High-repetition-rate, all-reflective optical guiding and electron acceleration in helium using an off-axis axicon

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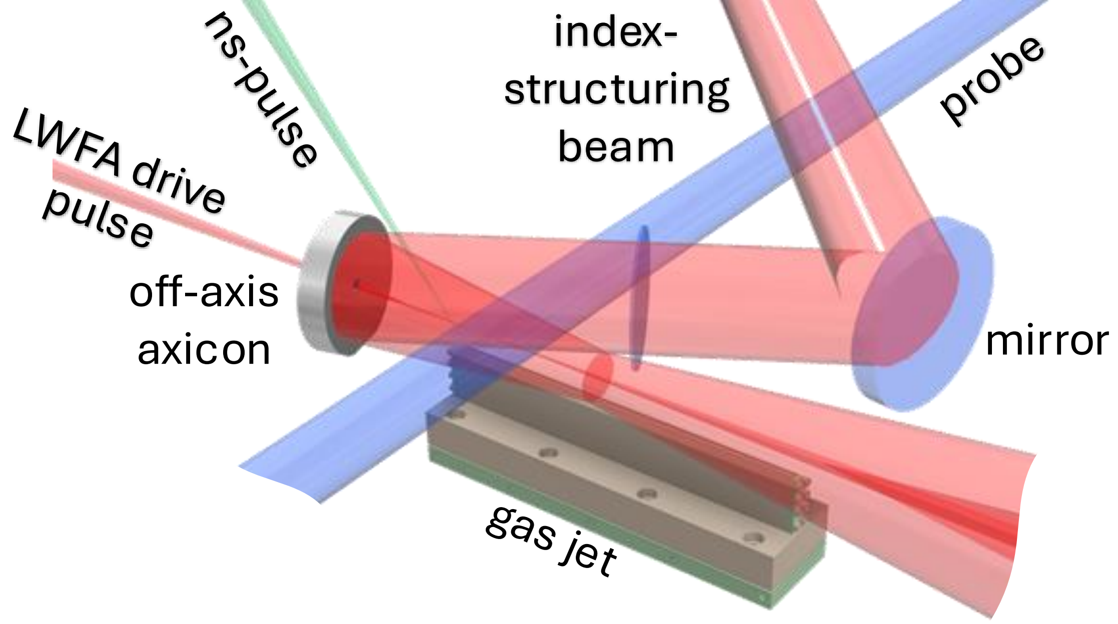
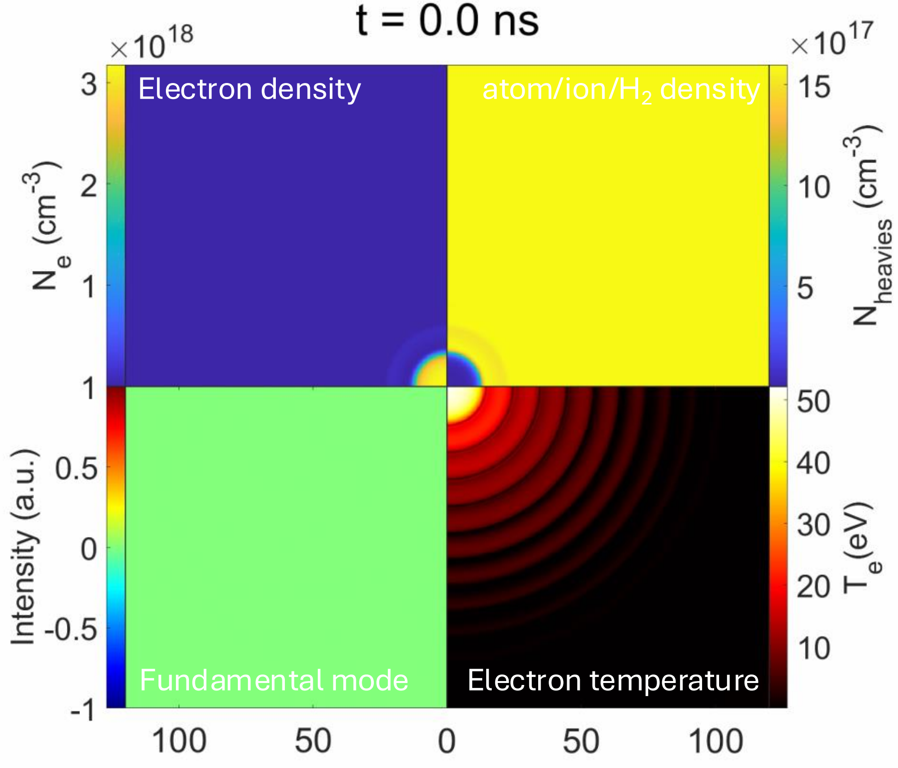
Outline

- Self-waveguided LWFA and waveguide formation mechanism
- Experimental area and guiding setup at ELBA in E5 using L3-HAPLS
- Laser parameters: simulations and measurements
- High power guiding results
- Electron acceleration results

Self-waveguided LWFA



- Three key limitations on energy gain in LWFA
  - dephasing
  - depletion
  - **diffraction**
- Plasma waveguides extend acceleration distance by preventing diffraction of the drive laser
- Hydrodynamic expansion of Optical-Field-Ionized plasma channel
- Control of plasma channel expansion by delay or energy – adjusting the channel size to given focal spot



Hydrodynamic expansion simulation
B. Miao *et al.*, Phys. Rev. Accel. Beams **27**, 08132 (2024)

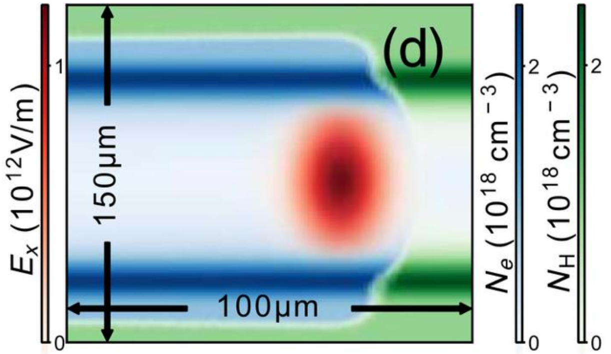
C. G. Durfee and H. M. Milchberg, Phys. Rev. Lett. **71**, 2409 (1993)
N. Lemos et al., Sci Rep **8**, 3165 (2018)
R. J. Shalloo *et al.*, Phys. Rev. E **97**, 053203 (2018)

Optical waveguide formation in plasma

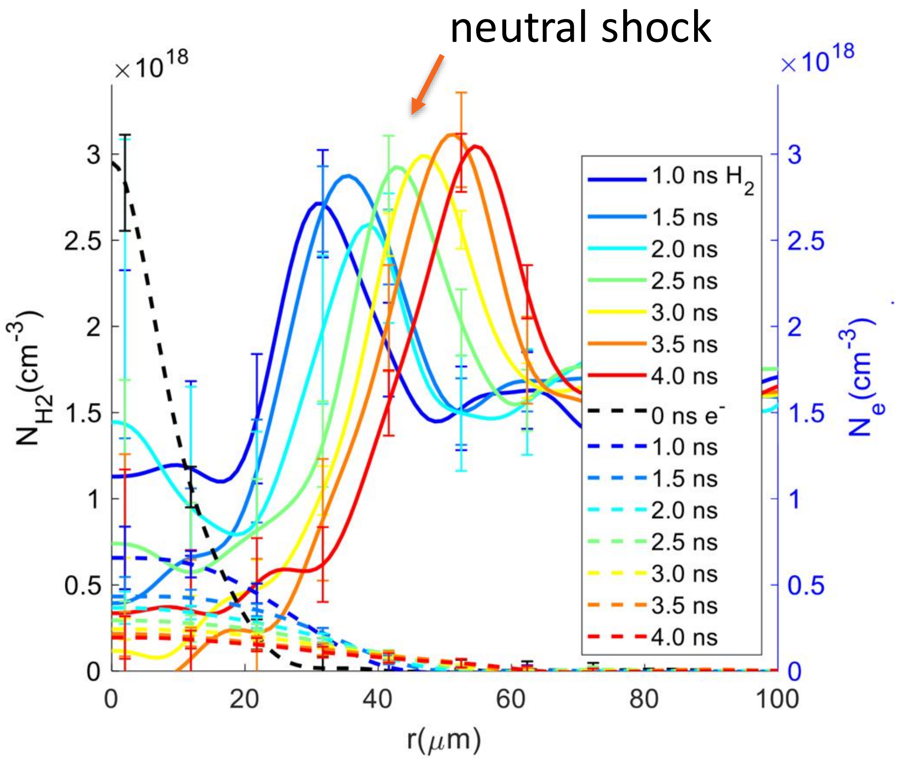
- Expanding OFI plasma channel alone may not form a waveguide structure at low density
- Waveguide cladding is formed after auxiliary ionization:

2-Bessel beam method	Self-waveguiding method
Miao *et al.*, PRL **129**, 074801 (2020)	Feder *et al.*, PRR **2**, 043173 (2020)

