Plasma sources for laser- and beam-driven plasma accelerators

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Acknowledgements

A very big thank you to everyone who sent me slides, photos, and thoughts including:

- Félicie Albert, Lawrence Livermore National Laboratory
- Brigitte Cros and Thomas Audet, Université Paris-Sud
- Jérôme Faure, CNRS & Ecole Polytechnique
- Spencer Gessner, SLAC (now at CERN)
- Leo Gizzi & Paolo Tomassini, INFN, Pisa
- Mark Hogan, SLAC
- Dino Jaroszynski, University of Strathclyde
- Andi Maier, University of Hamburg & CFEL, DESY
- Patric Muggli, Max-Planck-Institut für Physik
- Jens Osterhoff and Lucas Schaper, DESY
- Matthew Streeter, Lancaster University

Overview

- What would we like the plasma source to do?
- An overview of existing sources
- Challenges and conclusions

What would we like?

Common requirements

- Well-defined & controllable density
- Some degree of longitudinal uniformity
- Reproducibility
- Long operating lifetime
- Controllable transverse profile? (e.g. hollow channel)
- Accessible to diagnostics
- Limited gas load to rest of system
- Minimization of unwanted secondary beam generation (e.g. bremsstrahling)
- Others ...?

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Laser-driven

- Sharp entrance/exit boundaries
- Possibly, laser guiding
- Possibly, control of longitudinal profile ("tapering")
- Others …?

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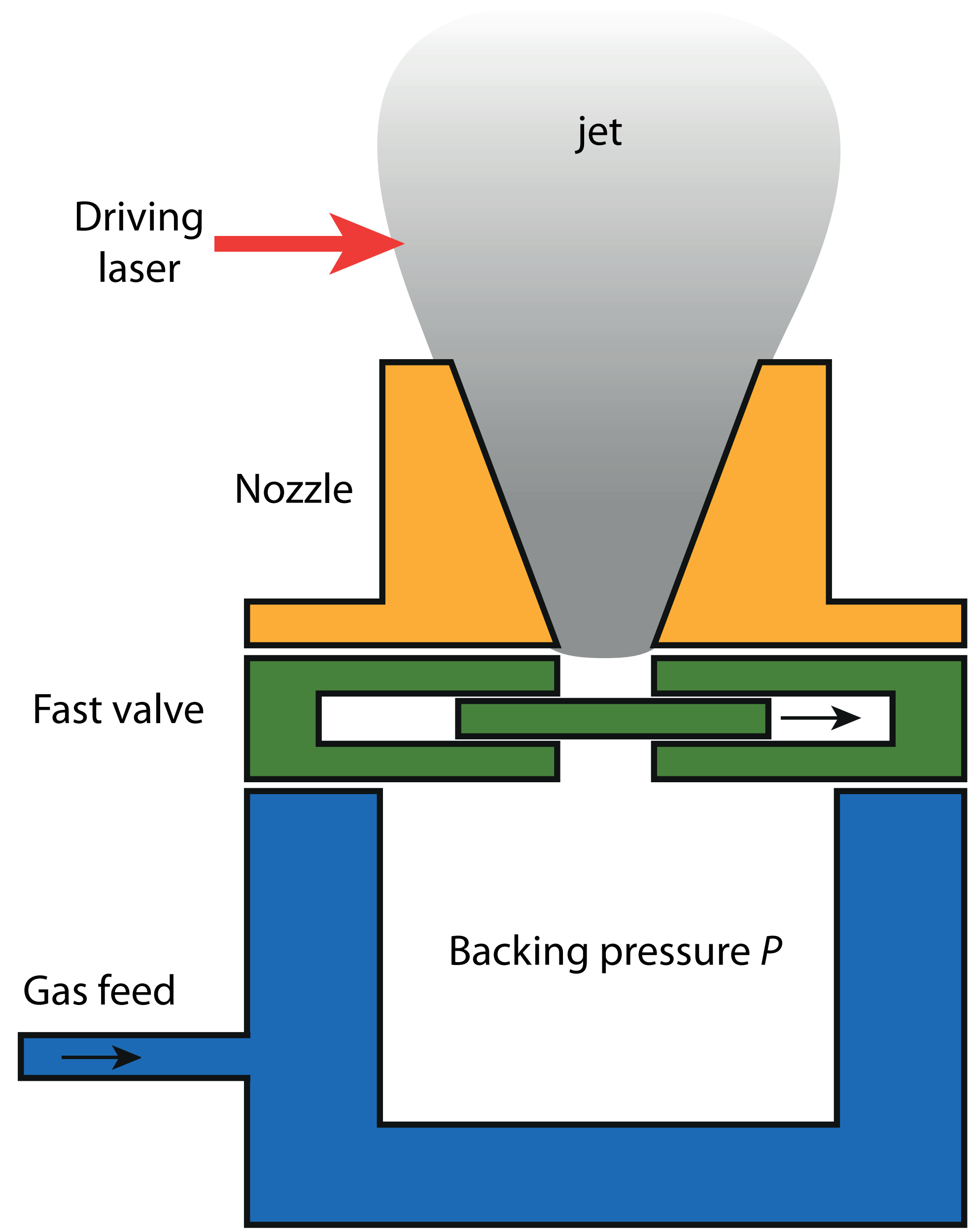
Beam-driven

- Possibly, provision of laser pulse for ionization

Gas jets

Gas jets

- Plasma density controlled by varying backing pressure behind jet -
  - 10 - 100 bar depending on nozzle diameter and desired density
- n_e typically 10^{17} - 10^{20} cm^{-3}
- Length typically few mm
- Supersonic nozzles provide near-flat-top density profile & sharper boundaries



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Thanks to Stuart Mangles, Imperial College London

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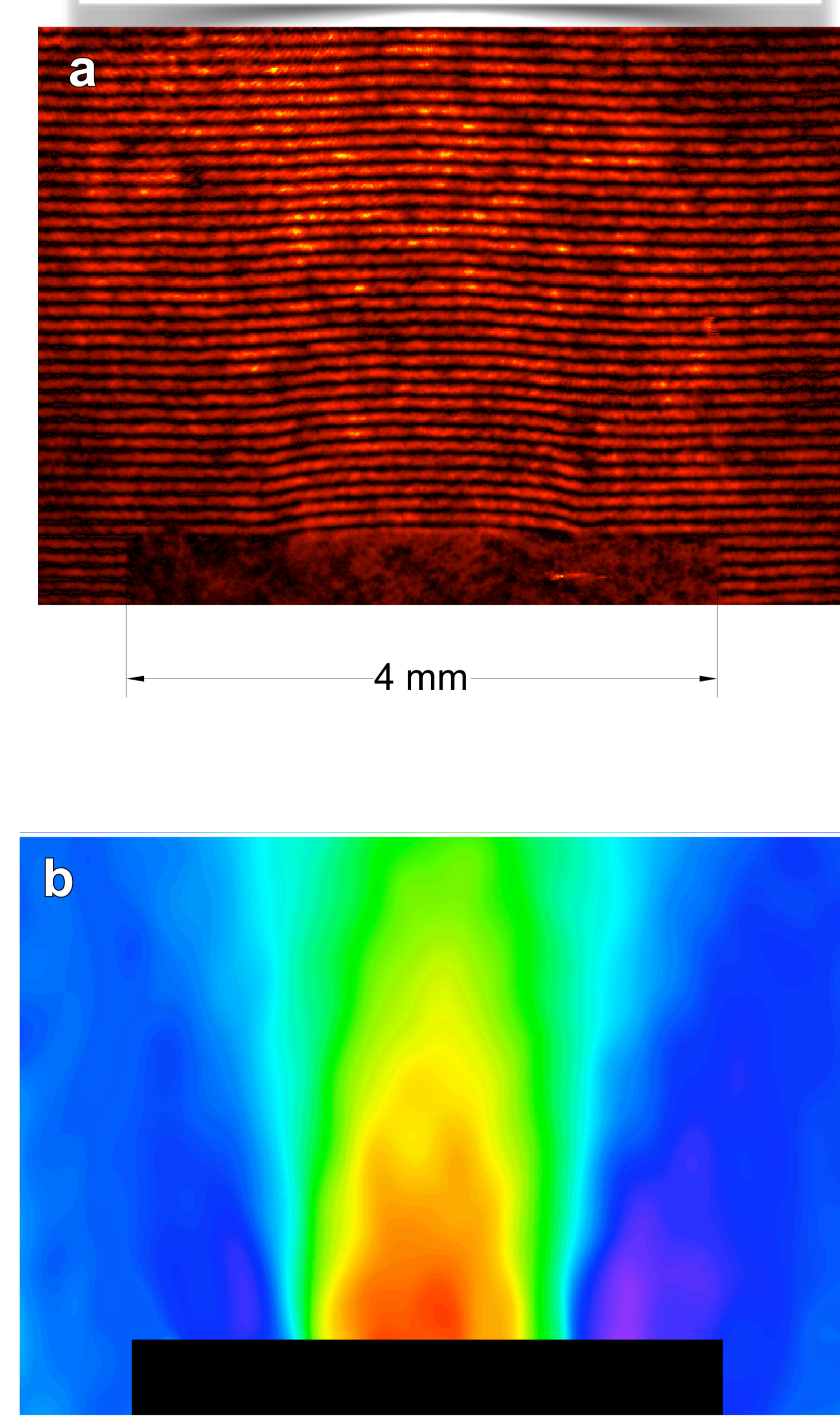

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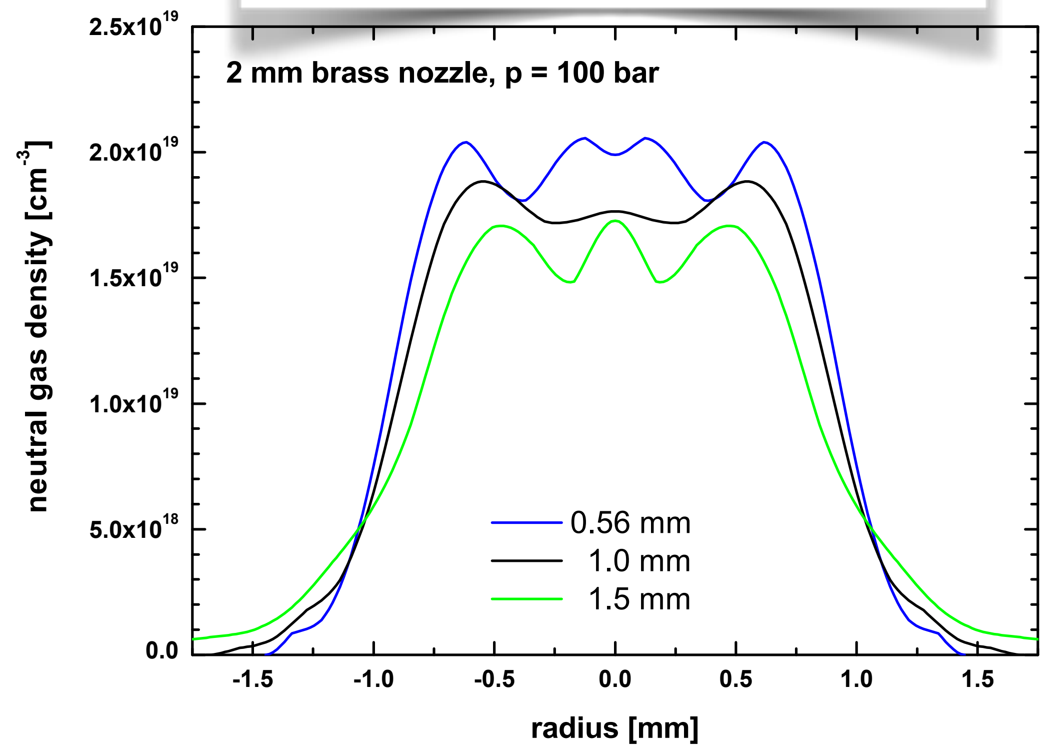
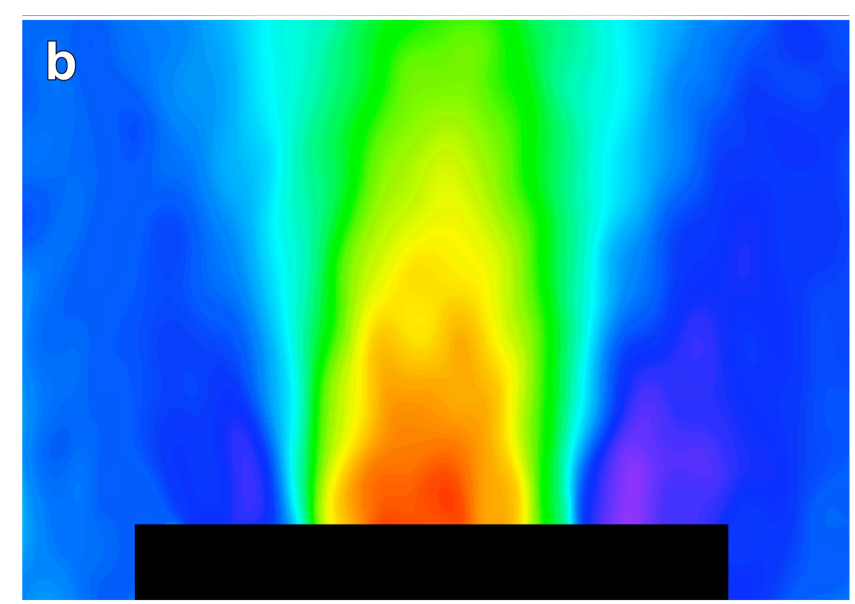
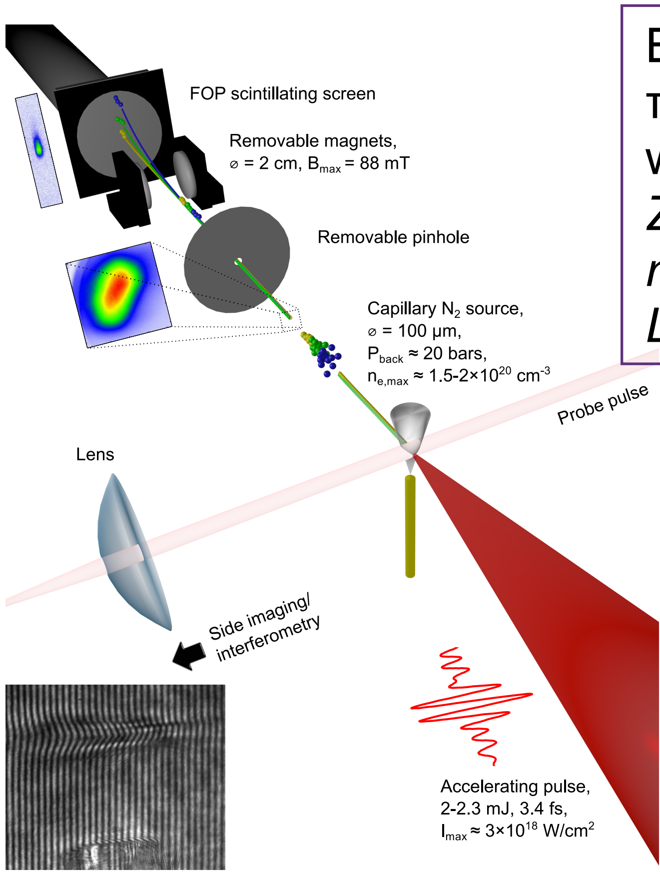




Gas jet: kHz laser-driven accelerator



E: 3 mJ
τ: 4 fs
w0: 2-3 μm
Z_R: ≈ 20-30 μm
n_e: ≈ 1-2 × 10^{20} cm-3
L_d: ≈ 10 - 30 μm

Thanks to: J. Faure (LOA, Ecole Polytechnique)

- Low pulse energy ⇒ tight focus, short length
- High rep-rate ⇒ small mass flow required
- Gas jet:
  - nozzle dia. < 100 μm
  - Sharp boundaries to avoid refraction

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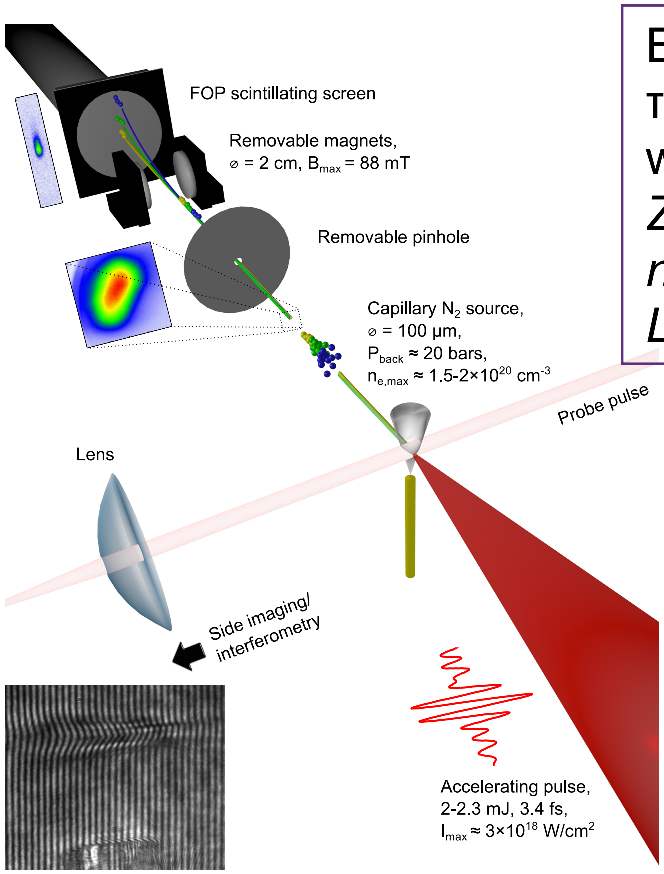

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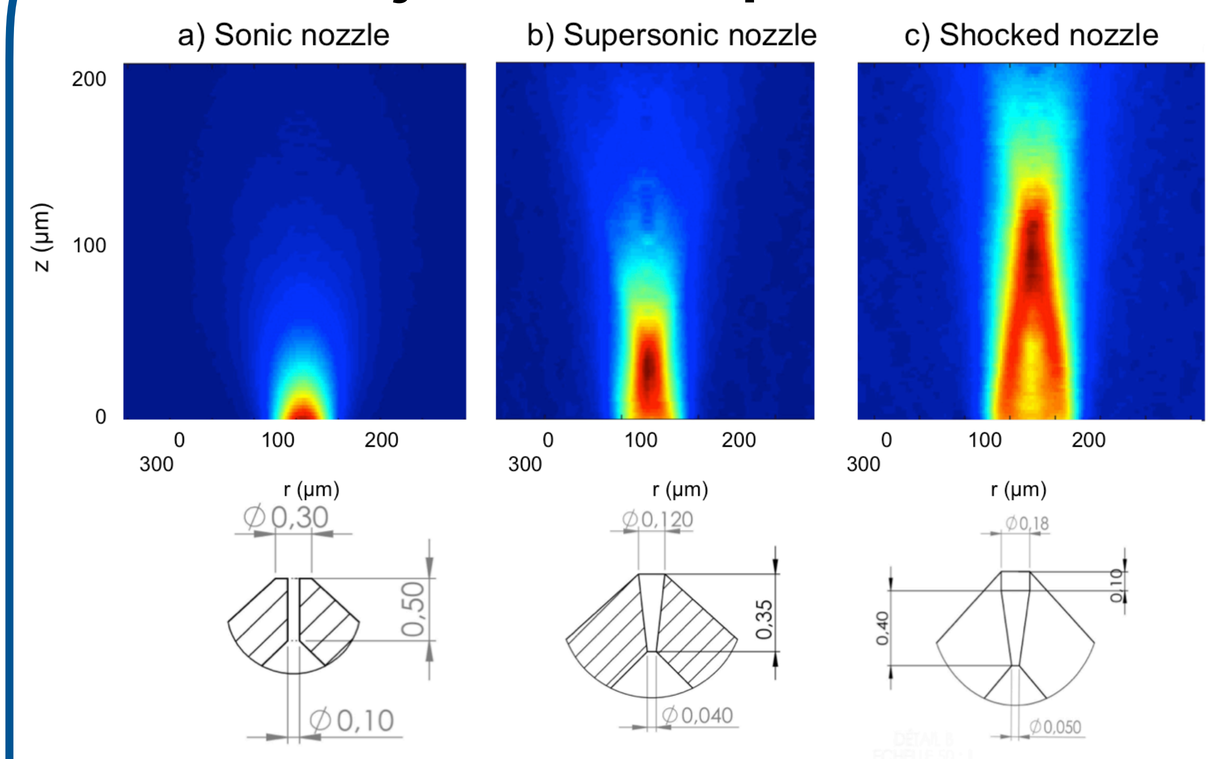
Gas jet nozzle optimization



- Sharper gradients
- Higher n_e above 100 µm (less nozzle damage)

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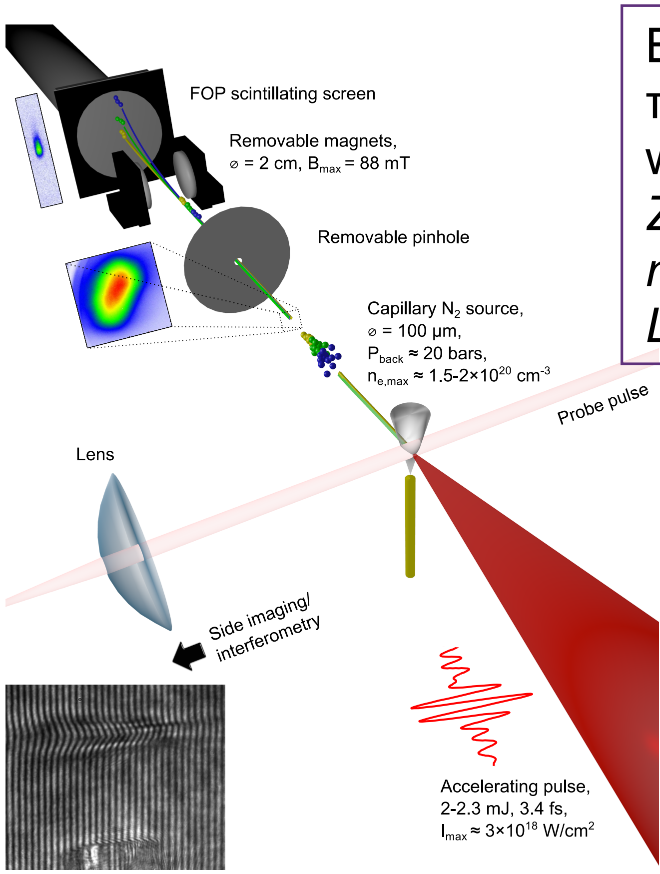

