EUROPEAN
PLASMA RESEARCH
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APPLICATIONS

EuPRAXIA
Preparatory Phase

Plasma Components and Systems for LPAs

K. Cassou on behalf of WP10

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Setting and Background

Disclaimer: A Note on the Laser Driven Facility

The laser driven EuPRAXIA facility site has not yet been selected (decision due later in 2025).

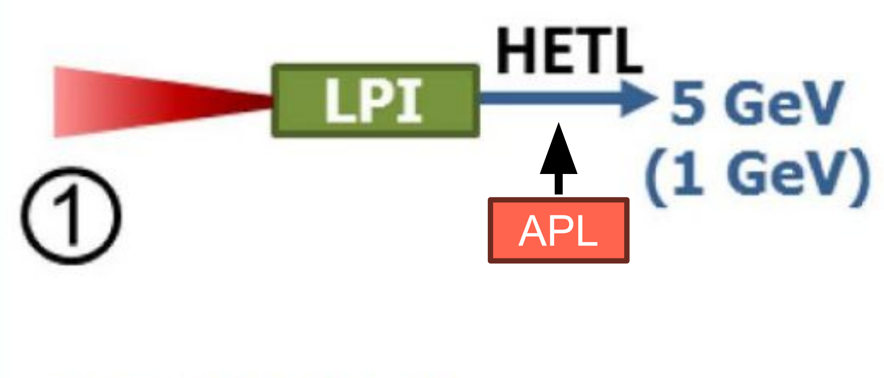
Without choice of facility (and so an understanding of any local constraints) there has been no opportunity to iterate the design configuration for the laser driven site. Thus in these discussions we will seek to evaluate a number of potential options which have so far been broadly considered.

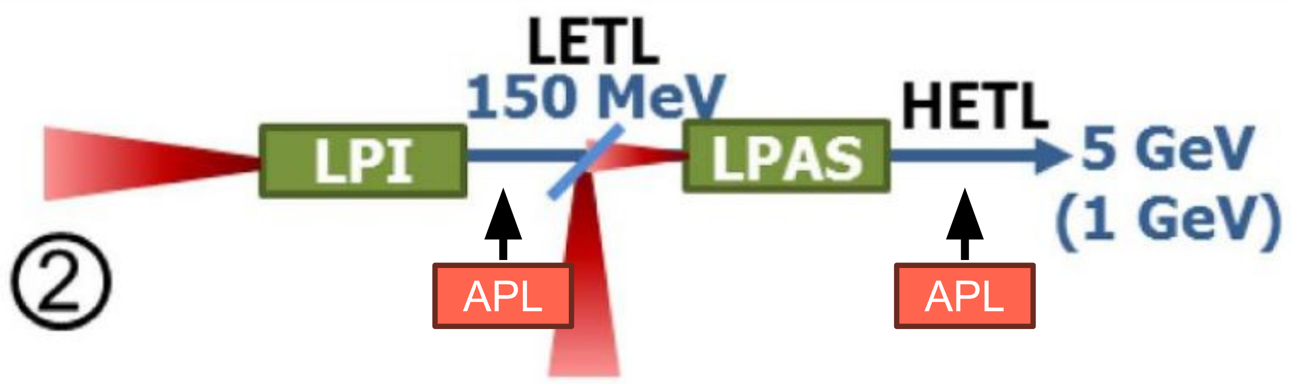
Information in these Slides

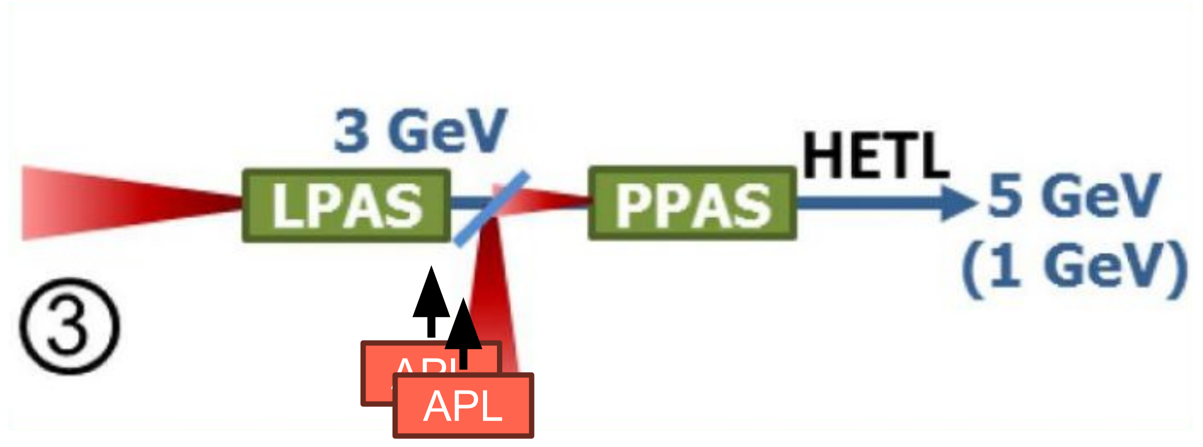
The information in these slides draws heavily upon the recent "Technical Status Report on Plasma Components and Systems in the context of EuPRAXIA" https://arxiv.org/pdf/2412.16910

Some figures are directly taken from here. For a full list of references, please refer to this paper!

Three Possible Configurations







LPI Laser plasma injector

LPAS Laser-driven plasma accelerator stage

PPAS Beam-driven plasma accelerator stage

APL Active Plasma Lens

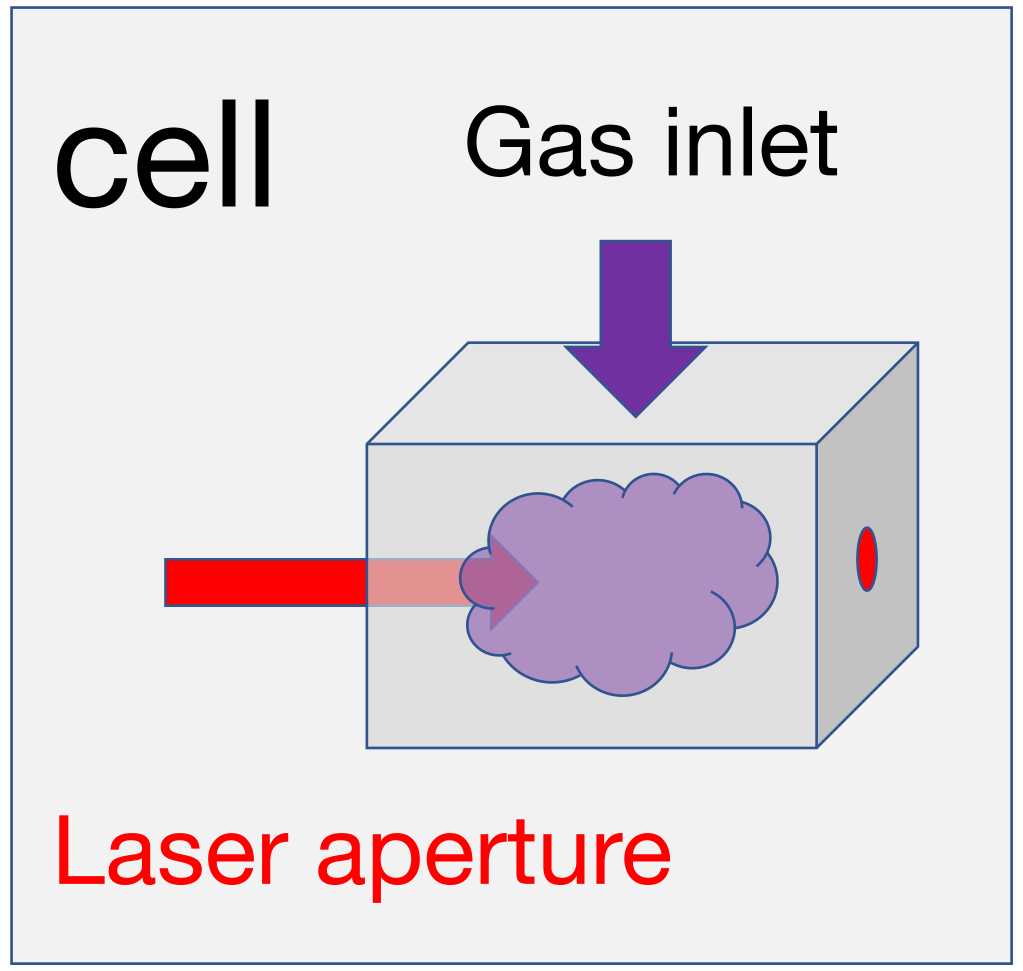
TABLE II. EuPRAXIA laser-driven general parameters from CDR[3] and references within.

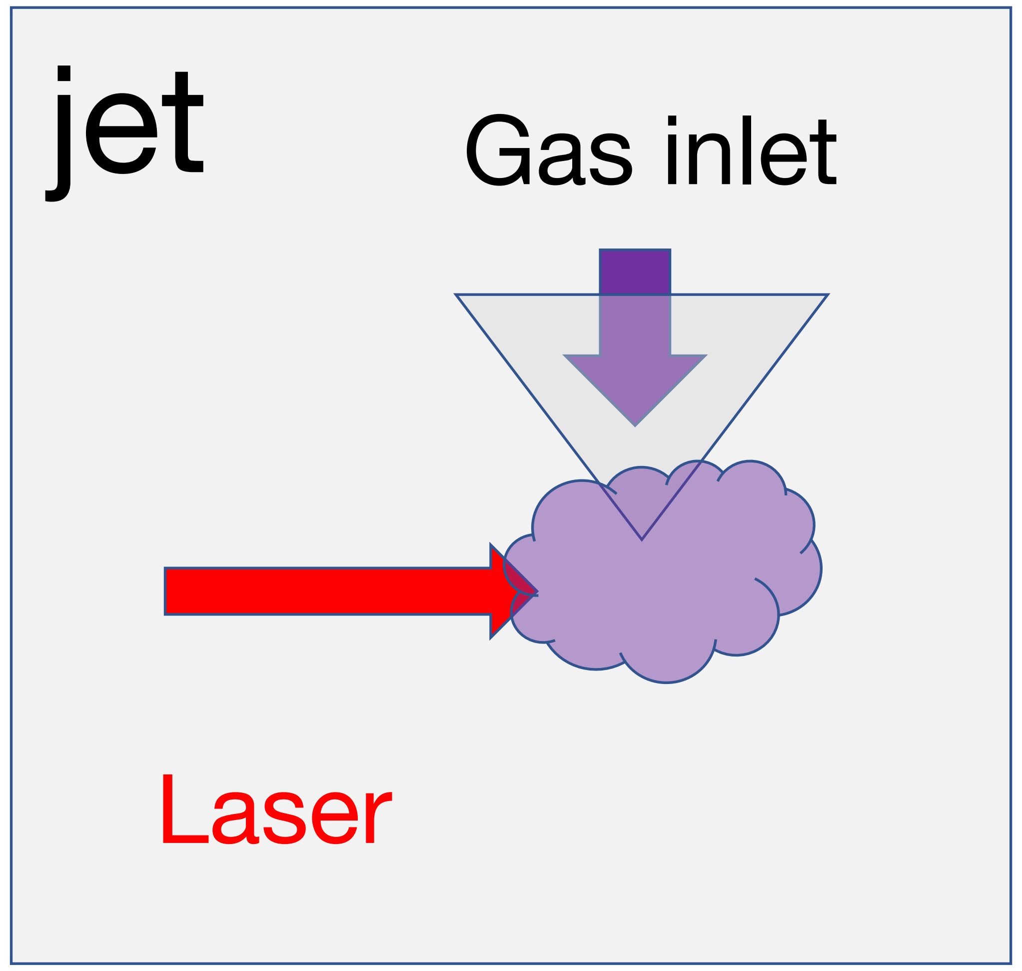
Scheme	Parameter	Value	Unit
LPI-LE	Energy Gain	0.25-0.5	GeV
	Density	10^{18} - 10^{19}	cm^{-3}
	Length	1-10	mm
	Repetition Rate	10-100	Hz
Active Plasma Lens	Strength	1-5	kT
	Density	$1 - 10 \times 10^{17}$	cm^{-3}
	Length	2-4	cm
	Repetition Rate	10-20	Hz
LPI-HE / LPAS	Energy Gain	1-5	GeV
	Density	10^{17} - 10^{18}	cm^{-3}
	Length	10-20	cm
	Repetition Rate	10-100	Hz

