Plasma Sources

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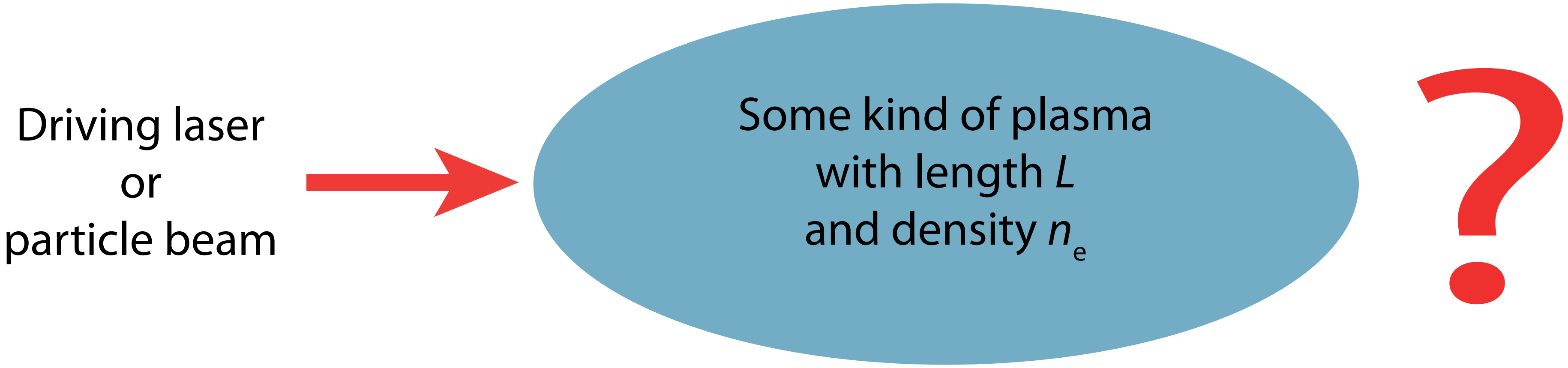
Department of Physics & John Adams Institute
University of Oxford

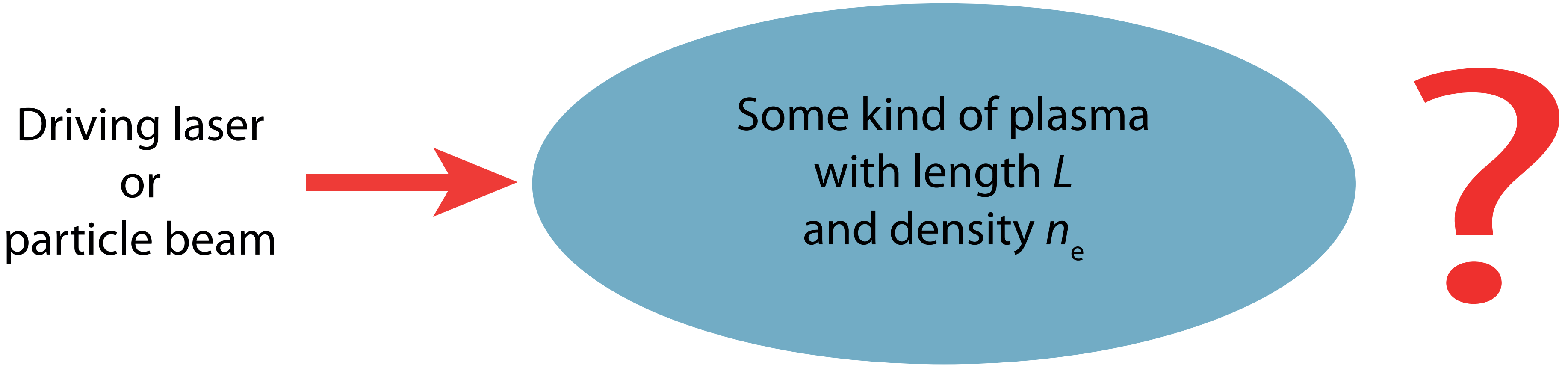


Driving laser
or
particle beam

Some kind of plasma
with length L
and density n_e

?

Outline



Driving laser
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Outline of talk

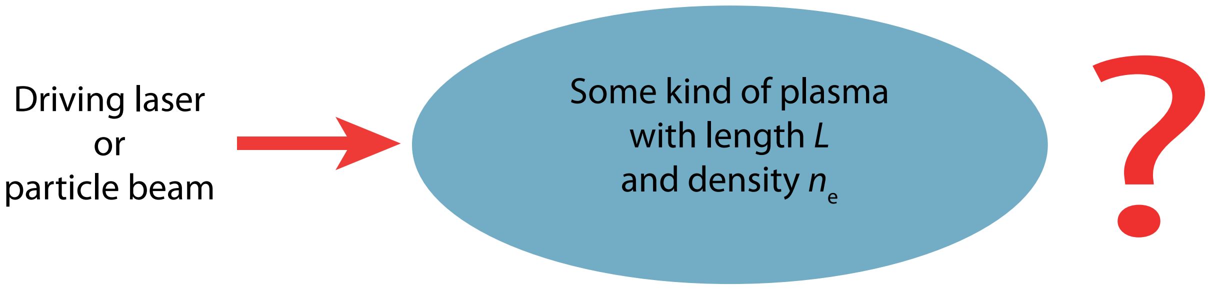
- Requirements of the plasma source (or "target")
- Turning gas into plasma: ionization mechanisms
- "Passive" targets
  - Heat-pipe ovens
  - Gas cells and gas jets
- Waveguide targets
  - Grazing-incidence guiding
  - Plasma channels

Acknowledgements

- Brigitte Cros, LPGP, Université Paris-Sud
- Stefan Karsch, Munich Centre for Applied Photonics
- Zulfikar Najmudin, Stuart Mangles & Nelson Lopes, Imperial College, London
- Patric Muggli, Max Planck Institute for Physics, Munich
- Current and former members of my group in Oxford

Possible requirements of a plasma source

- Adjustable plasma density
- Well defined (& possibly adjustable) length
- Species ionizable by drive beam (or additional beam)
- High degree of uniformity
- Accessible by drive beam and exit-able by generated beam
- Controllable longitudinal density profile
- Accessible to diagnostics
- Durable
- Low cost?
- …

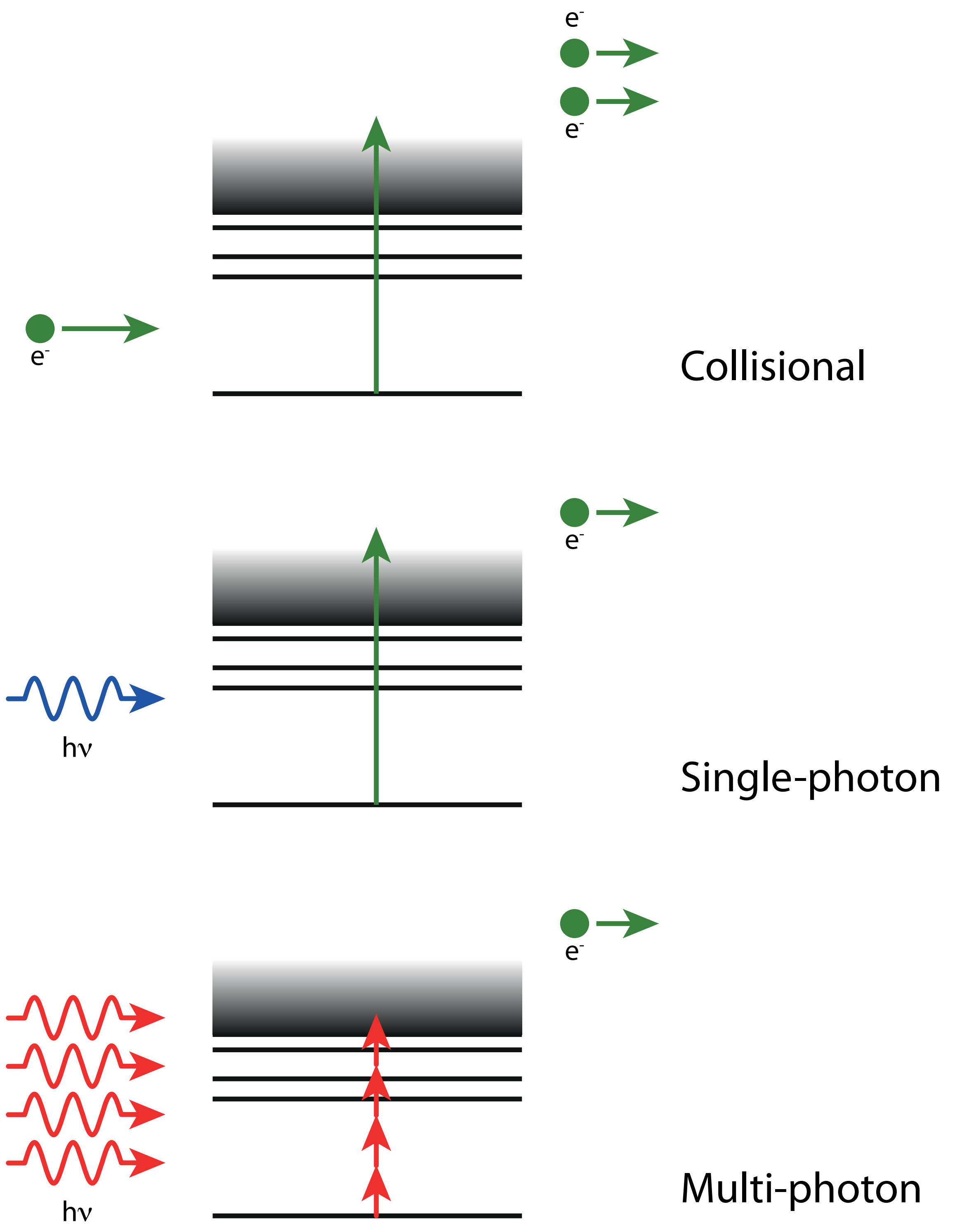


Ionization

Turning gas into plasma

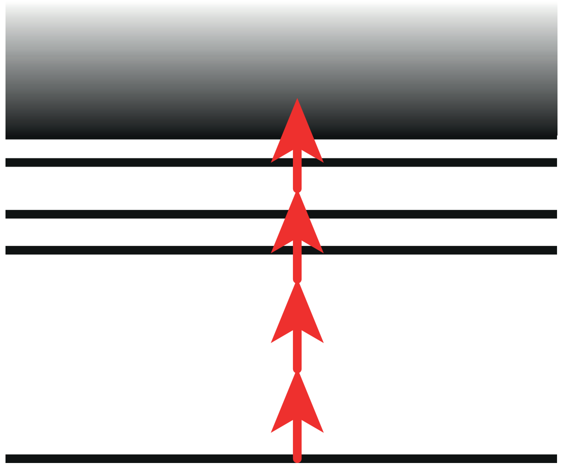
The plasma can be formed by several ionization mechanisms:

- Collisional ionization
  - E.g. discharge, laser-heated electrons, particle beam
  - Rate ∝ n_e^2
- Single-photon
  - $\hbar\omega > E_I$
- Multi-photon & tunnelling (or “field ionization”)



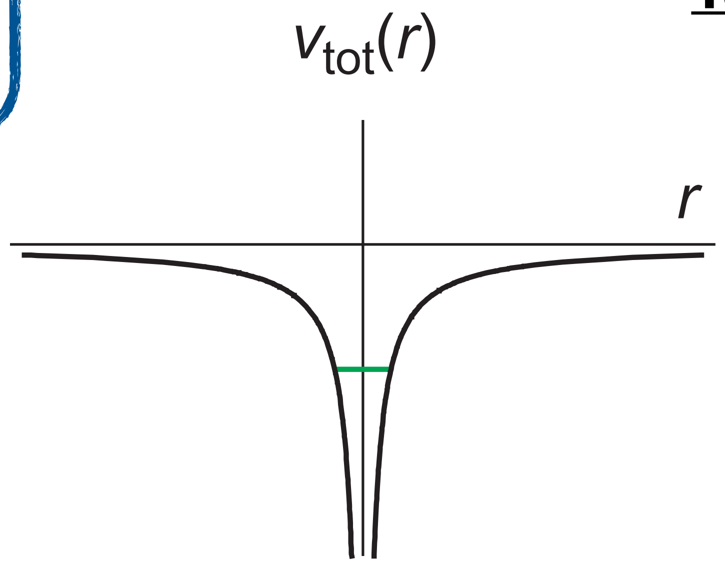
Lasers: multi-photon vs tunnelling ionization

Multi-photon



$$\boxed{\gamma_K = \frac{\omega\sqrt{2m_e E_I}}{eE_0}}$$

Tunnelling



- Occurs for Keldysh parameters $\gamma_K \gg 1$
- If no intermediate resonances rate $\propto I^N$
- Slower than tunnelling ionization

- Occurs for Keldysh parameters $\gamma_K \ll 1$
- E-field of laser comparable to field binding valance electrons
- Laser/bunch field distorts atomic potential
- Electrons can tunnel through barrier to be ionized
- At high fields the barrier is removed ("over the barrier ionization")

Lasers: multi-photon vs tunnelling ionization

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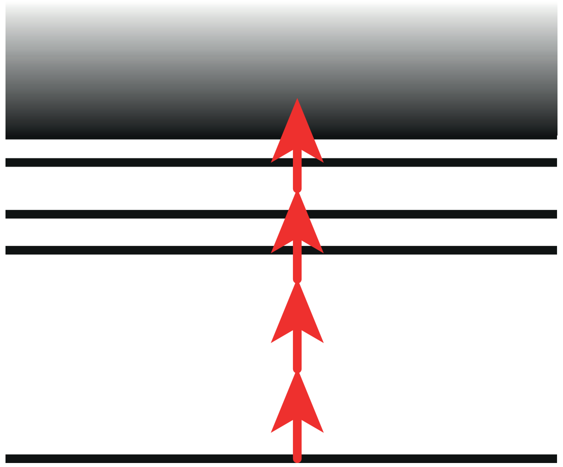

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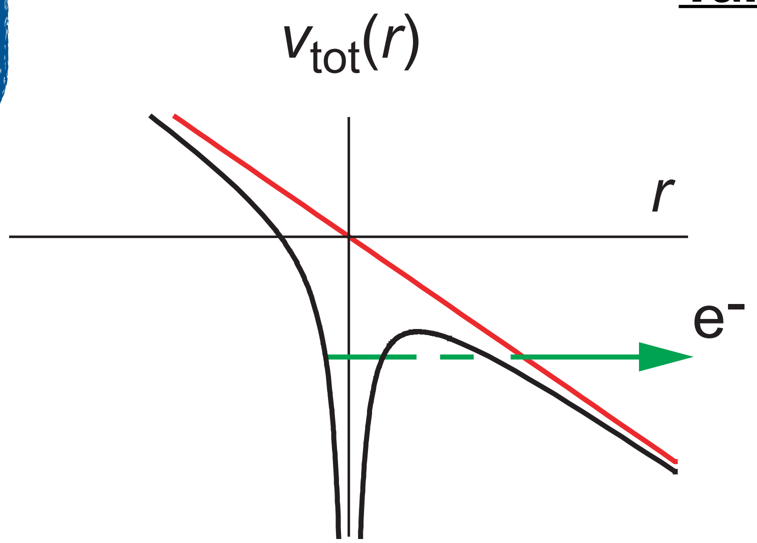

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Lasers: multi-photon vs tunnelling ionization

Tunnelling

- "ADK" ionization rate given by,

$$W[\mathrm{fs}^{-1}] = 1.52 \times \frac{4^{n*}}{n*\Gamma(2n*)}\left(20.5\frac{E_I}{E}\right)\exp\left(-6.83\frac{E_I^{3/2}}{E}\right)$$

$E_I =$ Ionization potential (eV)

$E =$ Electric field (GV / m)

$n* = 3.68Z/\sqrt{E_I}$ Effective quantum number

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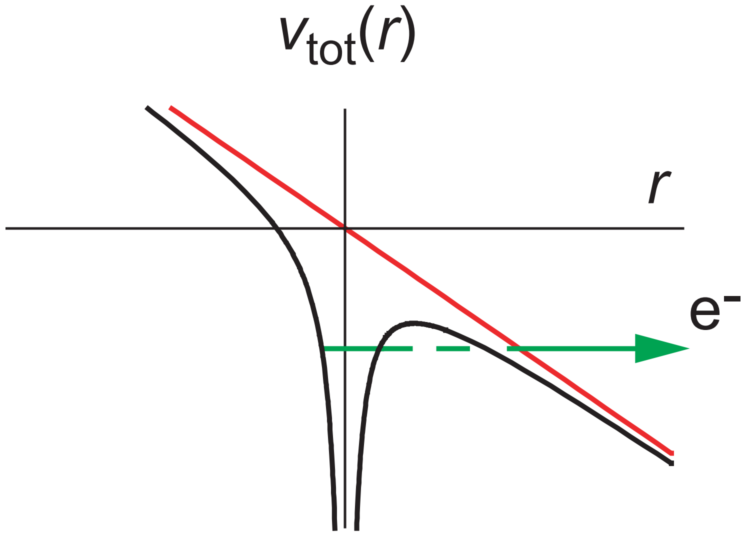
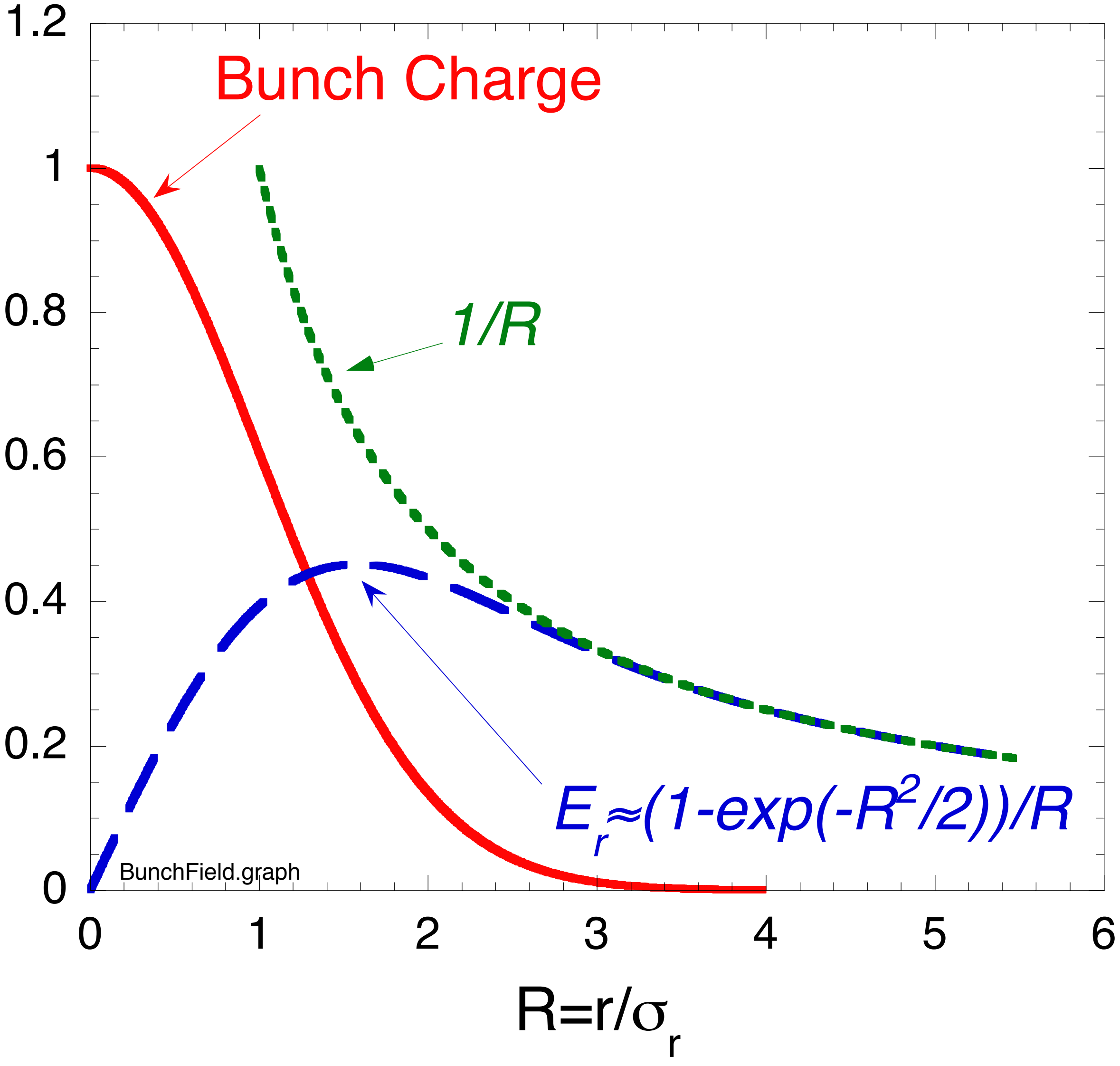
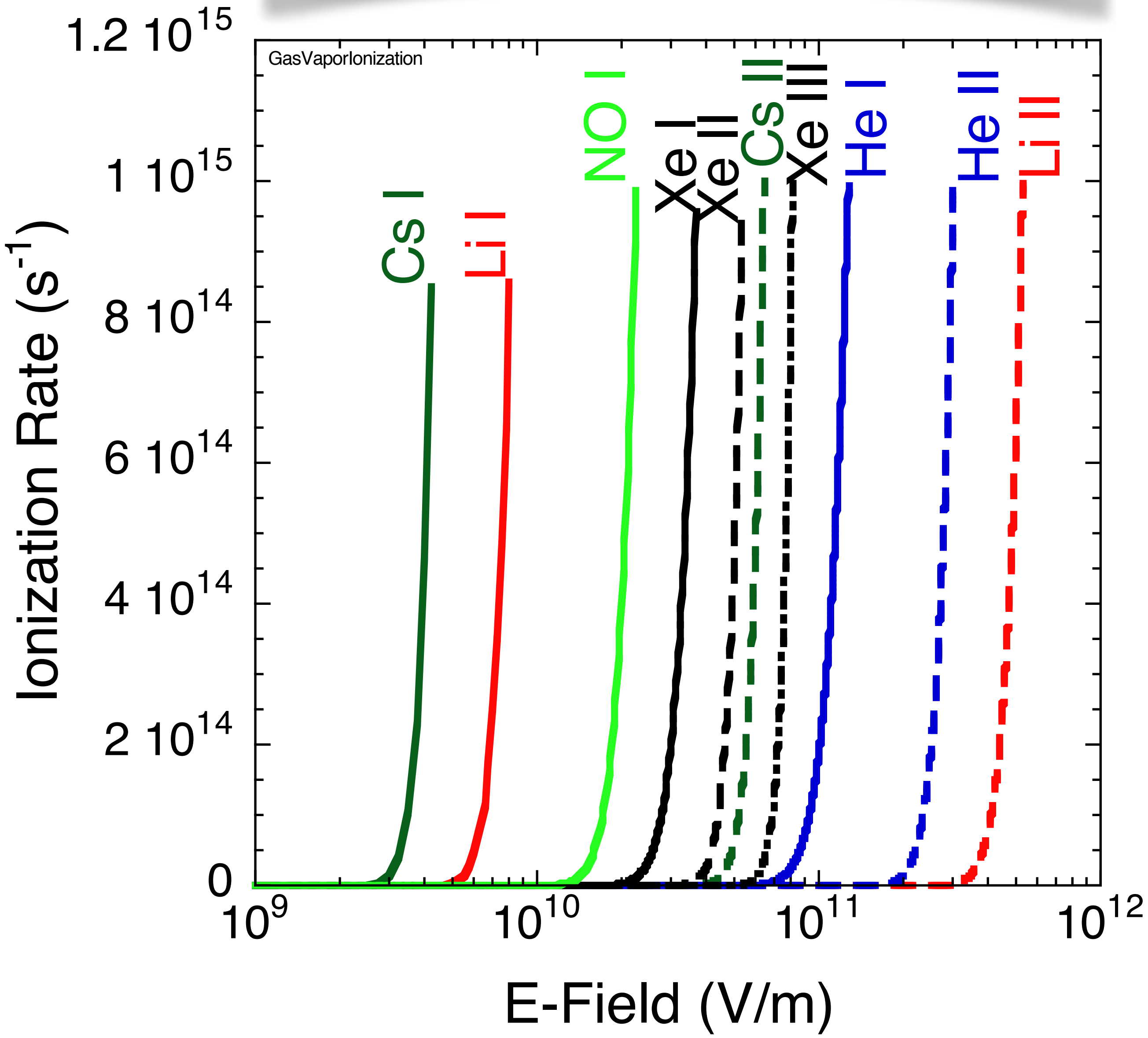


