

Bernhard Hidding, James B. Rosenzweig (E-310, E-312, E-314 PI's)
Andrew Sutherland, Paul Scherkl (E-315) *et al.*,
Daniel Ullmann (E-311) *et al.*, Fahim Habib (E-313) *et al.*,
Thomas Heinemann (E-316) *et al.*
and the E-31x collaboration

E-310: Trojan Horse-II

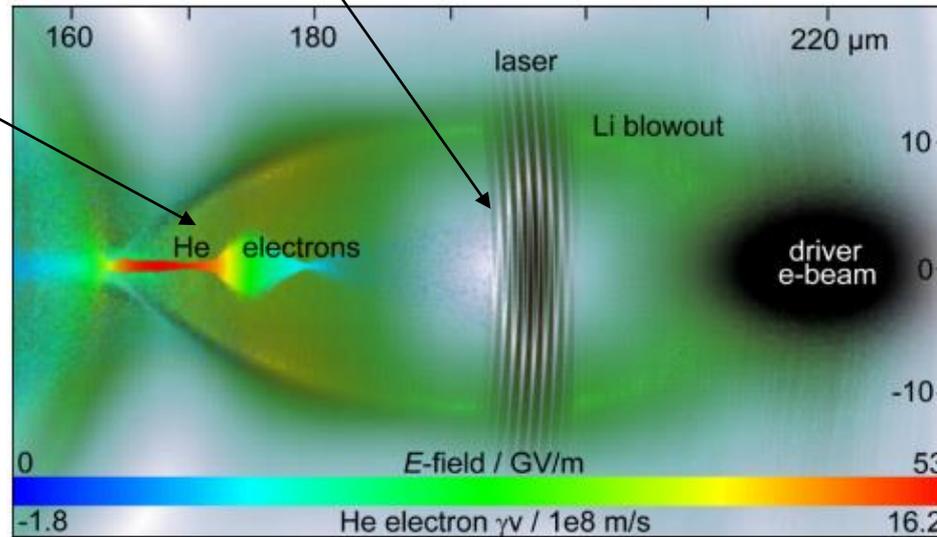
Scottish Centre for the Application of Plasma-Based Accelerators SCAPA,
Department of Physics, University of Strathclyde,
Scottish Universities Physics Alliance SUPA, UK
Strathclyde Centre for Doctoral Training P-PALS
Plasma-based Particle and Light Sources <http://ppals.phys.strath.ac.uk/>
& The Cockcroft Institute

Plasma photocathode a.k.a. Trojan Horse

Synchronized laser pulse tunnel ionizes in focus and releases ultracold electron population

Released electrons are rapidly accelerated and form bunch with ultralow emittance

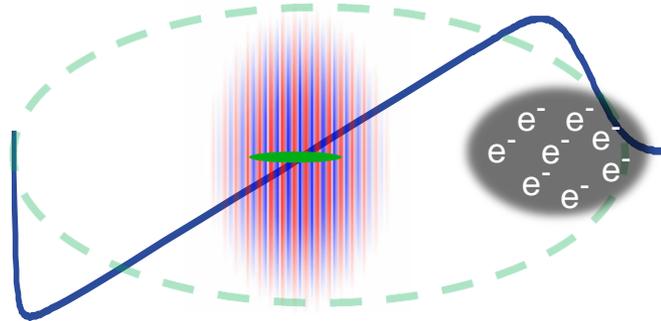
Two plasma components, one with low and one with high ionization threshold (e.g. H₂ and He)



Electron bunch generation largely decoupled from driver beam

Hidding *et al.*, *Phys. Rev. Letters* 108, 035001 (2012)

□ Prospect for nm rad emittance; brightness many orders of magnitude beyond even state-of-the-art X-FEL linacs

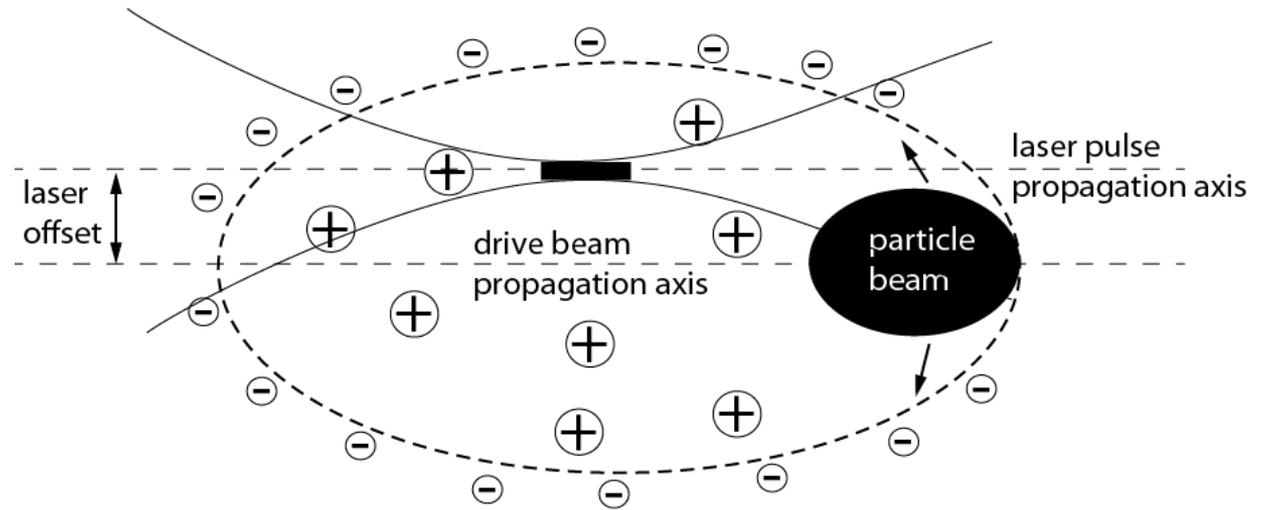


$$B = \frac{2I}{\epsilon_n^2}$$

□ Brightness transformer: Increase by factor up to 100000x

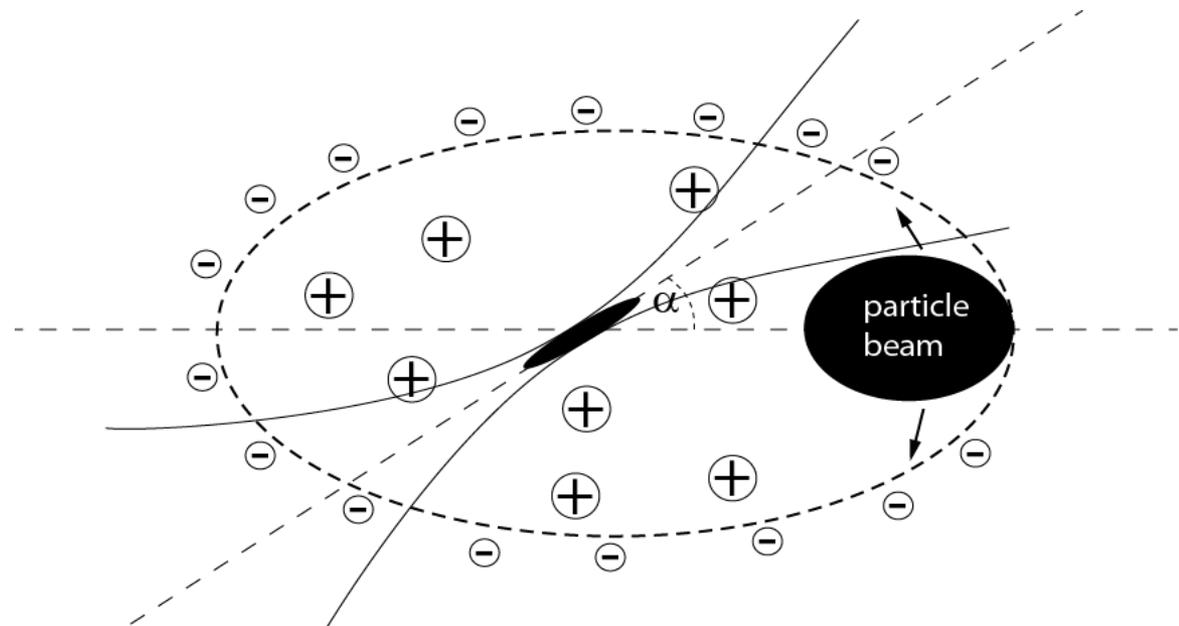
Trojan Horse: arbitrary geometry

- High degree of flexibility & tunability

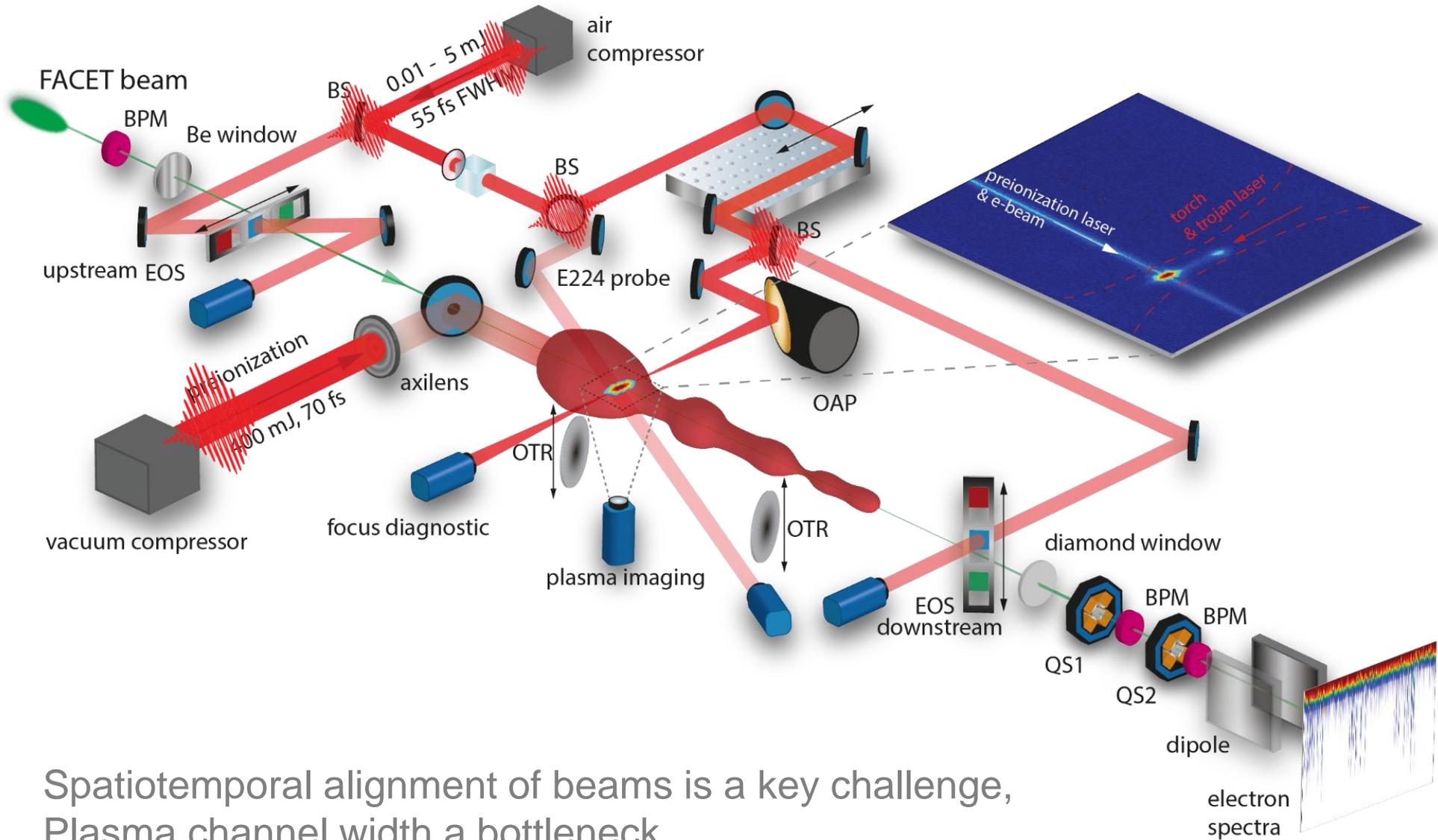


German & US Patent 2011 & 2012

- Injection possible at various angles and variations



FACET E-210: Trojan Horse in 90°



Spatiotemporal alignment of beams is a key challenge,
Plasma channel width a bottleneck

E-210: Trojan Horse Proof-of-concept w/ 90° injector angle



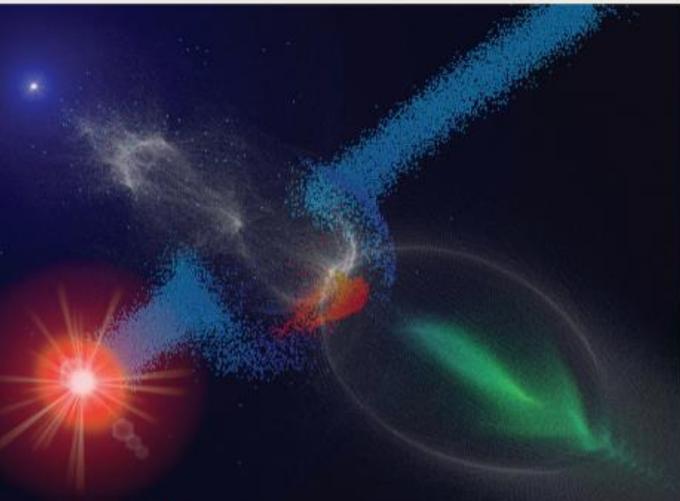
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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

MATHEMATICAL, PHYSICAL AND ENGINEERING SCIENCES

Directions in particle beam-driven plasma wakefield acceleration

Theo Murphy meeting issue compiled and edited by Bernhard Hidding, Mark Hogan, Patric Muggli, James Rosenzweig and Brian Foster



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nature
physics

LETTERS

<https://doi.org/10.1038/s41567-019-0610-9>

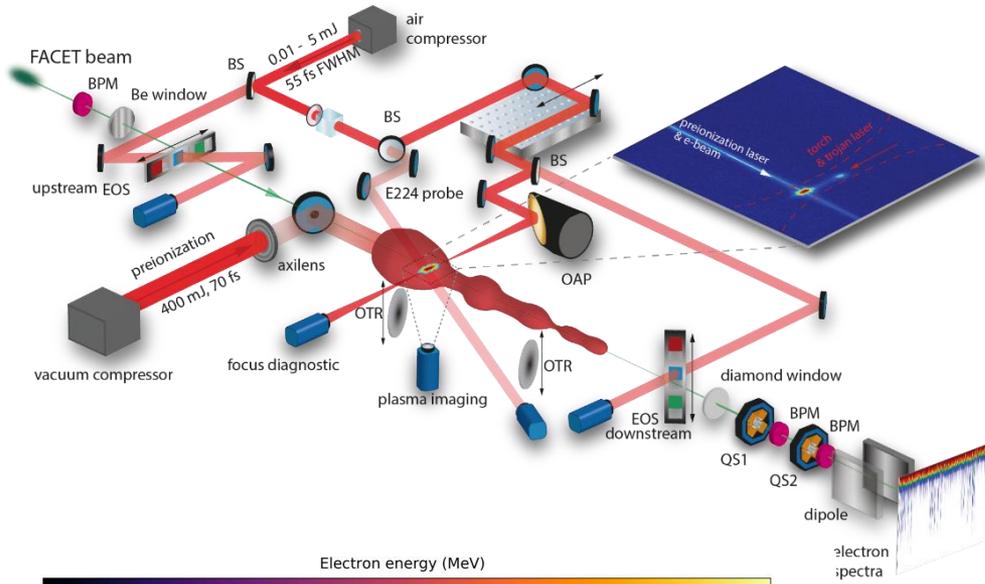
Generation and acceleration of electron bunches from a plasma photocathode

A. Deng^{1,2,14}, O. S. Karger^{3,14}, T. Heinemann^{4,5,6}, A. Knetsch⁶, P. Scherkl^{4,5}, G. G. Manahan^{4,5},
A. Beaton^{4,5}, D. Ullmann^{4,5}, G. Wittig³, A. F. Habib^{4,5}, Y. Xi¹, M. D. Litos⁷, B. D. O'Shea⁸, S. Gessner⁸,
C. I. Clarke⁸, S. Z. Green⁸, C. A. Lindström⁹, E. Adli⁹, R. Zgadzaj¹⁰, M. C. Downer¹⁰, G. Andonian^{1,11},
A. Murokh¹¹, D. L. Bruhwiler¹², J. R. Cary¹³, M. J. Hogan⁸, V. Yakimenko⁸, J. B. Rosenzweig¹
and B. Hidding^{4,5*}

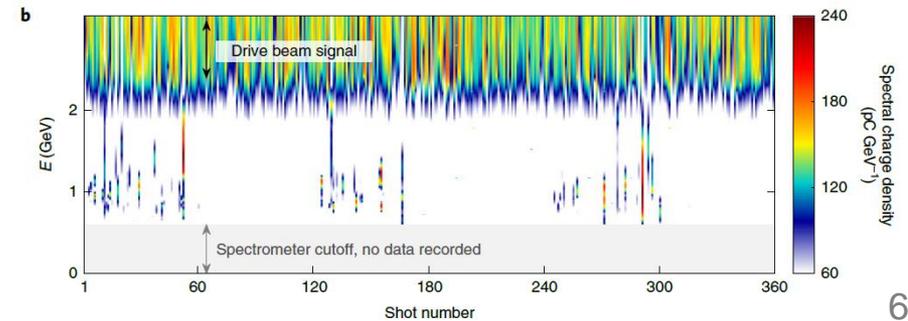
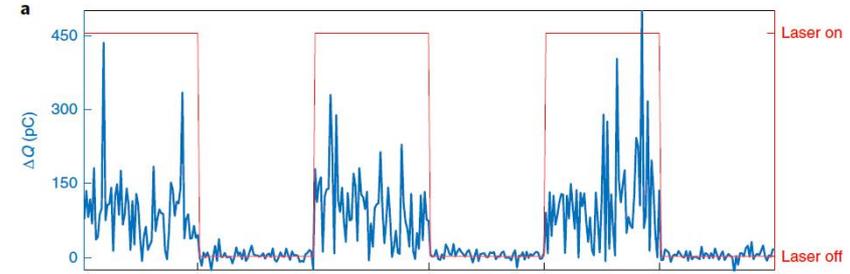
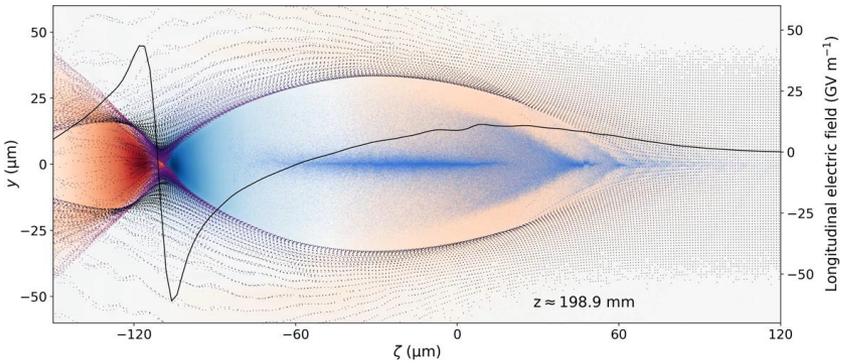
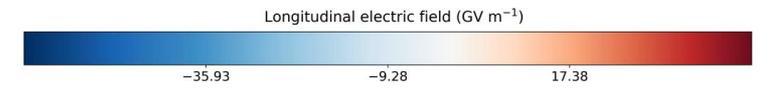
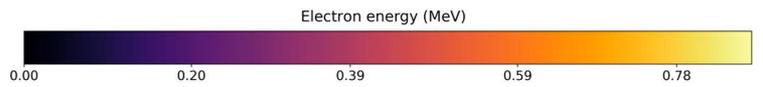
E-210: First density downramp injection in PWFA

❑ Concept of density downramp injection: H. Suk *et al.*, *Phys. Rev. Lett.* 86, 1011-1014 (2001)

❑ Concept of laser-generated density downramp injection a.k.a. **Plasma Torch**:
G. Wittig *et al.*, *Phys. Rev. Acc. Beams.* 18 081304 (2015)



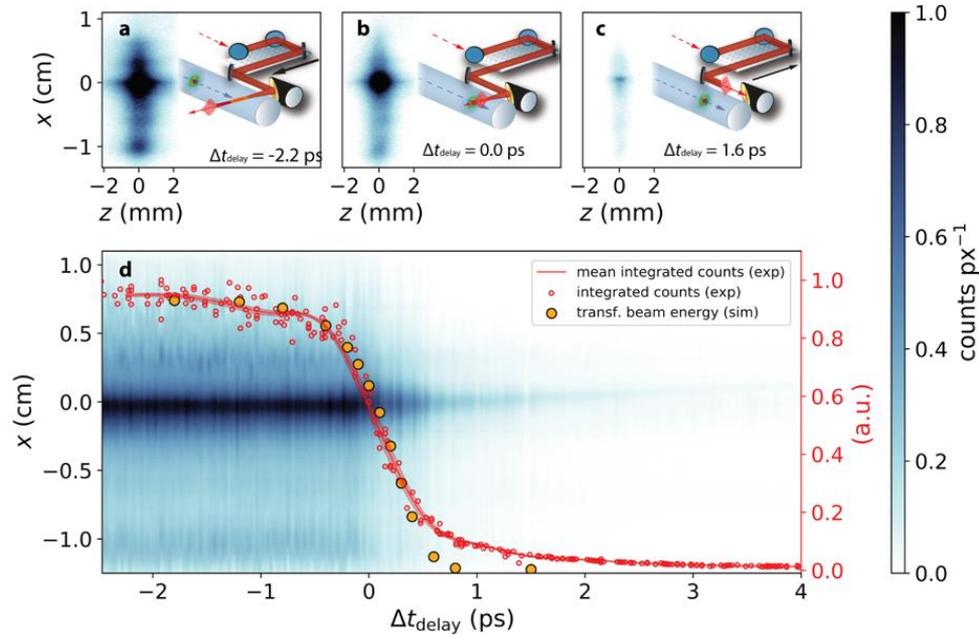
❑ Proof-of-concept at E-210:
D. Ullmann *et al.*, in prep.
A. Deng, O. Karger *et al.*, *Nat. Phys.* (2019)



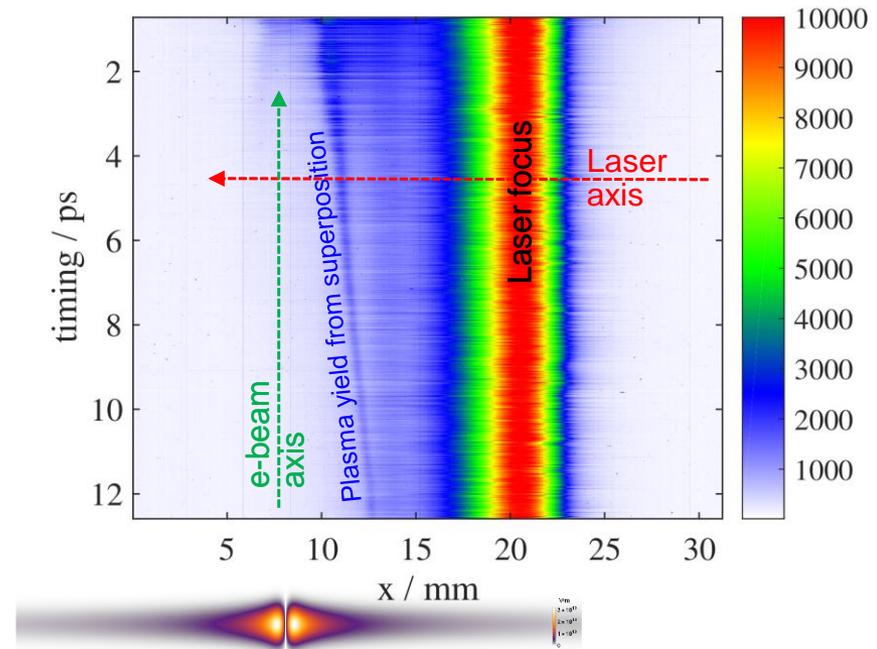
E-210: Plasma afterglow metrology

- Versatile, robust and minimally / non-intrusive class of methods to measure beam-laser-plasma interaction parameters

“Plasma-EOS”, “Plasma-OTR”,
“Plasma-Pyro”:



Icarus:

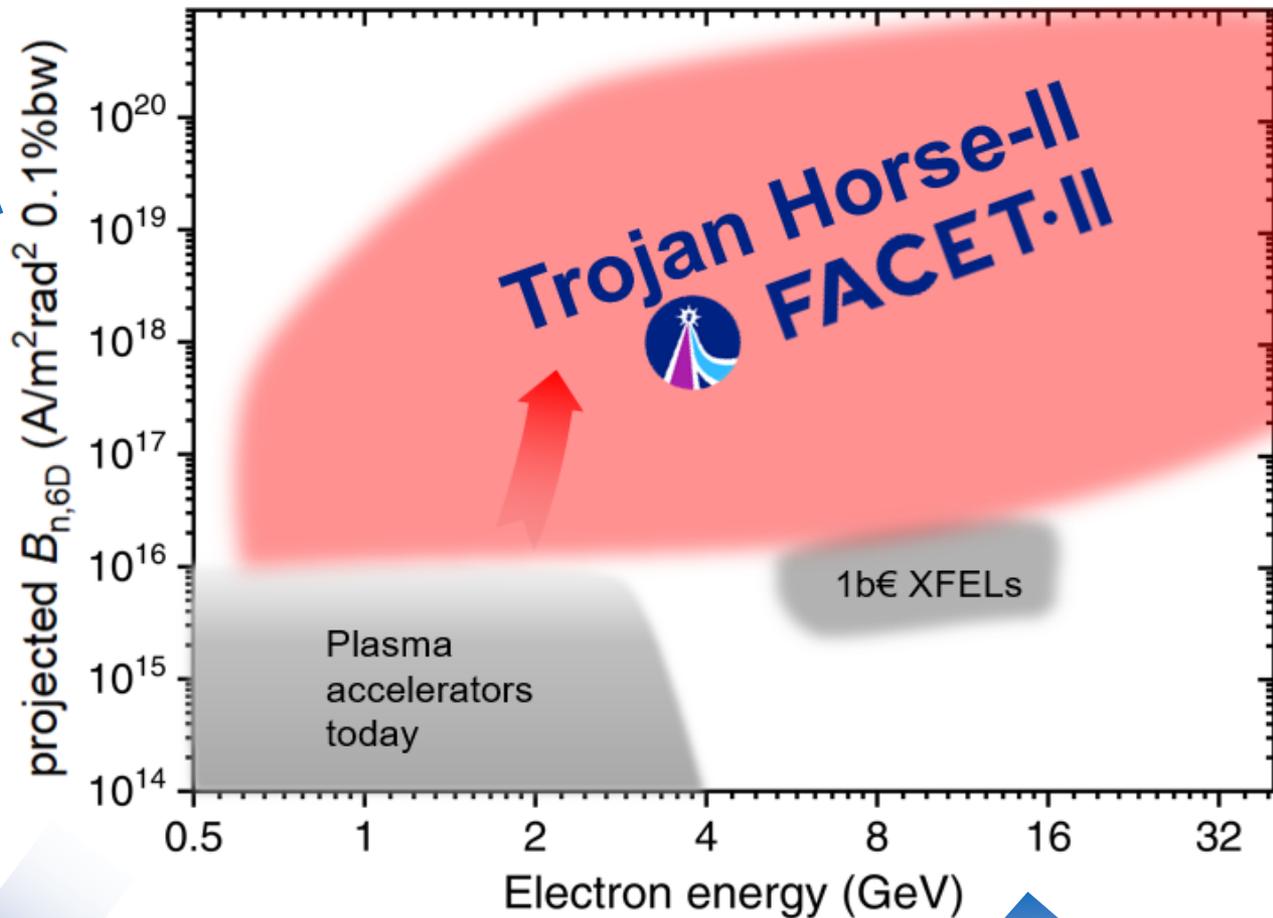


- P. Scherkl *et al.*, Plasma-photonic spatiotemporal synchronization of relativistic electron and laser beams, arXiv:1908.09263 (2019)

- T. Heinemann *et al.*, in preparation

E-310: Trojan Horse-II

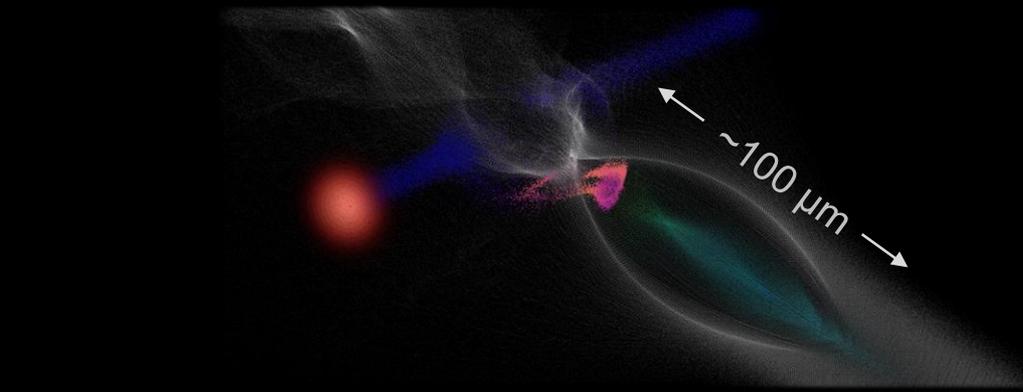
- In combination with
- E-311: Plasma Torch
- E-312: Dragon Tail
- E-313: Multibunch Dechirper
- E-314: Ion Collapse
- E-315: Plasma Afterglow
- E-316: Icarus



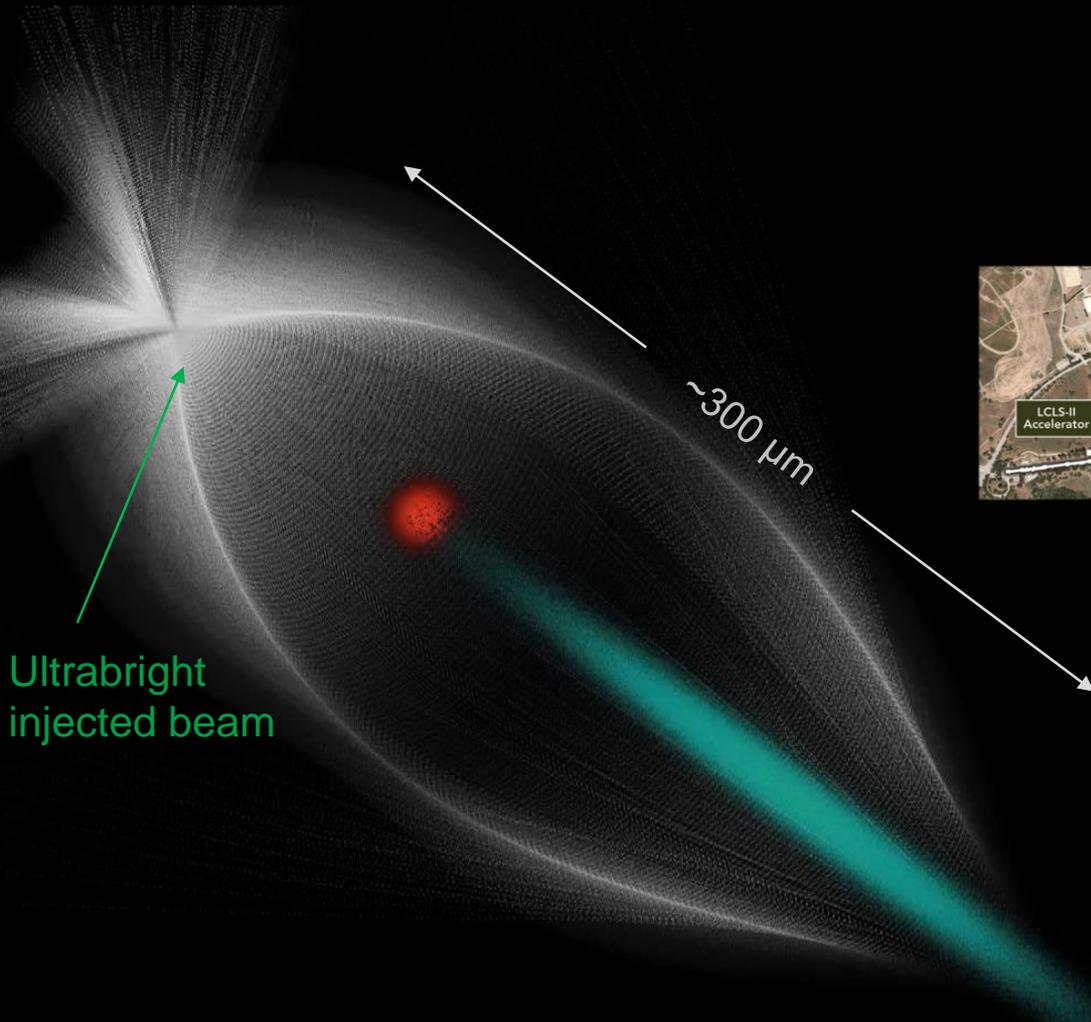
- ❑ Ultralow emittance beams for HEP
- ❑ Ultrabright beams for photon science (UK-US STFC “PWFA-FEL” project)
Friday session

$$B_{6D} = \frac{\text{multi-kA current } I}{\underbrace{\epsilon_n^2}_{\text{nm rad emittance}} \cdot \underbrace{0.1\% \sigma_W}_{\text{energy spread } <0.01\%}}$$

