EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA
Preparatory Phase

WP10 Plasma components and systems

K. Cassou, B. Cros, R. Demitra and M. Kirchen on behalf of WP10

This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773

WP10 - Plasma Components & Systems

Objectives

The goal of this WP is to assess the current design of plasma components and related systems and provide a sustainable roadmap to fulfil the EuPRAXIA scientific goals. In particular, this WP should explore:

1. Plasma source geometries and vacuum technologies.
2. Methodologies for plasma parameter control and diagnostics.
3. Steering of the technical and scientific design.
4. Proposing an integrated strategy for the development of plasma components and related systems.

kevin.cassou@ijclab.in2p3.fr; rob.shalloo@desy.de

This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. **101079773**

WP10 - Organisations

Participants:

CEA: Sandrine Dobosz Drufrénoy

CLF : Rajeev Pattathil, Dan Symes

CLPU: Giancarlo Gatti

CNRS (IJClab, LOA, LPGP) : Kevin Cassou, Brigitte Cros, Jérome Faure, Bruno Lucas, Cédric Thaury

CNR-INO : Fernando Brandi

DESY : Rob Shalloo

ELI-BL: Alexander Molodozhentsev, Gabriele Grittani

INFN-LNF: Angelo Biagioni

QU: Gianluca Sarri, Matthew Streeter

EuPRAXIA_PP WP10 seventh meeting
30 August 2024 11:00
...FN » Laboratori Nazionali di Frascati » Divisione Acceleratori » EUPRAXIA » EUPRAXIA PP

EuPRAXIA_PP WP10 sixth meeting
16 July 2024 10:00
...FN » Laboratori Nazionali di Frascati » Divisione Acceleratori » EUPRAXIA » EUPRAXIA PP

EuPRAXIA_PP WP10 fifth meeting
25 June 2024 10:00
...FN » Laboratori Nazionali di Frascati » Divisione Acceleratori » EUPRAXIA » EUPRAXIA PP

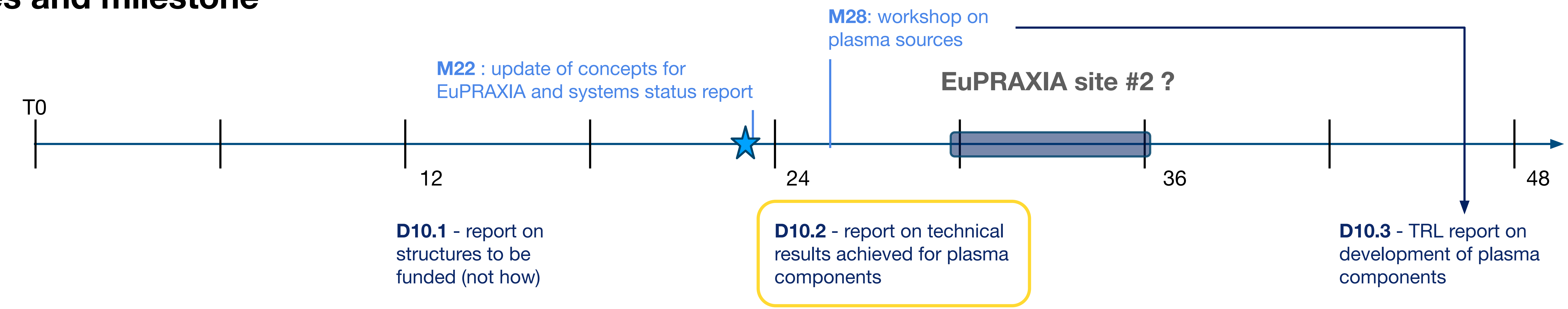
Introductory meeting WP10
Link:https://infn-it.zoom.us/j/98567023672?pwd=Q3hnQ2R6T01ZdG91dnB0QnVyYzlmQT09ID riunione: 985 6702 3672Codice d'accesso: 440133
09 April 2024 09:15
...FN » Laboratori Nazionali di Frascati » Divisione Acceleratori » EUPRAXIA » EUPRAXIA PP

EuPRAXIA_PP WP10 fourth meeting
16 April 2024 09:30
...FN » Laboratori Nazionali di Frascati » Divisione Acceleratori » EUPRAXIA » EUPRAXIA PP

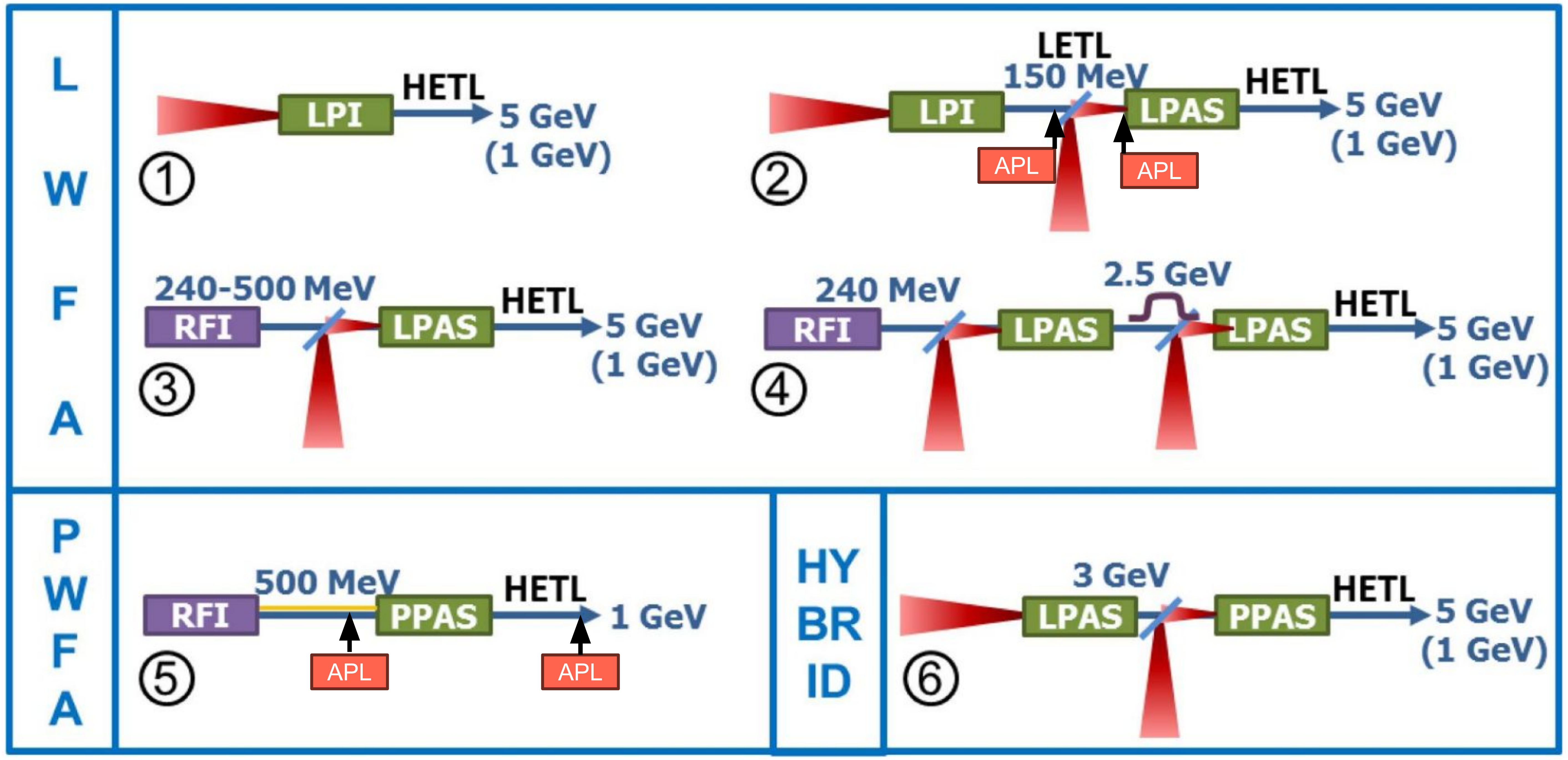
EuPRAXIA_PP WP10 third meeting
Zoom Link to the meetingMeeting ID: 950 4325 7240 - Code : 2024
26 January 2024 10:00
...FN » Laboratori Nazionali di Frascati » Divisione Acceleratori » EUPRAXIA » EUPRAXIA PP

WP10 members meet 6 times over the last 8 months by zoom.

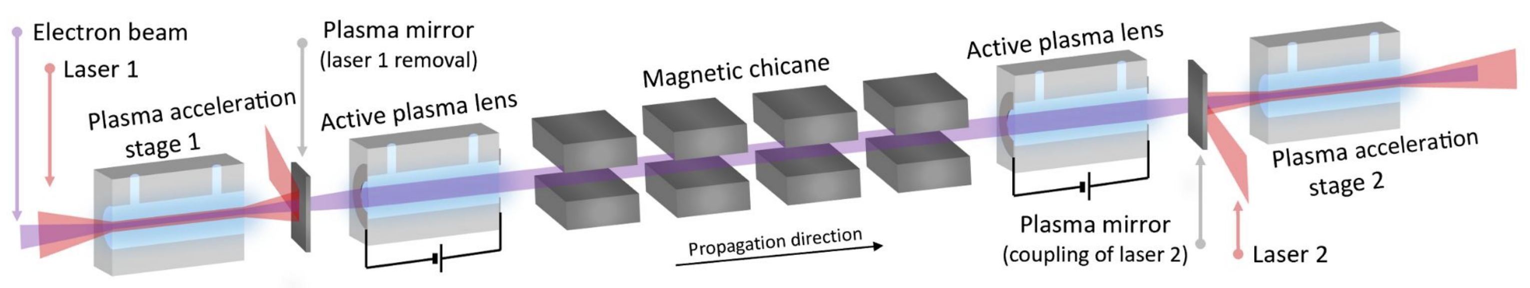
Deliverables and milestone



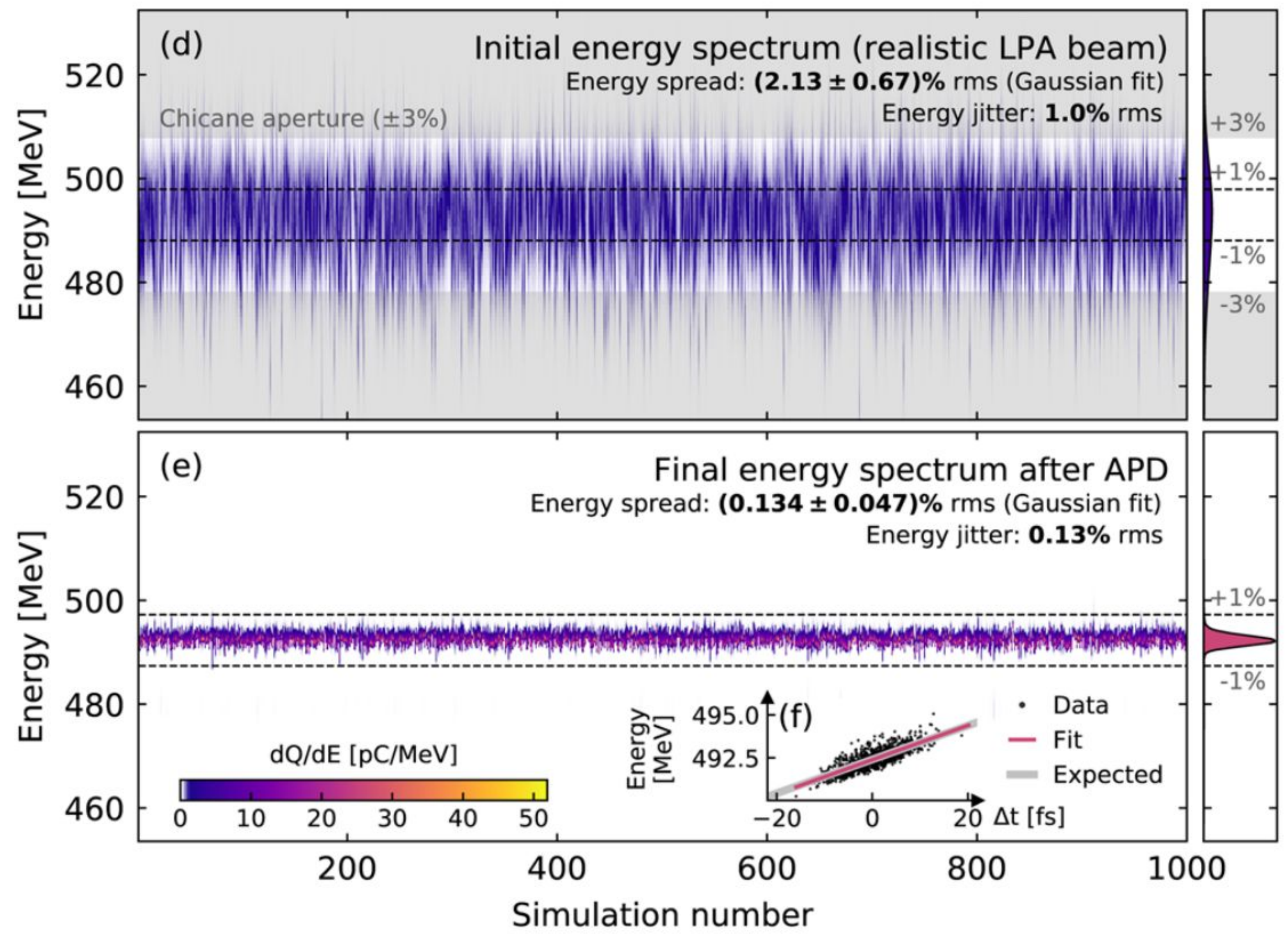
WP10 – Plasma systems in EuPRAXIA



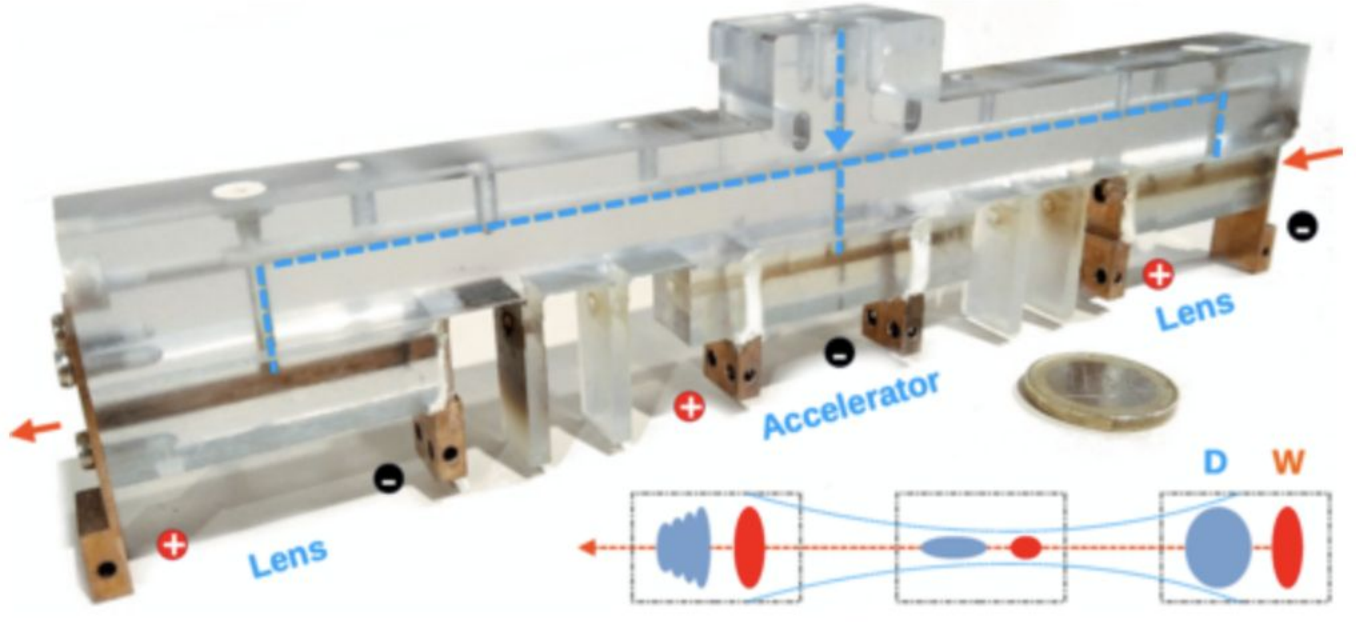
LPI	Laser plasma injector
LPAS	Laser-driven plasma accelerator stage
PPAS	Beam-driven plasma acceleration stage
APL/APD	Active Plasma Lens/ Active Plasma Dechirper



[1] Ferran Pousa *et al. Phys Rev. Lett.* **123**, 054801 (2019).



[2] Ferran Pousa, A. *et al. Phys Rev. Lett.* 129, 094801 (2022)

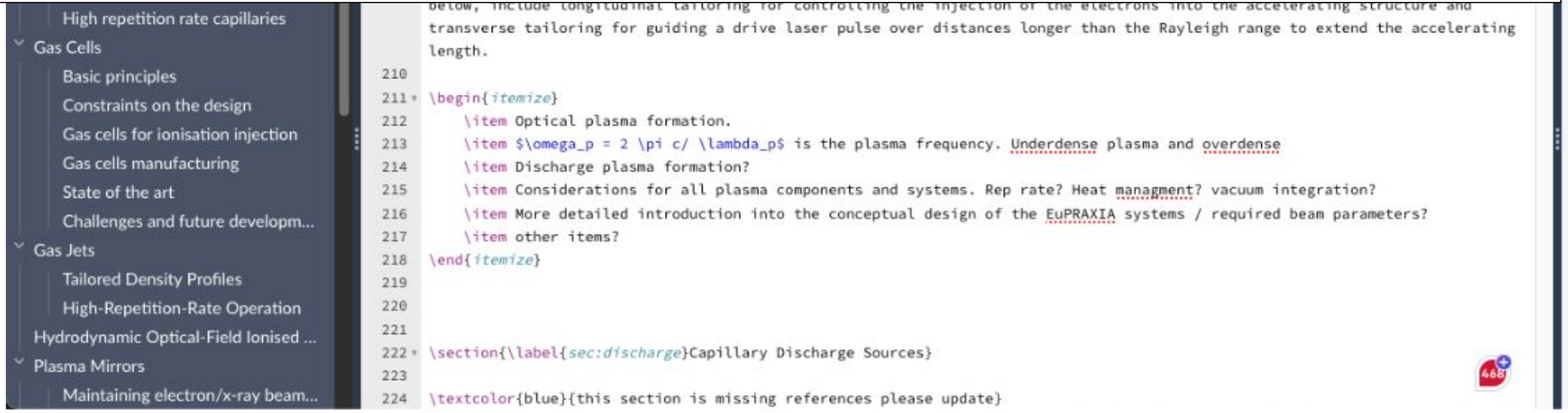


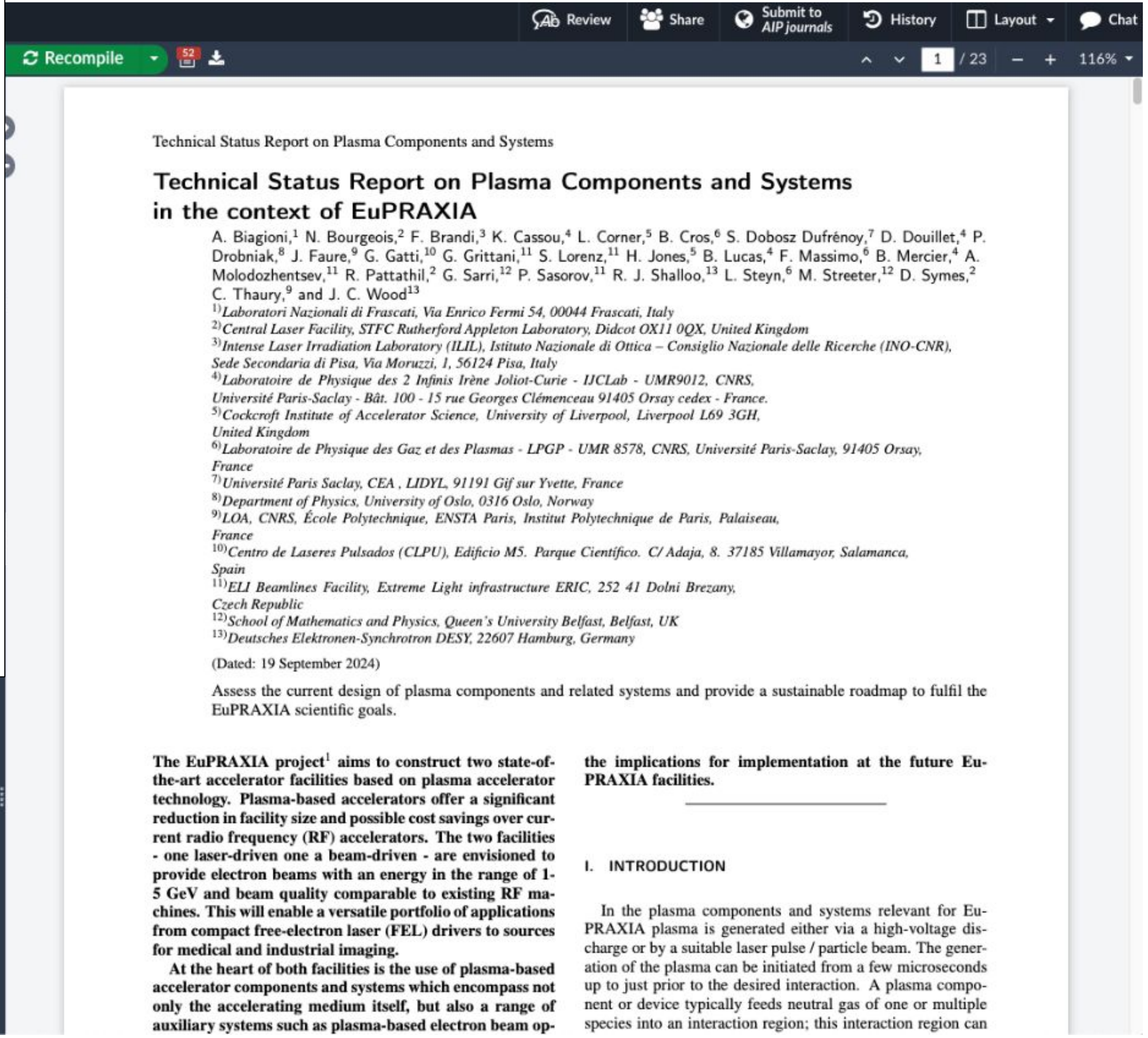
[3] Pompili, R. *et al. Phys. Rev. E* **109**, 055202 (2024).

Deliverable 10.2 report status

Progress but still a significant work to be performed before submission

- Brief report citing a review paper **“Technical Status Report on Plasma Components and Systems in the context of EuPRAXIA.”** **…** 16 authors, 25pp, more 100 references 🚧
- Submission to **AIP - Plasma Physics** (Gold open access for free in 2024) before end of october. Will be available on arxiv for EU.
- Current plan 🔥
  - **Until 27/09:** Review of all contributions
  - **15/10**: Update correction by all authors
  - **25/10**: second review
  - **31/10:** submission (arXiv) ! 🚀





Technical Status Report on Plasma Components and Systems

Technical Status Report on Plasma Components and Systems in the context of EuPRAXIA

A. Biagioni,[1] N. Bourgeois,[2] F. Brandi,[3] K. Cassou,[4] L. Corner,[5] B. Cros,[6] S. Dobosz Dufrénoy,[7] D. Douillet,[4] P. Drobniak,[8] J. Faure,[9] G. Gatti,[10] G. Grittani,[11] S. Lorenz,[11] H. Jones,[5] B. Lucas,[4] F. Massimo,[6] B. Mercier,[4] A. Molodozhentsev,[11] R. Pattathil,[2] G. Sarri,[12] P. Sasorov,[11] R. J. Shalloo,[13] L. Steyn,[6] M. Streeter,[12] D. Symes,[2] C. Thaury,[9] and J. C. Wood[13]

[1] Laboratori Nazionali di Frascati, Via Enrico Fermi 54, 00044 Frascati, Italy
[2] Central Laser Facility, STFC Rutherford Appleton Laboratory, Didcot OX11 0QX, United Kingdom
[3] Intense Laser Irradiation Laboratory (ILIL), Istituto Nazionale di Ottica – Consiglio Nazionale delle Ricerche (INO-CNR), Sede Secondaria di Pisa, Via Moruzzi, 1, 56124 Pisa, Italy
[4] Laboratoire de Physique des 2 Infinis Irène Joliot-Curie - IJCLab - UMR9012, CNRS, Université Paris-Saclay - Bât. 100 - 15 rue Georges Clémenceau 91405 Orsay cedex - France.
[5] Cockcroft Institute of Accelerator Science, University of Liverpool, Liverpool L69 3GH, United Kingdom
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[8] Department of Physics, University of Oslo, 0316 Oslo, Norway
[9] LOA, CNRS, École Polytechnique, ENSTA Paris, Institut Polytechnique de Paris, Palaiseau, France
[10] Centro de Laseres Pulsados (CLPU), Edificio M5. Parque Científico. C/ Adaja, 8. 37185 Villamayor, Salamanca, Spain
[11] ELI Beamlines Facility, Extreme Light infrastructure ERIC, 252 41 Dolni Brezany, Czech Republic
[12] School of Mathematics and Physics, Queen's University Belfast, Belfast, UK
[13] Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Germany

(Dated: 19 September 2024)

Assess the current design of plasma components and related systems and provide a sustainable roadmap to fulfil the EuPRAXIA scientific goals.

