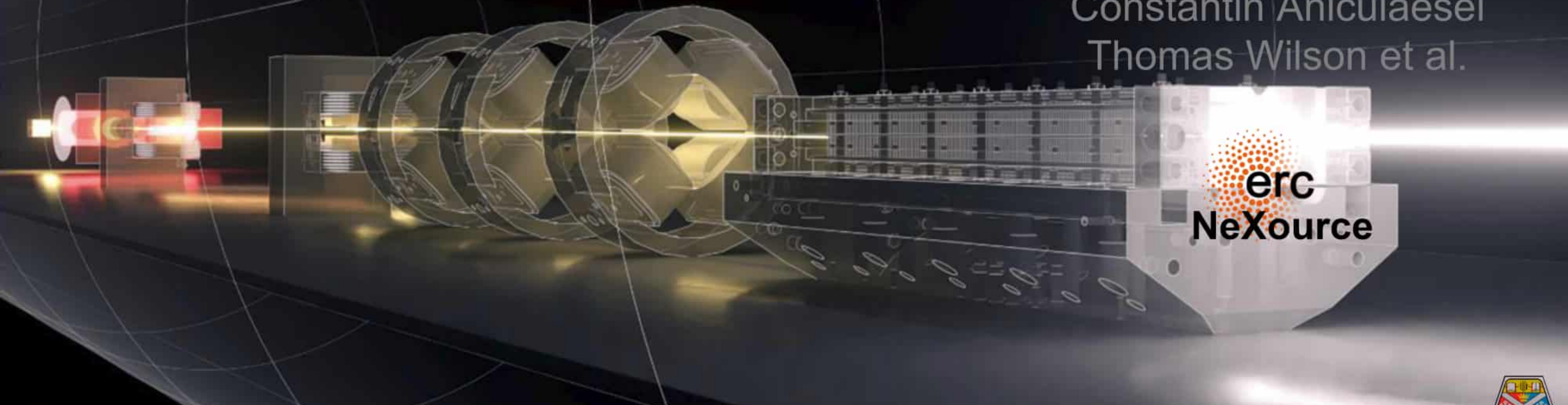

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ARCTURUS

2x200 TW + probe beam
Hybrid LWFA→PWFA
Trojan + X-FEL
Beamline
PHASER kHz system…

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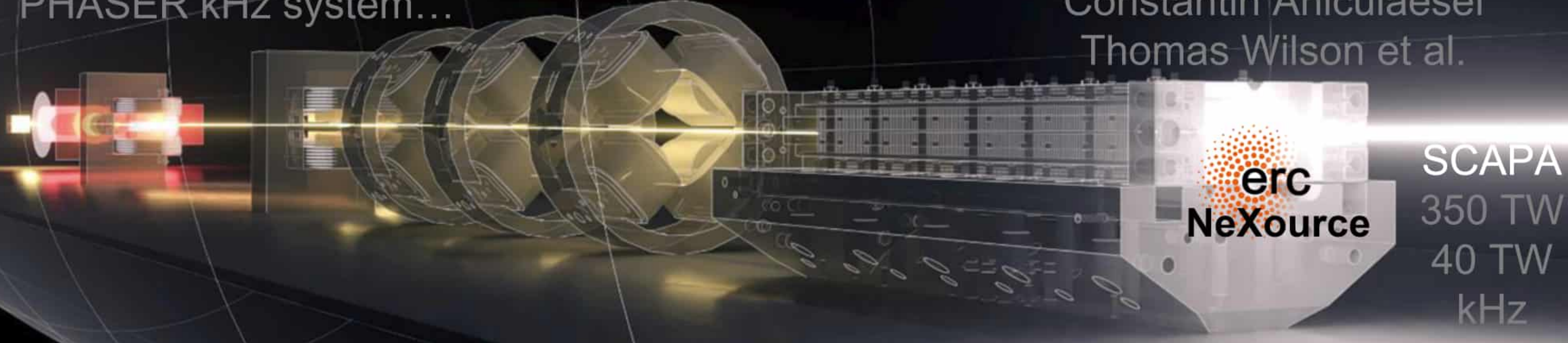

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SCAPA

350 TW
40 TW
kHz

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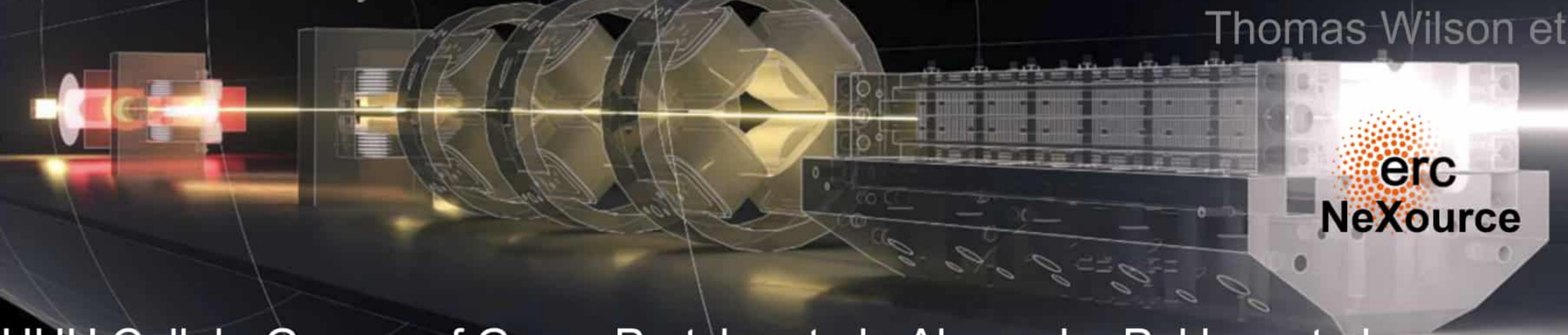

SCAPA

350 TW
40 TW
kHz

HHU Collab: Groups of Georg Pretzler et al., Alexander Pukhov et al.,
Carsten Müller et al., Markus Büscher et al. (Exp/Theory/HEP/QED)

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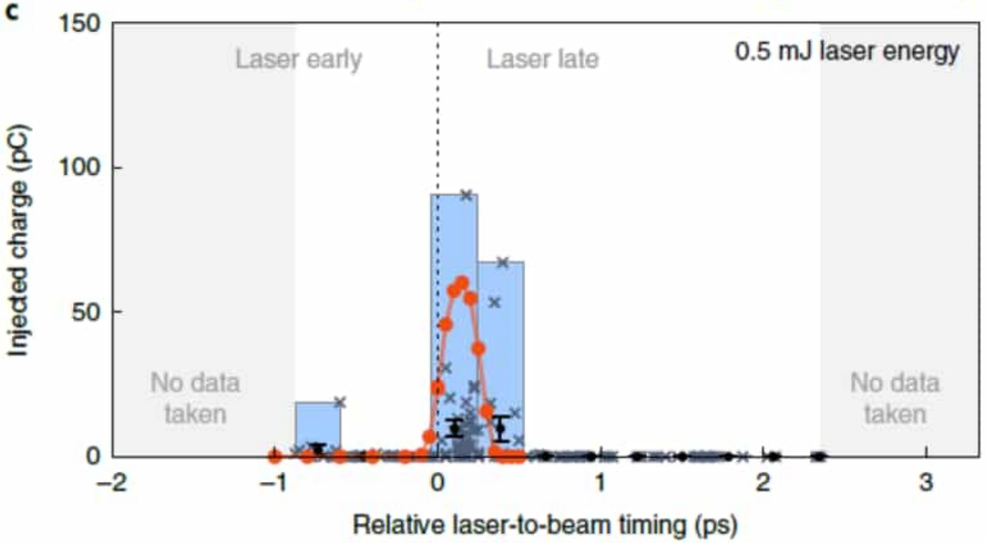
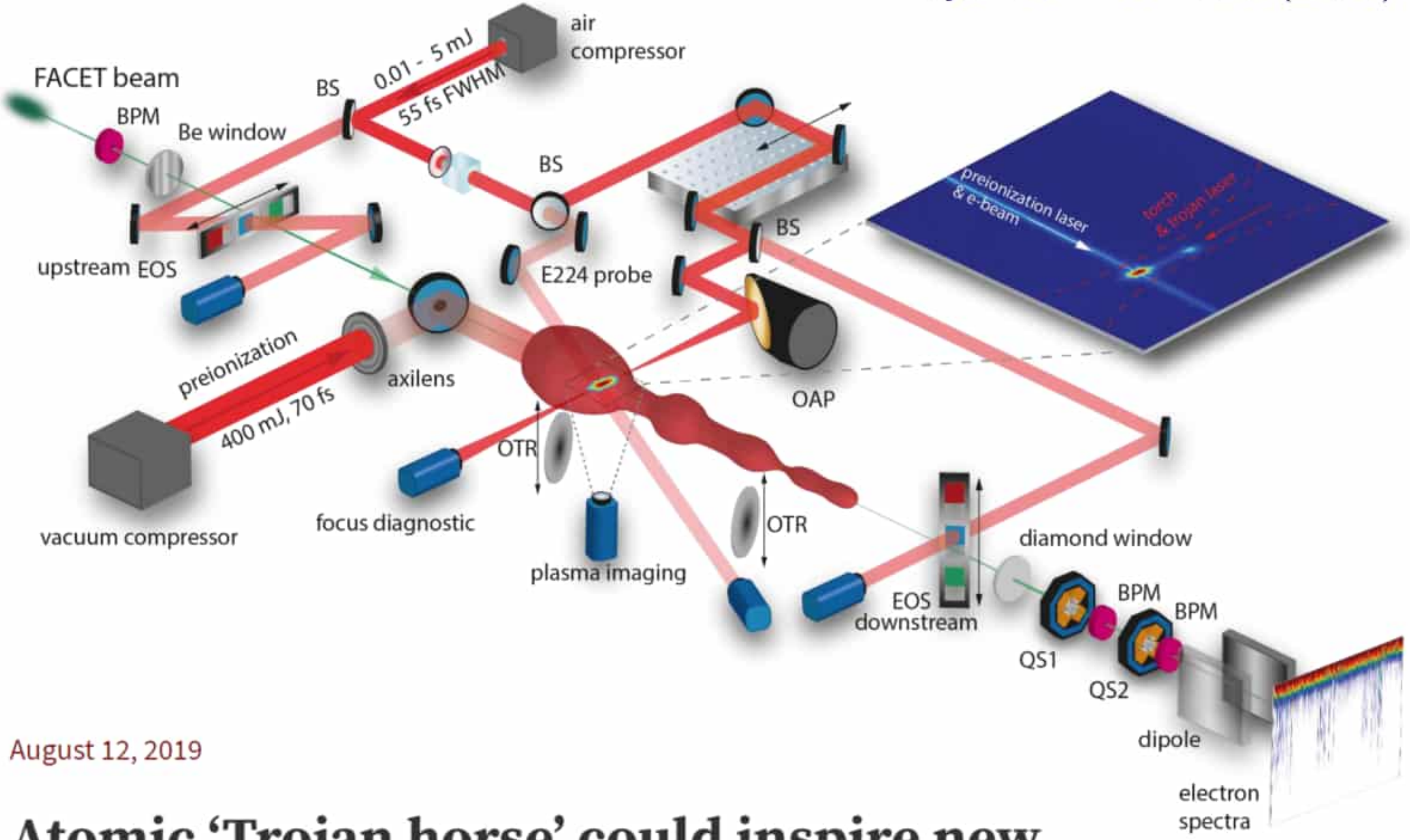
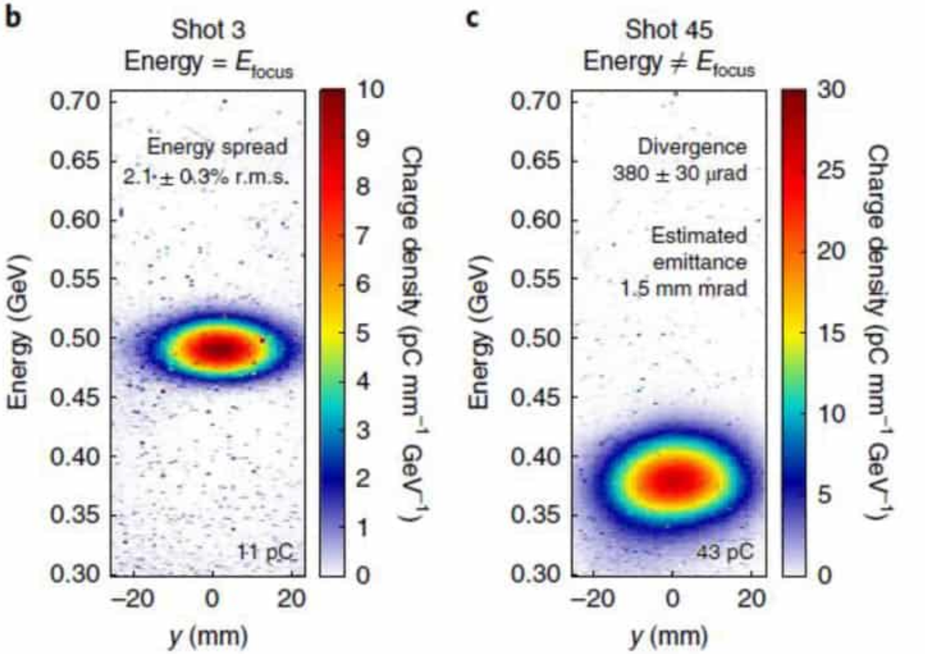
1st Realization of Plasma Photocathode

Deng, Karger *et al.*, *Nature Phys.* 15, 1156–1160 (2019)

❑ E-210 Trojan Horse, 90° geometry







August 12, 2019

Atomic 'Trojan horse' could inspire new generation of X-ray lasers and particle colliders

At SLAC's FACET facility, researchers have produced an intense electron beam by 'sneaking' electrons into plasma, demonstrating a method that could be used in future compact discovery machines that explore the subatomic world.

Plasma Photocathode review

- ❑ E-210 Trojan Horse review and cookbook
- ❑ Lessons learned and plans for E-310
- ❑ Plasma photocathode injector scans (spatiotemporal & a0)
- ❑ Wider plans and impact for X-FEL, HEP, QED etc.

REVIEW

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Plasma Photocathodes

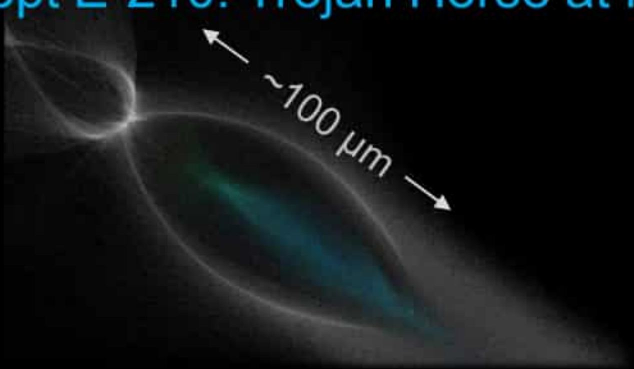
Ahmad Fahim Habib, Thomas Heinemann,* Grace G. Manahan, Daniel Ullmann, Paul Scherkl, Alexander Knetsch, Andrew Sutherland, Andrew Beaton, David Campbell, Lorne Rutherford, Lewis Boulton, Alastair Nutter, Oliver S. Karger, Michael D. Litos, Brendon D. O'Shea, Gerard Andonian, David L. Bruhwiler, Georg Pretzler, Thomas Wilson, Zhengming Sheng, Michael Stumpf, Lars Reichwein, Alexander Pukhov, John R. Cary, Mark J. Hogan, Vitaly Yakimenko, James B. Rosenzweig, and Bernhard Hidding**

Plasma wakefield accelerators offer accelerating and focusing electric fields three to four orders of magnitude larger than state-of-the-art radiofrequency cavity-based accelerators. Plasma photocathodes can release ultracold electron populations within such plasma waves and thus open a path toward tunable production of well-defined, compact electron beams with normalized emittance and brightness many orders of magnitude better than state-of-the-art. Such beams will have far-reaching impact for applications such as light sources, but also open up new vistas on high energy and high field physics. This paper reviews the innovation of plasma photocathodes, and reports on the experimental progress, challenges, and future prospects of the approach. Details of the proof-of-concept demonstration of a plasma photocathode in 90° geometry at SLAC FACET within the E-210: Trojan Horse program are described. Using this experience, alongside theoretical and simulation-supported advances, an outlook is given on future realizations of plasma photocathodes such as the upcoming E-310: Trojan Horse-II program at FACET-II with prospects toward excellent witness beam parameter quality, tunability, and stability. Future installations of plasma photocathodes also at compact, hybrid plasma wakefield accelerators, will then boost capacities and open up novel capabilities for experiments at the forefront of interaction of high brightness electron and photon beams.