E-210: Trojan Horse at FACET



E-310: Trojan Horse-II at FACET-II



With better precision and incoming beams, in larger blowout, in collinear geometry

E-210: Picnic Basket, produced by RadiaBeam as part of DOE SBIR Trojan Horse project: critical equipment for various experiments at FACET

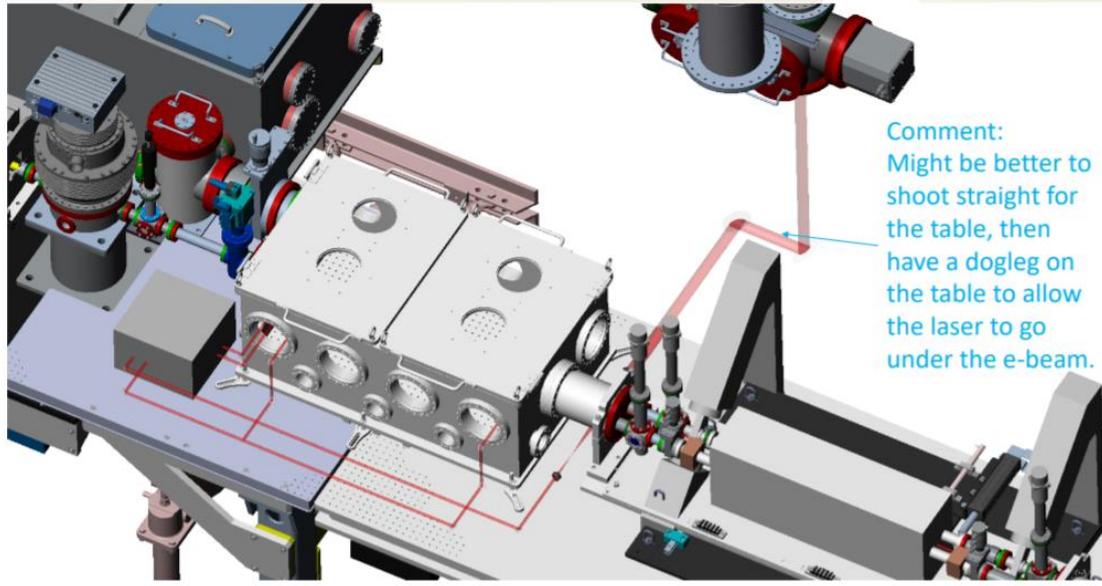
'Picnic Basket' SLAC



E310

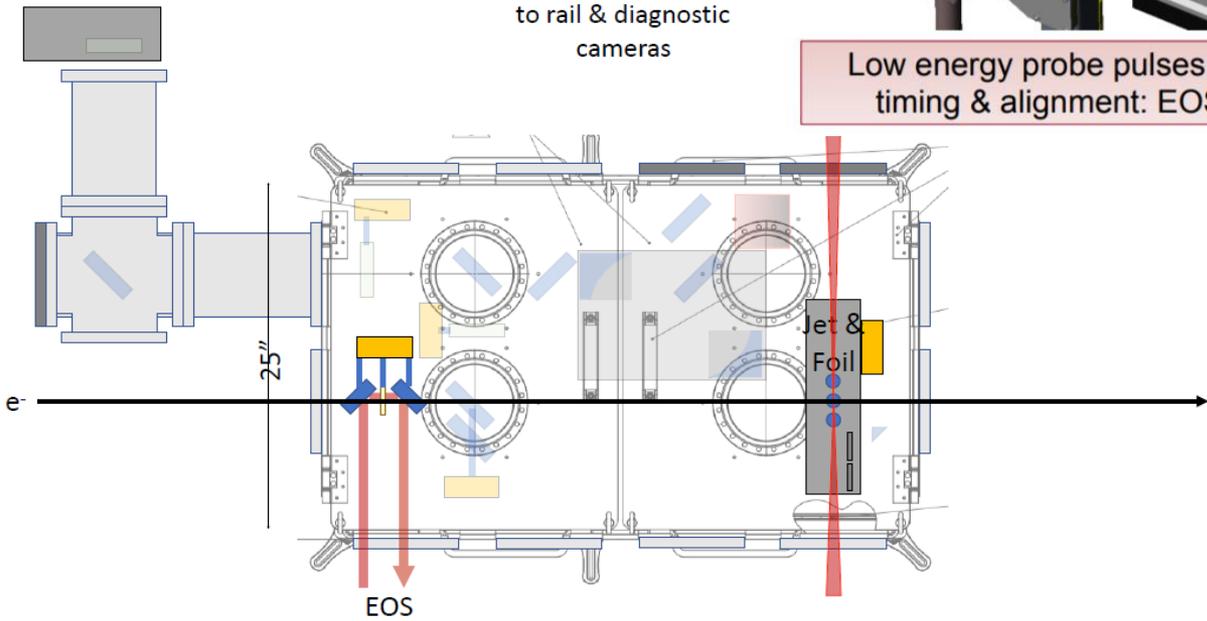
Probe Line Design Will Be Flushed Out in Plasma Sources WG

SLAC



Comment: Might be better to shoot straight for the table, then have a dogleg on the table to allow the laser to go under the e-beam.

Low energy probe pulses provide valuable diagnostic information e.g. timing & alignment: EOS, Afterglow and plasma evolution (E-224)



Now exploitation for E-310 and related experiments

Crucial for success of E-310: Spatiotemporal injection precision

- ❑ Recipes: a) measure & minimize absolute jitter of incoming pulses; b) increase blowout size (Deng, Karger *et al.*, *Nat. Phys.* 2019, supplemental discussion)

Small blowout, large jitter:
Poor injection precision

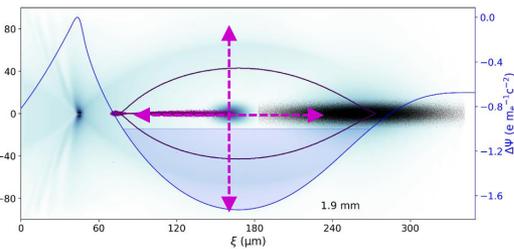
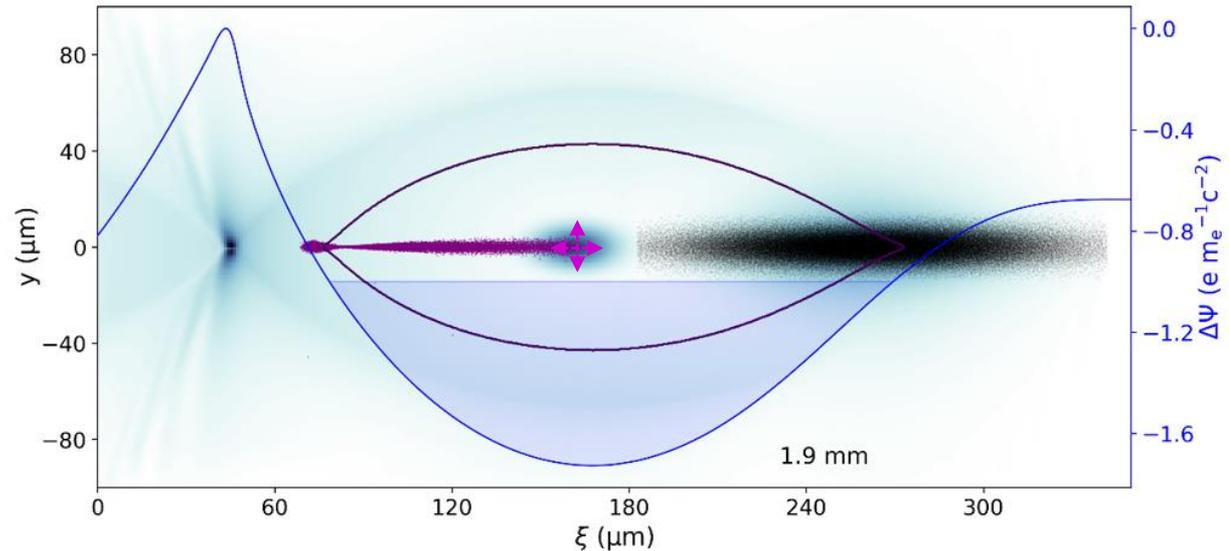


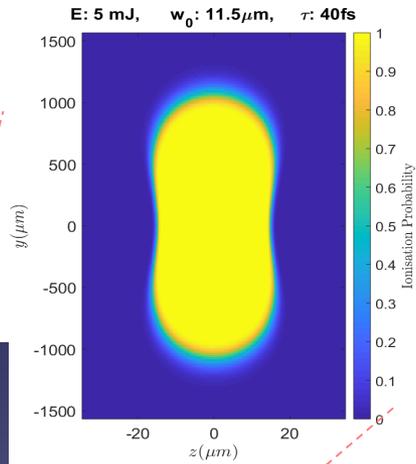
Figure of merit χ :
laser precision/ (λ_p)
33% at FACET

Large blowout, small jitter:
Excellent injection precision (sub-%), and tunability?



- ❑ Bonus: operation at lower plasma densities reduces residual energy spread (Manahan & Habib *et al.*, *Nat. Comm.* 8, 15705, 2017), and reduces requirements on driver beam (can in turn realize kickback by further increasing stability?)

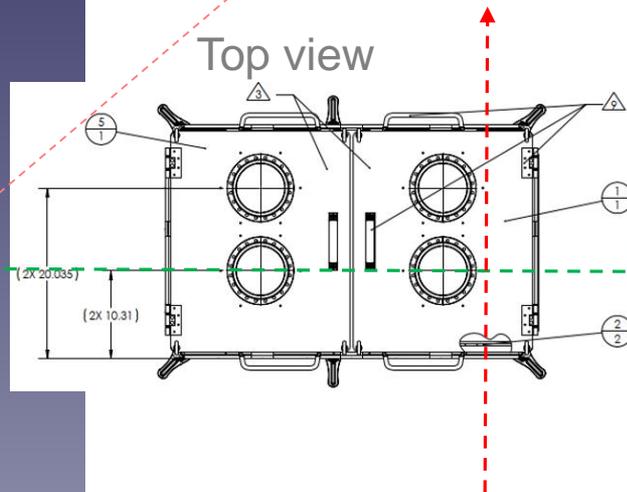
Phase 1 solution: Gaussian focusing with OAP through window.



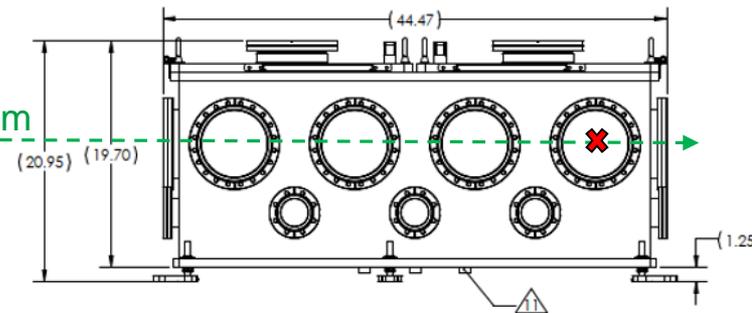
- Pros:** Robust configuration, no optics in vacuum, connects to E-210 experience, works over large range of input laser beam parameters
- Cons:** Damage thresholds, aberrations

Laser diagnostics

Top view



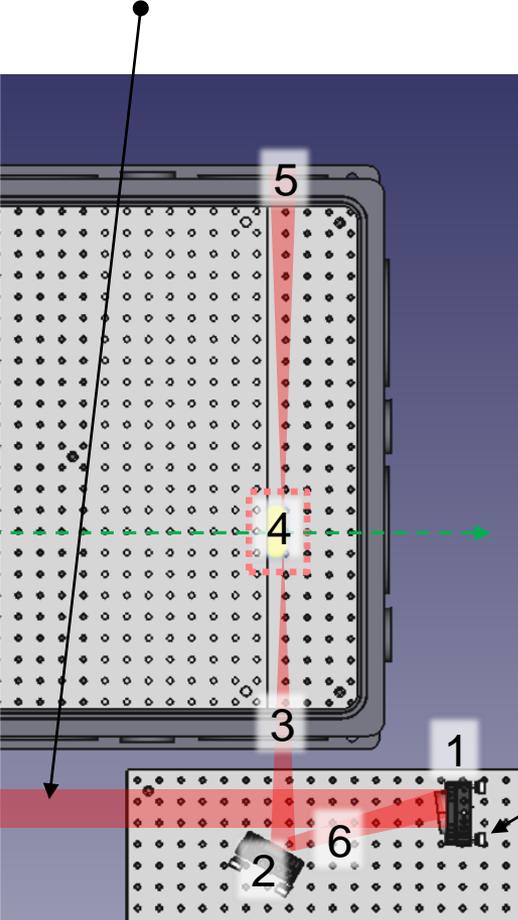
Side view



Vertical (alignment scan), z-translation, delay stage, attenuator, iris

Intensities & damage thresholds: 40 mm input laser beam diameter

Assumed probe laser pulse parameters:
 40 fs, 800 nm, (up to)
 5 mJ, 10-40 mm input
 diameter

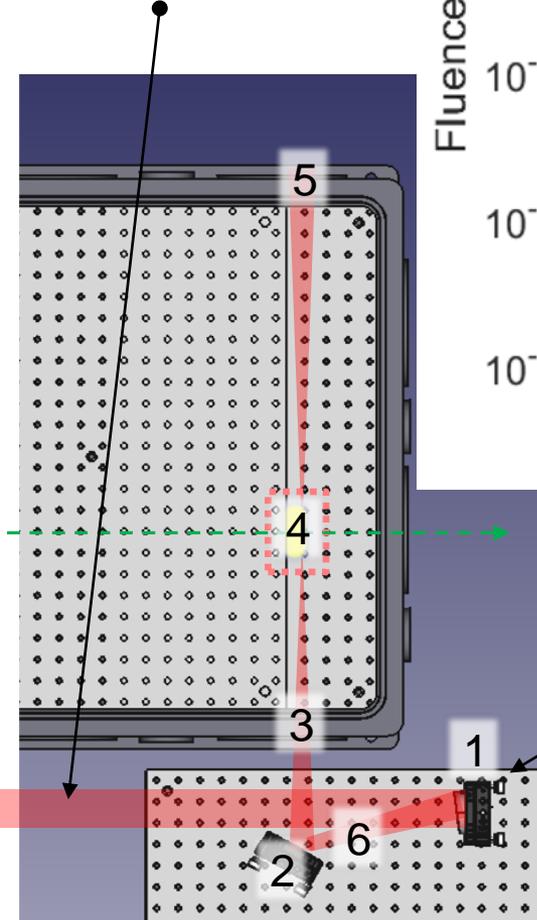
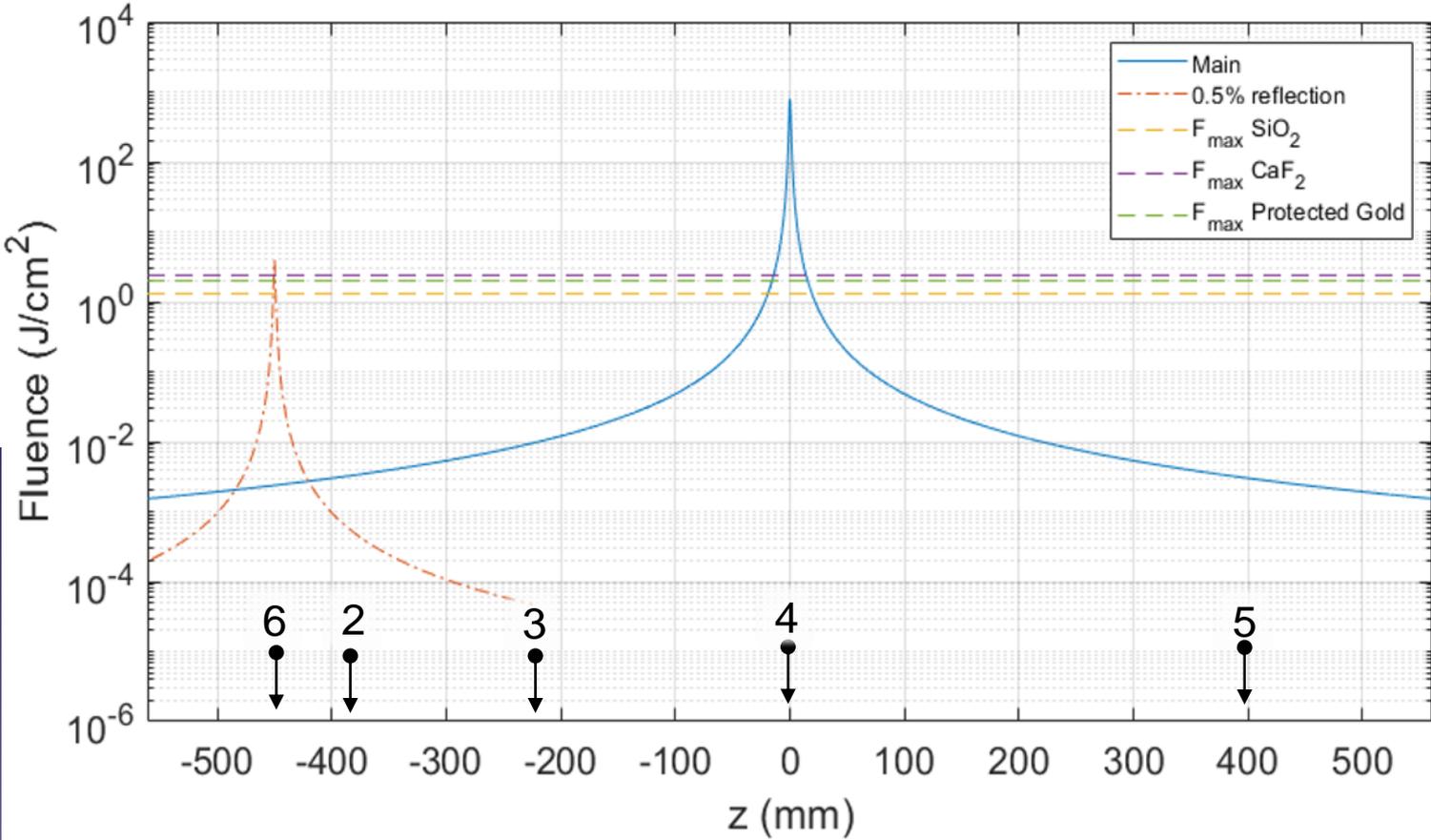


Item #	Item	Z location (mm)	FWHM Beam diameter (mm)	Peak Intensity (Wcm ⁻²)	Fluence (Jcm ⁻²)	B-Integral
1	15 deg OAP f=646mm (f/16.1)	-646	40	9.9 x10 ⁹	0.0004	
2	1" steering mirror	-388	24	2.8 x10 ¹⁰	0.001	
3	CaF ₂ 3mm Window [in]	-223	14	8.3 x10 ¹⁰	0.003	0.005
4	Focus (2w ₀)	0	0.023	2.9 x10 ¹⁶	1176	
5	CaF ₂ 3mm Window [out]	400	25	2.6 x10 ¹⁰	0.001	0.002
6	0.5% Back-reflected focus	-446	0.023	1.5 x10¹⁴	8.52	
(2)	0.5% Back reflection on mirror #2	-388	4	6.2 x10⁹	<0.001	

OAP: off-the-shelf 15° gold, Edmund #35-603:
 f/16.1, 50.8 mm diameter, 646 mm effective focal length.
 For 40 mm input beam diameter, $w_0 \approx 11.5 \mu\text{m}$, $Z_R \approx 500 \mu\text{m}$
 Currently in: SiO₂ window with coating

Intensities & damage thresholds: 40 mm input laser beam diameter

40 fs, 800 nm, (up to) 5 mJ, 10-40 mm input diameter

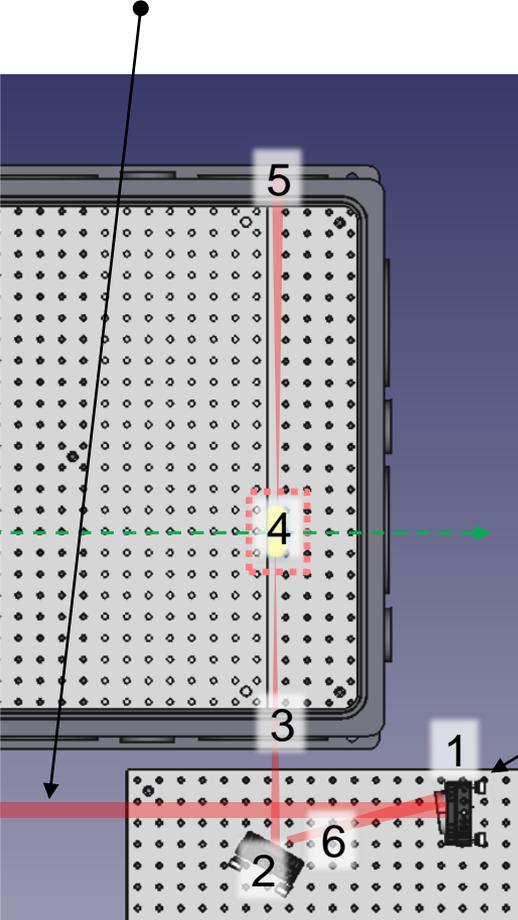


OAP: off-the-shelf 15° gold, Edmund #35-603: f/16.1, 50.8 mm diameter, 646 mm effective focal length.

Intensities & damage thresholds: 10 mm input laser beam parameter

Assumed probe laser pulse parameters:
 40 fs, 800 nm, (up to)
 5 mJ, 10-40 mm input
 diameter

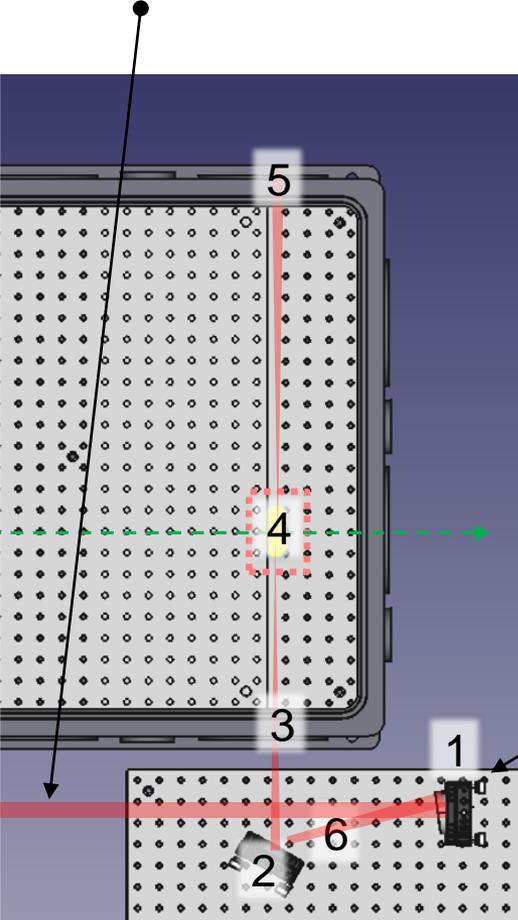
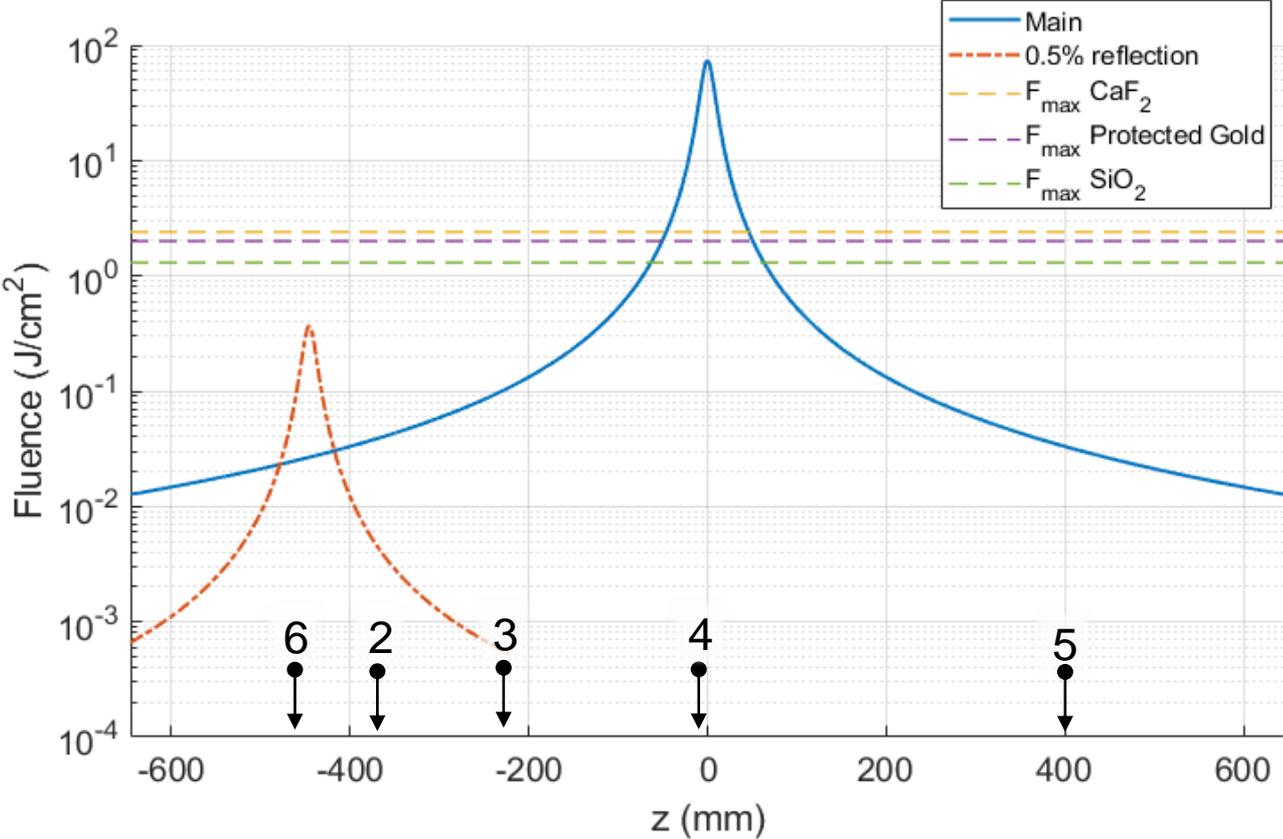
Item #	Item	Z location (mm)	Beam diameter (mm)	Peak Intensity (Wcm ⁻²)	Fluence (Jcm ⁻²)	B-Integral
1	15 deg OAP f=646mm f/16.1)	-646	10	1.6 x10 ¹¹	0.0064	
2	1" steering mirror	-388	6	4.4 x10 ¹¹	0.017	
3	CaF ₂ 3mm Window [in]	-223	3.4	1.3 x10 ¹²	0.053	0.052
4	Focus	0	0.093	1.8 x10 ¹⁵	73.5	
5	CaF ₂ 3mm Window [out]	400	6.2	4.1 x10 ¹¹	0.017	0.016
6	0.5% Back-reflected focus	-446	0.093	9.2 x10¹²	0.37	
(2)	0.5% Back-reflection on mirror #2	-388	0.9	9.7 x10¹⁰	0.004	



OAP: off-the-shelf 15° gold, Edmund #35-603:
 f/16.1, 50.8 mm diameter, 646 mm effective focal length.
 For 10 mm input beam diameter, $w_0 \approx 46.5 \mu\text{m}$, $Z_R \approx 8 \text{ mm}$
 Currently in: SiO₂ window with coating

Intensities & damage thresholds: 10 mm input laser beam parameter

40 fs, 800 nm,
up to 5 mJ,
10-40 mm
input diameter

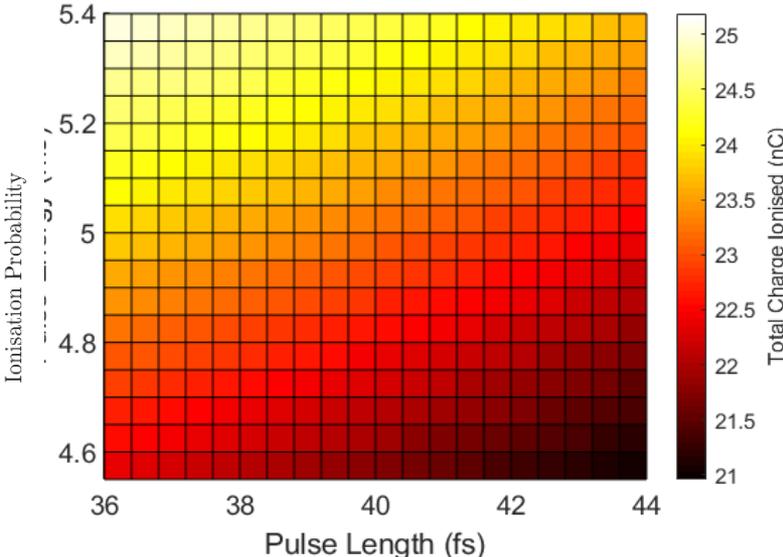
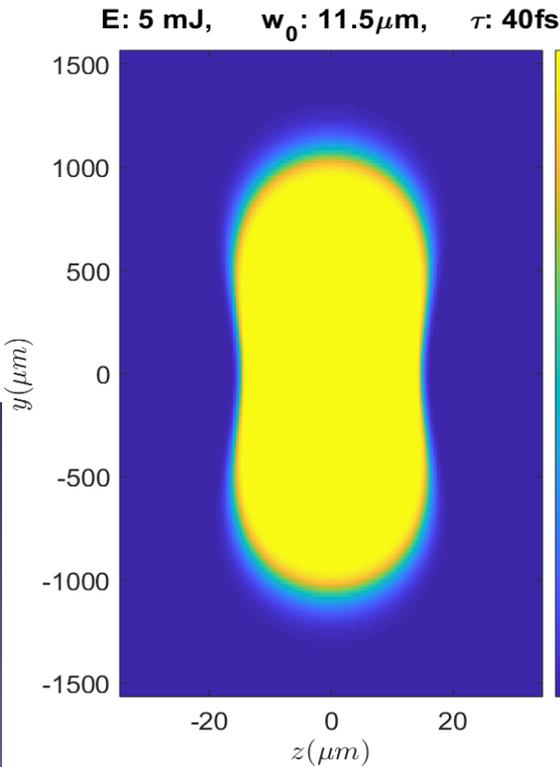
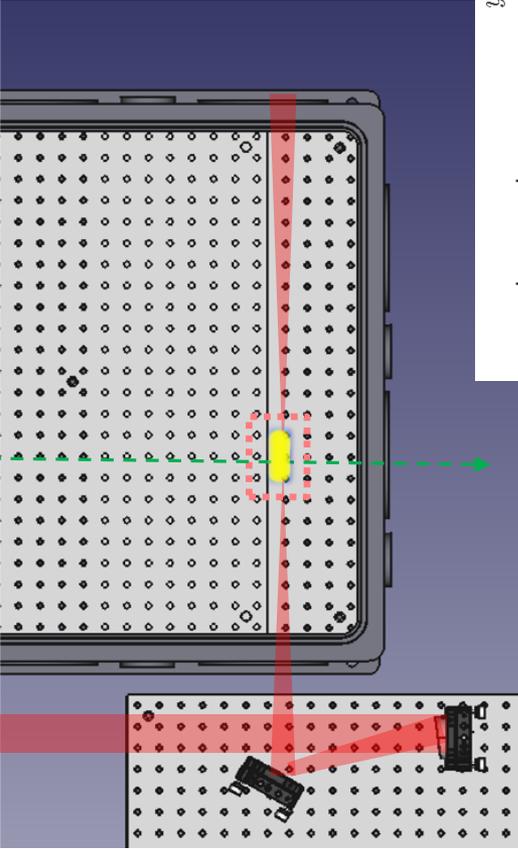


OAP: off-the-shelf 15° gold, Edmund #35-603:
f/16.1, 50.8 mm diameter, 646 mm effective focal length.