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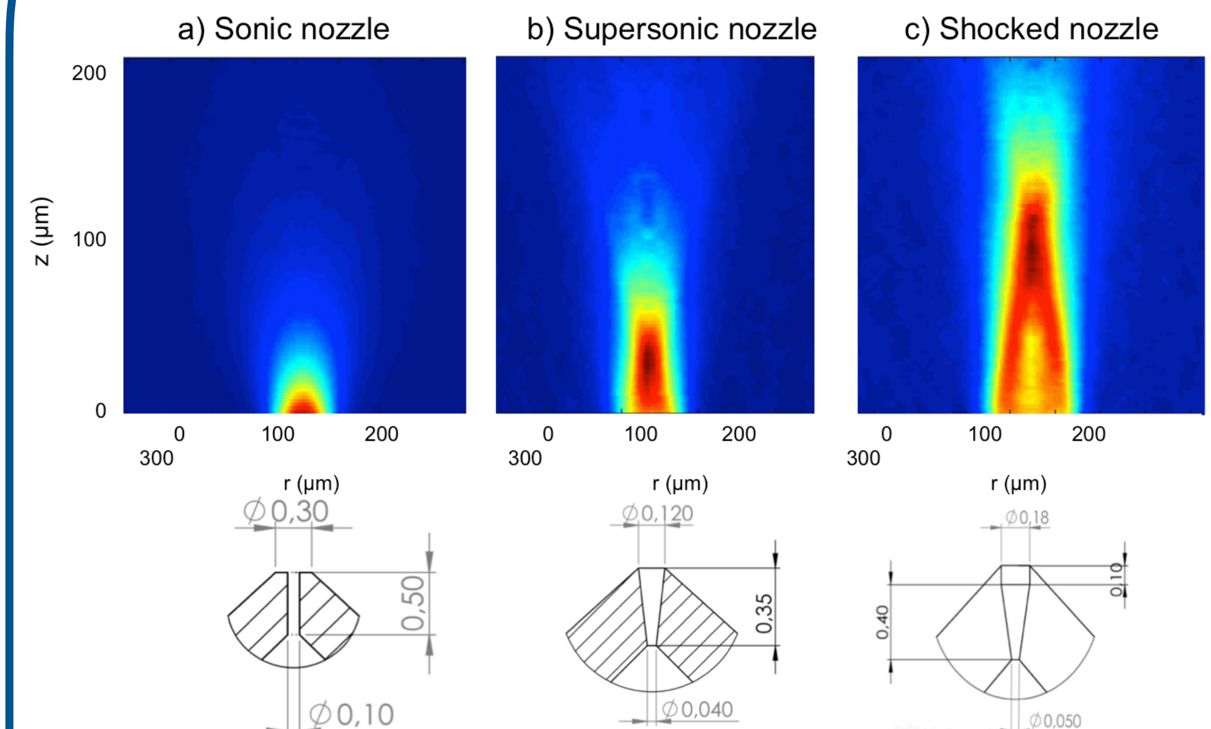
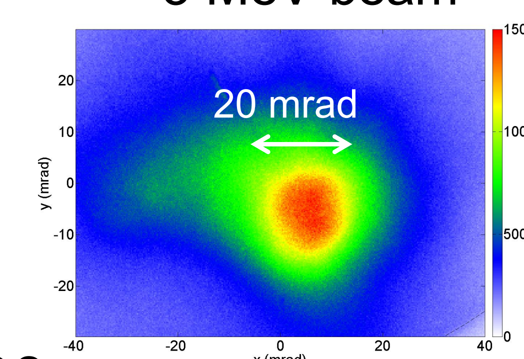


3 MeV beam

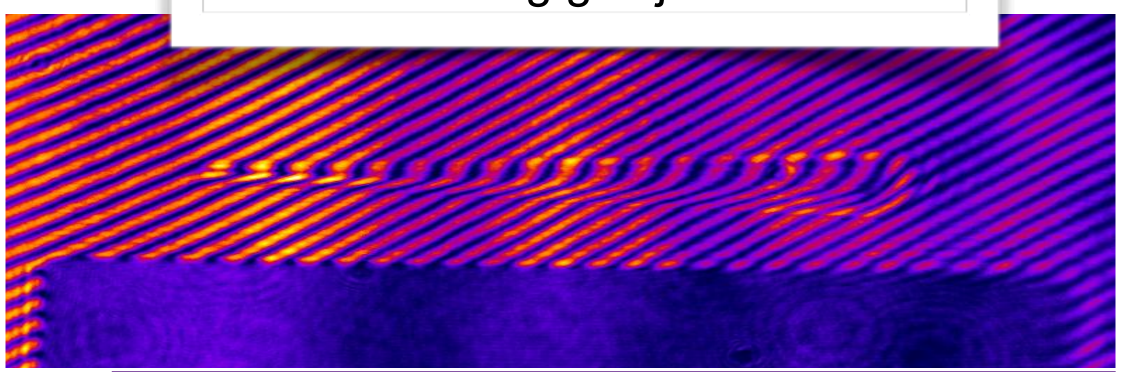


- Sharper gradients
- Higher n_e above 100 μm (less nozzle damage)
- Supersonic nozzle: 100 × charge & increased stability

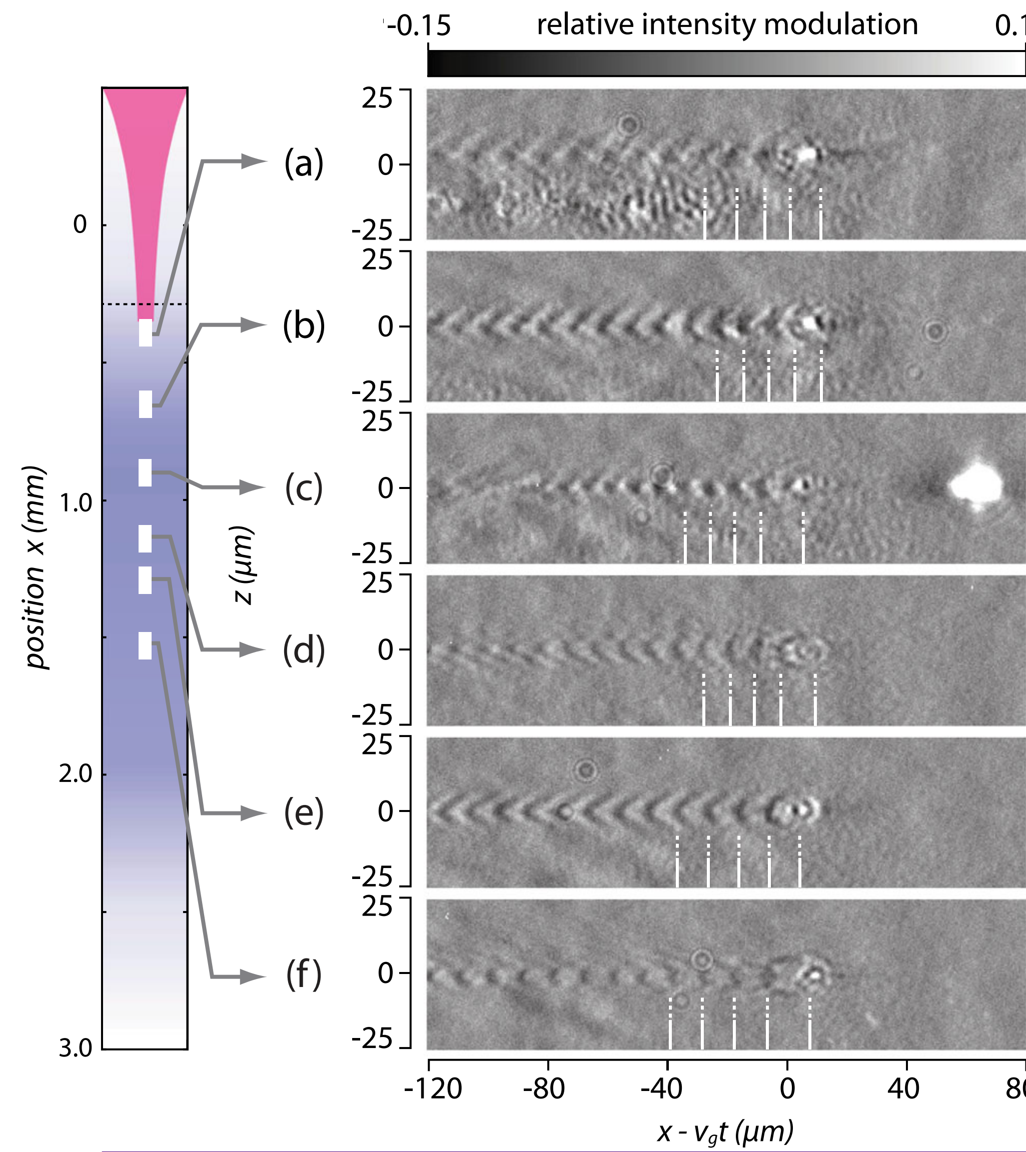
Gas jets give good diagnostic access

Thanks to Stuart Mangles, Imperial College London

On-shot interferogram of 10 mm long gas jet



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



Sävert *et al Phys. Rev. Lett.* ***115*** 055002 (2015)

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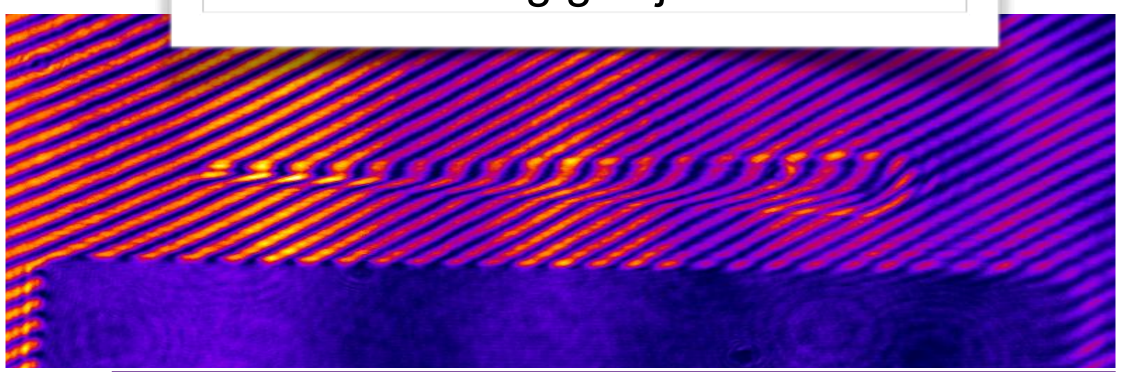
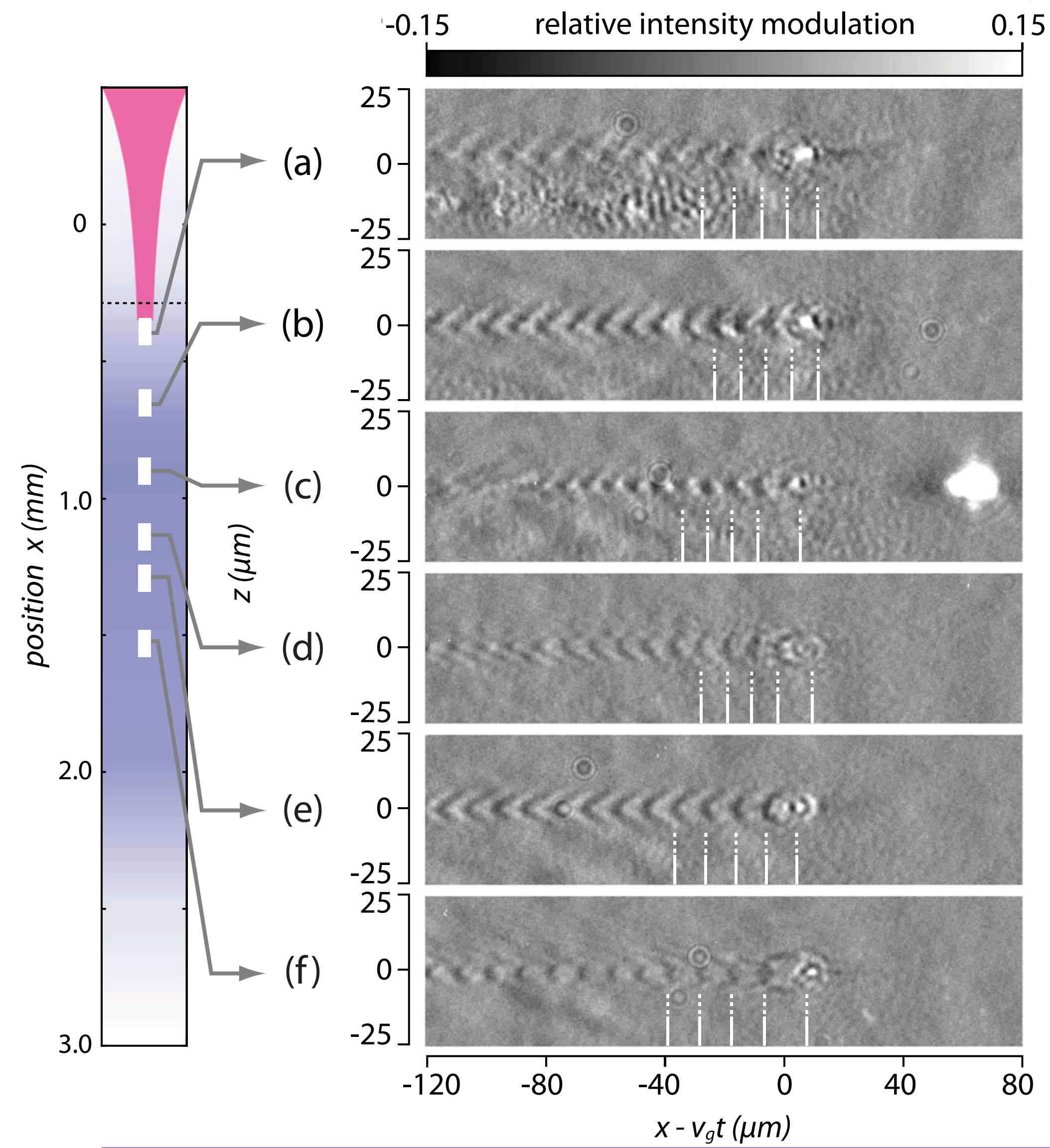


S. Kneip *et al Phys. Rev. Lett.* ***103*** 035002 (2009)

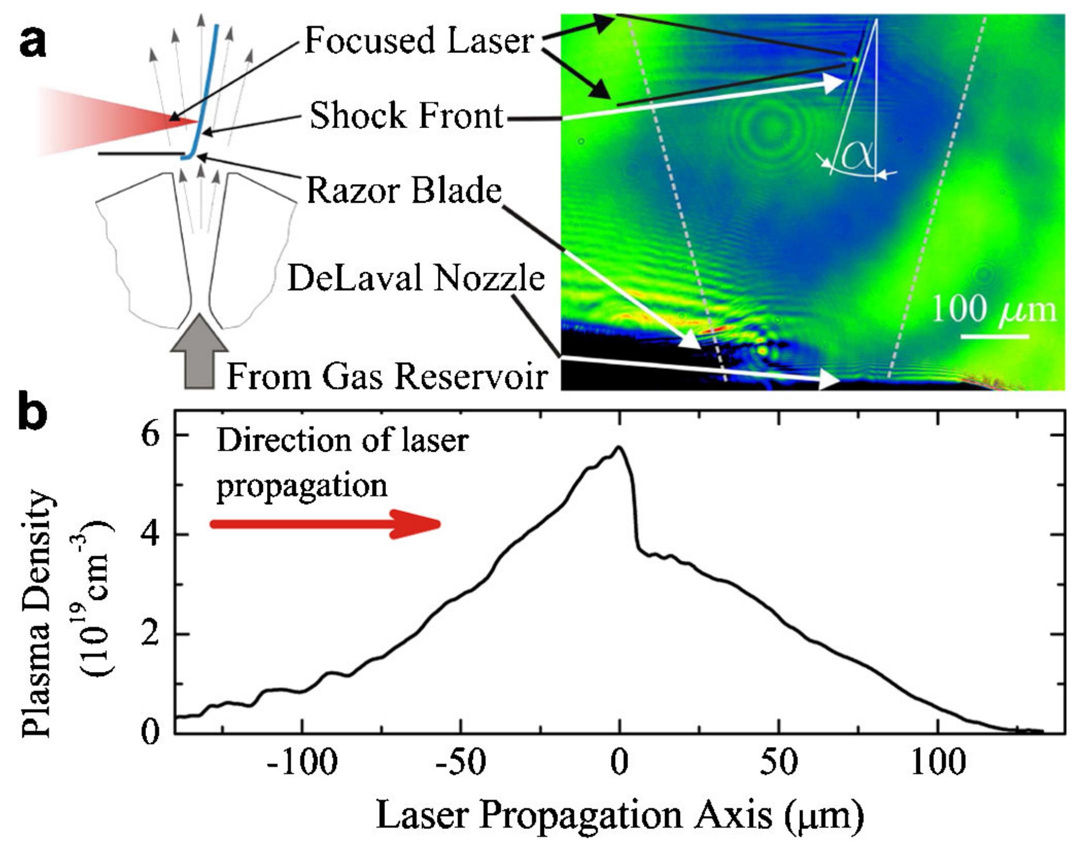
Few-fs shadowgraphy of a laser-driven wakefield

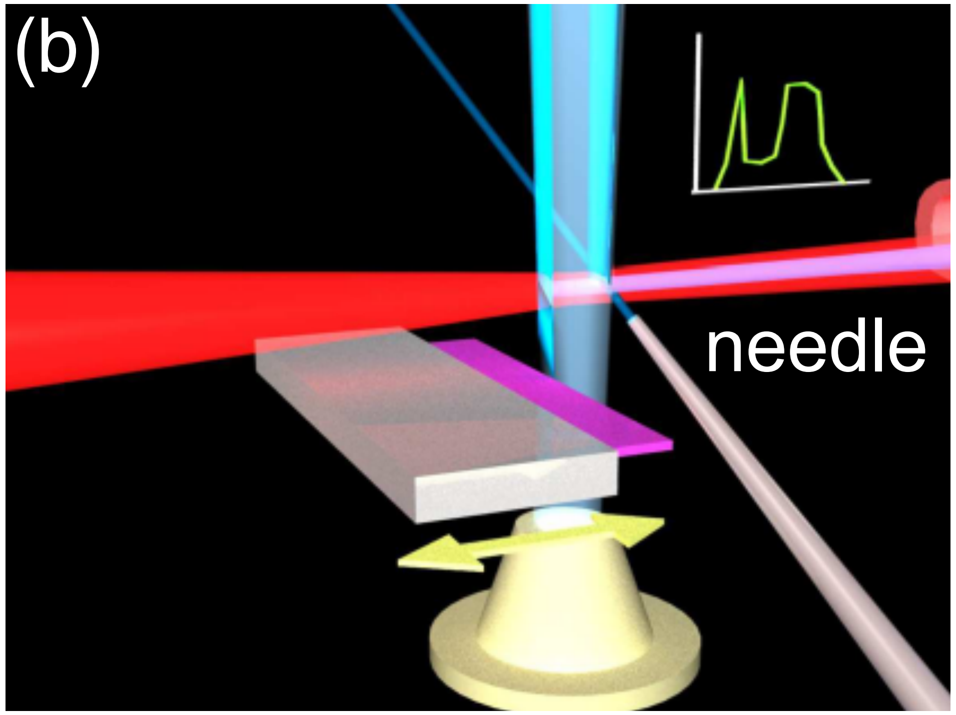


Sävert *et al Phys. Rev. Lett.* ***115*** 055002 (2015)

Gas jets: Control of longitudinal profile

- Control of longitudinal profile possible by introducing blades and/or additional gas sources:
  - K. Schmid *et al. PRSTAB* **13** 091301 (2010).
  - M. Hansson et al. *PRSTAB* **18** 071303 (2015).
  - C. Thaury *et al. Sci. Rep.* **1** 16310 (2015).
  - E. Guillaume *et al. PRL* **115** 155002 (2015).

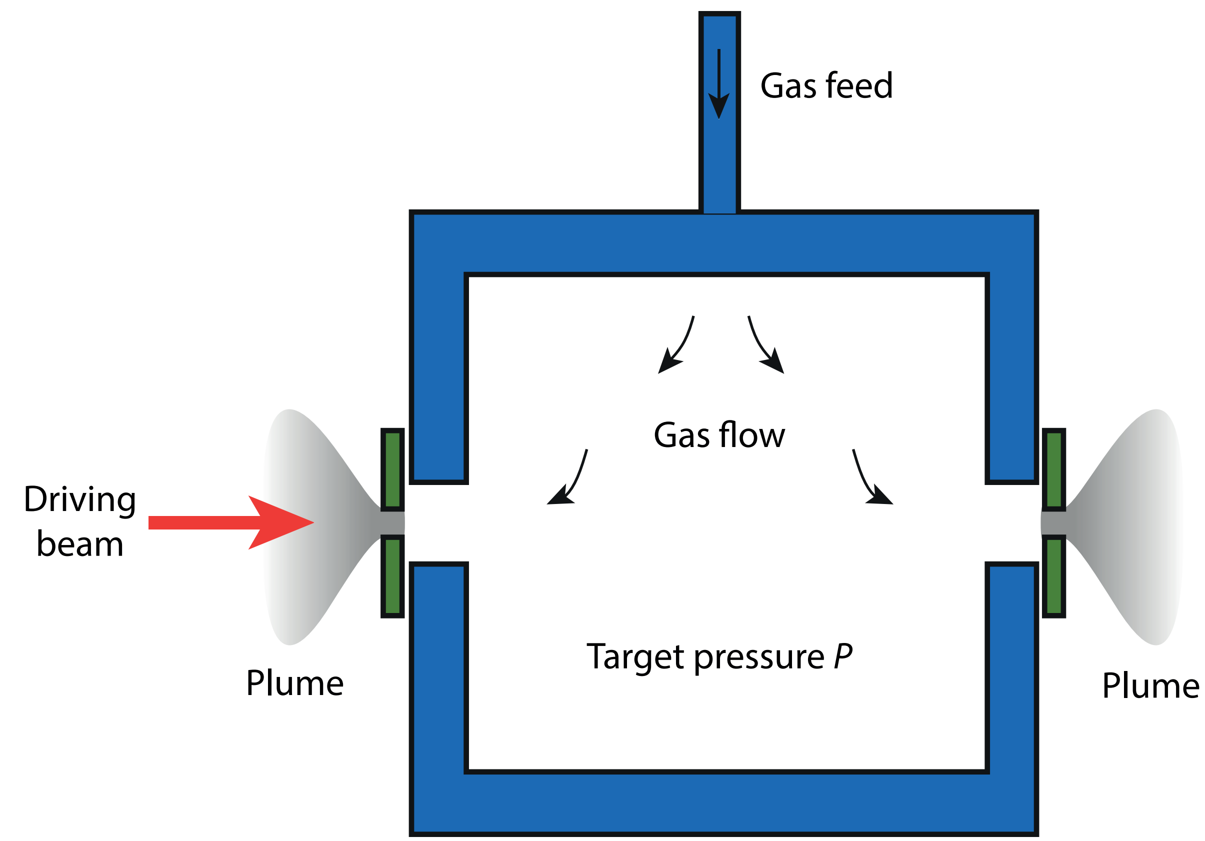




Gas cells

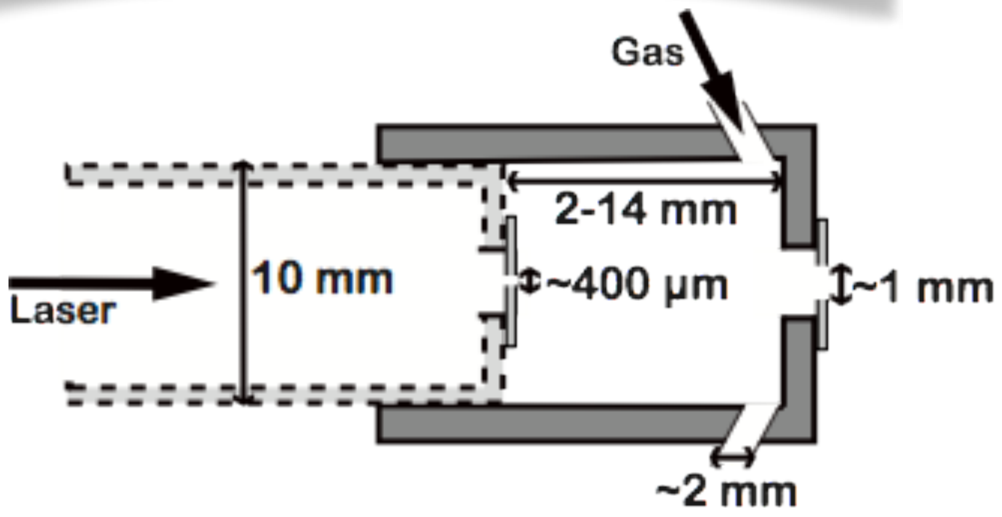
Gas cells

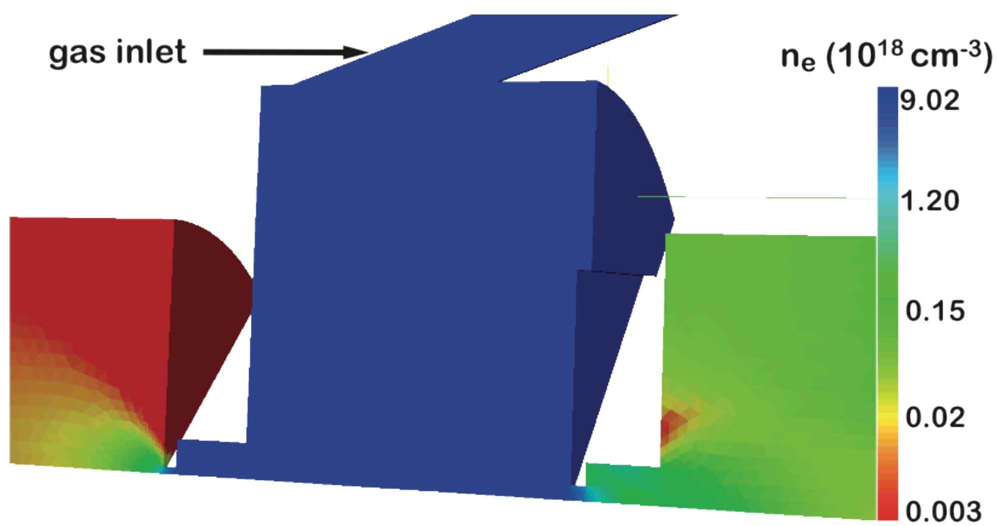
- Region of uniform neutral gas contained by differential pumping through coaxial pinholes
- Density fairly uniform between pinholes…
  - but plume of gas from front and back of cell
- Density easily adjusted by controlling gas flow
  - but erosion of pinholes will change density
- Several groups have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