1. Introduction

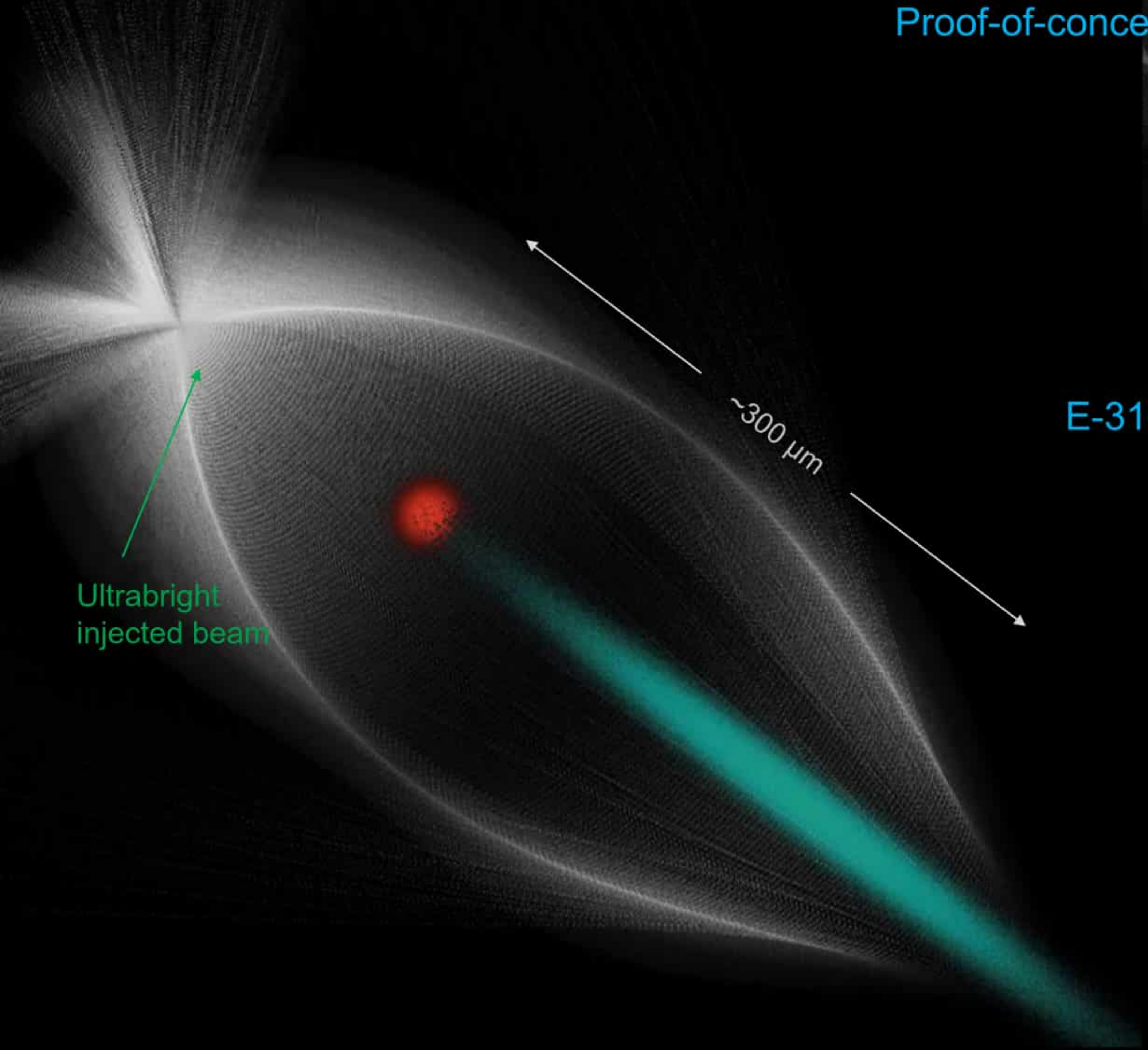
In 1887, Hertz discovered the photoelectric effect when experimenting with the generation of radiowaves.[1] Einstein's explanation of this effect[2] and the quantum theory of radiation[3] were foundational contributions for quantum and atomic physics, and the realization of the laser.[4] At the same time, particle accelerators were developed that allowed production of increasingly intense and energetic beams to investigate atomic and sub-atomic structures and processes. Prominently, the photoelectric effect is exploited in the photocathodes of modern linear accelerators, where typically infrared but then frequency-upconverted laser pulses release bursts of electrons from suitable photocathode materials. These electrons are then captured and accelerated by high-frequency radiowaves in accelerator cavities. This technologically advanced combination of Einstein's photoelectric effect and the laser, and Hertz' radiowaves, is a foundation for

Proof-of-concept E-210: Trojan Horse at FACET: µm-rad



E-310: Trojan Horse-II at FACET-II: 10 nm-rad

Collinear geometry
incoming beam precision
larger blowout



Key components for E-310, E-311 etc.

1. Stable electron beam > 5 kA, long acceleration lengths. Need strong wake that can trap cold electrons from rest.

2. Two-component gas with low ionization threshold (LIT) and high ionization threshold (HIT) component. LIT supports the wake, HIT is used to be hit by plasma photocathode laser etc. LIT and HIT combinations can be H_2/He (as at FACET) or He/He^+ or Ar/Ar^+…

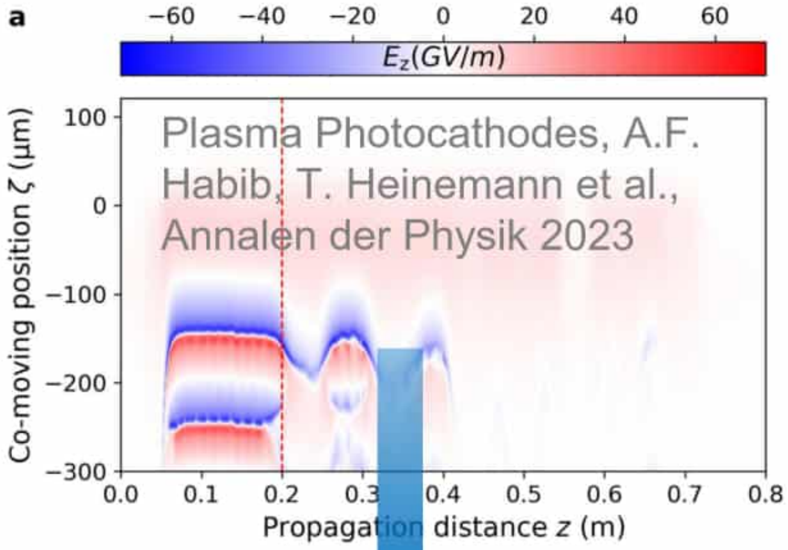
3. Wide preionized plasma channel with selective ionization capability (e.g. only LIT, not HIT)

4. Spatiotemporally synchronized injector laser pulse for Trojan Horse and Plasma Torch in 90° or collinear geometry

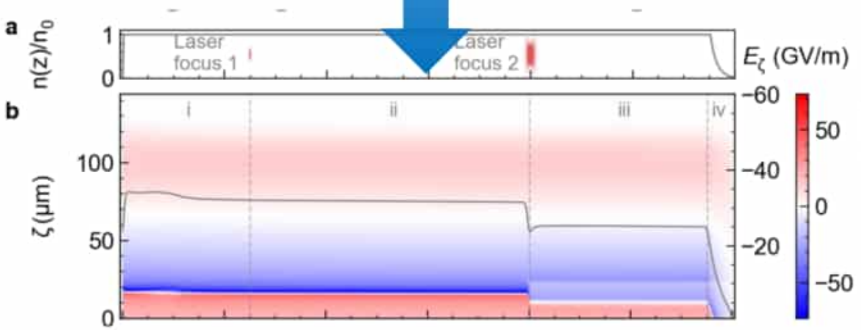
5. Injection chamber at DS plasma position for injection

Plasma source

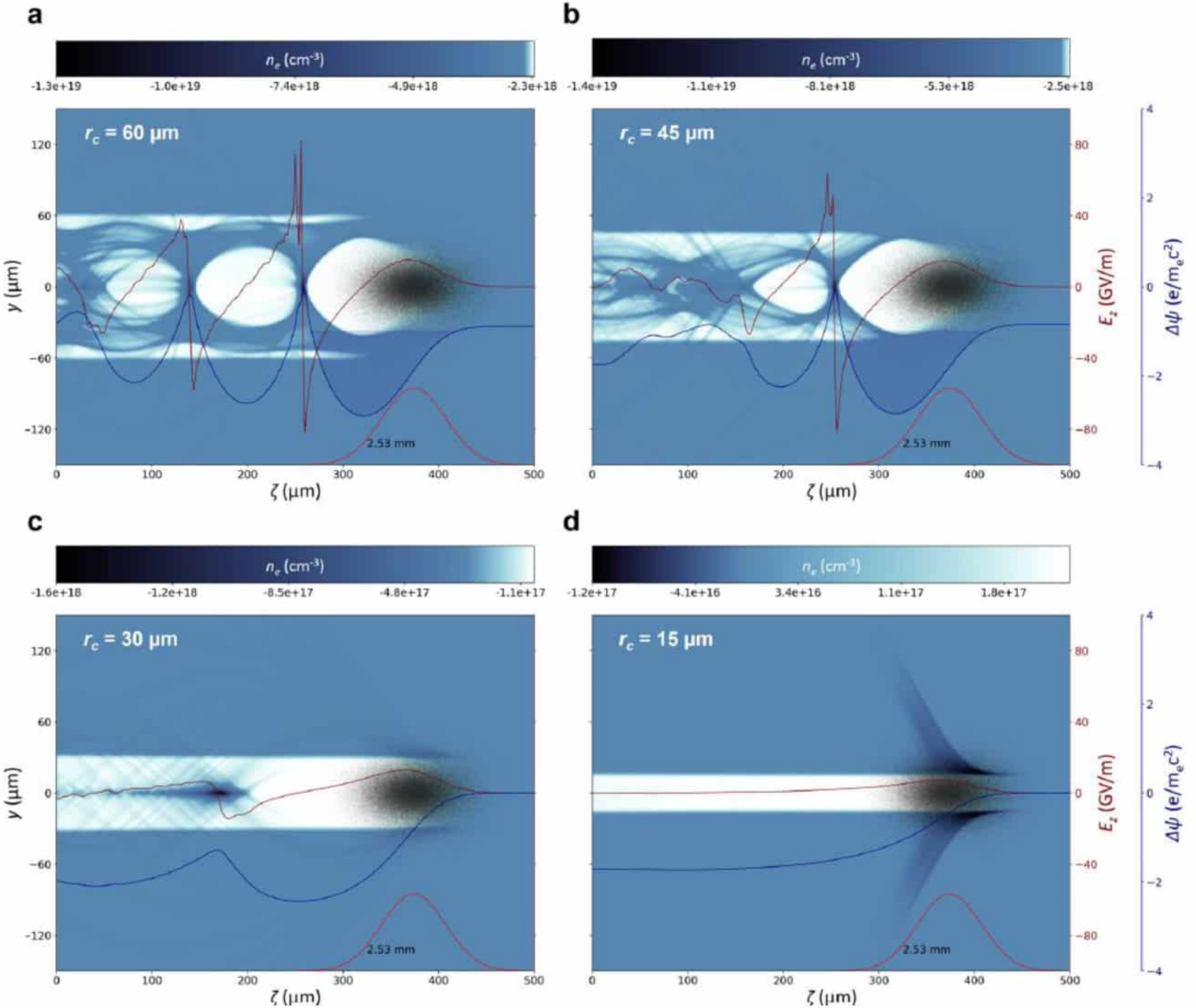
- ❑ Want wide plasma channel to host the plasma wave. If not, varying and even decelerating E-Fields, the E-210 scenario:



Plasma Photocathodes, A.F. Habib, T. Heinemann et al., Annalen der Physik 2023



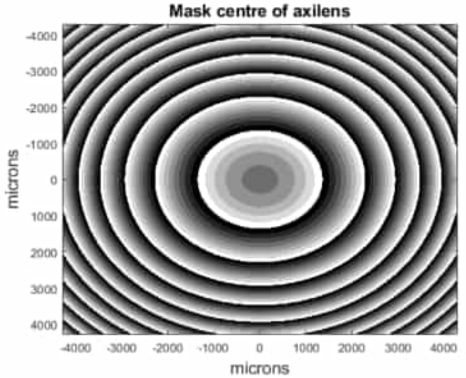
Attosecond-Angstrom Plasma-X-FEL, A.F. Habib et al, Nat. Comm. 2023



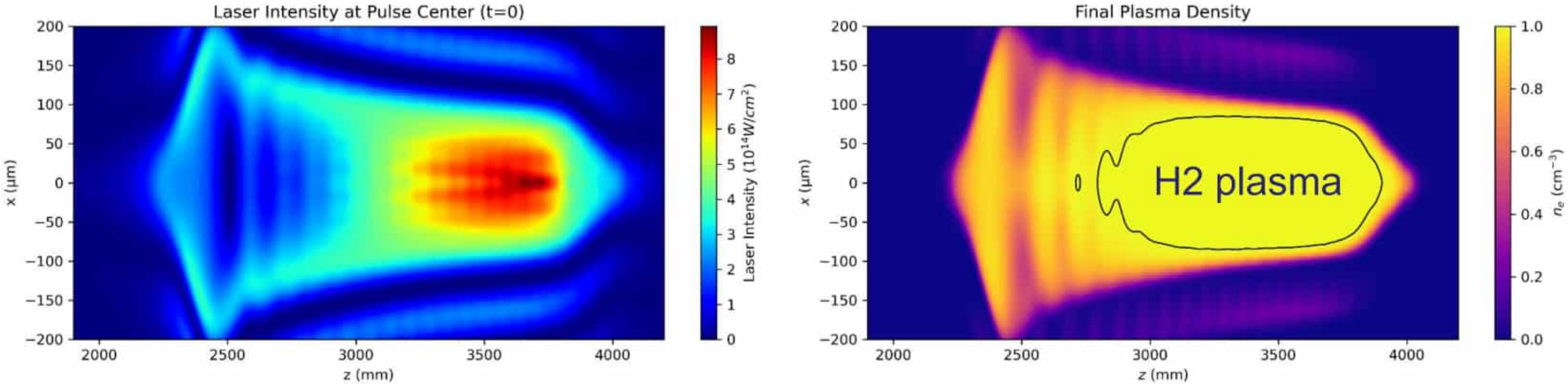
Plasma source E31x

- Used U Colorado code (M. Litos et al., link to E-301) to design optimum optics for plasma channel generation (Adam Hewitt)

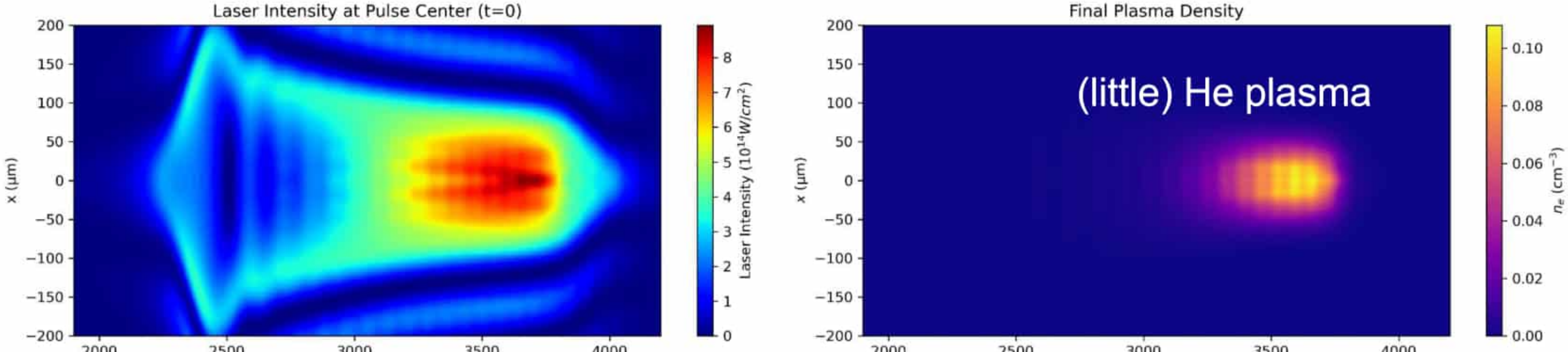
> Chip size: 44 mm
> Active area: 40 mm diam.
> Substrate thickness: 1 mm>
> Material: Fused silica
> Total depth: 1160 nm
> Levels: 8



- E.g. w/ 212 mJ, 55 fs FWHM, 20 mm top-hat intensity profile in H2/He:

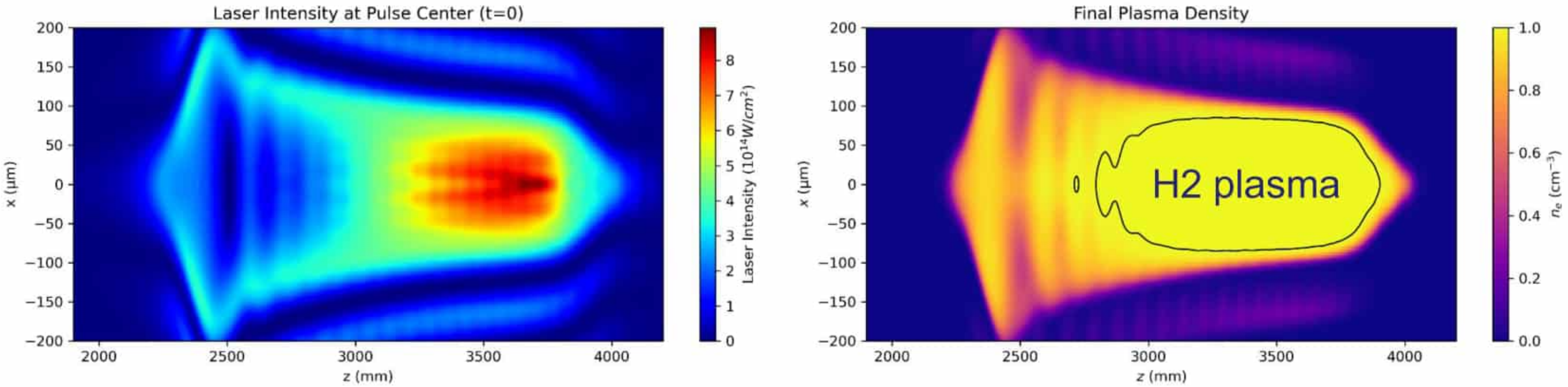


Big fat H2 plasma in 3.6e16 cm^{-3}, λ_p~175 μm

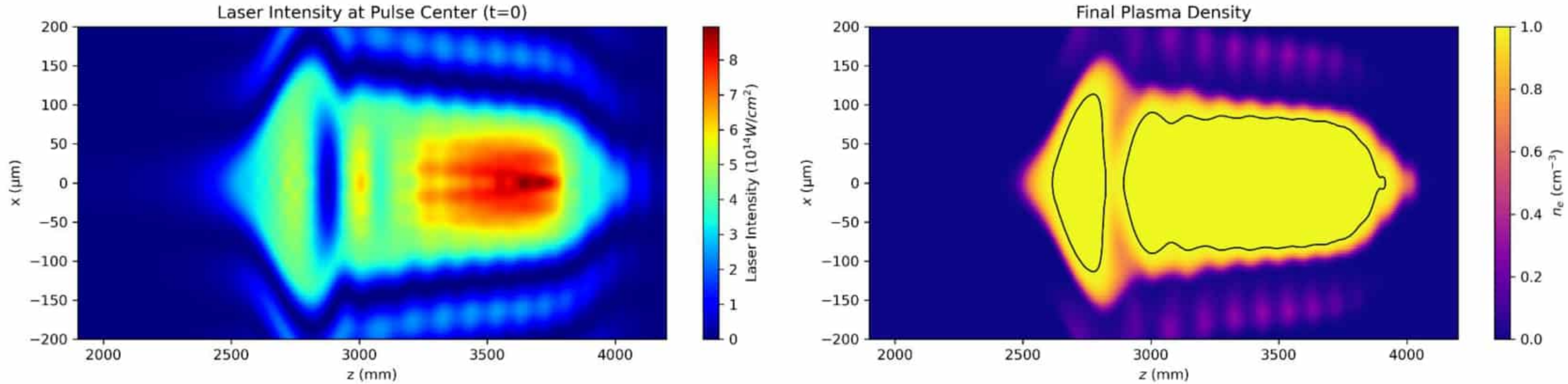


Plasma source E31x

- ❑ First plasma blob not fully ionized, not useful.

