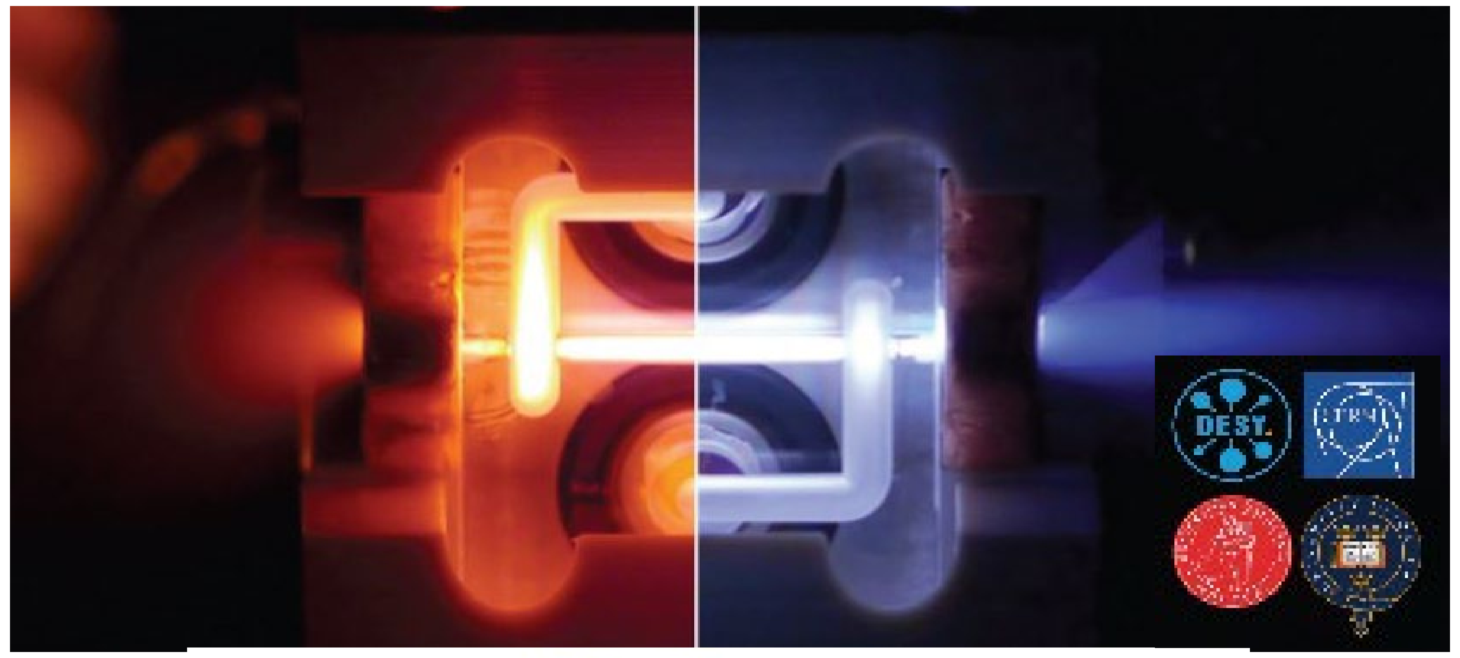
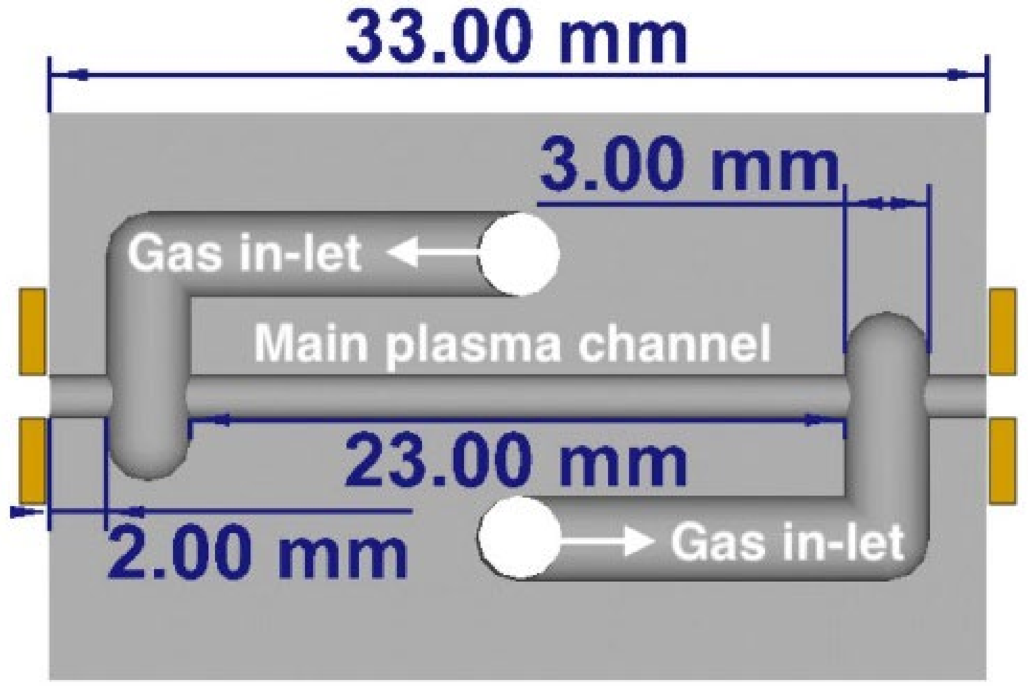
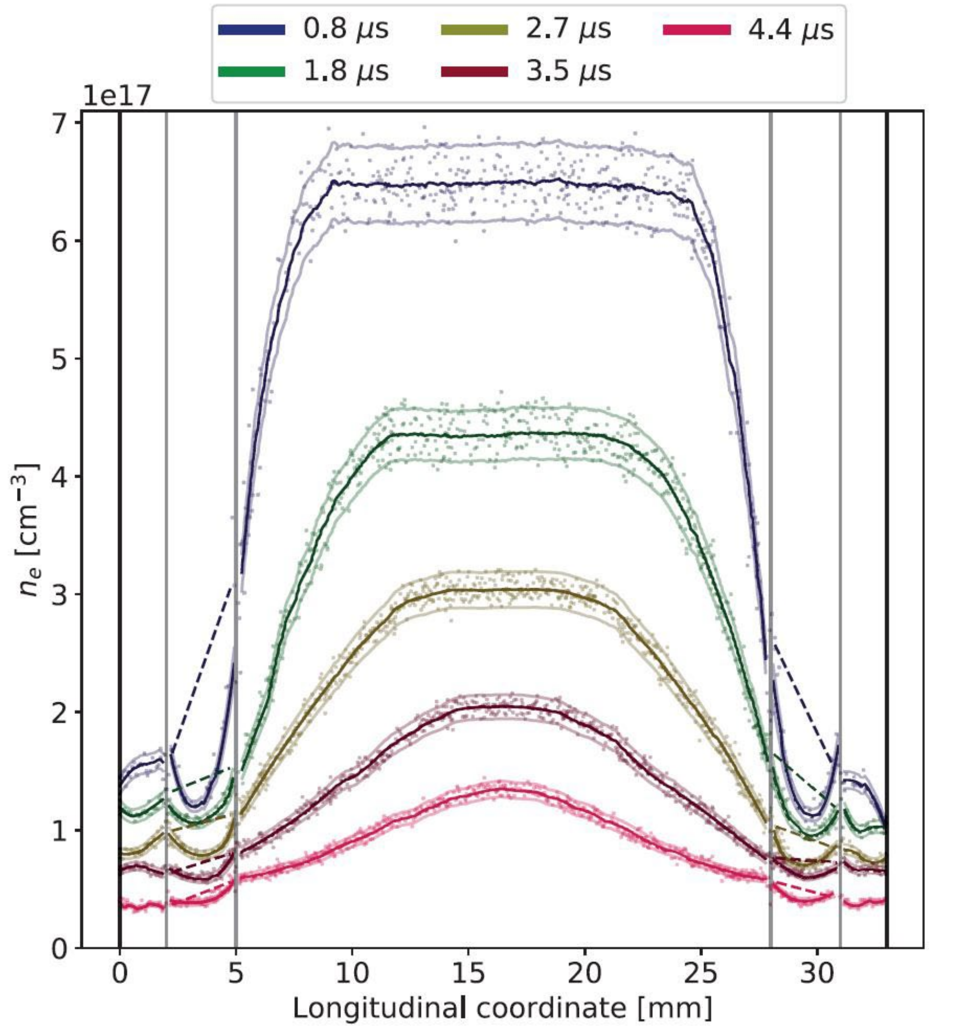
Capillary discharges