The EuPRAXIA project[1] aims to construct two state-of-the-art accelerator facilities based on plasma accelerator technology. Plasma-based accelerators offer a significant reduction in facility size and possible cost savings over current radio frequency (RF) accelerators. The two facilities - one laser-driven one a beam-driven - are envisioned to provide electron beams with an energy in the range of 1-5 GeV and beam quality comparable to existing RF machines. This will enable a versatile portfolio of applications from compact free-electron laser (FEL) drivers to sources for medical and industrial imaging. At the heart of both facilities is the use of plasma-based accelerator components and systems which encompass not only the accelerating medium itself, but also a range of auxiliary systems such as plasma-based electron beam op- the implications for implementation at the future EuPRAXIA facilities.

I. INTRODUCTION

In the plasma components and systems relevant for EuPRAXIA plasma is generated either via a high-voltage discharge or by a suitable laser pulse / particle beam. The generation of the plasma can be initiated from a few microseconds up to just prior to the desired interaction. A plasma component or device typically feeds neutral gas of one or multiple species into an interaction region; this interaction region can

Workshop on Plasma components and system for EuPRAXIA

Progress but still a significant work

Milestones

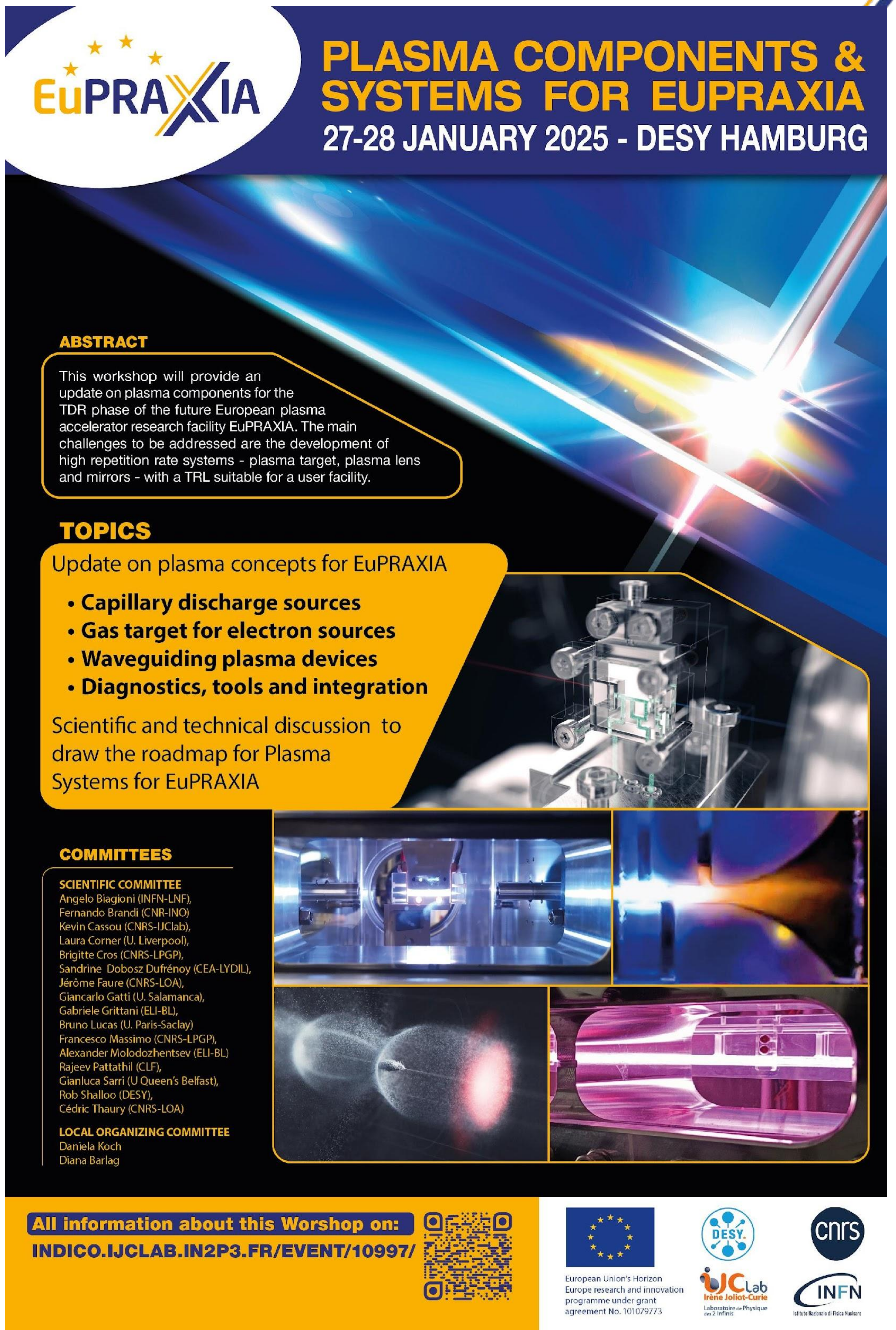
MG.1 Update of concepts for EuPRAXIA, systems status report (M24)

M10.1 Workshop on EuPRAXIA plasma concept (M28)

Opening registration by the end of the week 🚀

Participation limited to **30-40 persons.** 📝

Scientific and technical discussion to define the roadmap for plasma components and system for EuPRAXIA

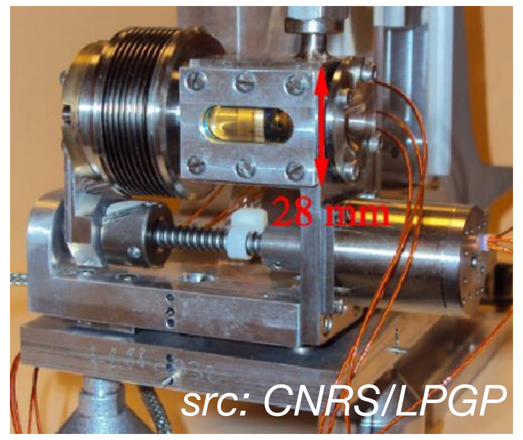


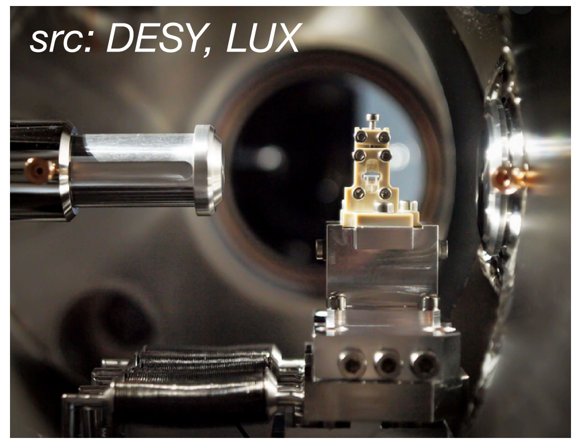
WP10 - Plasma Components & Systems

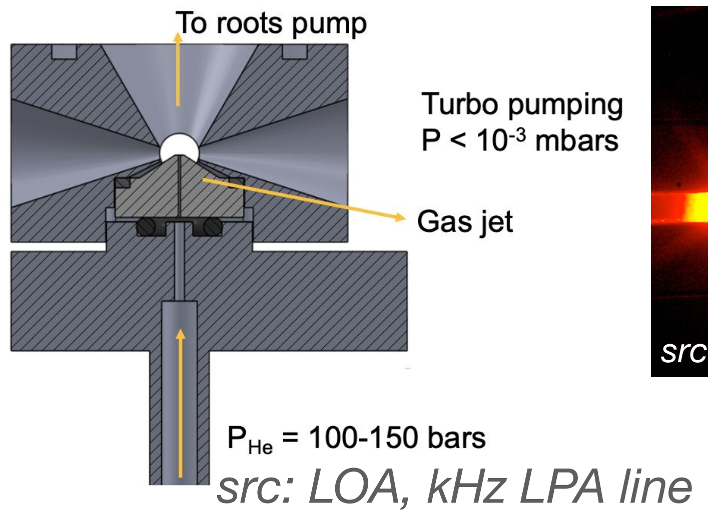
Partial view of the current review …

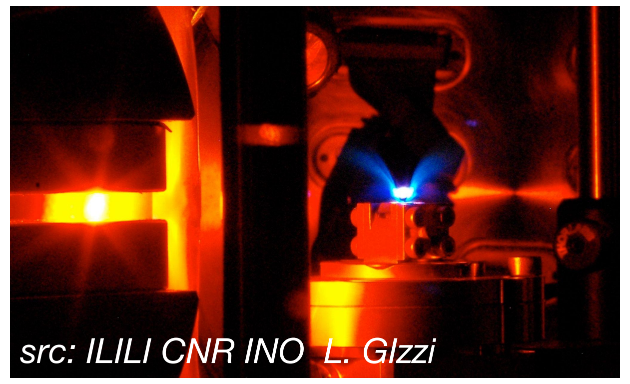
1. **Gas cell and gas jet for laser-plasma electron sources**

   Brigitte Cros (CNRS-LPGP)



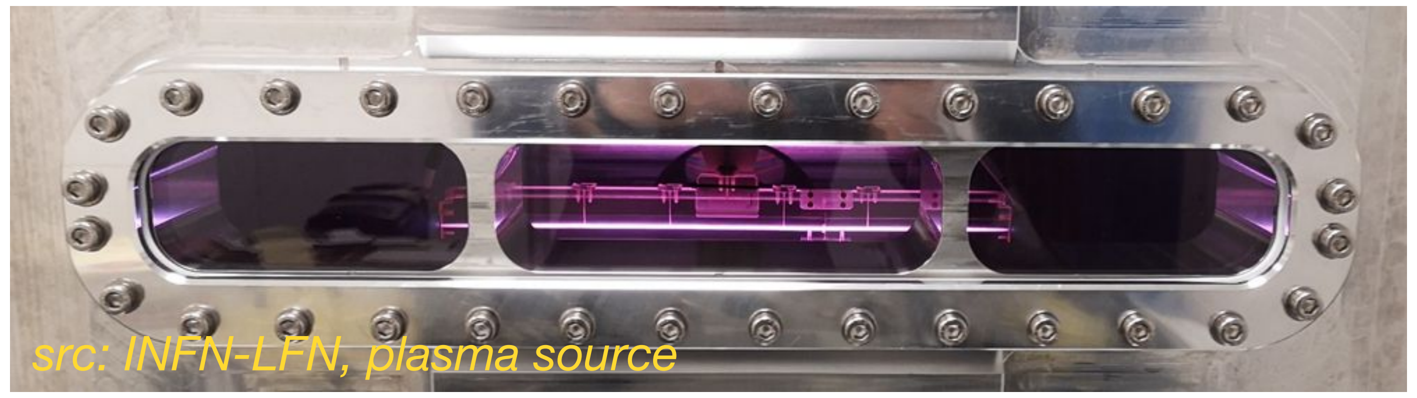


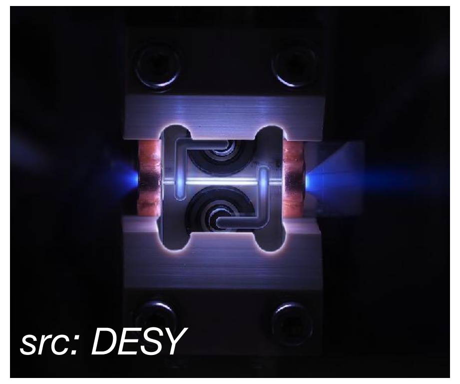




2. **Discharge-based plasma sources and plasma lenses**

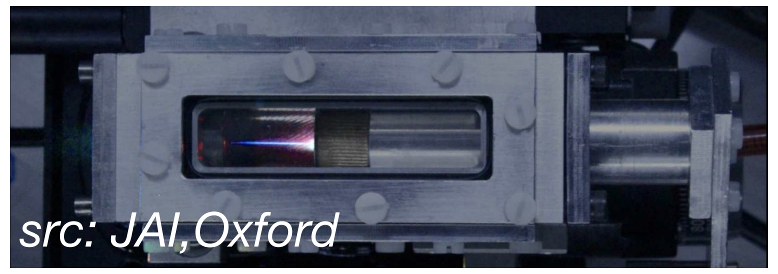
   Romain Demitra (INFN-LNF)

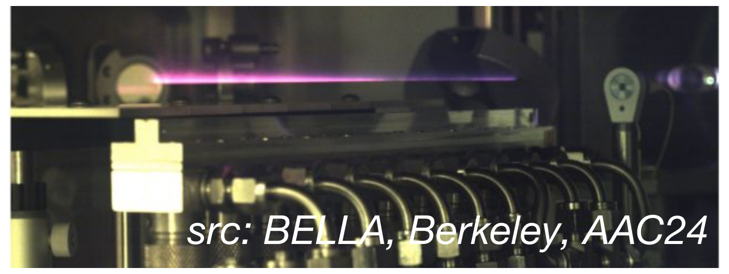




3. **Plasma waveguide (HOFI channels)**

   Manuel Kirchen on behalf of Rob Shalloo (DESY)





4. **Consideration on integration and future challenges**

not cover today: plasma diagnostics - very nice review lead by Fernando Brandi (CNR-INO, ILIL, Pisa)

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EuPRAXIA
Preparatory Phase

Gaz cell and gas jet for Eupraxia

B Cros LPGP CNRS U Paris Saclay on behalf of :

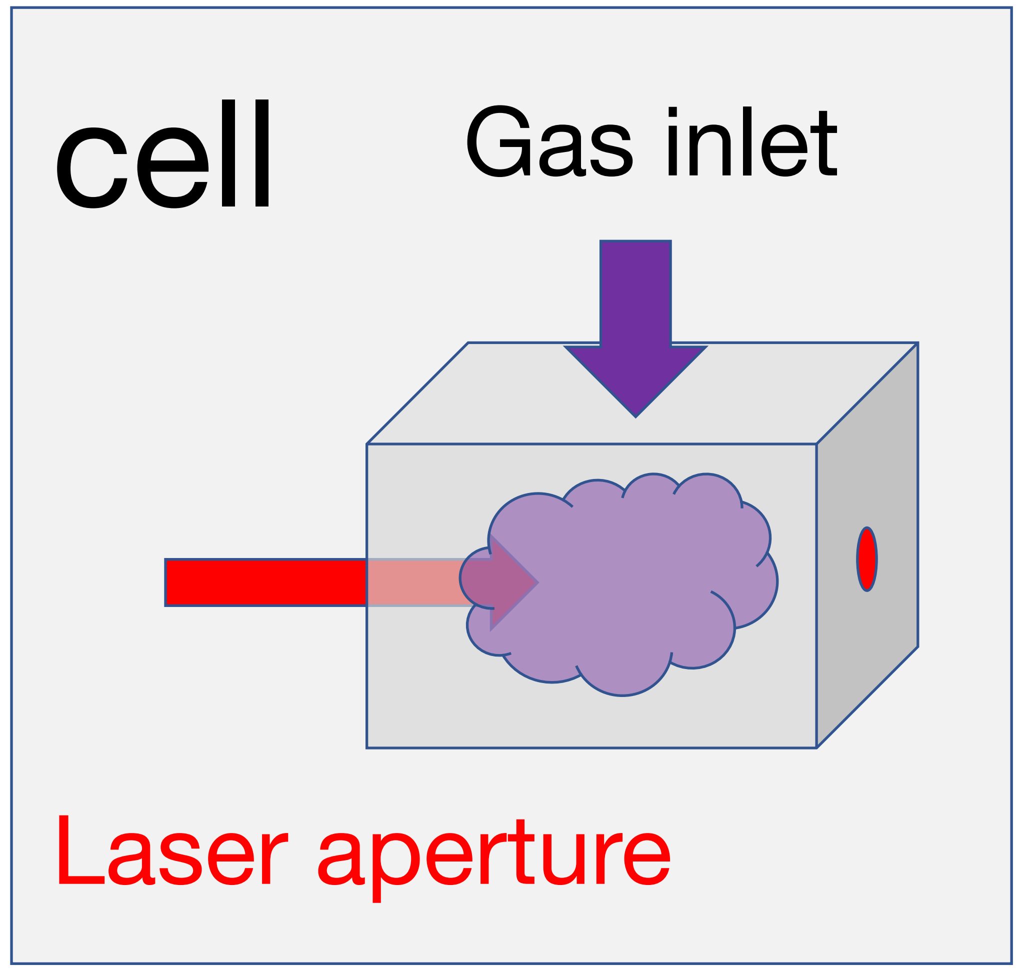
L. Steyn - LPGP, S.Dobosz Dufrénoy - CEA, P. Drobniak - Univ. Oslo, B. Lucas - CNRS IJClab, L. Corner - Univ. Liverpool, J. Faure - CNRS LOA

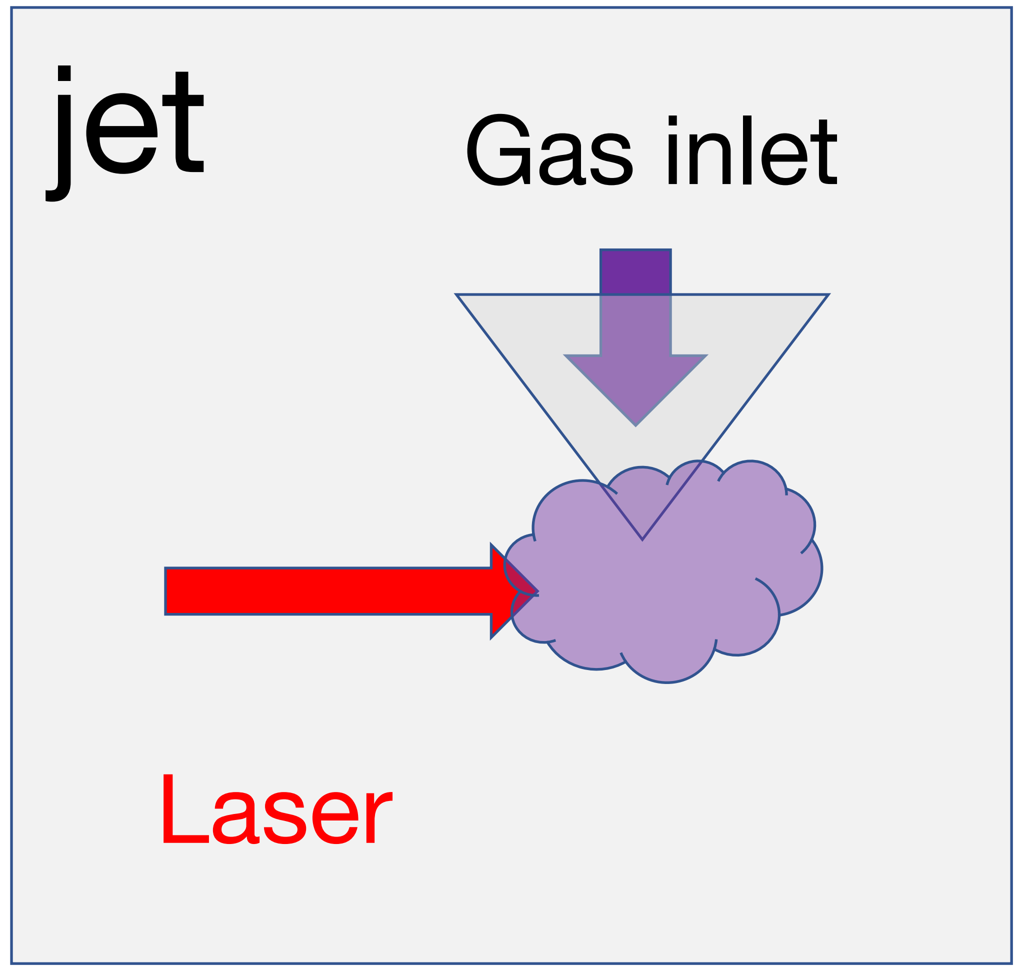
This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773

Constraints on the design of an electron source in gas cells/jets

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

Objective	Gas cell	Gas jet
Minimise gas flow into vacuum	Differential pumping	Differential pumping
Control density gradients along laser propagation	Geometry	Shock, nozzle geometry
Control gas density and composition	Geometry, gas inlet	Number of jets
Minimise shot to shot fluctuations	Low density, continuous flow	Nozzle design
Maximise life-time	Laser control, geometry	Laser control
Maximise repetition rate	Continuous flow	Continuous flow

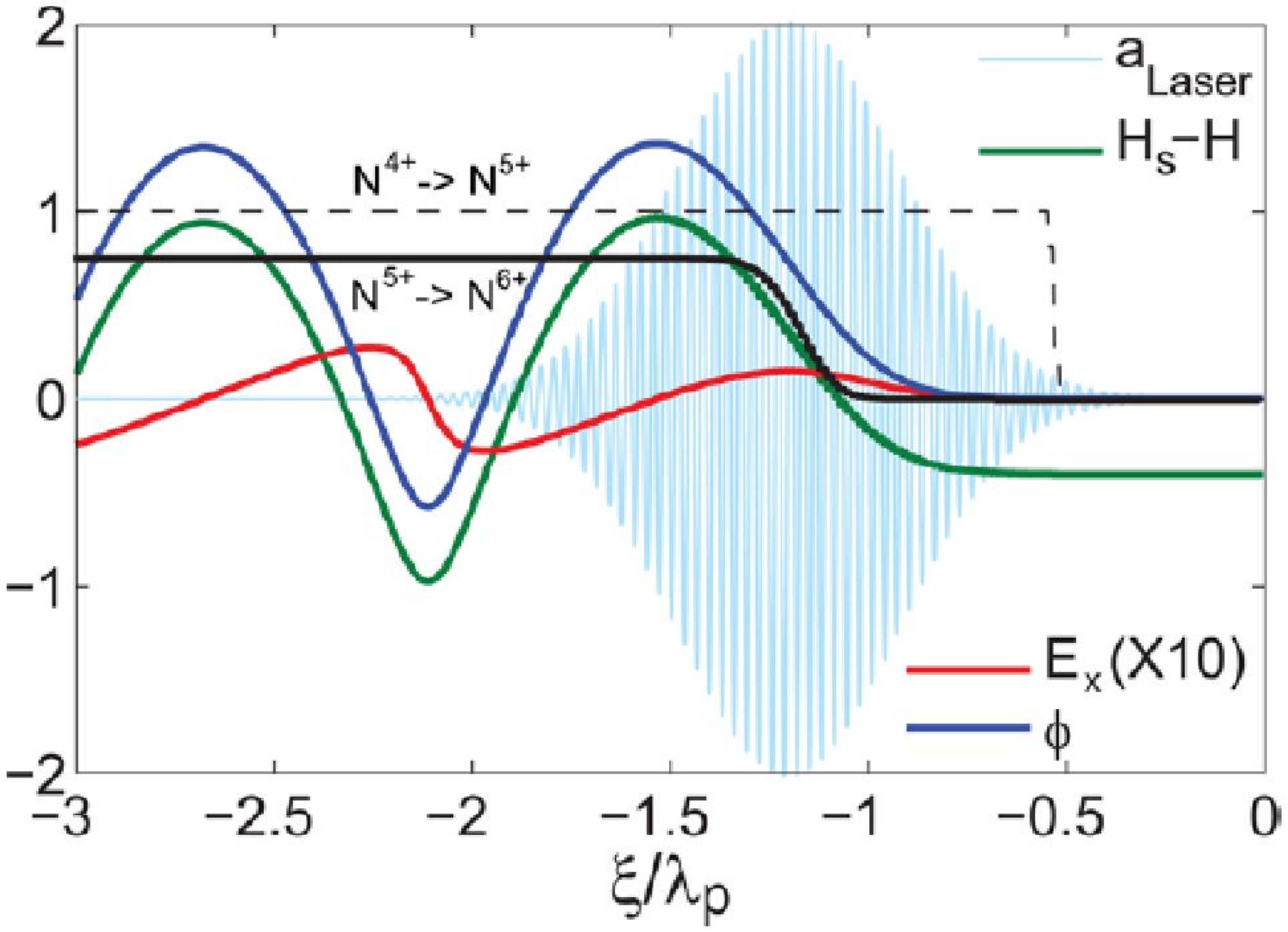




Ionisation induced injection combined with tailored density profile

- **Provides control on electron beam**
- Operates at **moderate laser intensity** and **plasma density**: good quality beam while maintaining high beam charge
- Single laser beam required
- Final electron beam properties can be tuned using the longitudinal electron distribution

III controls ionisation and trapping



Trapping for Hs-H >0

Chen et al, PoP 19, 033101 (2012)

