Laser-Driven Plasma Acceleration II

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Outline of lectures

Lecture 1: Basic concepts

- First make your plasma…
- Electrostatic and electromagnetic waves in plasma
- Single-particle motion
- Fluid theory

Lecture 2: Practical realization

- A brief history of LWFAs
- Particle injection
- Limitations
- Beating defocusing
- Beating dephasing
- Other schemes
- Remaining challenges

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5th - 10th February 2023
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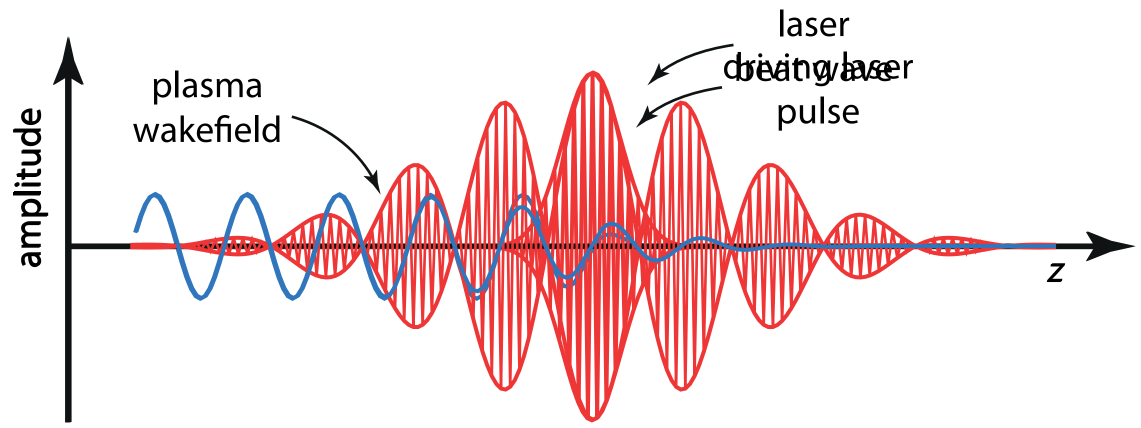
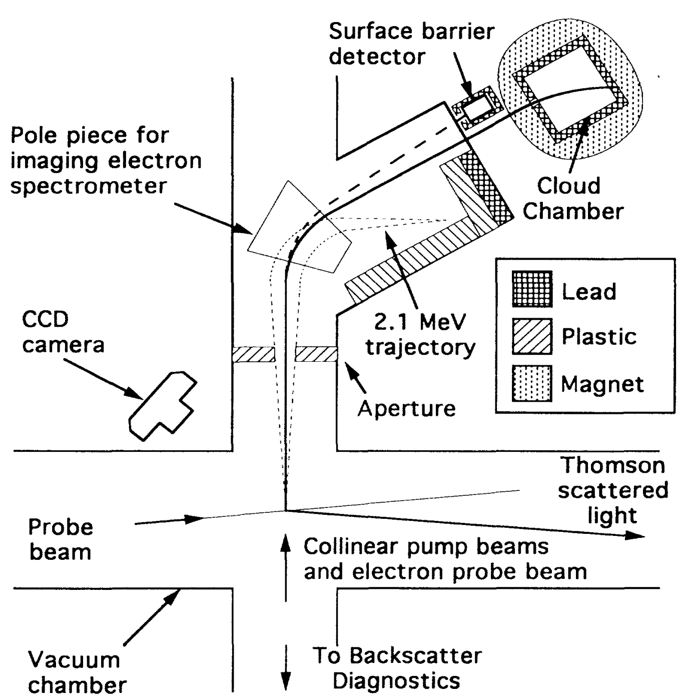
A brief history of progress in LWFAs

Progress linked to advances in laser technology



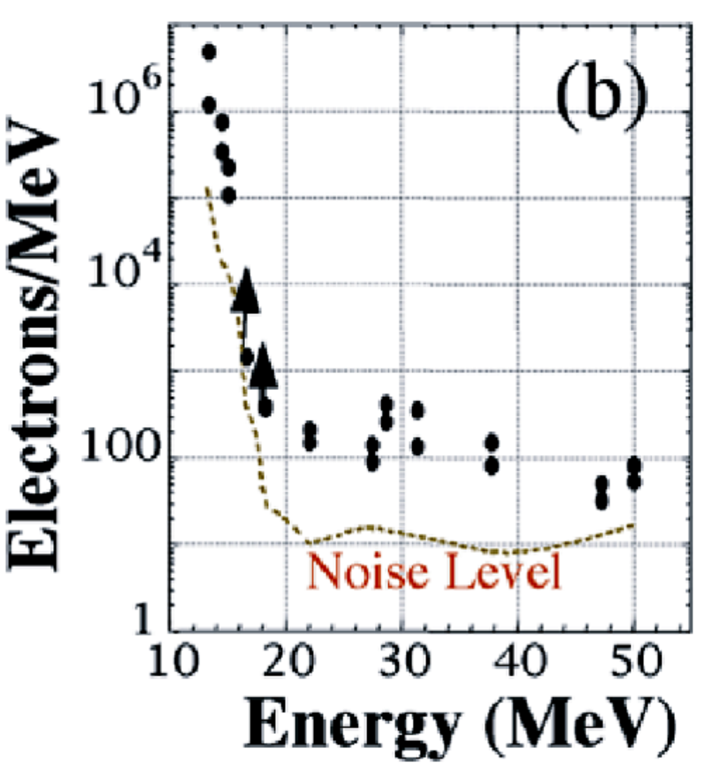
Plasma beat-wave

- Combine 2 long pulses with freqs $\omega_2 - \omega_1 = \omega_p$
  - Wake amplitudes of 28%
  - ΔW = 38 MeV (external injection)
- But wakefield saturates due to relativistic increase in electron mass (Rosenbluth & Liu limit)



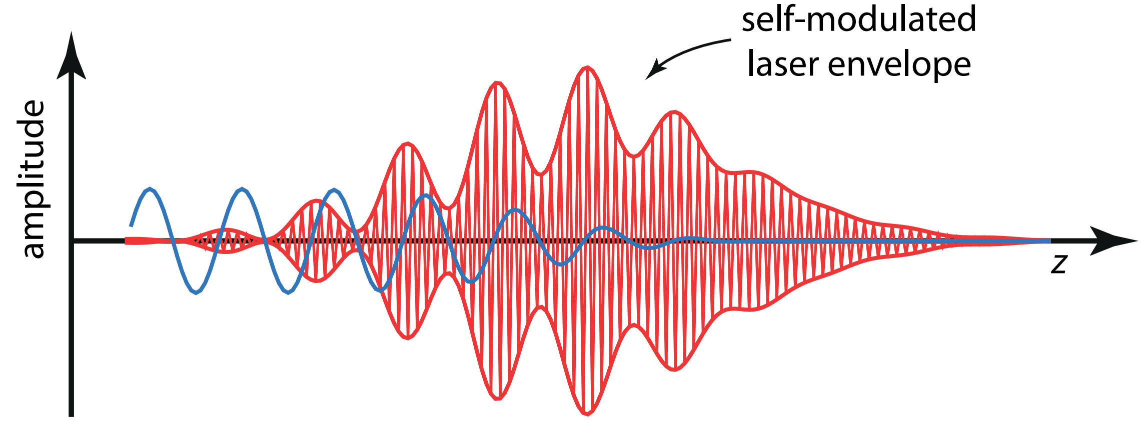
Clayton et al. *Phys Rev. Lett.* **70** 37 (1993)

Tochitsky *et al. Phys Rev. Lett.* **92** 095004 (2004)
Laser: 200 J, 400 ps (CO_2)
Plasma: $n_e \sim 9 \times 10^{15}$ cm^{-3}
Injected electrons: 12 MeV



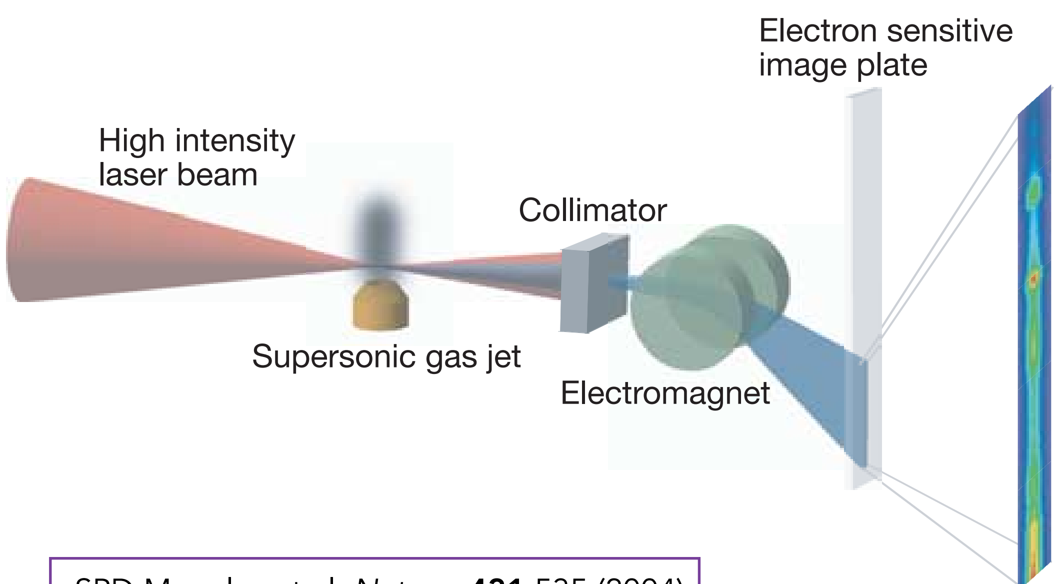
Rosenbluth and Liu, *Phys Rev Lett* **29** 701 (1972)

Progress linked to advances in laser technology

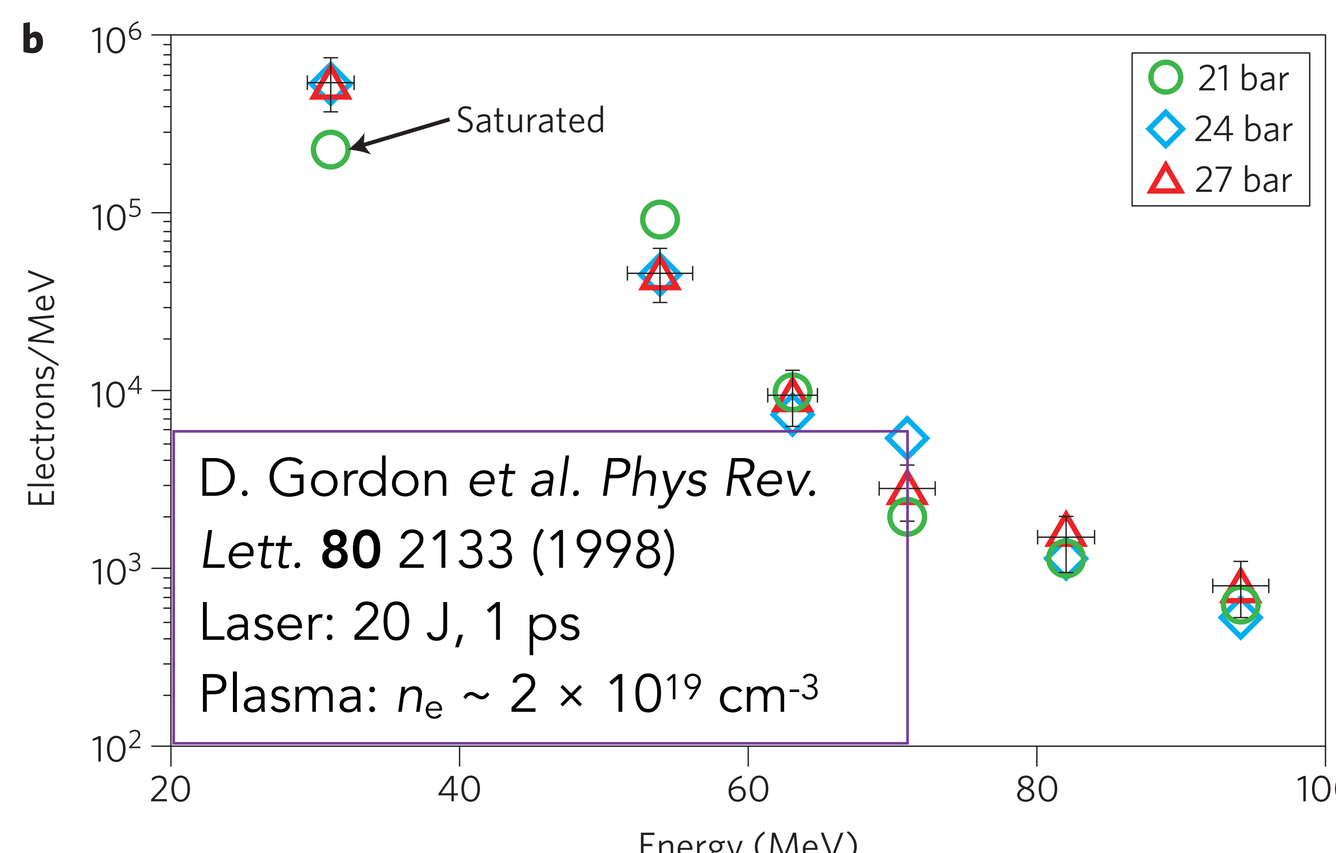


Self-modulated LWFA

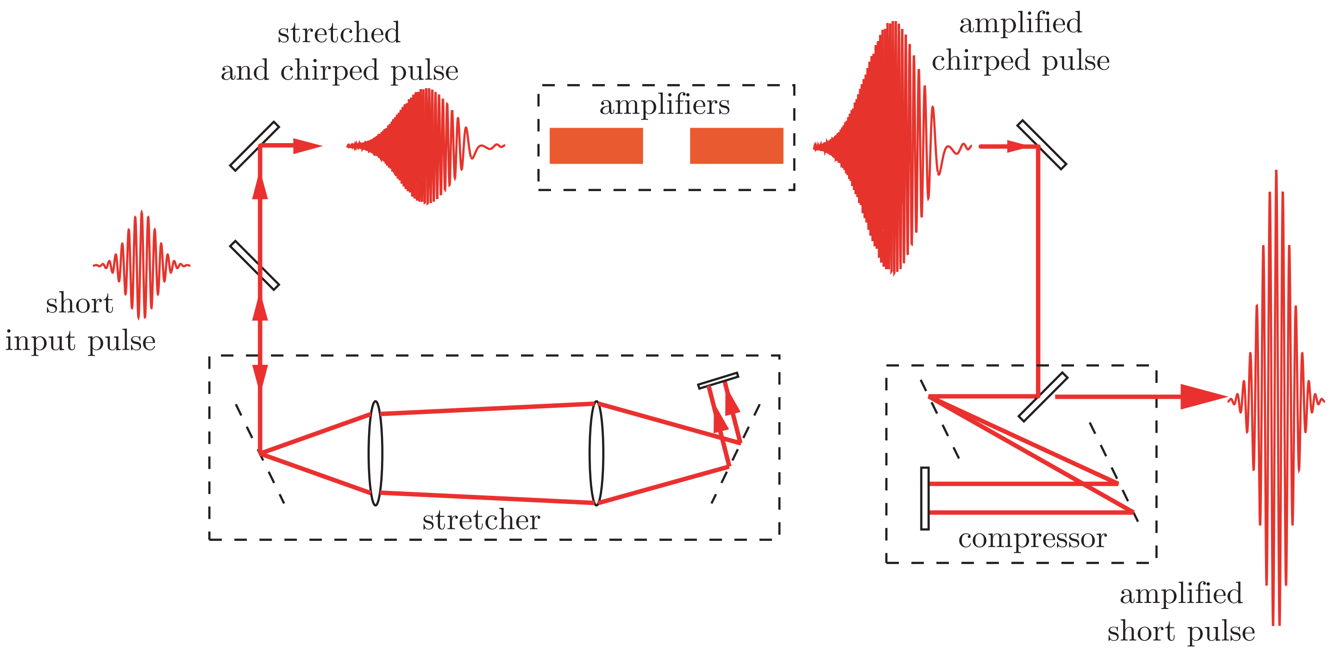
- Long laser pulse modulated by plasma
- Automatically maintains resonance
- *W* ~ 100 MeV
- Very broad-band energy spectra



SPD Mangles et al. *Nature* **431** 535 (2004)



An aside: Chirped-pulse amplification



- CPA has allowed the generation of short (< 50 fs) pulses with reasonable energy
- State of art is the BELLA laser at Berkeley:
  - E = 40 J
  - τ = 40 fs
  - P = 1 PW

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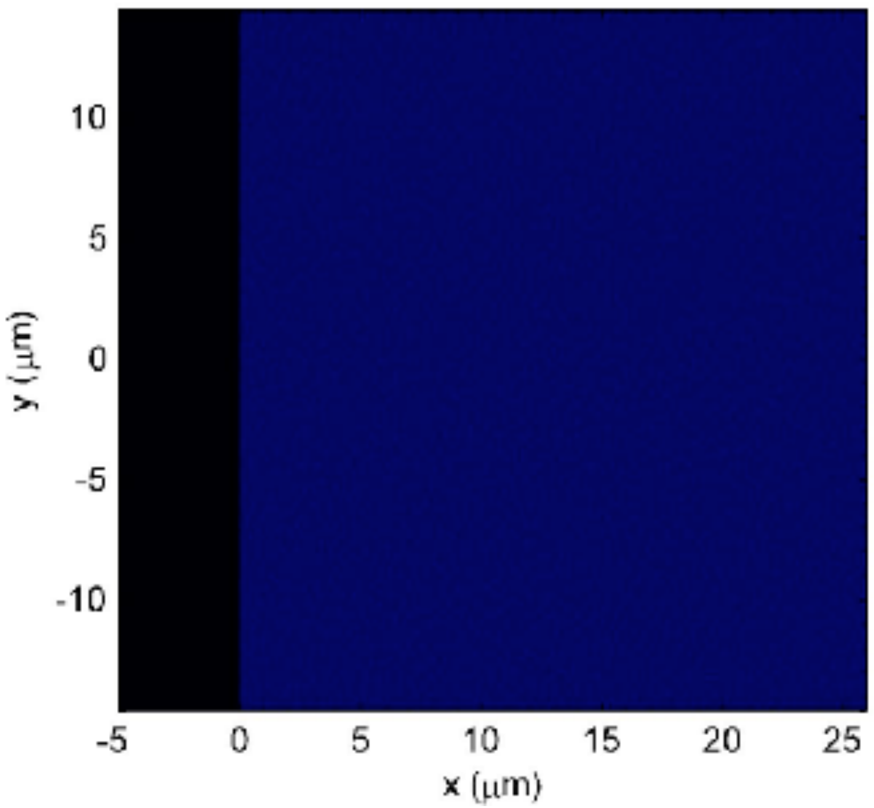
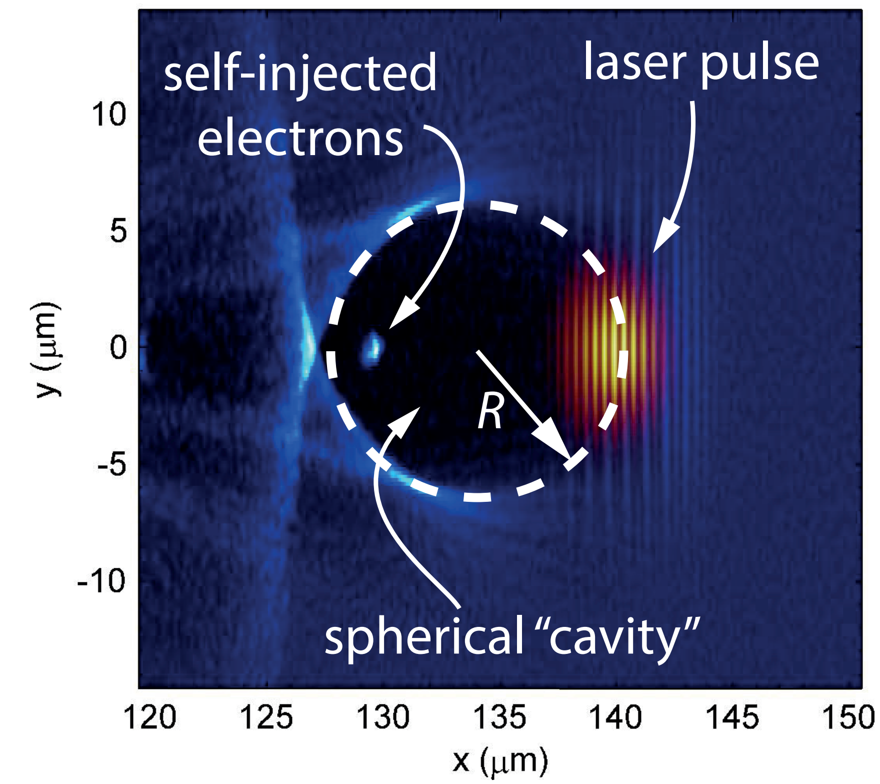
High-intensity ultrafast lasers: The bubble regime

- For short, high-intensity pulses ponderomotive force expels all electrons from region behind laser pulse
- Condition $a_0 > 2$ and:

$$c\tau < w_0 \approx R \approx \frac{\lambda_p}{\pi}\sqrt{a_0}$$

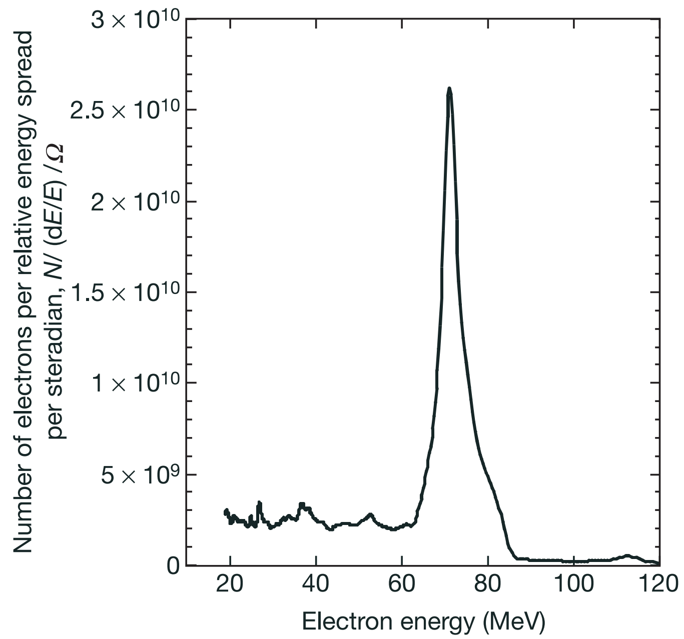
- Approx spherical cavity ("bubble") of radius R formed
- Ideal focusing fields (linear in r)
- Laser pulse relativistically guided over many Z_R
- Electrons self-injected
- Can give near-monoenergetic beams



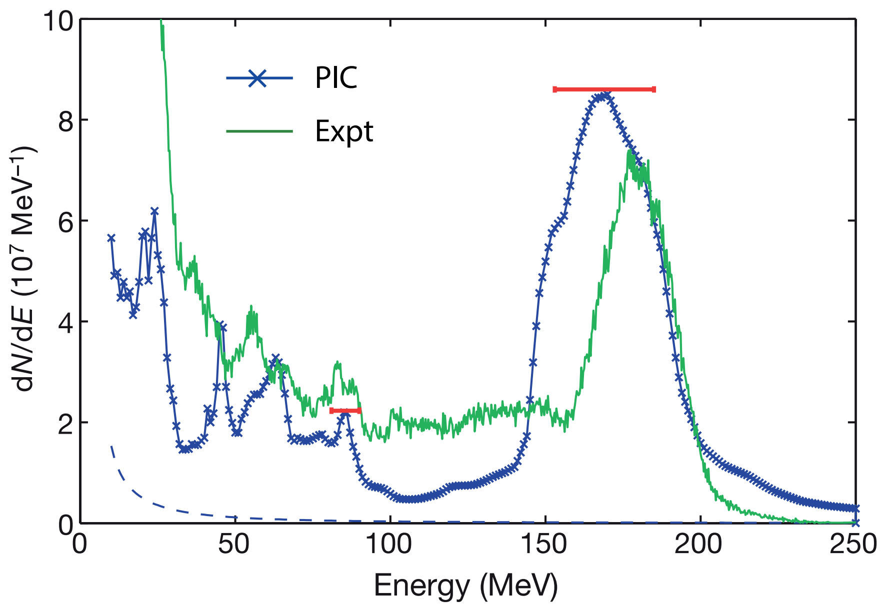


A. Pukhov & J. Meyer-ter-Vehn *Appl. Phys. B* **74** 355 (2002)
Kostyukov et al., *Phys. Plasm.* **11** 5256 (2004)
W. Lu, *et al.*, *Phys. Rev. Lett.* **96** 165002 (2006)
W. Lu et al. *PRSTAB* **10** 061301 (2007)

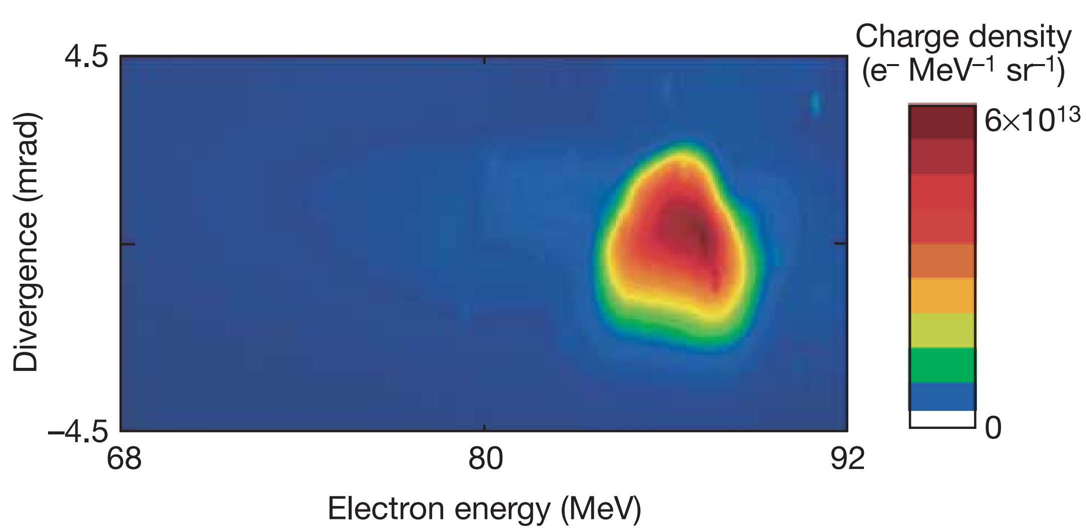
Dream beams!