Plasma filaments in spe: 40 mm input laser pulse, helium

Baseline parameters:
40 fs±10%, 5 mJ±10%

Tunneling ionization calculations (He):

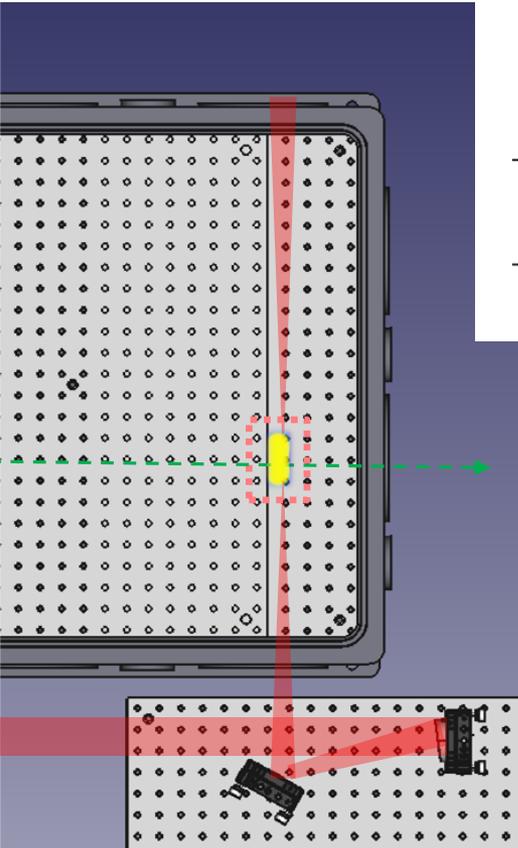
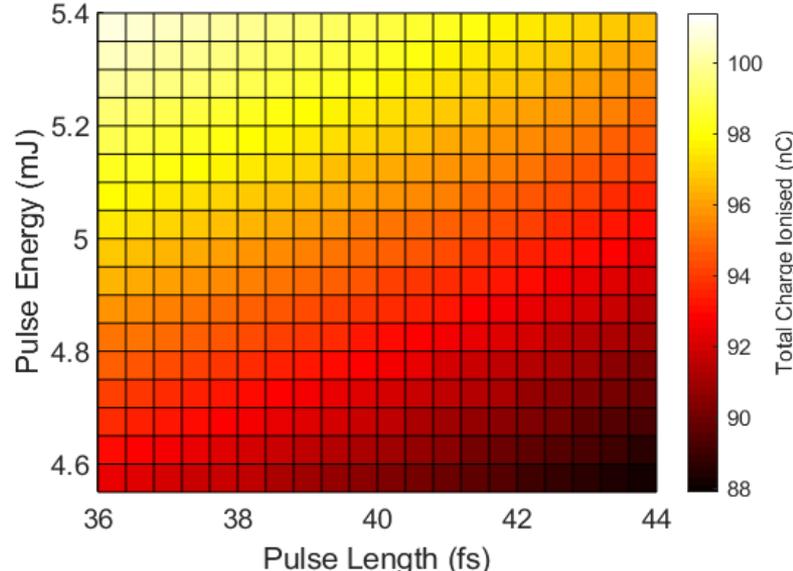
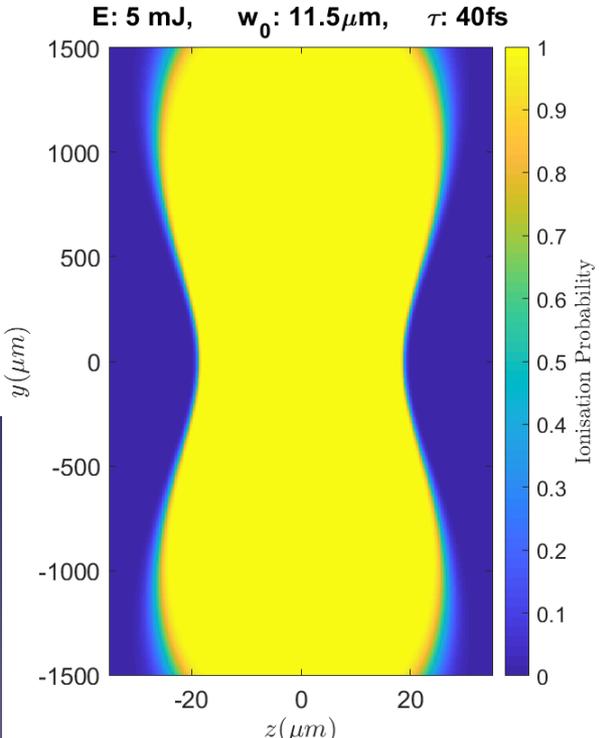


Gas	He (24.6 eV)
Density	$10^{17}/\text{cc}$
Plasma filament full-width (μm)	29.2 ± 0.2
Plasma filament length	2 mm
Charge (nC)	23.1 ± 1 (4.3%)

Plasma filaments in spe: 40 mm input laser pulse, hydrogen

Baseline parameters:
 40 fs \pm 10%, 5 mJ \pm 10%

Tunneling ionization calculations (H):

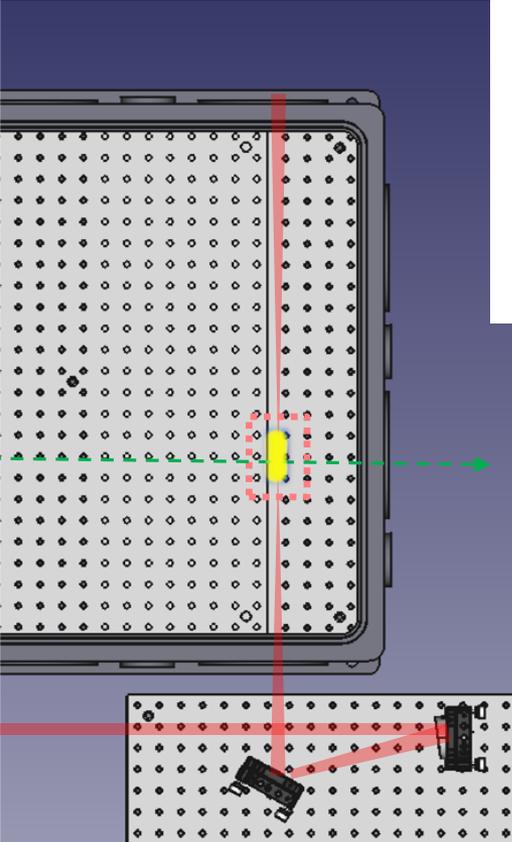
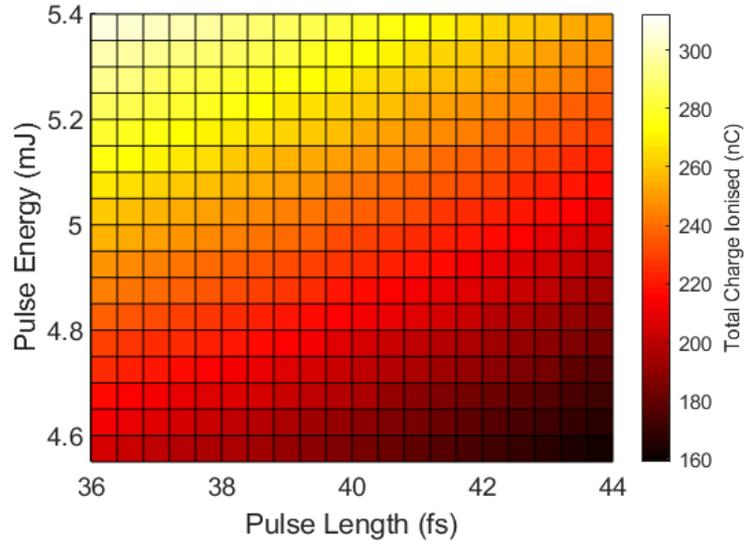
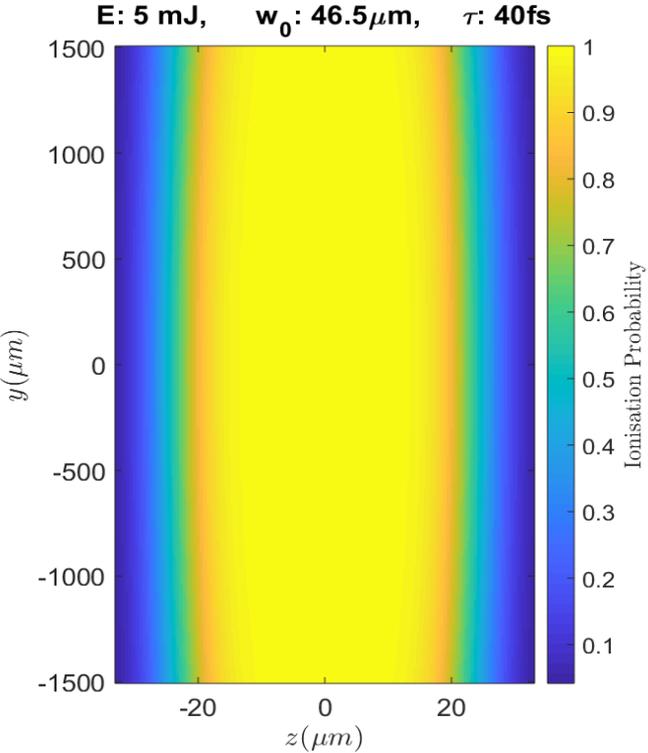


Gas	H (13.6 eV)
Density	10 ¹⁷ /cc
Plasma filament full-width (μ m)	37.2 \pm 0.4
Plasma filament length	3.8 mm
Charge (nC)	94.9 \pm 3.0 (3.2%)

Plasma filaments in spe: 10 mm input laser pulse, helium

Baseline parameters:
 40 fs \pm 10%, 5 mJ \pm 10%

Tunneling ionization
 calculations (He):

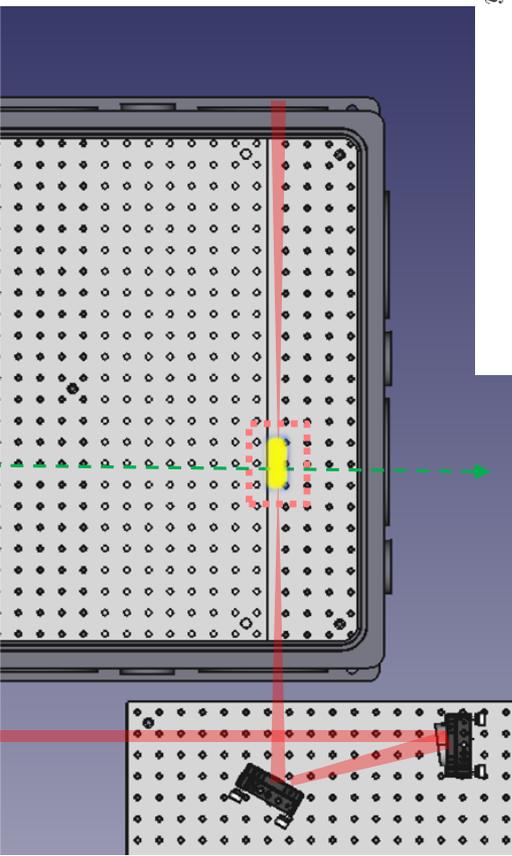
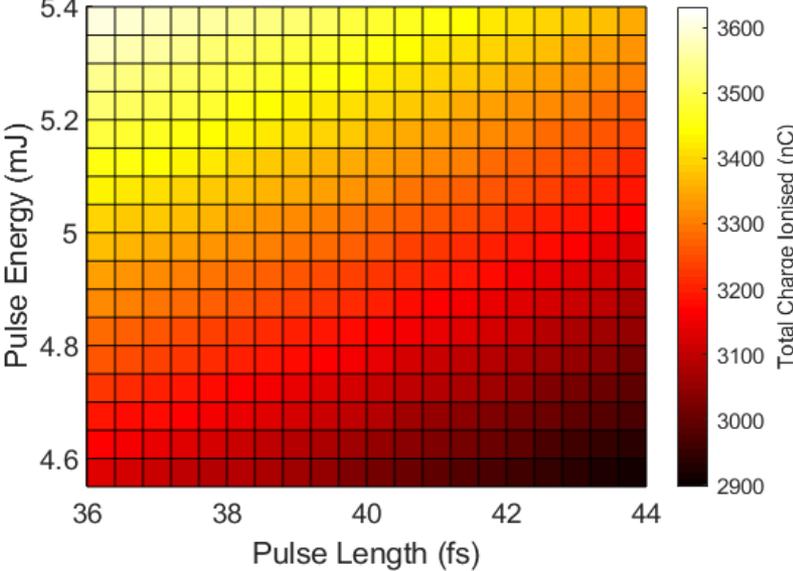
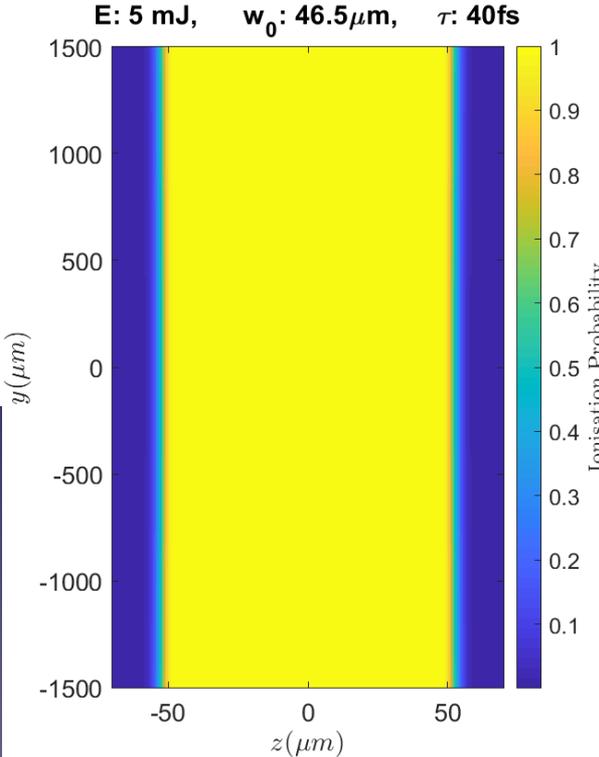


Gas	He (24.6eV)
Density	$10^{17}/\text{cc}$
Plasma filament full-width (μm)	46.8 ± 2.8
Plasma filament length	9.4 mm
Charge (nC)	233 ± 35 (15%)

Plasma filaments in spe: 10 mm input laser pulse, hydrogen

Baseline parameters:
 40 fs \pm 10%, 5 mJ \pm 10%

Tunneling ionization
 calculations (H):

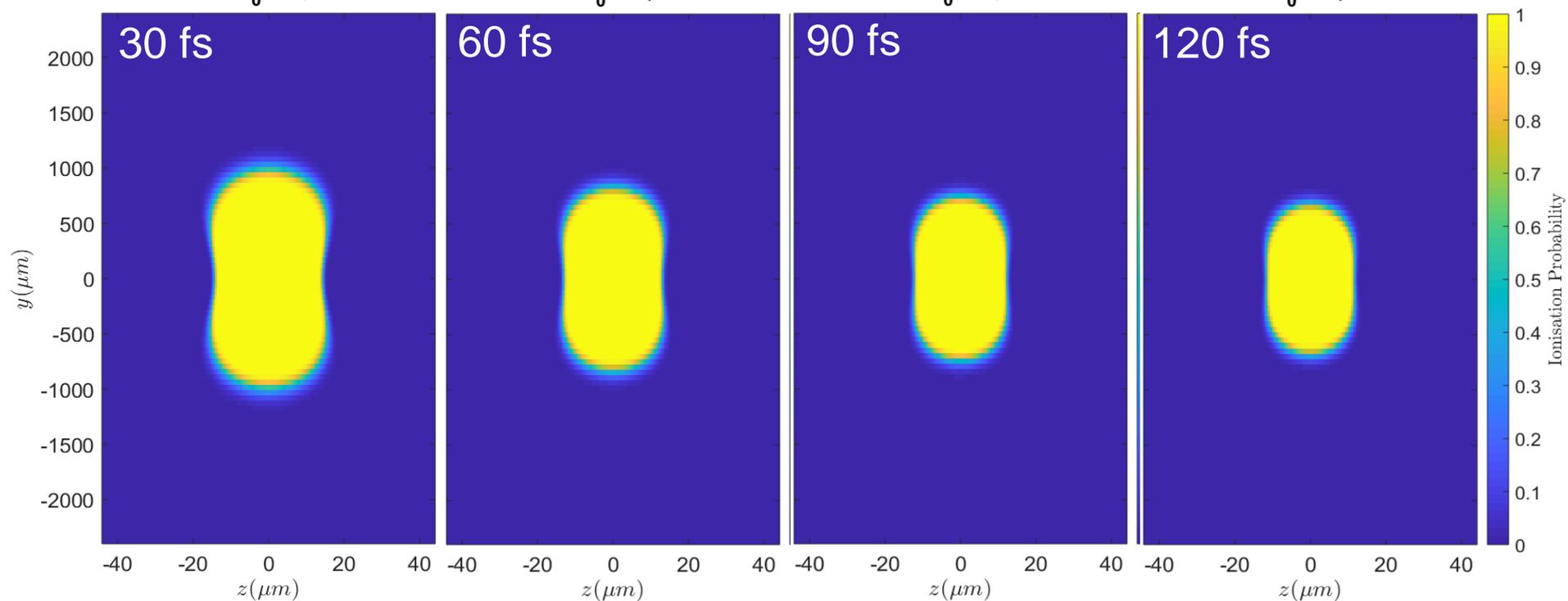


Gas	H (13.6 eV)
Density	$10^{17}/\text{cc}$
Plasma filament full-width (μm)	102.8 ± 1.4
Plasma filament length	26 mm
Charge (nC)	3260 ± 170 (5.1%)

Active tuning: Plasma yield variation by laser input diameter (iris), laser energy (attenuator), species & density, laser pulse duration

Ionization profiles for input beam diameter 40 mm, $w_0=11\ \mu\text{m}$, **0.5 mJ** in He

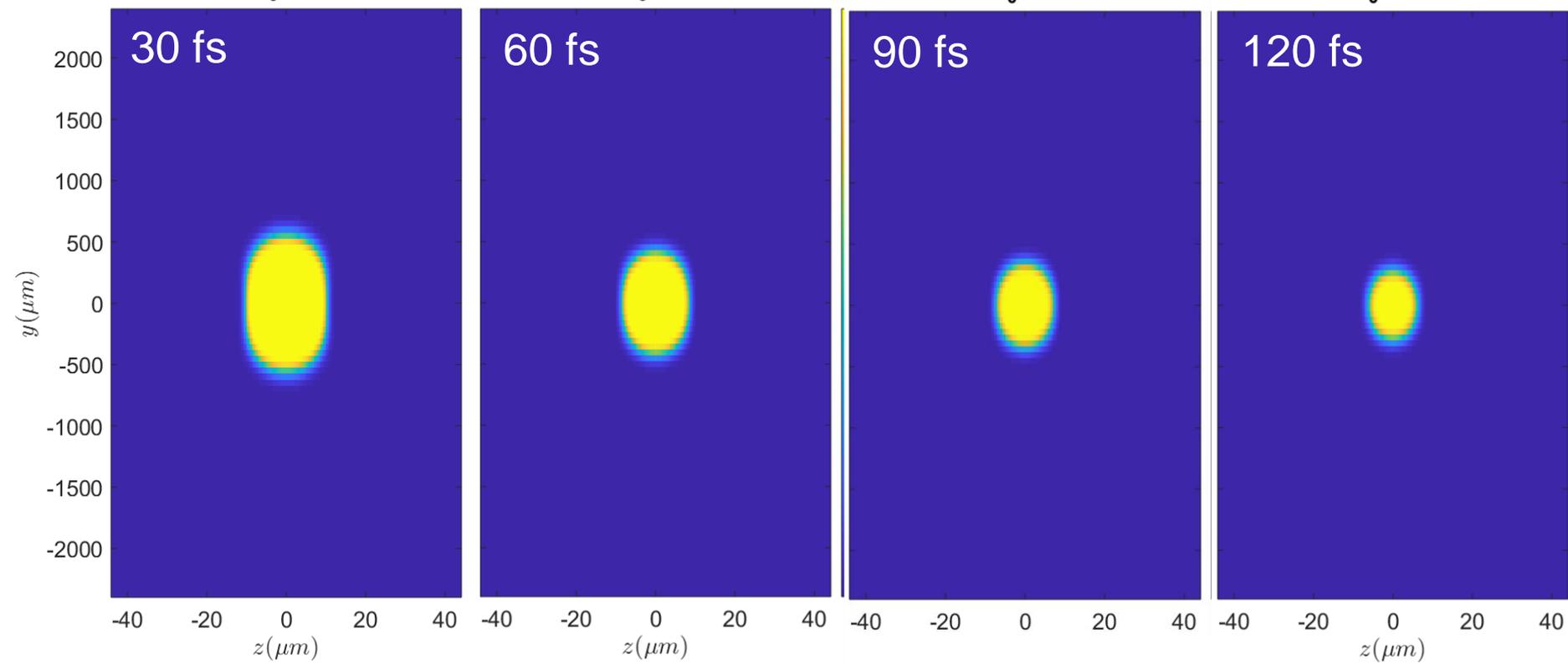
E: 0.5 mJ, $w_0: 11\ \mu\text{m}$, $\tau: 30\text{fs}$; E: 0.5 mJ, $w_0: 11\ \mu\text{m}$, $\tau: 60\text{fs}$; E: 0.5 mJ, $w_0: 11\ \mu\text{m}$, $\tau: 90\text{fs}$; E: 0.5 mJ, $w_0: 11\ \mu\text{m}$, $\tau: 120\text{fs}$



Active tuning: Plasma yield variation by laser input diameter (iris), laser energy (attenuator), species & density, laser pulse duration

Ionization profiles for input beam diameter 40 mm, $w_0=11\ \mu\text{m}$, **0.1 mJ** in He

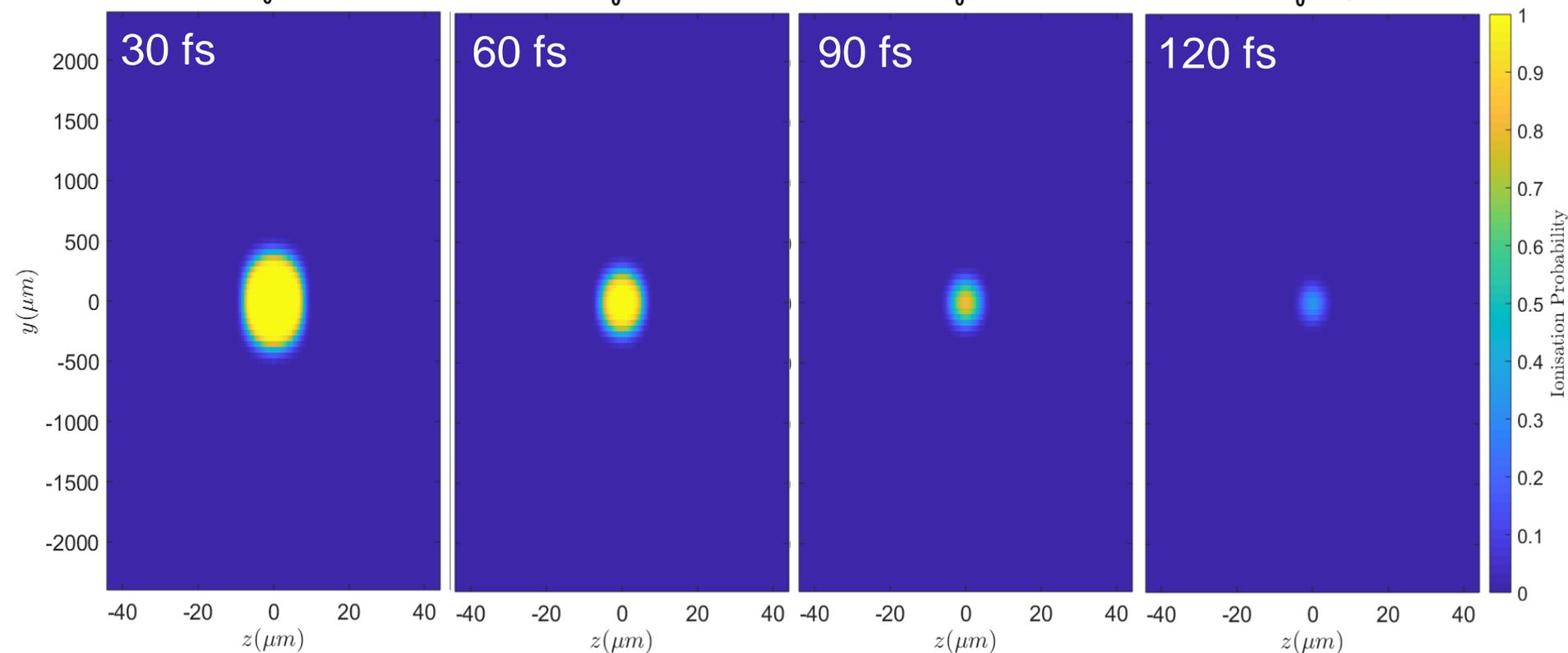
$E: 0.1\ \text{mJ}, w_0: 11\ \mu\text{m}, \tau: 30\ \text{fs}$ $E: 0.1\ \text{mJ}, w_0: 11\ \mu\text{m}, \tau: 60\ \text{fs}$ $E: 0.1\ \text{mJ}, w_0: 11\ \mu\text{m}, \tau: 90\ \text{fs}$ $E: 0.1\ \text{mJ}, w_0: 11\ \mu\text{m}, \tau: 120\ \text{fs}$



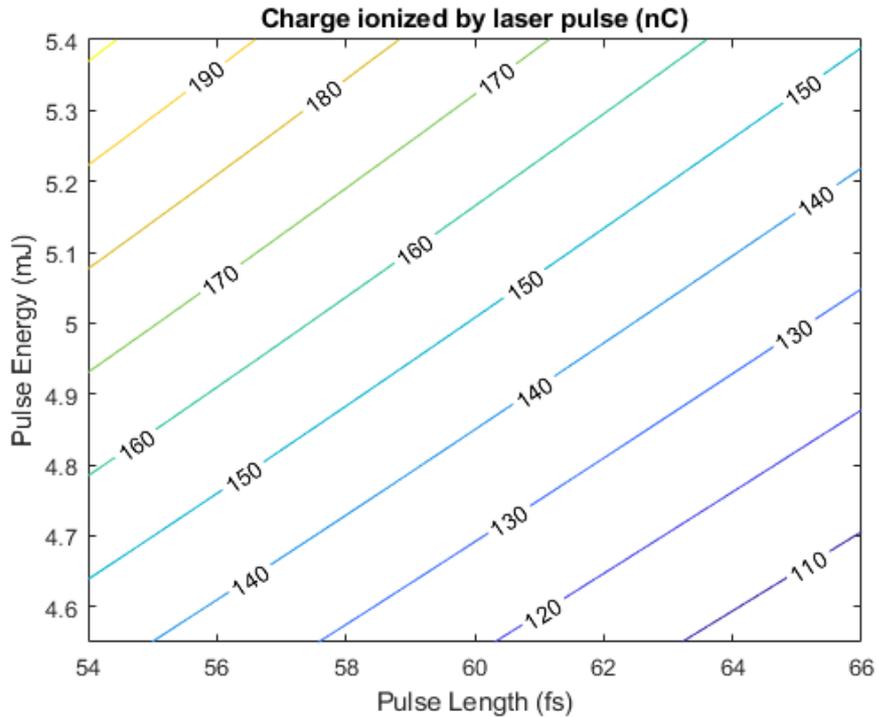
Active tuning: Plasma yield variation by laser input diameter (iris), laser energy (attenuator), species & density, laser pulse duration

Ionization profiles for input beam diameter 40 mm, $w_0=11\ \mu\text{m}$, **0.05 mJ** in He

E: 0.05 mJ, $w_0: 11\ \mu\text{m}$, $\tau: 30\text{fs}$ **E: 0.05 mJ, $w_0: 11\ \mu\text{m}$, $\tau: 60\text{fs}$** **E: 0.05 mJ, $w_0: 11\ \mu\text{m}$, $\tau: 90\text{fs}$** **E: 0.05 mJ, $w_0: 11\ \mu\text{m}$, $\tau: 120\text{fs}$**

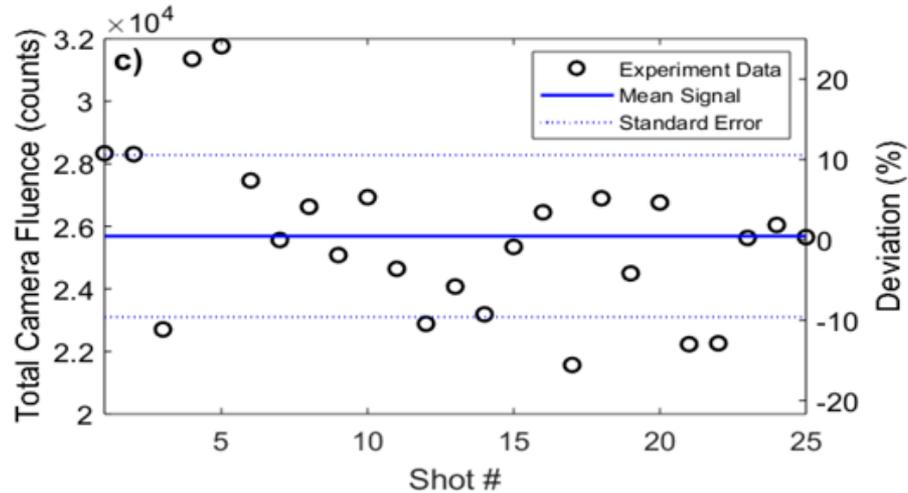
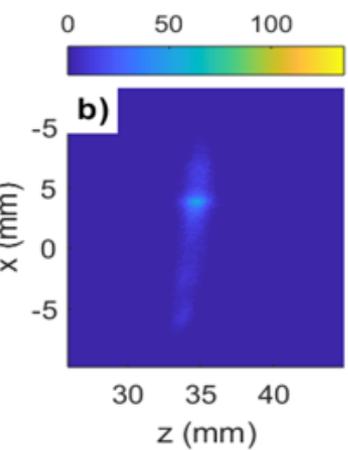