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

Funded by the European Union

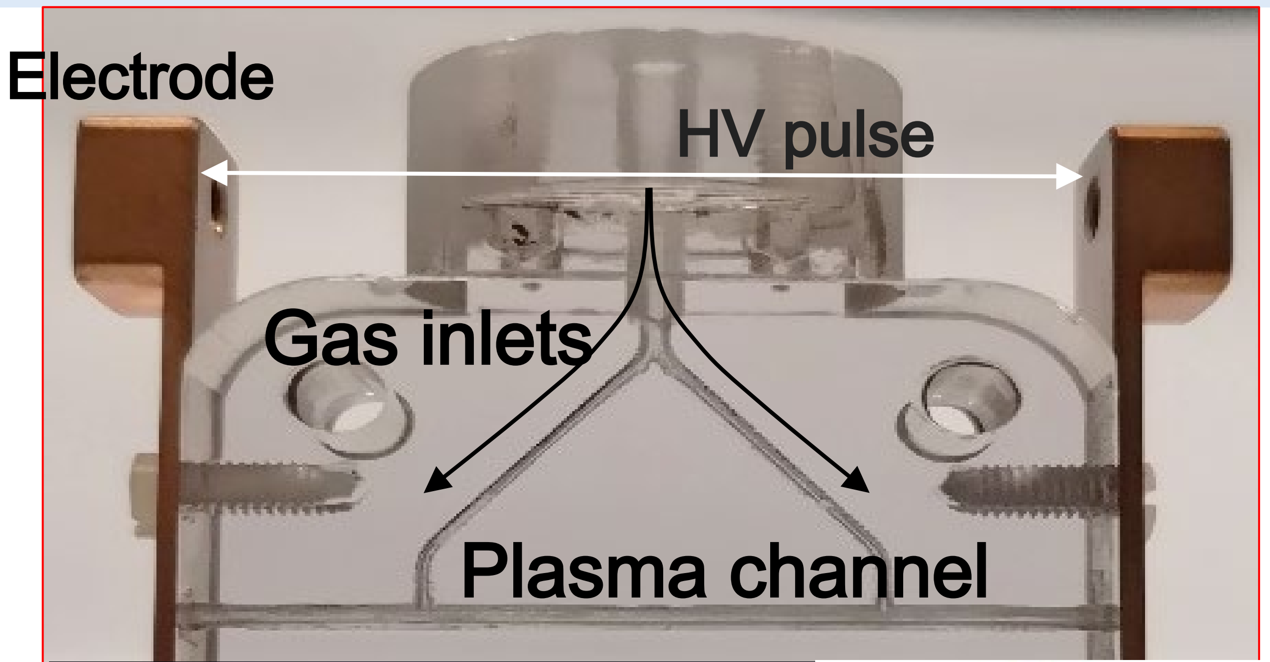


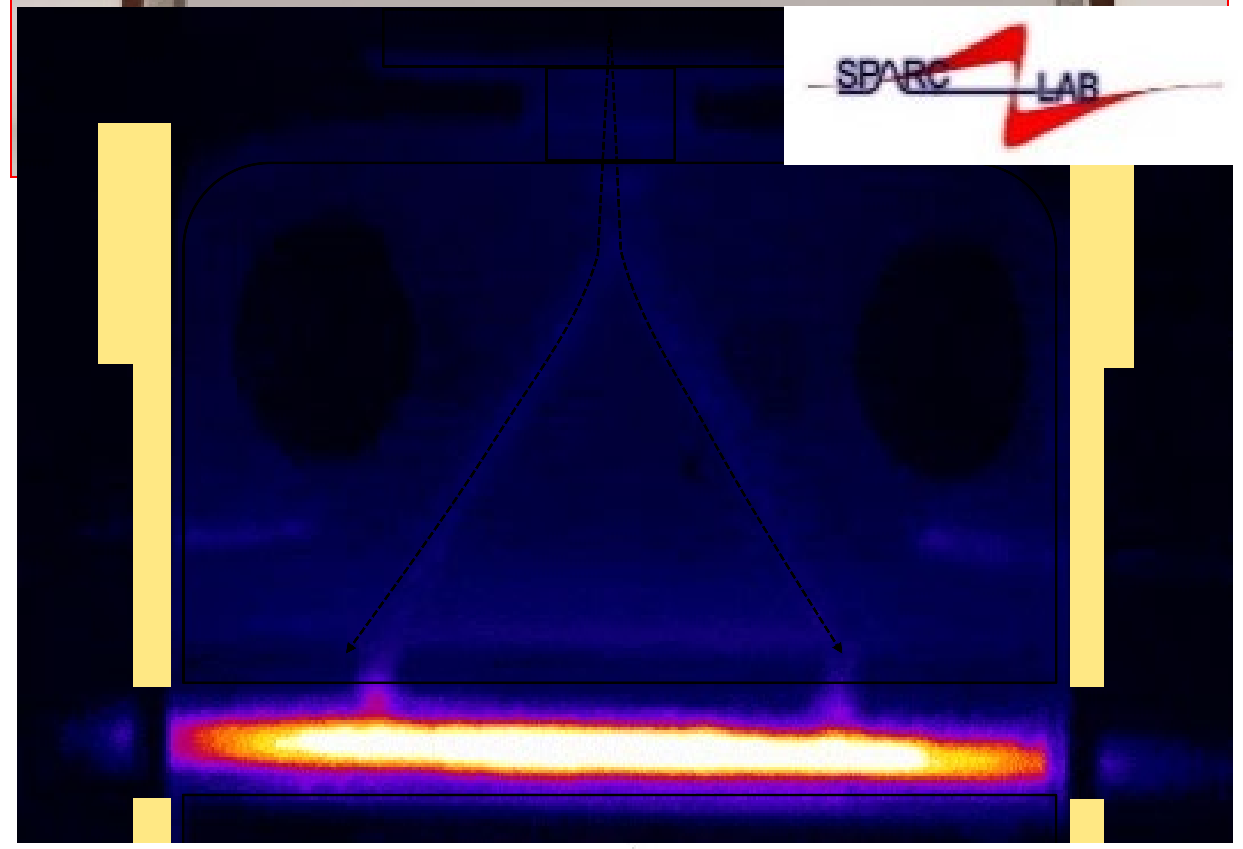


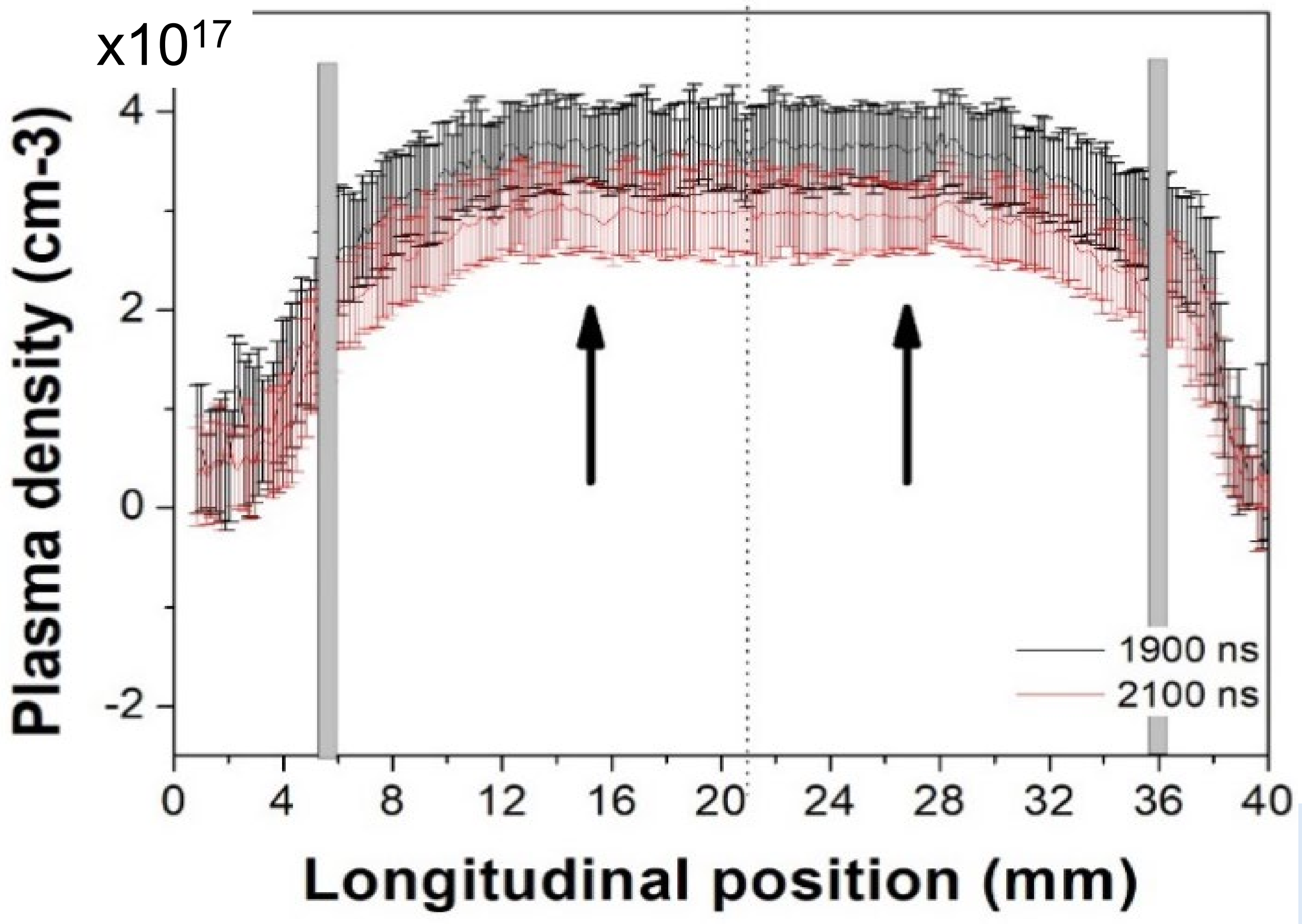


Capillary discharges properties

- 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