Examples of gas cells

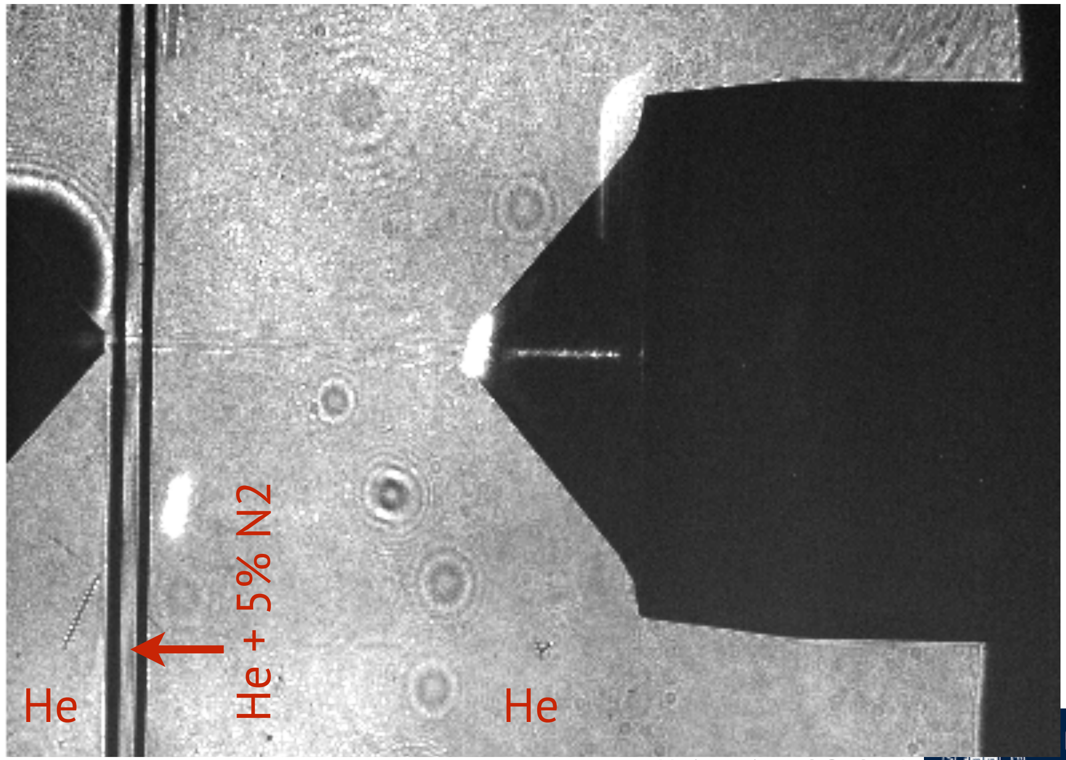
Thanks to: Stefan Karsch
Munich Centre for Advanced Photonics





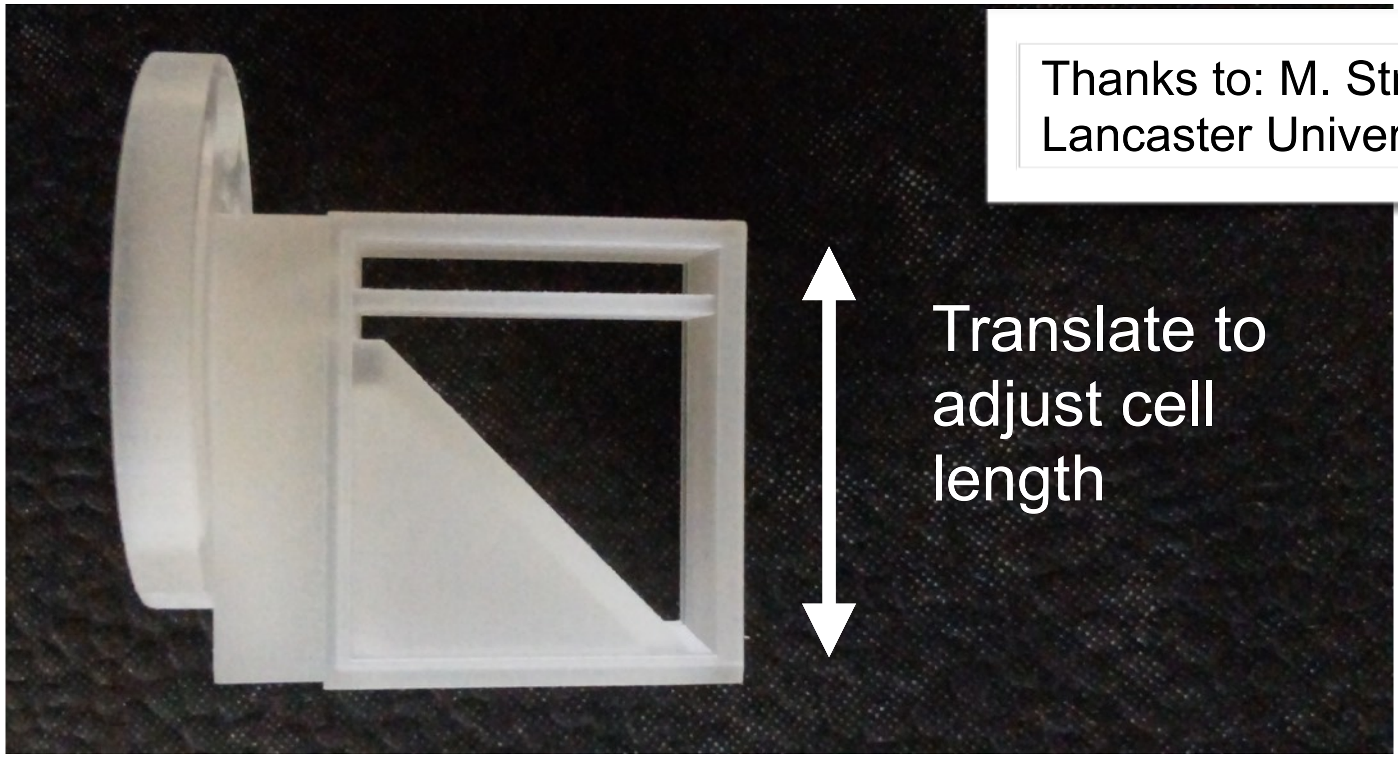
OpenFoam simulations show uniform density within cell & extent of plumes

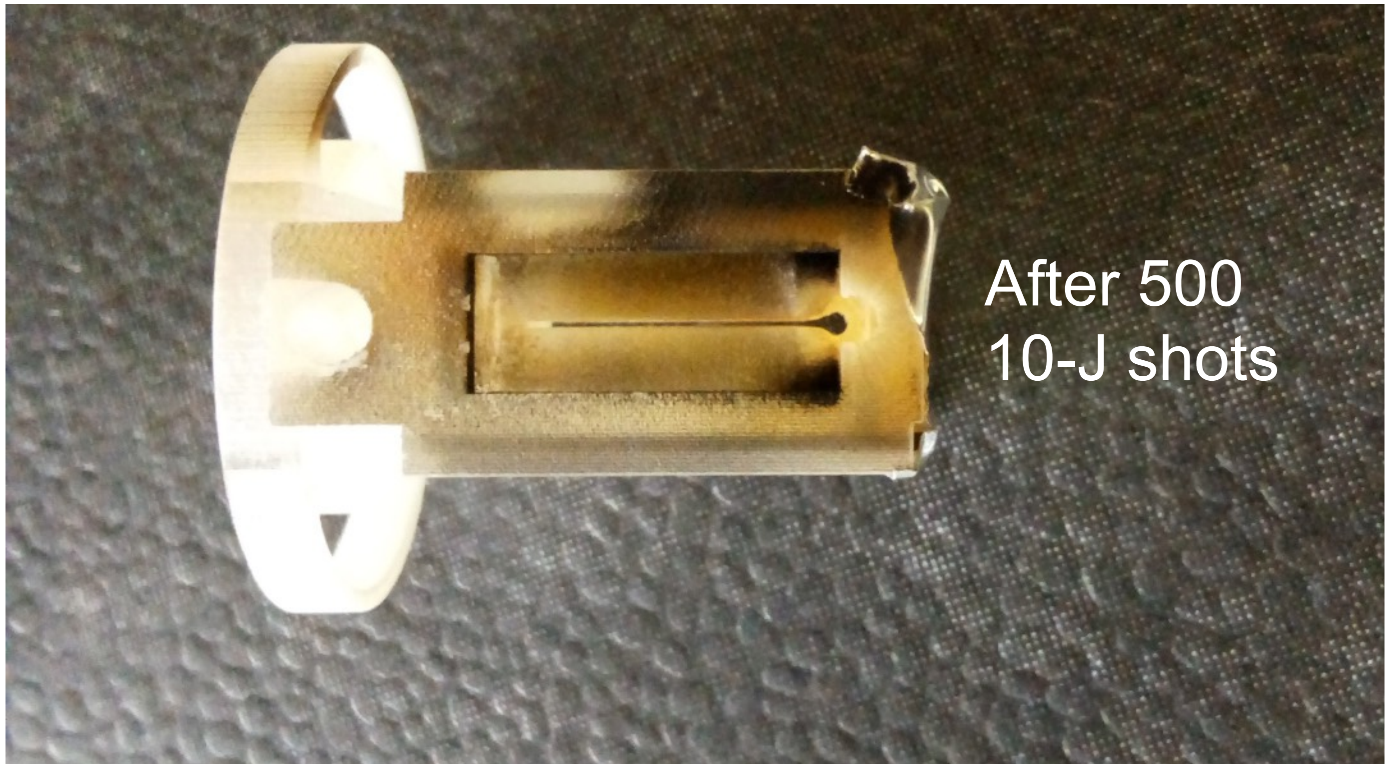
Thanks to: Zulfikar Najmudin
Imperial College, London, UK



Disposable gas cells

- Gas cell made by 3D printing

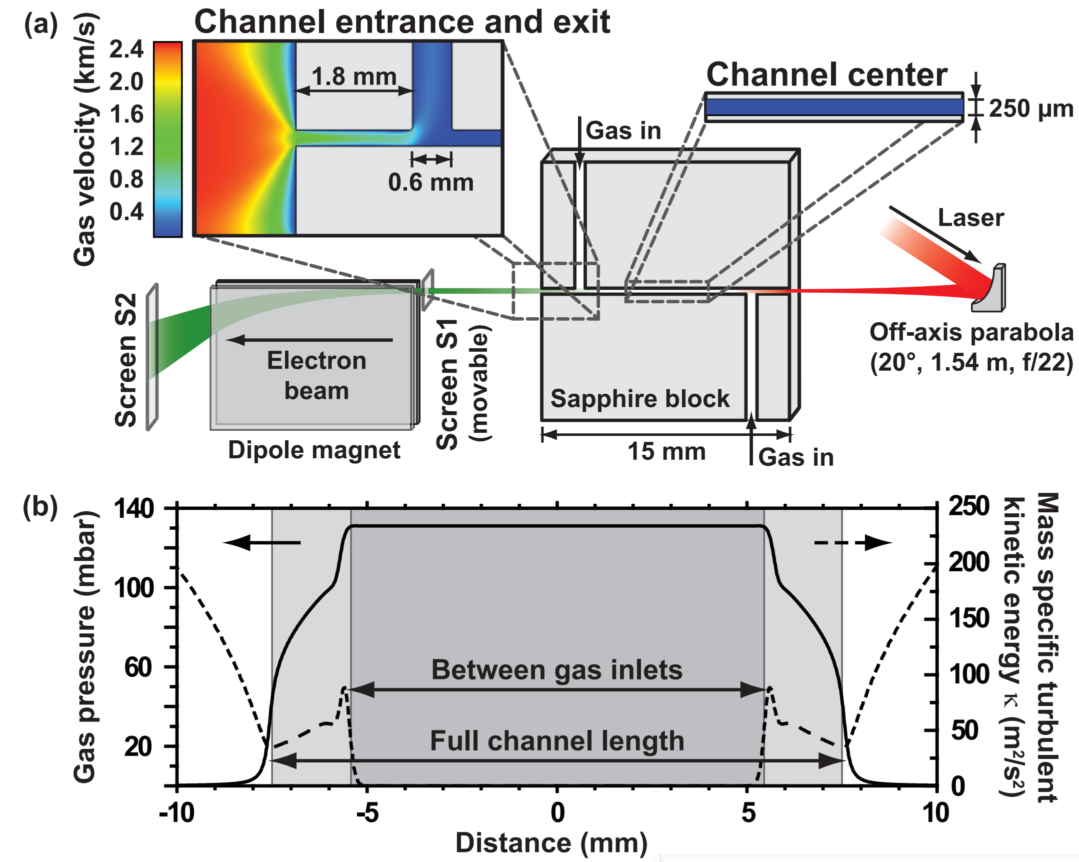




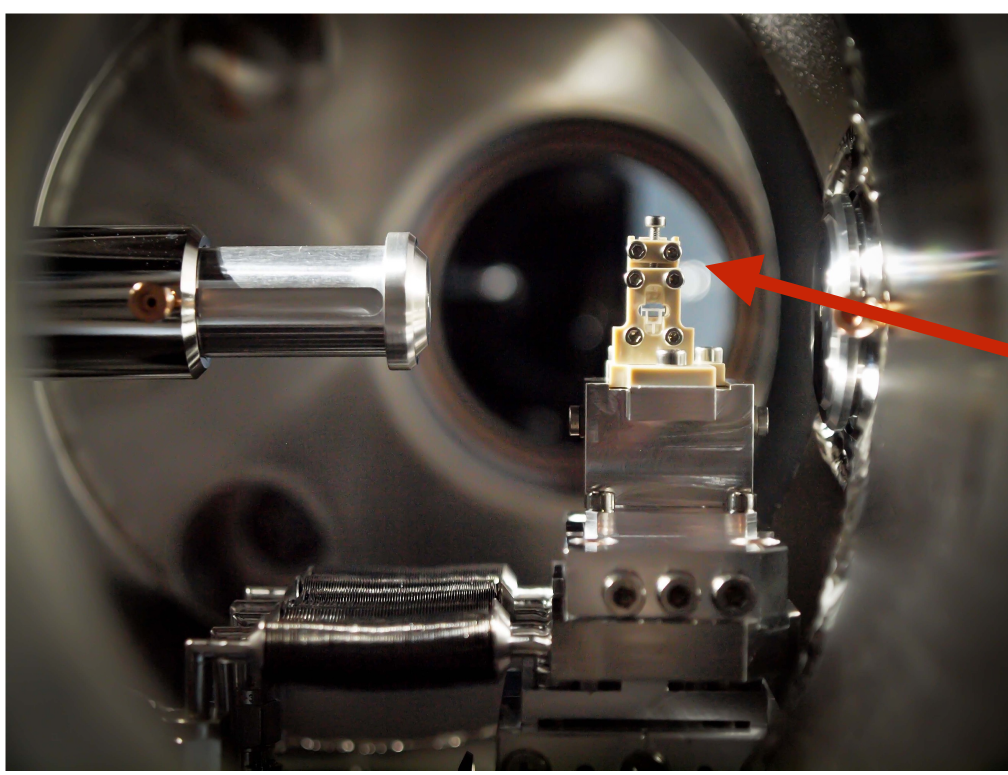
Capillary gas cells

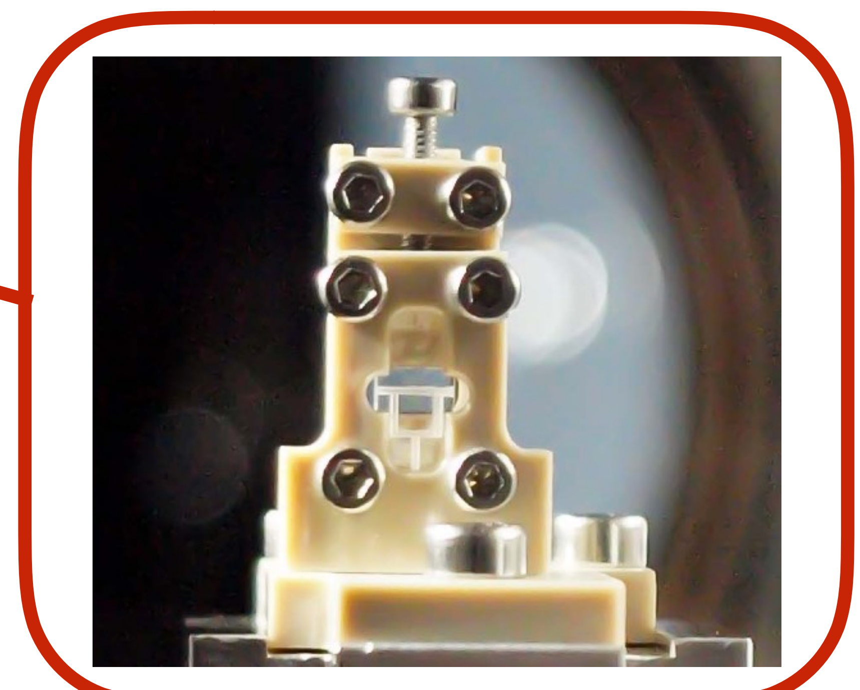
- Highly homogeneous region between gas slots
- No shocks or turbulence
- Reproducible when pulsed
- Low gas load at continuous flow
- Reduces turbulence caused by non-reproducible gas valve

J. Osterhoff *et al.* *PRL* **101** 085002 (2008)



Thanks to: Andi Maier, DESY

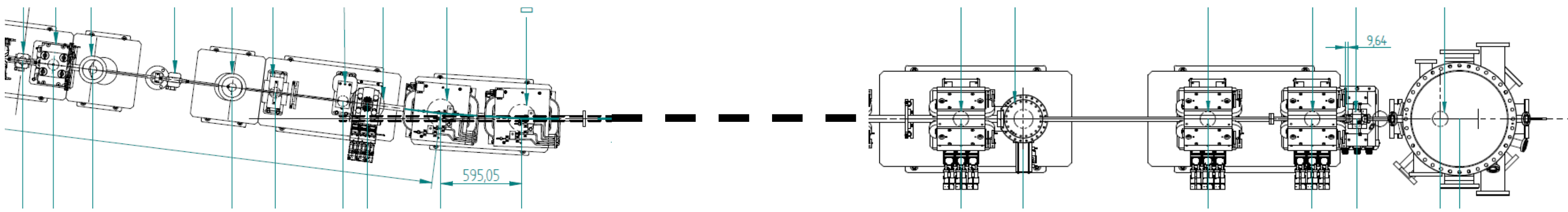




LUX Plasma Target, lux.cfel.de
Image credit: Niels Delbos (Hamburg University)

A gas cell for a beam-driven accelerator

Thanks to: J. Osterhoff & L. Schaper, DESY



FLASHForward▸▸ experiment

Design requirements:

- No emittance spoilers
- Full transverse (optical) probing
- Supporting multiple injection scenarios
- Easily replaceable (8h)
  - Limited access to FLASH2 tunnel
  - No contamination of FLASH vacuum
- Plasma density
  - Acceleration: up to 5 x 10^{17} cm^{-3}
  - Injection: up to 5 x 10^{18} cm^{-3}

John Adams Institute for Accelerator Science

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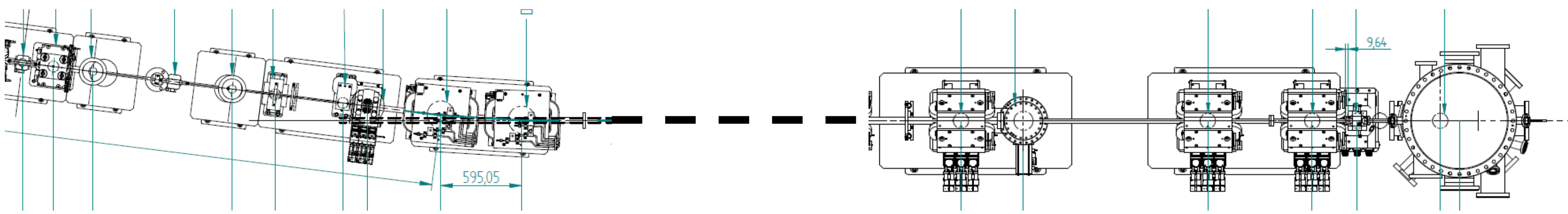
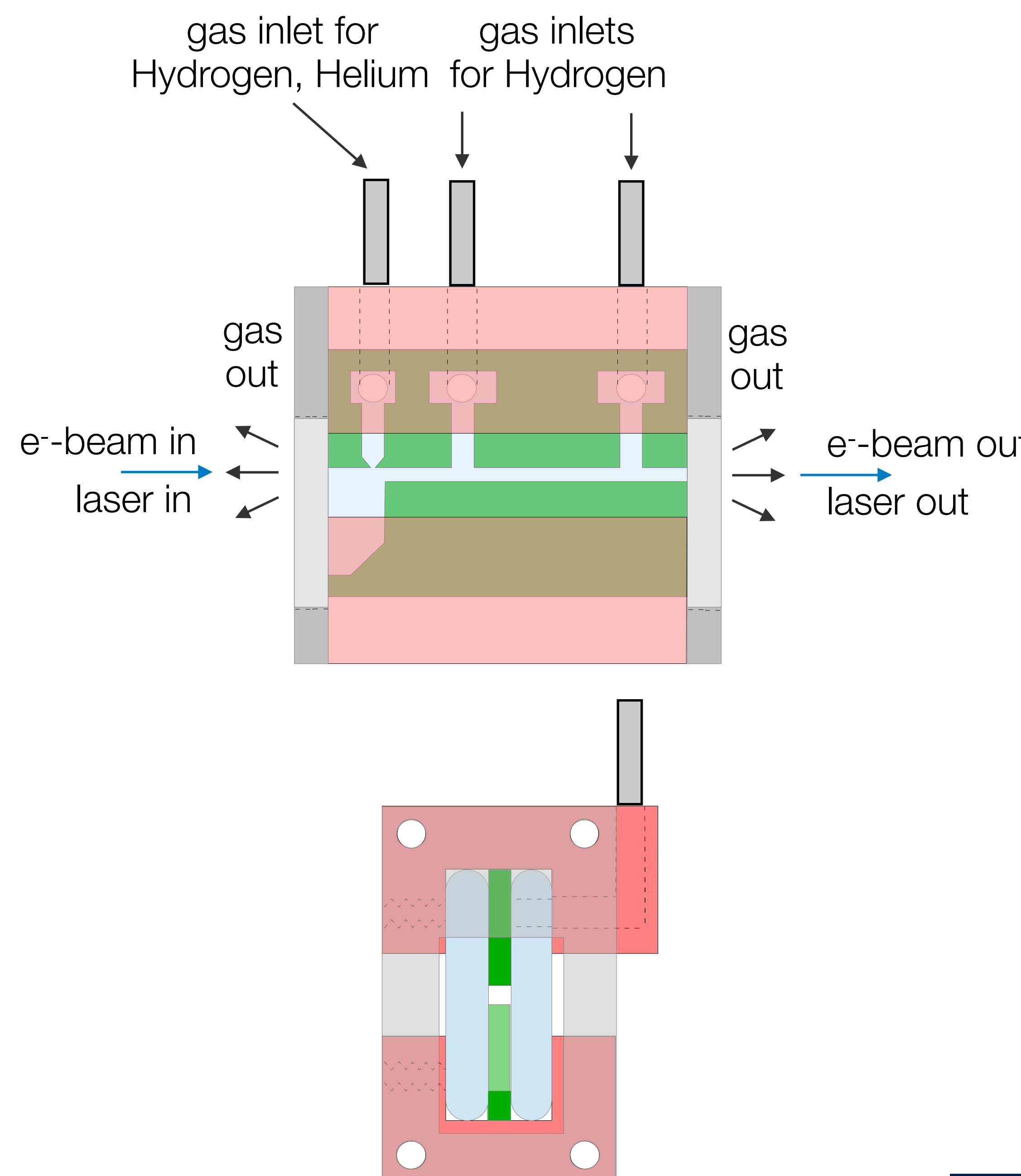