Passive: Stability of laser-only plasma afterglow signal at FACET



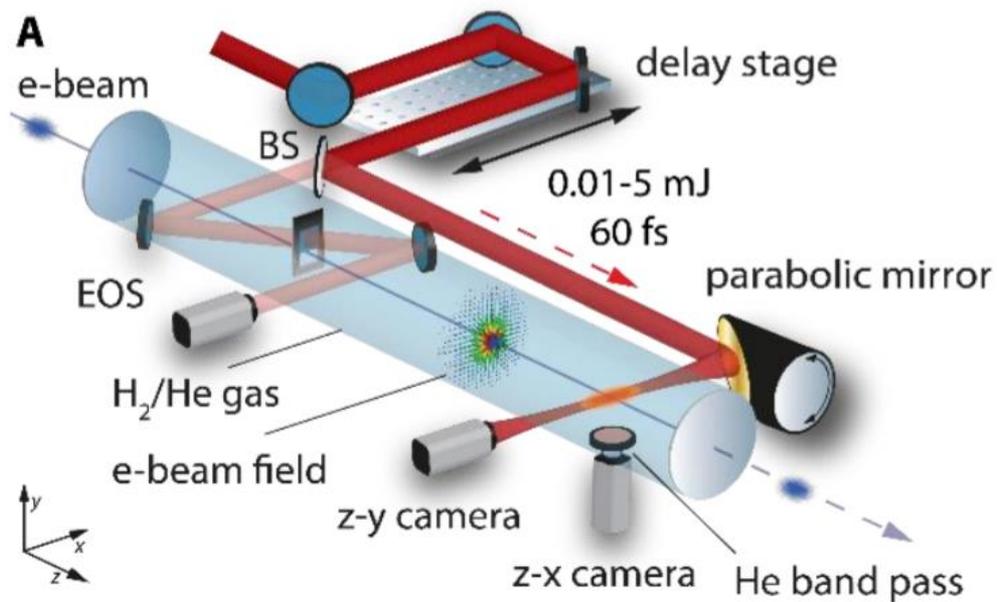
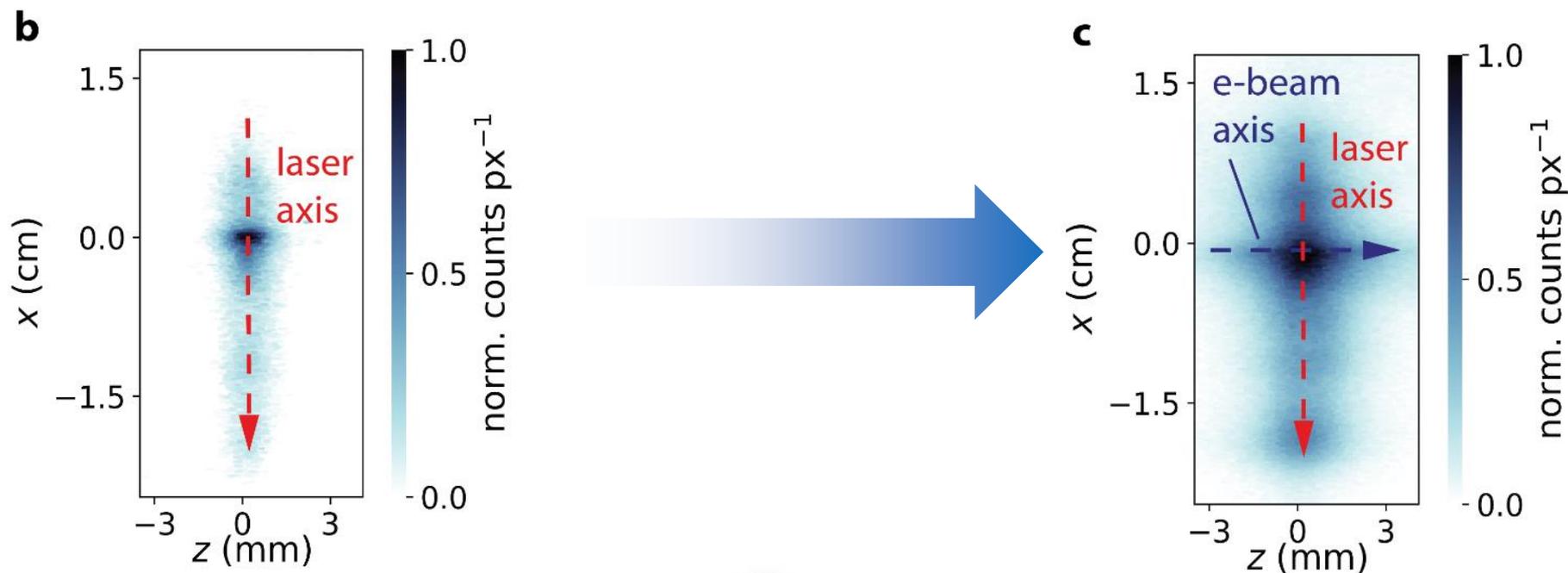
At FACET: detection of plasma recombination afterglow signal via bandpass filter and CCD
Laser pulse ~60 fs, ~5 mJ

Known laser pulse energy ($5 \text{ mJ} \pm 10\%$) and duration ($60 \text{ fs} \pm 10\%$) jitters calculated to produce a 5.5% standard deviation in produced charge in He

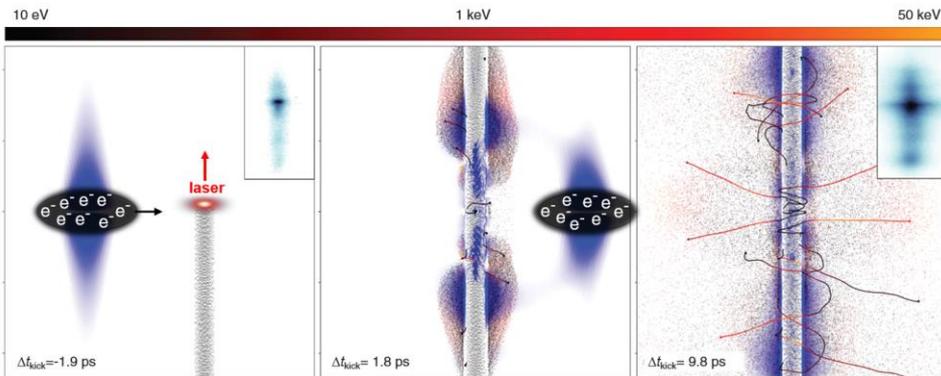
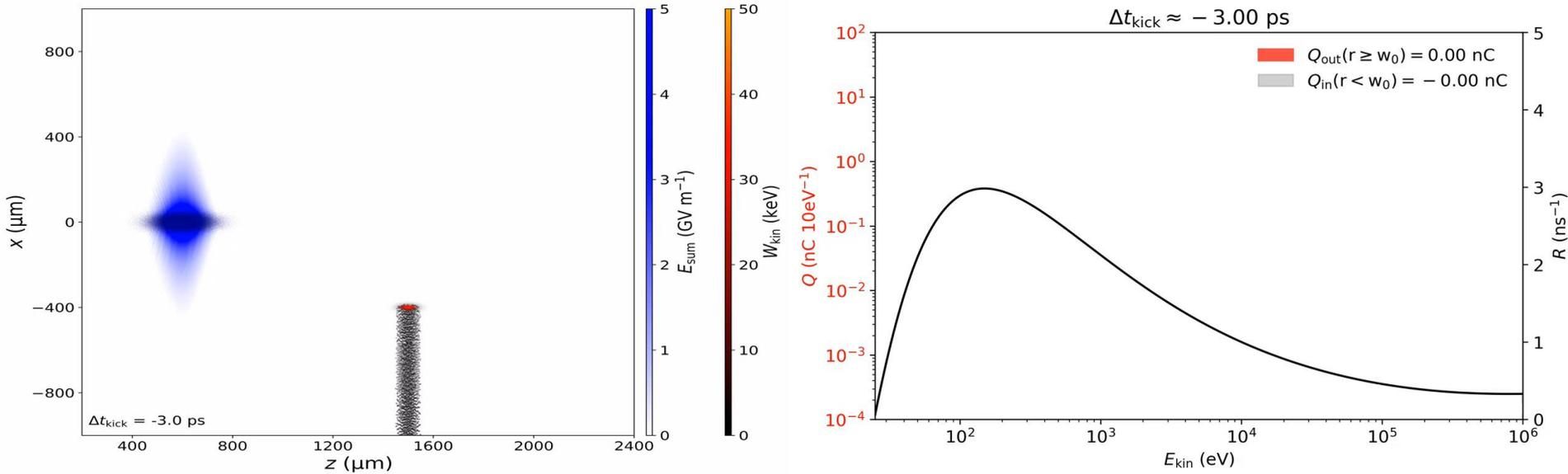


Experimental: 10% standard deviation in afterglow signal

E-beam enhanced plasma afterglow



- ❑ Plasma photocathode requires spatiotemporal precision injection
- ❑ Developed and demonstrated powerful plasma afterglow avalanche method for beam metrology and spatiotemporal synchronization and alignment

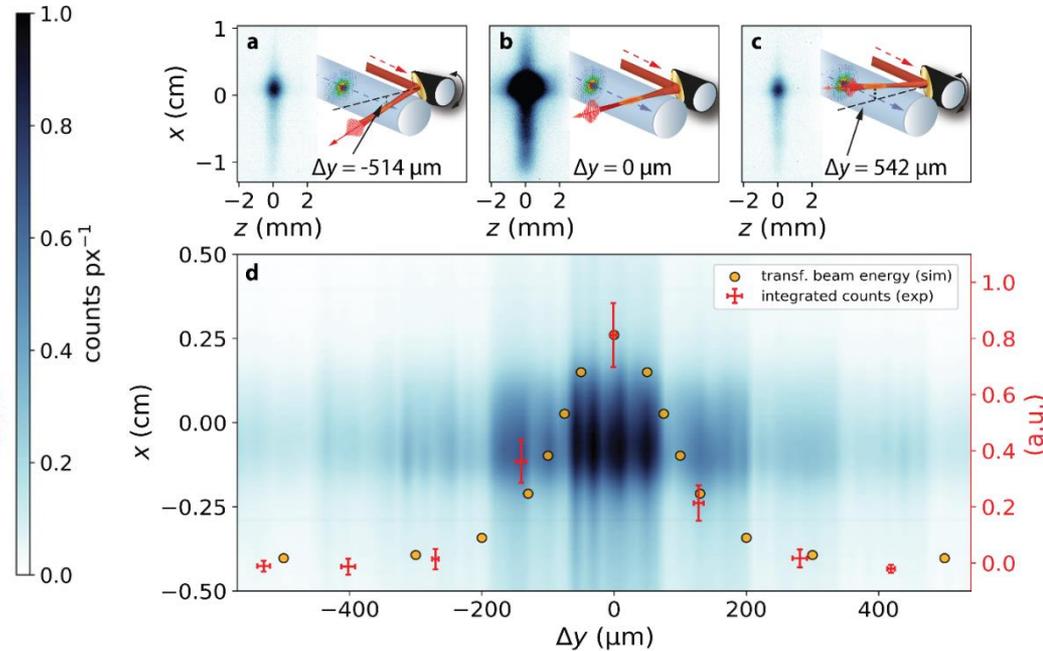
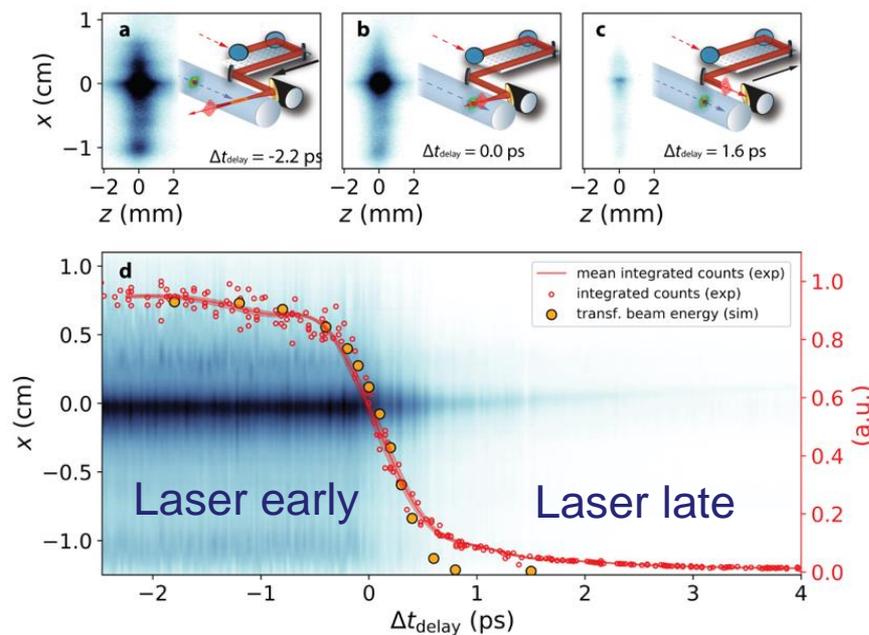


Transition from laser-only afterglow to enhanced afterglow is robust observable and allows various laser, e-beam and laser vs. e-beam metrology

Plasma afterglow metrology: spatiotemporal synchronization & alignment

Temporal data:

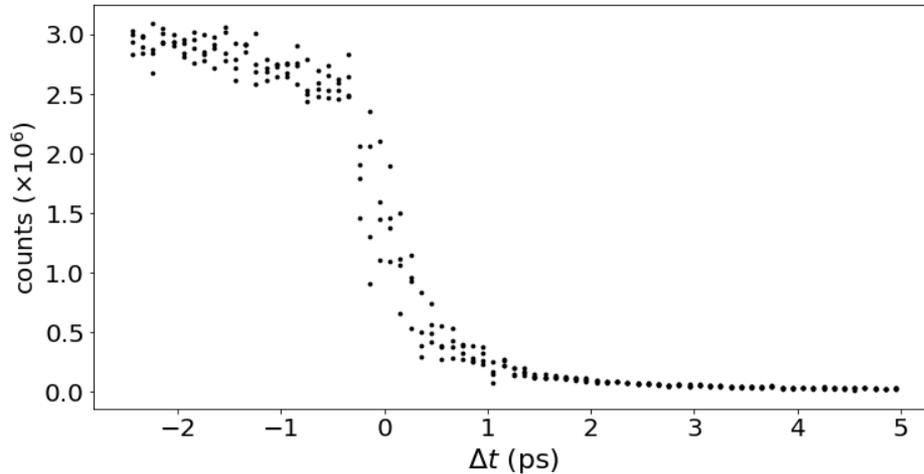
Spatial data:



Red: experimental (which takes into account experimental jitters at FACET),
yellow: simulations of energy transfer from beam to plasma (no jitter)
Very good agreement!

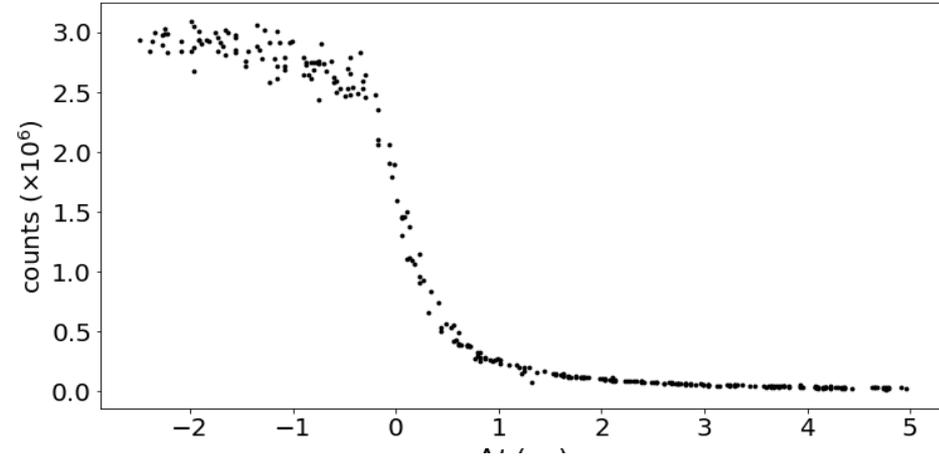
Plasma afterglow metrology: spatiotemporal synchronization *works also standalone*

w/o EOS time stamps



Accuracy: 55 fs

sorted by EOS time stamps

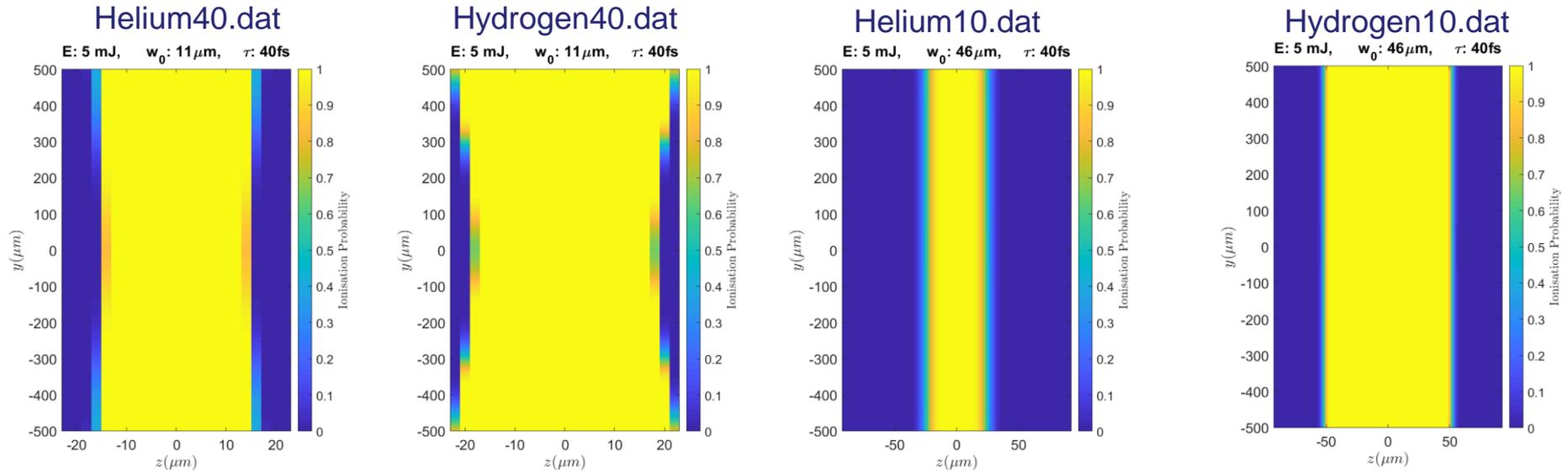


Accuracy: 16 fs

Slope steepness determines limit of diagnostics (no errors): can do significantly better for better stability of incoming beams

- P. Scherkl *et al.*, Plasma-photonic spatiotemporal synchronization of relativistic electron and laser beams, arXiv:1908.09263 (2019)

Ionization profiles for experimentally expected implementations as discussed implemented into PIC (VSim), e.g.:



Extensive parameter scan, e.g.:

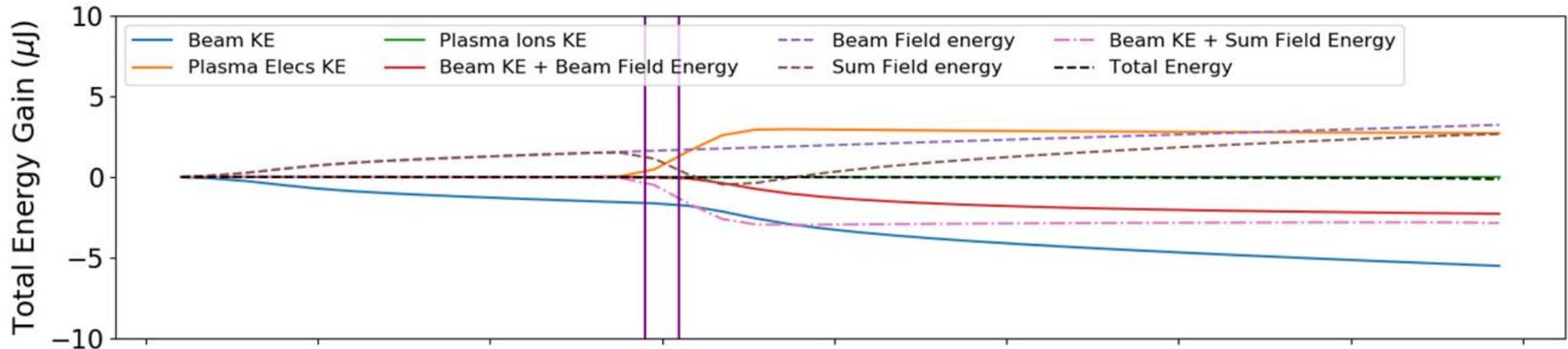
Overdense regime: From FACET we know observed plasma afterglow is proportional to beam-plasma energy transfer in PIC

Beam energy	10 GeV
Beam charge	1 nC
Beam width, length	20 μm , (20 – 50) μm
Beam Density	$\sim 10^{16}/ \text{cc}$
Plasma density	$10^{15}/ \text{cc}$, $10^{17}/ \text{cc}$
Plasma column radius	$\sim (10 - 50) \mu\text{m}$



Kinetic energy of particles vs. energy stored in fields by integrating EM energy density

$$u = \frac{1}{2} \left(\epsilon_0 \mathbf{E}^2 + \frac{1}{\mu_0} \mathbf{B}^2 \right),$$

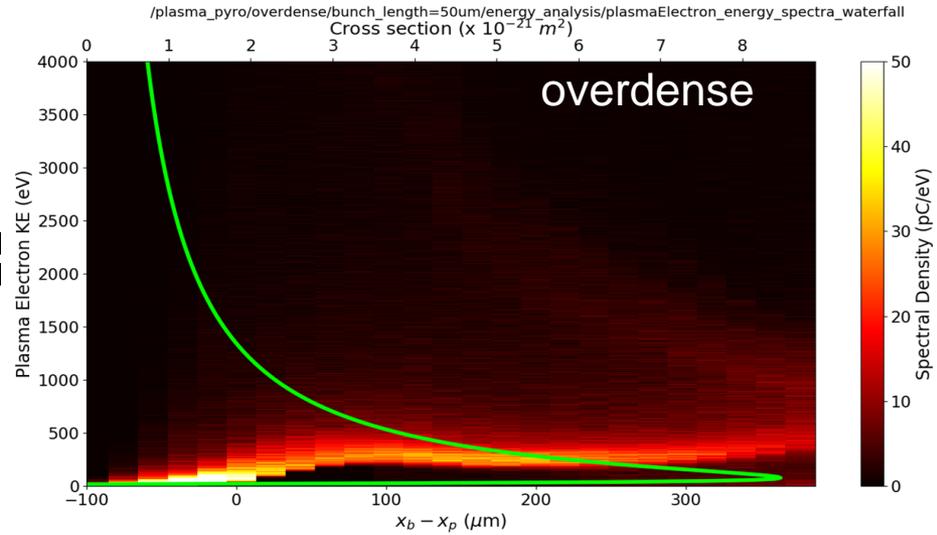
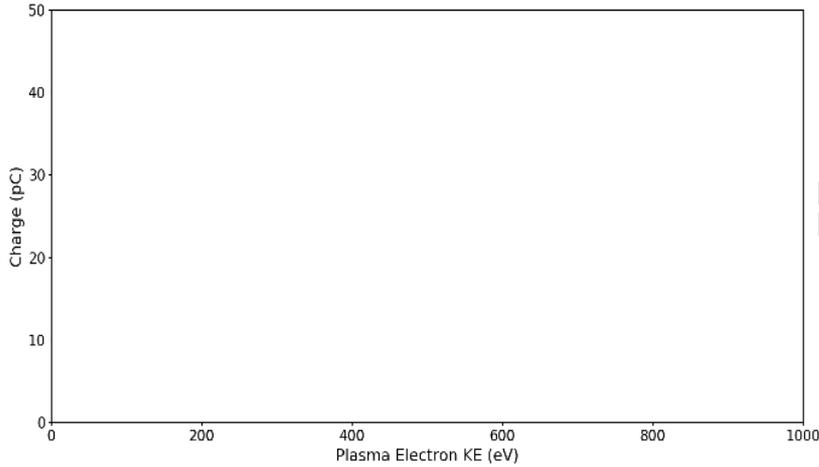


A lot is going on as regards physics, and numerics...

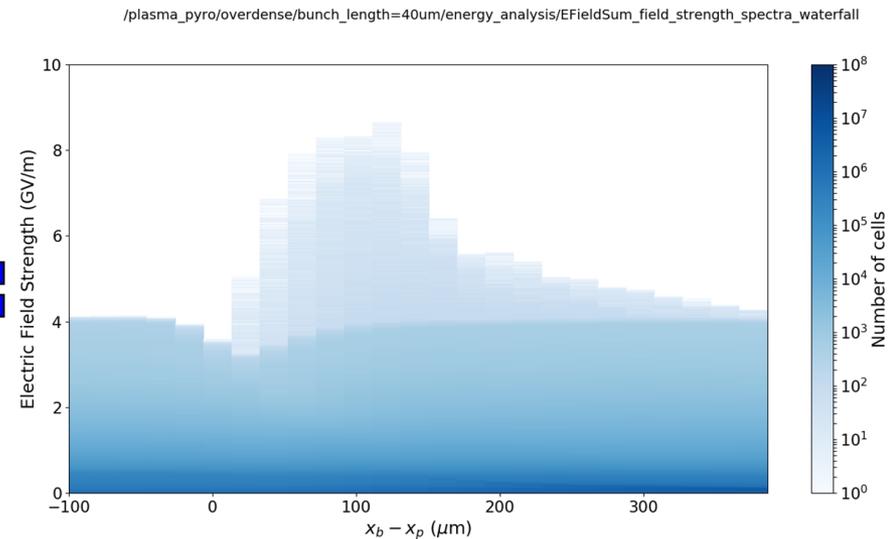
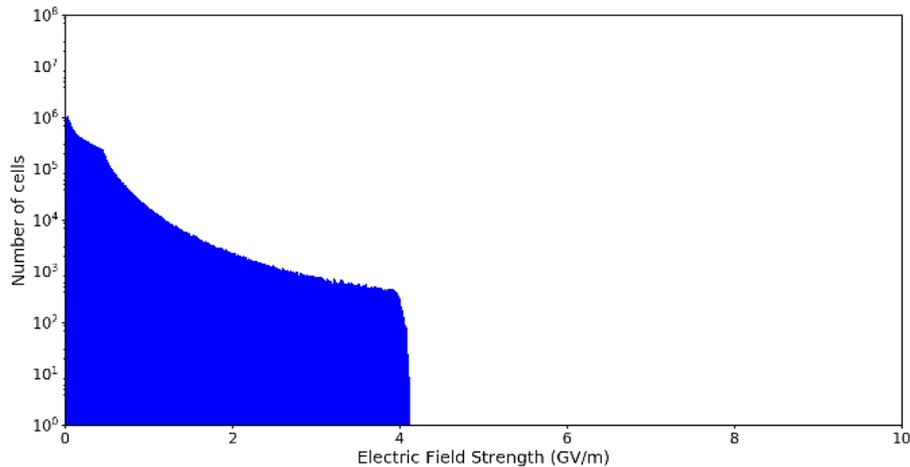
Sanity check: total energy conservation

Energy transfer in total: very low! Minimally intrusive diagnostics..

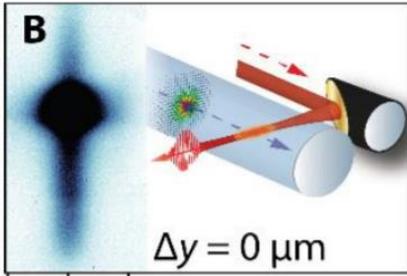
Energy distribution of kicked seed plasma electrons:



Field strength evolution:



Plasma afterglow pyro

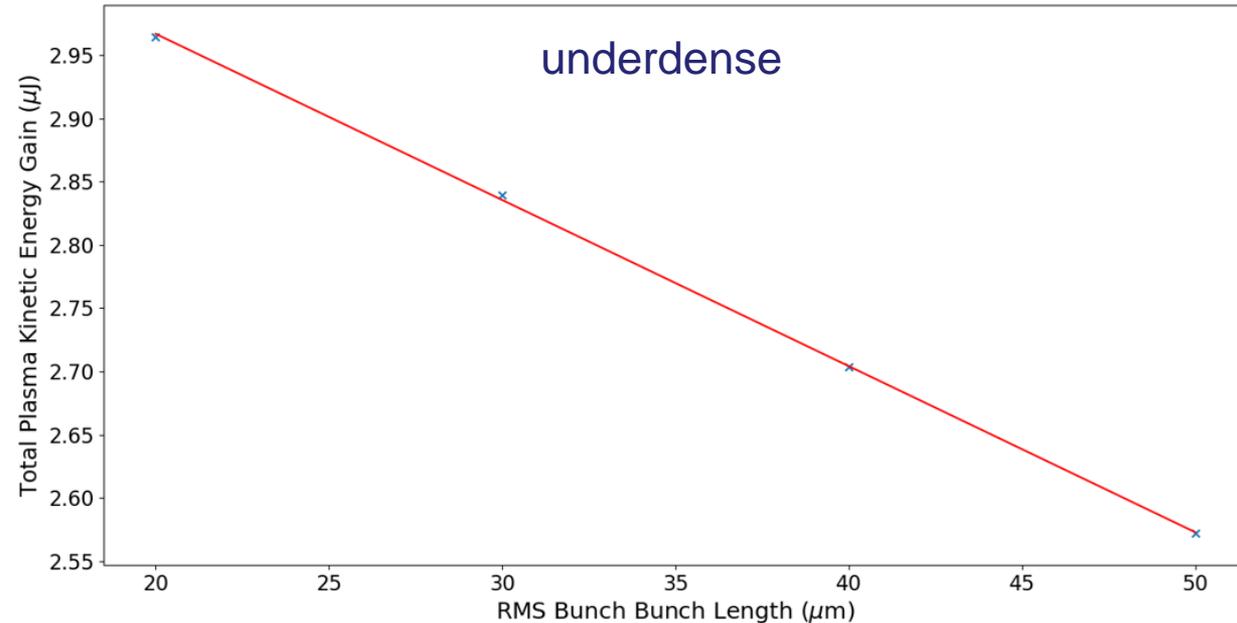
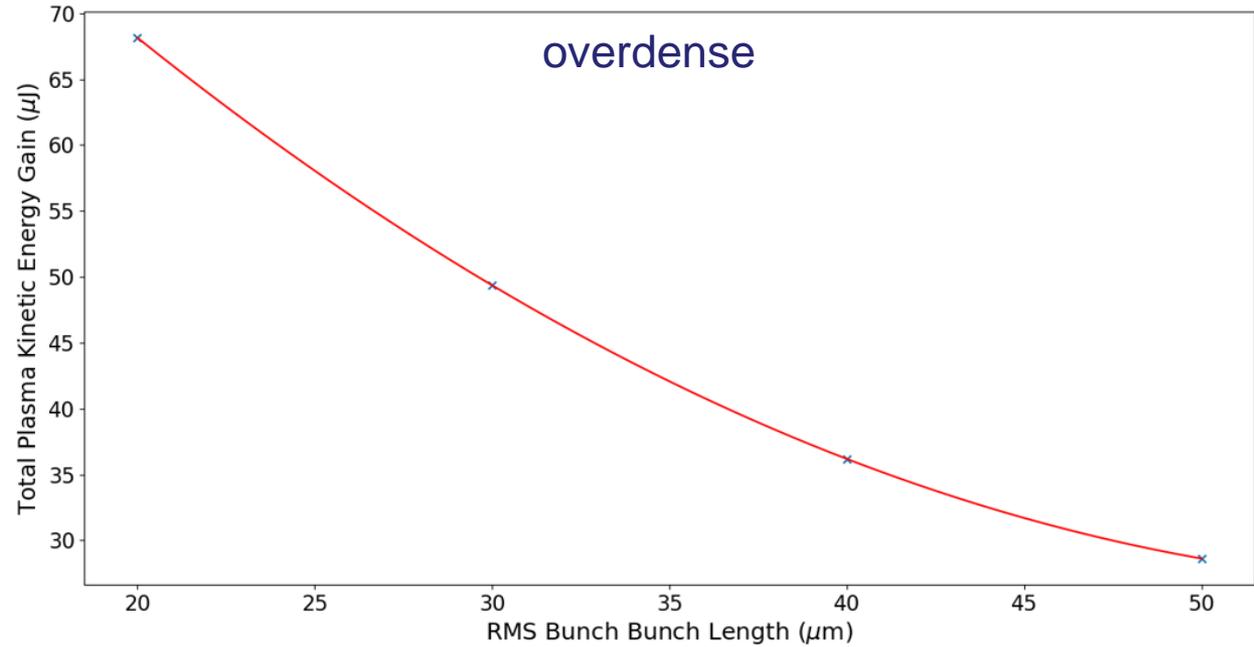


Laser early mode

Beam length variation (all other parameters assumed constant):

Note 10x larger energy transfer in overdense regime

Can be used to measure beam duration with high accuracy?