Mangles *et al. Nature* **431** 535 (2004)
E = 0.5 J
τ = 40fs
a0 ≈ 1
$n_e = 2 \times 10^{19}$ cm^{-3}



Faure *et al. Nature* **431** 541 (2004)
E = 1 J
τ = 33fs
a0 ≈ 1.2
$n_e = 6 \times 10^{18}$ cm^{-3}



Geddes *et al. Nature* **431** 538 (2004)
E = 0.5 J
τ = 55 fs
a0 ≈ 2.3
$n_e = 2 \times 10^{19}$ cm^{-3}

Injection & trapping

Particle injection

- To be injected & trapped, an electron must reach velocity of wake
- Several possible methods
    - External injection from another accelerator (conventional or plasma)
    - Self-injection
    - Controlled injection

External injection

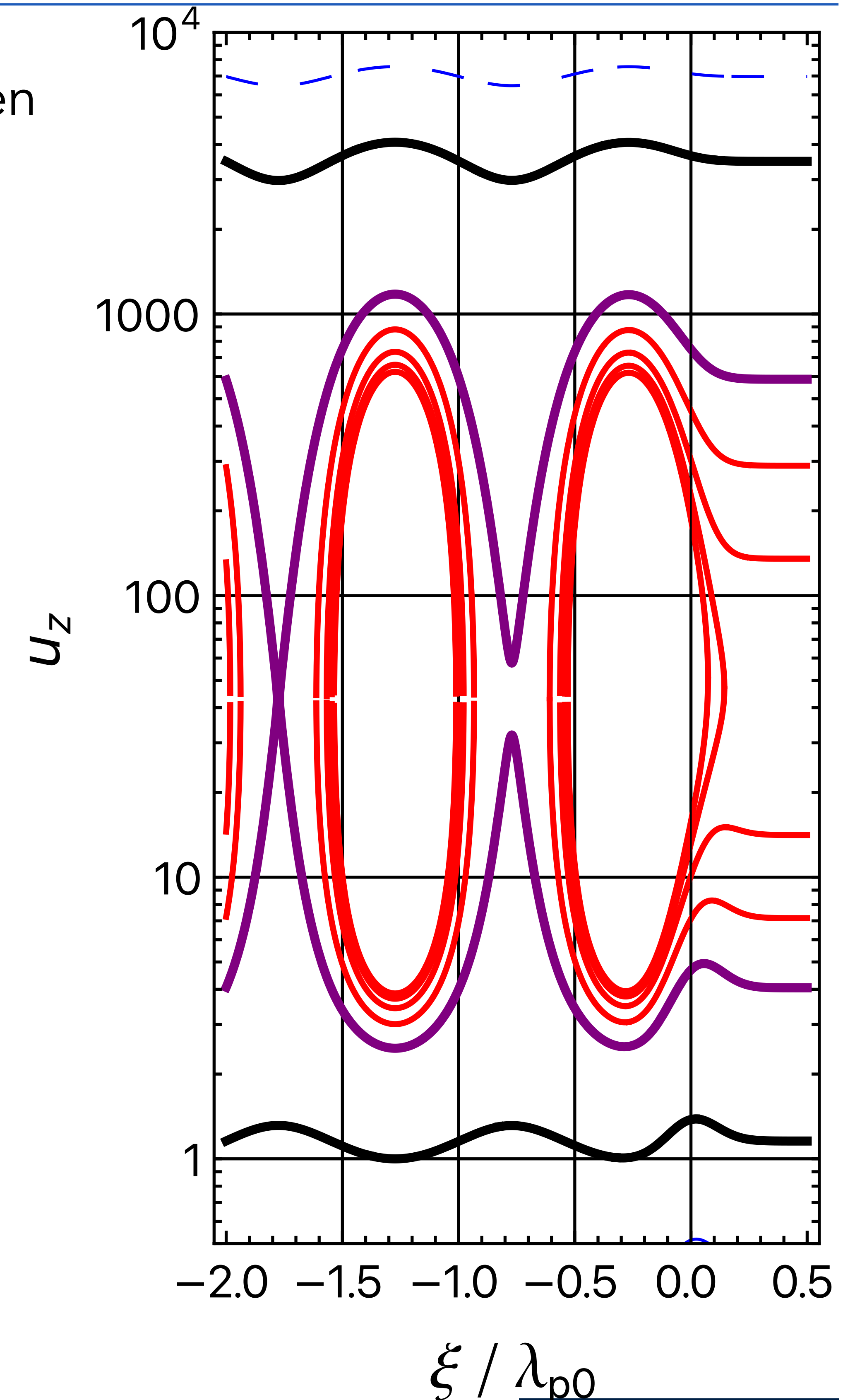
- Our 1D treatment suggests electrons trapped when

$$u_z(+\infty) > u_{z,\mathrm{sep}}(+\infty) = \beta_p \gamma_p^2 H_{\mathrm{sep}} - \gamma_p \sqrt{\gamma_p^2 H_{\mathrm{sep}}^2 - 1}$$

- Hence the trapping energy (kinetic energy) is,

$$W_{\mathrm{trap}} = m_e c^2 \left(\sqrt{1 + u_{z,\mathrm{sep}}(+\infty)^2} - 1 \right)$$

- Threshold trapping energy decreases for:
  - Larger wake amplitudes
  - Slower wake velocities



Wenz & Karsch, CERN Accelerator School (2019)

External injection

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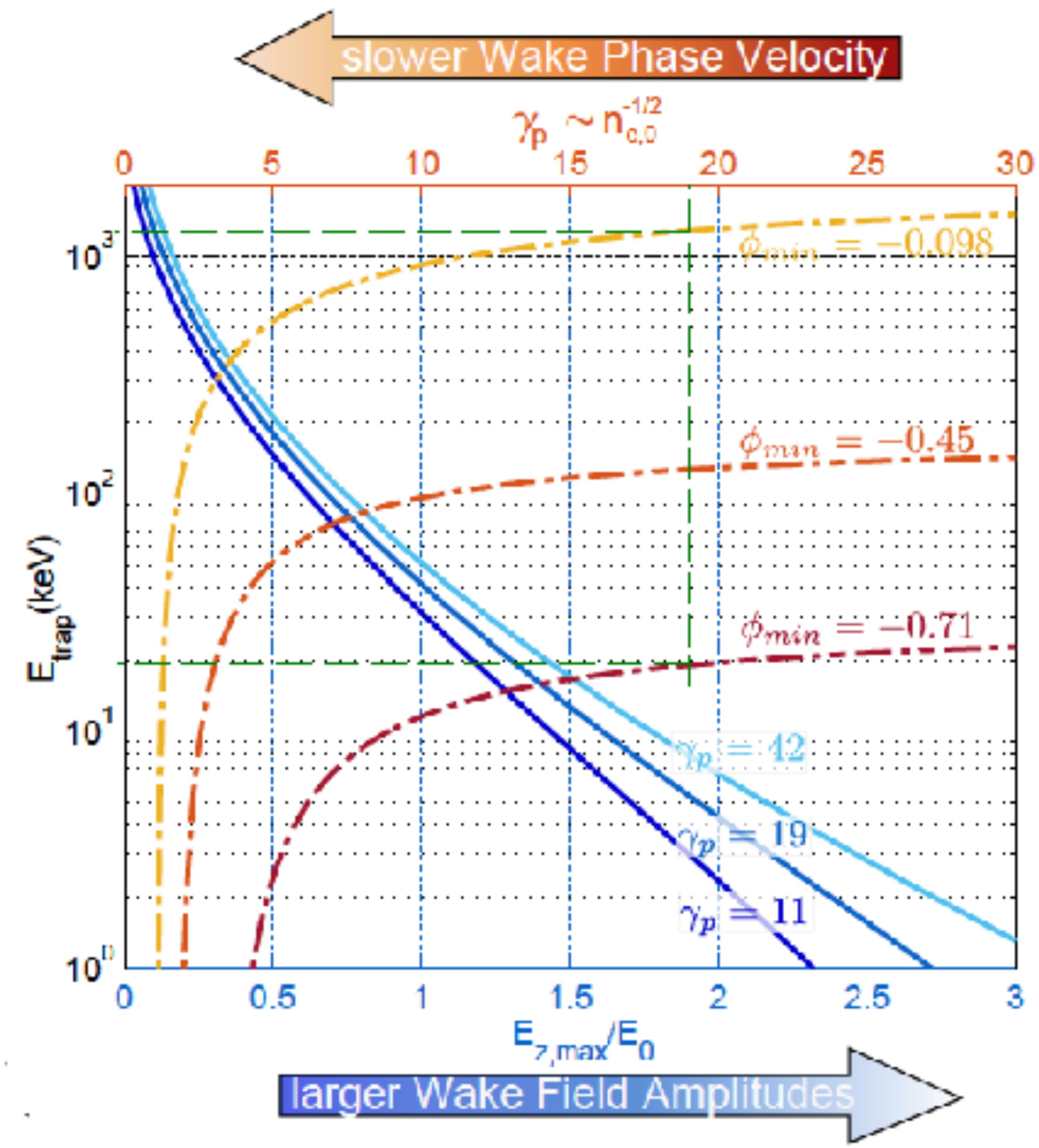


Wenz & Karsch, CERN Accelerator School (2019)

Self-injection in1D

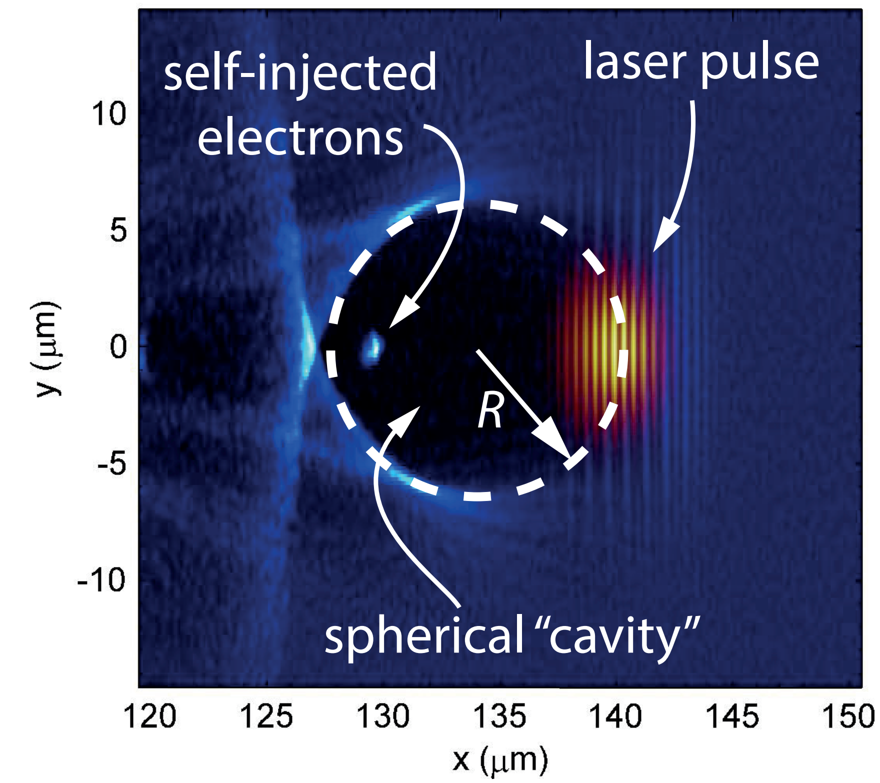
- As a_0 increases separatrix gets closer to fluid orbits
- When fluid and separatrix overlap:
  - Fluid velocity = phase velocity
  - Wave breaks
  - Background electrons injected & trapped
- Requires large values of a_0 (i.e. $a_0 \gtrsim 6$ for $n_e = 5 \times 10^{18}\,\mathrm{cm}^{-3}$)
- In practice self-injection observed at lower threshold

Self-injection in 3D: Transverse injection

- Transverse injection in bubble regime:
  - Large density spike formed at rear of bubble
  - Off-axis electrons pulled into the cavity by radial fields, scattered by density spike & trapped
- Threshold laser energy for transverse injection given by,

$$\alpha_L W_L > \frac{\pi \epsilon_0 m_e^2 c^5}{e^2} \left[\ln \left(\frac{2 n_c}{3 n_e} \right) - 1 \right]^3 \frac{n_c}{n_e} \tau(z)$$

where α is fraction of laser energy in FWHM of focal spot



Pros

- Relatively simple to do

Cons

- Injected electrons have large transverse momentum large emittance
- Injection can occur at multiple points along accelerator large energy spread
- Injection typically different for each shot large shot-to-shot jitter

S.P. D. Mangles et al., *Phys. Rev. STAB* **15** 011302 (2012)

Controlled injection

- The most interesting (and demanding) applications require generation of **high quality** electron bunches
- Requires electrons to be **injected and trapped in a controlled way**
- Many schemes have been devised
  - Density down-ramp
  - Optical injection
  - Ionization injection
  - etc..

Down-ramp injection: long ramp

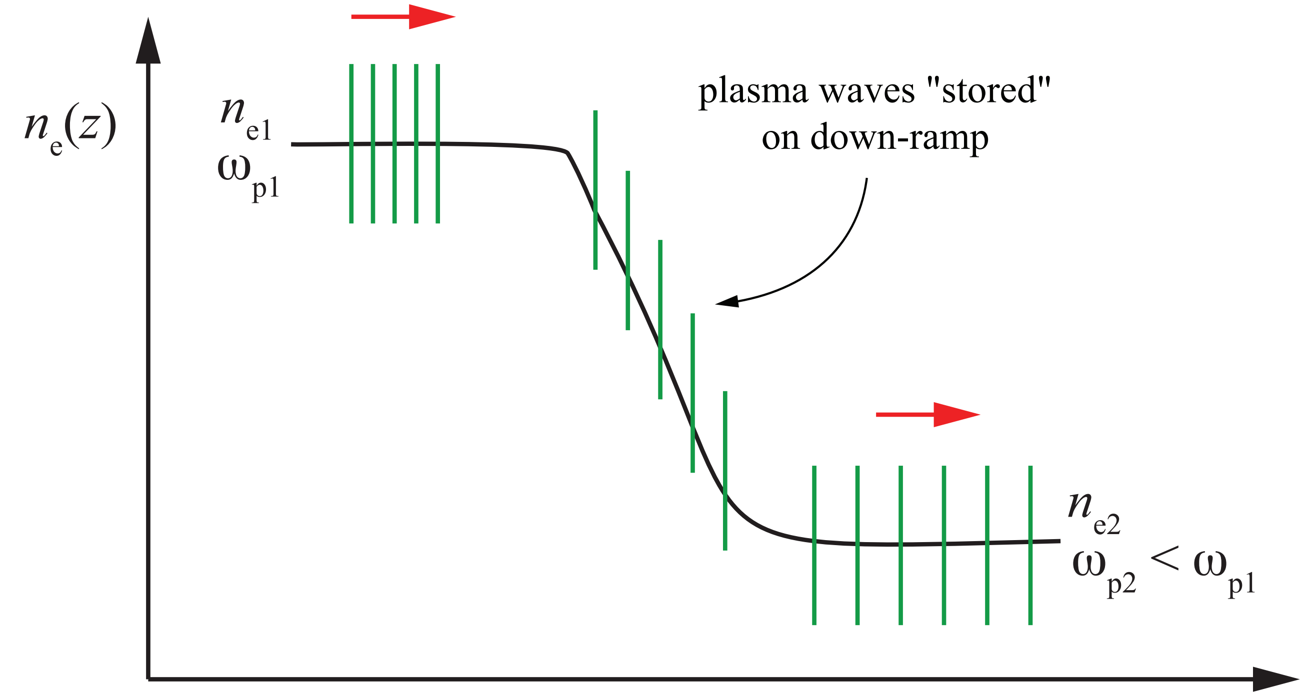
- Long density ramp ($L_{\rm ramp} > \lambda_p$)
- Phase of plasma wave is,

$$\psi = k_p(z)\left[z - v_g t\right]$$

$$\Rightarrow t = \frac{1}{v_g}\left[z - \frac{\psi}{k_p(z)}\right]$$

$$\Rightarrow \left(\frac{\partial t}{\partial z}\right)_\psi = \frac{1}{v_p} = \frac{1}{v_g}\left[1 + \frac{\psi}{k_p(z)^2}\frac{dk_p}{dz}\right]$$

$$\Rightarrow v_p = v_g\left[1 + \frac{\xi}{2n_e(z)}\frac{dn_e}{dz}\right]^{-1}$$



- Behind laser pulse $\xi < 0$, and hence a down-ramp causes phase velocity to decrease
- Velocity decreases with distance behind laser

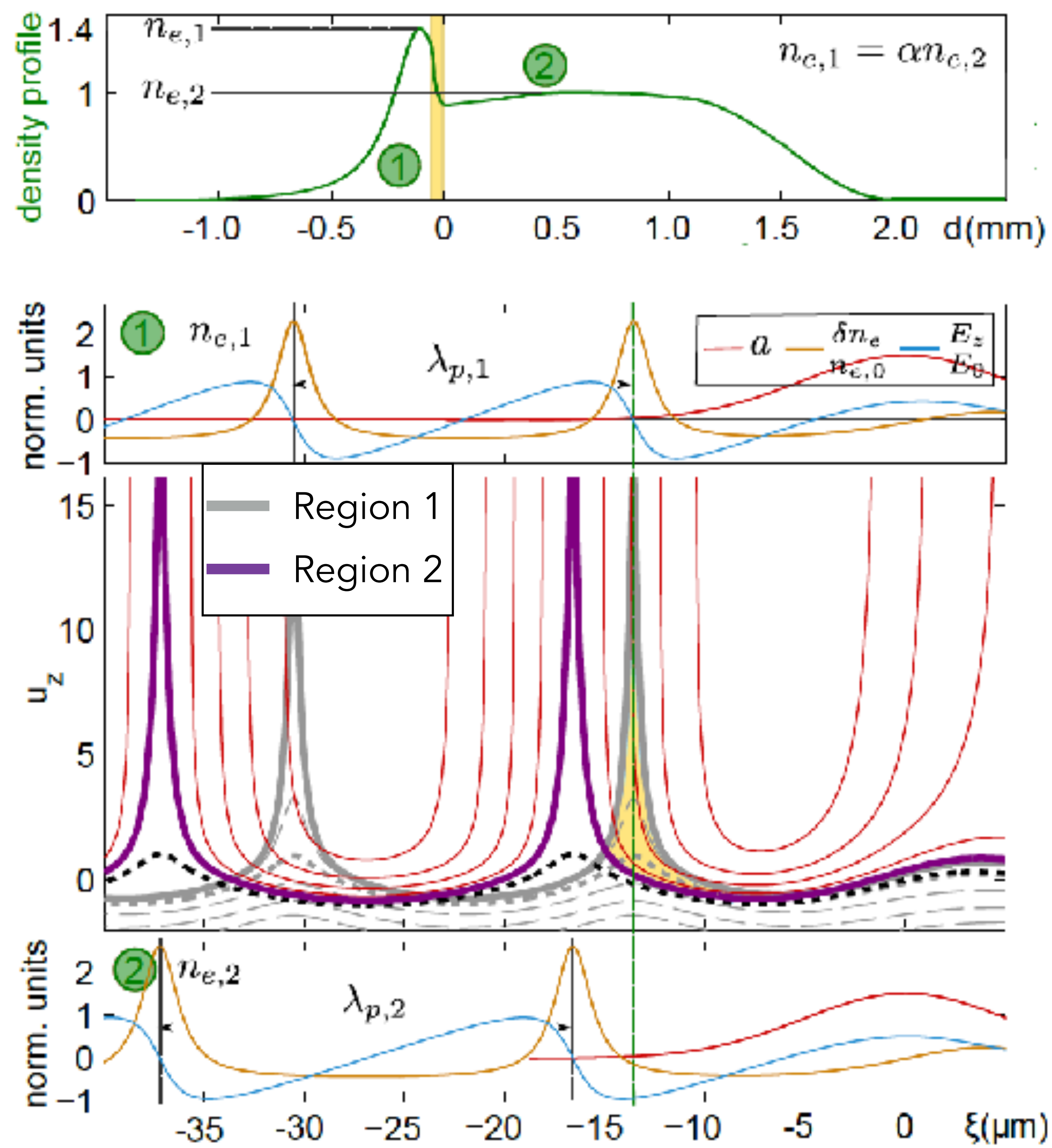
Disadvantages

- Injection at all points on ramp
- Injection into several buckets

Bulanov et al., *Phys. Rev. E* **58** R525 (1988)
Geddes et al. *Phys. Rev. Lett.* **100** 215004 (2008)
Faure et al., *Phys. Plas.* **17** 083107 (2010)
Gonsalves et al., *Nat. Phys.* **7** 862 (2011)

Down-ramp injection: Sharp ramp ("Shock injection")

- Sharp density ramp ($L_{\text{ramp}} \ll \lambda_p$)
  - Proposed by Suk et al. in 2001
- Sudden change of plasma wavelength causes electrons to move from open to closed orbit



Wenz & Karsch, CERN Accelerator School (2019)