FLASHForward▸▸ experiment

Target concept:

- Laser ionized
- Gas filling
  - Separate pressure control
  - Multiple species operation
  - Localised density peak and downramp possible
- Continuous gas flow design
  - No windows required
  - Compatible with FLASH vacuum standards
- Transverse access



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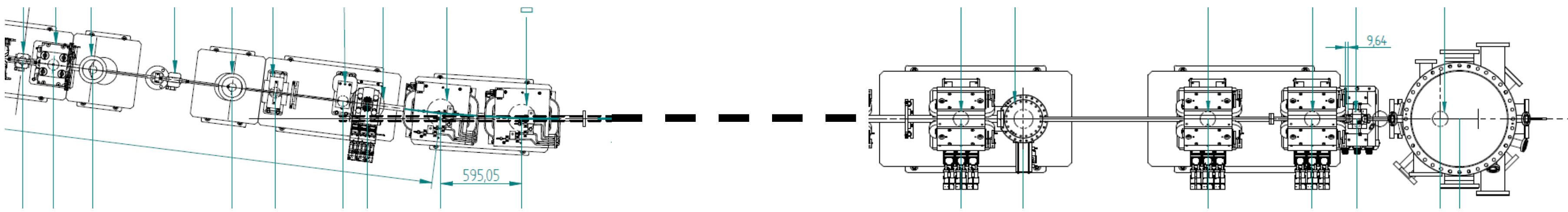

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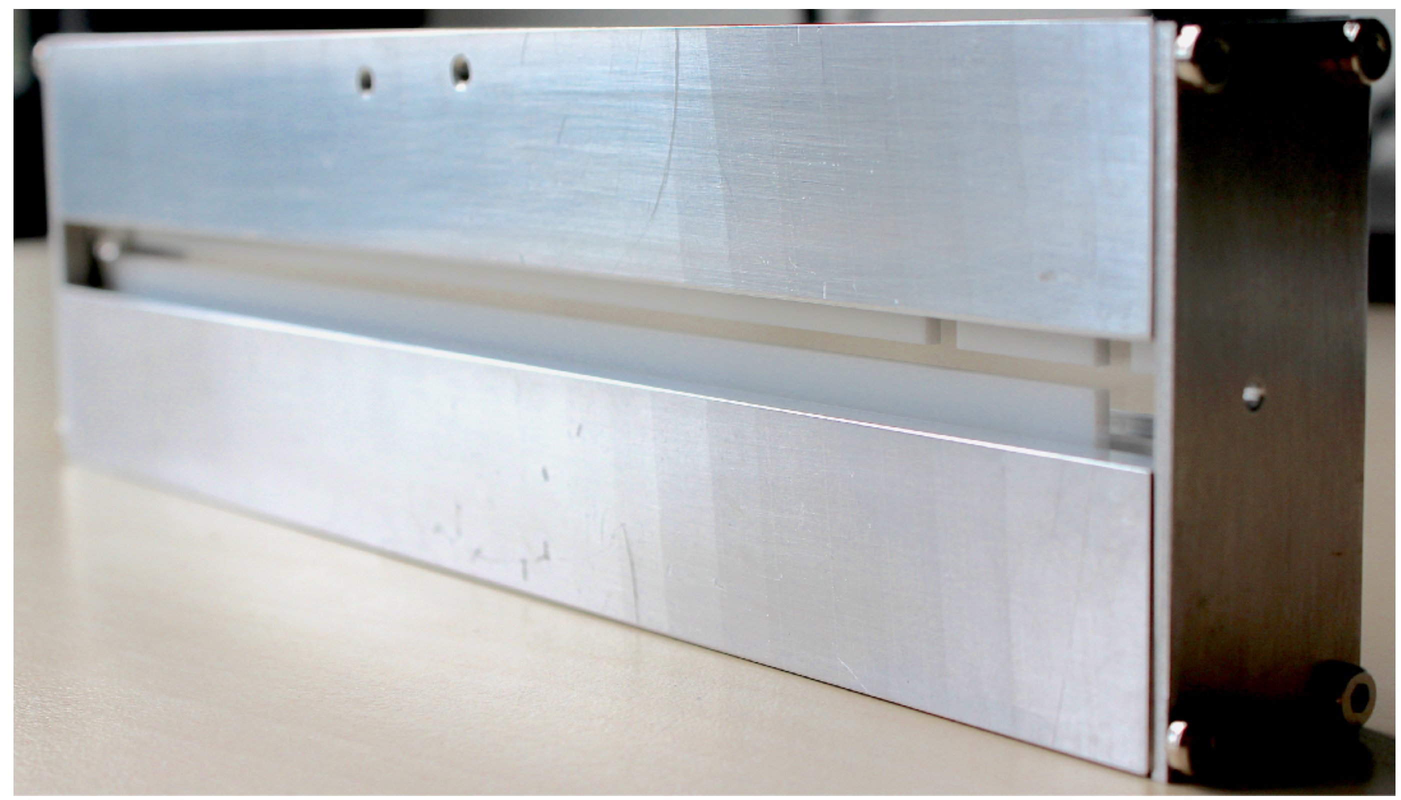

Gas removal

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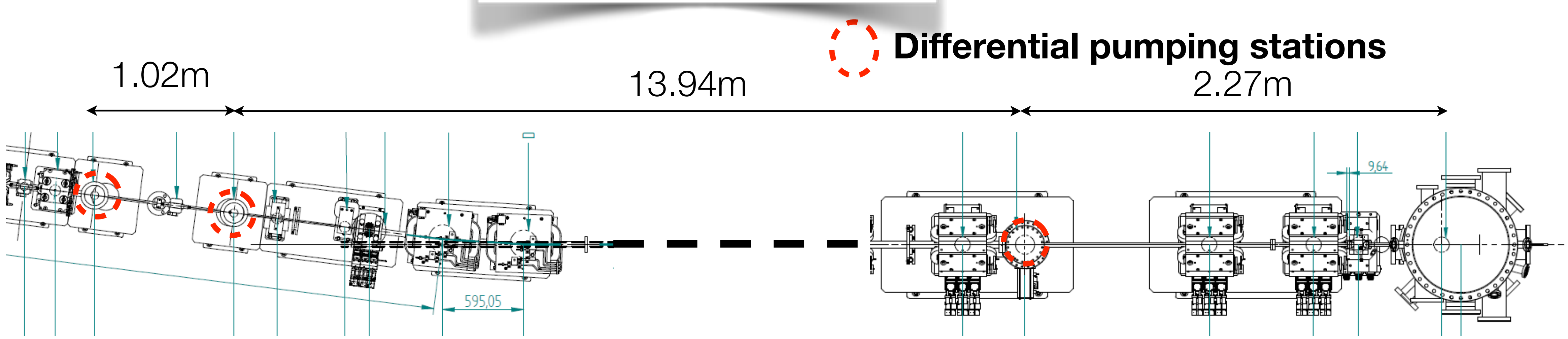
Thanks to: J. Osterhoff & L. Schaper, DESY



- Maximum continuous gas flow of **20 mbar l/s** hydrogen into main chamber
  - at beamline intersection to FLASH2 pressure has to be **< 10-8 mbar**
  - additionally to main chamber 3 differential pumping sections in beam-line
  - efficient for pumping: small diameter pipes,
    bending magnet

Pumping speeds required:

- Experimental chamber:
  - 2500 l/s turbo pump, 450 m3/h backing pump
- First stage:
  - 600 l/s turbo pump, 35m3/h backing pump
- Second stage:
  - 600 l/s turbo pump, 35m3/h backing pump
- Third stage:
  - 450 l/s turbo backed by 300l/s turbo, 35m3/h backing pump

Heat-pipe ovens & similar

Heat-pipe ovens

Many <u>beam-driven</u> plasma accelerators require:

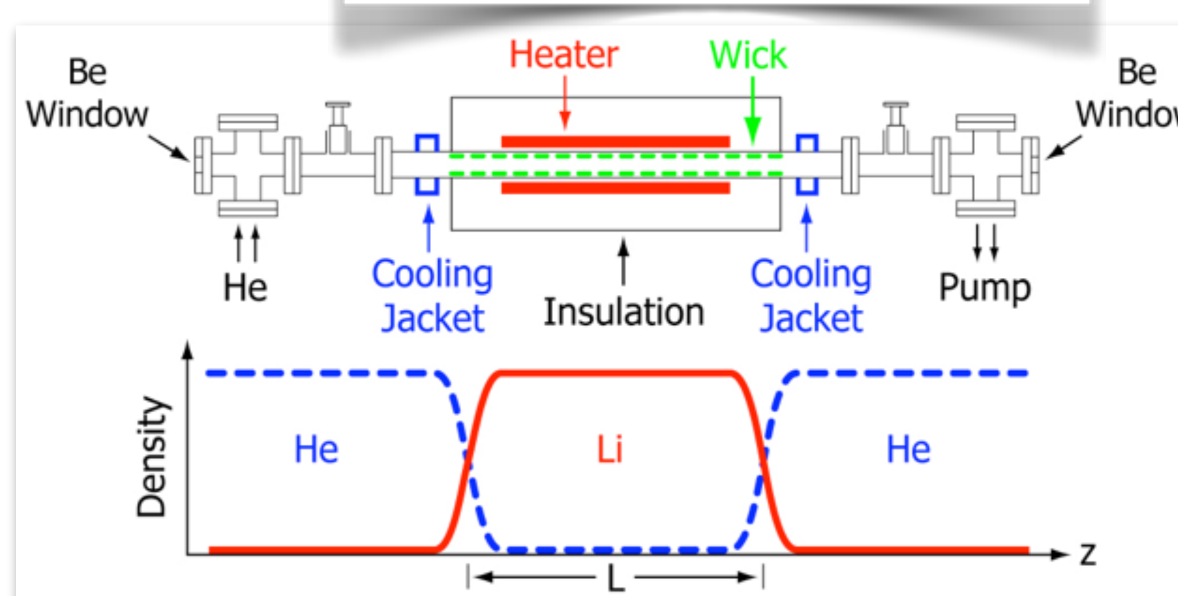
- Long targets (metre scale)
- Relatively low density $n_e = 10^{14}$ - 10^{16} cm^{-3}
- Ionizable by drive beam or a laser pulse (⇒ low-Z target)
- Minimize ionization by collisions with driver (⇒ low-Z target)
- In some cases, high uniformity

FACET Experiments Use Meter Scale Plasmas: Laser or Beam Field Ionization, Alkali Metal Vapour or Hydrogen Gas

Thanks to Mark Hogan, FACET

Lithium or Rubidium Vapor Produced in a Heat Pipe Oven:

- Scalable over wide range in density & length:
  - $n_0 = 10^{14}$-10^{17} e^-/cm^3, L = 20-200 cm
- 'Easy' first ionization:
  - e.g. Li 5.4 eV lessens ionization laser requirements
- Developed in collaboration with UCLA, used in most acceleration experiments since 1998

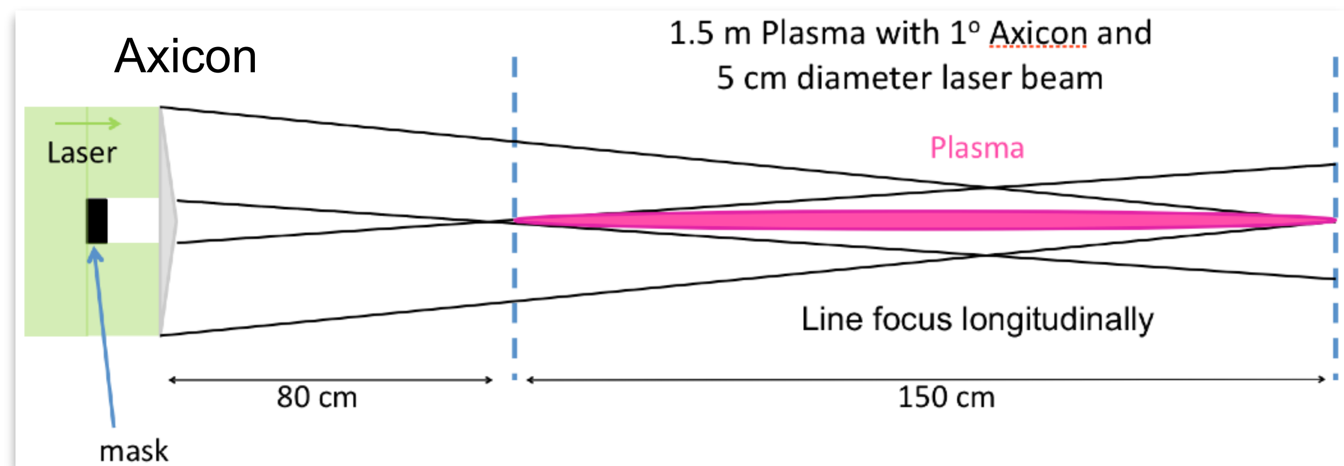


Enabled Many Advances in PWFA Physics:

- 42 GeV E-gain in one meter – ***Nature 2007***
- High efficiency acceleration – ***Nature 2014***
- Multi-GeV e^+ PWFA – ***Nature 2015***
- Hollow Channel e^+ PWFA – ***Nature Communications 2016***
- Wakefield Mapping – ***Nature Communications 2016***
- Ionization Injection – ***PRL 2014***

Hydrogen Gas Cells:

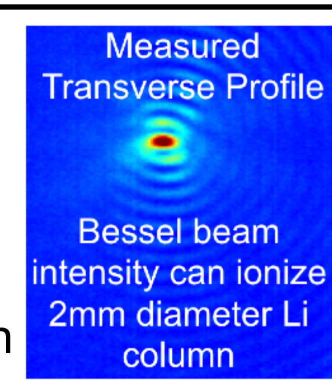
- Flexible optical access for probe pulses and injection laser pulses (e.g. Trojan Horse injection, *in preparation for publication 2017*)

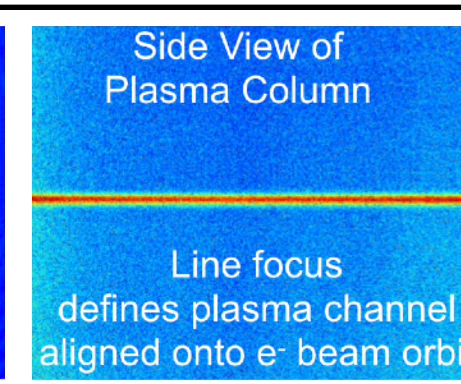


Ionization:

- Possible with beam fields directly for single compressed e- beams
- Pre-ionization laser pulse gives additional flexibility
- Specialized optics for uniform (Axicon) or hollow channel plasmas (Spiral Phase Grating)

Axicon optic provides transversely uniform extended line focus for long, uniform plasmas for electron acceleration



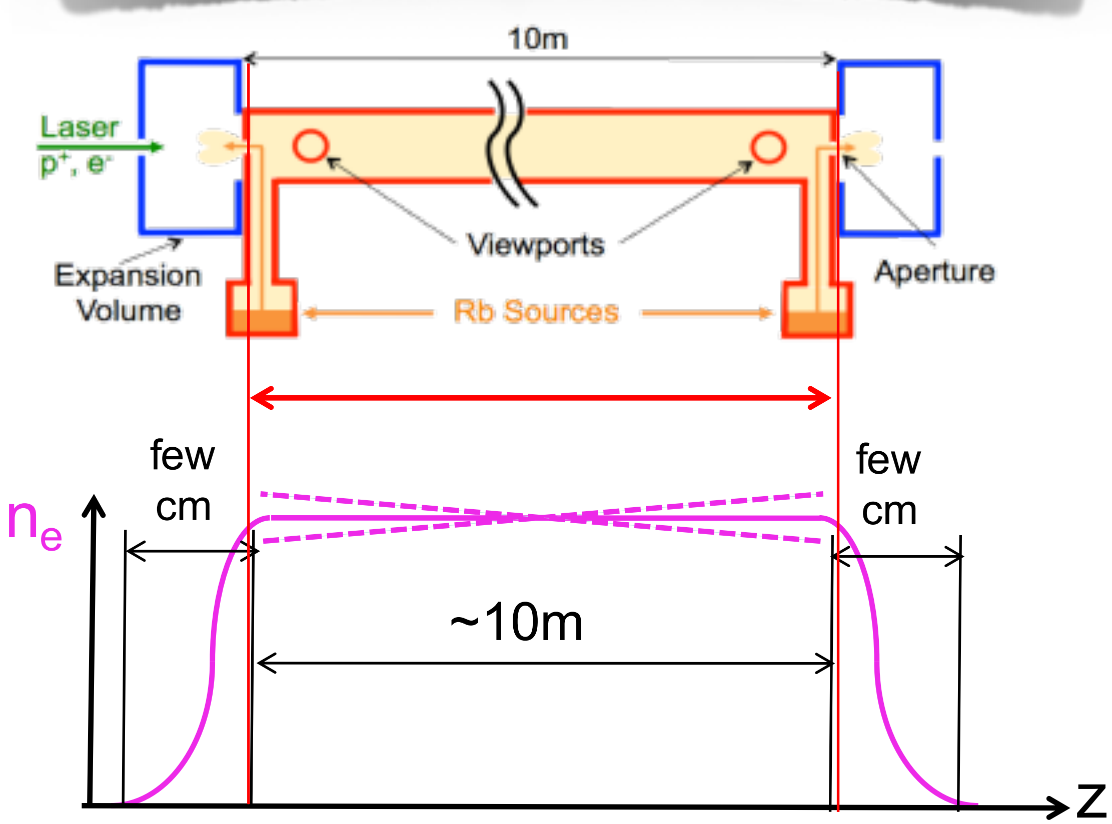


AWAKE plasma source

Thanks to: P. Muggli (MPP), E. Oz (MPP), F. Batsch (MPP), F. Braunmuller (MPP), R. Kersevan (CERN), G. Plyushchev (CERN/MPP/EPFL), J. Moody, M. Huether, MPP, V. Fedosseev, F. Friebel, CERN

Source requirements

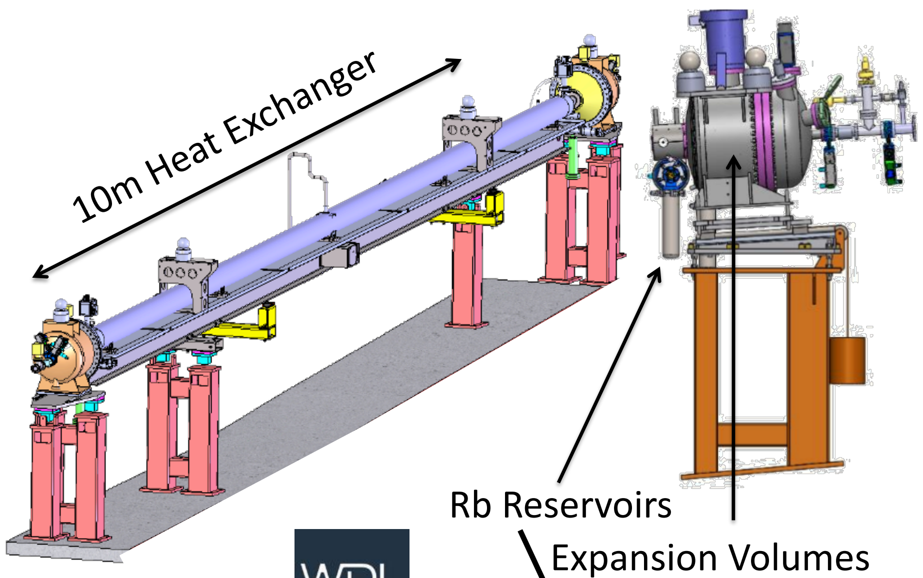
- $10^{14} \lesssim n_e \lesssim 10^{15}$ cm^{-3} ($k_p\sigma_r \approx 1$)
- $\Delta n_e < 0.2\%$ (SSM & acceleration)
- Length several metres
- Few cm ramp (electron trapping)
- Seed for self-modulation



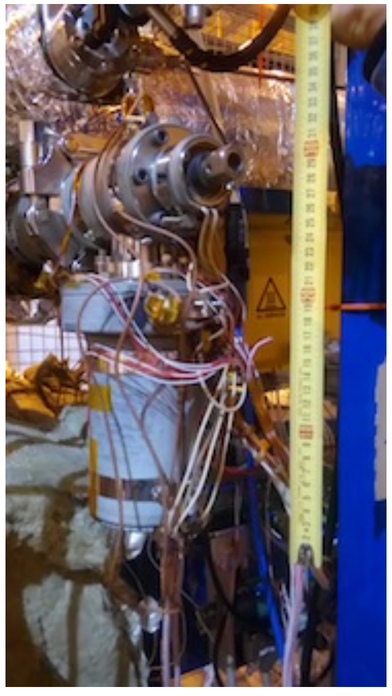
Rb vapour source (not heat-pipe oven)