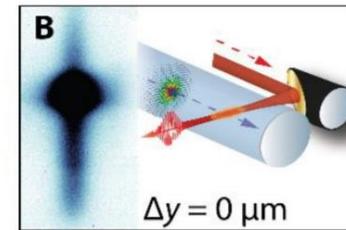
Assuming FACET level diagnostics & light collection:

Energy transfer → Camera signal

SLAC

Assumptions

- Converting from energy transfer to pixel counts
 - $1\text{eV} \approx 5\text{e-}10$ counts [taken from FACET data/simulation pairing]
- Minimum detectable change in the camera
 - 707 counts [taken from FACET cube3vert background]
- Completely free of random errors

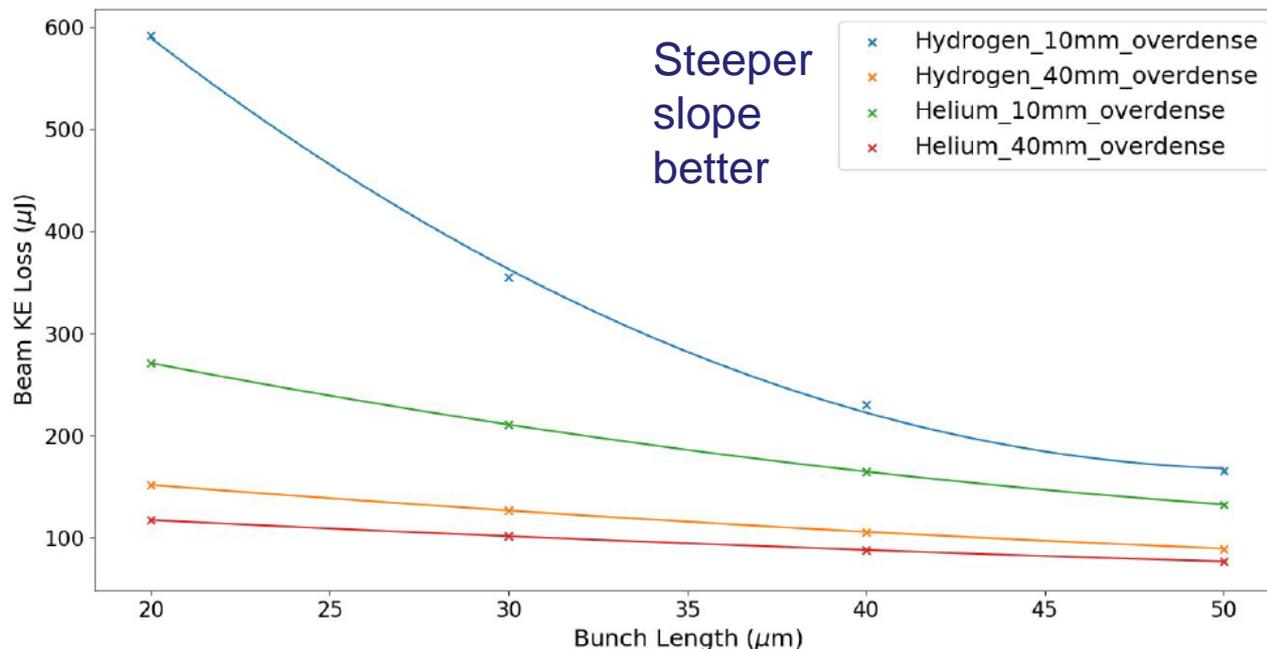


Bunch Length

SLAC

Hydrogen	<i>Theoretically Detectable change</i>
40mm input laser	0.10 μm
10mm input laser	0.016 μm

Helium	<i>Theoretically Detectable change</i>
40mm input laser	0.17 μm
10mm input laser	0.10 μm



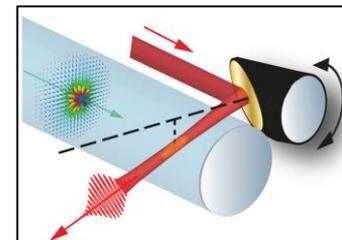
Assuming FACET level diagnostics & light collection:

Energy transfer → Camera signal

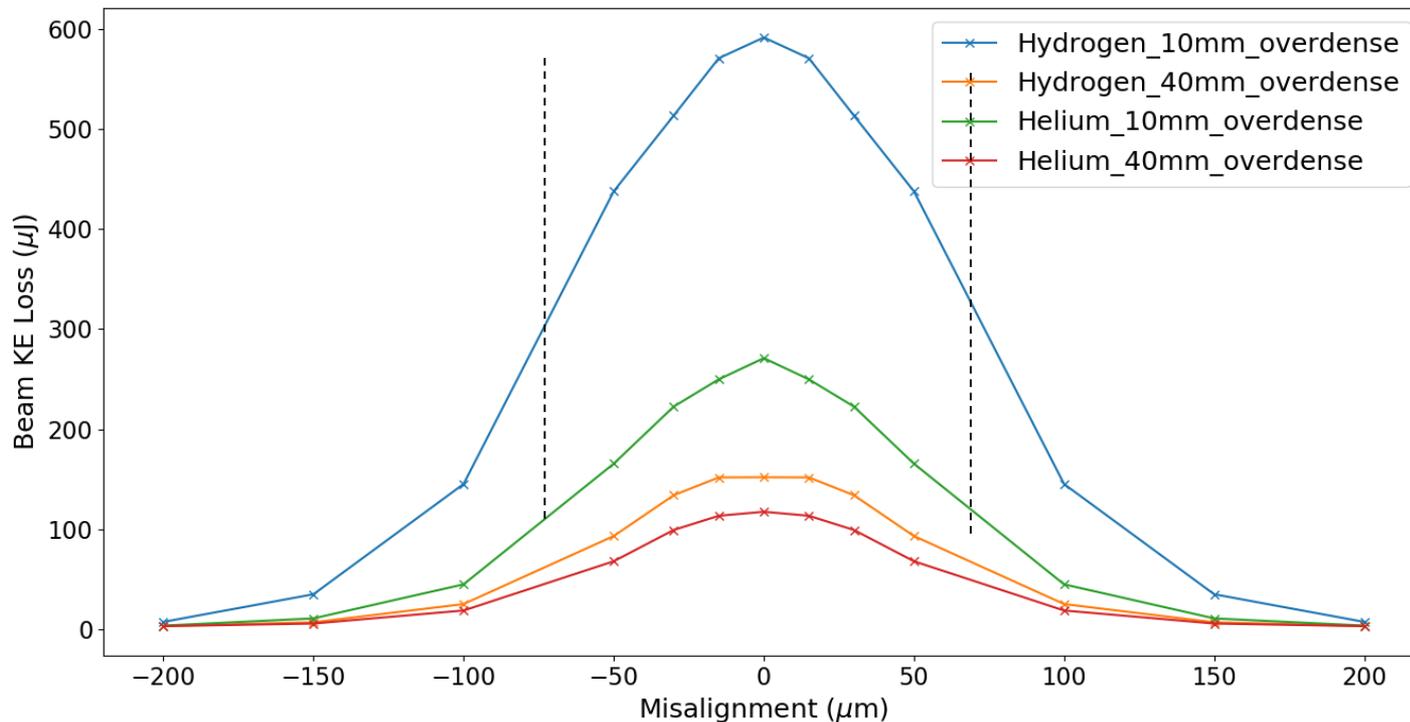
SLAC

Assumptions

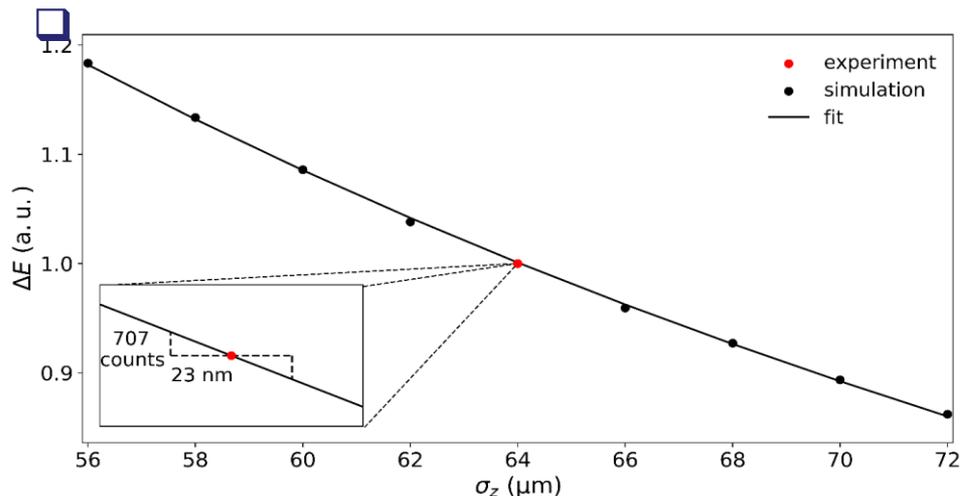
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 - $1\text{eV} \approx 5\text{e-}10$ counts [taken from FACET data/simulation pairing]
- Minimum detectable change in the camera
 - 707 counts [taken from FACET cube3vert background]
- **Completely free of random errors**



Few μm alignment precision, in case of good shot-to-shot stability *much* better



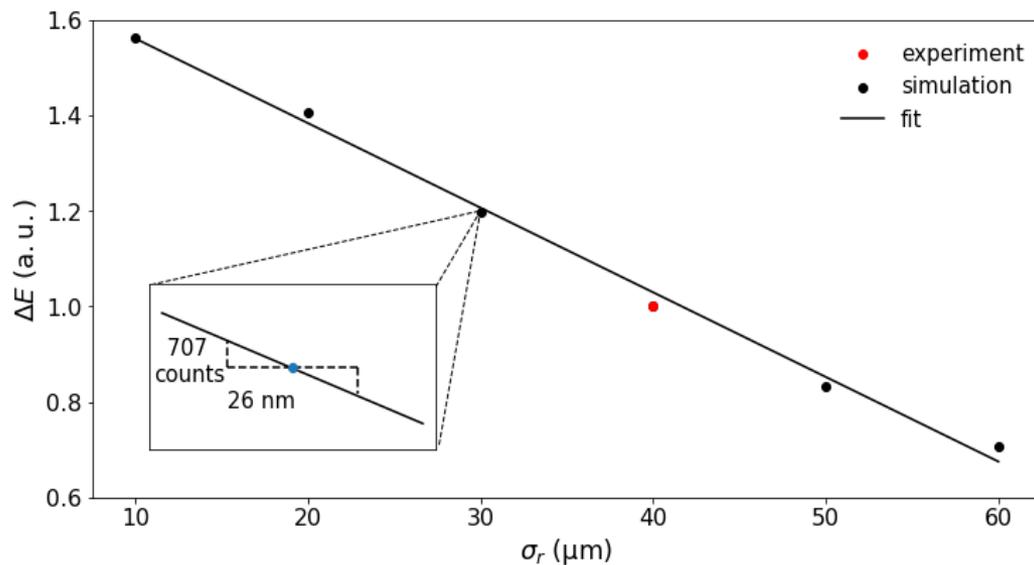
□ *Potential* for attosecond bunch metrology. In agreement with predictions from P. Scherkl *et al.*, Plasma-photonic spatiotemporal synchronization of relativistic electron and laser beams, arXiv:1908.09263 (2019)



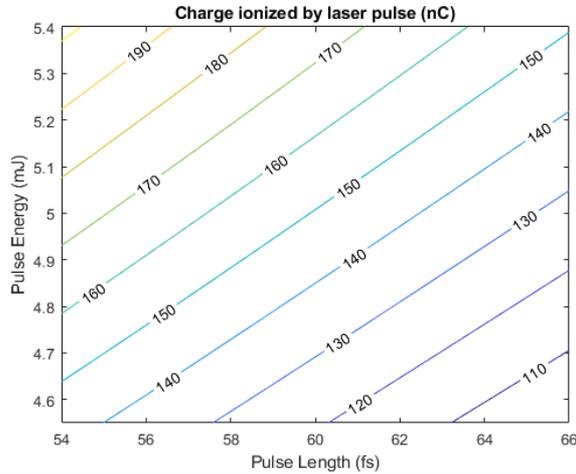
← Assuming imaging quality as used at FACET (707 CCD counts detection threshold) and stable, tunable beams: **23 nm bunch length limit**. “Plasma Pyro”

All kept constant but transverse e-beam size scan:
26 nm transverse bunch size
 measurement limit →

Plasma afterglow yield highly sensitive, but highly sensitive on number of parameters!



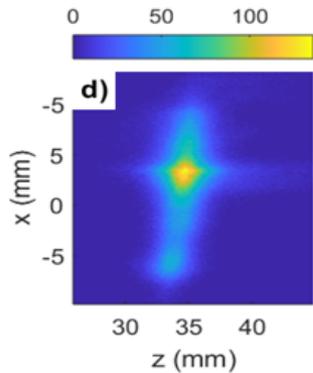
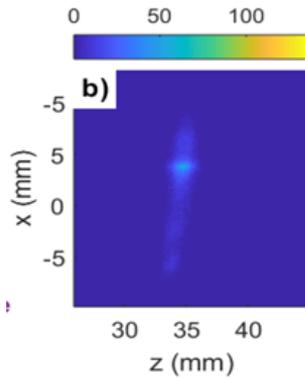
Simulation



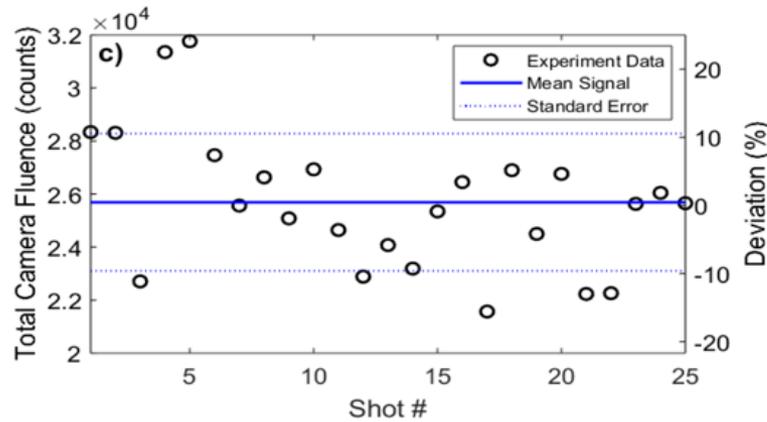
At FACET: detection of plasma recombination afterglow signal via bandpass filter and CCD
Laser pulse ~ 60 fs, ~ 5 mJ

Known laser pulse energy ($5 \text{ mJ} \pm 10\%$) and duration ($60 \text{ fs} \pm 10\%$) jitters calculated to produce a 5.5% standard deviation in produced charge in He

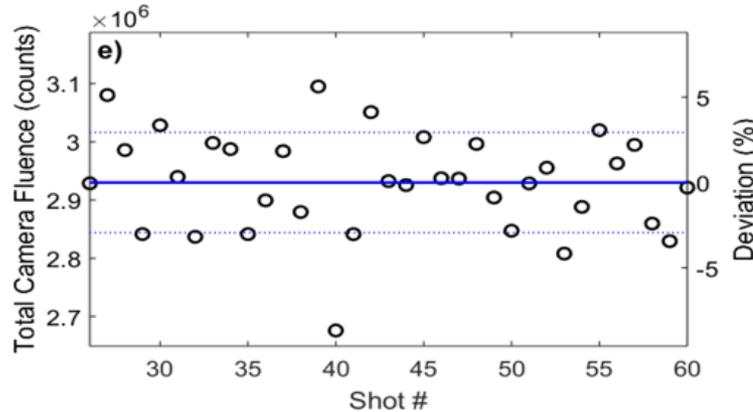
Experimental (laser-only)



Experimental (e-beam enhanced)



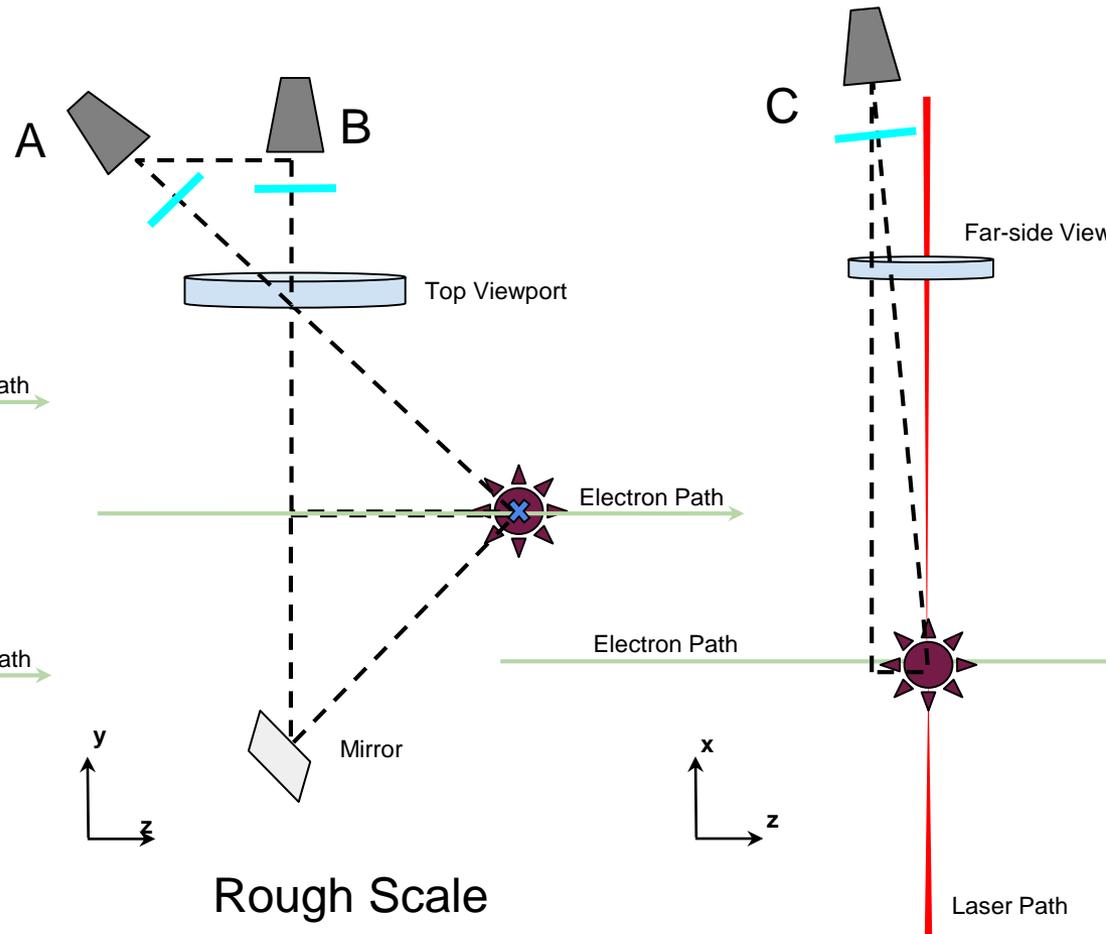
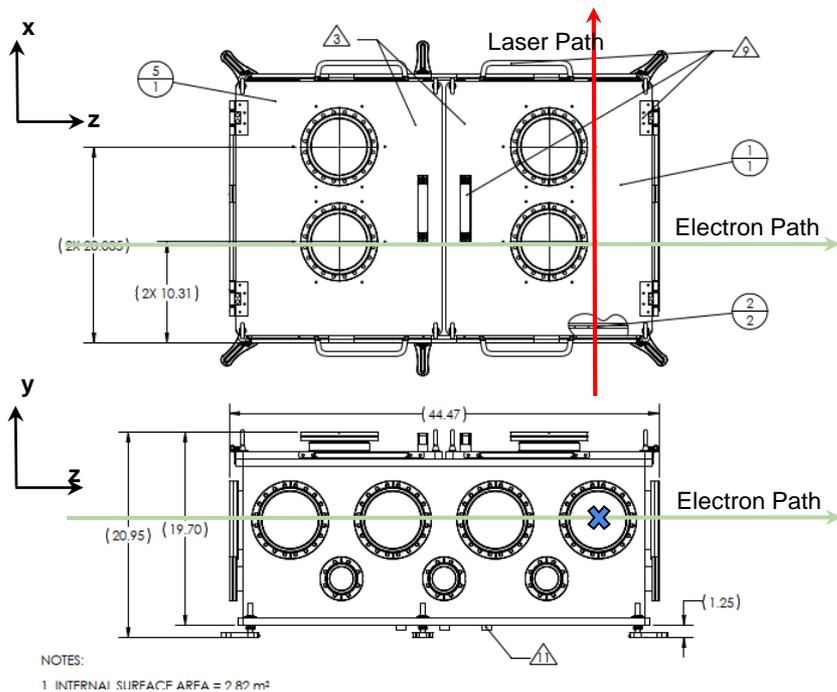
Experimental: 10% standard deviation in afterglow signal



Experimental: 5% standard deviation in afterglow signal

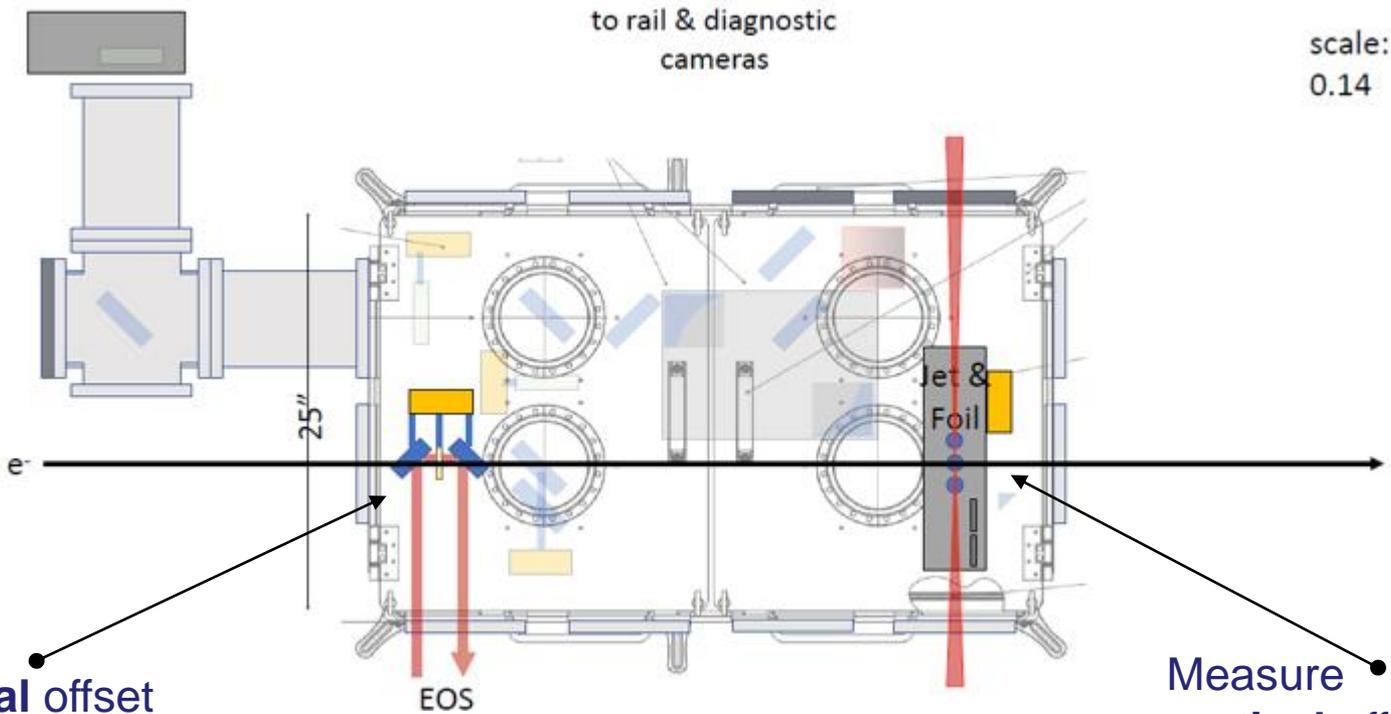
Afterglow collection plans

- Allow much straighter path than at FACET, collect more light
- 3D topography of afterglow desirable (asymmetries)
- Spectrally resolve (multi-lines), investigate dynamics with fast photodiodes...



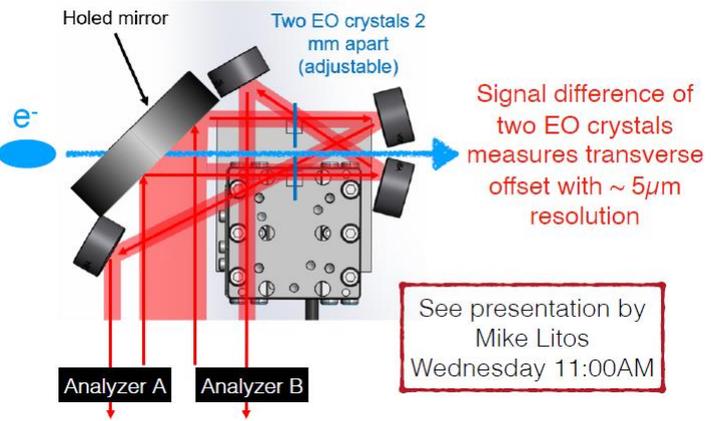
Strong synergies with other experiments & building blocks

- ❑ Use plasma afterglow to find coarse timing range of EOS (as in E-210)
- ❑ Use EOS to time-stamp incoming timing jitter for plasma afterglow
- ❑ Cross-check both vice versa



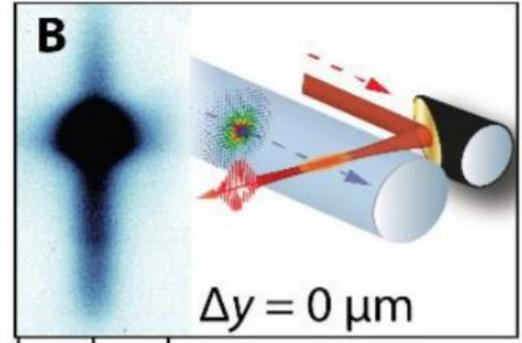
Measure horizontal offset

Measure vertical offset



See presentation by Mike Litos Wednesday 11:00AM

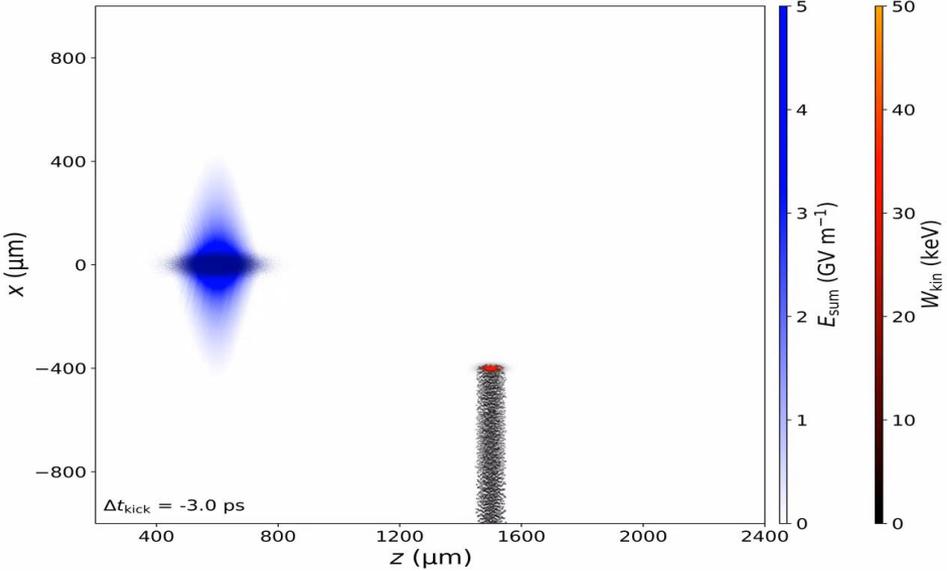
Useful also for E-300, E-301, E-320...?



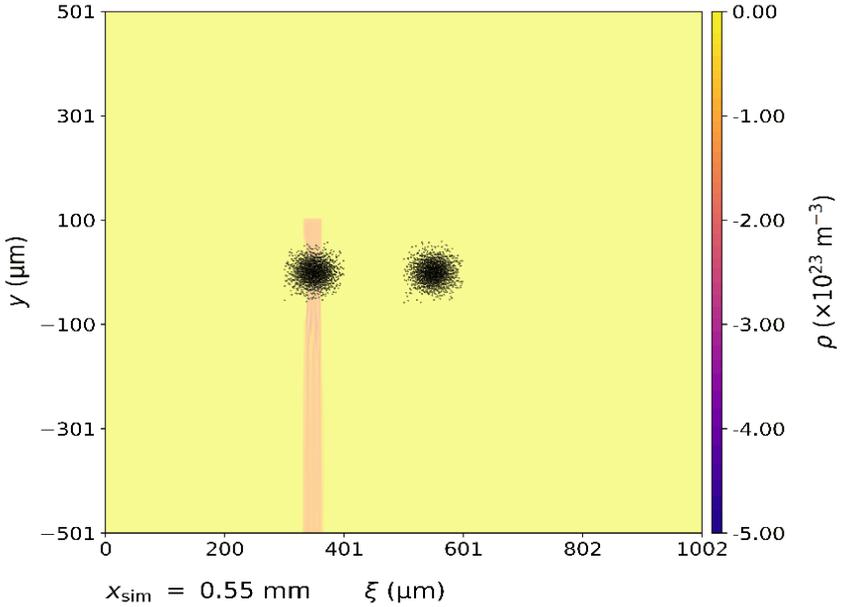
Measure double bunches with plasma torch

□ Timing and duration:

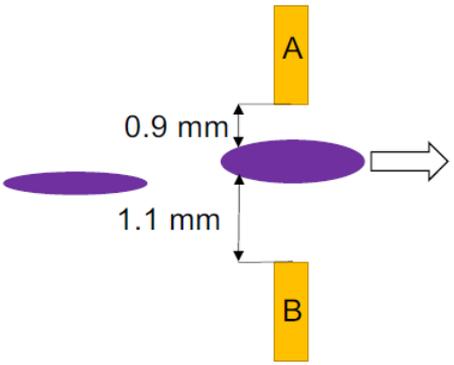
Single bunch



Witness bunch (and distance)

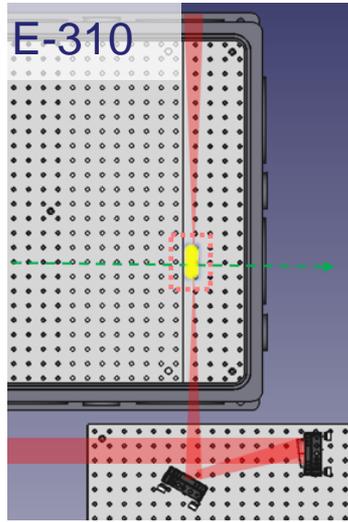
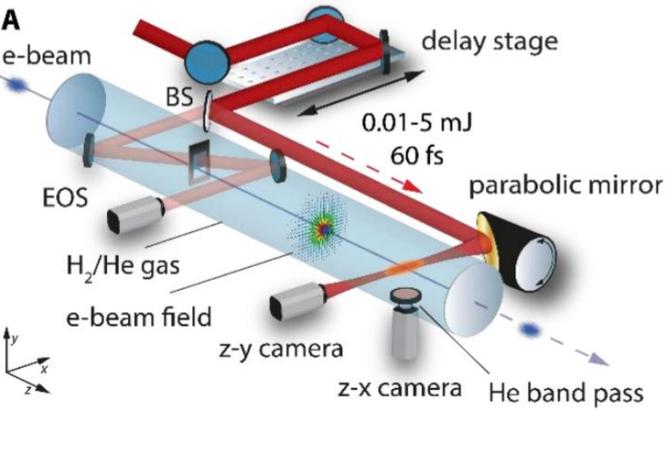


□ Transverse offset (vertical easier)