Example: Ionization by electron bunch

Courtesy Patric Muggli
Max Planck Institute for Physics, Munich

$$E_{r,\mathrm{peak}}(r \approx 1.6\sigma_r) \approx 5.2 \times 10^{-10} \frac{N}{\sigma_r \sigma_z}$$





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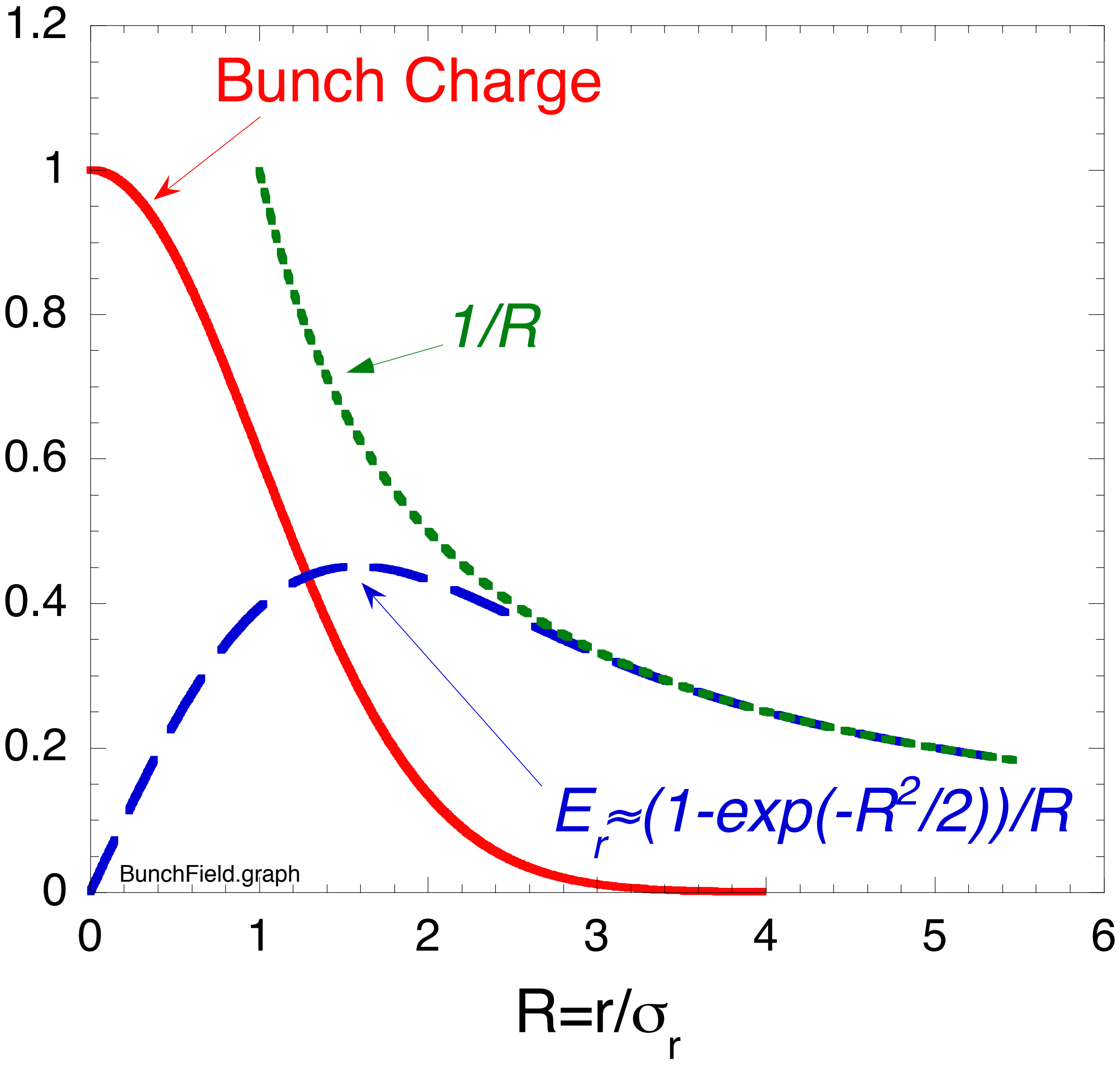
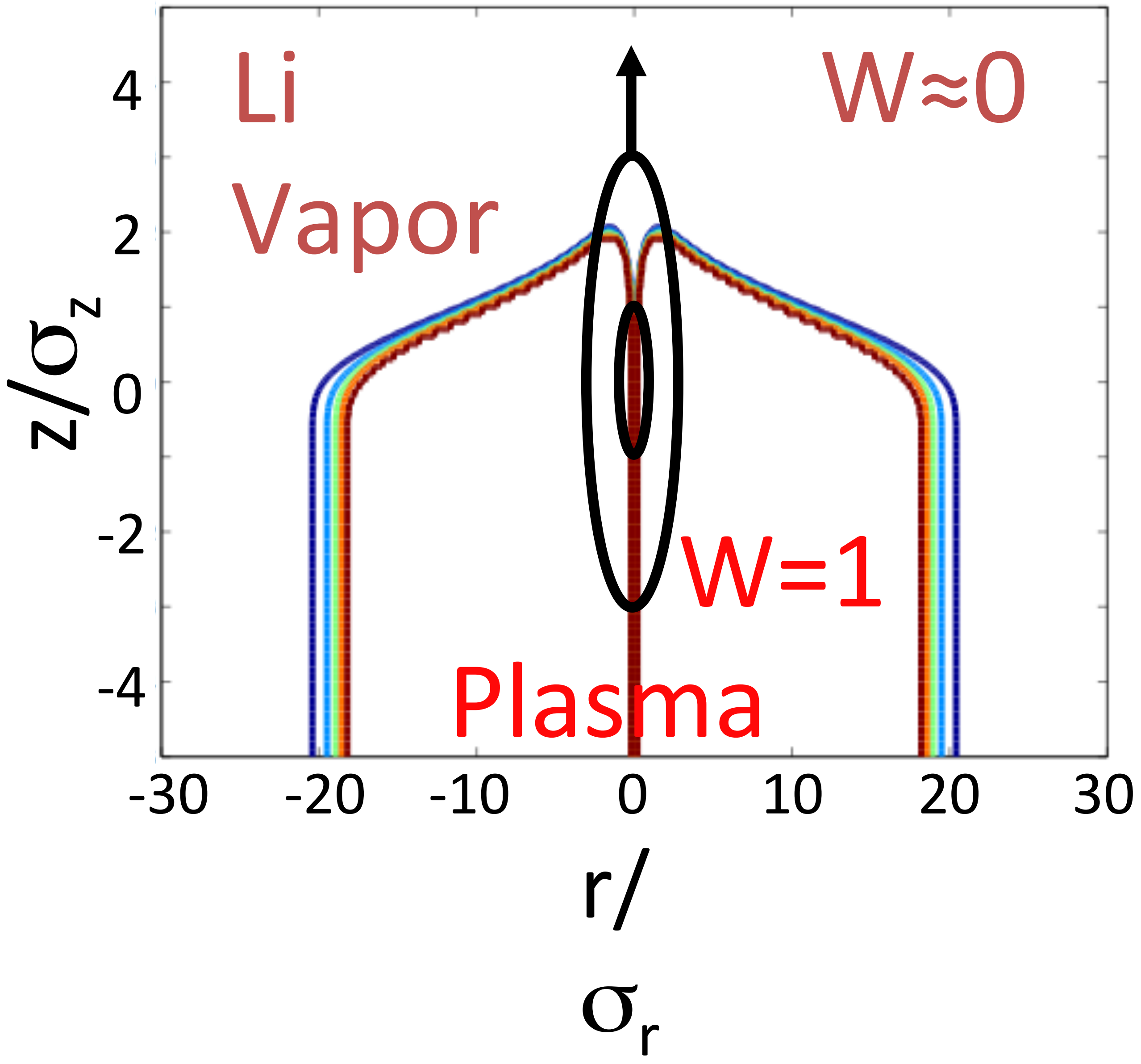
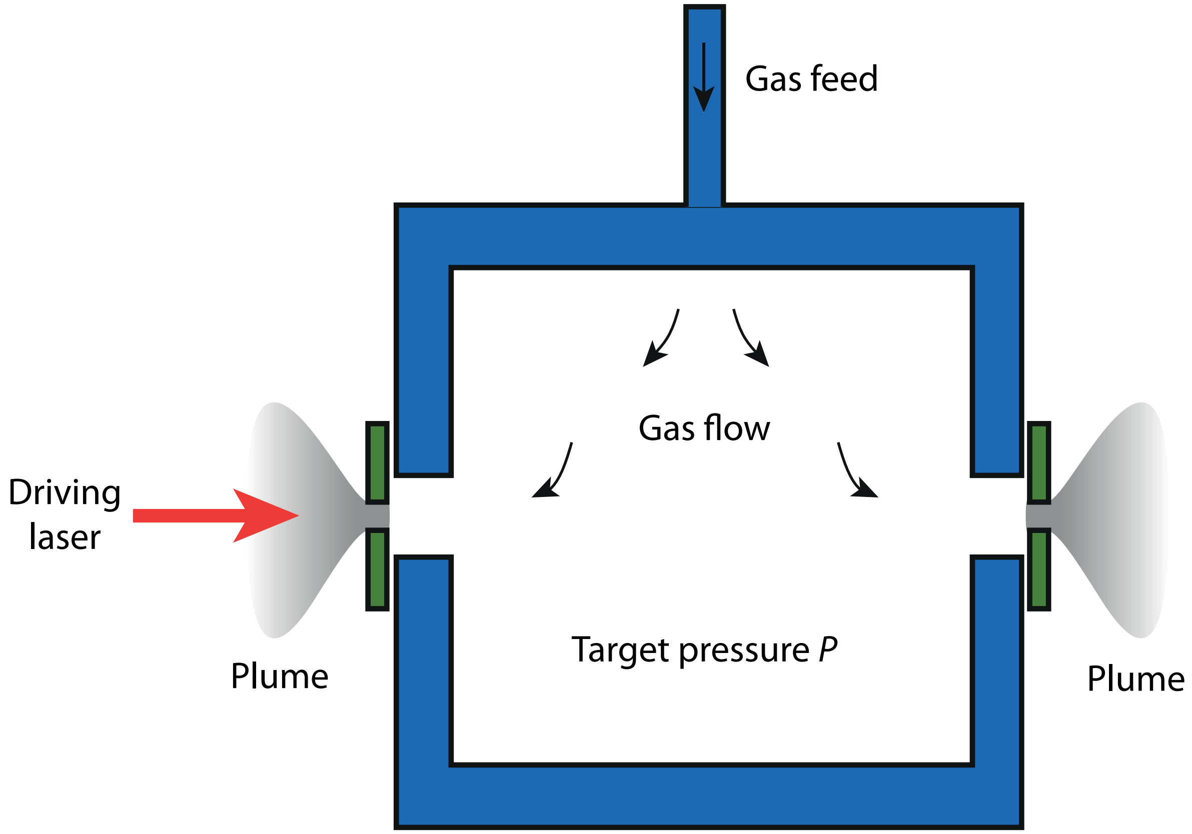




Gas cells and gas jets

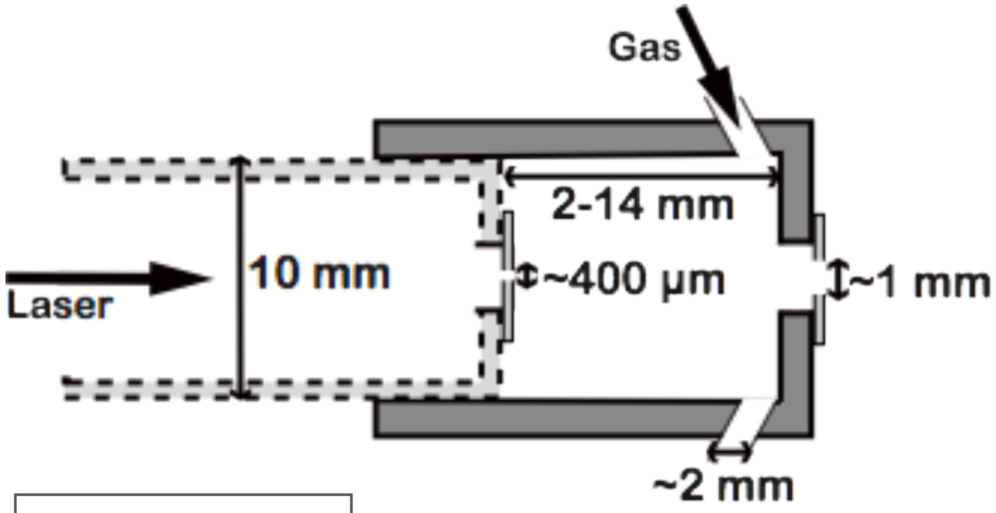
Gas cells

- Region of uniform neutral gas contained by differential pumping through coaxial pinholes
- Density fairly uniform between pinholes…
  - but plume of gas from front and back of cell
- Density easily adjusted by controlling gas flow
  - but erosion of pinholes will change density
- Munich and Imperial groups have designed variable length gas cells

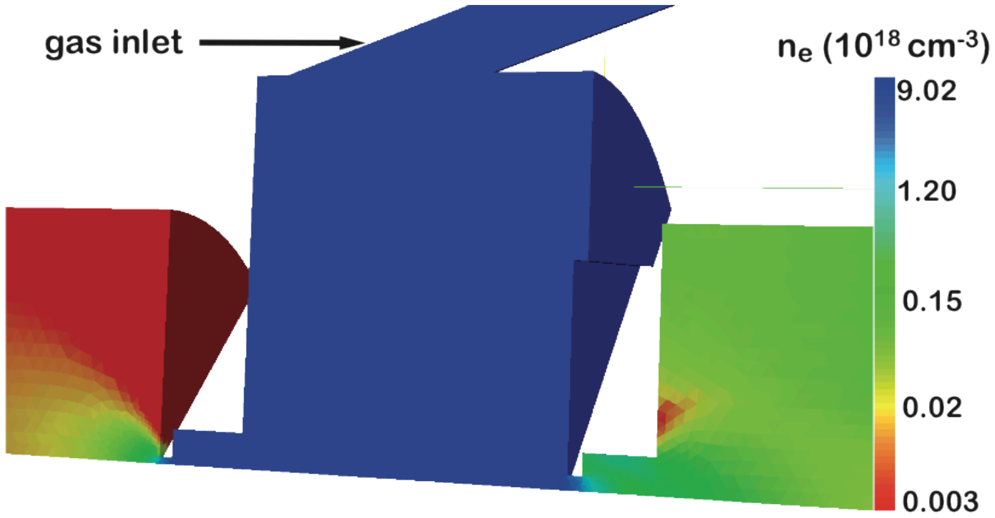


Variable-length gas cell

Courtesy Stefan Karsch
Munich Centre for Advanced Photonics



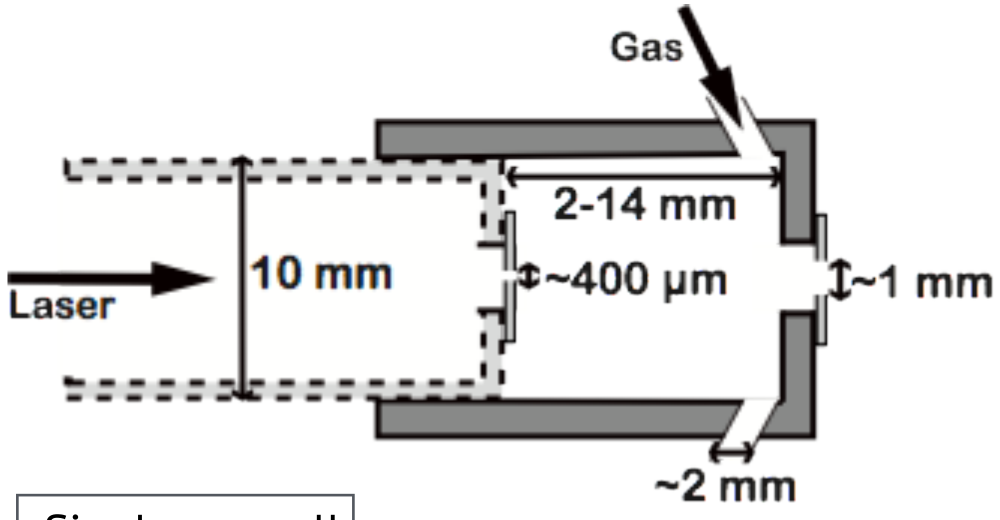
Single gas cell



OpenFoam simulations show uniform density within cell & extent of plumes

Variable-length gas cell

Courtesy Stefan Karsch
Munich Centre for Advanced Photonics



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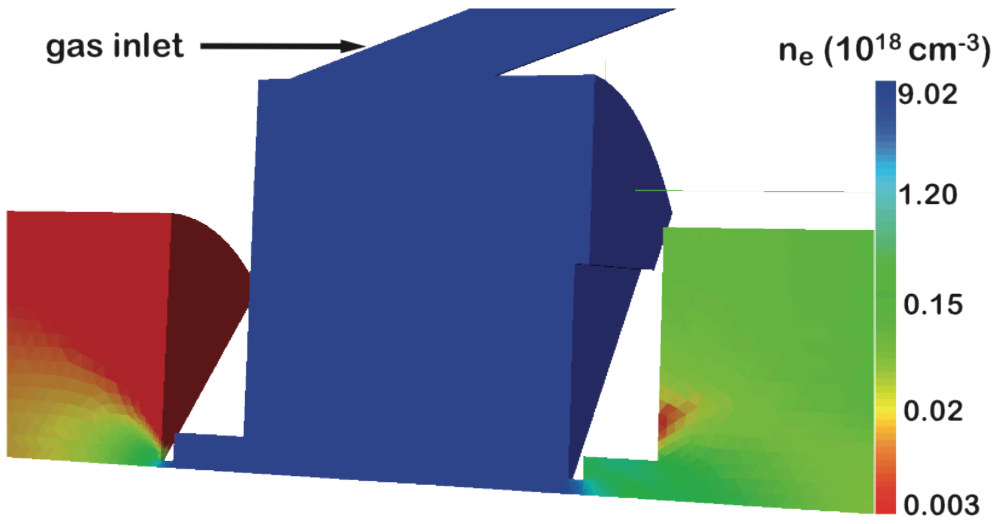