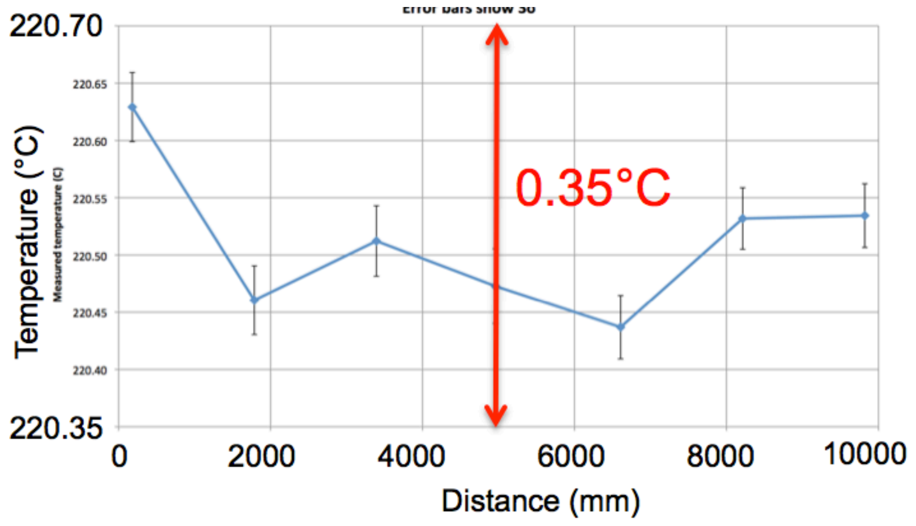
- $n_e = n_{Rb}$
- Laser ionized
  - EI = 4.177 eV
  - $I_{th} = 1.7 \times 10^{12}$ W cm^{-2}
- Impose very uniform T
  - $\delta n_{Rb} / n_{Rb} = \delta T / T < 0.2\%$
- 160 °C $\lesssim T \lesssim$ 220 °C for $10^{14} \lesssim n_{Rb} \lesssim 10^{15}$ cm^{-3}
- Control Rb gradient with Rb source temp
- Short scale length: heat-pipe design
- n_{Rb} measured at each end by white light interferometry

AWAKE plasma source



WDL





Rb vapour source

- $(\delta T / T)_{meas} < 0.1\%$

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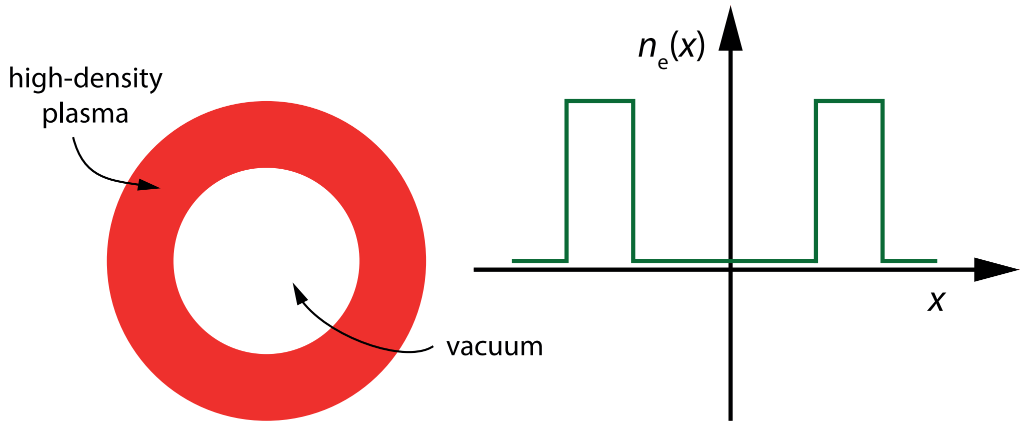
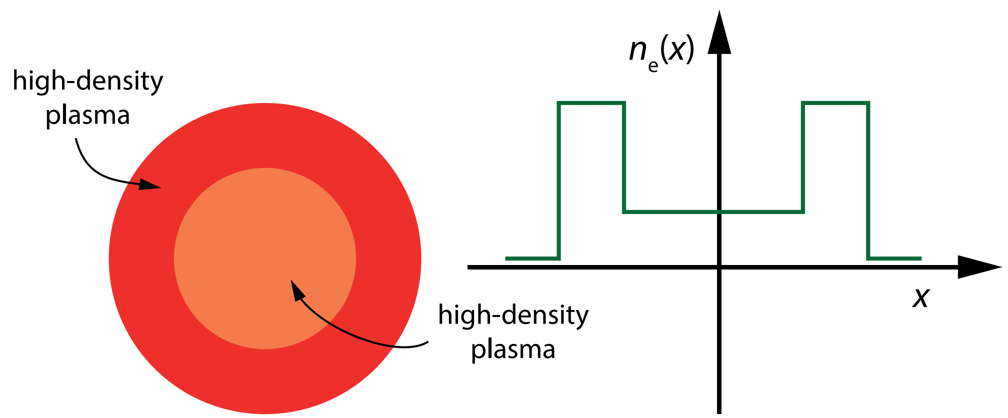
UNIVERSITY OF OXFORD

Plasma sources with controlled transverse profile

Why is control of transverse profile important?

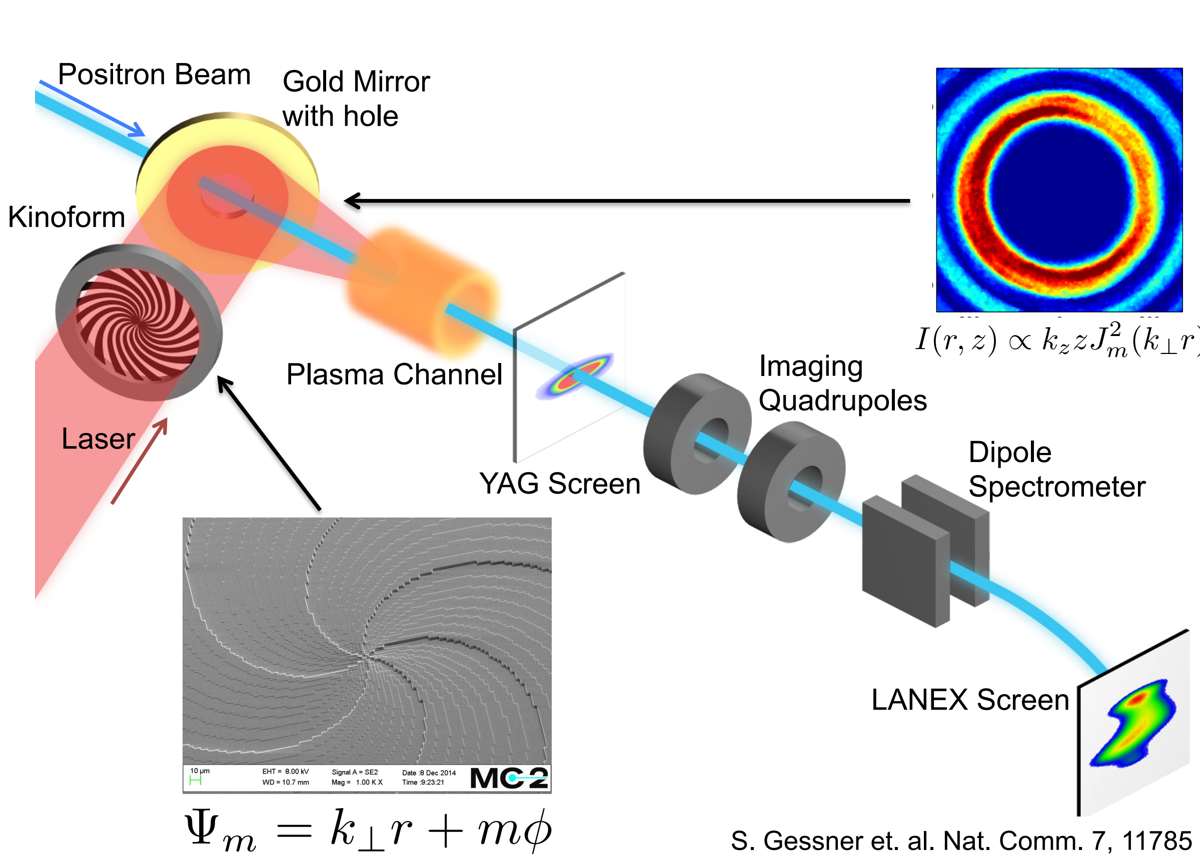
- For LWFA, guiding of the drive pulse
- Transverse variation of n_e:
  - Causes phase differences between on- and off-axis wake oscillations
  - Affects relation between accelerating and focusing phases
  - N. E. Andreev *et al. PoP* **4** 1145 (1997)
- Hollow plasma channels
  - Have uniform acceleration gradients, independent of transverse profile of driver
  - Weak, linear focusing forces
  - T. C. Chiou & T. Katsouleas *PRL* **81** 3411 (1998)
  - C. B. Schroeder *et al. PRL* **82** 1177 (1999)
- Near-hollow channels
  - Independent control of focusing & accelerating forces
  - C. B. Schroeder *et al. PoP* **20** 080701 (2013).



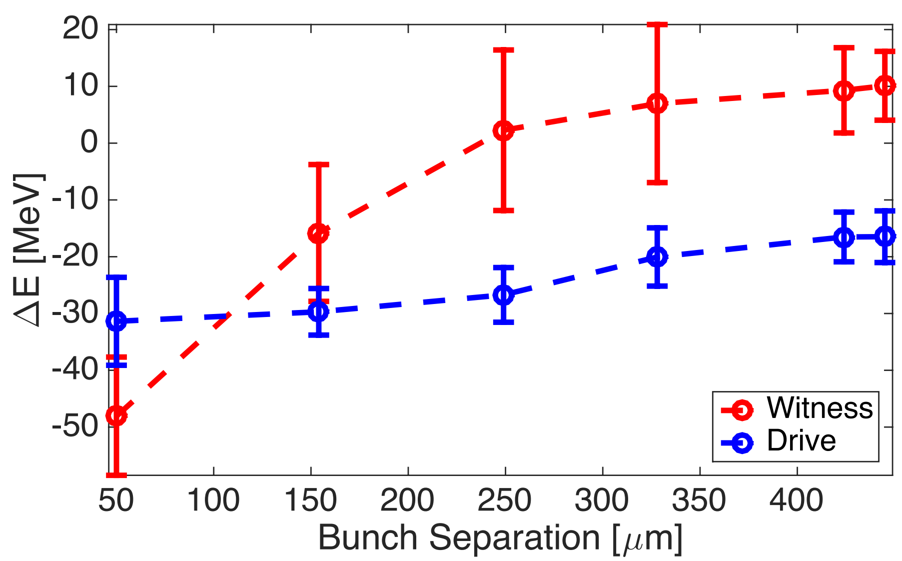


FACET: Generation of hollow plasma channels

Thanks to: S. Gessner
(SLAC, now @ CERN)



S. Gessner et. al. Nat. Comm. 7, 11785 (2016)

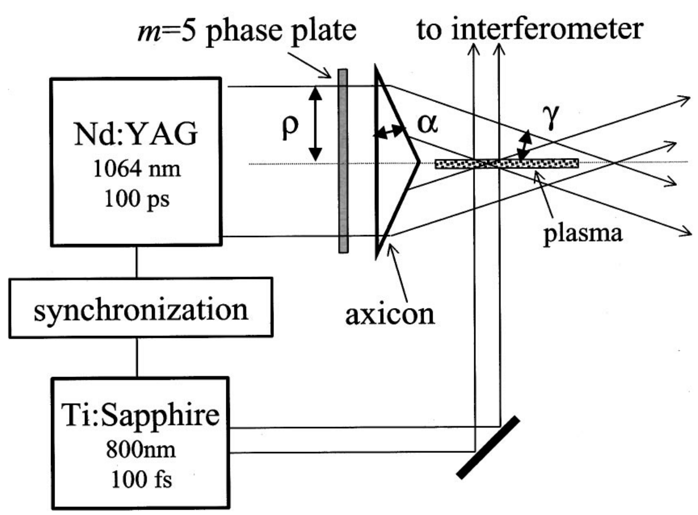


- High-order Bessel beam formed by kinoform
- Ionizes Li vapour in heat-pipe to form annular plasma (with unionized gas on axis)
  - Ti:sapphire laser: 34 mJ, 100 fs
  - $n_{\mathrm{Li}} = 8 \times 10^{16}$ cm^{-3}
  - Oven 130 cm long

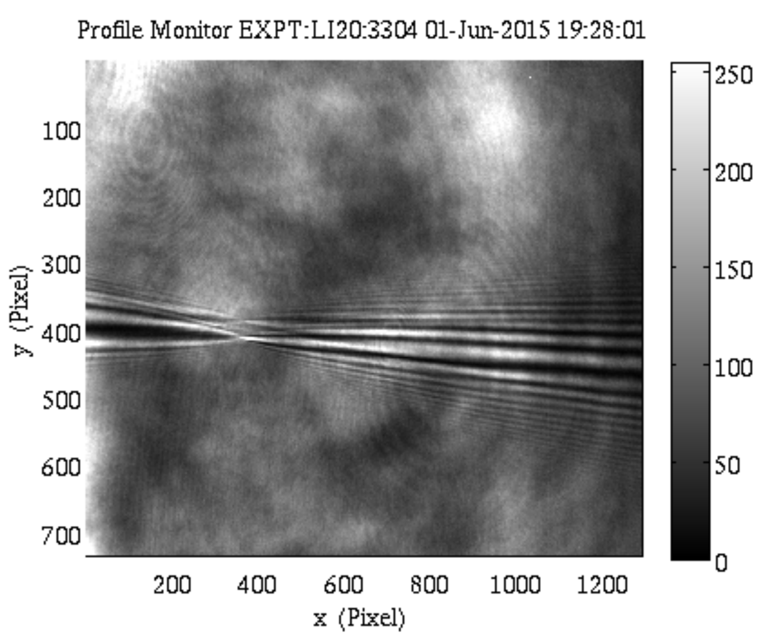
FACET: Generation of hollow plasma channels

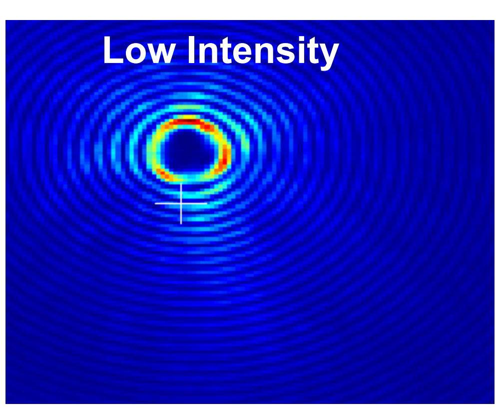
John Adams Institute for Accelerator Science

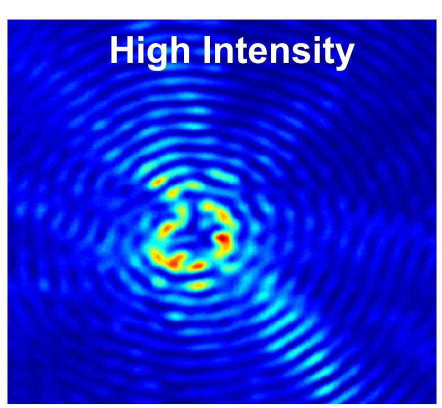
Thanks to: S. Gessner (SLAC, now @ CERN)



J. Fan, et. al. PRE 2000







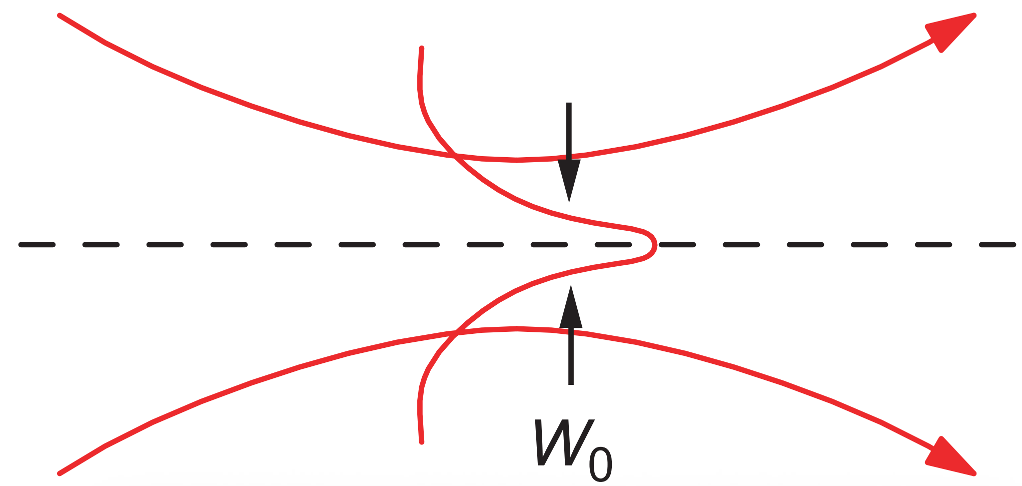
- Method extended to gas cells
  - Direct observation of channel profile
  - Can use a high-charge drive beam without field ionization by beam
- But…
  - Gases more difficult to ionize
  - Self-phase modulation can affect laser pulse

Waveguides

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

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

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



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

Example :

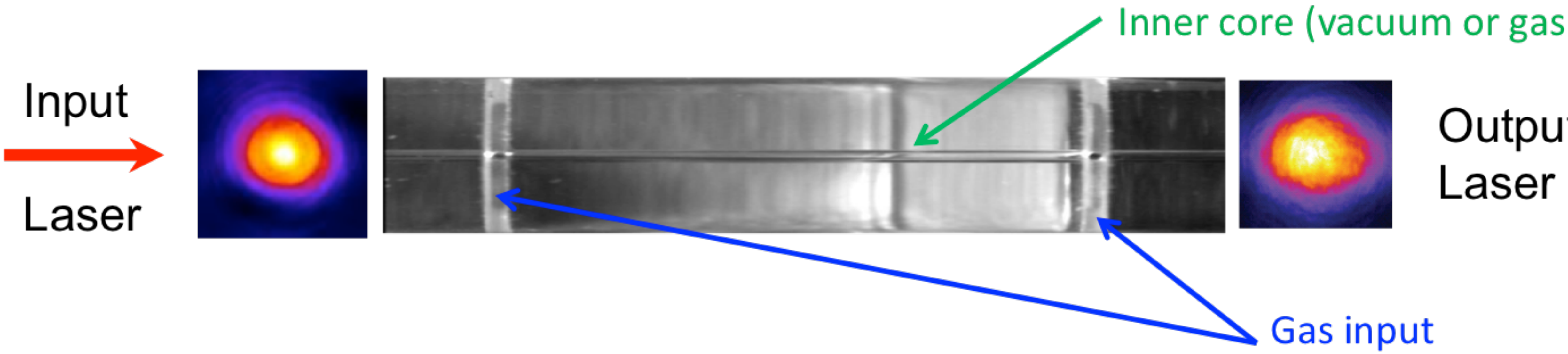
$$w_0 = 10\,\mu\text{m};\ \lambda = 1\,\mu\text{m}$$

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

- Laser-driven plasma accelerators need the driving pulse to be guided since Rayleigh range is typically only few mm
- Relativistic and ponderomotive effects greatly increase interaction length without external waveguide
- Waveguides come in two types:
  - Step-index waveguides (hollow capillaries)
  - Gradient refractive waveguides: Plasma channels

Step-index: hollow capillaries

Thanks to: Brigitte Cros & Thomas Audet
LPGP, CNRS-Université Paris-Sud

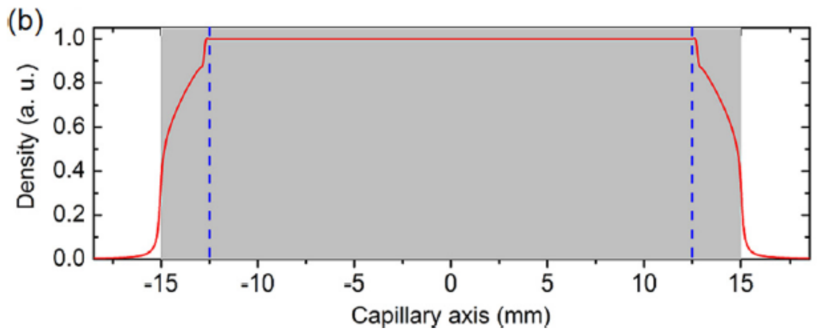


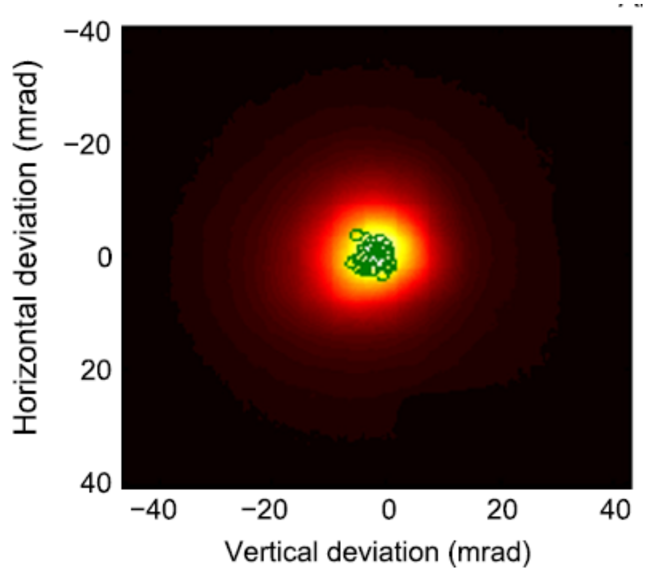
Operation in a large parameter range:

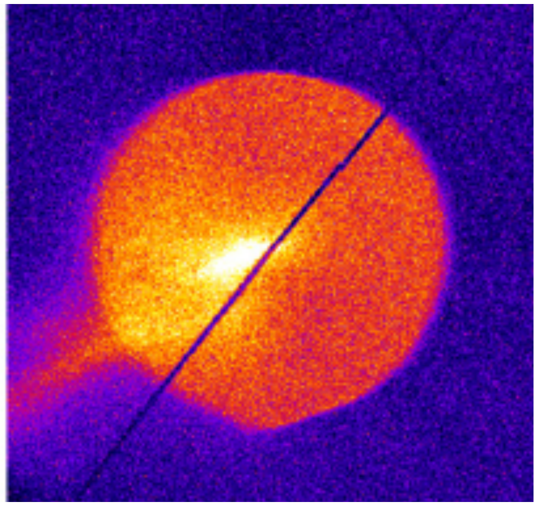
- Inner diameter: 50 - 500 µm,
- Glass walls: optically smooth
- Length : limited by laser damping length (several meters for 100µm diameter capillary)
- Laser intensity: the main limitations are due to poor beam quality and stability
- Gas : H_2 to control the density easily (laser ionisation)
- Gas pressure control: 0-500 mbar, pulsed (1shot /10s).

