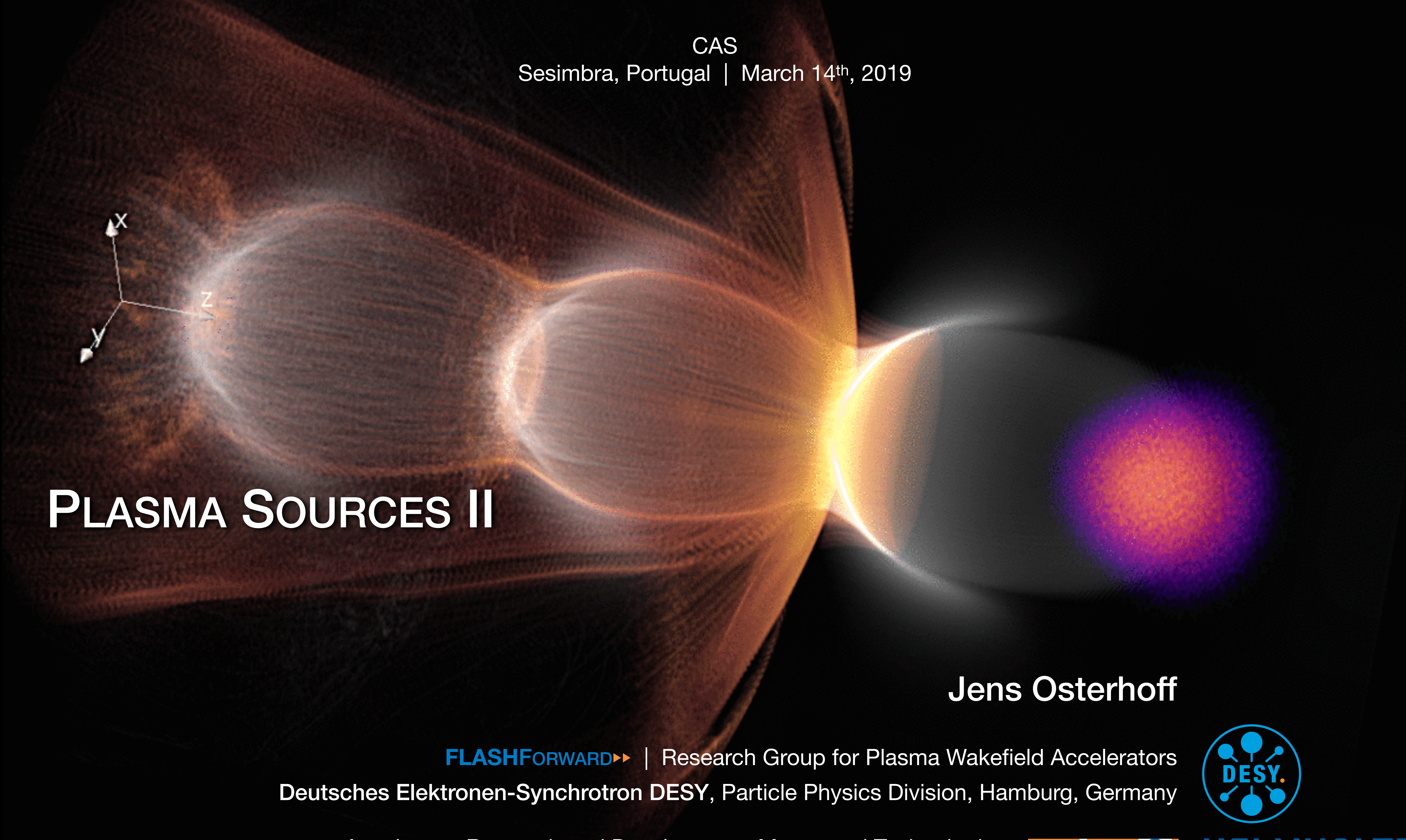
CAS
Sesimbra, Portugal | March 14th, 2019



PLASMA SOURCES II

Jens Osterhoff

FLASHFORWARD▸▸ | Research Group for Plasma Wakefield Accelerators
Deutsches Elektronen-Synchrotron DESY, Particle Physics Division, Hamburg, Germany

Accelerator Research and Development, Matter and Technologies
Helmholtz Association of German Research Centres, Berlin, Germany

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

simulation by Alberto Martinez de la Ossa

Many thanks for support and material to…

<u>Simon Hooker (Oxford University)</u>

Nelson Lopes (IST Lisbon)

Timon Mehrling (LBNL)

Greg Boyle, Severin Diederichs, Carl Lindstrøm,
Gegor Loisch, Kris Põder (all DESY)

<u>Disclaimer:</u> presentation is only an incomplete and subjective snapshot of the field!

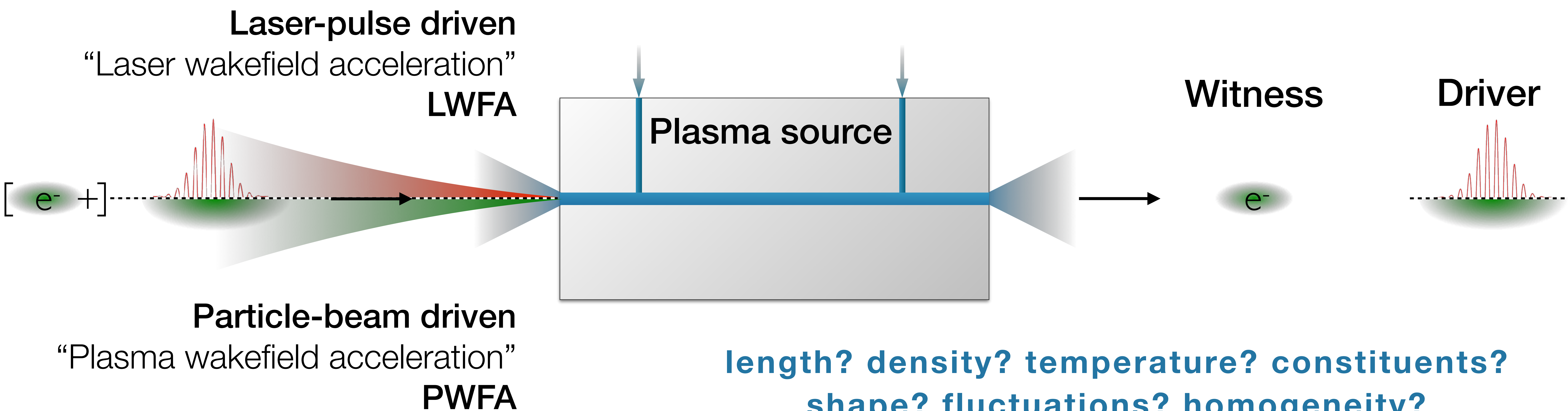
Lecture Series on Plasma Sources and Diagnostics

> **Plasma Sources I**
  - Thursday, March 14, 9:00 - 10:00
  - **Conceptual aspects**

> **Plasma Sources II**
  - Friday, March 15, 9:00 - 10:00
  - **Technical aspects**

> **Plasma Diagnostics**
  - Tuesday, March 19, 10:00 - 11:00
  - **Diagnostics:** how to measure plasmas

Outline - Plasma Sources II - Technical implementation

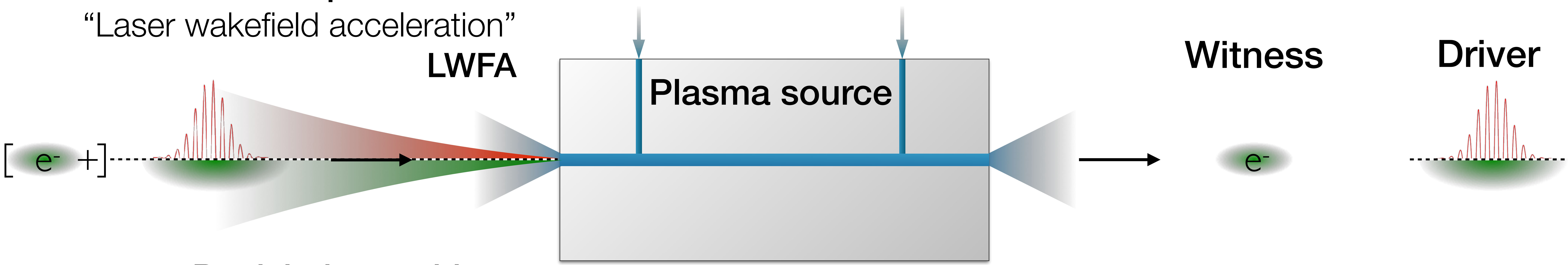


length? density? temperature? constituents?
shape? fluctuations? homogeneity?
technical compatibility?

how to actually realize plasma sources
with the desired properties?

Outline - Plasma Sources II - Technical implementation

Laser-pulse driven
"Laser wakefield acceleration"
LWFA



Particle-beam driven
"Plasma wakefield acceleration"
PWFA

length? density? temperature? constituents? shape? fluctuations? homogeneity? technical compatibility?

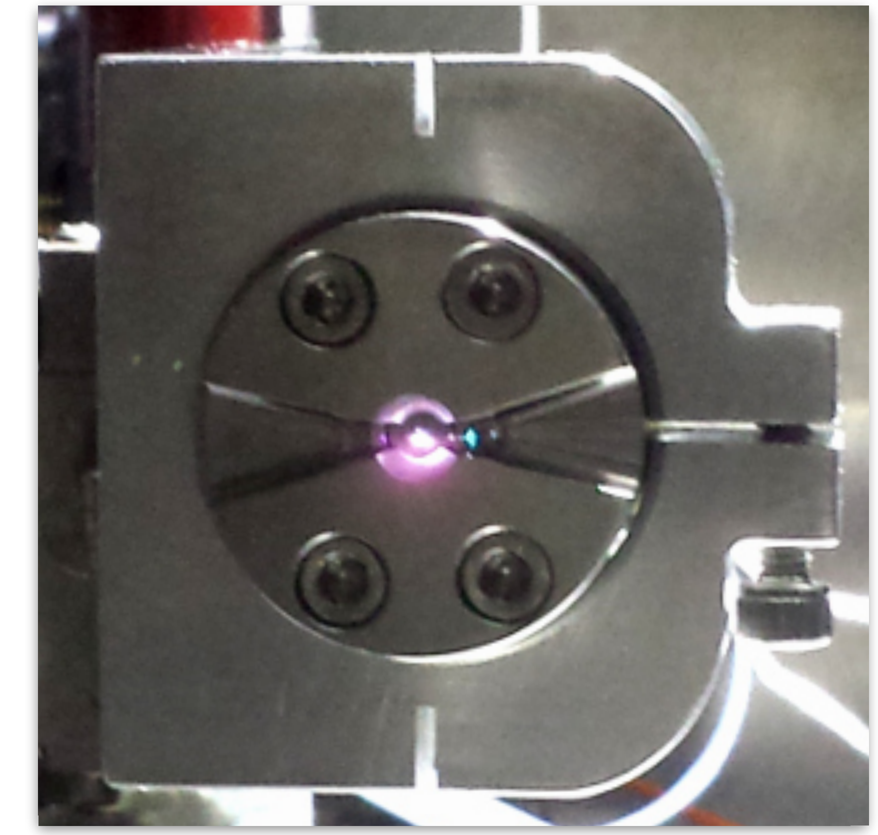
- **Gas jets**
- **Heat-pipe ovens**
- **Gas cells**
- **Plasma sources as waveguides**

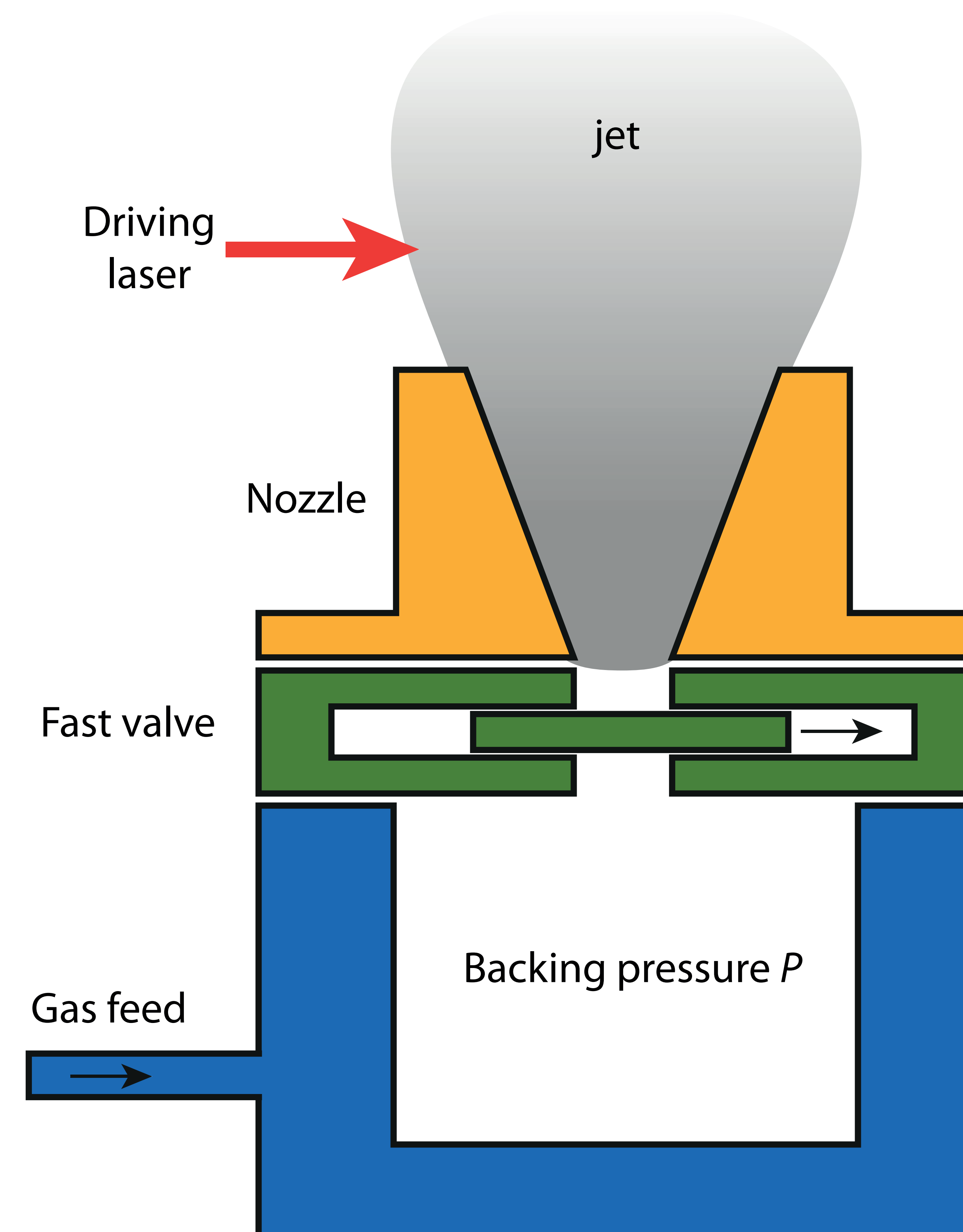
how to actually realize plasma sources with the desired properties?

Gas jets

Gas jets

- Supersonic nozzles provide a near-flat-top density profile for laser wakefield experiments
- Plasma density controlled by varying backing pressure *P*
  - Typically 10 - 100 bar depending on nozzle diameter and desired density
  - n_e typically 10^{17} - 10^{20} cm^{-3}
  - Length typically a few mm
- Larger nozzle diameters give lower densities for same *P*
- Feature high gas flow rates, operation in pulsed mode
  - Requires rapid mechanical opening of fast valve (usually a solenoid)
  - Typical opening times of few ms
  - Opening can lead to vibrations
  - Mechanical parts can wear out
- Provide open geometry for on-shot diagnostic access





Gas jets

Courtesy Stuart Mangles
Imperial College

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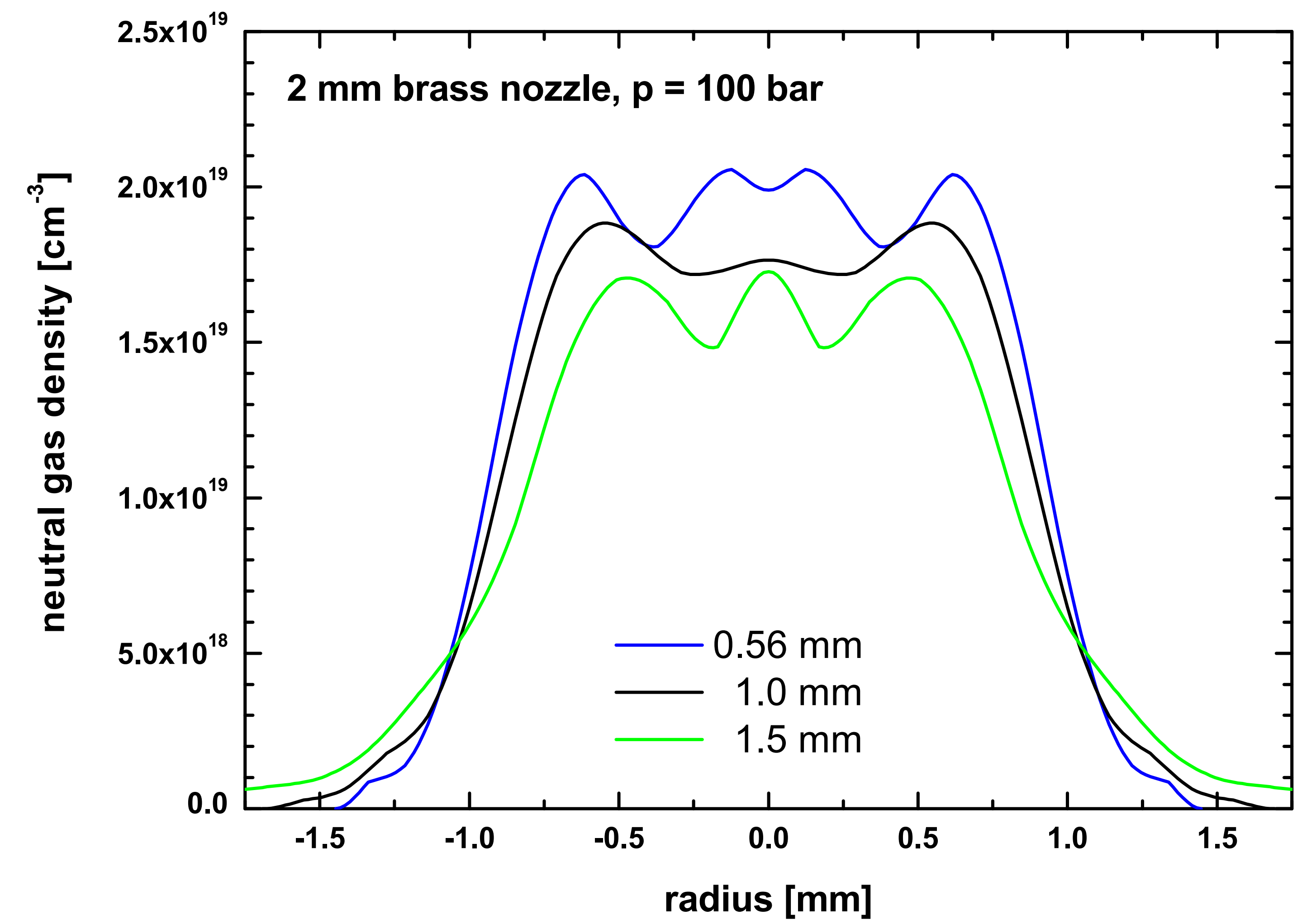
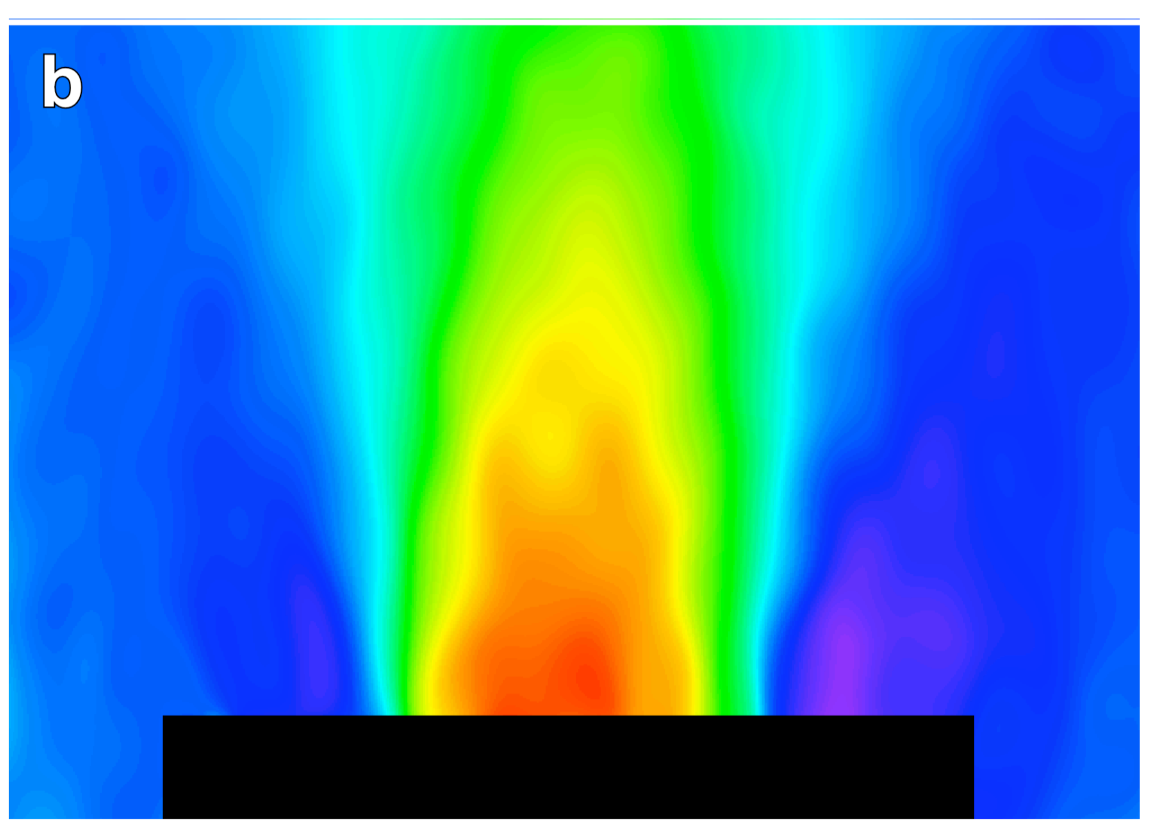
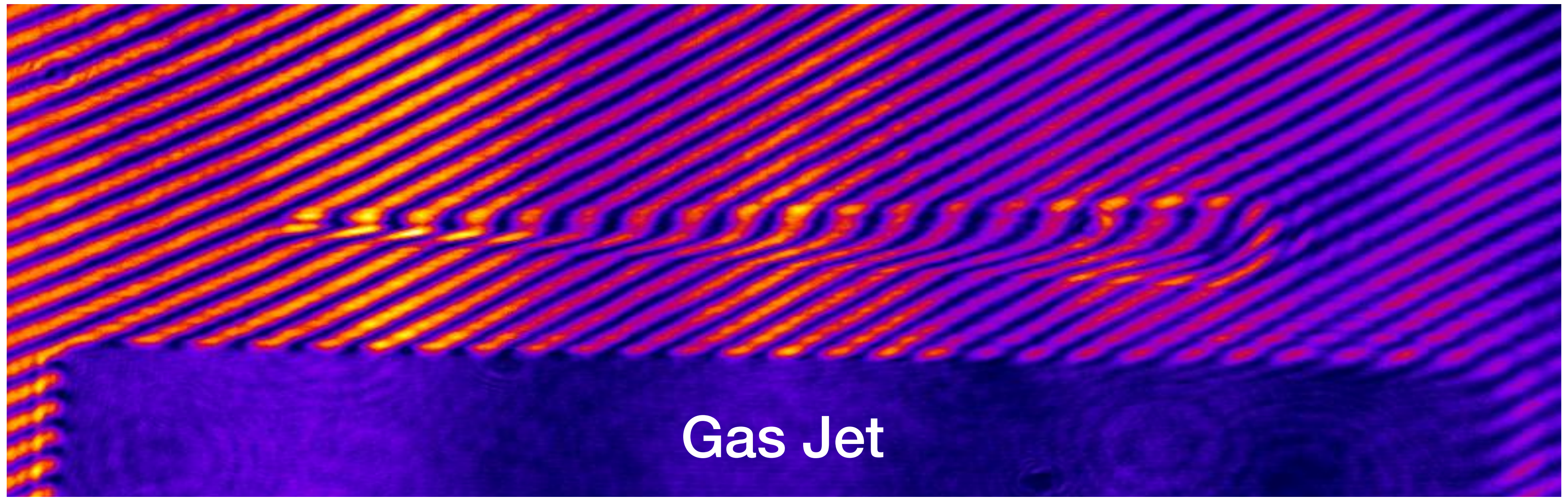
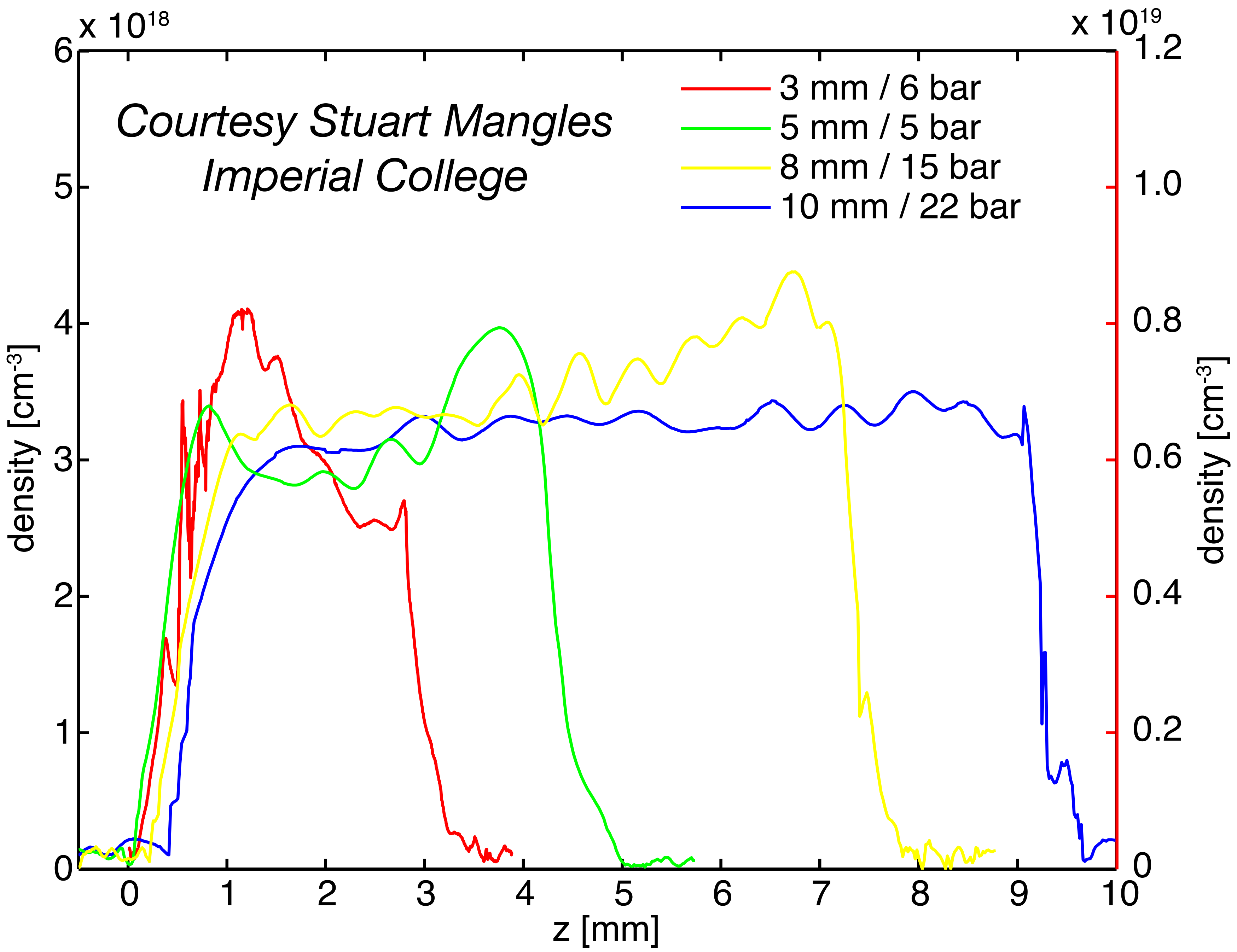