Neutral Gas Targets

Gas density distribution determines electron density distribution through optical field ionisation and needs to be carefully designed and controlled

target type	jet	cell	unit
gas flow	supersonic	transonic	-
access	open	limited	
length	0.100 – 100	2 – 100	mm
density	$10^{18} - 10^{20}$	$10^{17} - 10^{19}$	cm^{-3}
density control	1	0.3	%
repetition rate(*)	1 – 1000	1 – 10	Hz
driver average power	∼ 2	∼ 2	W
density tailoring	yes, sharp	yes, smooth	-
species distribution	yes	yes	-
multi- driver beam	yes, any angle	yes, co-linear	-
gas load	high	moderate	
wear part	nozzle	aperture / channel	



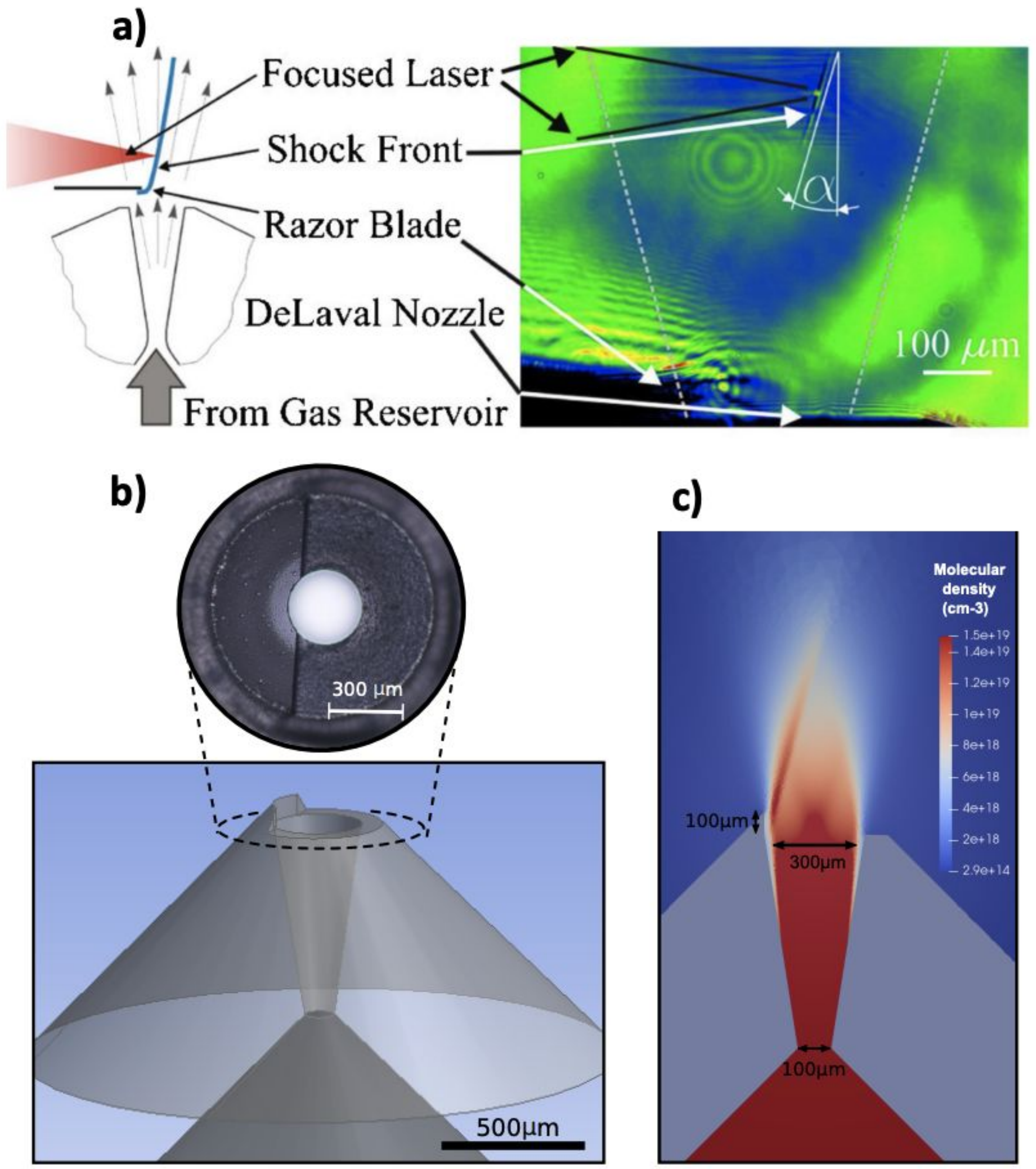


EuPRAXIA repetition rate 20-100 Hz but average power 40-200 W

Tailored Neutral Gas Profiles - Gas Jets

[1]

[2]



Obstructions to the supersonic flow can be used to structure the gas density profile. There are several flavours:

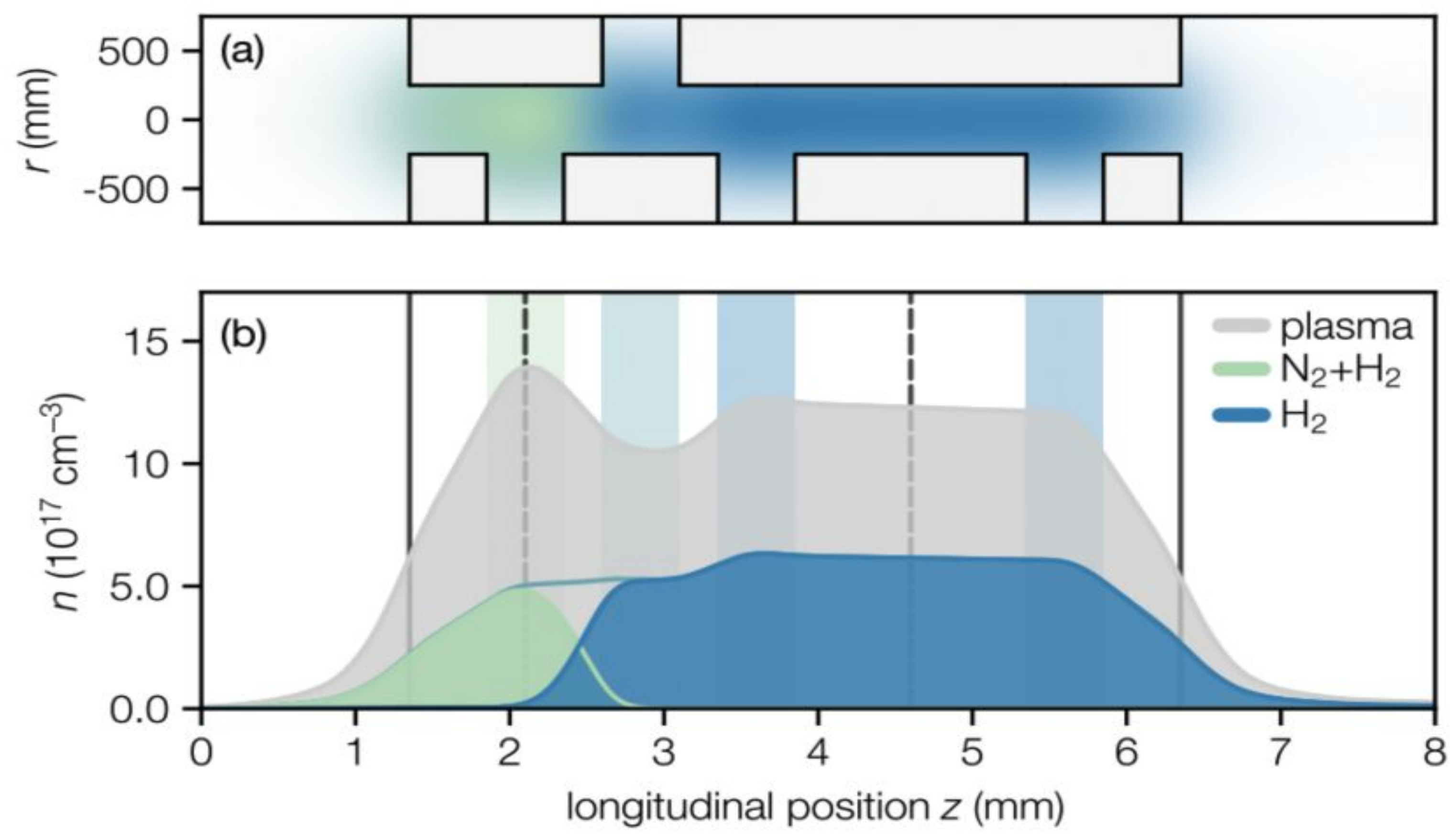
- Blade / Wire placed in flow of gas Jet
- Modified nozzle shapes (see figure left)
- Laser generate shocks expanding transversely to the accelerator axis

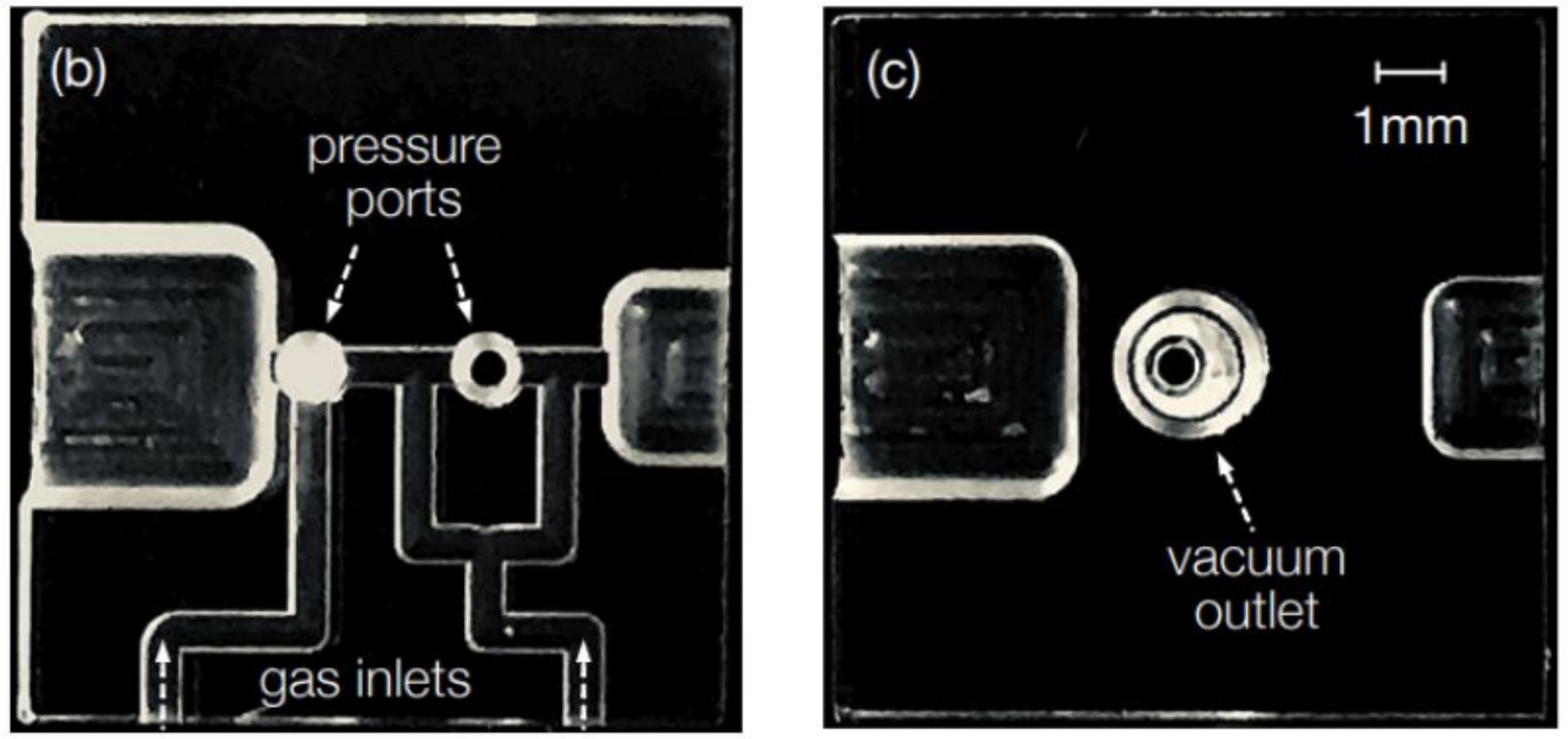
Can generate structures suitable for controlled injection and generation of FEL quality beams!