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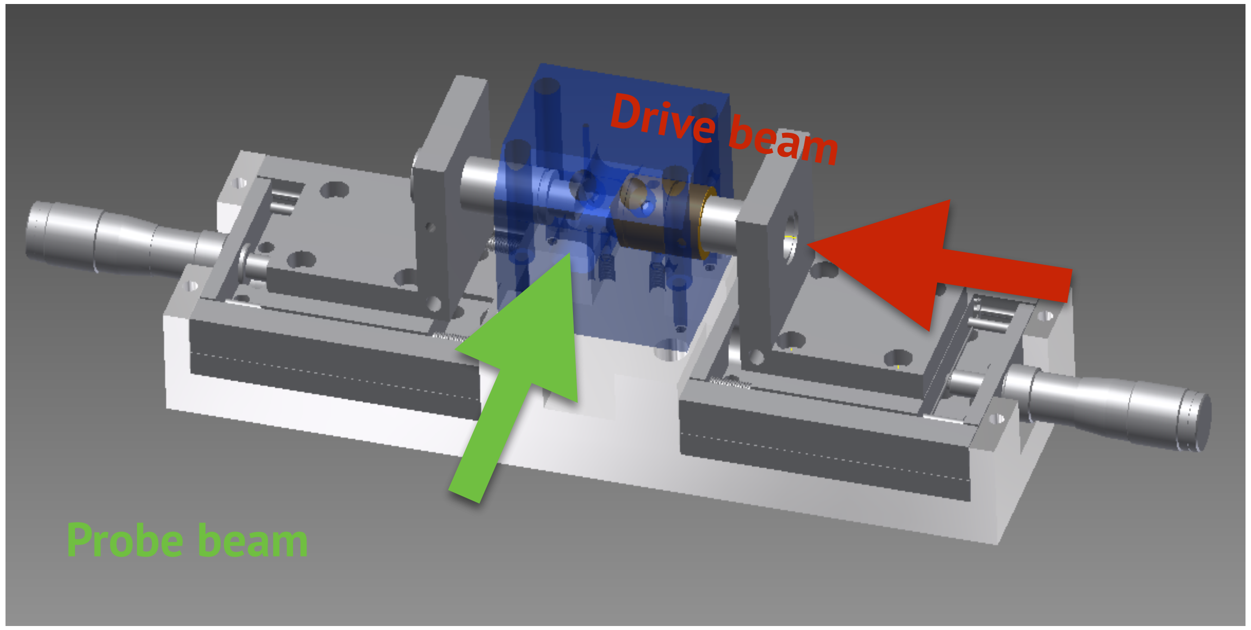
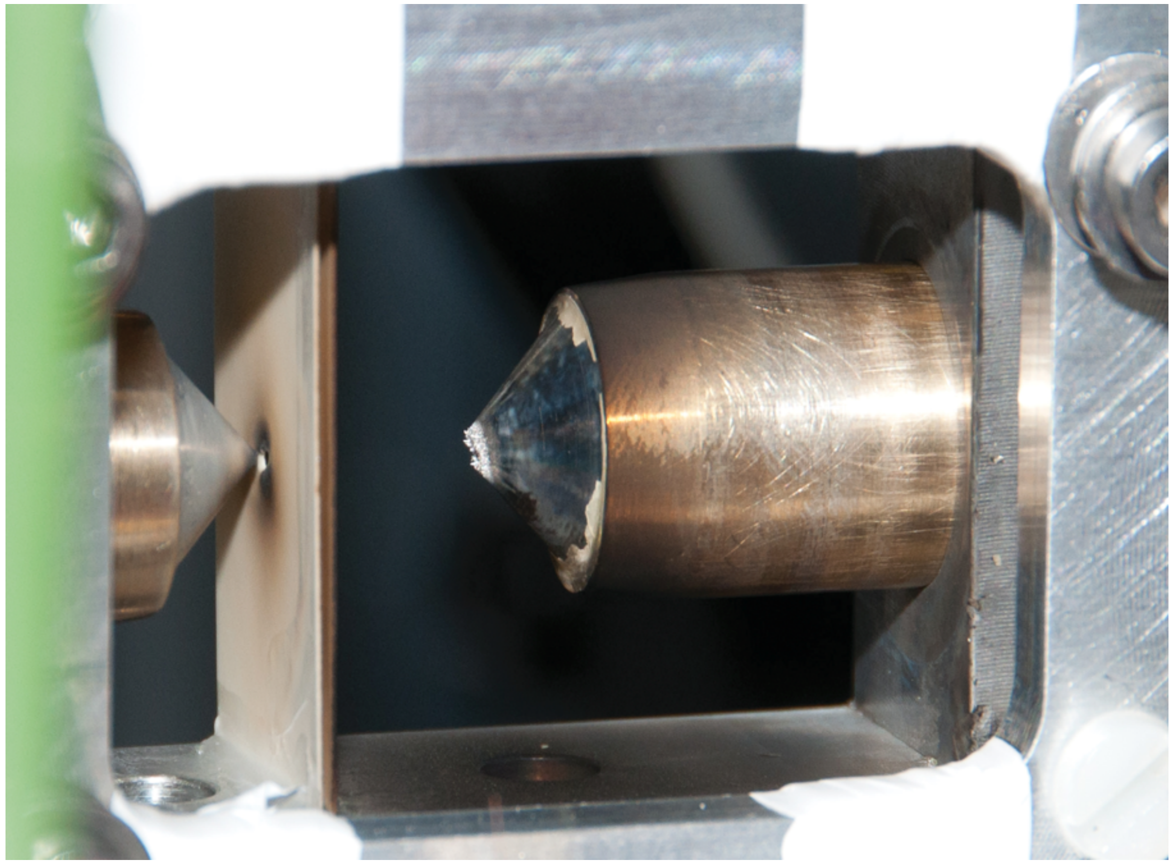
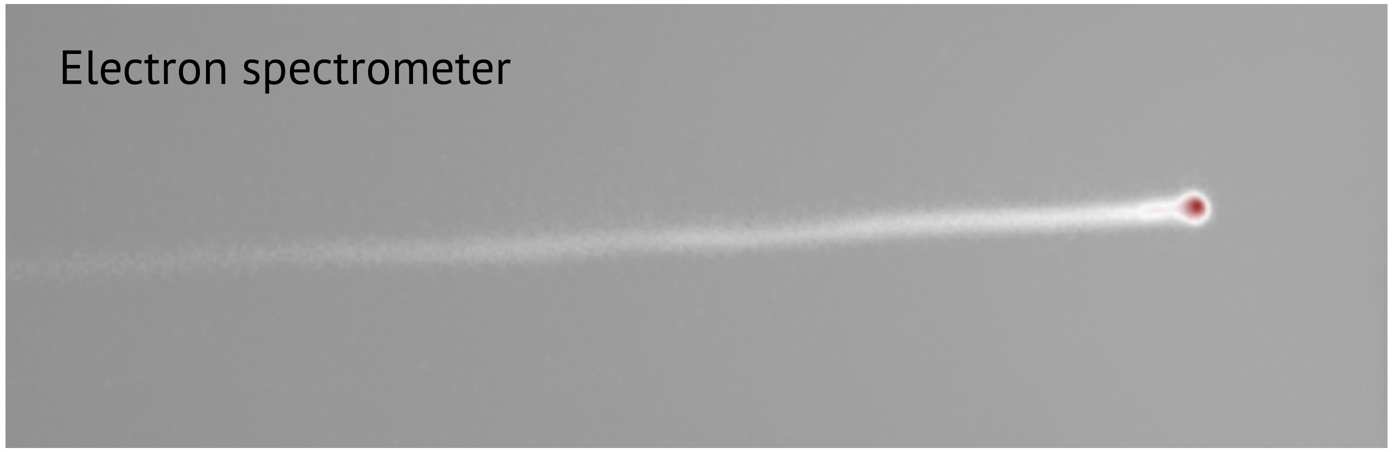


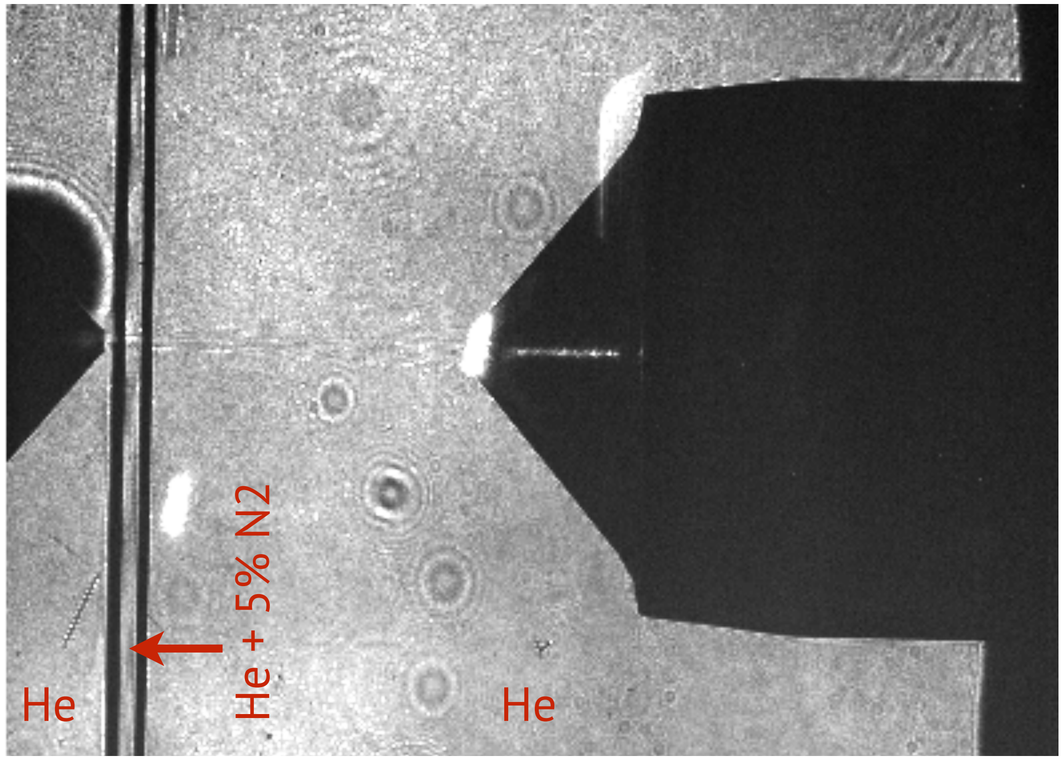
Double gas cell: allows gas gradients & transverse probing

Three-chamber gas cell

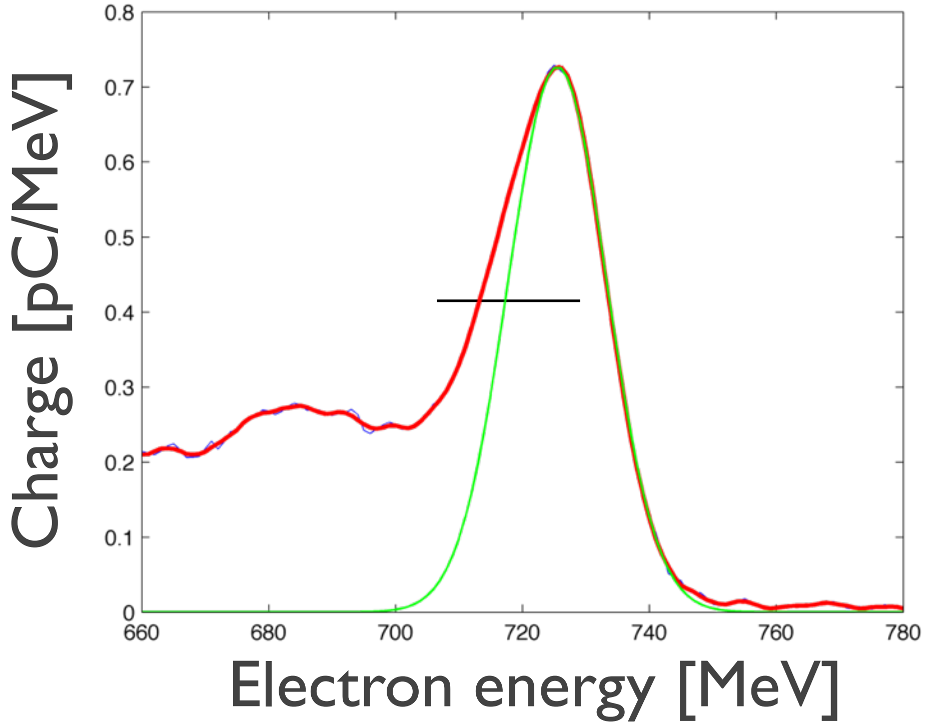
Courtesy Zulfikar Najmudin
Imperial College, London





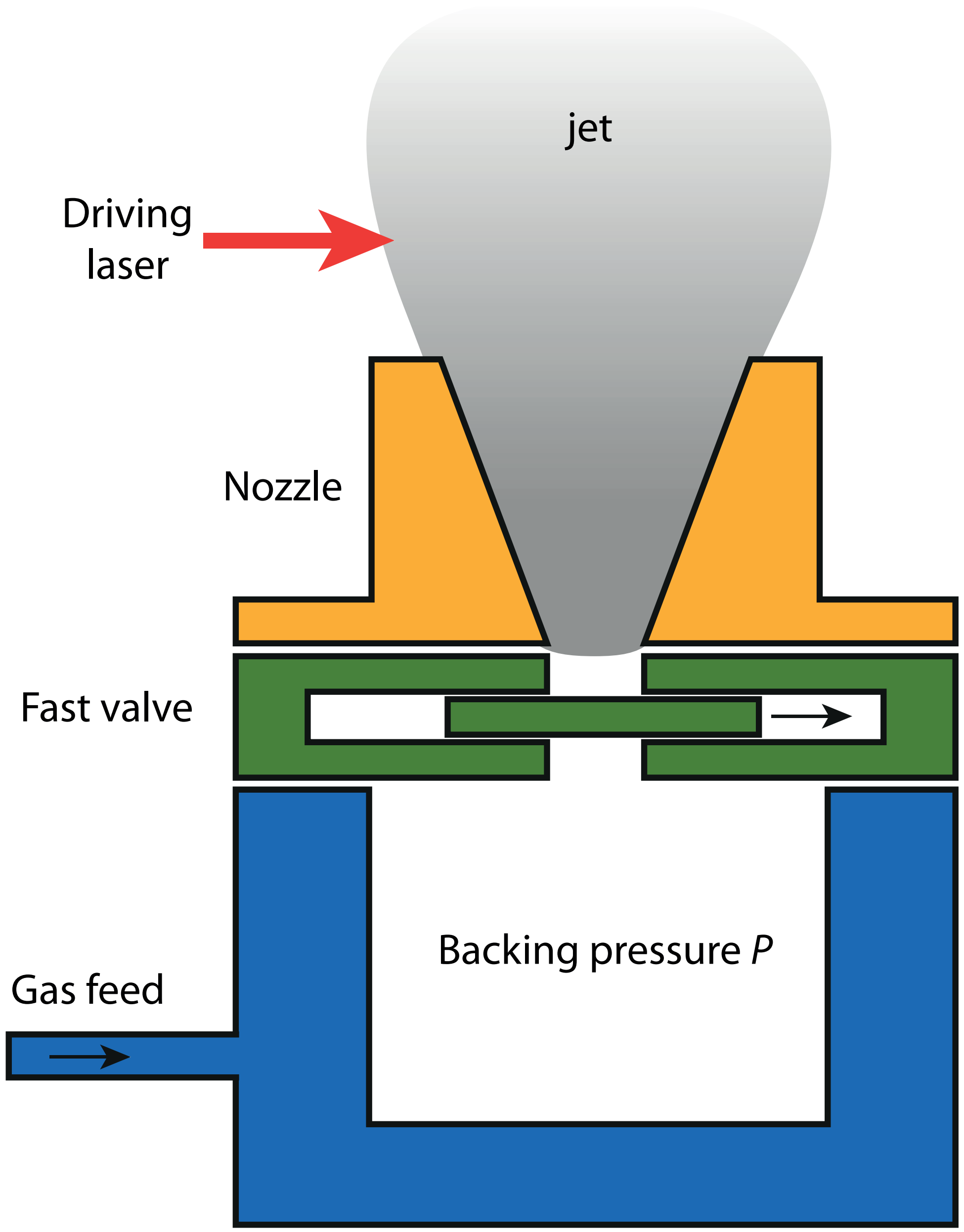


E_e= 726 MeV
ΔE = 3.0%
Charge ≈ 17 pC



Gas jets

- Supersonic nozzles provide near-flat-top density profile for laser wakefield experiments
- Plasma density controlled by varying backing pressure behind jet -
  - Typically 10 - 100 bar depending on nozzle diameter and desired density
- n_e typically 10^{17} - 10^{20} cm^{-3}
- Length typically few mm
  - larger nozzle diameters give lower densities (fortuitously matched to increase in dephasing length)



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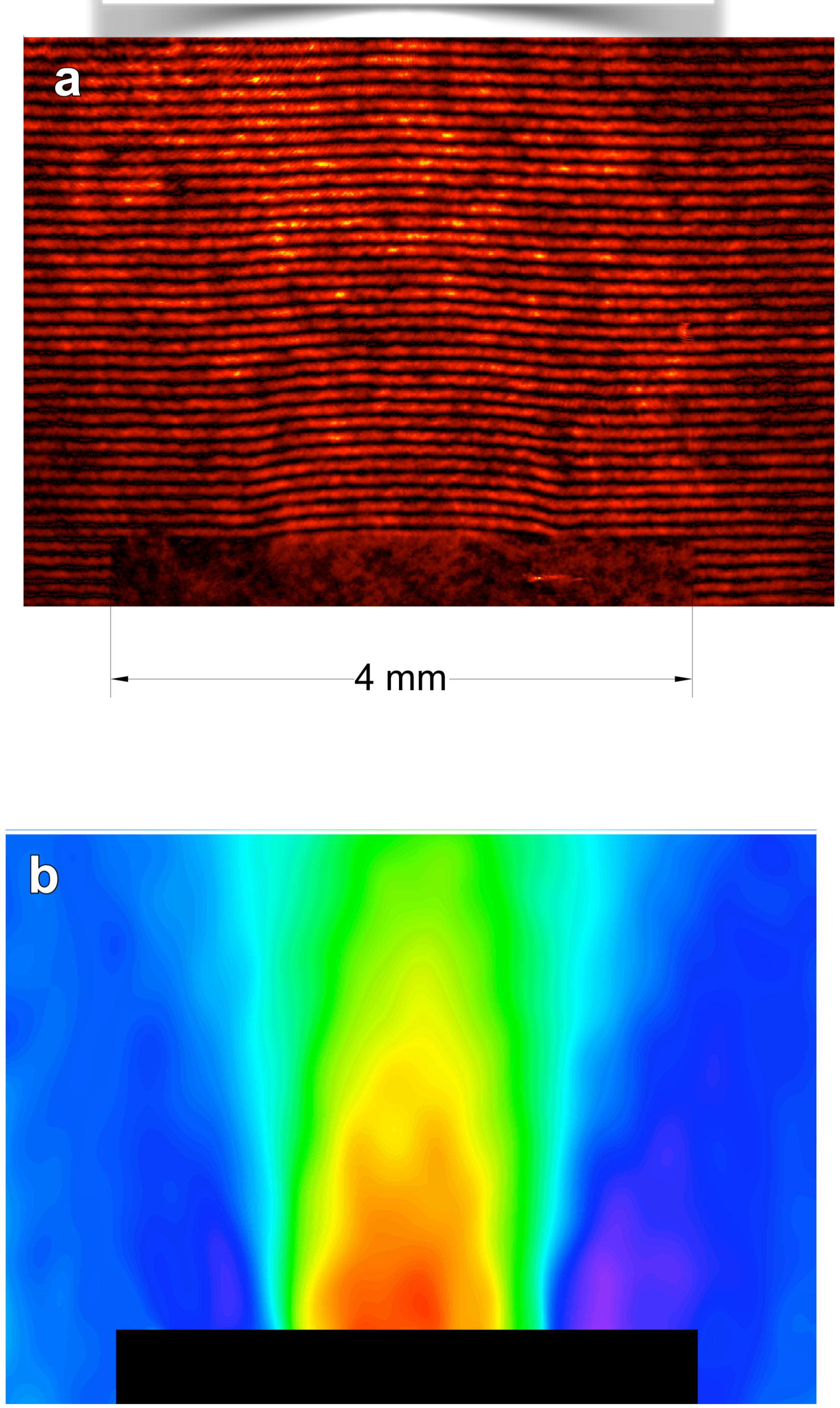
- Provide open geometry for on-shot diagnostic access ...