Gas jets - diagnostic access

On-shot interferogram of 10 mm plasma on Astra-Gemini, Rutherford Lab, UK





S. Kneip *et al.*,
Phys. Rev. Lett. **103,** 035002 (2009)

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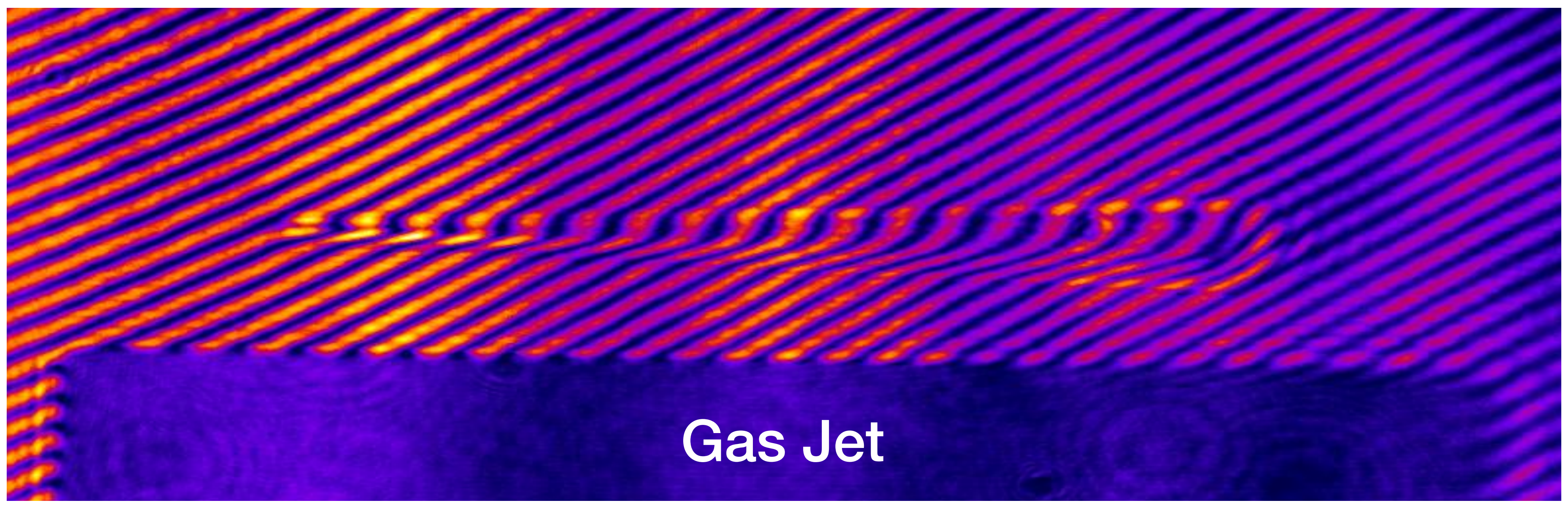
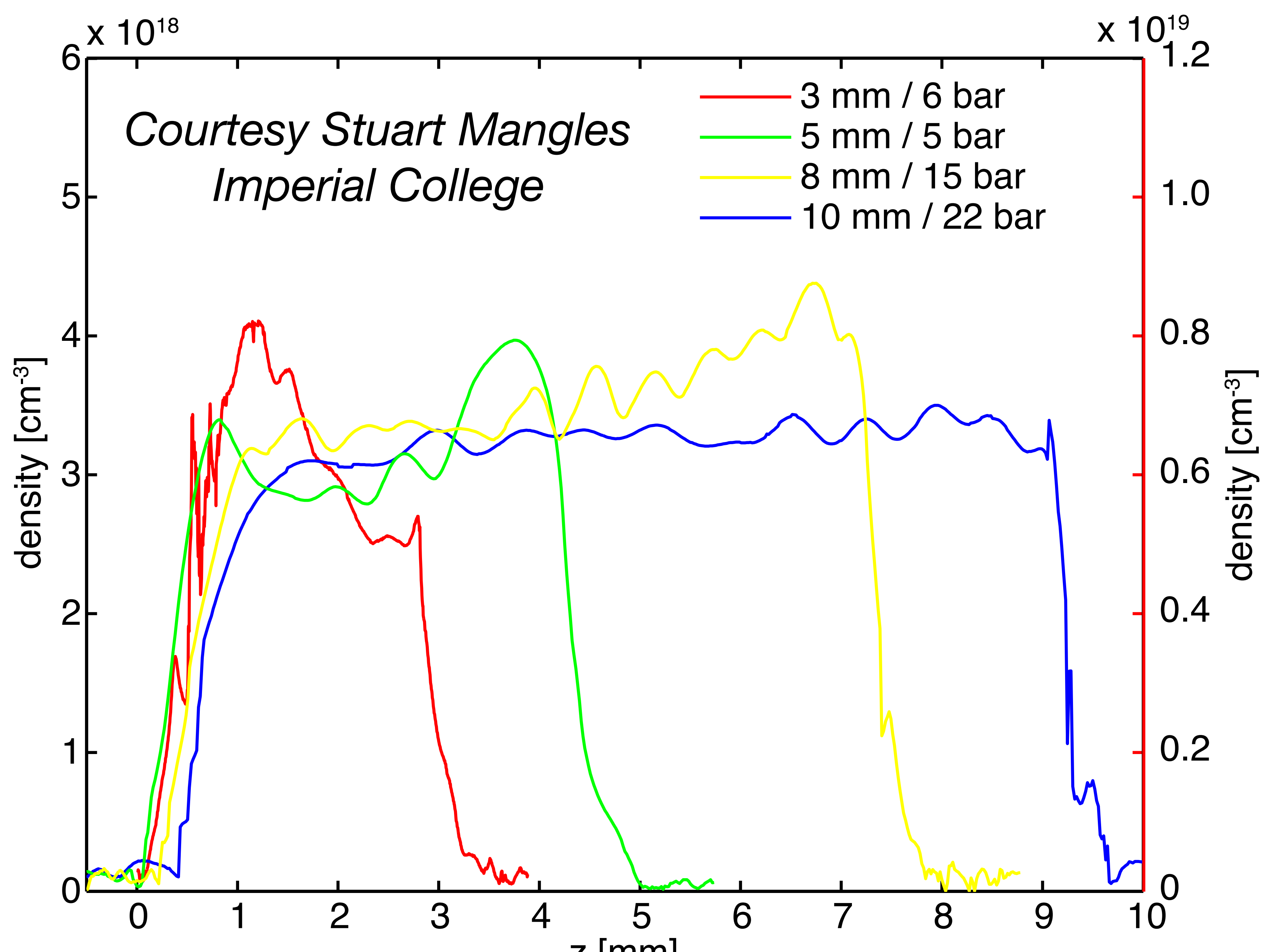
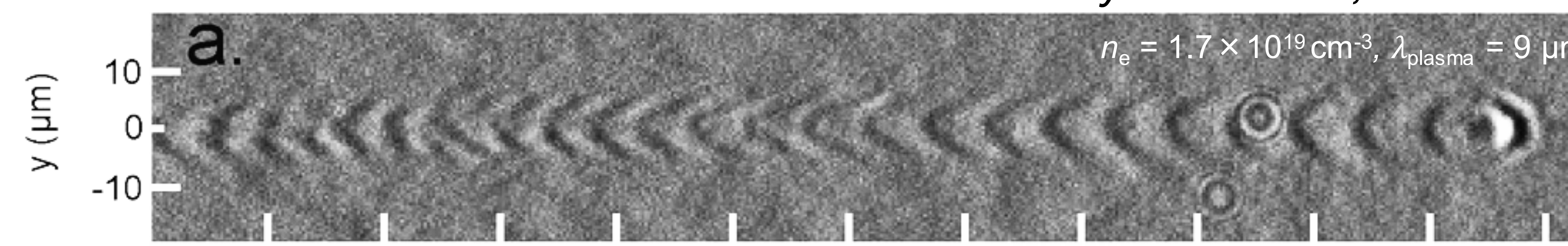




Few-fs shadowgraphy of a laser-driven wakefield, Jena, Germany

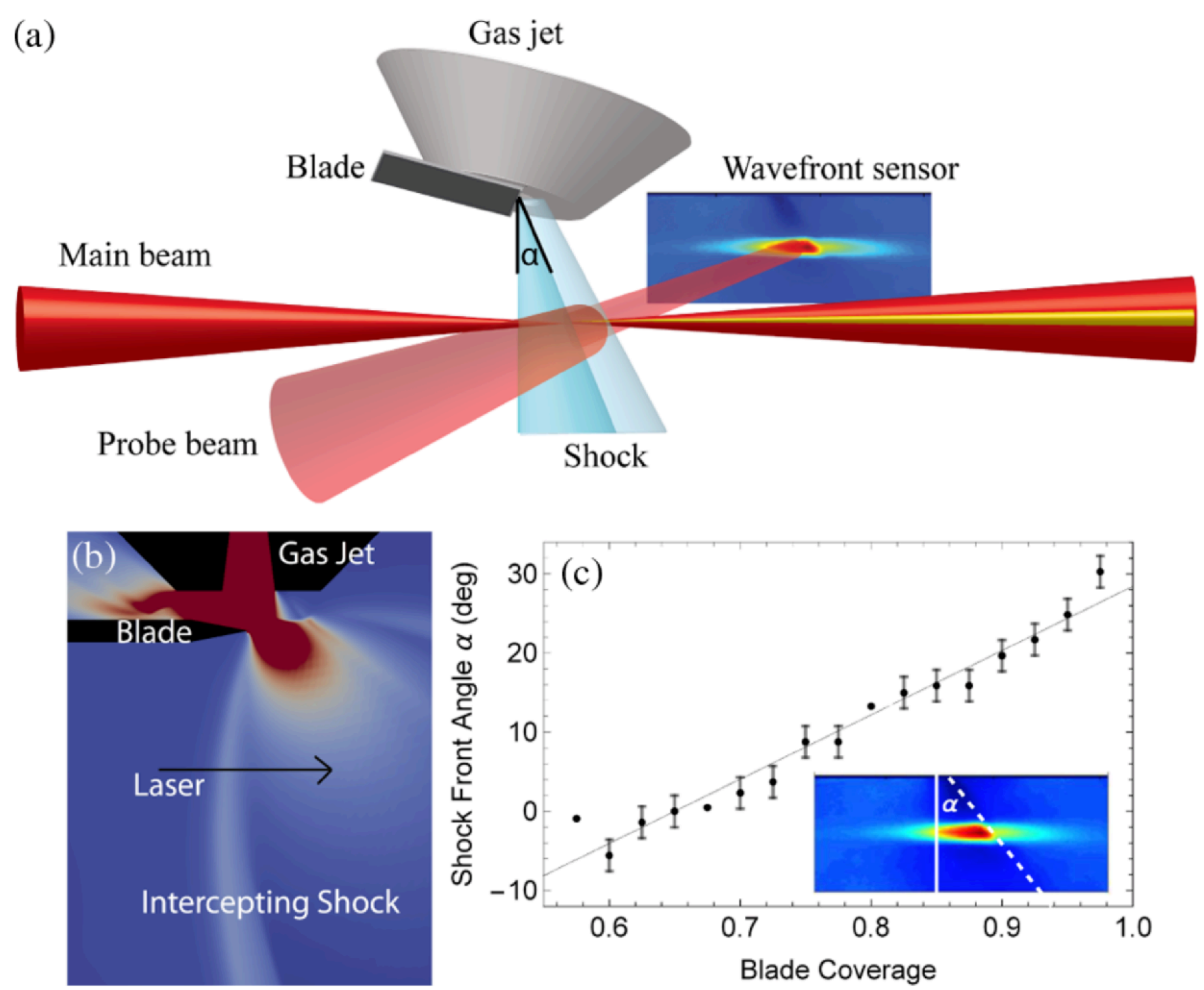
Courtesy M. Kaluza, FSU Jena

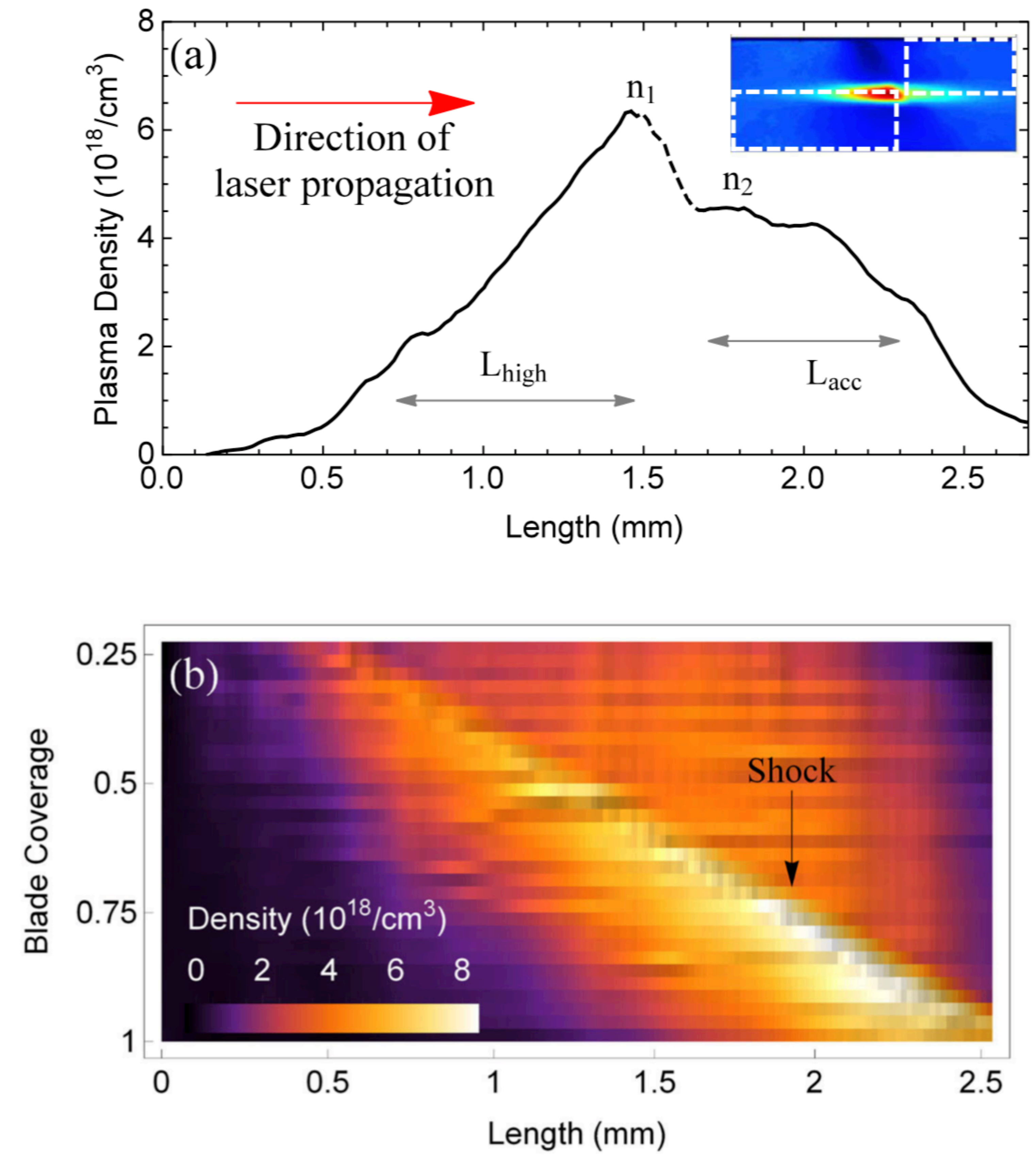


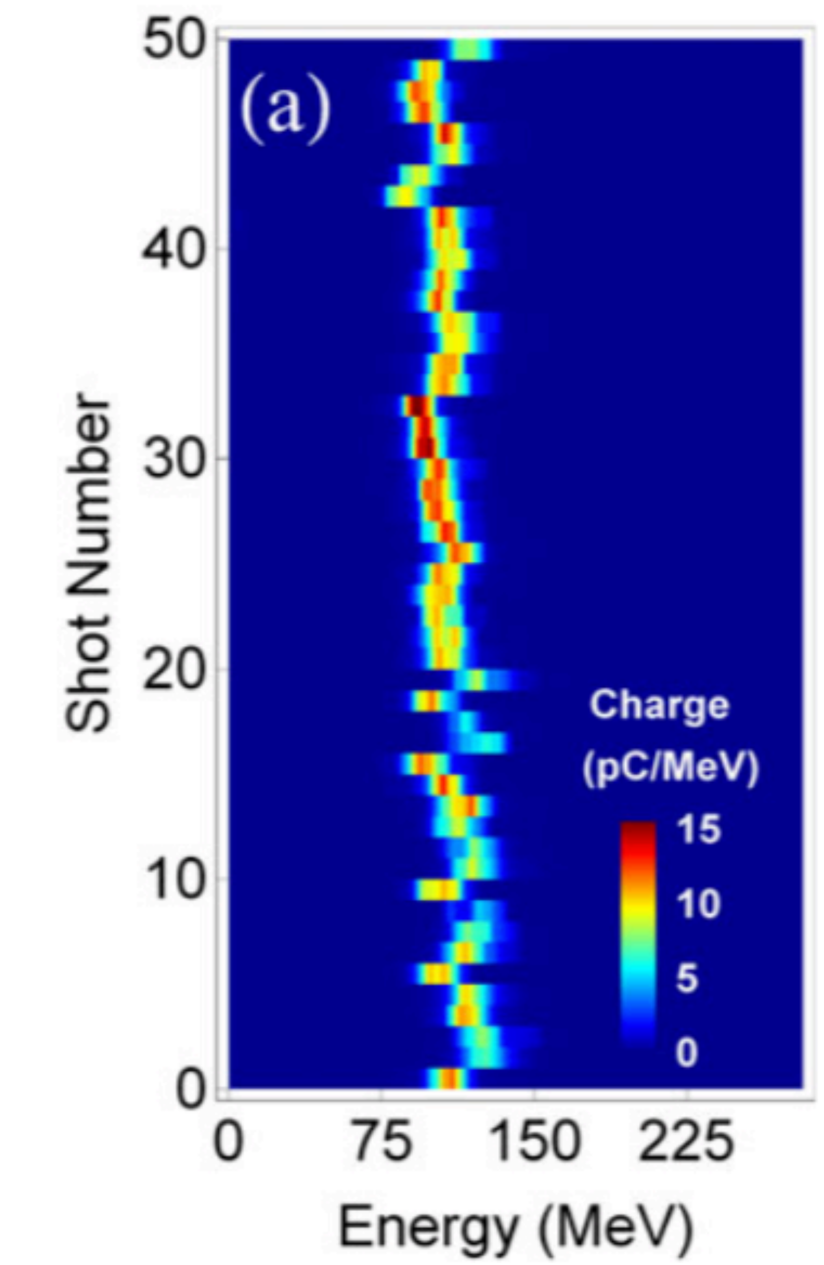
M. Schnell *et al.*, Nat. Comm. **4**, 2421 (2013)

S. Kneip *et al.*,
Phys. Rev. Lett. **103,** 035002 (2009)

Gas jets - shock fronts







> Gas jets allow for the creation of strong density gradients by shocks

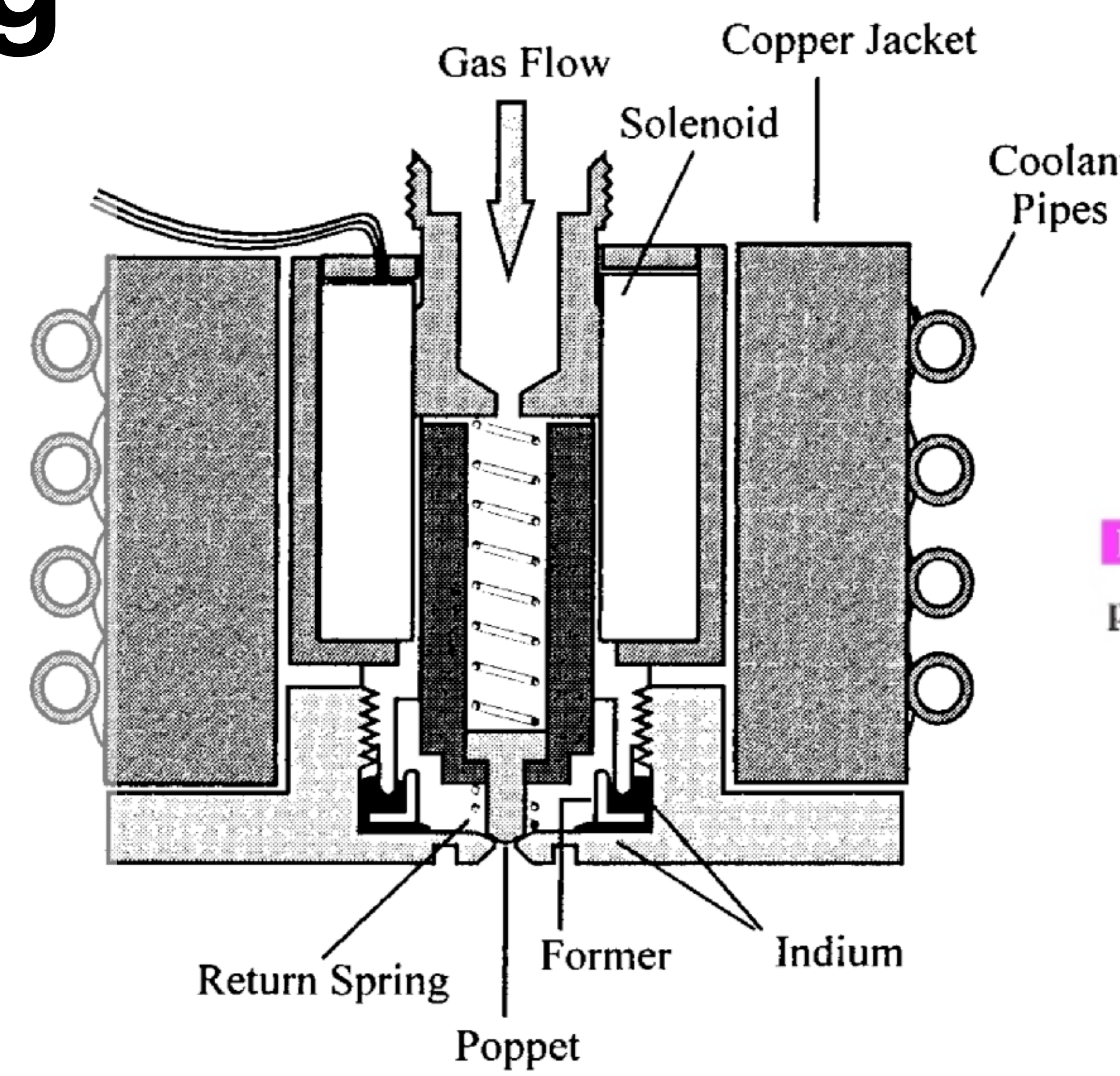
> Facilitates controlled injection of high-quality beams

