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Optical guiding of high intensity laser pulses for laser wakefield acceleration

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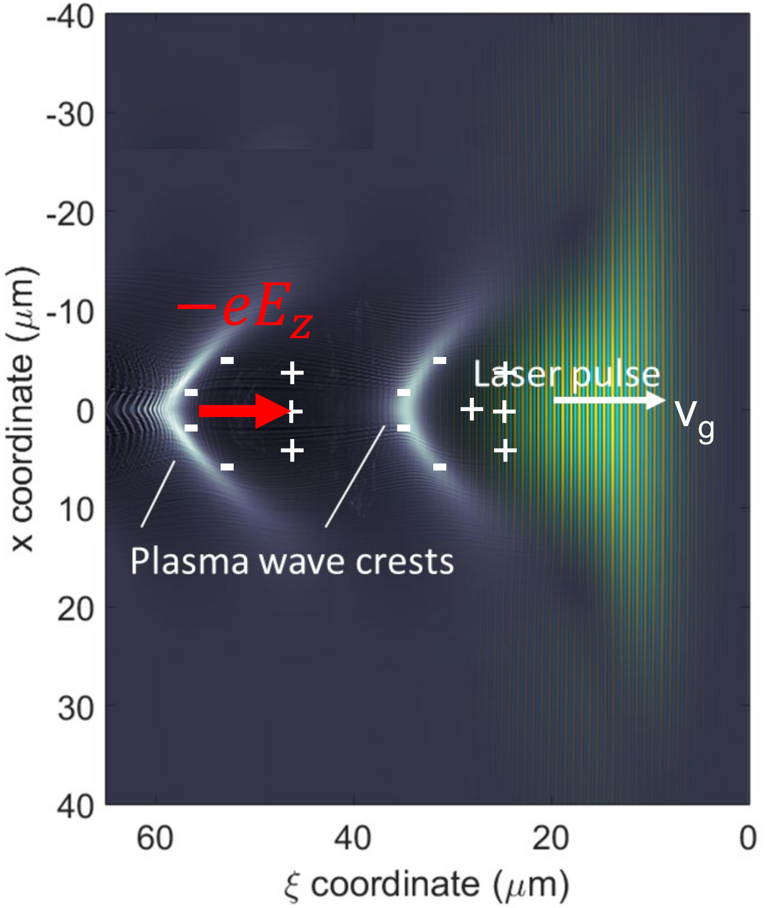
Outline

- Laser wakefield acceleration (LWFA) and its laser/plasma requirements for multi-GeV bunches
- Optical guiding in plasmas
  - relativistic self-guiding
  - preformed plasma waveguides
    - laser-generated waveguides
    - capillary discharge waveguides
  - “self-waveguiding”
- Recent multi-GeV acceleration results

  metre-scale, low density plasma optical fibres (for future high rep. rate 10 GeV stage)

Laser wakefield acceleration (LWFA)

Ponderomotive force $\boldsymbol{F}_p$ expels electrons from high intensity region and drives plasma wave



$$\boldsymbol{F}_p \propto -\nabla(a^2)$$

$$a = \frac{eA}{mc^2}$$

normalized vector potential

$a \lesssim 1$ quasi-linear regime

$a > 1$ 'bubble' regime

- wakefield $E_z \propto N_e^{1/2}$
- accelerating force $F = -eE_z$
- energy gain $\Delta W = eE_zL_d$

dephasing length

Density and intensity scaling in LWFA

- Dephasing length = $L_d \propto N_{cr}/N_e^{3/2}$, $E_z \propto N_e^{1/2} \longrightarrow \Delta W = E_z L_d \propto N_e^{-1}$

- Scaling of single stage energy gain in LWFA

$$\frac{\Delta W_{max}}{m_e c^2} \sim a_0^2 \frac{N_{cr}}{N_e}$$

quasi-linear regime

$$\frac{\Delta W_{max}}{m_e c^2} \sim a_0 \frac{N_{cr}}{N_e}$$

bubble regime

W. Lu et al., Phys. Rev. Spec. Top. - Accel. Beams ***10****, 061301 (2007).*

S. Gordienko and A. Pukhov, Phys. Plasmas ***12****, 043109 (2005).*

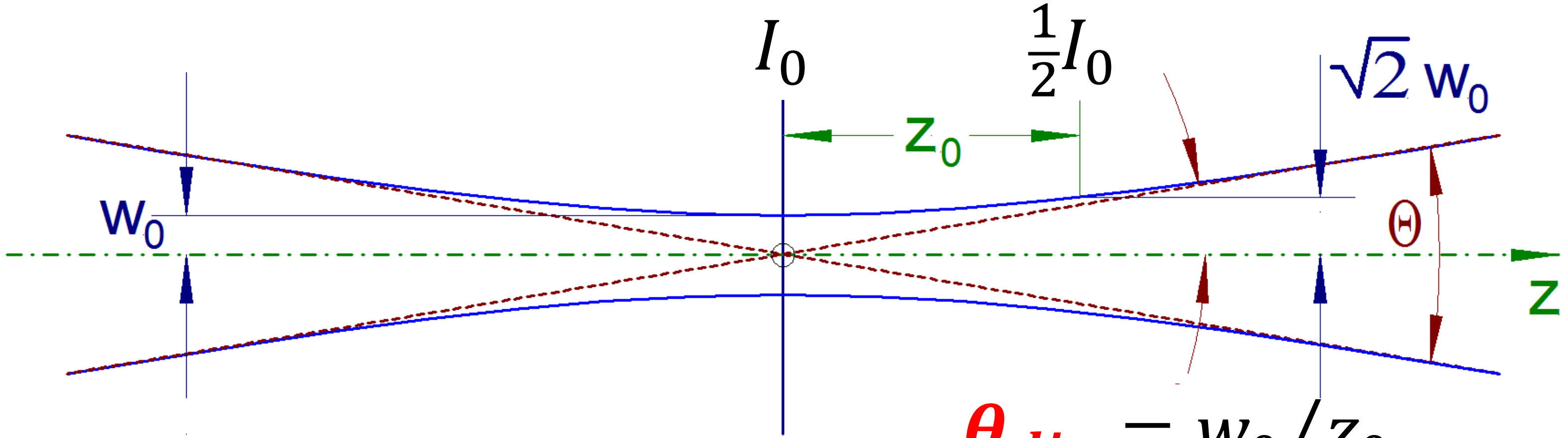
Employ guiding to make acceleration length as long as possible so $L_{guide} \lesssim L_d$

For example: $\Delta W_{max} \sim 10\ \mathrm{GeV}$ satisfied by $\frac{N_{cr}}{N_e} \sim 10^4$, $a \sim 2.5$, $L_{guide} = 20\ \mathrm{cm} \lesssim L_d$

Low density ($\sim 10^{17}$ cm^{-3}), “modest” intensity, metre scale acceleration length

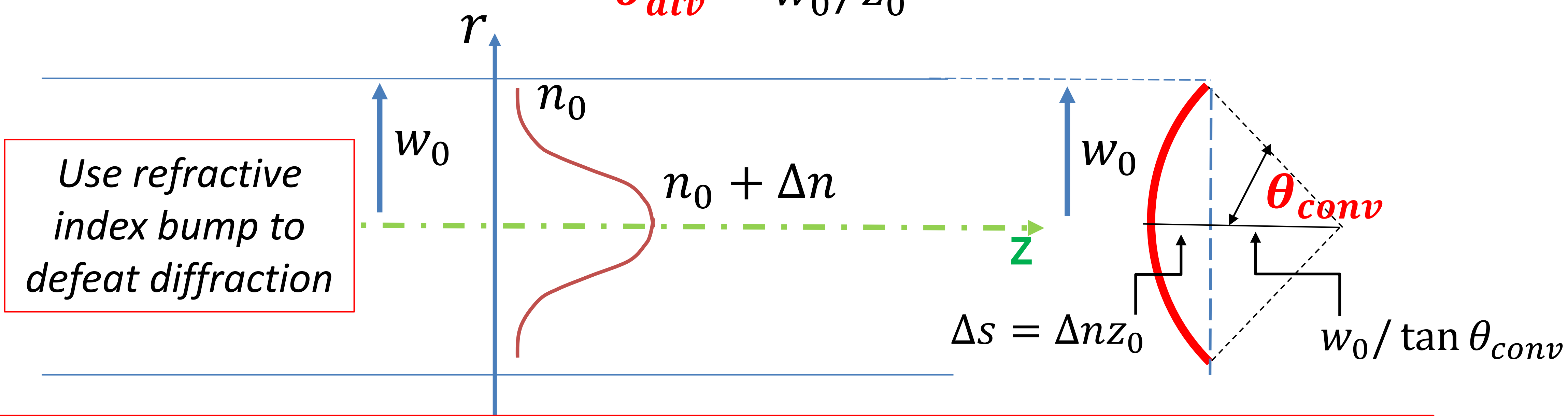
Laser couples efficiently (resonantly) to the plasma wave when $c\tau_{laser} \approx \frac{\lambda_p}{2} \propto N_e^{-1/2}$

Optical waveguides: requirements



diffractive divergence of Gaussian beam

$$\boldsymbol{\theta_{div}} = w_0/z_0$$



Use refractive index bump to defeat diffraction

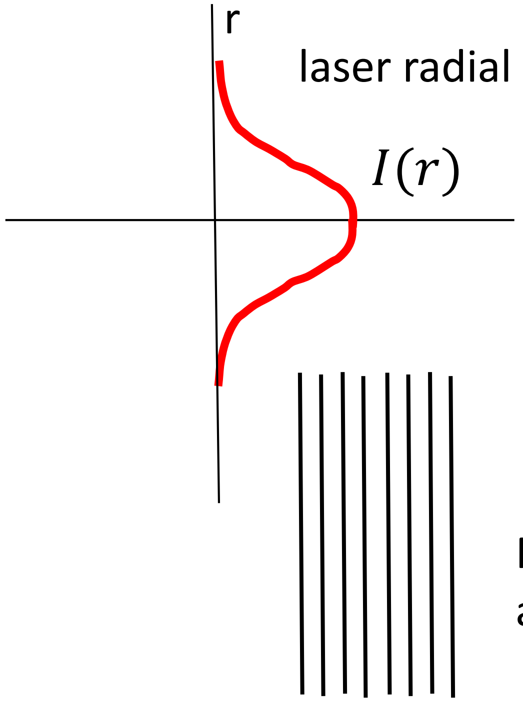
Find index bump Δn so that $\boldsymbol{\theta_{conv}}$=$\boldsymbol{\theta_{div}}$ → $\Delta n = \frac{1}{2}(kz_0)^{-1}$

Nonlinear self-focusing and waveguiding

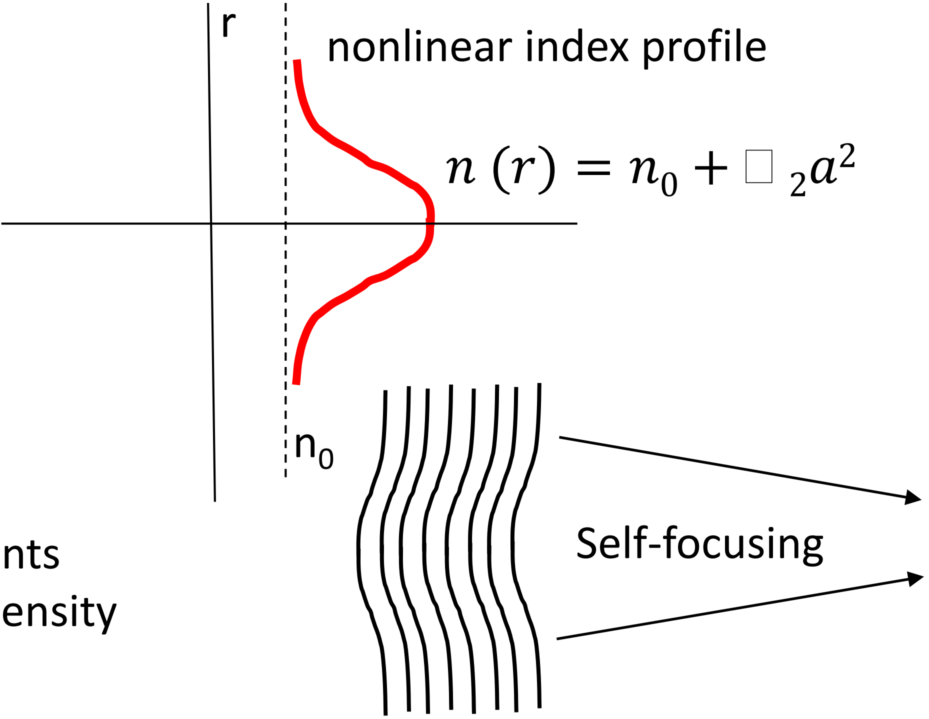
In perturbation theory,

$$P = \square(1)E + \cancelto{0}{\chi(2)E^2} + \chi^{(3)}E^3 + \ldots \longrightarrow P = \overbrace{(\chi^{(1)} + \chi^{(3)}E^2)}^{\chi_{eff}}E + \cdots$$

$$n^2 = 1 + 4\square_{eff} \longrightarrow n = n_0 + n_2 E^2 \longrightarrow n = n_0 + \eta_2 a^2$$



Phase fronts at low intensity



Self-focusing

Relativistic self-focusing in plasma: requirements

$n = n_0 + \eta_2 a^2$ ➞ index bump $\Delta n = \eta_2 a^2$, where $\eta_2 = \frac{1}{4}\frac{N_e}{N_{cr}}$ in plasma

Defeat diffraction requirement: $\Delta n = \frac{1}{2}(kz_0)^{-1} = \eta_2 a^2$

➞ $\boxed{P_{SF} \sim 17.4\ N_{cr}/N_e\ \text{(GW)}}$

Message: low plasma density demands high peak laser power:

At $\lambda = 800\ nm$ and $N_e = 10^{17}\ cm^{-3}$, $P_{SF,\ min}$ ~"petawatt class"

By contrast, for 'near critical' densities $\frac{N_e}{N_{cr}} > 0.1$, have $\boldsymbol{P_{SF} < 1}$ **TW**

A. Goers *et al*., PRL **115**, 194802 (2015)
D. Guénot *et al*., Nat. Phot. **11**, 293 (2017)
F. Salehi *et al*., PRX **11**, 021055 (2021)

Optical waveguides in plasma

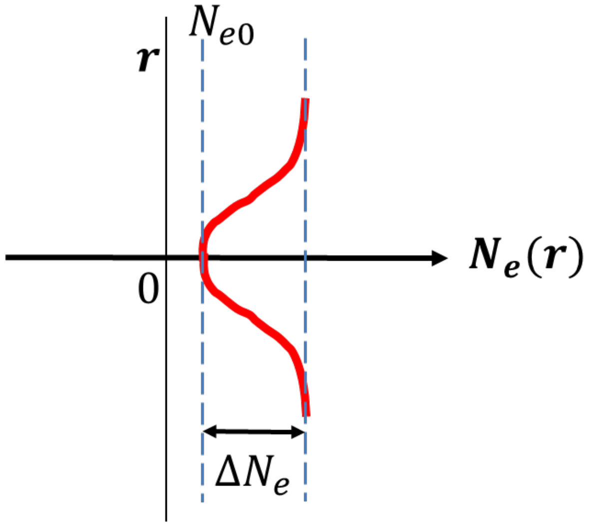
Collisionless plasma refractive index: $n^2 = 1 - \omega_p^2/\omega^2 = 1 - N_e/N_{cr}$