[1] K. Schmid et al., PRSTAB **13**, 091301 (2010)
[2] L. Rovige et al., Rev. Sci. Instrum. **92**, 083302 (2021)

Tailored Neutral Gas Profiles - Gas Cells

[1]





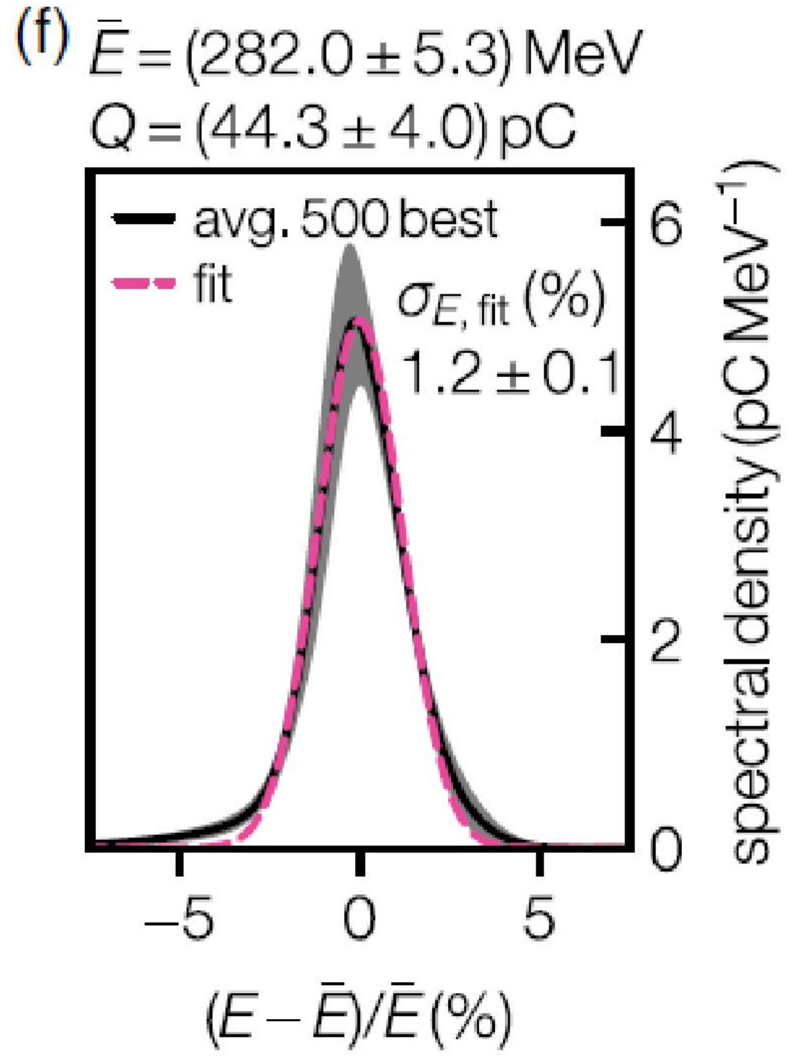
Tailoring the density profile in a gas cell can be achieved through a variety of methods

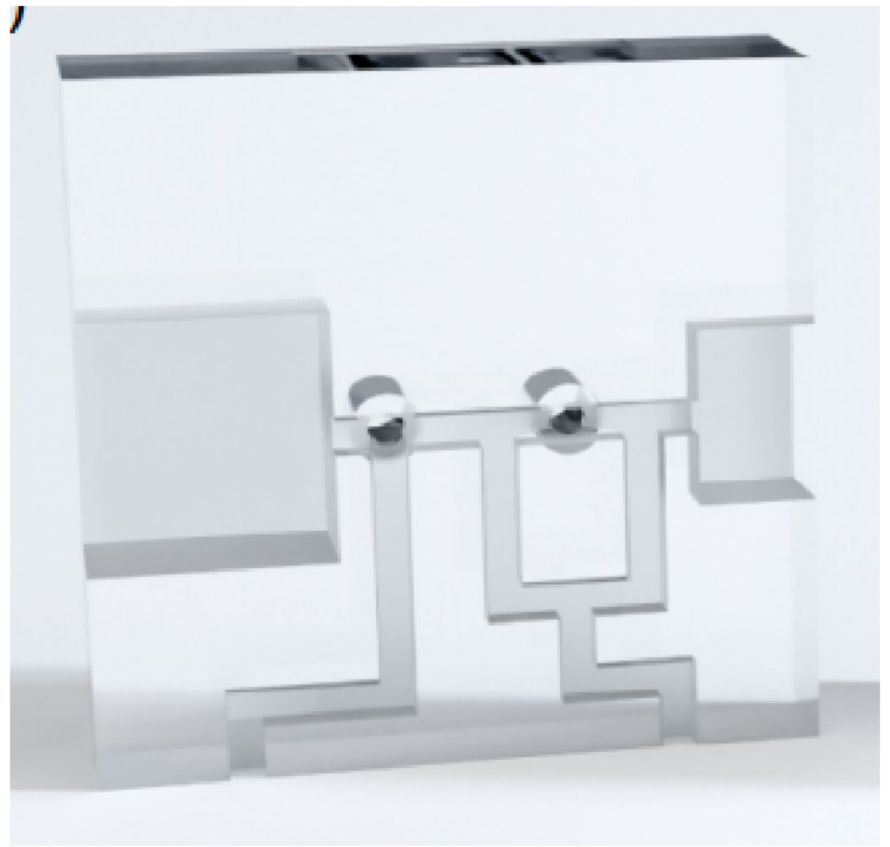
- Geometric design of the cell
- Manipulating flow rates / gas mixing
- Use of several sub-compartements

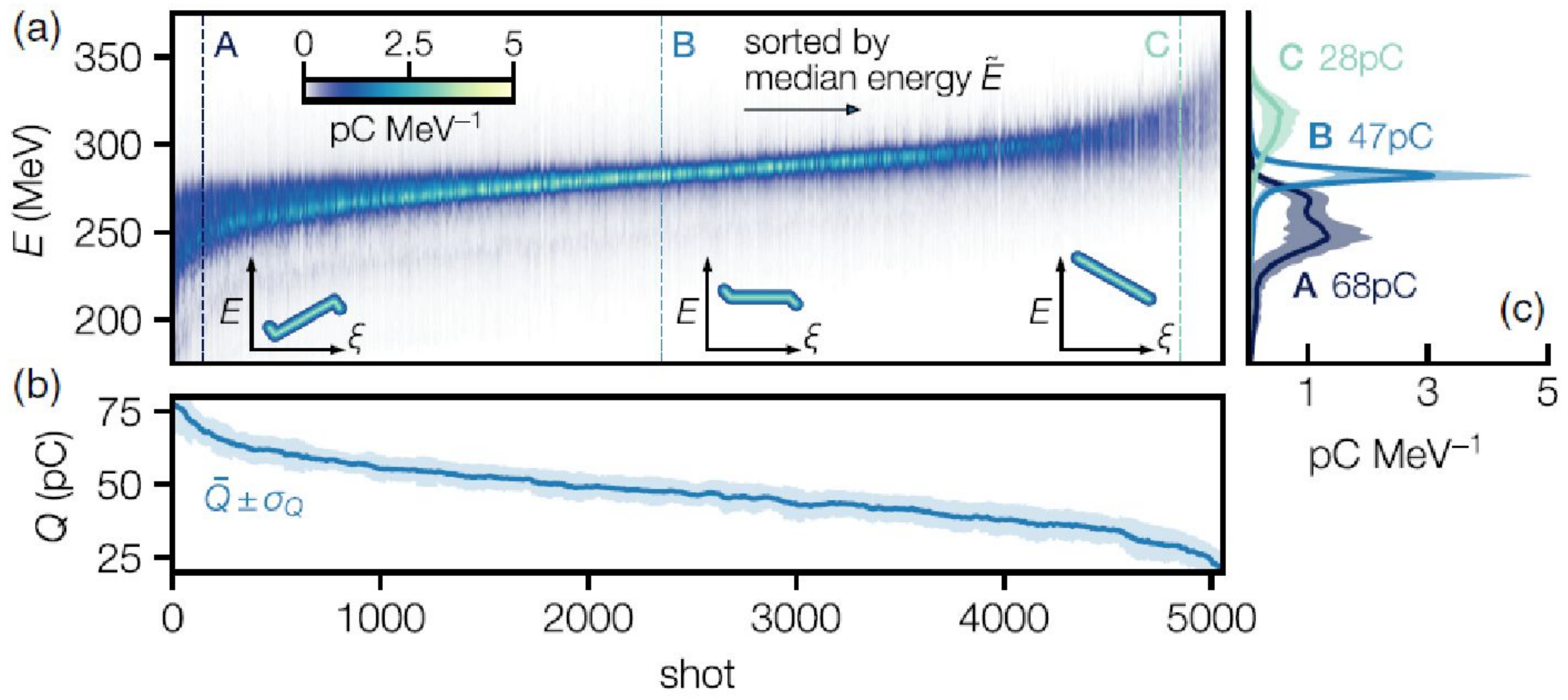
Can generate stable high-quality electron beams.

[1] M. Kirchen, PhD Thesis University of Hamburg (2021)

State-of-the-art: beam parameters







Two-region gas cells in “channel “geometry

- **1st compartment of 0.5mm length with 10% nitrogen doping**
- **2nd compartment of 4mm of pure hydrogen**

Generation of beams over **5,000 shots, at 1 Hz [1]**

Charges between **28 and 60 pC**

Average energies between **250 and 300 MeV**

Energy spreads of **7 MeV** FWHM

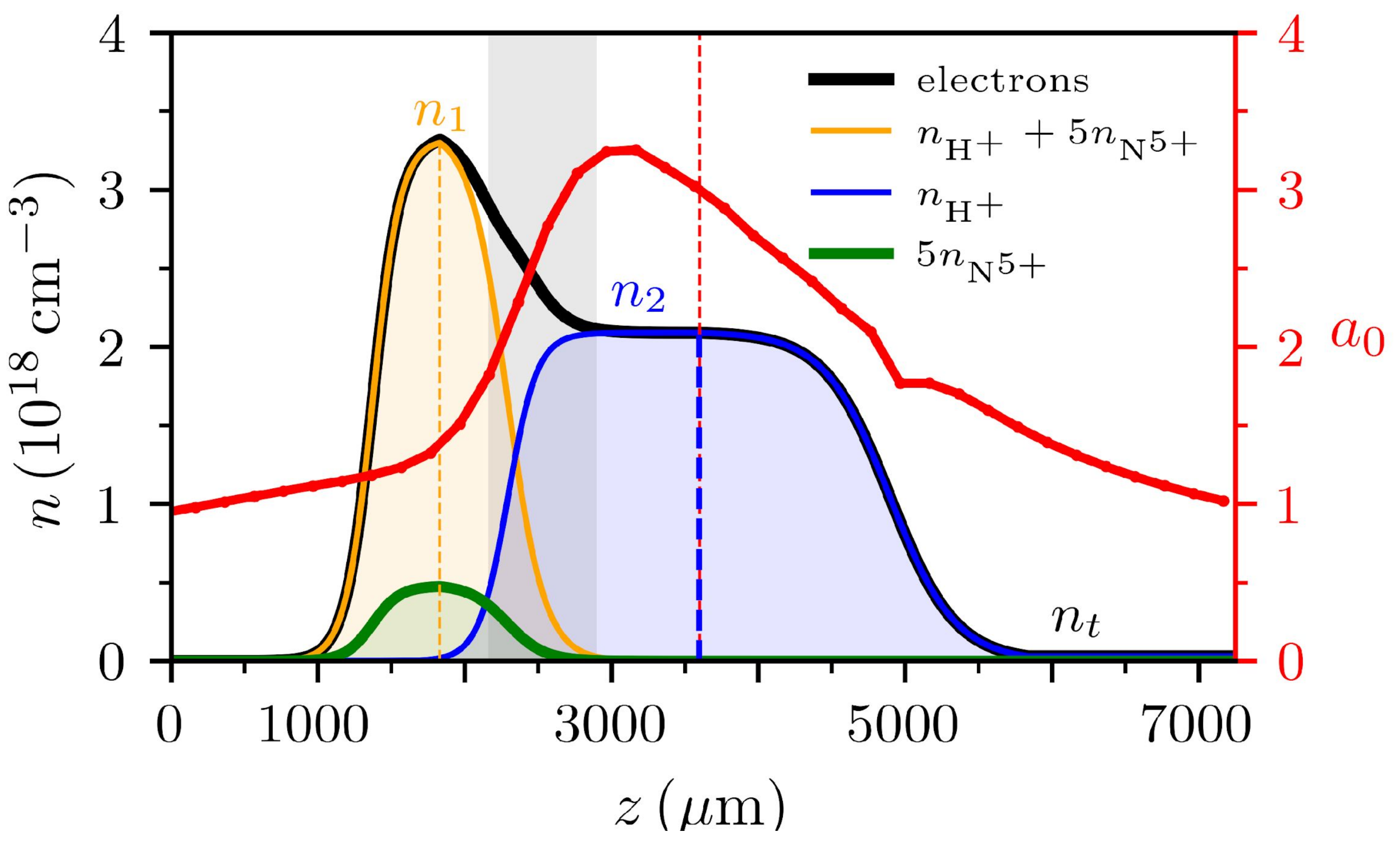
80% of variability claimed to be derived from the laser.