Pros

- Simple to implement

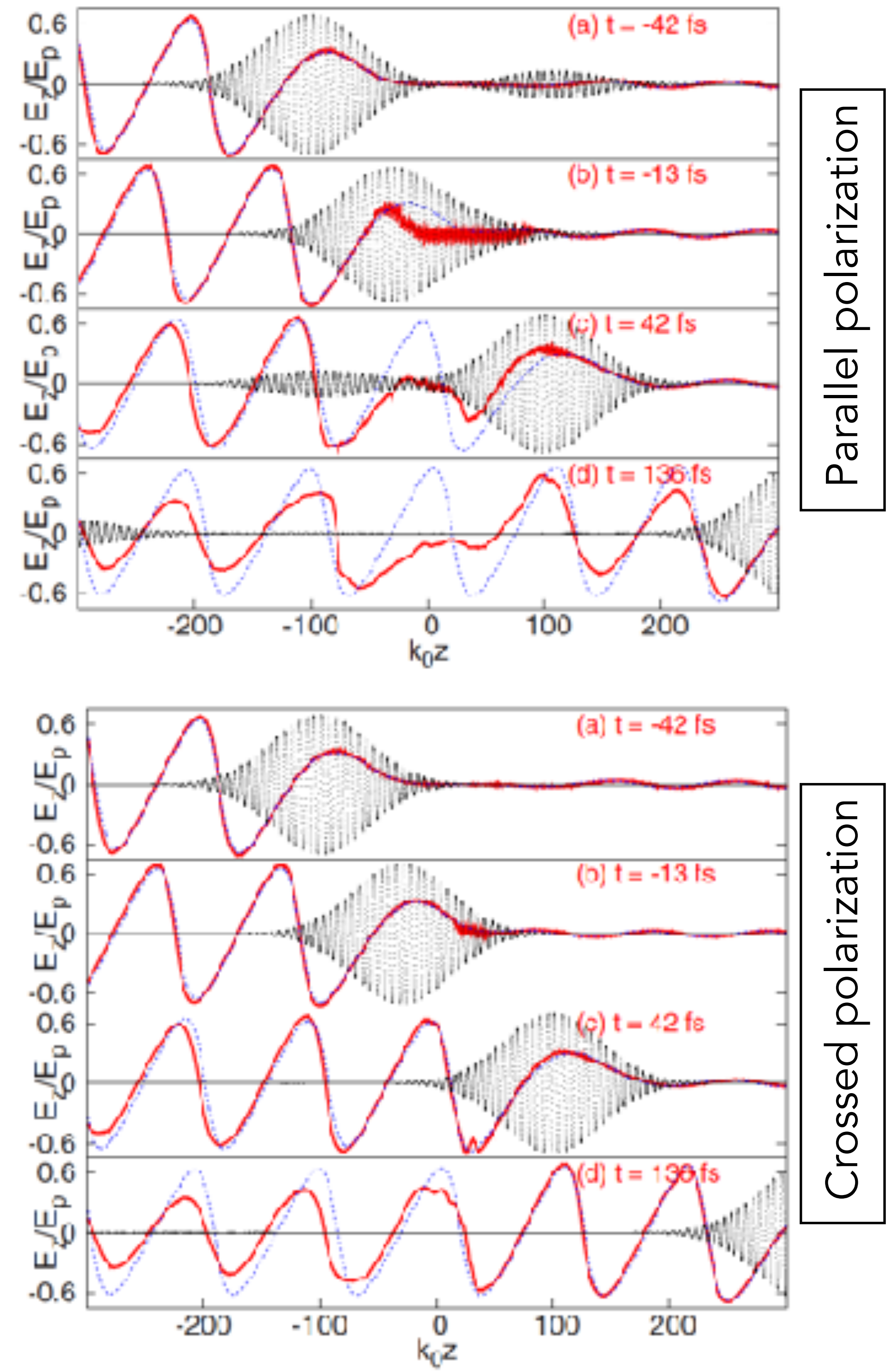
Cons

- Only works for some targets, e.g. gas jet

Suk et al., *Phys Rev. Lett.* **86** 1011 (2001)
Bratov et al., *Phys. Plasm.* **15** 073111 (2008)
Schmidt et al., *PRAB* **13** 091301 (2010)
Buck et al., *Phys. Rev. Lett.* **110** 185006 (2018)

Optical injection

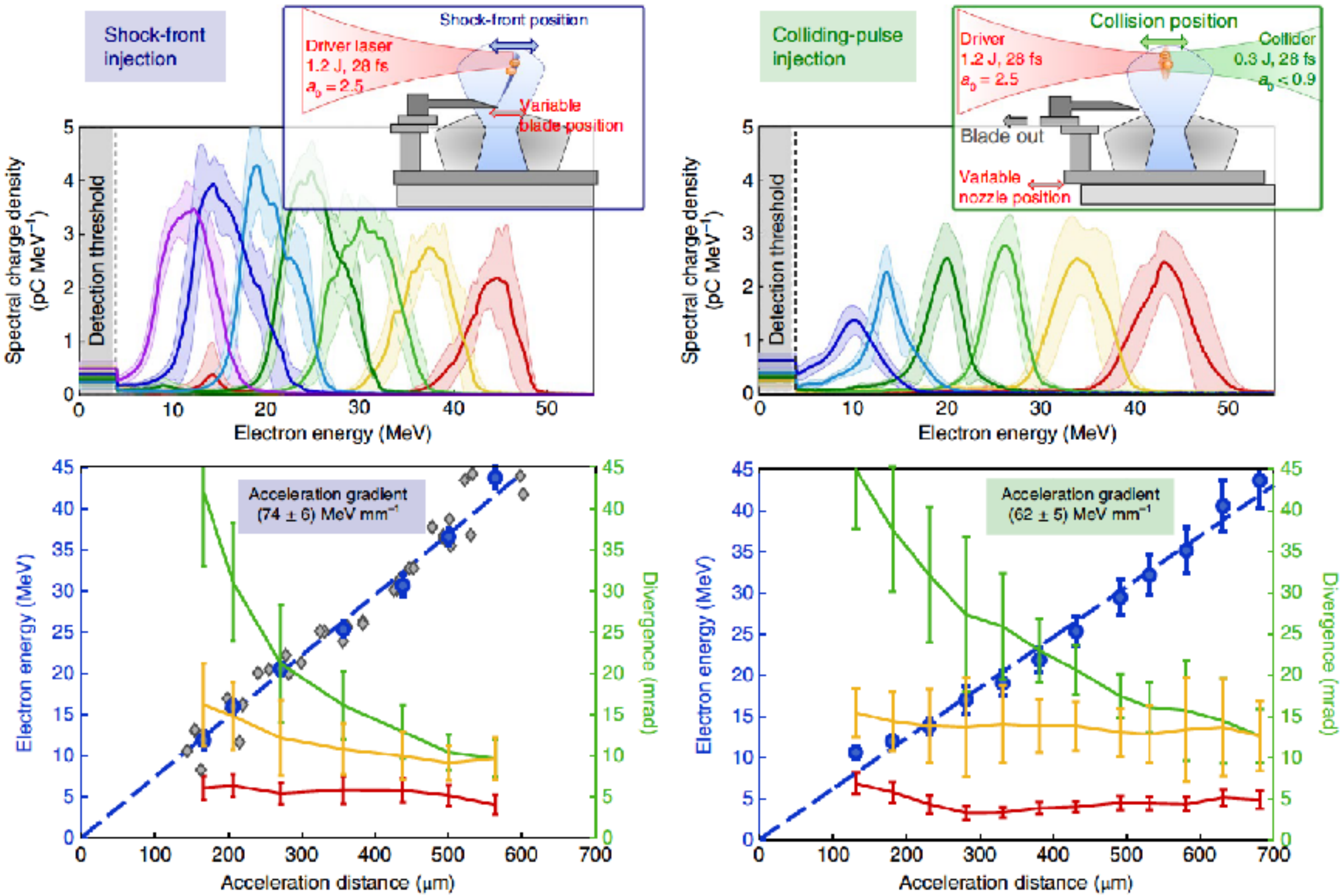
- A counter-propagating laser pulse can be used to produce localized injection
- Parallel polarization:
  - Stationary beat-wave formed with spatial scale $\lambda/2$
  - Beat-wave stochastically heats electrons
  - Also inhibits plasma wave (bad for trapping)
- Crossed-polarization
  - Electrons still heated (coupling via $\vec{v} \times \vec{B}$)
  - No suppression of wakefield (helps trapping)



Malka et al., *Phys. Plasma.* **16** 056703 (2009)

Fubiani et al., *Phys Rev E* **70** 016402 (2004)
Faure et al., *Nature* **444** 737 (2006)
Malka et al., *N. J. Phys.* **11**(2009)

Comparison of shock and colliding pulse injection



Wenz et al., *Nat. Photon.* **13** 263 (2019)

Ionization injection

Concept

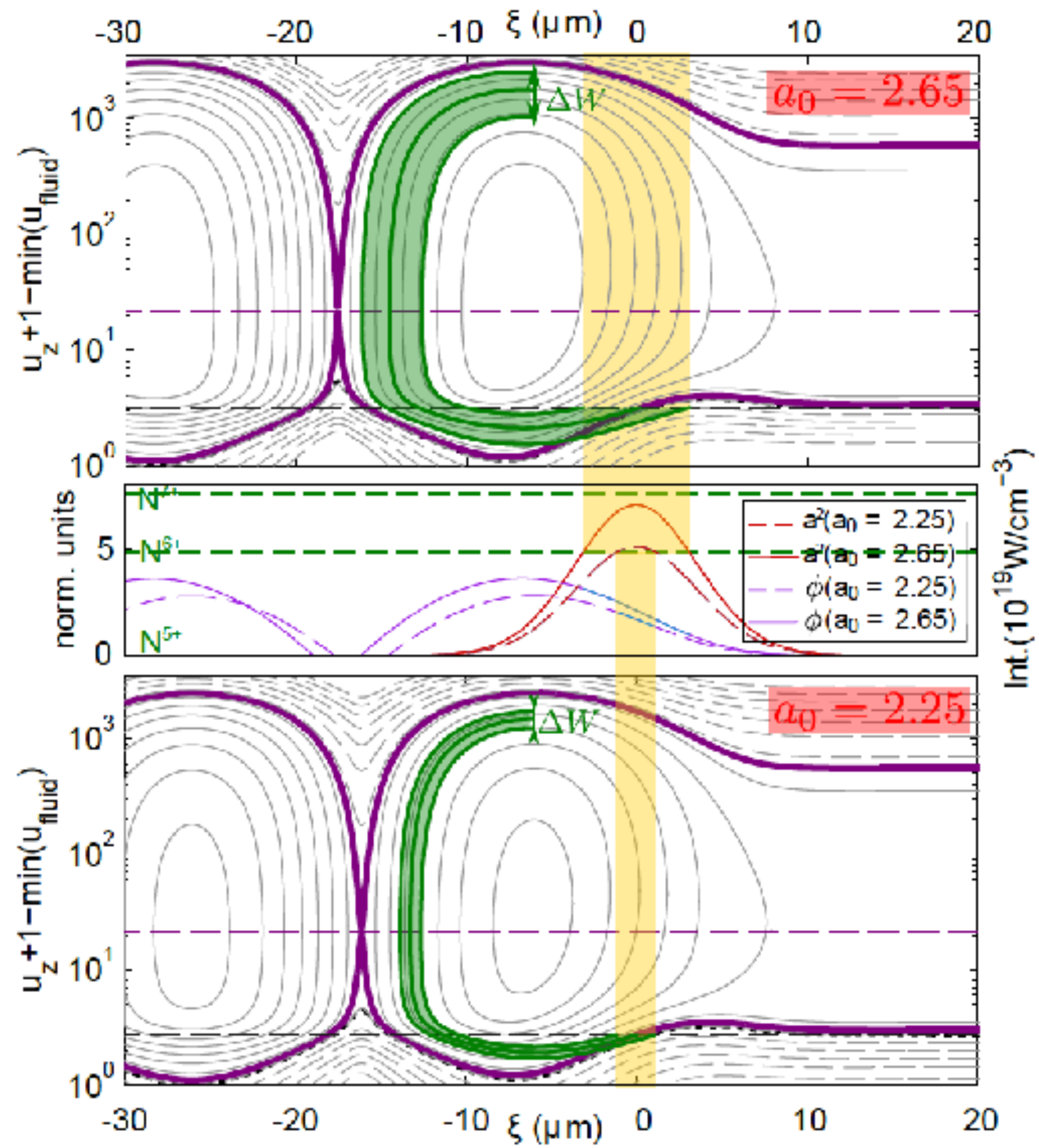
- Ionize dopant species with drive or auxiliary laser pulse
- Electrons "born" in wakefield with $u_z \approx 0$ whilst fluid electrons moving backwards

Pros

- Easy to implement; widely used

Cons

- Injection throughout accelerator ⇒ large energy spread

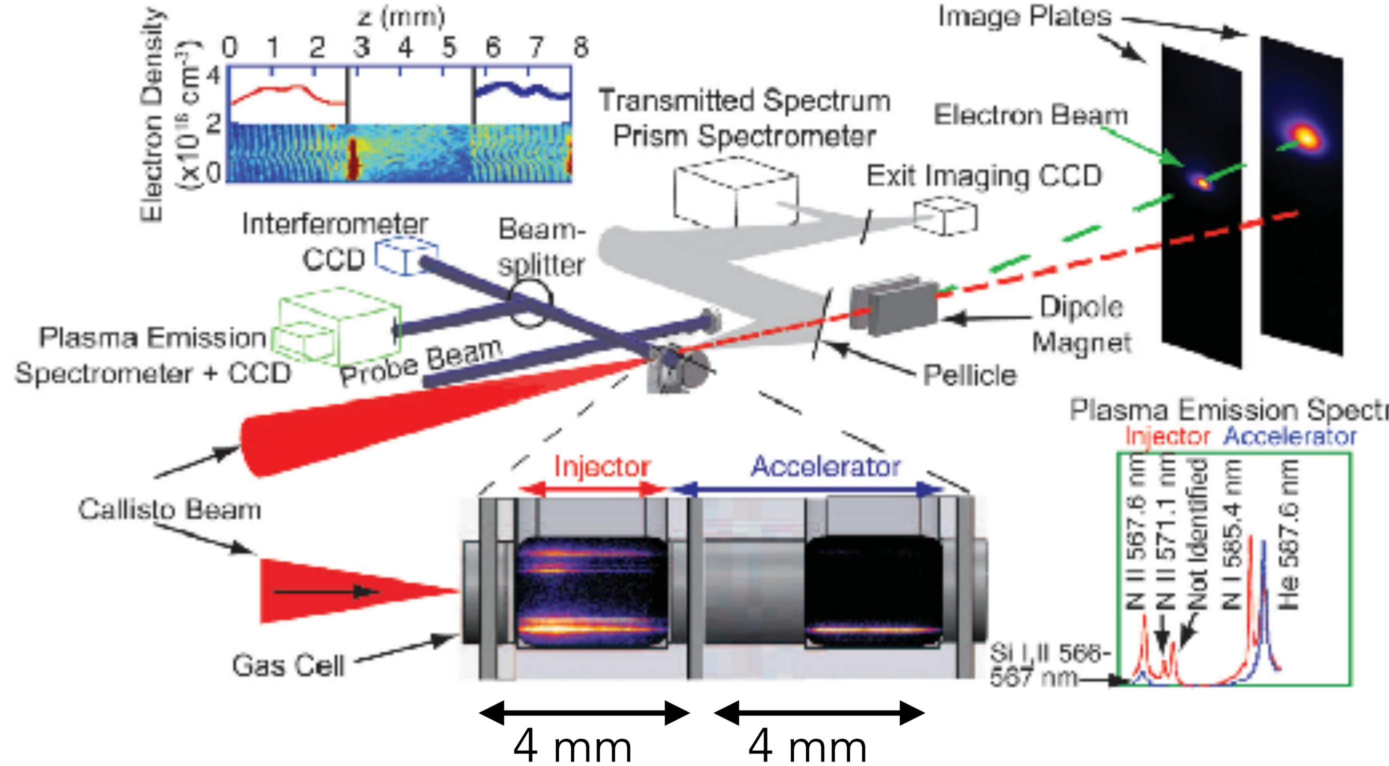


Wenz & Karsch, CERN Accelerator School (2019)

Rowlands-Rees et al., *Phys. Rev. Lett.* **100** 105005 (2008)
Mcguffey et al. *Phys. Rev. Lett.* **104** 025004 (2010).
Pollock et al., *Phys. Rev. Lett.* **107** 045001 (2011)

Ionization injection

Pollock et al., *Phys. Rev. Lett.* **107** 045001 (2011)



Concept

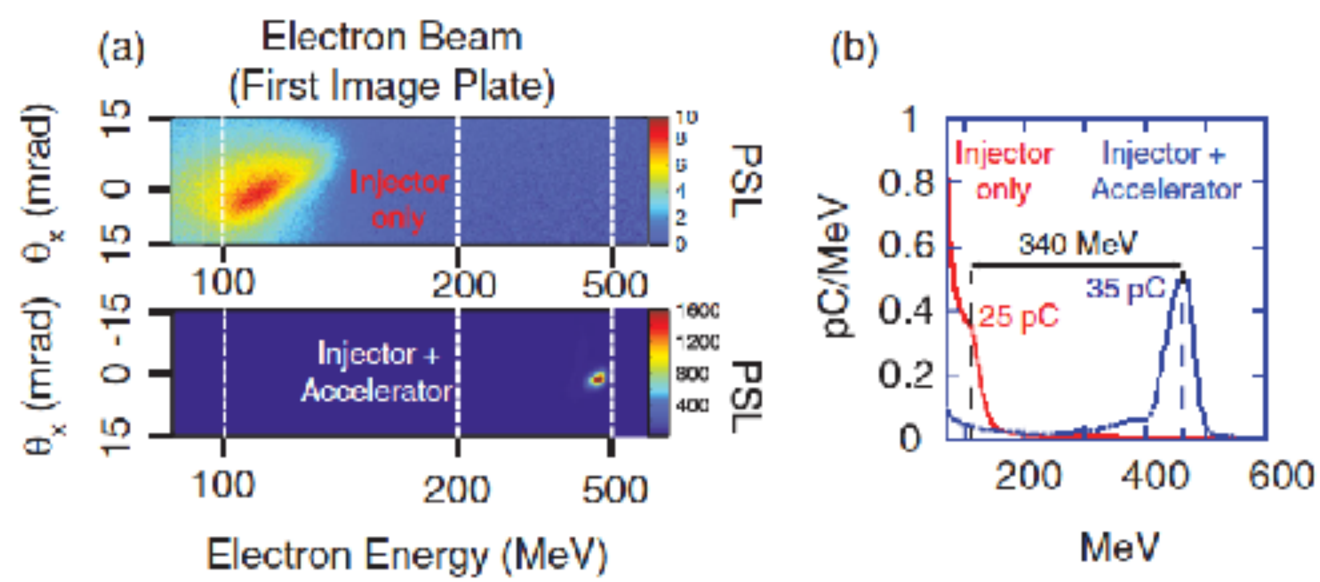
- Ionize dopant species with drive or auxiliary laser pulse
- Electrons “born” in wakefield can be trapped
- Widely used

Pros

- Easy to implement; widely used

Cons

- Injection throughout accelerator
- ⇒ large energy spread unless can restrict region of ionization



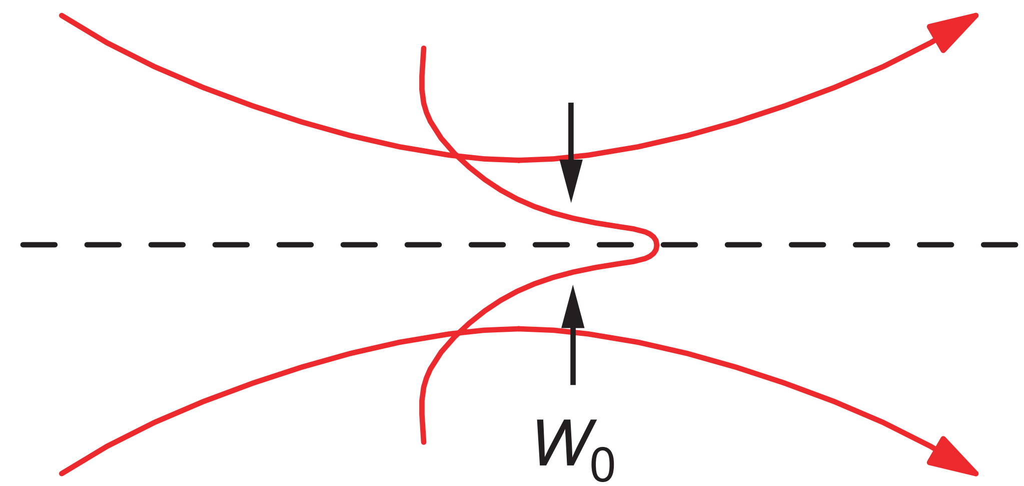
E ~ 0.5 GeV, $\Delta E/E \approx 5\,\%$

Rowlands-Rees et al., *Phys. Rev. Lett.* **100** 105005 (2008)
Mcguffey et al. *Phys. Rev. Lett.* **104** 025004 (2010).
Pollock et al., *Phys. Rev. Lett.* **107** 045001 (2011)

Limitations … the 3 Ds

1. Defocusing of pump laser

- In vacuum, laser would diffract ~ z_R
- Some method of guiding the drive laser over tens cm will be needed



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

Example :

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

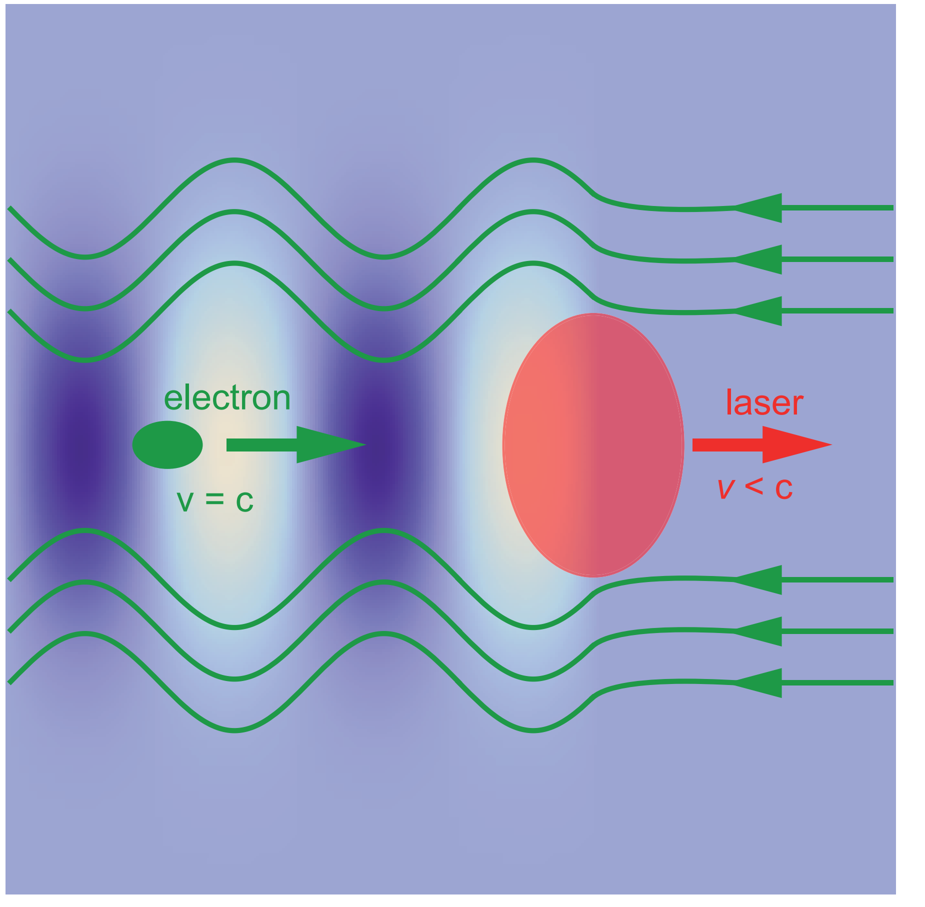
$$\Rightarrow Z_R = 0.3\,\text{mm}$$

2. Dephasing

- Electrons move from accelerating to decelerating phase in the dephasing distance
- In linear regime:

$$(c - v_g)\frac{L_d}{c} = \frac{\lambda_p}{4}$$

$$\Rightarrow L_d = \frac{\lambda_p}{2}\left(\frac{\omega}{\omega_p}\right)^2$$



- For linearly-polarized square pulse:

$$L_d = \left(\frac{\omega}{\omega_p}\right)^2 \lambda_p \begin{cases} \frac{1}{2} & a_0^2 \ll 1 \\ \frac{a_0}{\pi} & a_0^2 \gg 1 \end{cases}$$

Wenz & Karsch, CERN Accelerator School (2019)

3. Pump depletion

- Laser loses energy to wake (don't panic — this is what we want to do!)
- Estimate pump depletion length by comparing energy in wake to laser energy

$$\left(\frac{1}{2}\epsilon_0 E_z^2\right)\pi w_0^2 L_{pd} = \left(\frac{1}{2}\epsilon_0 E_0^2\right)\pi w_0^2 c\tau$$

$$\Rightarrow L_{pd} = \left(\frac{E_0}{E_z}\right)^2 c\tau$$

- Using $E_z \approx a_0^2 E_{wb}$., this can be written

$$L_{pd} = \frac{\omega^2}{\omega_p^2}\frac{c\tau}{a_0^2} \approx \frac{\lambda_p^3}{\lambda^2 a_0^2}$$

- For linearly-polarized square pulse:

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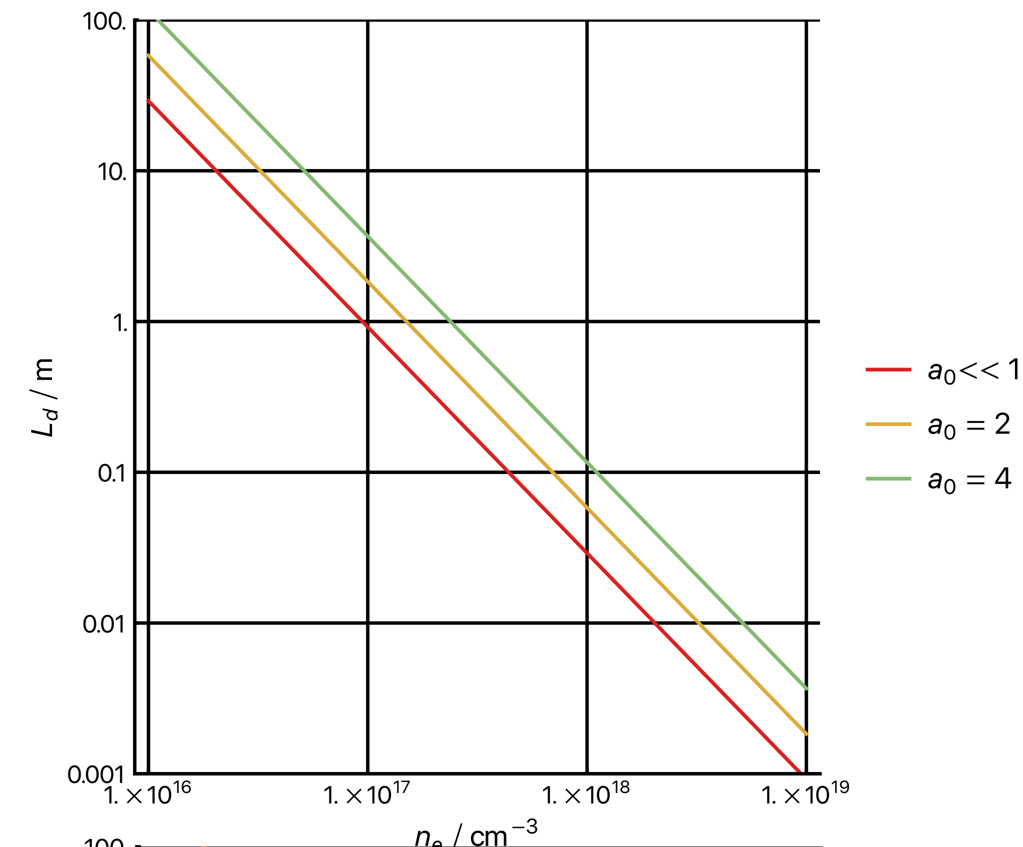
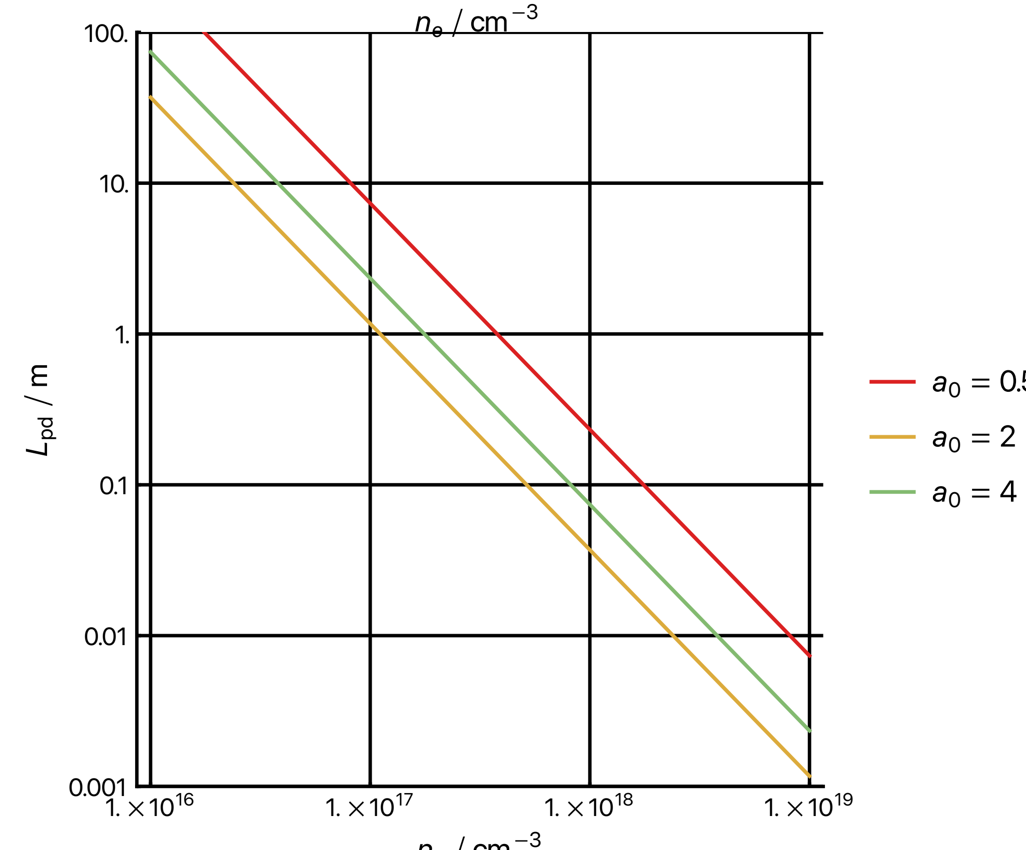


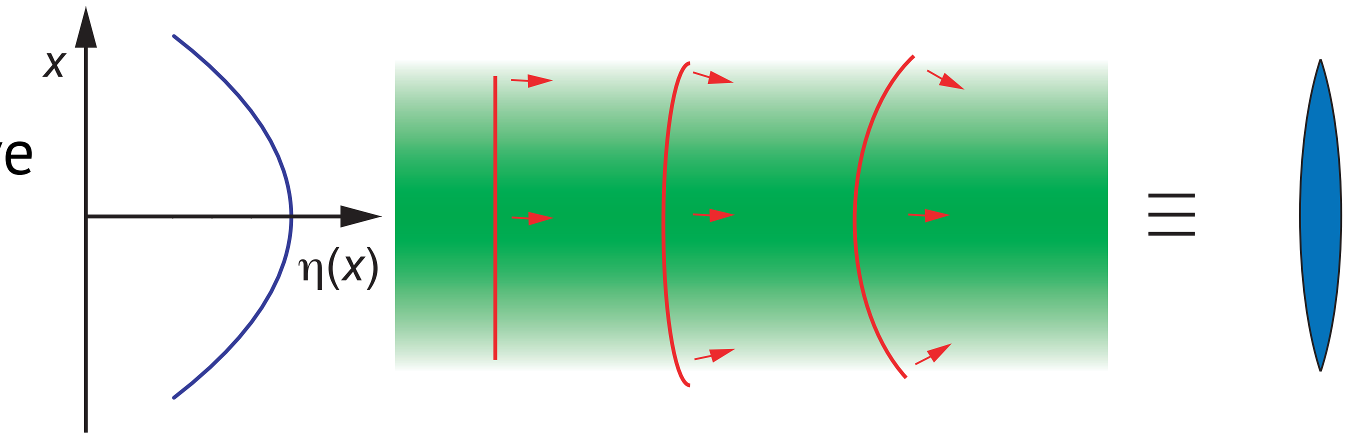


Wenz & Karsch, CERN Accelerator School (2019)

1. Beating defocusing

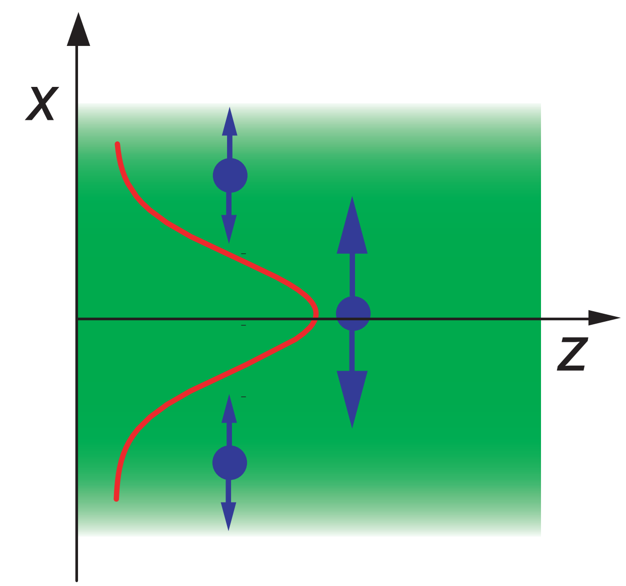
Gradient refractive index guiding

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



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

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



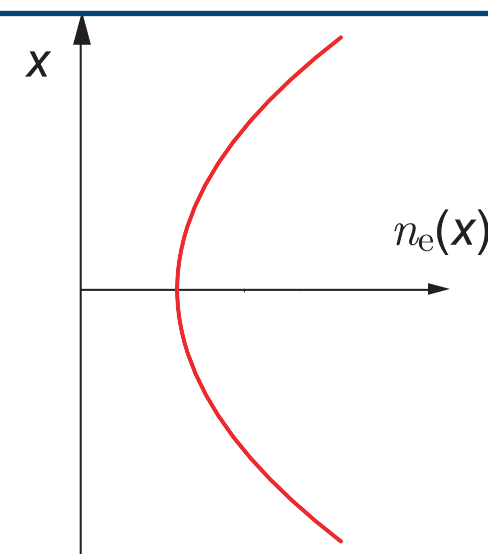
$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \approx 1 - \frac{1}{2}\frac{n_e e^2}{\gamma(r) m_e \epsilon_0 \omega^2}$$

Example :

$n_e = 10^{18}\ \mathrm{cm}^{-3}$, $\lambda = 800\ \mathrm{nm}$

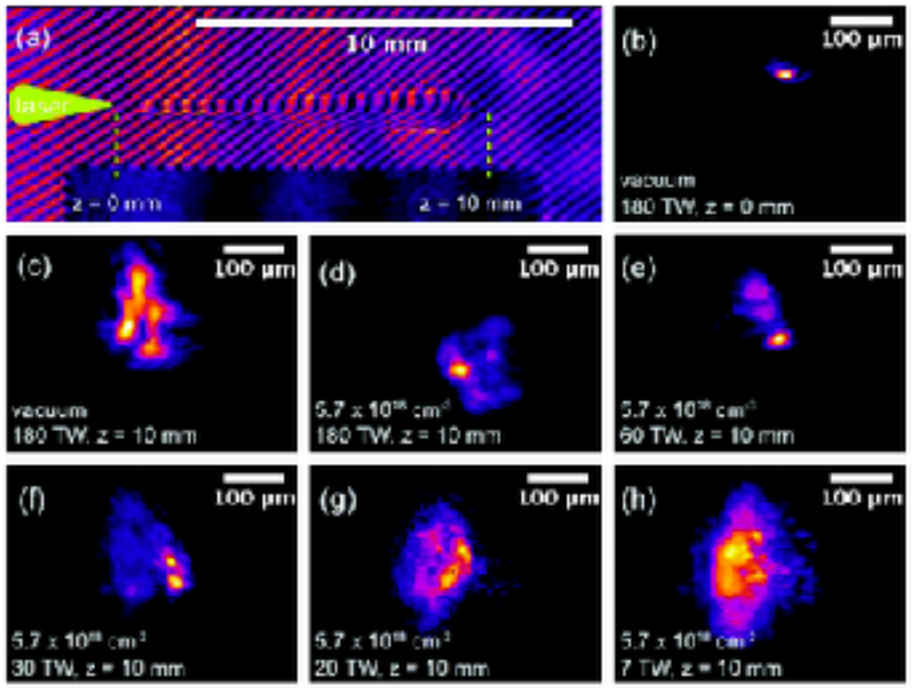
$P_c = 8\ \mathrm{TW}$

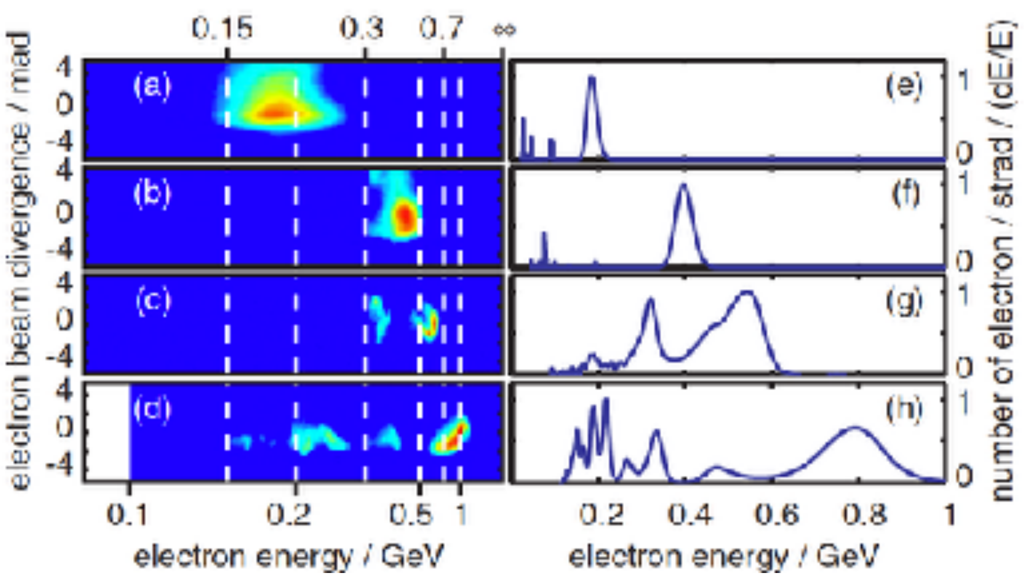
- **Plasma channel**: transverse variation of electron density gives correct refractive index profile



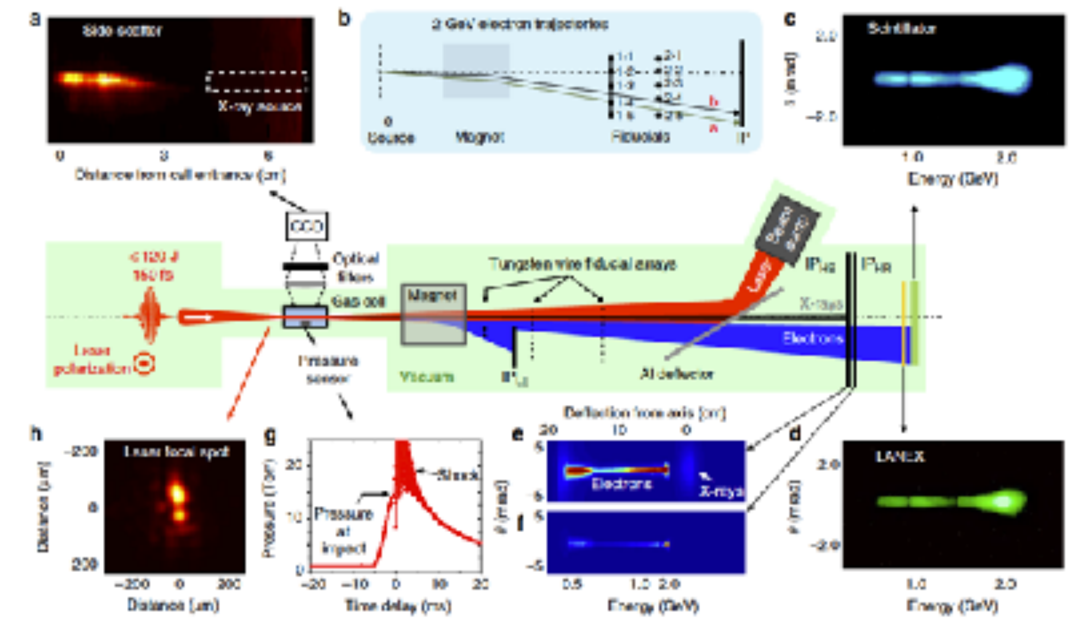
$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \approx 1 - \frac{1}{2}\frac{n_e(r) e^2}{\gamma m_e \epsilon_0 \omega^2}$$

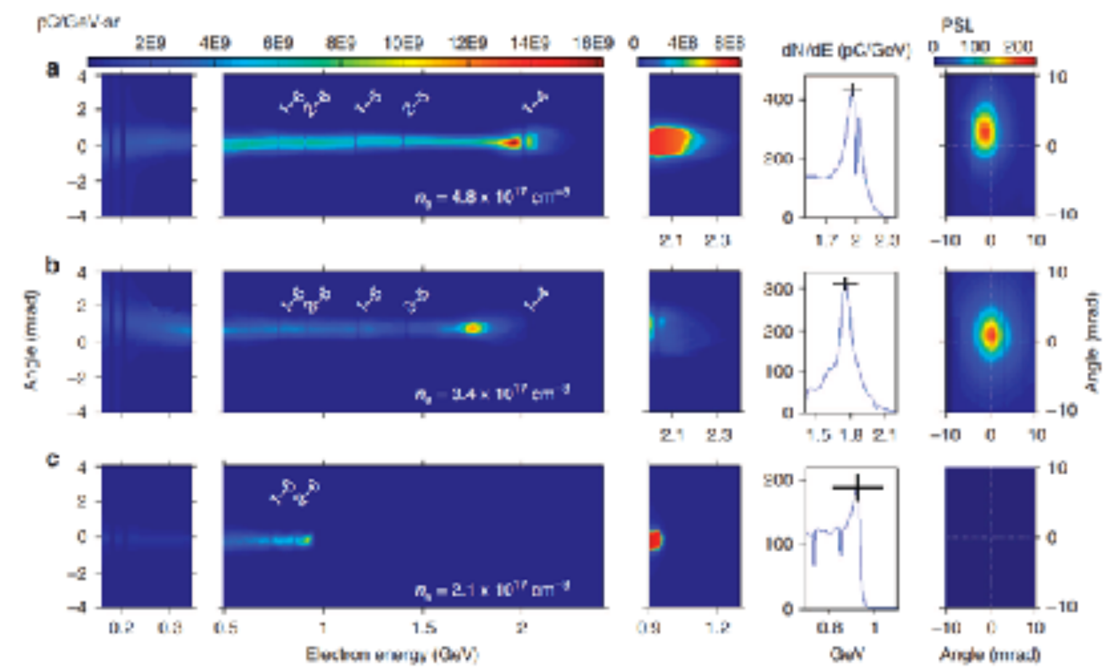
Acceleration by self-guided beams





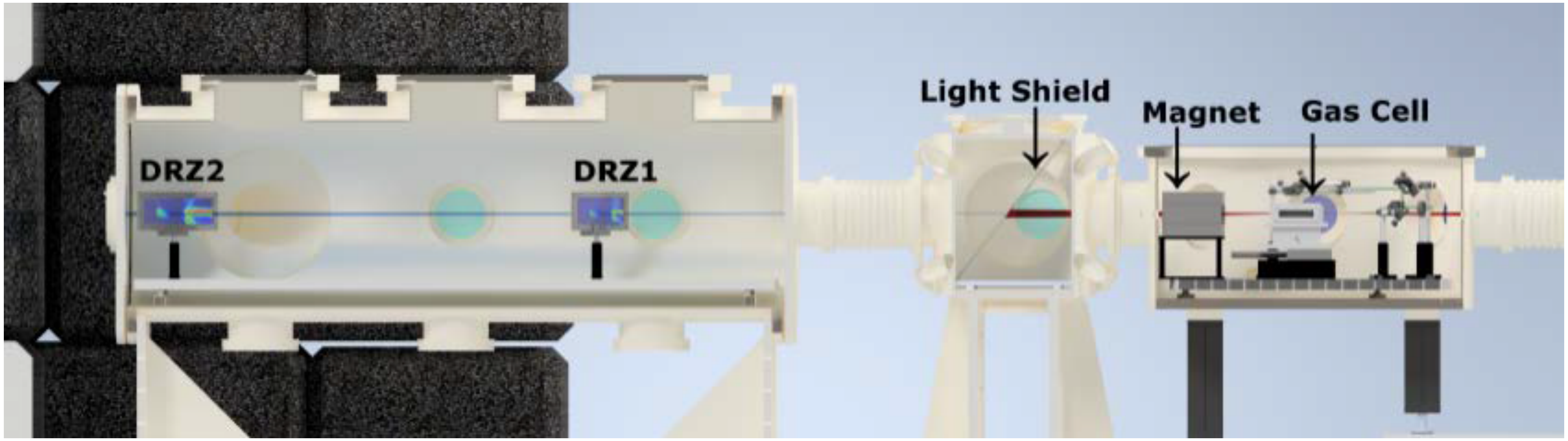
Kneip *et al. Phys. Rev. Lett.* **103** 035002 (2009)
Electrons: 0.8 GeV
Laser: E = 11 J, τ = 55 fs, $a0 \approx 3.9$
Plasma: $n_e = 5.7 \times 10^{18}$ cm^{-3}

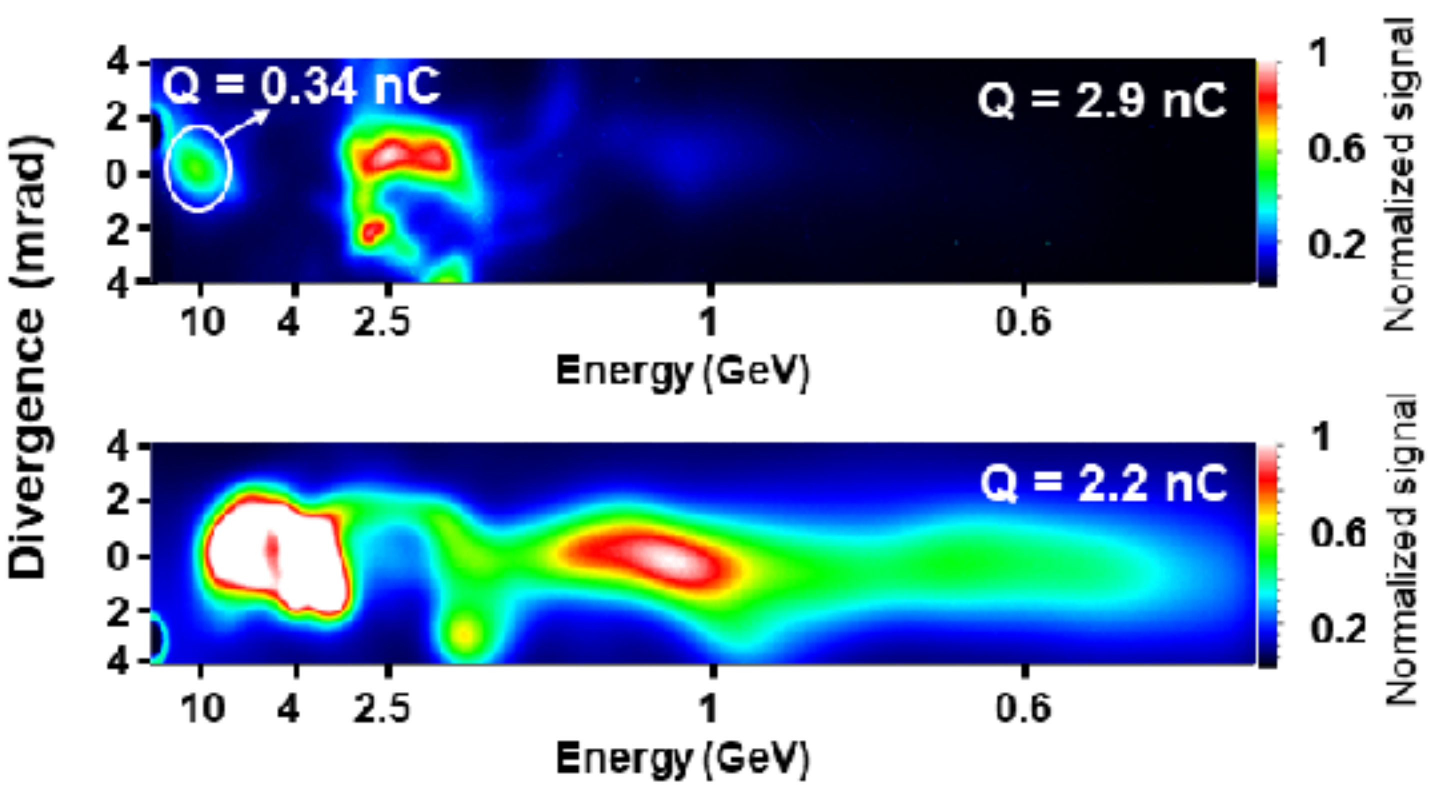




Wang *et al. Nat. Comm.* **4** 1988 (2013)
Electrons: ~ 2 GeV
Laser: E = 100 J, τ = 160 fs
Plasma: $n_e = 4.8 \times 10^{17}$ cm^{-3}