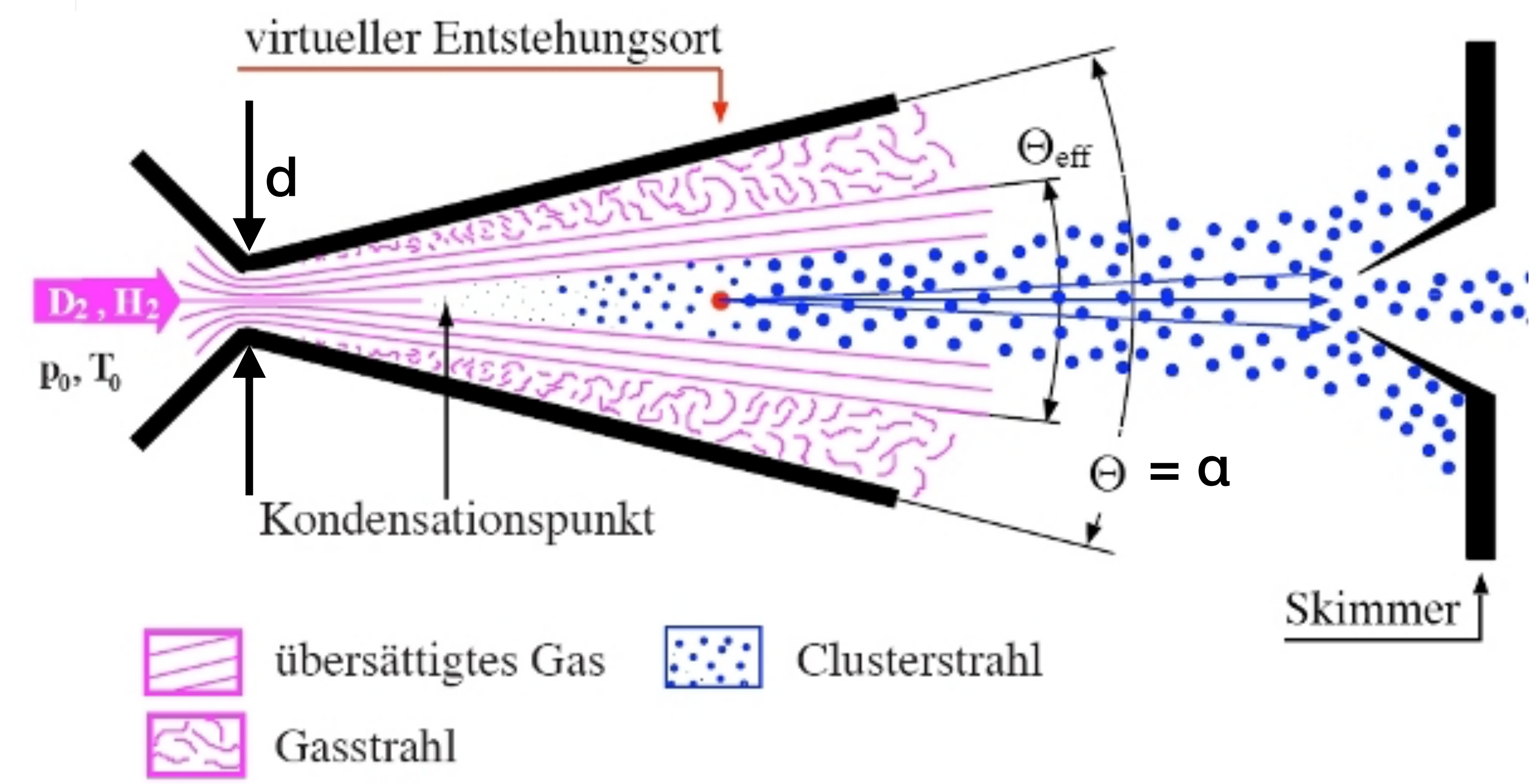
from K. K. Swanson *et al.*, Phys. Rev. AB 20, 051301 (2017)

basic idea: A. Buck *et al.*, Phys. Rev. Lett. 110, 185006 (2013)

Gas jets - clustering

- Expansion of gas through a nozzle into vacuum results in cooling in frame of moving gas
- Atoms and molecules can conglomerate due to van der Waals or hydrogen bonding
- Hagena parameter $\Gamma^* \gg 100$ describes onset of clustering
- Cluster Features
  - Efficient laser energy absorption
  - Distinct ionization and fragmentation dynamics
  - Can vary in size from a few to 10^4 atoms per cluster (N_c)





$$\Gamma^* = k \frac{(d/\tan\alpha)^{0.85}}{T_0^{2.29}} P_0 \qquad N_c \propto \Gamma^{*2.0-2.5}$$

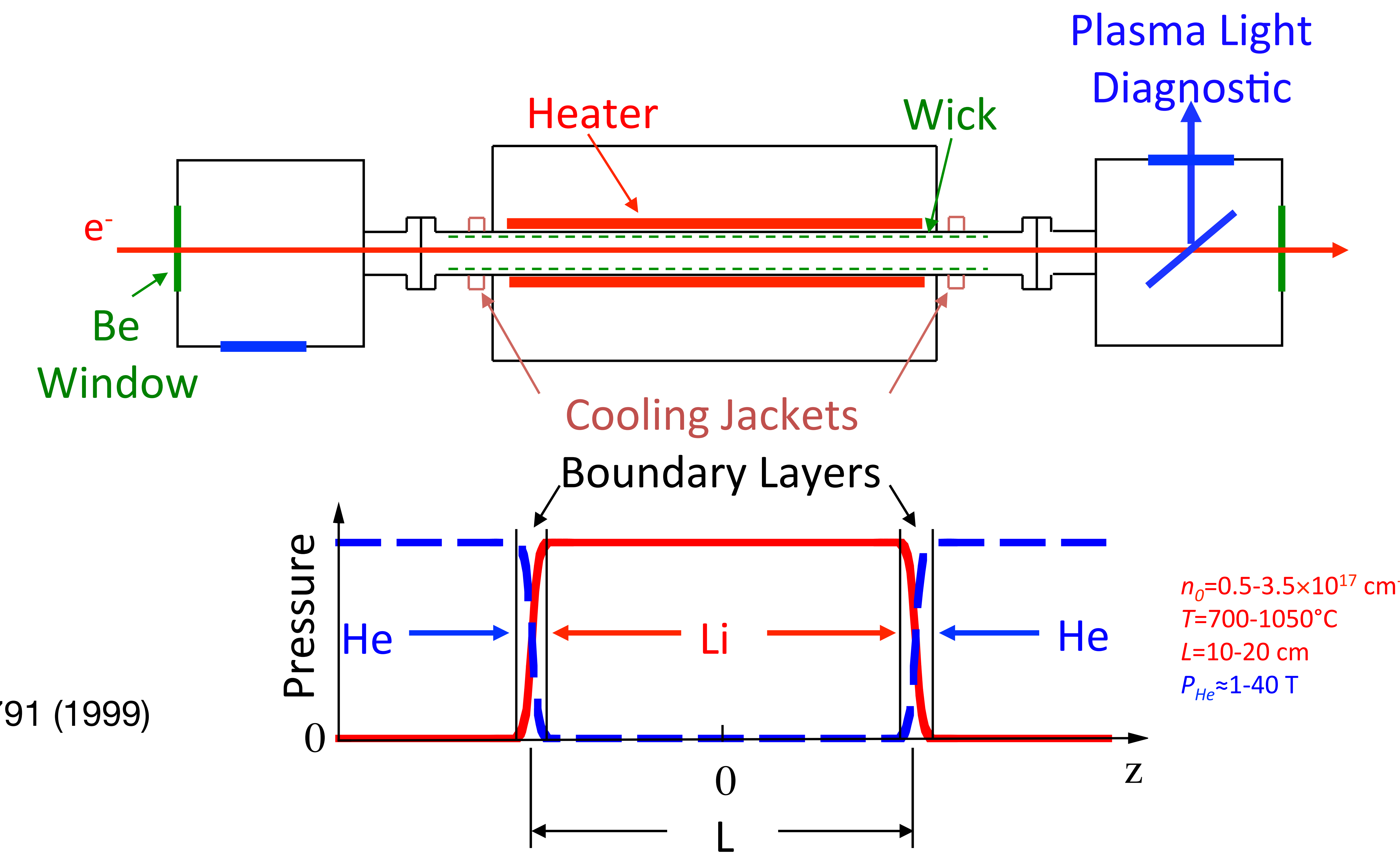
Gas	H_2	D_2	N_2	O_2	CO_2	CH_4	He	Ne	Ar	Kr	Xe
k	184[a]	181[a]	528[a]	1400[a]	3660[a]	2360[b]	3.85[b]	185[b]	1650[b]	2890[b]	5500[b]

from R. A. Smith *et al.,* Rev. Sci. Instrum. 69, 3798 (1998)

Heat-pipe ovens

Heat-pipe ovens

- Beam-driven plasma accelerators may require
  - Long targets (meter scale)
  - Relatively low density $n_e = 10^{14}$ - 10^{17} cm^{-3}
  - Ionizable by drive beam or a laser pulse (low *I*p)
  - High uniformity (e.g. in AWAKE)

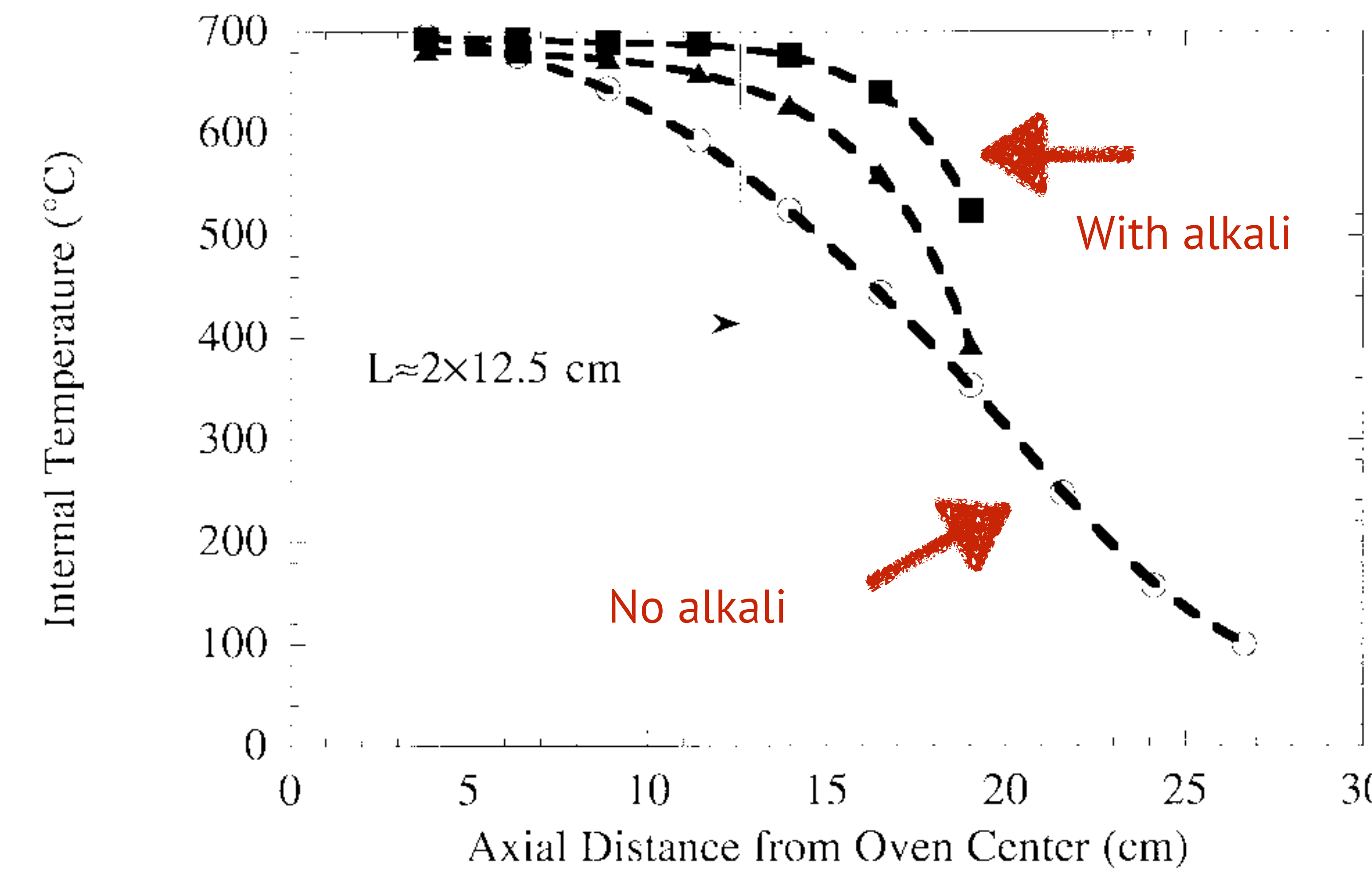


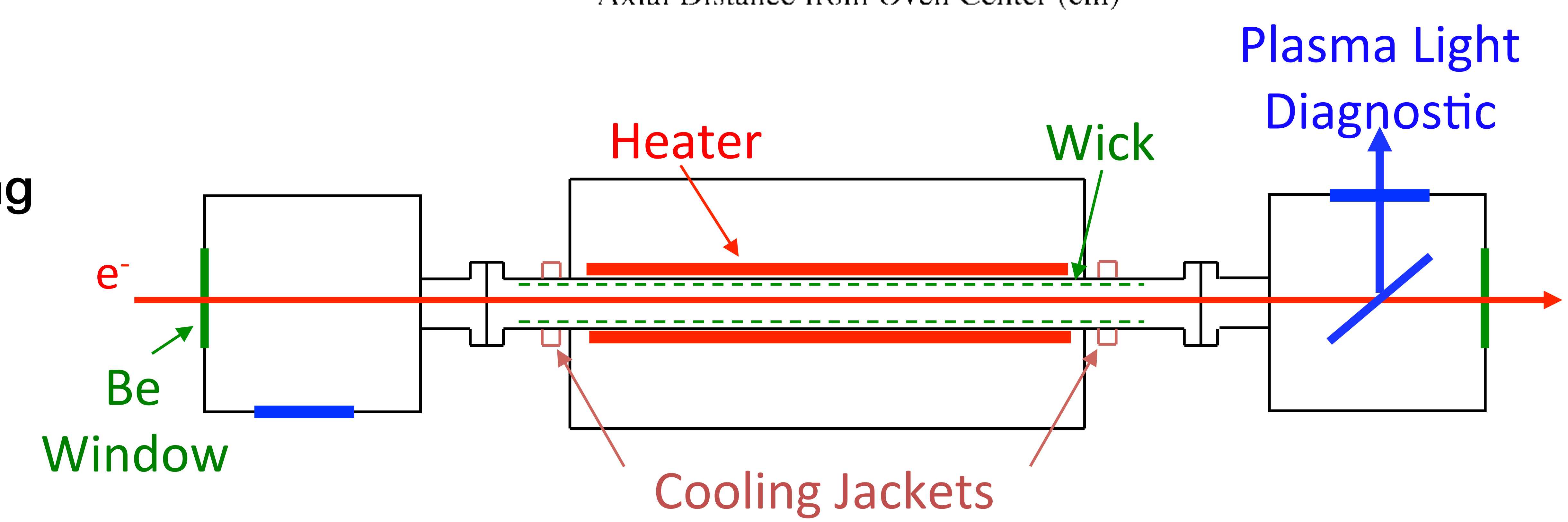
P. Muggli *et al.,* IEEE Trans. Plasm. Sci. **27,** 791 (1999)

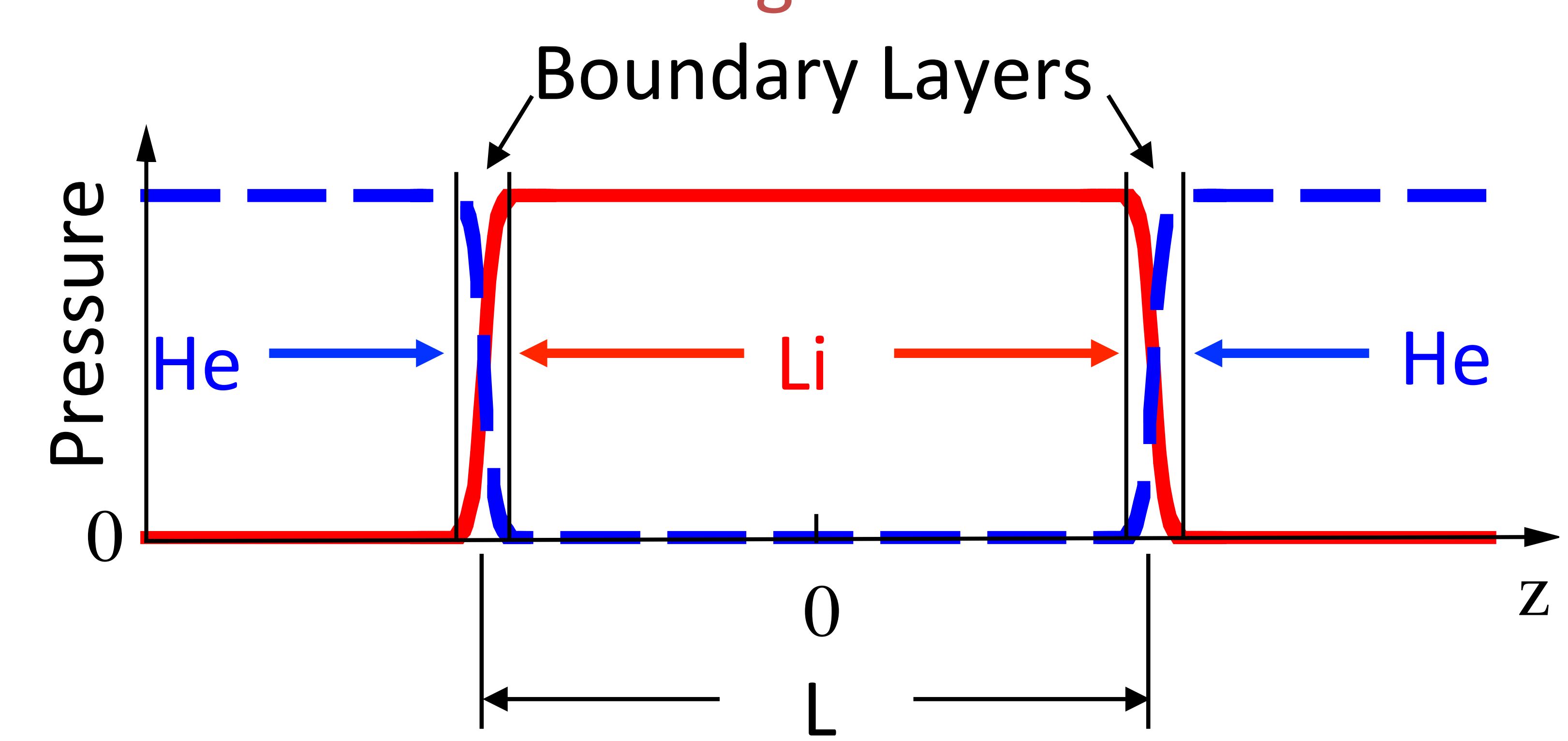
Heat-pipe ovens

- Alkali metal (Li, Rb, Cs,…) heated to form vapor
- Alkali vapor expels buffer (e.g. He) from heated region by collisions
- Helps to match masses (Li & He, Rb & Kr,…)
- Steady-state when $P_{alkali} = P_{buff}$
- Alkali vapor will diffuse into buffer gas for few mean-free paths before condensing
- The “wick” returns condensed alkali
- Increasing heater power increases evaporation rate but not T_{alkali}
- Pressure fixed by P_{buff}, hence length of alkali vapor increases
- Transverse diagnostic access difficult

P. Muggli *et al.,* IEEE Trans. Plasm. Sci. **27,** 791 (1999)







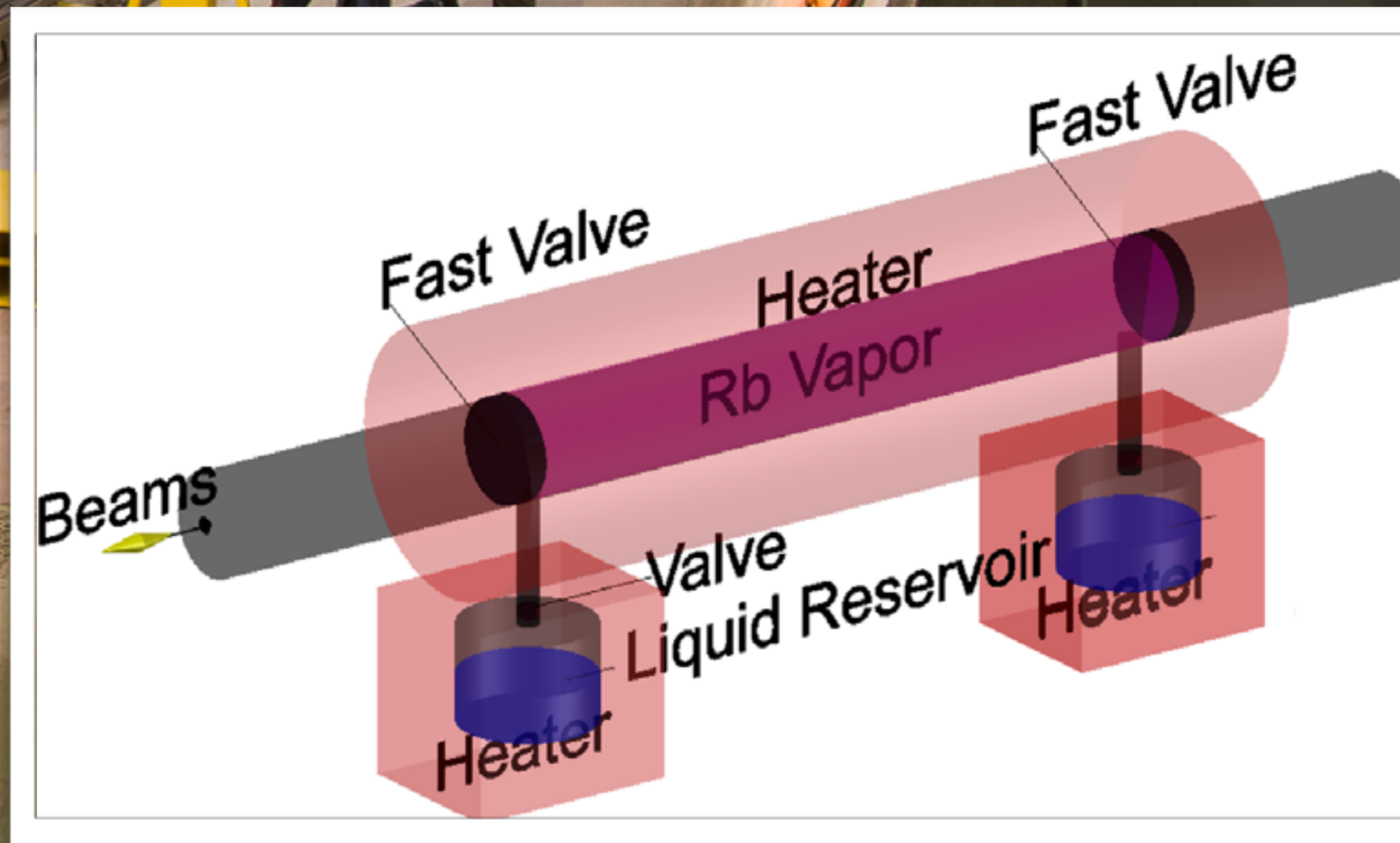
n_0=0.5-3.5×10^{17} cm^{-3}
T=700-1050°C
L=10-20 cm
P_{He}≈1-40 T

Heat pipe example: AWAKE

Not strictly a heat-pipe oven…

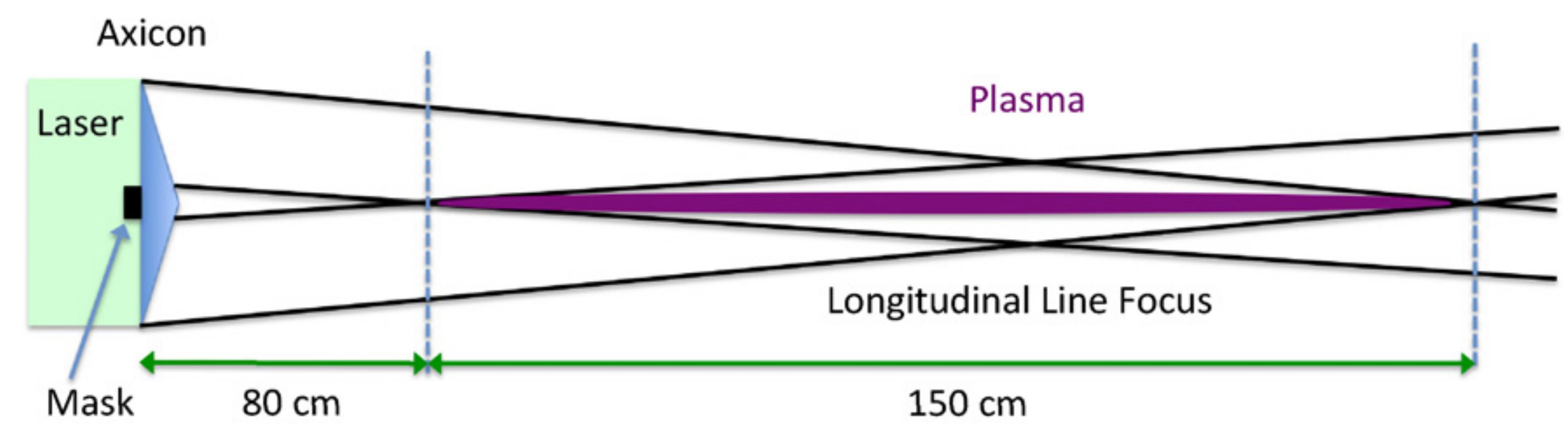
- 10 m long, 40 mm diam. oil-heated pipe
- No buffer gas: fast valves contain vapor
- Density variations related to temperature variations
- Better density uniformity than heat-pipe oven
- Plasma is laser ionized

E. Öz & P. Muggli, Nucl. Inst. Meth A **740,** 197 (2014)

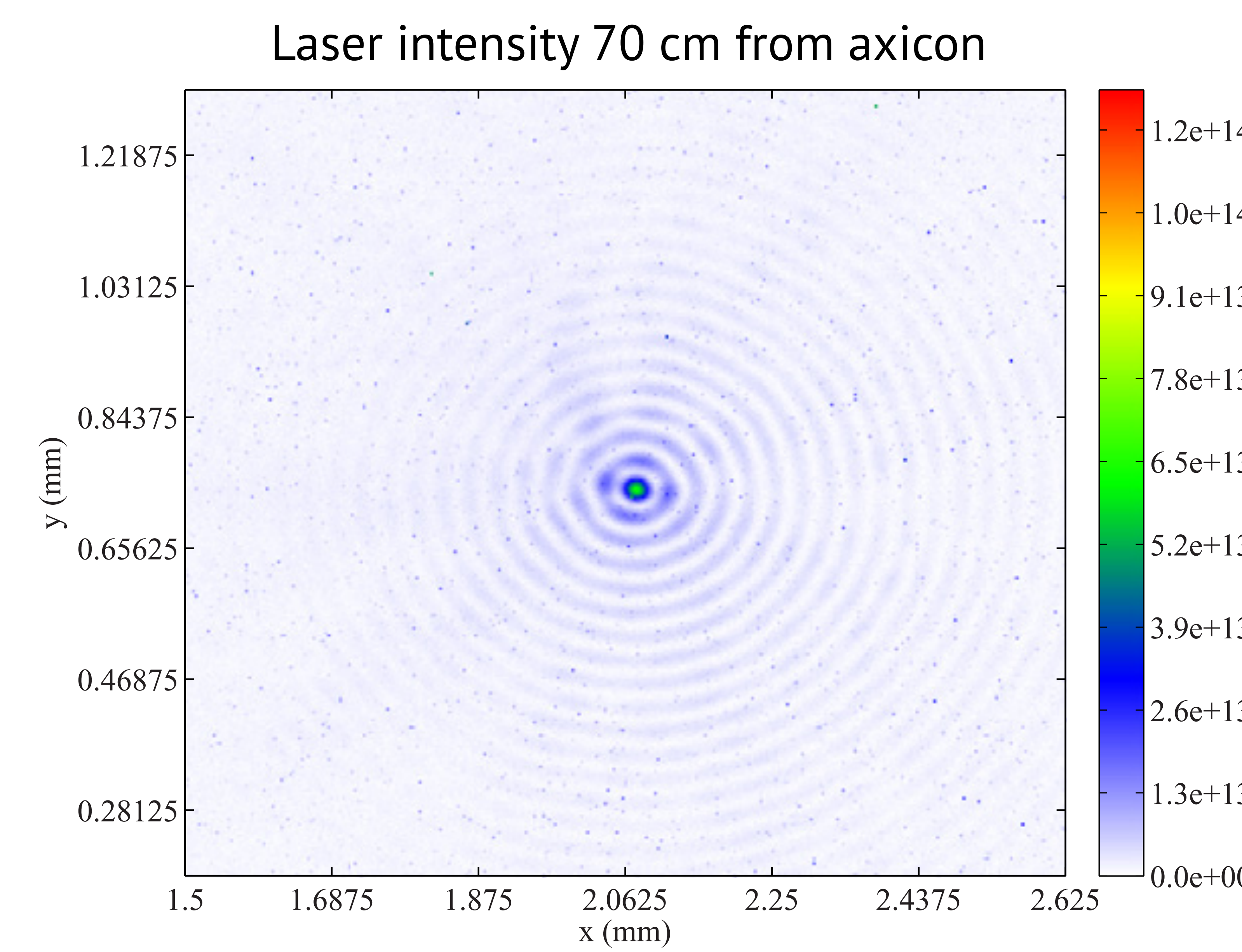


Heat-pipe ovens: laser ionization

- Pre-ionized plasma often preferable since head of driver beam not guided by neutral gas → head erosion
- AWAKE: ionization laser triggers ionization front inside 20 cm long proton beam → seeds self-modulation
- Laser ionization
  - Need to maintain required laser intensity over long distance (plasma source length)
  - Need large spot size (transverse wake size)
  - Long focal length lens or “axicon”
- Ionization mechanism
  - Tunneling/BSI as threshold process yields flat-top profile
  - SPI/MPI scales with power of *n*-photons required and varies with laser intensity profile