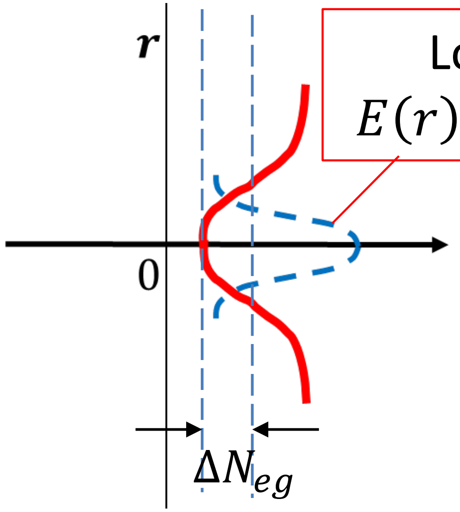
For $\lambda_{laser} = 800\ nm$, $N_{cr} = 1.7 \times 10^{21}\ cm^{-3}$

For $N_e\ <\ 10^{19}\ cm^{-3}$ typically used for LWFA, $N_e/N_{cr} < 0.005$

$$\rightarrow \quad n \approx 1 - N_e/2N_{cr} \quad \rightarrow \quad \Delta n = -\,\Delta N_e/2N_{cr}$$

Defeat diffraction requirement: $\Delta n = \frac{1}{2}(kz_0)^{-1} = -\Delta N_e/2N_{cr}$





Lowest order mode:
$E(r) = E_0 \exp(-r^2/w_{ch}^2)$

$$\boxed{|\Delta N_{eg}| = \ (\pi r_e w_{ch}^2)^{-1}}$$

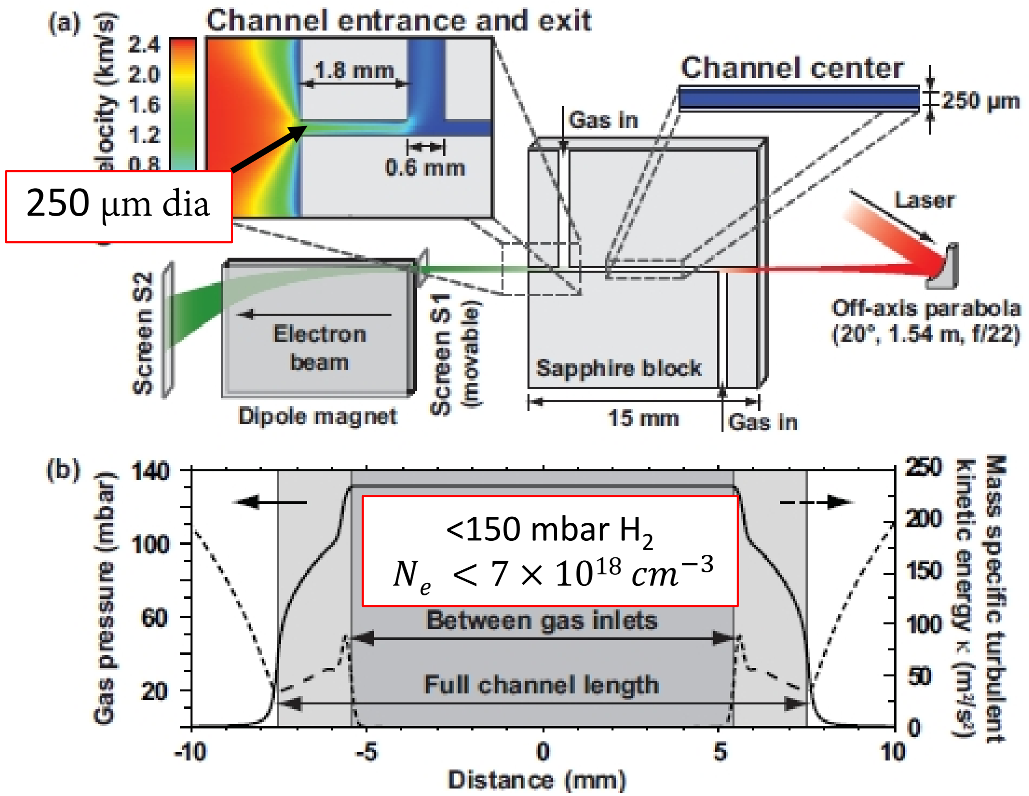
Example: $w_{ch}\ = 35\ \mu m \rightarrow \Delta N_{eg} \sim 10^{17}\ cm^{-3}$

Relativistically self-guided laser pulses

Relativistic self-focusing leads to pulse “collapse”, which saturates or ‘arrests’ due to ponderomotive charge expulsion, giving rise to self-guiding in a self-consistent plasma density depression

gas cells

~25 TW, 500 MeV



250 μm dia

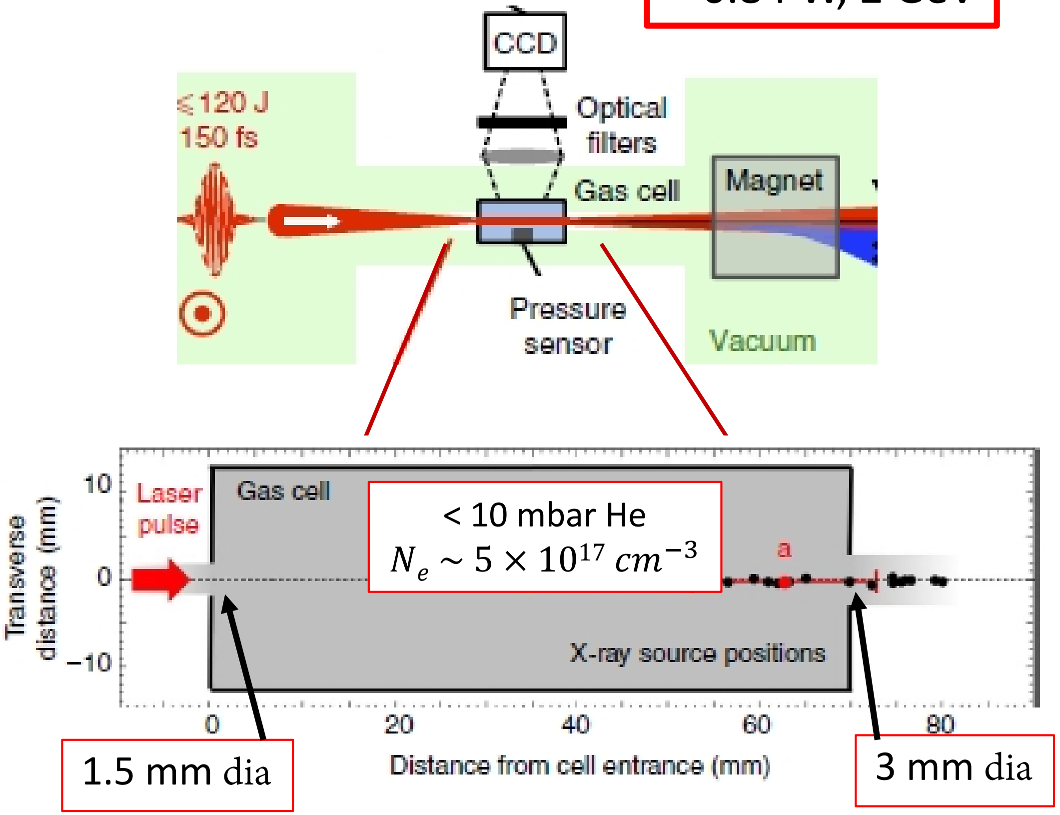
<150 mbar H_2
$N_e < 7 \times 10^{18}\ cm^{-3}$

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

F. Dorchies *et al.*, Phys. Rev. Lett. 82, 4655 (1999) *non-discharge capillary*

G. Genoud *et al.*, Appl. Phys. B (2011) **105**:309

~0.8 PW, 2 GeV



< 10 mbar He
$N_e \sim 5 \times 10^{17}\ cm^{-3}$

1.5 mm dia

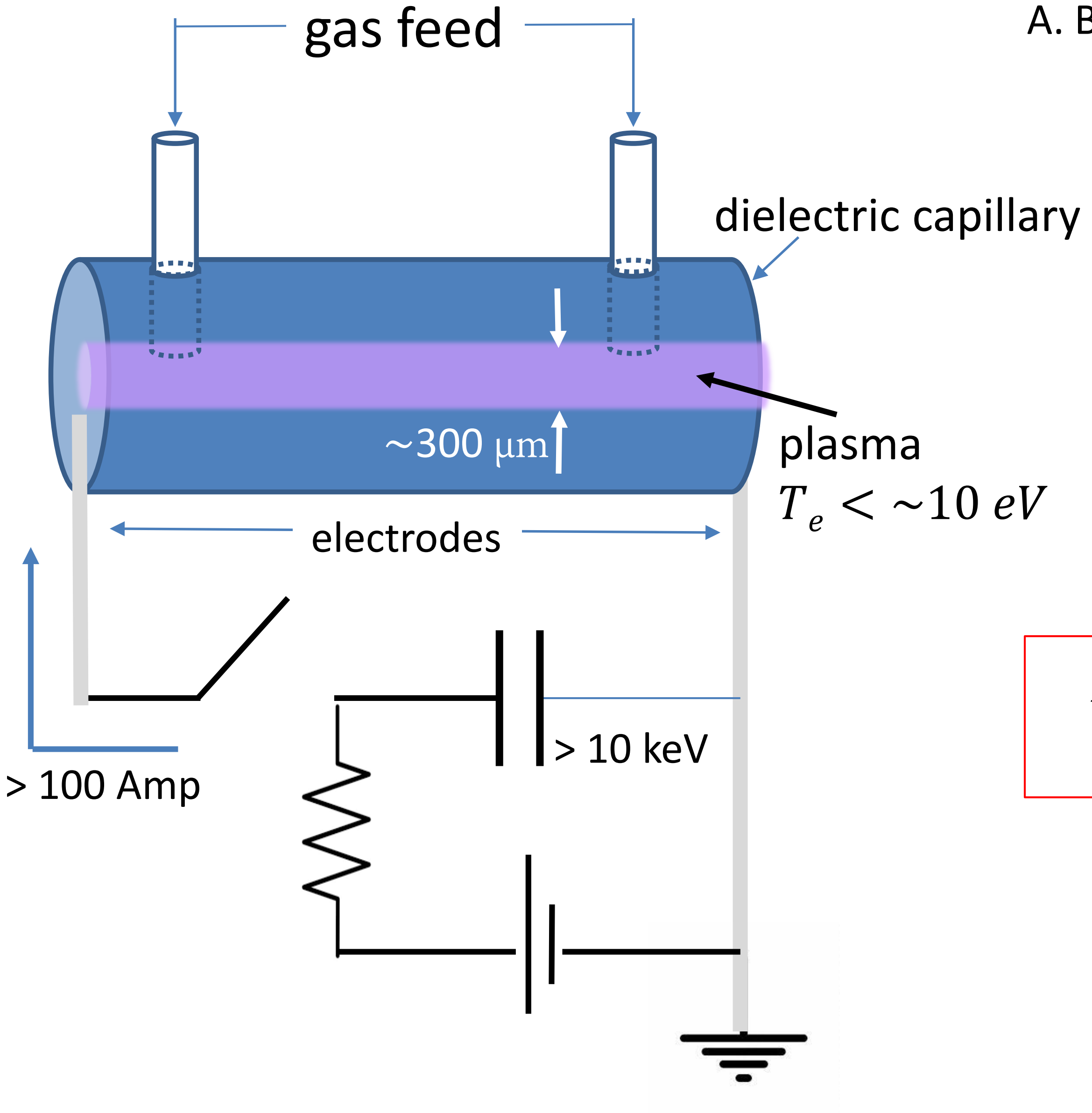
3 mm dia

X. Wang *et al.*, Nat. Comm. **4**, 1988 (2013)

Preformed plasma waveguides: capillary discharge

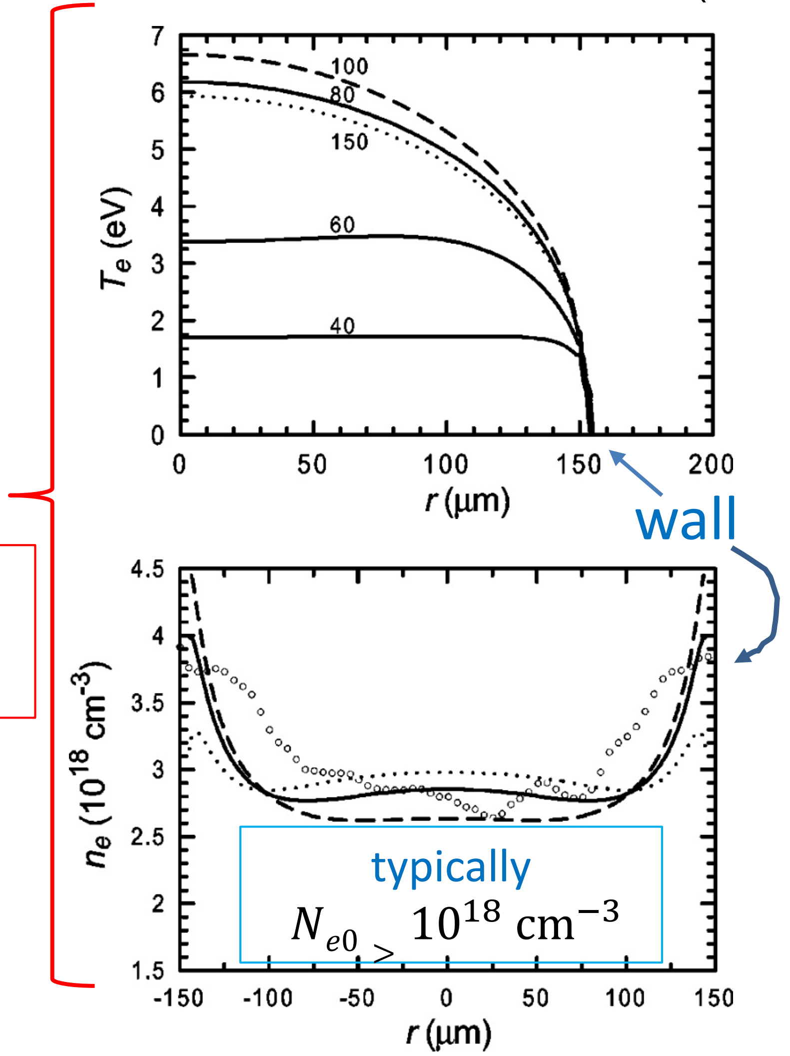
Y. Ehrlich *et al.*, PRL **77**, 4186 (1996) ← *no gas fill*