- ***Self-waveguiding:*** Leading wings of an injected high intensity pulse ionize neutral shock driven by expanding OFI plasma column

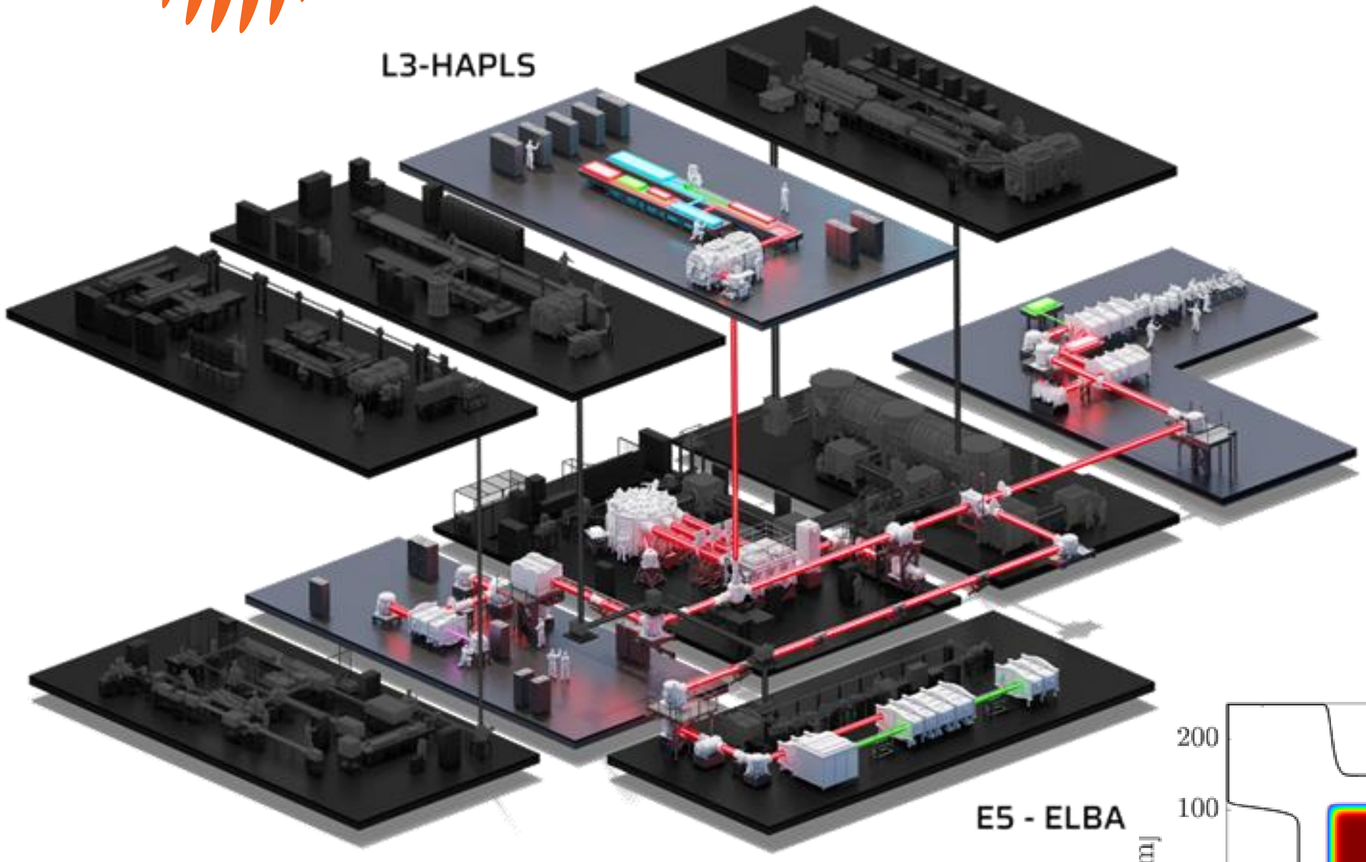


FBPIC simulation of self-waveguiding
B. Miao *et al.* Phys. Rev. X **12**, 031038 (2022)



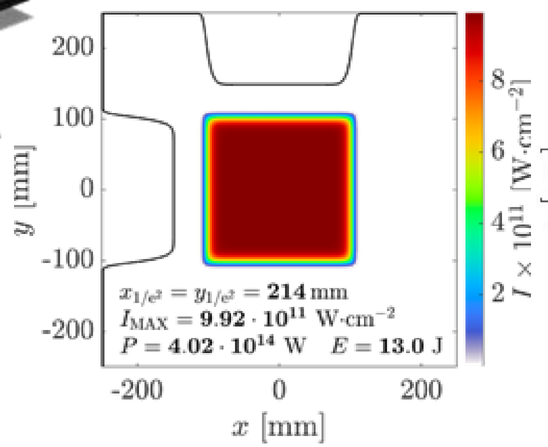
Measured hydrodynamic plasma channel expansion
L. Feder *et al.* Phys. Rev. Research **2**, 043173 (2020)

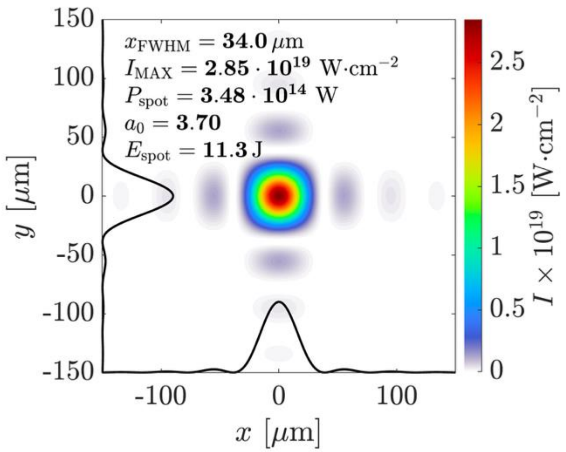
Experimental area & L3 laser parameters

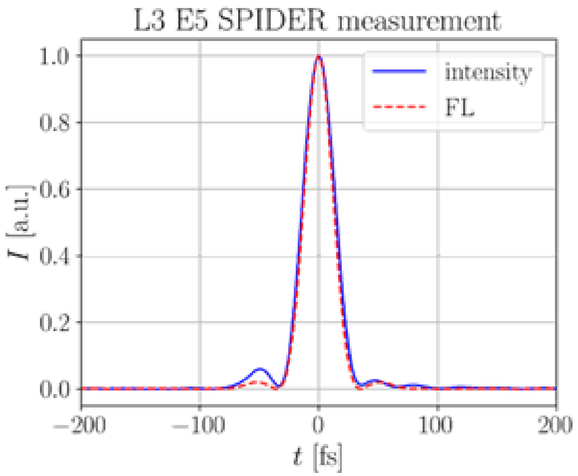


Laser and experimental halls

parameter	current performance
Laser technology	CPA: Ti:sapphire single aperture
Pulse energy	13 J *(8 J @ 3.3 Hz)*
Pulse duration	30.4 fs *(measured in E5)*
Repetition rate	0.2 Hz (3.3 Hz)
Peak power	401.7 TW
Beam format	rectangular superGaussian
Beam size	214 x 214 mm