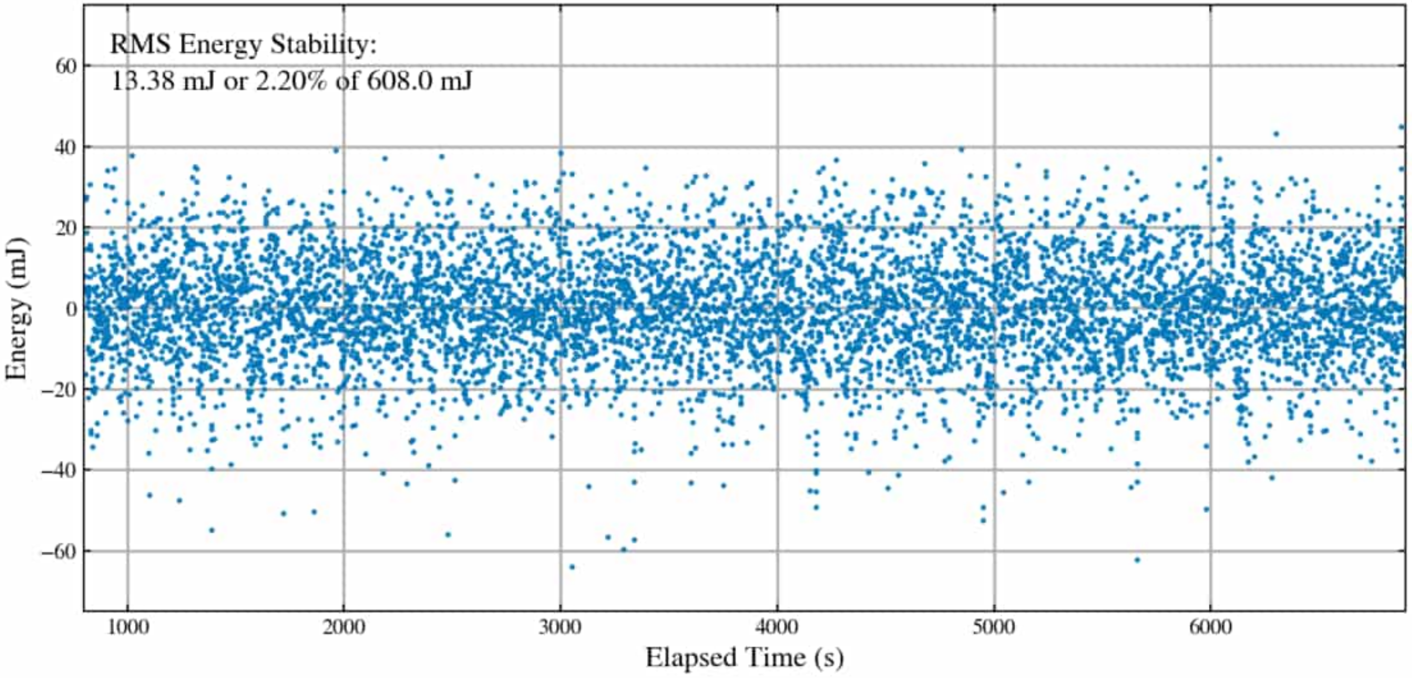


- ❑ Can get rid of this part by using central masks:

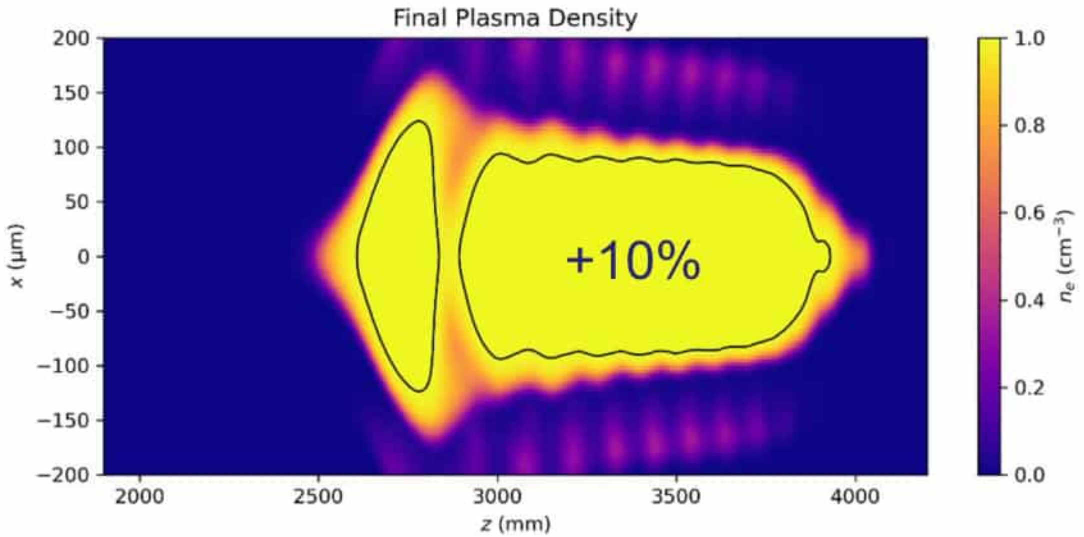


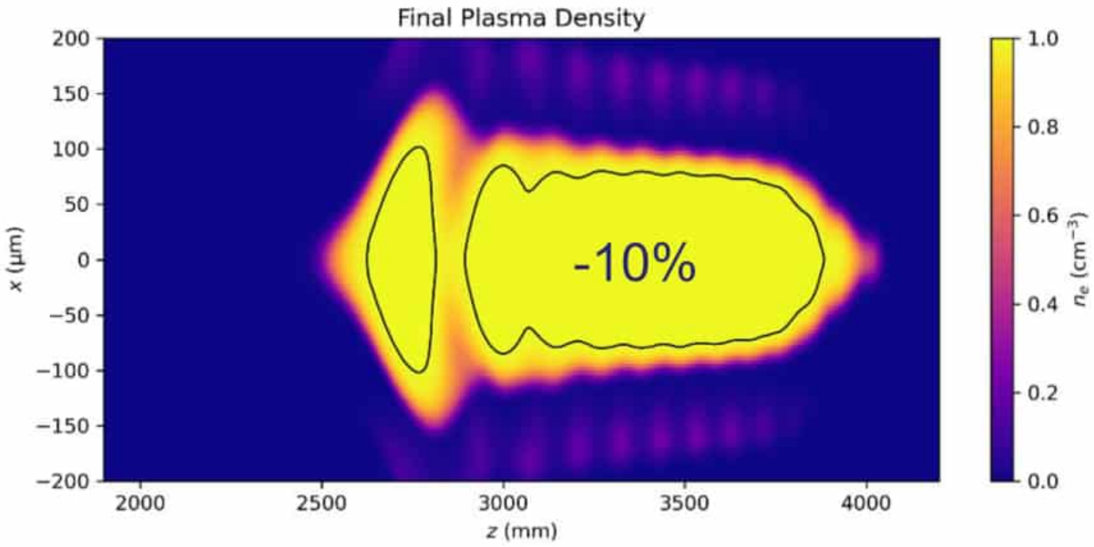
Plasma source E31x

- ❑ Is preionization laser energy jitter critical?



Maximum variance 60 mJ, so ~10% at 600 mJ

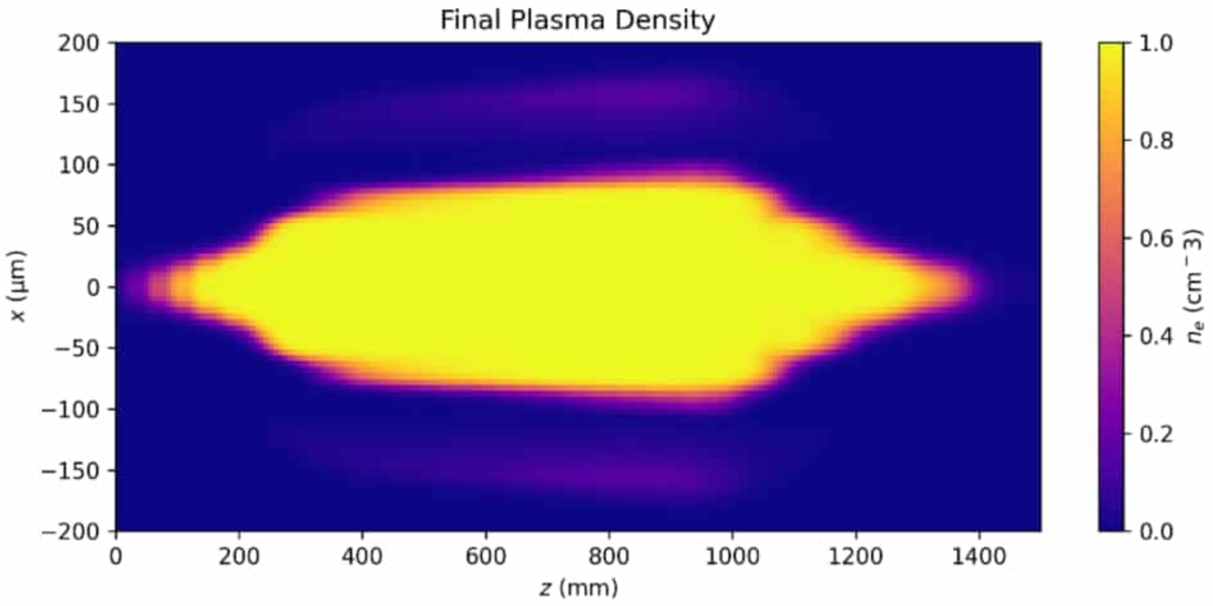


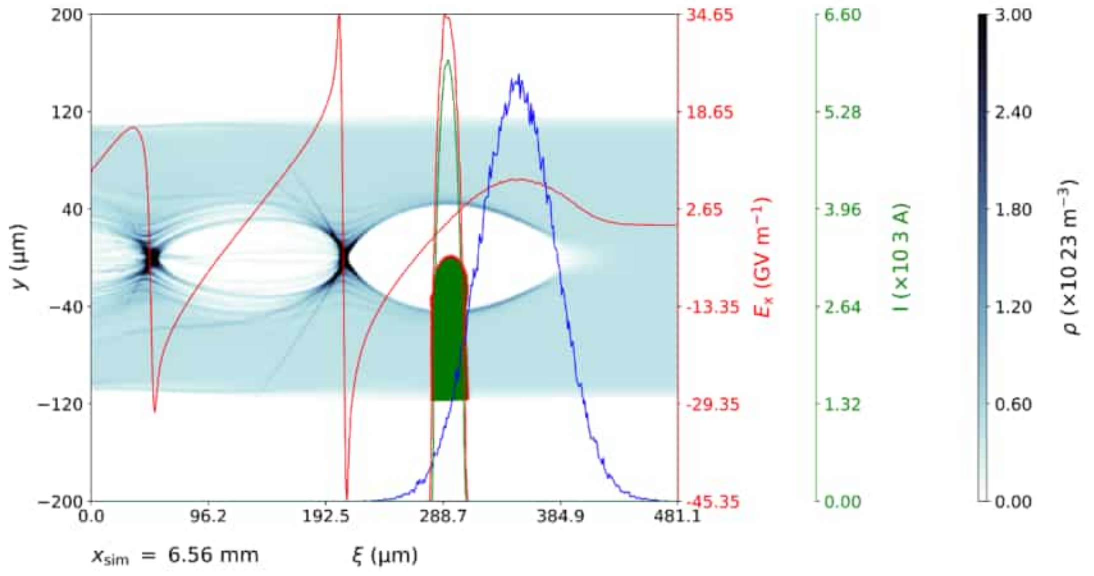


- ❑ No, plasma is robust. There is a bit more He in the hot spot region, but no problem for acc. or injection

Plasma source: tandem lens (E-301)

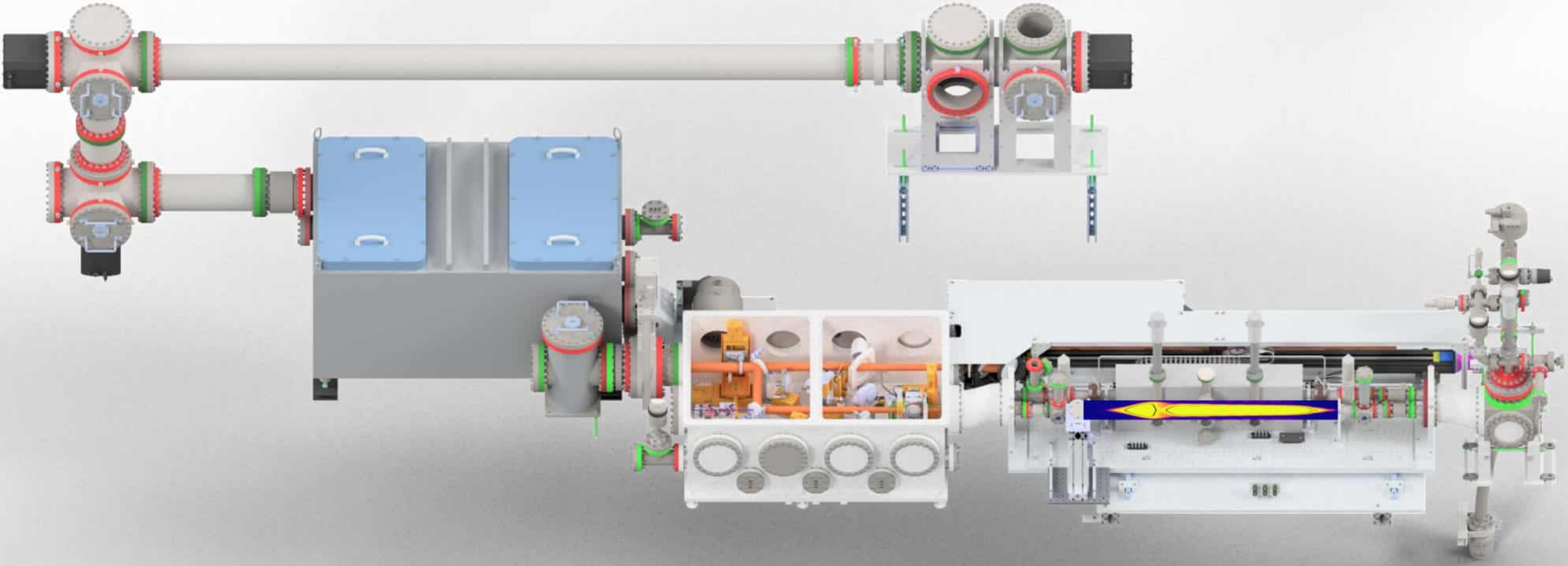
- Can also operate with tandem lens in first runs
- Using a slightly higher gas density of 4.5e16 cm^{-3} produces a good plasma channel that can be used for Trojan Horse (or plasma torch) injection, shown here in 90° geometry



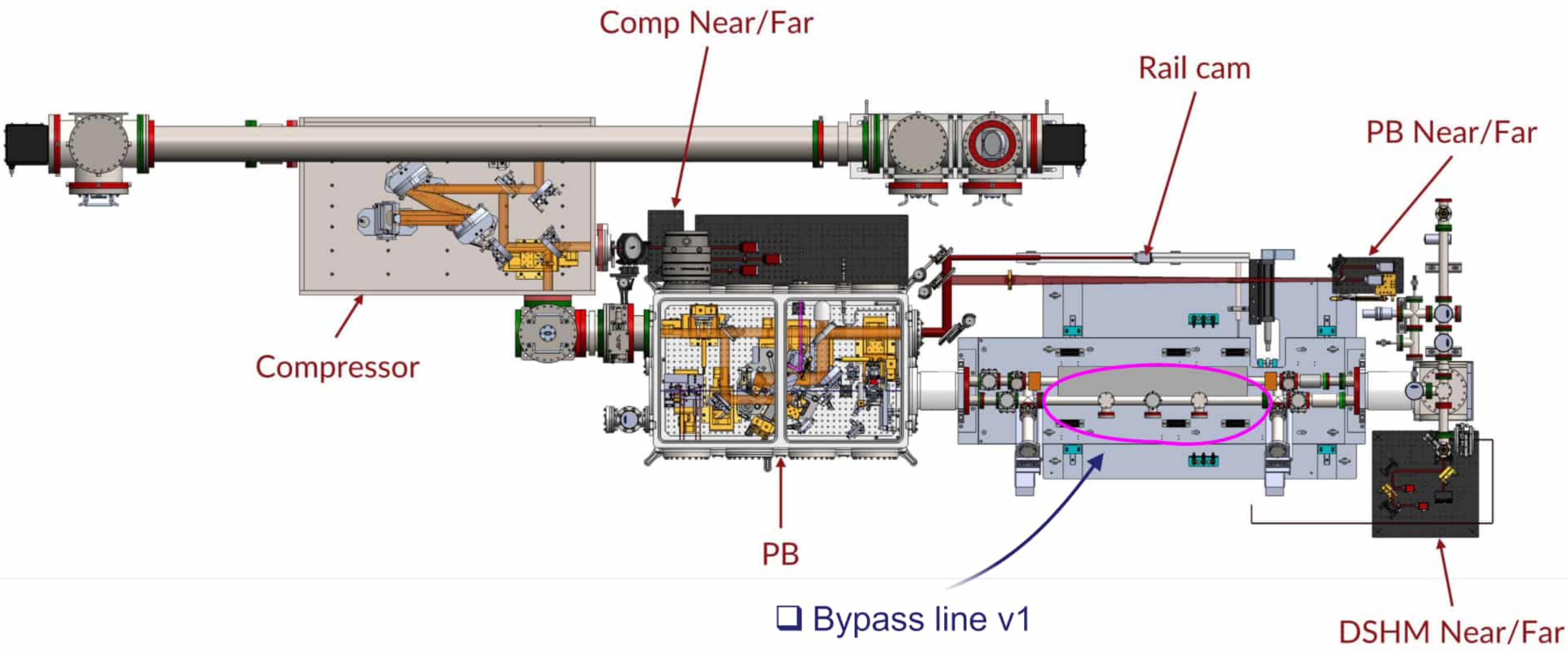


Plasma source

- Plasma to be generated in “bypass line v2.0”