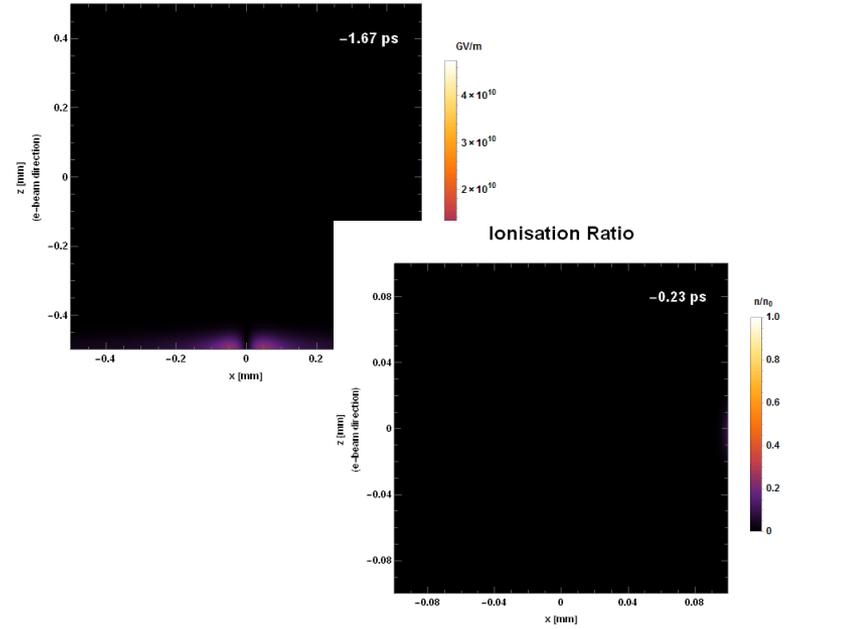


Same setup will also be used for Icarus

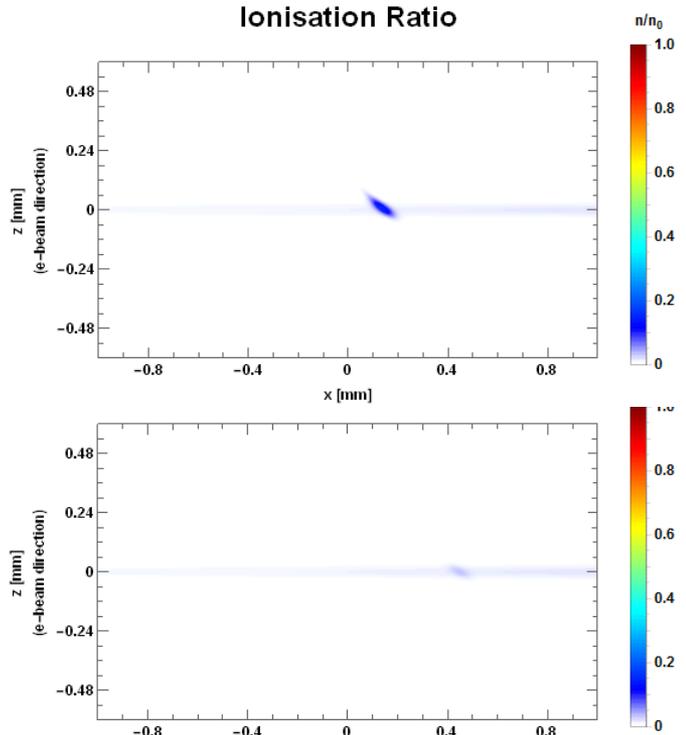
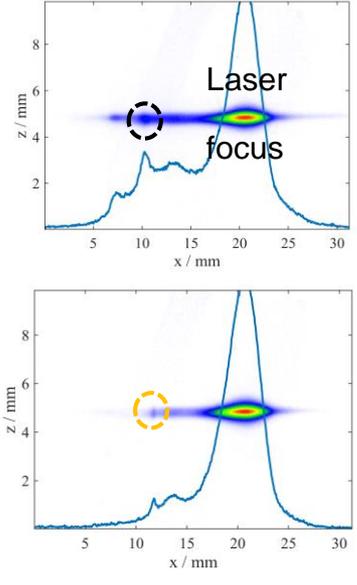
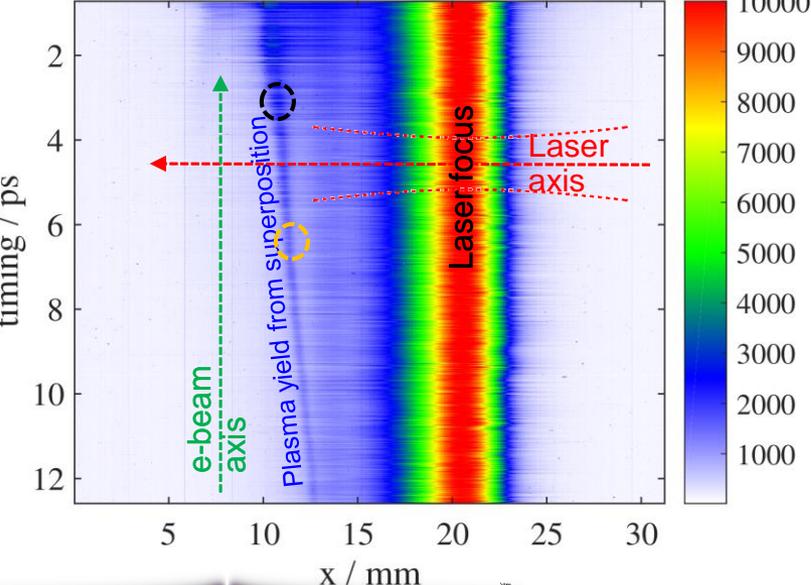
E-210



Electric Field



E-210: laser itself ionizes in focus, but additional Icarus hump after focus:



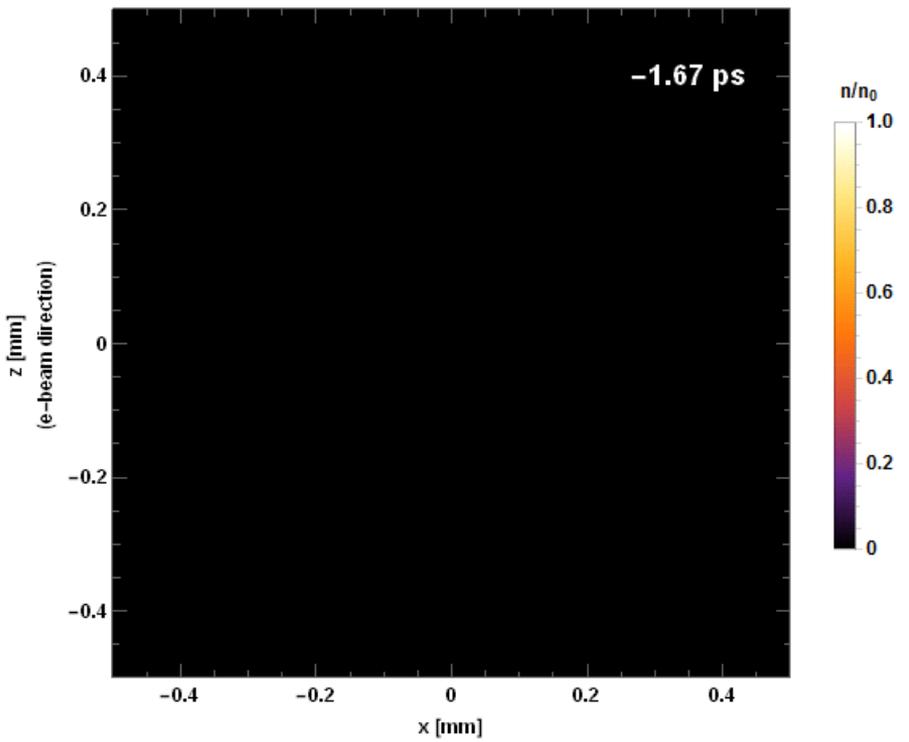
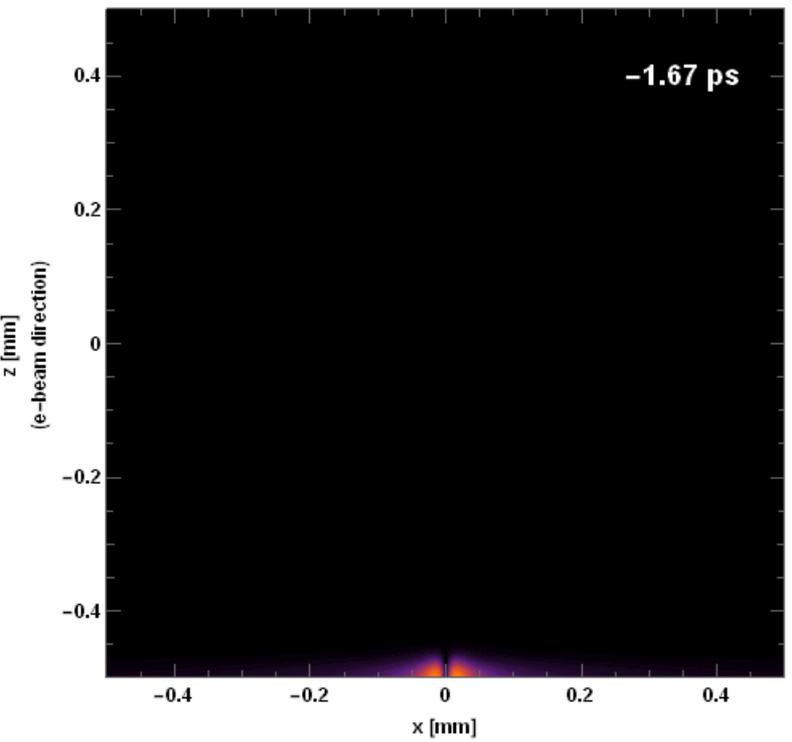
Also double bunches: Hydrogen, “long” beams, ≈ 10 mm input beam

parameter	driver	witness	laser
duration	60 fs (rms)	30 fs (rms)	50 fs (FWHM)
spot size	10 μm (rms)	10 μm (rms)	50 μm ($1/e^2$)
Q	1.5 nC	0.5 nC	--
Delay	0	-300 fs	-500fs

Hydrogen (H₂)
 Laser energy = 400 μJ

Electric Field

Ionisation Ratio



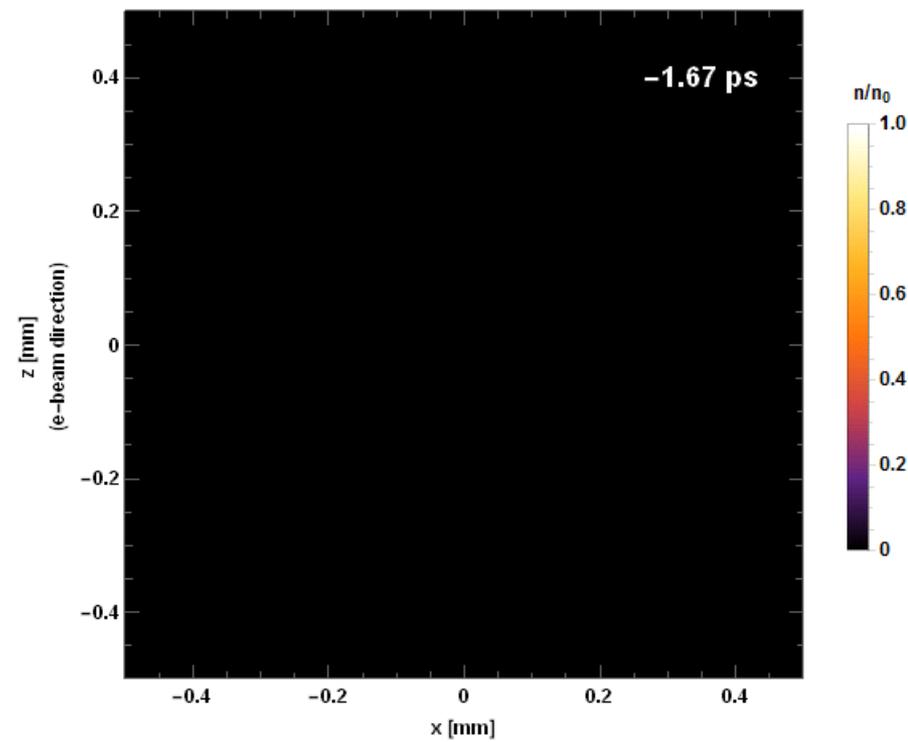
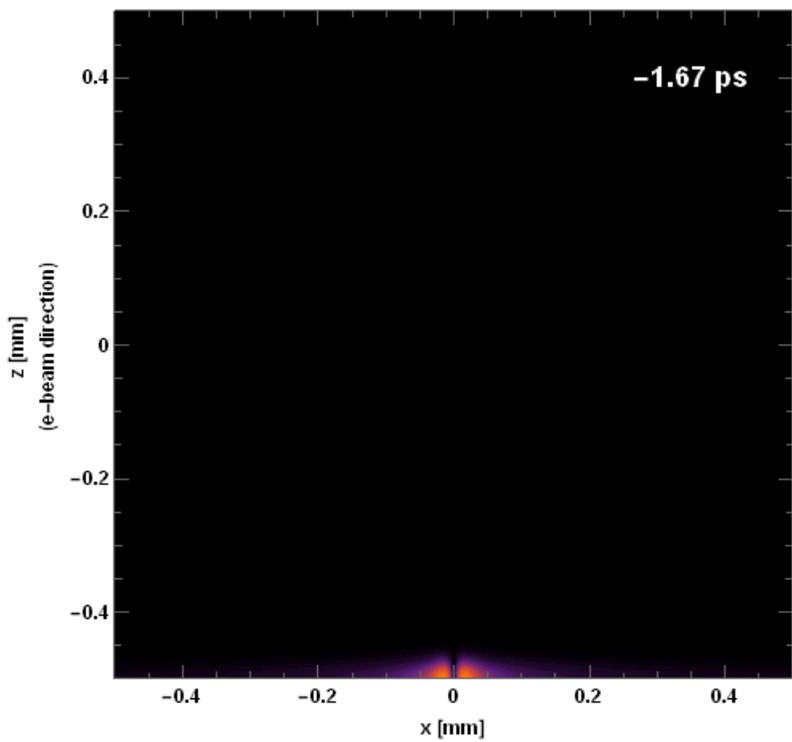
Hydrogen, “long” beams, ≈ 10 mm input beam

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spot size	10 μm (rms)	10 μm (rms)	50 μm ($1/e^2$)
Q	1.5 nC	0.5 nC	--
Delay	0	-250 fs	-500fs

Hydrogen (H₂)
Laser energy = 400 μJ

Electric Field

Ionisation Ratio

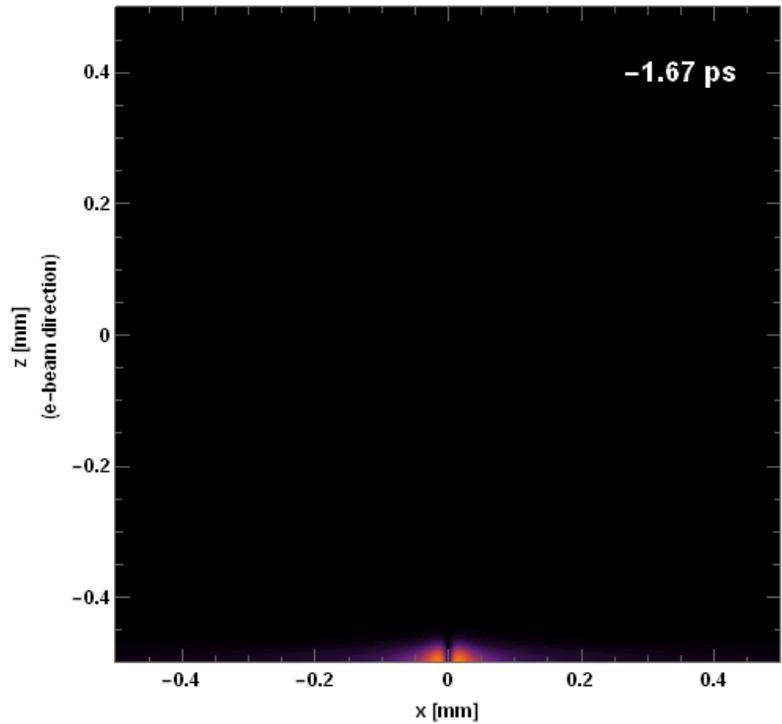


Hydrogen, “long” beams, ≈ 10 mm input beam

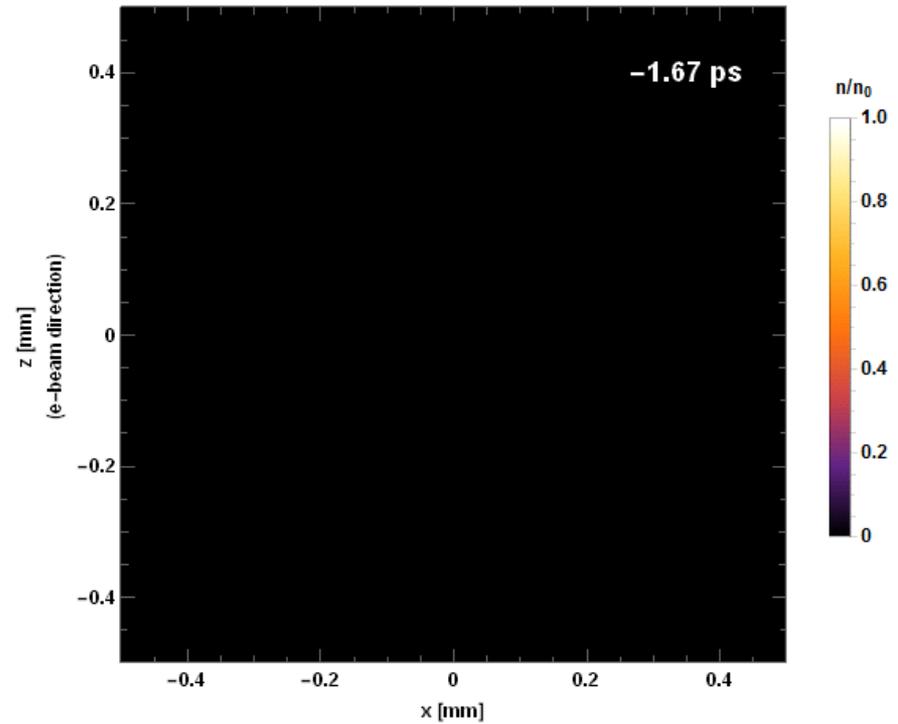
parameter	driver	witness	laser
duration	60 fs (rms)	30 fs (rms)	50 fs (FWHM)
spot size	10 μm (rms)	10 μm (rms)	50 μm ($1/e^2$)
Q	1.5 nC	0.5 nC	--
Delay	0	-200 fs	-500fs

Hydrogen (H₂)
Laser energy = 400 μJ

Electric Field



Ionisation Ratio

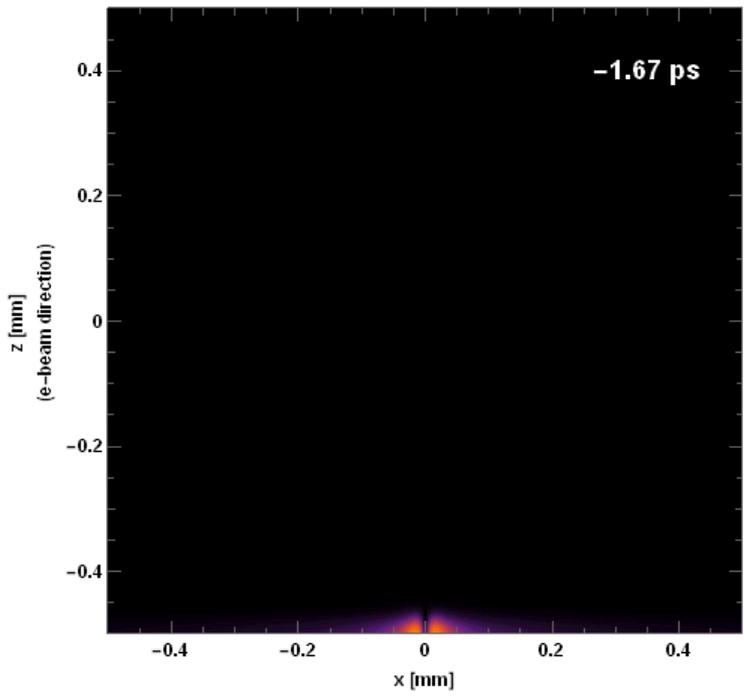


Hydrogen, “long” beams, ≈ 10 mm input beam

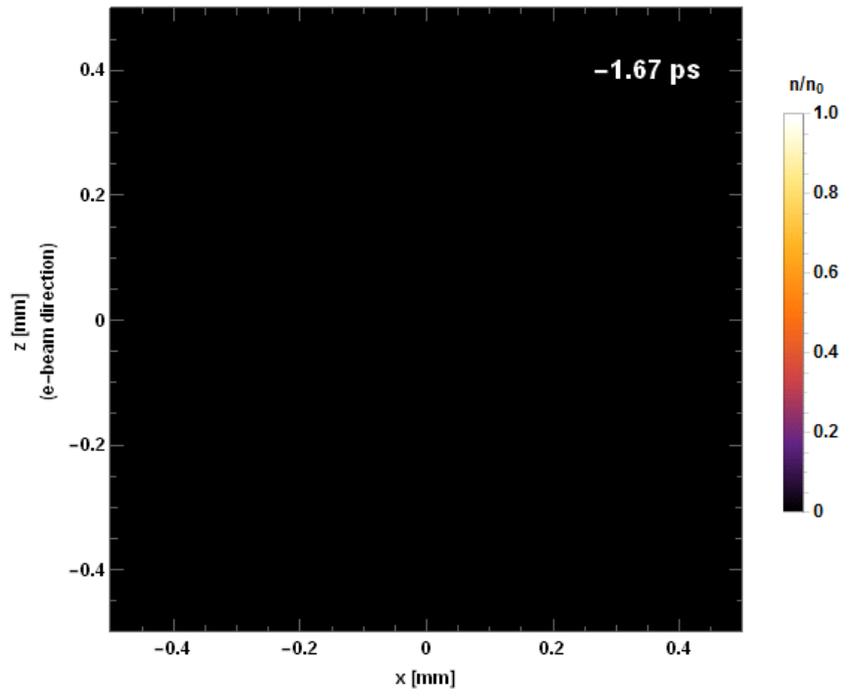
parameter	driver	witness	laser
duration	60 fs (rms)	30 fs (rms)	50 fs (FWHM)
spot size	10 μm (rms)	10 μm (rms)	50 μm ($1/e^2$)
Q	1.5 nC	0.5 nC	--
Delay	0	-150 fs	-500fs

Hydrogen (H2)
Laser energy = 400 μJ

Electric Field



Ionisation Ratio

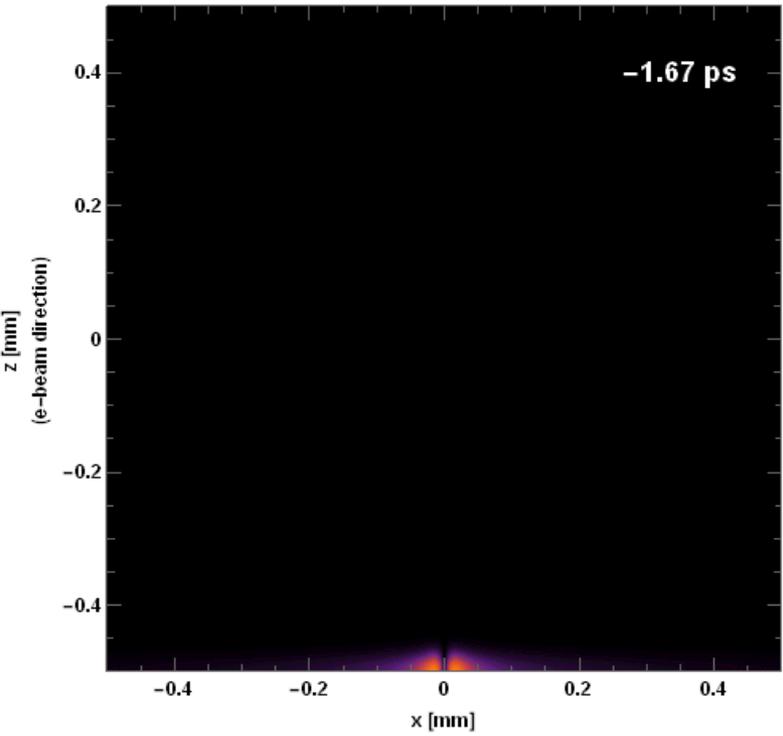


Hydrogen, “long” beams, ≈ 10 mm input beam

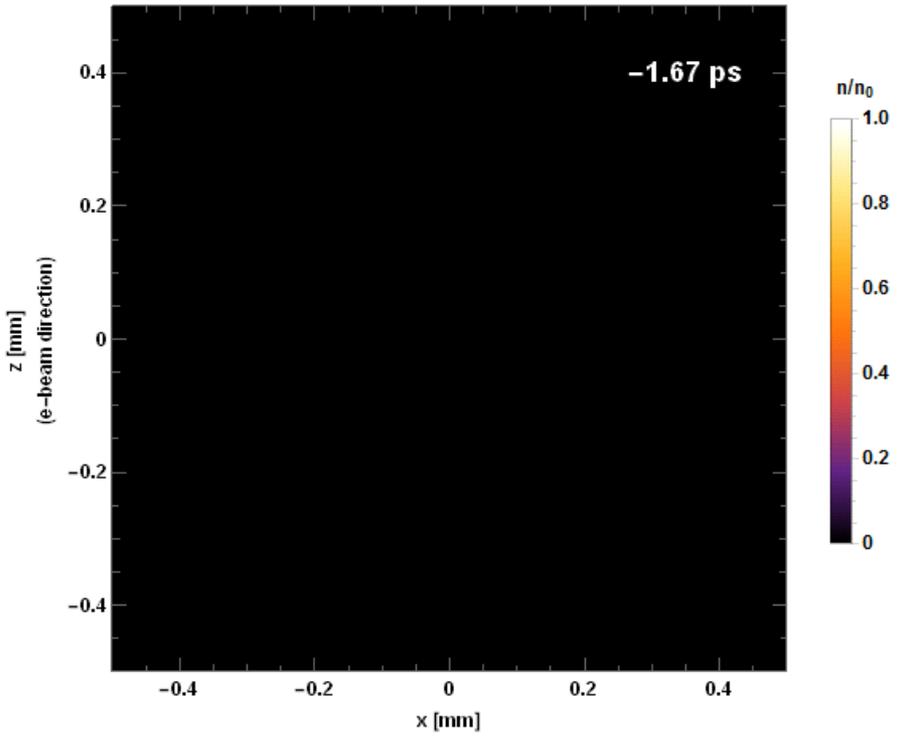
parameter	driver	witness	laser
duration	60 fs (rms)	30 fs (rms)	50 fs (FWHM)
spot size	10 μm (rms)	10 μm (rms)	50 μm ($1/e^2$)
Q	1.5 nC	0.5 nC	--
Delay	0	-100 fs	-500fs

Hydrogen (H₂)
Laser energy = 400 μJ

Electric Field



Ionisation Ratio

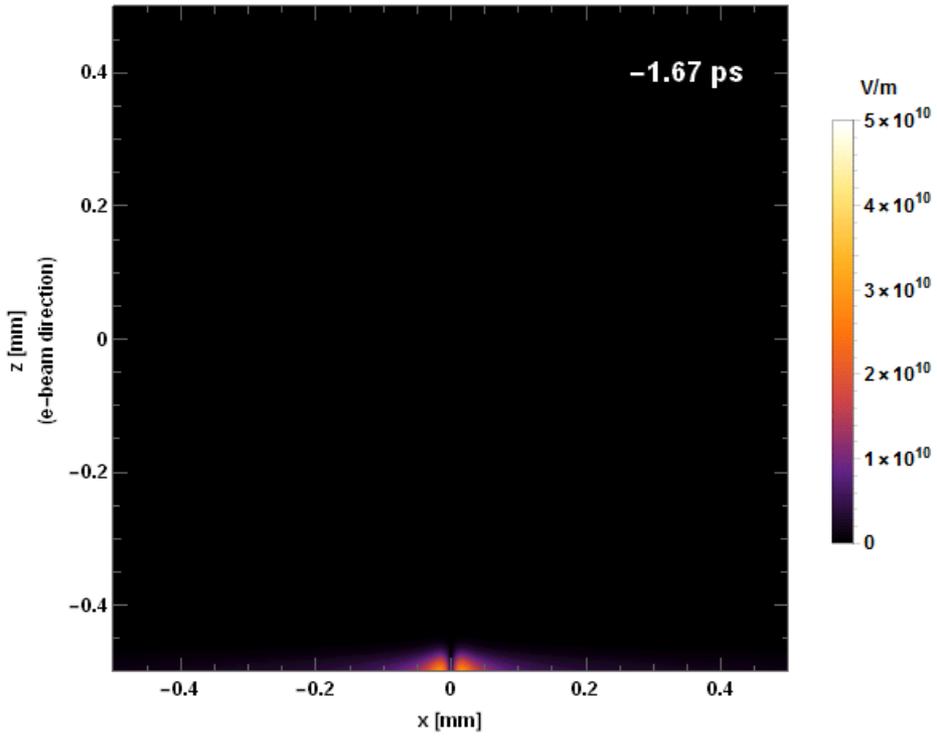


Hydrogen, “long” beams, ≈ 10 mm input beam

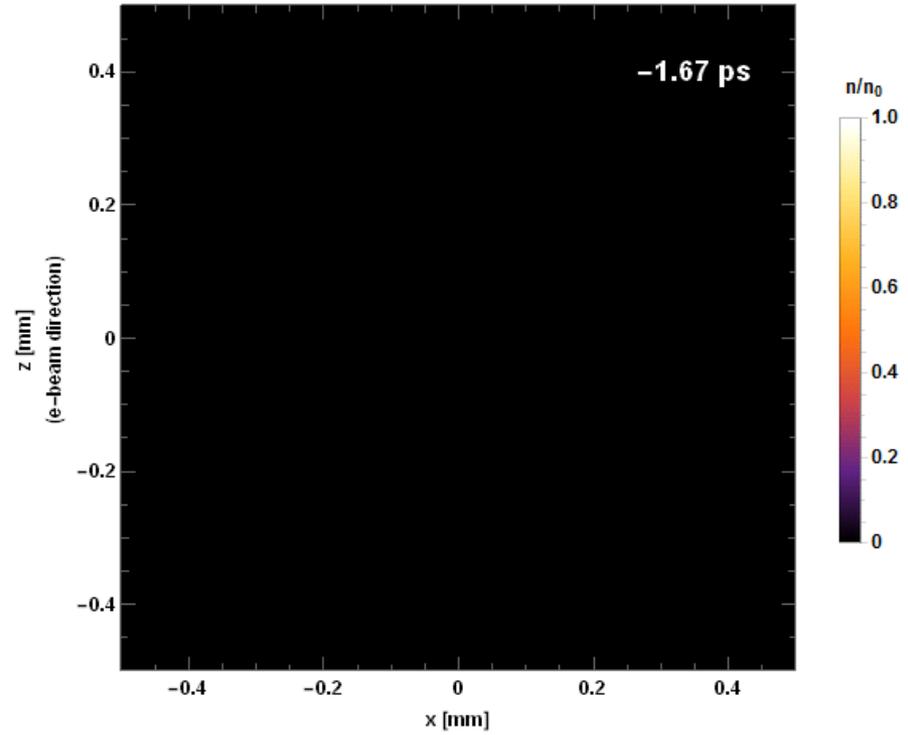
parameter	driver	witness	laser
duration	60 fs (rms)	30 fs (rms)	50 fs (FWHM)
spot size	10 μm (rms)	10 μm (rms)	50 μm ($1/e^2$)
Q	1.5 nC	0.5 nC	--
Delay	0	-50 fs	-500fs