A. Butler, D. J. Spence, and S. M. Hooker, PRL **89**, 185003 (2002)



Quasi steady state pressure equilibrium across channel

$$P = N_e(r) k_B T_e(r) = const$$



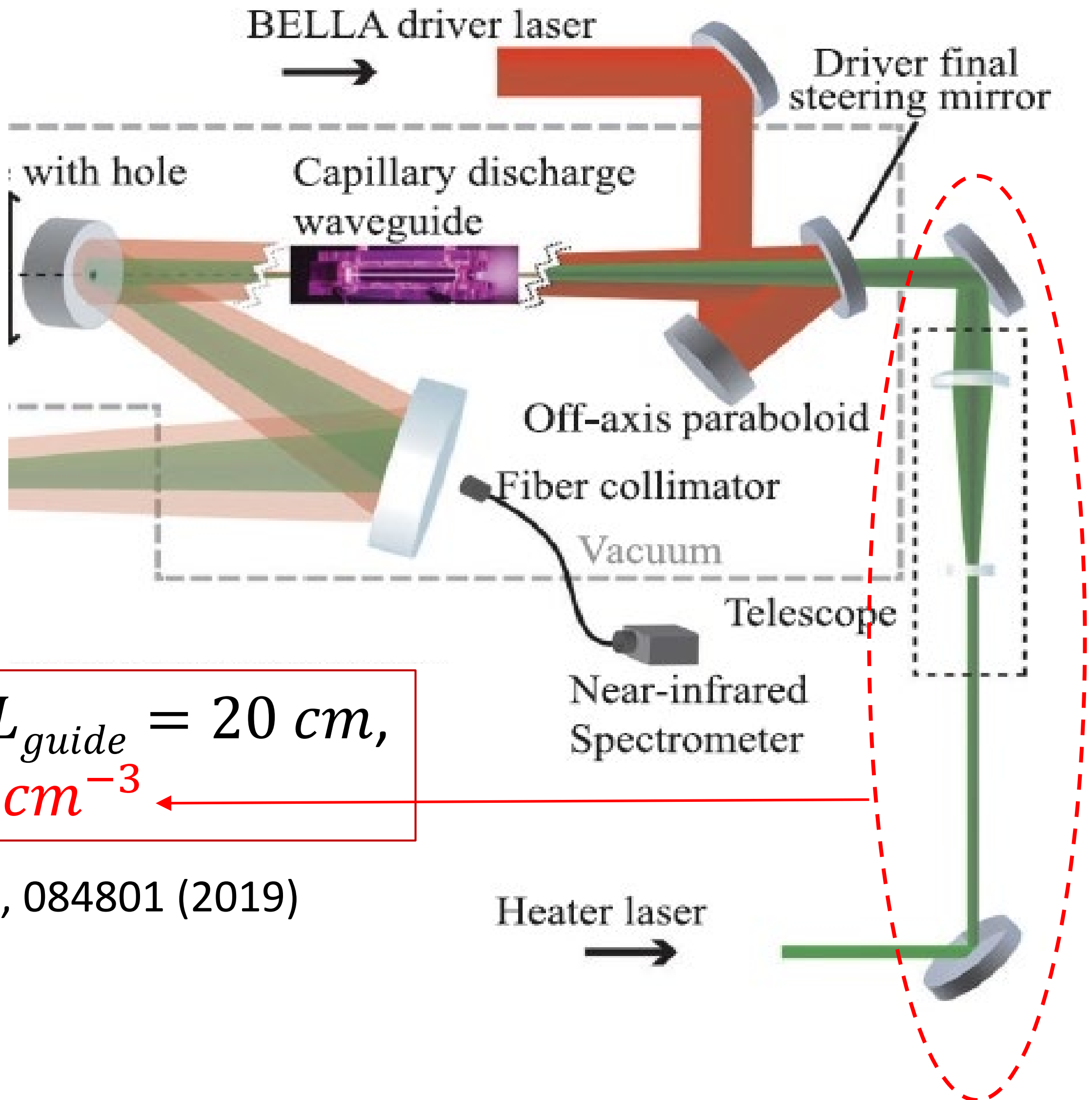
N. A. Bobrova *et al.*, PRE 65, 016407 (2001)

typically $N_{e0} \gtrsim 10^{18}\ \mathrm{cm}^{-3}$

~4 GeV and ~8 GeV results with capillary discharge waveguide

4 GeV results: 0.3 PW, $L_{guide} = 10\ cm,$
$N_{e0} \sim 10^{18}\ cm^{-3}$

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

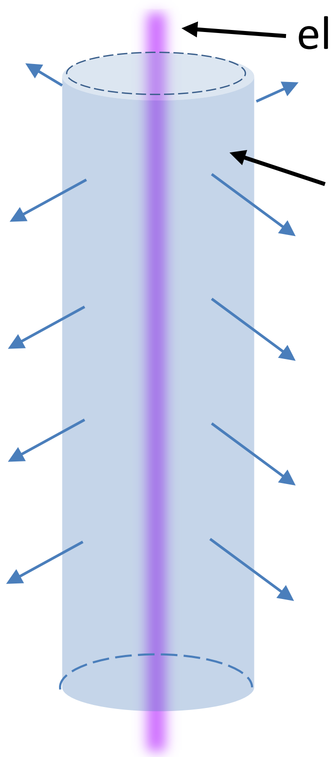


8 GeV results: 0.85 PW, $L_{guide} = 20\ cm,$
$N_{e0} \sim 3 \times 10^{17}\ cm^{-3}$

A. J. Gonsalves *et al.*, PRL 122, 084801 (2019)

Laser-generated waveguides

principle



elongated hot plasma

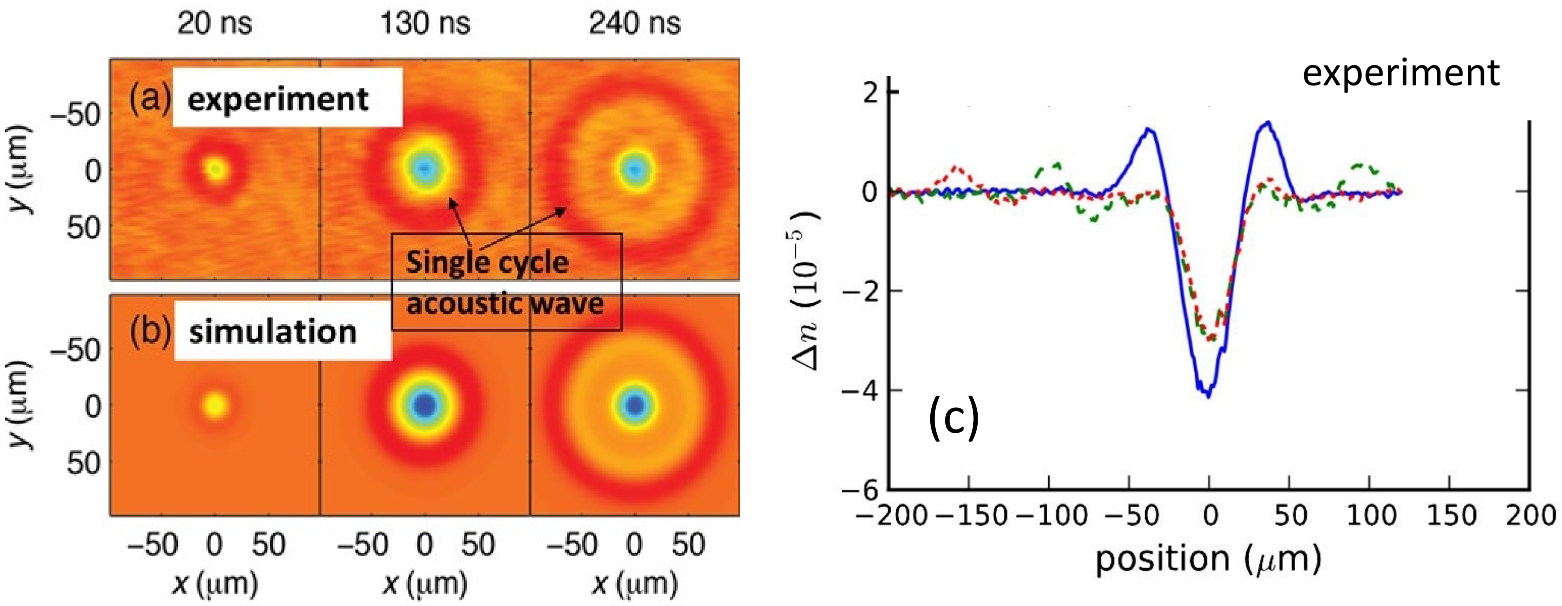
launches

single-cycle
acoustic wave

into

ambient gas

femtosecond filament-induced single-cycle acoustic wave



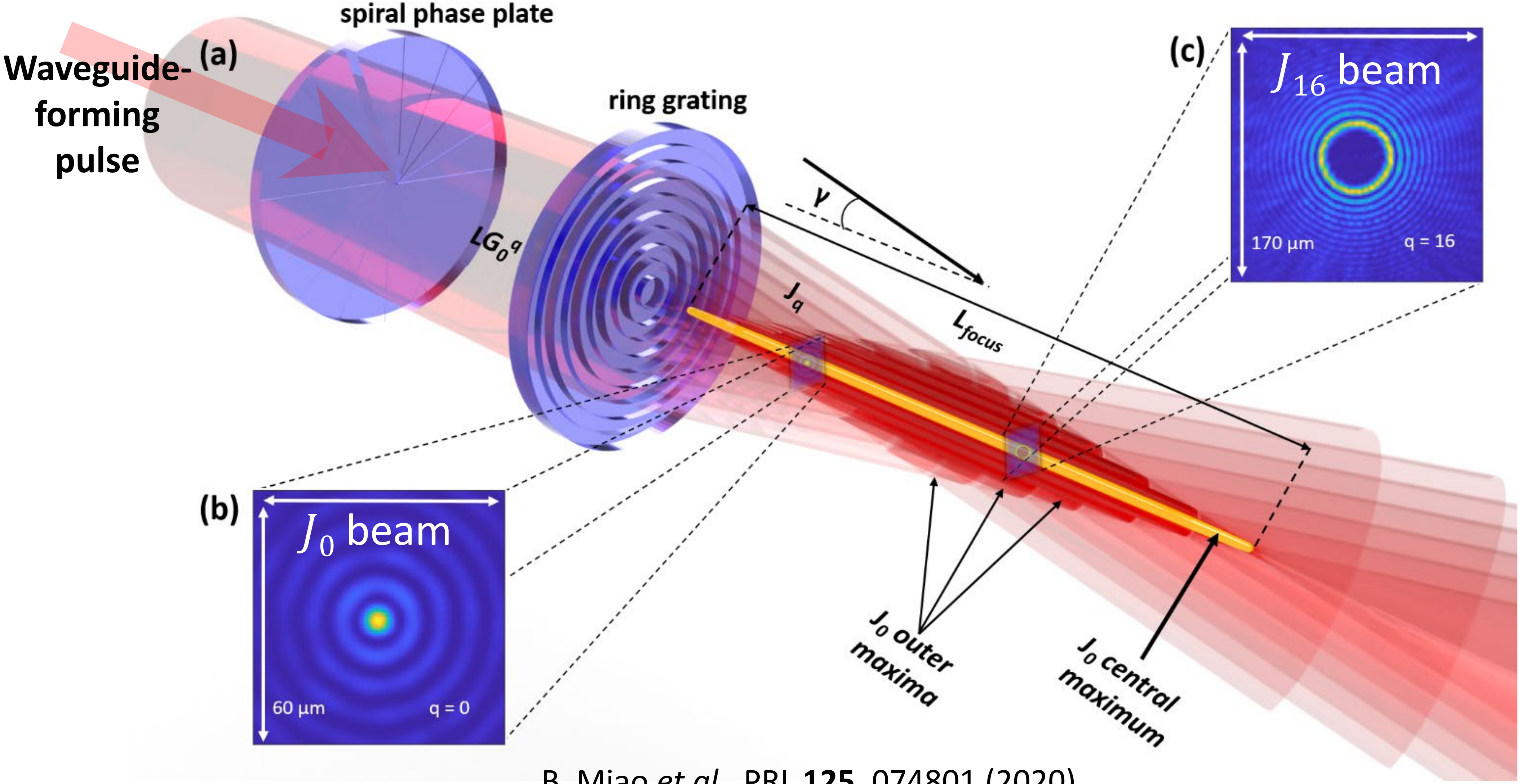
J.K. Wahlstrand *et al*. Opt. Lett. **39**, 1290 (2014)

N. Jhajj *et al*., PRX **4**, 011027 (2014) *neutral air waveguides, much slower timescales than for plasma*

Recent results: 40 meter air waveguides

Preformed plasma waveguides: *Bessel beam-generated*

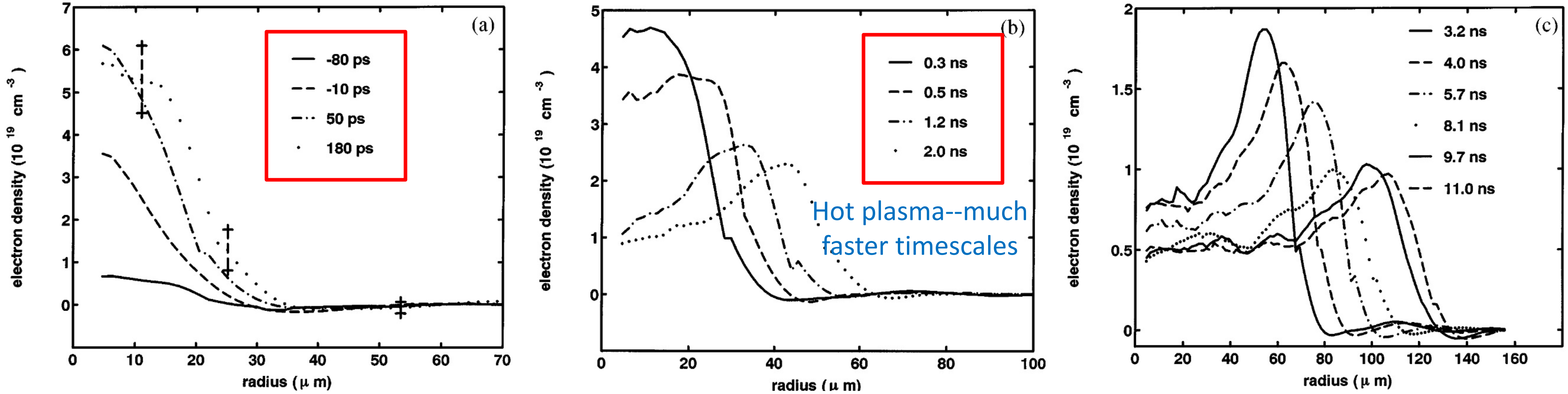
(self-interfering conical wavefronts)



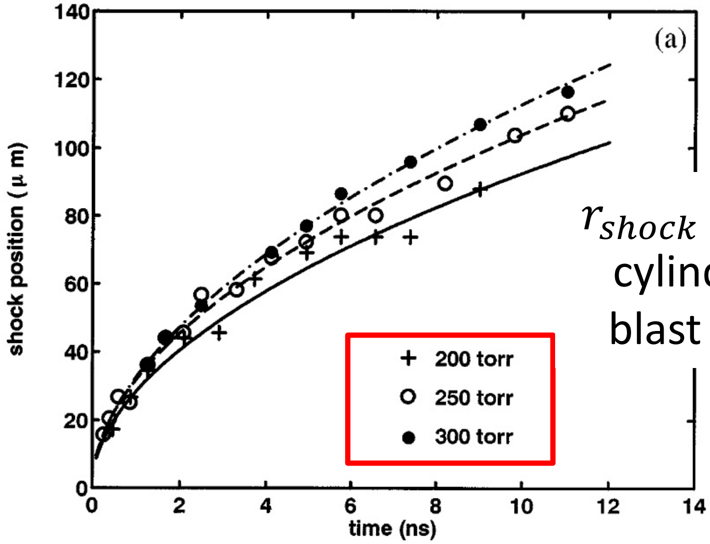
B. Miao *et al.*, PRL **125**, 074801 (2020)