Courtesy Stuart Mangles
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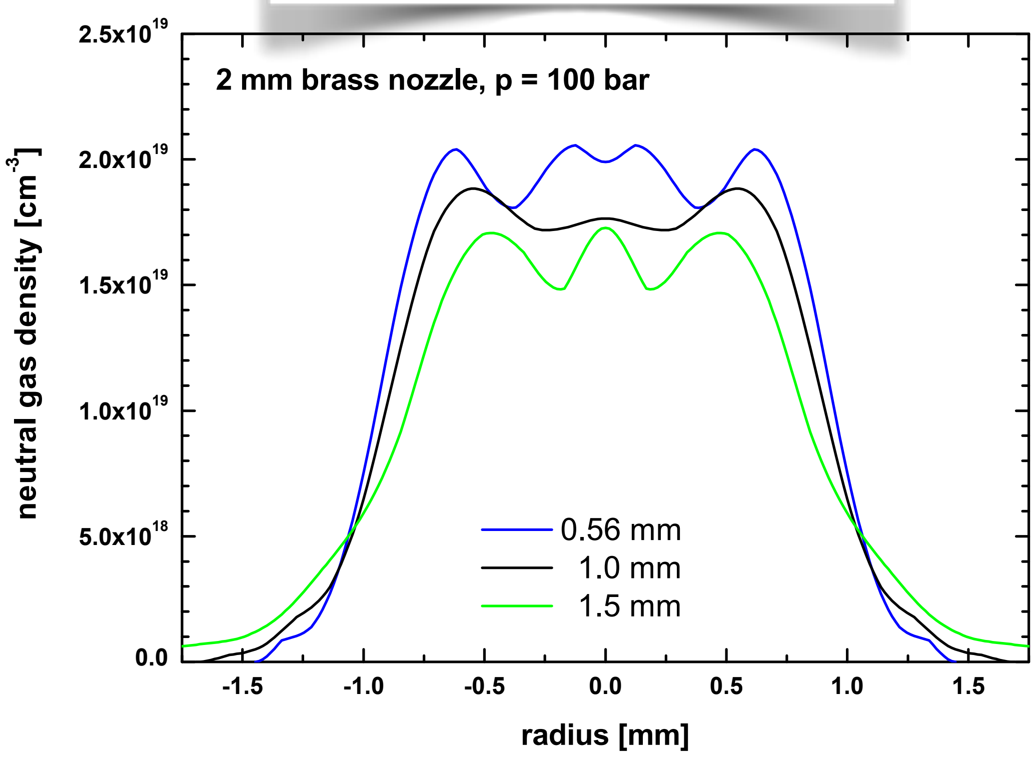

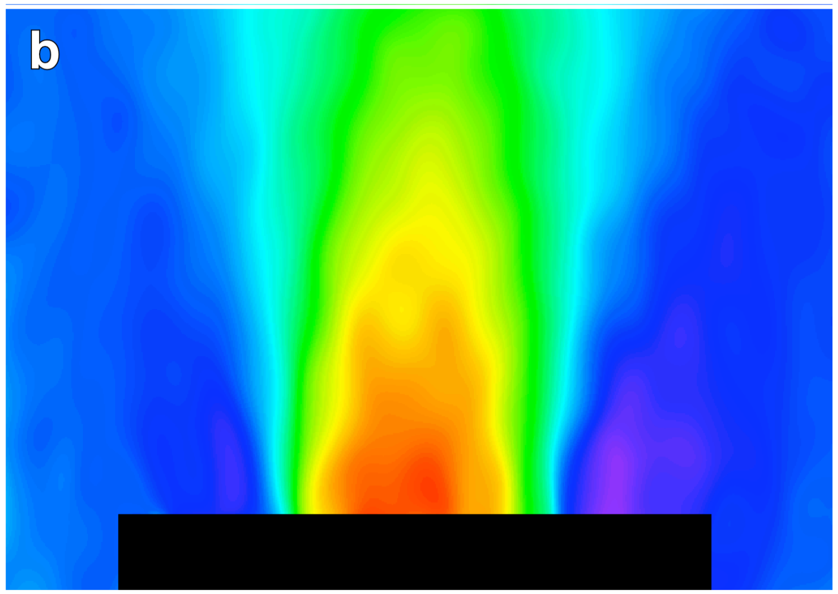

Gas jets: Examples

Courtesy Stuart Mangles
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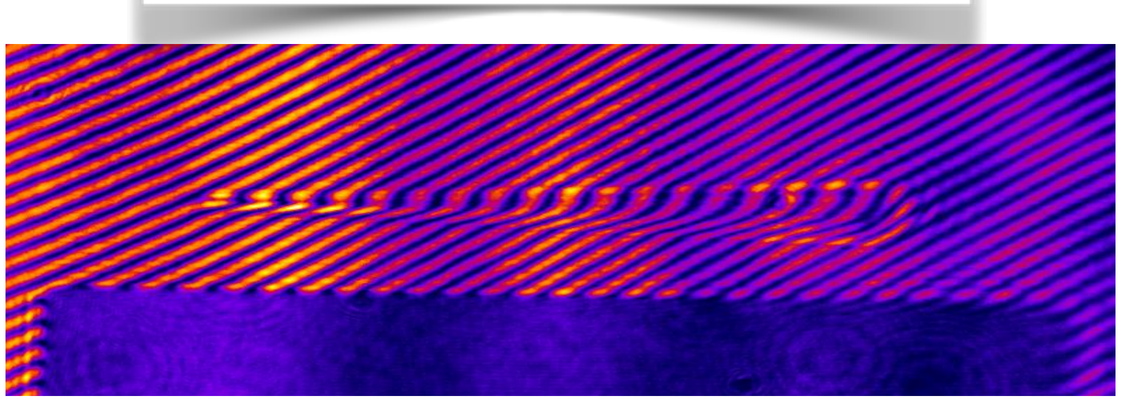
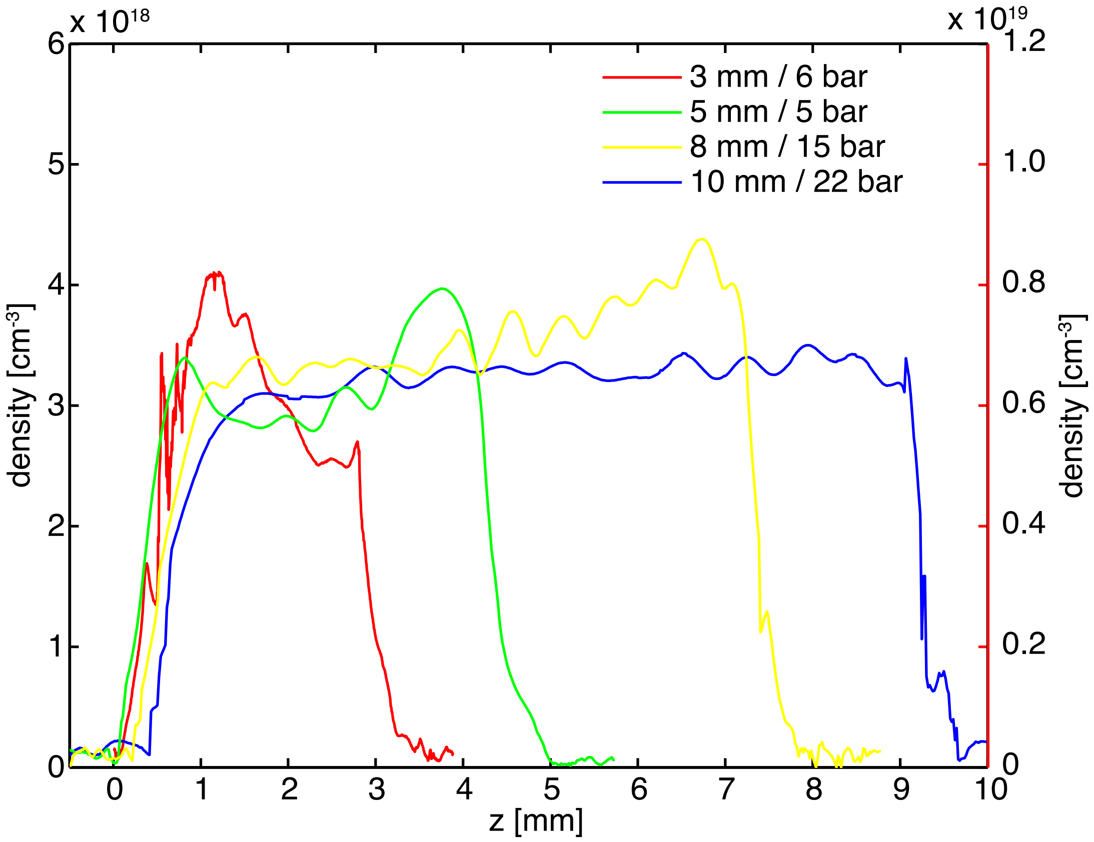
On-shot interferogram of 10 mm
plasma on Astra-Gemini





S. Kneip *et al Phys. Rev. Lett.* ***103*** 035002 (2009)
Sävert arXiv:1402.3052

Gas jets: Examples

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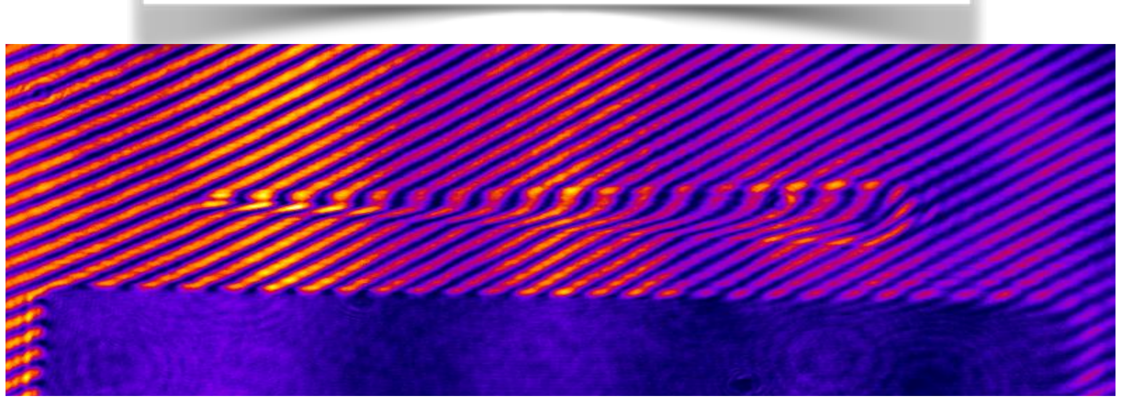

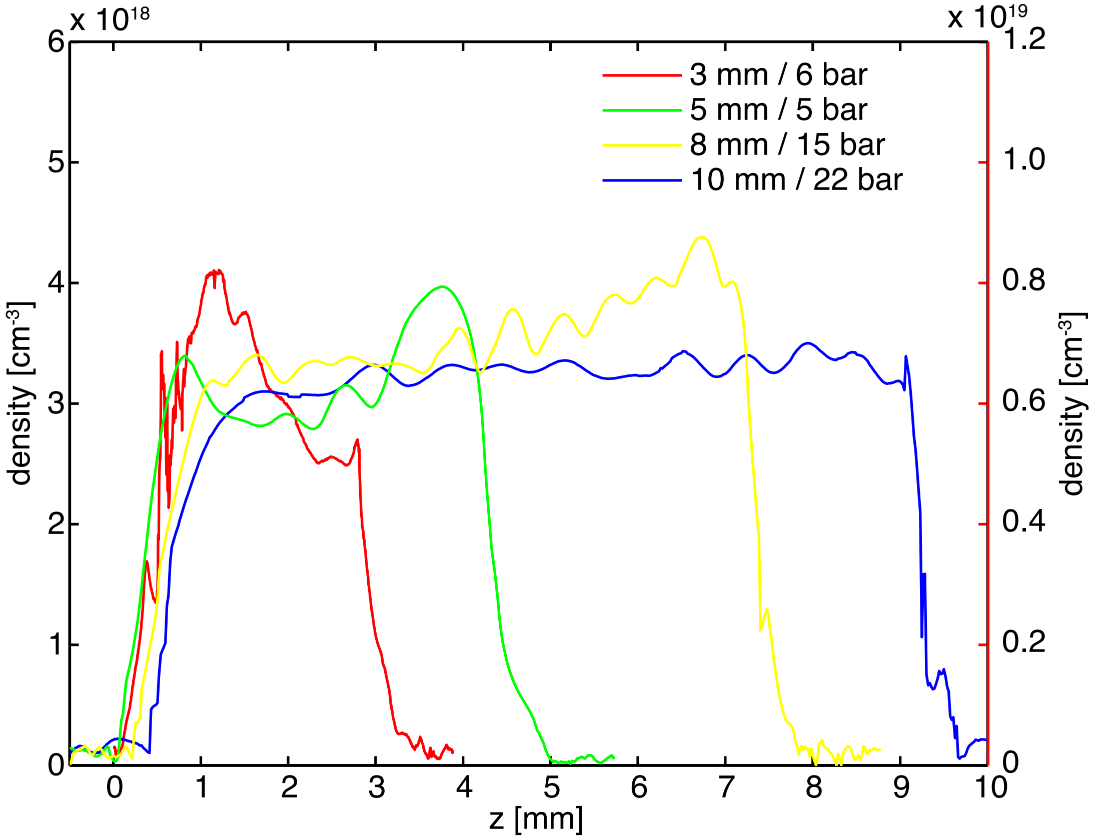

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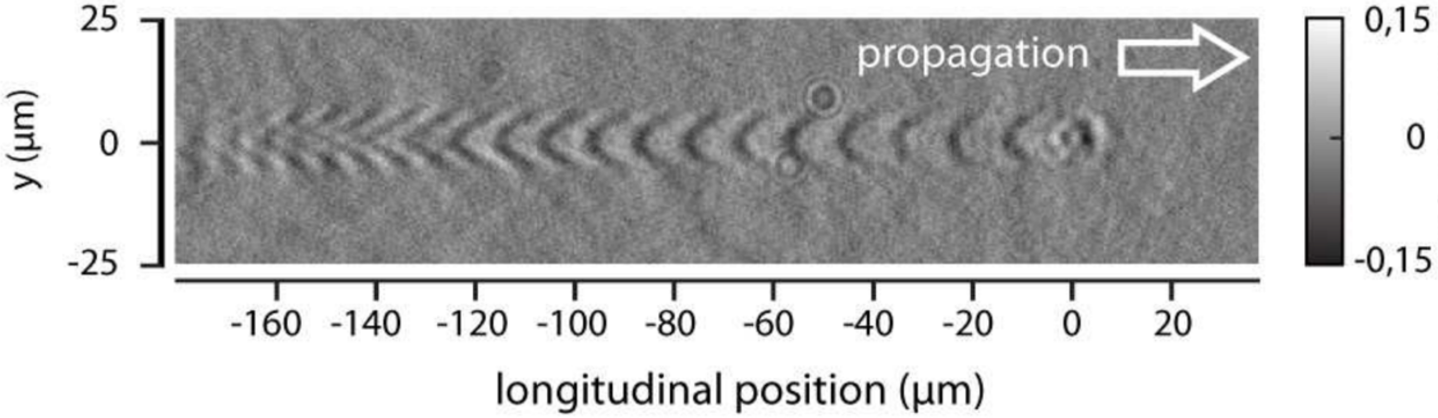

Few-fs shadowgraphy of a laser-driven wakefield

S. Kneip *et al Phys. Rev. Lett.* ***103*** 035002 (2009)
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Heat-pipe ovens (and similar)

Heat-pipe ovens

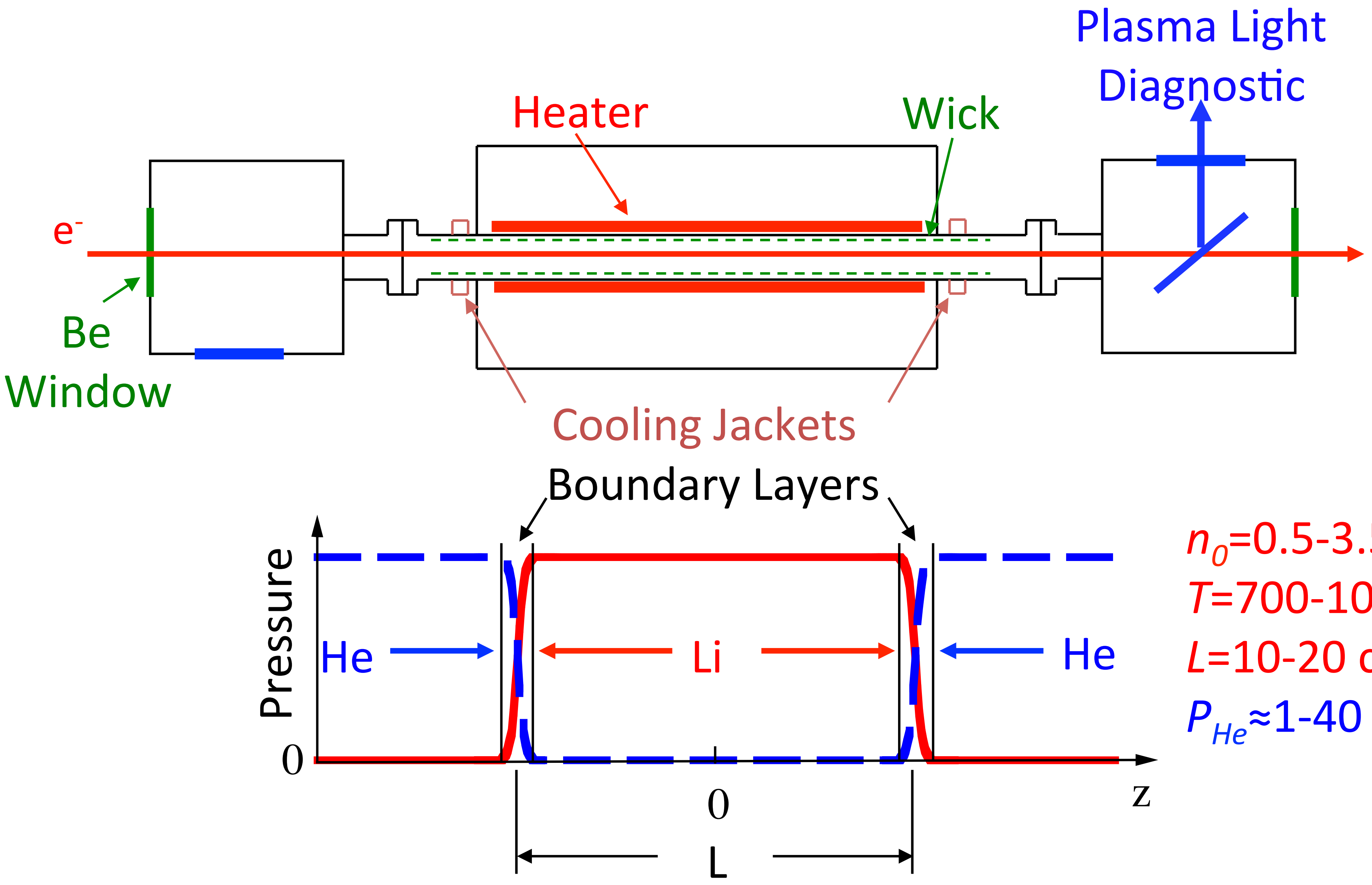
Many beam-driven plasma accelerators require:

- Long targets (metre scale)
- Relatively low density $n_e = 10^{14} - 10^{16}\ \text{cm}^{-3}$
- Ionizable by drive beam or a laser pulse (⇒ low-Z target)
- Minimize ionization by collisions with driver (⇒ low-Z target)
- In some cases, high uniformity

- How can we make long, uniform length of alkali metal vapour?
- How can this be ionized over 1 m by a laser pulse?