Hydrogen (H₂)
Laser energy = 400 μJ

Electric Field



Ionisation Ratio

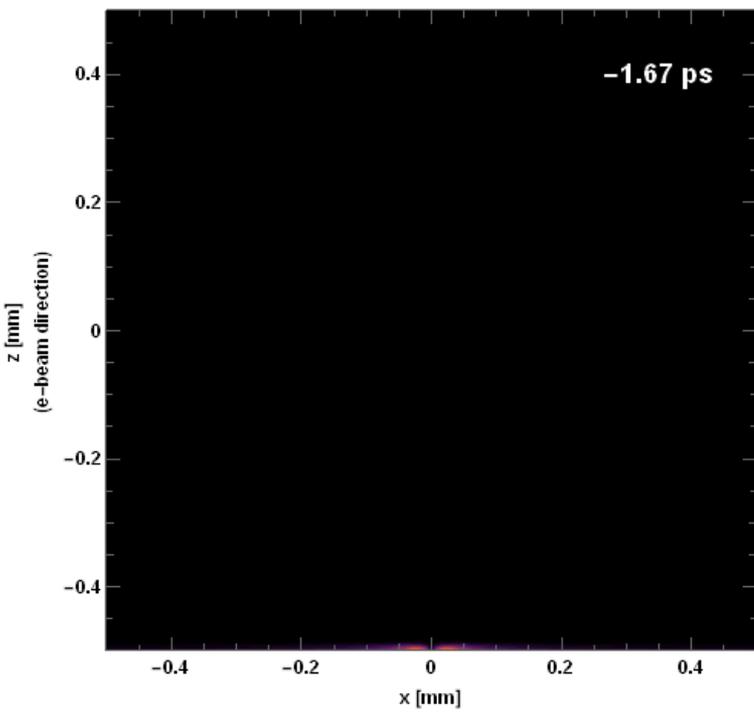


Helium, short beams ($I_d \sim 30$ kA, $I_w \sim 15$ kA peak), 10 mm input beam

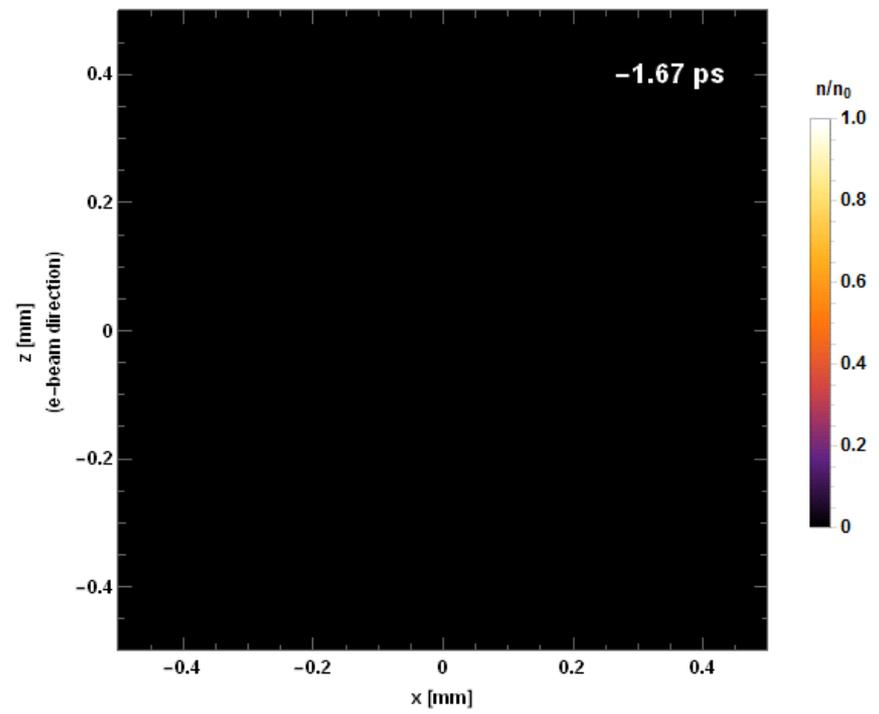
parameter	driver	witness	laser
duration	18 fs (rms)	16 fs (rms)	40 fs (FWHM)
spot size	15 μm (rms)	15 μm (rms)	w0=11.5 μm (1/e ² rad. int.)
Q	1.3 nC	0.6 nC	--
Delay	0	-500 fs	-600fs

Helium
Laser energy = 100 μJ

Electric Field



Ionisation Ratio

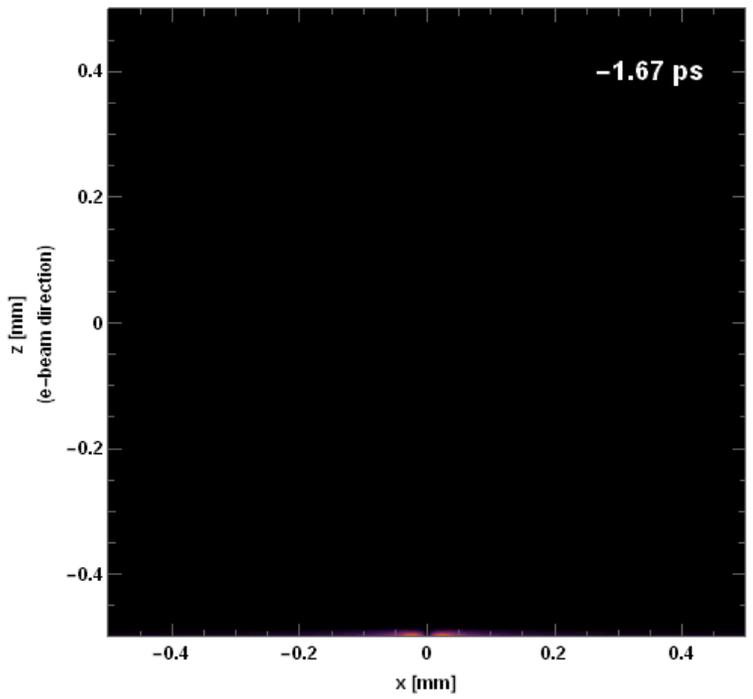


Helium, short beams ($I_d \sim 30$ kA, $I_w \sim 15$ kA peak), 10 mm input beam

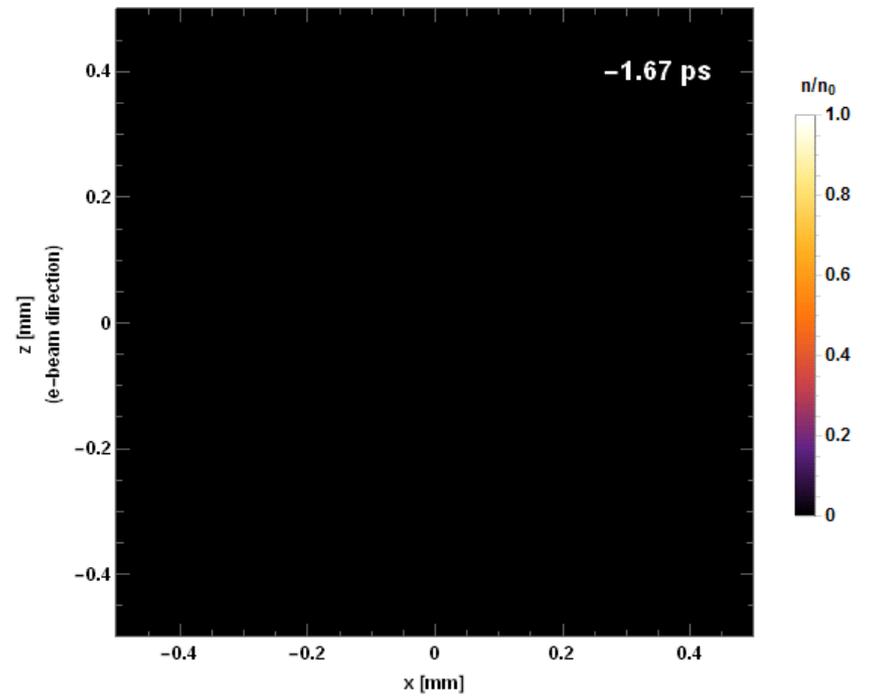
parameter	driver	witness	laser
duration	18 fs (rms)	16 fs (rms)	40 fs (FWHM)
spot size	15 μ m (rms)	15 μ m (rms)	w0=11.5 μ m (1/e ² rad. int.)
Q	1.3 nC	0.6 nC	--
Delay	0	-500 fs	-800fs

Helium
Laser energy = 100 μ J

Electric Field

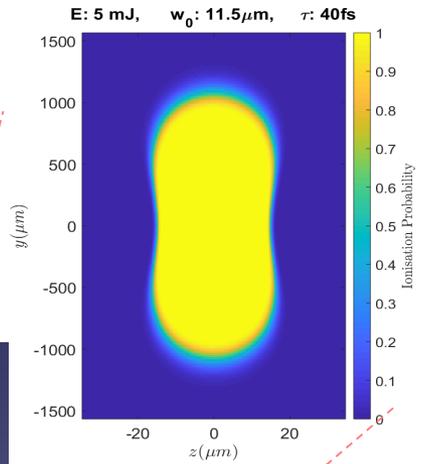


Ionisation Ratio

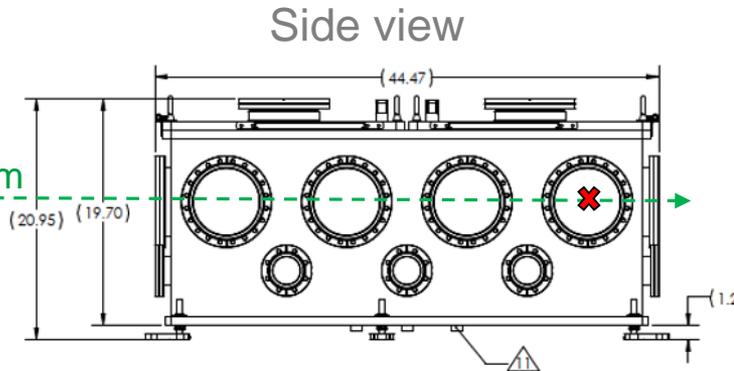
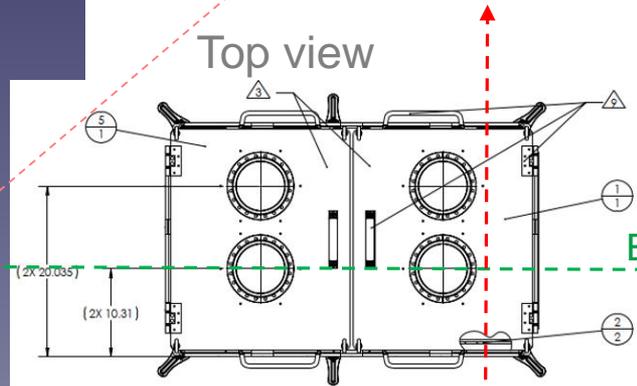
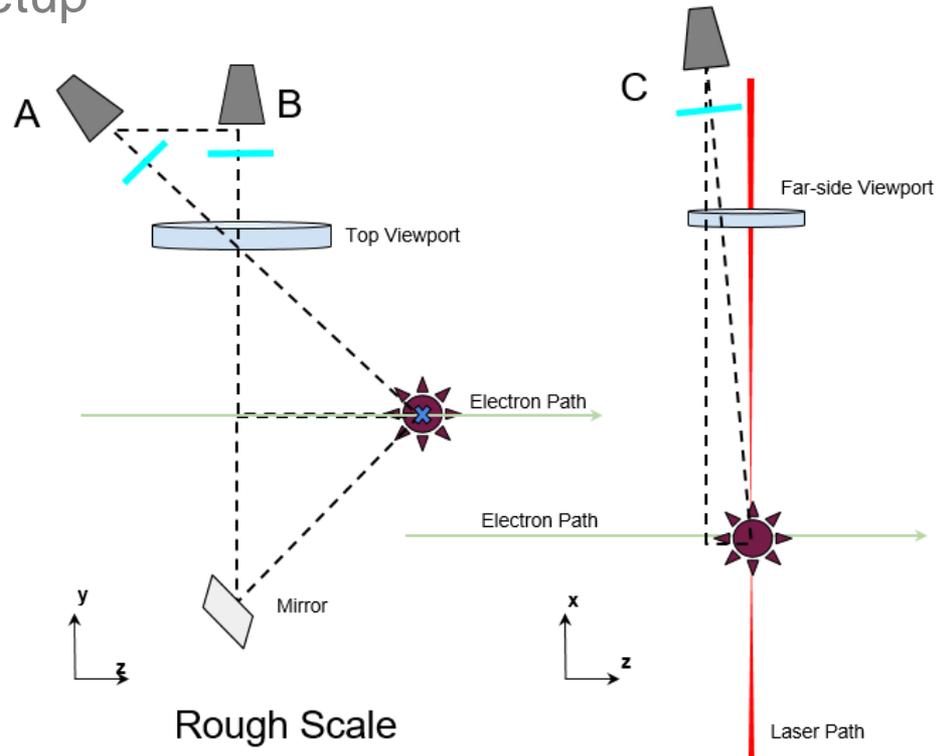


Summary of torch & Icarus afterglow setup

- 10-40 mm input pulse, up to 5 mJ, ~40 fs



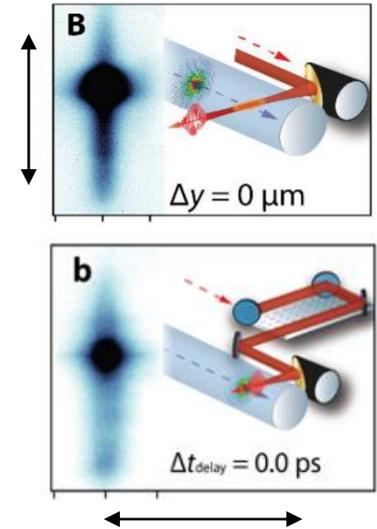
Focus diagnostics



Vertical (alignment scan), z-translation, delay stage, attenuator, iris

Summary of torch & Icarus measurements and procedure

- ❑ Informed by E-210 experience & success
- ❑ Torch in laser early mode: e-beam plasma pyro (duration), e-beam diameter & alignment via plasma torch afterglow, vertical shift
- ❑ Torch in TOA mode: scan laser torch arrival time with delay stage. Also use for two-bunch systems (distance & witness duration)
- ❑ Up to 5 mJ with 10-40 mm input laser beam (He, H₂, mixes..)

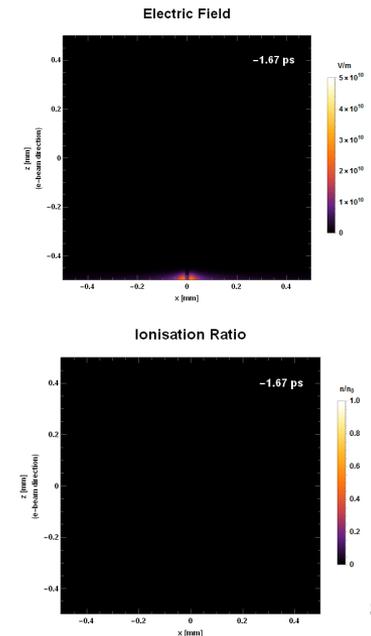


- ❑ After finding spatiotemporal overlap position, realize Icarus in TOA mode with same setup: single shot diagnostics, ~100 μJ

- ❑ For single beams
- ❑ For double beams

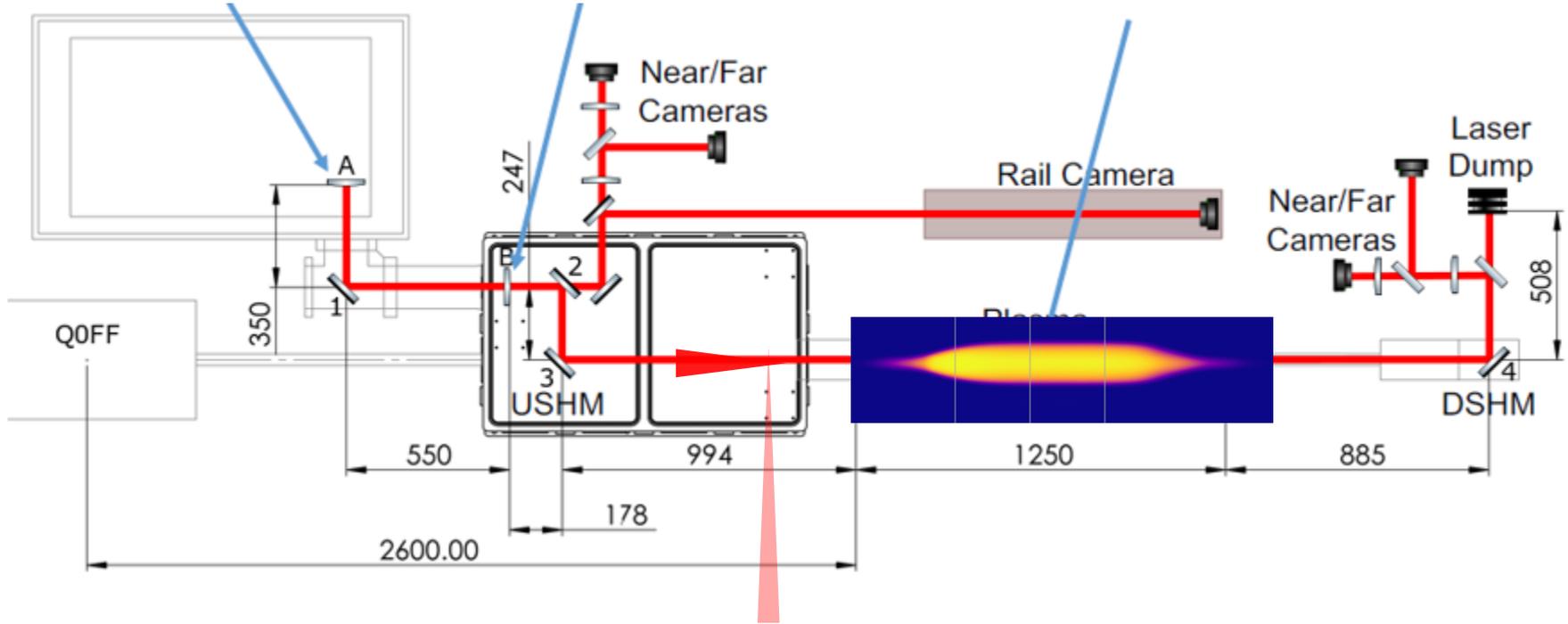
- ❑ Def. of success: Level 1: Do above scans in both modes; determine spatiotemporal accuracy at interaction point, Level 2 (dependent on incoming beam stability): achieve sub-20 fs and sub-5 μm accuracy

- ❑ Parts all off-the-shelf, Andrew Sutherland

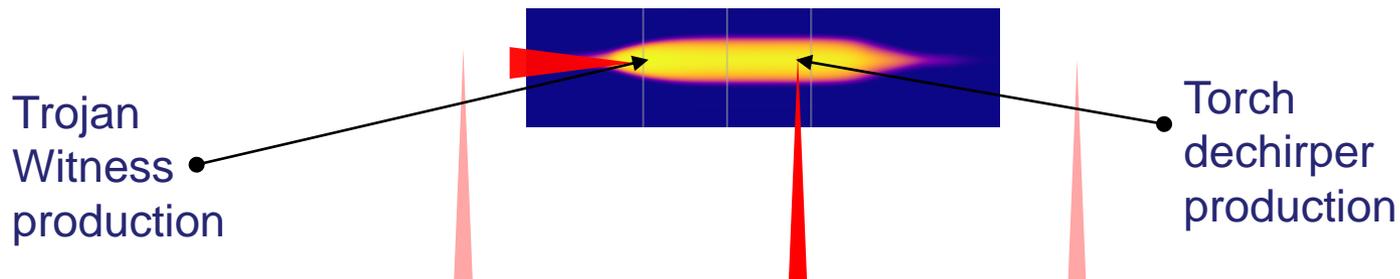


Trojan Horse in big fat plasma

- ❑ Once absolute spatiotemporal injection precision is known:
- ❑ Bring plasma upstream? (countercollinear?)
- ❑ Move injector pulses downstream?



- ❑ Conceptually: want to have upstream and downstream plasma afterglow(s) / Icarus' as diagnostics



First Pass Plasma Design (E-301, courtesy R. Ariniello)

Laser Parameters

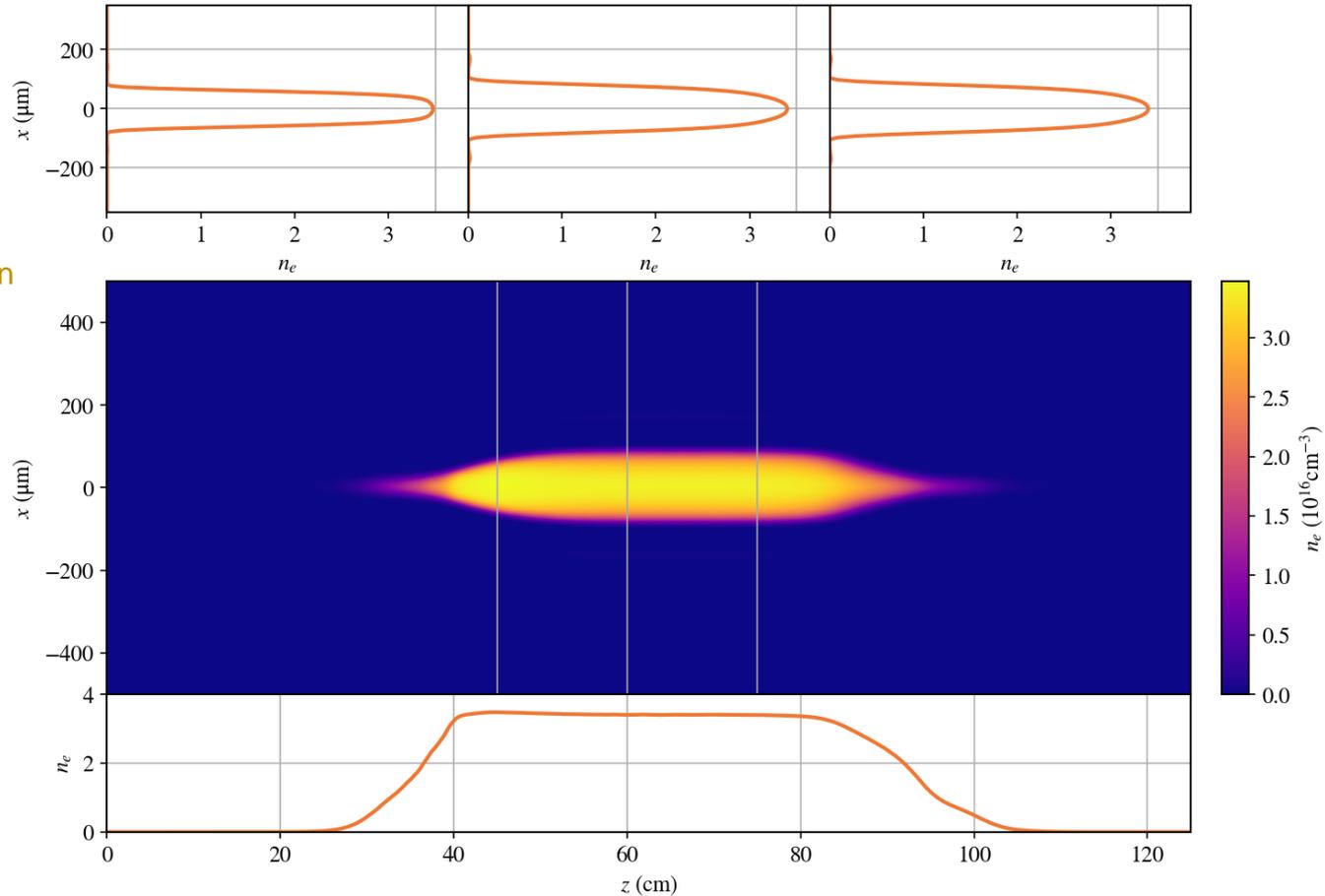
Laser energy: 105mJ
Pulse duration: 70fs
Wavelength: 796nm
Beam width: 40mm FWHM
Beam profile: Super Gaussian

Beam Energy

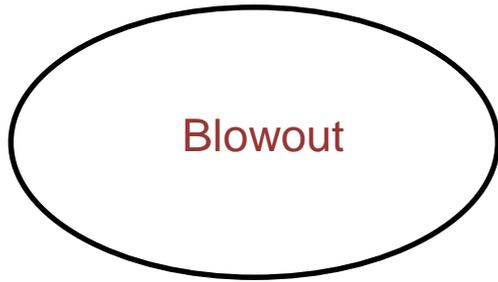
Energy to ionize: 0.62mJ
Plasma heating energy: ~1mJ
Energy after optics: 45.4mJ
Optics efficiency: 80%
Energy before optics: 56.8mJ
Lost to aberrations: 15mJ
Lost to aperture: 30mJ
Required energy: 102mJ

Laser refraction simulation

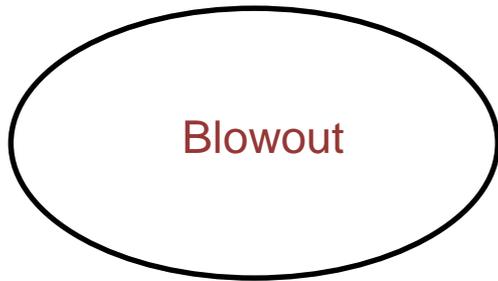
Split step Fourier based code.
Energy loss due to ionization.
No dispersion, no self-focusing.



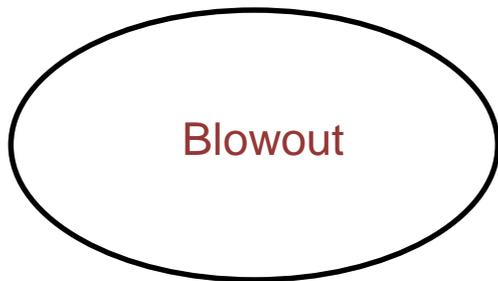
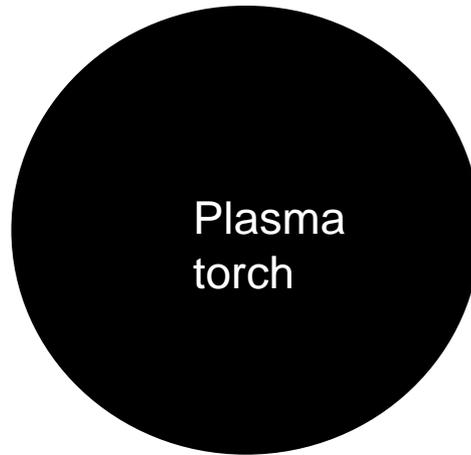
Flexibility of plasma torch scheme allows to study extreme cases of density downramp injection (and beyond):



□ Plasma torch-produced density spike much **smaller** than blowout size



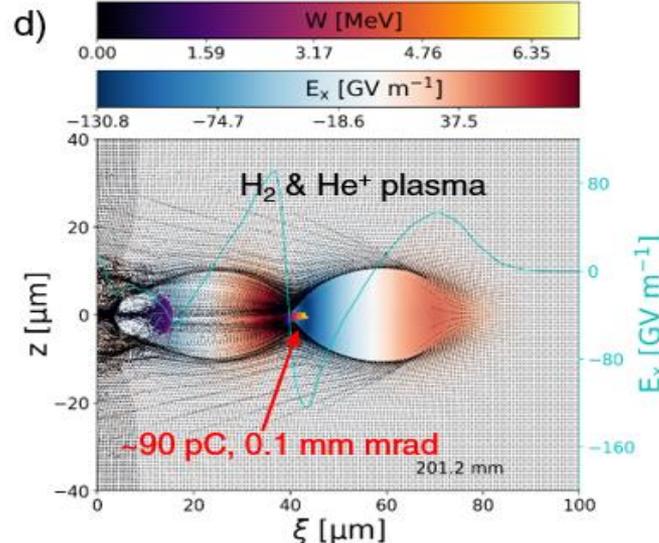
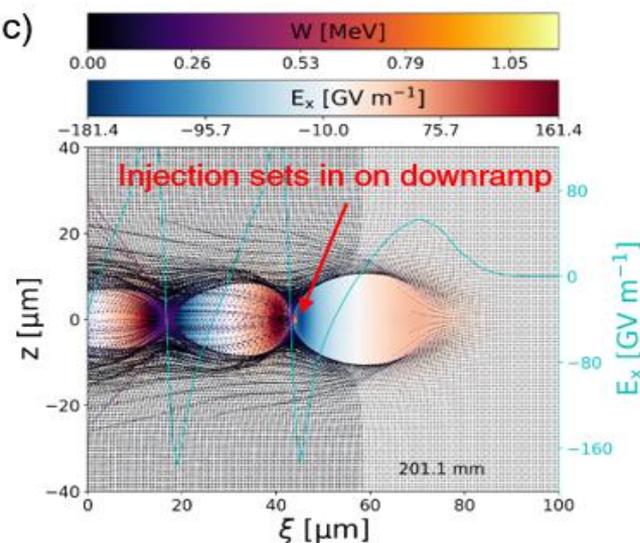
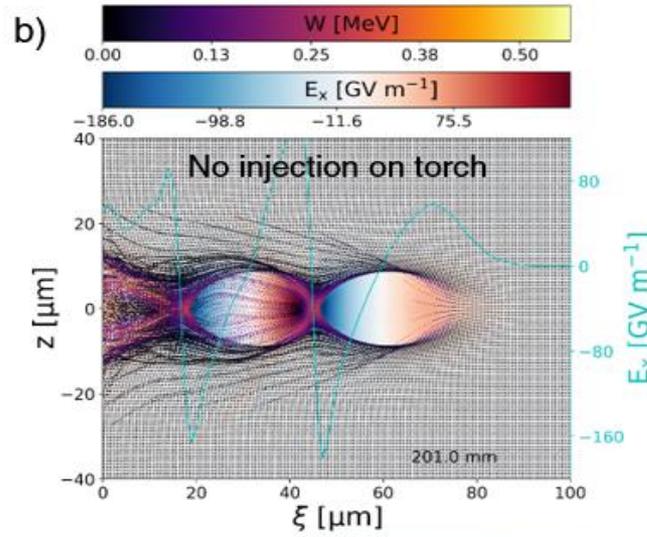
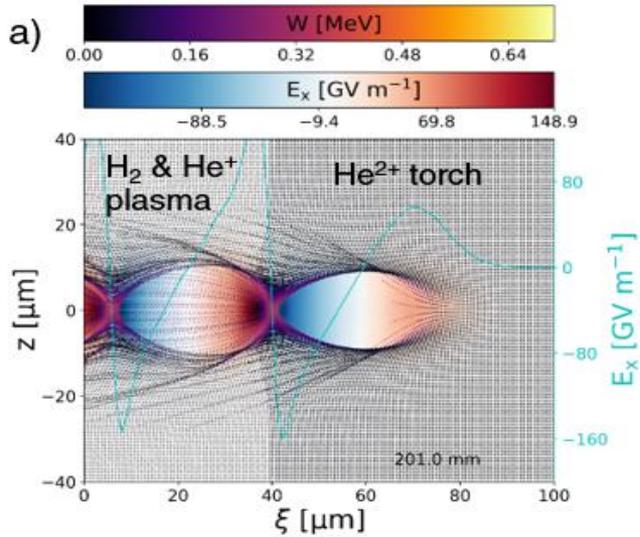
□ Plasma torch-produced density spike much **larger** than blowout size



Also for plasma pyro

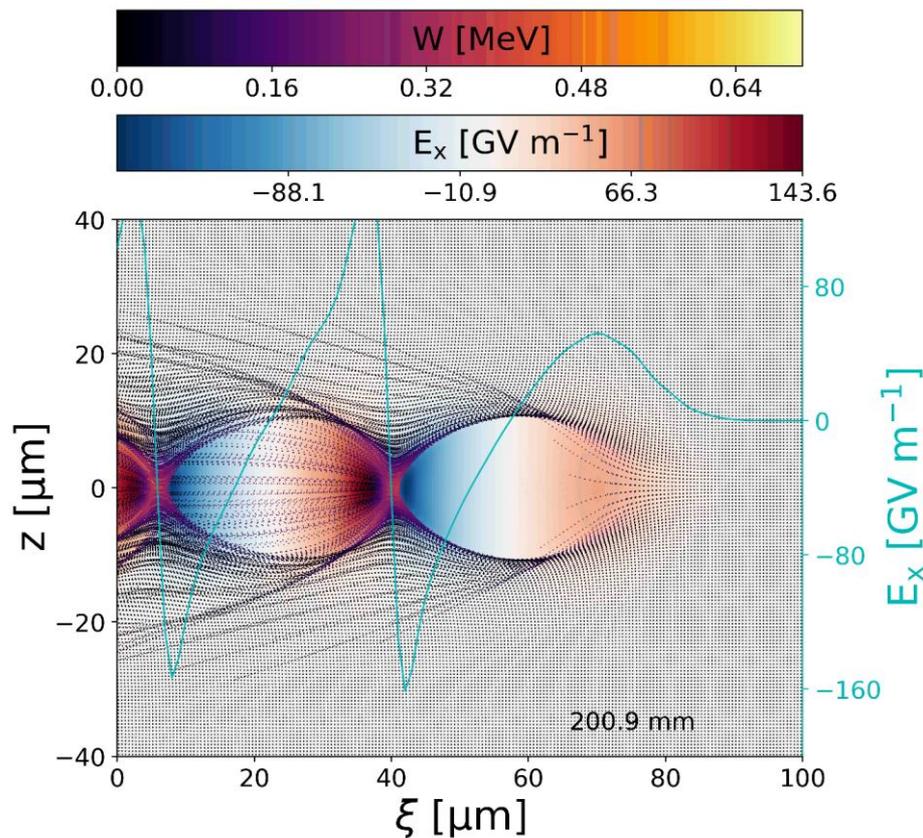
Exploit higher stability, and shorter driver bunches at

- Wider preionized channel: here not necessarily needed, may want to go to higher densities instead (shorter FACET-II bunch allows this without suffering from drive beam kick)

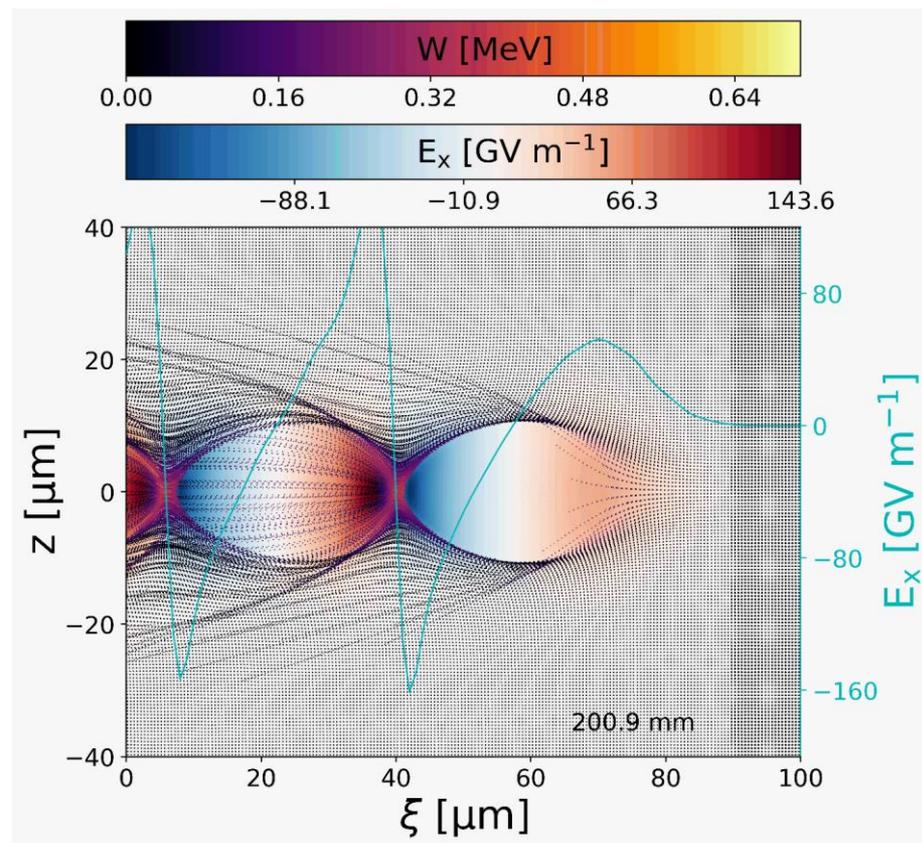


- ~ 500 pC, ~ 7 μm rms length FACET-II driver (not shown)
- Preionized H_2 & He (combined density $1.2 \times 10^{18}/\text{cc}$),
- Use He^{2+} as plasma torch medium.

