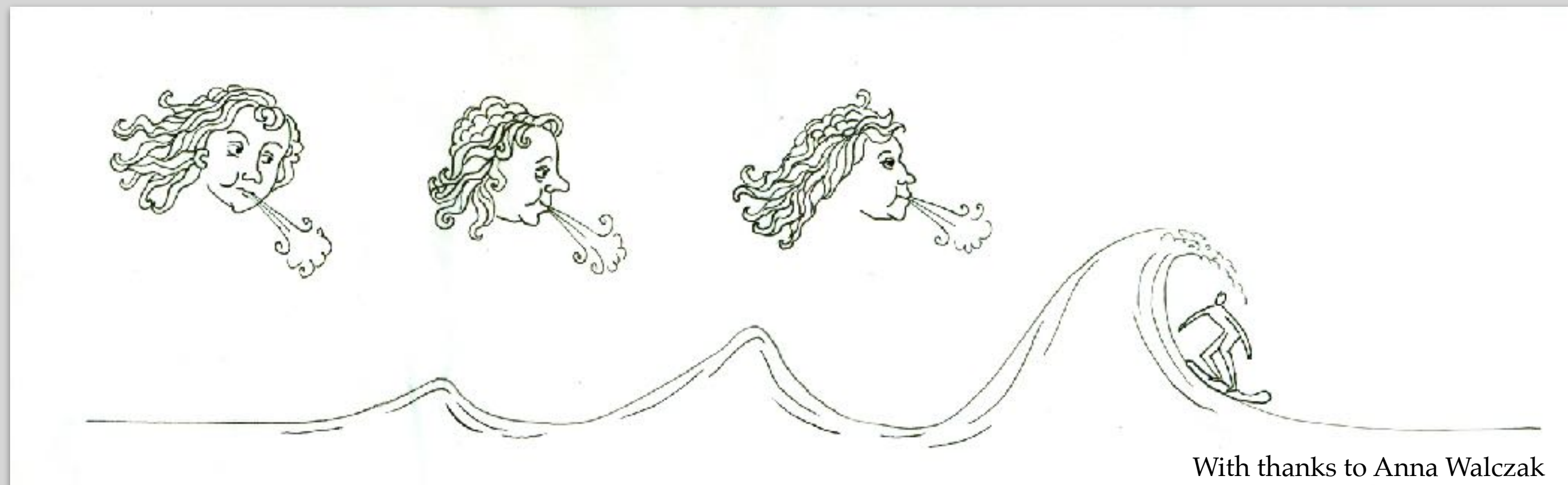


Progress towards high-repetition-rate laser-plasma accelerators

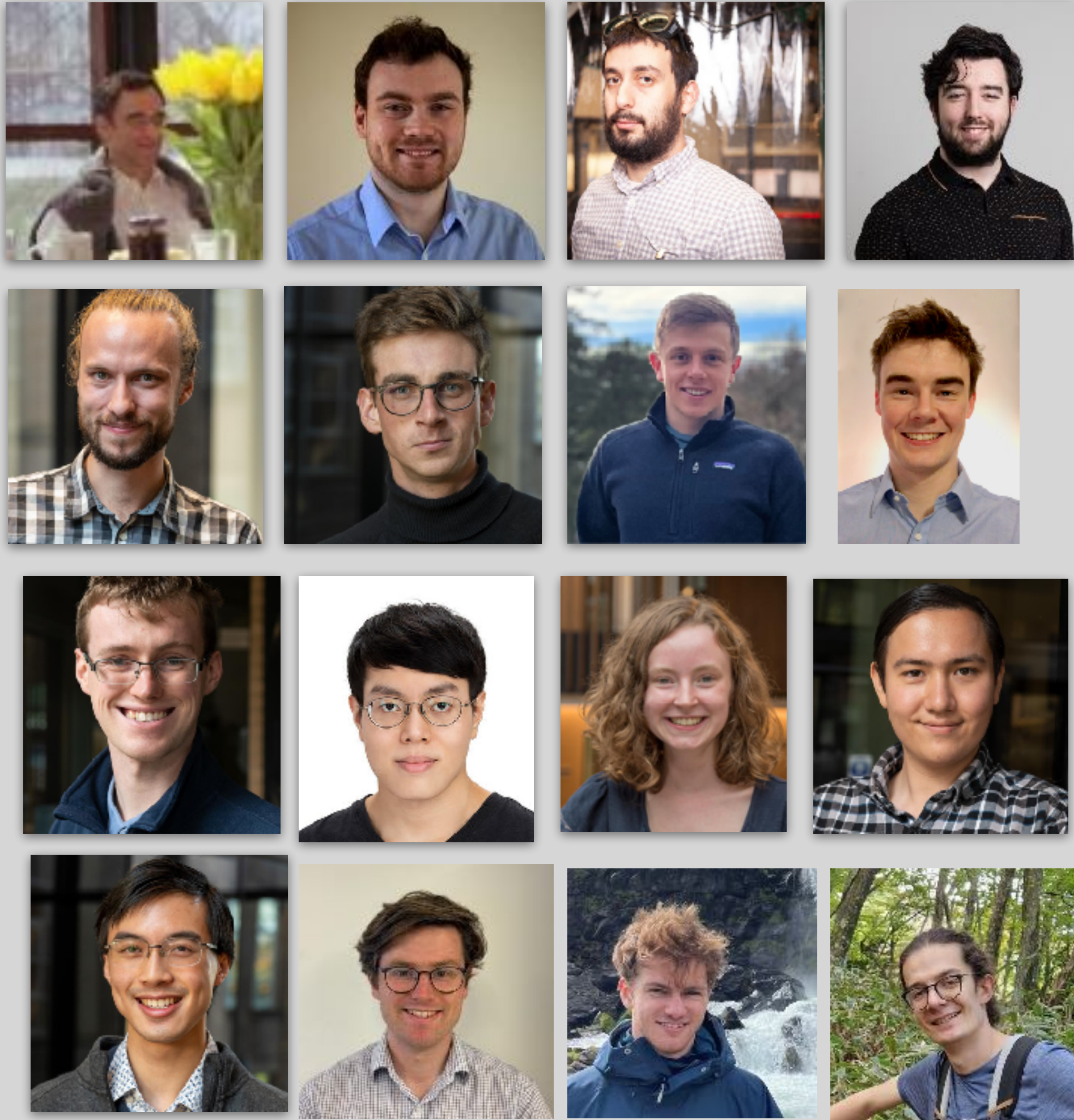
Simon Hooker

Department of Physics & John Adams Institute for Accelerator Science,
University of Oxford



With thanks to Anna Walczak

Acknowledgements



- ▶ Past & current members of the Oxford group
 - Alexander von Boetticher*, Emily Archer*, Darren Chan, James Chappell*, James Cowley*, Ben Greenwood, Linus Feder*, Alexander Harrison, Theodore Hirt Madden, Oscar Jakobsson*, Sebastian Kalos, Ronan Lahaye, David McMahon*, Mariana Moreira, Alex Picksley*, Aimee Ross*, Rob Shalloo*, James Thistlewood, Johannes van de Wetering*, Roman Walczak, & Wei-Ting Wang*
- ▶ UK Central Laser Facility
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- ▶ Ludwig Maxilians Universität, München
 - Stefan Karsch, Mathias Krüger, Andreas Muenzer, & Alexander Podhrazsky
- ▶ University of Liverpool
 - Laura Corner, Harry Jones*, & Lewis Reid

Acceleration gradient determines the size (& cost) of any accelerator

- ▶ Electrical breakdown limits RF accelerators to a gradient of $\lesssim 100 \text{ MV/m}$
- ▶ ... plasma-based accelerators can reach gradients of $\sim 100 \text{ GV/m}$