Bessel-generated hydrodynamic plasma waveguides

C. G. Durfee and H. M. Milchberg, PRL **71**, 2409 (1993)
T. R. Clark and H. M. Milchberg, PRL **78**, 2373 (1997)



Hot plasma--much faster timescales

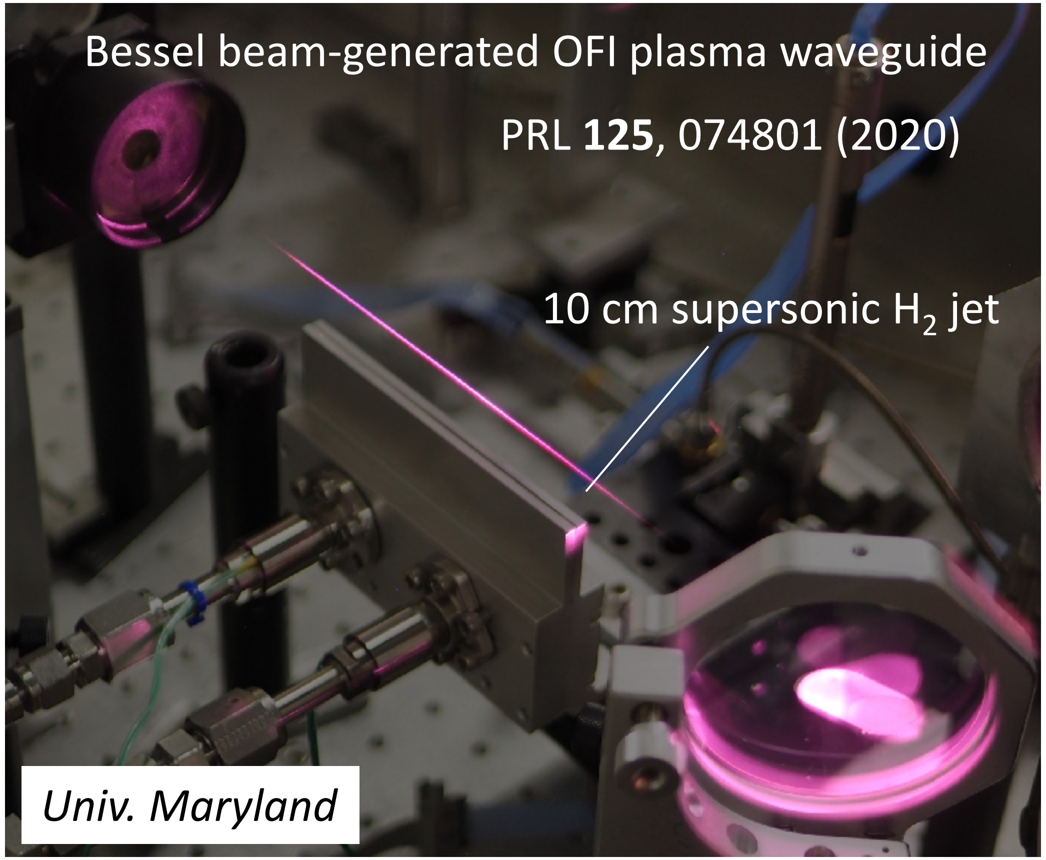


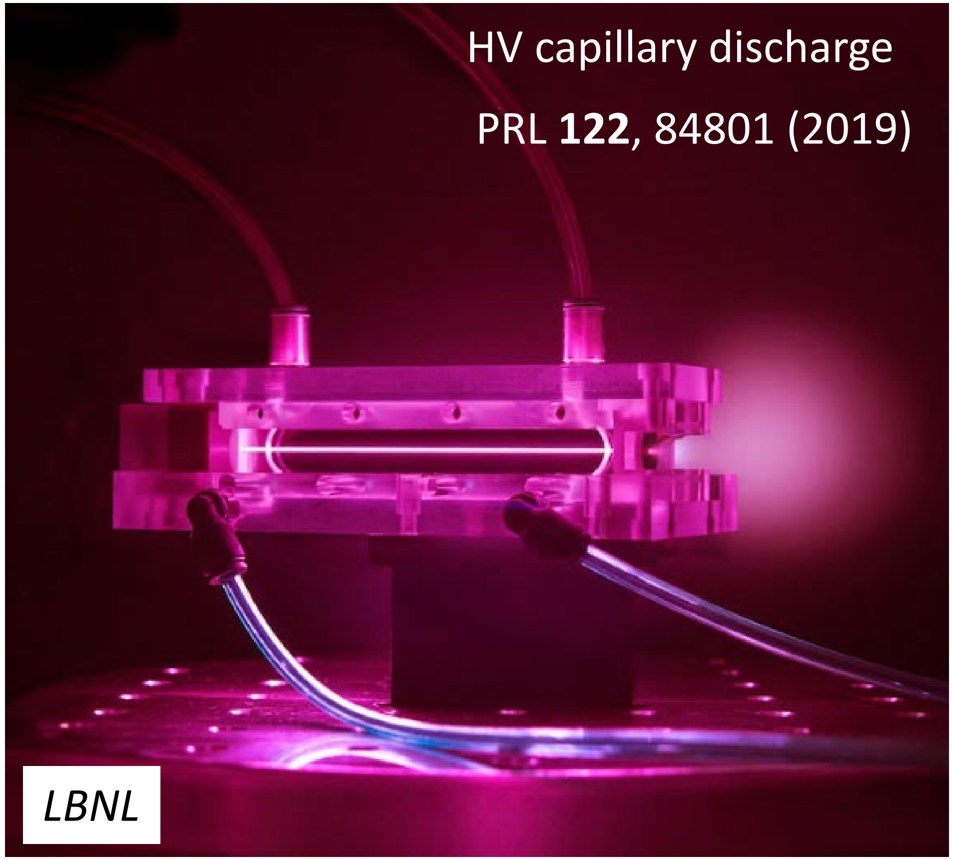
$r_{shock} \propto t^{1/2}$
cylindrical
blast wave

Early results

- Plasma heated resistively (inverse Bremsstrahlung) using $\sim 100\ ps$ pulses.
- Need $N_e > 10^{19}\ cm^{-3}$ for efficient heating
- Initial temperature T_{e0} =tens of eV

Laser-generated plasma waveguide vs. capillary discharge



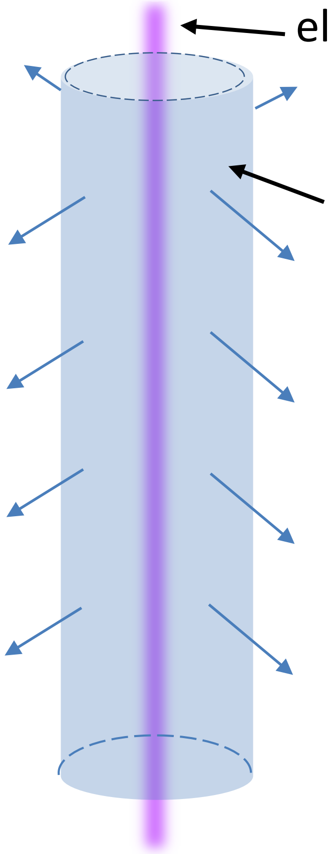


- capable of high rep. rate, limited by laser technology
- thermally cool, plasma standoff from structures
- negligible material surface erosion
- design flexibility for core, cladding, and z-variation
- Diagnostic access from all directions

- Rep. rate limited by local heat load and capillary surface erosion
- Damage from drive pulse misalignment or poor focus
- Core/cladding geometry fixed by capillary inner diameter; laser conditioning of plasma necessary
- Diagnostic access challenging

OFI-heated hydrodynamic waveguides using < 100 fs pulses

Optical field ionization:
depends on peak
intensity only



elongated plasma

launches

single-cycle
acoustic wave

into

ambient gas

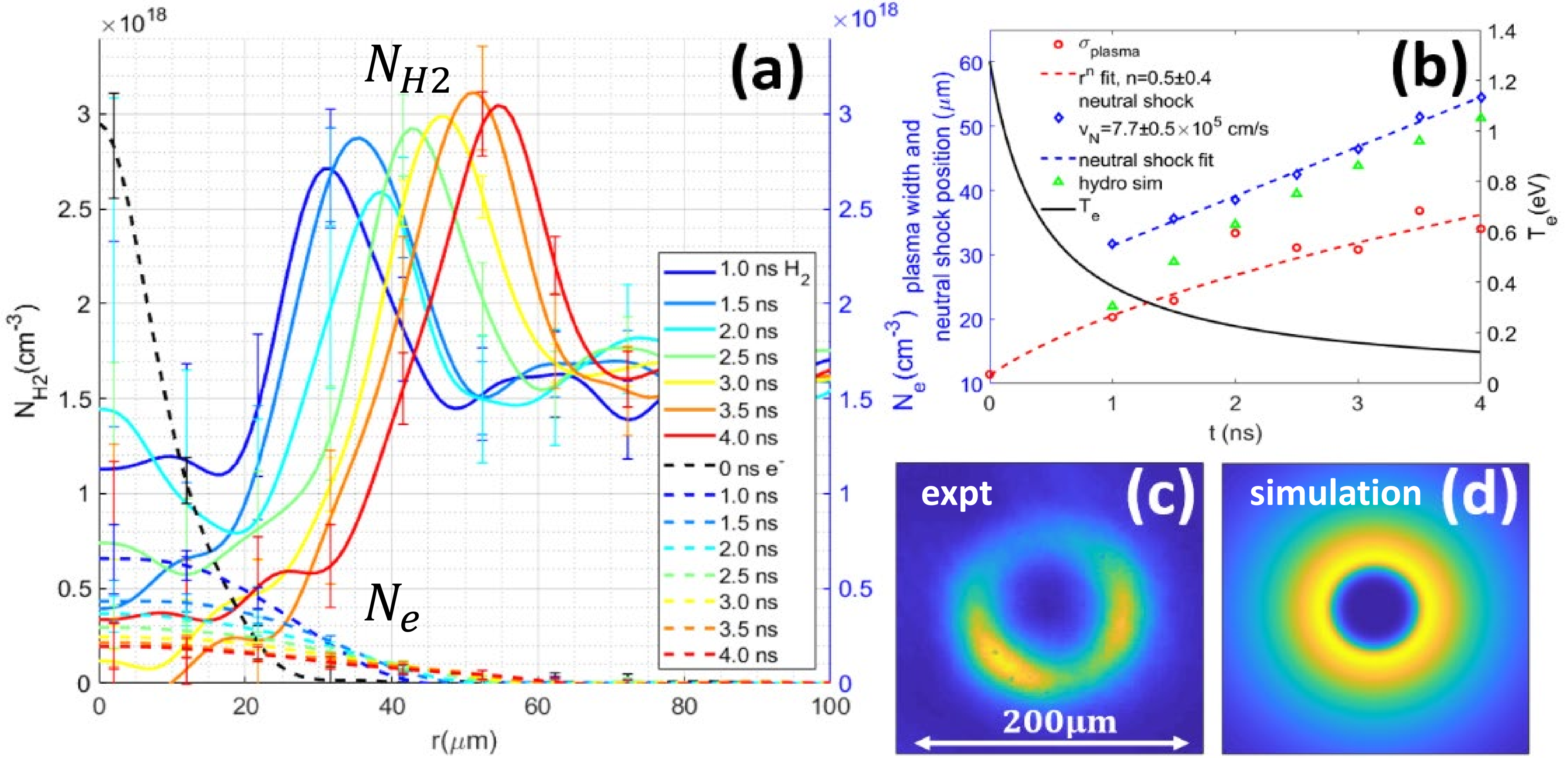
N. Lemos *et al*., Phys. Plasmas 20, 063102 (2013).
R. J. Shalloo *et al*., Phys. Rev. E 97, 053203 (2018)
N. Lemos *et al*., Sci. Rep. 8, 3165 (2018).
R. J. Shalloo *et al*., Phys. Rev. Accel. Beams 22,041302 (2019).
S Smartsev, Opt. Lett. 44,3414 (2019)
A.Picksley *et al*., Phys. Rev. Accel. Beams 23, 1 (2020).
B. Miao *et al*., PRL 125, 074801 (2020).
L. Feder *et al*., PRR 2, 043173 (2020).

BUT

$k_B T_e \sim U_{ponder}\ (I_{OFI}) < 10\ \mathrm{eV}$ at
$I_{OFI} \sim 10^{14}\,\frac{W}{cm^2}$ for hydrogen

- In low density H_2, get wimpy plasma ‘shockwave’ with low walls or no walls
- In low density H_2, OFI-based heating leads to *very leaky* guides or no guides at all !
- Must somehow provide the waveguide ‘cladding’

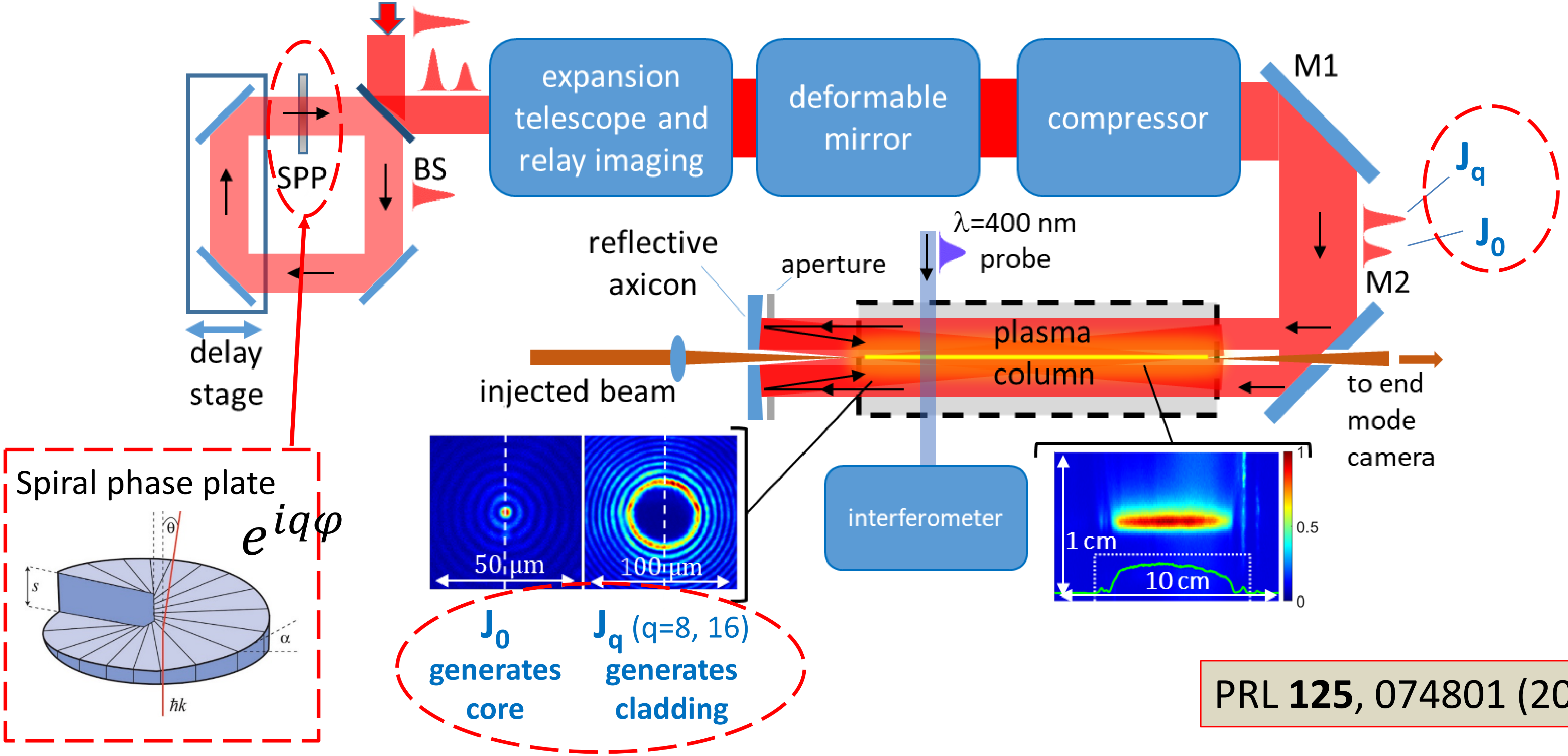
2 colour interferometer probing reveals separate plasma and neutral H_2 contributions