Operation at 150 MeV, 100pC, 3% energy spread [2]

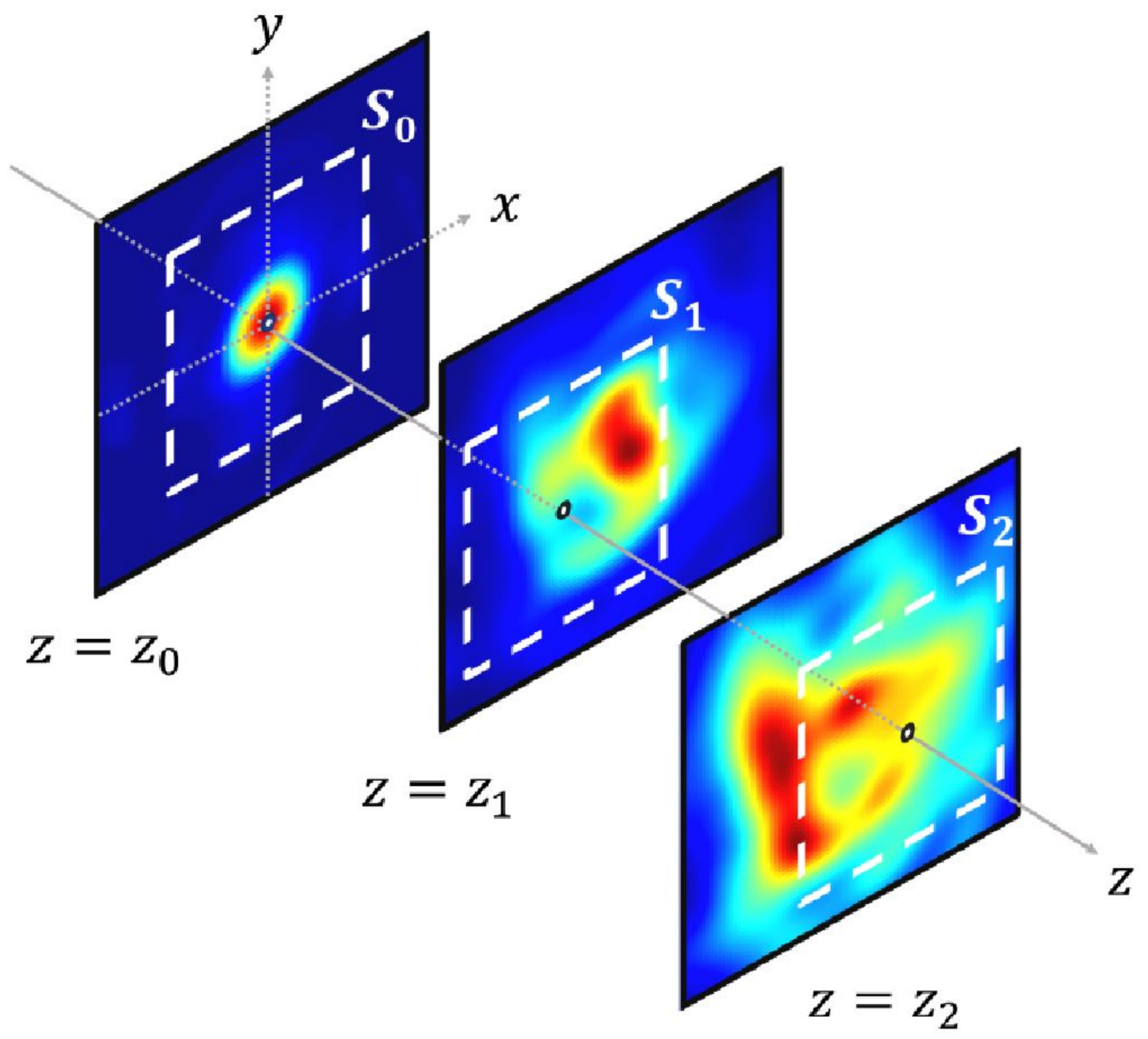
[1] M. Kirchen et al PRL 126, 174801 (2021)

[2] S. Jalas et al PRAB 26, 7, 071302 (2023)

Challenges and future developments



[1] S. Marini, et al. PRAB 27, 063401



[2] Moulanier et al, JOSAB, 40,9 2450(2023).

- **Promising schemes** have already been identified for electron sources in gas cells
- Need to explore further mechanisms leading to high charge (100 pc) while maintaining beam quality [1,5]:

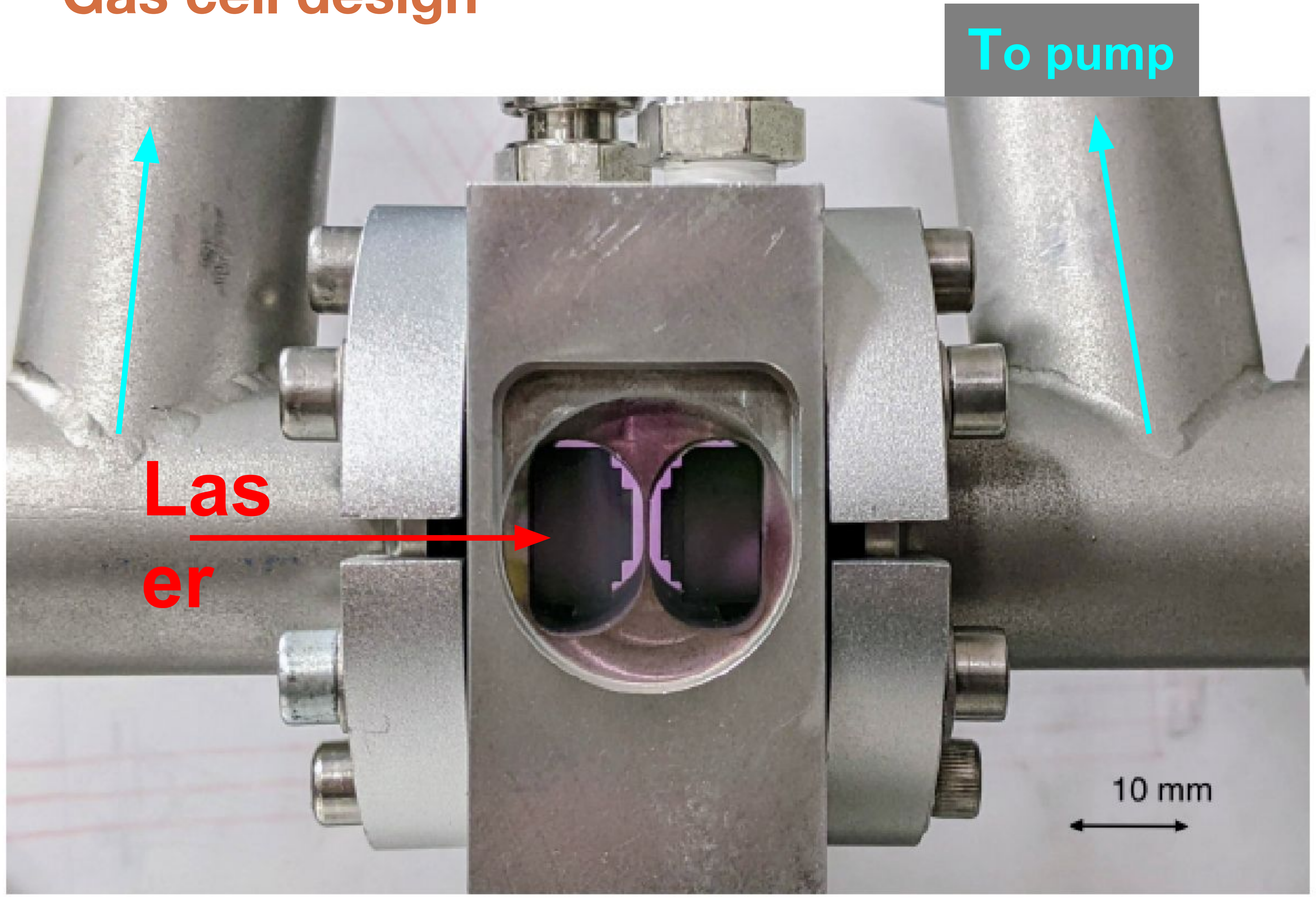
  >> Achieved numerically, need to be extensively tested in experiments

- Understand in detail the **cause of instabilities** and develop solutions:
  - **Laser quality and stability**, modeling for data analysis and diagnostics coupled to AI [3,4]
  - **Gas profile fine control reproducibility**

[3] Dickson thesis 2023, https://theses.hal.science/tel-04606600U .
[4] Shalloo et al, NatComm (2020) 11:6355
[5] P.Drobniak et a. PRAB 26, 9, 091302 (2023)