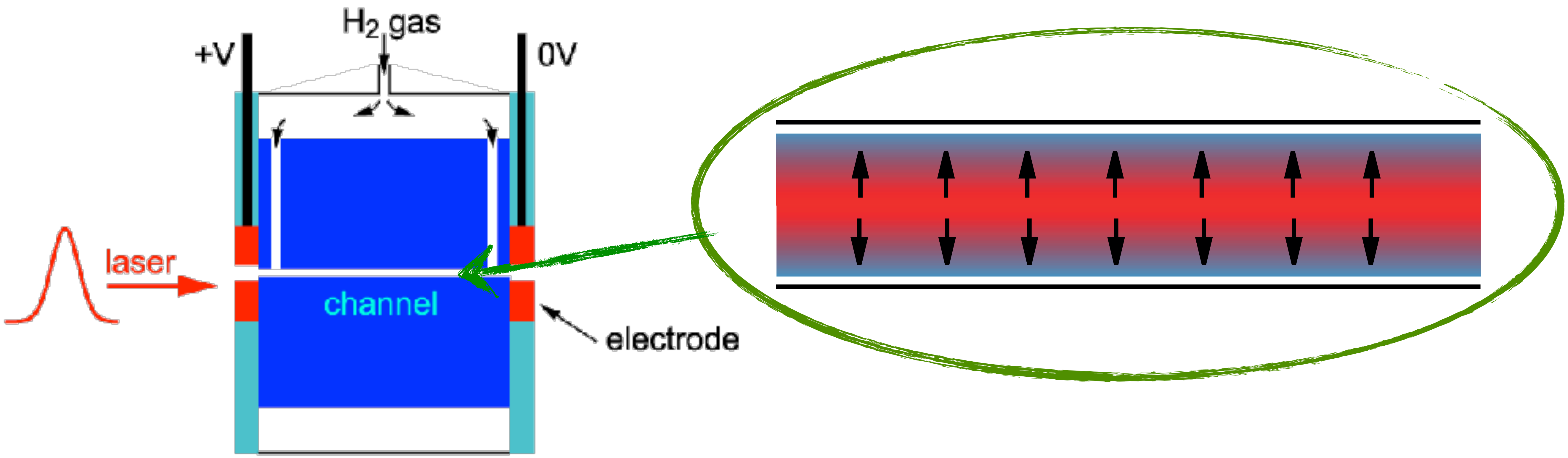
Acceleration by self-guided beams

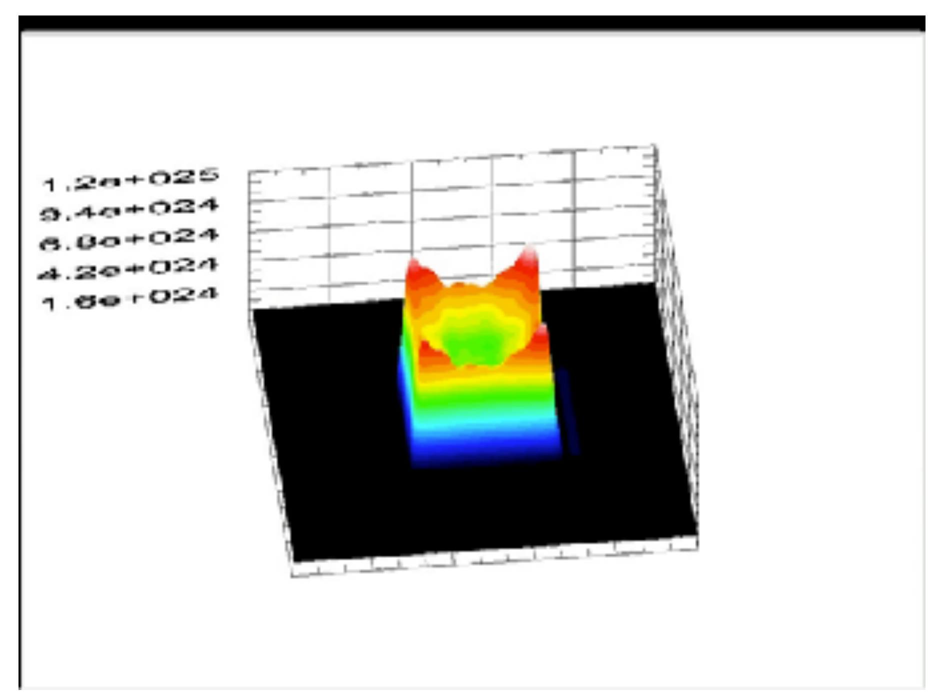




Aniculaesei *et al. ArXiv 2207.11492*
Electrons: ~ 10 GeV
Laser: E = 135 J, τ = 135 fs
Plasma: $n_e = 6 \times 10^{17}$ cm^{-3} **+ nanoparticles**

Plasma channels: capillary discharge waveguide

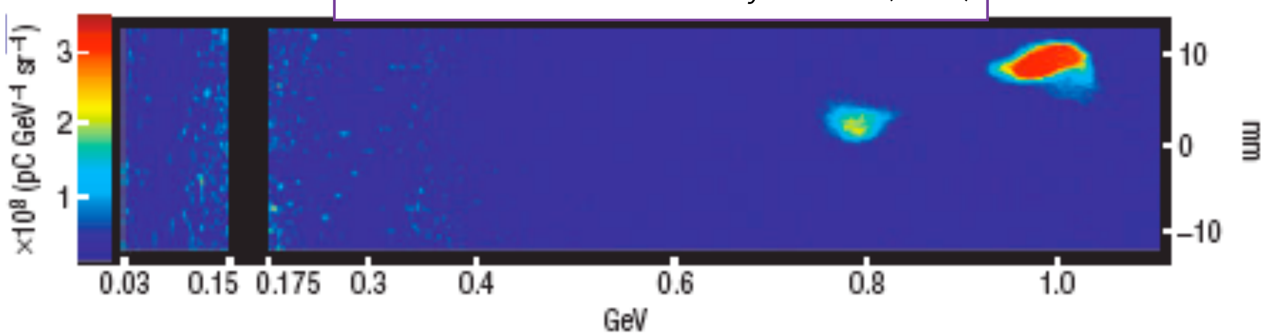




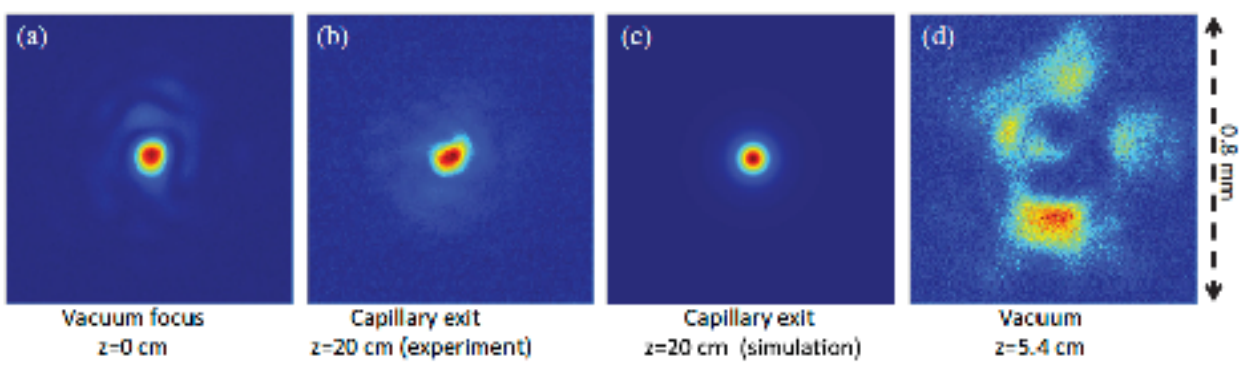
- Plasma formed by pulsed discharge
  - ~300 A peak
  - ~ 200 ns half-period
- Plasma channel formed by heat conduction to capillary wall.
- Channel is fully ionized and stable.

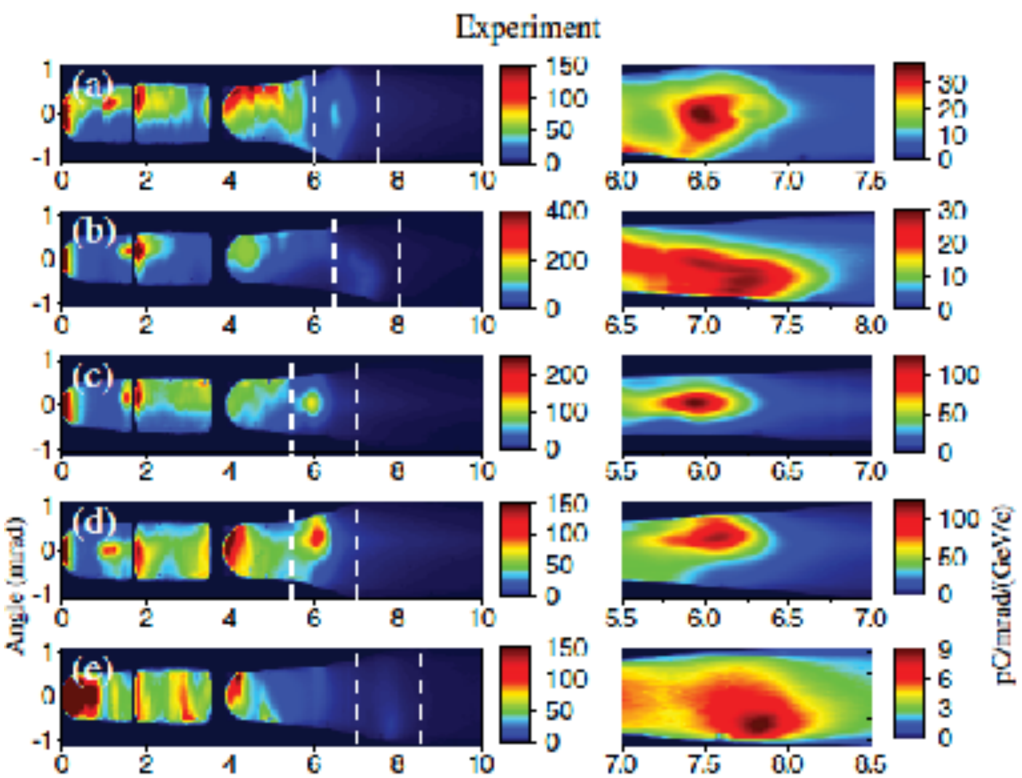
D. J. Spence et al. *Phys. Rev. E* **63** 015401(R) (2001)
A. Butler et al. *Phys. Rev. Lett.* **89** 185003 (2002)

GeV beams!



W.P. Leemans et al. *Nat. Phys.* **2** 696 (2006)





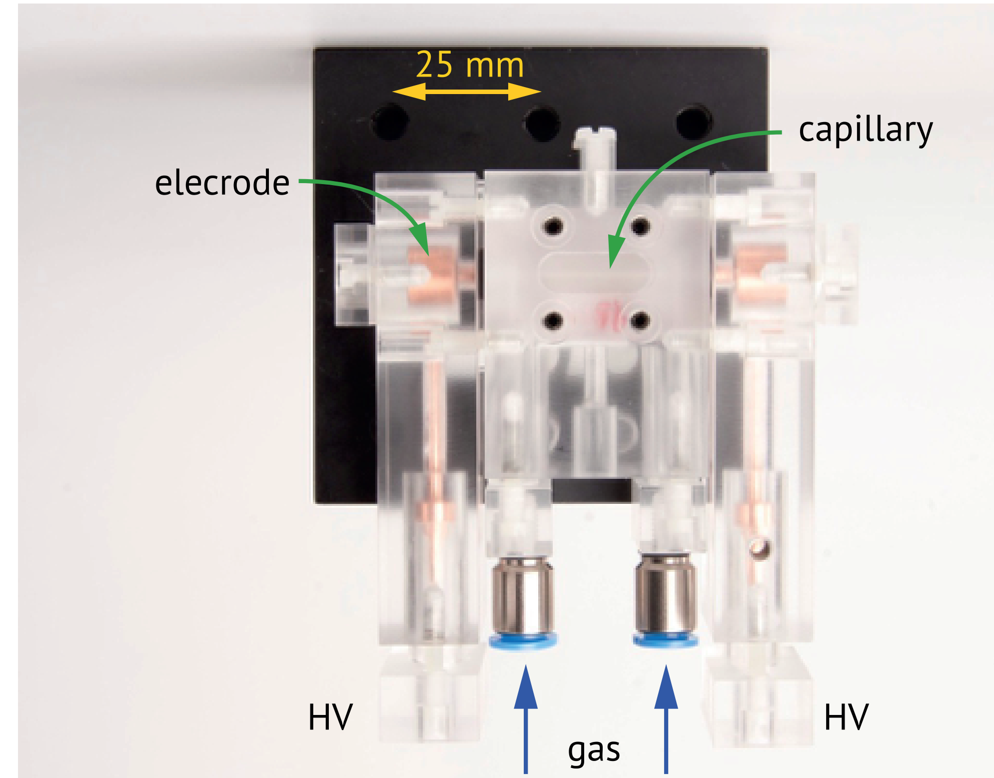
Gonsalves et al. Phys. Rev. Lett. **122** 084801 (2019)

- Used in experiments at LBNL to reach GeV milestone for first time
- 33 mm long capillary

- Laser-heated variant used to generated ~ 8 GeV beams
- 200 mm long capillary

Why are new waveguides needed?

- 10 GeV stages **require decrease in plasma density** from $n_e \approx 10^{18}$ cm^{-3} to $n_e \approx 10^{17}$ cm^{-3}
- Roadmaps require **increase in repetition rate** to kHz range
- Capillary discharges:
  - Successfully operated at $n_e \approx 10^{17}$ cm^{-3}
  - f_{rep} = 1 kHz demonstrated
  - Use of additional laser heater gives deeper channels

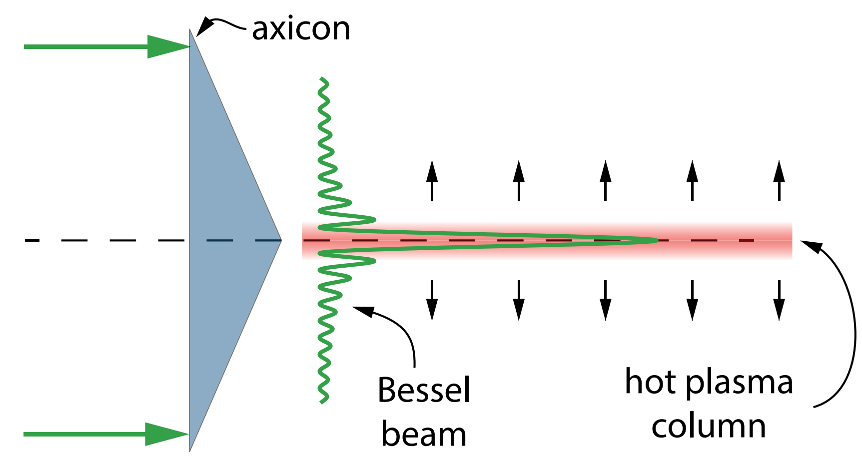


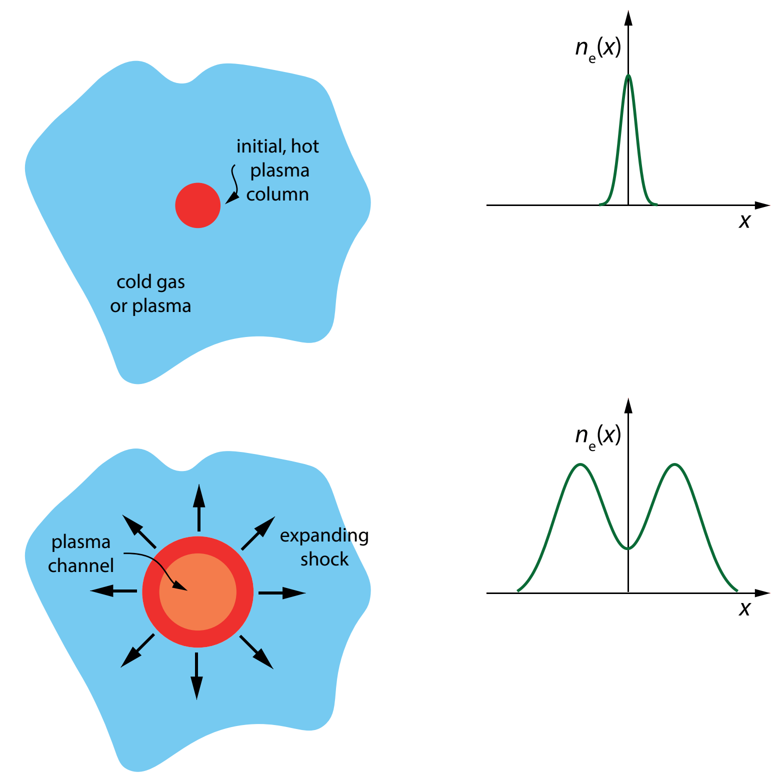
- … but, long-term operation at kHz repetition rates when guiding multi-joule laser pulses will be challenging!

A. J. Gonsalves et al. *J. Appl. Phys.* **119** 033302 (2016)
N. A. Bobrova et al. *Phys Plasmas* **20** 020703 (2013)

All-optical plasma channels

- Create & heat column of hot plasma
  - ~ 100 ps laser pulse creates and heats plasma **collisionally**
  - Expansion into surrounding cold gas / plasma drives cylindrical blast wave
  - Plasma channel formed within expanding shell
- **Free-standing and "indestructible" !**

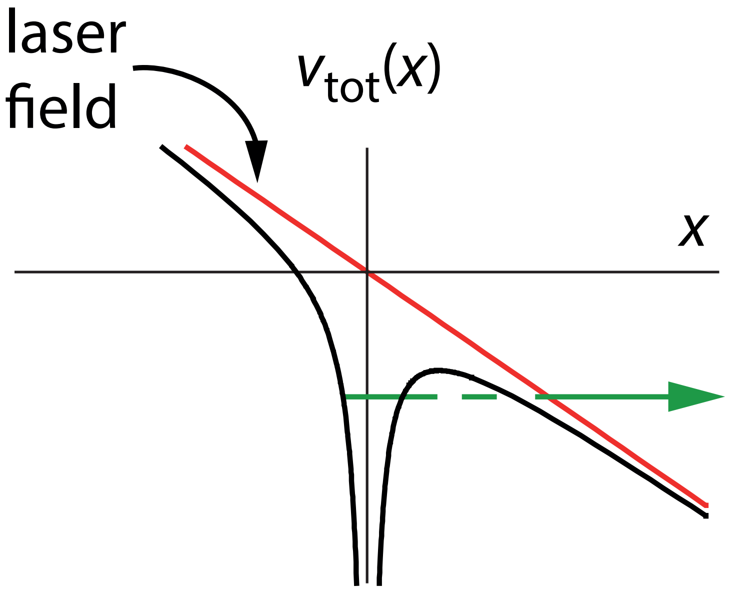




- … but, fast collisional heating requires high density
  - Limits axial density to $\sim 10^{18}\,\mathrm{cm}^{-3}$

Durfee & Milchberg, *Phys. Rev. Lett.* **71** 2409 (1993)
Volbeyn et al. Phys. Plasma. **6** 2269 (1999)

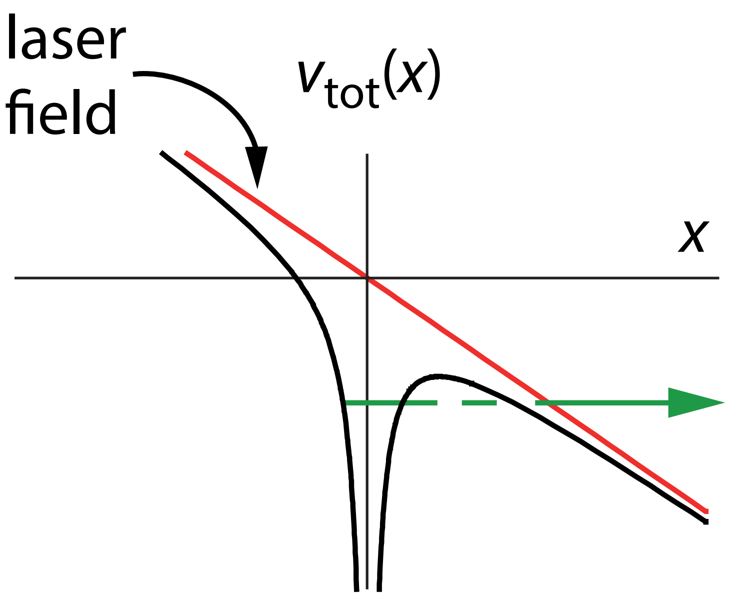
Hydrodynamic Optical-Field-Ionized (HOFI) plasma channels



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

S. M. Hooker et al., Advanced Accelerator Conference (2016
R. Shalloo, Ph.D. thesis, University of Oxford (2018).
R.J. Shalloo et al. Phys Rev. Acc. Beam 22 041302 (2019)
A. Picksley et al. Phys. Rev. E 102 53201 (2020)