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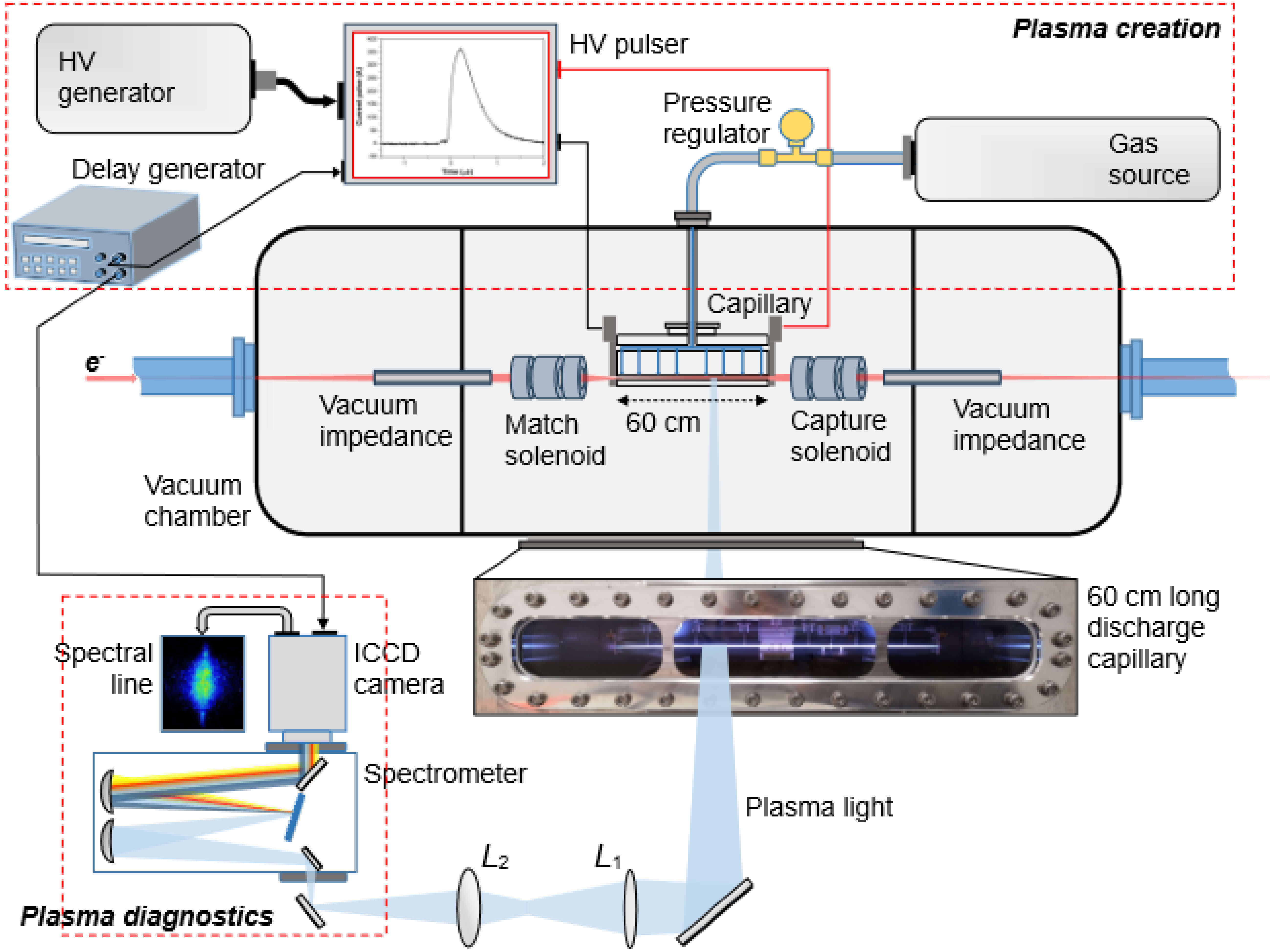
Capillary Discharge Design:

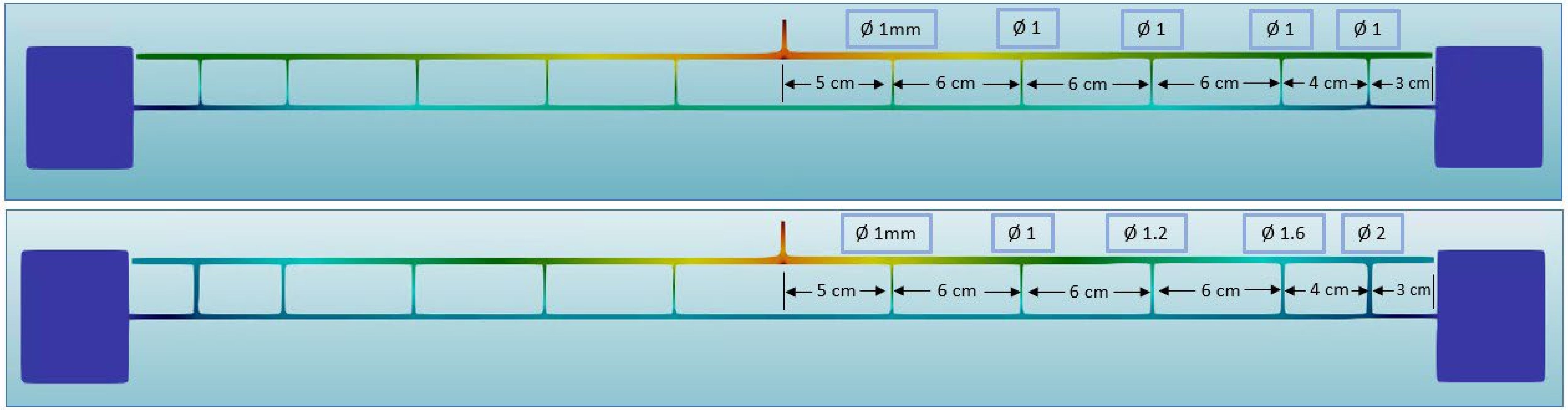
- 60 cm long, 2 mm diameter capillary
- High-voltage pulses (7-15 kV) create a stable plasma channel
- Gas pressure control (10-100 mbar) critical for plasma density stability
- Uniform plasma density ensures beam quality and particle acceleration