Guiding in neutral H_2 shock annulus

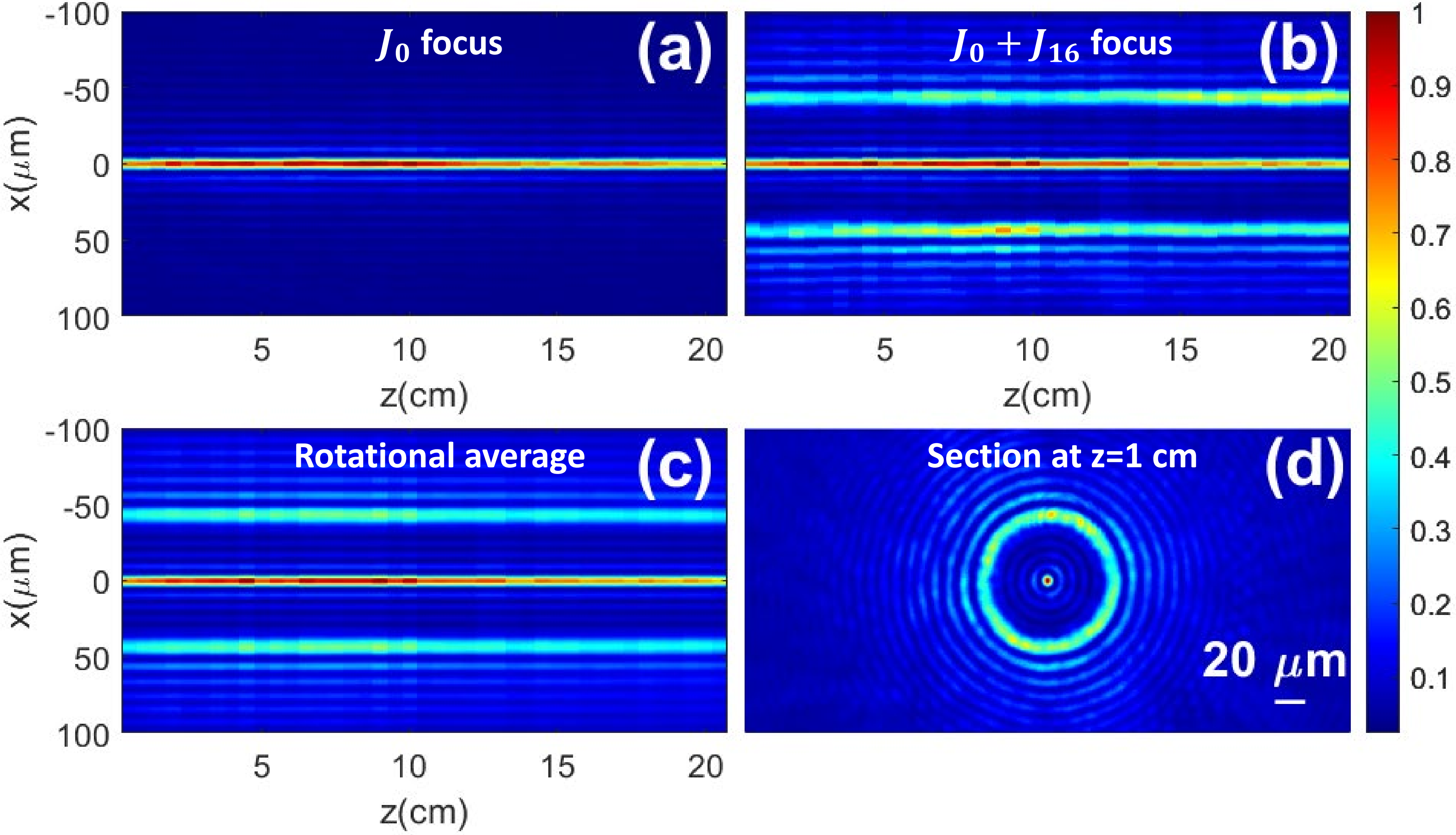
L. Feder et al., PRR 2, 043173 (2020).

Cladding solution #1: 2-Bessel method for separately imprinting core and cladding plasma



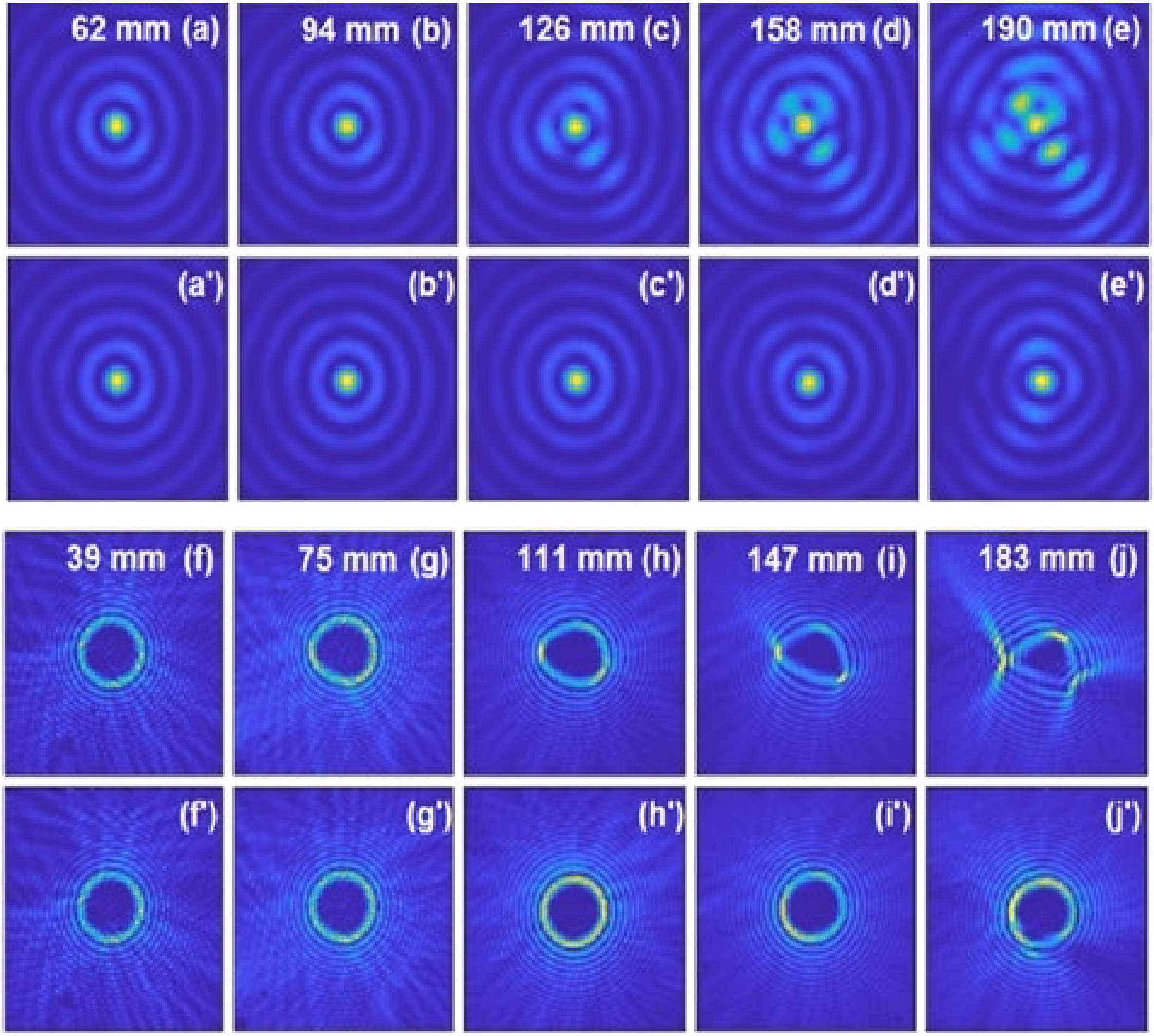
PRL **125**, 074801 (2020)

Measurement of Bessel beam focus



Important considerations if you want to do this

1. ***You need a high quality Bessel beam profile along meter-scale distances***



J_0 uncorrected

J_0 corrected w/deformable mirror

Opt. Express **30**, 11360 (2022)

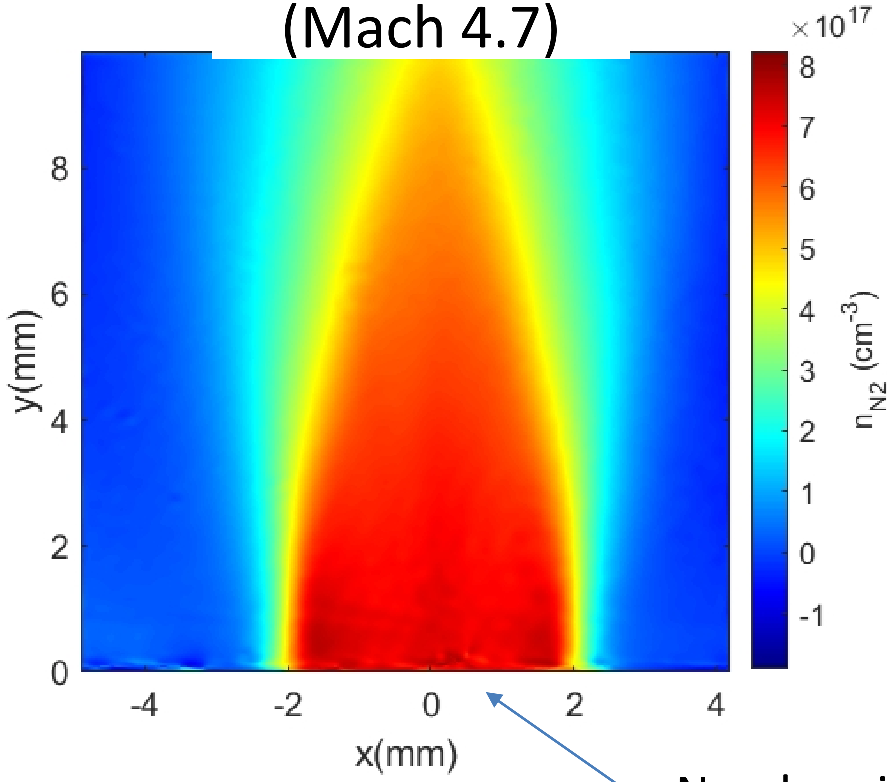
J_{16} uncorrected

J_{16} corrected w/deformable mirror

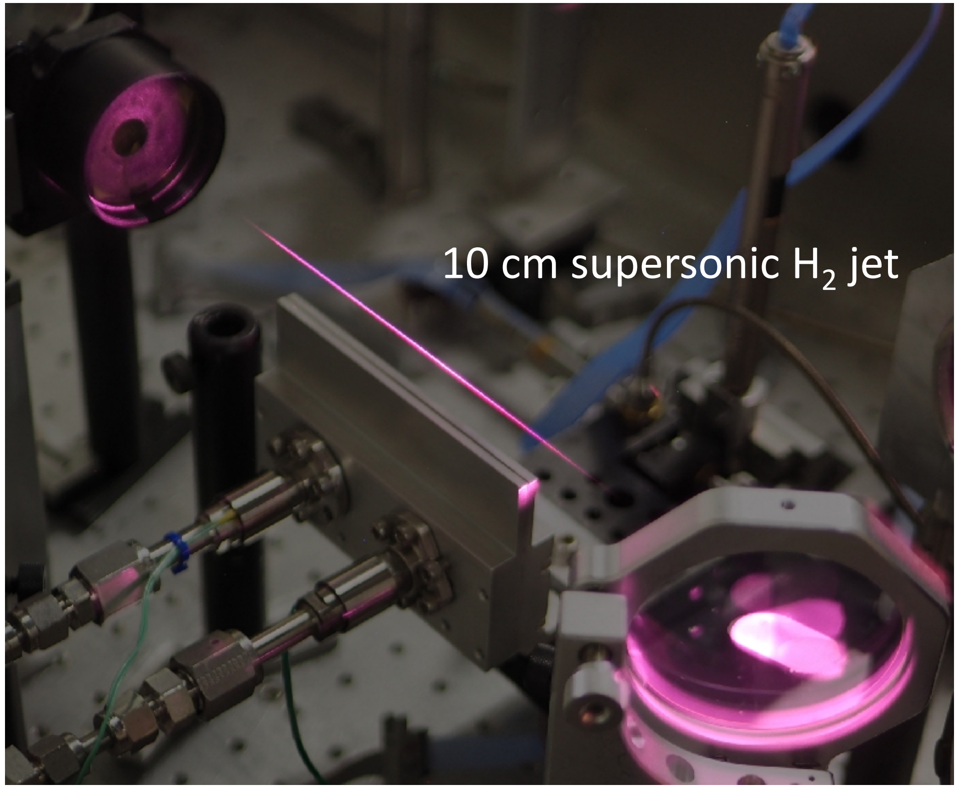
Important considerations if you want to do this

2. ***You need meter-scale supersonic gas jets---***

End-view density profile of 10 cm long supersonic jet (Mach 4.7)