Hydrodynamic Optical-Field-Ionized (HOFI) plasma channels



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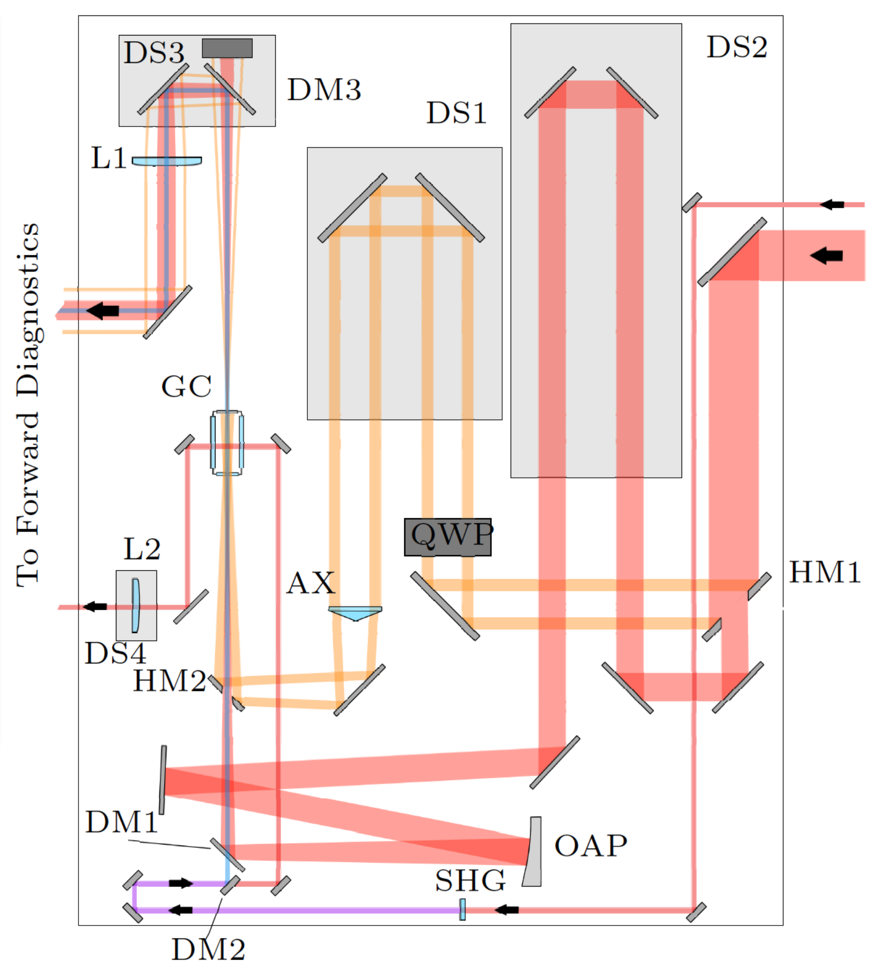
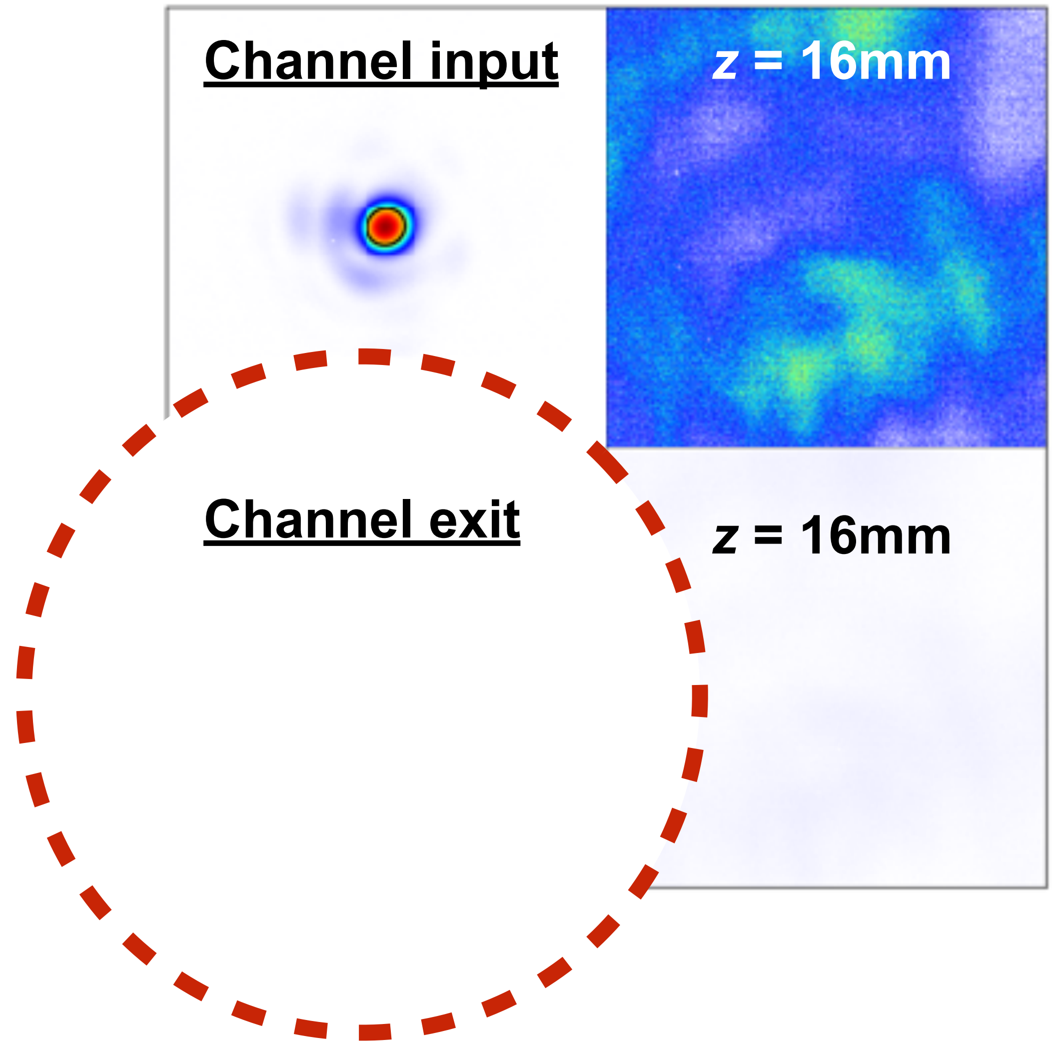
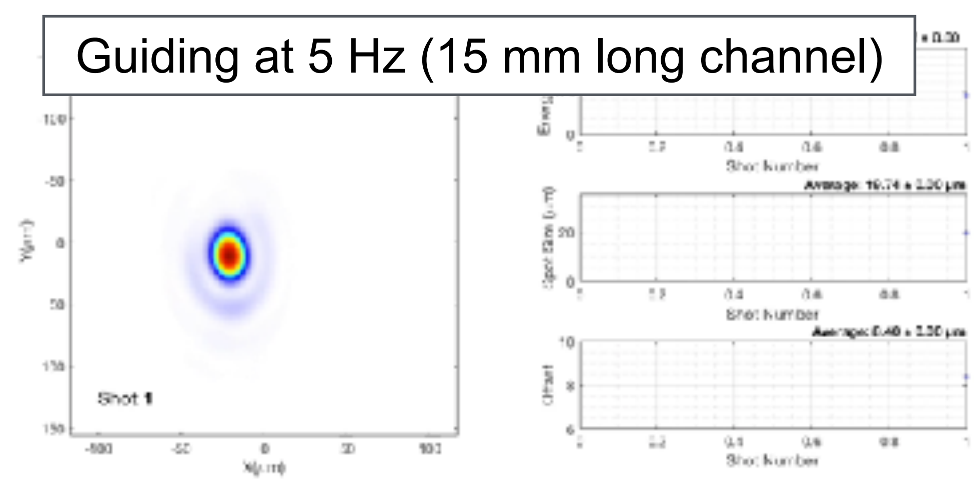


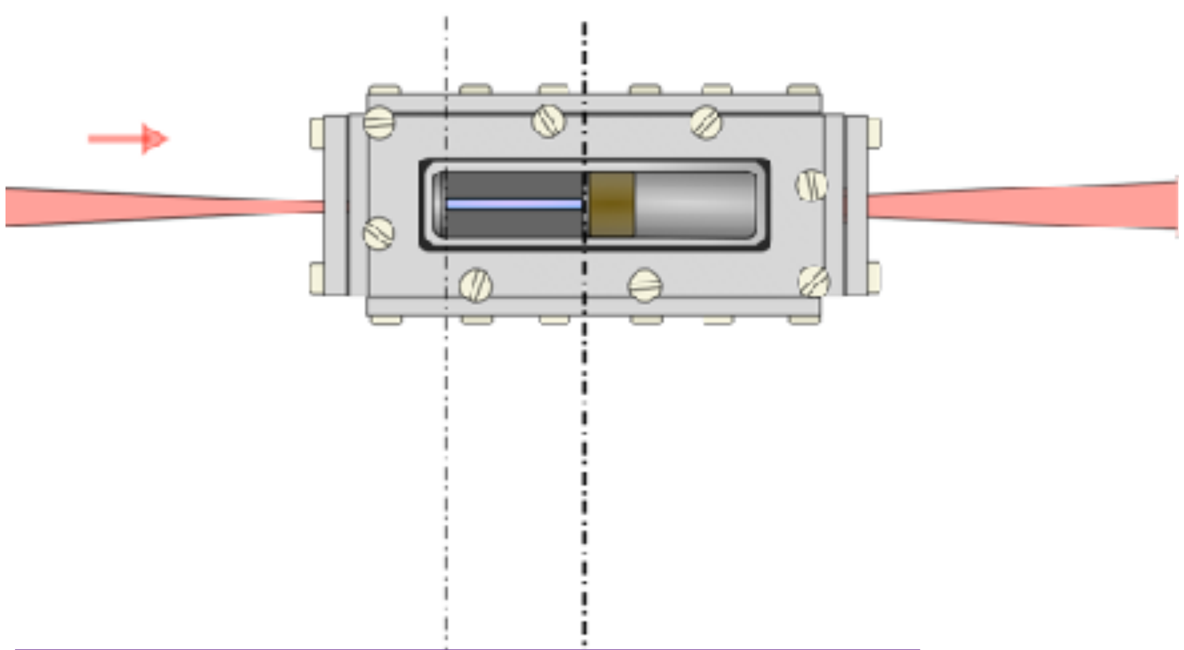
S. M. Hooker et al., Advanced Accelerator Conference (2016
R. Shalloo, Ph.D. thesis, University of Oxford (2018).
R.J. Shalloo et al. Phys Rev. Acc. Beam 22 041302 (2019)
A. Picksley et al. Phys. Rev. E 102 53201 (2020)

HOFI channels: first results

- Guided beam injected into channel after 1.5 ns
- On-Axis Density ~ 6.5 x 10^{17} cm^{-3}
- Demonstration of High Intensity Guiding over 14.5 Rayleigh Ranges (16 mm)
- Guided Intensity > 10^{17} W cm^{-2}
- Consistently 40-60% energy throughput



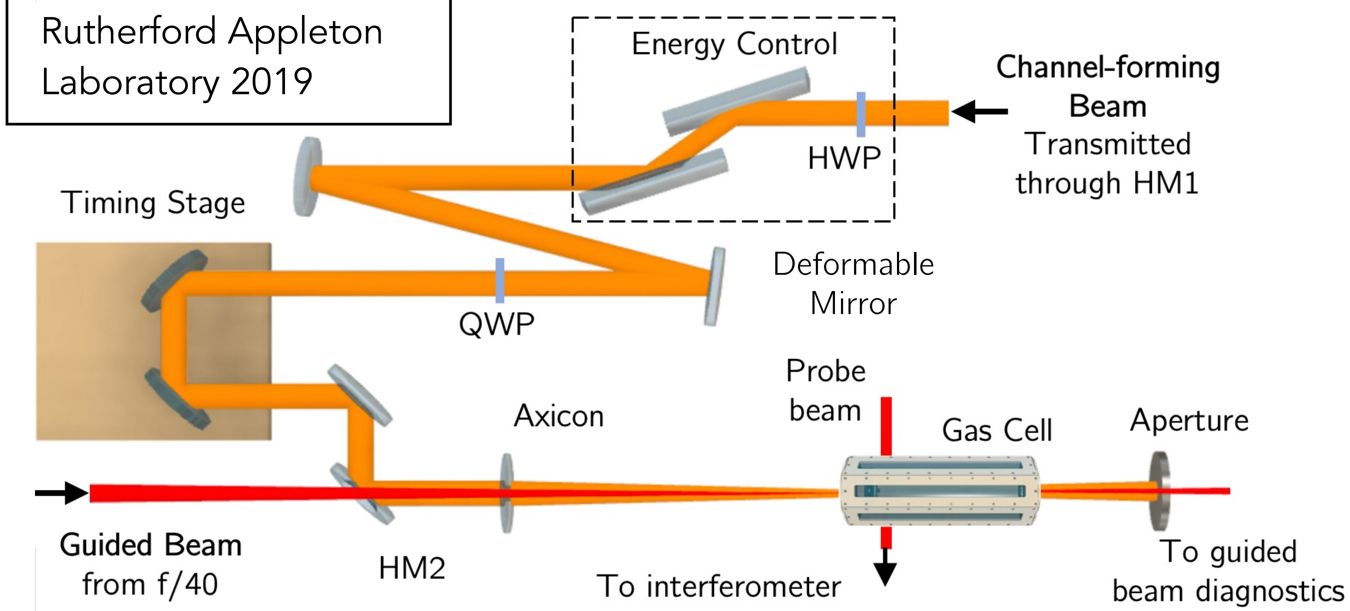


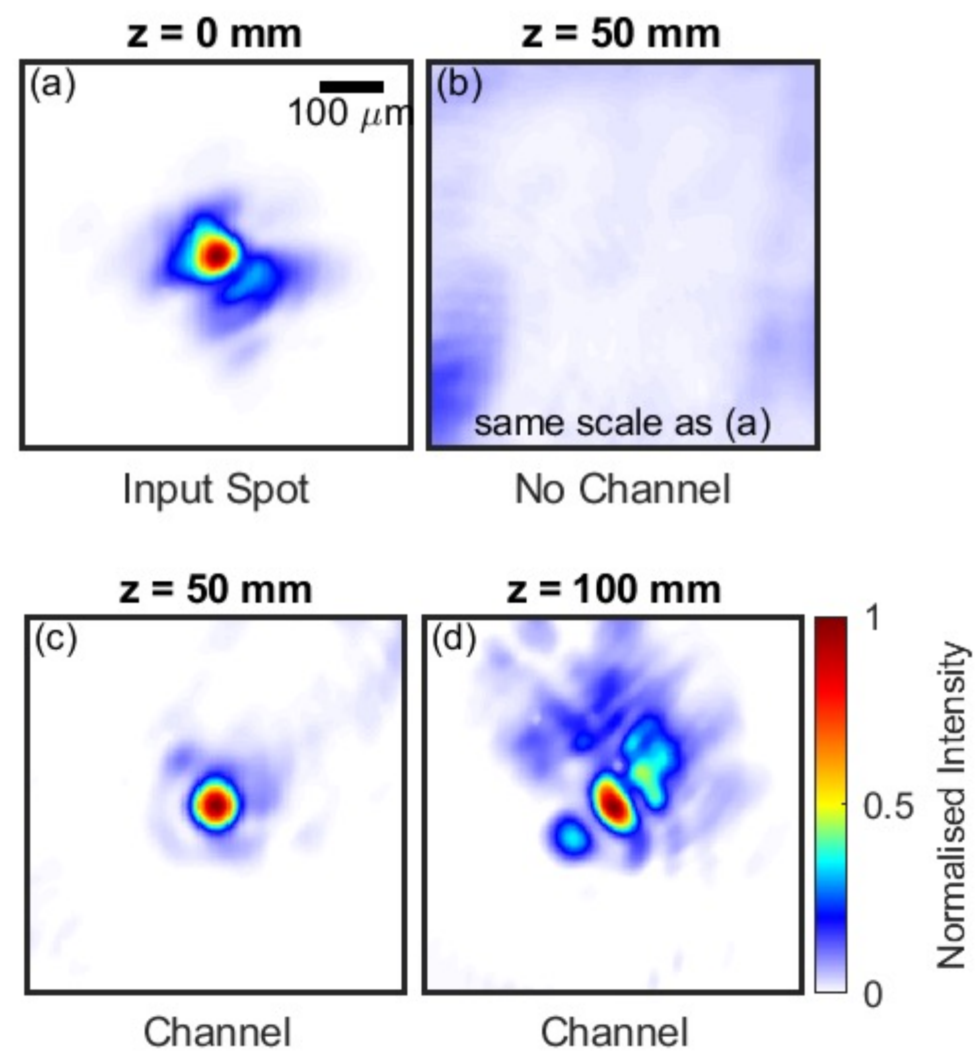


S. M. Hooker et al., Advanced Accelerator Conference (2016
R. Shalloo, Ph.D. thesis, University of Oxford (2018).
R.J. Shalloo et al. Phys Rev. Acc. Beam 22 041302 (2019)

HOFI channels: Guiding over 100 mm

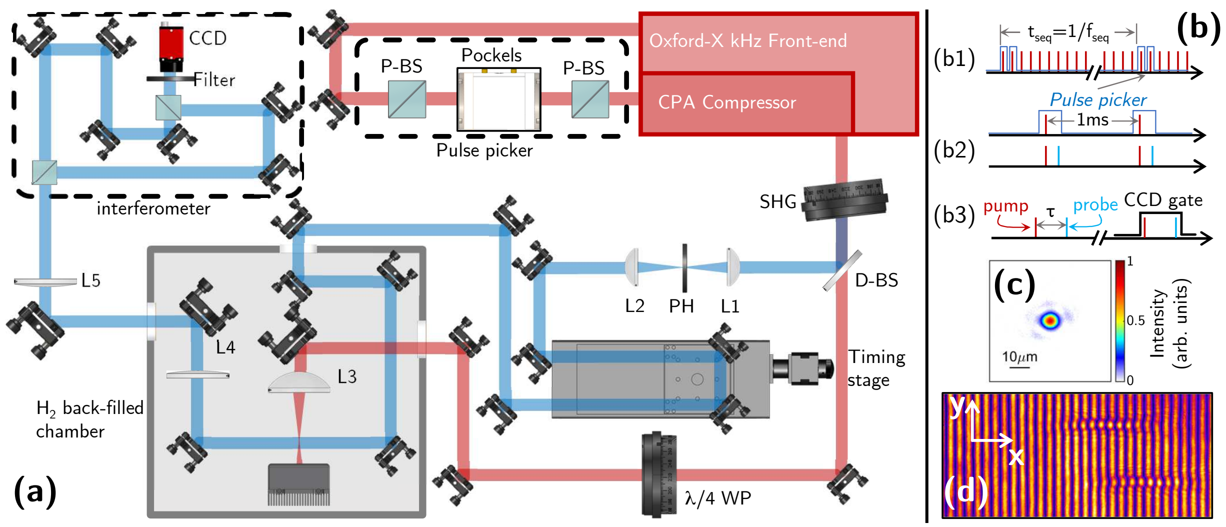
Gemini TA3 laser, Rutherford Appleton Laboratory 2019

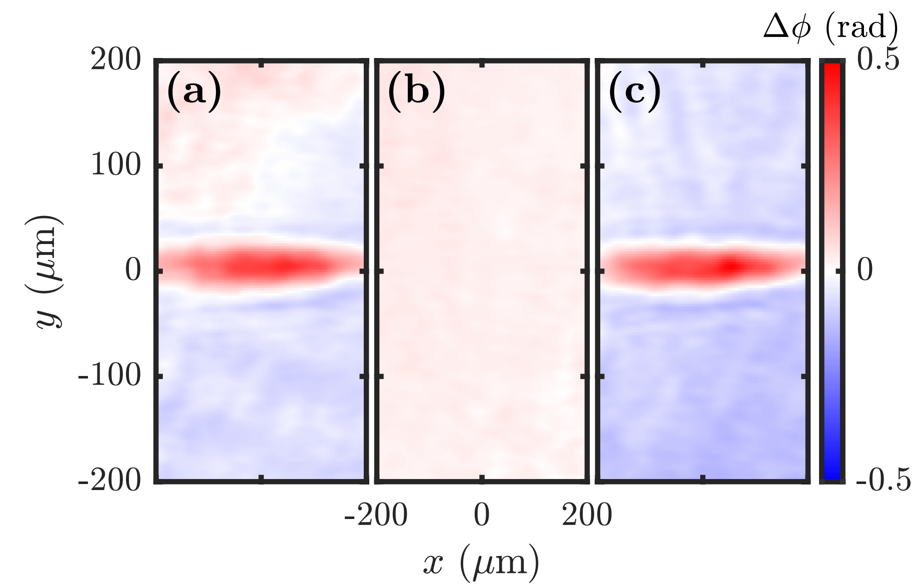


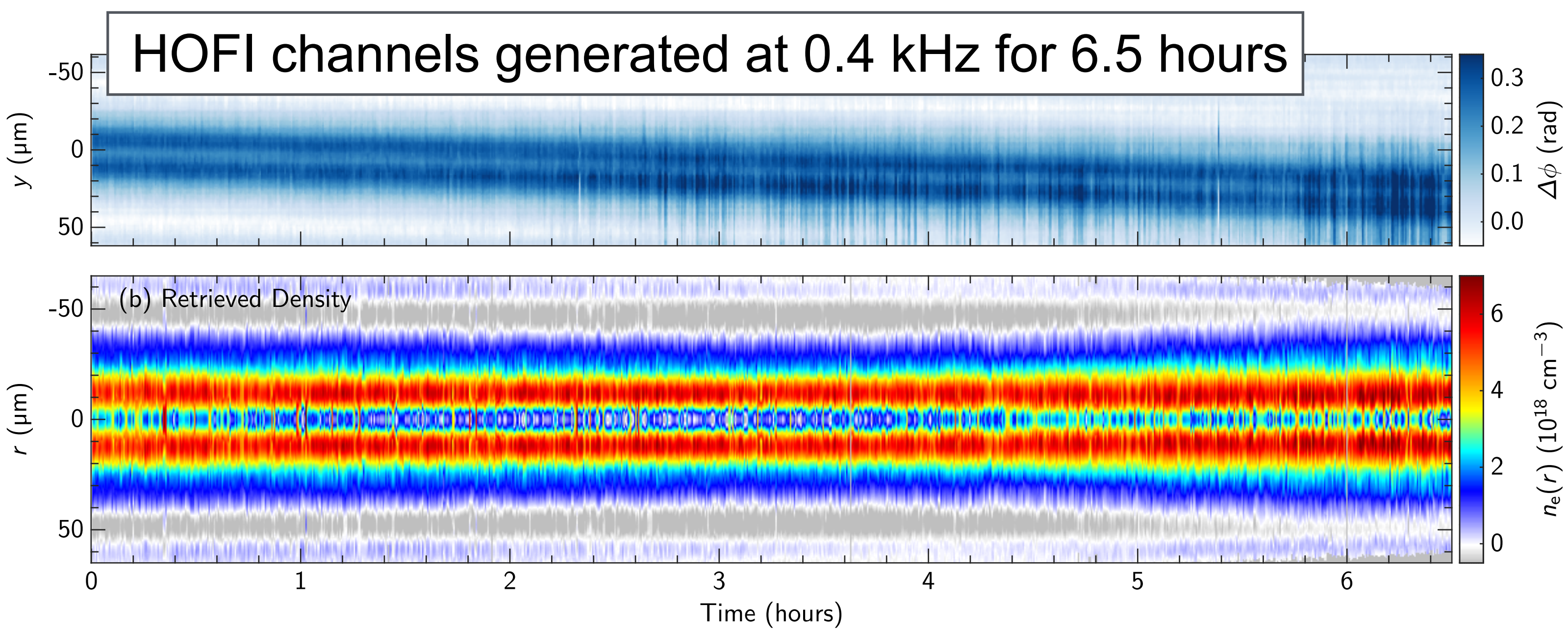


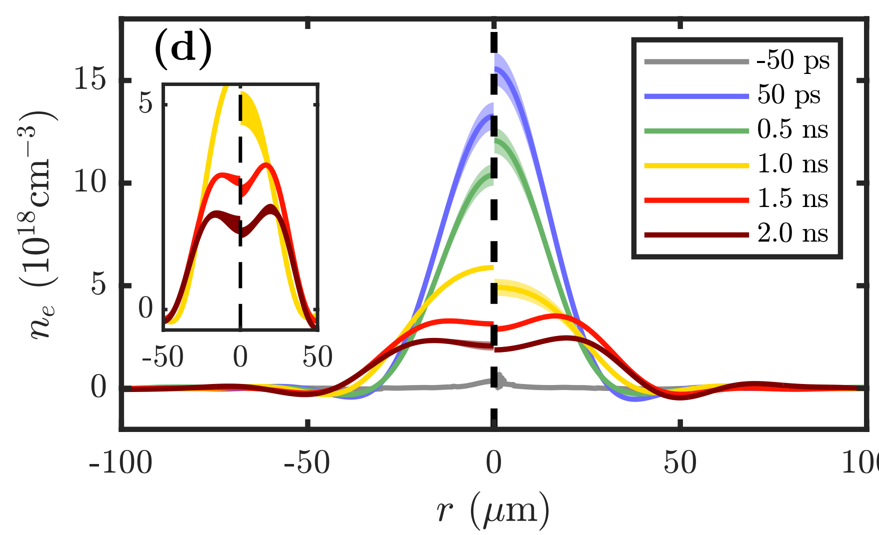
A. Picksley et al. *Phys Rev Accel Beam* **23** 81303 (2020)