Hollow capillaries: Progress

Thanks to: Brigitte Cros & Thomas Audet
LPGP, CNRS-Université Paris-Sud







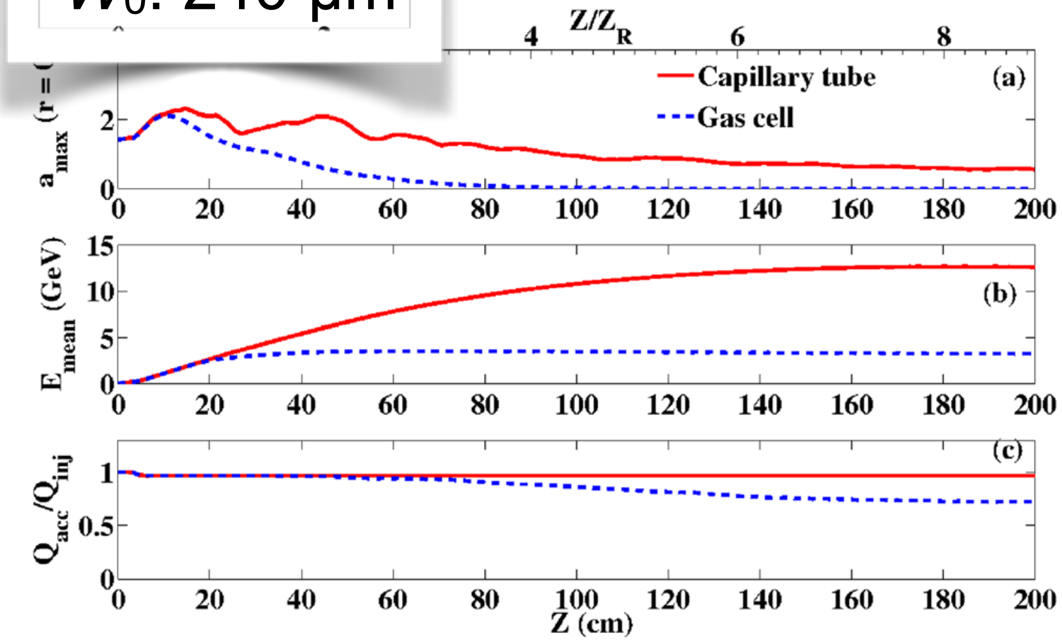
- Stable gas confinement (measurement by interferometry and fluid simulations)
  - J. Ju *et al. J. Appl. Phys.* **112** 113102 (2012)
- Laser wakefield acceleration in capillary tubes to ~ 300 MeV:
  - J. Ju *et al. Phys Plasmas* **20** 083106 (2013). F. G. Desforges *et al. Nucl. Instr. Meth. A* **740** 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)

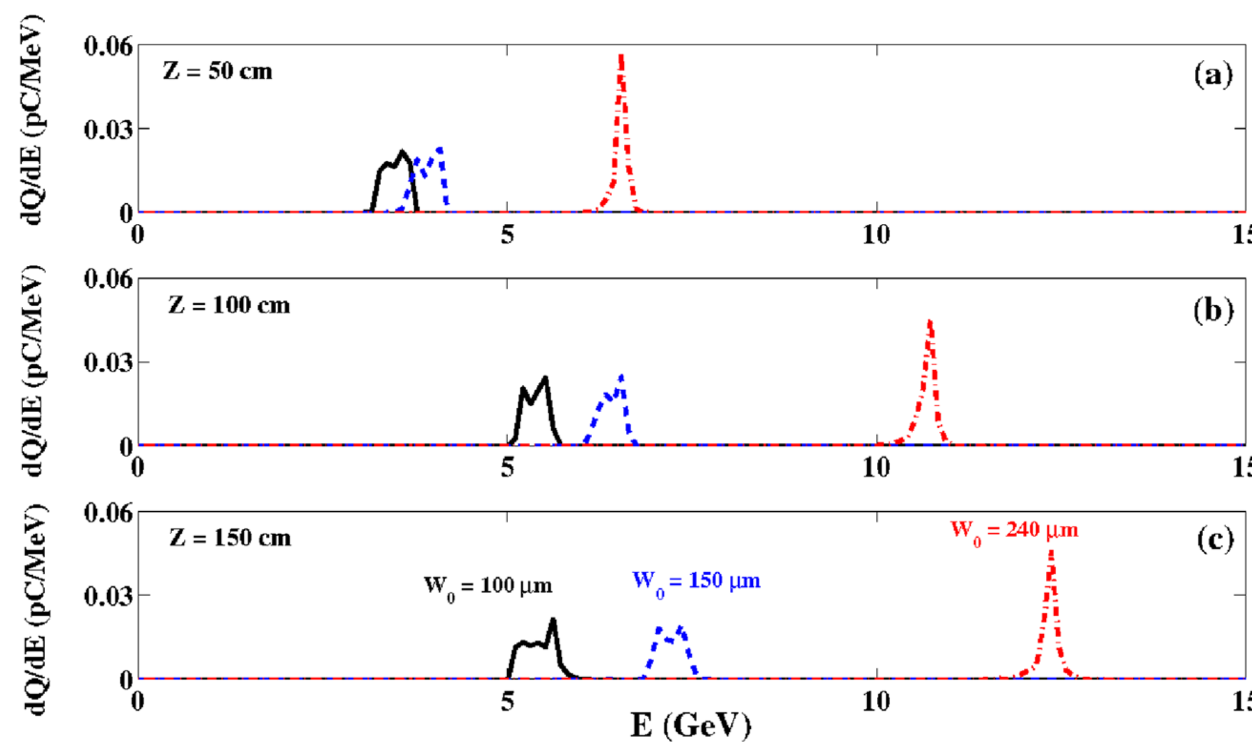
Hollow capillaries: Progress

Thanks to: Brigitte Cros & Thomas Audet
LPGP, CNRS-Université Paris-Sud

Paradkar *et al. PoP* **20** 083120 (2013)

W_0: 240 μm



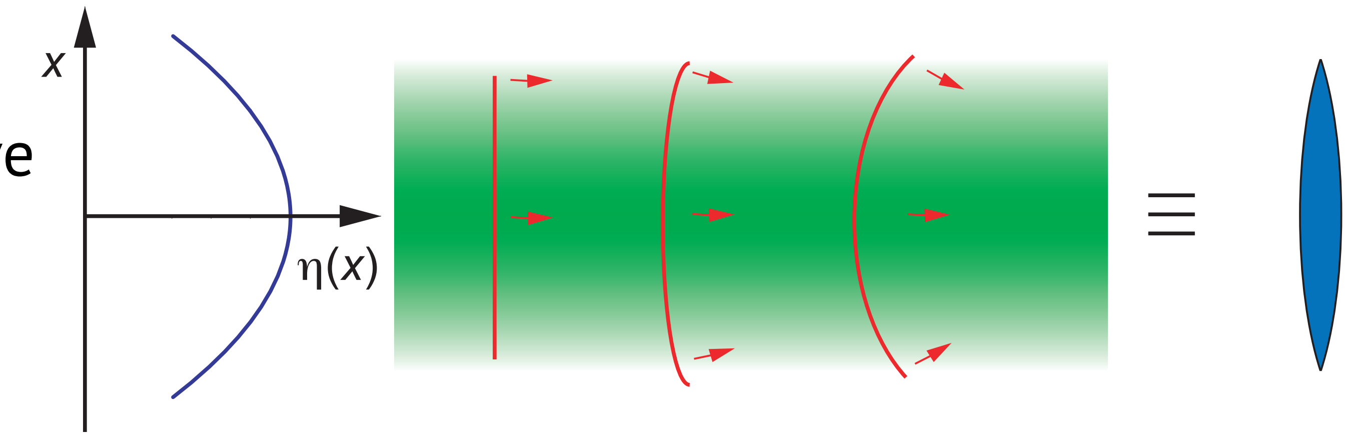


E_L: 30 - 165 J
$a0$: 1.42
τ: 40 fs
n_{e0}: 1 × 10^{17} cm^{-3}

- Simulations show acceleration of externally-injected electrons up to 10 GeV

Gradient refractive index guiding

- Laser beam will be focused if the refractive index decreases with distance from axis



Gradient refractive index guiding

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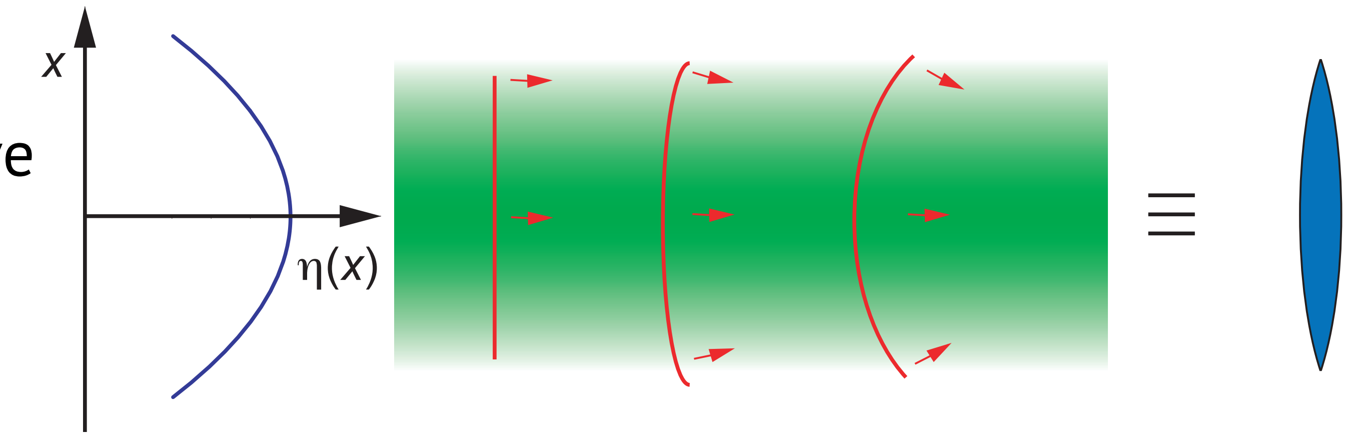
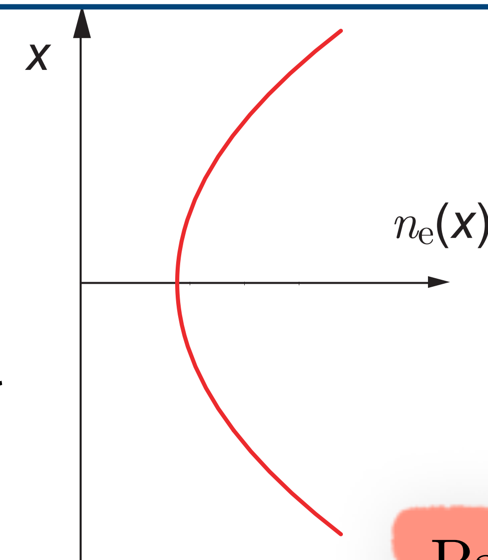


- **Plasma channel**: transverse variation of electron density gives correct refractive index profile
- Lowest-order mode of parabolic channel is Gaussian...
- ... but shape of channel is not very important: matched spot size mainly determined by channel depth.
  - See Durfee *et al. Opt. Lett.* **19** 1937 (1994)



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

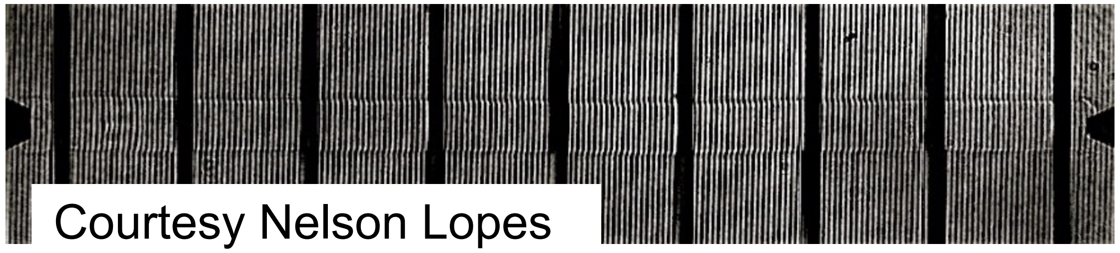
$$\approx 1 - \frac{1}{2}\frac{n_e(r)e^2}{\gamma m_e \epsilon_0 \omega^2}$$

Parabolic channel:

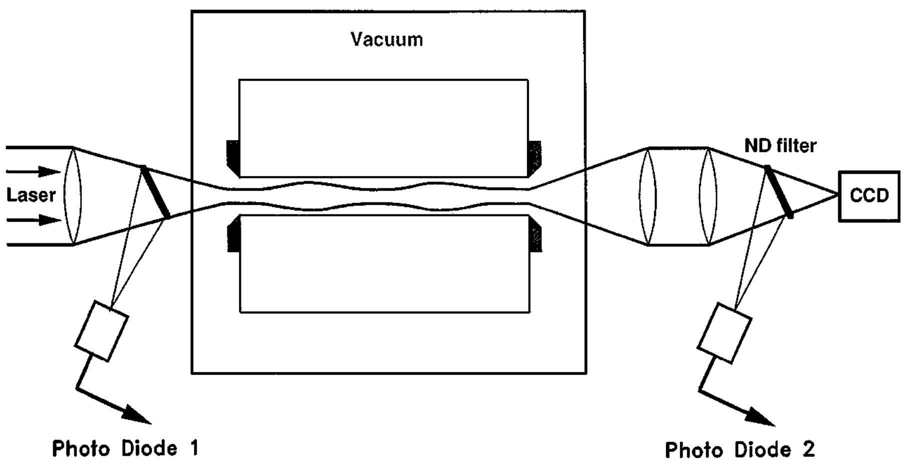
$$n_e(r) = n_e(0) + \Delta n_e\,(r/r_{ch})^2$$

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

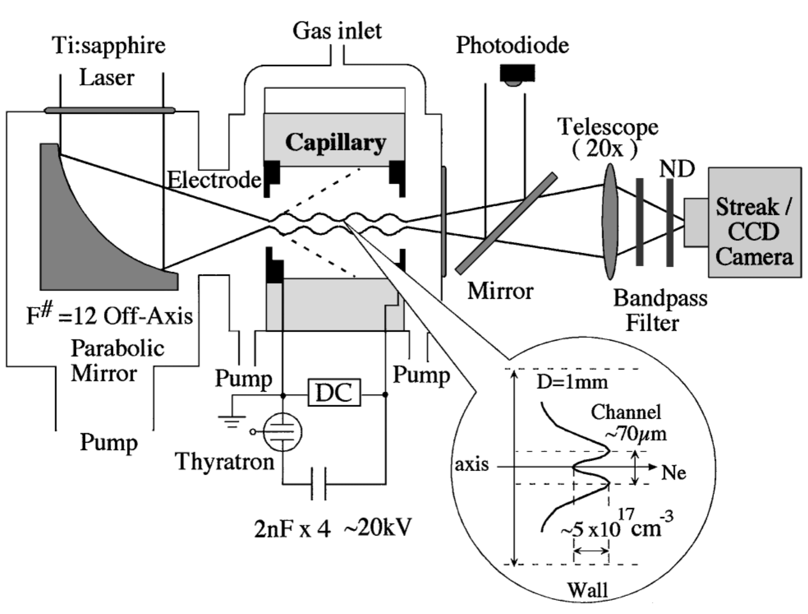
Plasma channels generated by discharges



Courtesy Nelson Lopes
Imperial College, London



Ehrlich *et al. PRL* **77** 4186 (1996)

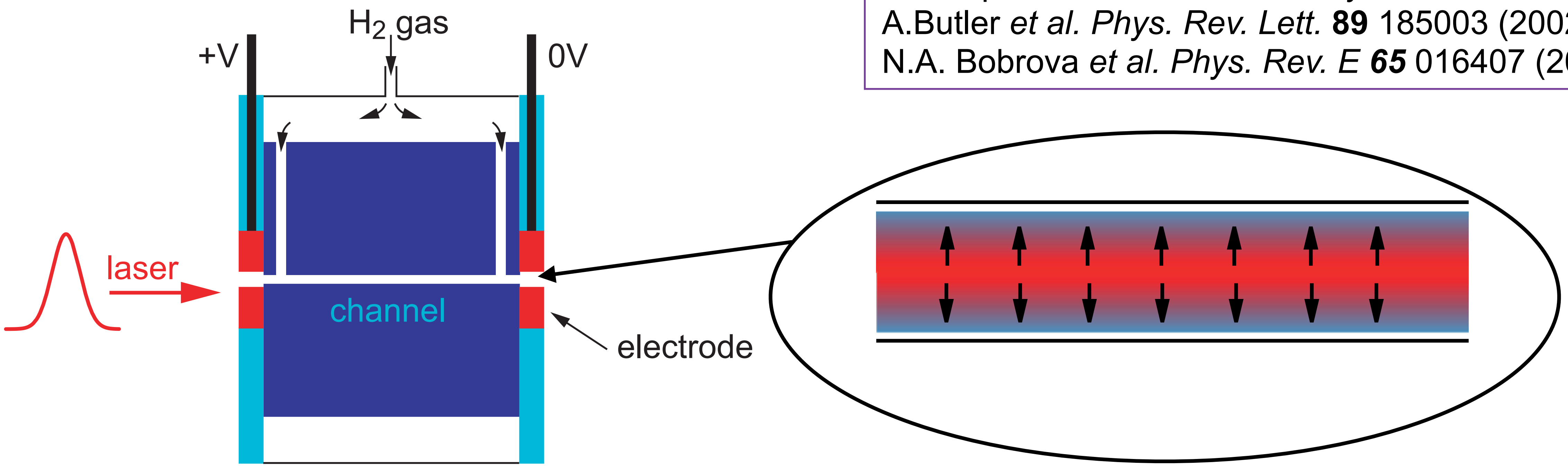


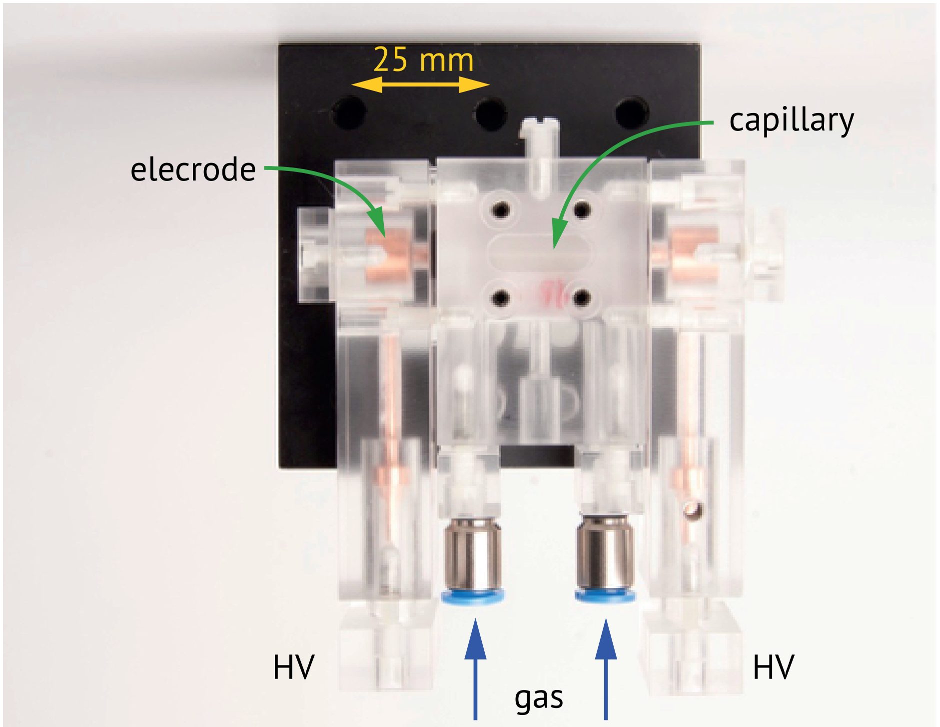
Hosokai *et al. Opt. Lett.* **25** 10 (2000)

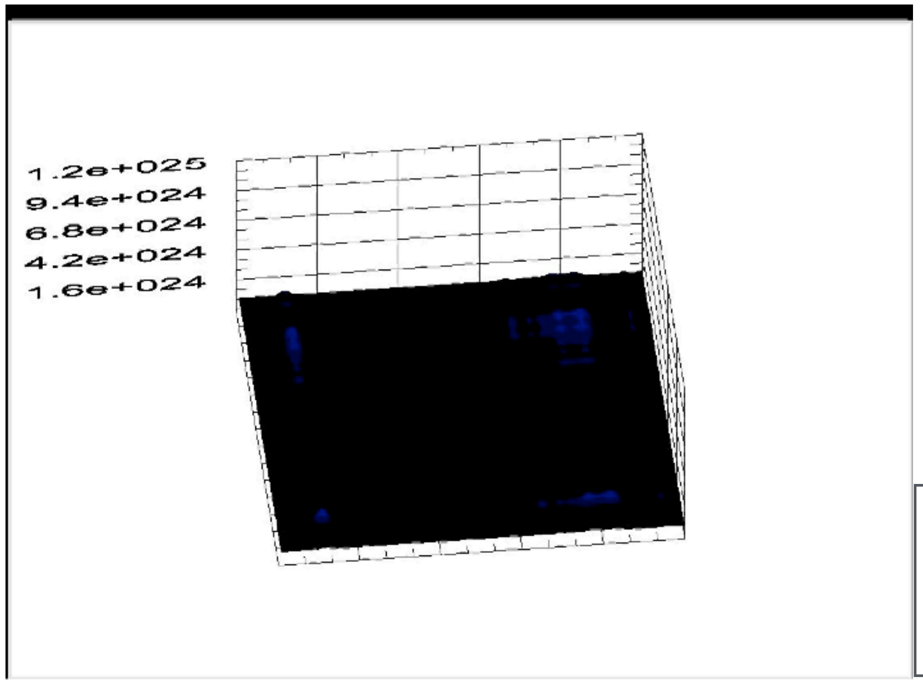
- Open discharges
  - N. C. Lopes et al. *Phys Rev E* **68** 035402 (2003).
  - R. Bendoyro, at al., *IEEE Trans. Plasma Science* **36** 1729 (2008)
- Ablated capillary discharges
  - Y. Ehrlich et al. *Phys Rev Lett* **77** 4186 (1996).
  - D. Kaganovich *et al. Phys Rev E* **59** R4769 (1999).
  - D. Kaganovich *et al. Appl. Phys. Lett.* **78** 3175 (2001).
- Gas-filled capillary discharges
- Fast capillary discharges
  - Hosokai *et al. Opt Lett* **25** 10 (2000).