High-Repetition Rate Operation: Differential Pumping

Gas cell design

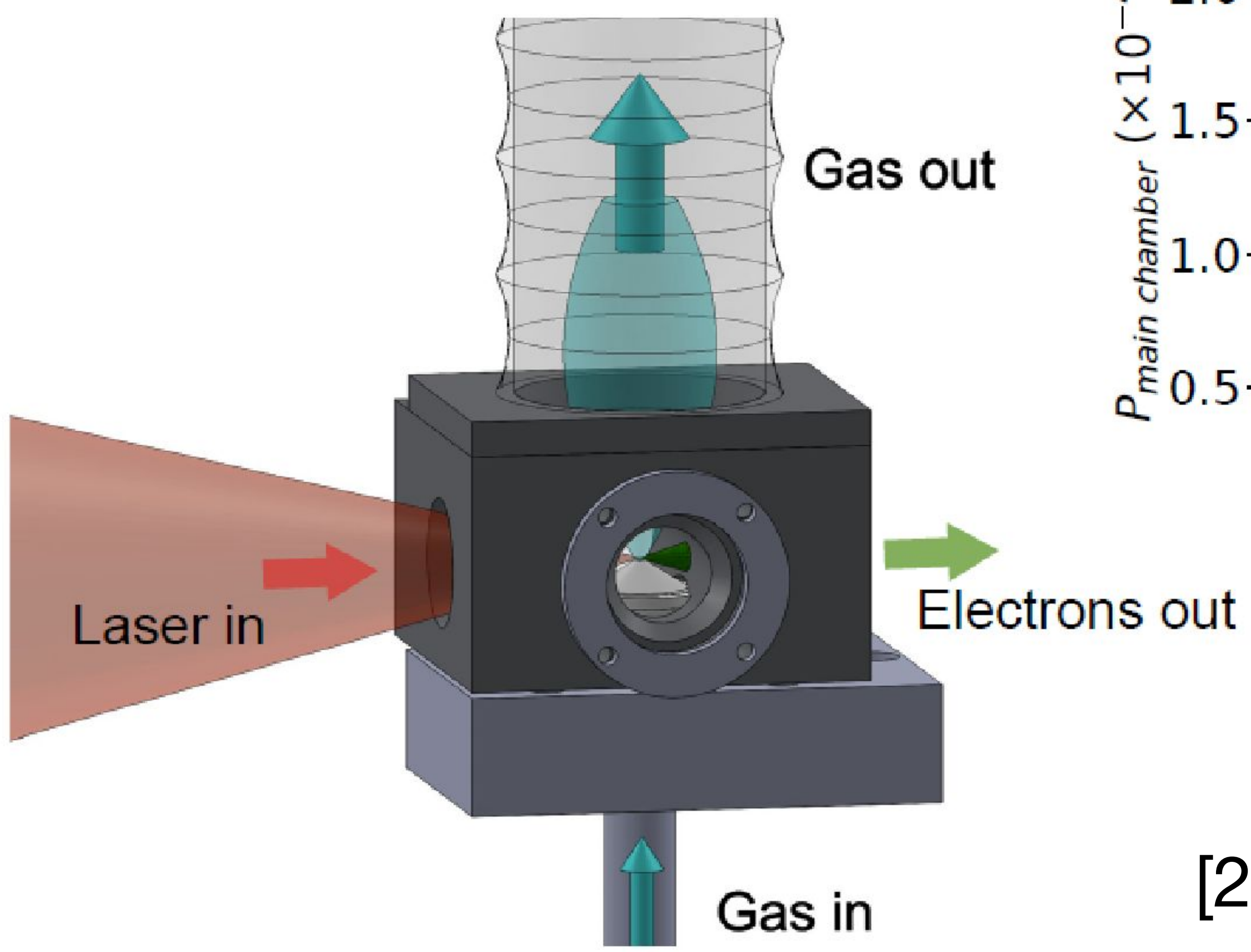


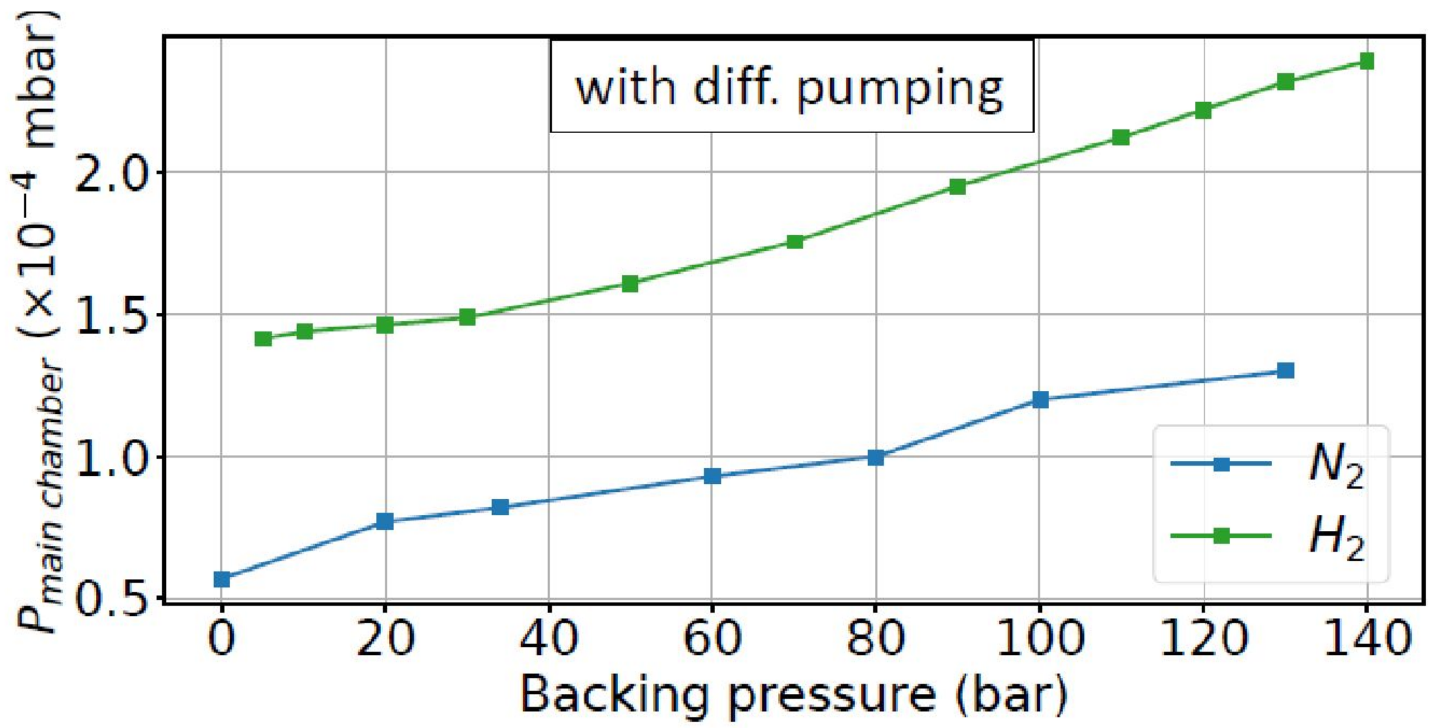
Continuous flow beamline-integrated multicell target

- Two-region gas cell prototype [1]
- Ceramic input and output nozzles
- Left region length is 0.7mm
- Continuous gas flow

[1] P. Drobniak et al. arXiv:2309.11921 (2023)

Gas jet design





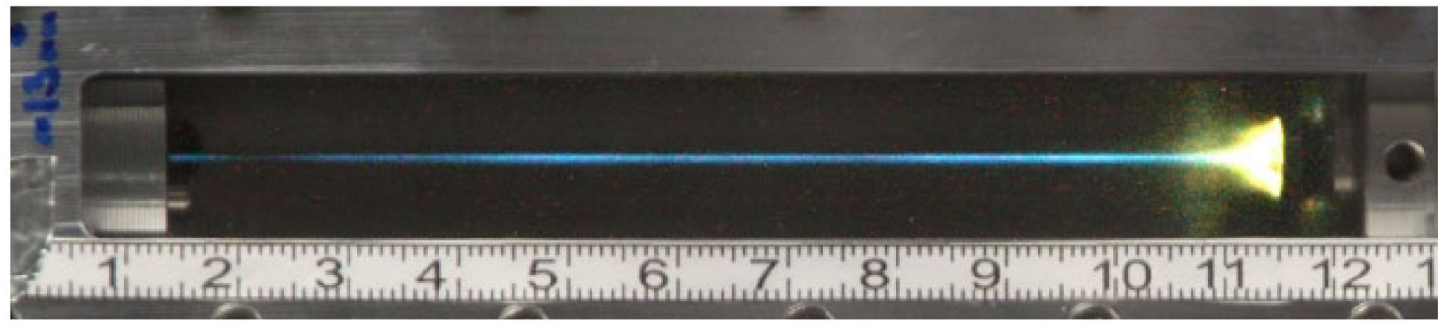
[2] J. Monzac et al, in preparation, LOA

Continuous flow operation kHz H2

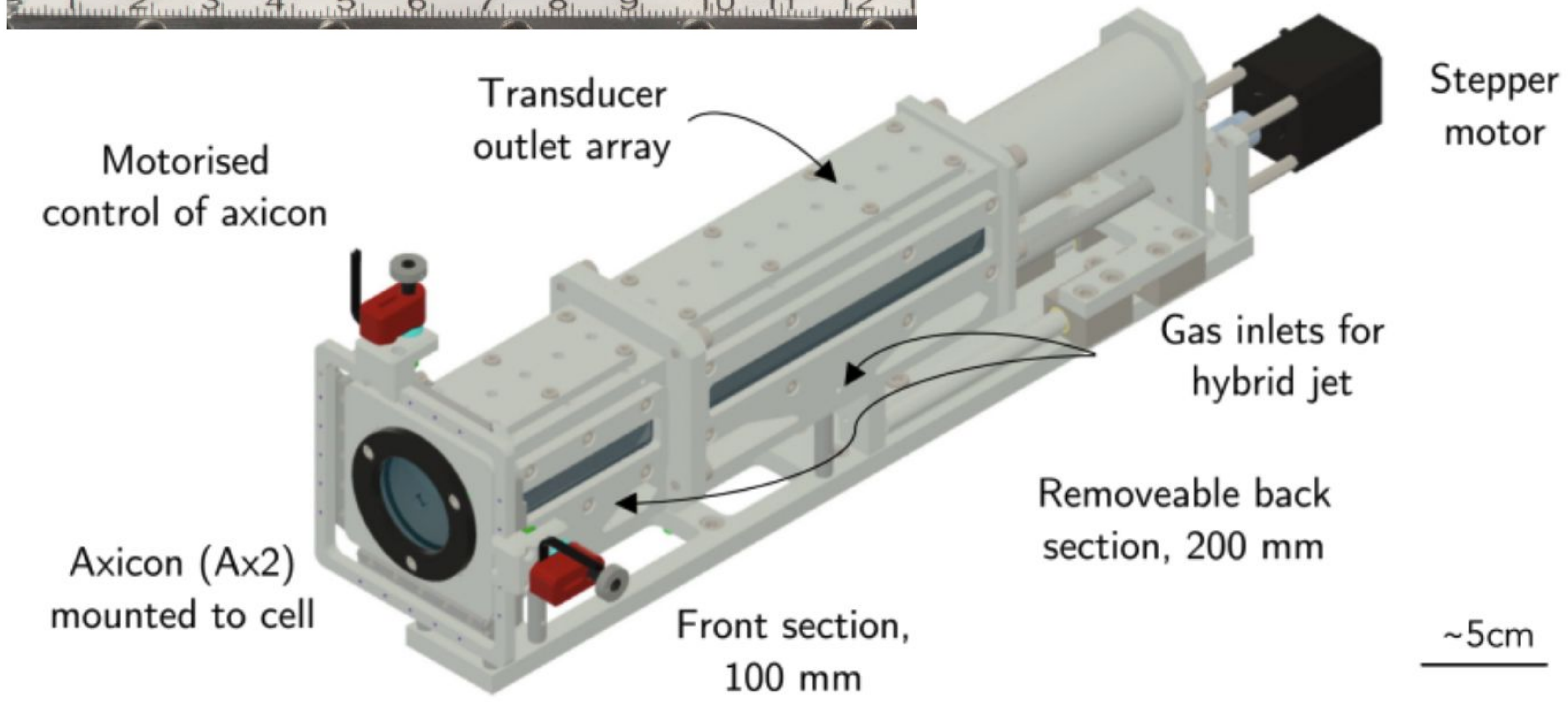
- Continuous gas flow for kHz laser operation [2,3]
- Gas jet in a small chamber inside main chamber
- Maintains pressure in the main chamber around 10^{-4}mbar

[3] J. Monzac et al. arXiv:2406.17426(2024)

Long Neutral Gas Profiles

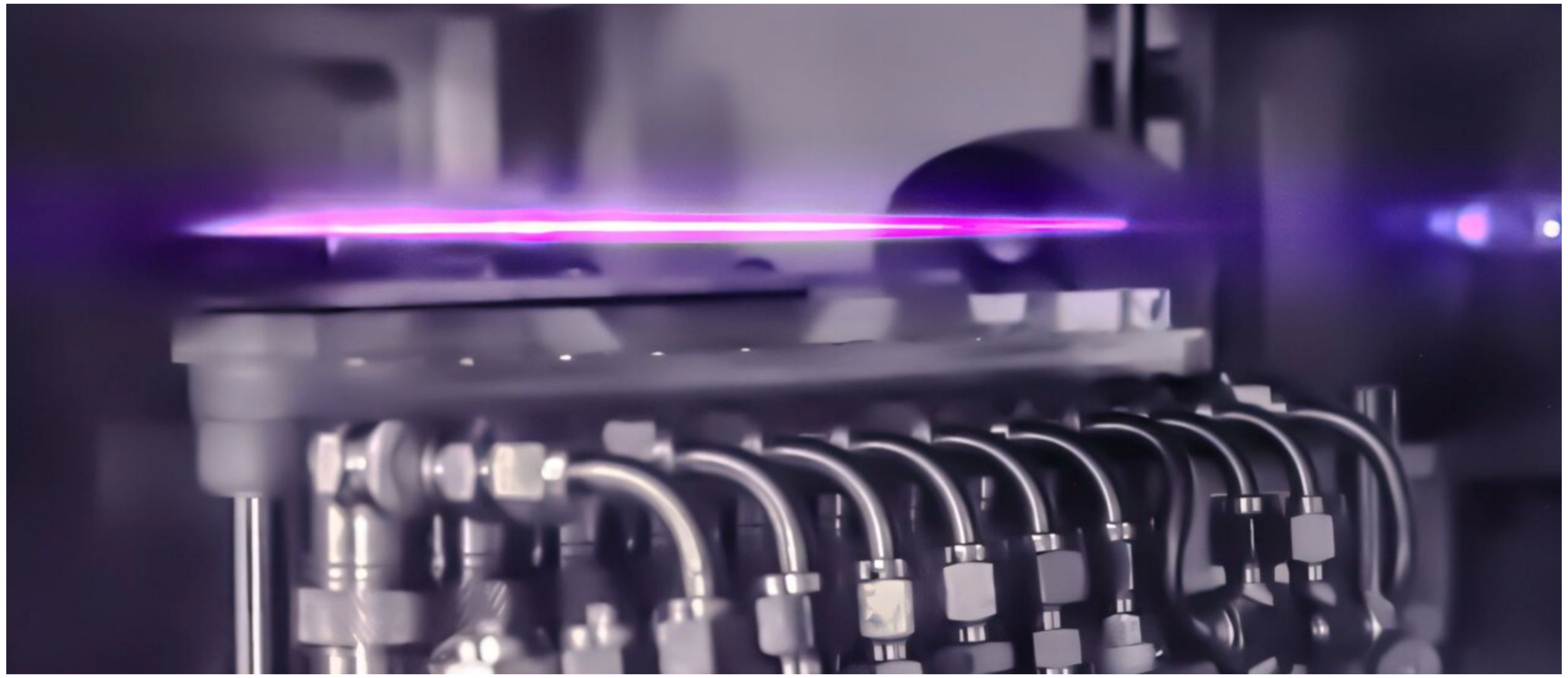


[1]



Both gas jets and gas cells at the 100 mm scale and beyond have been developed.