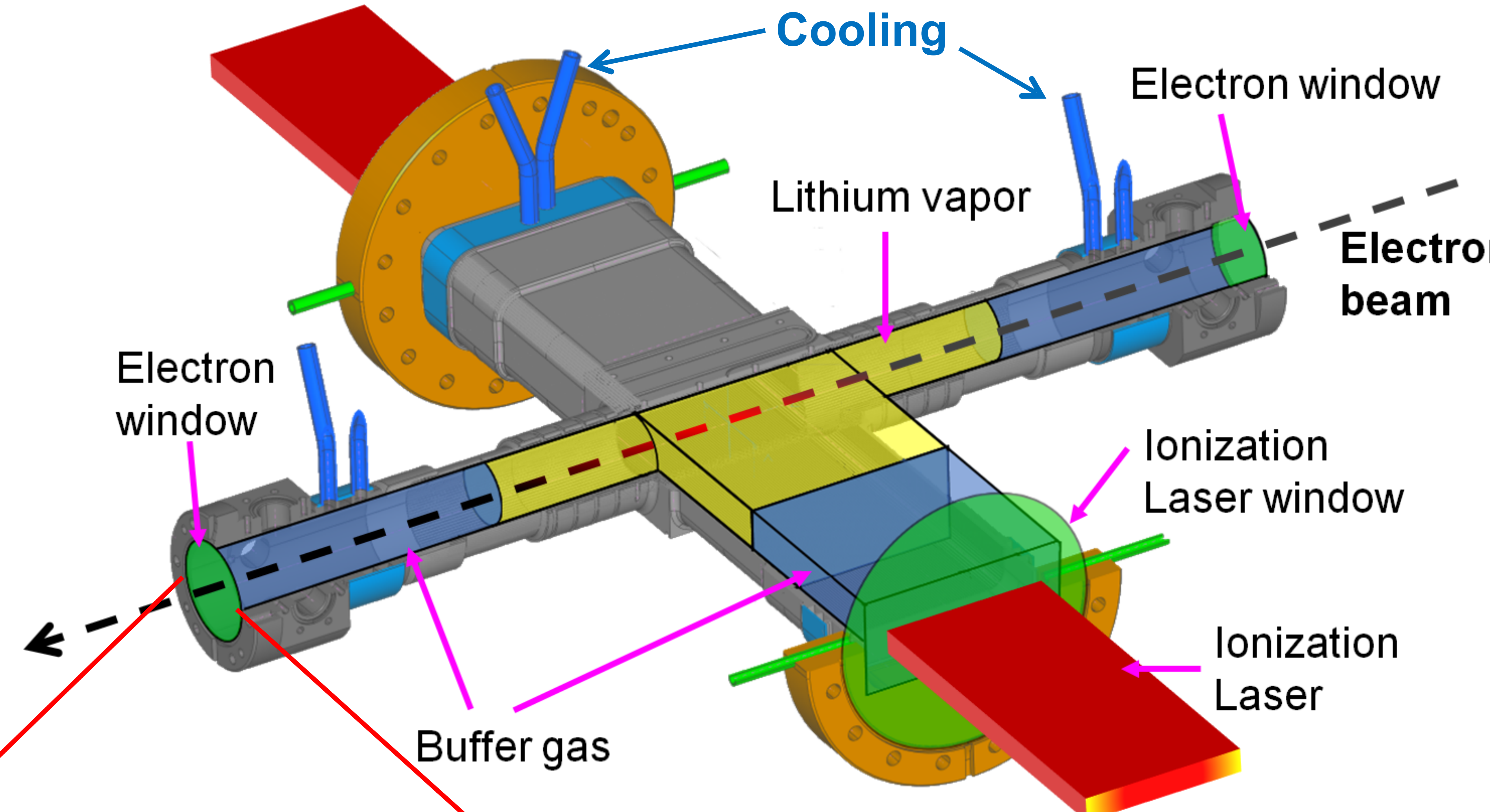


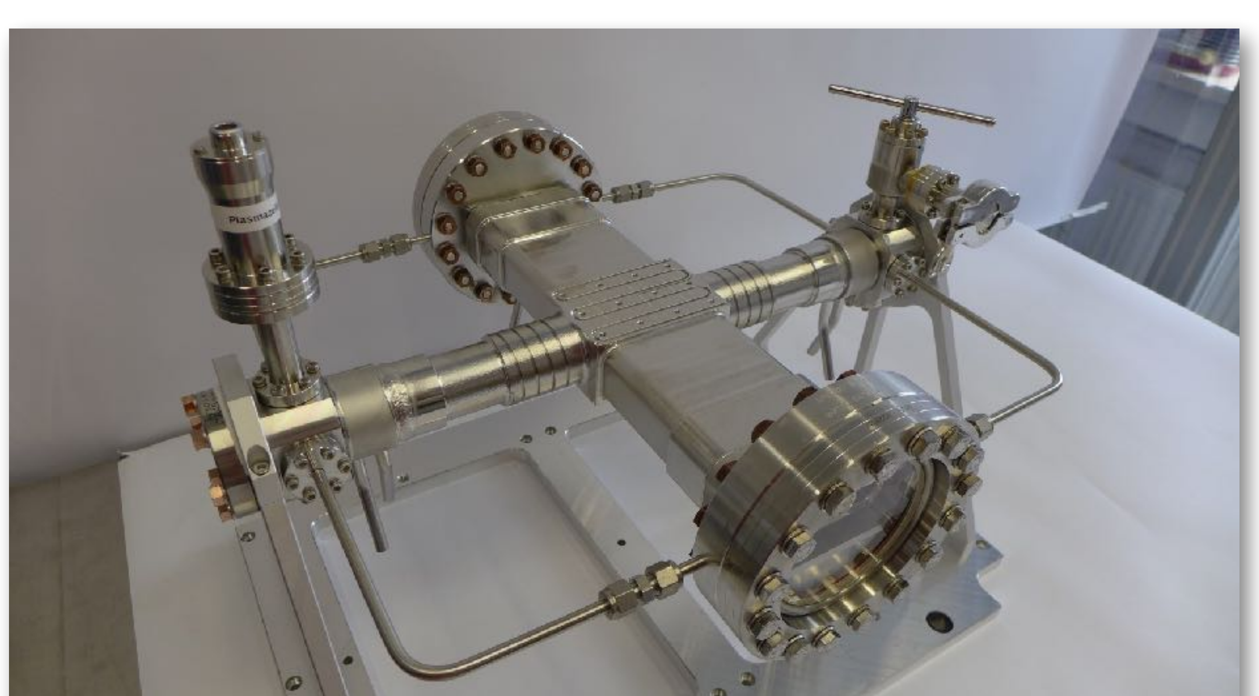
S.Z. Green *et al.,* Plasma. Phys. Cont. Fusion **57,** 084011 (2014)



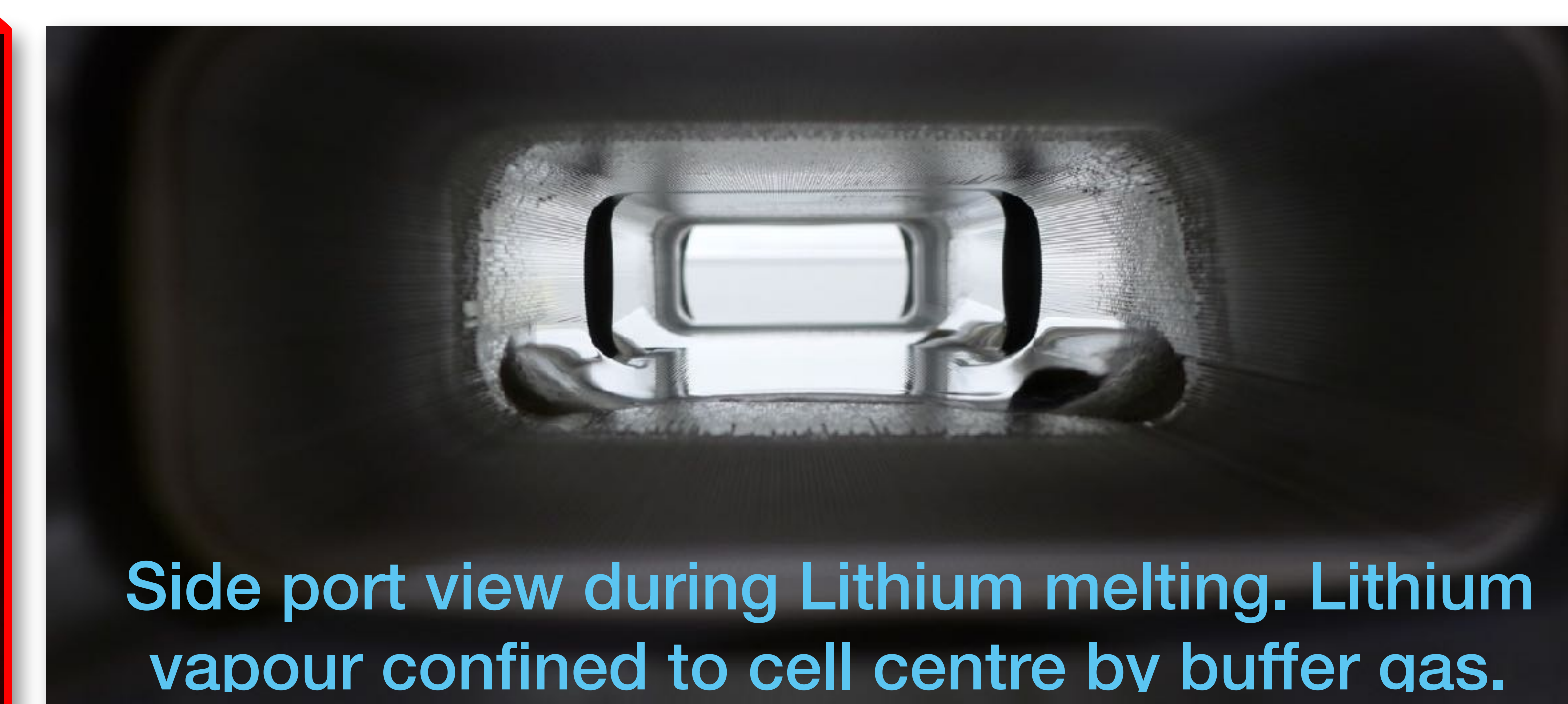
Laser-ionized heat-pipe example: PITZ

- Cross-shaped Li vapor oven
- Side ionization with UV-laser (SPI)
- Max. design plasma density 10^{15} cm^{-3}
- Ionisation degree ~10%
- Typical operation temperature in centre ~750°C
- Longitudinal profile shaping of plasma density possible
- Gas-vacuum separation with µm-thin polymer windows





"Beam" view with ionisation laser on

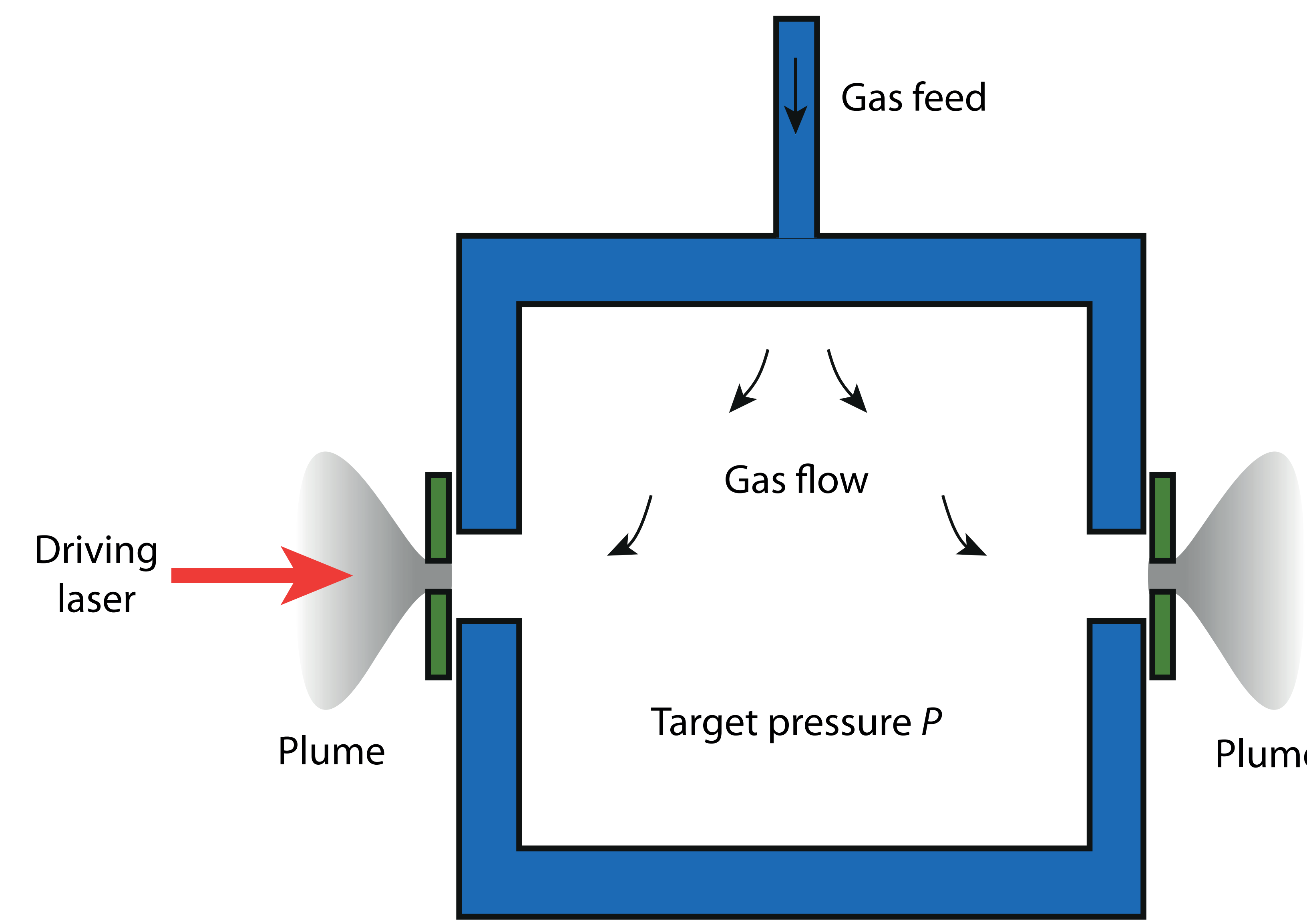


Side port view during Lithium melting. Lithium vapour confined to cell centre by buffer gas.

Gas cells

Gas cells

- Region of uniform neutral gas contained by differential pumping through coaxial pinholes
- If flow resistance of outlets > inlets, uniform density distribution in central volume
- Finite filling time (typically 100s of ms)
- Gas flow small enough to operate in steady state regime with continuous flow
- No mechanically moving parts
  → low-vibration, no shocks
- Plume of gas from front and back of cell
  → extended density transitions
- Density easily adjusted by controlling gas flow in range: 10^{17} - 10^{19} cm^{-3}
- Potential issue: erosion of outlet pinholes will change density



Variable-length gas cell

Courtesy Stefan Karsch
LMU Munich

- Region of uniform neutral gas contained by differential pumping through coaxial pinholes
- If flow resistance of outlets > inlets, uniform density distribution in central volume
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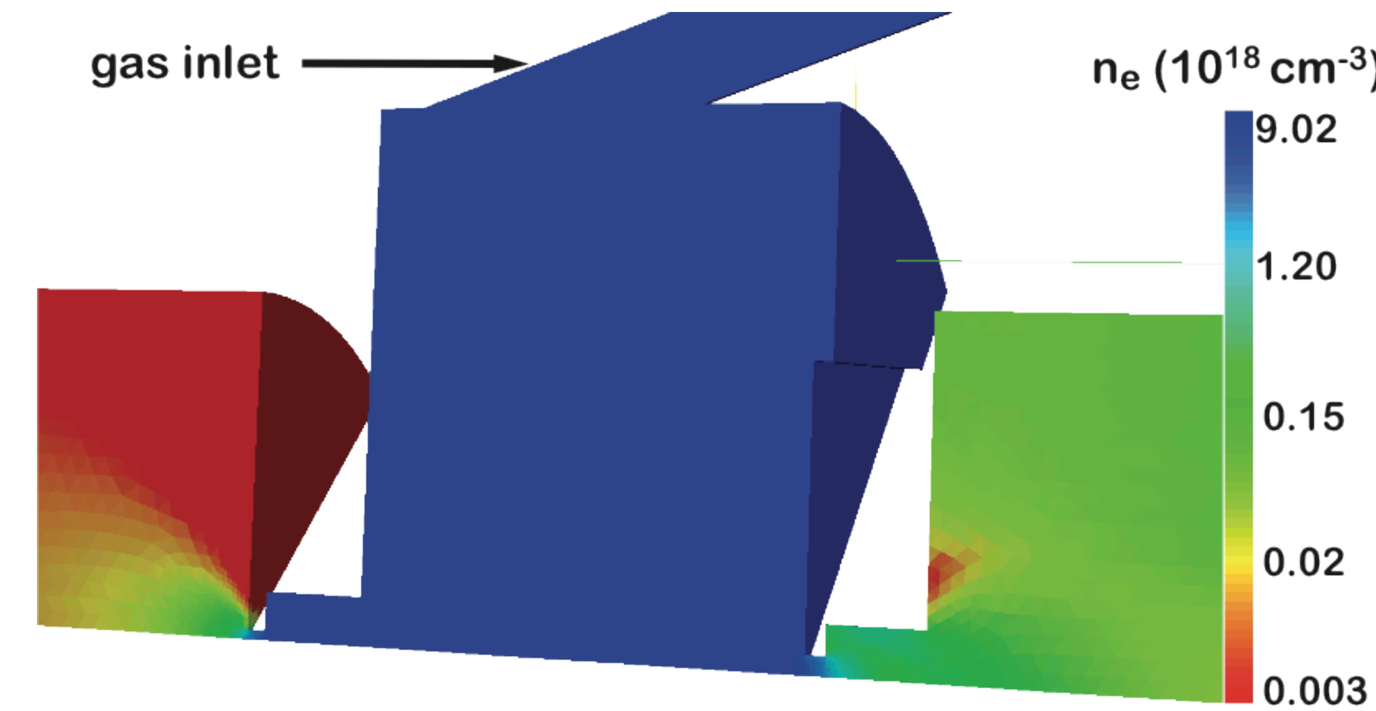
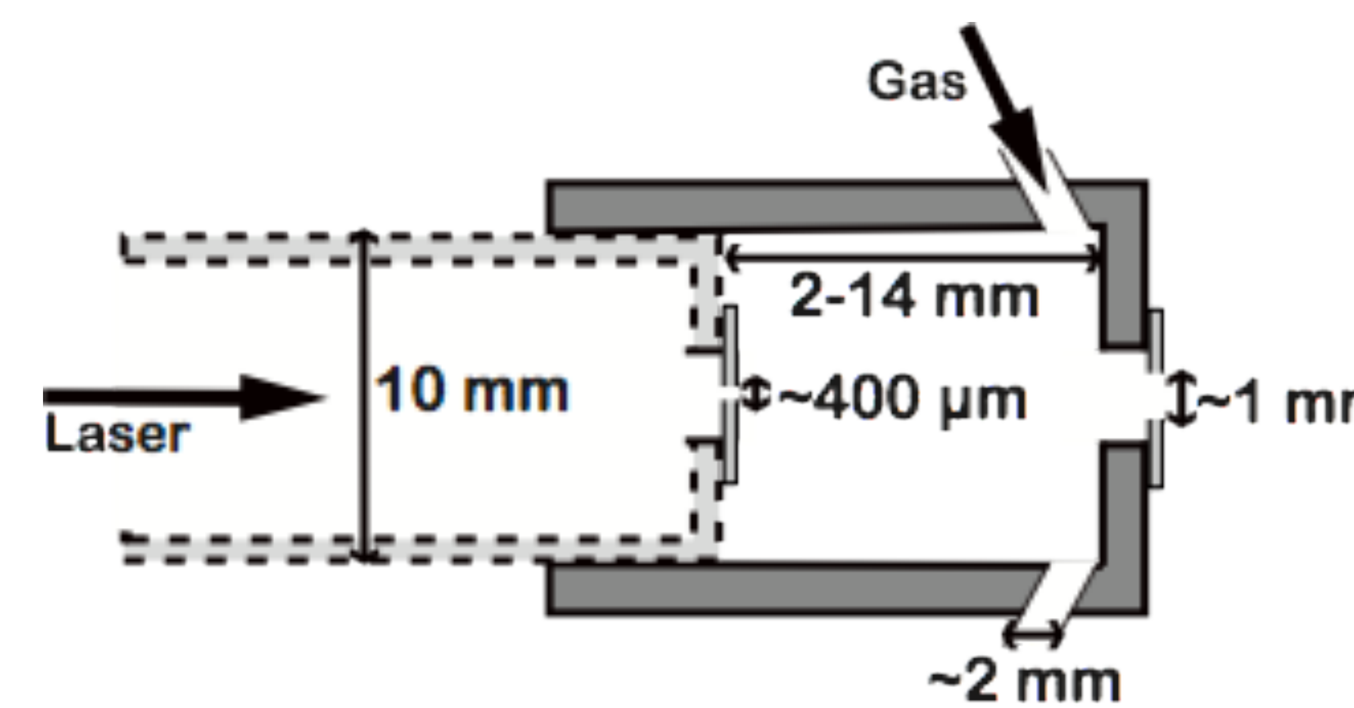
- Plume of gas from front and back of cell → extended density transitions
- Density easily adjusted by controlling gas flow in range: 10^{17} - 10^{19} cm^{-3}
- Potential issue: erosion of outlet pinholes will change density
- Variable length gas cell designs exist (e.g. LMU Munich, Imperial College London)