Plasma module:

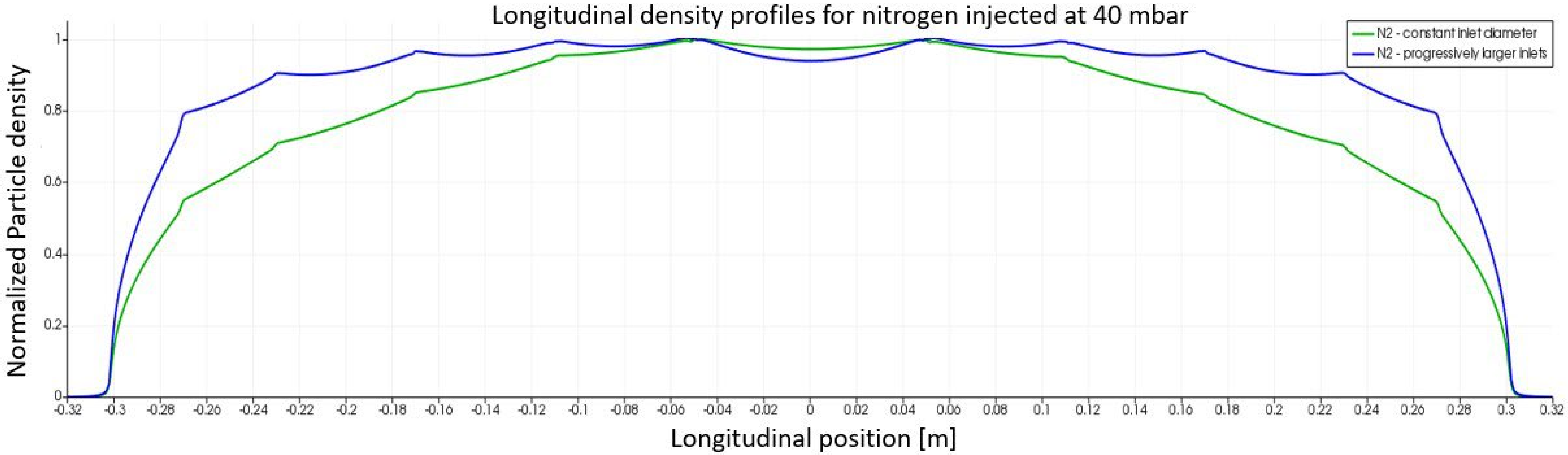
- Hydrogen gas in continuous flow
- Vacuum chamber at $10^{-2} mbar$(scroll pumps, turbo-molecular pump)
- High-voltage generator powering µs-short pulses to capillary electrodes
- Delay generator sets repetition rate (10-150 Hz)
- Cooling: water for pump, fan for HV pulser