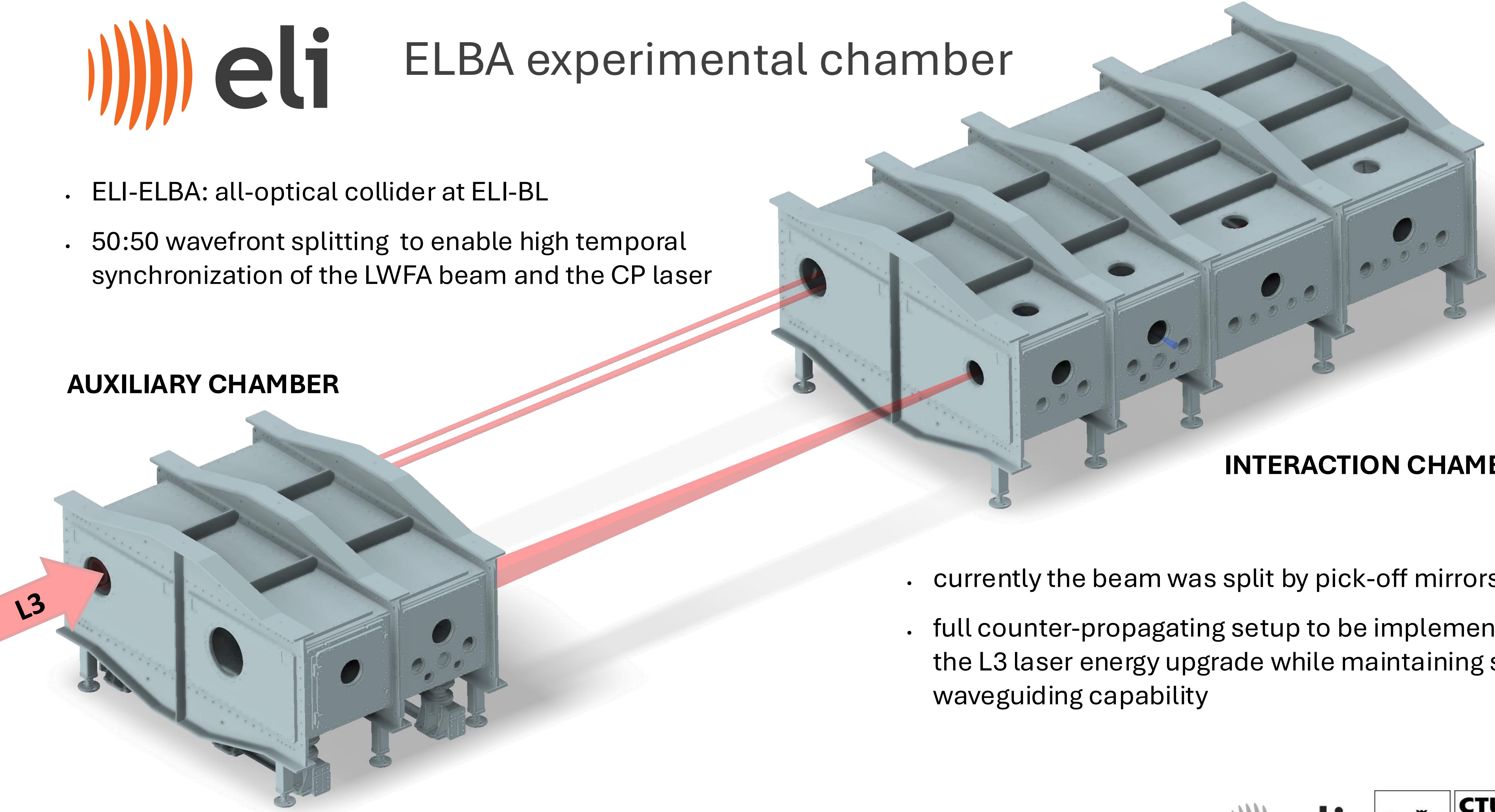






ELBA experimental chamber

- ELI-ELBA: all-optical collider at ELI-BL
- 50:50 wavefront splitting to enable high temporal synchronization of the LWFA beam and the CP laser

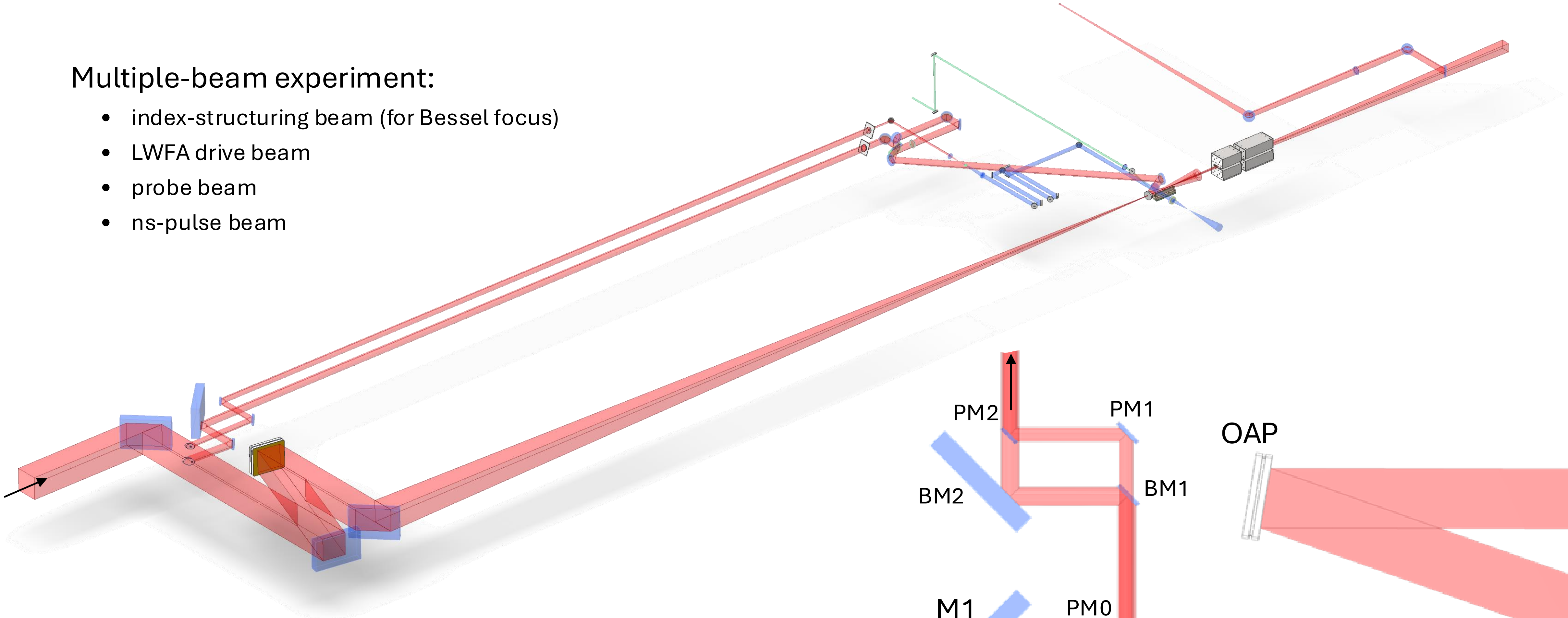


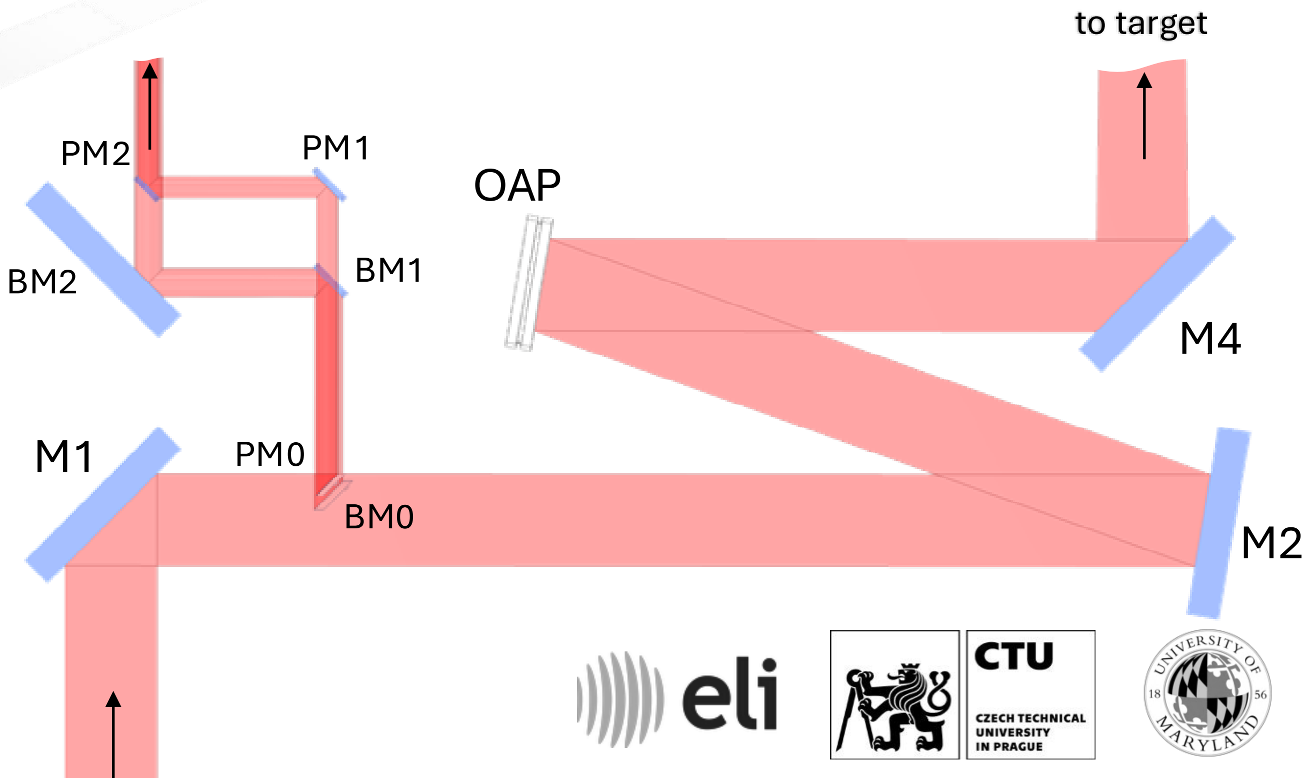
- currently the beam was split by pick-off mirrors
- full counter-propagating setup to be implemented with the L3 laser energy upgrade while maintaining self-waveguiding capability