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)







Evolution of plasma channel during discharge pulse

Gas-filled capillary discharge waveguides

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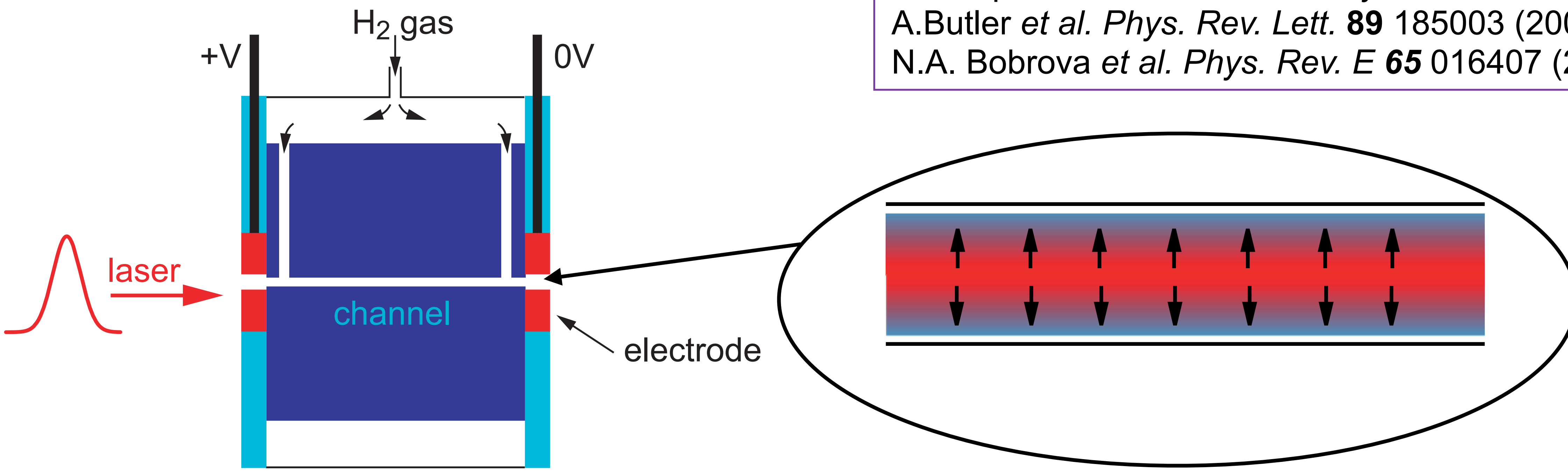
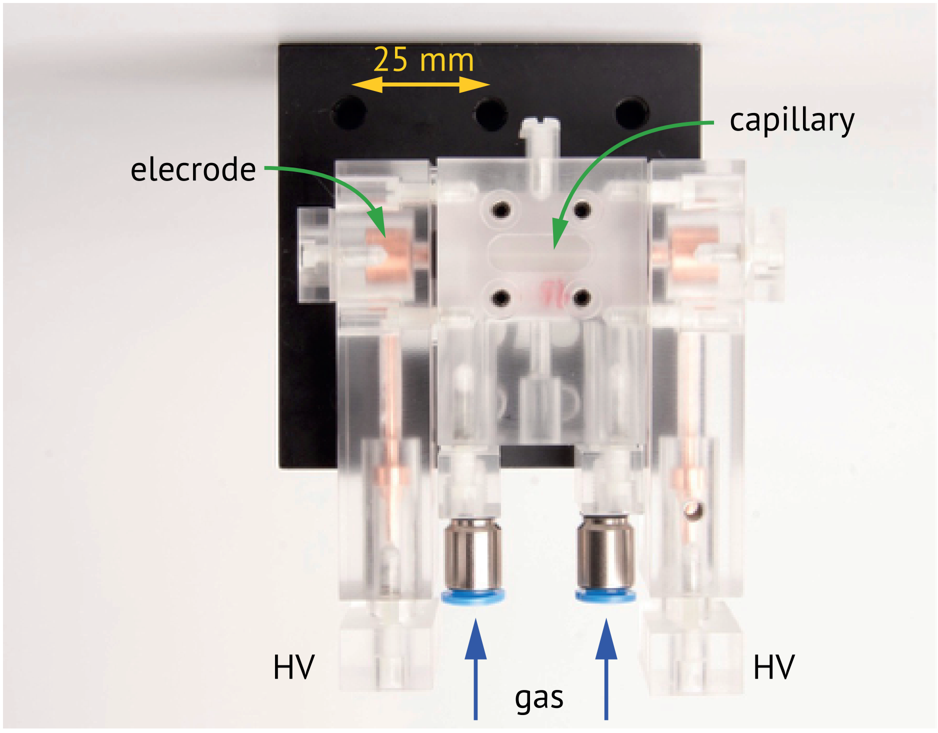
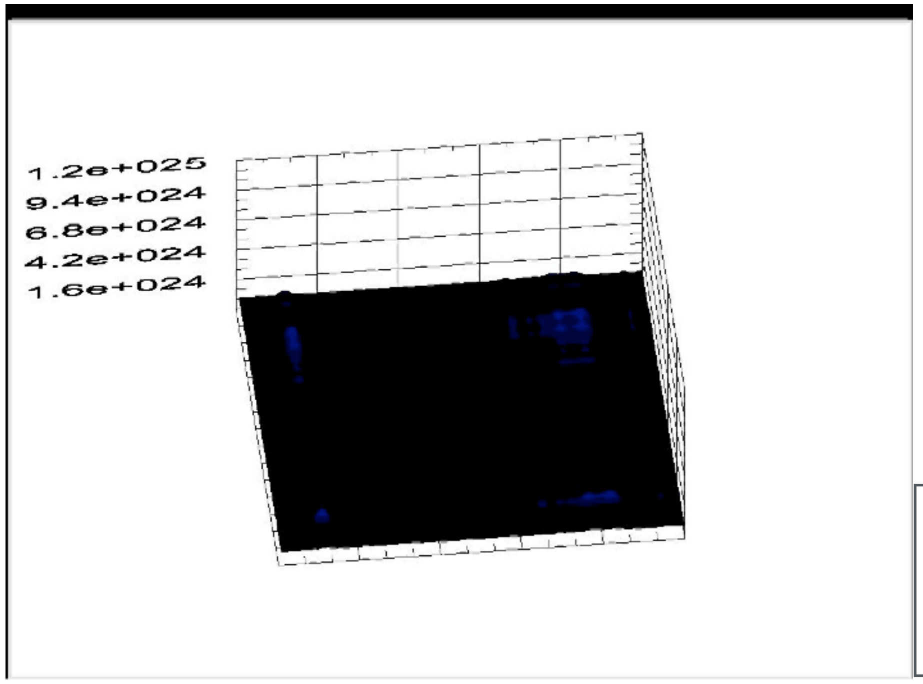
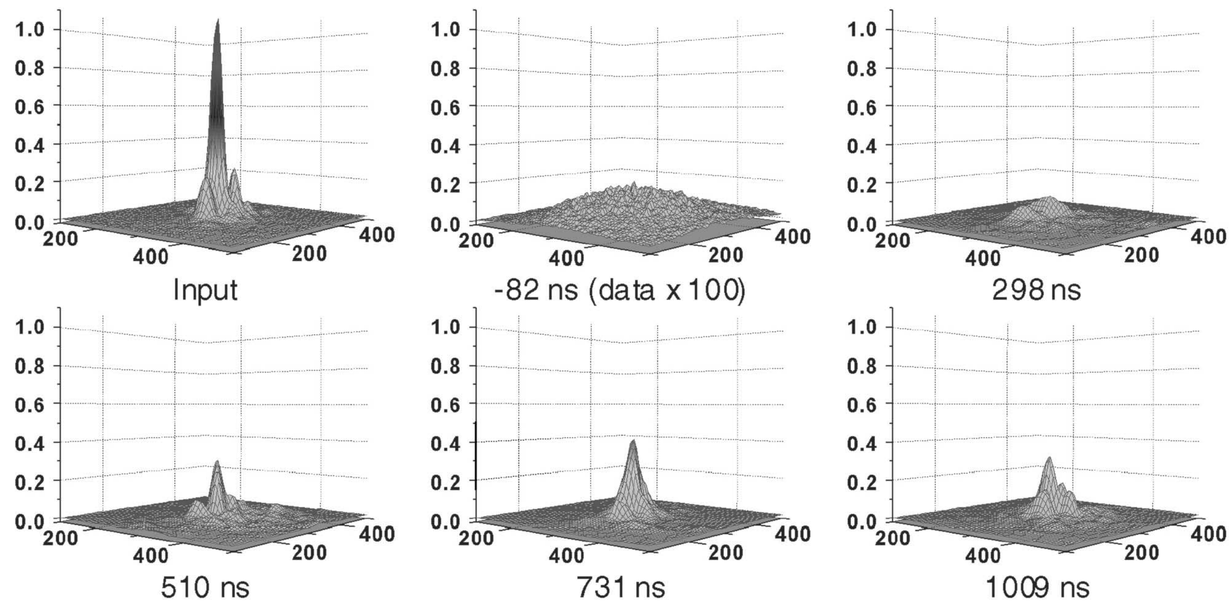


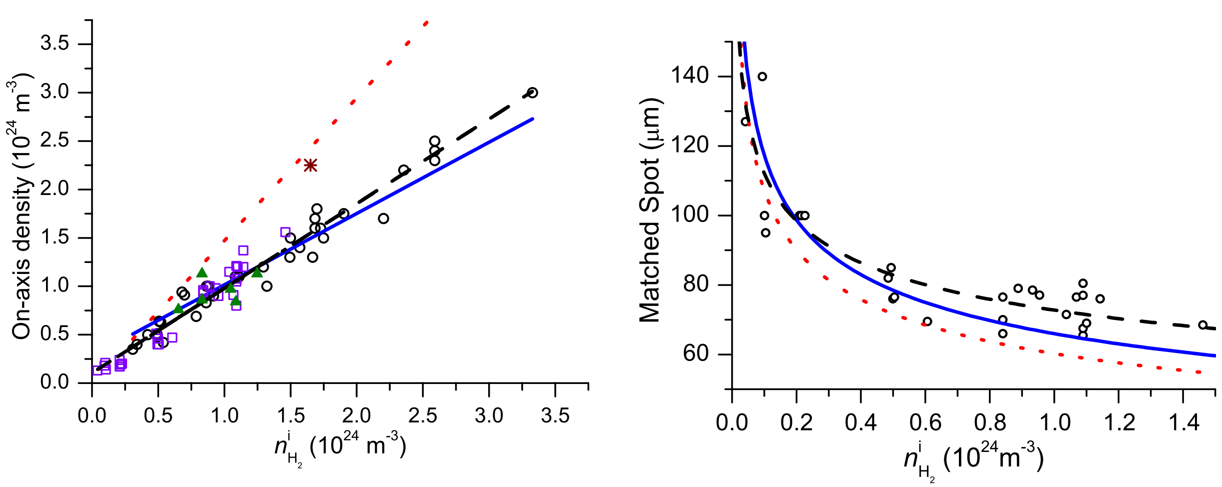




Evolution of plasma channel during discharge pulse

Progress with CDWs





- Demonstration of guiding
  - A.Butler *et al. PRL* **89** 185003 (2002)
- Laser machining of capillaries
  - D.A. Jaroszynski *et al. Phil. Trans. Roy. Soc. A* **364** 689-710 (2006)
  - S. M. Wiggins *et al. Rev. Sci. Inst.* **82** 096104 (2011).
- Scaling laws for channel properties
  - A. J. Gonsalves *et al. PRL* **98** 025002 (2007)
- Modelling of discharge
  - N.A. Bobrova *et al. PRE* **65** 016407 (2002)
  - B. H. P. Broks *et al. PoP* **14** 023501 (2007)
  - B. H. P. Broks *et al. PRE* **71** 016401 (2005).
  - G. Bagdasarov *et al. PoP* **24** 053111 (2017).
- Generation of GeV beams
  - W. P. Leemans *et al. Nat. Phys.* **2** 696 (2006)

Progress with CDWs

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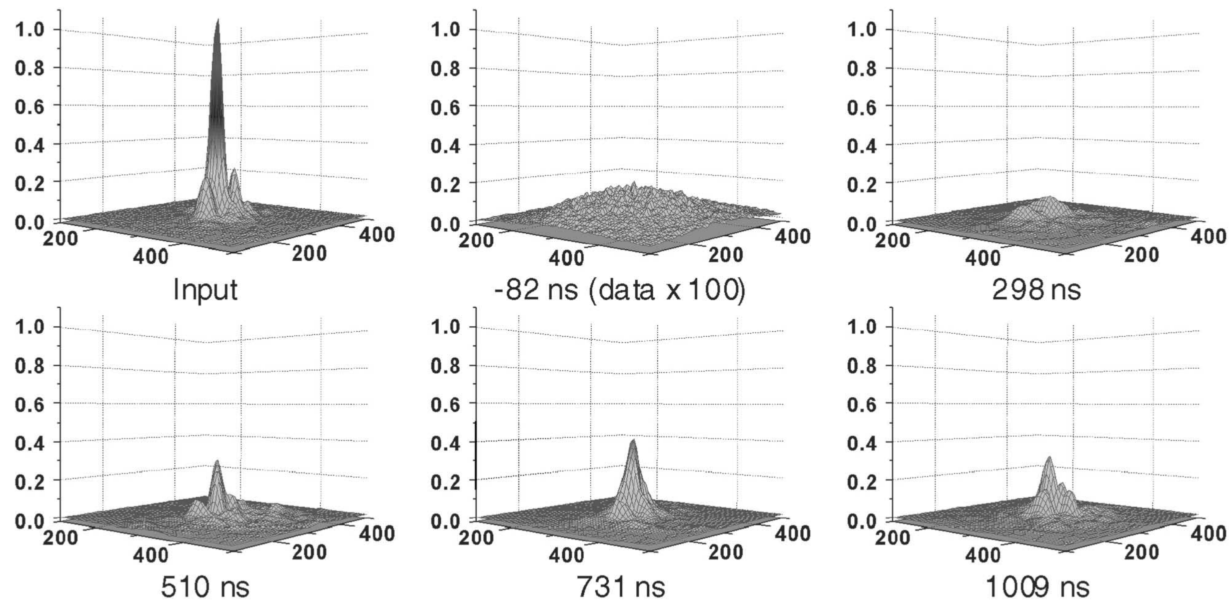
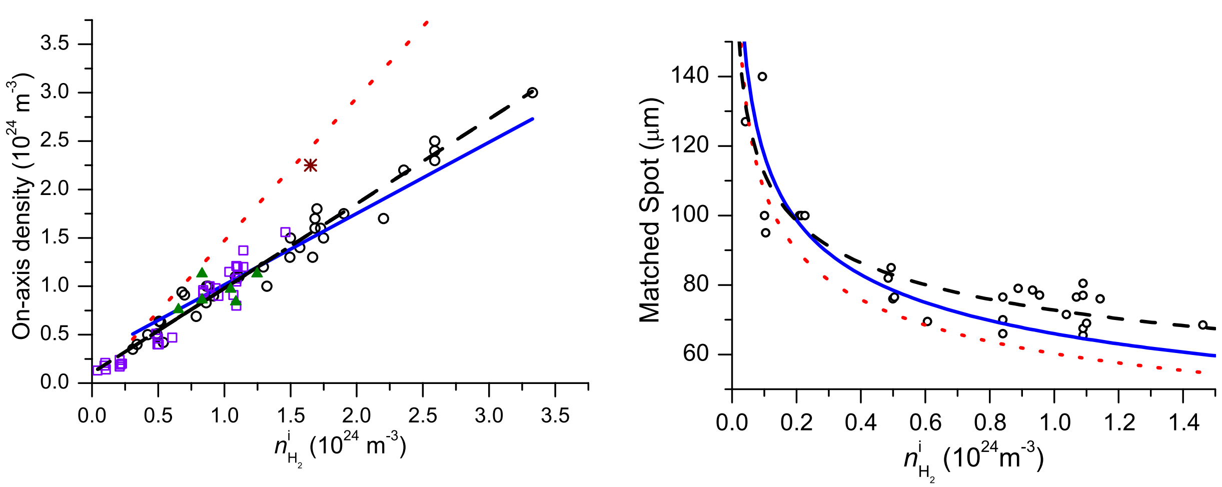
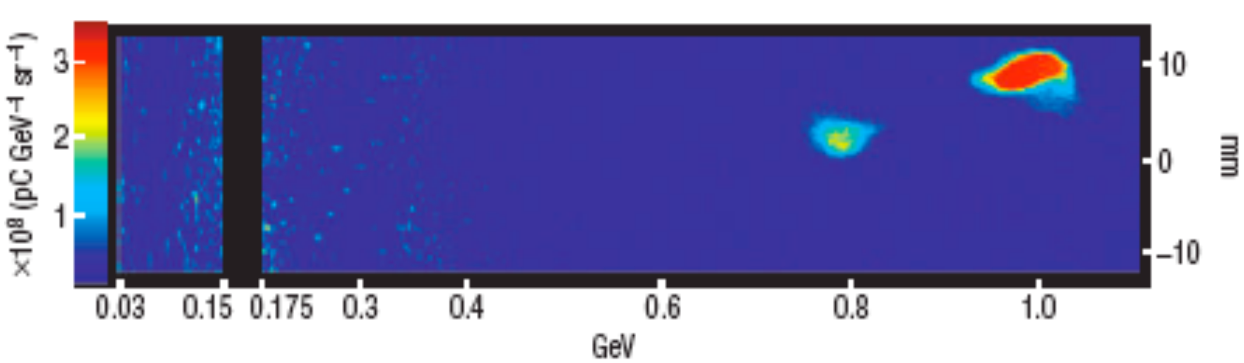
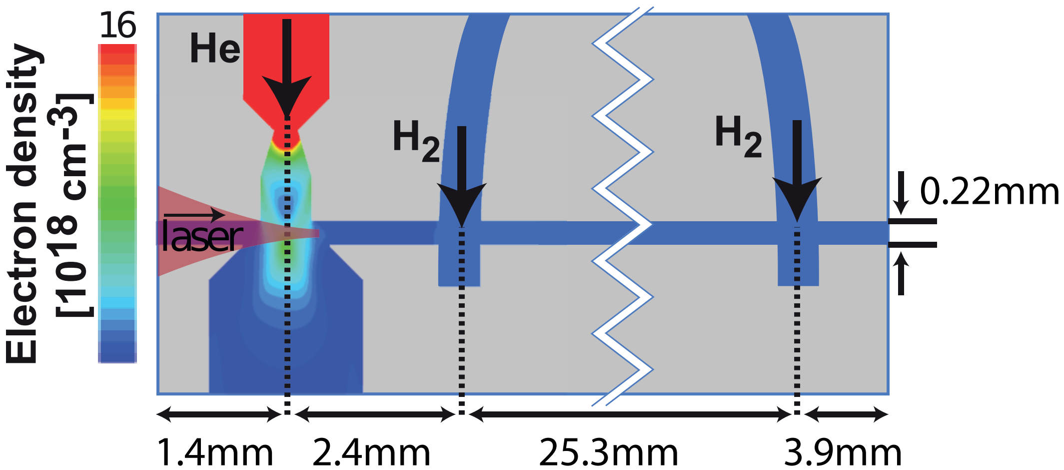


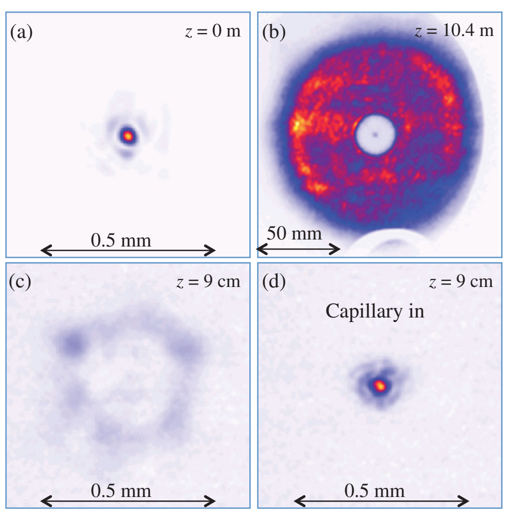




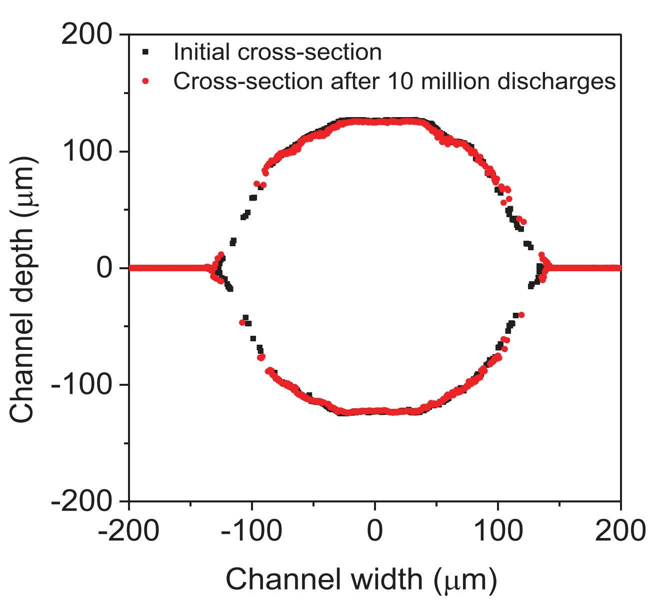
Progress with CDWs

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





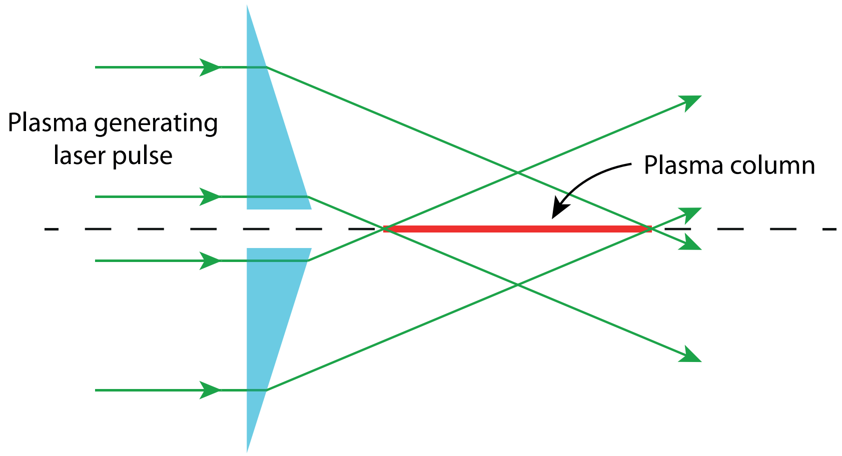
W. P. Leemans *et al.*
PRL **113** 245002 (2014)

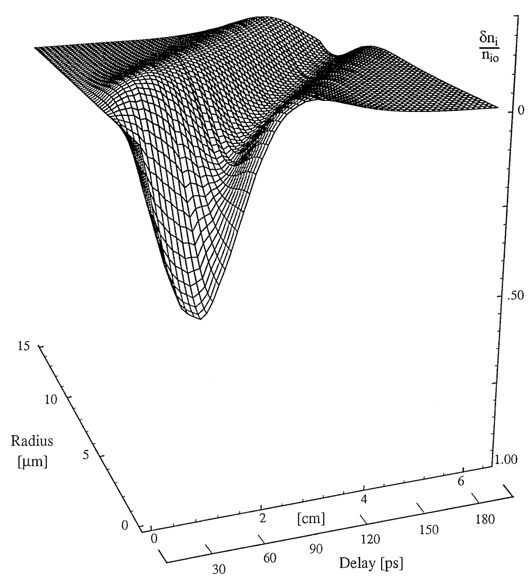


A. J. Gonsalves *et al.*
J. Appl. Phys. **119**
033302 (2016)

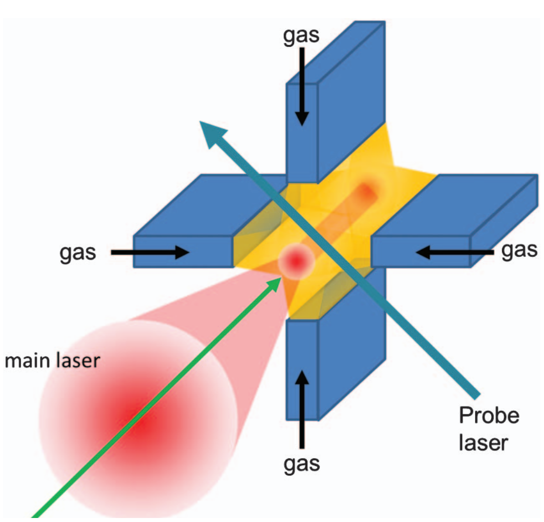
- Incorporation of gas jet to control injection
- Channel length increased to 90 mm
  - 4.2 GeV electron beams generated
  - Guiding observed for $n_{e0} \gtrsim 2 \times 10^{17}$ cm^{-3}
- Repetition rate increased to 1 kHz
- Laser heating of channel to decrease n_{e0} and *WM*
  - N. A. Bobrova *et al. PoP* **20** 020703 (2013)

Hydrodynamically-generated plasma channels





Krushelnick *et al.* *PRL* **78** 4047 (1997)

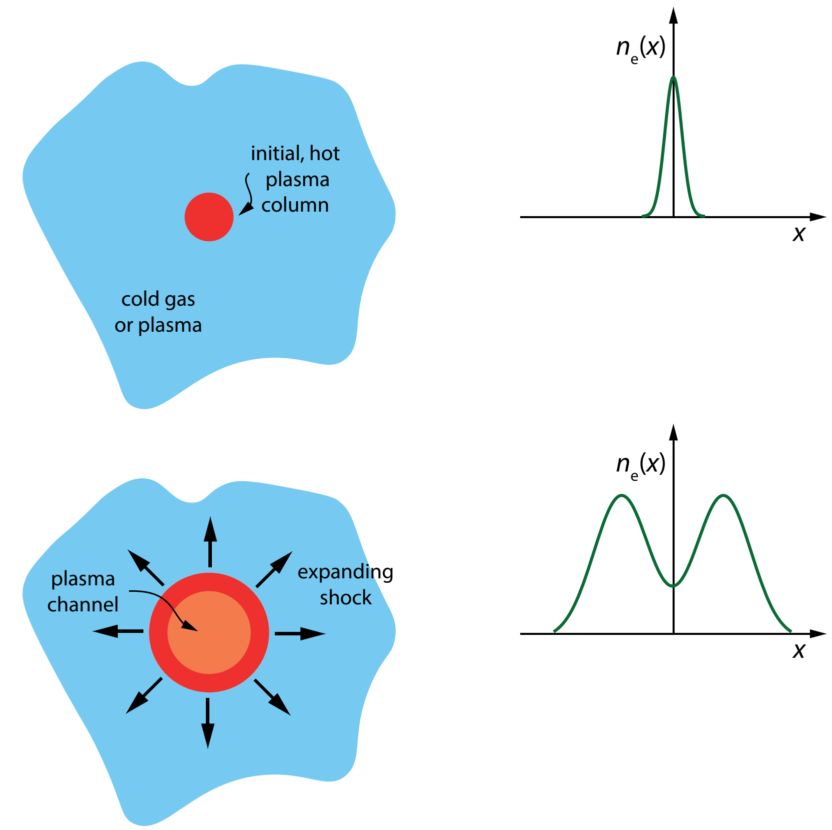


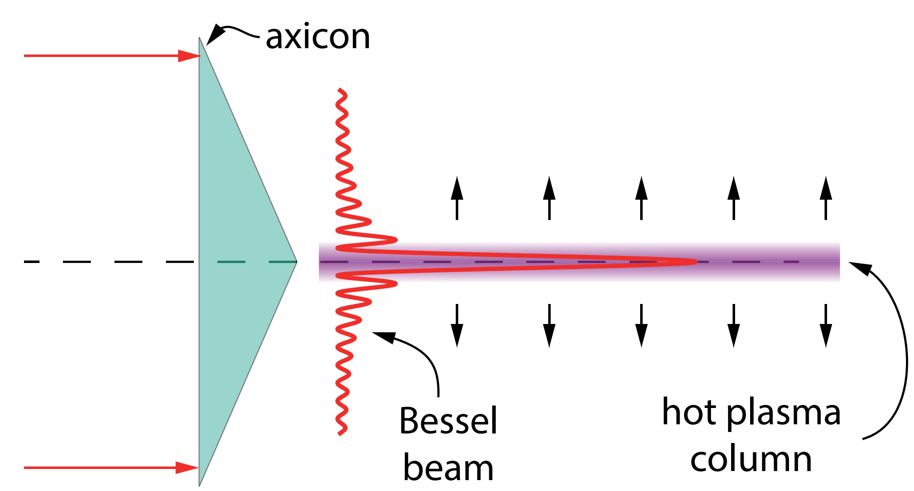
Kaganovich *et al.* *Appl. Opt.* **54** F144 (2015)

- Hydrodynamic expansion
  - C. G. Durfee & H. M. Milchberg, *Phys Rev Lett* **71** 2409 (1993).
  - T. R. Clark & H. M. Milchberg, *Phys Rev E* **61** 1954 (2000).
  - V. Kumarappan, *et al. Phys Rev Lett* **94** 205004 (2005).
- Ponderomotive channels
  - K. Krushelnick *et al. Phys Rev Lett* **78** 4047 (1997).
- Colliding gas flows
  - D. Kaganovich *et al. Appl Optics* **54** F144 (2015).