Capillary Discharge : Geometry control of density

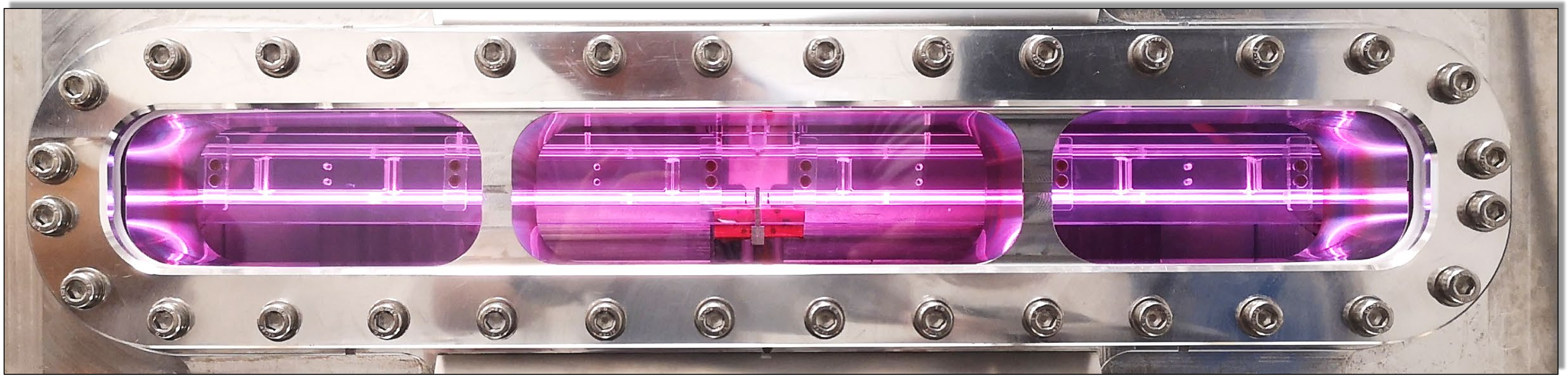


- OpenFOAM simulation of gas distribution
- 10 gas injector
- 2 different configuration of diameter injections
- Critical point near the exit where the gas exit
- Density around $3 \times 10^{17} cm^{-3}$



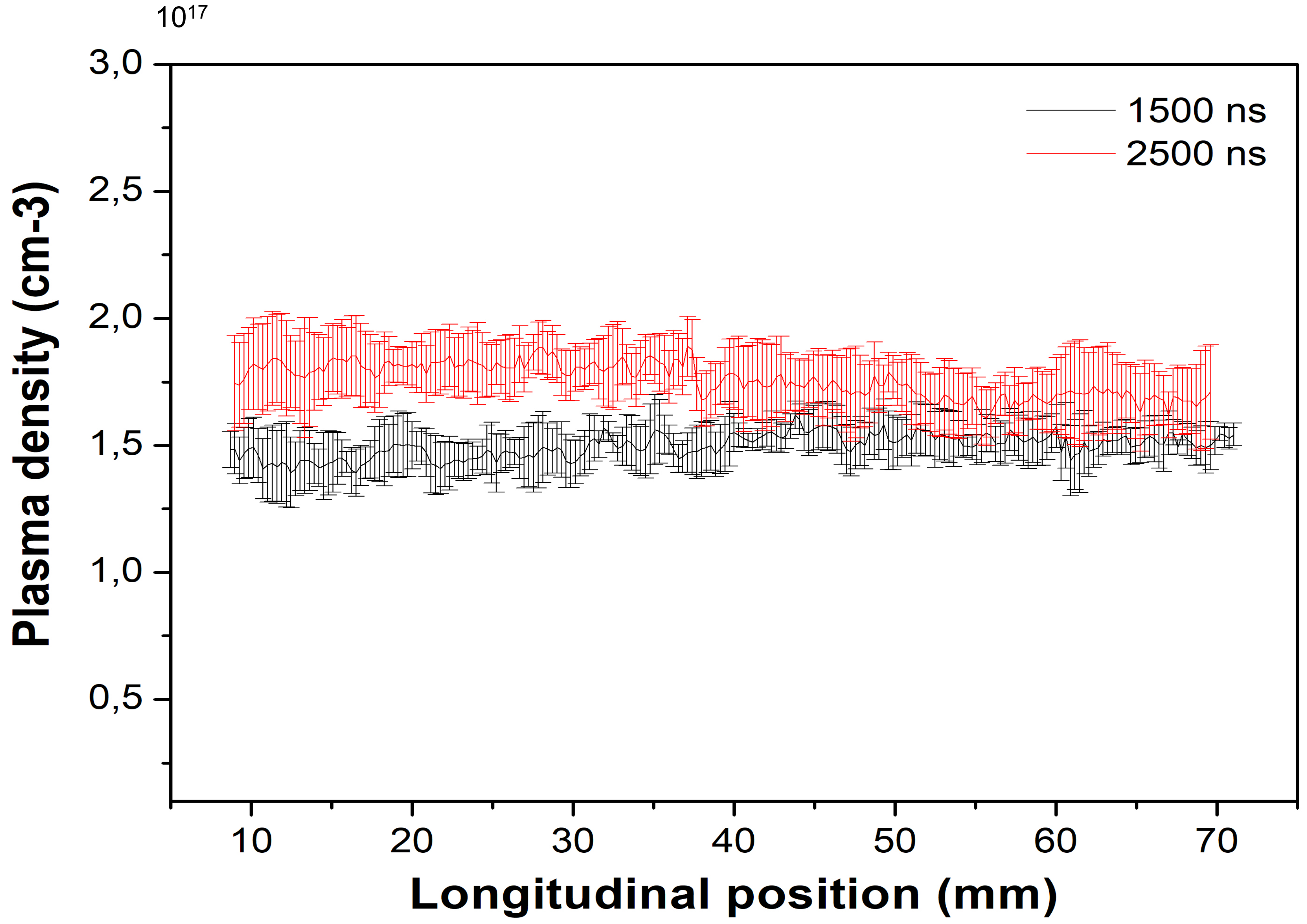
- Possibility to control plasma profile = better matching between beams and plasma
- Diverse average density achievable by playing with pressure and voltage