Ionisation induced injection combined with tailored density profile

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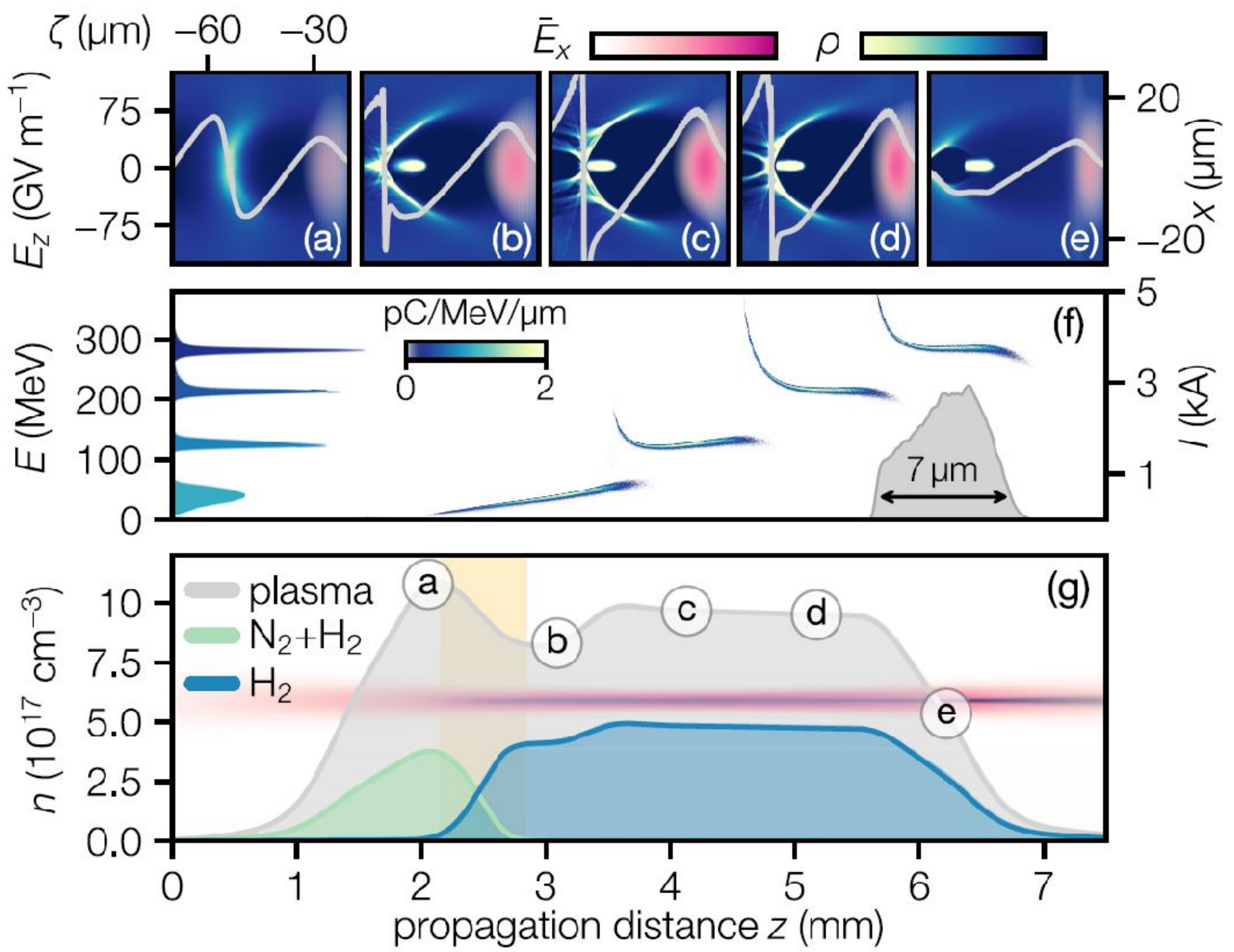
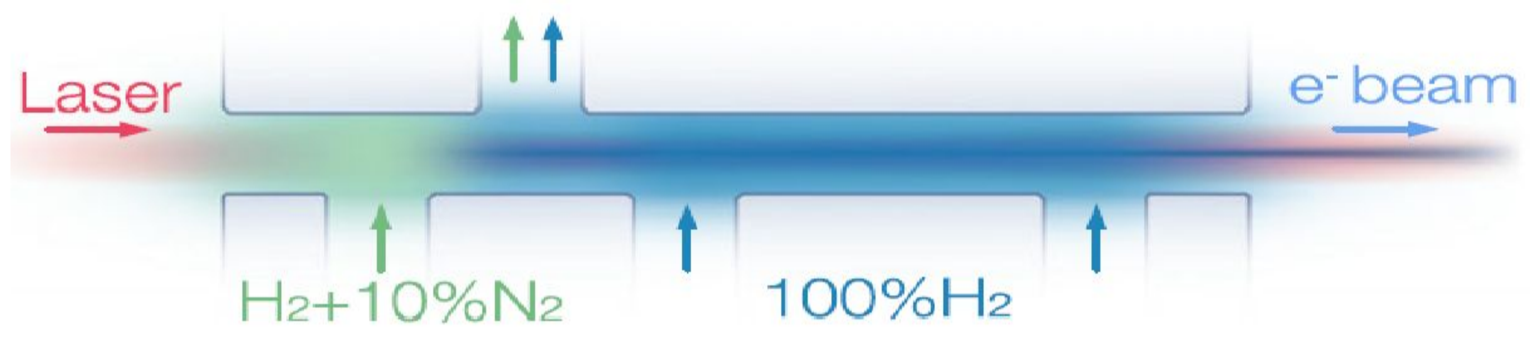


Multi zone profile for gas cell operation

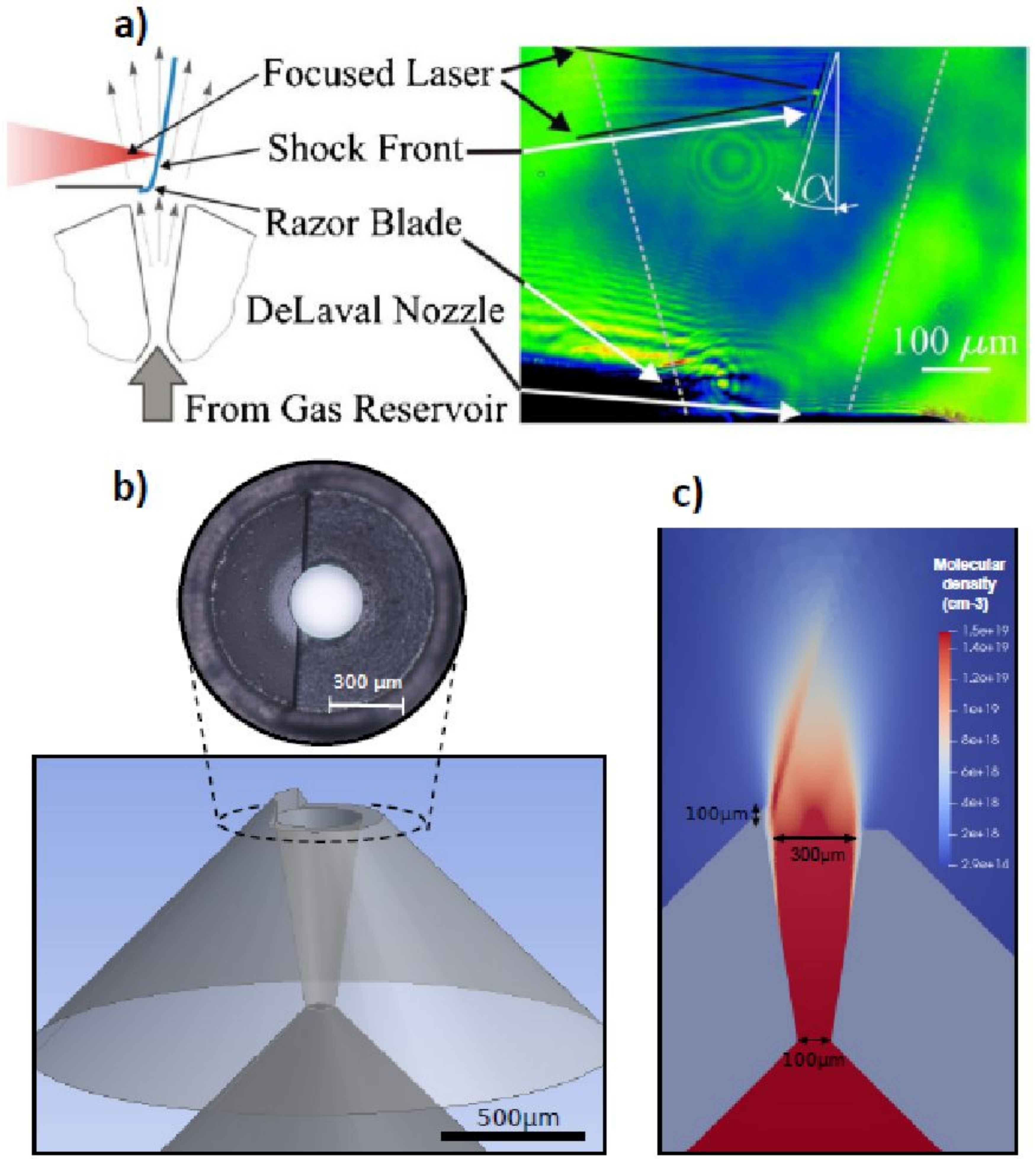


Kirchen et al PRL 126, 174801 (2021)

Ionisation induced injection combined with tailored density profile

- **Provides control on electron beam**
- Operates at **moderate laser intensity** and **plasma density**: good quality beam while maintaining high beam charge
- Single laser beam required
- Final electron beam properties can be tuned using the longitudinal electron distribution

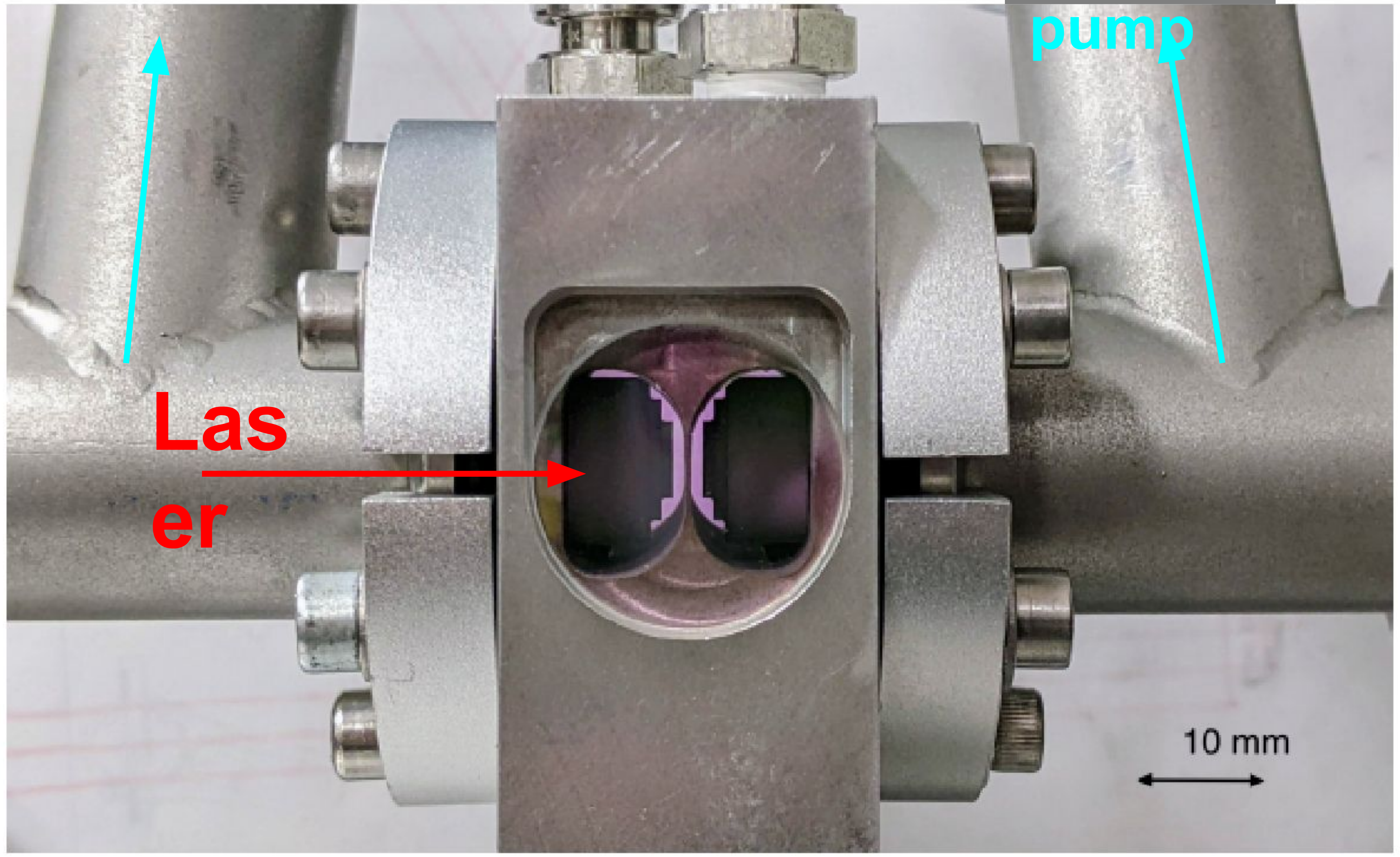
Combined with shock front in gas jets



Schmid, et al PRSTAB, 13, 091301 (2010), Rovige, et al. RSI 92, 083302 (2021).

Example of solutions: differential pumping

Gas cell design

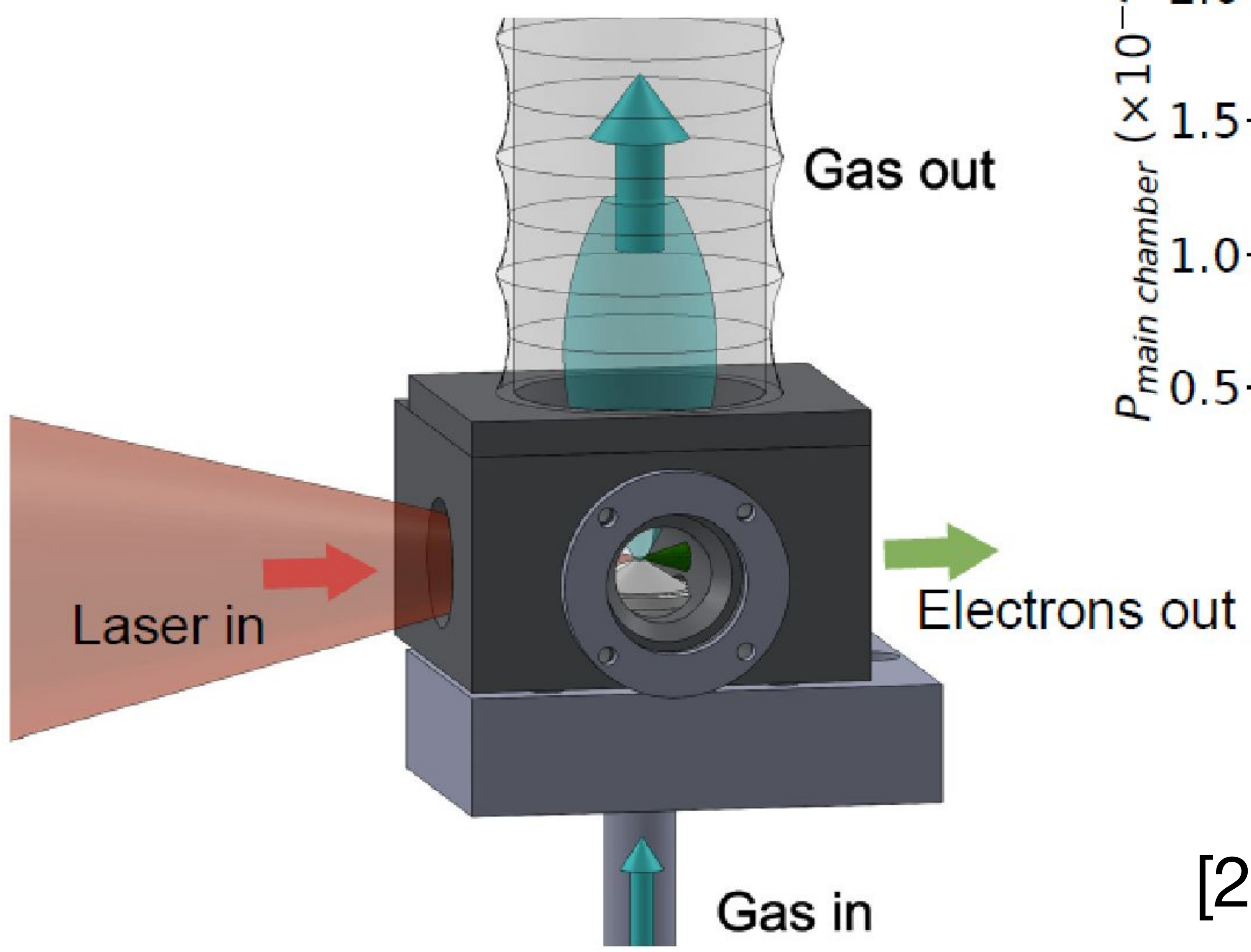


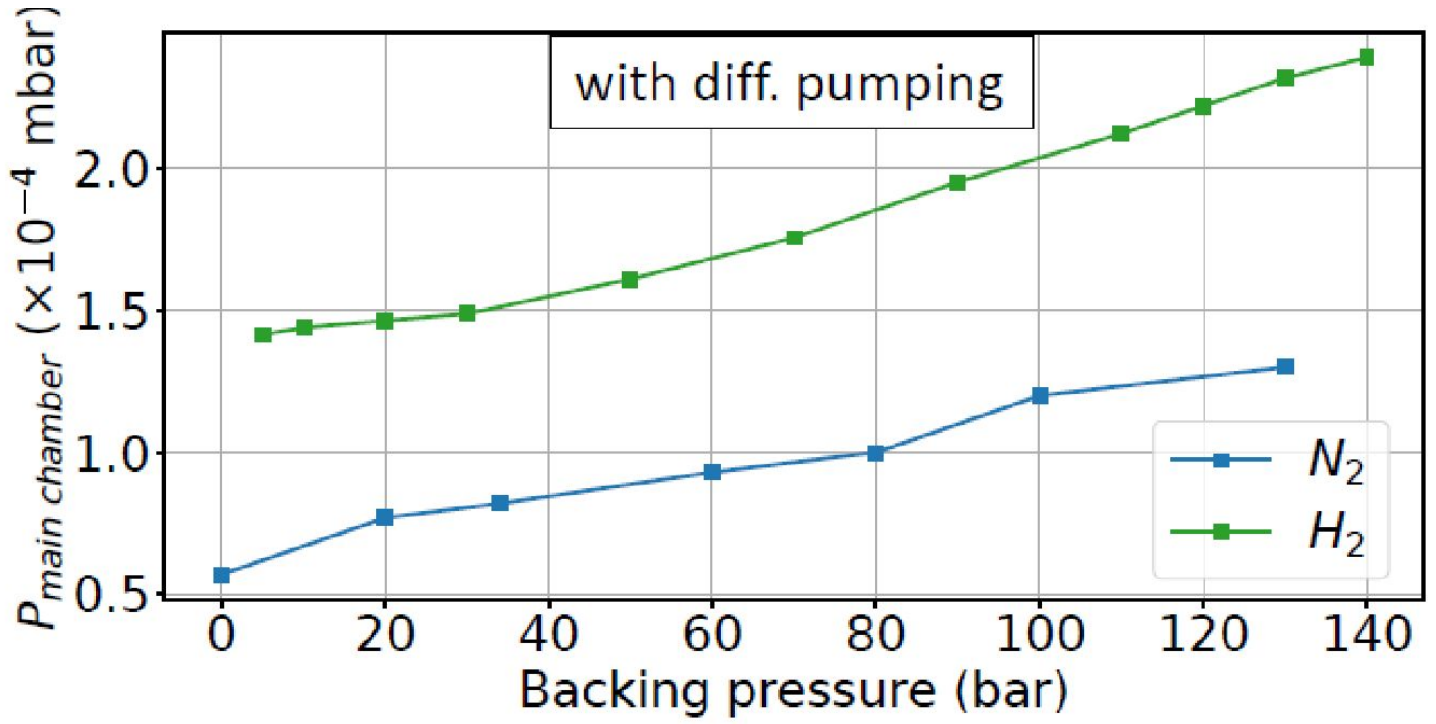
Continuous flow beamline-integrated multicell target

- 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





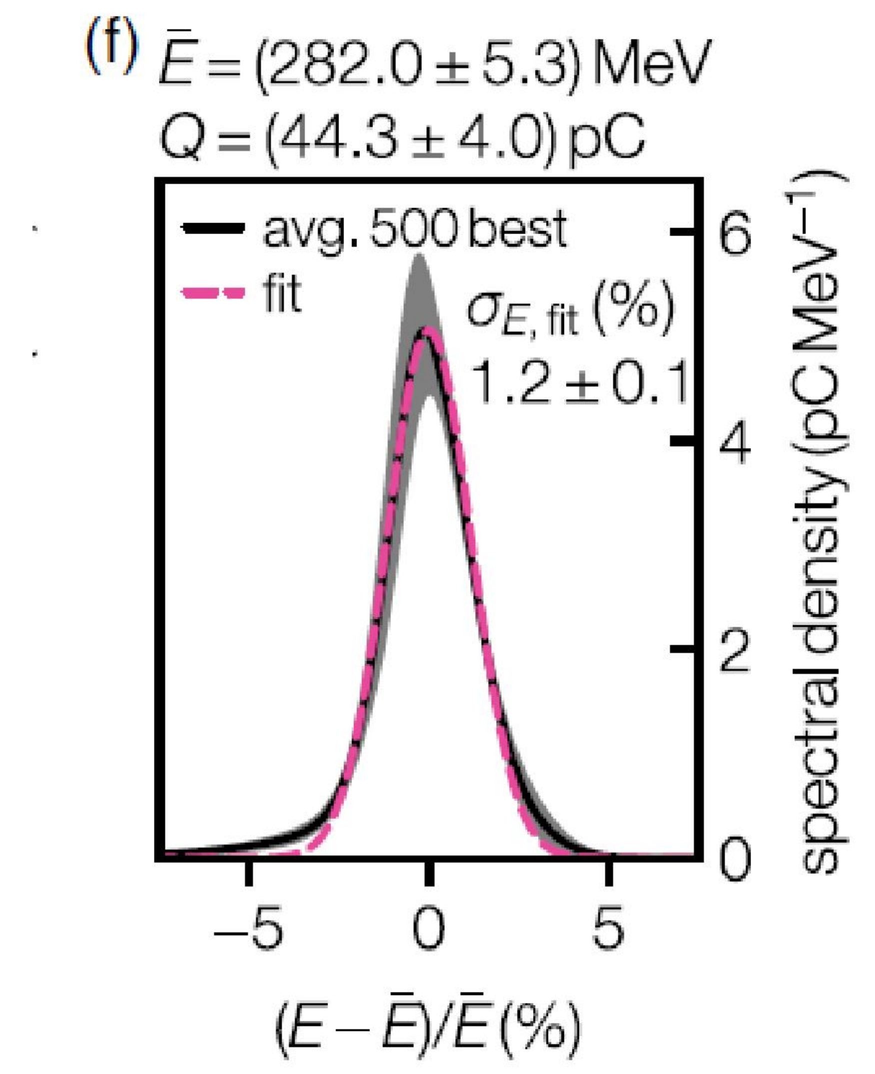
[2] J. Monzac et al, in preparation, LOA