OpenFoam simulations show uniform density within cell & extent of plumes

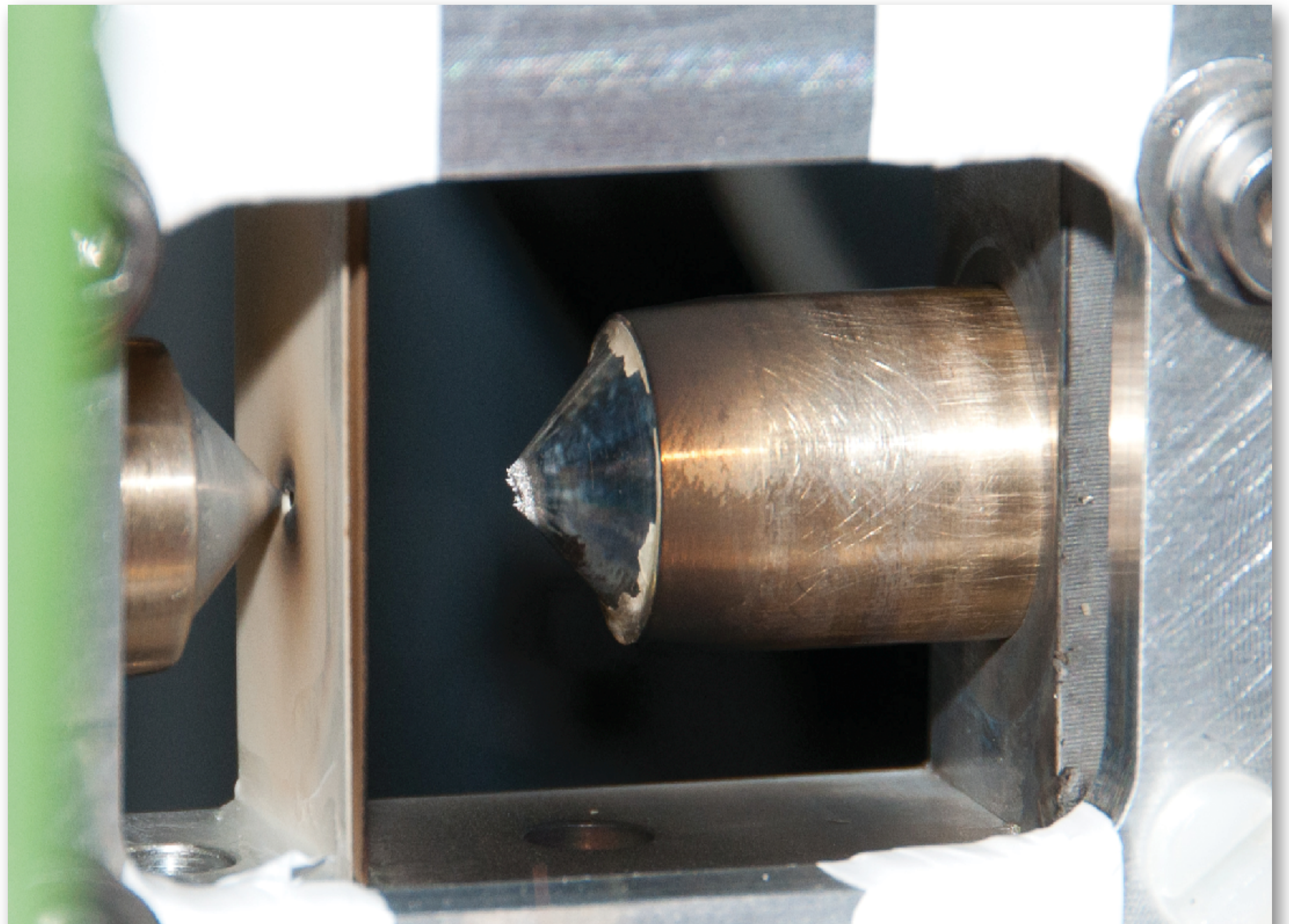


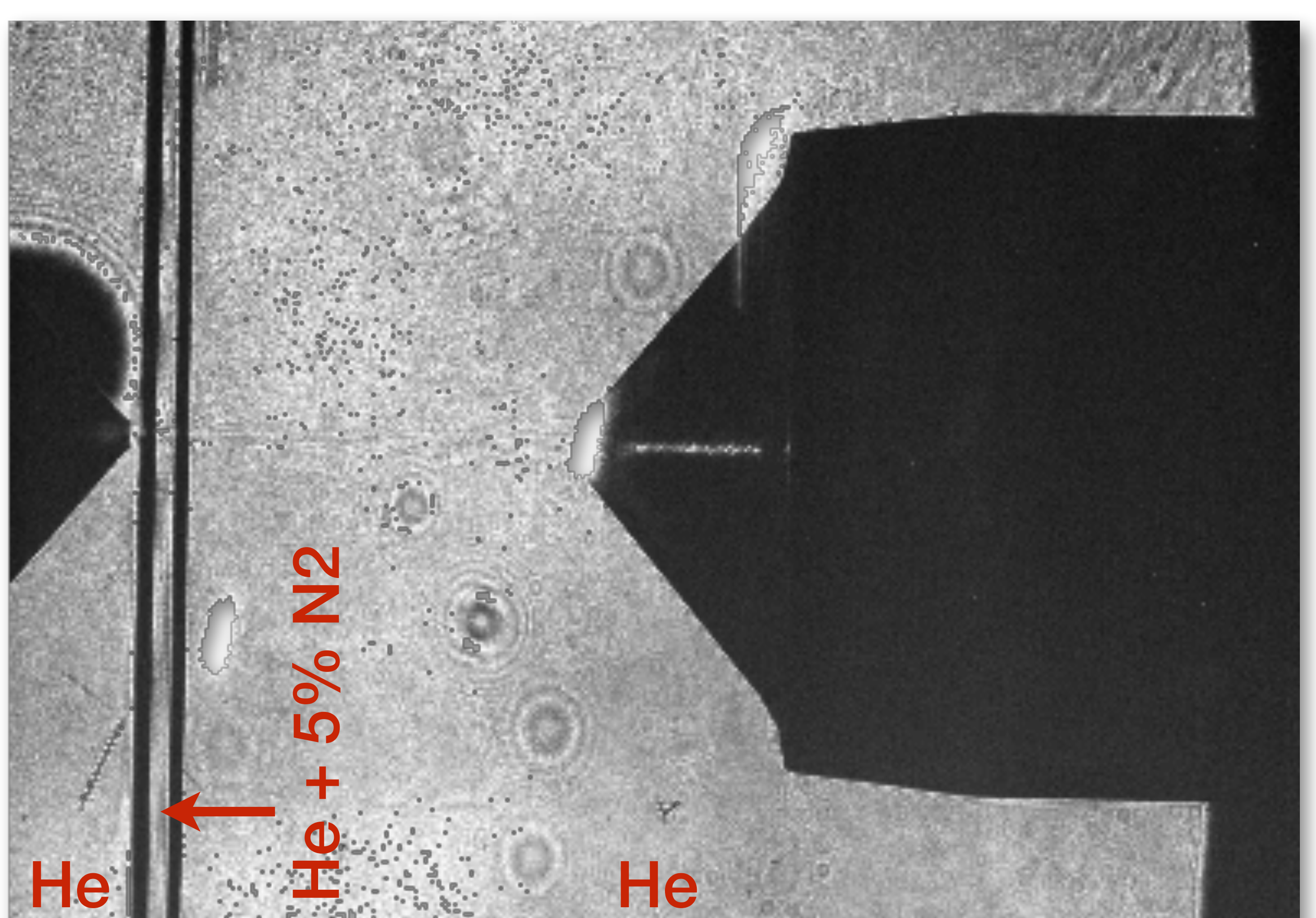


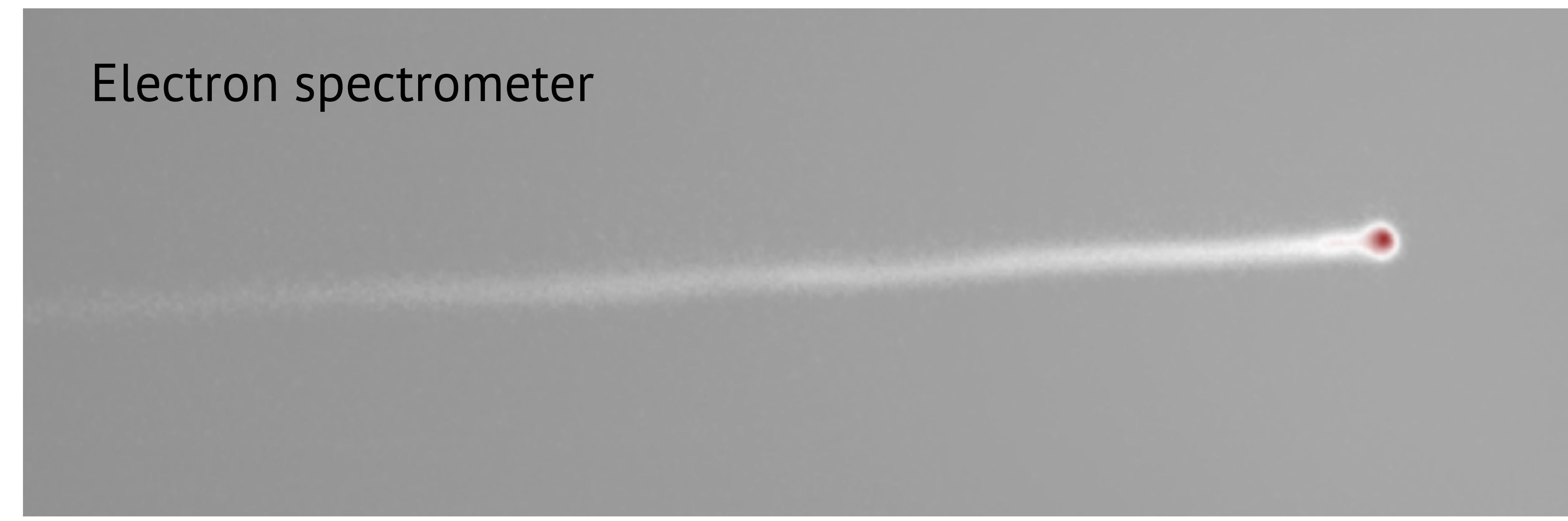
Variable length gas cell

Three-chamber gas cell

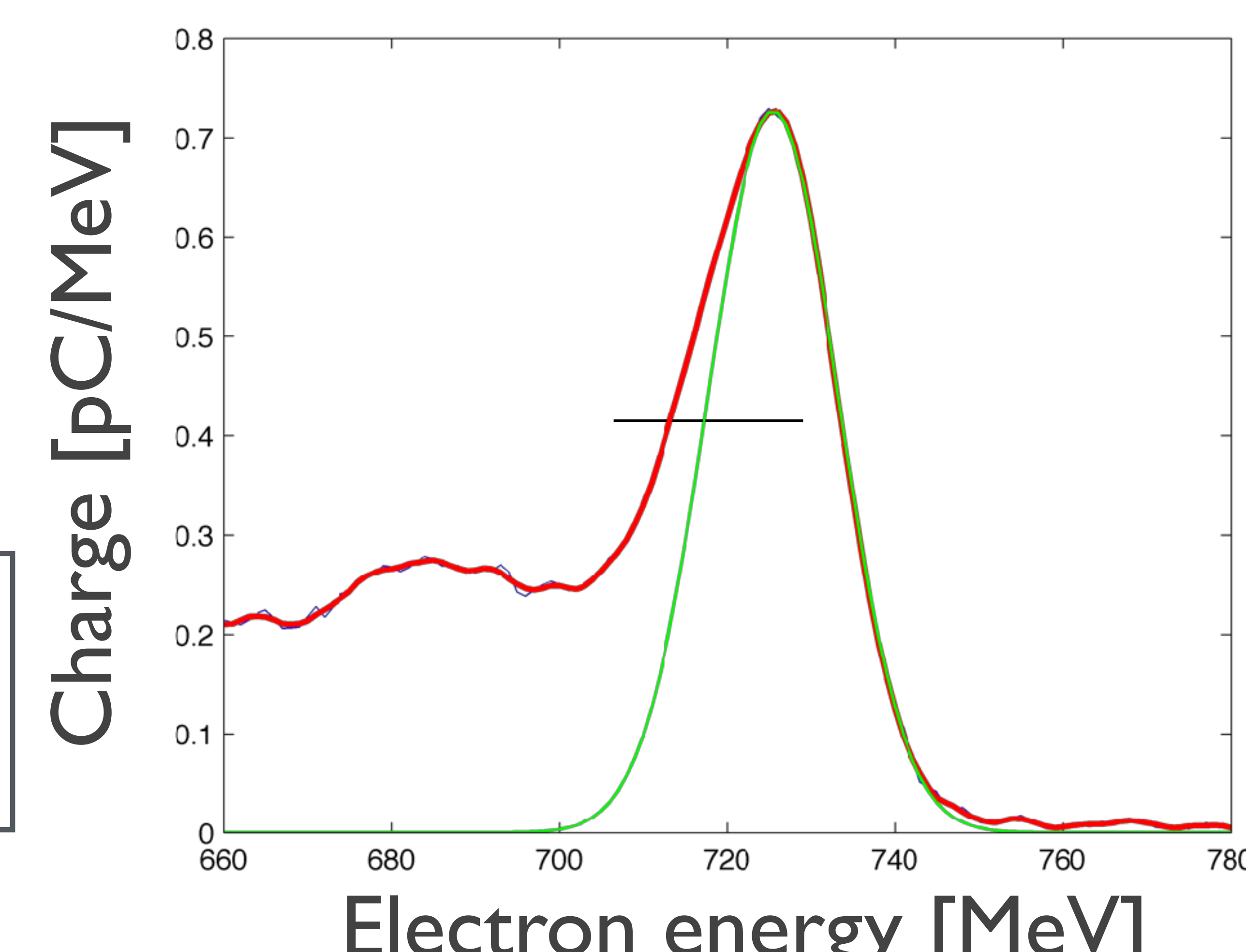
Courtesy Zulfikar Najmudin
Imperial College London

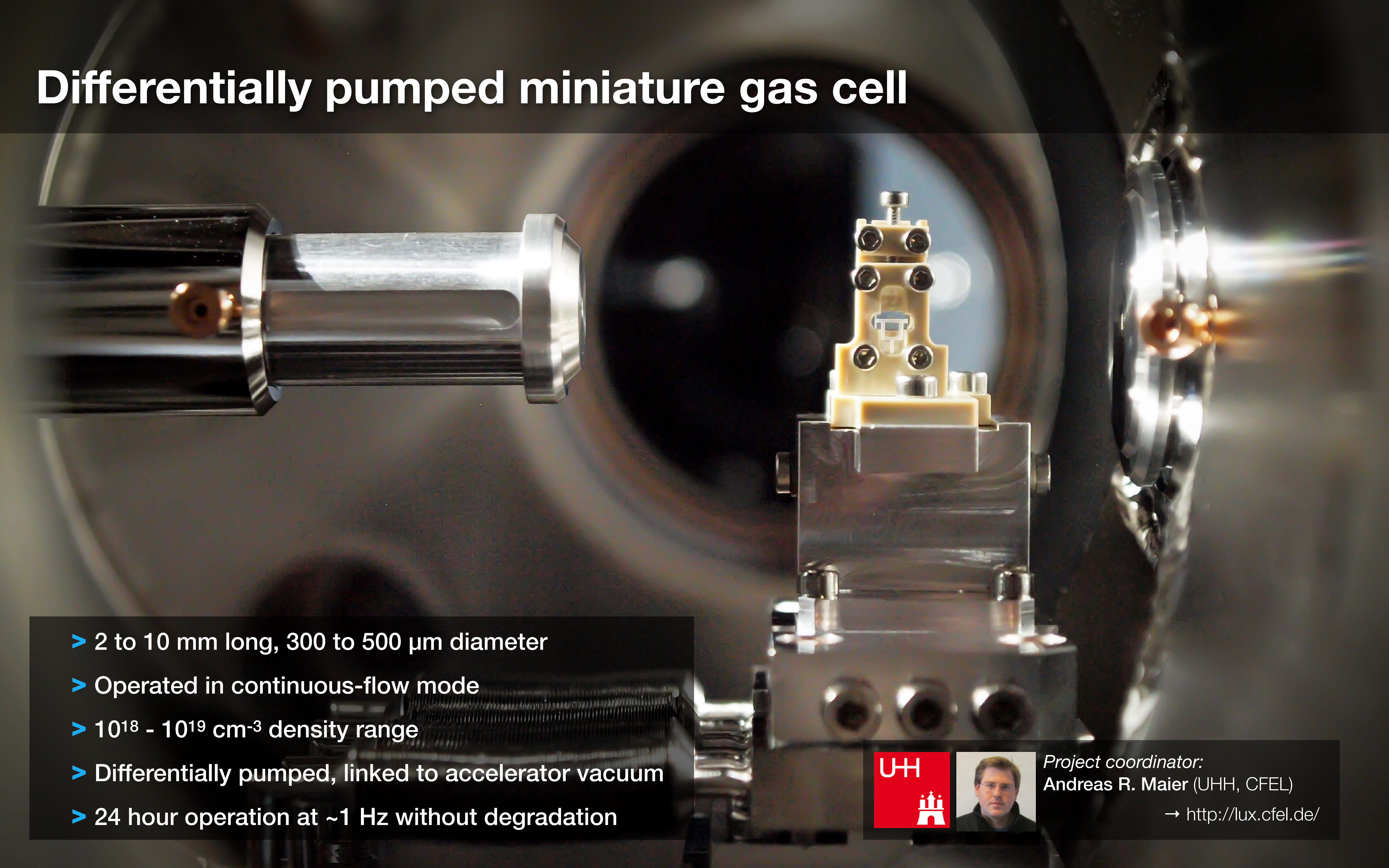






E_e= 726 MeV
ΔE = 3.0%
Charge ≈ 17 pC





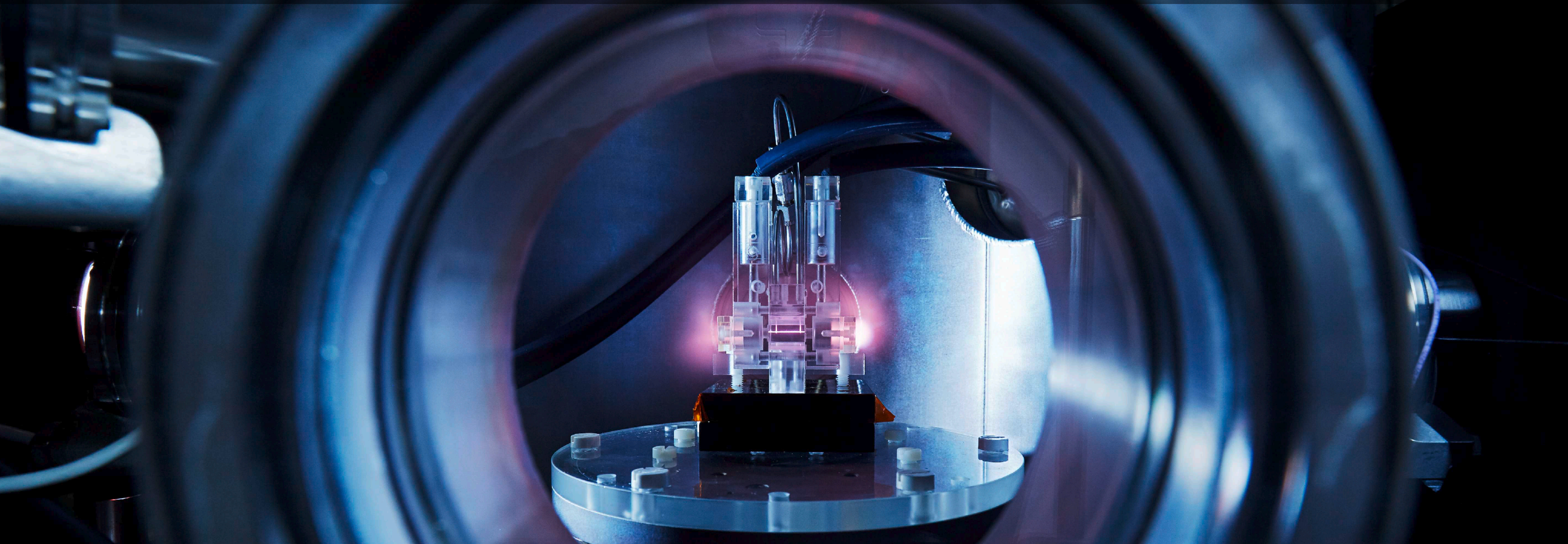
Differentially pumped miniature gas cell

- 2 to 10 mm long, 300 to 500 µm diameter
- Operated in continuous-flow mode
- 10^{18} - 10^{19} cm^{-3} density range
- Differentially pumped, linked to accelerator vacuum
- 24 hour operation at ~1 Hz without degradation

Project coordinator:
Andreas R. Maier (UHH, CFEL)

→ http://lux.cfel.de/

Discharge/laser ignited gas cell



- 10 to 195 mm long (plans for 450 mm exist), 200 to 2000 µm diameter
- Operated in continuous-flow mode
- 10^{14} - 10^{19} cm^{-3} density range
- Differentially pumped, linked to SRF accelerator vacuum
- 72 hour operation at ~1 Hz without degradation

DESY.

FLASHFORWARD

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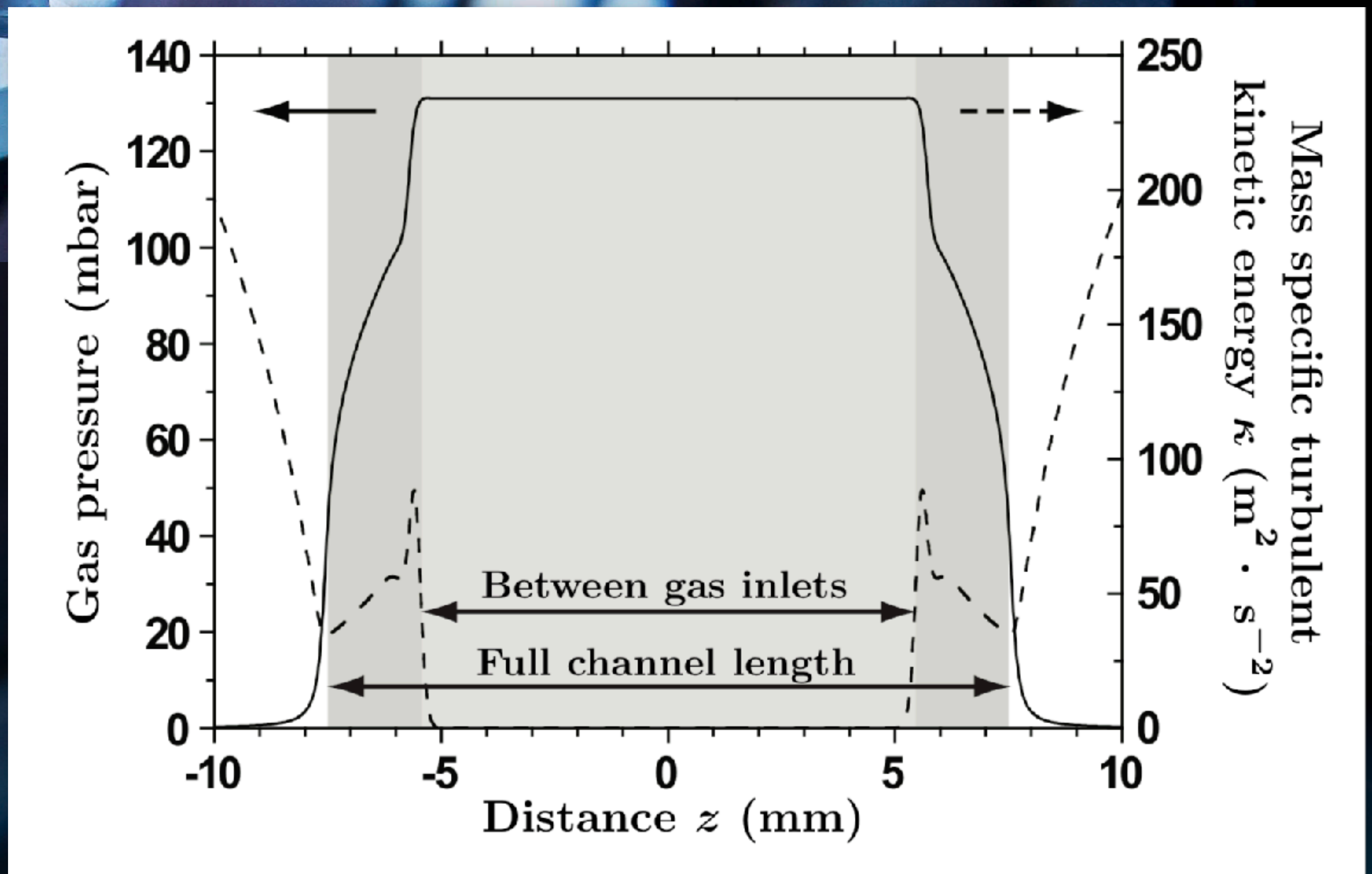
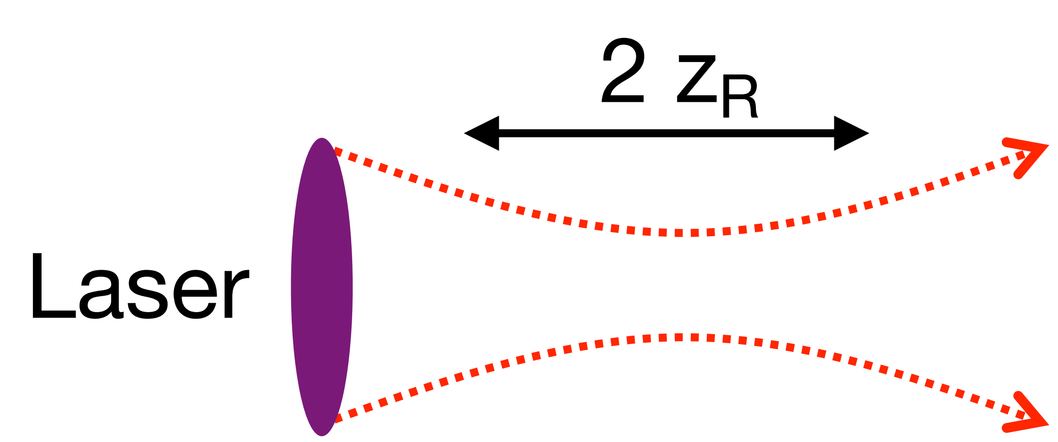
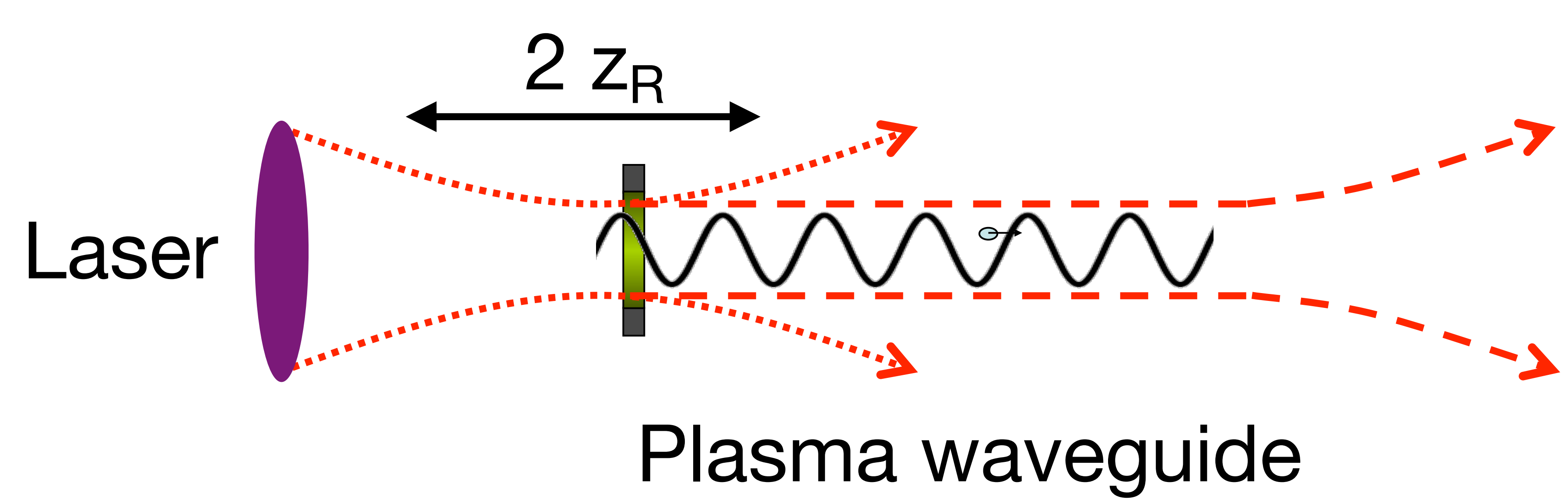