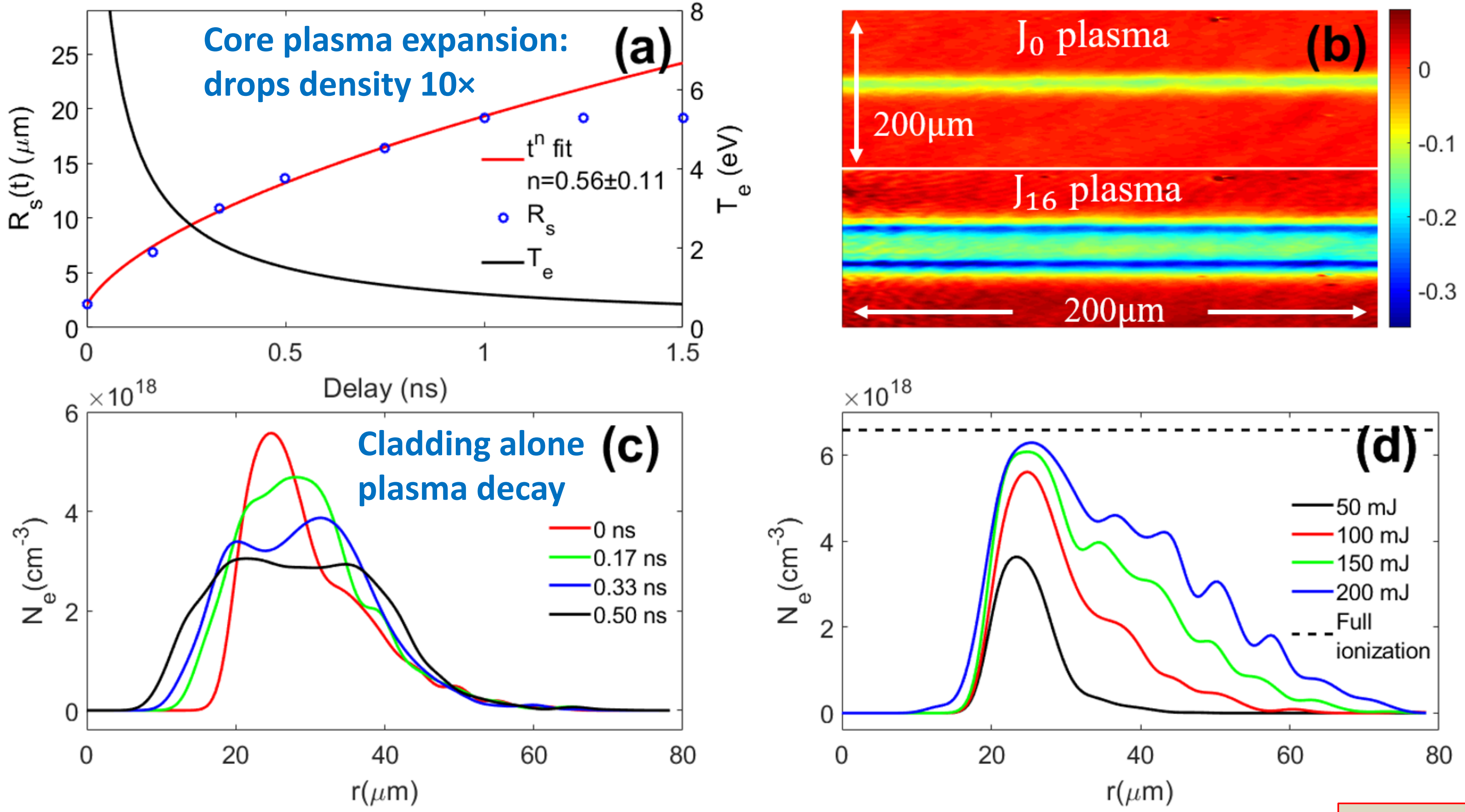


Nozzle orifice



10 cm supersonic H_2 jet

Interferometric measurements of plasma fiber structure



Core plasma expansion: drops density 10×

core plasma

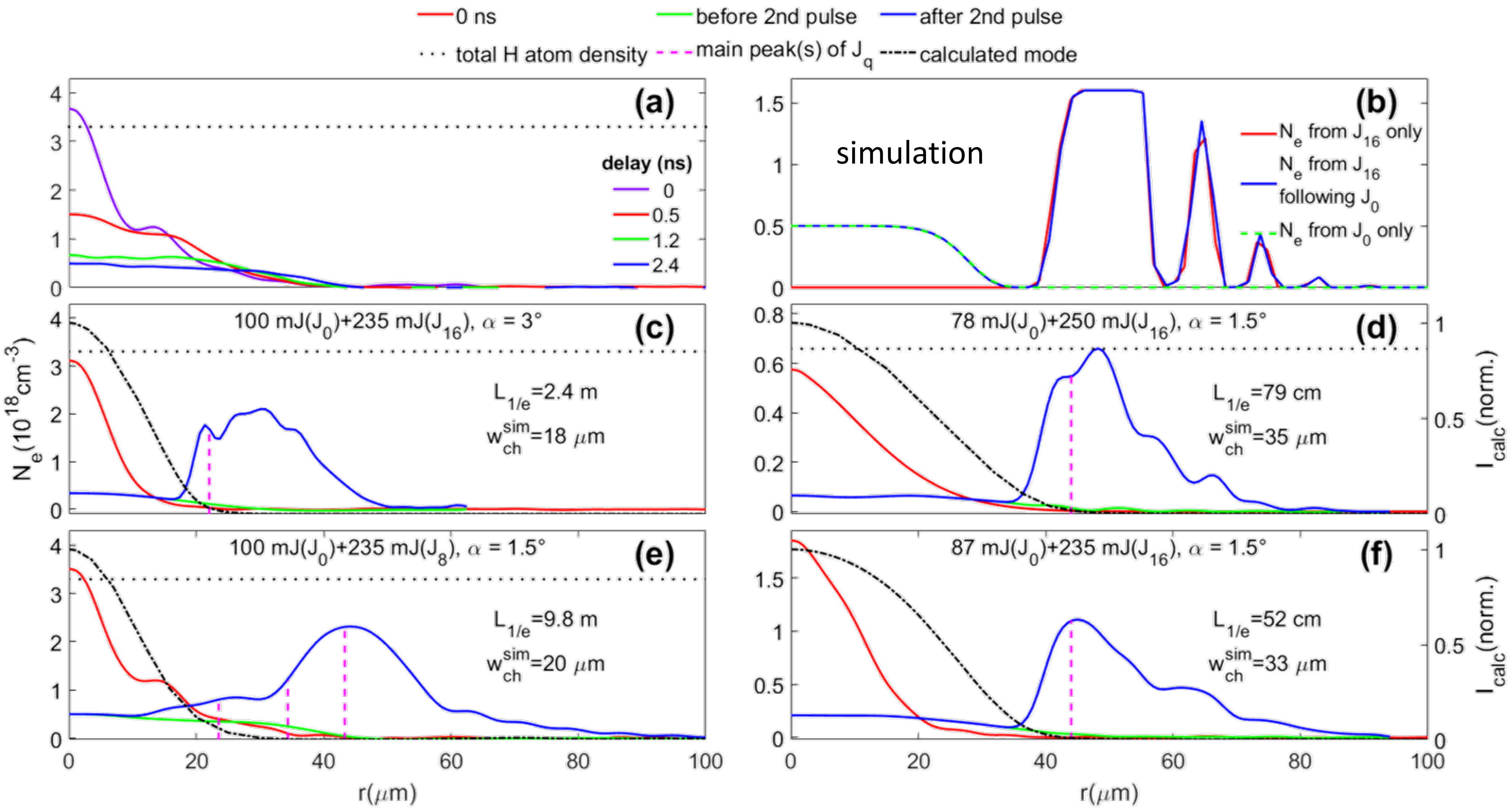
cladding plasma

Cladding alone plasma decay

cladding plasma vs. J_{16} energy

PRL **125**, 074801 (2020)

$J_0 + J_q$ plasmas: flexible step index optical fibre



P_{H2}=
50 torr

10 torr

50 torr

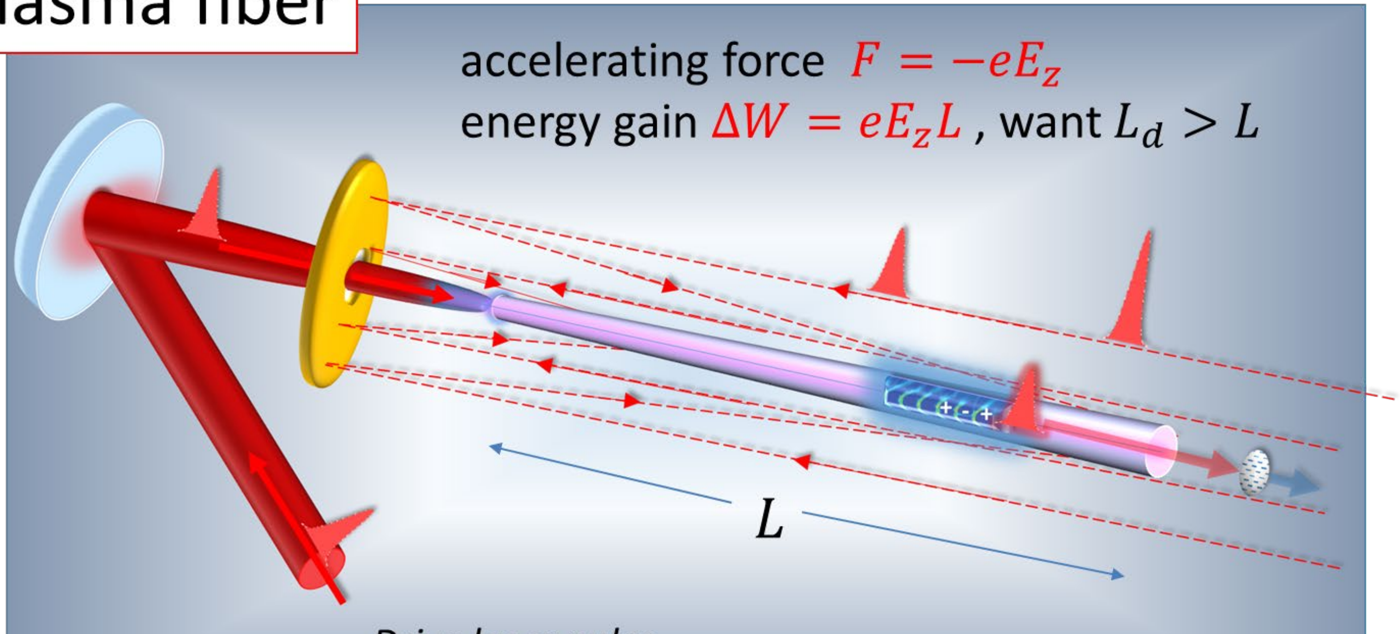
30 torr

PRL **125**, 074801 (2020)

Guiding experiments

PRL **125**, 074801 (2020)

Plasma fiber



accelerating force $F = -eE_z$

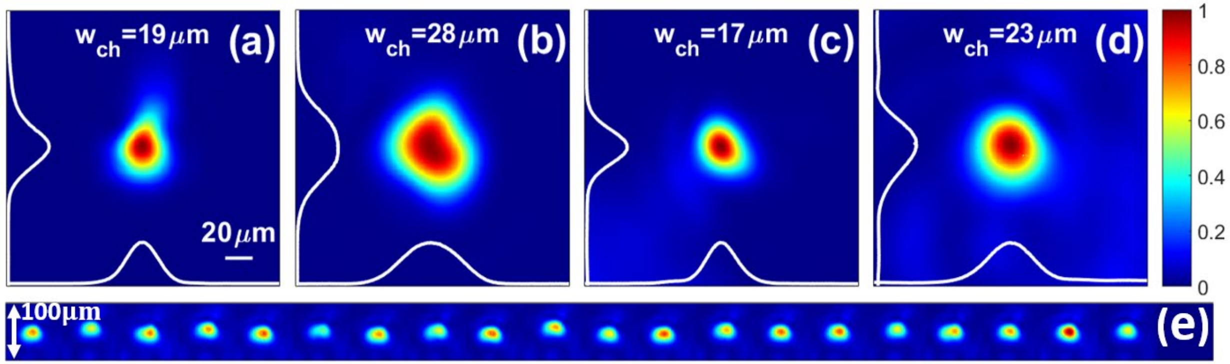
energy gain $\Delta W = eE_zL$, want $L_d > L$