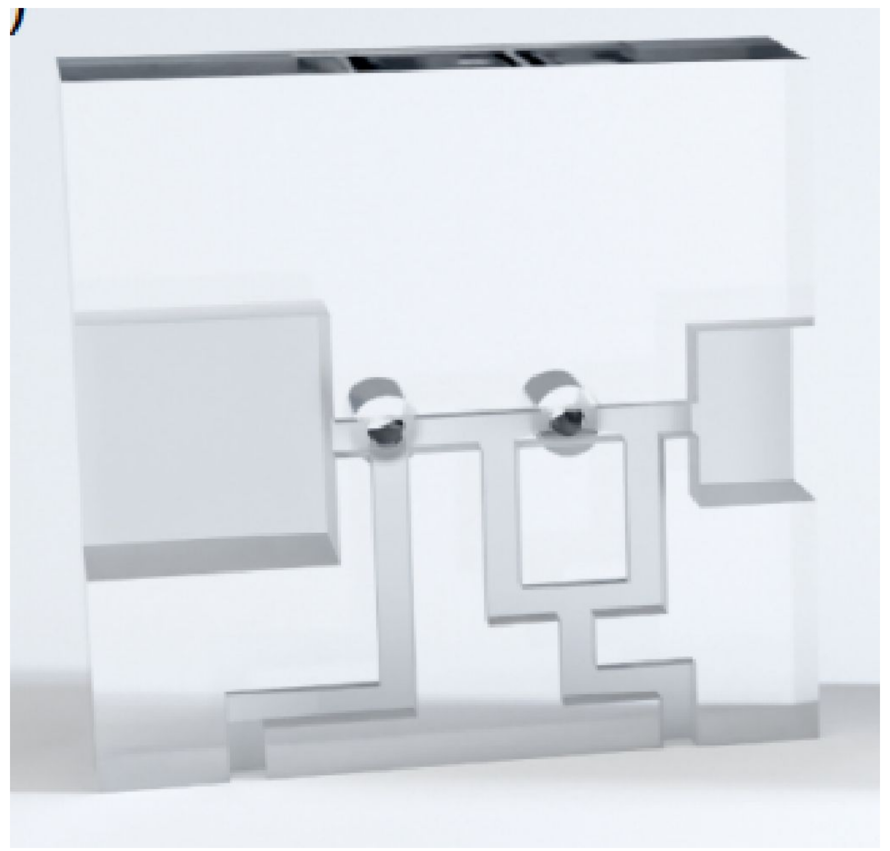
Continuous flow operation kHz H2

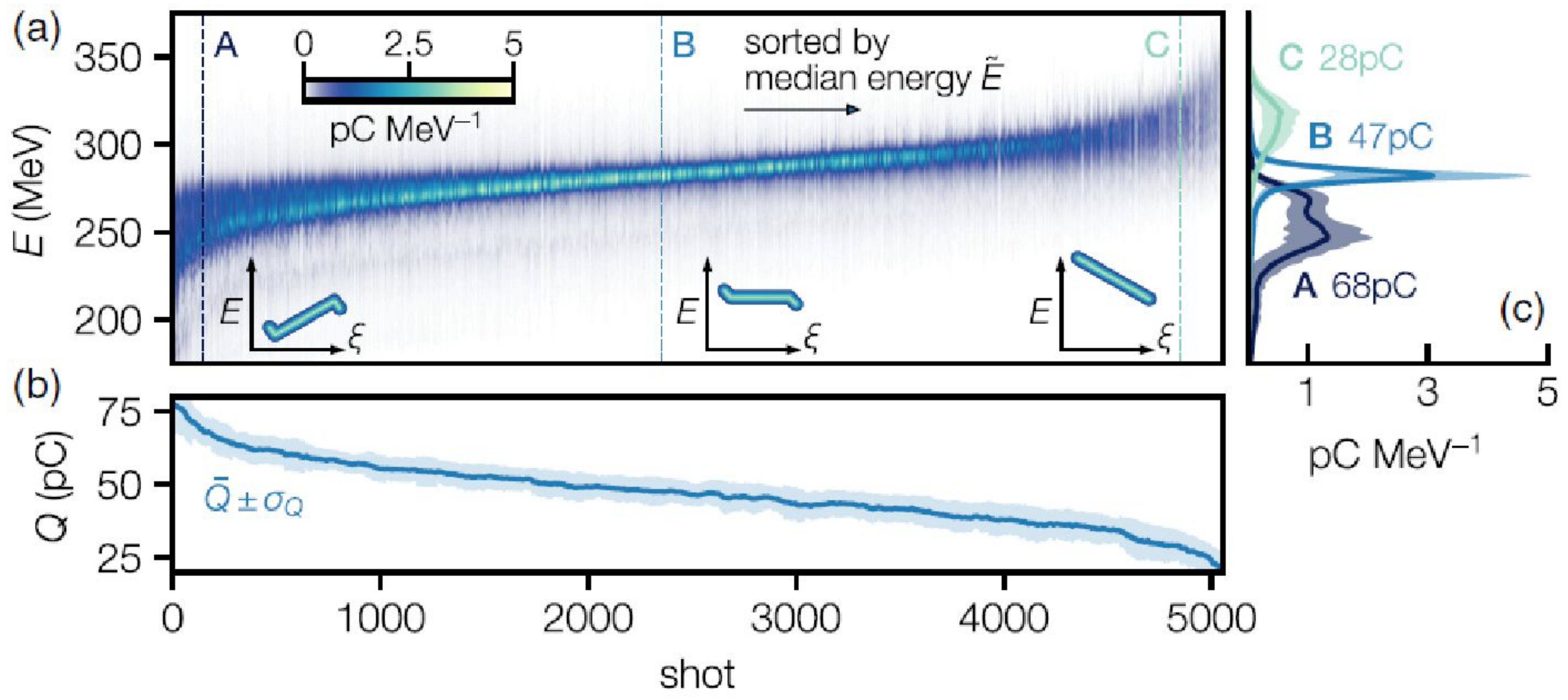
- Continuous gas flow for kHz laser operation [2,3]
- Gas jet in a small chamber inside main chamber
- Maintains pressure in the main chamber around 10^{-4}mbar

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

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

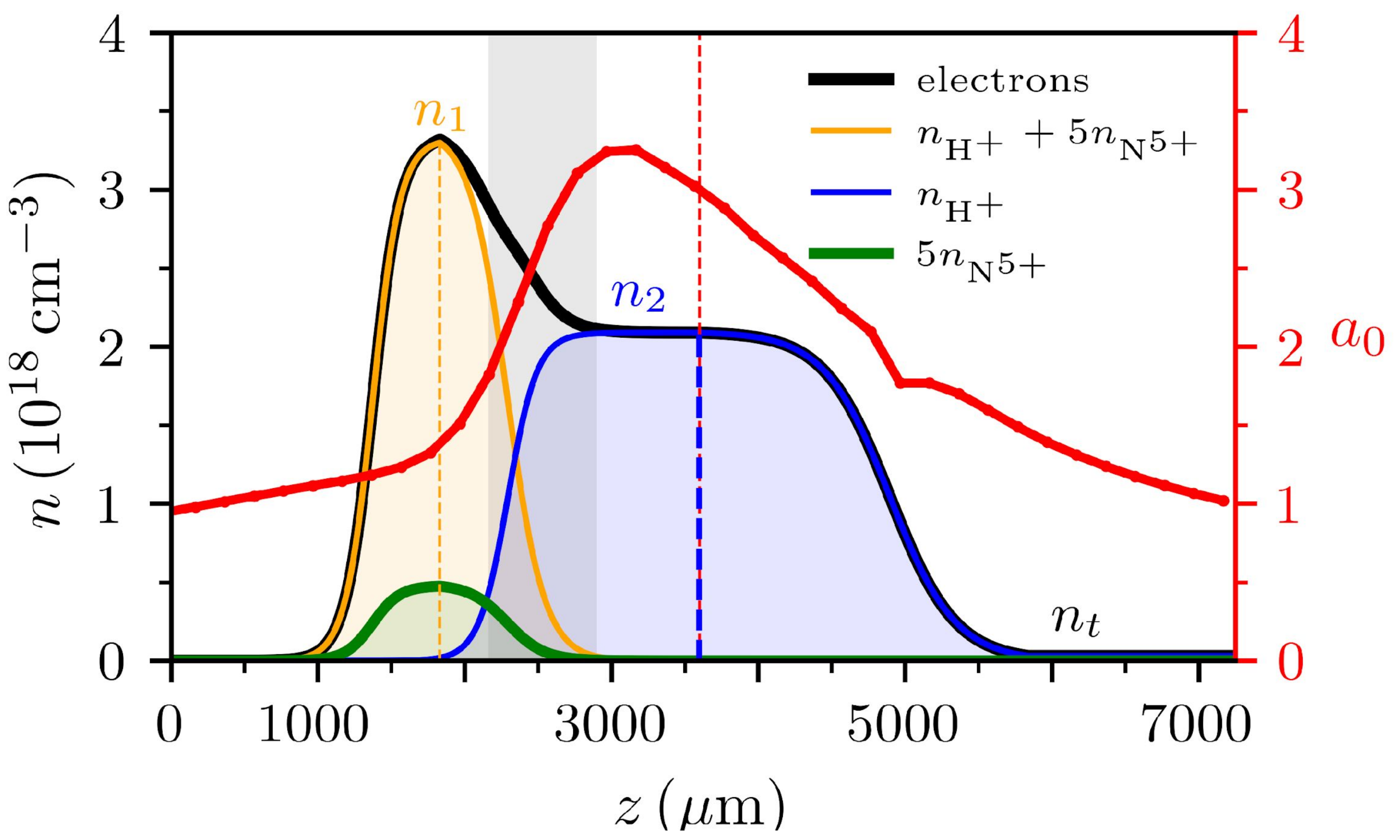
80% of variability claimed to be derived from the laser.

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

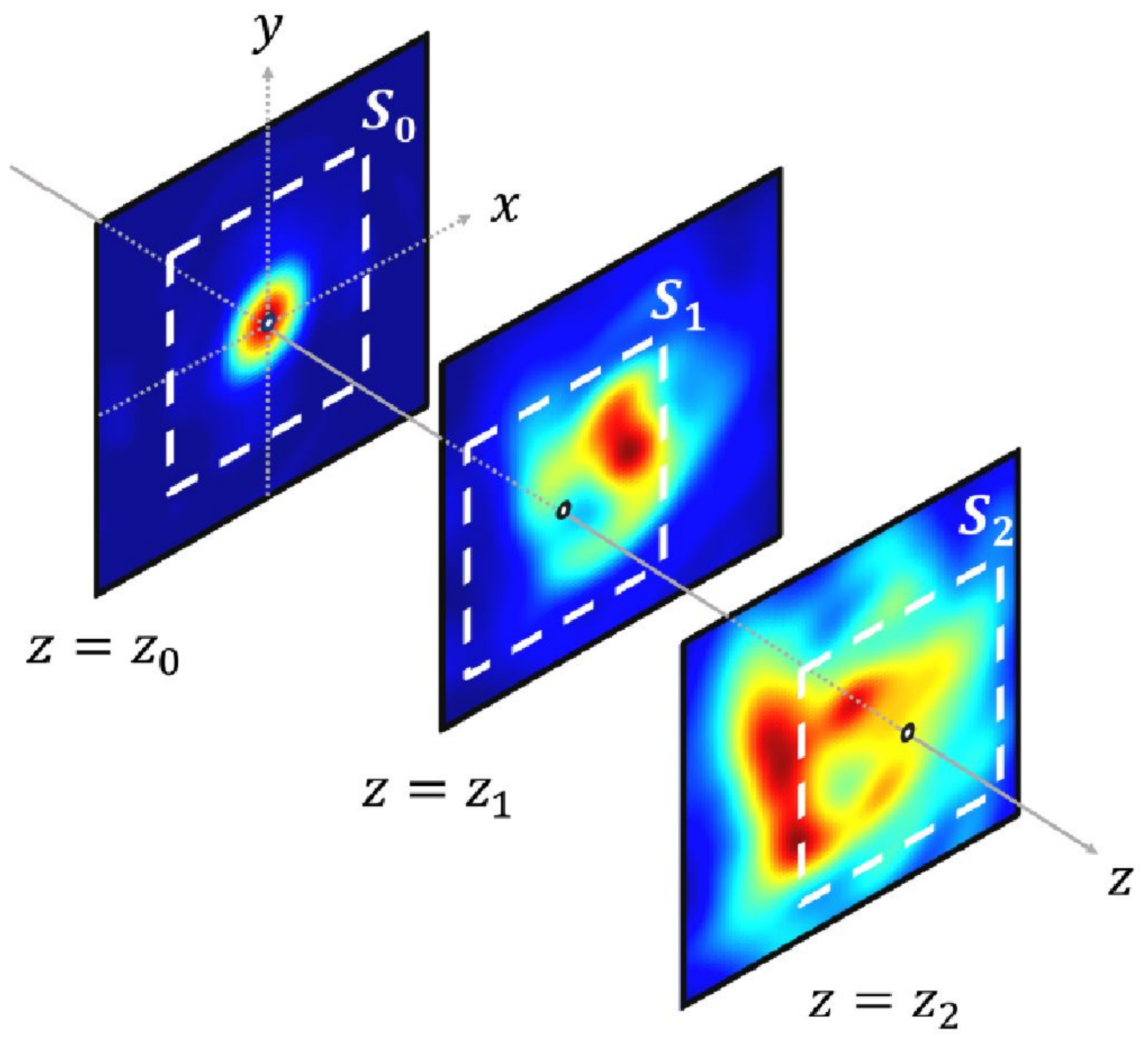
[1] M. Kirchen et al PRL 126, 174801 (2021)

[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)

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Plasma discharges

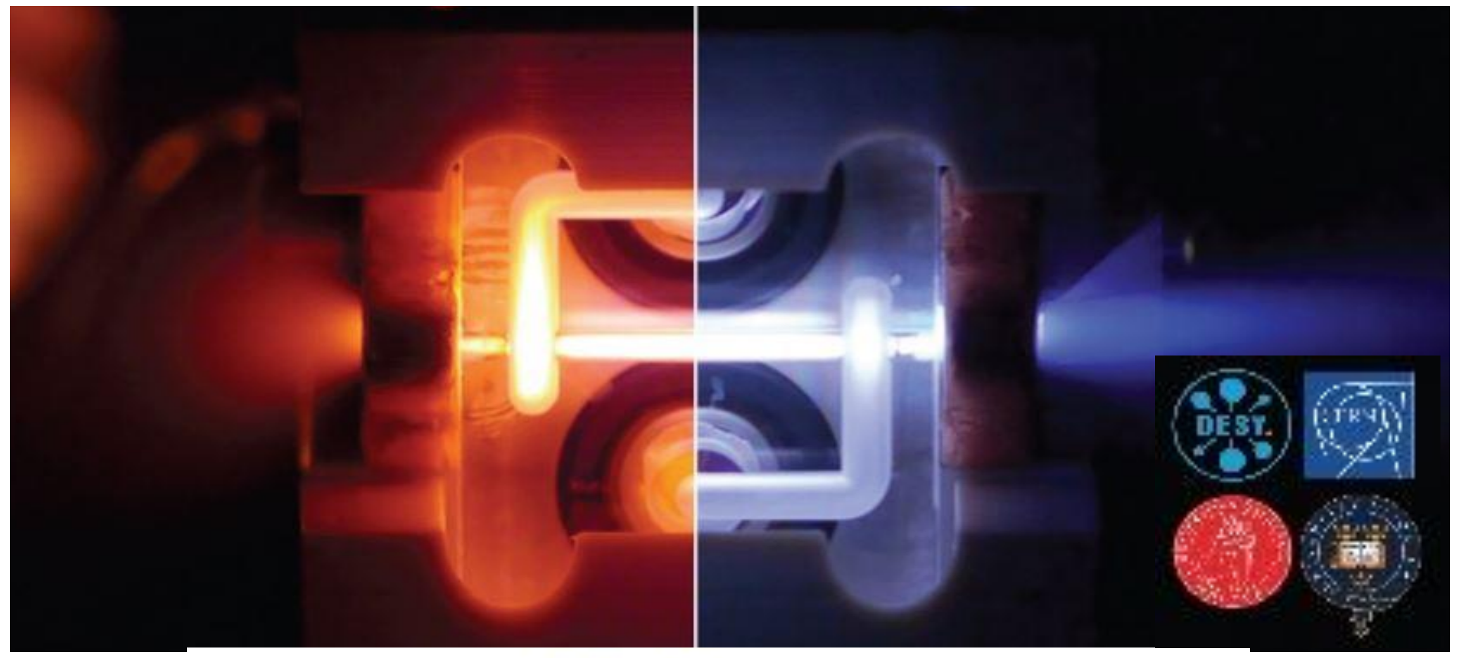
R. Demitra on behalf of A. Biagioni - INFN-LNF and G. Gatti CLPU - A. Molodozhentsev, P. Sasorov ELI-BL

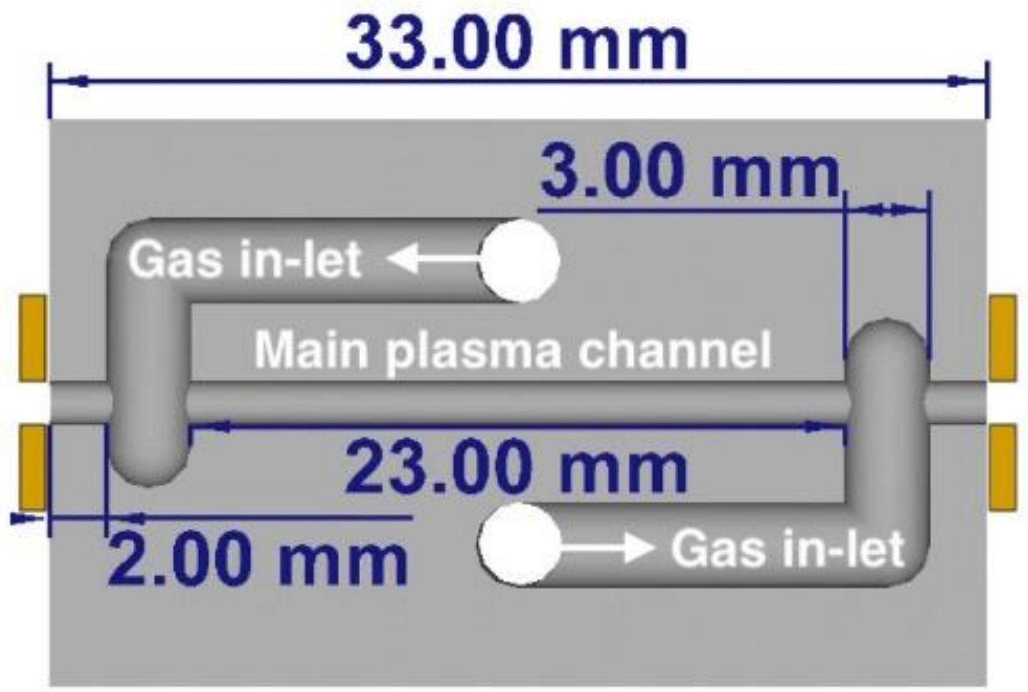
This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773