Heat-pipe ovens

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

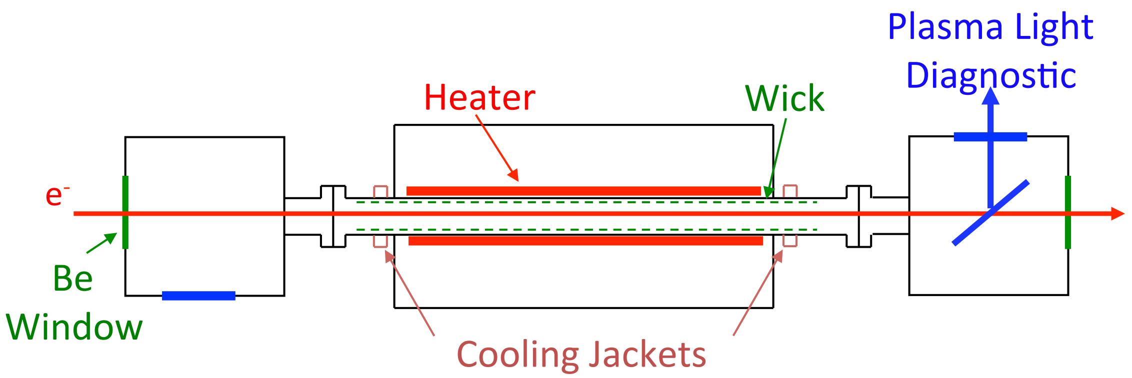
L=10-20 cm

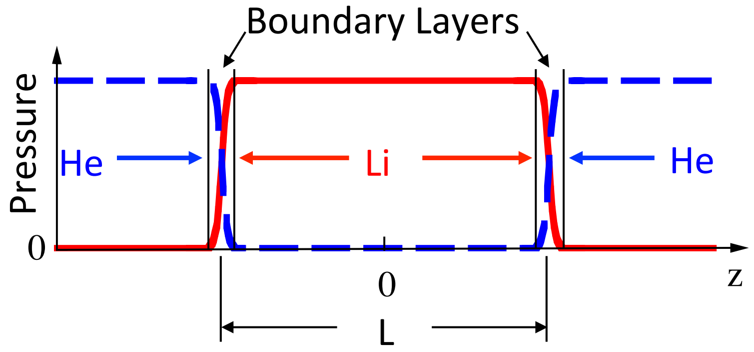
P_{He}≈1-40 T

Heat-pipe ovens

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

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





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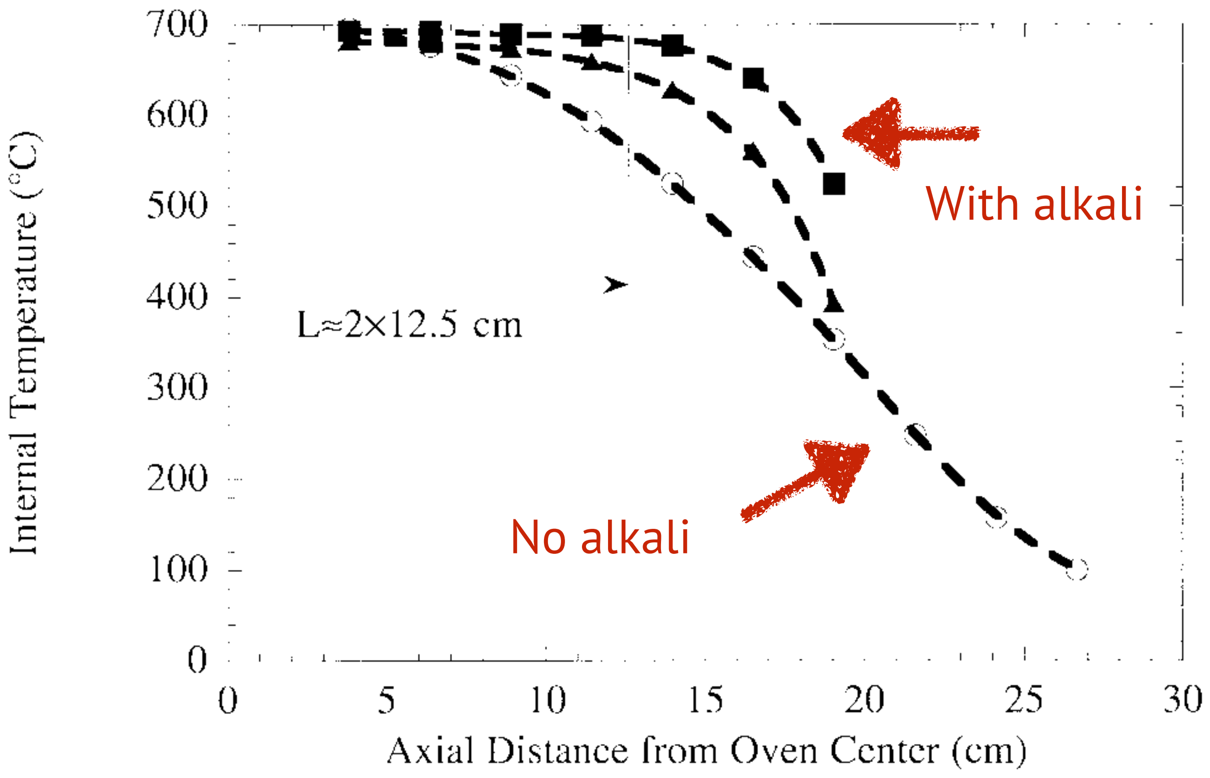
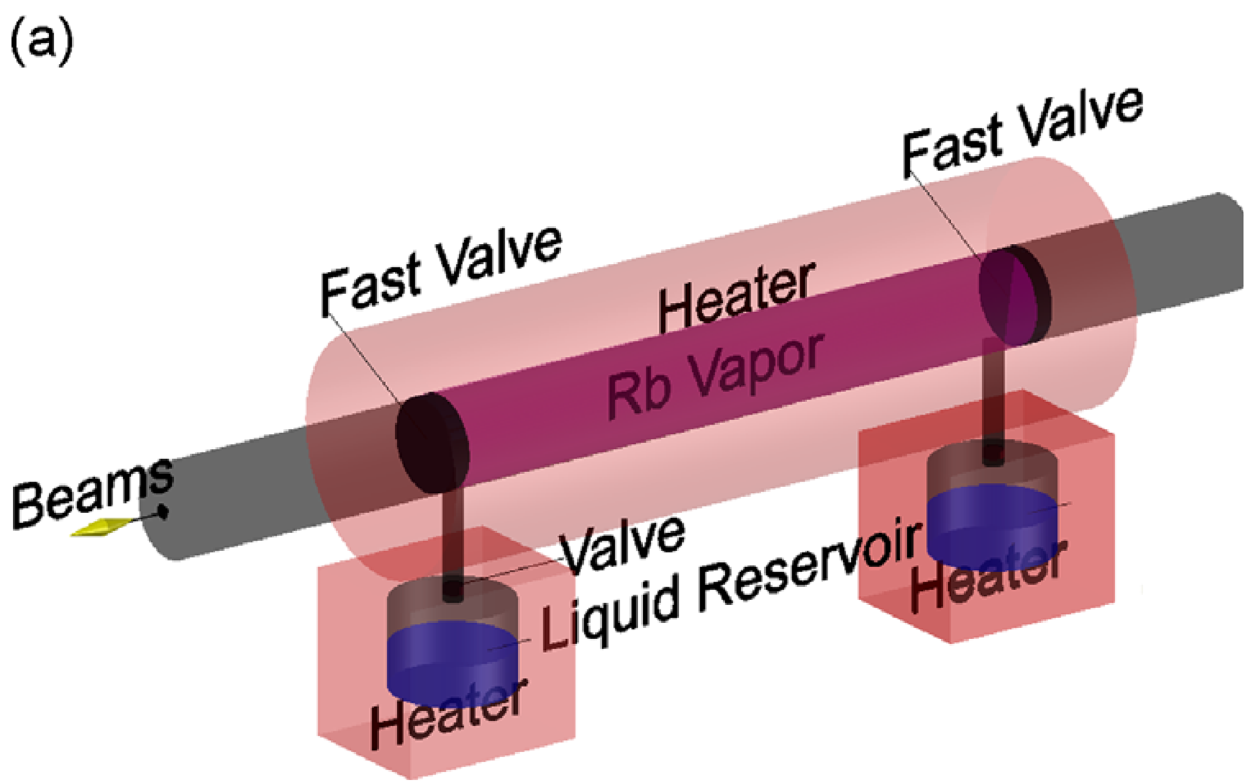


Heat-pipe ovens

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



Heated Rb reservoir
and fast valve

Not strictly a heat-pipe oven…

- Designed for AWAKE expt
- 10 m long, 40 mm diam. oil-heated pipe
- No buffer gas: fast valves contain vapour
- Density variations related to temperature variations

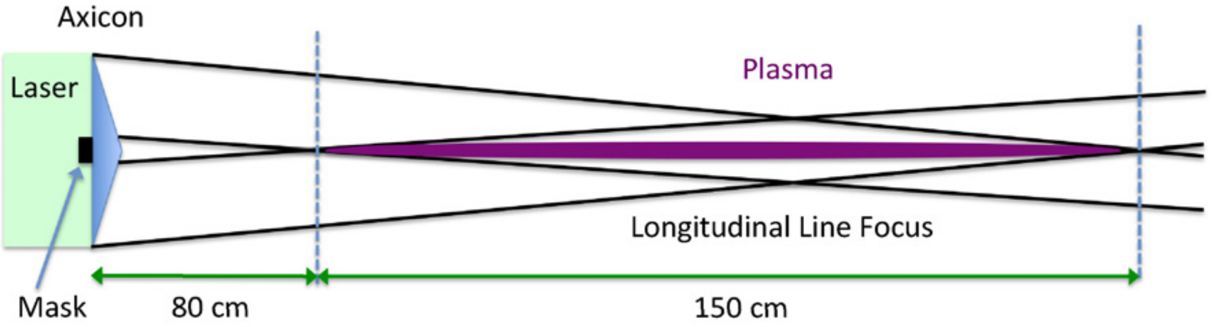
Heat-pipe ovens: Example parameters

Parameter	**Heat-pipe 1**	**Heat-pipe 2**	**Vapour cell**
Alkali density (cm	2 - 4×10	0.5 - 3.5 ×10	~ 2×10
Electron density (cm	3 - 8 ×10	0.5 - 3.5 ×10	~ 2×10
Fractional ionization η (%)	15 - 20	100	100
Plasma length *L* (m)	1.4	0.1 - 1.3	10
Oven temp.	700	700 - 1050	150 - 200
Alkali	Li	Li	Rb
Buffer gas, Pressure (Torr)	He, 0.3	He, 1 - 40	None
Ionization	UV laser (ArF @ 193 nm)	Electron bunch	Laser (Ti:sapphire @ 800 nm)

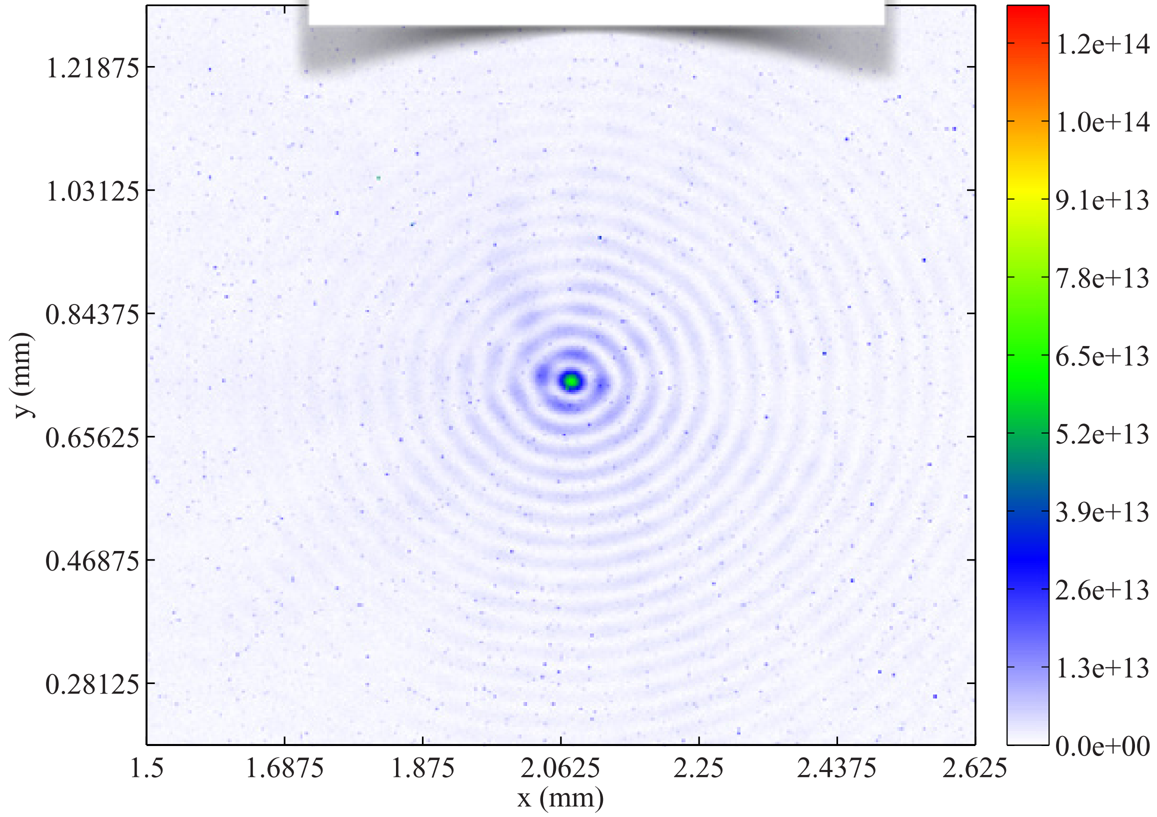
Heat-pipe ovens: Laser ionization

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

- Pre-ionized plasma often preferable since head of driver beam not guided by neutral gas
- Need to maintain threshold laser intensity over long distance
  - Need large spot size
  - Or use "axicon"
- System on right used to generate 36 cm long, 1.2 mm diam. plasma in Li oven
- Measurements suggest laser intensity sufficient to ionize H



Laser intensity 70 cm from axicon



Waveguides

Why guiding is necessary in LWFAs

Linear scaling for LWFAs

$$\text{Accelerating field}: \quad E_z \propto \omega_p \propto \sqrt{n_e}$$

$$\text{Dephasing length}: \quad L_d \approx \frac{\lambda_p^3}{\lambda^2} \propto \frac{1}{n_e^{3/2}}$$

$$\text{Energy gain}: \quad \Delta W = E_z L_d \propto \frac{1}{n_e}$$

- Simple scaling (in linear regime) shows that factor 10 increase in energy requires:
  - Factor 10 decrease in electron density: 10^{19} cm^{-3} → 10^{18} cm^{-3} → 10^{17} cm^{-3}
  - Factor 30 increase in length: 1 - 2mm → 30 - 60 mm → 900 - 1800 mm

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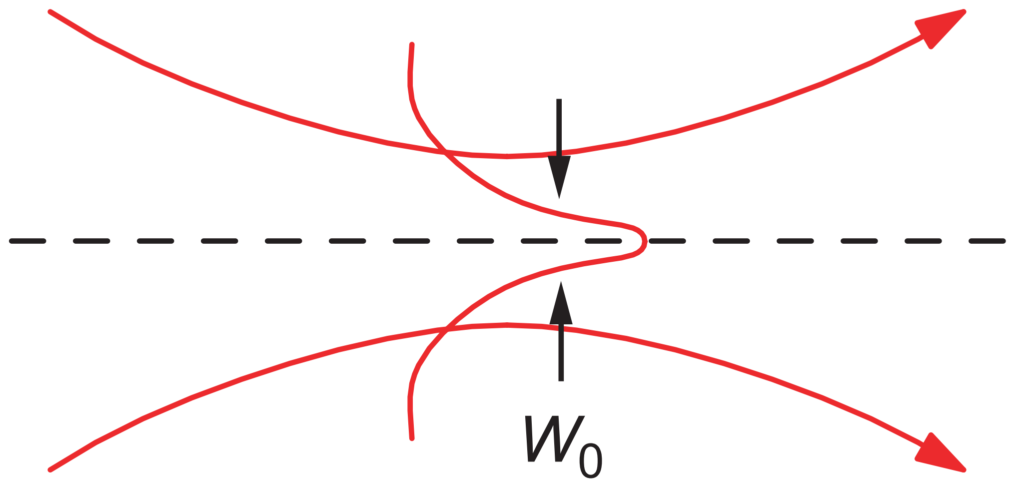


$$Z_R = \frac{\pi w_0^2}{\lambda}$$

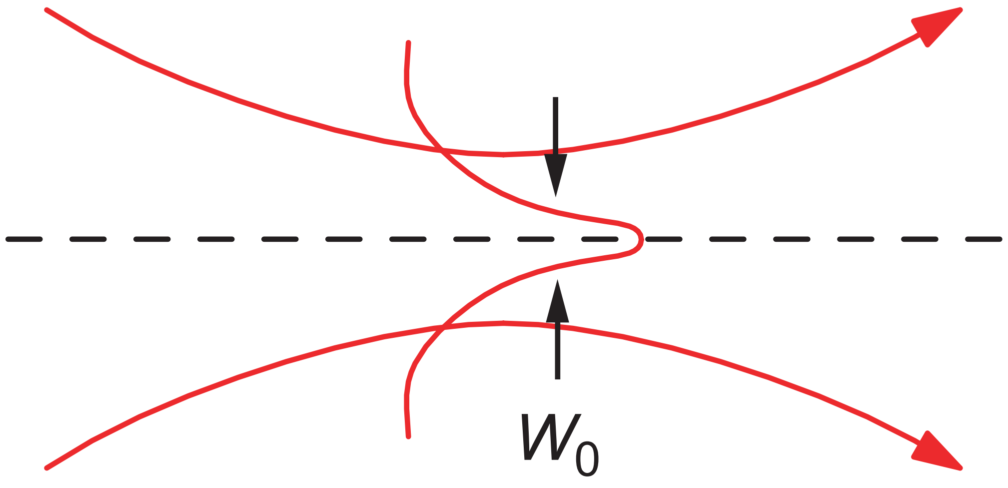
- The laser intensity must be maintained over the acceleration length
  - Set by diffraction of laser beam
  - Rayleigh range is typically only a few mm

Example :

$$w_0 = 10\,\mu\text{m};\ \lambda = 1\,\mu\text{m}$$

$$\Rightarrow Z_R = 0.3\,\text{mm}$$

Why guiding is necessary in LWFAs



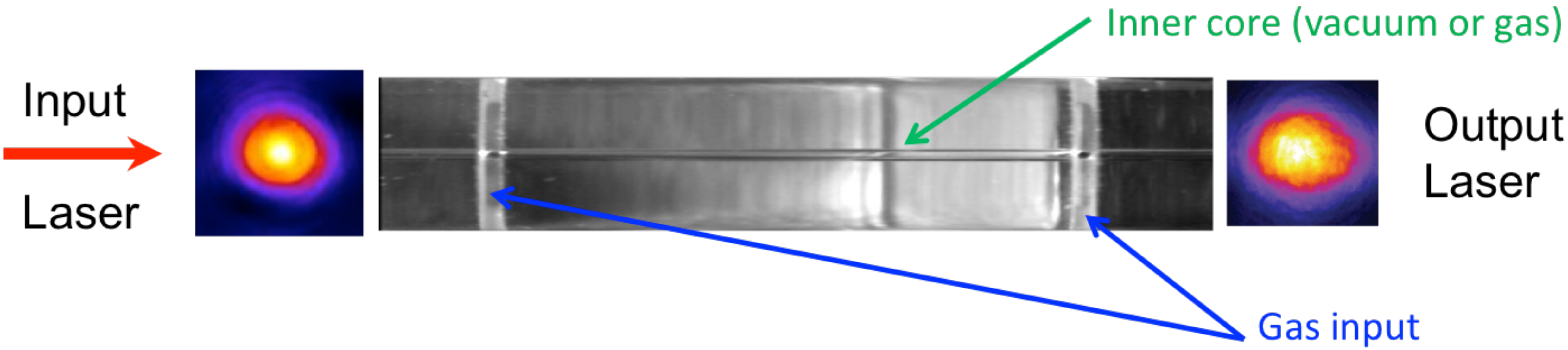
$$Z_R = \frac{\pi w_0^2}{\lambda}$$

There are two broad categories of waveguide:

- Grazing-incidence waveguides
    - Technically "lossy" guiding, but losses are low
- Gradient refractive index guides

Grazing-incidence waveguides

Courtesy Brigitte Cros
LPGP, CNRS-Université Paris-Sud

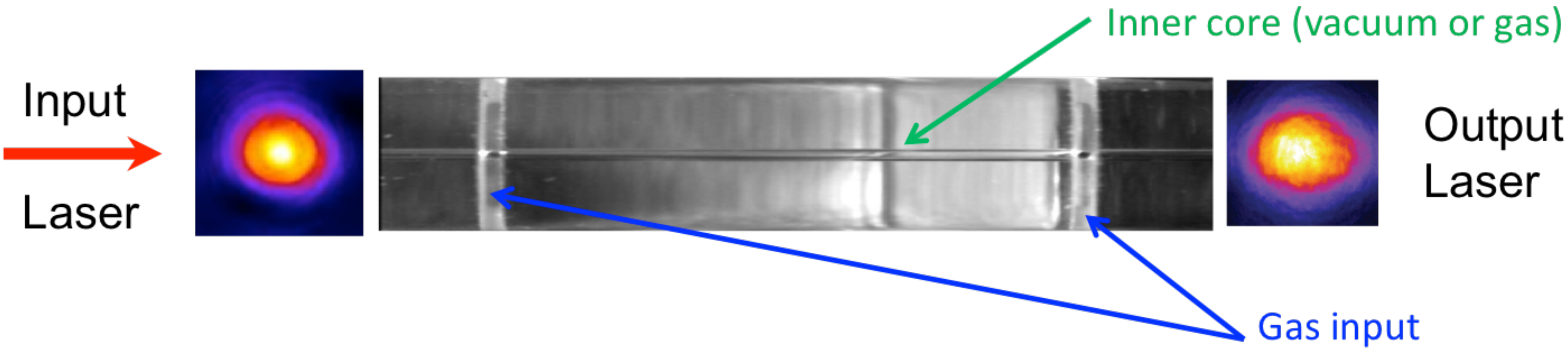


Operation in a large parameter range:

- Inner diameter: 50 - 500 µm,
- Glass walls: optically smooth
- Length : limited by laser damping length (several meters for 100µm diameter capillary)
- Laser intensity: the main limitations are due to poor beam quality and stability
- Gas : H2 to control the density easily (laser ionisation)
- Gas pressure control: 0-500 mbar, pulsed (1shot /10s).