Drive laser pulse

$$L_{max} \sim 30 \text{ cm}$$

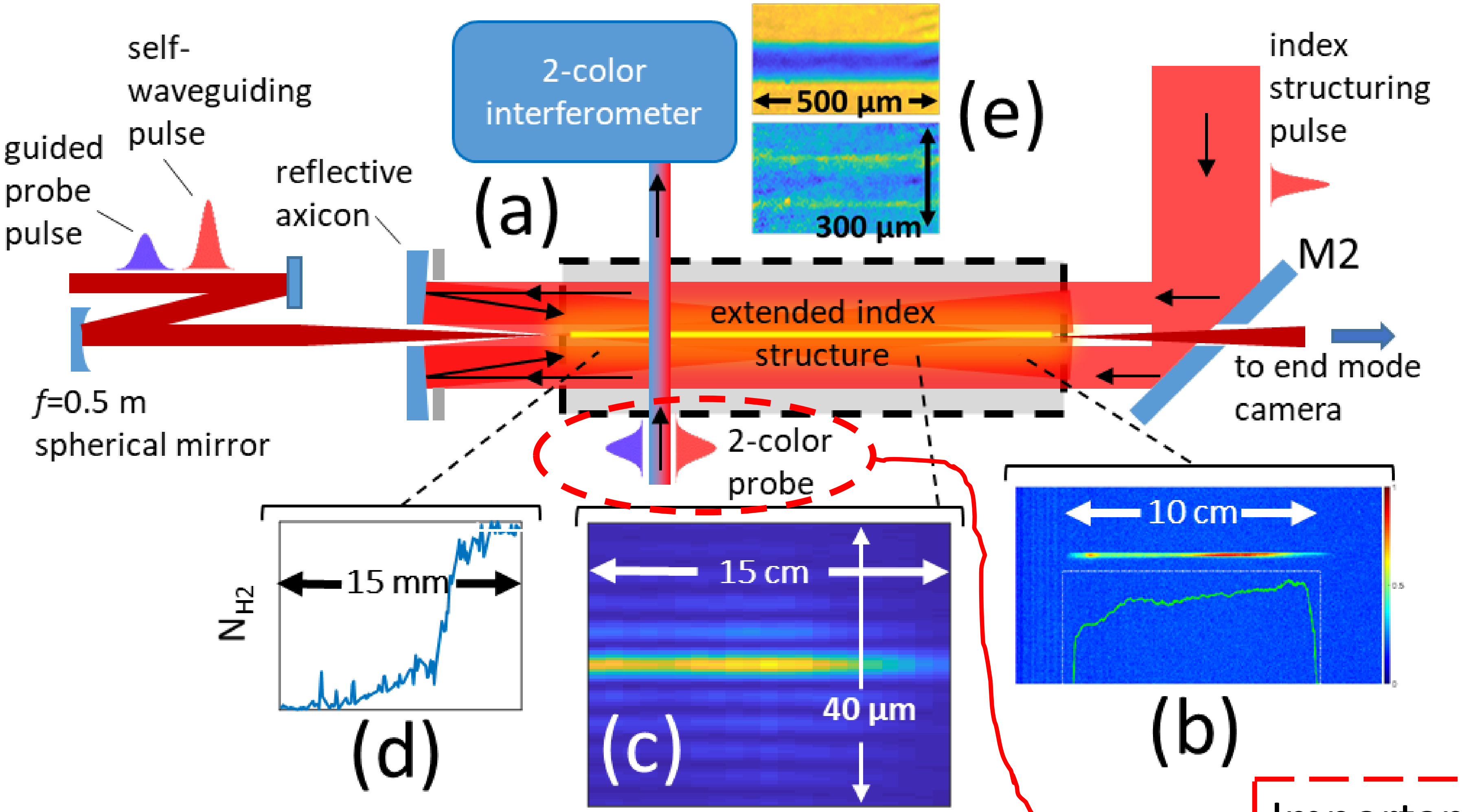
$$\frac{L_{max}}{z_0} \sim 260$$

guided laser exit modes from various waveguides



20 consecutive shots in gas jet

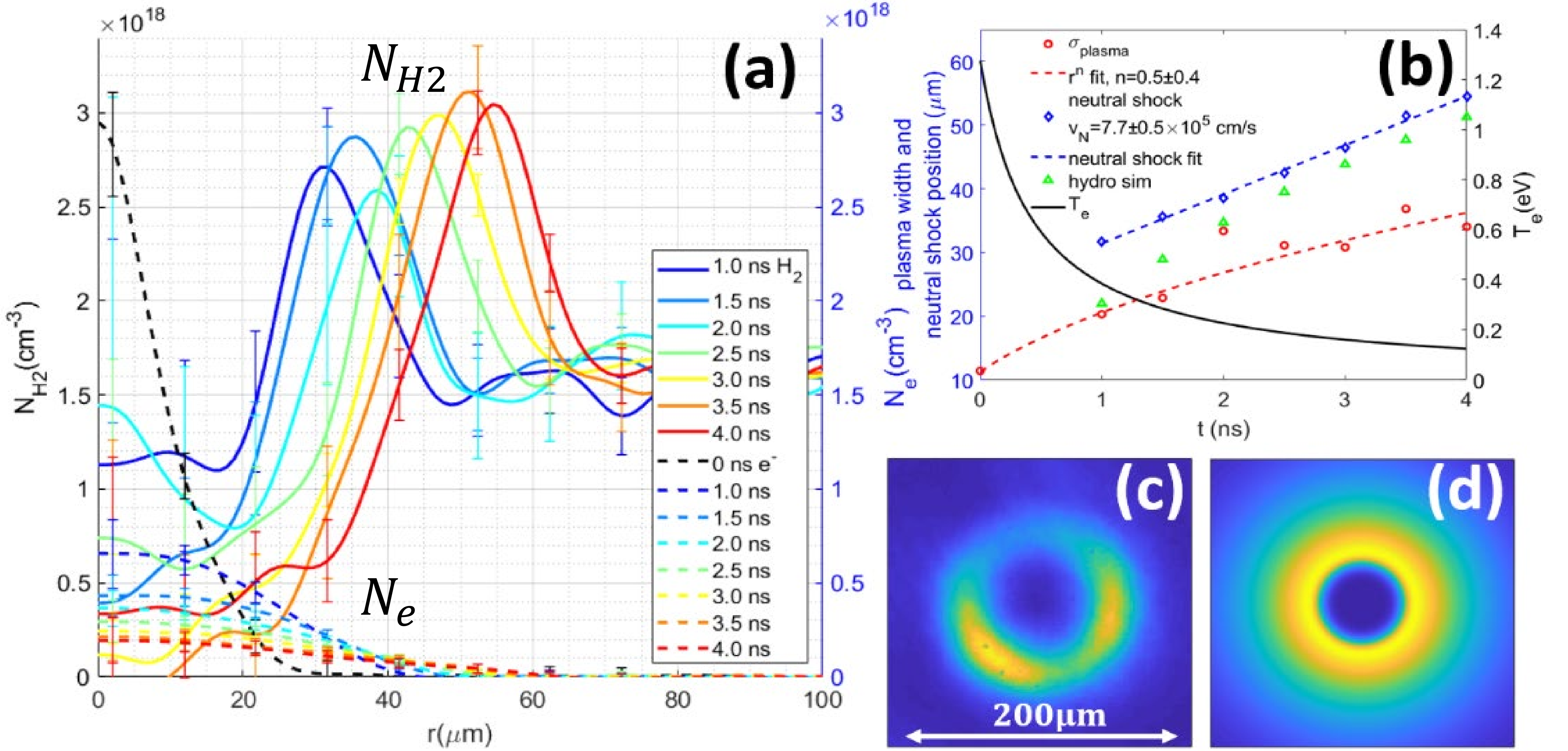
*Cladding solution #2: “**Self-waveguiding**” – no J_q used.*



L. Feder *et al*., Phys. Rev. Res. **2**, 043173 (2020)

Important: two colour interferometric probe

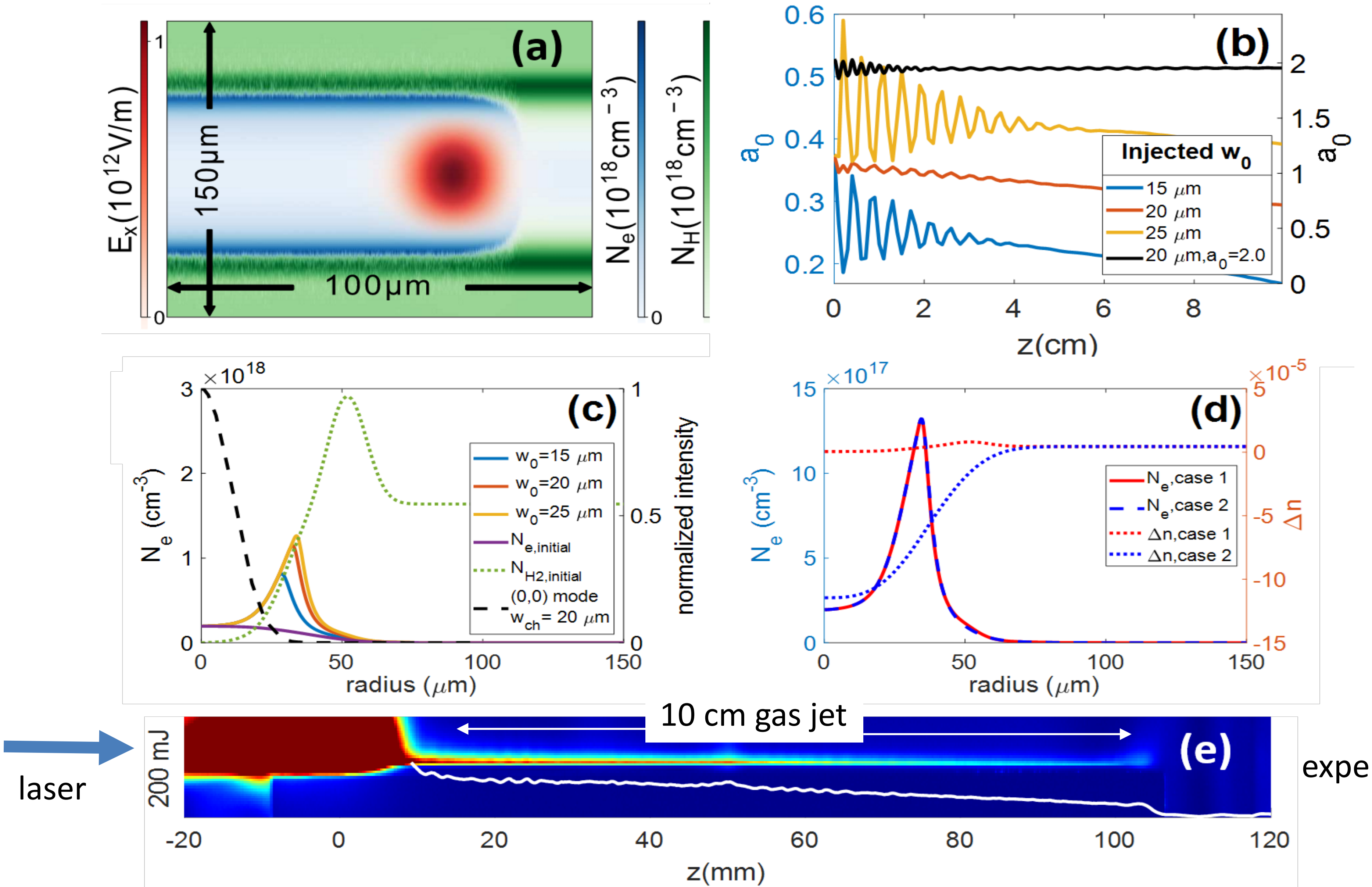
Two-colour interferometric probing reveals separate plasma and neutral H_2 contributions



Guiding in neutral H_2 shock annulus

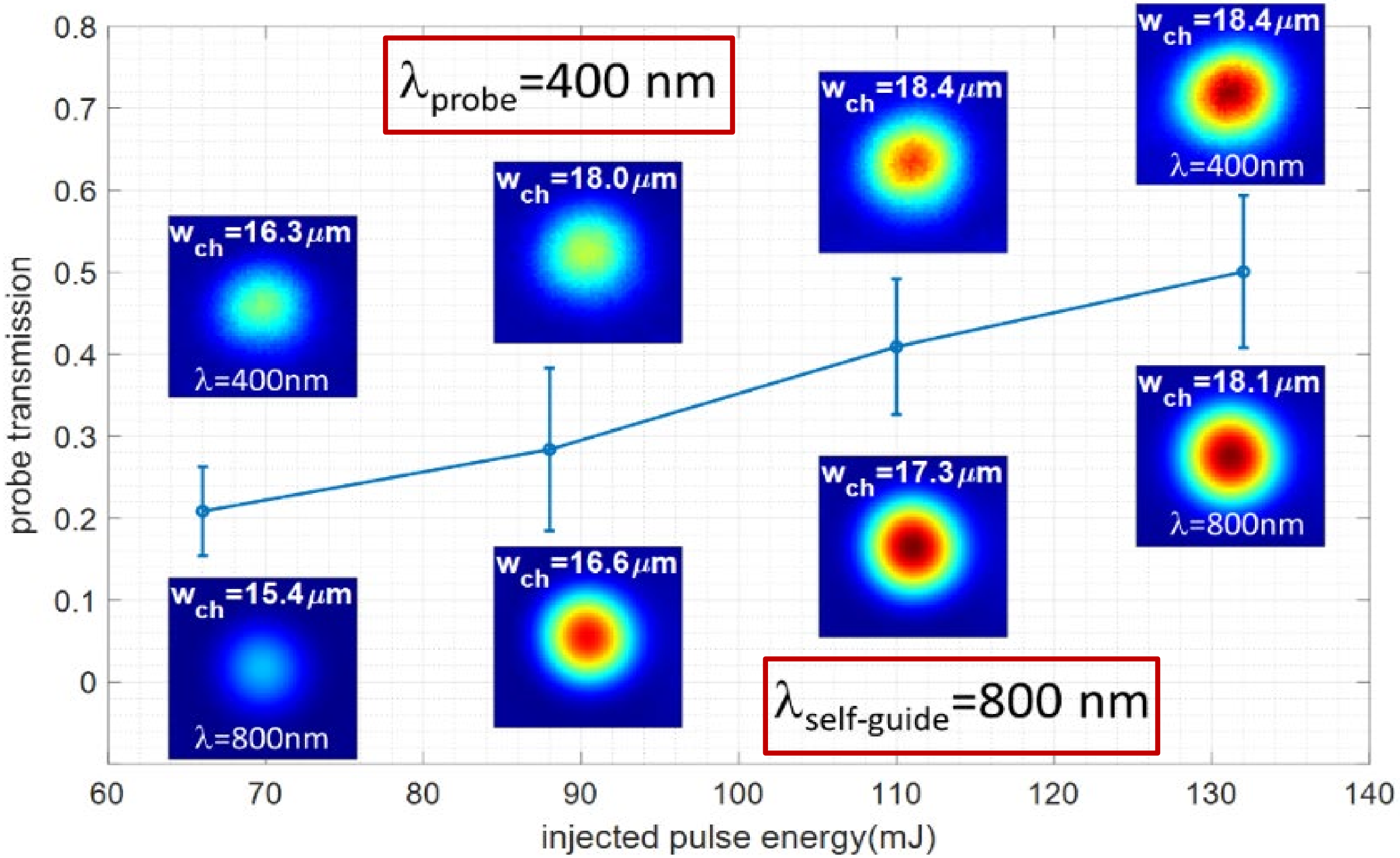
Self-waveguiding: simulations and experiment

L. Feder *et al.*, Phys. Rev. Res. **2**, 043173 (2020)



experiment

400nm probe guiding & 800 nm self-waveguiding

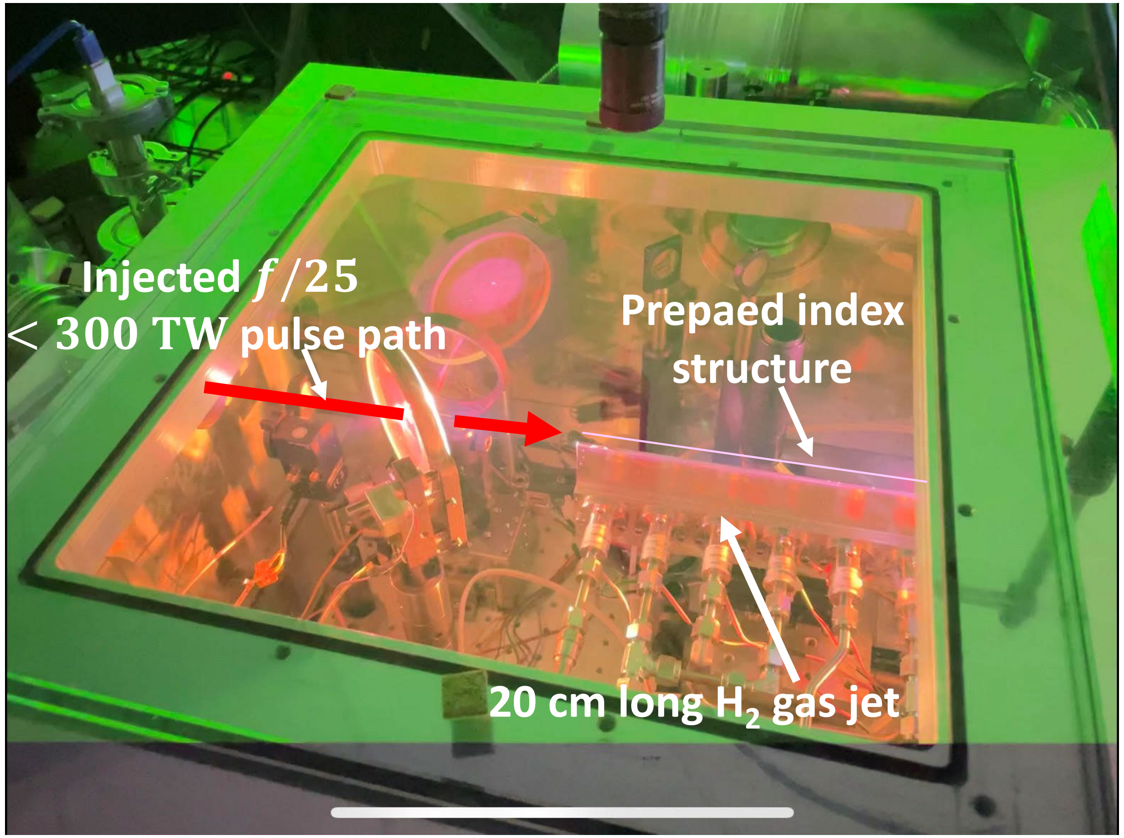


Also verifies that plasma waveguide mode size is λ-independent

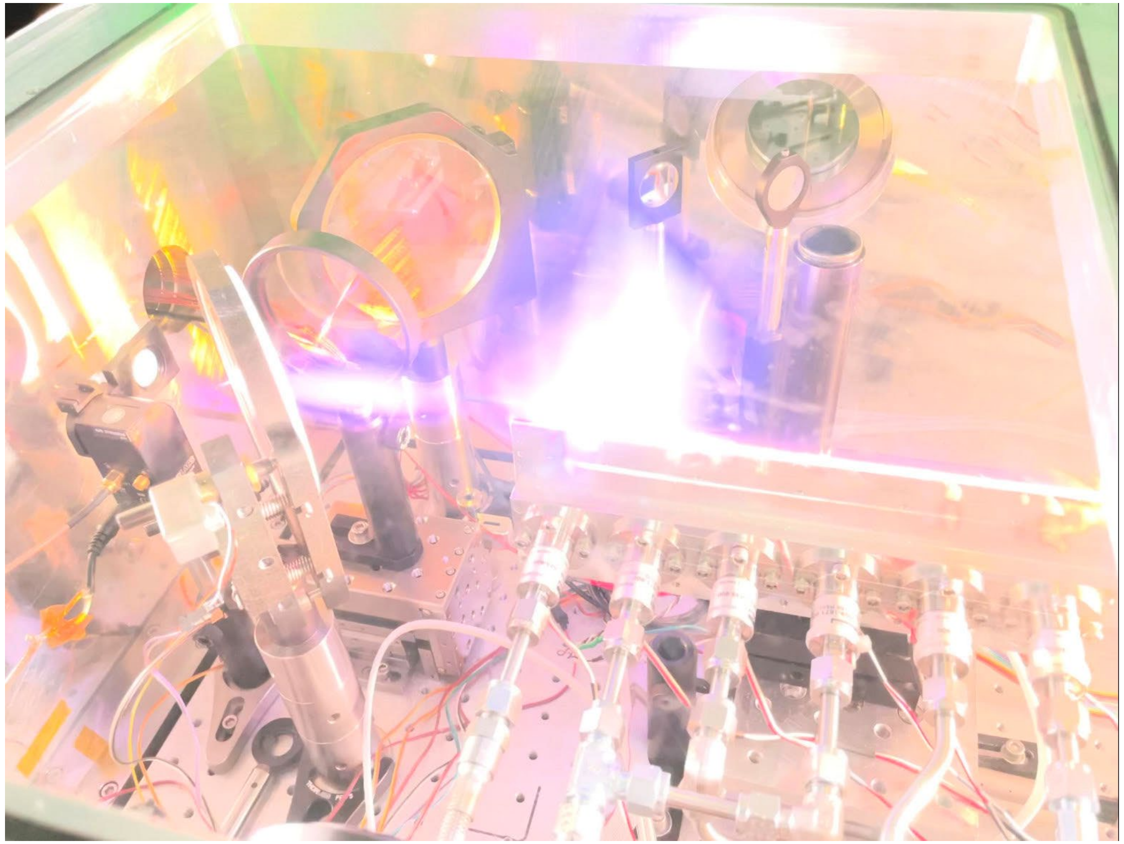
L. Feder *et al.*, Phys. Rev. Res. **2**, 043173 (2020)