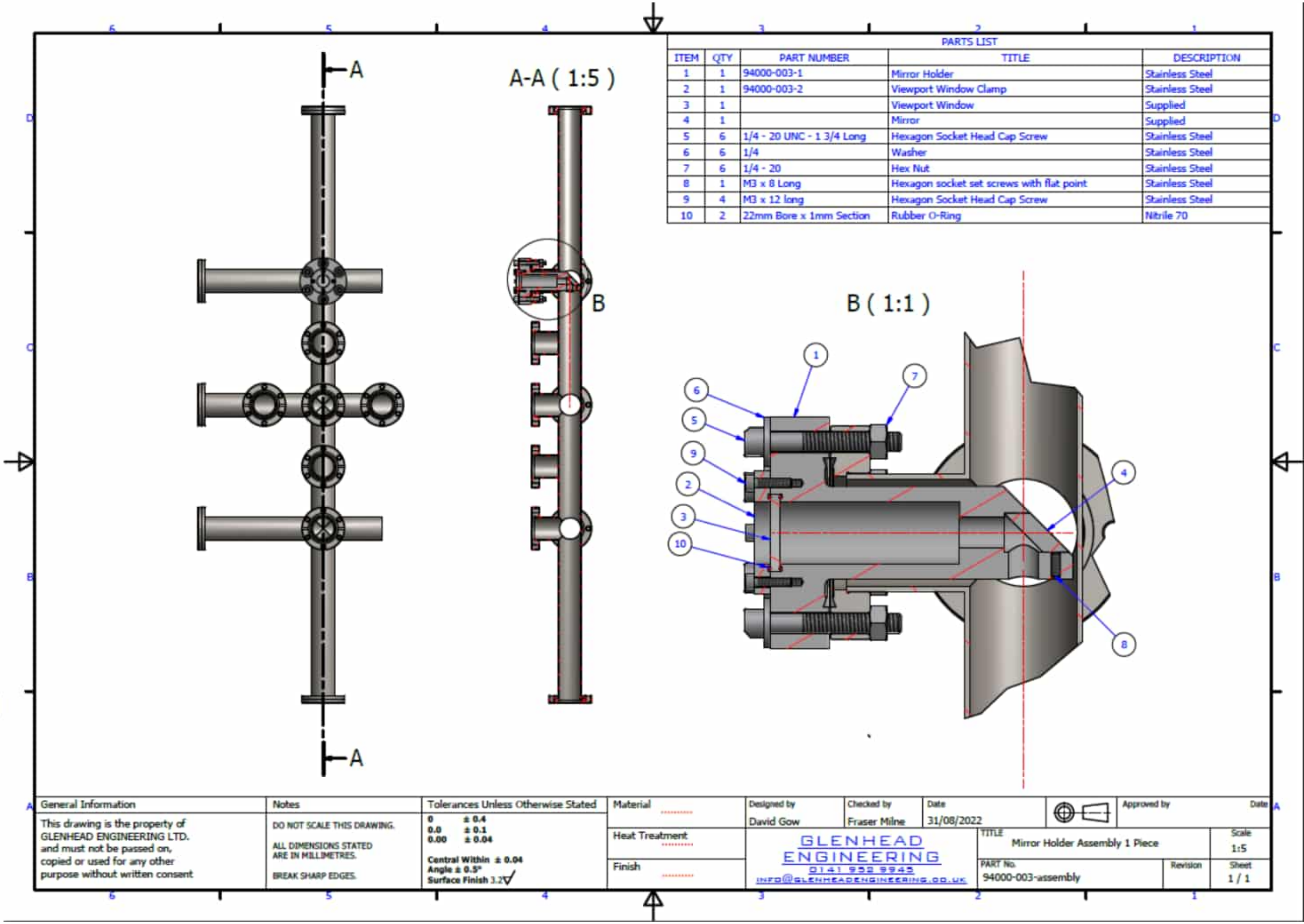
Optical setup in the tunnel before 2023



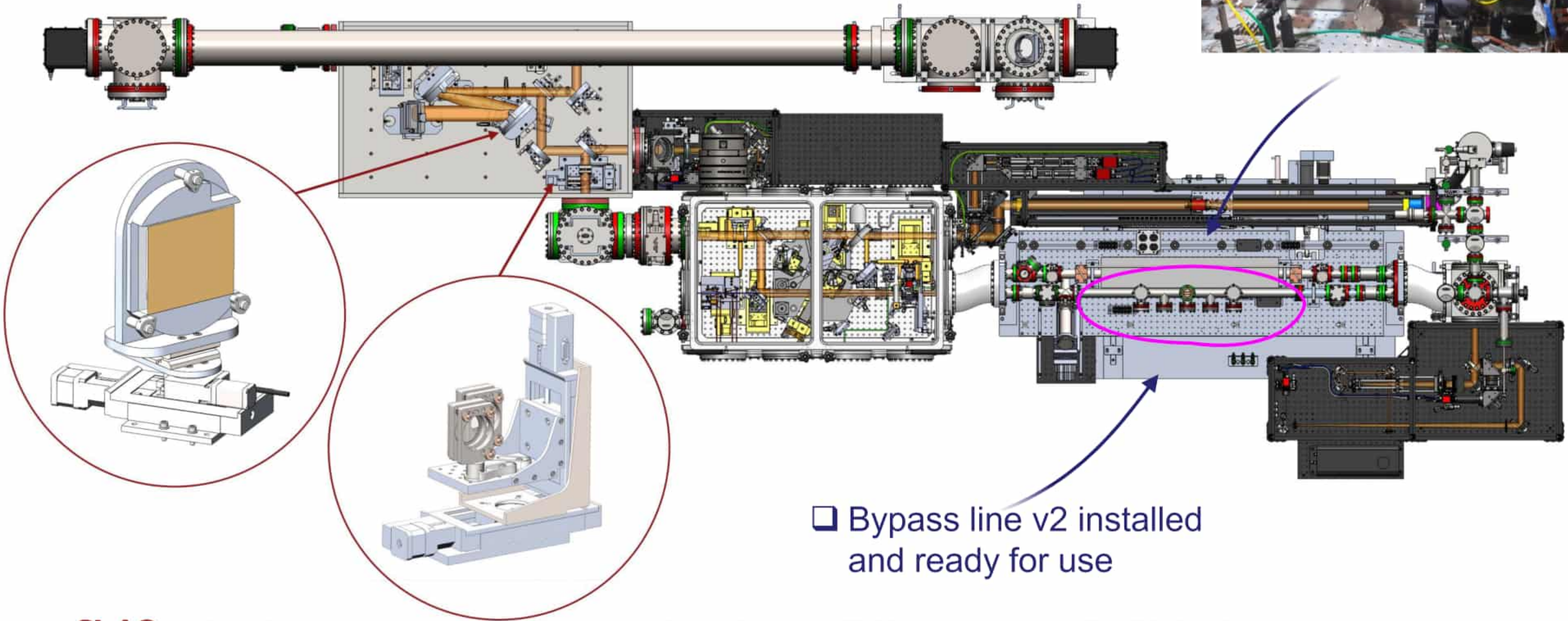
- ❑ Bypass line v1

Bypass line 2.0

- ❑ 2 twins produced in Scotland (Sutherland)
- ❑ One shipped to SLAC, the other kept in UK&Germany used for further prototyping
- ❑ Designed to facilitate
  a) more viewports (e.g. for plasma source imaging such as E-301 and E-31x) and
  b) to allow Trojan and plasma torch injection in 90° and collinear



Optical setup in the tunnel now



- Bypass line v2 installed and ready for use

Bypass line 2.0

- 2 twins produced in Scotland (Sutherland)
- One shipped to SLAC, the other kept in UK&Germany used for further prototyping
- Designed to facilitate
  a) more viewports (e.g. for plasma source imaging such as E-301 and E- 31x) and
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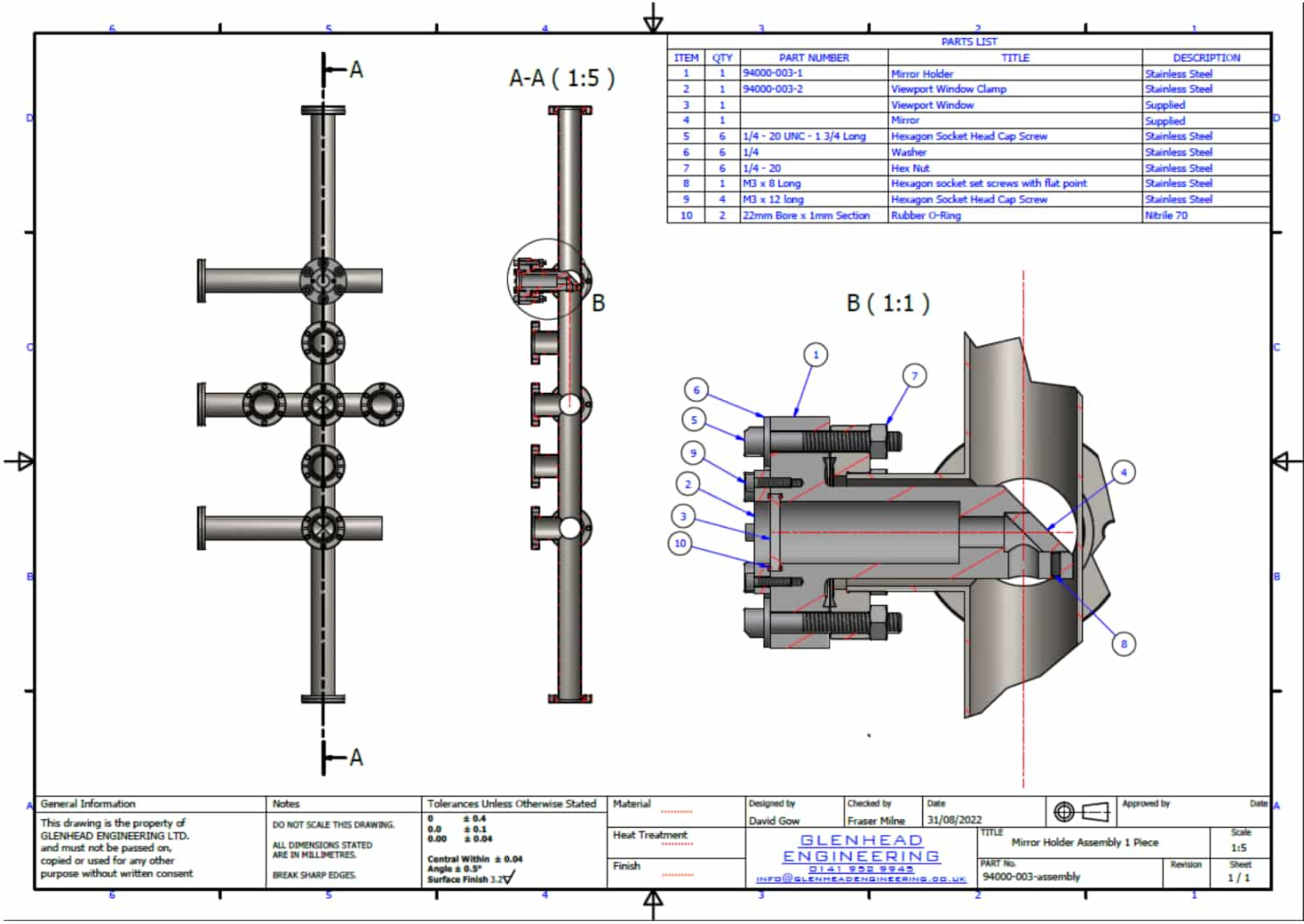
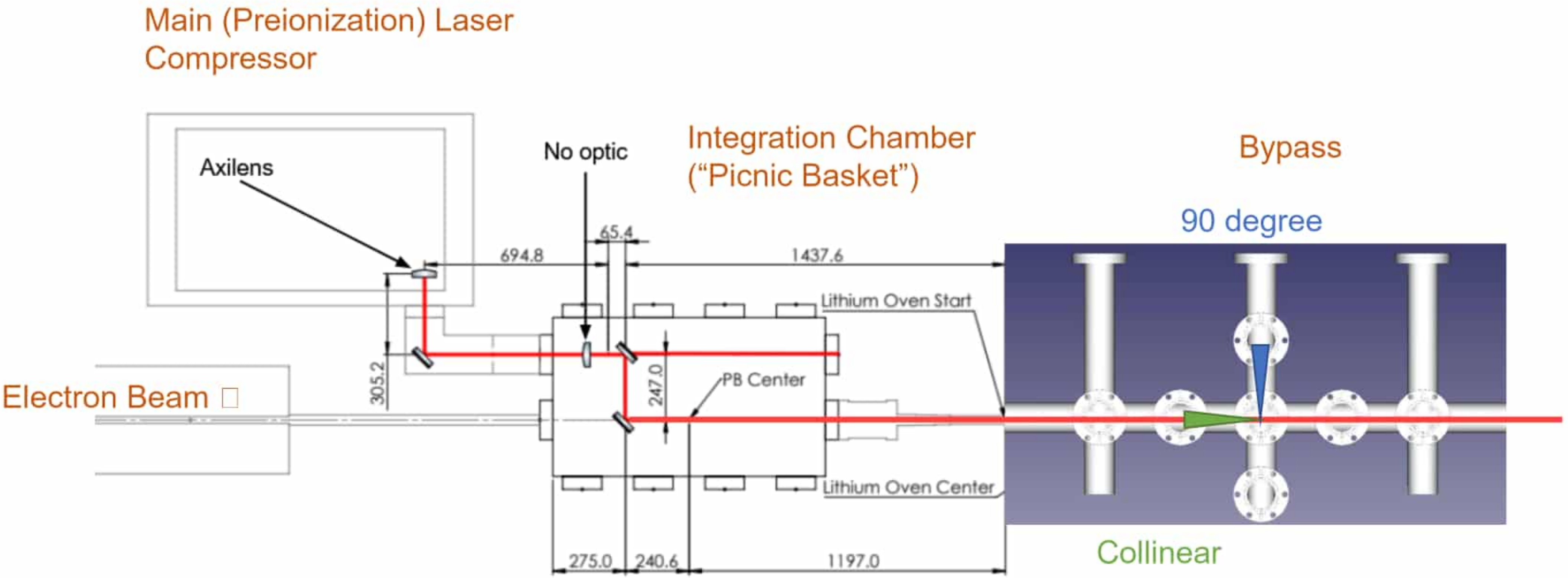
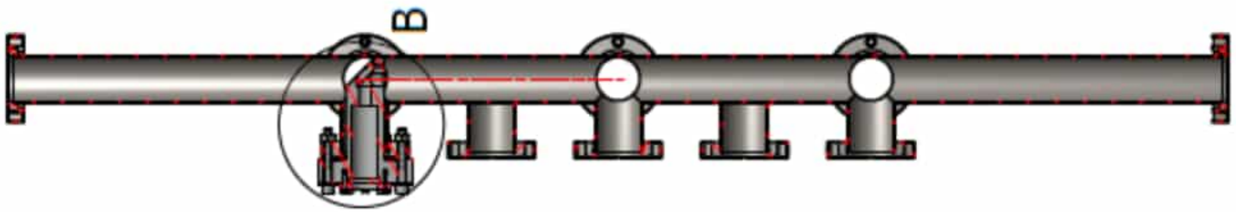


Bypass line 2.0 can facilitate collinear and 90° injection

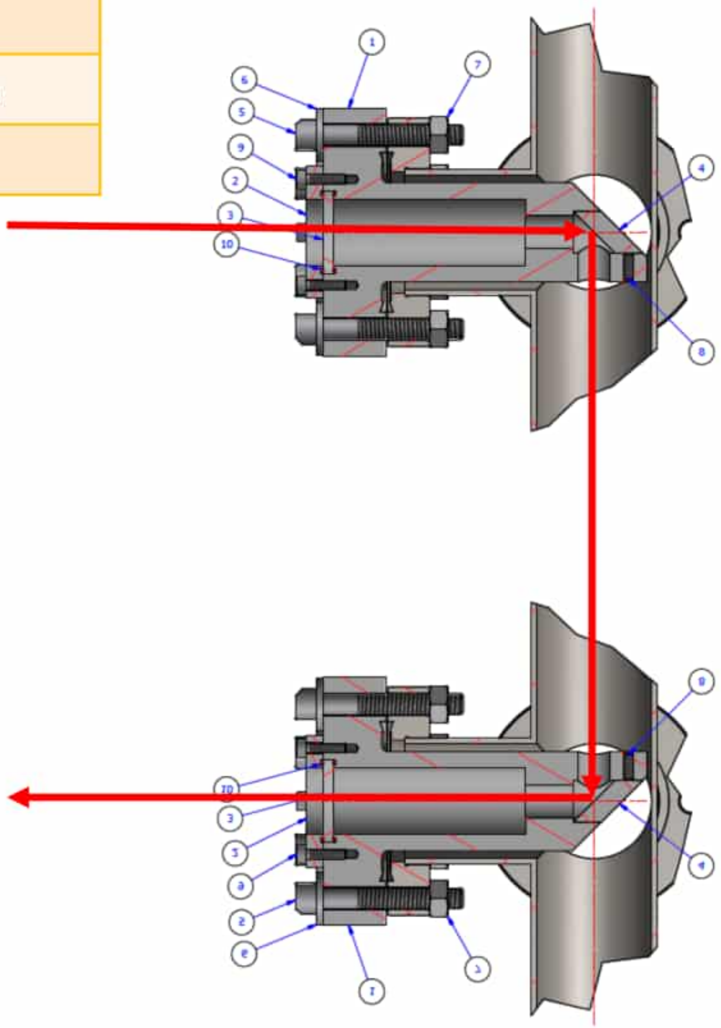


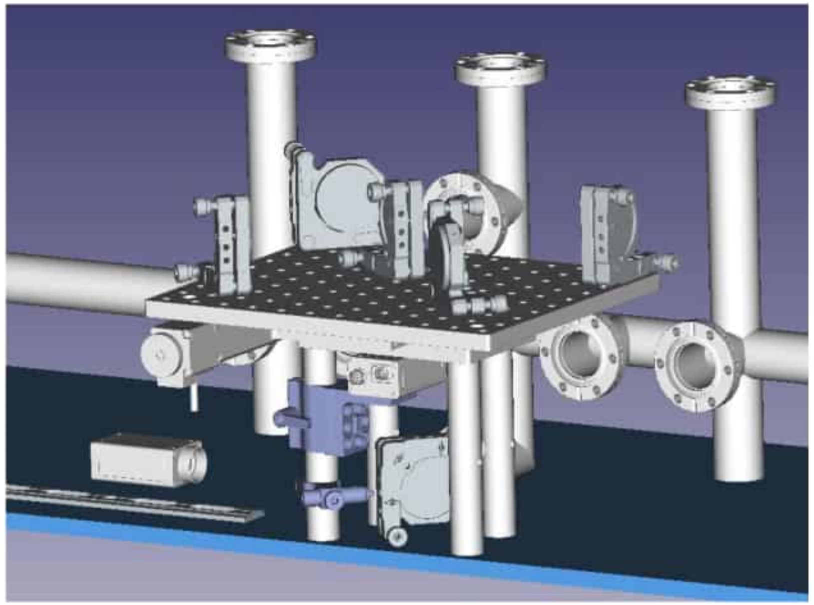
E-310 injection prototyping



Energy	0.5	mJ
Duration	60	fs
waist	9	um
a0	0.0489	

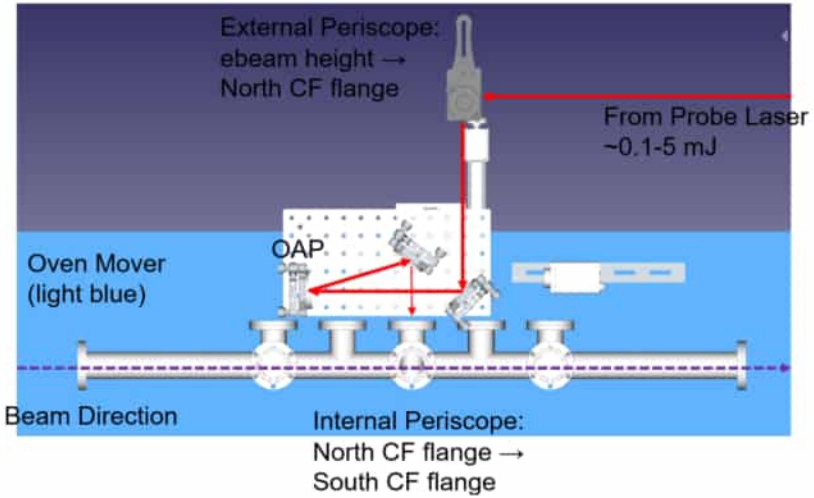
❑ 90° Internal Mirror Holders





❑ Equipment for Trojan Horse designed to accommodate injection in bypass.