Plasma sources as waveguides

Plasma sources as waveguides

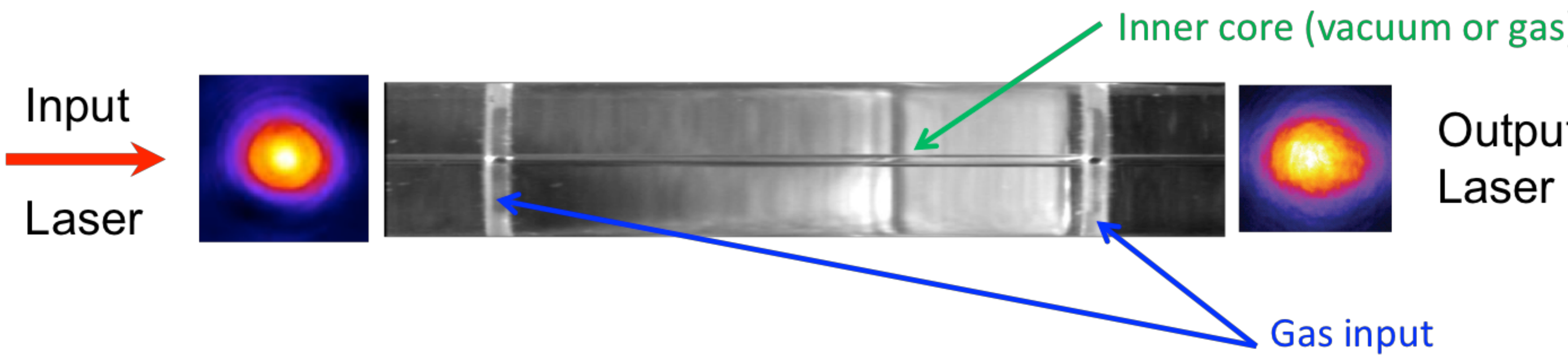


Plasma sources as waveguides



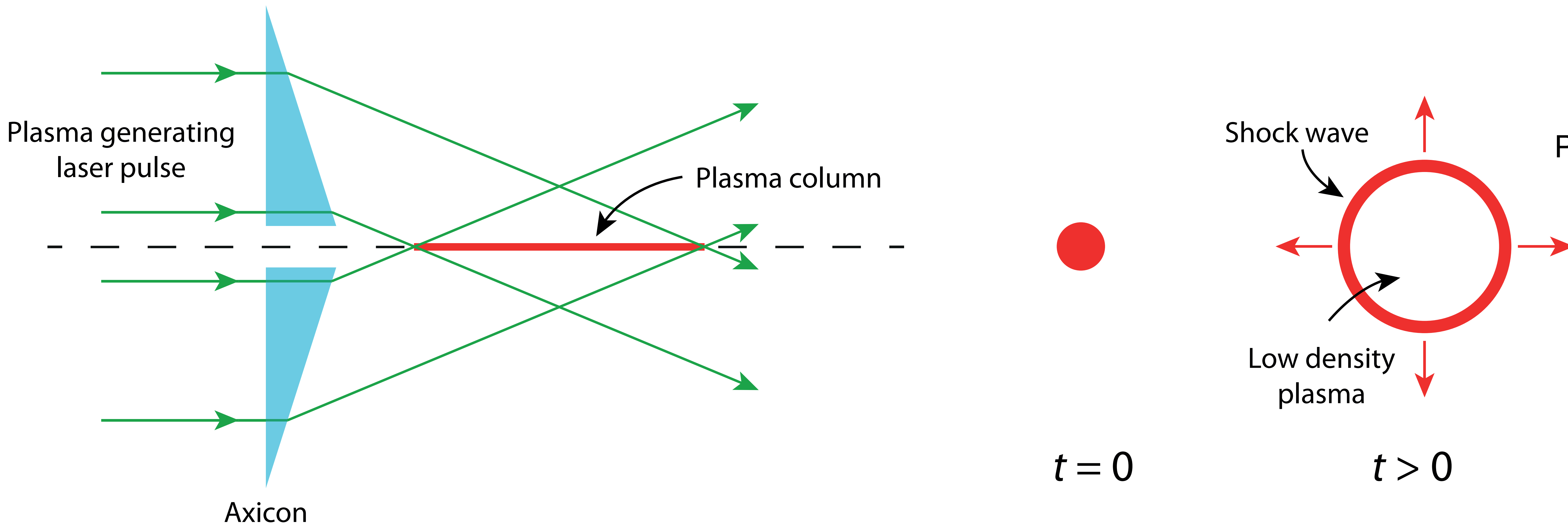
Grazing-incidence waveguides

Courtesy Brigitte Cros
LPGP, CNRS-Université Paris-Sud



- Laser is guided by the index of refraction change from vacuum/gas/plasma to wall under grazing incidence
- Operation in a large parameter range
  - Inner diameter: 50 - 500 µm
  - Glass walls: optically smooth
  - Length: limited by laser damping length
    (several meters for 100µm diameter capillary)
  - Laser intensity: limitations owing to imperfect beam quality and stability
  - Gas pressure control: 0-500 mbar, pulsed (1shot / 10s)

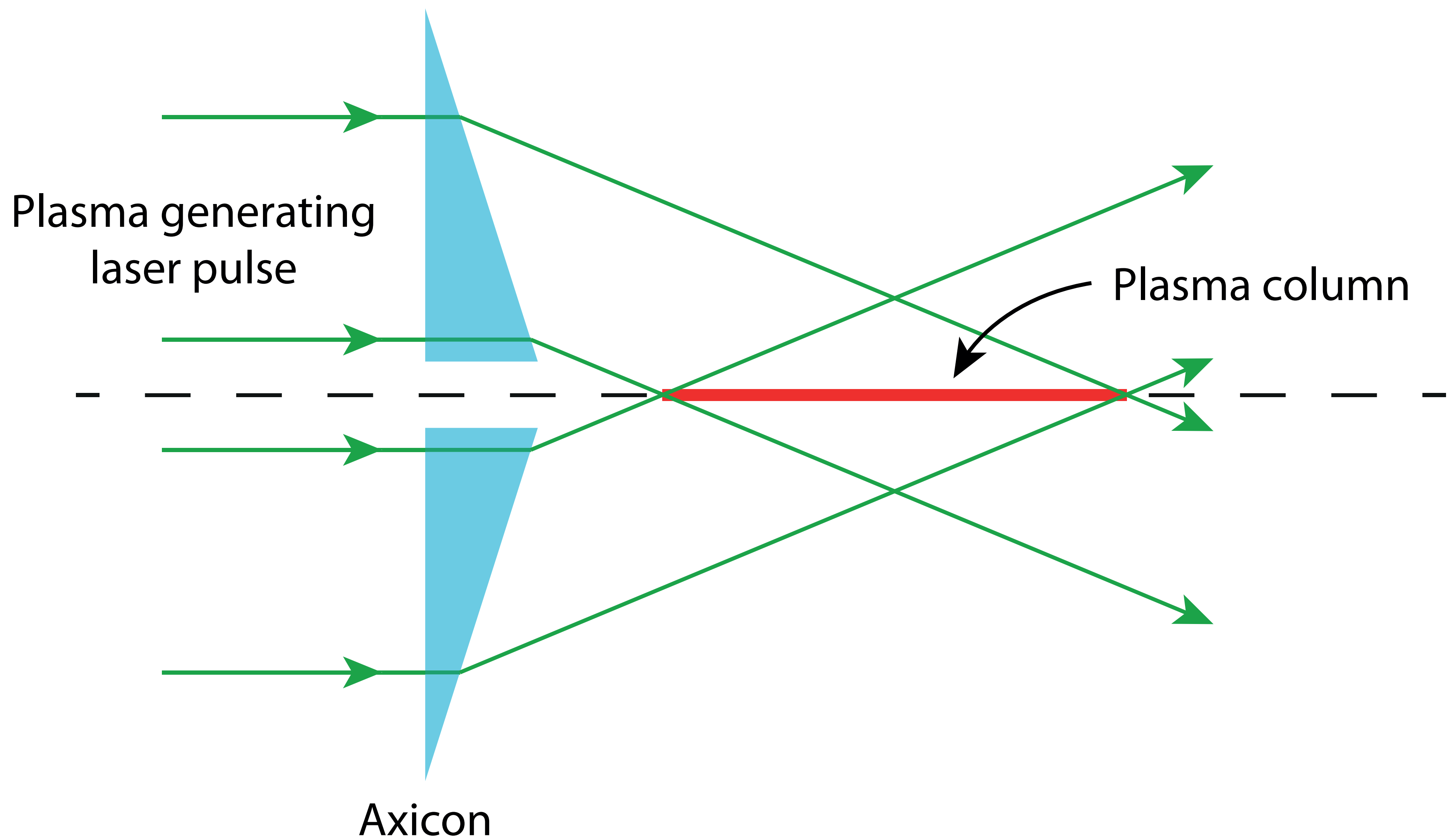
Plasma waveguide: hydrodynamic expansion

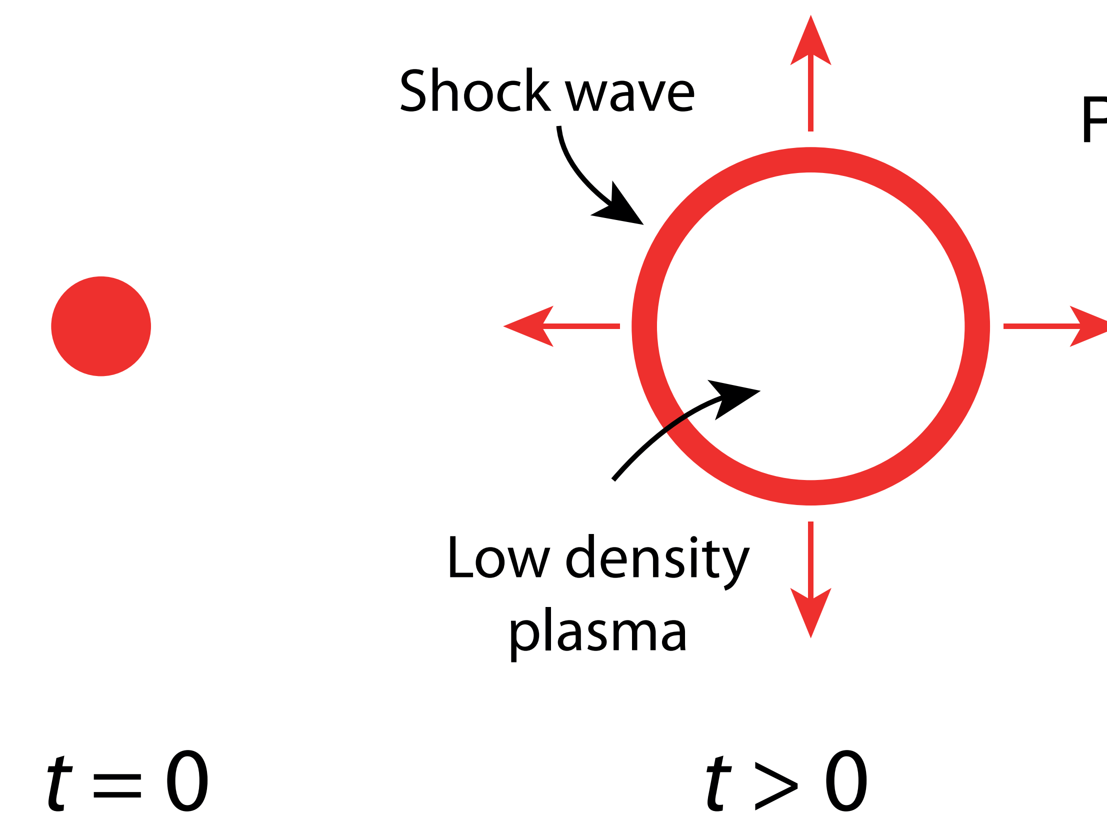


C.G. Durfee & H.M. Milchberg, Phys. Rev. Lett. **71,** 2409 (1993)

- Hot plasma column produced by longitudinal line focus
- Plasma expands rapidly, driving shock into surrounding gas
- On-axis density well is formed

Plasma waveguide: hydrodynamic expansion





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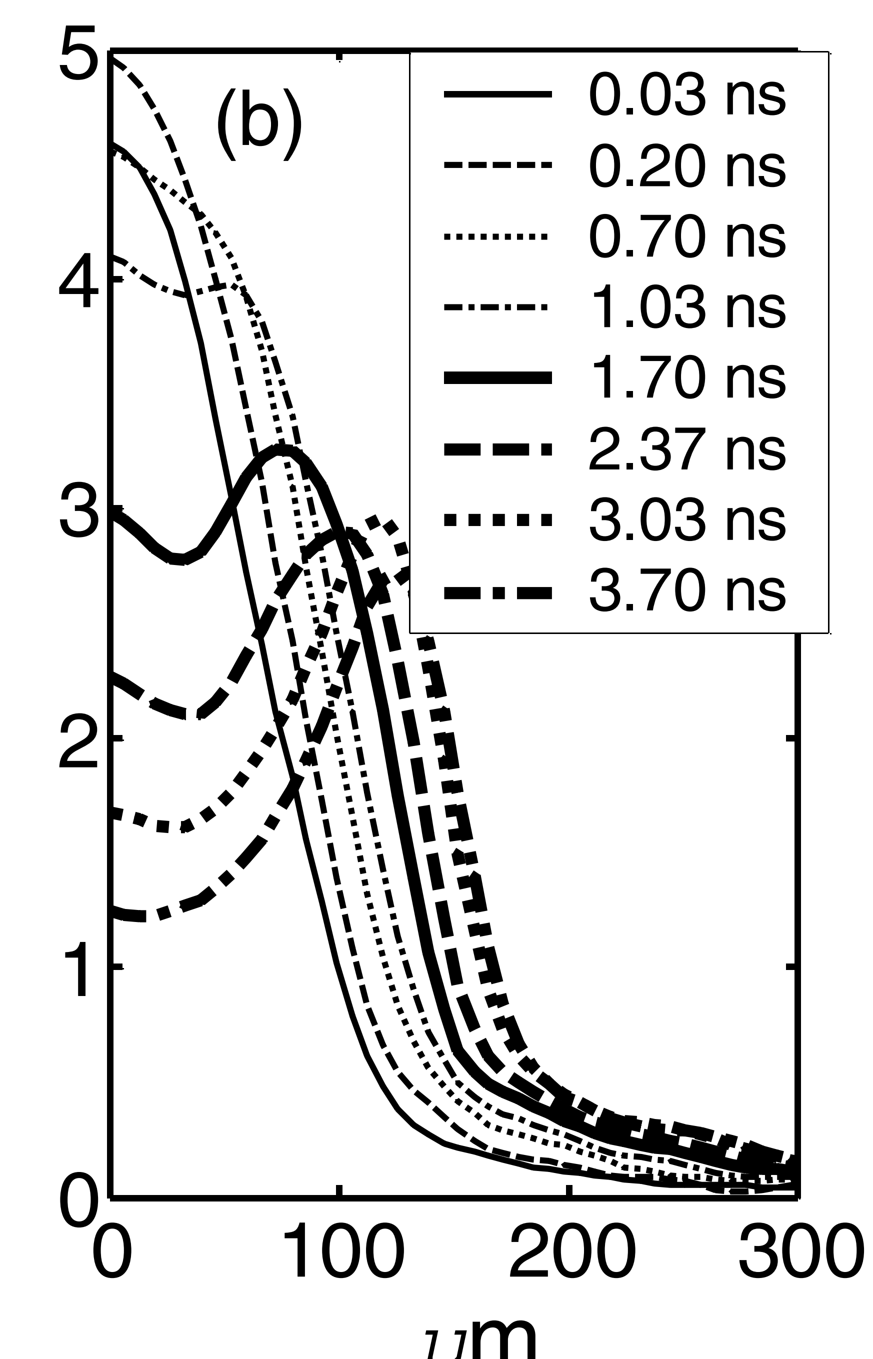
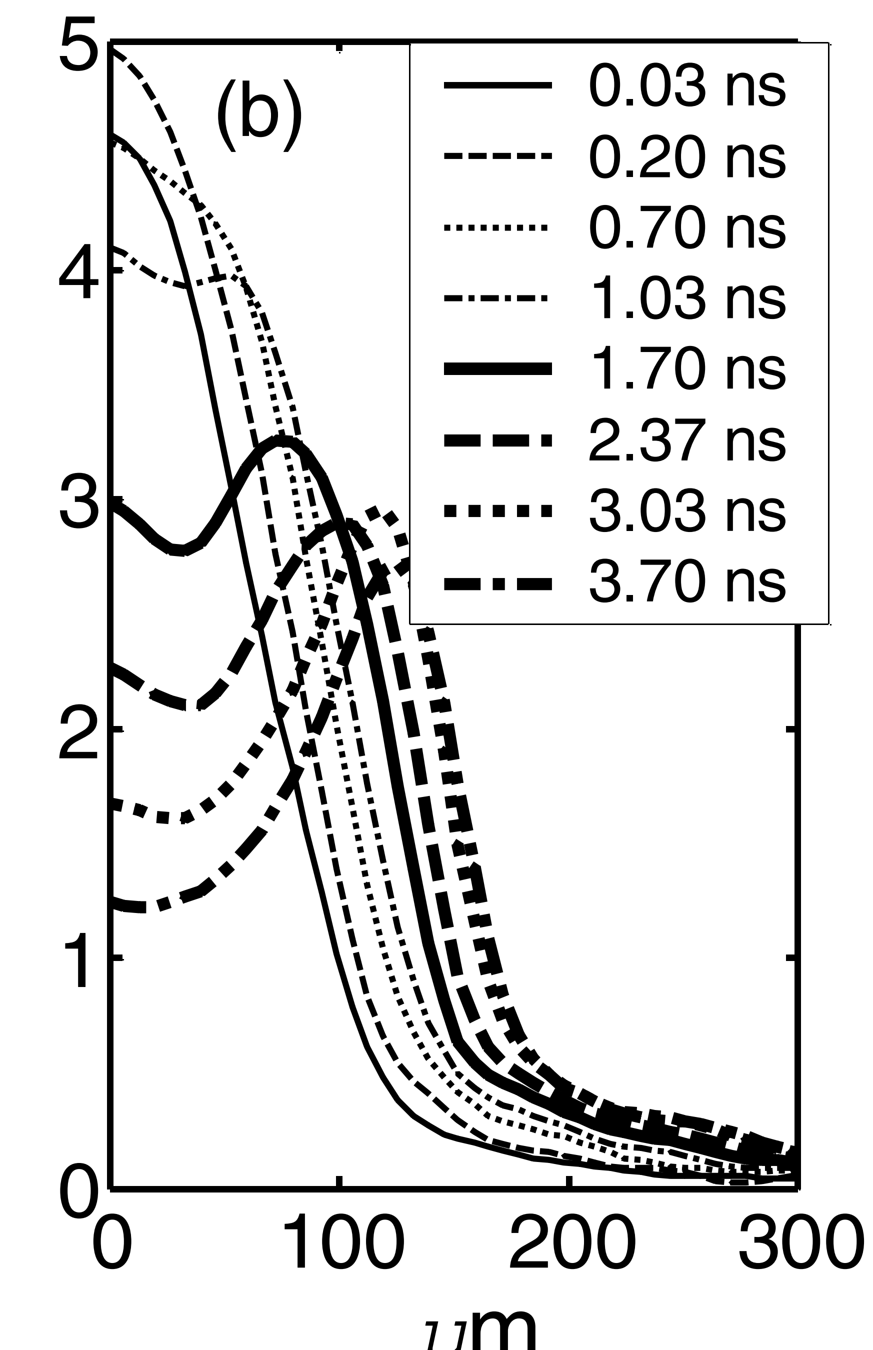
V. Kumarappan *et al.,* Phys. Rev. Lett. **94,** 205004 (2005)



Evolution of plasma density (10^{18} cm^{-3}) in clustered Ar gas jet (113K, 20 bar)

Plasma waveguide: hydrodynamic expansion

- Original scheme
  - ~100 ps laser pulse creates and heats plasma
  - On-axis density ~5×10^{18} cm^{-3}
  - Matched spot WM ~10-20 μm
  - Length < 30 mm
- Ignitor-heater method
  - Two, crossed beams create plasma:
  - fs-duration "ignitor"
  - ps-duration "heater"
- Clustered gases
  - Efficient energy absorption of clusters facilitates heating
  - Ionized and heated by fs-duration pulse
  - Generates lower on-axis densities ~1×10^{18} cm^{-3}



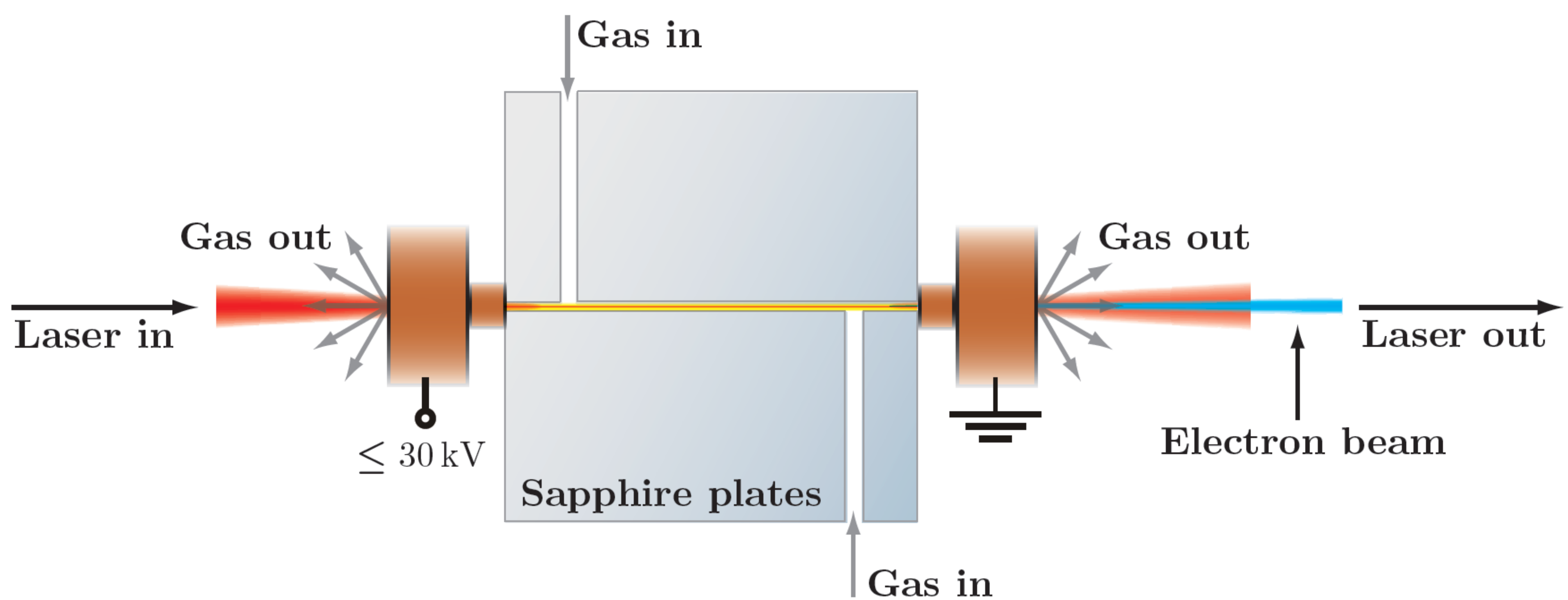
Evolution of plasma density (10^{18} cm^{-3}) in clustered Ar gas jet (113K, 20 bar)

V. Kumarappan *et al.,* Phys. Rev. Lett. **94,** 205004 (2005)

Capillary discharge waveguides

<u>Original work</u>
D. J. Spence & S.M. Hooker, Phys. Rev. E **63,** 015401 (2000)
A. Butler *et al.,* Phys. Rev. Lett. **89,** 185003 (2002)
N.A. Bobrova *et al.,* Phys. Rev. E **65,** 016407 (2002)

- Plasma ignition by high-voltage discharge
- After t ~ 80 ns plasma is in quasi-equilibrium:
  Ohmic heating is balanced by conduction of heat to wall
- Ablation rate small: cap. lasts for >10^6 shots
- $n_e \approx 10^{17} - 10^{19}$ cm^{-3}