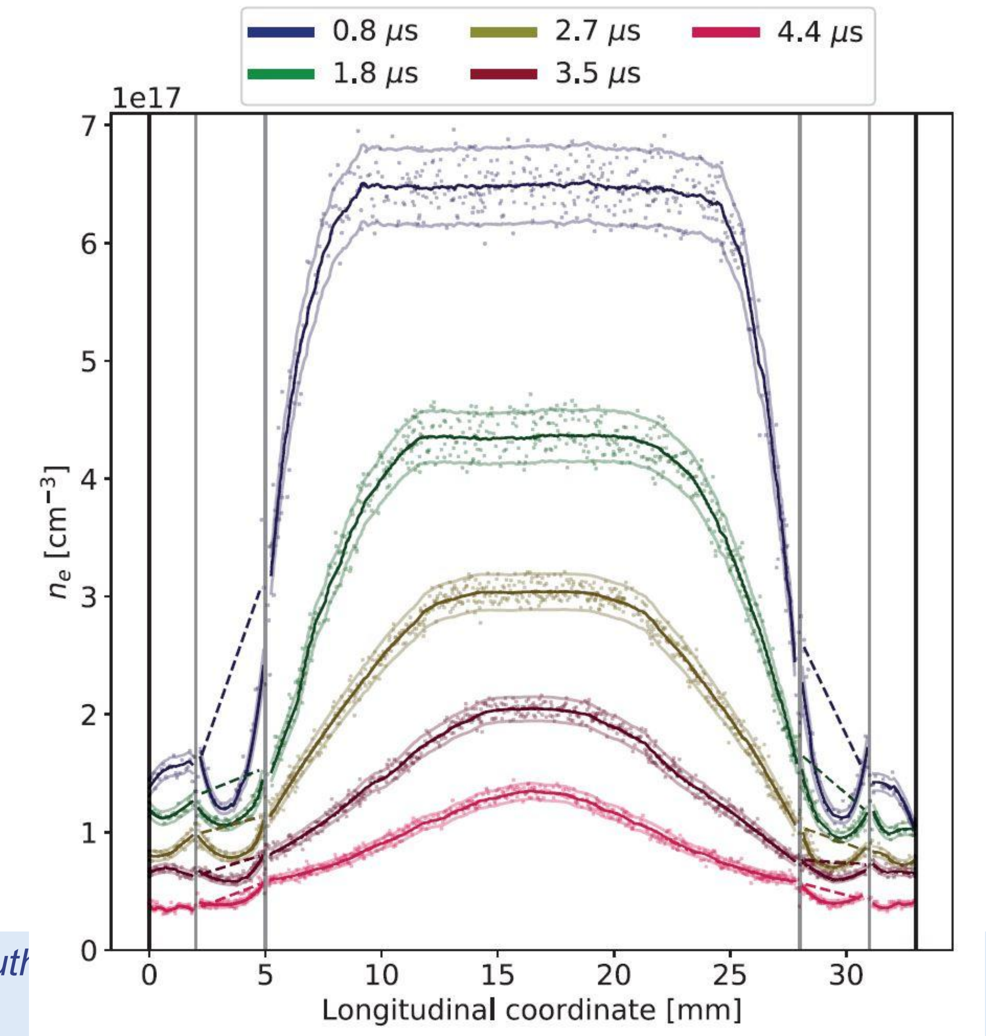
Capillary discharges

On the behalf of Angelo Biagioni, Alexander Molodozhentsev and Giancarlo Gatti

Funded by the European Union

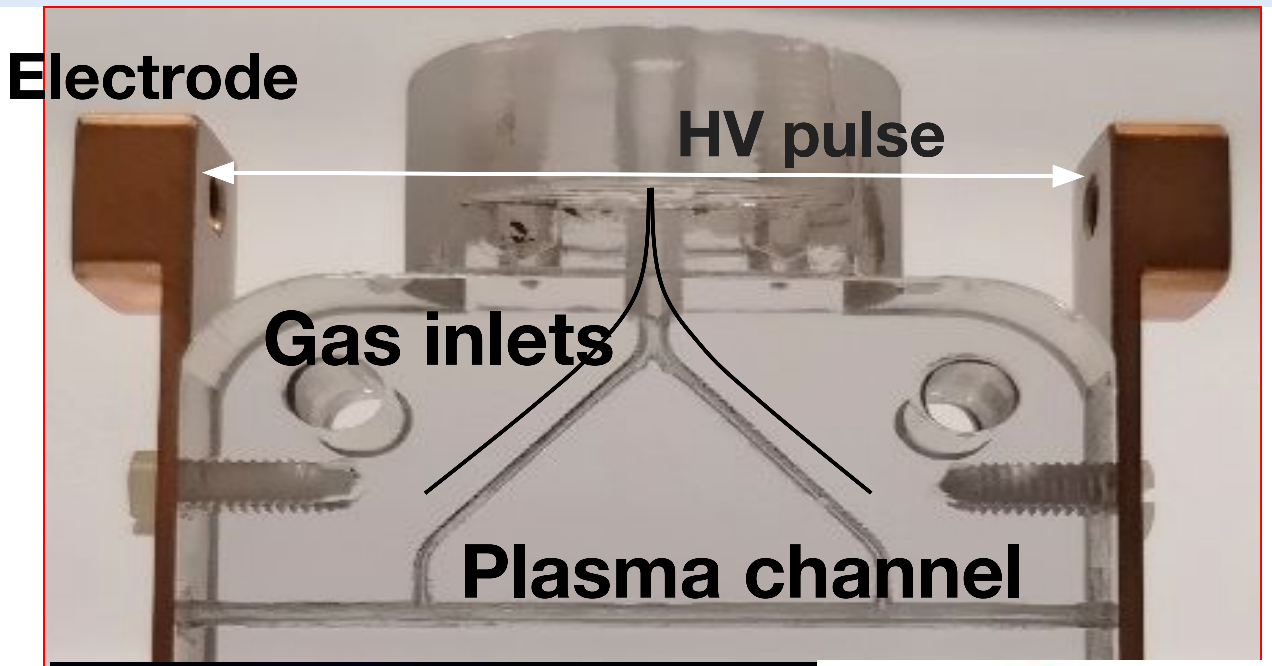


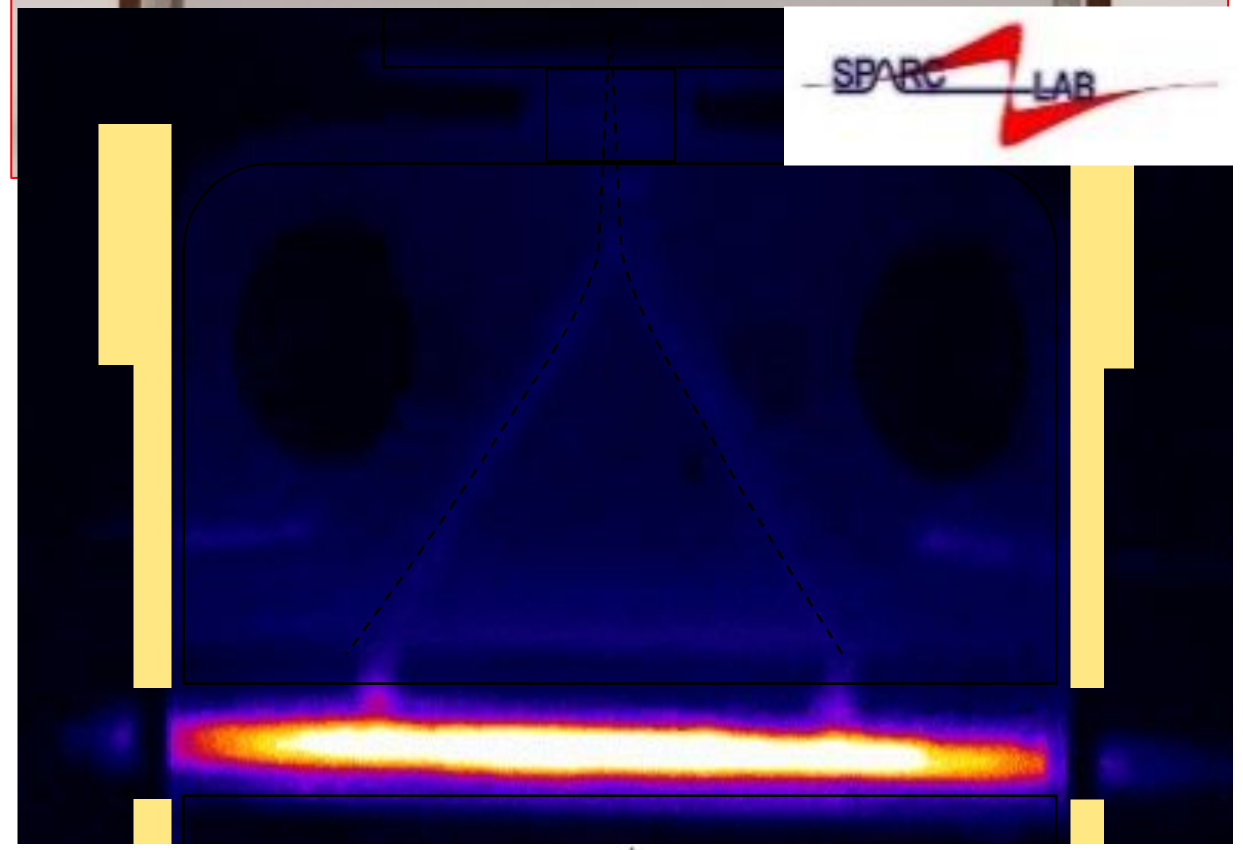


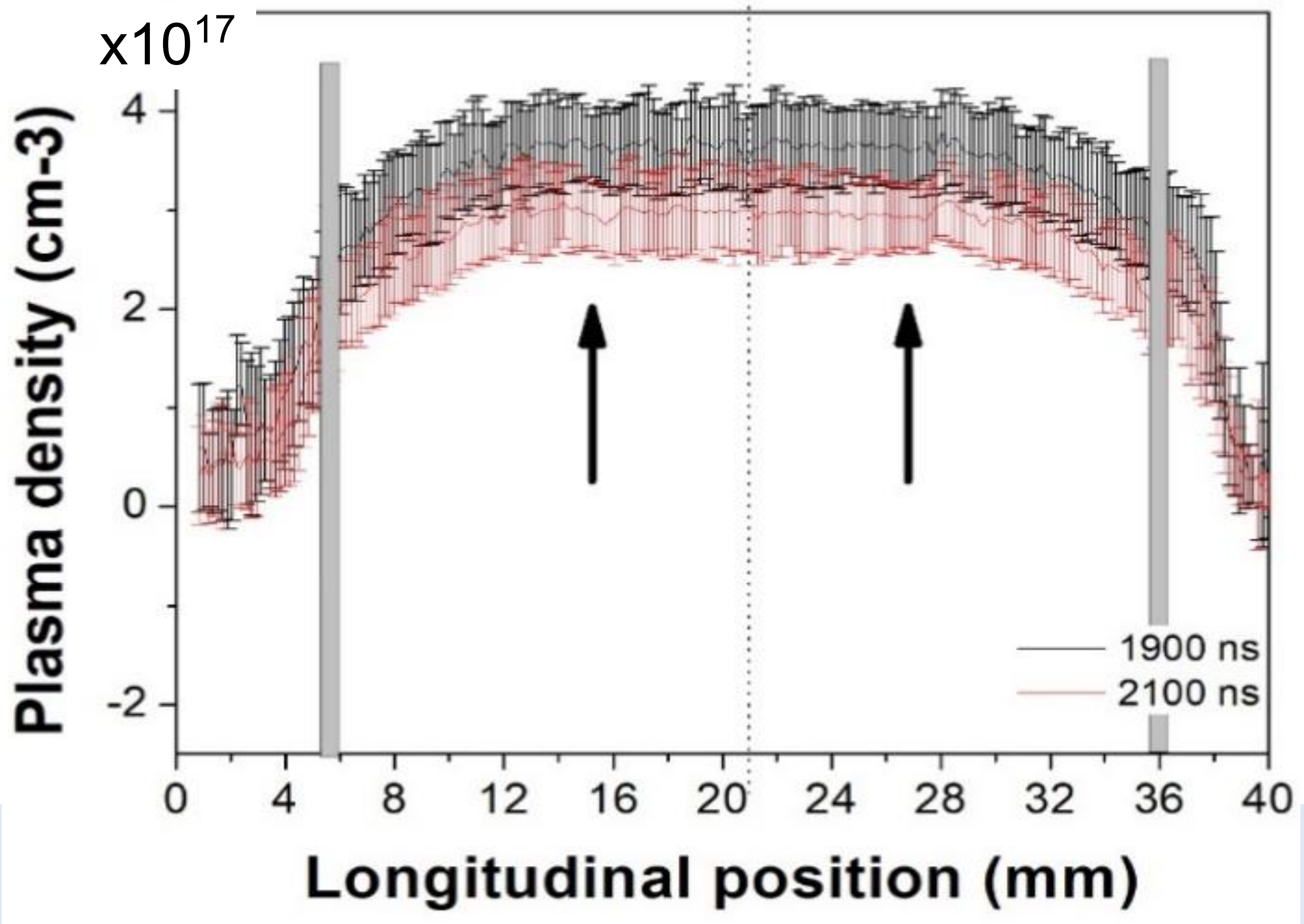


Capillary discharges properties

- Longitudinal and transverse density profile tailoring
- Stability/reproducibility
- Lifetime
- $10^9 - 10^{10}\ Vm^{-1}$ acceleration gradient
- $10^{15} - 10^{19} cm^{-3}$ density







Capillary Discharge : Design and control system

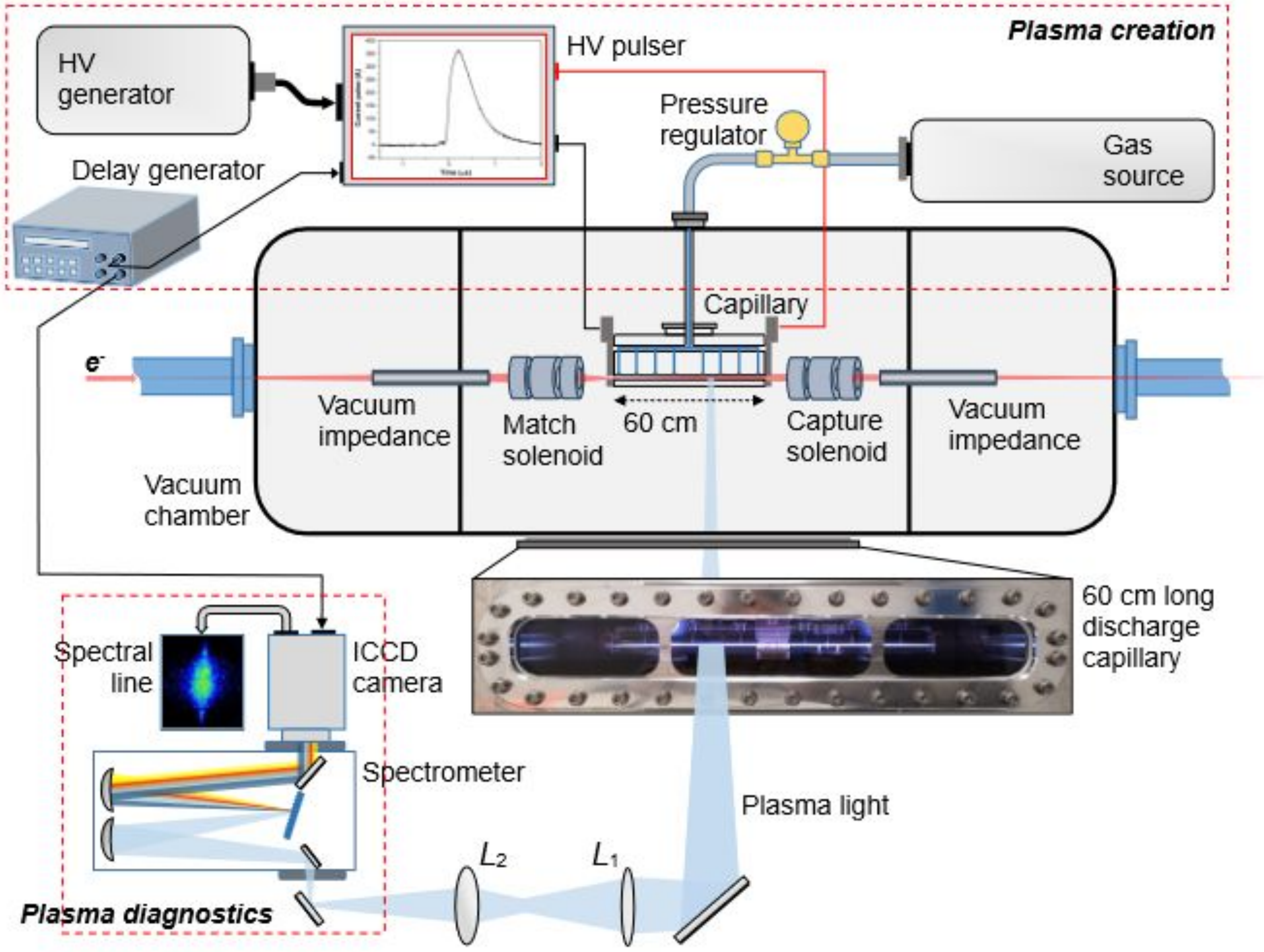
Funded by the European Union

Capillary Discharge Design:

- 60 cm long, 2 mm diameter capillary
- High-voltage pulses (7-15 kV) create a stable plasma channel
- Gas pressure control (10-100 mbar) critical for plasma density stability
- Uniform plasma density ensures beam quality and particle acceleration

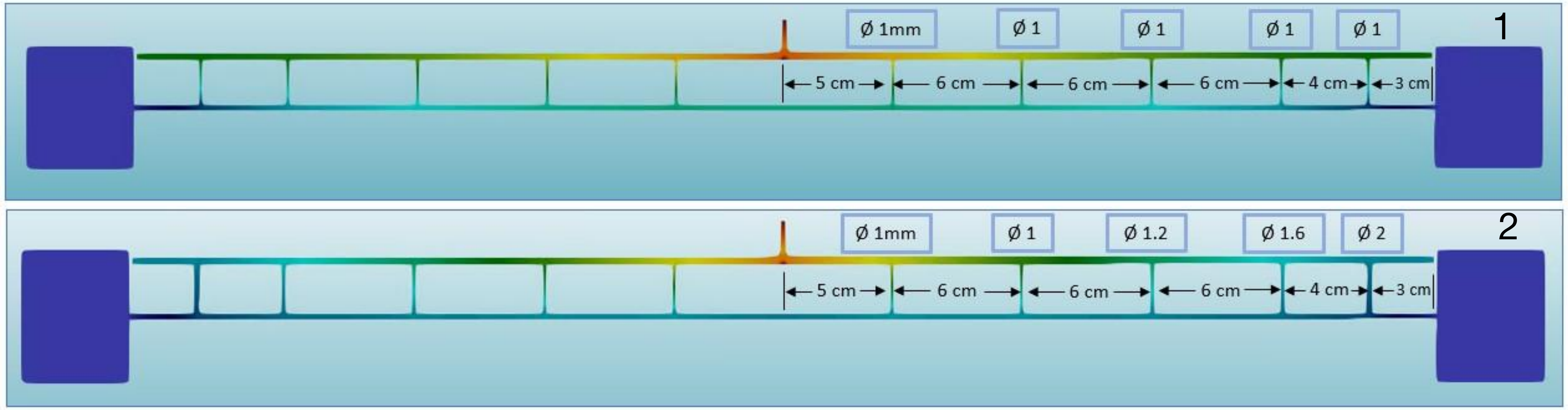
Plasma module:

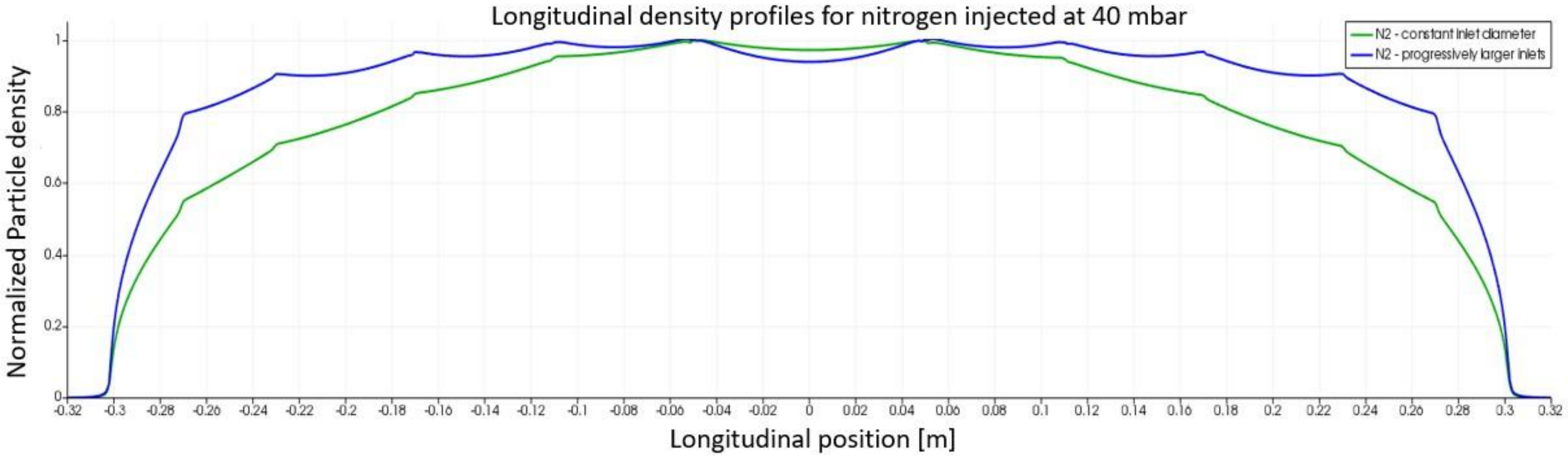
- Hydrogen gas in continuous flow
- Vacuum chamber at $10^{-2} mbar$(scroll pumps, turbo-molecular pump)
- High-voltage generator powering μs-short pulses to capillary electrodes
- Delay generator sets repetition rate (10-150 Hz)
- Cooling: water for pump, fan for HV pulser



Capillary Discharge : Geometry control of density

Funded by the European Union



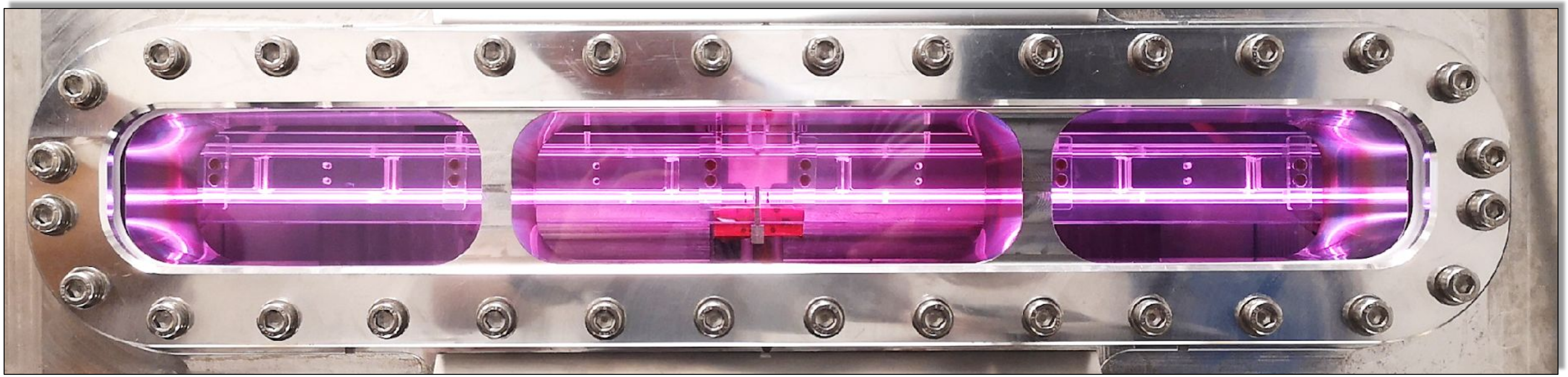


- OpenFOAM simulation of gas distribution
- 10 gas injector
- 2 different configuration of diameter injections
- Critical point near the exit where the gas exit
- Density around $3 \times 10^{17} cm^{-3}$

- Possibility to control plasma profile = better matching between beams and plasma
- Diverse average density achievable by playing with pressure and voltage

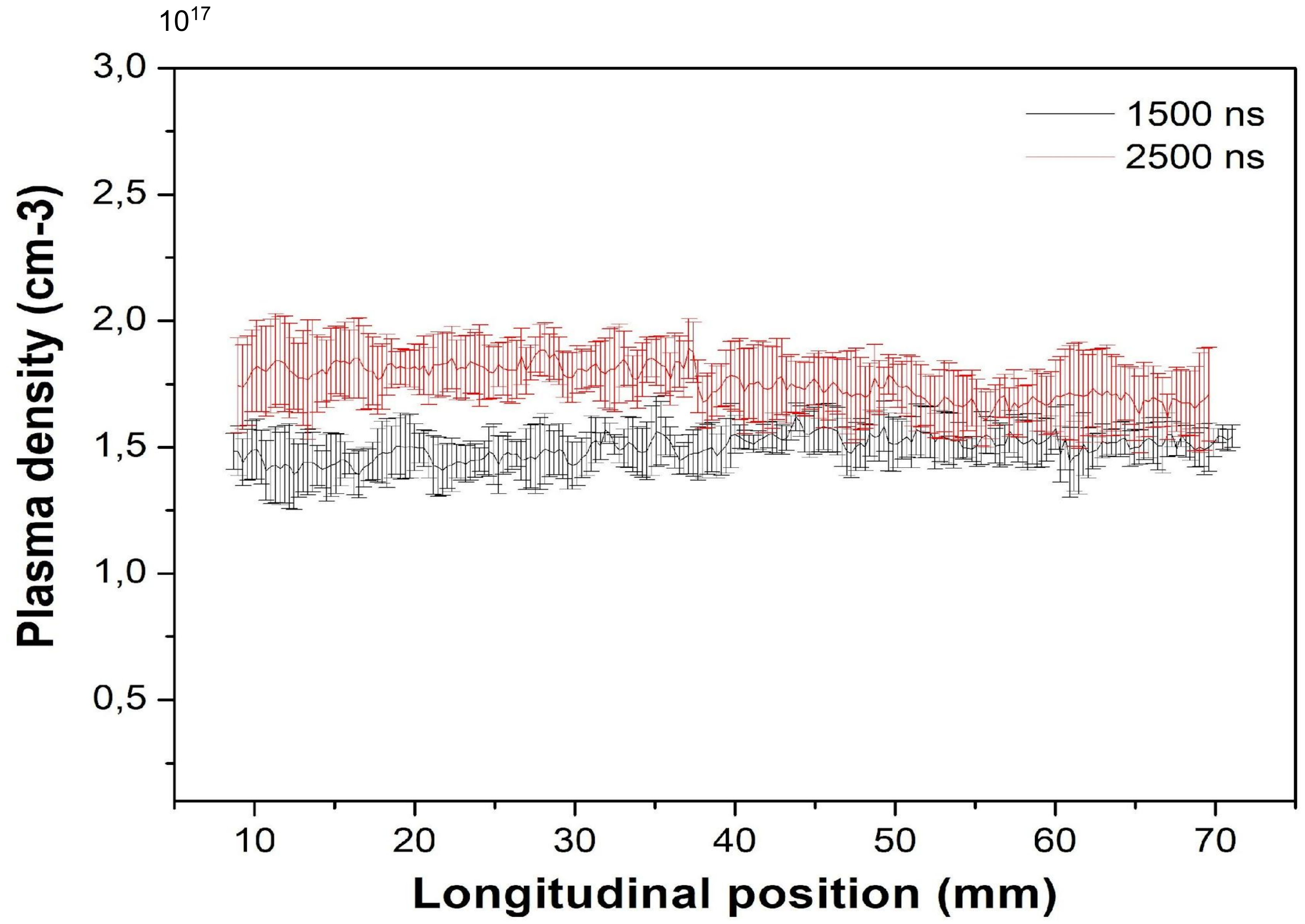
Capillary discharge : 60 cm prototype

Funded by the European Union



1.1 GeV (1 GV/m 600 MeV in **60cm** long capillary - density 10^{16} cm-3):

- Fabrication by machining
- 10 increasing diameters
- Density range 10^{16} -10^{17} cm^{-3}
- 13 kV with 500 A
- **100 Hz rep Rate**



Capillary discharge : Active Plasma Lens

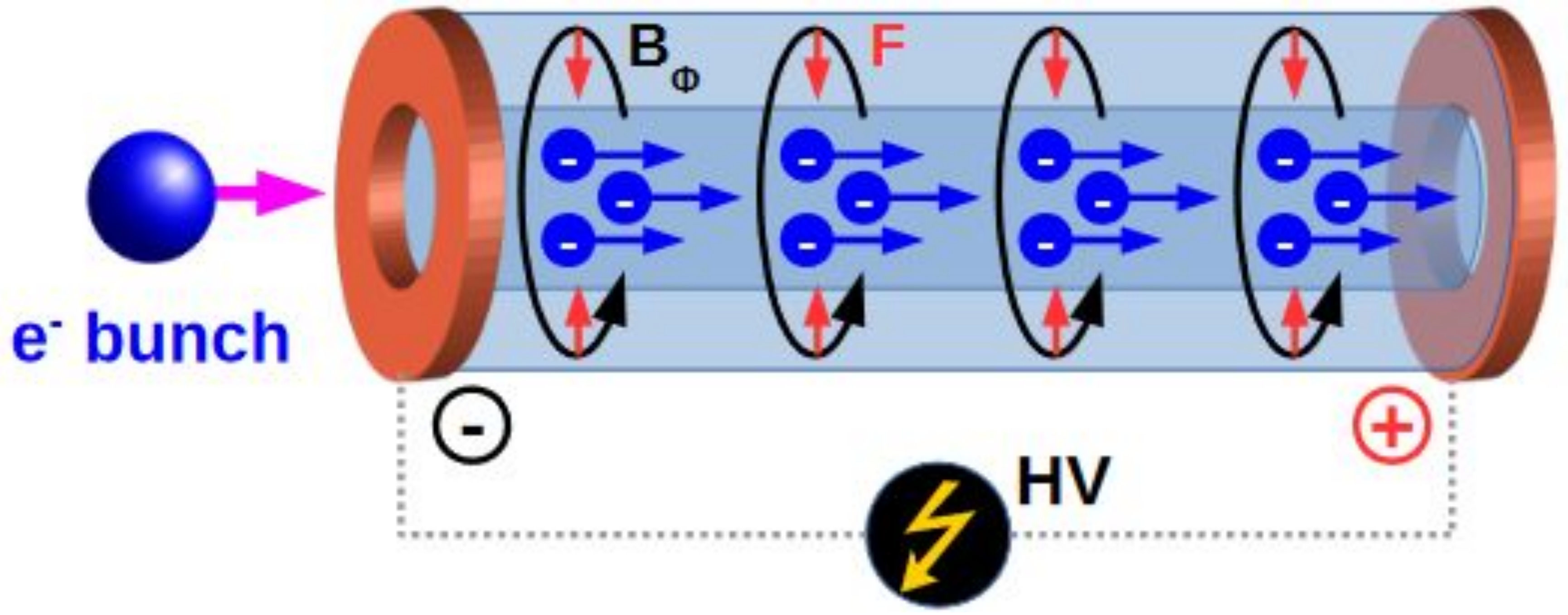
Funded by the European Union

What is an APL?:

- A compact lens that uses azimuthal magnetic fields to focus particle beams.
- Plasma lenses are more effective than traditional quadrupole magnets for beam focusing.

APL Design:

- Diameter ranging to hundreds of µm to few mm.
- Operates with light gases like hydrogen at pressures between 15-150 mbar.
- Current of ~500 A generates strong magnetic fields for beam focusing.

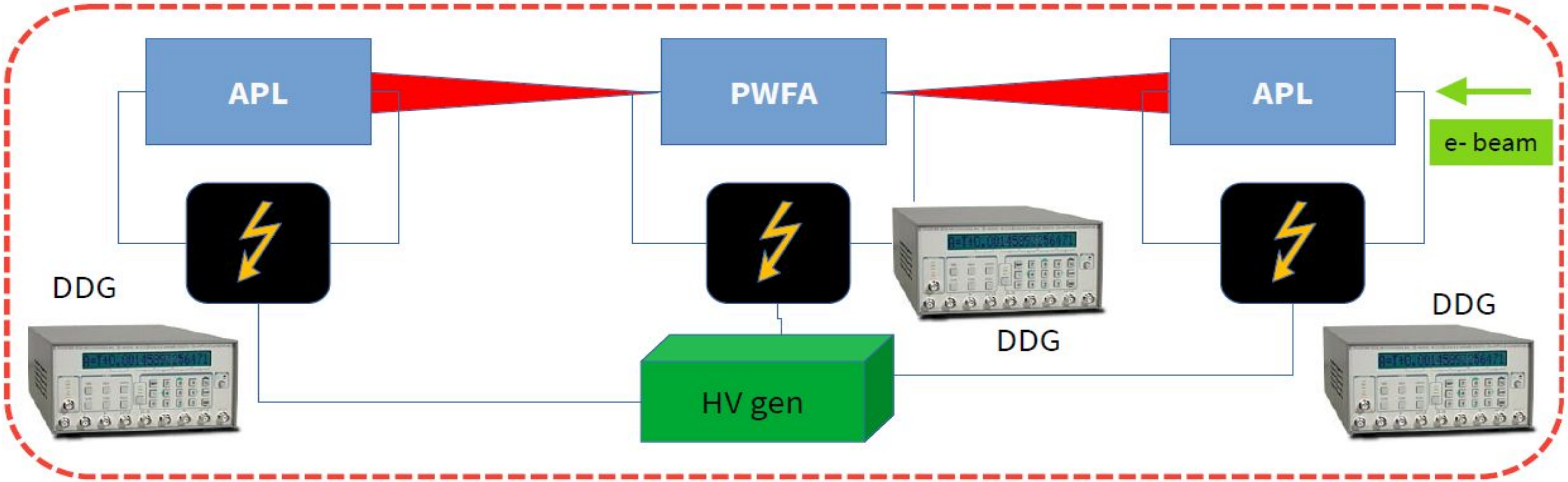


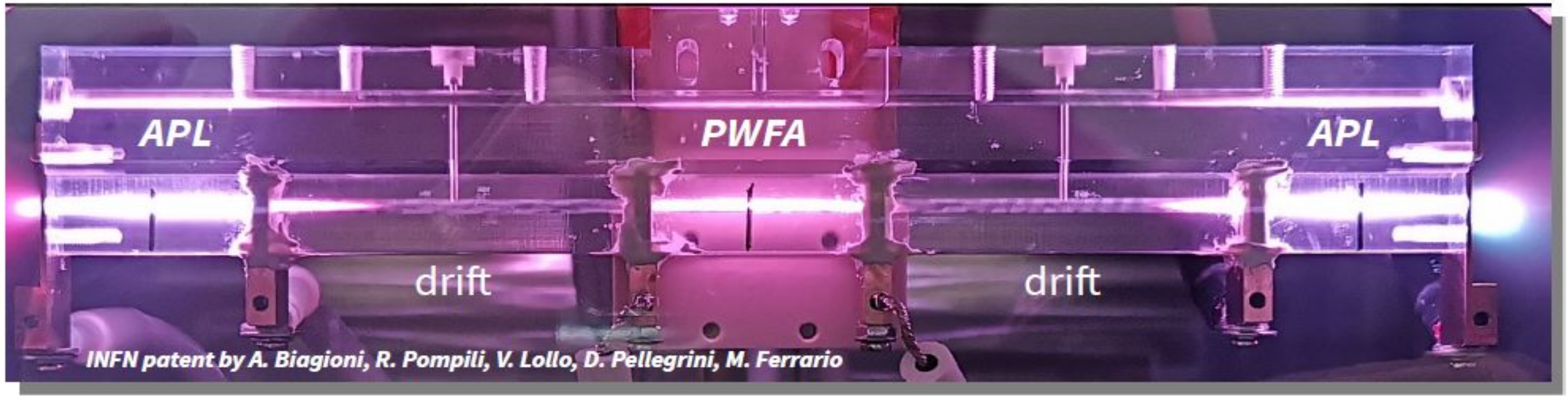
$$\partial B_\phi / \partial r = \mu_0 I_0 / (2\pi R^2)$$

- ***R*** capillary radius
- I_0 peak current

Benefits:	Challenges:
Produce radially symmetric magnetic fields. Much stronger than conventional quadrupoles and solenoids (range of kT/m for APL)	Non-linear radial magnetic fields can lead to strong emittance growth. Focus on design, must match the beam profile to the focusing field to improve linearity (via increased plasma temperature).