Plasma channels: hydrodynamic expansion

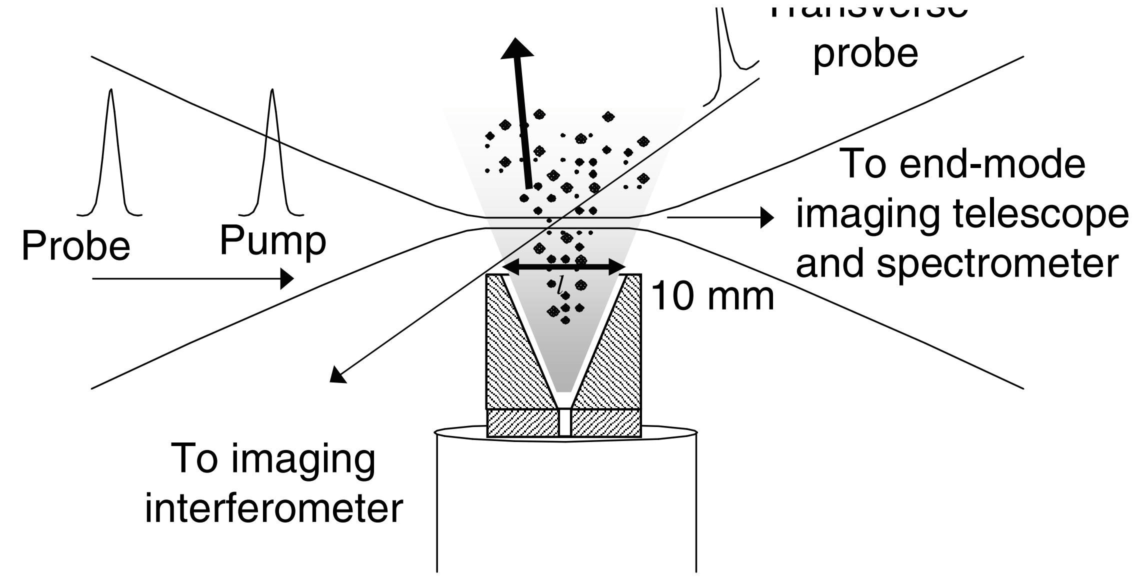
- Create & heat column of hot plasma
  - ~ 100 ps laser pulse creates and heats plasma
- Expansion into surrounding cold gas / plasma drives cylindrical blast wave
- Plasma channel formed within expanding shell
- Attractive for high repetition rates since "indestructible"
- Extensively studied
  - C. G. Durfee & H. M. Milchberg, *Phys Rev Lett* **71** 2409 (1993).
  - T. R. Clark & H. M. Milchberg, *Phys Rev E* **61** 1954 (2000).
  - "Ignitor-heater" : P. Volfbeyn et al. PoP 6 2269 (1999).

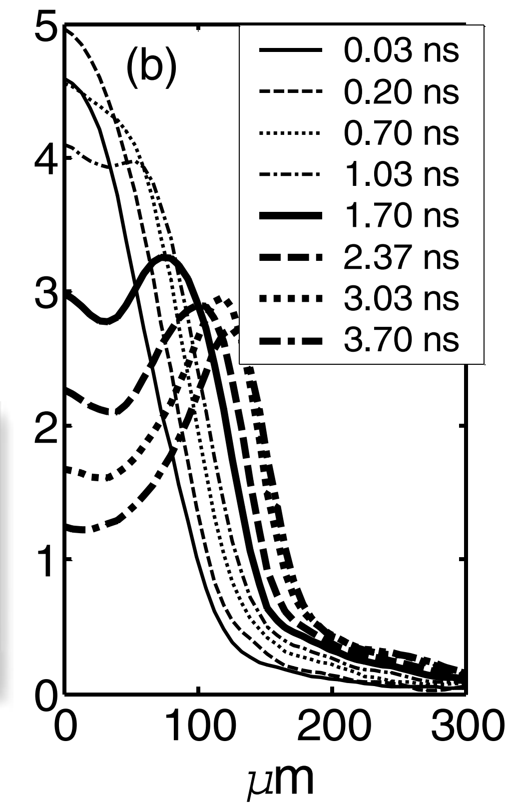




Plasma channels: hydrodynamic expansion

- Requirement for rapid collisional heating limits on-axis density to ne(0) ≳ 5 × 10^{18} cm^{-3}
- Using clustered gases can reduce this to ne(0) ≳ 1 × 10^{18} cm^{-3}
  - V. Kumarappan *et al. PRL* **94** 205004 (2005)

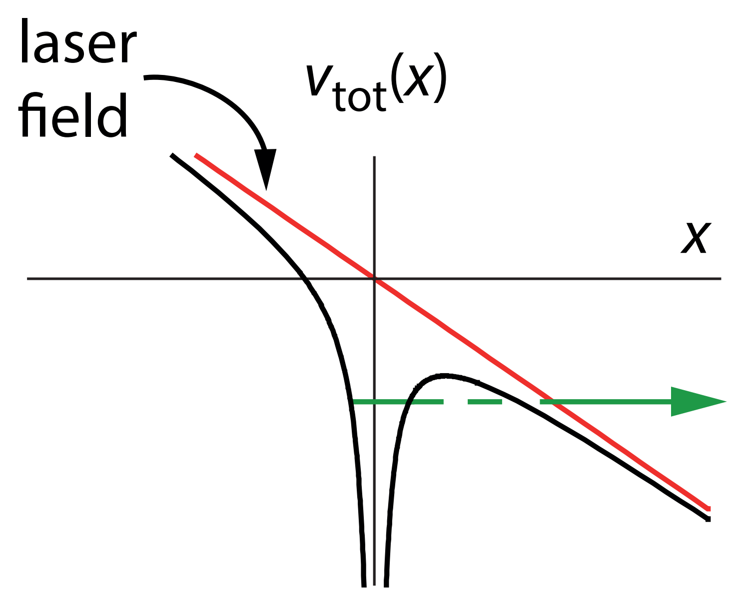


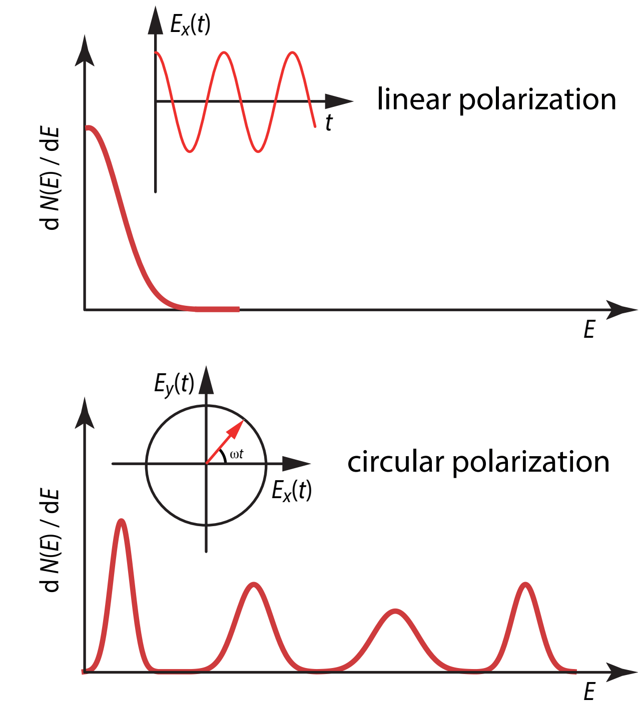


Evolution of plasma density (10^{18} cm^{-3}) in clustered Ar gas jet (113K, 20 bar)

OFI-heated hydrodynamic plasma channels

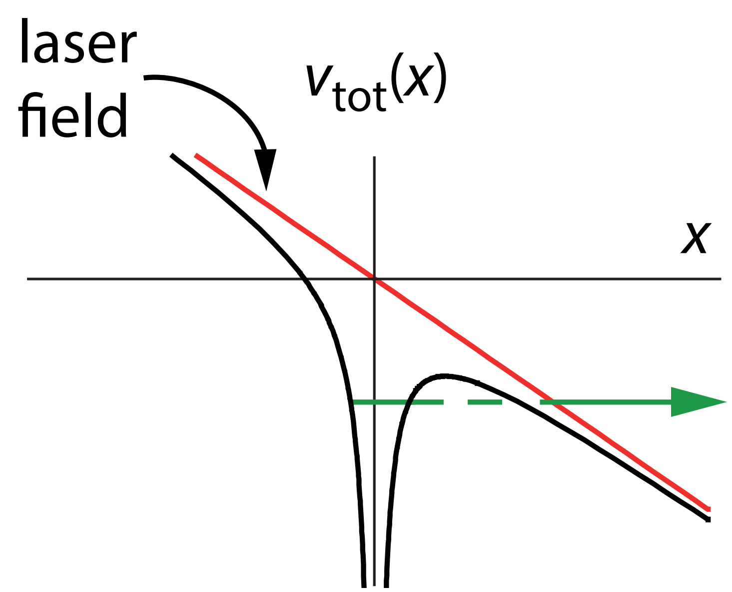
- Optical field ionization gives
  - Hot electrons & cold ions
  - Electron energy controlled by polarization
- Heating independent of density ⇒ low density channels

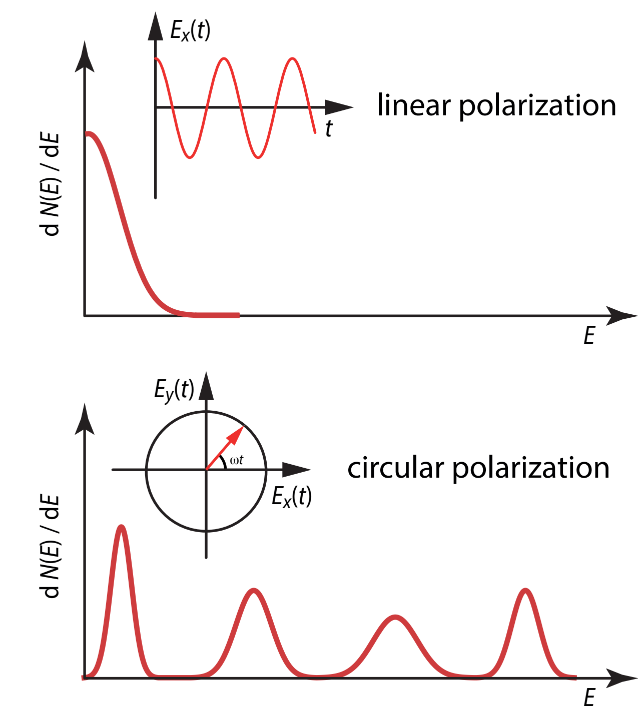


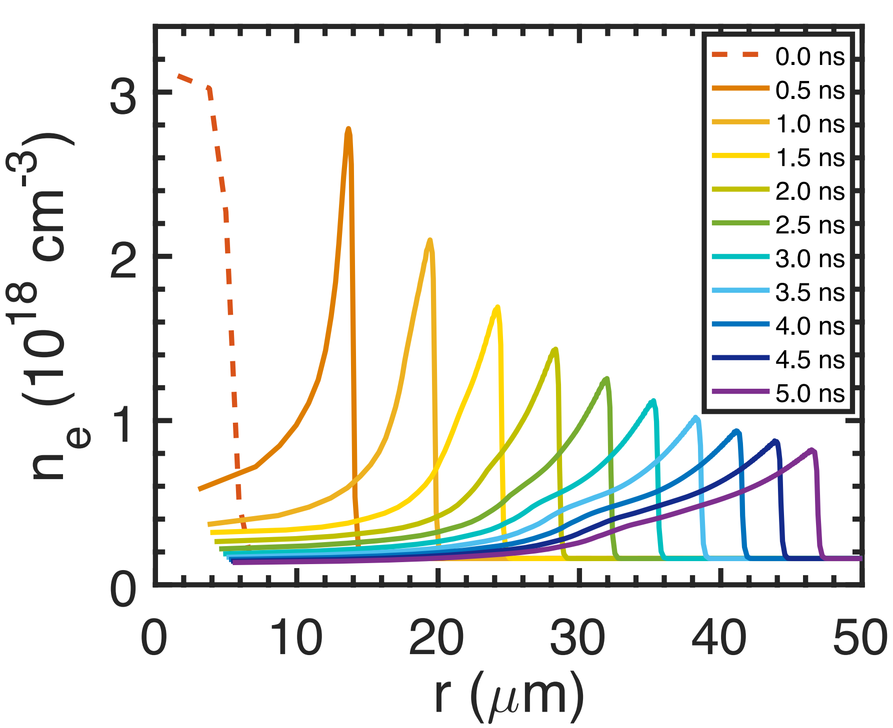


OFI-heated hydrodynamic plasma channels

- Optical field ionization gives
  - Hot electrons & cold ions
  - Electron energy controlled by polarization
- Heating independent of density ⇒ low density channels
- HELIOS simulations show channels with $n_e(0) \approx 7 \times 10^{17}$ cm^{-3}







See poster by Chris Arran, Wed 19:30

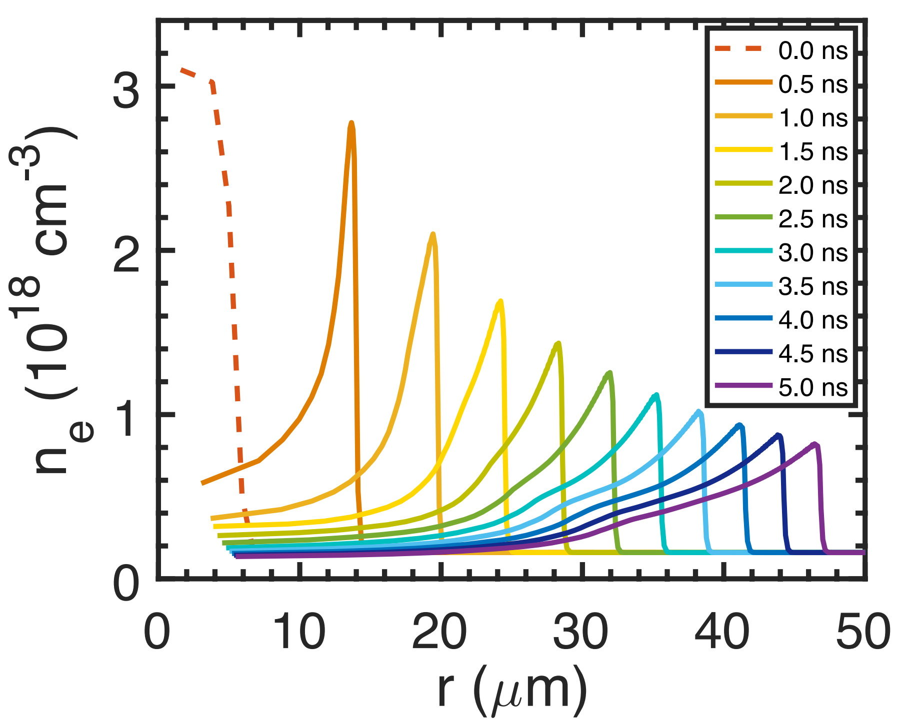
HELIOS simulations

n_H:	3×10^{18} cm^{-3}
E_L:	50 mJ
τ:	50 fs
L_{chan}:	600 mm

OFI-heated hydrodynamic plasma channels

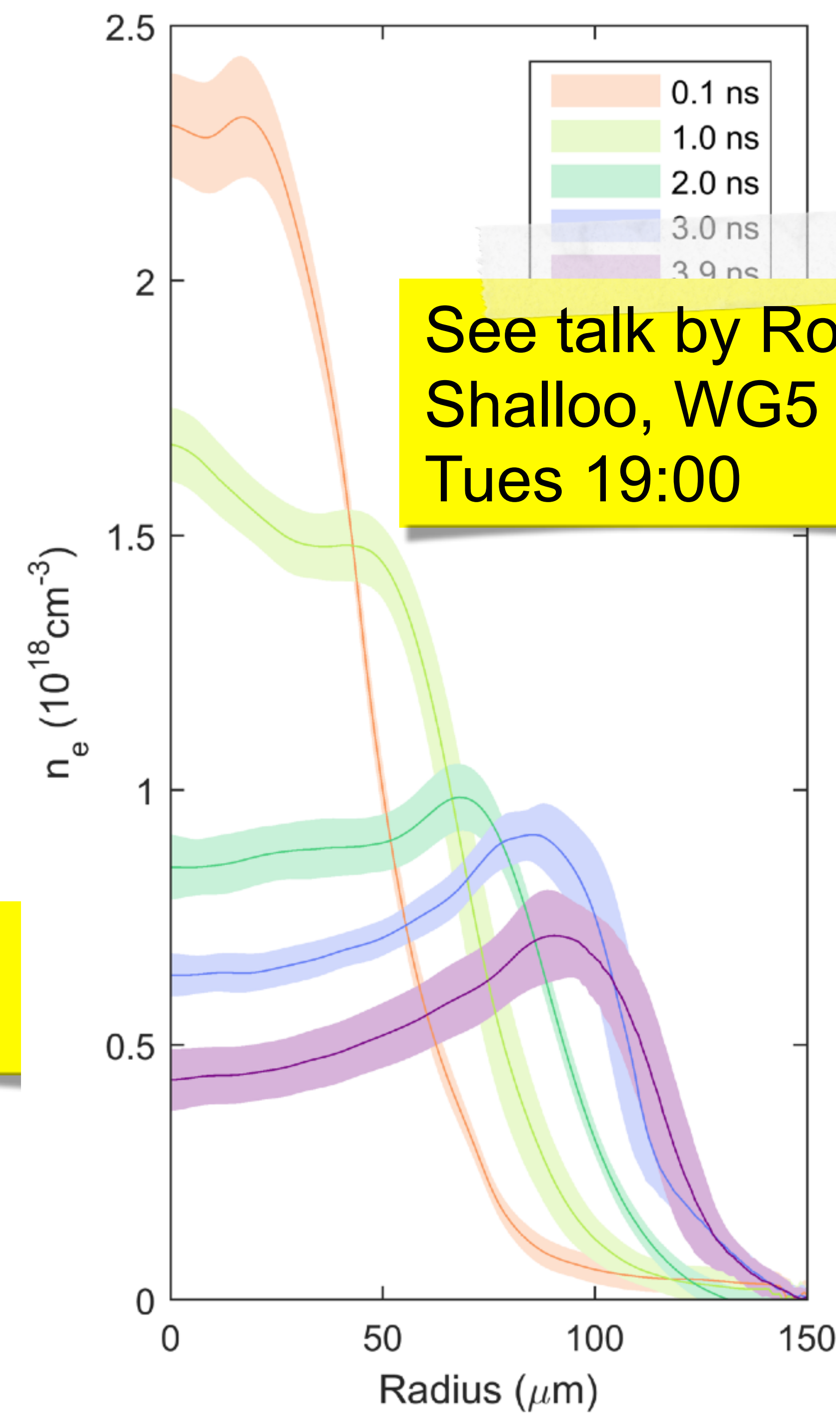
John Adams Institute for Accelerator Science

- Optical field ionization gives
  - Hot electrons & cold ions
  - Electron energy controlled by polarization
- Heating independent of density ⇒ low density channels
- HELIOS simulations show channels with ne(0) ≈ 7×10^{17} cm^{-3}
- Confirmed in preliminary experiments with lens focus



See poster by Chris Arran, Wed 19:30

HELIOS simulations
n_H: 3×10^{18} cm^{-3}
E_L: 50 mJ
τ: 50 fs
L_{chan}: 600 mm



See talk by Rob Shalloo, WG5 Tues 19:00

Class:	Non-guiding			Waveguides			
Source:	Jet	Cell	Cap. Cell	Vap. Oven	Hollow cap	CDW	Hydro expansion
n_e / cm^{-3}							
L / mm							
W_M / µm							
Gas load							
Lifetime							
Rep. rate							
Homog.?							
Ramps?							
Reproduce?							
Long. profile?							
Trans. profile?							
Diag. access							

Yes / Good / High

Not known / Medium

No / Difficult

Summary

- Many factors must be considered when designing the plasma source
- Wide range of solutions have been developed
- Important issues & future challenges
  - Operation at lower densities and over longer lengths
  - Control of longitudinal profile (controlling injection, reduce emittance growth)
  - Improved control of transverse profile (e.g. hollow channels)
  - Long operating life
  - Operation at high repetition rates
  - Reducing gas load to rest of system (affects repetition rate)
  - Reducing/avoiding unwanted background from interaction with structure (e.g. bremsstrahlung)