Self-waveguiding setup at ELBA

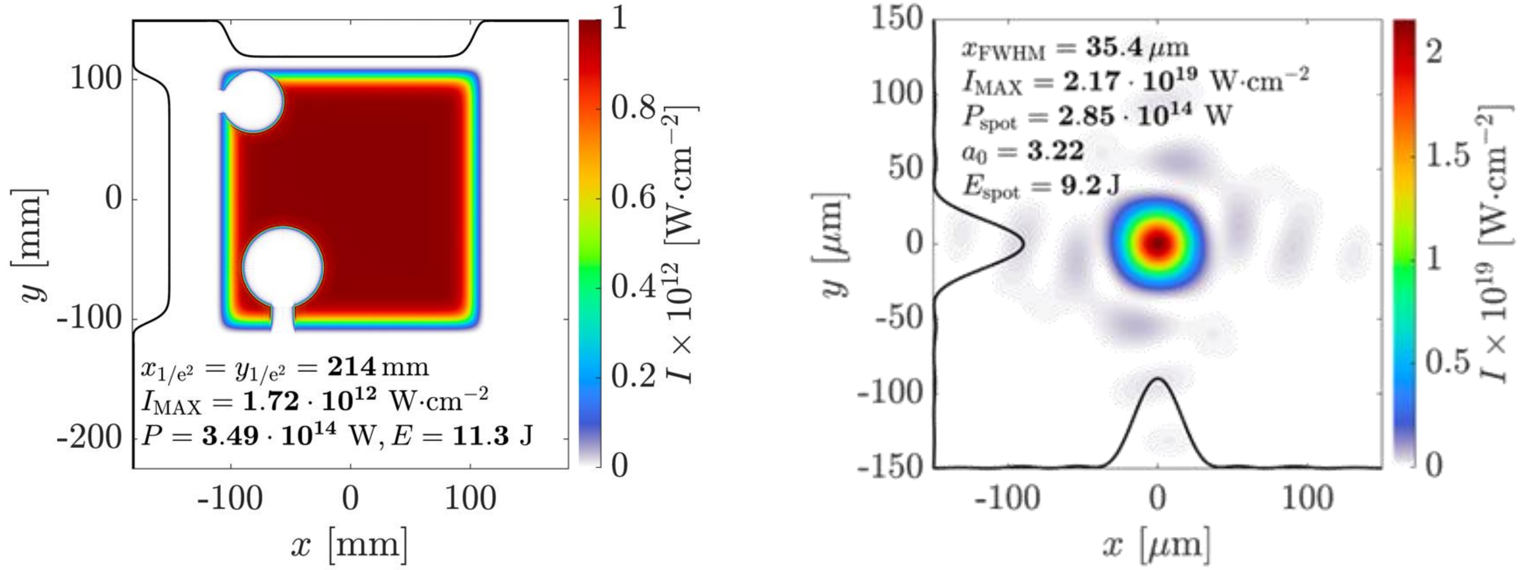
Multiple-beam experiment:

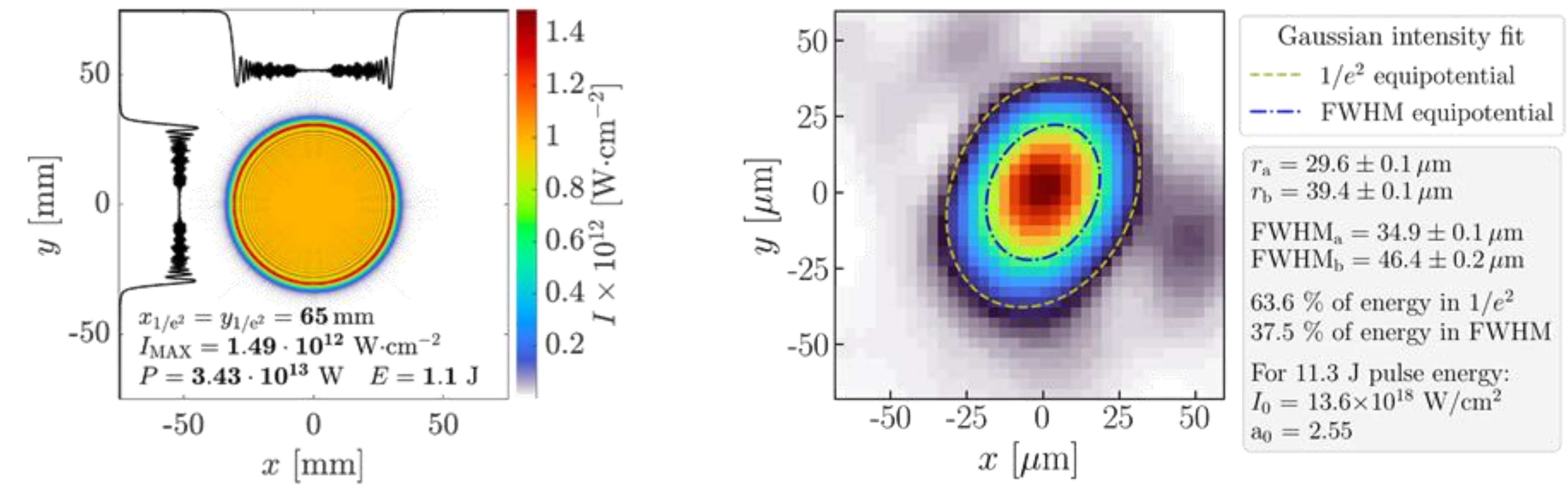
- index-structuring beam (for Bessel focus)
- LWFA drive beam
- probe beam
- ns-pulse beam





LWFA drive & Bessel beam parameters



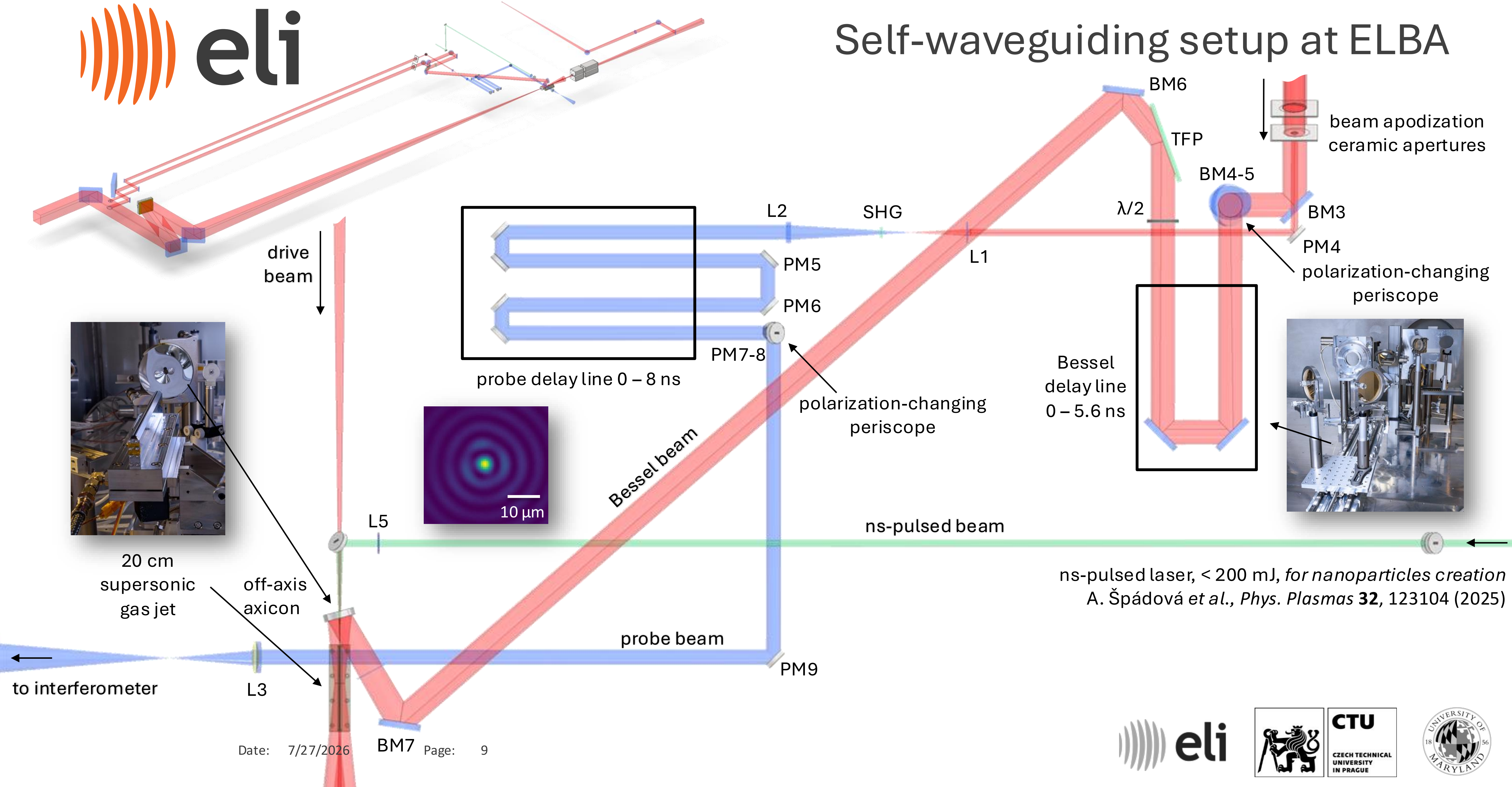


L3 full size	13 J
LWFA drive beam	**11.3 J**
Bessel beam	**1.1 J**
Probe pick-off beam	**0.6 J**