[2]



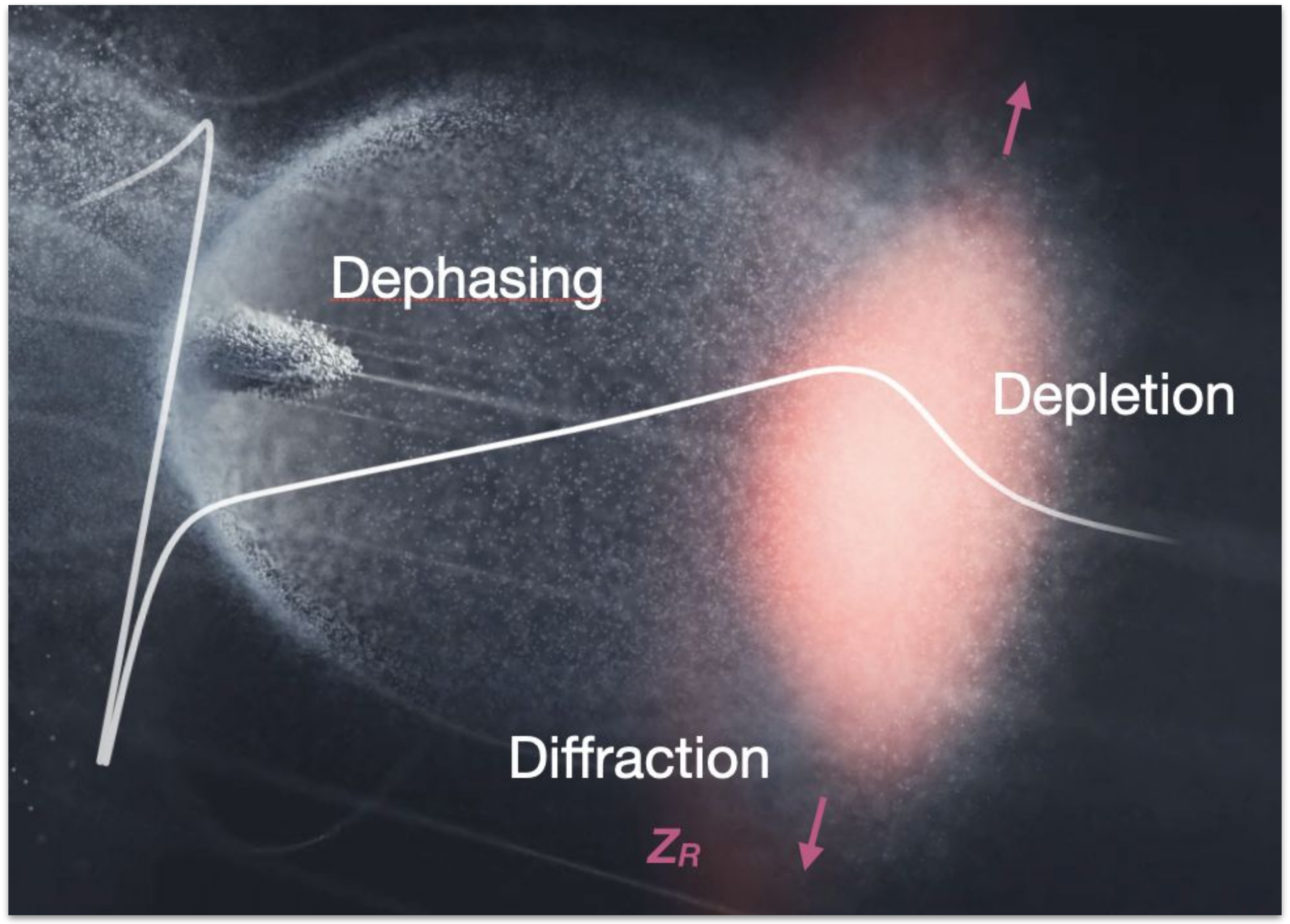
[1] A. Picksley, PhD Thesis University of Oxford (2021)
[2] BELLA Center, Lawrence Berkeley National Laboratory

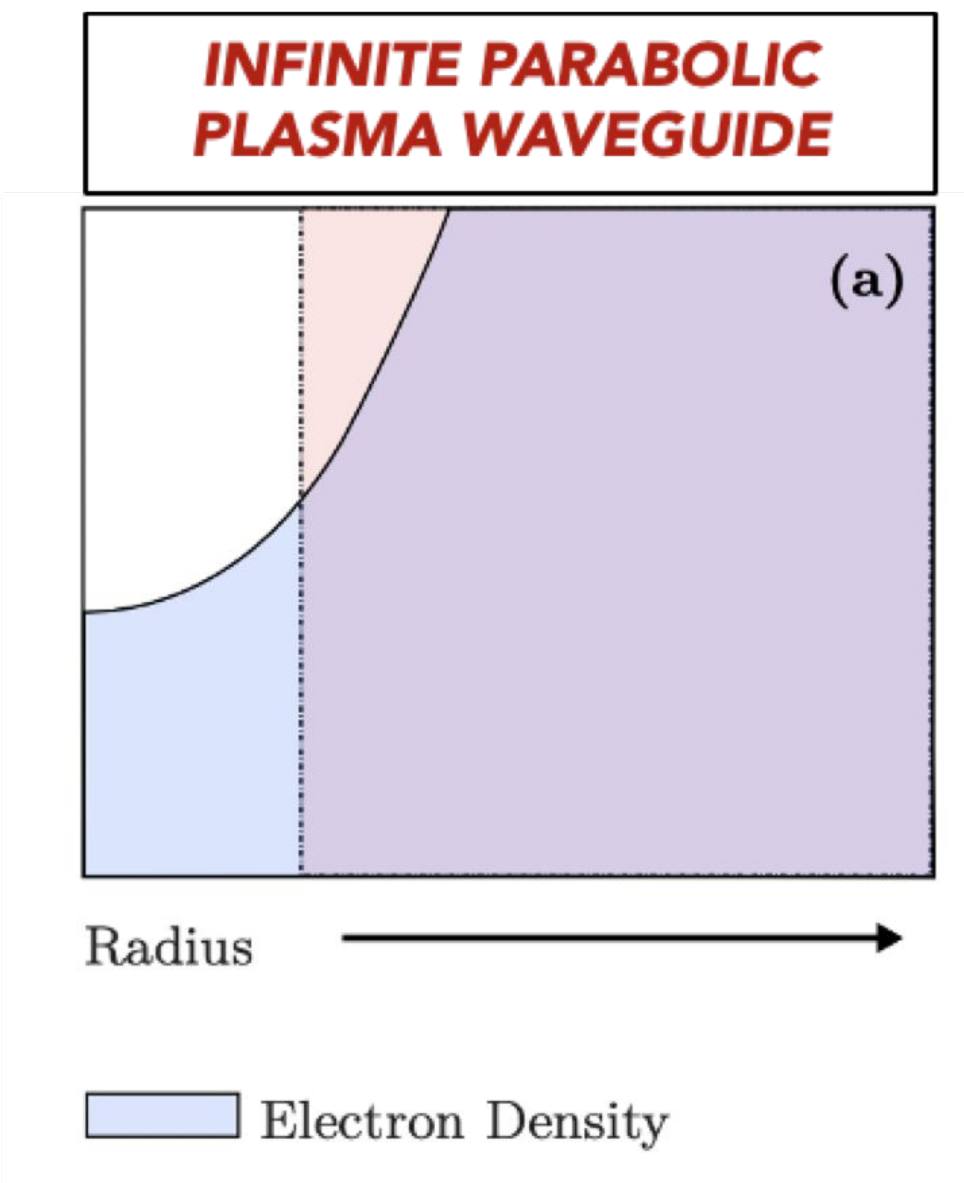
Plasma Waveguides for Multi-GeV Energy Gain

Achieving high energy gain and efficiency requires guiding of the laser pulse

- **Self-focusing through relativistic & wakefield effects**
- **Guiding in pre-formed plasma waveguide**
  - Capillary discharge & cooling at the walls
  - Hydrodynamic radial shocks

Laser diffraction is the main acceleration limit





Plasma refractive index

$$\eta \approx 1 - \frac{1}{2}\frac{\omega_p^2}{\omega_0^2}\left(1 + \frac{\delta n}{n} - \frac{\langle a^2 \rangle}{2} - 2\frac{\delta\omega_0}{\omega_0}\right)$$

Guiding via external density variation

Self-guiding due to transverse wakefield

Self-focusing due to relativistic mass increase

Change in carrier frequency

HOFI Plasma Waveguides

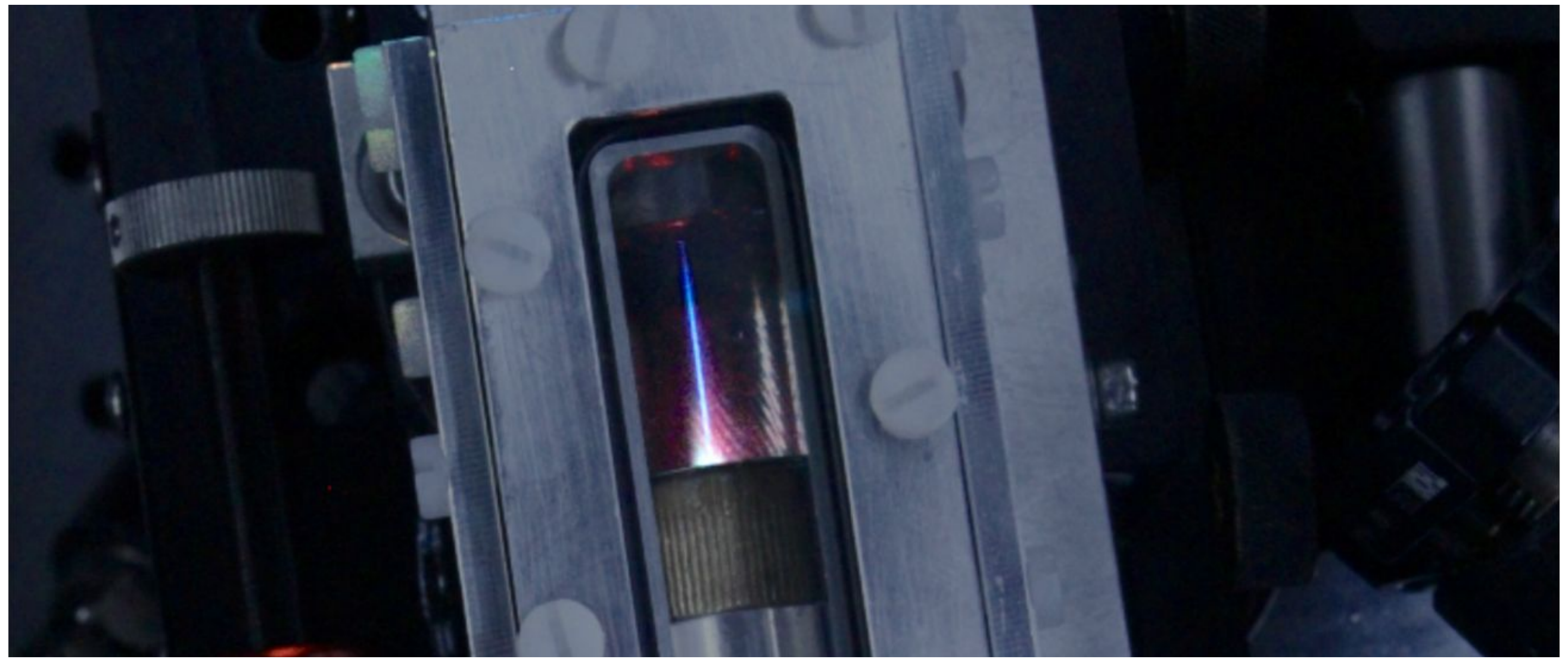
A Plasma Source for High-Repetition-Rate Multi-GeV Laser Plasma Accelerators