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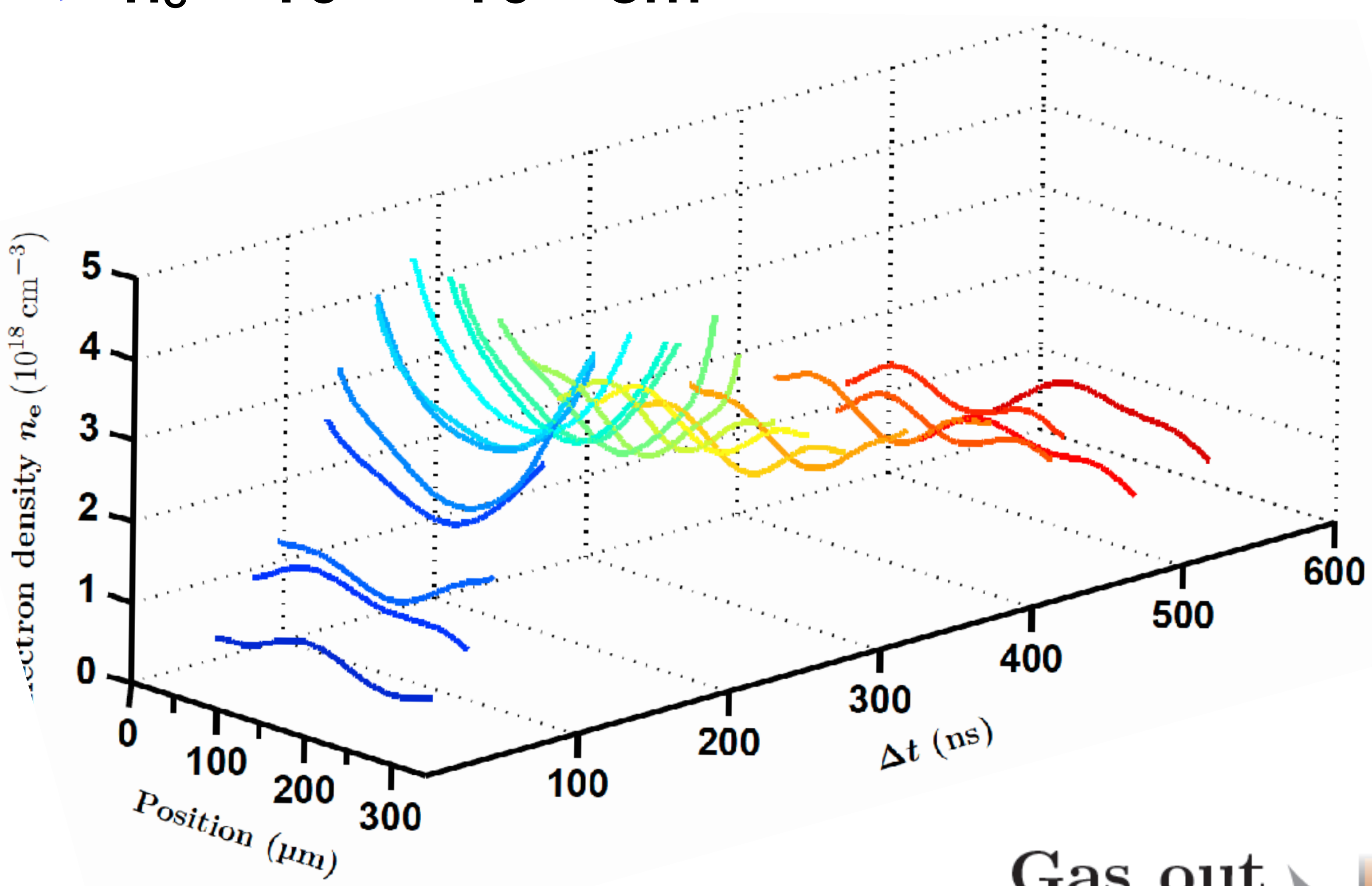
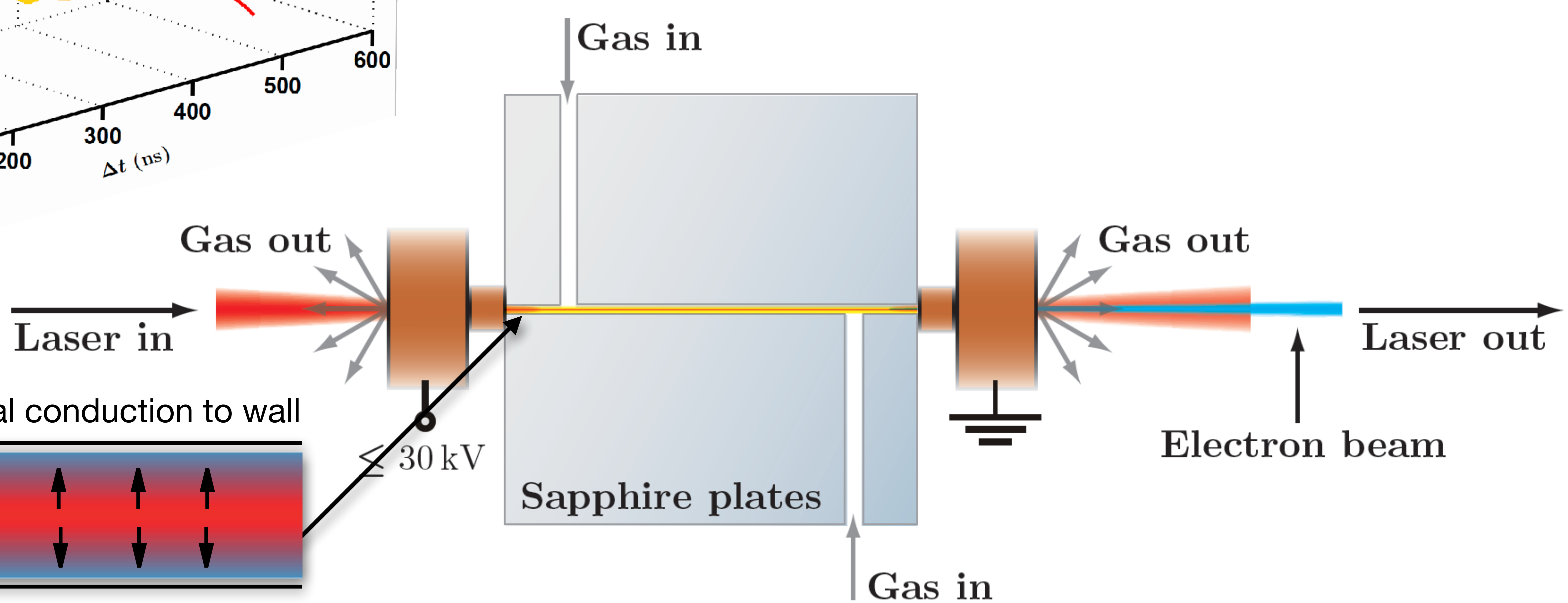
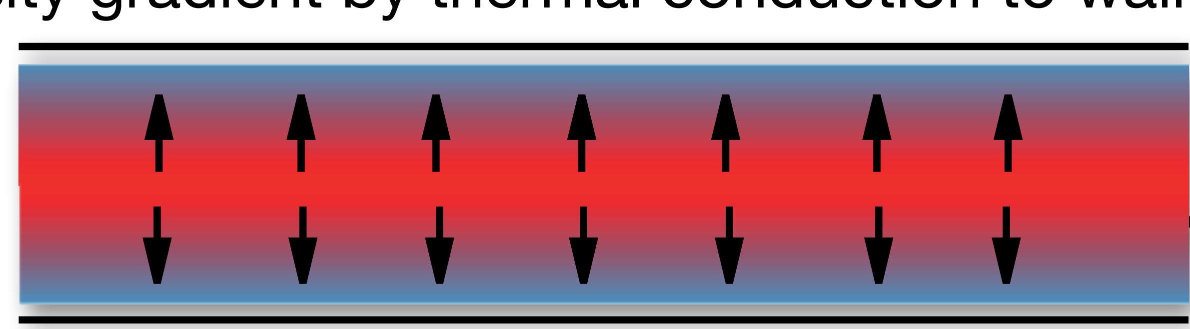




Density gradient by thermal conduction to wall



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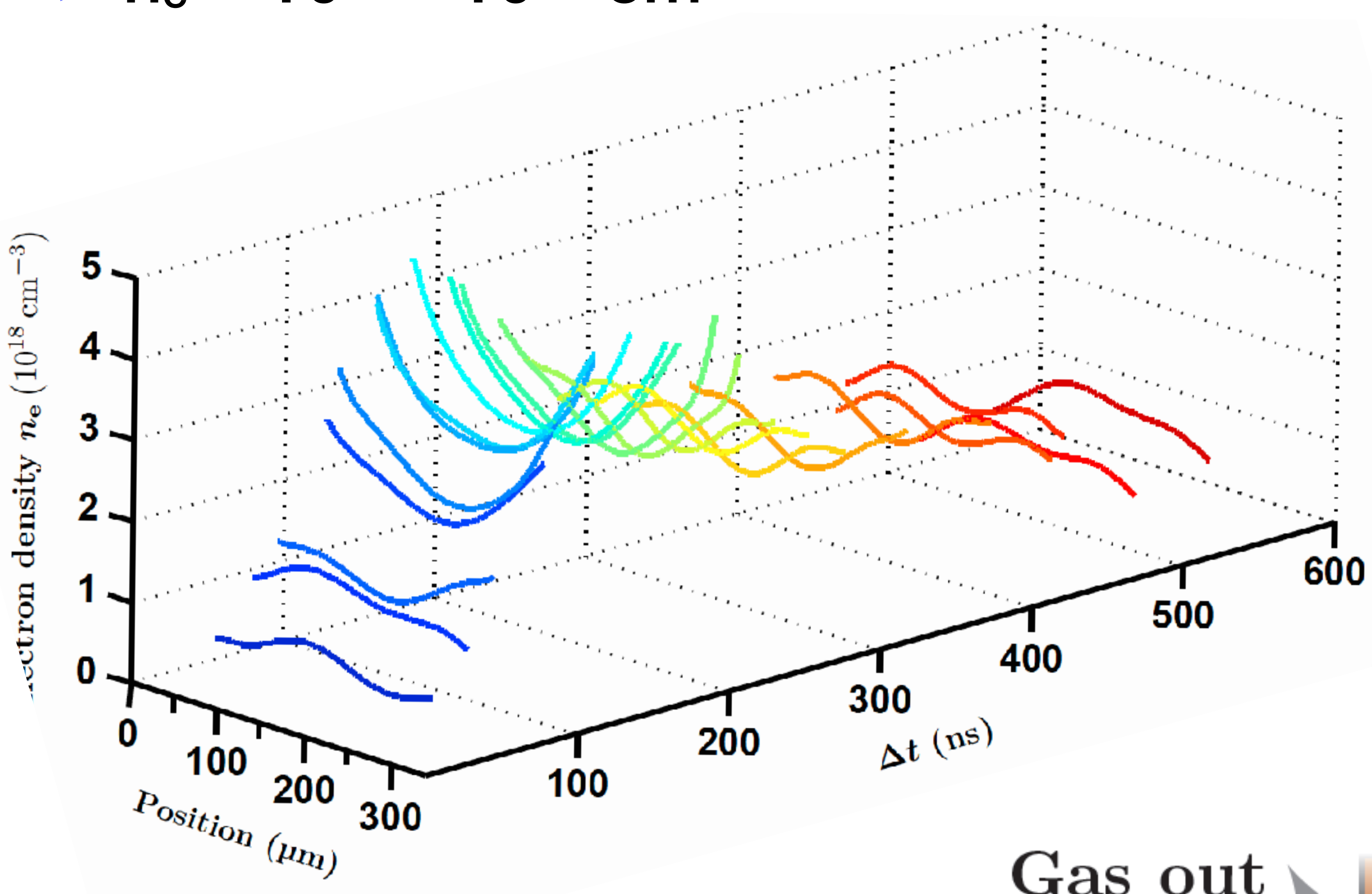
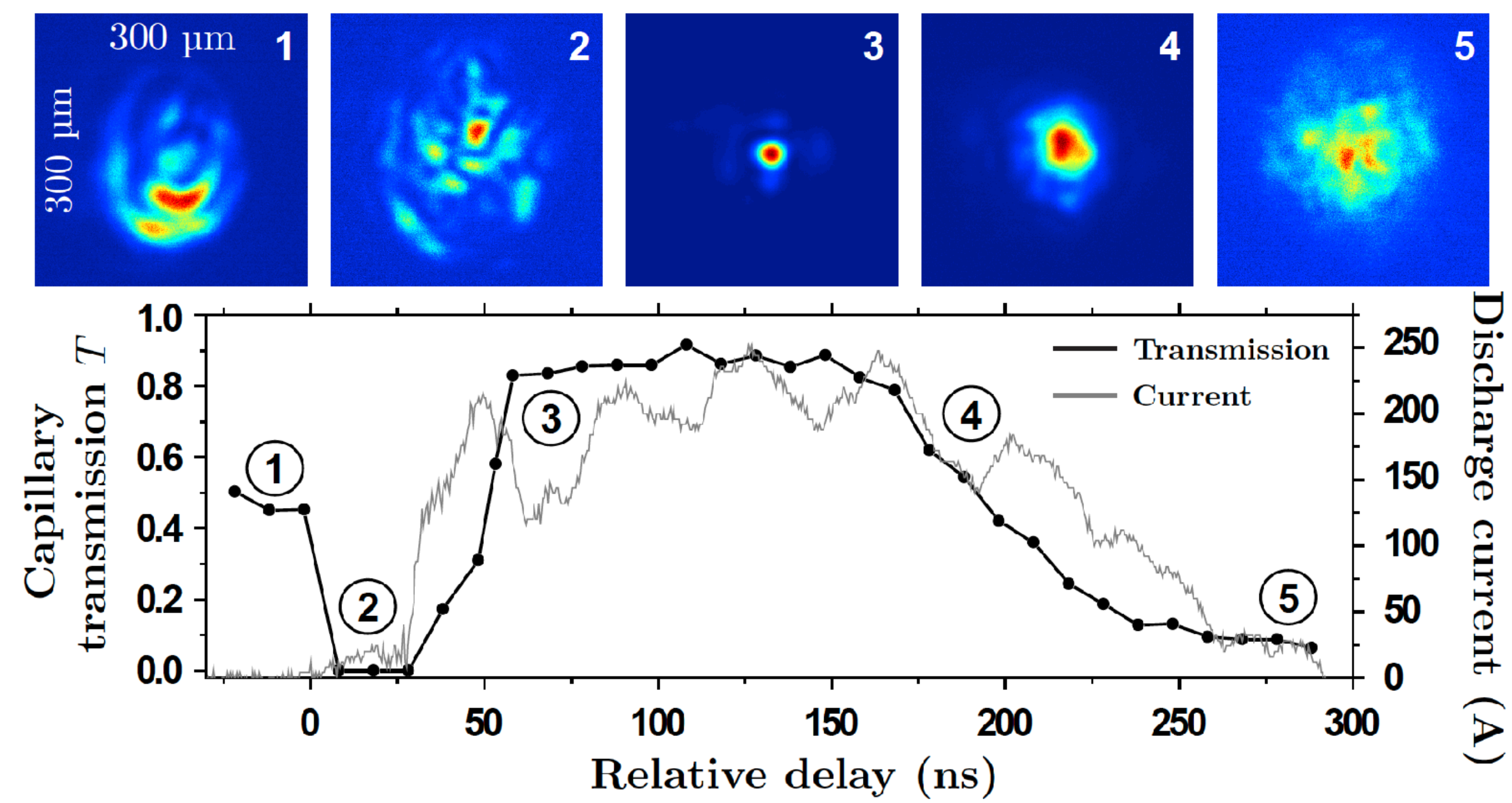
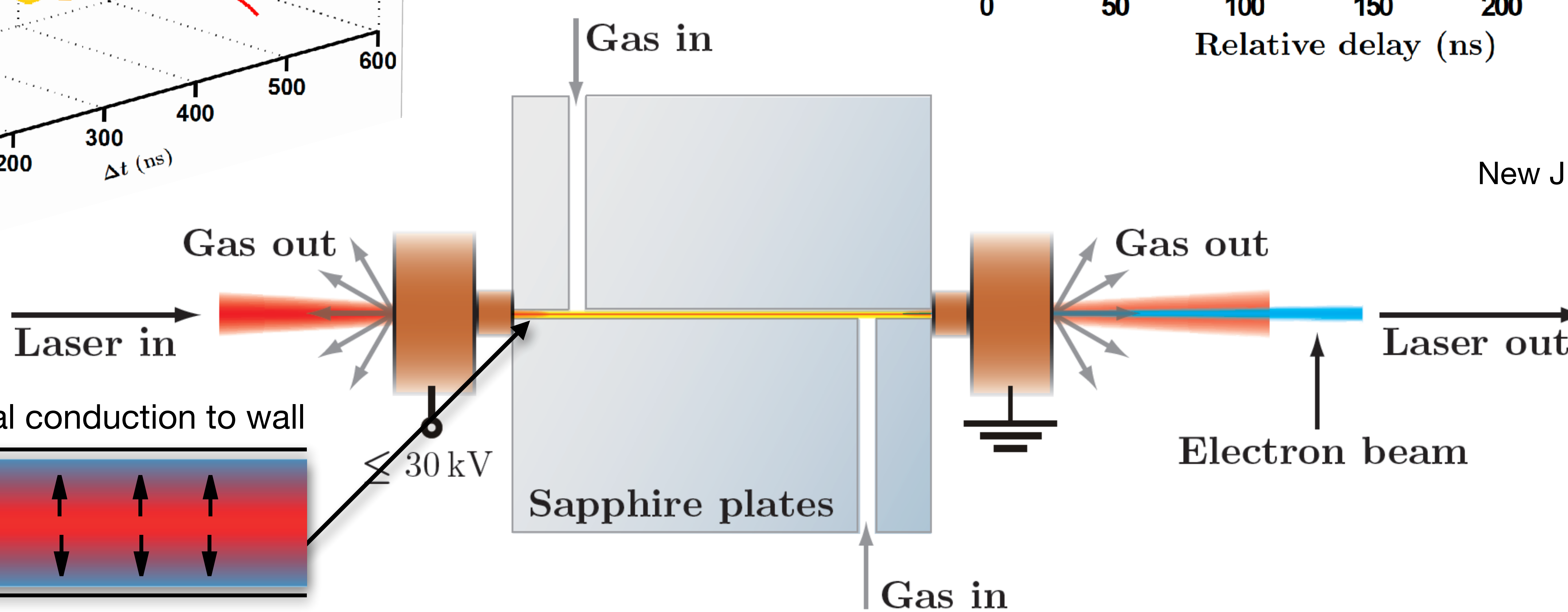


Z_R = 2 mm, guiding over 16 mm, guiding efficiency > 90 %





from Karsch *et al.*,
New J. Phys. **9**, 415 (2007)

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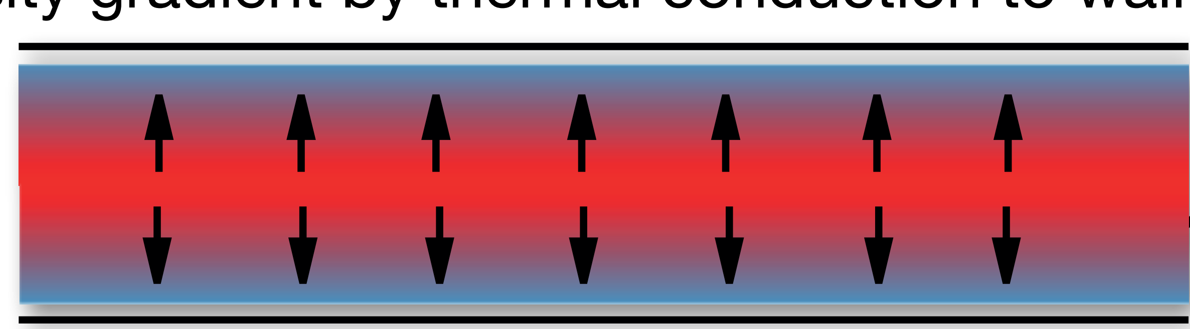
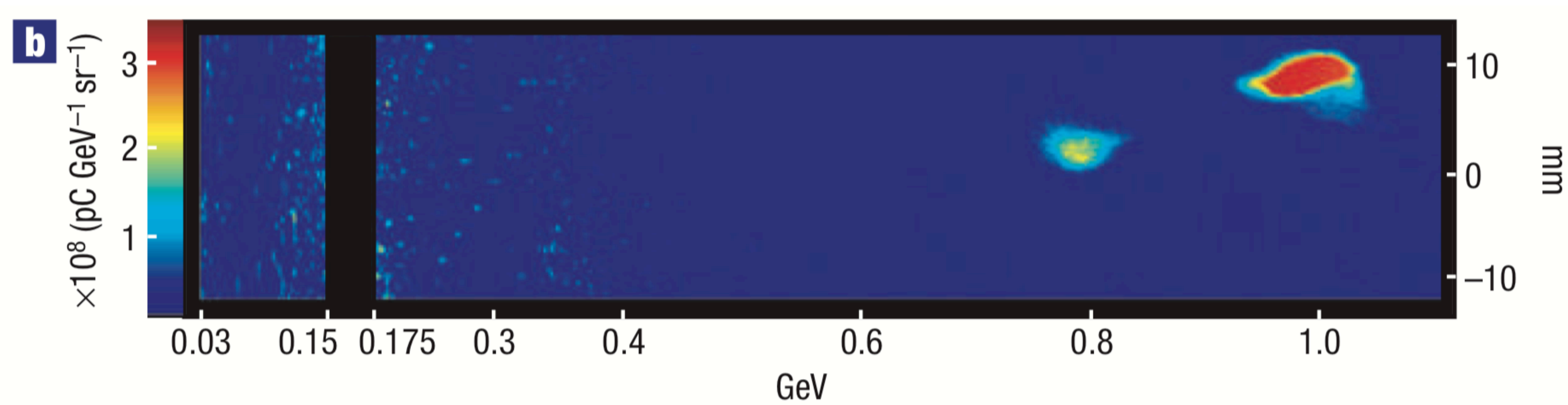


Capillary discharge waveguides

> Path to highest LWFA electron energies



Capillary diameter	312 um
Input laser power	40 TW
Input intensity	> 10^{18} W cm^{-2}
Plasma	4.3×10^{18} cm^{-3}

E = (1.0 +/- 0.06) GeV
ΔE = 2.5% RMS
$\Delta\theta$ = 1.6 mrad RMS
Q = 30 pC

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W. P. Leemans *et al.*,
Nature Physics **2,** 696 (2006)

Capillary discharge waveguides

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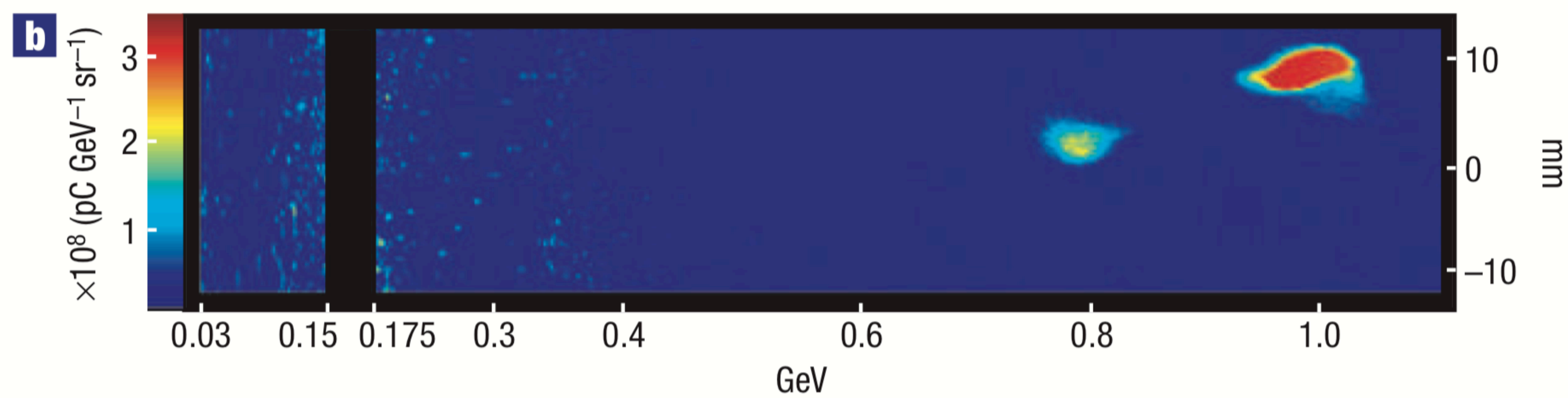

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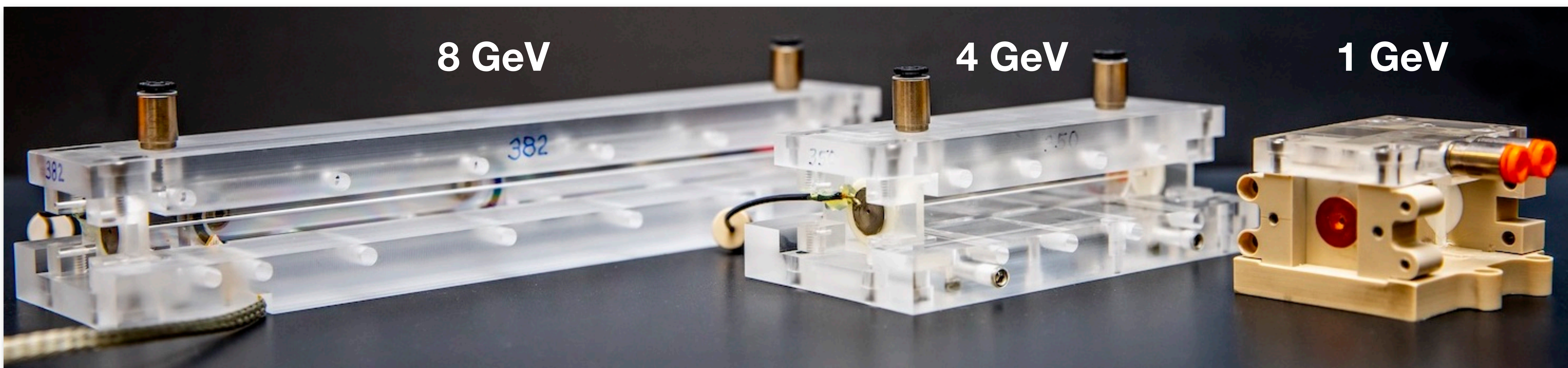