- **86.2 %** energy in LWFA drive beam
- **8.5 %** energy in Bessel beam

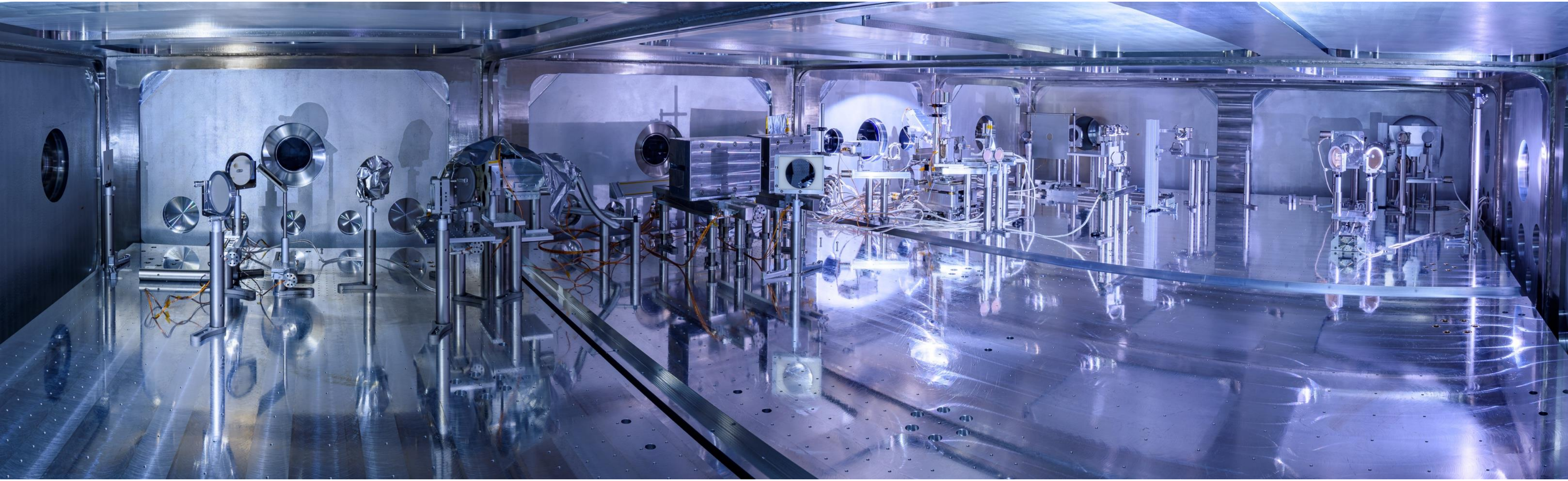
- **~ 64 %** energy measured on target
- **~ 7.2 J** used for guiding and acceleration
- *Strehl ratio: 0.79*

Self-waveguiding setup at ELBA

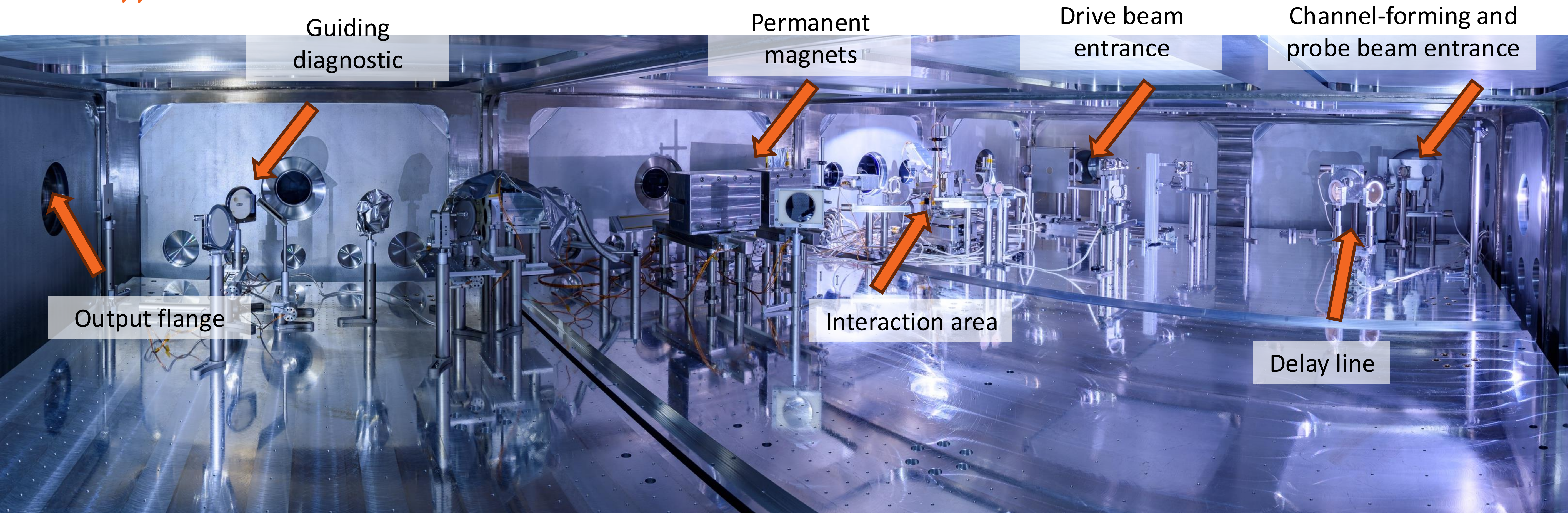


ns-pulsed laser, < 200 mJ, *for nanoparticles creation*
A. Špádová *et al.*, *Phys. Plasmas* **32**, 123104 (2025)