Capillary discharge : 60 cm prototype



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

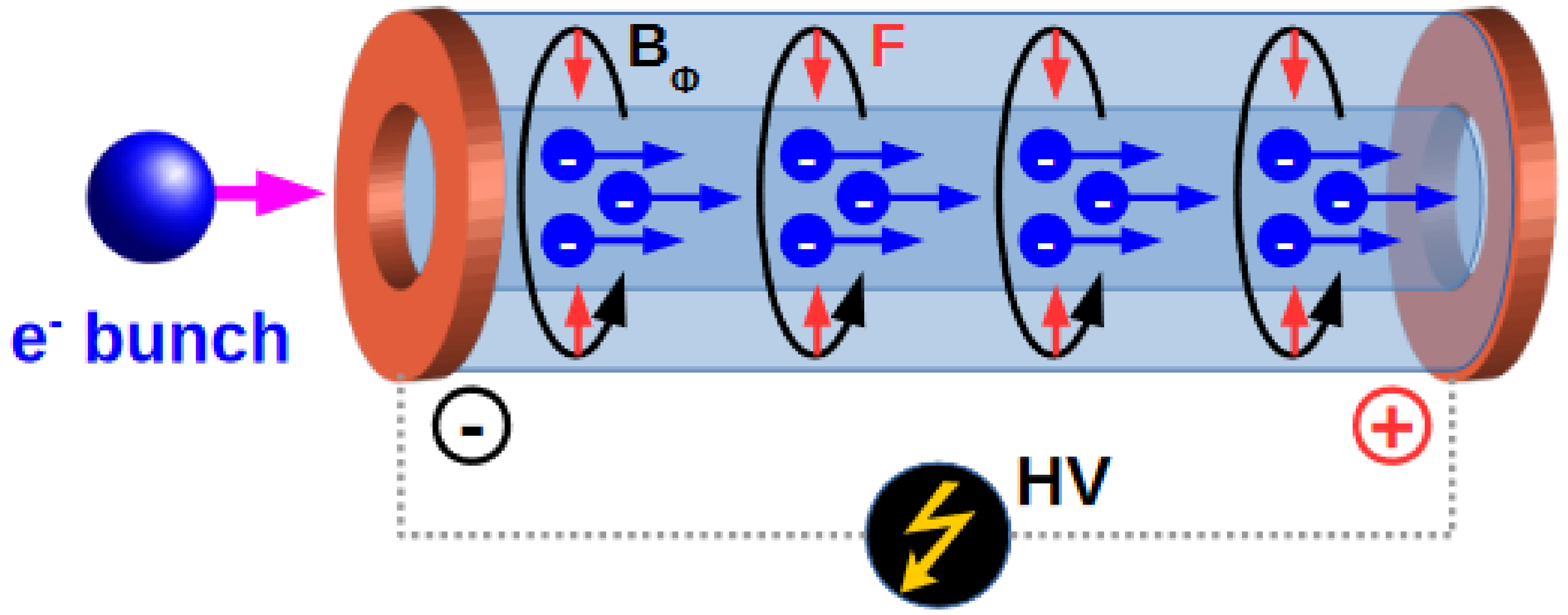
- Fabrication by machining
- 10 increasing diameters
- Density range 10^{16} -10^{17} cm^{-3}
- 13 kV with 500 A
- **100 Hz rep Rate**



Capillary discharge : Active Plasma Lens

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.



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

- *R* capillary radius
- I_0 peak current

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.

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

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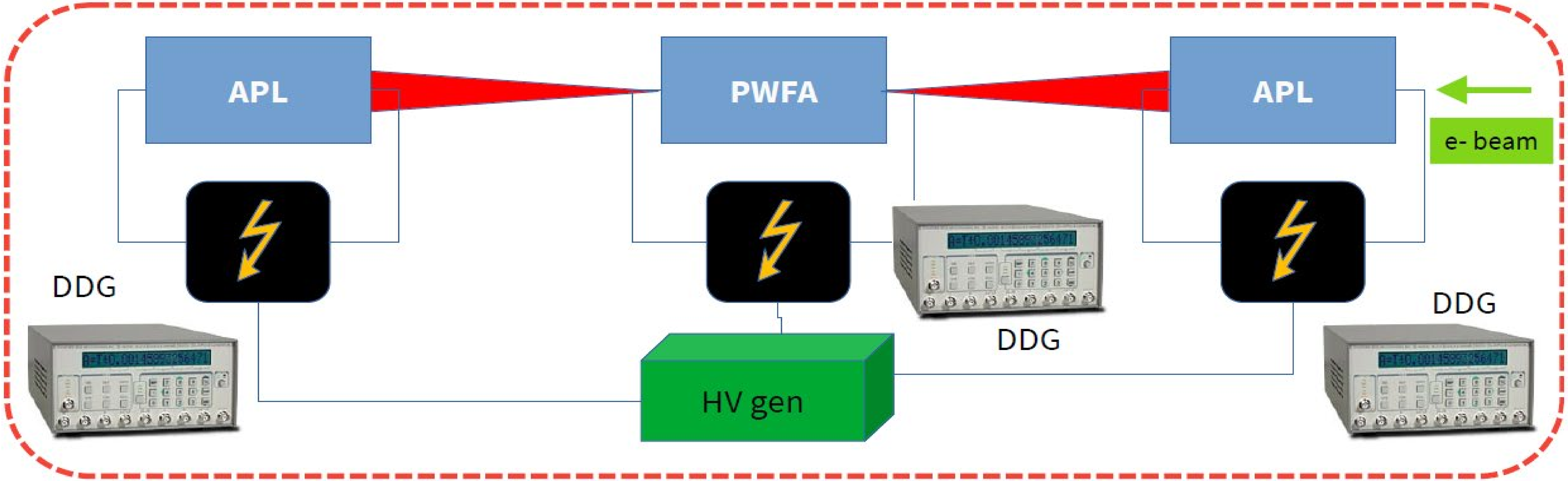
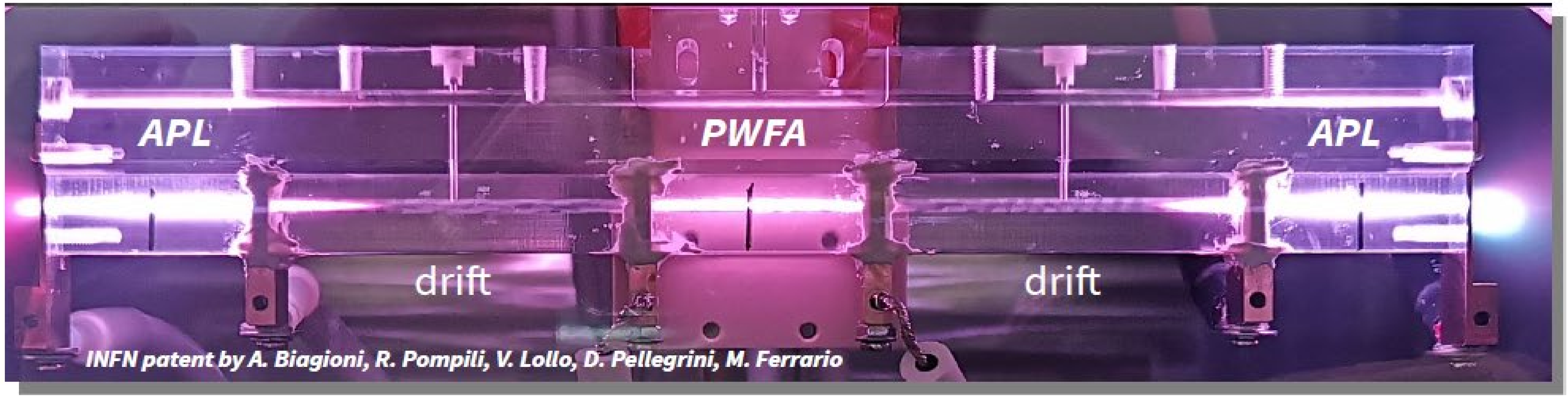