HOFI channels: kHz operation



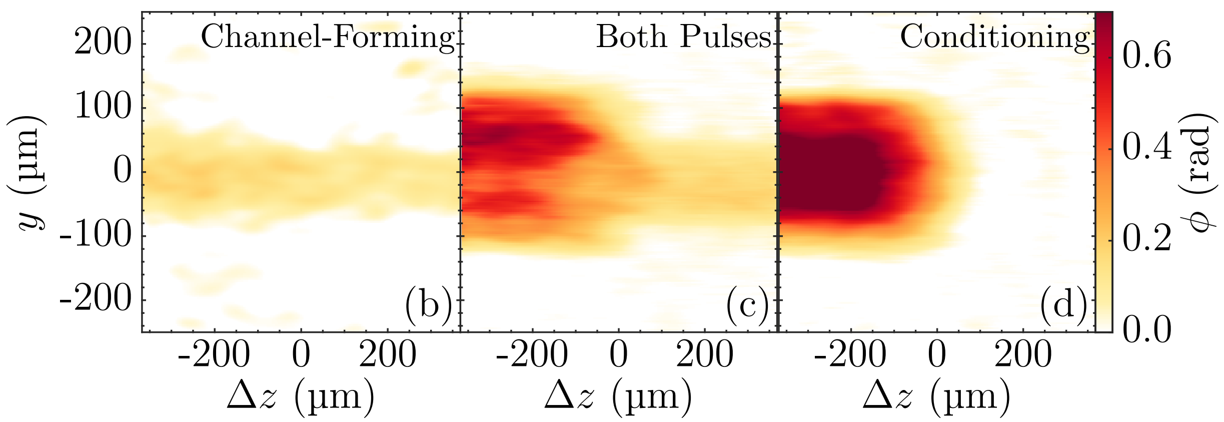


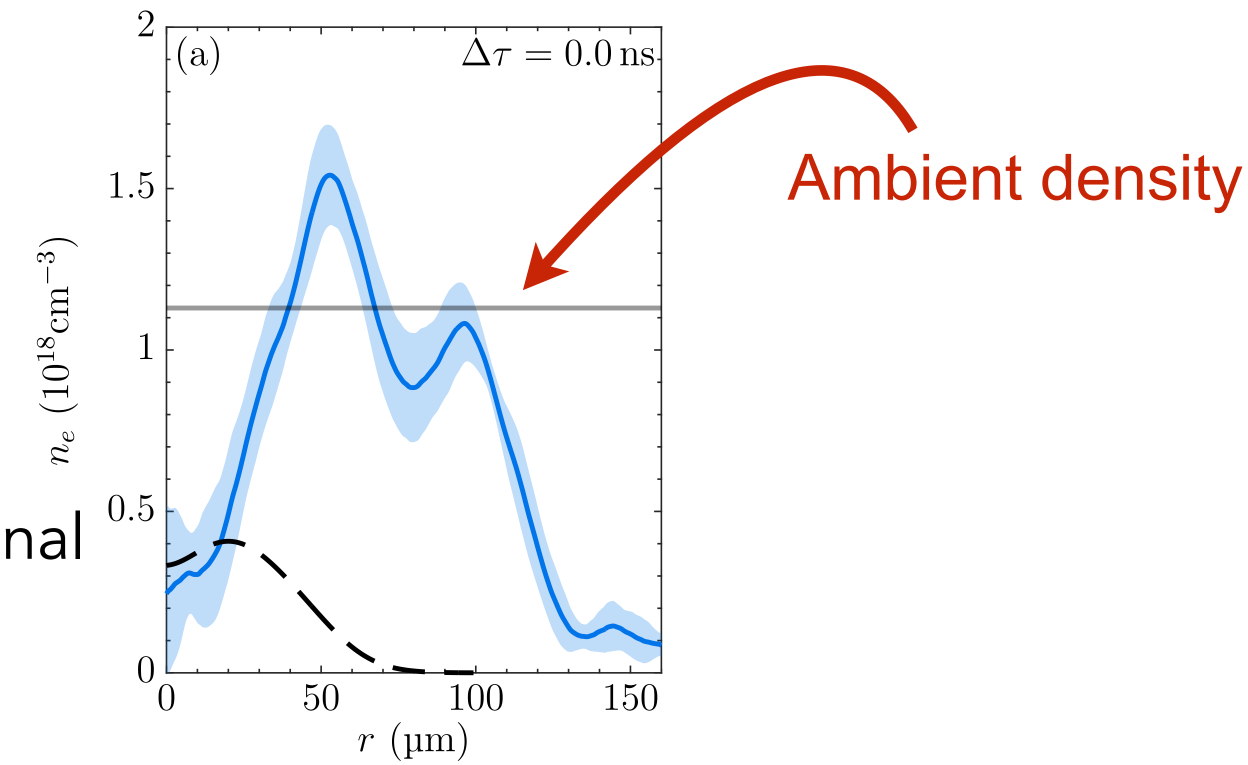




A. Alejo et al. *Phys Rev Acc. Beams* **25** 011301 (2022)

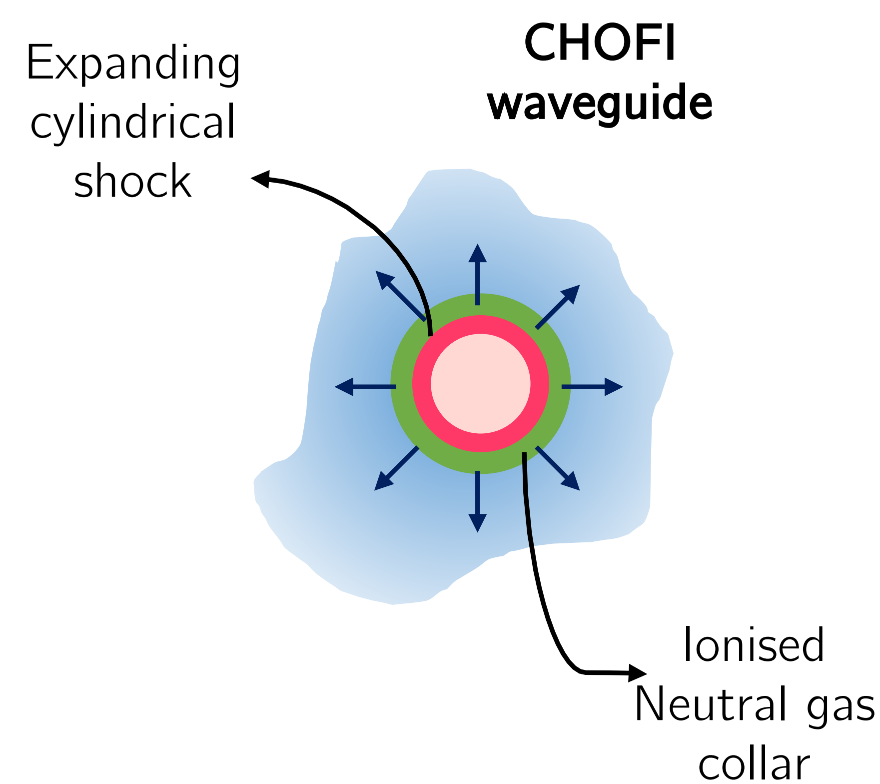
Conditioned HOFI (CHOFI) channels





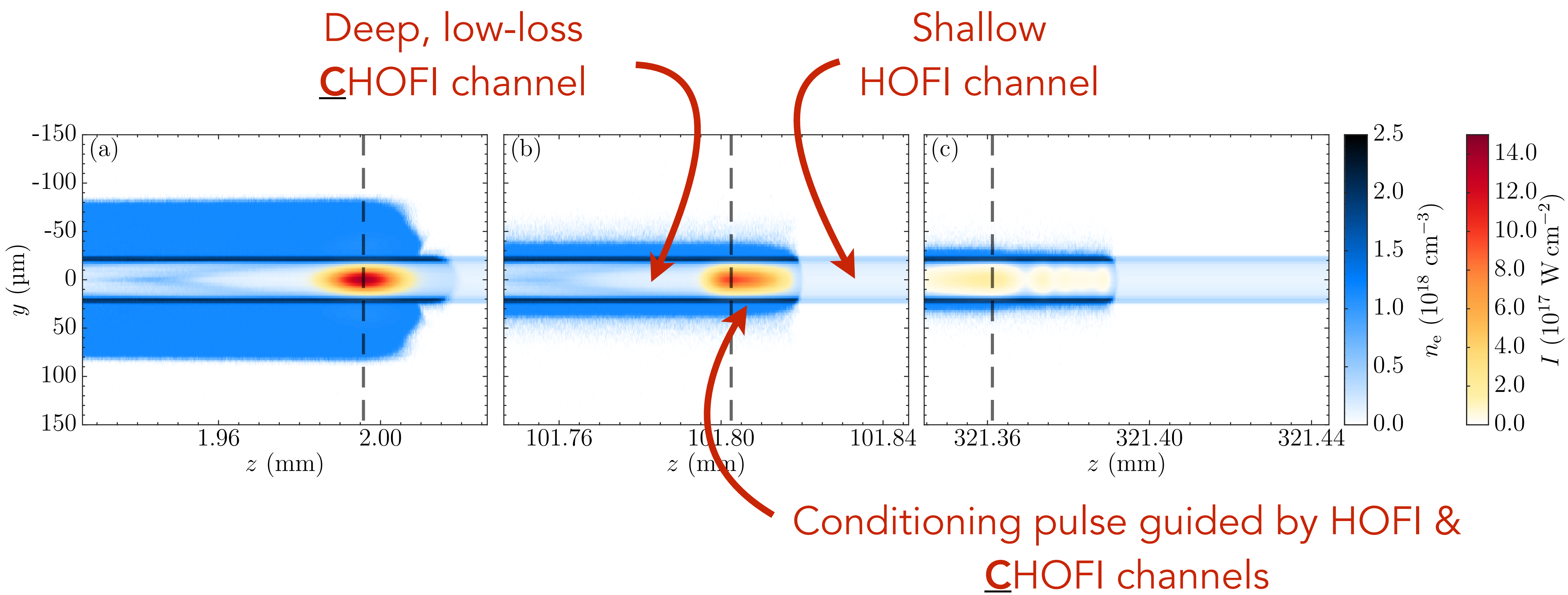
- Transverse interferometry shows additional ionization outside initial channel

- Collar of neutral gas pushed out by initial shock
- Collar ionized by transverse wings of guided / conditioning pulse



Shalloo, Ph.D. thesis, University of Oxford (2018).
Shalloo et al. *Phys Rev. Acc. Beam* **22** 041302 (2019)
Picksley et al. *Phys. Rev. E* **102** 53201 (2020)
Feder et al., Phys. Rev. Res. **2** 043173 (2020)
Shrock et al., Phys Plasm. **29** 073101 (2022).

Conditioned HOFI (CHOFI) channels



- Cylindrically symmetric FBPIC simulations using electron & neutral density profiles from FLASH simulations
- Laser parameters matched to 2018 Astra experiment
- Calculated power attenuation length of CHOFI channel is **L_{att} = 2.5 m!**

R. Shalloo, Ph.D. thesis, University of Oxford (2018).
R.J. Shalloo et al. *Phys Rev. Acc. Beam* **22** 041302 (2019)
A. Picksley et al. *Phys. Rev. E* **102** 53201 (2020)

2. Beating dephasing

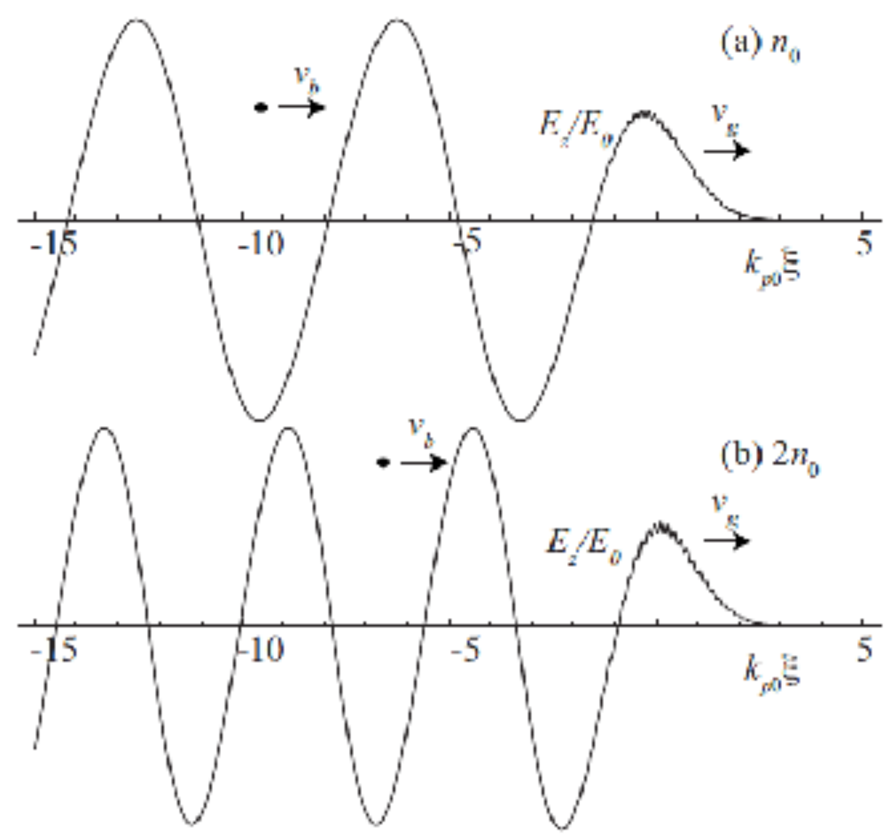
Can dephasing be overcome?

Longitudinal tapering

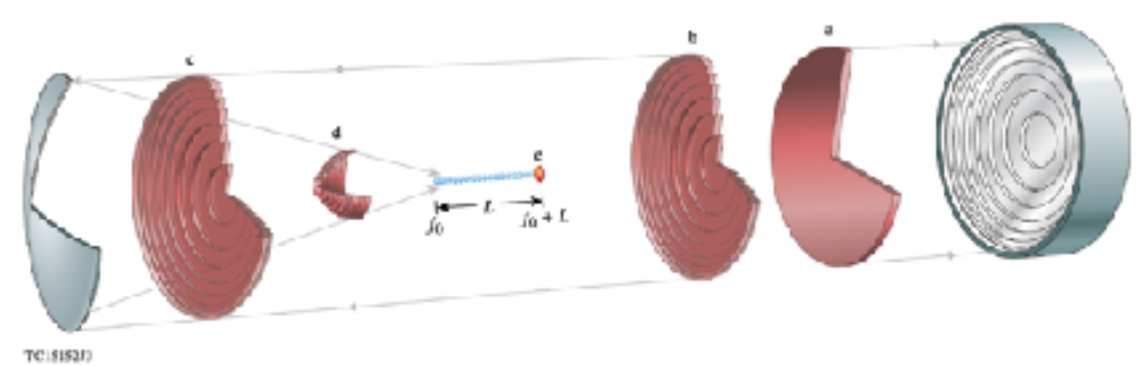
- Use a longitudinally-varying (“tapered”) plasma density
- Essentially opposite of down-ramp injection: increasing density speeds wake up!

“Flying focus”

- Use spatio-temporal methods to generate a flying focus propagating at $v_g = c$



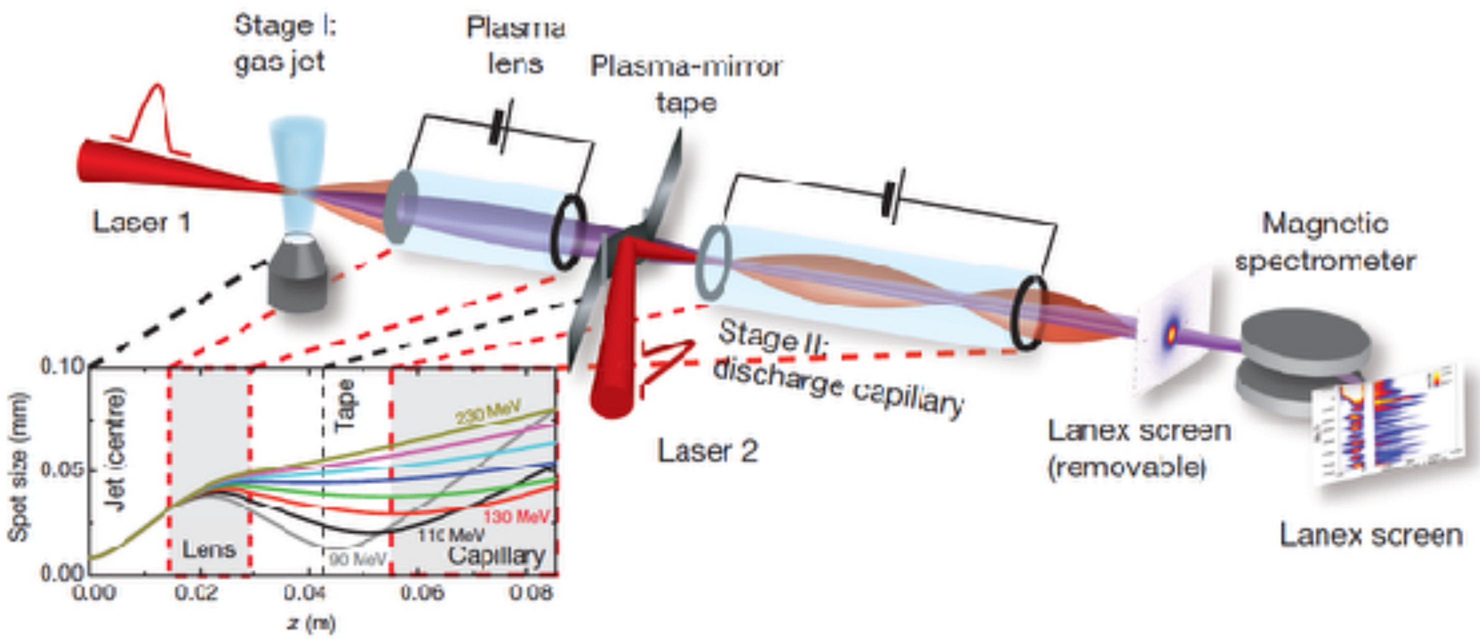
Rittershofer et al., *Phys. Plasm.* **17** 063104 (2010)

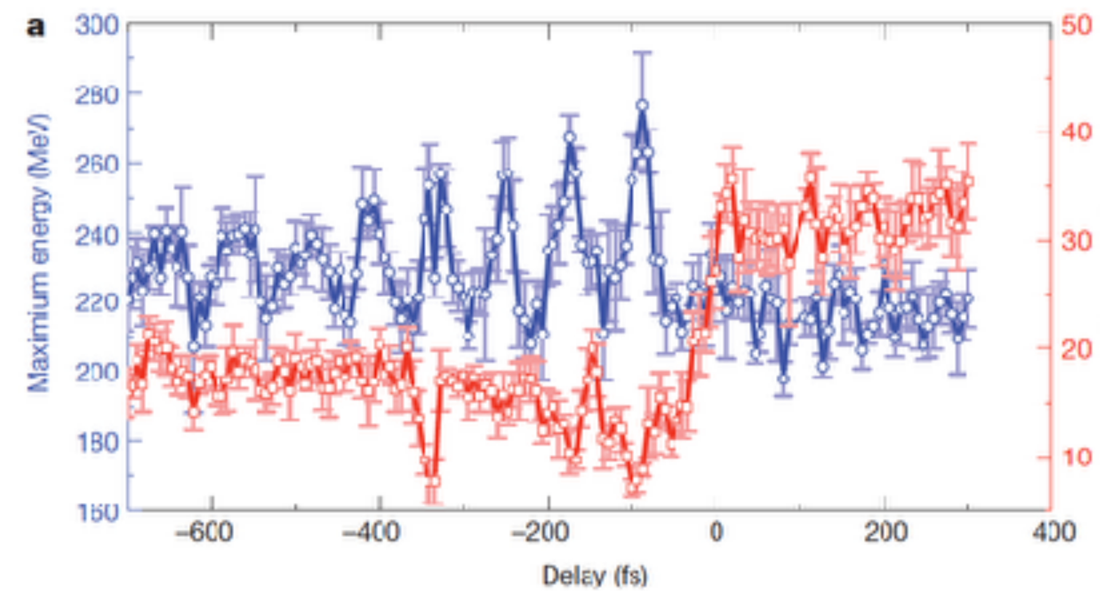


Palastro et al., *Phys. Rev. Lett.* **124** 134802 (2020)

Sprangle et al., *Phys Rev E* **63** 056405 (2001)
Pukhov & Kostyukov, *Phys. Rev. E* **77** 025401 (2008)
Rittershofer et al., *Phys. Plasm.* **17** 063104 (2010)
Palastro et al., *Phys. Rev. Lett.* **124** 134802 (2020)

Staging





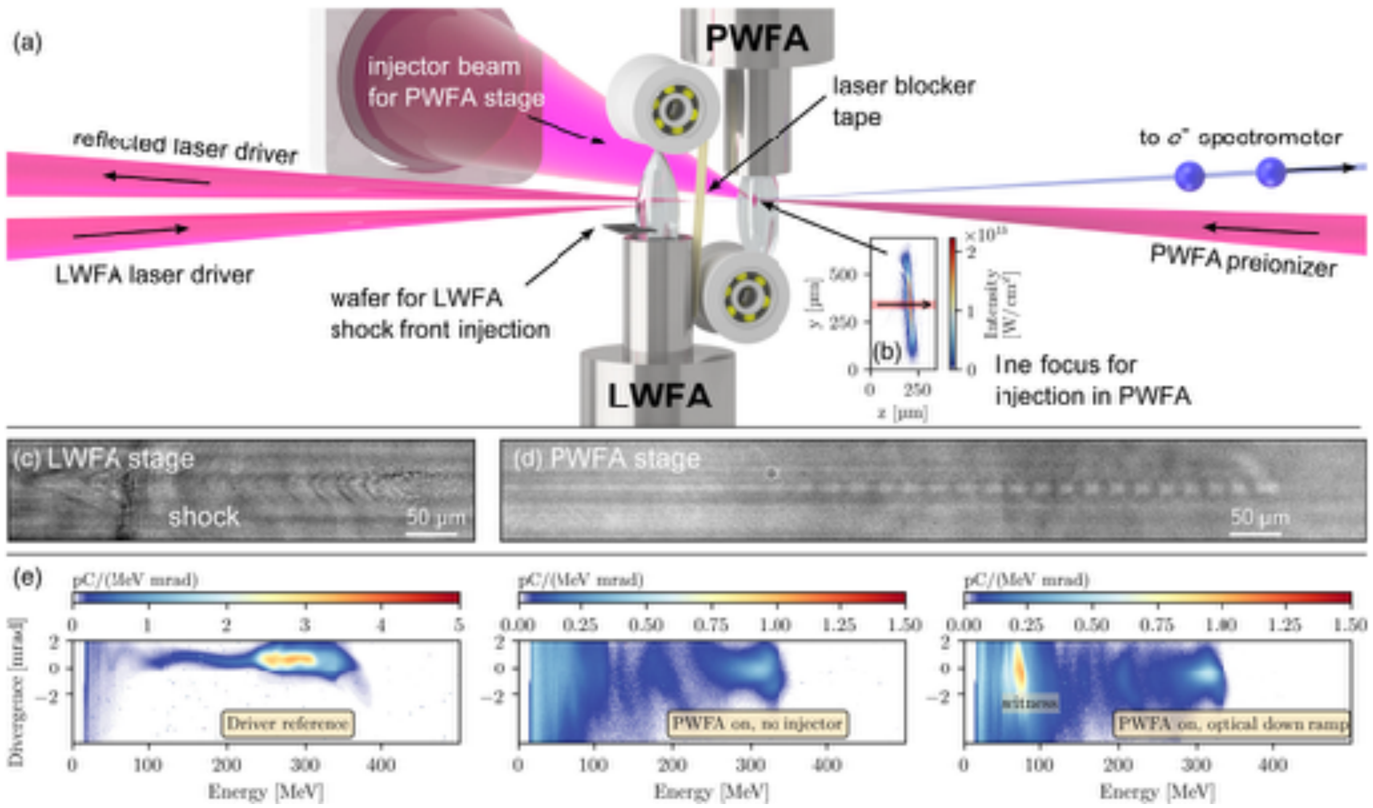
- If not, can only increase energy by connecting multiple accelerator stages
- Challenges
  - Getting rid of spent laser pulse
  - Introducing fresh laser pulse
  - Transporting electron bunch between stages with high efficiency and without degrading bunch quality

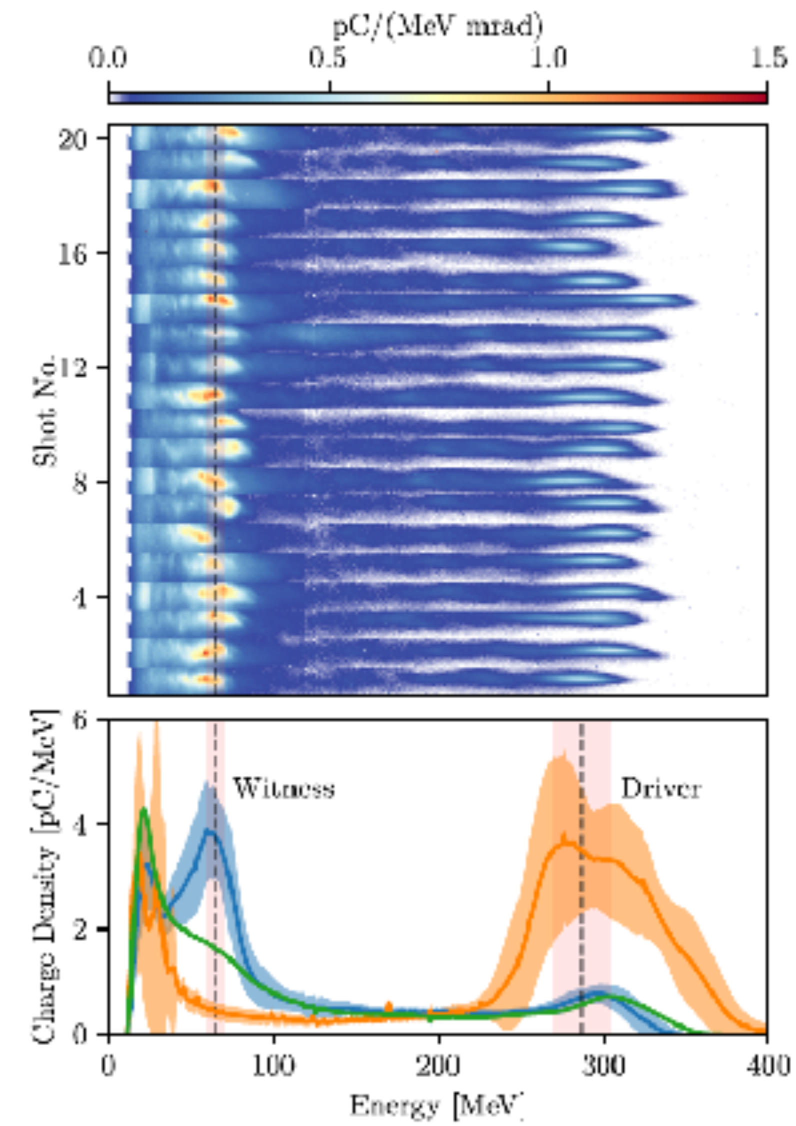
<u>Results</u>
Approx 100 MeV energy gain
Capture efficiency ~ 3.5%