ELBA experimental chamber

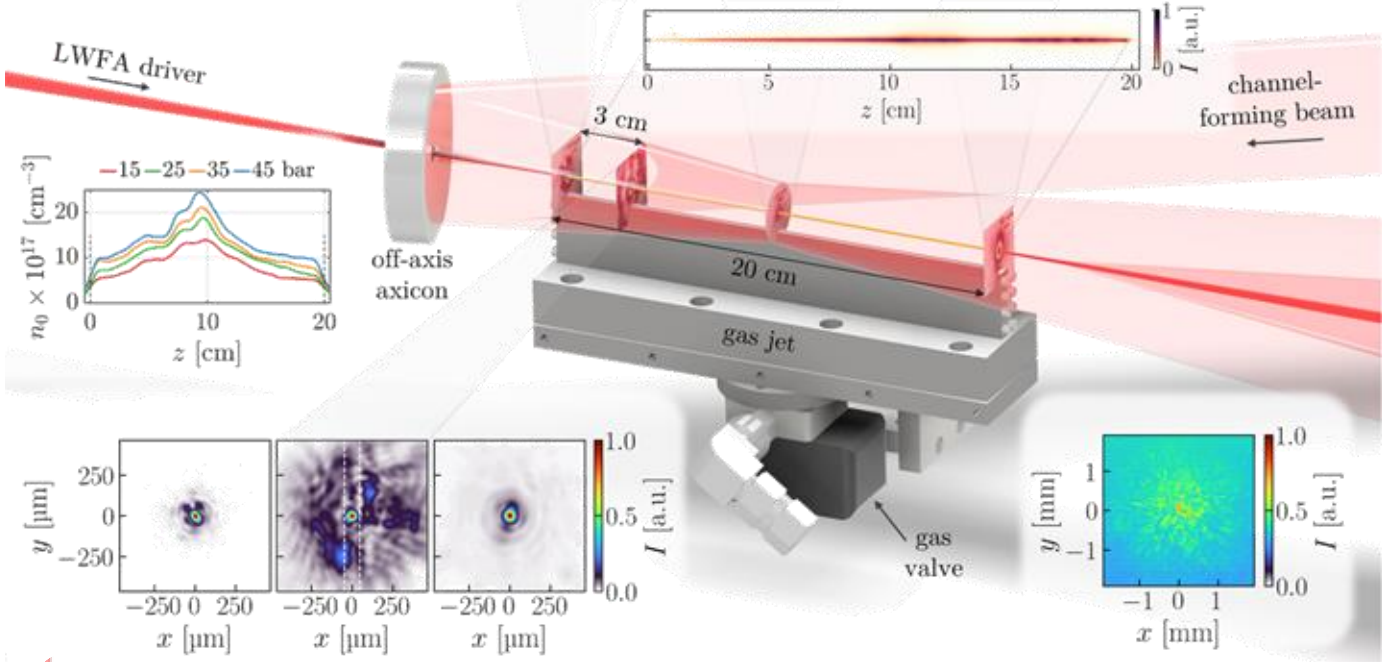


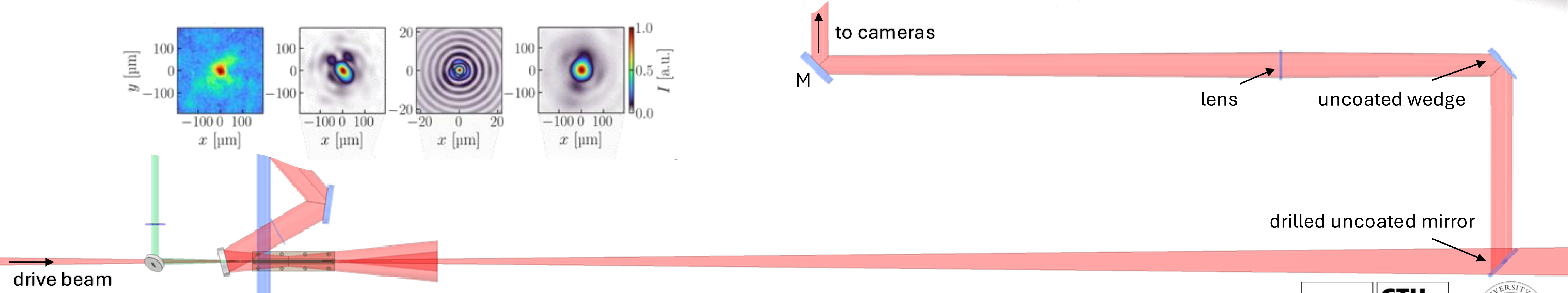
ELBA experimental chamber



High power guiding at 0.2 Hz and 3.3 Hz

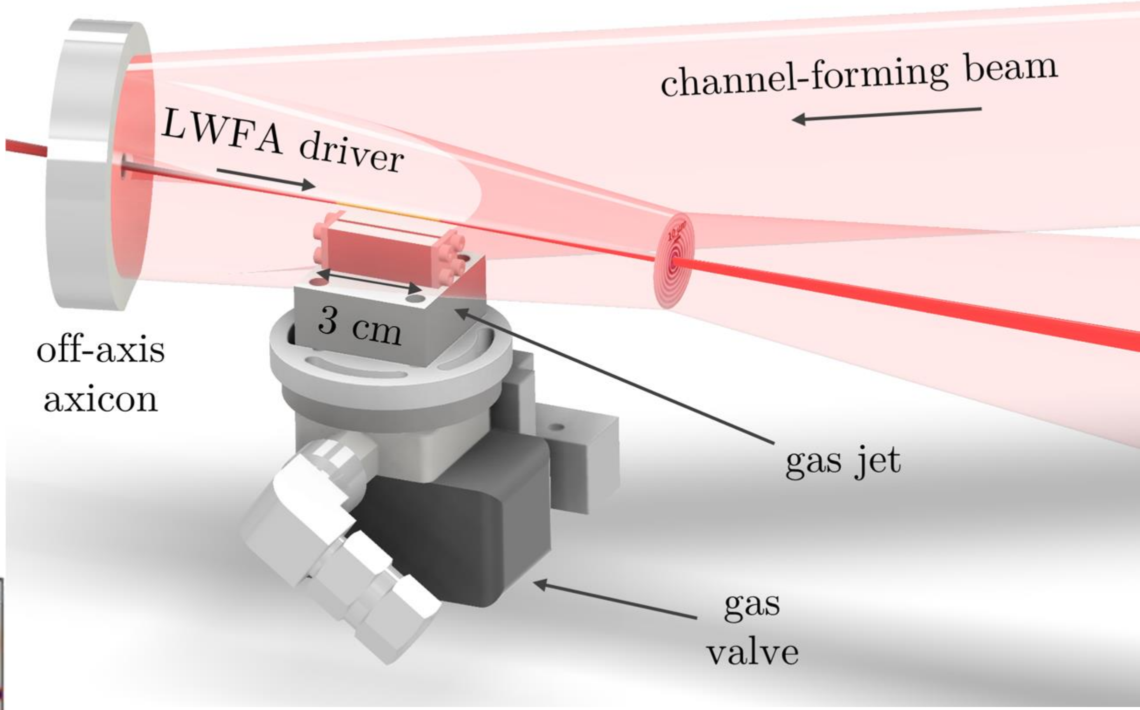
- High power guiding mode diagnostic for monitoring pointing (entrance to waveguide) and exit mode (single lens imaging)
- Demonstrated high power guiding in 20 cm plasma channel at 0.2 Hz at 6 - 10 J in pure helium (dopped gases for electron acceleration)
- Neutral density was measured 8 mm above the nozzle orifice using "fluorescence" method – comparison with backfilled chamber

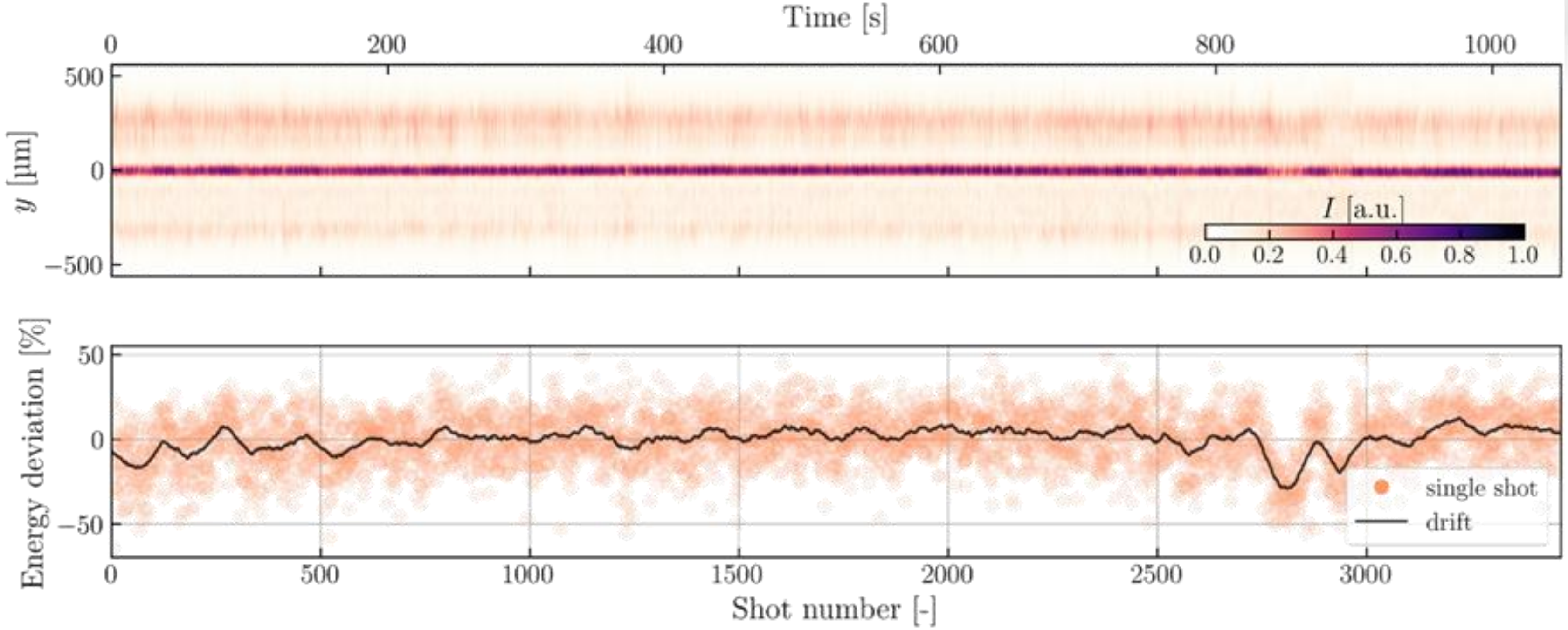


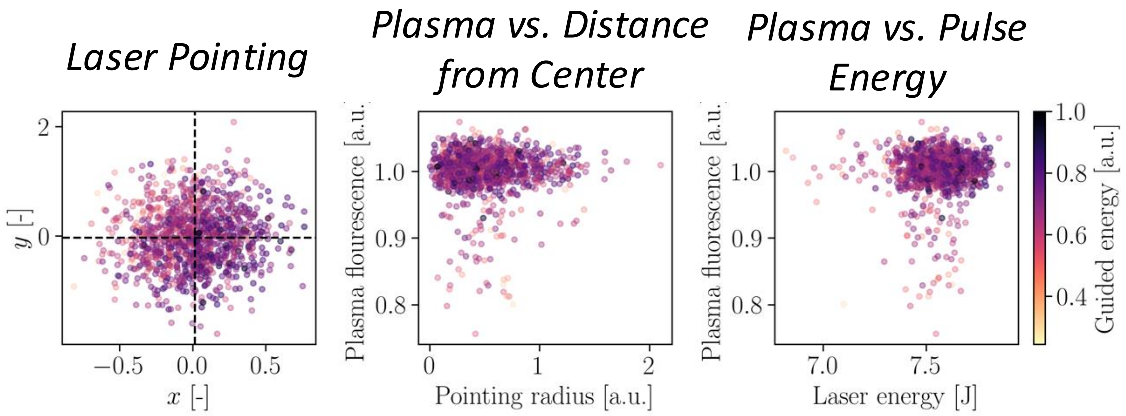


High power guiding at 3.3 Hz

- Demonstrated guiding in 3 cm plasma channel at 3.3 Hz at 6 - 8 J (250 TW)
- Backing pressure 6 bar, 2 ms opening time
- Corresponding neutral density ~ 9.4 x 10^{17} cm^{-3}
- Limited by pumping system – LWFA ionization injection requires higher pressure (only high-power guiding)