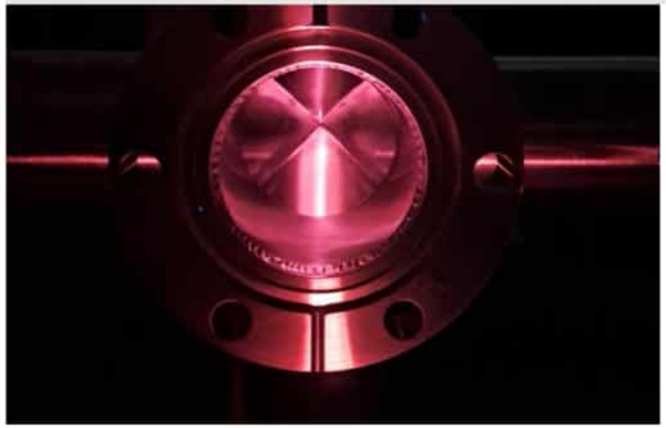
❑ Opto-mechanical layout designed for integration onto oven mover table

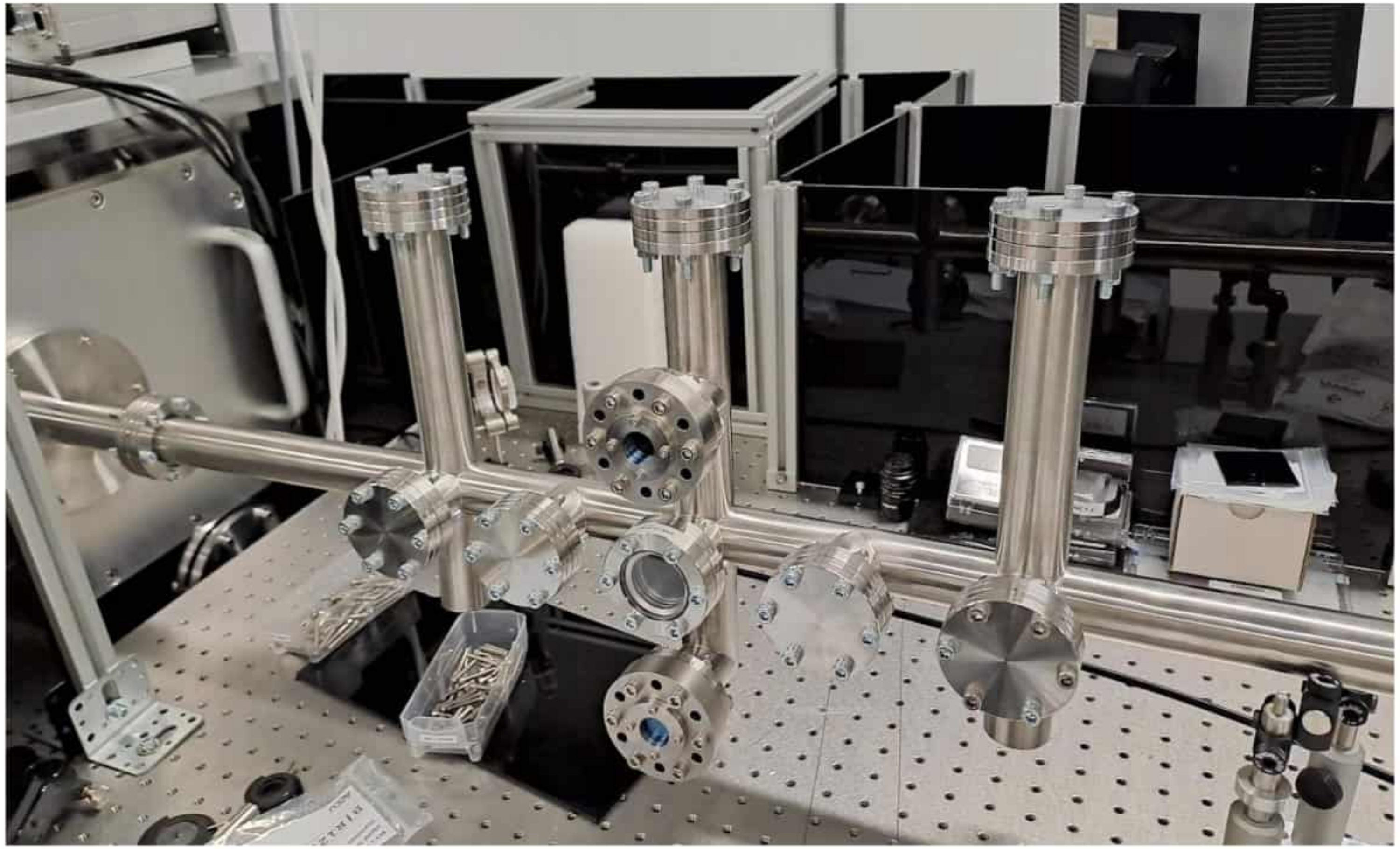


E-310 injection prototyping

- ❑ 90° Internal Mirror Holders

- ❑ Air alignment and ionization

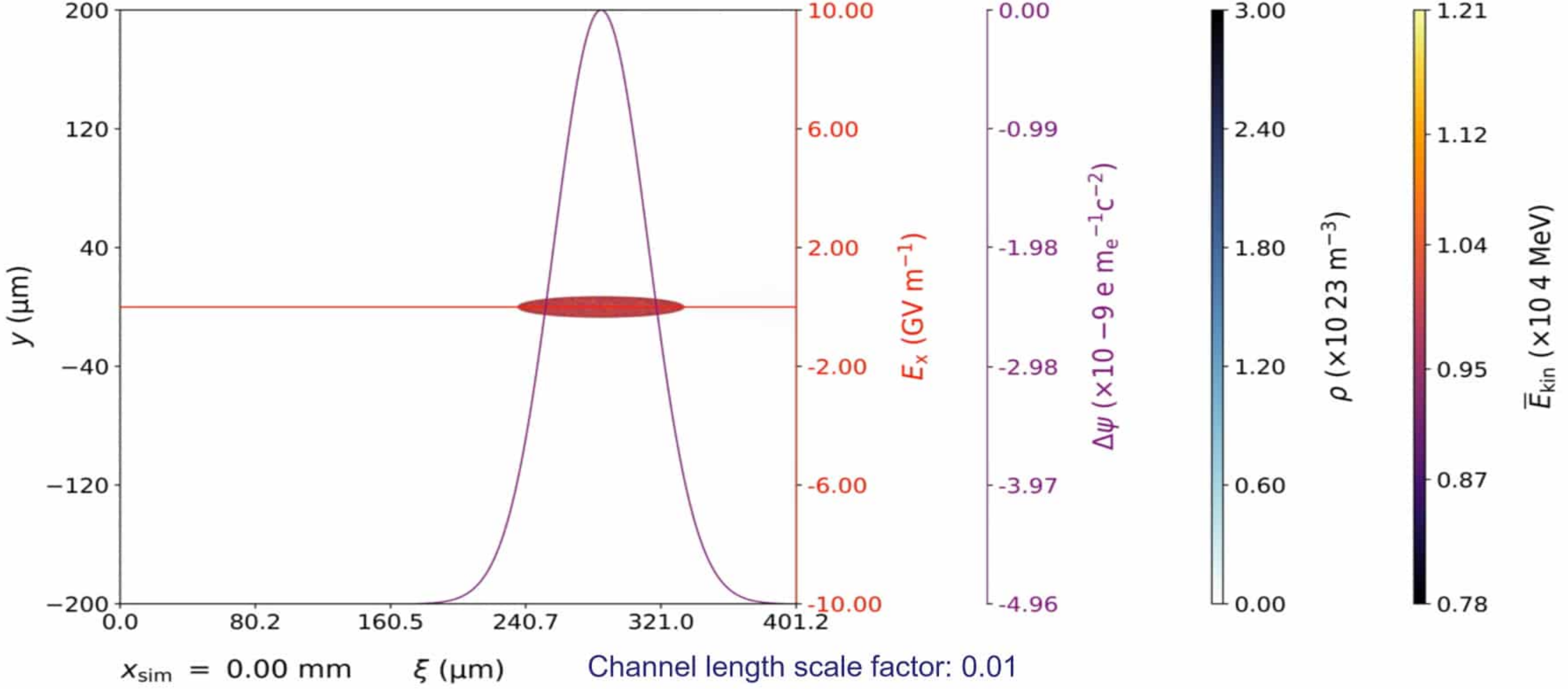




- ❑ Replica bypass and optical path successfully tested at Strathclyde
- ❑ Next step: ionization and observation of afterglow at replica gas FACET-II conditions

Example PWFA simulation in E-310 axilens

- ❑ Import plasma channel profile into simulation
- ❑ Collinear injector laser, a_0 = 0.0172



E-310 plasma photocathode jitter scans

- Various scans of plasma photocathode jitter, spatiotemporal timing and transverse offset, a0

- E.g. transverse offset by 10 µm:

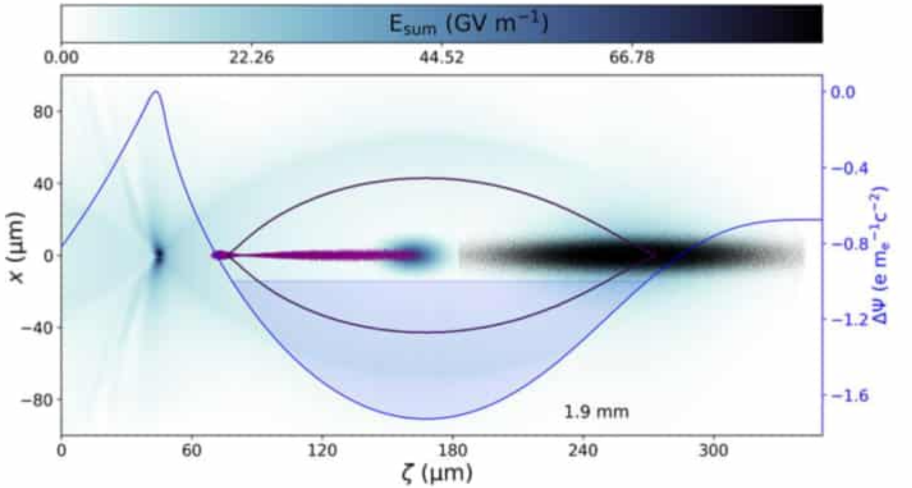
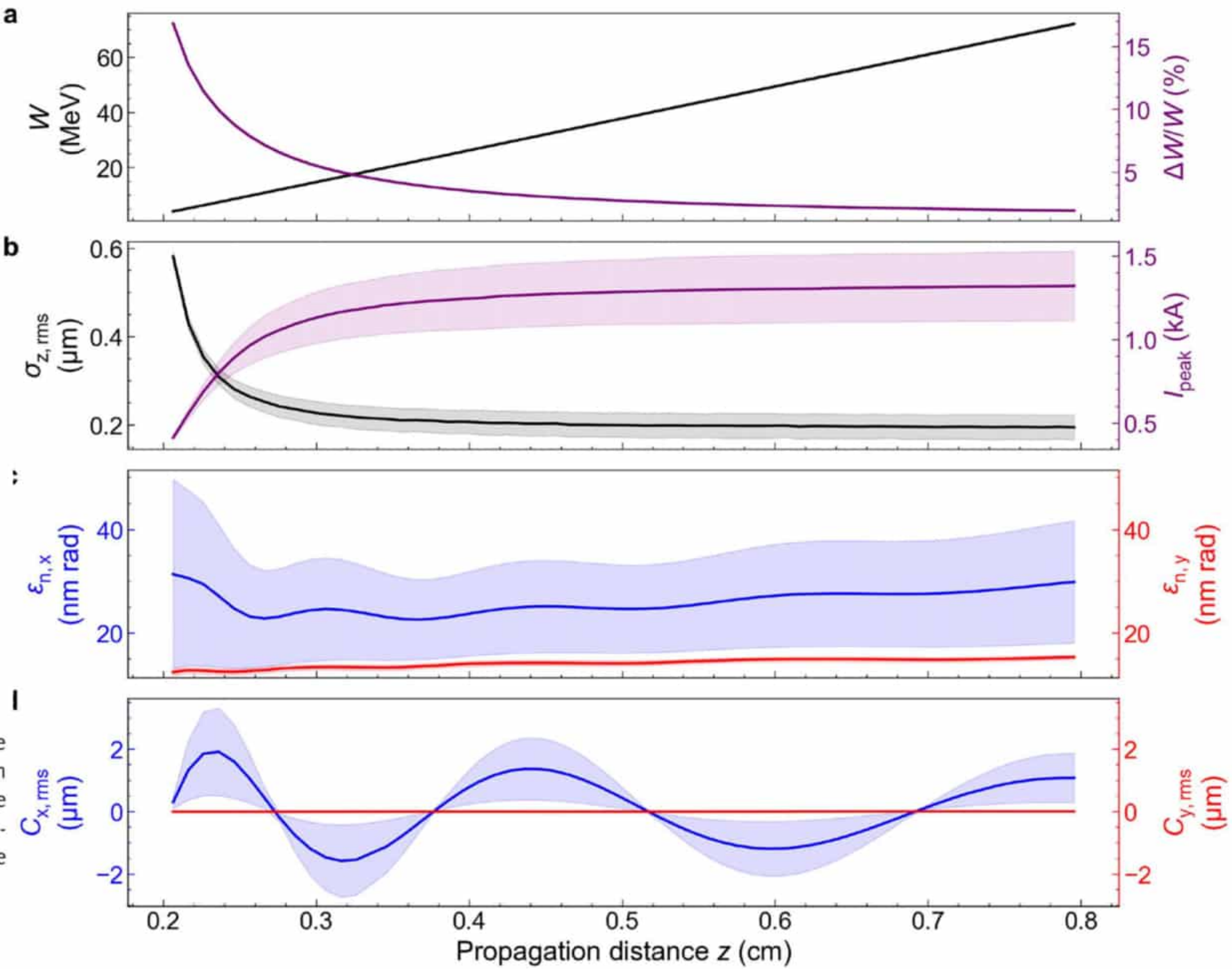
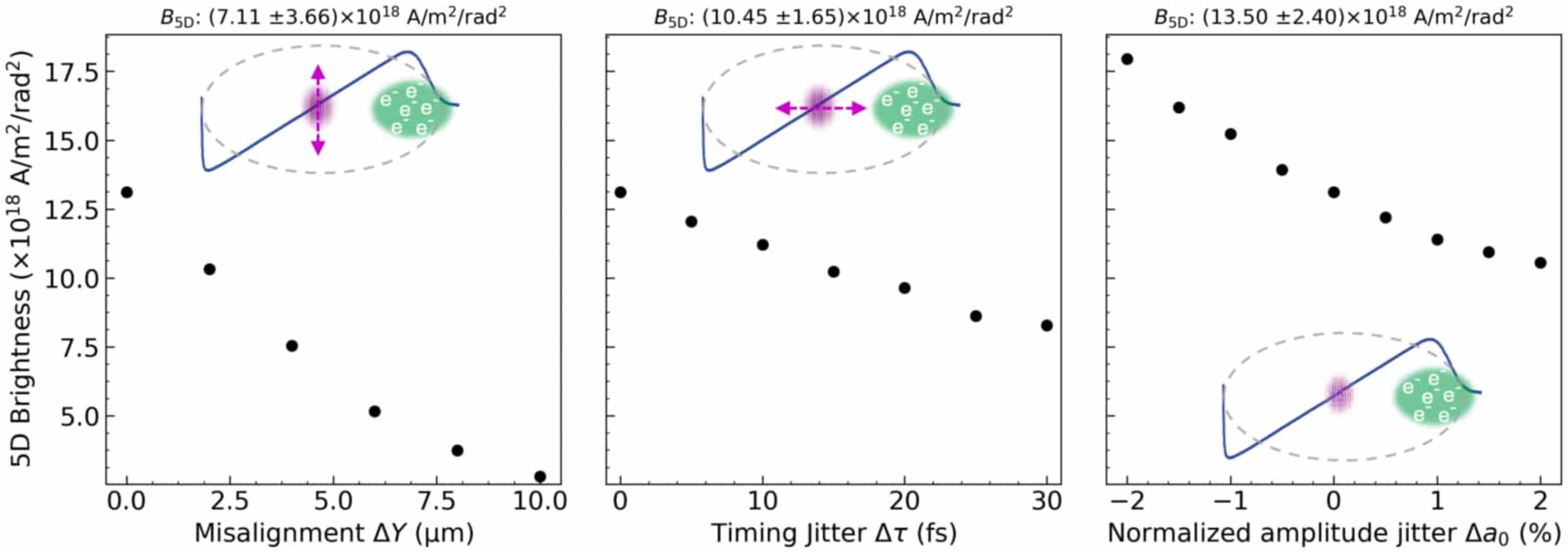


Figure 13. Visualization of the plasma wakefield scenario used for the plasma photocathode parameter sensitivity studies. The driver beam (black) propagates to the right and the plasma photocathode laser pulse releases He electrons (purple) in the centre of the blowout. The purple ellipse indicates the extent of the region where electrons released would be trapped.