Steinke et al., *Nature* **530** 190 (2016)

Other schemes

Hybrid





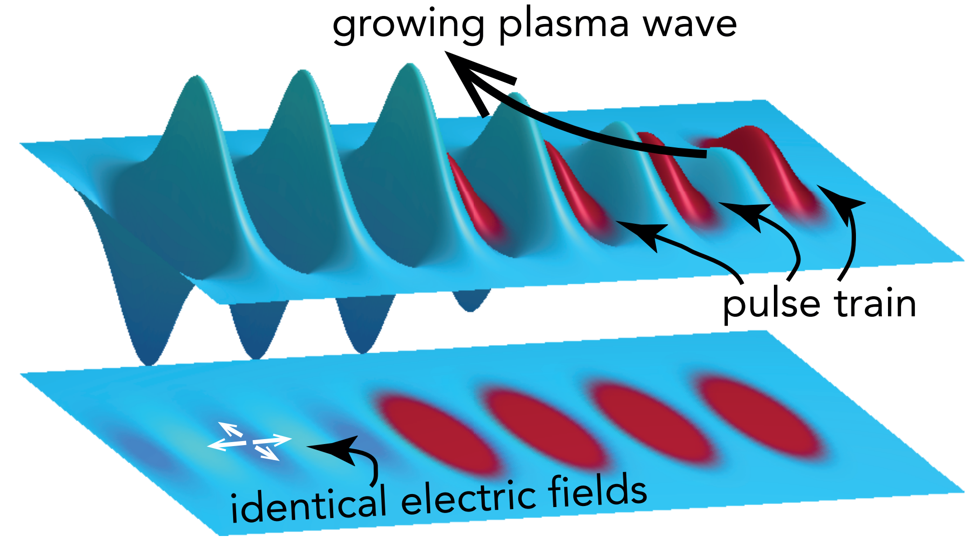
Concept

- Self-injection in LWFA generates high-charge, low quality electron bunch
- This bunch drives a PWFA stage
- Plasma photocathode or shock injection used inject high-quality electron bunch into PWFA stage

Hidding et al., *Phys. Rev. Lett.* **104** (2010)
Foerster et al., *Phys Rev X* **12** 041016 (2022)
Hidding et al. *Photonics* **10** 99 (2023)

Multi-pulse laser wakefield acceleration

- Drive wakefield with train of low-energy laser pulses
- Resonant excitation if pulse spacing matched to plasma period
  - Not a new idea - many theory papers published in 1990s
  - Similar efforts underway for PWFAs
- Could open LWFAs to novel & efficient laser technologies capable of high-rep-rate operation

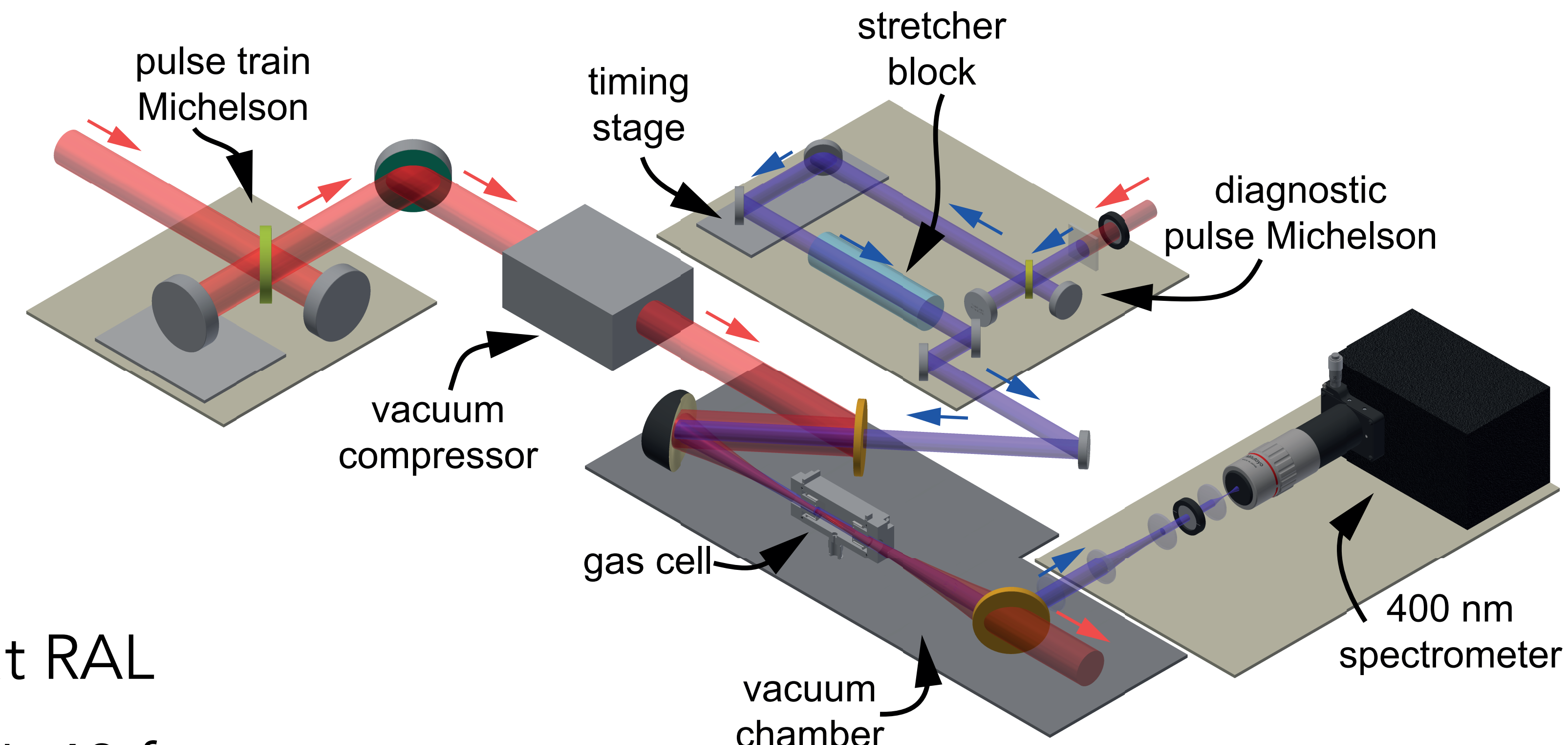


Multi-pulse LWFA
Only 4 laser pulses shown. In reality would use several 10s of pulses

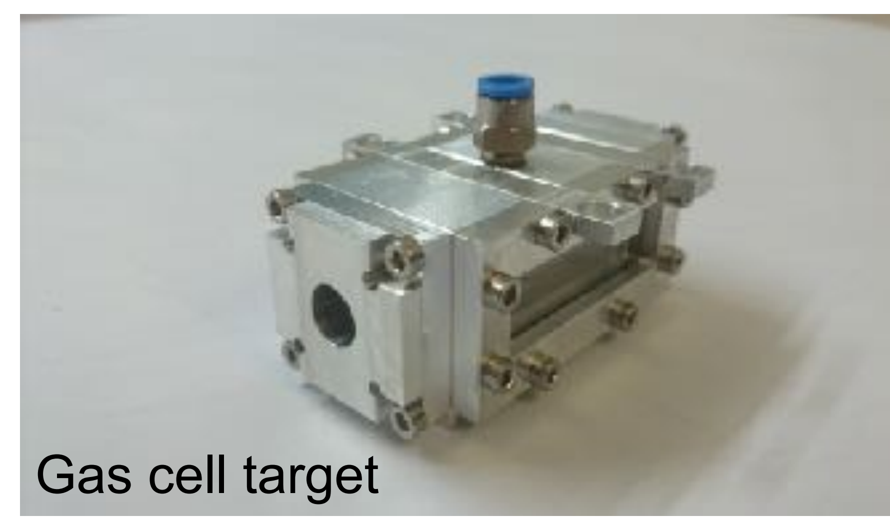
S.M. Hooker et al. *J. Phys. B* **47** 234003 (2013)

MP-LWFA: Proof-of-principle demonstration

E_L: 160 - 270 mJ
w_0: (35 ± 5) μm
L_{cell}: 3 mm



- Expts with Astra TA2 laser at RAL
- Astra delivers single 500 mJ, 40 fs Ti:sapphire pulses
- Converted single pulses into train of N = 1 - 7 pulses
- Wakefield measured by frequency-domain holography & TESS

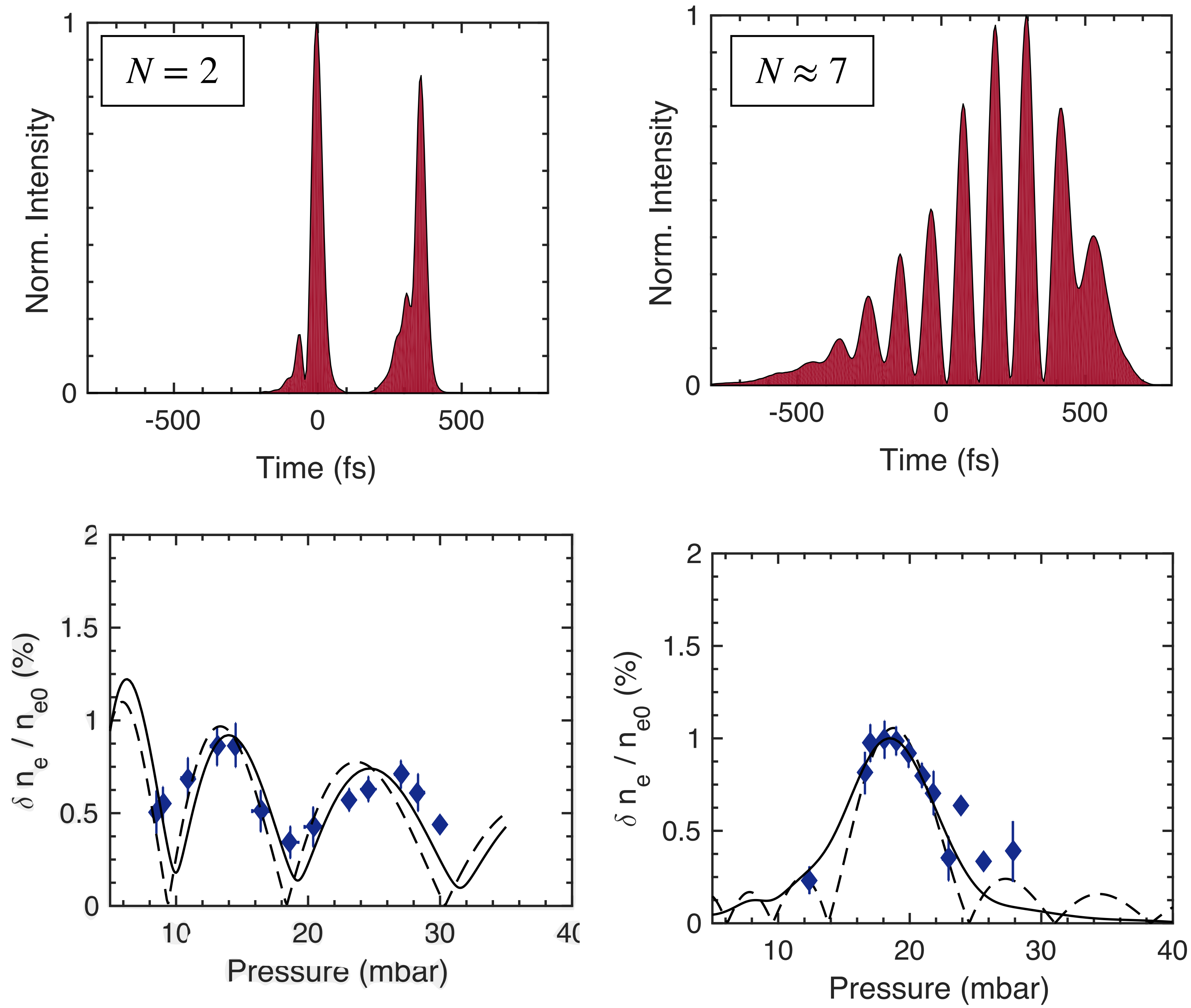

Gas cell target

J. Cowley et al. *Phys. Rev. Lett.* **119** 044802 (2017)

MP-LWFA: Proof-of-principle demonstration

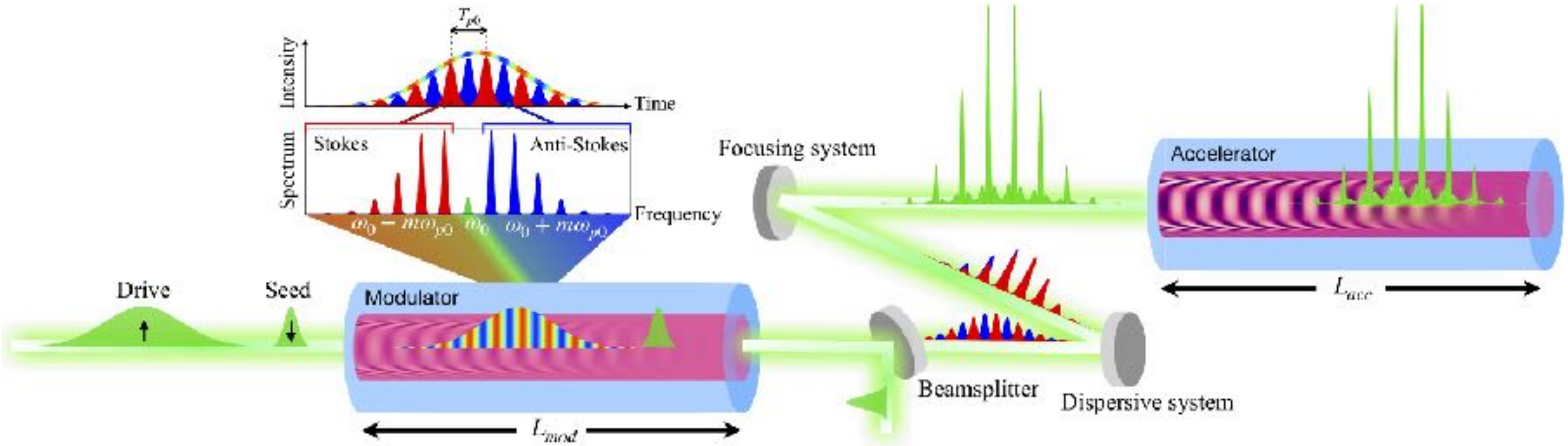
$$\left[\frac{\delta n_\mathrm{e}}{n_\mathrm{e0}}\right]_N = \left[\frac{\delta n_\mathrm{e}}{n_\mathrm{e0}}\right]_{N=1} \times \left|\frac{\sin\left(\frac{1}{2}N\omega_\mathrm{p0}\delta\tau\right)}{\sin\left(\frac{1}{2}\omega_\mathrm{p0}\delta\tau\right)}\right|$$

- Resonant excitation observed
- **First step to energy recovery!**
  - Out of phase trailing pulse reduces wake amplitude by (44 ± 8)%



J. Cowley et al. *Phys. Rev. Lett.* **119** 044802 (2017)

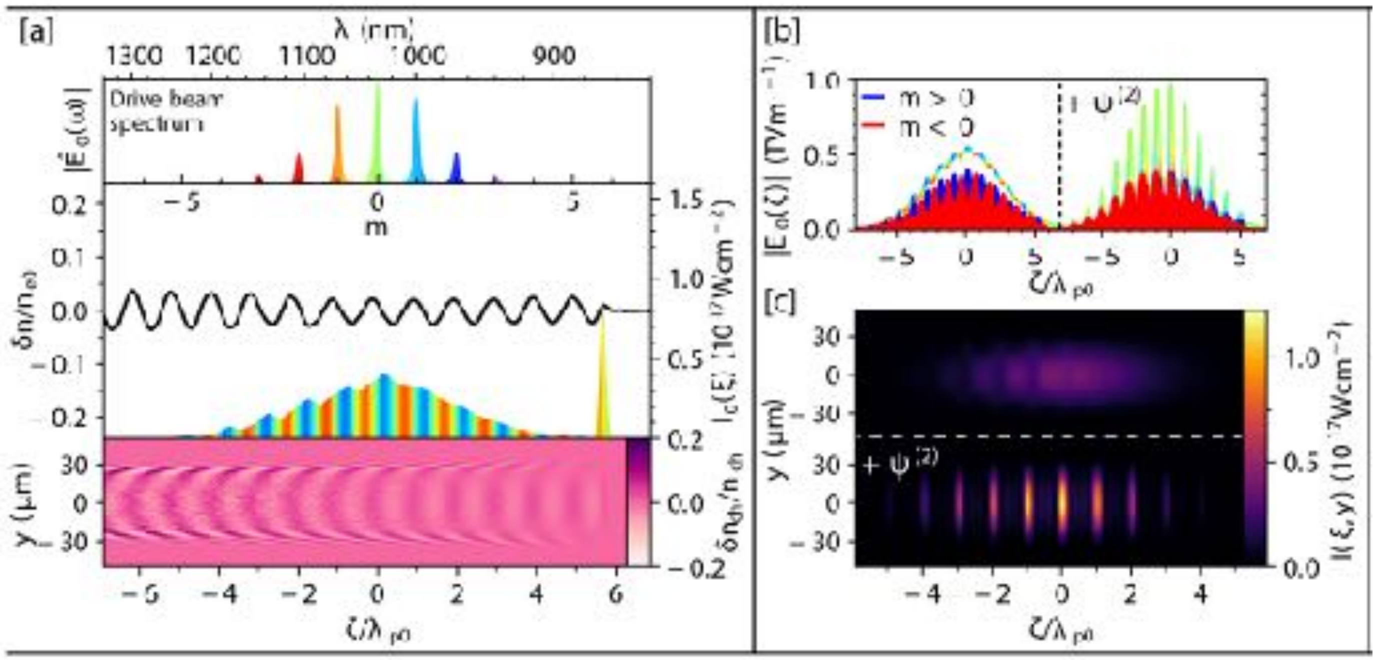
P-MoPA: Plasma-modulated plasma accelerator

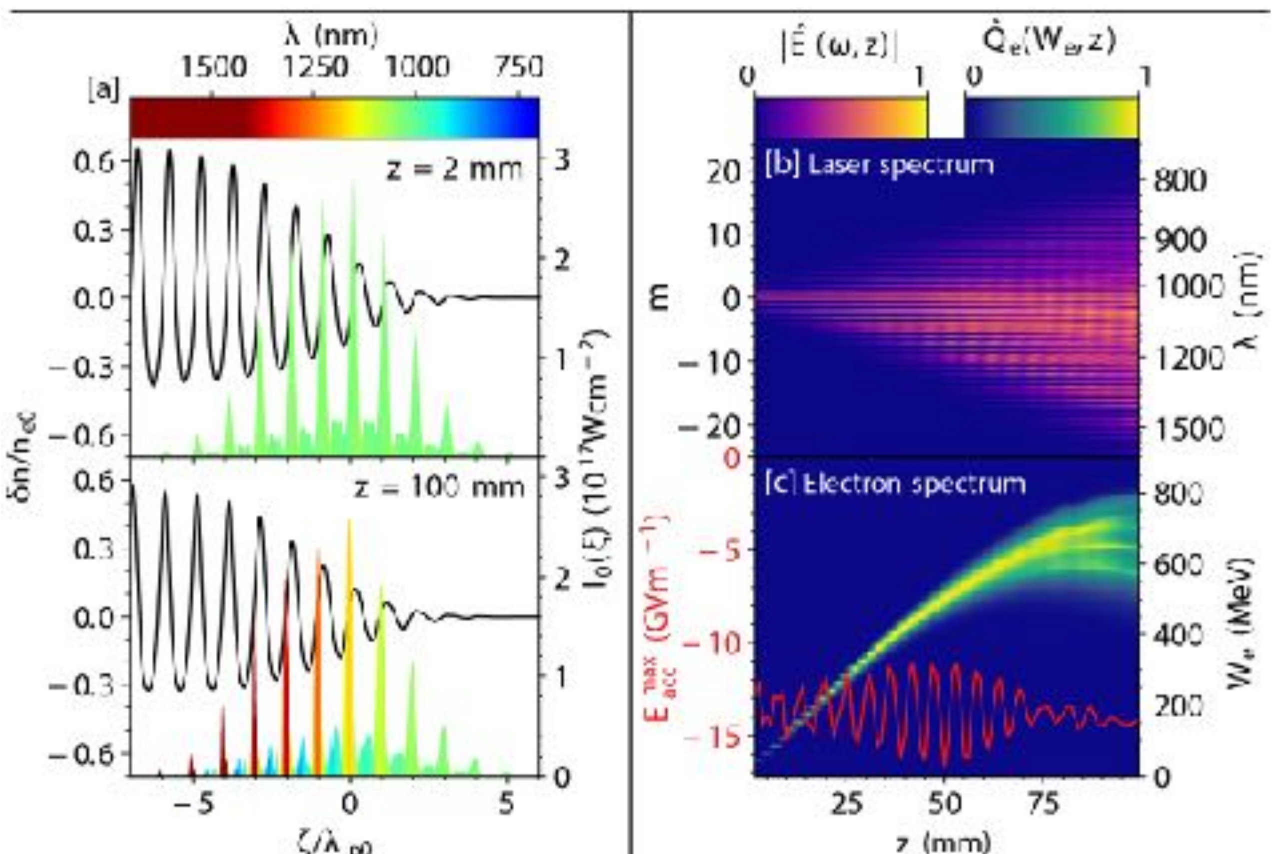


- Three-step scheme for MP-LWFA with single driving laser:
  - Modulate spectrum of long, high-energy drive pulse with weak wake driven by short, low-energy seed pulse
  - Convert temporal modulation to temporal modulation
  - Resonantly drive strong wakefield in accelerator stage

O. Jakobsson et al. *Phys. Rev. Lett.* **127** 184801 (2021)

P-MoPA: Plasma-modulated plasma accelerator





- In temporal domain red ($m < 0$) and blue ($m > 0$) sidebands form pair of pulse trains separated by $T_{p0}/2$
- Adding correct GDD aligns the two trains to form single train of pulses separated by T_{p0}

- PIC simulations show 1.7 J, 1 ps driver could generate 0.65 GeV electrons
- 1 J, 1 ps, 1 kHz thin-disk lasers already available
- Opens new route to GeV-scale, kHz-rep-rate plasma accelerators

O. Jakobsson et al. *Phys. Rev. Lett.* **127** 184801 (2021)

Challenges ...

... or, don’t worry, there is plenty left to do!

JAI John Adams Institute for Accelerator Science

Some challenges

Laser driven plasma accelerators can "routinely" generate GeV-scale electron beams

BUT! There are many unsolved problems. Here are some of them:

- Bunch quality
  - The most demanding (and interesting) applications require very high bunch quality (low energy spread, low transverse emittance, high 6D brightness…)
- Repetition rate
  - Most LWFAs operate at < 10 Hz, but many applications require operation at kHz repetition rates and beyond
- Shot-to-shot jitter & reliability
  - Just imagine trying to keep a lot of users happy…
- Positrons!
  - A future e+-e- collider will also need high-quality positron beams.
  - Not straightforward, and little work to date
- Efficiency
  - A particle collider would need to be 100 - 1000 x more efficient than achieved to date