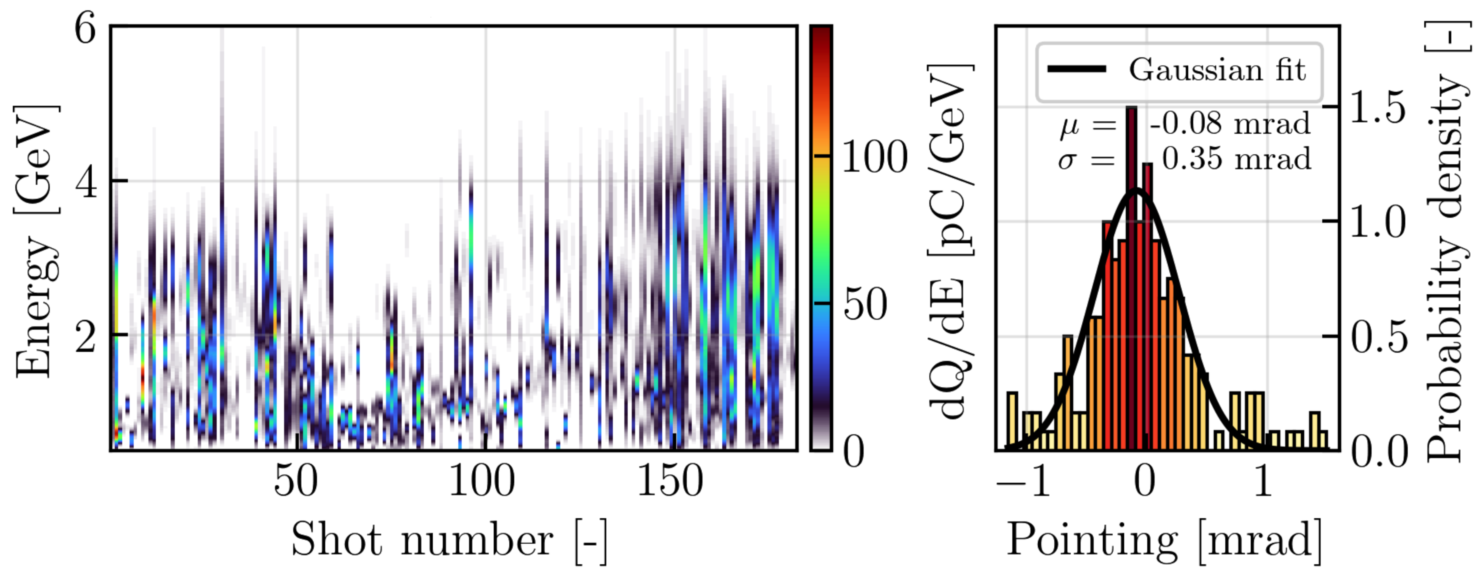


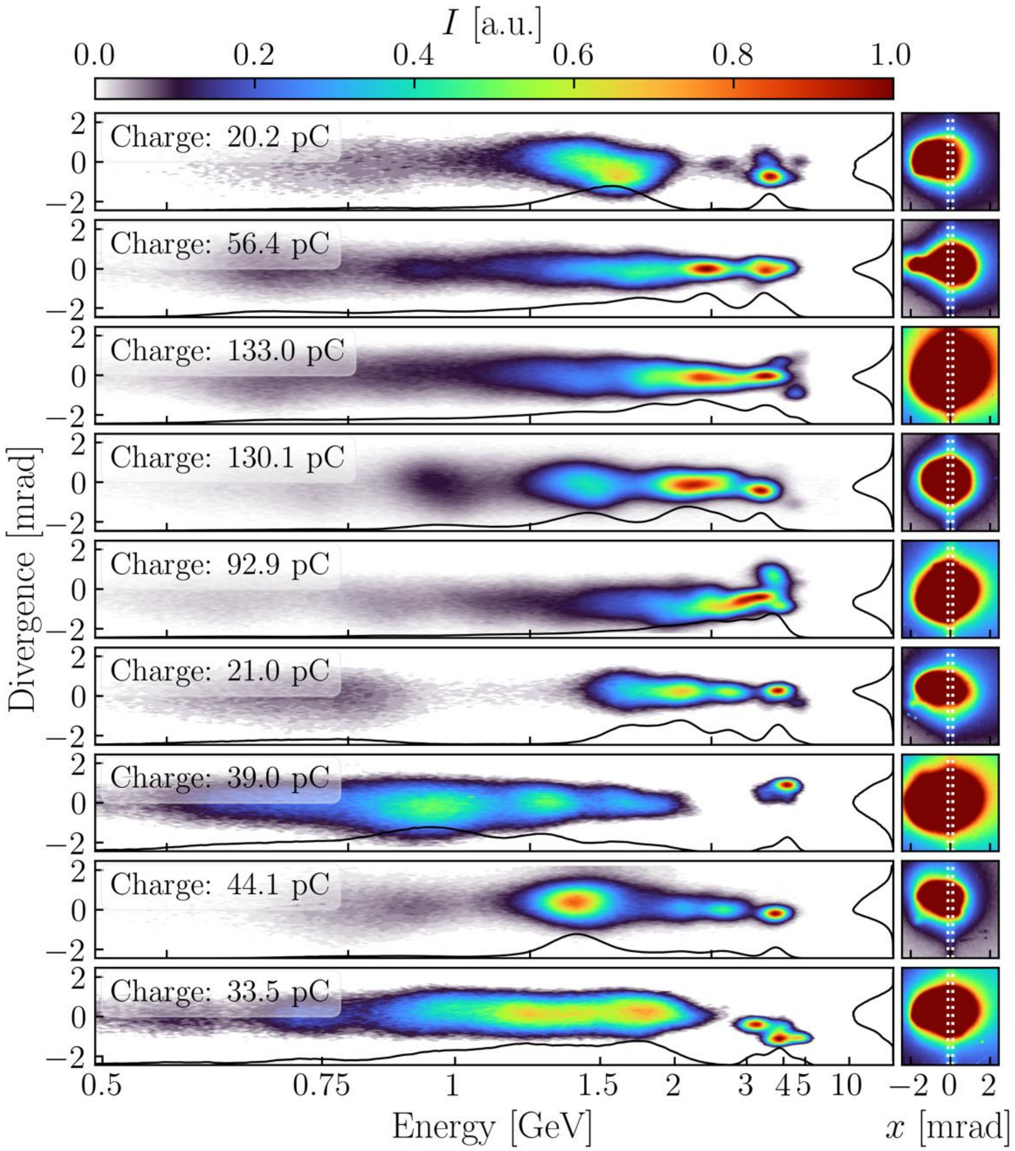




Electron energy results

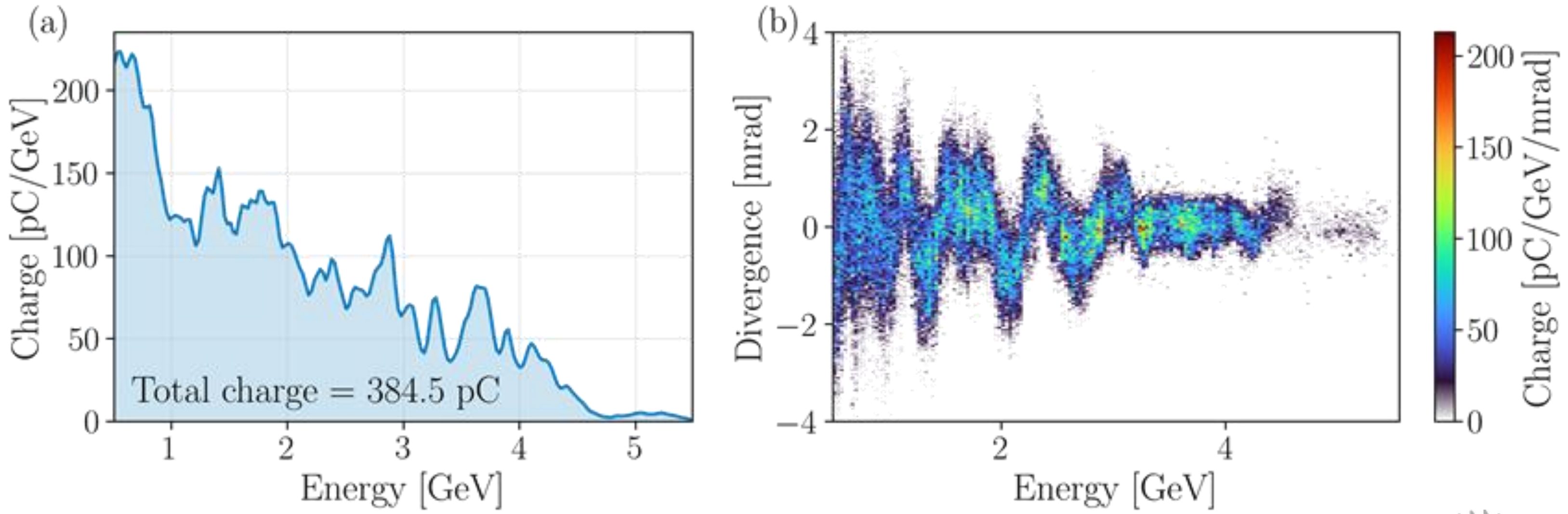
- Electromagnet outside the chamber **0.6 T, 50 cm** (4 meters away from waveguide exit)
- Tungsten slit **1 mm**, block length 6 cm
- ELI designed slit supersonic nozzle **20 cm** working with only one SmartShell valve, backing pressure **20 – 42 bar**, 10 ms opening time
- Dopant in the full length on the gas jet
- Broadband spectra, mean electron energy **~3.5 GeV** (15 % uncertainty), high-energy features extending up to **5 GeV** (20 % uncertainty)