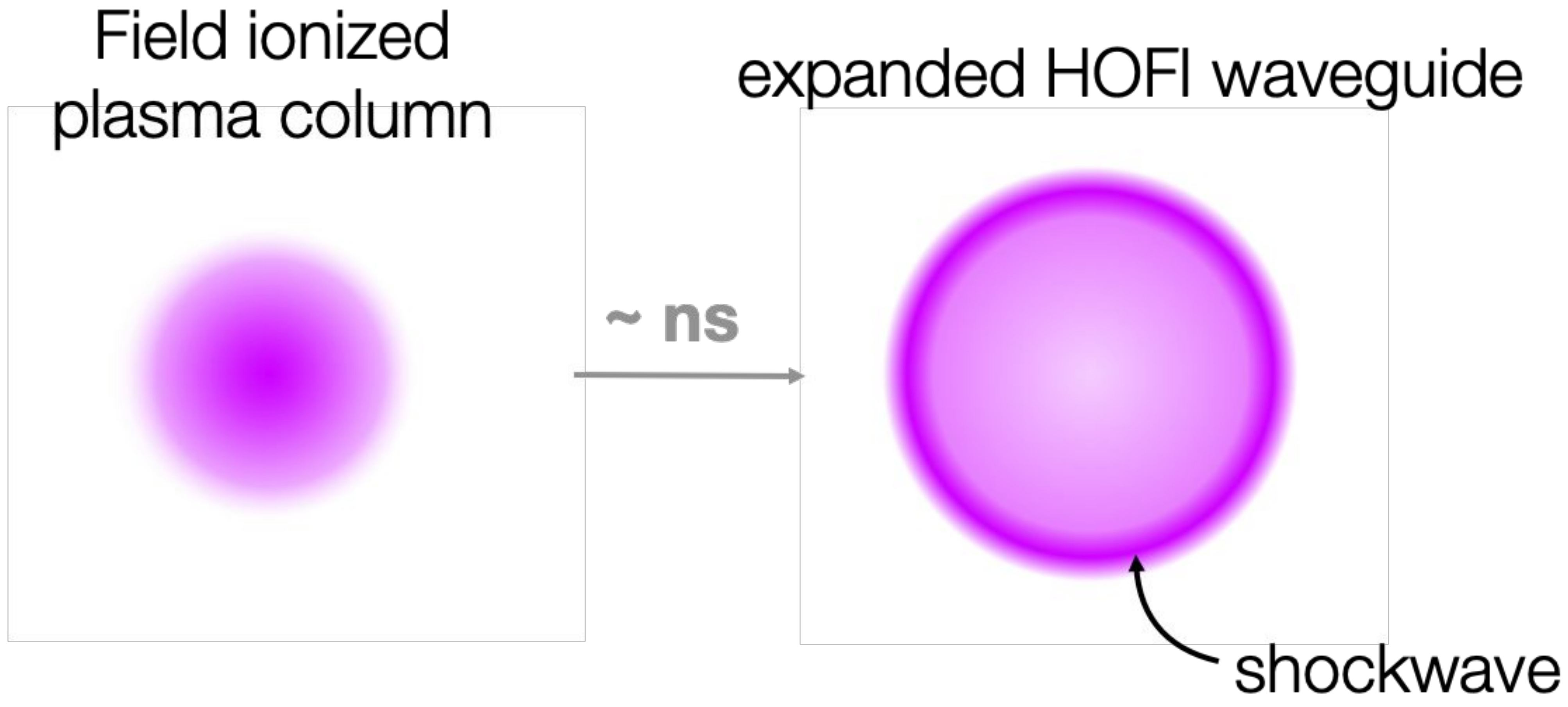
Plasma waveguides based on hydrodynamic shocks were pioneered by the Milchberg Group and have been in use since the 1990s [1,2]

- Plasma column created via **collisional ionisation / heating**
- Expanding plasma drives shock into surrounding gas
- Generates radial density profile suitable for guiding
    - **Limited to on-axis densities > 10^{18} cm^{-3}**

Low-Density Hydrodynamic Optical-Field-Ionized (HOFI) Plasma Waveguides [3,4]

- Plasma column created and heated via **field ionisation**
- Ionization / heating is independent of density
- Generates radial density profile suitable for guiding
    - **Can achieve to on-axis densities ~ 10^{17} cm^{-3}**





[1] C. G. Durfee & H. M. Milchberg, PRL **71**, 2409 (1993)
[2] T. R. Clark & H. M. Milchberg, PRL **78**, 2373 (1997)
[3] R. J. Shalloo et al., PRE **97**, 053203 (2018)
[4] R. J. Shalloo et al., PRAB **22**, 041302 (2019)

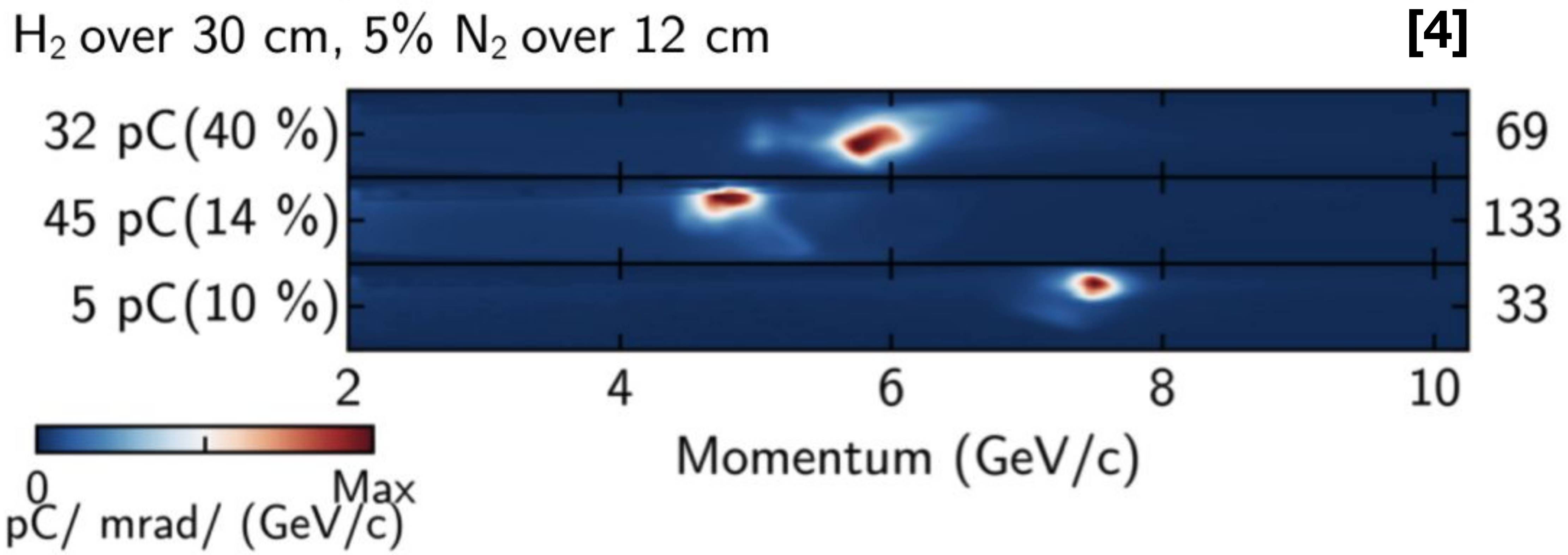
Funded by the European Union

HOFI Plasma Waveguides

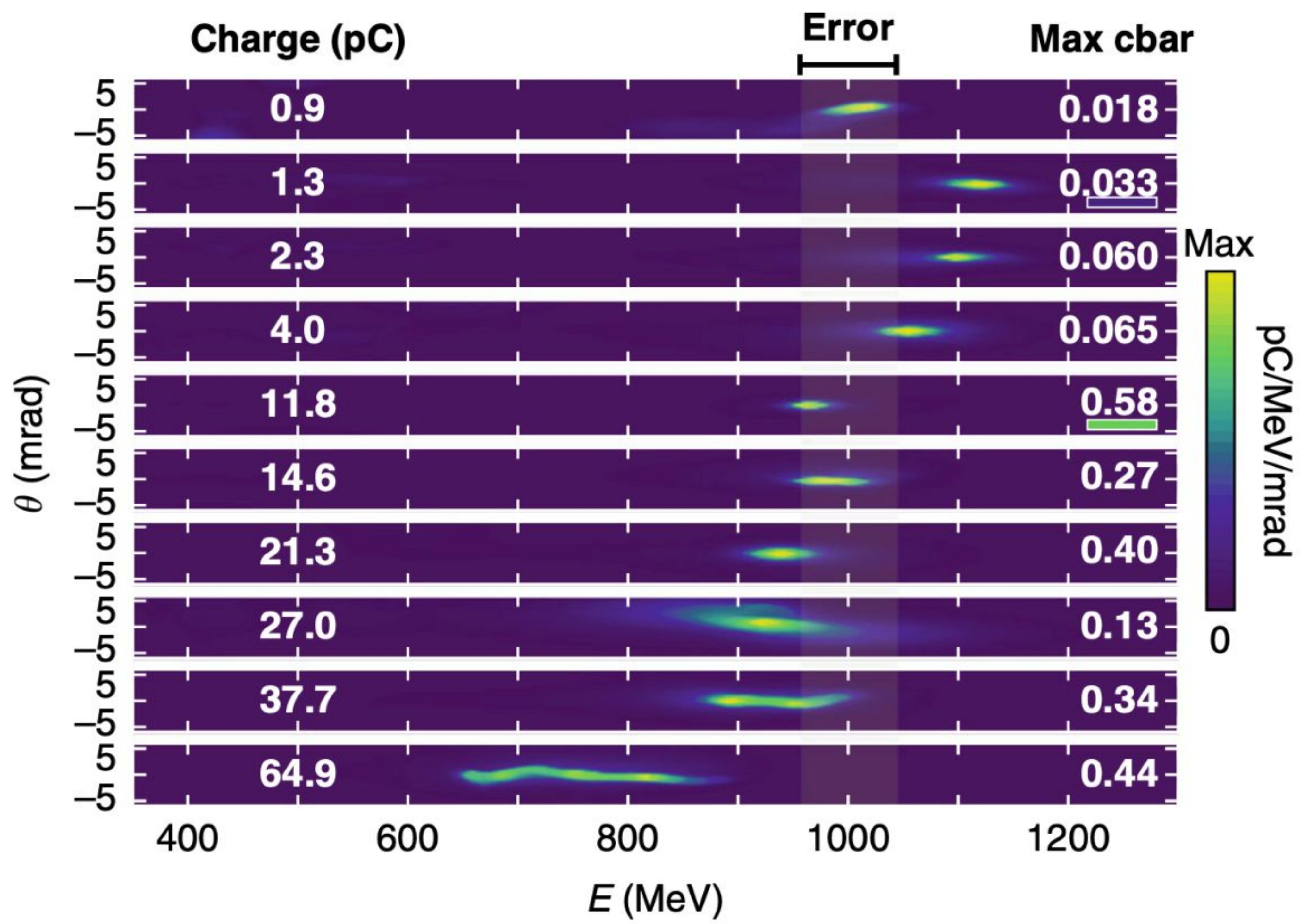
Multi-GeV Electron Acceleration

- **Multi-GeV electron beams demonstrated [1]**
- **Several mechanisms for controlling injection demonstrated experimentally with few percent energy spreads [2,3,4]**
- **Energies up to ~10 GeV Demonstrated [4]**

[4]