See Habib, Heinemann et al.,
Plasma Photocathodes, Annalen der Physik 2023

Excellent stability even when plasma photocathode jitters considerably

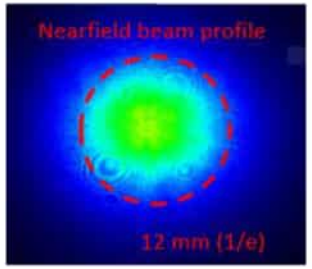


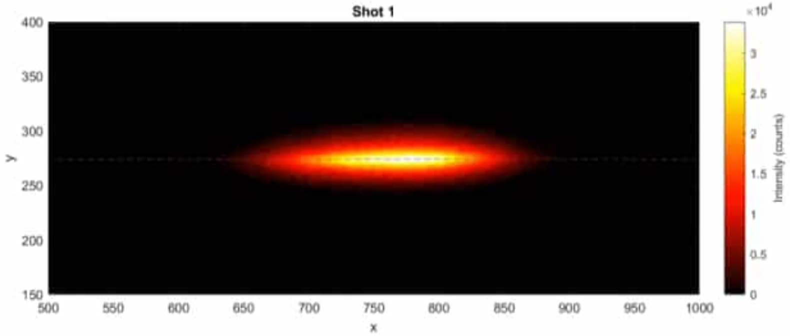
- ❑ No variation of driver, but here plasma photocathode laser offset, timing, a0 scans

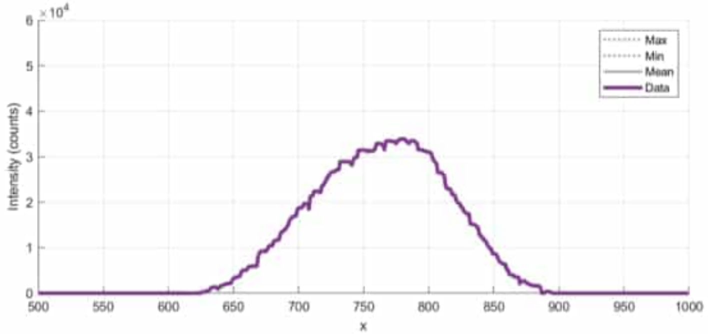
See Habib, Heinemann et al., Plasma Photocathodes, Annalen der Physik 2023

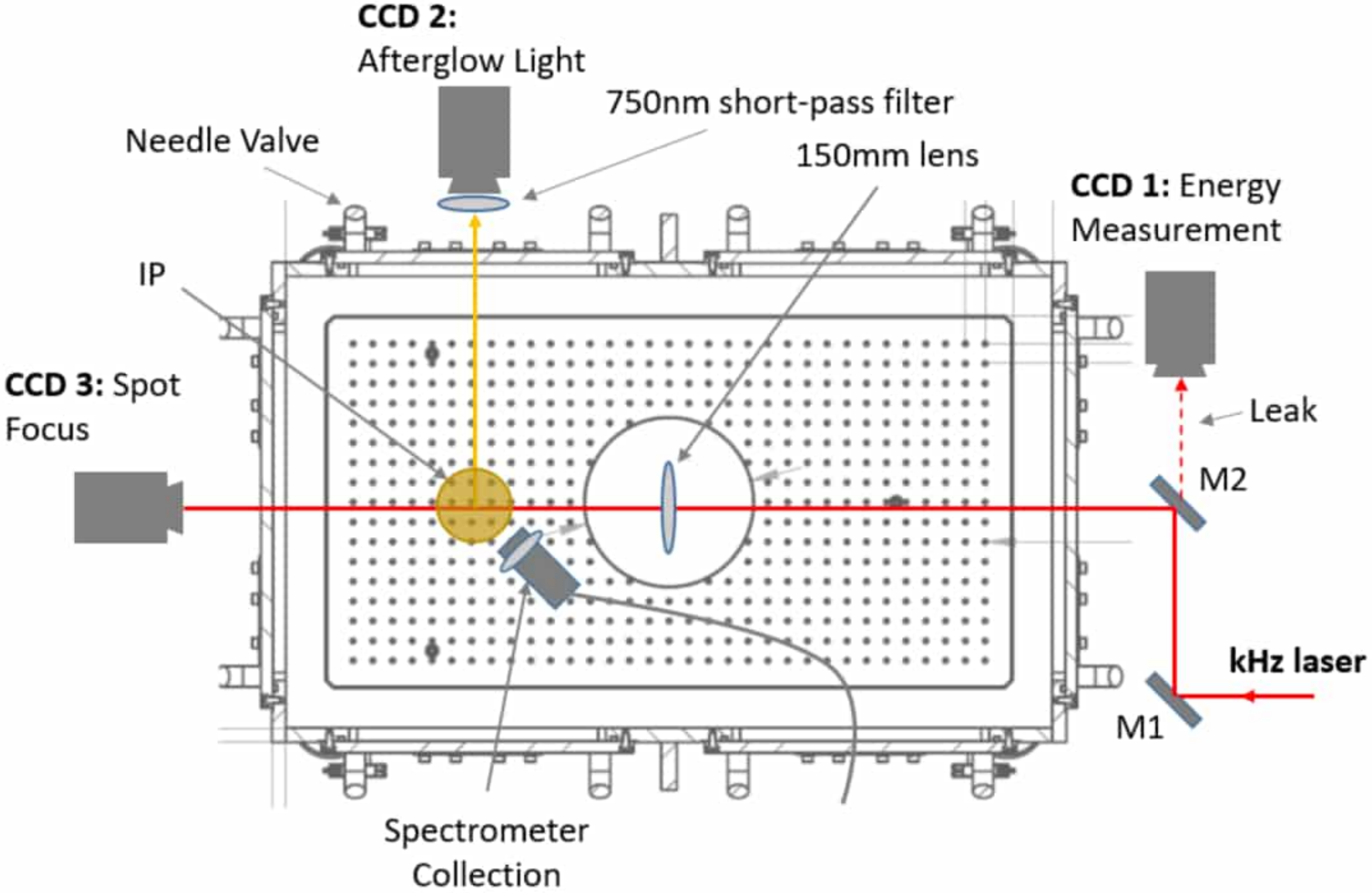
Plasma photocathode & afterglow testing at SCAPA w/ kHz laser (CI & NeXource)

- ❑ Shows that when beam quality is good enough, plasma photocathode and afterglow seed ionizer can pass windows etc.



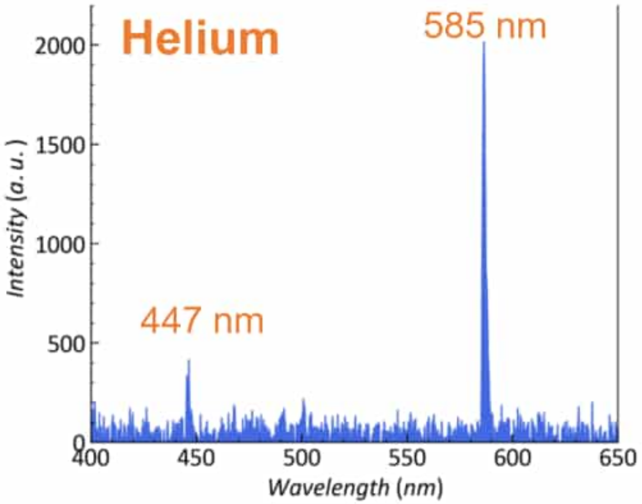




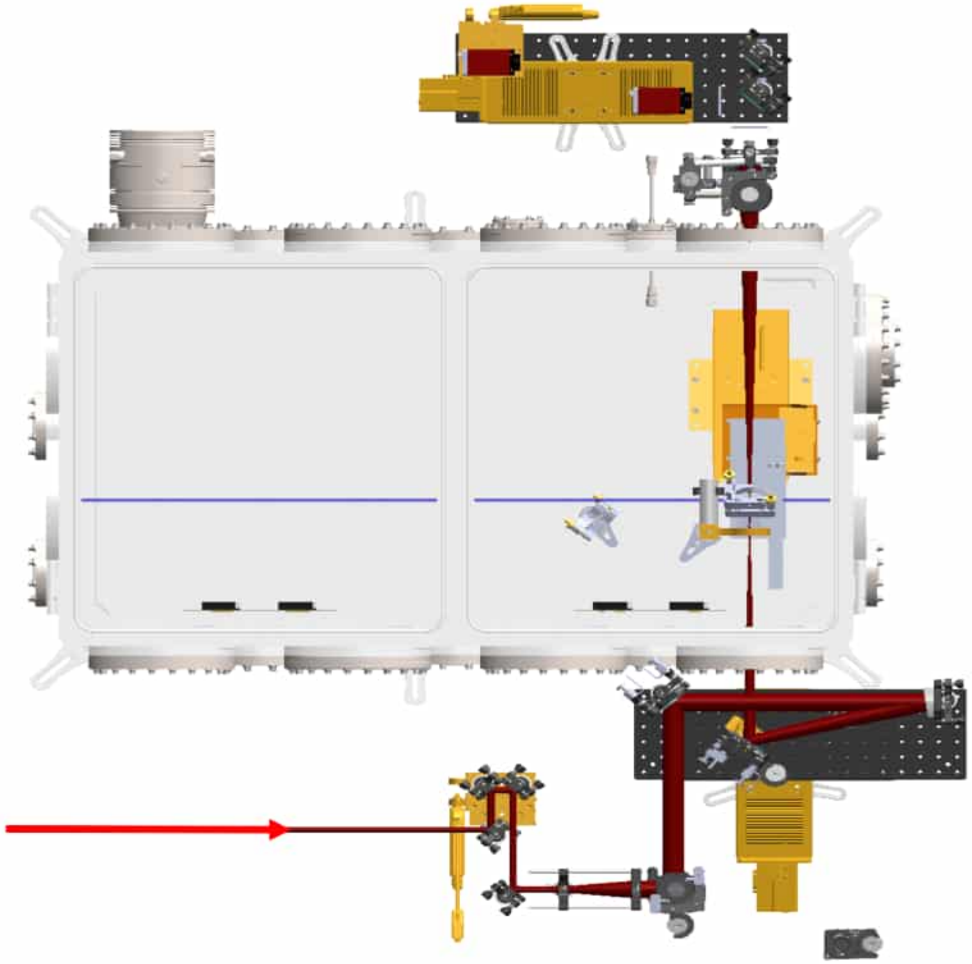


Spectrometer

- ❑ Strong lines of gas species can be observed



E-315/E-308 ionizer

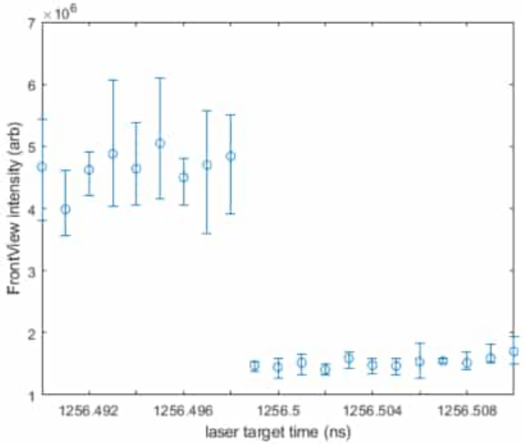


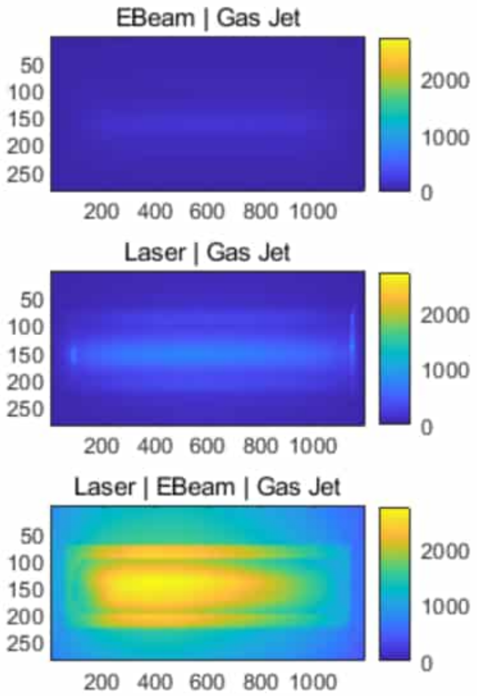
Ionizer Probe Arm

- ❑ Designed to produce ~10x1000 μm plasma transversely to beam vector

Topview

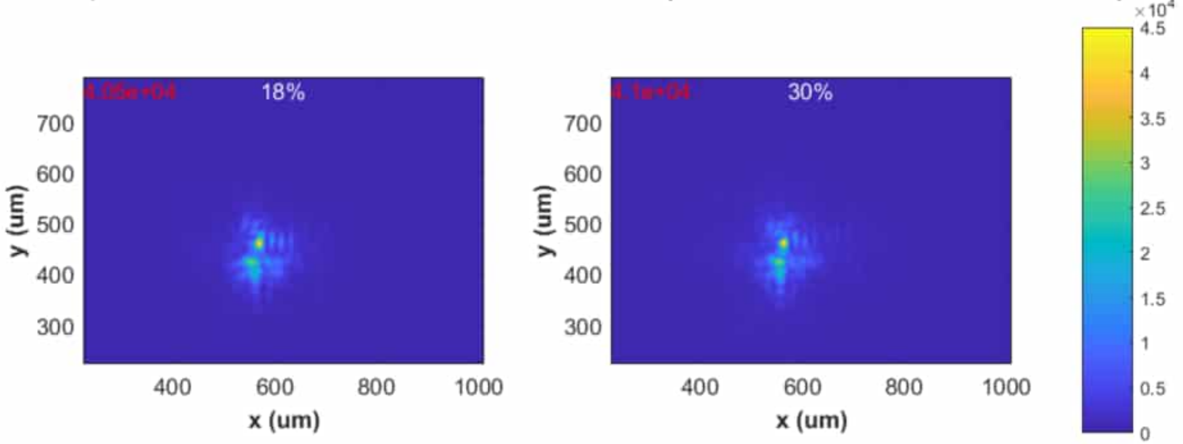
- ❑ Main laser ionisation in the gas jet – afterglow is detectable



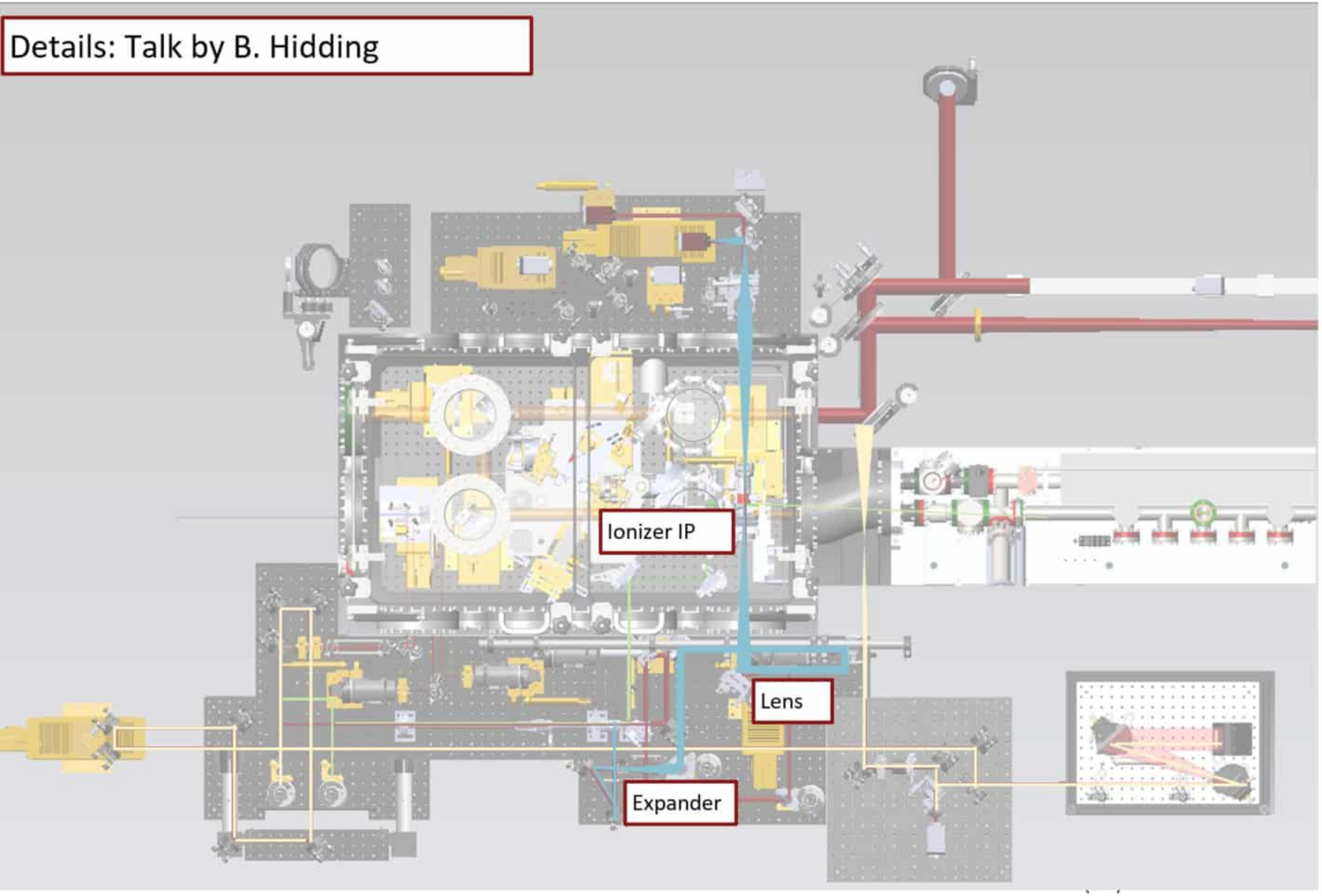


Ionizer Focus Camera

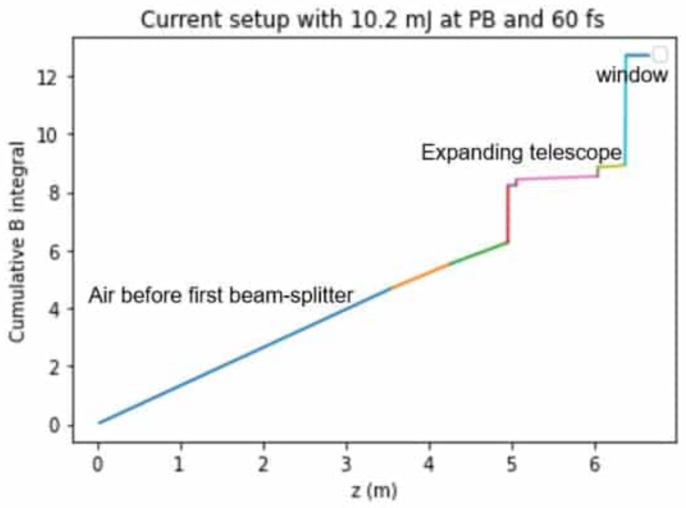
- ❑ Best attempt at focus in early days, many laser improvements now achieved (see A. Knetsch et al.)