Electron energy results

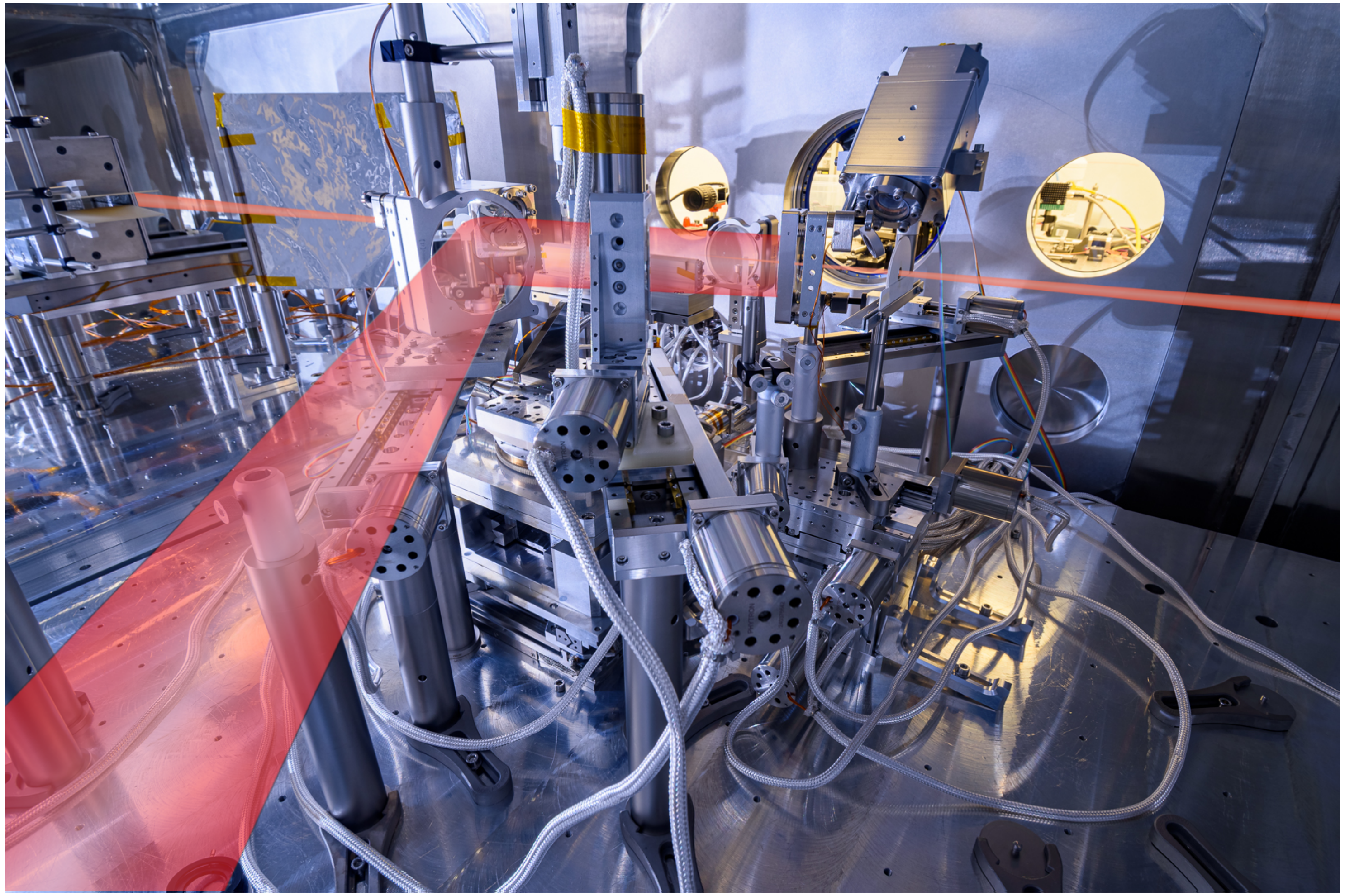
- Stable pointing and low divergence, typically **1.2 ± 0.3 mrad** (FWHM) for electrons above 0.5 GeV and less than 0.6 mrad for electrons exceeding 3 GeV, shot-to-shot variations in beam pointing **~ 0.35 mrad**
- Only **7.2 J** contained within the $1/e^2$ focal-spot radius for delays from 1.7 to 2.1 ns between the channel-forming pulse and the LWFA driver
- With $\boldsymbol{a0 = 2.55}$, $\boldsymbol{\tau_{FWHM} = 30.4}$ **fs**, $\boldsymbol{w_0 = 32.1}$ **μm**, $\boldsymbol{n_e = 2.7 \times 10^{17}}$ $\mathbf{cm^{-3}}$ and a corresponding dephasing length l_{deph} = 15 cm, resulting maximum electron energy is **~ 5.5 GeV** (Lu et al., Phys. Rev. ST Accel. Beams **10**, 061301)
- The maximum energy reached also corresponds to particle-in-cell simulation performed by Ela Rockafellow using FBPIC



New approaches in an SW-LWFA experiment

Conclusion

- **Off-Axis Reflective** Axicon – all reflective setup
- **Single – compressor** beamline
- **Helium** as a working gas
- Energy up to **5 GeV** (7.2 J in *$1/e^2$* radius)



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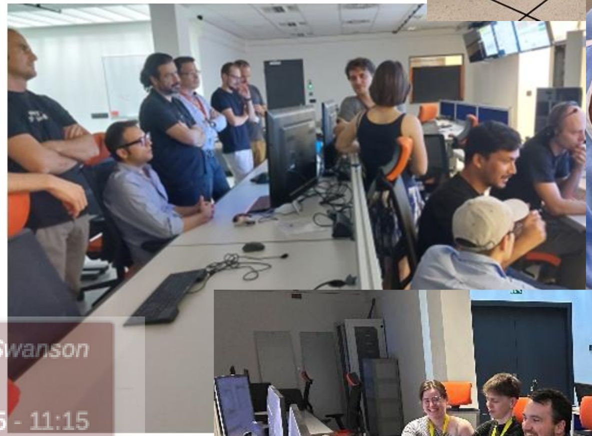
Available and already used for user experiments

- Stabilized electron beam pointing, high electron energies
  - **Betatron radiation** imaging and measurement by F. Treffert and I. Pagano et al. (LLNL)
  - **Muon production** measurement by S. Bountempo (INFN) et al. and A. Giammanco (CERN) et al.
  - **Inverse Compton scattering** experiment performed by E. Gerstmayr and G. Sarri et al. (QUB)
  - VHEE Dosimetry by **Cherenkov radiation** by A. Pifferi et al. (Politecnico di Milano)
- Guided electron beamline available at ELBA available for users

  (check next ELI user call at https://up.eli-laser.eu/)

- **Plenary talk by Gabriele M. Grittani on Thursday morning at 11:15**

11:00	Plasma-based compression of electron beams *Ballroom, Luskin Conference Center*	*Kelly Swanson* 10:45 - 11:15
	High repetition rate LWFA with all-optical guiding for user experiments at ELI Beamlines *Ballroom, Luskin Conference Center*	*Gabriele Maria Grittani* 11:15 - 11:45
12:00	Spectrotemporal shaping of attosecond X-ray free-electron laser pulses *Ballroom, Luskin Conference Center*	*River Robles* 11:45 - 12:15



Thank you
for your attention!

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RESEARCH ARTICLE

High-repetition-rate, all-reflective optical guiding and electron acceleration in helium using an off-axis axicon

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