A. J. Gonsalves *et al.*,
Phys. Rev. Lett **122,** 084801 (2019)

W. P. Leemans *et al.*,
Phys. Rev. Lett **113,** 245002 (2014)

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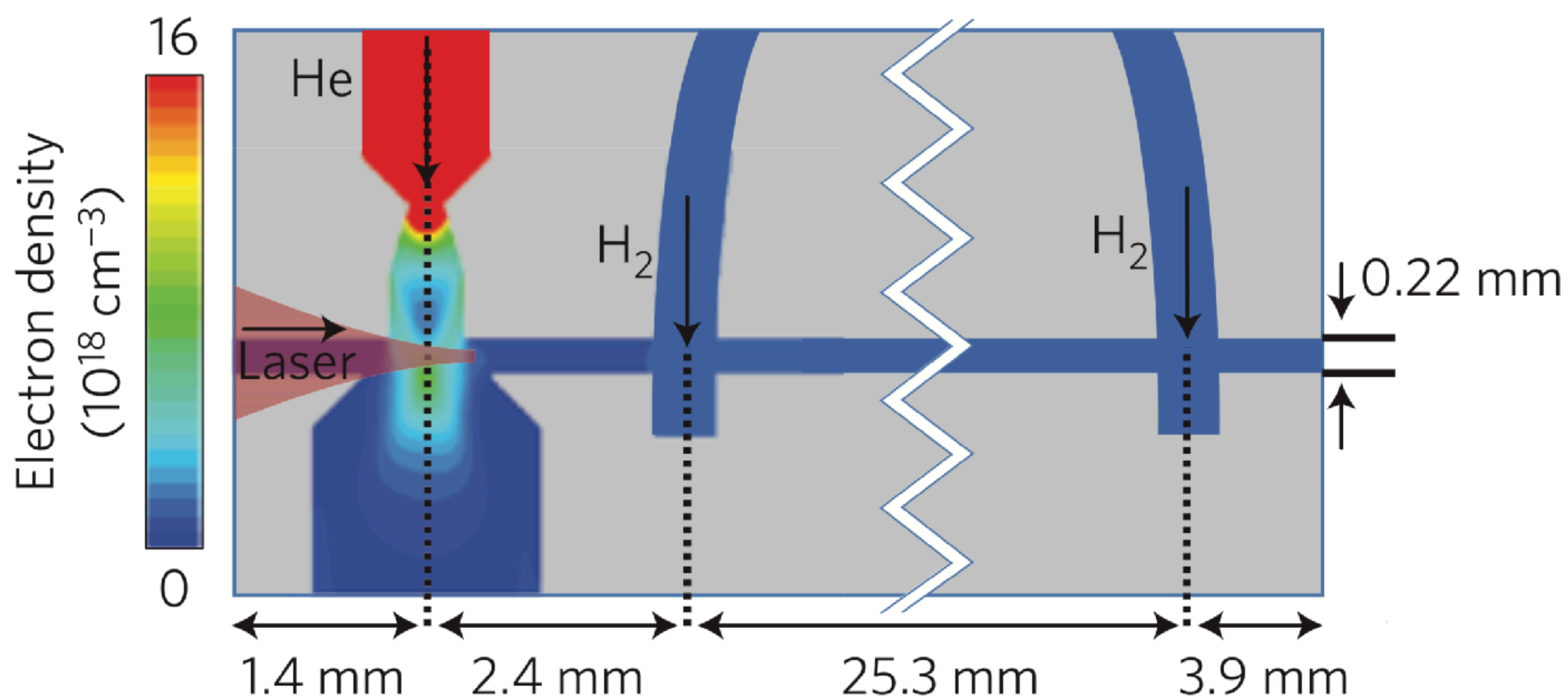
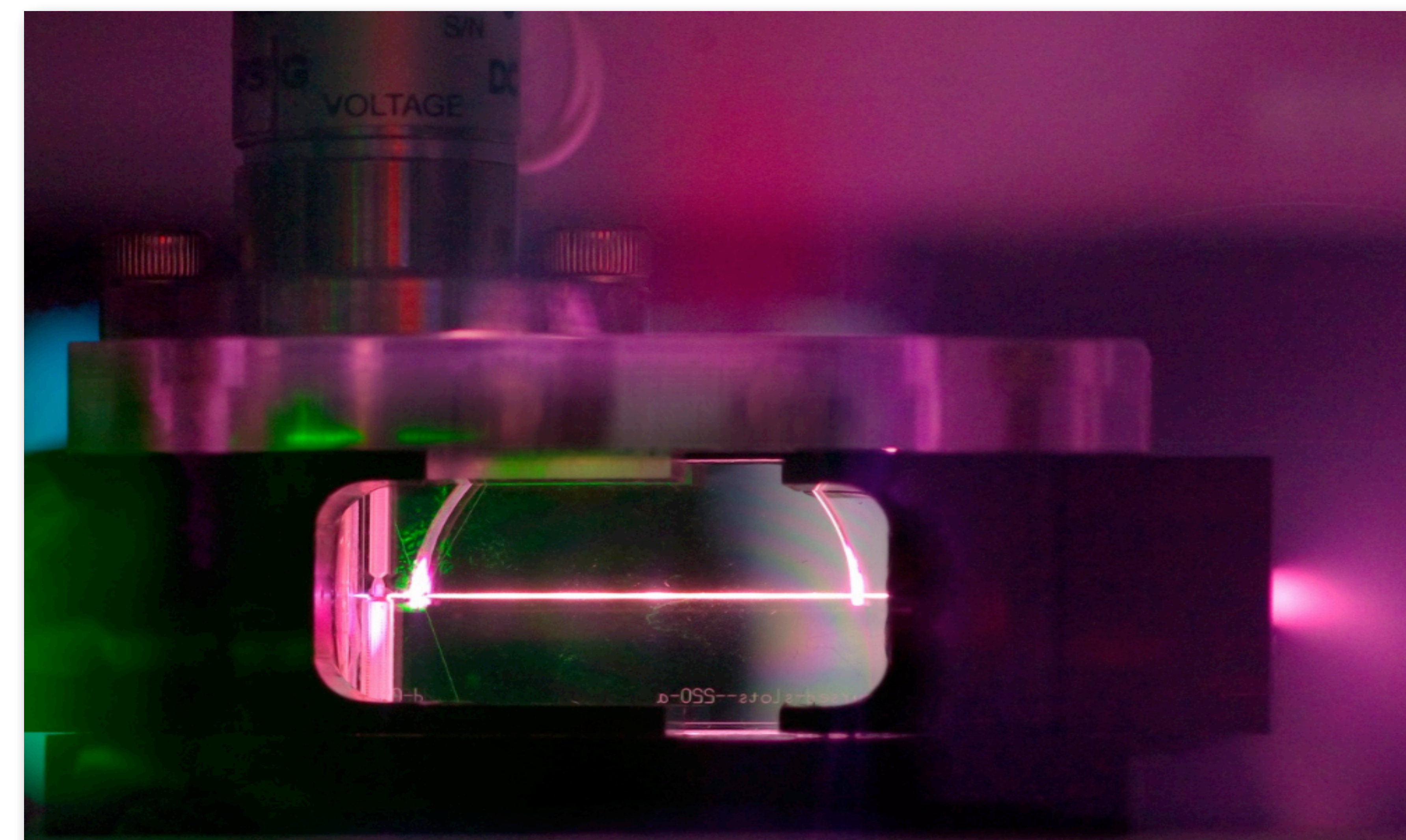
Advanced capillary discharge waveguides

- Combination of gas jet and capillary for controlled injection
- Beam energy controlled by adjusting position of laser focus
- ΔE_{RMS} = 1.9%, ΔQ_{RMS} = 45%, $\Delta\theta_{RMS}$ = 0.57 mrad

A.J. Gonsalves *et al.,* Nat. Phys. **7,** 862 (2011)





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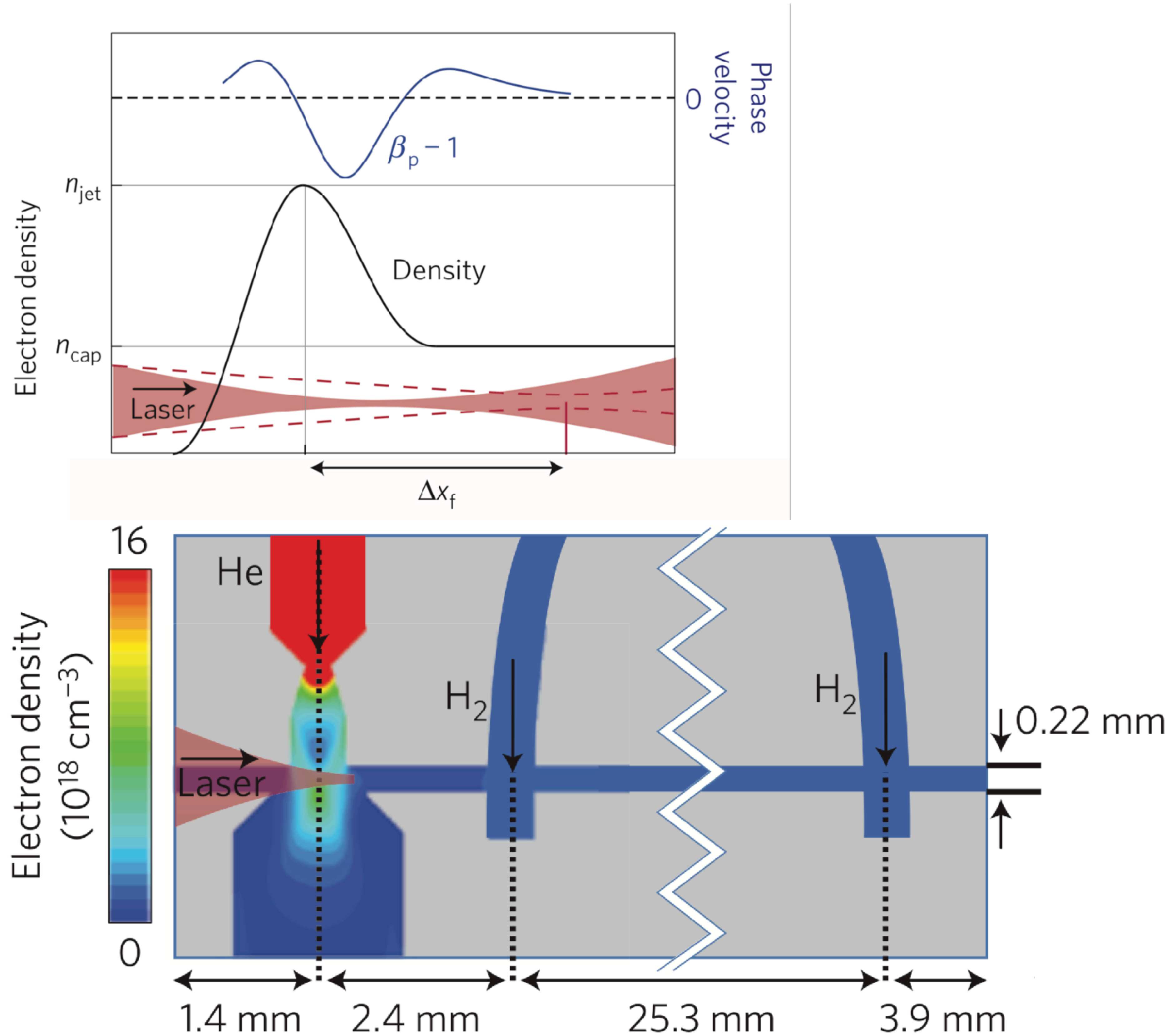
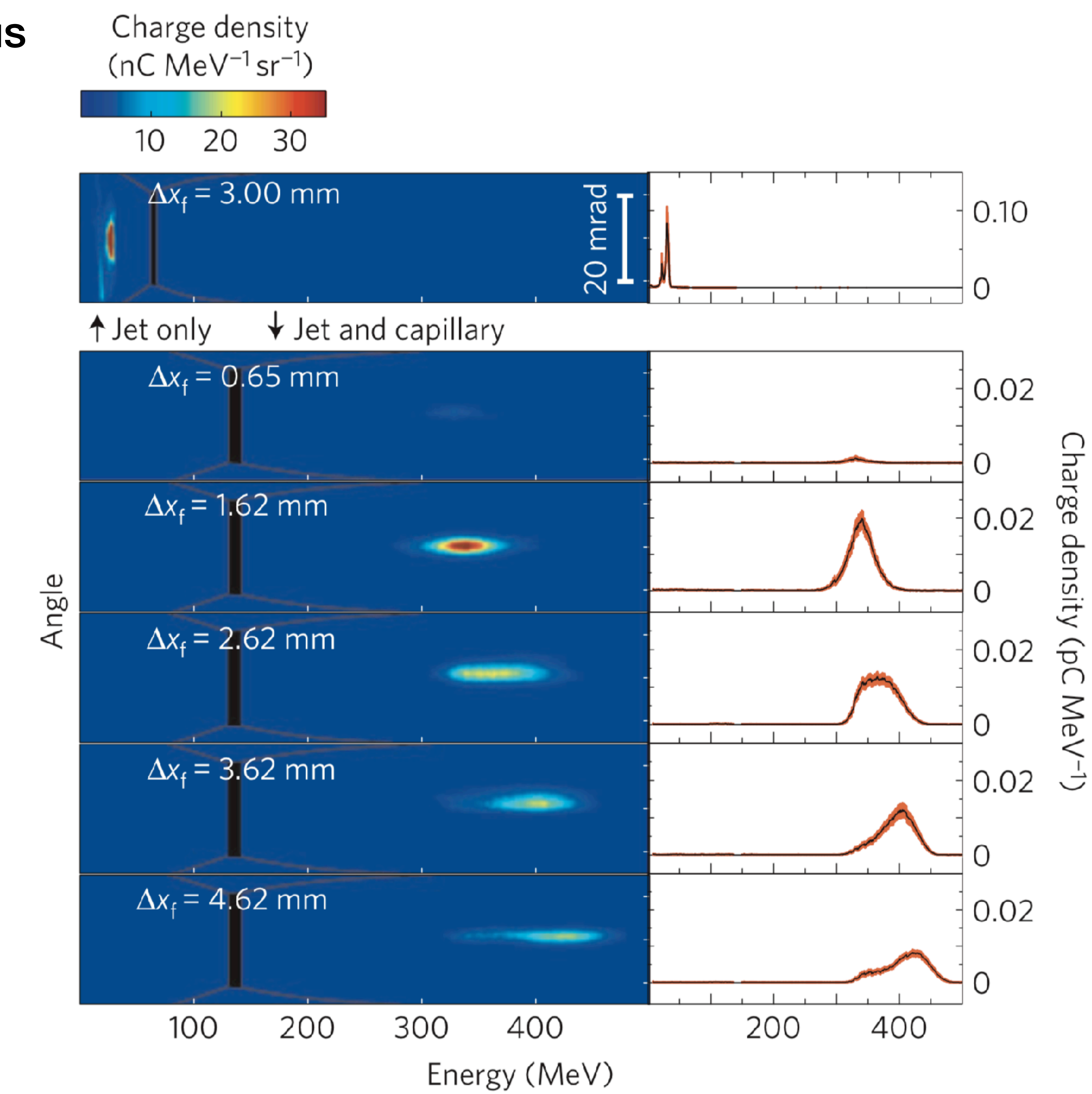
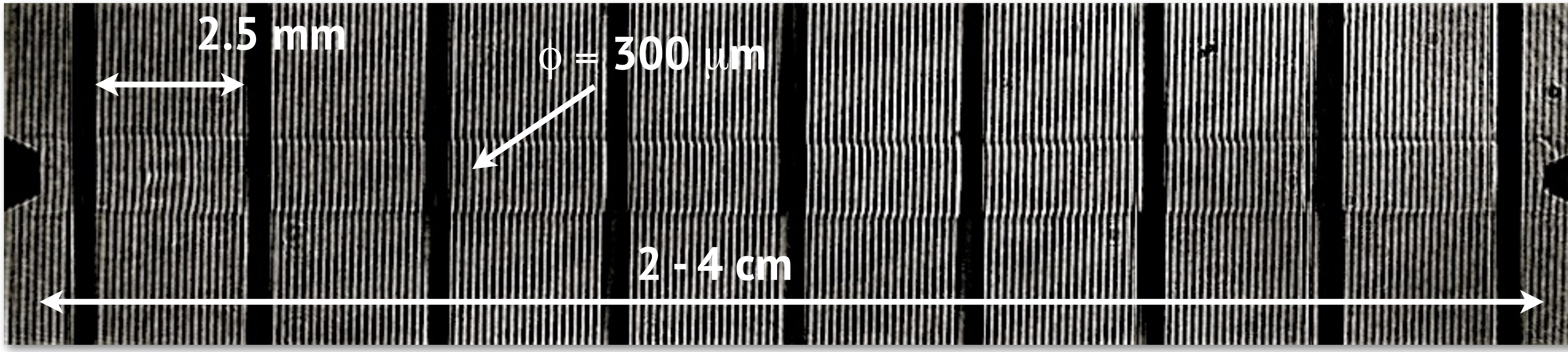
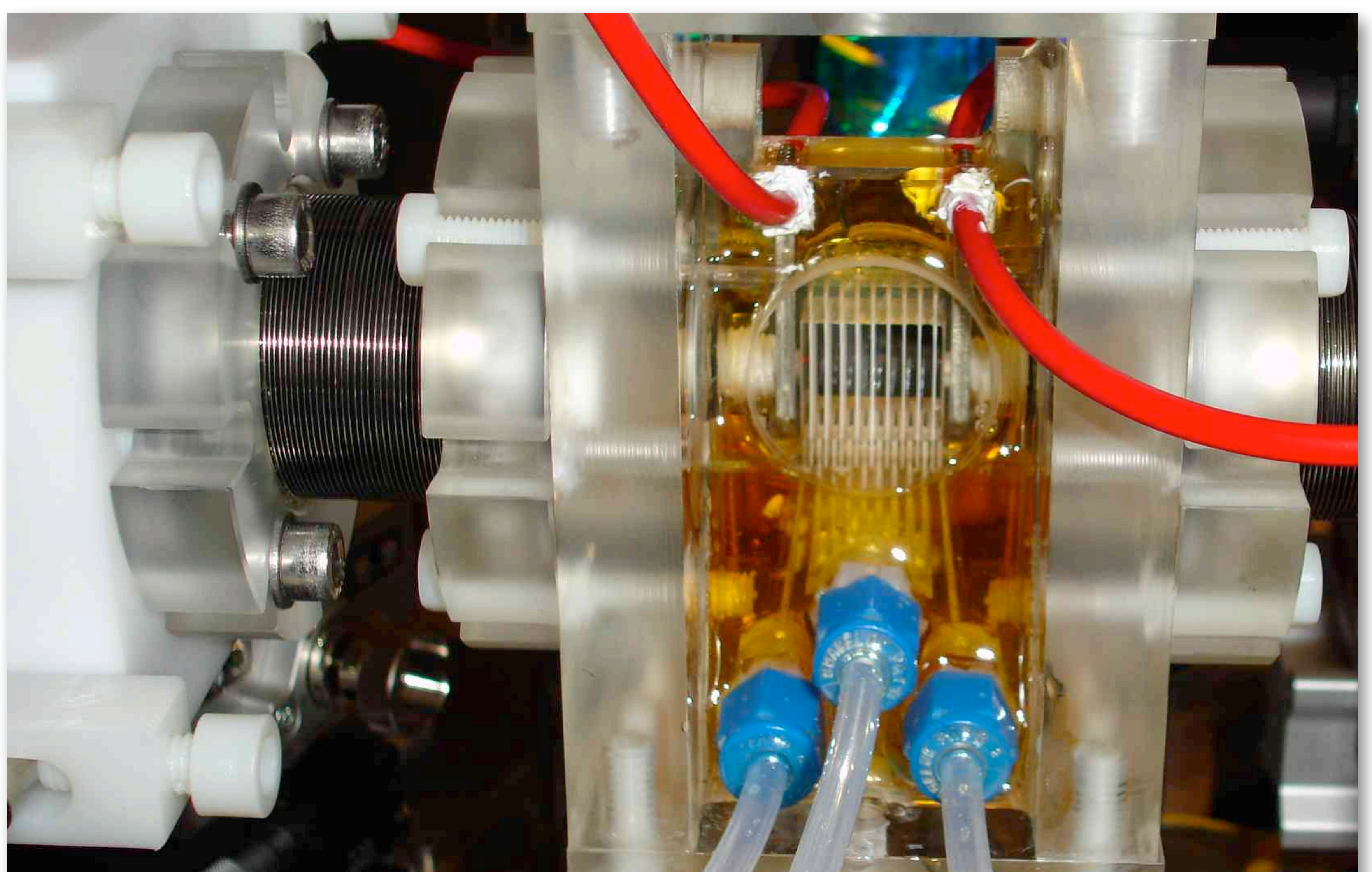


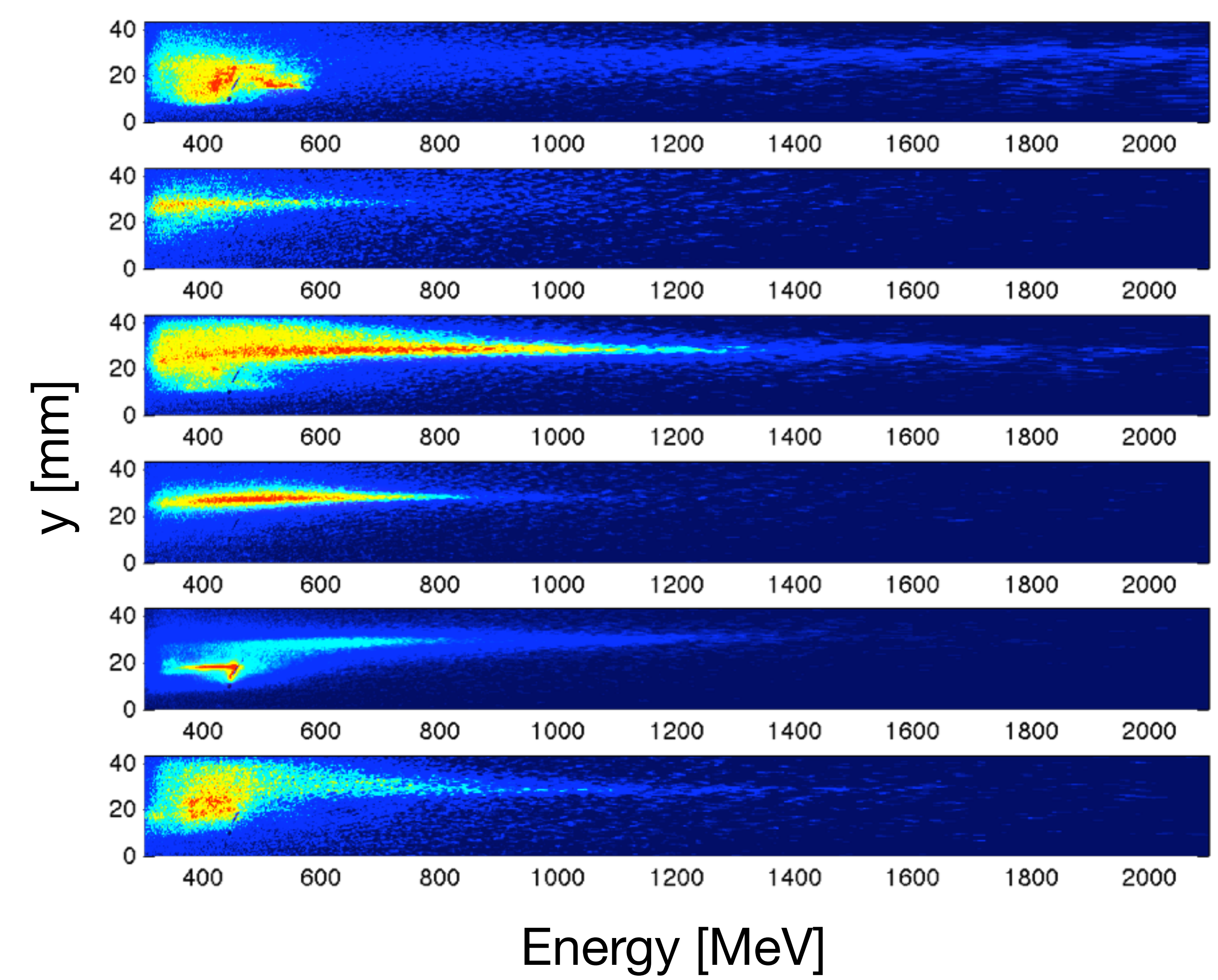


Open-geometry discharge plasma channel

Courtesy Nelson Lopes
IST, Lisbon





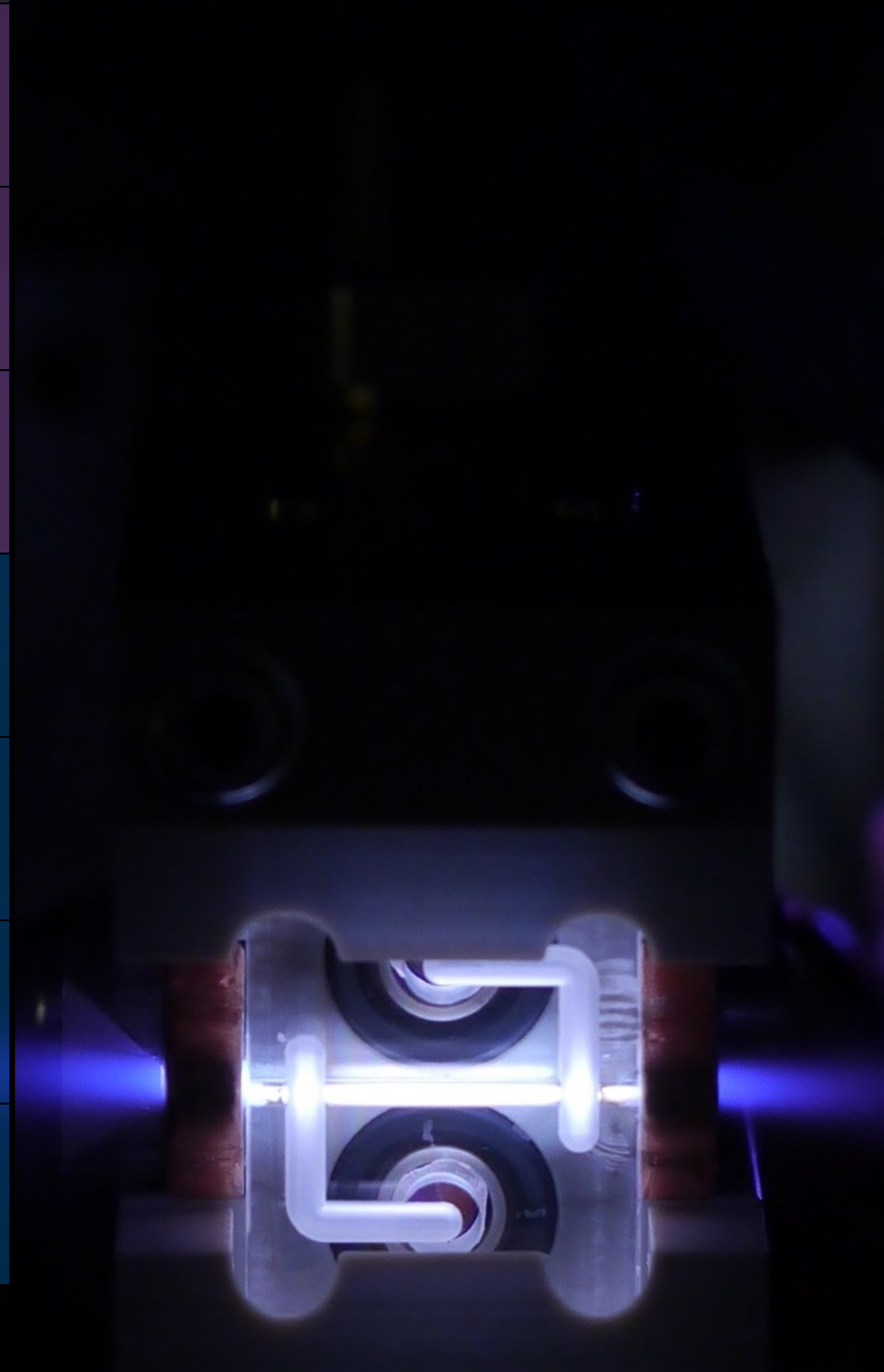


R. Bendoyro *et al.,* IEEE Trans. Plasma Science **36**, 1729 (2008)

Summary of Plasma Sources II

Plasma source	ne (cm^{-3})	Length	Trans. diag. access	Matched spot (µm)
Gas cell	10^{15} - 10^{19}	2 - 500 mm	✔ (+ restricted)	NA
Gas jet	10^{17} - 10^{20}	1 - 10 mm	✔	NA
Vapour oven	10^{14} - 10^{17}	300 - 10^{4} mm	✘ (+ restricted)	NA
Grazing-incidence	0 - 10^{19}	5 - 1000 mm	restricted	15 - 150
Capillary discharge	10^{17} - 10^{19}	7 - 100 mm	restricted	30 - 50
Hydrodynamic expan.	10^{18} - 10^{19}	$\lesssim$ 30 mm	✔	10 - 30
Open-discharge	~ 10^{17}	20 - 40 mm	✔	60 - 70

Warning! All figures approximate!



Summary of Plasma Sources II

- Many factors must be considered when choosing a source type
- Wide range of solutions have been developed for different scenarios

- Future challenges
    - Operation at lower densities and over longer lengths
    - Operation at high repetition rates/high average power
    - Long operating life, 24/7 in user facilities