Capillary discharge : APL – Segmented capillary





Capillary discharge : High repetition rate

Thermal balance of the capillary:

•Determined by energy deposition and heat transport within the capillary.
•Two energy sources:
- Ohmic heating from gas discharge.
- Laser pulse energy deposition (LWFA)

Gas Distribution Recovery:

- After discharge, plasma outflows from capillary ends, depleting gas inside.
- Gas density recovers due to continuous gas flow from the supply system.
- Simulations show gas density recovers to within 1% accuracy after 100 μs.

Capillary discharge in the high repetition rate regime, P. Sasorov, G. Bagdasarov, N. Bobrova, G. Grittani, A. Molodozhentsev, and S. V. Bulanov, Phys. Rev. Res. 6, 013290 (2024)

A third limit exist : the plasma module ability so sustain high repetition rate !

↓

Lucio Crincoli presentation on Thursday, High repetition rate plasma sources

Capillary discharge : Laser guiding

Funded by the European Union

LETTERS

GeV electron beams from a centimetre-scale accelerator

W. P. LEEMANS[1*†], B. NAGLER[1], A. J. GONSALVES[2], Cs. TÓTH[1], K. NAKAMURA[1,3], C. G. R. GEDDES[1], E. ESAREY[1*], C. B. SCHROEDER[1] AND S. M. HOOKER[2]

[1]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA
[2]University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK
[3]Nuclear Professional School, University of Tokyo, 22-2 Shirane-shirakata, Tokai, Naka, Ibaraki 319-1188, Japan
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†e-mail: WPLeemans@lbl.gov

Abstract

Gigaelectron volt (GeV) electron accelerators are essential to synchrotron radiation facilities and free-electron lasers, and as modules for high-energy particle physics. Radiofrequency-based accelerators are limited to relatively low accelerating fields (10–50 MV m^{-1}), requiring tens to hundreds of metres to reach the multi-GeV beam energies needed to drive radiation sources, and many kilometres to generate particle energies of interest to high-energy physics. Laser-wakefield accelerators[1,2] produce electric fields of the order 10–100 GV m^{-1} enabling compact devices. Previously, the required laser intensity was not maintained over the distance needed to reach GeV energies, and hence acceleration was limited to the 100 MeV scale[3,4,5]. Contrary to predictions that petawatt-class lasers would be needed to reach GeV energies[6,7], here we demonstrate production of a high-quality electron beam with 1 GeV energy by channelling a 40 TW peak-power laser pulse in a 3.3-cm-long gas-filled capillary discharge waveguide[8,9].

Consolidating Multiple FemtoSecond Lasers in Coupled Curved Plasma Capillaries

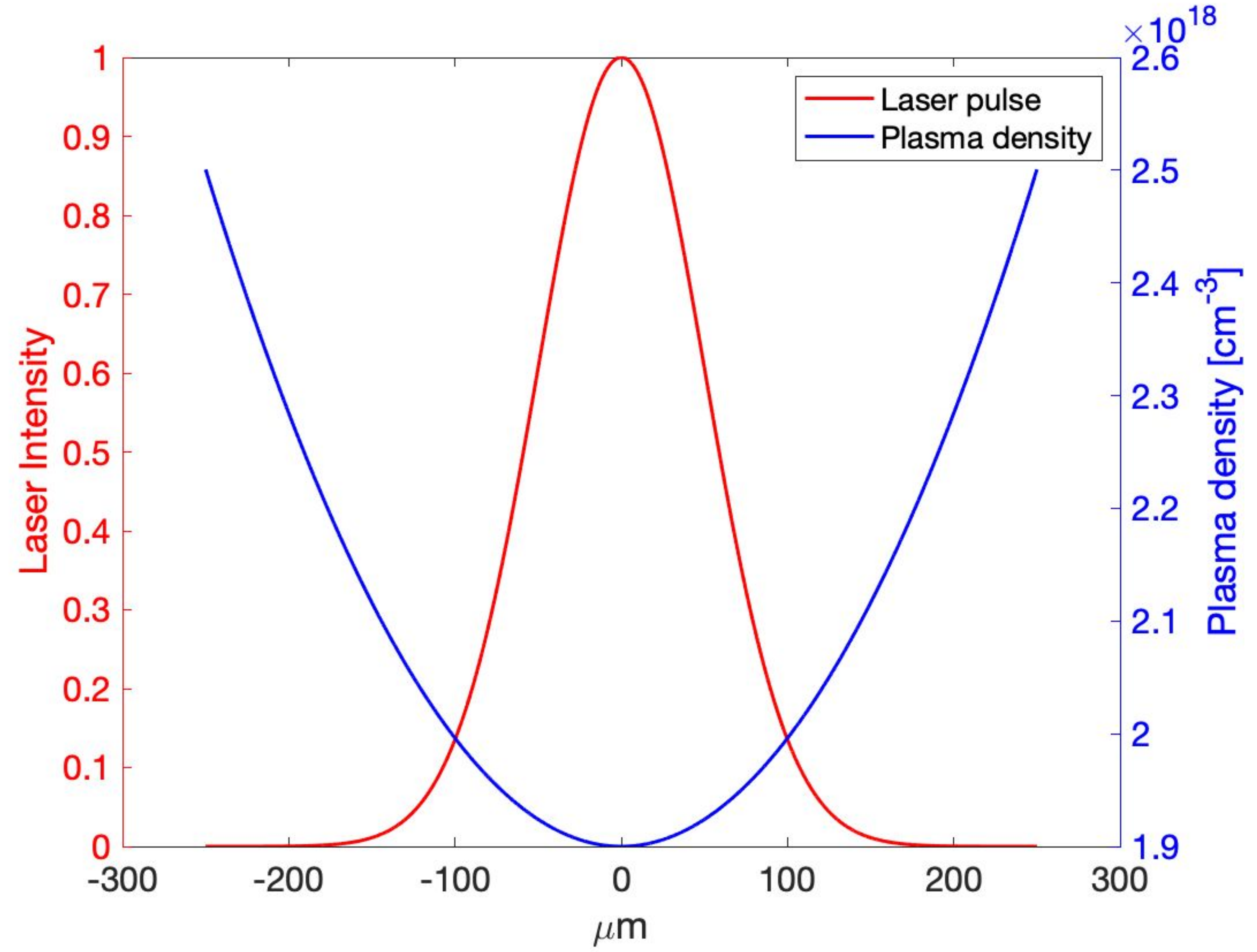
A Zigler,[1] M Botton,[1,*] F Filippi,[2] Y Ferber,[1] G. Johansson,[1] O Pollack,[1] M.P. Anania,[2] F. Bisesto,[2] R. Pompili,[2] M. Ferrario,[2] and E Dekel[1]

[1]*Hebrew University of Jerusalem, Jerusalem 91904, Israel*
[2]*Laboratori Nazionali di Frascati, INFN, Via E. Fermi, Frascati, Italia*

(Dated: May 3, 2018)

Consolidating multiple high-energy femtosecond scale lasers is expected to enable implementation of cutting edge research areas varying from wakefield particle accelerators to ultra-high intensity laser pulses for basic fresearch. The ability to guide while augmenting a short-pulse laser is crucial in future laser based TeV particle accelerators where the laser energy depletion is the major setback. We propose, analyze and experimentally demonstrate consolidating multiple femtosecond pulse lasers in coupled curved capillaries. We demonstrate a proof of principle scheme of coupled curved capillaries where two femtosecond laser pulses are combined. We found that the details of the coupling region and injection scheme are crucial to the pulse consolidations. Furthermore, our simulations show that high-intensity short pulse laser can be guided in a small curvature radius capillary. Incorporating these finding in a curved capillary laser coupler will be a significant step towards realization of meters long TeV laser based particle accelerators.

PACS numbers: 52.38.-r,52.40.Db,41.75.Jv



- Radial parabolic density distribution in the plasma channel
- Gaussian intensity laser pulse
- Uniform longitudinal density distribution

EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA Preparatory Phase

HOFI Plasma waveguides

M. Kirchen on behalf of R. Shalloo - DESY

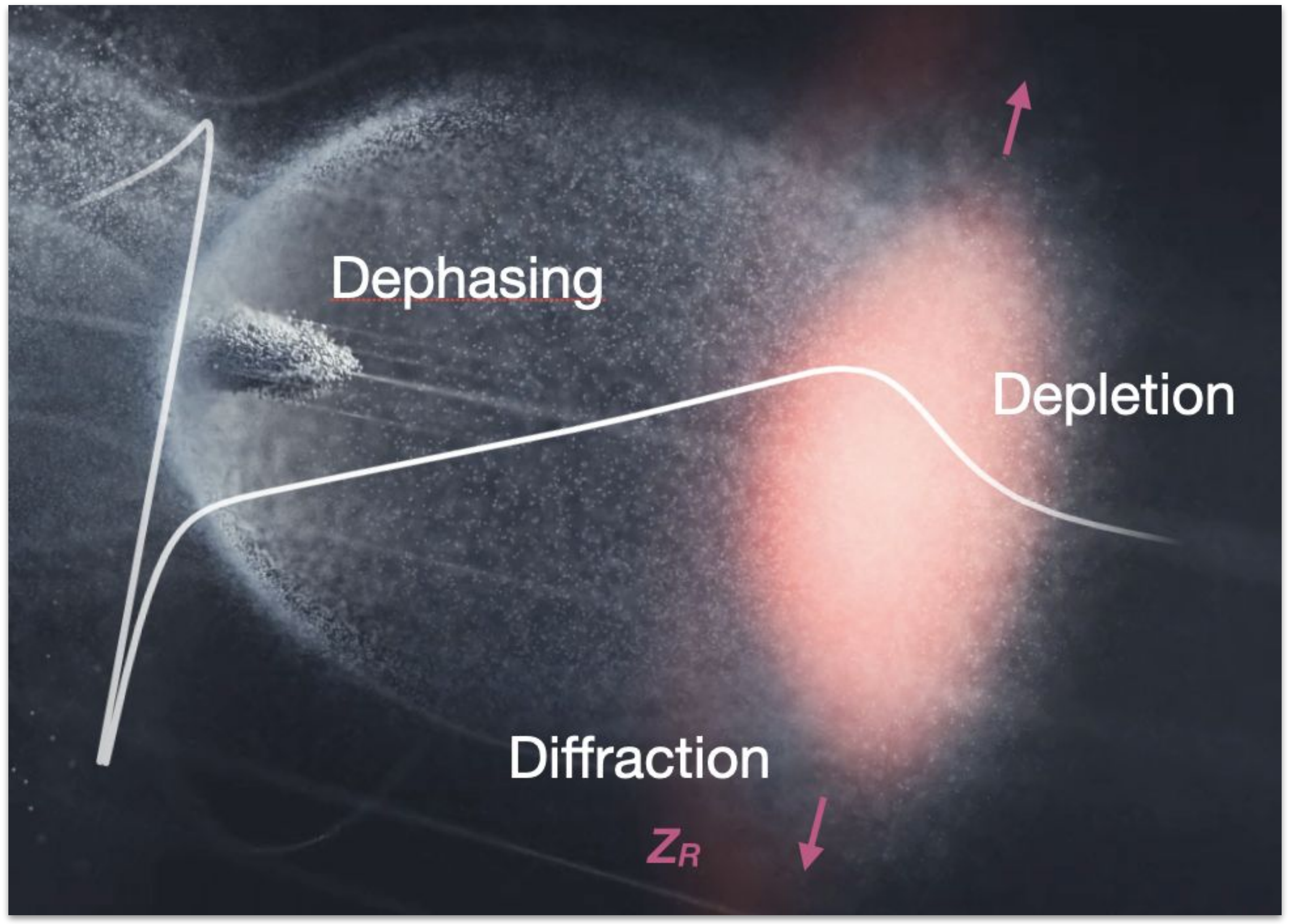
This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773

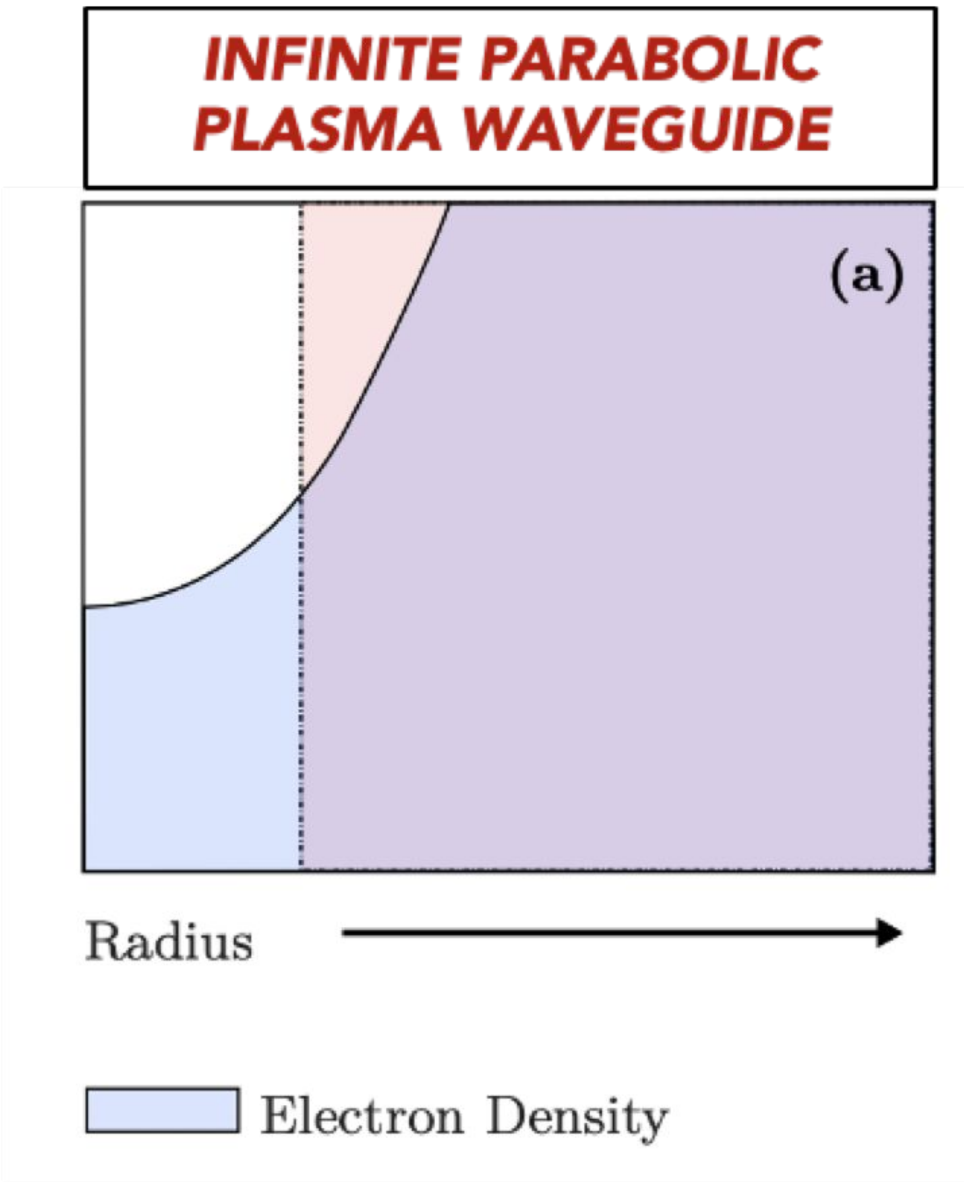
HOFI Plasma Waveguides

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

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

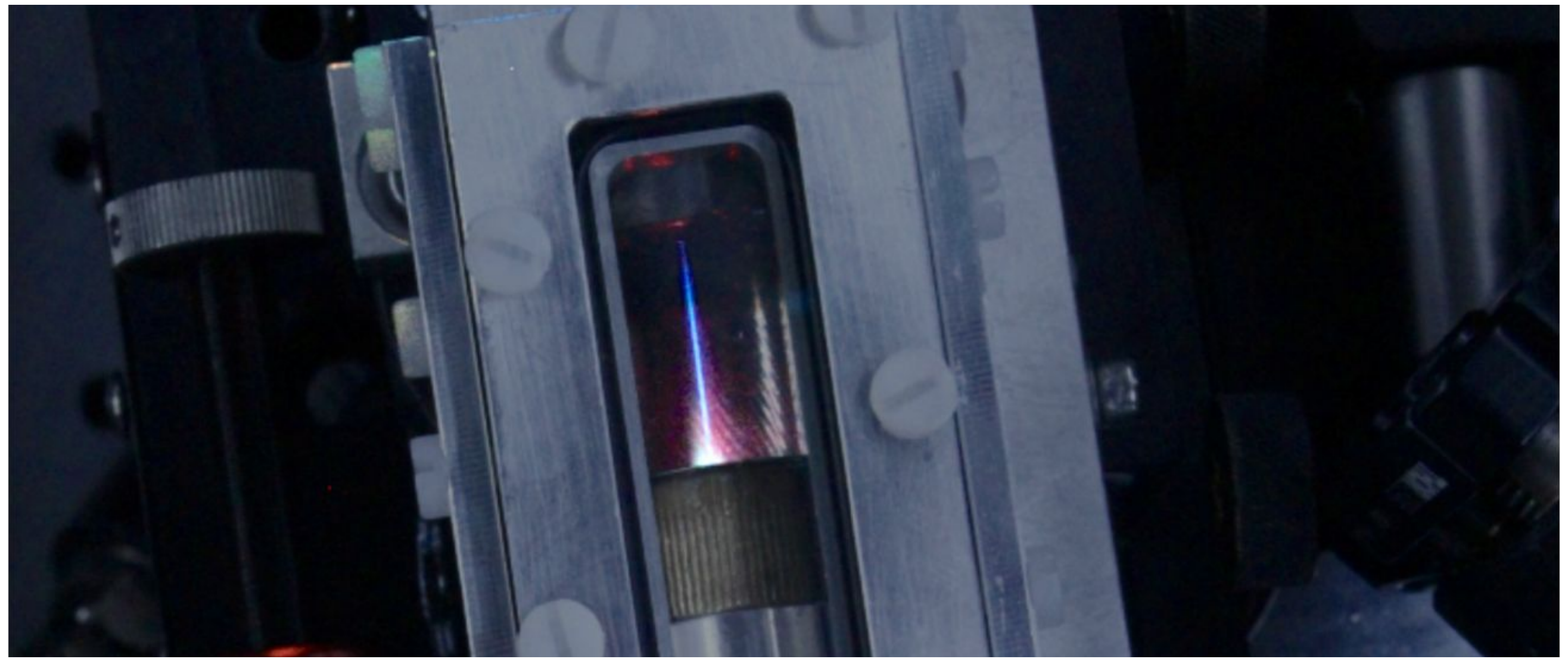
- Guiding via external density variation
- Self-guiding due to transverse wakefield
- Self-focusing due to relativistic mass increase
- Change in carrier frequency

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]

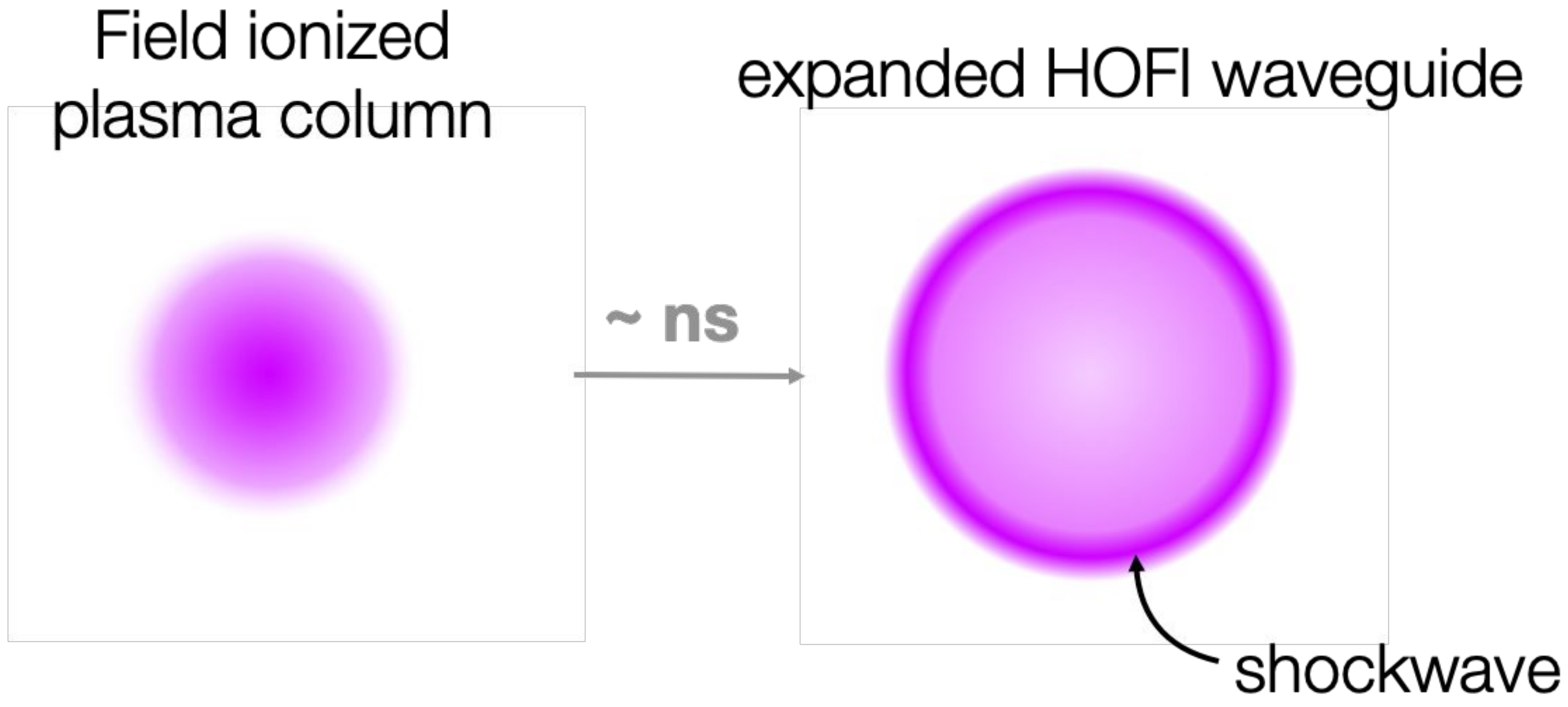
- Plasma column created via **collisional ionisation / heating**
- Expanding plasma drives shock into surrounding gas
- Generates radial density profile suitable for guiding
  - **Limited to on-axis densities > 10^{18} cm^{-3}**