Experiments at Colo. St. Univ. using self-waveguiding

guided pulse off

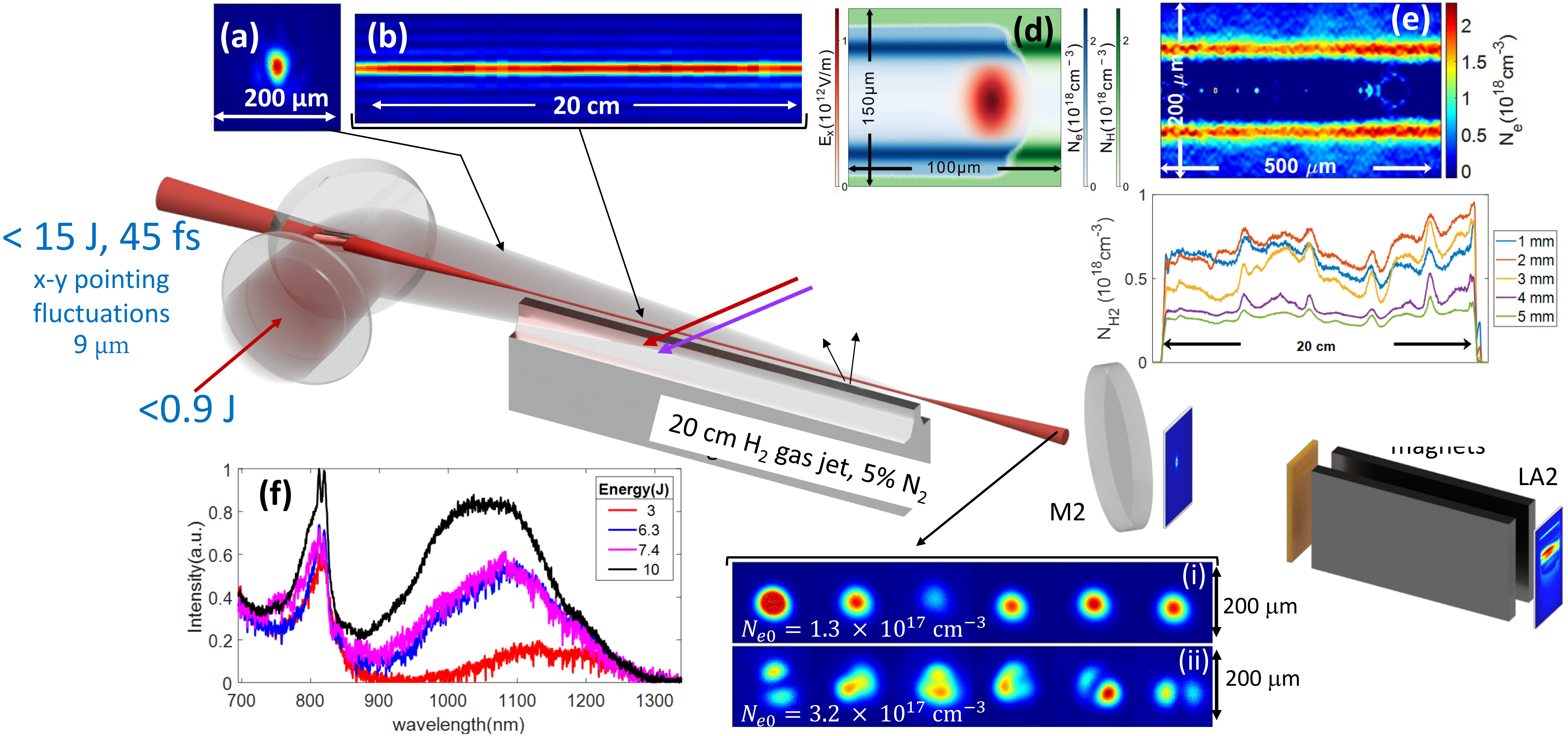


guided pulse on



B. Miao *et al,* arXiv

LWFA Experiments at Colo. St. Univ. using ***diffractive axicons*** and ***self-waveguiding***



< 15 J, 45 fs

x-y pointing fluctuations

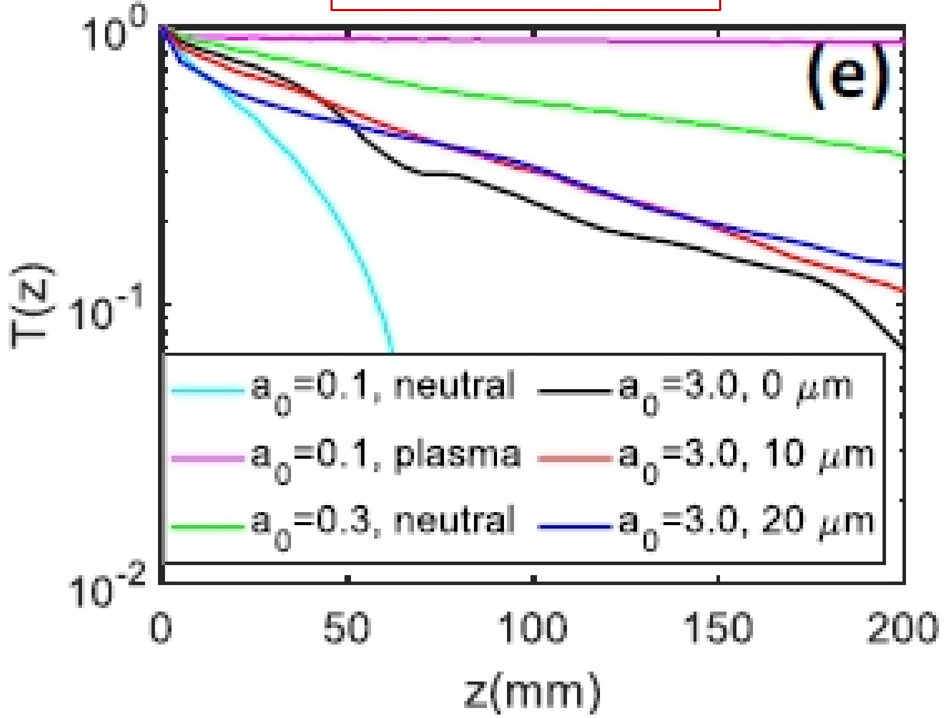
9 μm

<0.9 J

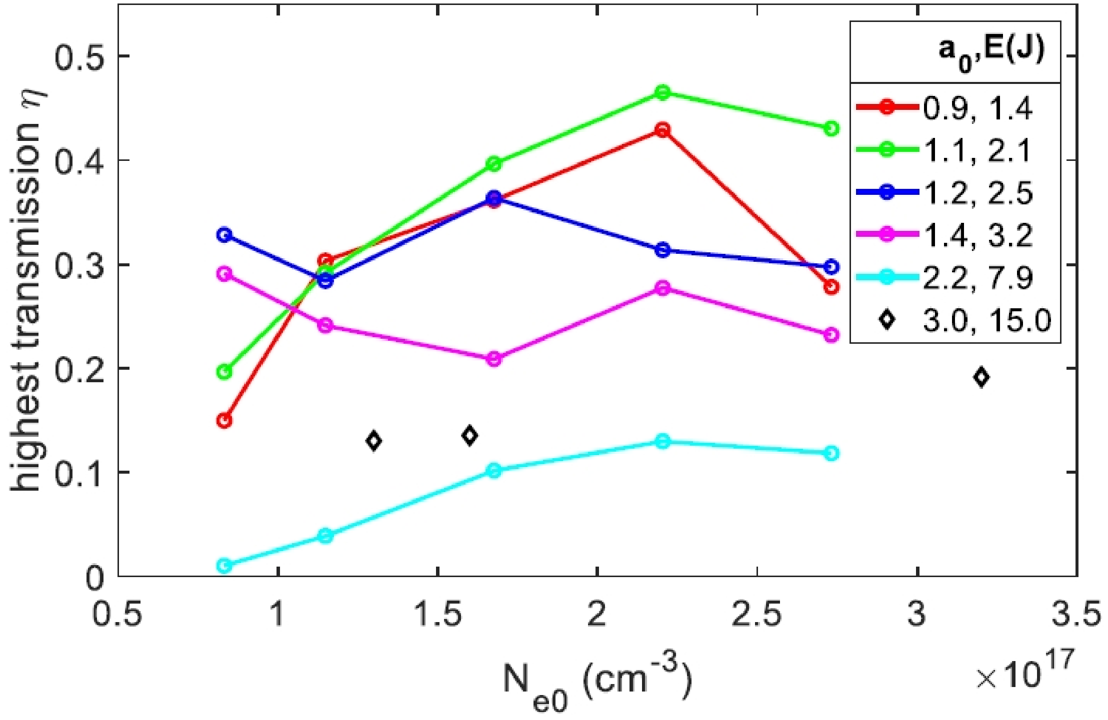
20 cm H_2 gas jet, 5% N_2

20 cm guide transmission vs density and injected pulse energy, pure hydrogen guide

WarpX simulation

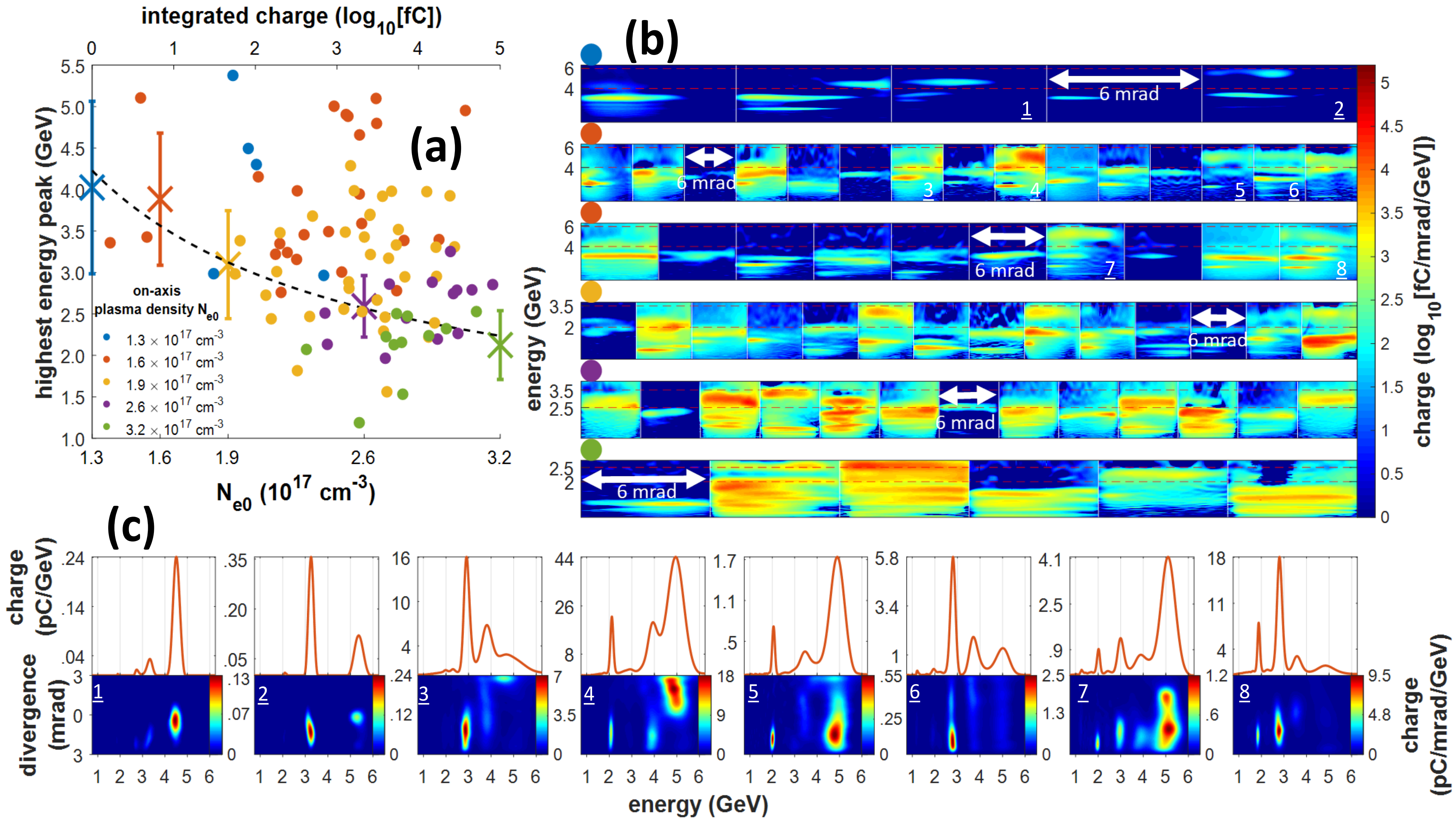


measurement



- At low a_0 , transmission loss from self-waveguiding erosion.
- At higher a_0, laser energy→ plasma waves

Shots to 5-6 GeV, beam charge ~ 10 pC, divergence ~ 1 mrad



Summary

- Optical guiding in low density plasma—self-guiding and in plasma waveguides—is crucial for a 10 GeV accelerator stage. Ultimately, efficiency and control favour plasma waveguides.

- Meter-scale, low density plasma waveguides are now here, at a (compressed) laser energy cost of ~1-2 J/m. We demonstrated 2 techniques for low density waveguide generation: the “2-Bessel method” and “self-waveguiding”. Results show 5-6 GeV acceleration with 20cm guides.

- Flexibility, control, and diagnosability enabled by our methods using *Bessel beams* and *meter-scale supersonic gas jets* will lead to significant improvements in e-beam quality, stability, and energy in the near future.