Grazing-incidence waveguides: Recent results

Courtesy Brigitte Cros
LPGP, CNRS-Université Paris-Sud



Inner core (vacuum or gas)

Input
Laser

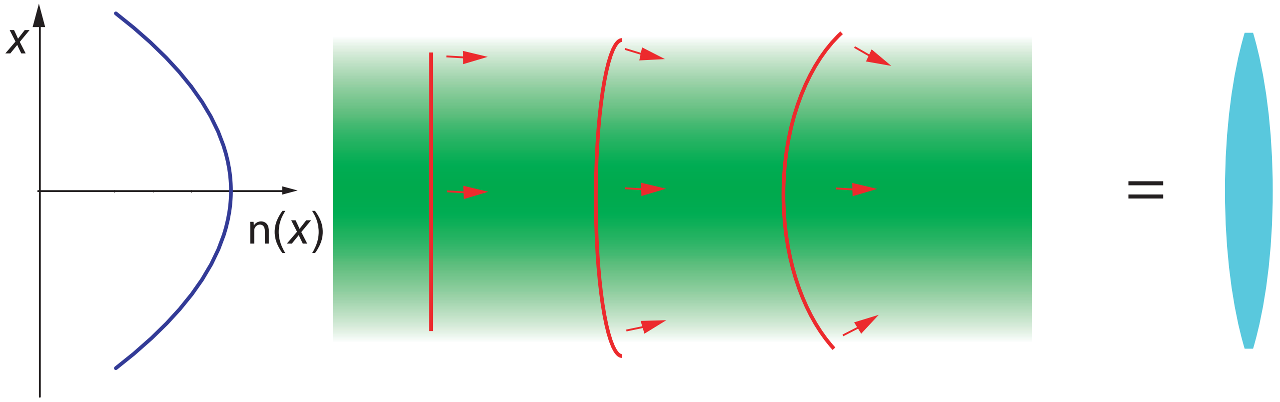
Output
Laser

Gas input

- Stable gas confinement (measurement by interferometry and fluid simulations)
  - J. Ju *et al. J. Appl. Phys.* **112** 113102 (2012)
- Laser wakefield acceleration in capillary tubes:
  - F. G. Desforges *et al. Nucl. Instr. Meth. A* **740** 54 (2014)
  - M. *Hansson et al. Phys. Rev. STAB* **17** 031303 (2014).
- Use of capillary exit as pinhole for imaging of radiation and diagnostic of electron acceleration:
  - J. Ju *et al. Phys. Plasmas* **20** 083106 (2013)
  - J. Ju *et al. Phys. Rev. STAB* **17** 051302 (2014)

Gradient refractive index waveguides

- Higher refractive index on axis curves wavefront
- Each slice acts as a thin lens



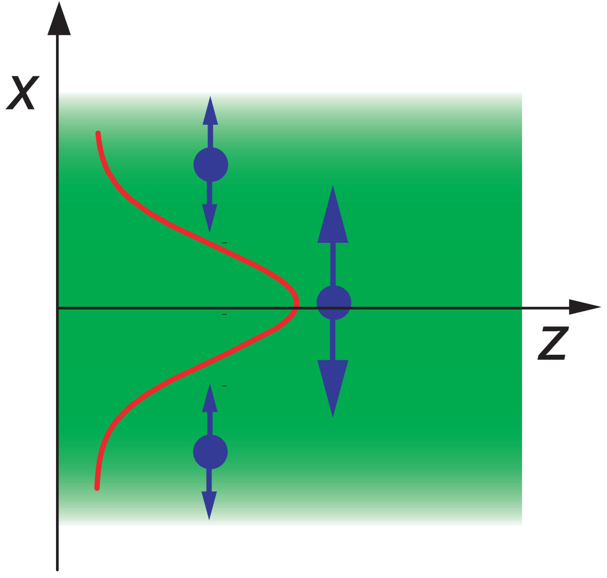
Relativistic self-focussing

- **Relativistic self-focusing**: transverse variation of intensity gives correct refractive index profile
- Leads to self-focusing/guiding above a critical power

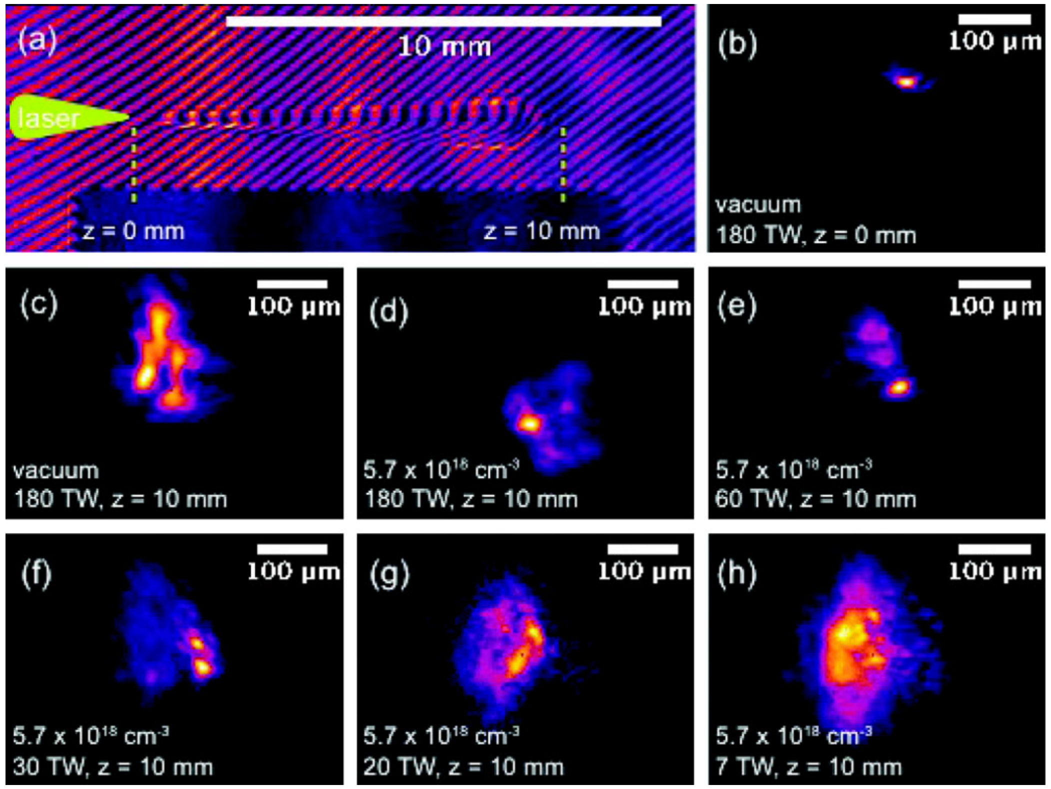
$$P_c = 17.4 \left(\frac{\omega}{\omega_p}\right)^2 \text{ GW}$$

Example :

$$n_e = 10^{18}\,\text{cm}^{-3}, \lambda = 800\,\text{nm}$$
$$P_c = 8\,\text{TW}$$



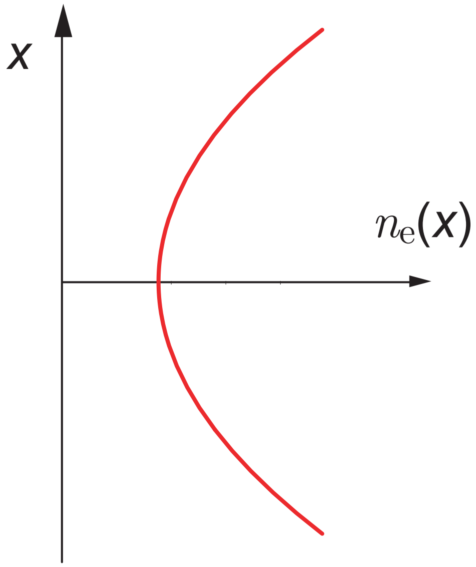
$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2}$$
$$\approx 1 - \frac{1}{2}\frac{n_e e^2}{\gamma(r) m_e \epsilon_0 \omega^2}$$



Relativistic self-guiding with the Gemini laser
S. Kneip *et al Phys Rev Lett* **103** 035002 (2009)

Plasma channels

- **Plasma channel**: transverse variation of electron density gives correct refractive index profile
- Parabolic channel will match Gaussian beam of spot size W_M
- Shape of channel is not very important: matched spot size *mainly determined by channel depth*.
  - See Durfee *et al. Opt. Lett.* **19** 1937 (1994)



$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2}$$

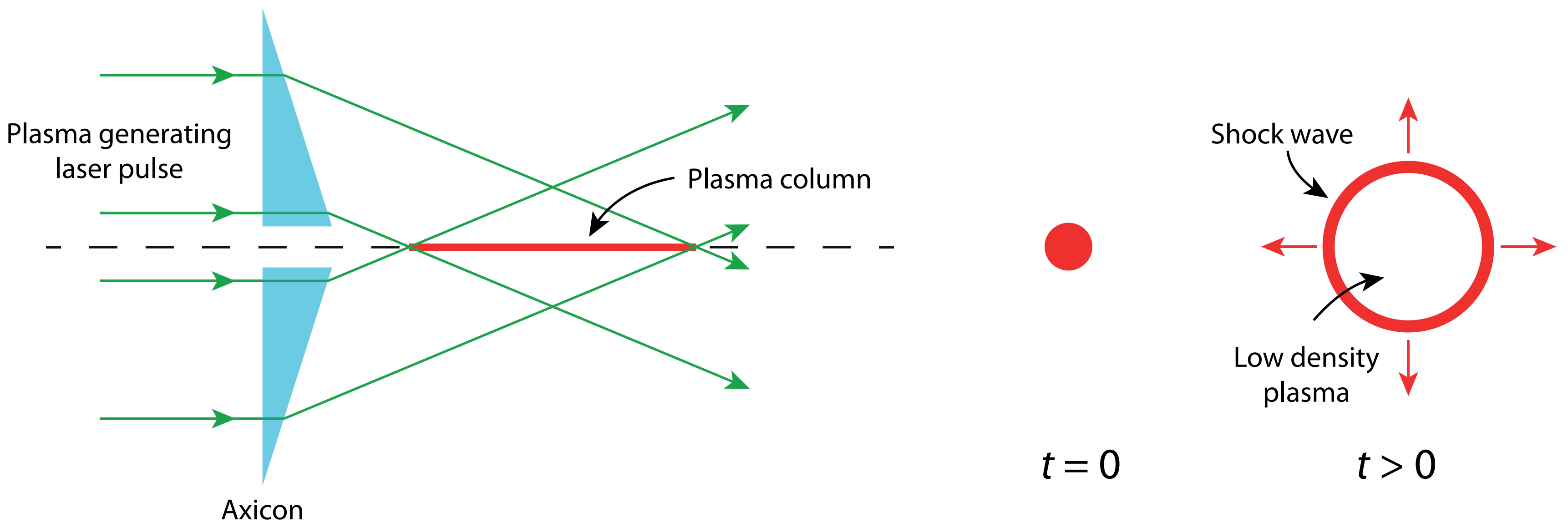
$$\approx 1 - \frac{1}{2}\frac{n_e(r) e^2}{\gamma m_e \epsilon_0 \omega^2}$$

$$n_e(r) = n_e(0) + \Delta n_e \left(r/r_{ch}\right)^2$$

$$W_M = \left(\frac{r_{ch}^2}{\pi r_e \Delta n_e}\right)^{1/4}$$

Plasma channels: hydrodynamic expansion

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

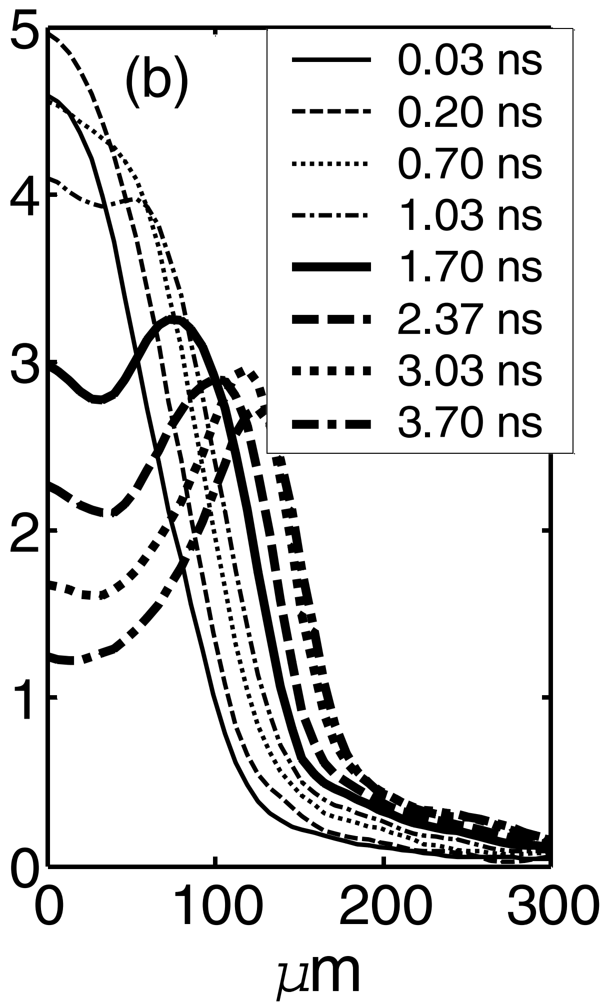


- Hot plasma column produced by line focus
- Plasma expands rapidly, driving shock into surrounding gas
- On-axis density well is formed

Plasma channels: hydrodynamic expansion

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

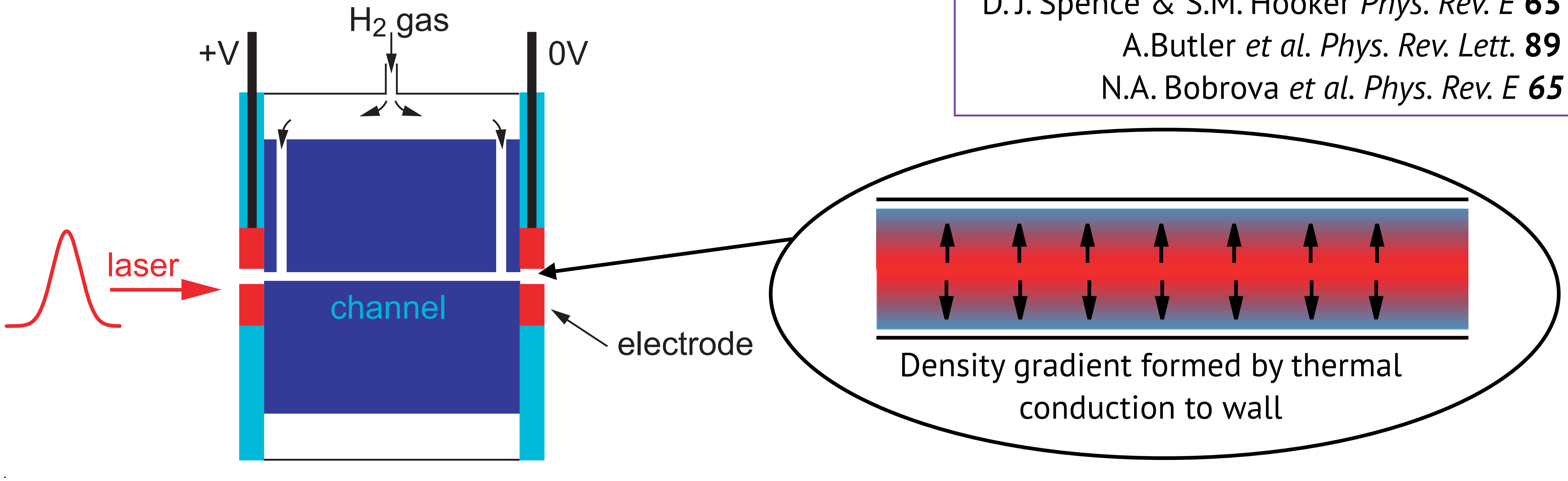
- Original scheme:
  - ~ 100 ps laser pulse creates and heats plasma
  - On-axis density ~ 5 × 10^{18} cm^{-3}
  - Matched spot W_M ~ 10 - 20 μm
  - Length < 30 mm
- Ignitor-heater method
  - Two, crossed beams create plasma:
  - fs-duration "ignitor"
  - ps-duration "heater"
- Clustered gases
  - Ionized 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)

Gas-filled capillary discharge waveguides

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)