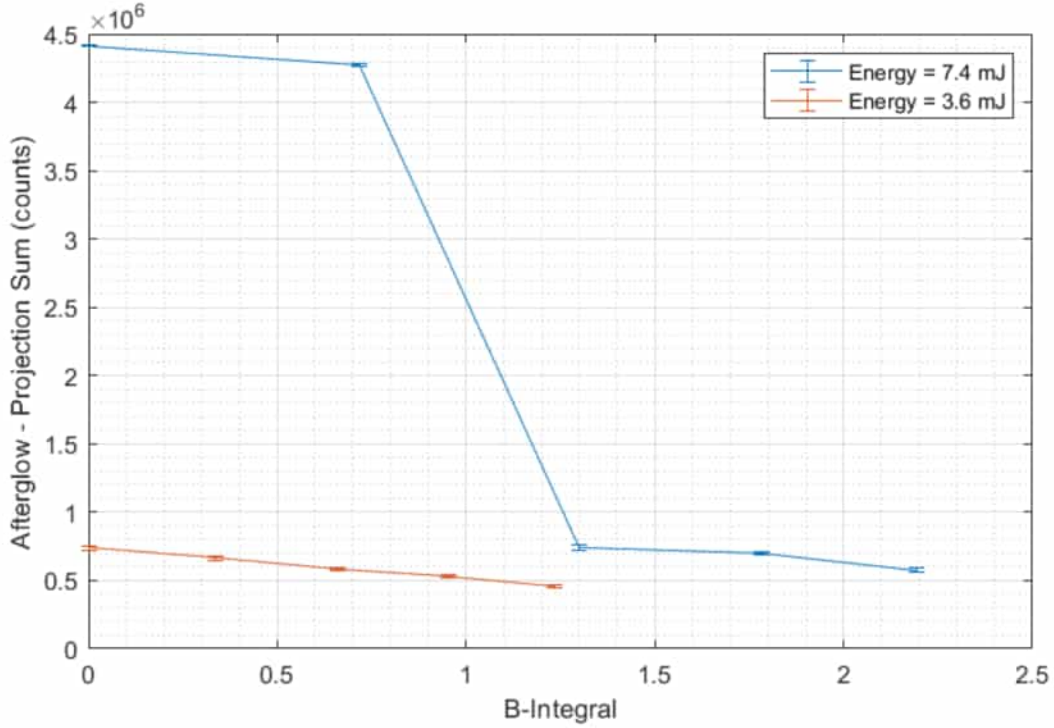
Sector 20 probe beam: ionizer

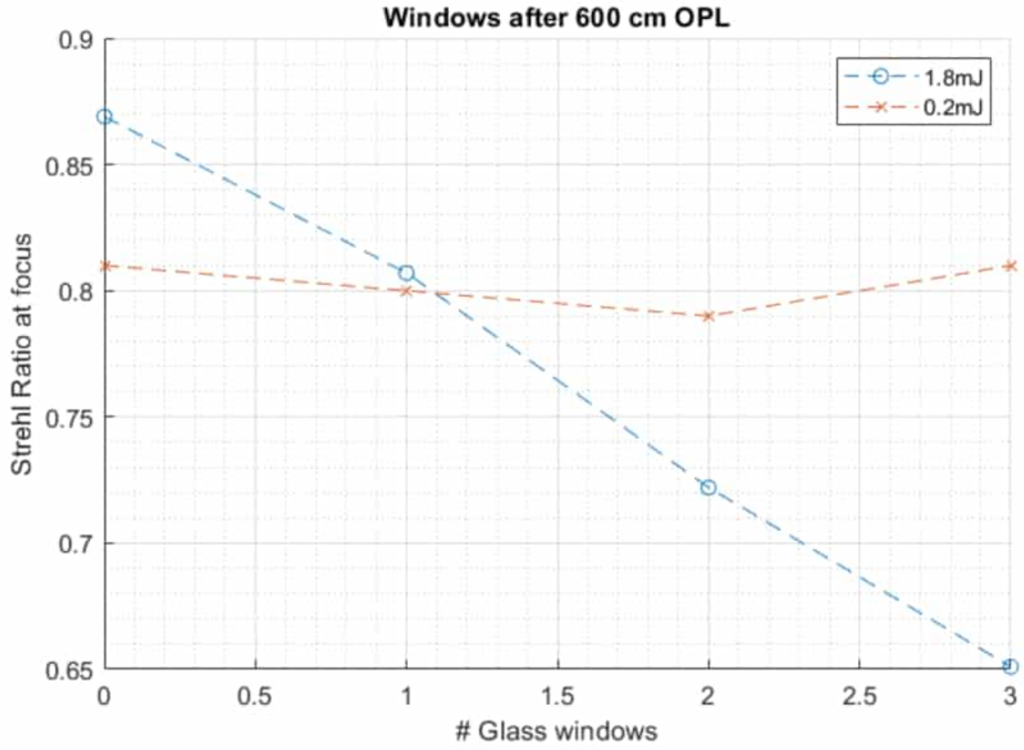


- OAP replaced with f=600 mm lens
- No ionization, yet
- B-integral studies performed by L. Berman and A. Sutherland



B-Integral study





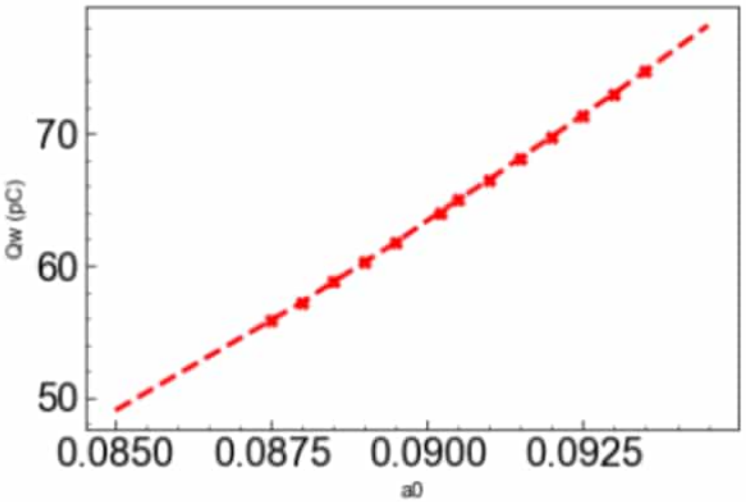
<u>Ionization tests at Strathclyde</u>

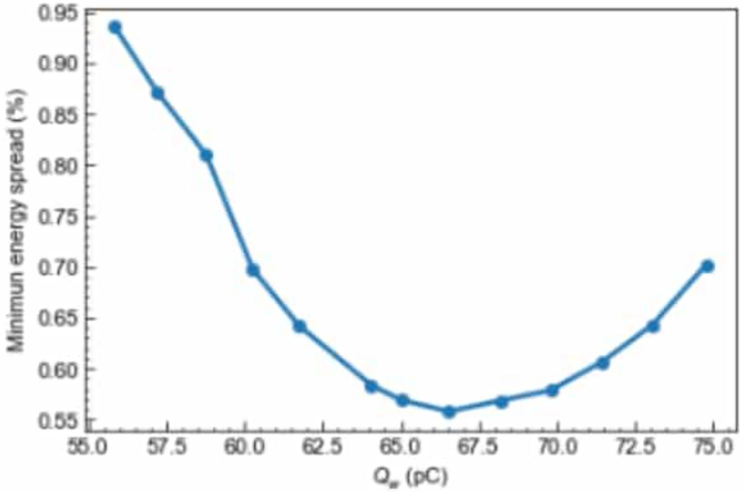
- ❑ Ionization cuts-off when $\int B > 1$
- ❑ Becomes a worse problem when compensating poor focus quality with increased energy

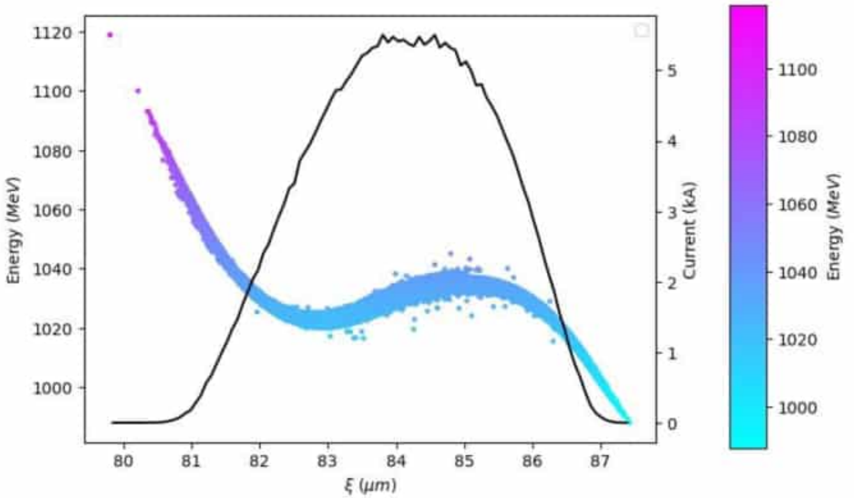
<u>Focus Quality tests at FACET-II</u>

- ❑ Air path length not significantly affecting quality
- ❑ SiO2 Glass window makes a measurable difference

Production of beam-loaded witness with single laser e.g. by a0 variation





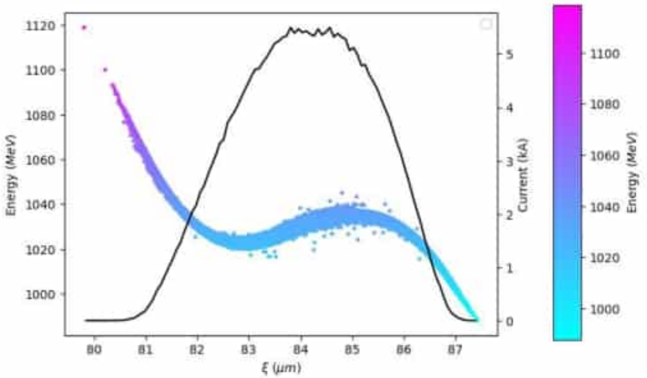


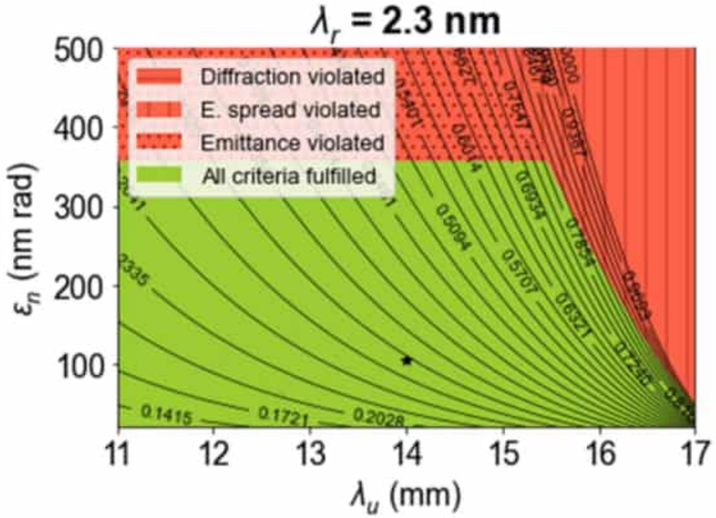
Witness properties	
Charge (pC)	64
Energy (GeV)	1
Projected energy spread (%)	0.58
Avg. slice energy spread	0.062%
Avg. slice normalised emittance (nm rad)	106
Peak current (kA)	6.0
RMS bunch length (μm)	2.8
Avg. slice 5D brightness (A/m^2/ rad^2)	2.0e18
Avg. slice 6D brightness (A/m^2/ rad^2/0.1% BW)	3.4e18

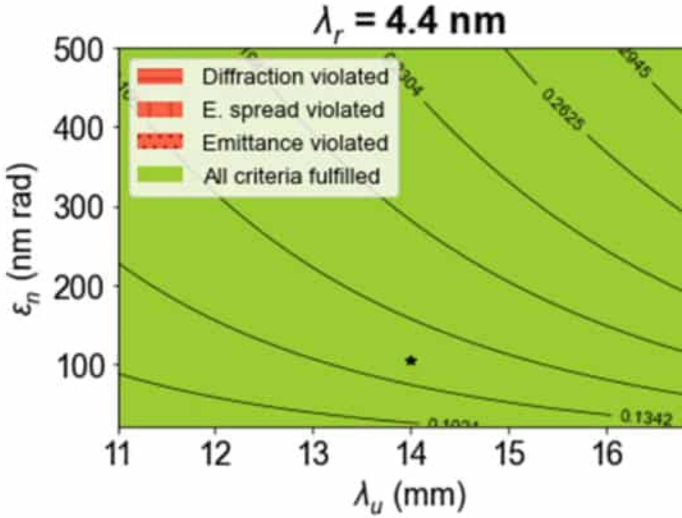
PWFA parameters	
Plasma wavelength (μm)	250
Driver charge (nC)	1 - 1.5
Driver energy (GeV)	1 - 10
Laser strength (a_0), duration and waist	0.09, 50 fs, 7 μm

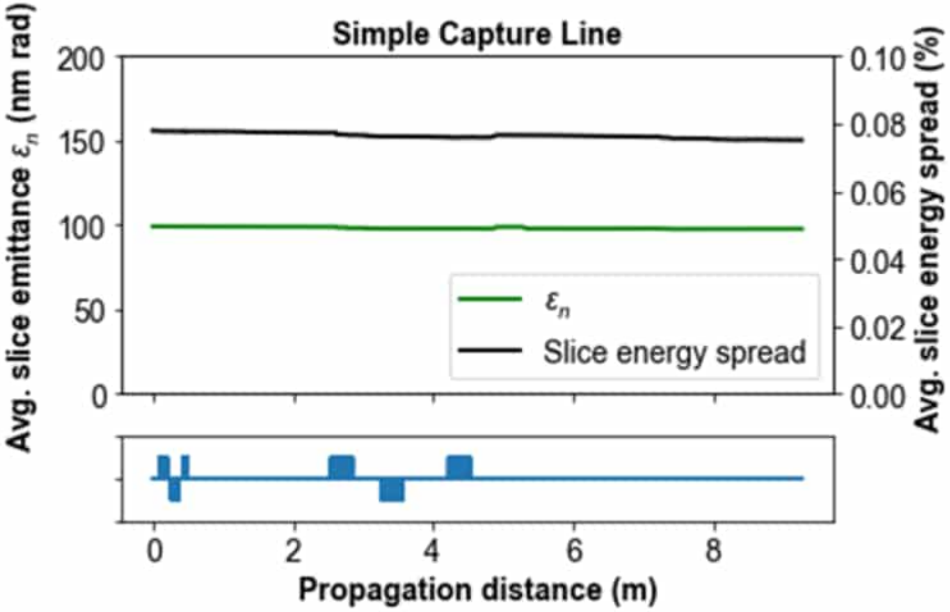
- Simulations (FBPIC) produce single bunch with < 1 % energy spread, ~ 100 nm rad emittance and multi-kA peak current using FACET-II-like parameters
- 'High charge' configuration (10s of pC) makes bunches easier to detect
- Exp. scan of injected charge with probe laser energy and detect resulting change in energy spread with spectrometer

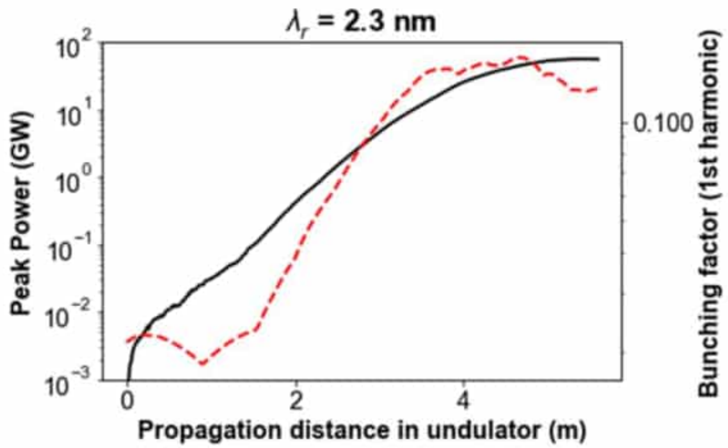
PWFA-X-FEL with single plasma photocathode & direct beamloading

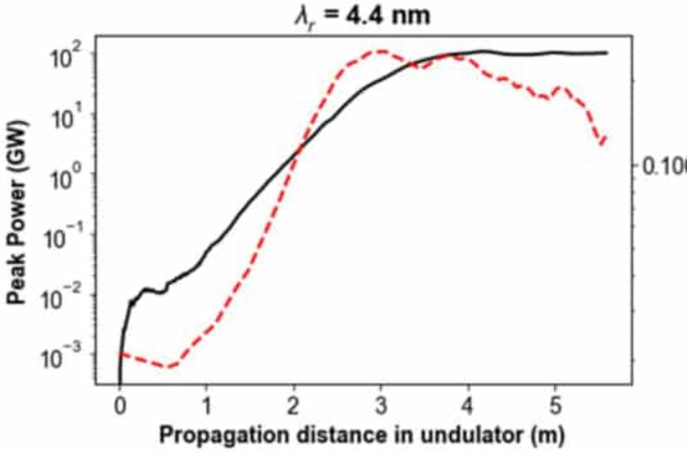












Easier than energy spread control via additional escort beams

nature COMMUNICATIONS

ARTICLE

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Single-stage plasma-based correlated energy spread compensation for ultrahigh 6D brightness electron beams

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Attosecond-Angstrom free-electron-laser towards the cold beam limit