Exploit higher stability, and shorter driver bunches at



Spot size $\sim 20 \mu\text{m} <$ blowout
size
 $\sim 140 \text{ pC}$
 $\sim 0.3 \text{ mm mrad}$

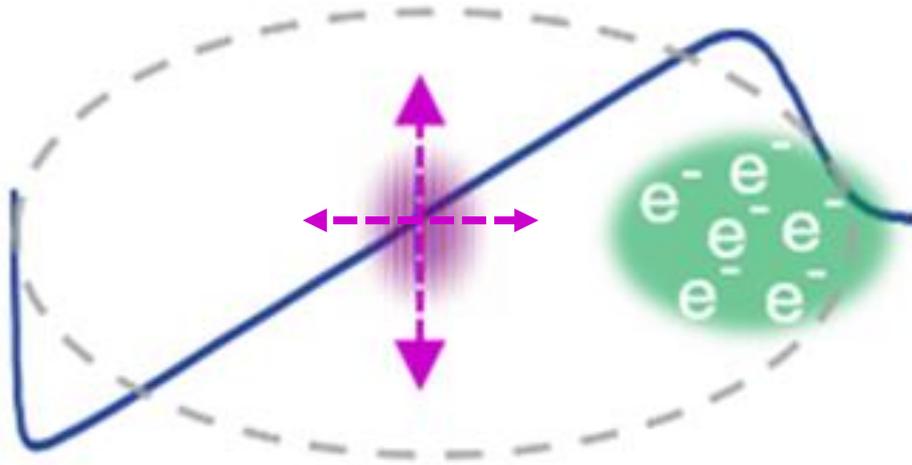


Torch length $100 \mu\text{m} \gg$ blowout
size
 $\sim 90 \text{ pC}$
 $\sim 0.1 \text{ mm mrad}$

Path to high charge, low emittance beams

Key question: How precise does the spatiotemporal injection need to be?

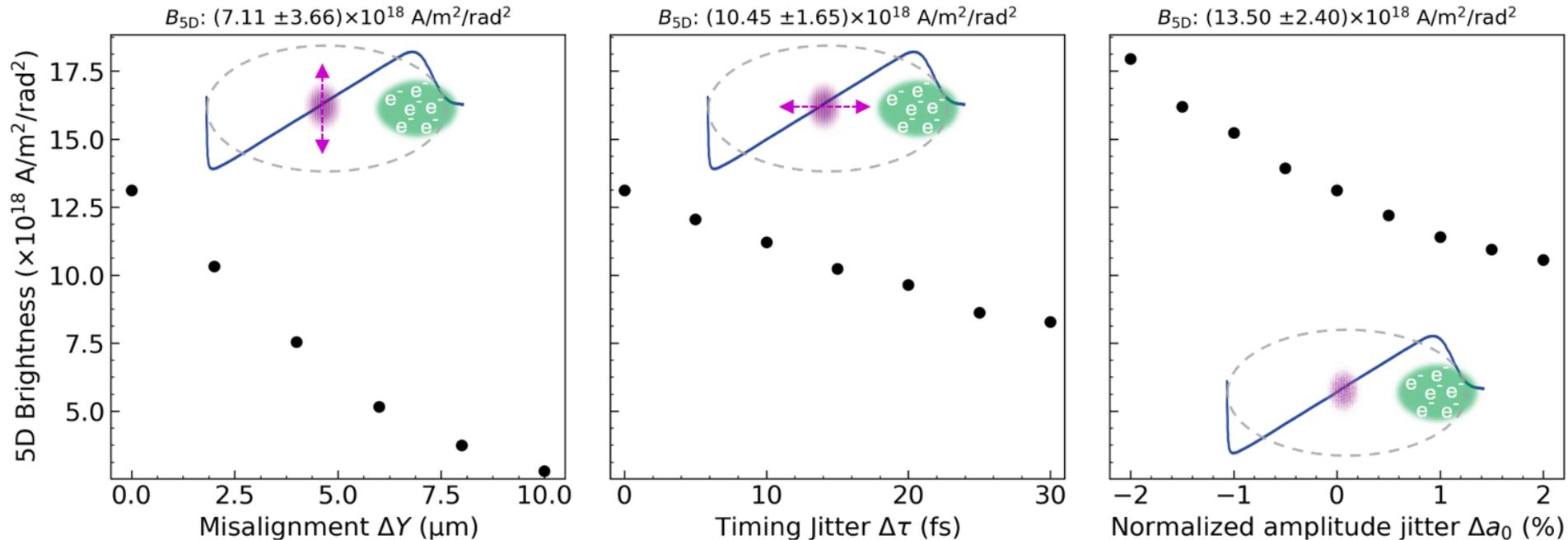
- ❑ Once absolute spatiotemporal injection precision is known:
- ❑ Injection precision is dependent on size of the plasma wave, and absolute jitter of incoming laser and delectron beam \Rightarrow work at lower plasma densities
- ❑ E.g. 500 μm plasma wavelength, with 30 fs r.m.s. timing jitter (LCLS aims at <10 fs) and similar pointing accuracy, an injection precision of $\sim 1\%$ can be achieved



Follow up: What does this mean for obtainable beam quality and stability (5D)?

- Sensitivity analysis done for 250 μm plasma wavelength: vary temporal desync. from 0-30 fs, misalignment from 0-10 μm , laser intensity a_0 0-2%

Resulting 5D brightness:
$$B_{5D} = \frac{2I_p}{\epsilon_{n,x} \epsilon_{n,y}}$$



Note: X-FEL 5D brightness is at 1e12 level

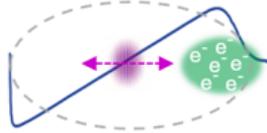
Timing varied up to 30 fs in $\sim 250 \mu\text{m}$ blowout ($\chi \approx 4\%$): **excellent output beam stability!**

Energy Stability: (72.38 ± 0.69) MeV

Emittance Y Stability: (15.11 ± 0.13) nm rad

Emittance Z Stability: (15.51 ± 0.12) nm rad

Bunch Length Stability: (0.22 ± 0.04) μm

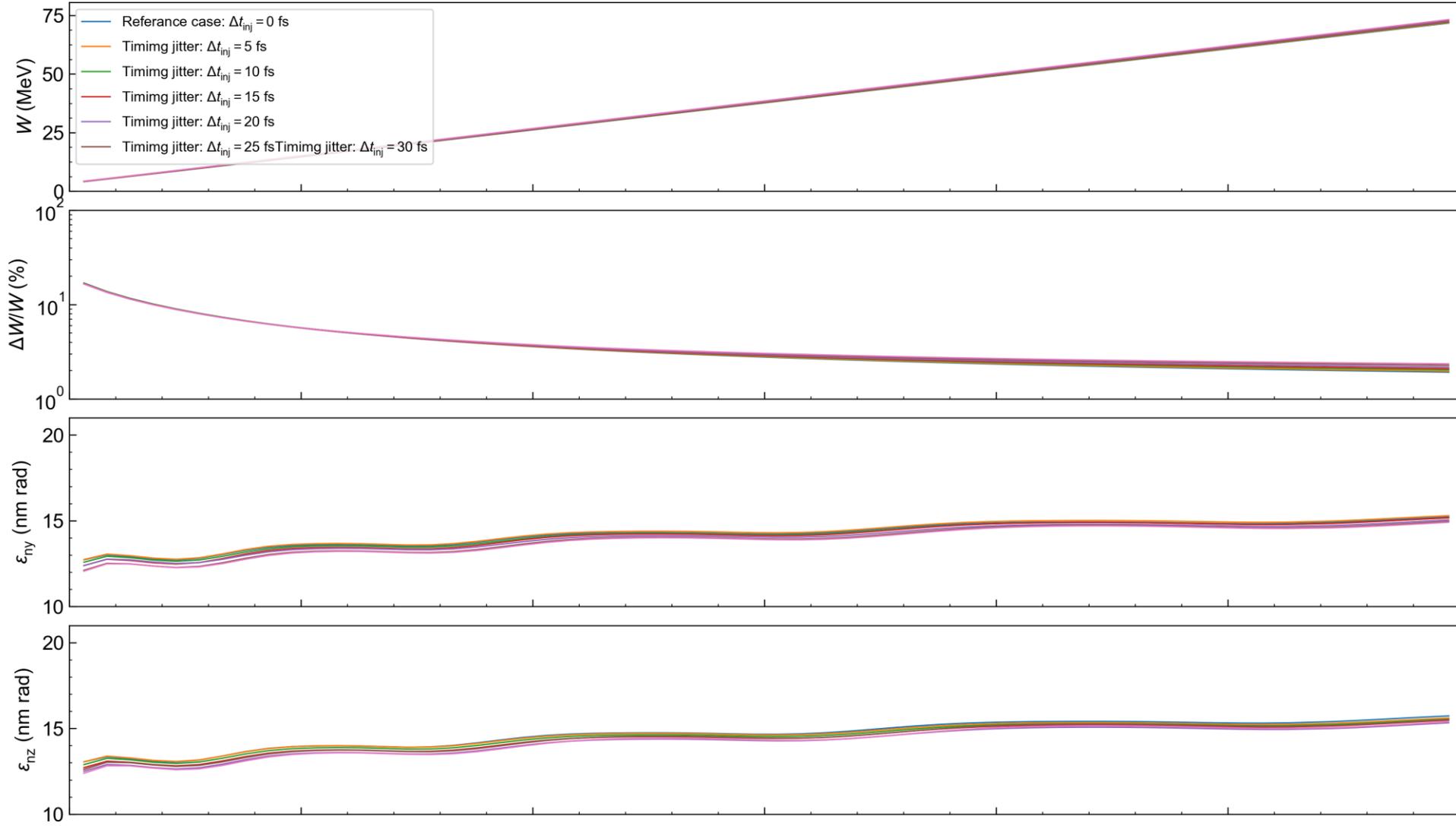


Charge Stability: (2.375 ± 0.006) pC

Rel. Energy Spread Stability: (1.52 ± 0.11) %

5D Brightness Stability: $(10.45 \pm 1.65) \times 10^{18}$ $\text{A nm}^{-2} \text{rad}^{-2}$

Peak Current Stability: (1.23 ± 0.21) kA



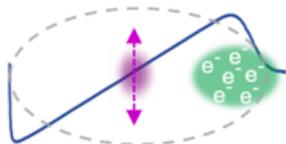
Transverse plasma photocathode release laser offset jitter study in 250 μm length blowout

Energy Stability: (72.15 ± 0.59) MeV

Emittance Y Stability: (29.91 ± 11.8) nm rad

Emittance Z Stability: (15.38 ± 0.48) nm rad

Bunch Length Stability: (0.19 ± 0.03) μm

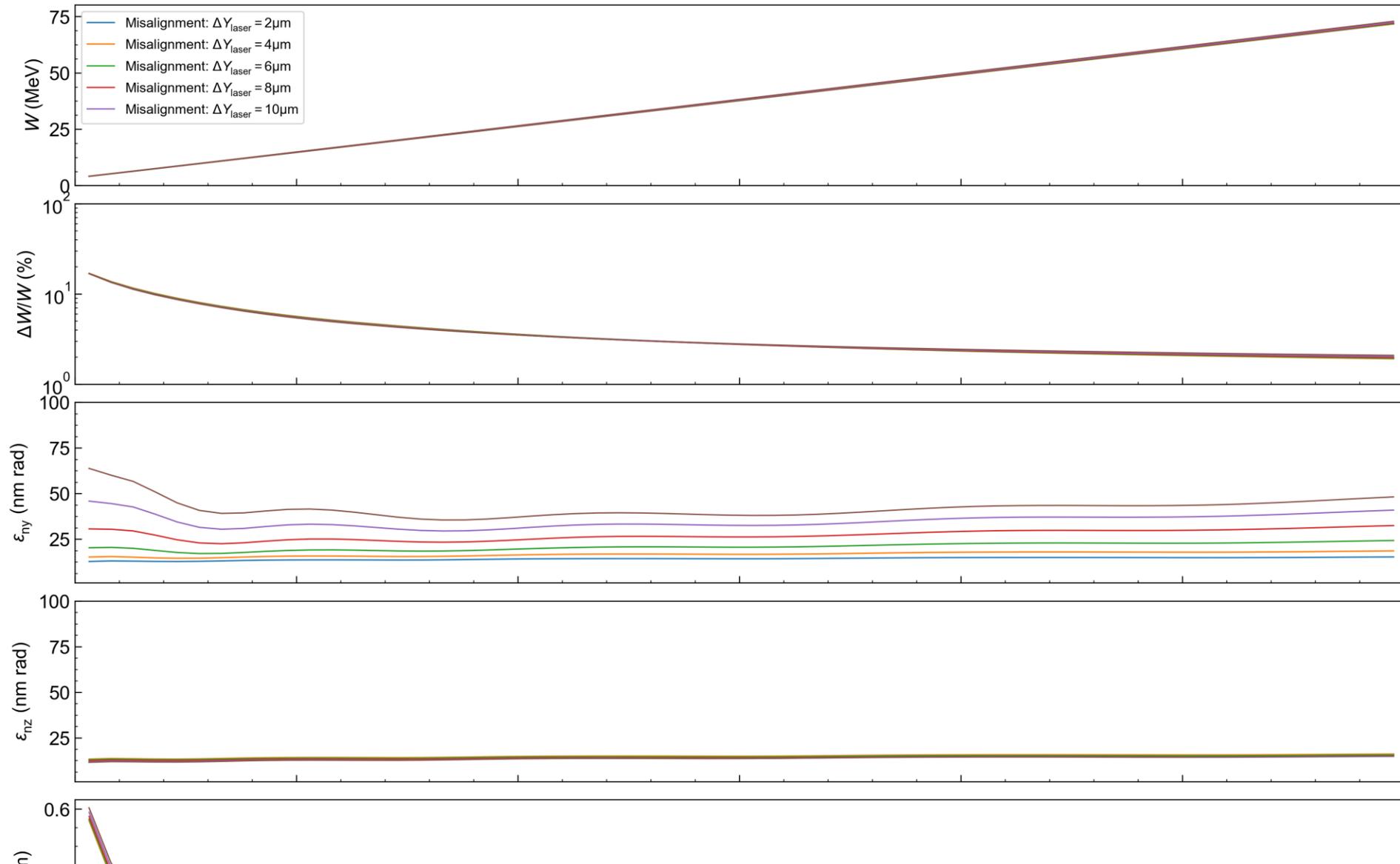


Charge Stability: (2.371 ± 0.005) pC

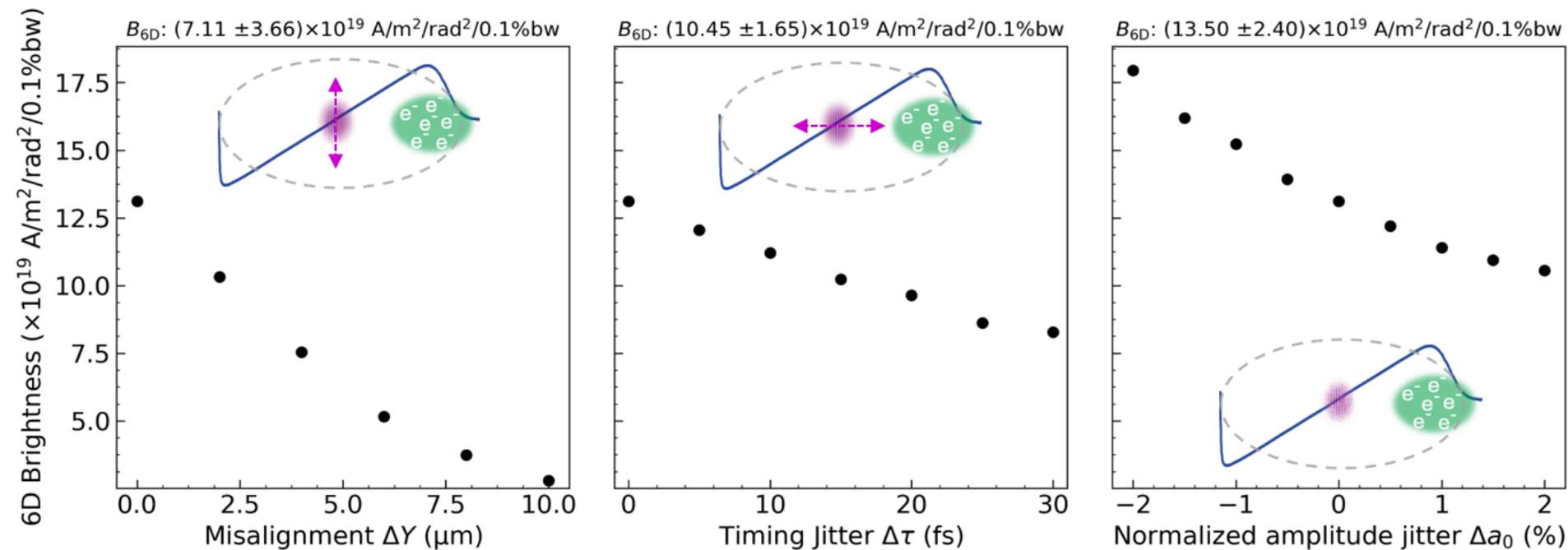
Rel. Energy Spread Stability: (1.41 ± 0.05) %

5D Brightness Stability: $(7.11 \pm 3.66) \times 10^{18}$ $\text{A nm}^{-2} \text{rad}^{-2}$

Peak Current Stability: (1.32 ± 0.21) kA



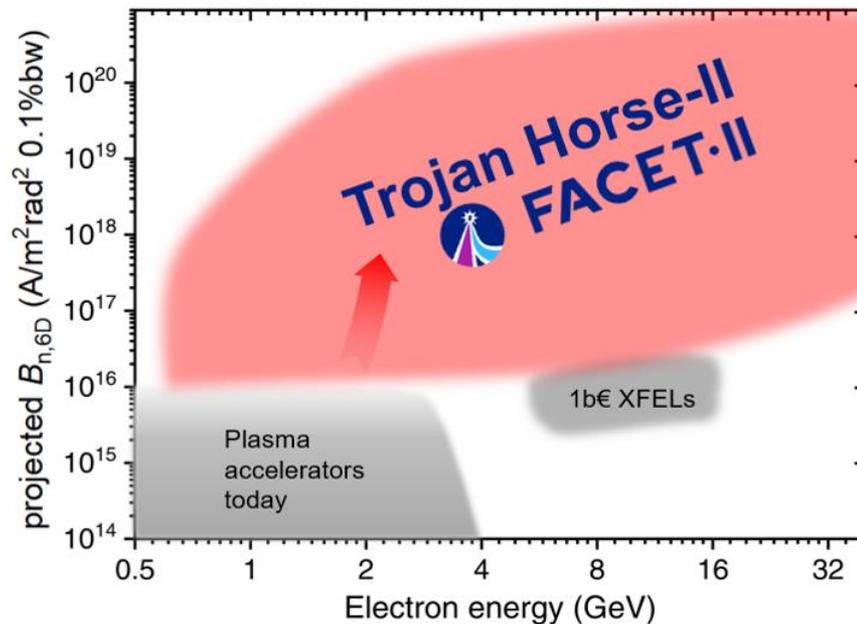
Follow up: What does this mean for obtainable beam quality and stability (6D)?

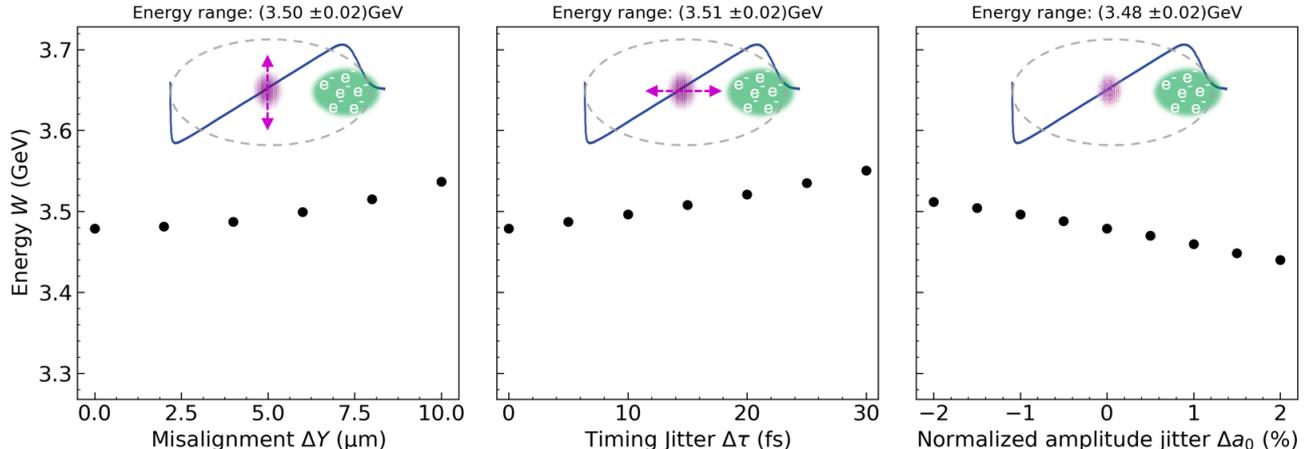


Resulting 6D brightness:

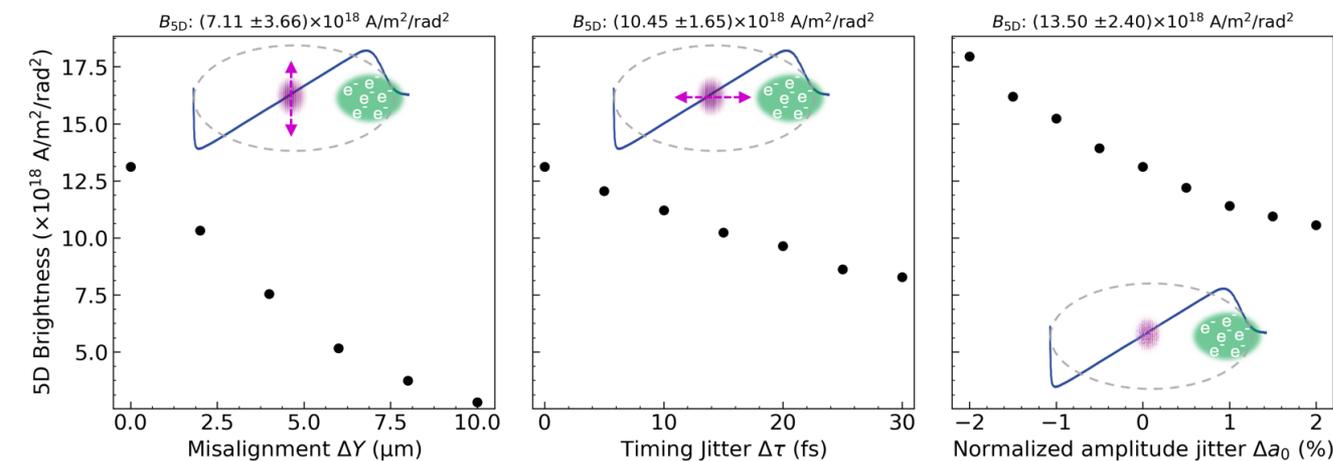
$$B_{6D} = \frac{I_p}{\epsilon_{n,x} \epsilon_{n,y} 0.1\%BW}$$

Note: LCLS 6D brightness is at $1e16$ level

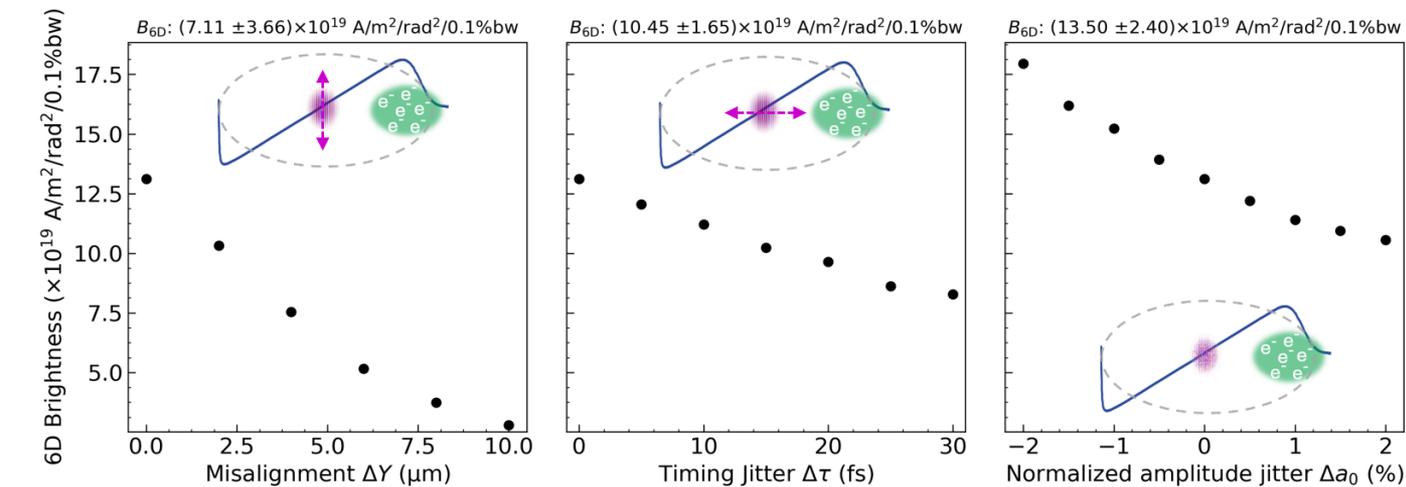




Output beam energy stability better than 1% (linac level)



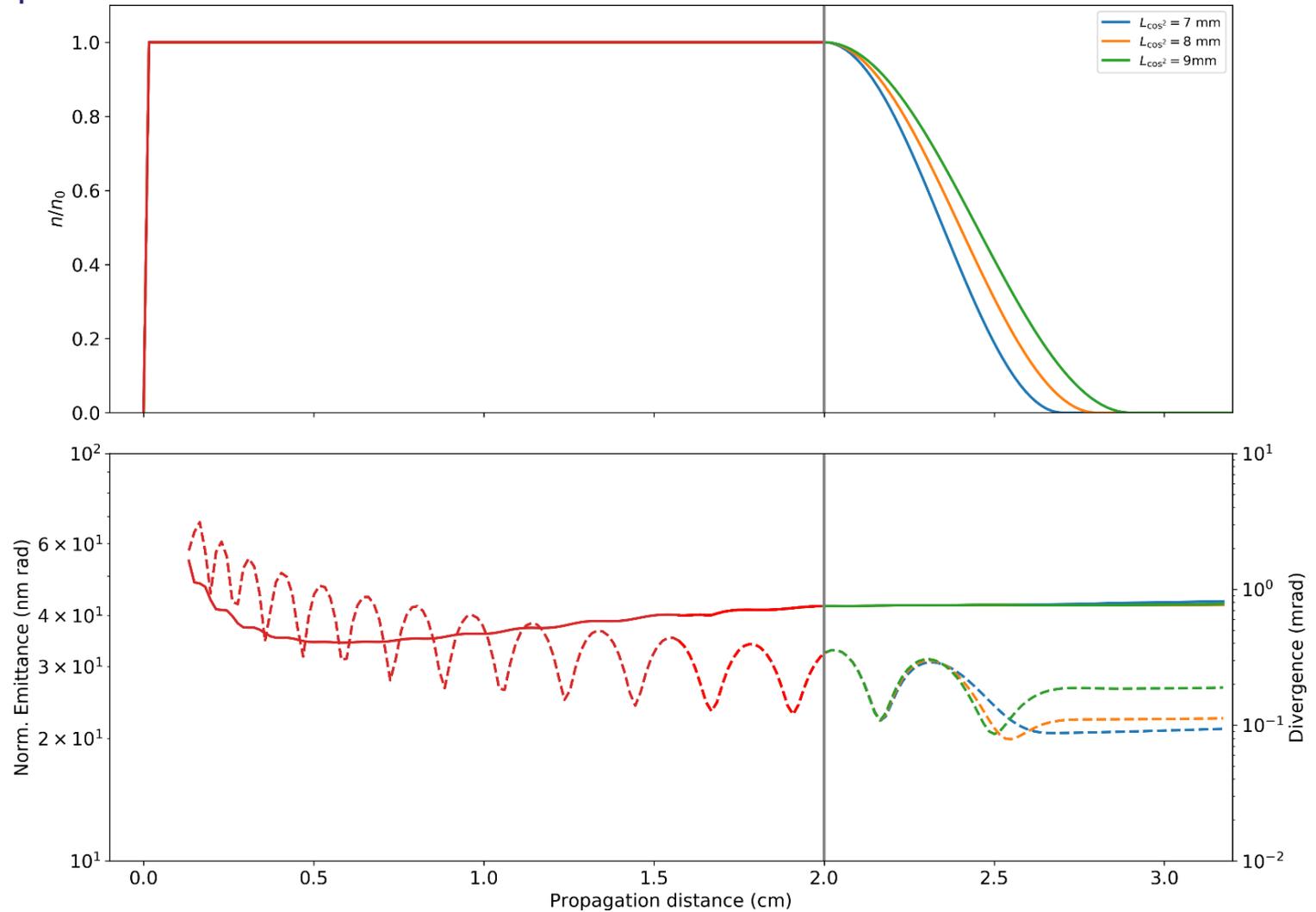
5D brightness orders of magnitude better than today's X-FEL's



6D brightness orders of magnitude better than today's X-FEL's (estimated)

Emittance preservation during extraction

- ❑ Decreasing plasma density at the exit
- ❑ With “escort”-bunch dechirping
- ❑ Emittance is preserved!



Summary

- ❑ *Absolute* injection precision and afterglow diagnostics focus of Run 1
- ❑ Plasma afterglow torch & Icarus identical setup
- ❑ Many synergies with other experiments
- ❑ Big fat plasma and *relative* injection precision for upcoming runs
- ❑ Sensitivity studies (30 fs, 10 μm in 250 μm blowout, 2% intensity) indicate excellent witness output stability possible
- ❑ Will use FACET-II S2E e-beams for simulations (afterglow & injection)
- ❑ Escort beamloading dechirper for 5D \rightarrow 6D brightness
- ❑ Plasma torch (aka optical density downramp injection) also very similar setup, can be used for escort