Density gradient formed by thermal conduction to wall

Gas-filled capillary discharge waveguides

D. J. Spence & S.M. Hooker *Phys. Rev. E* **63** 015401 (2000)
A.Butler *et al. Phys. Rev. Lett.* **89** 185003 (2002)
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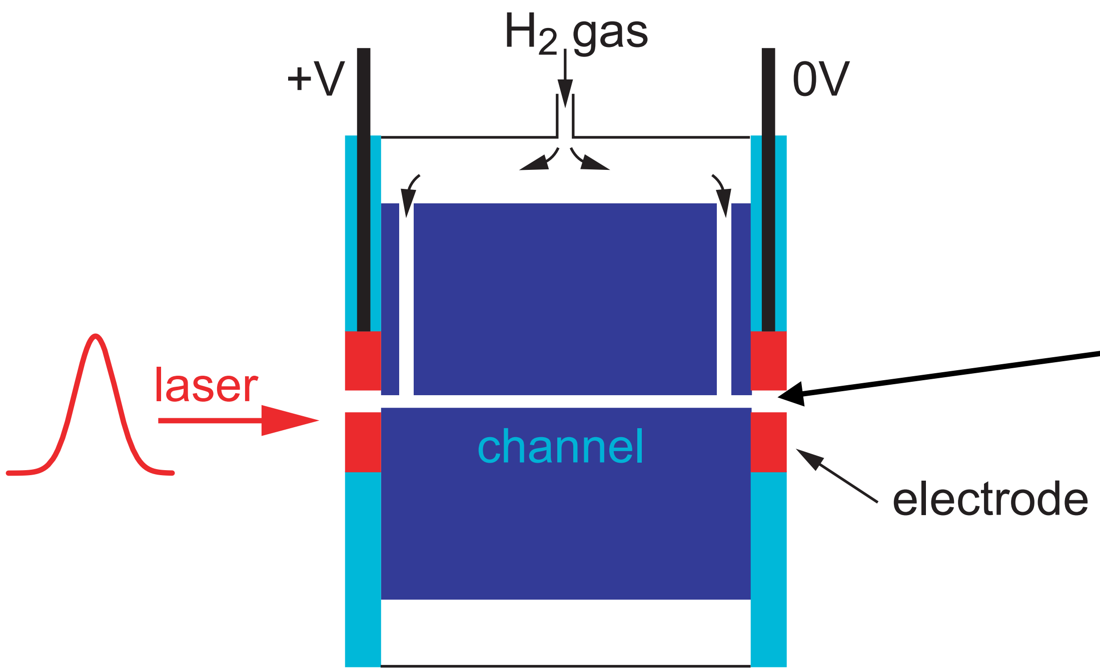
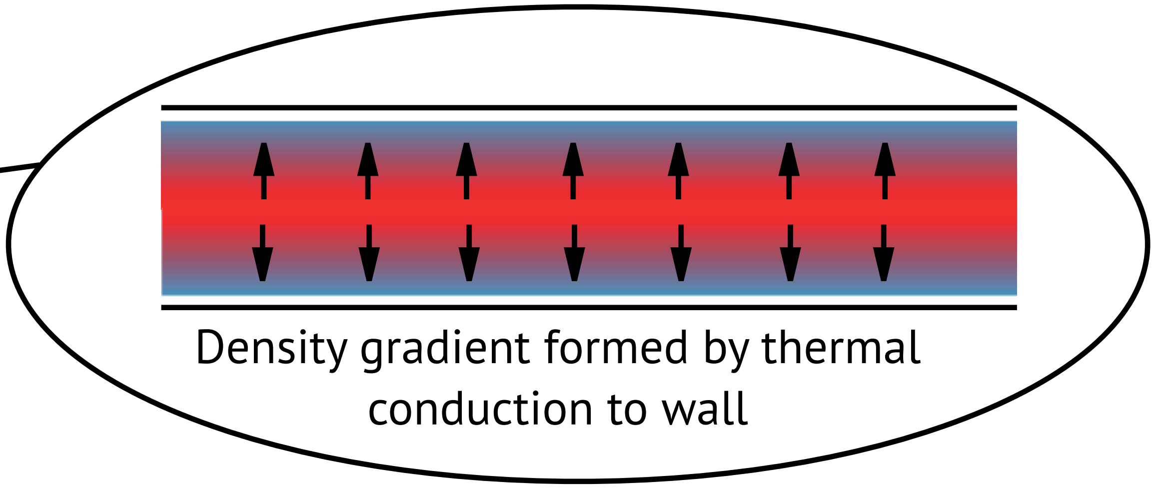
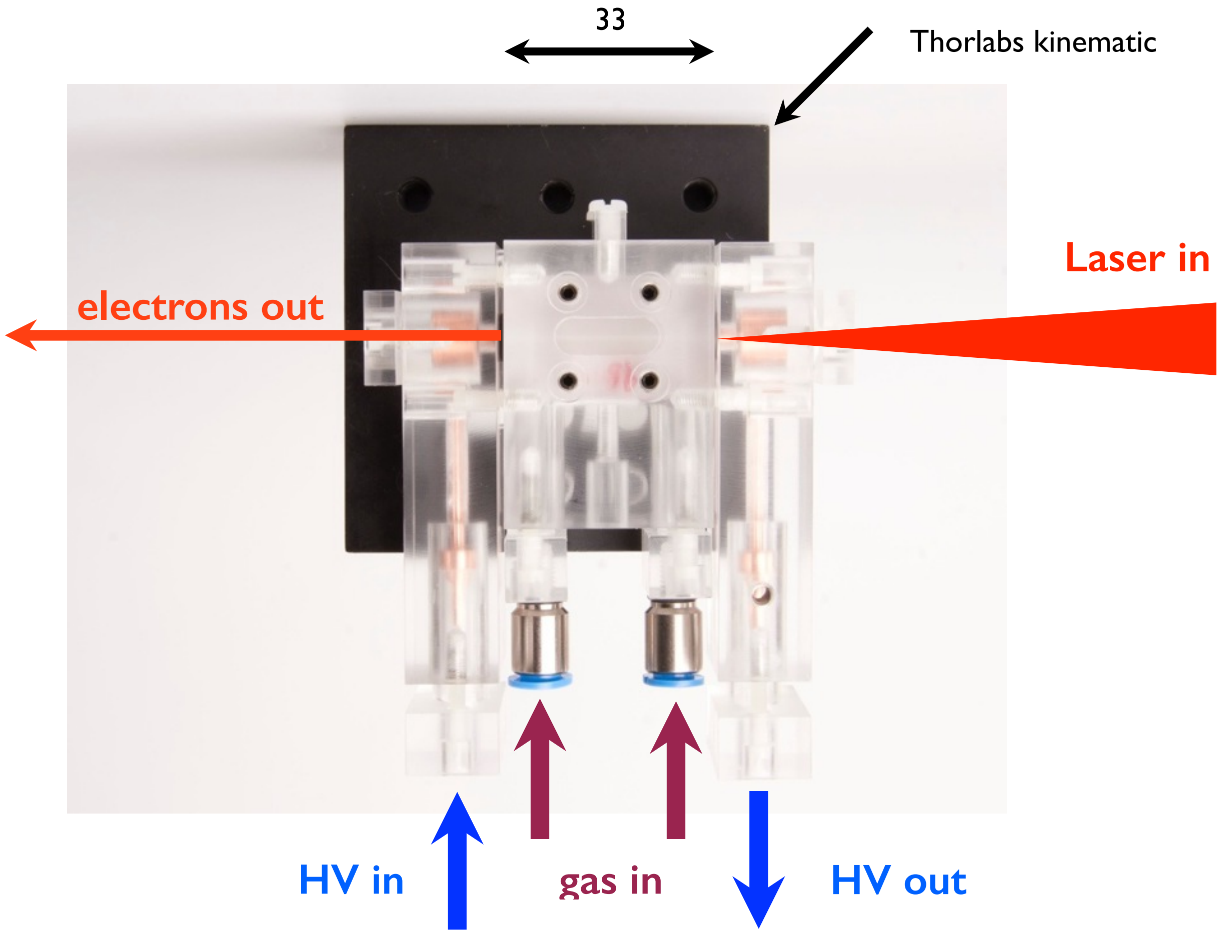
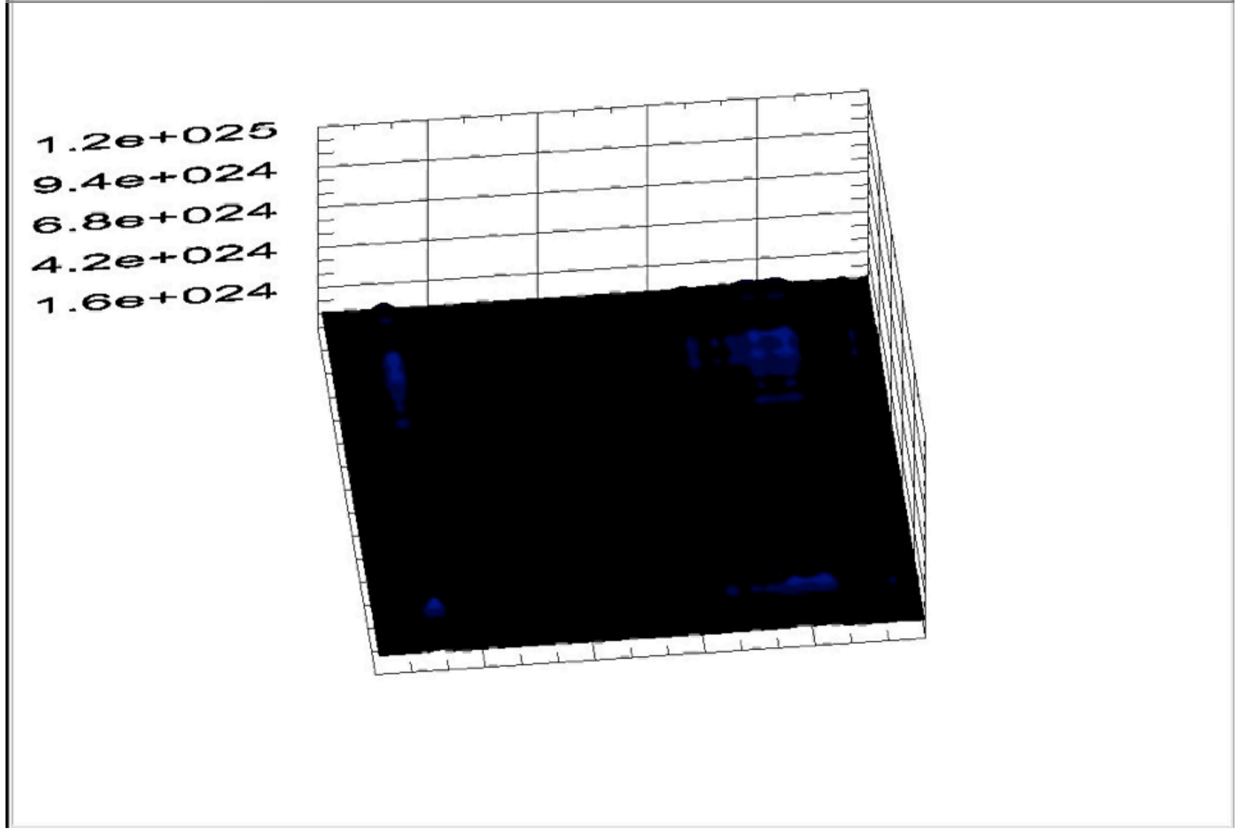






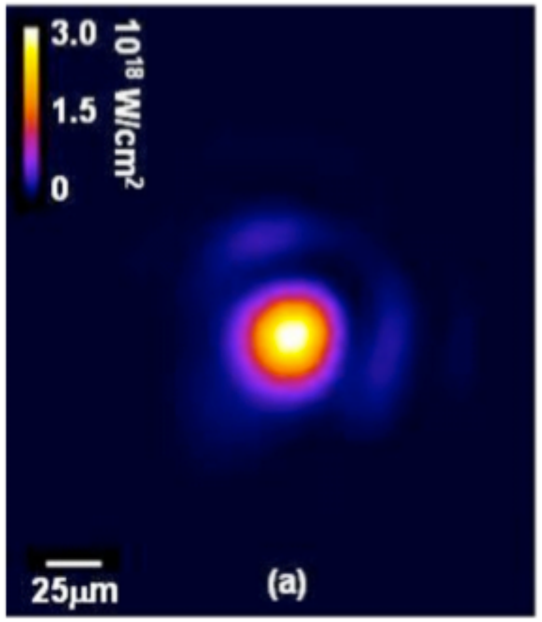


Measured formation of plasma channel

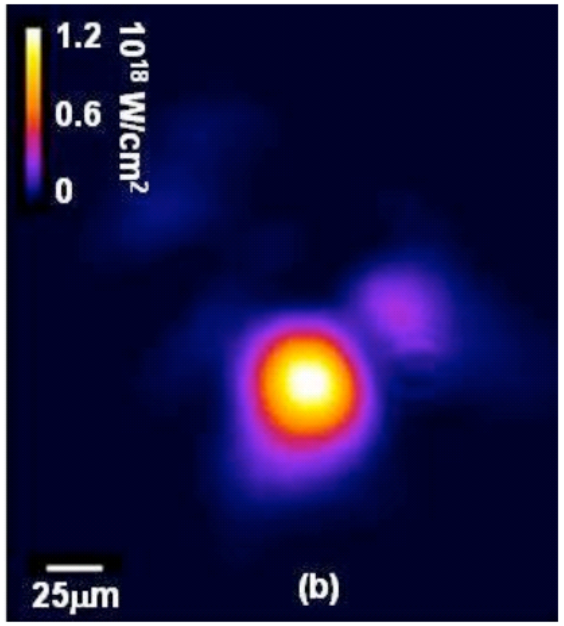
Electron acceleration in a gas-filled CDW

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

Entrance



Exit

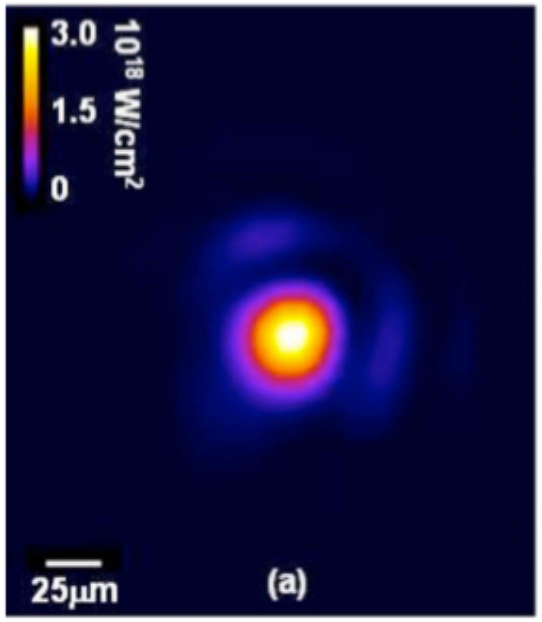


Capillary diam.	190 um
Input laser power	40 TW
Input intensity:	> 10^{18} W cm^{-2}
Plasma:	3×10^{18} cm^{-3}
Spot size (entrance):	26 μm
Spot size (exit):	33 μm

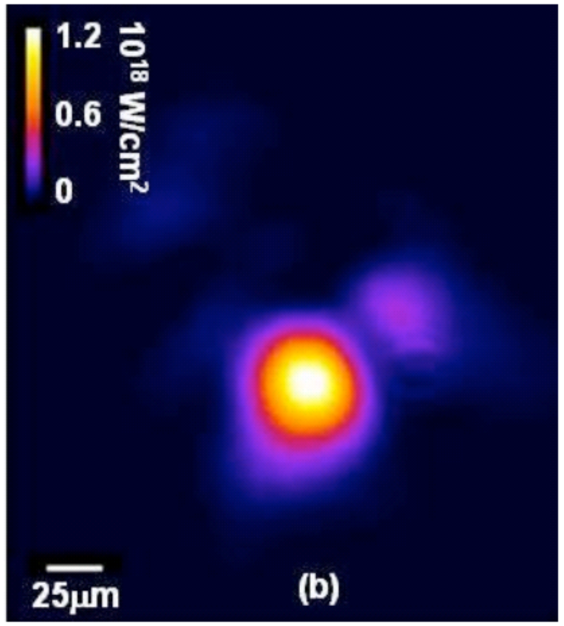
Electron acceleration in a gas-filled CDW

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

Entrance



Exit



Capillary diam.	190 um
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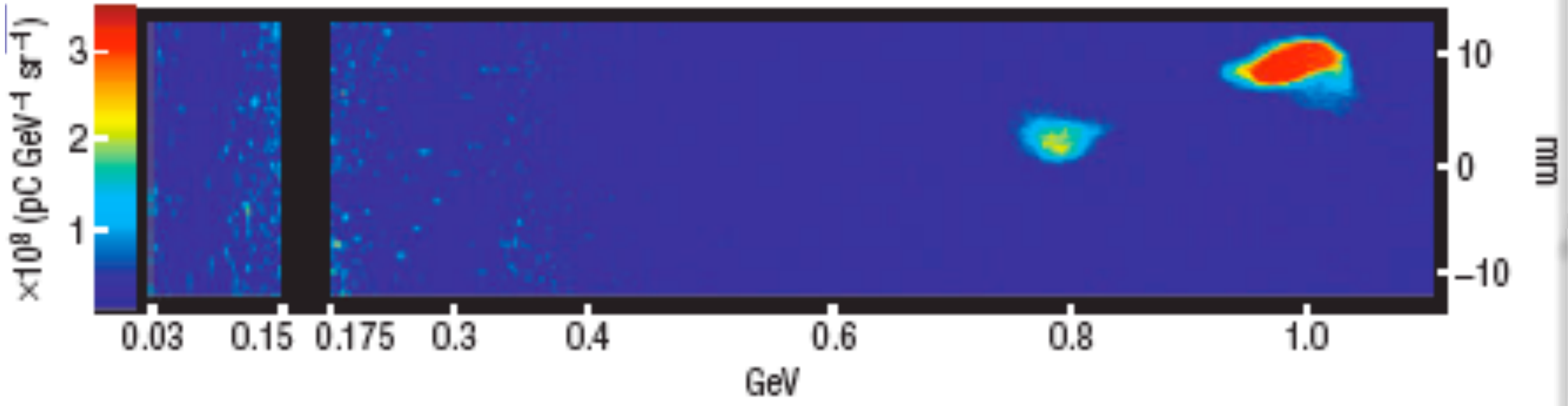
Plasma:	3×10^{18} cm^{-3}
Spot size (entrance):	26 μm
Spot size (exit):	33 μm