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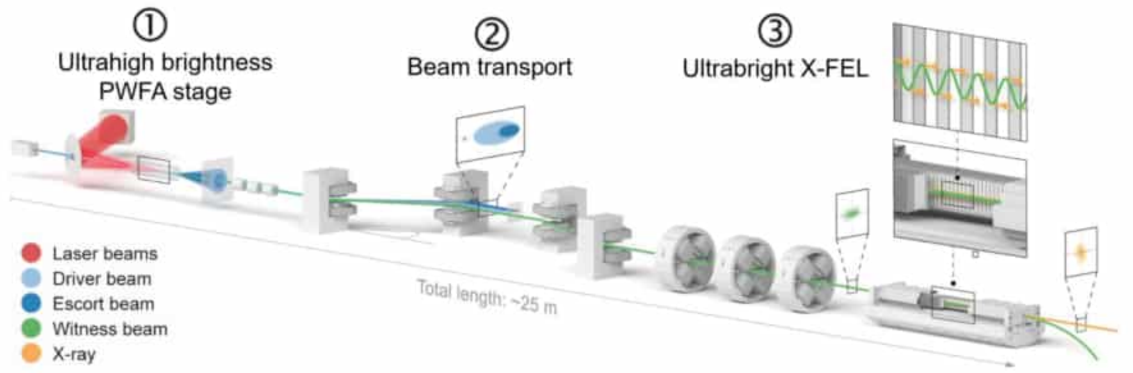
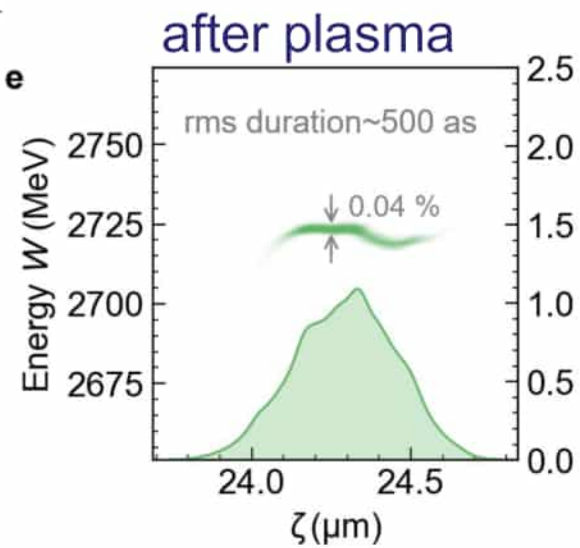
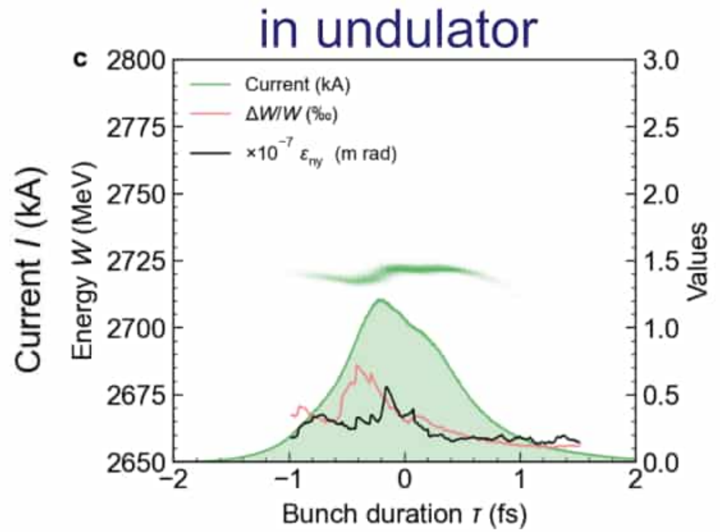
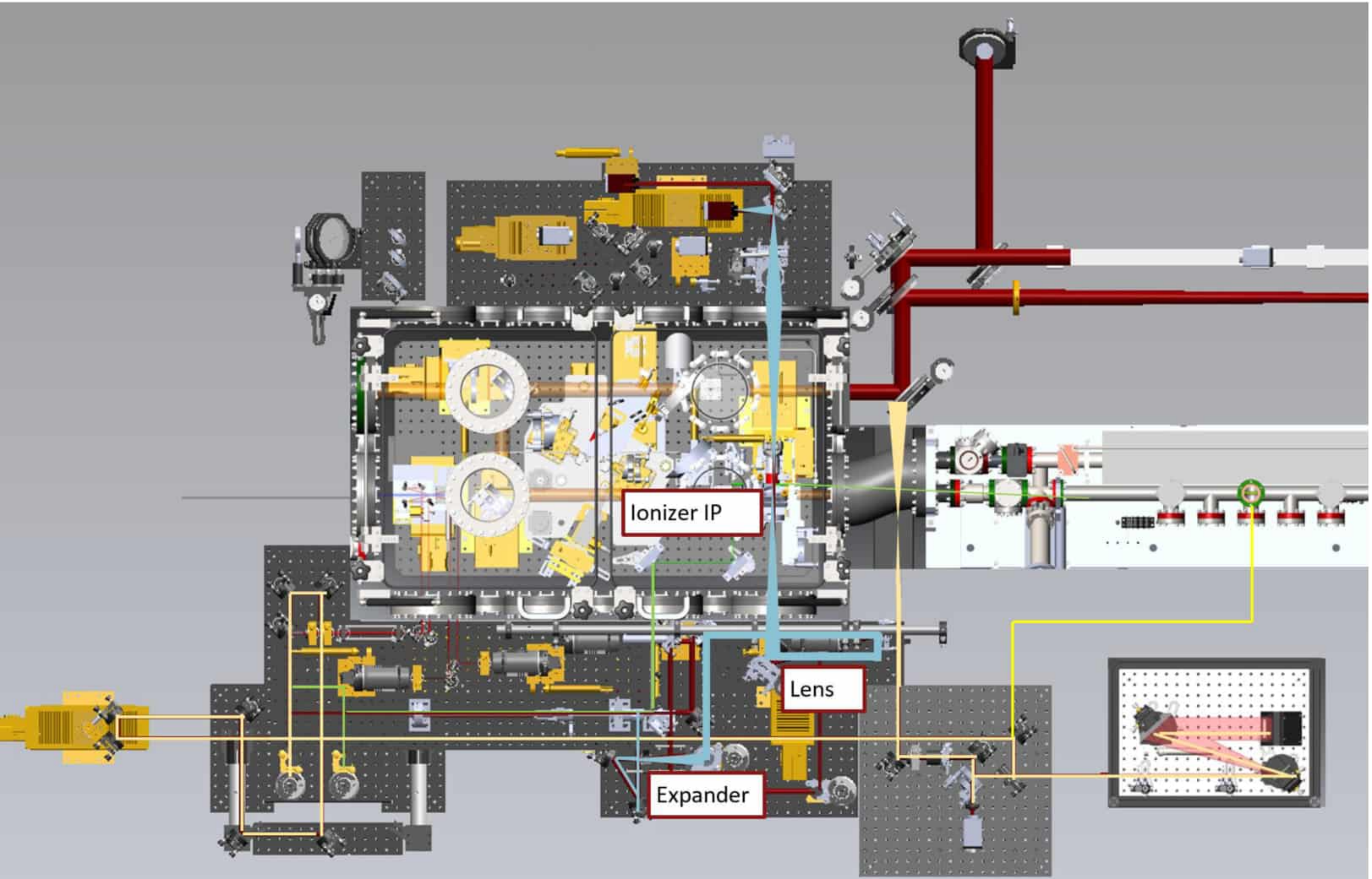


- ❑ Exploit tailored beam loading via “escort beams“ to locally flip field accelerating field gradient
- ❑ Operation at low plasma density minimizes residual energy spread, and e.g. energy spreads < 0.01% can be reached at few GeV energies
- ❑ Among E-313 goals
- ❑ Escort bunch technique was then applied for Plasma-X-FEL blueprint S2E (VSim, elegant, Puffin)





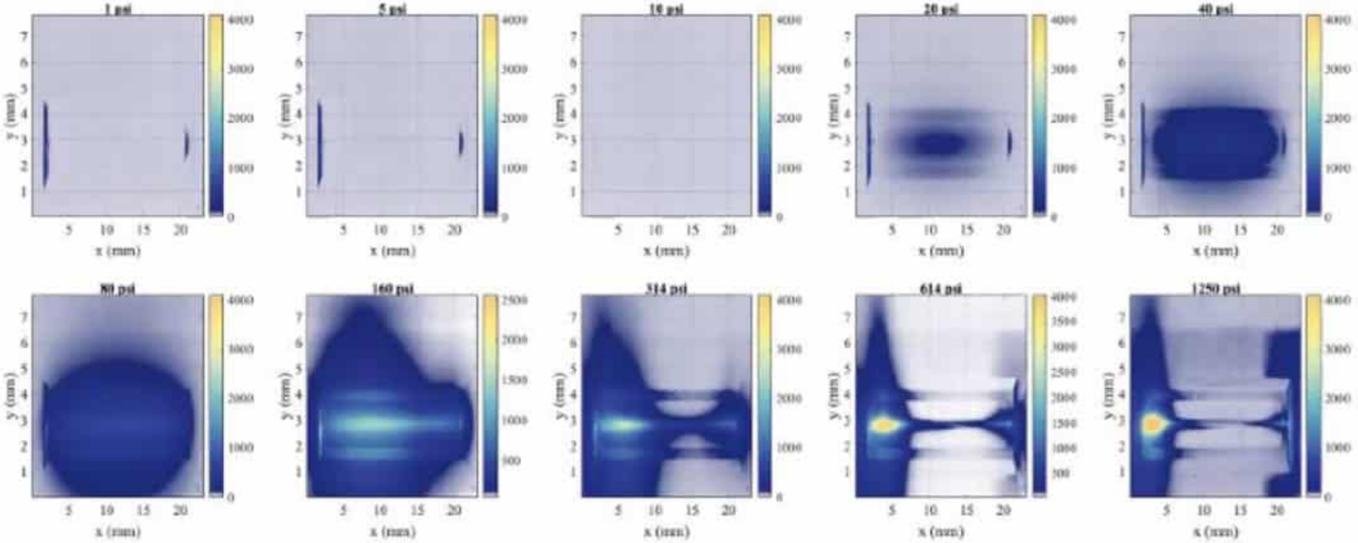
Outstanding task: get probe ionizer split off to DS bypass line v2 for injection



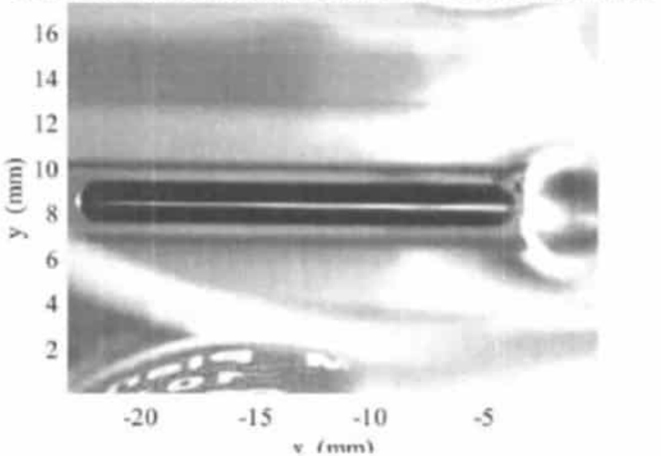
E-315: not yet have had official beamtime, but already produced results via Topview

Top view

- Collects plasma afterglow light from gas jet
- Great tool to find synchronous time-of-arrival with electron beam
- Can detect inhomogeneities in axilens ionization



Gas jet pressure scan



Plasma afterglow R&D at ARCTURUS

- ❑ Laser-driven plasma afterglow, spe
- ❑ This is an E-315 goal and

Embargo’ed

gation

Plasma afterglow R&D at ARCTURUS

- Laser-driven plasma afterglow, spec

- This is an E-315 goal and

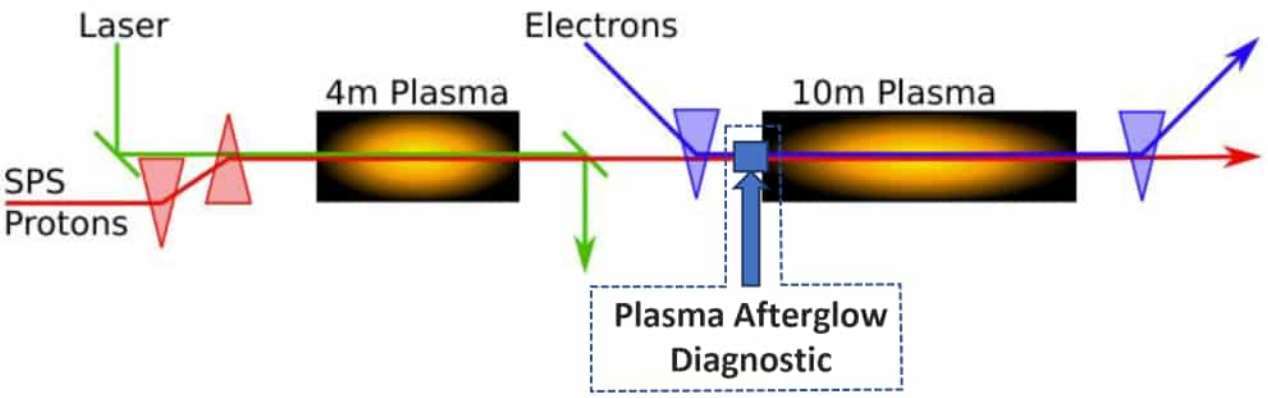
2/He etc.

ation

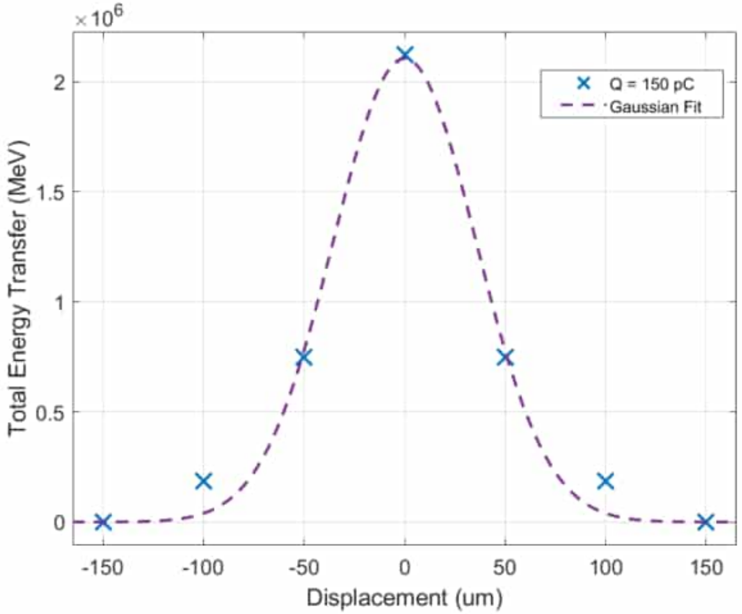
Embargo’ed

Plasma afterglow diagnostic also for AWAKE-2

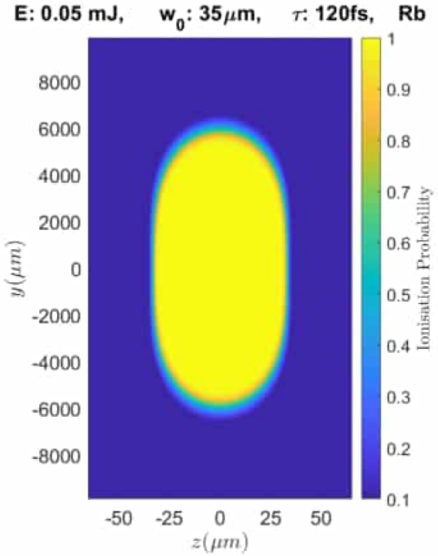
University of Strathclyde

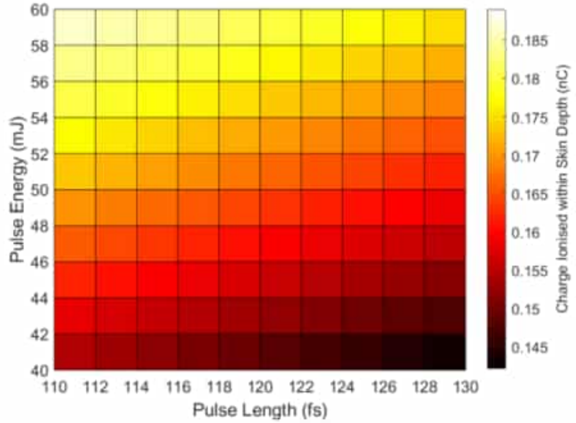


Measured afterglow data w/ Muggli et al. (Sutherland)

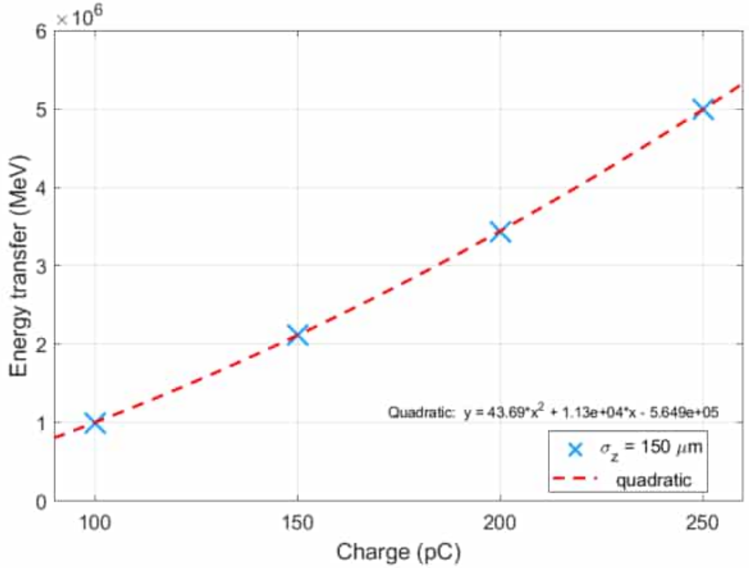


Electron alignment at µm level





AWAKE specific plasma distribution has been studied



Same diagnostic can be used to measure initial injection charge

Key components for E-310, E-311 etc.

1. Stable electron beam > 5 kA, long acceleration lengths. Need strong wake that can trap cold electrons from rest. ✔ Nearly there…

2. Two-component gas with low ionization threshold (LIT) and high ionization threshold (HIT) component. LIT supports the wake, HIT is used to be hit by plasma photocathode laser etc. LIT and HIT combinations can be H_2/He (as at FACET) or He/He^+ or Ar/Ar^+… ✔ No problem

3. Wide preionized plasma channel with selective ionization capability (e.g. only LIT, not HIT) ✔ Soon there…

4. Spatiotemporally synchronized injector laser pulse for Trojan Horse and Plasma Torch in 90° or collinear geometry ✔ Soon there…

5. Injection chamber at DS plasma position for injection ✔ Soon there w/ bypass line… but would like real chamber

Some potential early scans for E-31x

1. Plasma source with tandem lens and bypass line 2.0 in hydrogen (E-301)
2. Plasma source with tandem lens any bypass line 2.0 in H2/He (E-310, E-311, E-313)
3. PWFA in tandem lens-produced H2/He plasma
4. Self-ionized PWFA scans in H2/He
5. Plasma afterglow-based energy transfer monitor (see Muggli 2004, Boulton arXiv)
6. Plasma source with E-310 axilens in H2/He plasma
7. PWFA in axilens-produced H2/He plasma
8. E-315/E-308 PB ionization success and extensive E-315 afterglow scans
9. E-315 afterglow e-beam diagnostics combined with bypass line 2 PWFA
10. E-315/E-316 afterglow current spike laser heater checks
11. E-308 plasma lensing into bypass line 2 PWFA
12. PWFA with 90° injection in PB
13. E-310/E-311 DS ionization success and E-310/E-311 injection

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