INFN patent by A. Biagioni, R. Pompili, V. Lollo, D. Pellegrini, M. Ferrario

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:

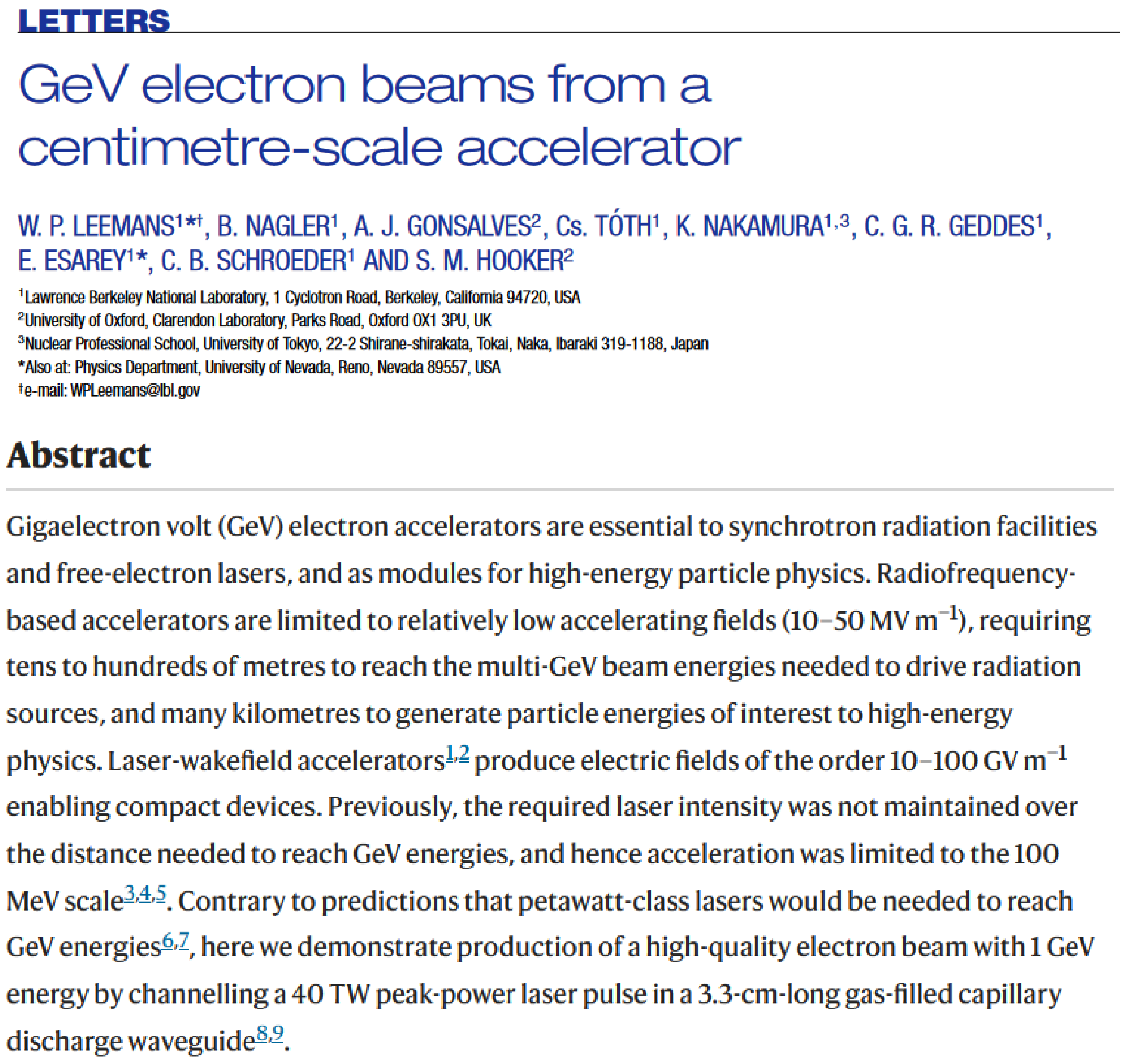
- After discharge, plasma outflows from capillary ends, depleting gas inside.
- Gas density recovers due to continuous gas flow from the supply system.
- Simulations show gas density recovers to within 1% accuracy after 100 µs.