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

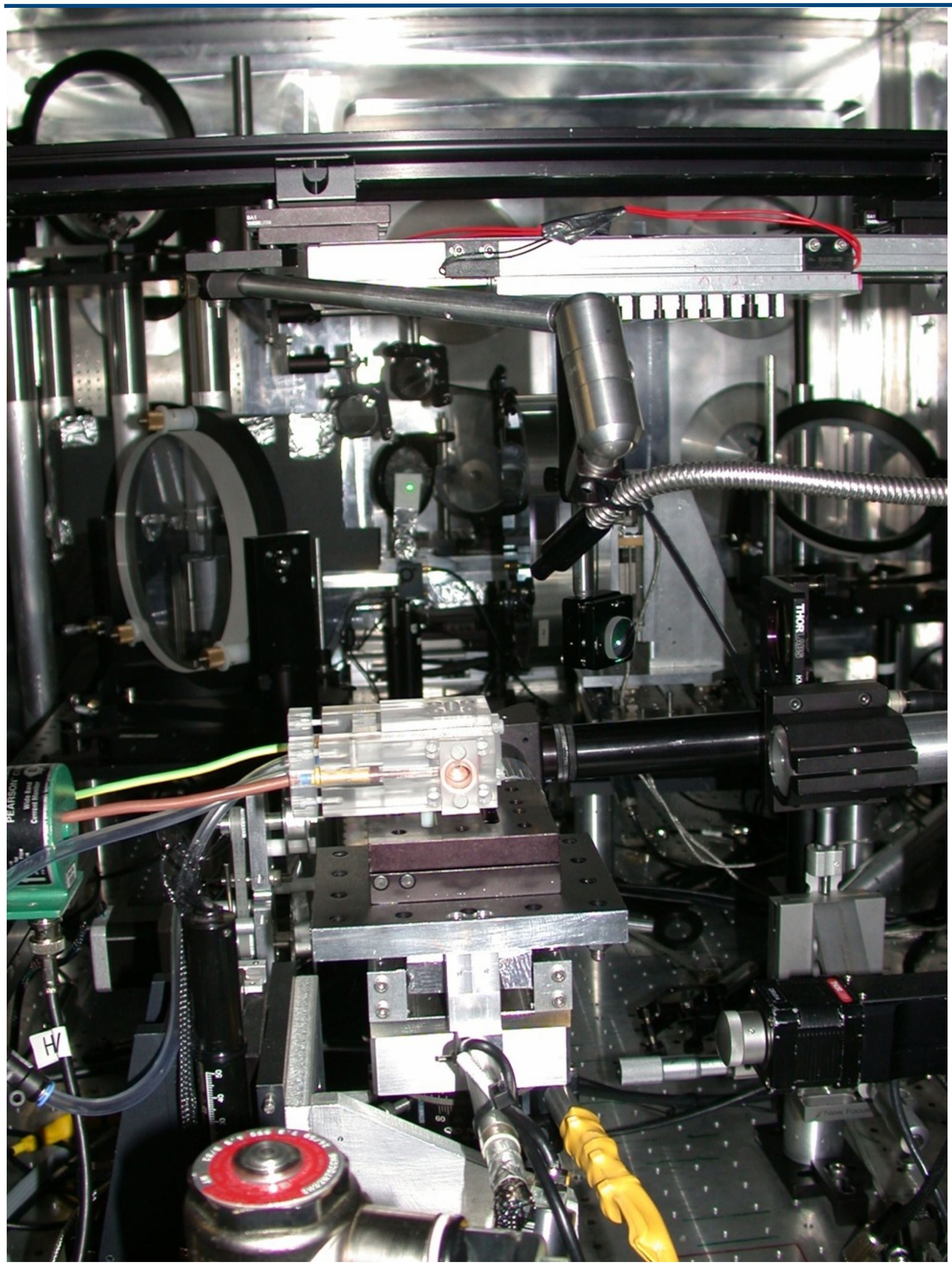
E = (1.0 +/- 0.06) GeV

ΔE = 2.5% RMS

$\Delta\theta$ = 1.6 mrad RMS

Q = 30 pC

Gas-filled capillary discharge waveguides



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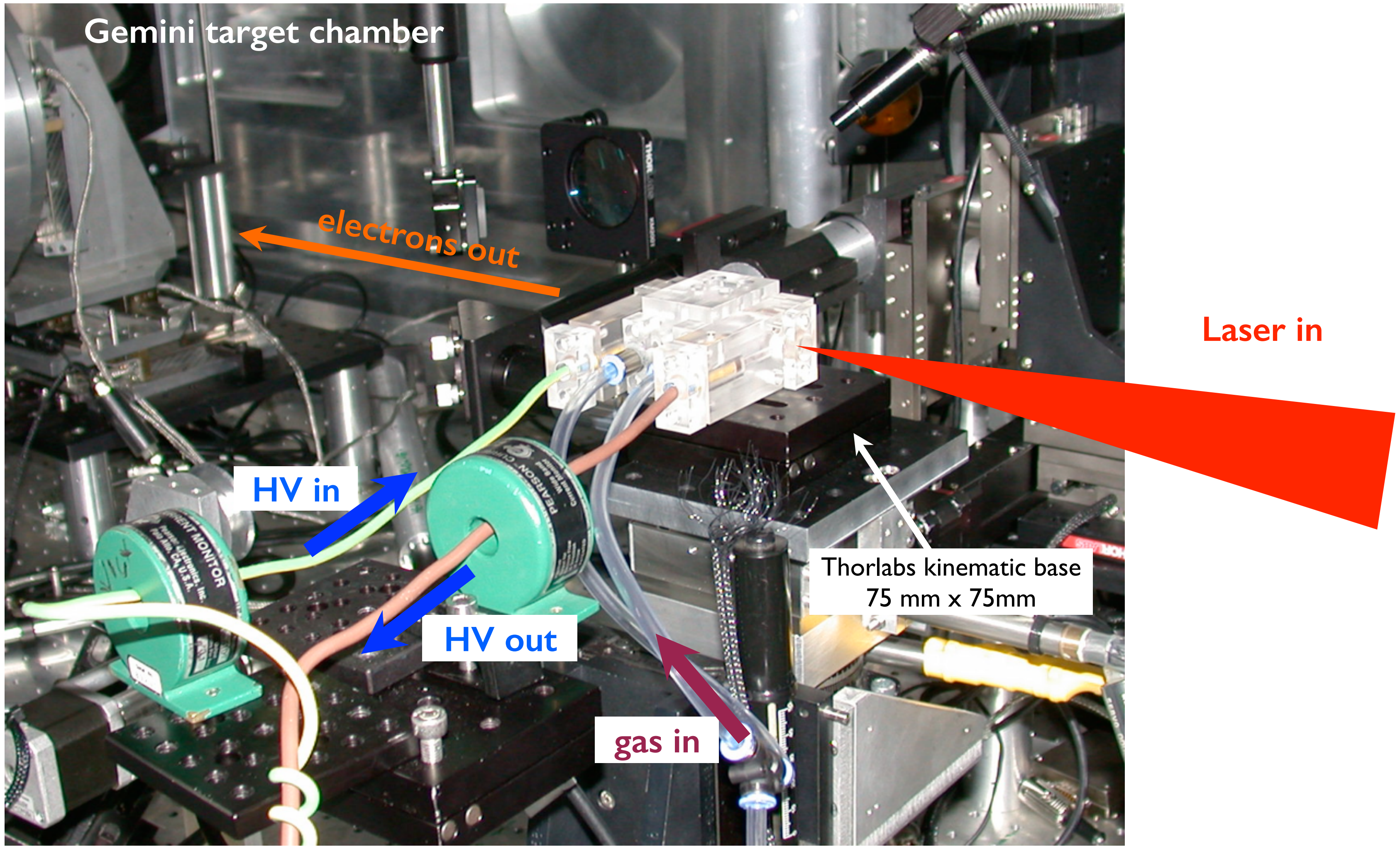
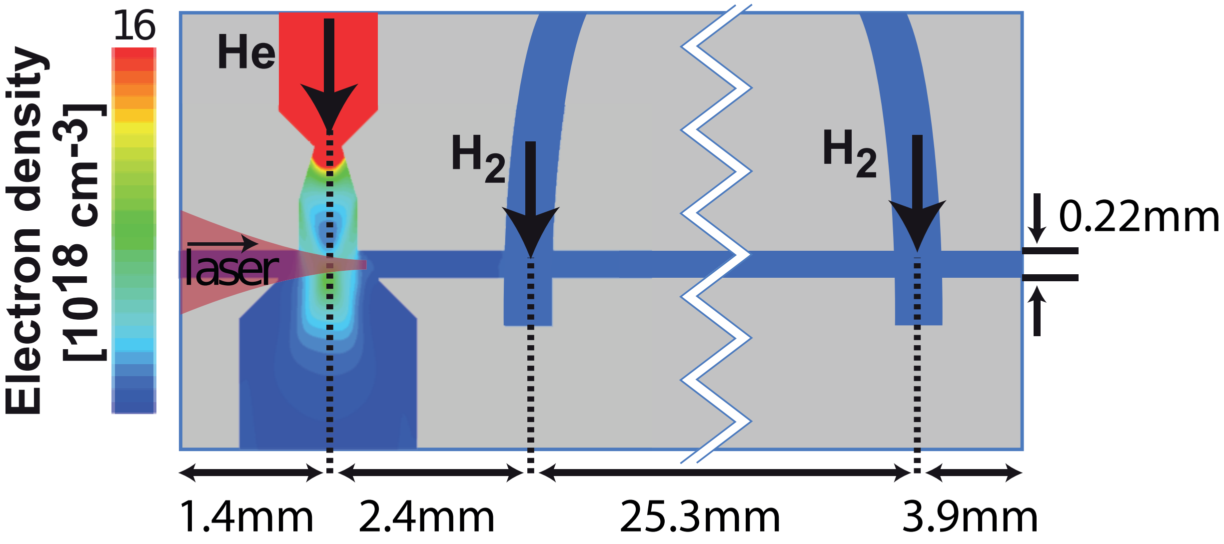
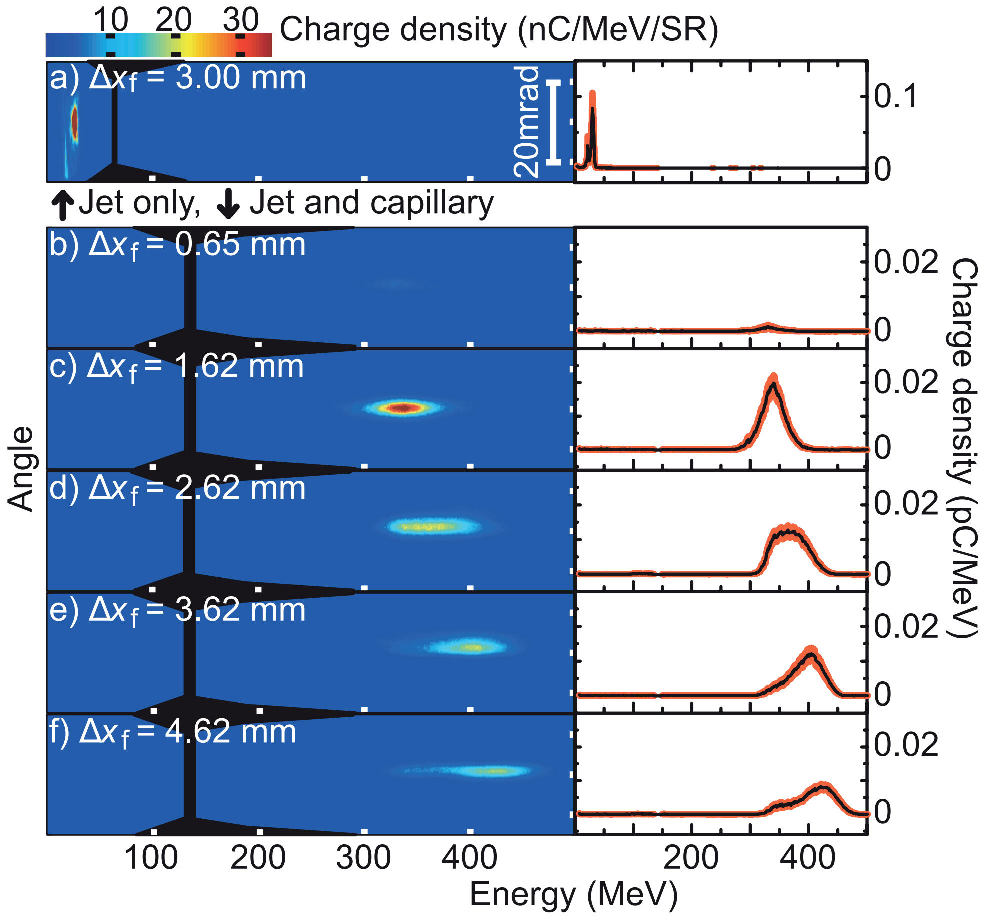


Advanced CDWs

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

- The LBNL group have incorporated a gas jet within a gas-filled CDW
- Gas jet controls injection
  - Beam energy controlled by adjusting position of laser focus
  - $\Delta E_{\mathrm{RMS}} = 1.9\%$
  - $\Delta Q_{\mathrm{RMS}} = 45\%$
  - $\Delta \theta_{\mathrm{RMS}} = 0.57$ mrad

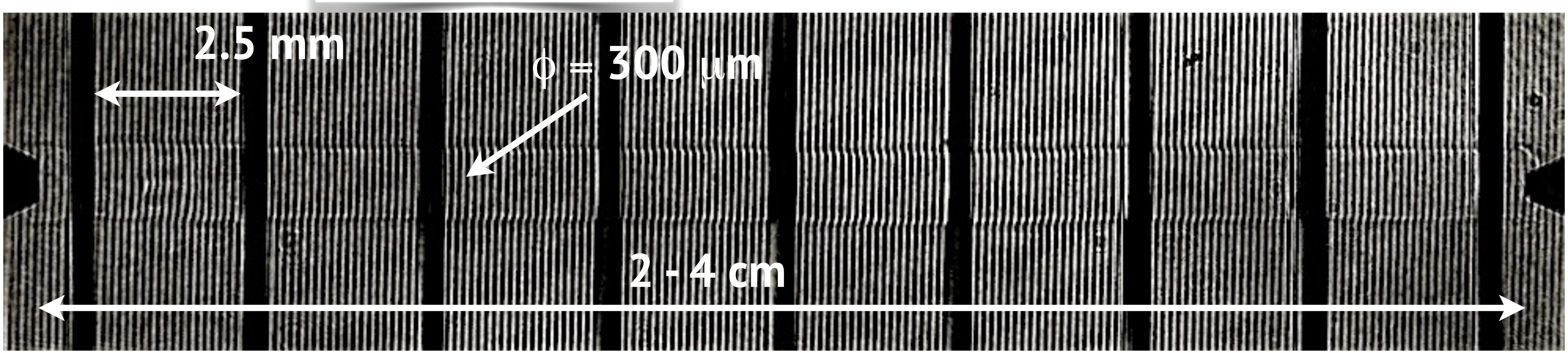


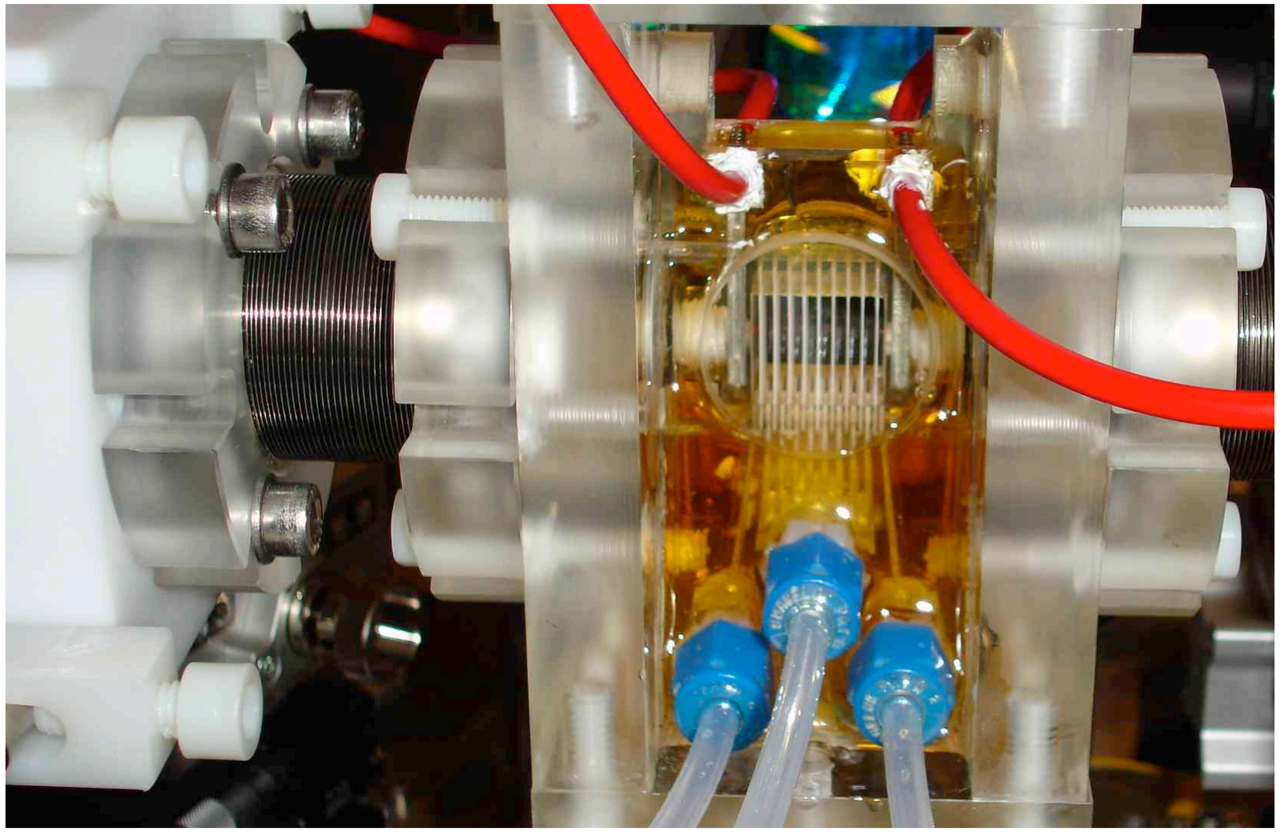


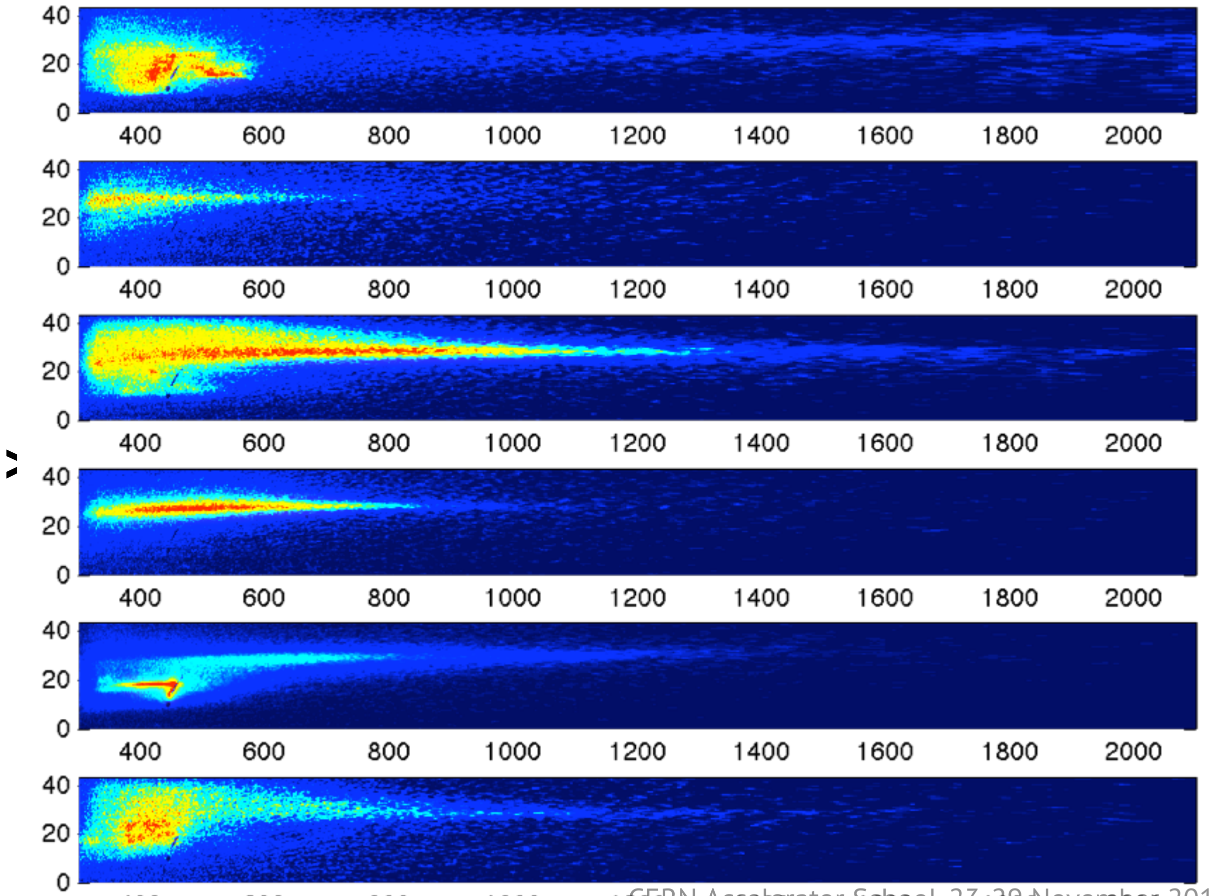
Open-geometry discharge plasma channel

Courtesy Nelson Lopes
Imperial College, London

R. Bendoyro, at al., IEEE Trans. Plasma Science, 36, 1729 (2008)
C. Russo, et al., submitted (2013)







Plasma sources: Summary

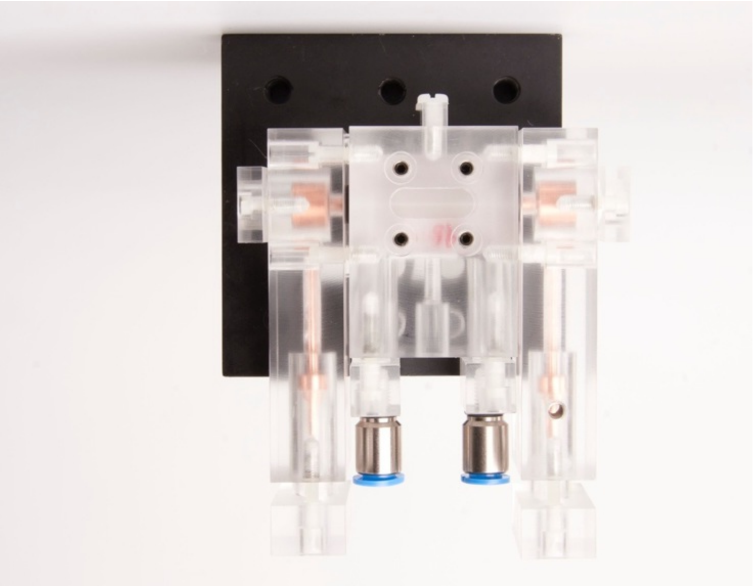
Warning! All figures approximate!

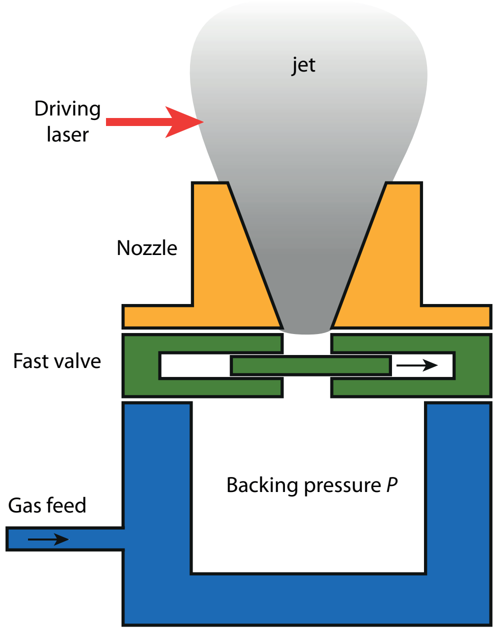
Plasma source	ne (cm	Length	Tran diag. access	Matched spot (µm)
Gas cell	10	≳ 2mm	✔	NA
Gas jet	10	1 - 10 mm	✔	NA
Vapour oven	10	1 - 10 m	✘	NA
Grazing-incidence	0 - 10	5 mm - 1 m	restricted ?	15 - 150
Capillary discharge	10	7 - 100 mm	✘	30 - 50
Hydrodynamic expan.	10	≲ 30 mm	✔	10 - 30
Open-discharge	~ 10	20 - 40 mm	✔	60 - 70

Summary

- Many factors must be considered when choosing a target geometry
- 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
  - Long operating life





(a)