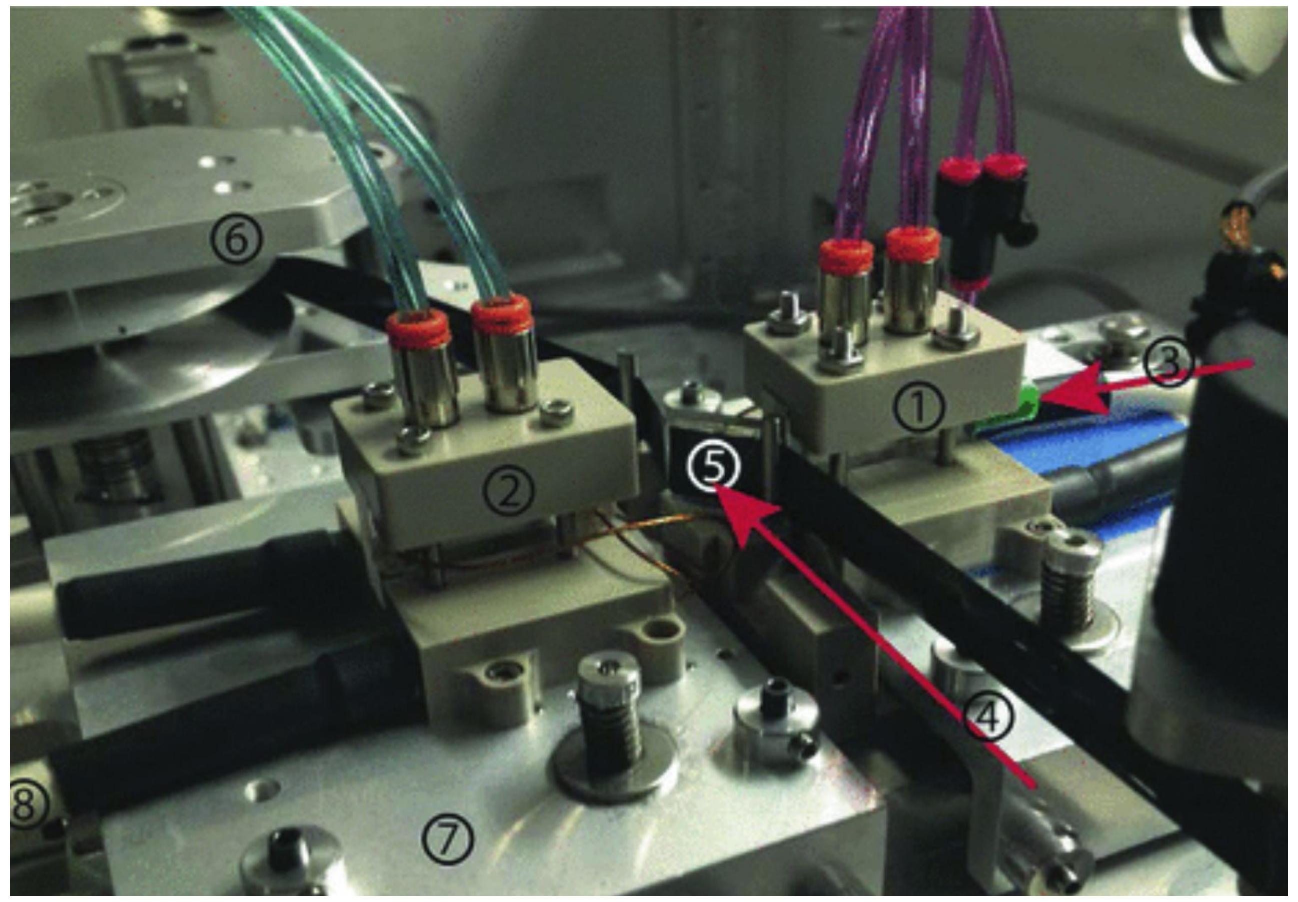
[2]



[1] B. Miao et al., PRX **12**, 031038 (2022)
[2] K Oubrerie et al., Light Sci. Appl. **11**, 180 (2022)
[3] A. Picksley et al., PRL **131**, 245001 (2023)
[4] A. Picksley et al., arXiv:2408.00740 (2024)

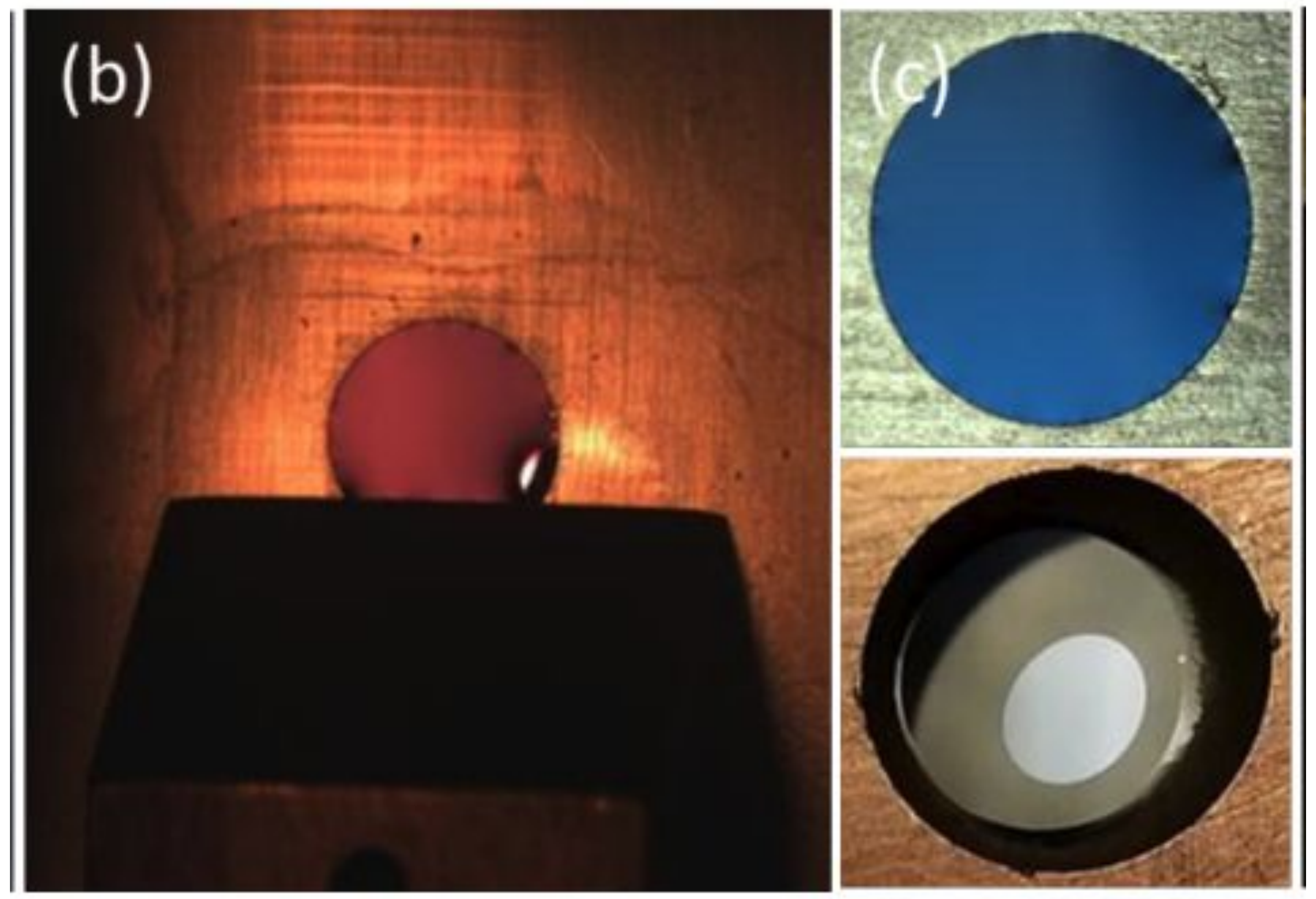
Plasma Mirrors

Tape Drives



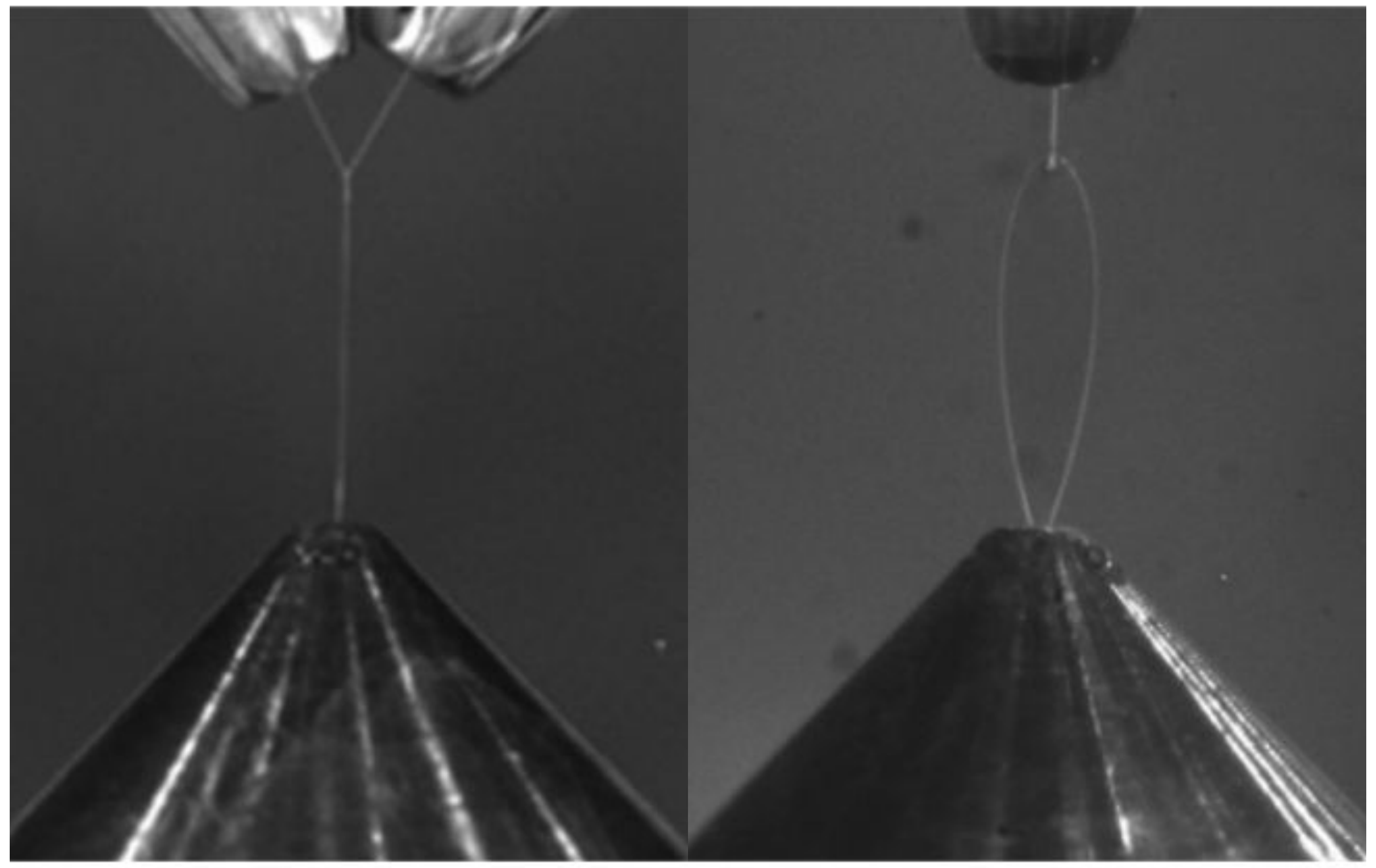
[1]

Liquid Crystal Mirrors



[2]

Liquid Sheets



[3]

[1] Satomi Shiraishi, PhD Thesis (2013)
[2] D. W. Schumacher et al., JINSTR. **12** C04023 (2017)
[3] M. Füle et al., HPLSE **12** (2024)

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A Sample of the Challenges

Neutral Gas Targets

Improved neutral gas tailoring

Improved stability / quality of neutral gas density profiles

Gas recirculation

Plasma Waveguides

Capillary waveguides: laser damage / achieving small matched spot sizes

HOFI waveguides: neutral gas delivery for high-repetition rates / stabilisation of laser / improved density tailoring

Active Plasma Lenses

Emittance preservation for high-current beams

Material Robustness / Longevity

Extending high-repetition-rate targets to J-class lasers

Laser and plasma damage

Heat management

Plasma Mirrors

Scalability to high-repetition rates

Vacuum integration / contaminants

Optimising positioning within a setup

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