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



LETTERS

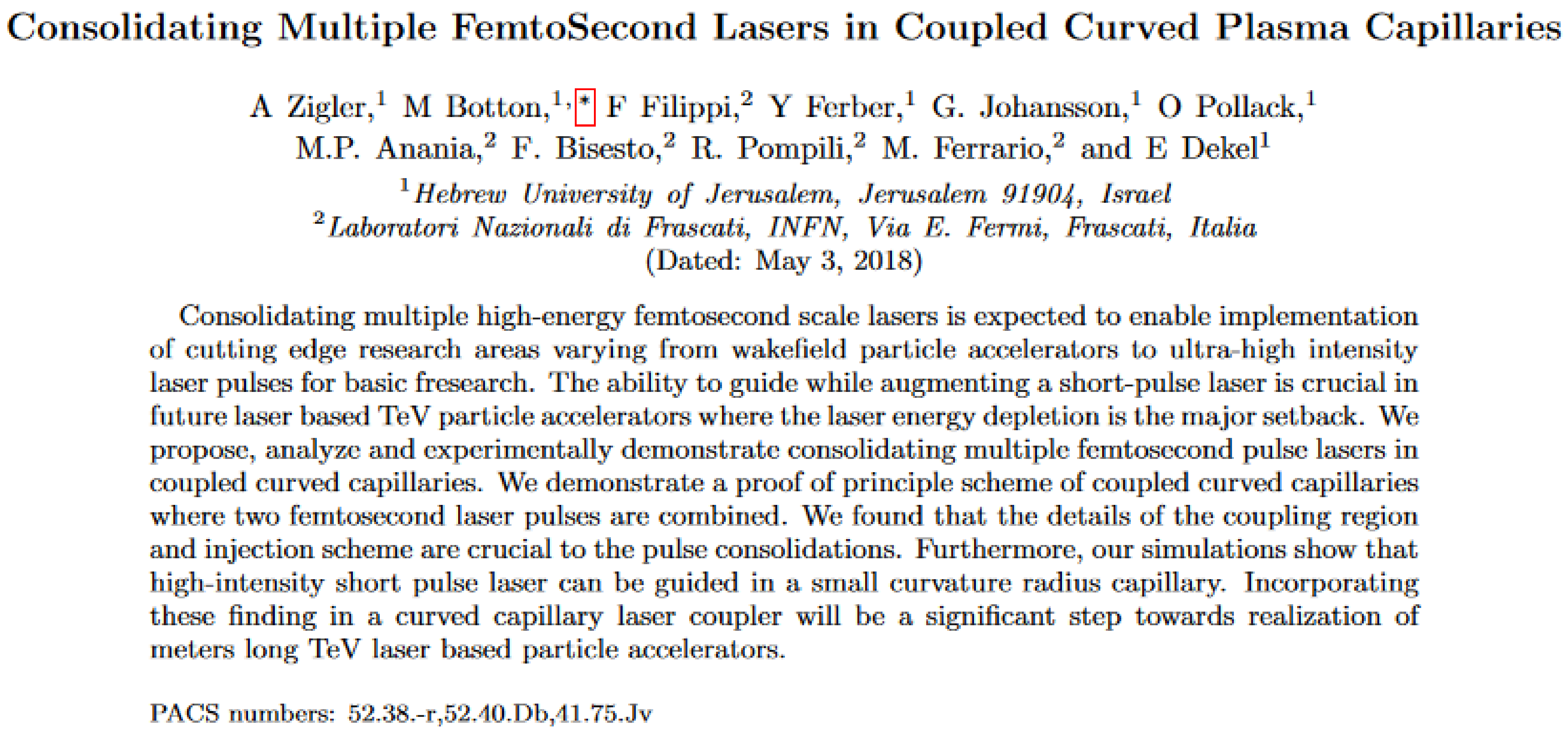
GeV electron beams from a centimetre-scale accelerator

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
*Also at: Physics Department, University of Nevada, Reno, Nevada 89557, USA
†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].

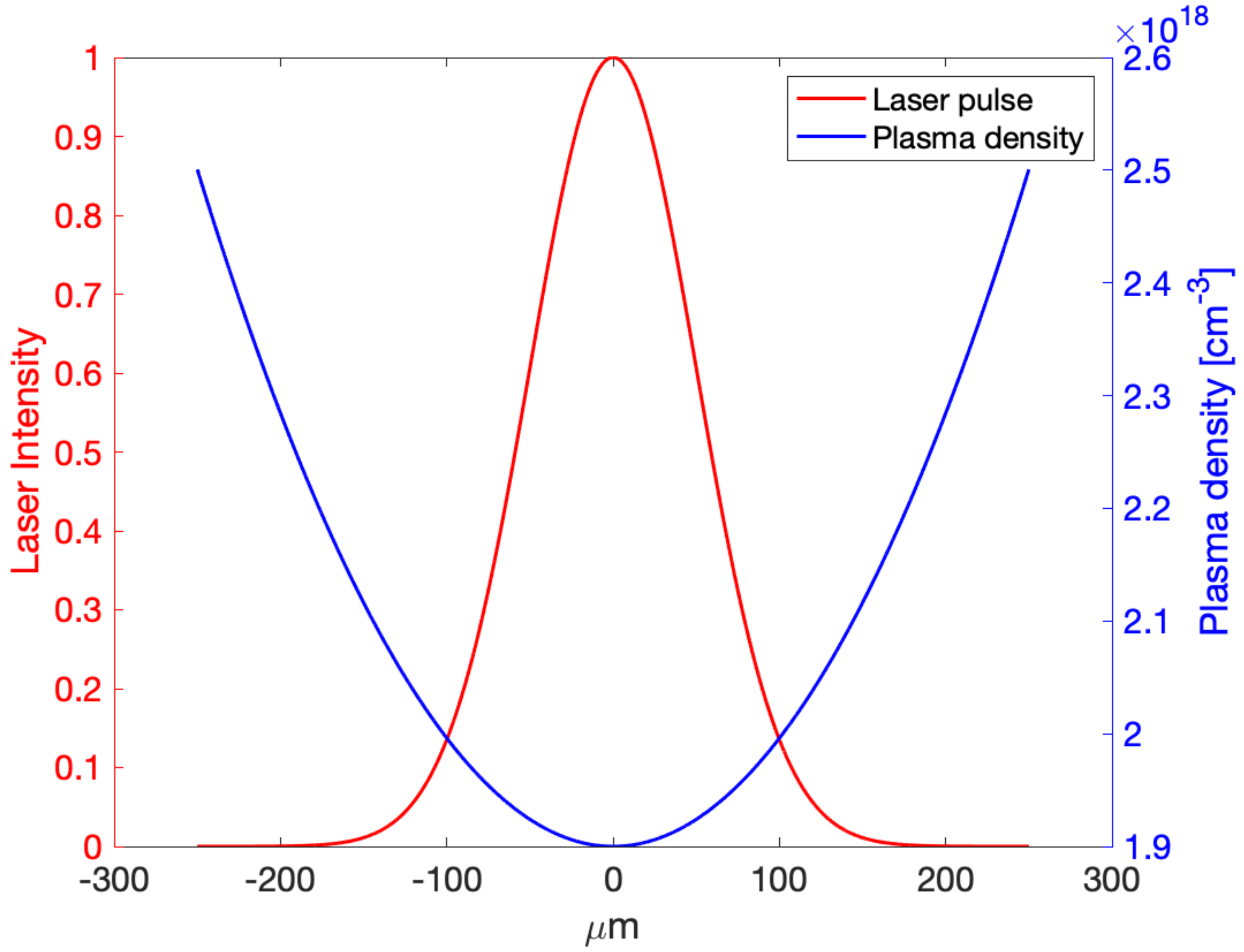


Consolidating Multiple FemtoSecond Lasers in Coupled Curved Plasma Capillaries

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 femtoscond 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