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

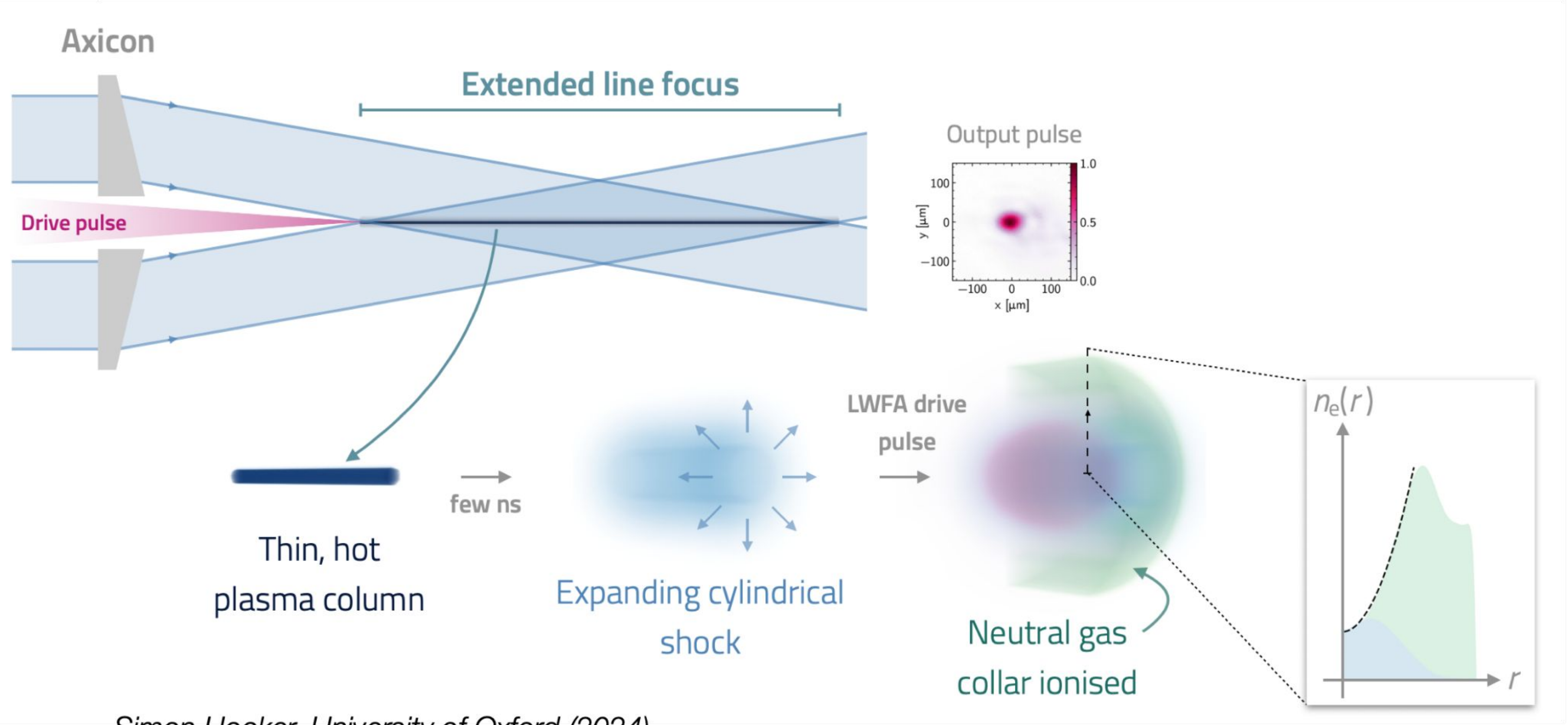
Can achieve to on-axis densities ~ 10^{17} cm^{-3}



[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)

HOFI Plasma Waveguides

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



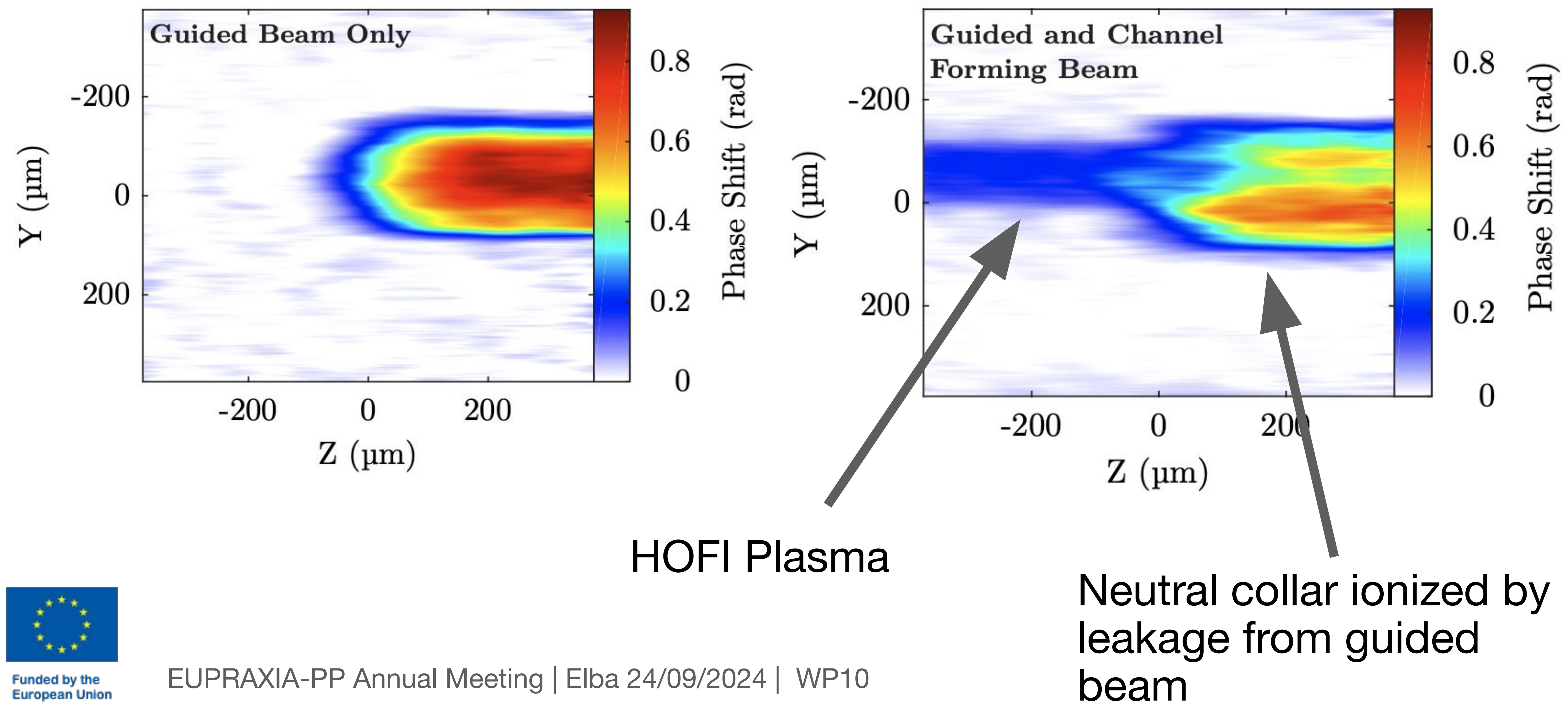
Simon Hooker, University of Oxford (2024)
https://www.physics.ox.ac.uk/research/group/laser-plasma-accelerator-group

HOFI Plasma Waveguides

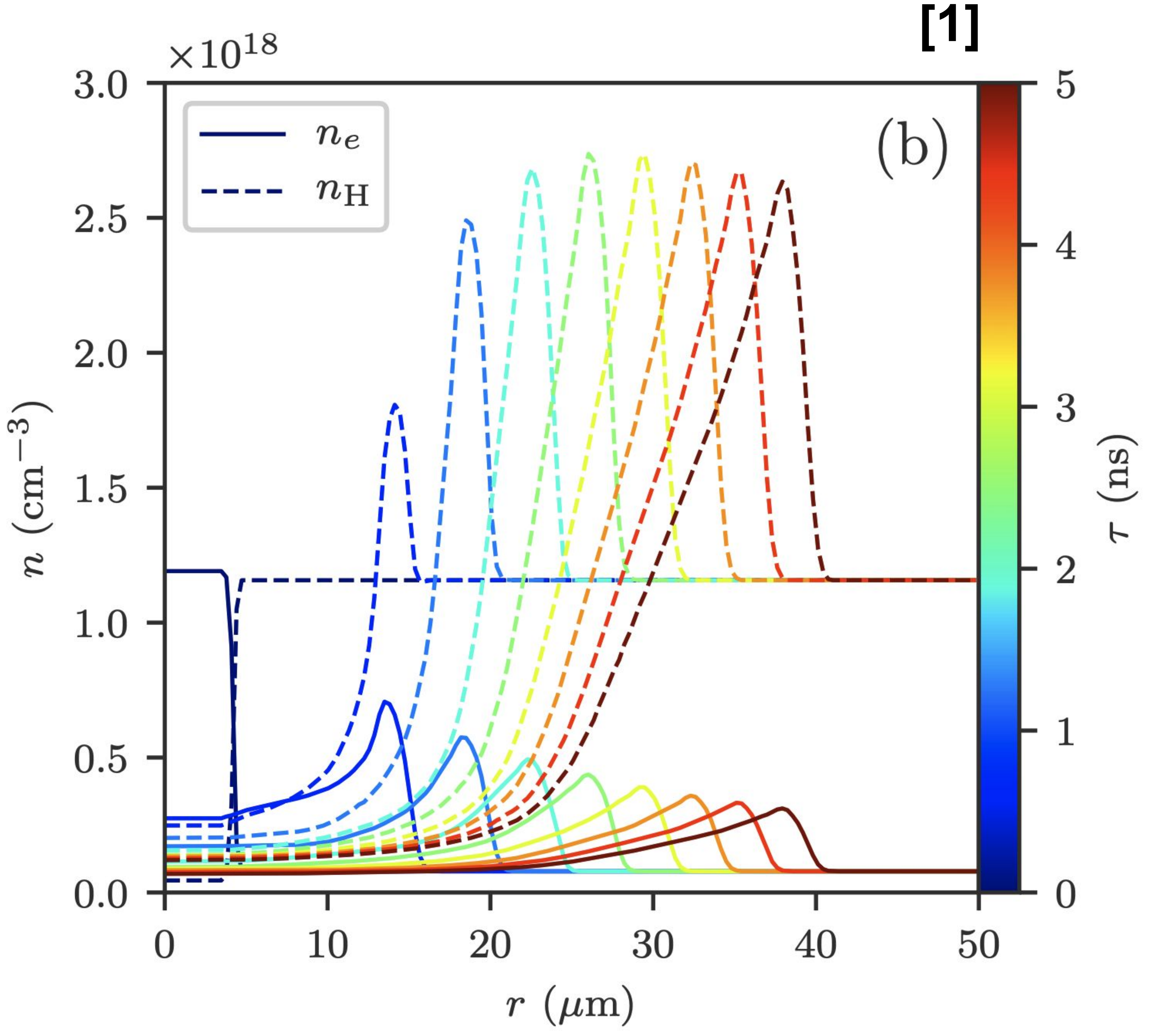
High-Density Neutral Collar Surrounding Waveguide can Enhance Guiding Properties

- **As the waveguide expands, it drives a shockwave into the surrounding neutral gas**
- **Ionisation of this neutral collar by guided / auxiliary pulse has been demonstrated to <u>significantly improve guiding confinement</u> [1,2]**

[3]



[1]

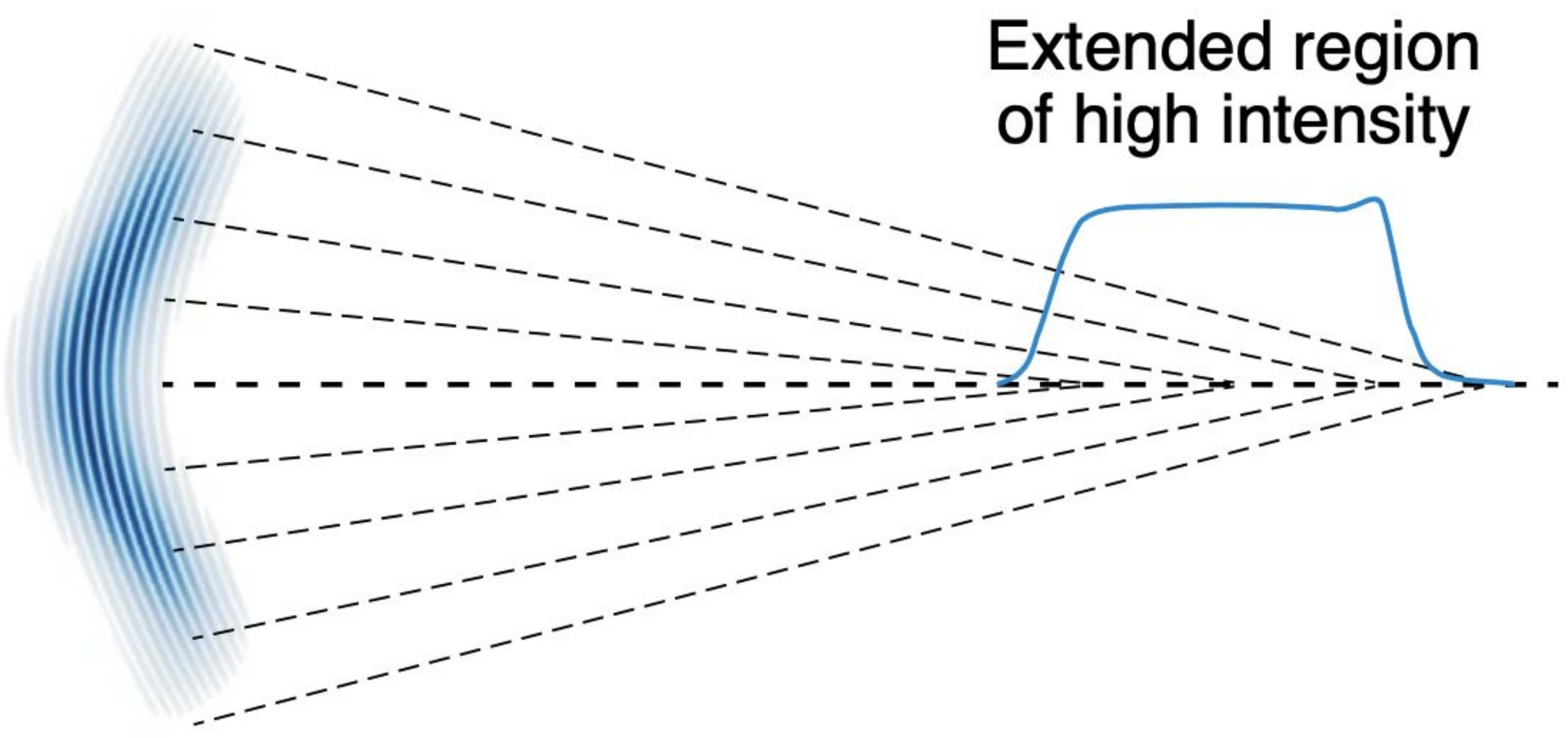


[1] A. Picklsey et al., PRE **102**, 053201 (2020)
[2] L. Feder et al., PRR **2**, 1043173 (2020)
[3] R. J. Shalloo, PhD Thesis, University of Oxford (2018)

HOFI Plasma Waveguides

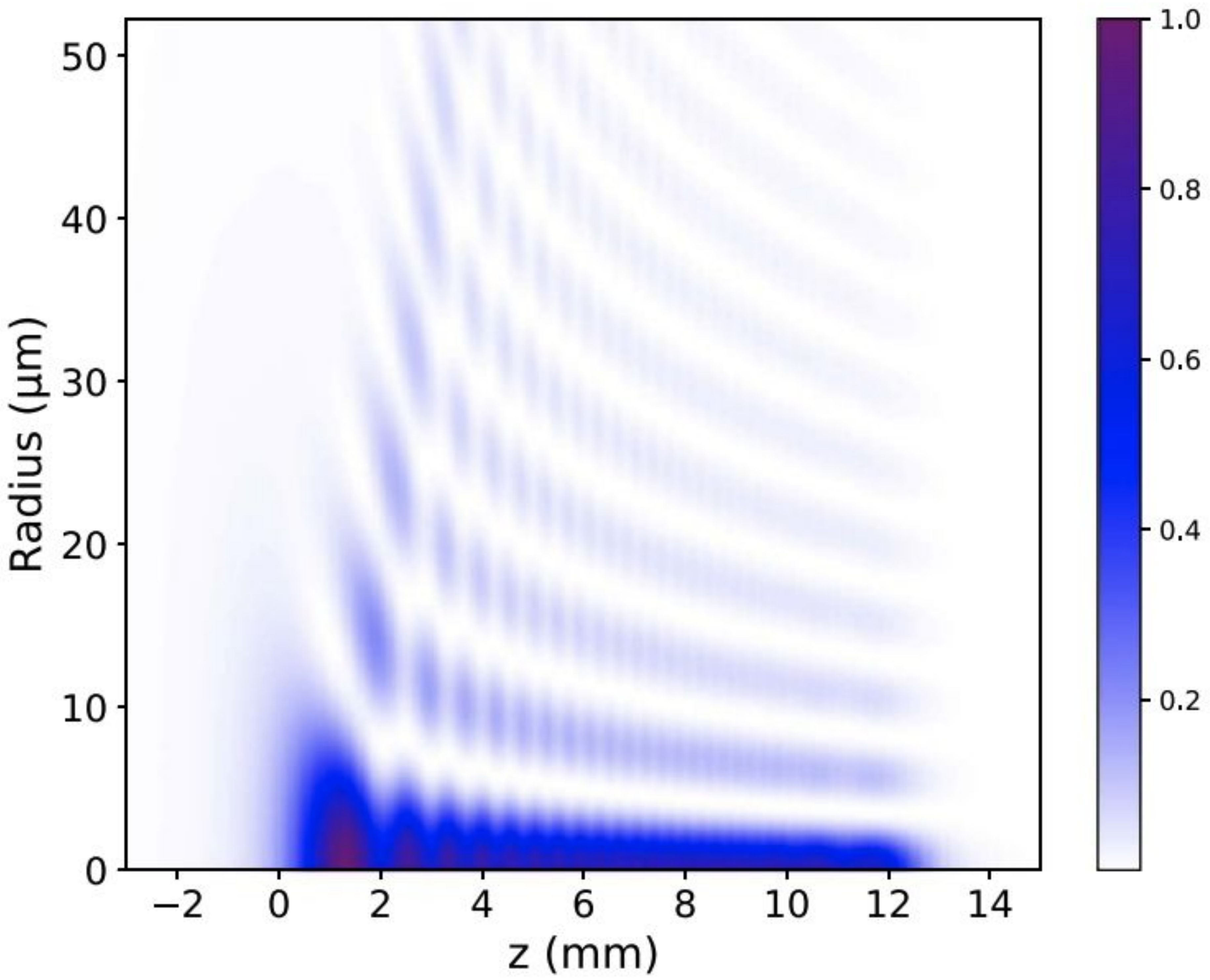
Developments in Channel Forming Optics Enable Efficient Plasma Formation

- **Transmissive [1], Reflective [2] and Diffractive [3] Axicons have been used for HOFI channel formation.**
  - Can be inefficient unless beam size matched to channel length
- **Axiparabola combines the benefits of a parabola and an axicon to shape an elongated intensity profile around the focal region [4,5,6].**
  - Can allow for a more efficient use of laser energy



Focusing with axiparabola

[5]



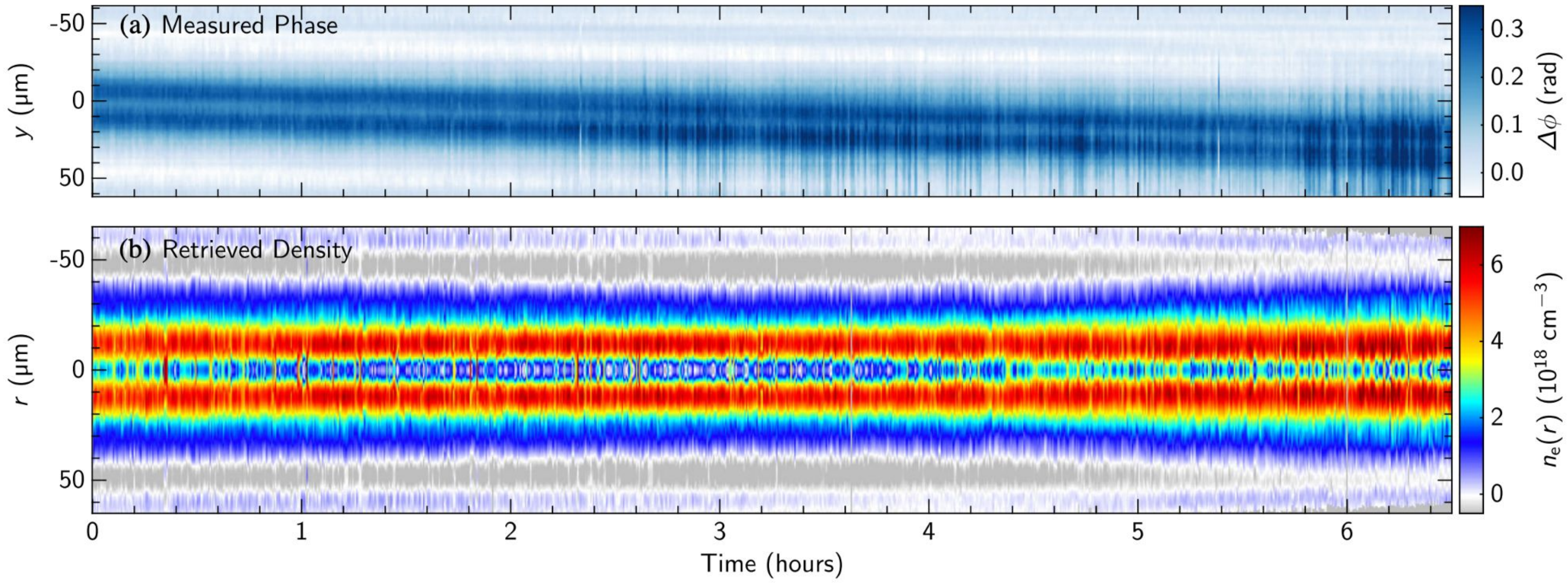
[1] R. J. Shalloo et al., PRAB **22**, 041302 (2019)
[2] L. Feder et al., PRR **2**, 1043173 (2020)
[3] B. Miao et al., PRX **12**, 031038 (2022)
[4] S. Smartsev et al., Opt. Lett. **44**, 3414 (2019)
[5] K. Oubrerie et al., J. Opt. **24**, 045503 (2022)
[6] K Oubrerie et al., Light Sci. Appl. **11**, 180 (2022)

HOFI Plasma Waveguides

High-Repetition-Rate Channel Formation Demonstrated

- **Channel formation demonstrated a 0.4 kHz repetition rates for several hours [1]**
- **Channel properties essentially unchanged when channel forming pulses separated by 1 ms [1]**

[1]



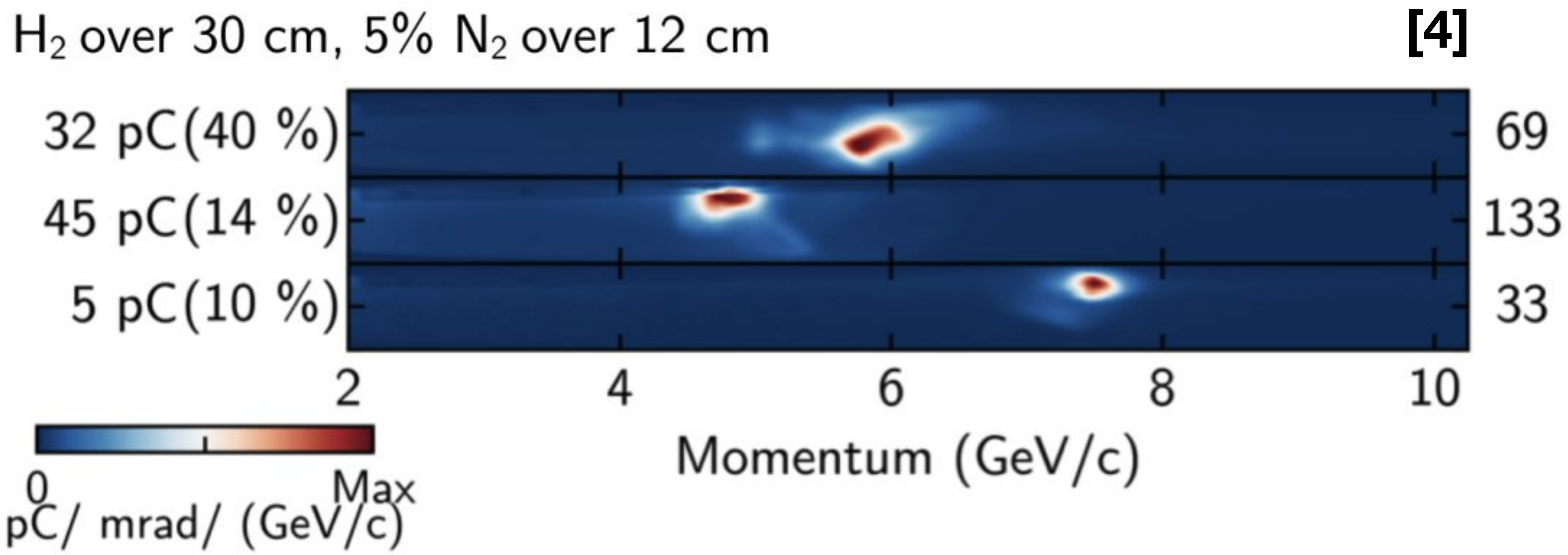
[1] A. Alejo et al., PRAB **25**, 011301 (2022)

HOFI Plasma Waveguides

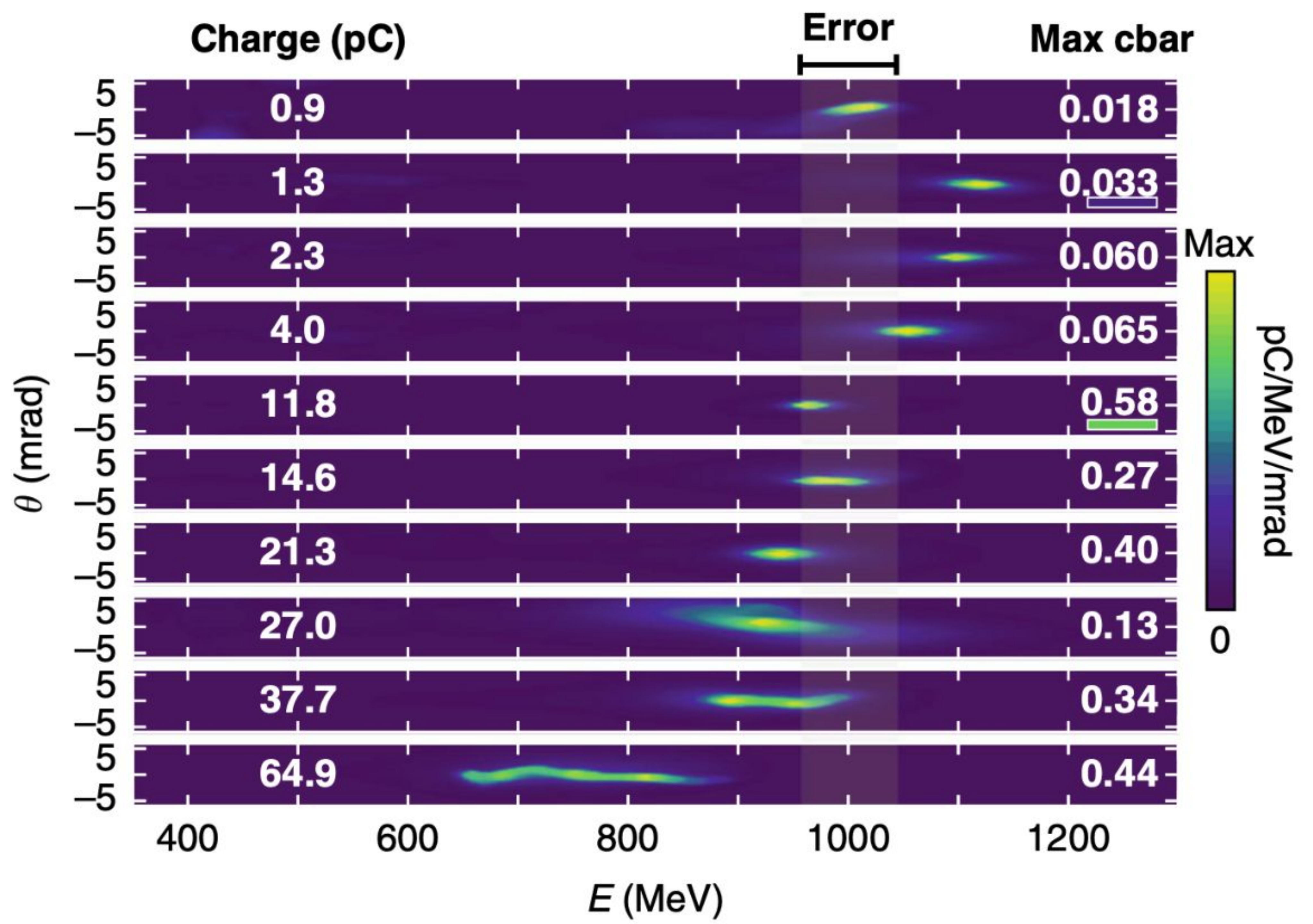
Multi-GeV Electron Acceleration

- **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)

HOFI Plasma Waveguides

HOFI fulfills our key requirements

Key Features of HOFI

- Enables small matched spot sizes at low plasma densities
- Can be combined with controlled injection techniques
- Suitable for high repetition rate operation

Expected Future Developments & Challenges

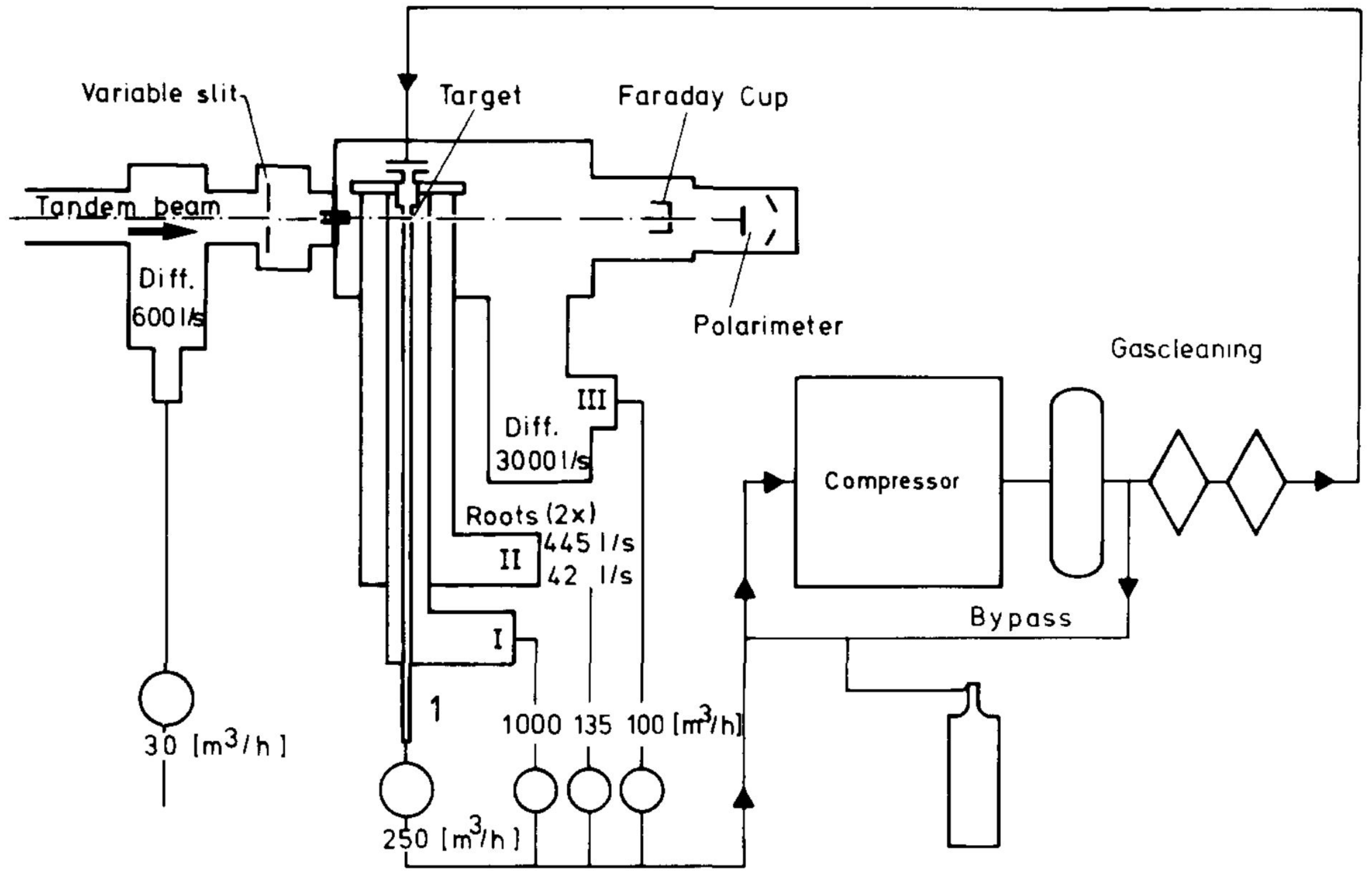
- Further beam quality improvements through precise control of injection & guiding
- Demonstration of stable, long-term operation of a guided LPA
- Evolution from proof-of-concept towards reliable operation at the 10 GeV level

Funded by the European Union

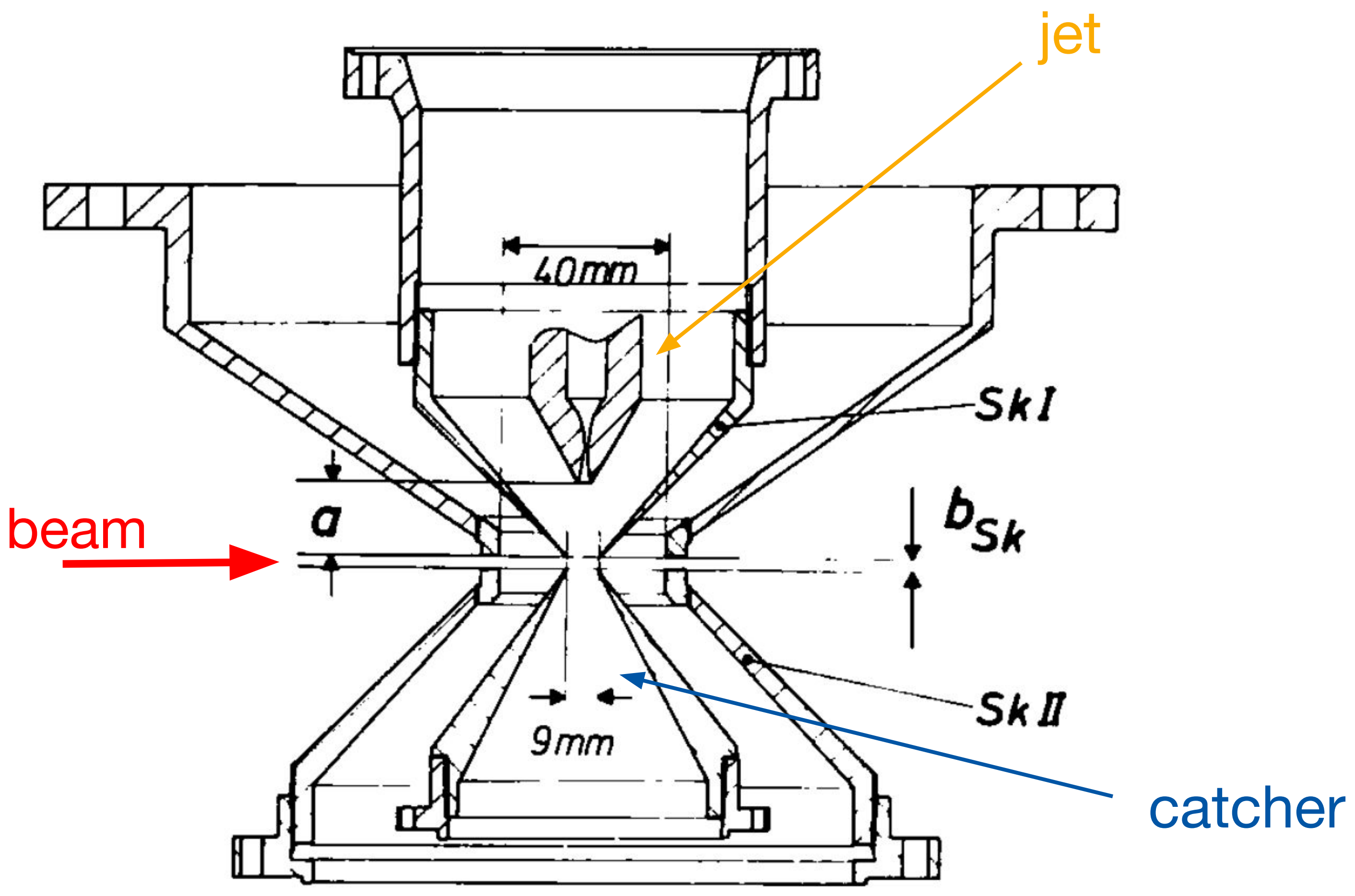
WP10 Plasma system integration

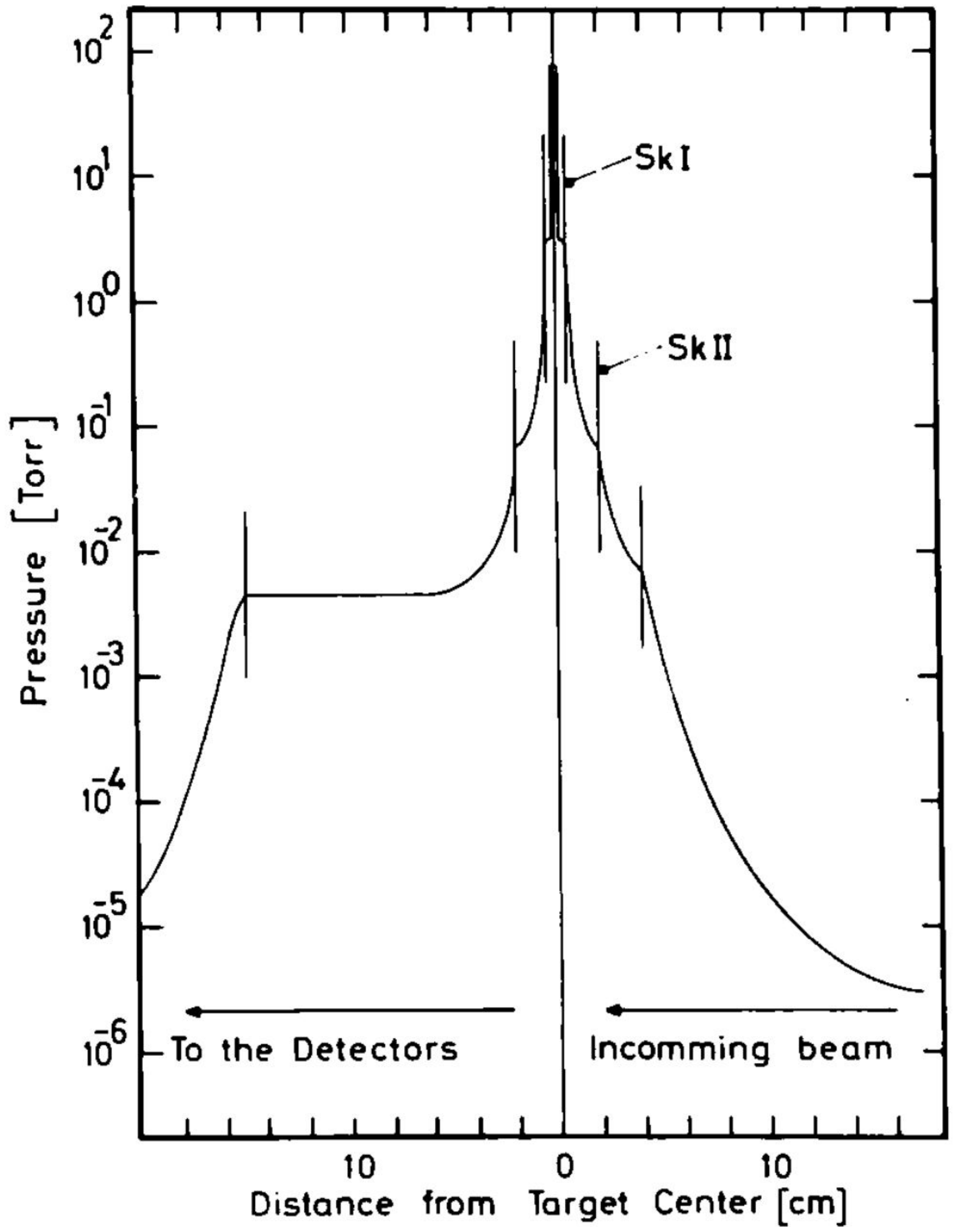
Vacuum

Integration of **gas target** in ultra high vacuum(**UHV**) -started in the 1970's for nuclear experiment and still today (JENSA[1], Prad[2], ERNA[3]…etc)



[4] Bittner, et al. *NIM* 167, 1–8 (1979).





[5] Tietsch, *et al.* NIM 158, 41–50 (1979).

Similar **differential pumping** have allow integration of high density target in **HV/UHV beamline for LPA** [6,7,8]

Move to close or open geometry in continuous flow is key aspect for high repetition rate operation

[1] K. Schmidt, *et al.,* Nucl. Instrum. Methods Phys. Res. A 911 (2018) 1-9.
[2] W. Xiong, *et al.,* Nature 575 (2019) 147.
[3] D. Schurmann *et al.* Eur. Phys. J. A (2013) 49:80
[6] N. Delbos et al. NIMA 909 318 (2018)
[7] P. Drobniak *et al.* arXiv:2309.11921 (2023)
[8] J. Monzac *et al.* arXiv:2406.17426v1 (2024)

WP10 Plasma system integration

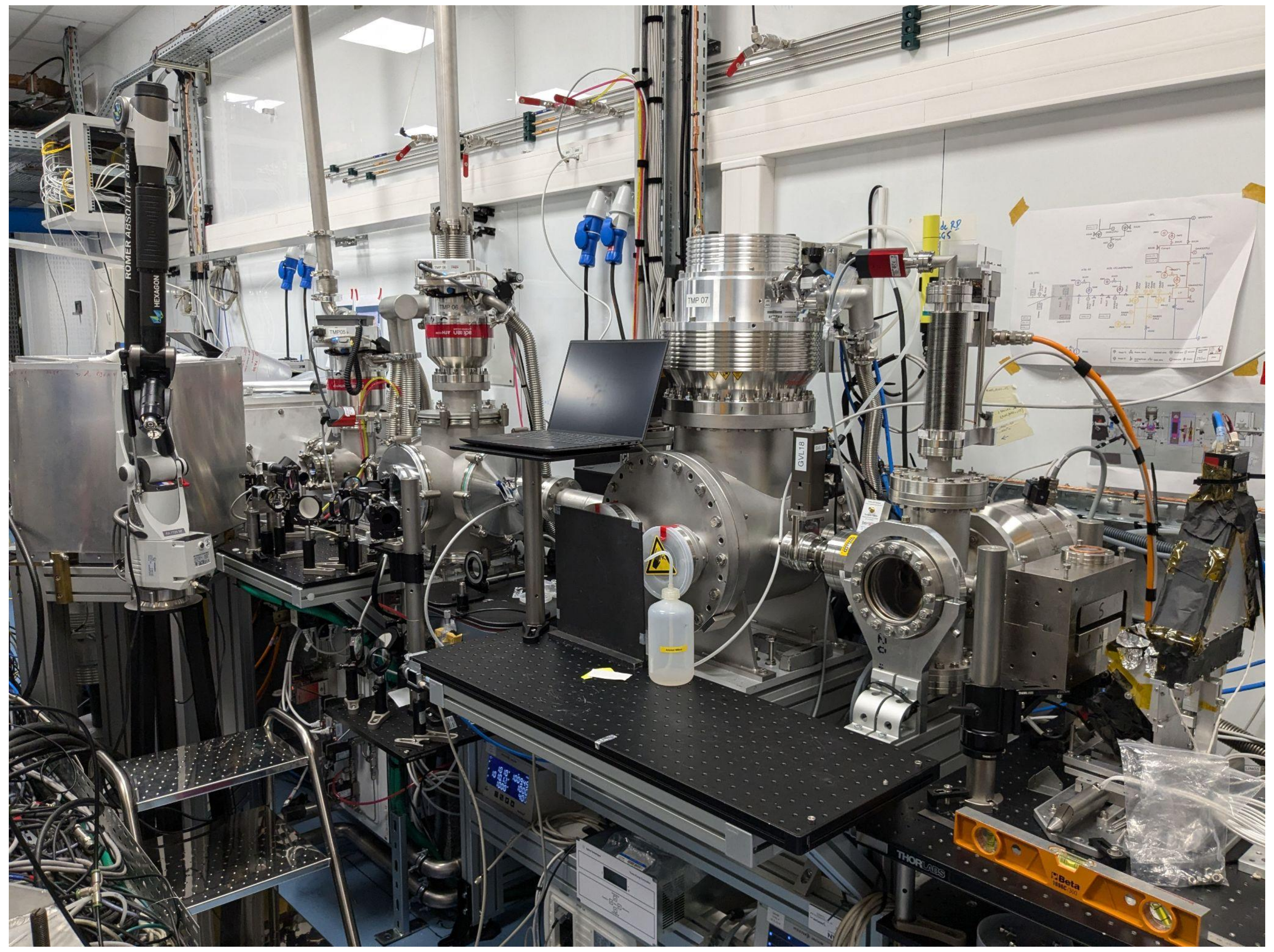
Alignment

Plasma systems alignment can be challenging and must be take as initial design constraint.

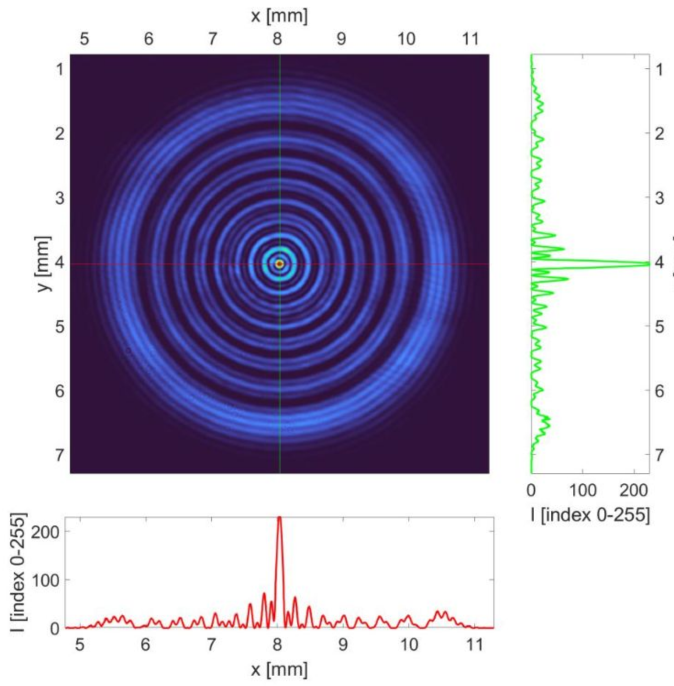
Typical length of EuPRAXIA beamline are 100-150m [1].

- Dependant on BD studies / electron source mechanical design
- 3 axis to overlap: *mechanical, laser, magnetic*
- Compactness can be challenging:
  - combination of coordinate measuring machine **CMM** [2], **optical axis transfert tool** and l**aser tracker** for global positioning and monitoring: *preliminary test* <0.1 mm (rms) [3]
- laser based alignment with **Structured laser beam** (SLB)[4] pseudo non-diffractive beams

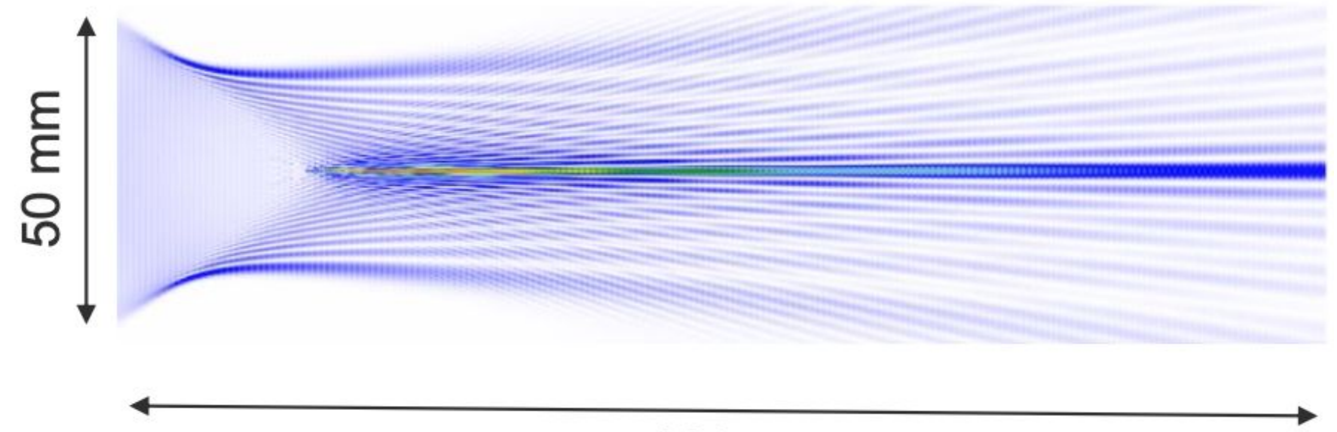
- Beam based alignment (BBA) [5] and Beam Pointing Alignment Compensation (BPAC) for LPA electron source[6]



[3] PALLAS LPI beamline, CMM + LT + OATT (2024)



SLB – Real image



SLB – Simulation of a longitudinal profile

https://kt.cern/technologies/structured-laser-beam

[1] F. Villa et al. EuPRAXIA@SPARC LAB Status Update, SPIE,12581 (2023)
[2] Romer arm, Hexagon (2024),IWAA 2022 - CERN
[4] K. Polak et al. Euspen Conf., vol. EUSPEN2022, p. 4, (2022)
[5] P. Emma, et al. Phys. Res., Sect. A 429, 407 (1999).
[6] T. André et al., Nat. Commun. 9, 1334 (2018).

Funded by the European Union

Futures challenges

Current identified issues

- **Long term reliability**
- **High repetition rate (≥10 Hz) :**
  - **material robustness (laser / plasma) erosion**
  - **high temperature / heat management**
- **Plasma components integration**
- **For beam driven component (plasma discharge):**
  - central part material
  - Anode / cathode material optimisation

    L. Crincoli *et al.* High repetition rate plasma sources https://agenda.infn.it/event/41613/contributions/235522/
- **For laser-driven component:**
  - **Laser quality:** assess more in details laser parameters requirement
  - **Manufacturing:** hard material, sub-mm structures (LPI), integration of heat dissipation

→ **TRL?**

We are looking forward to see you at the **Workshop on Plasma components and systems for EuPRAXIA in DESY the 27-28 January 2025**

To discuss update concept and define a roadmap for the development plasma components and sources for EuPRAXIA!

Thanks for your attention

Funded by the European Union