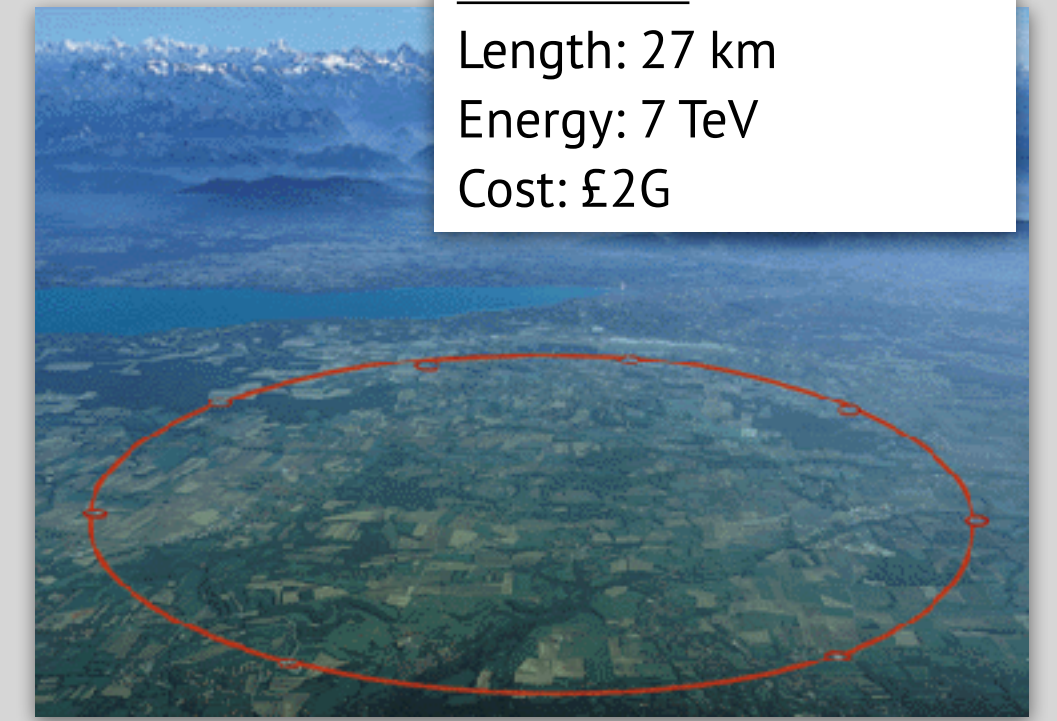
Diamond

Length: 150 m
Energy: 3 GeV
Cost: £370M



CERN LHC

Length: 27 km
Energy: 7 TeV
Cost: £2G

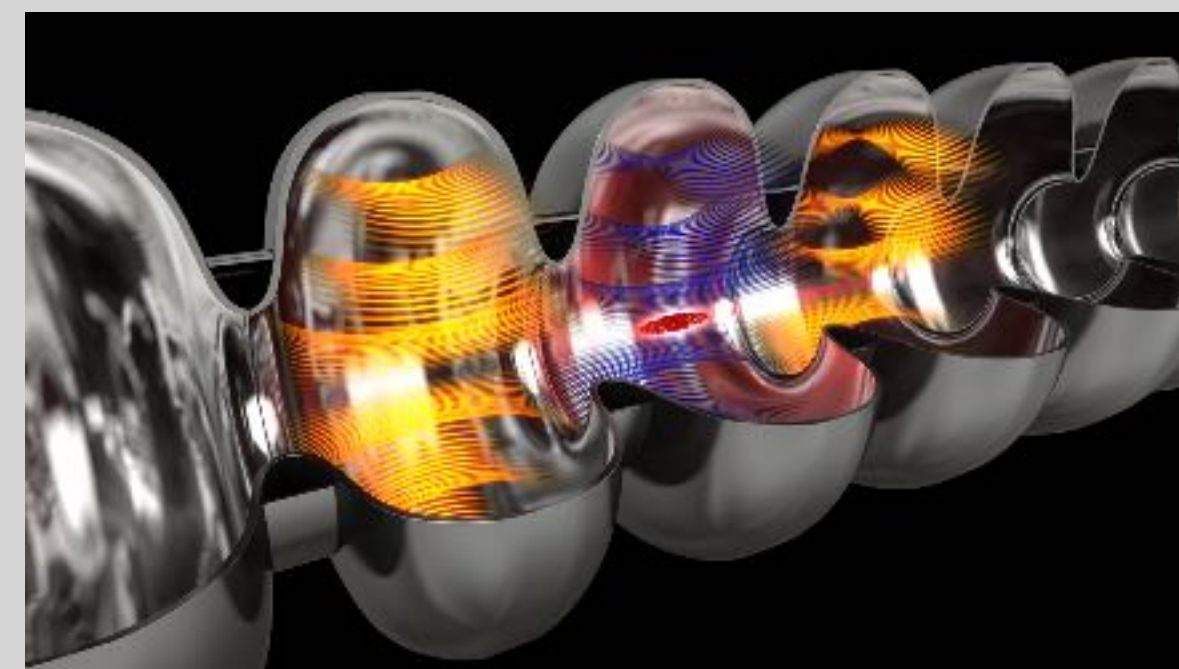


European XFEL

Length: 3.4 km
Energy: 17.5 GeV
Cost: €1.25G



Copyright European XFEL



Copyright European XFEL

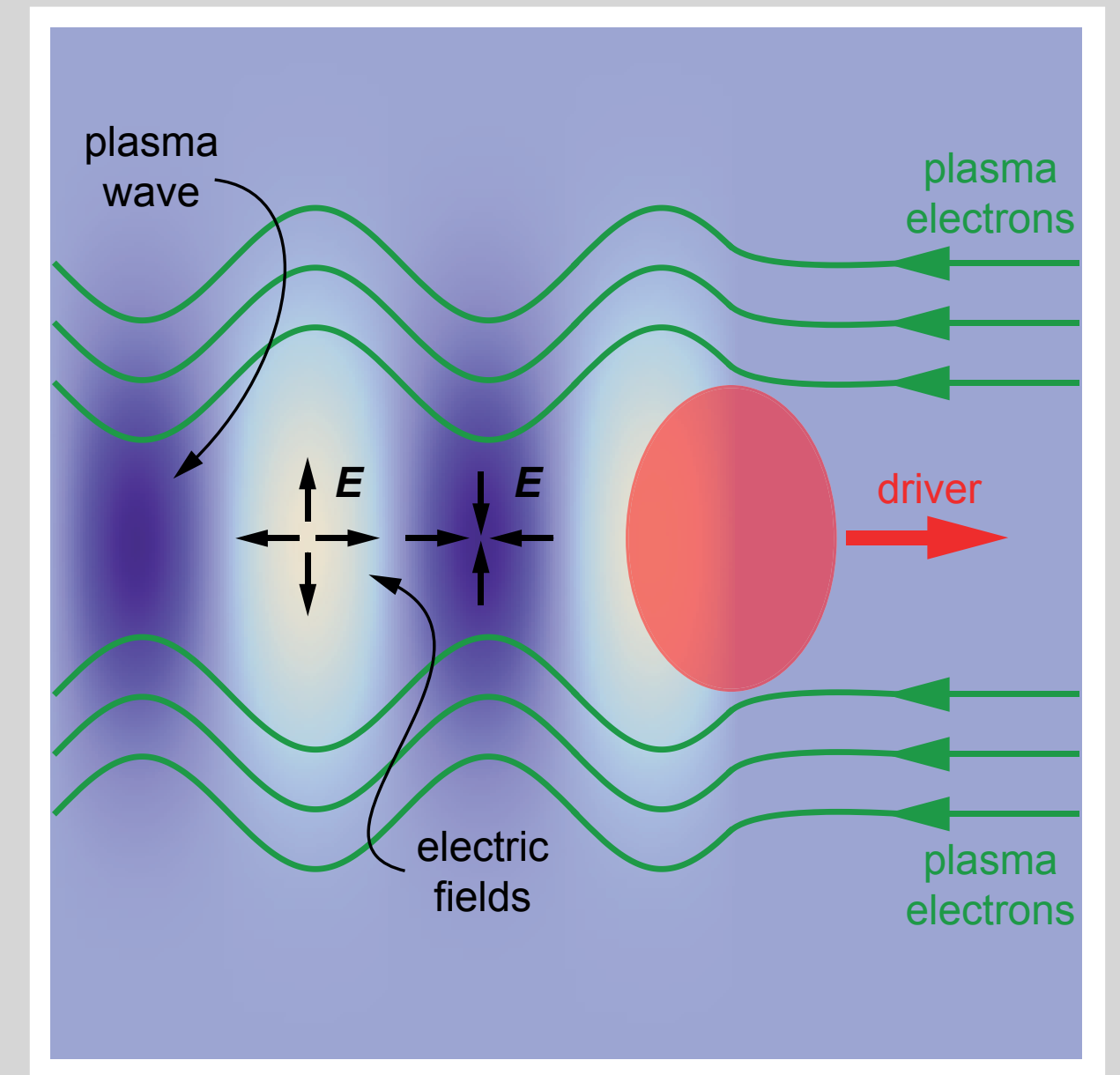
Outline

- ▶ Some key concepts for laser-plasma accelerators
- ▶ Progress in laser-driven plasma accelerators
- ▶ Increasing the particle energy: plasma channels
- ▶ Status & challenges
- ▶ Increasing the repetition-rate: Plasma-modulated plasma accelerators
- ▶ Summary

Some key concepts for laser-driven plasma accelerators

Plasma accelerators: basic concepts

- ▶ An intense laser pulse, or a particle bunch, expels electrons from its location to form a trailing plasma wakefield (a Langmuir wave).
- ▶ Force responsible:
 - Particle driver: Coulomb
 - Laser driver: ponderomotive force
- ▶ The wakefield moves at speed of laser pulse (close to speed of light)
- ▶ Electric fields within wakefield can accelerate charged particles



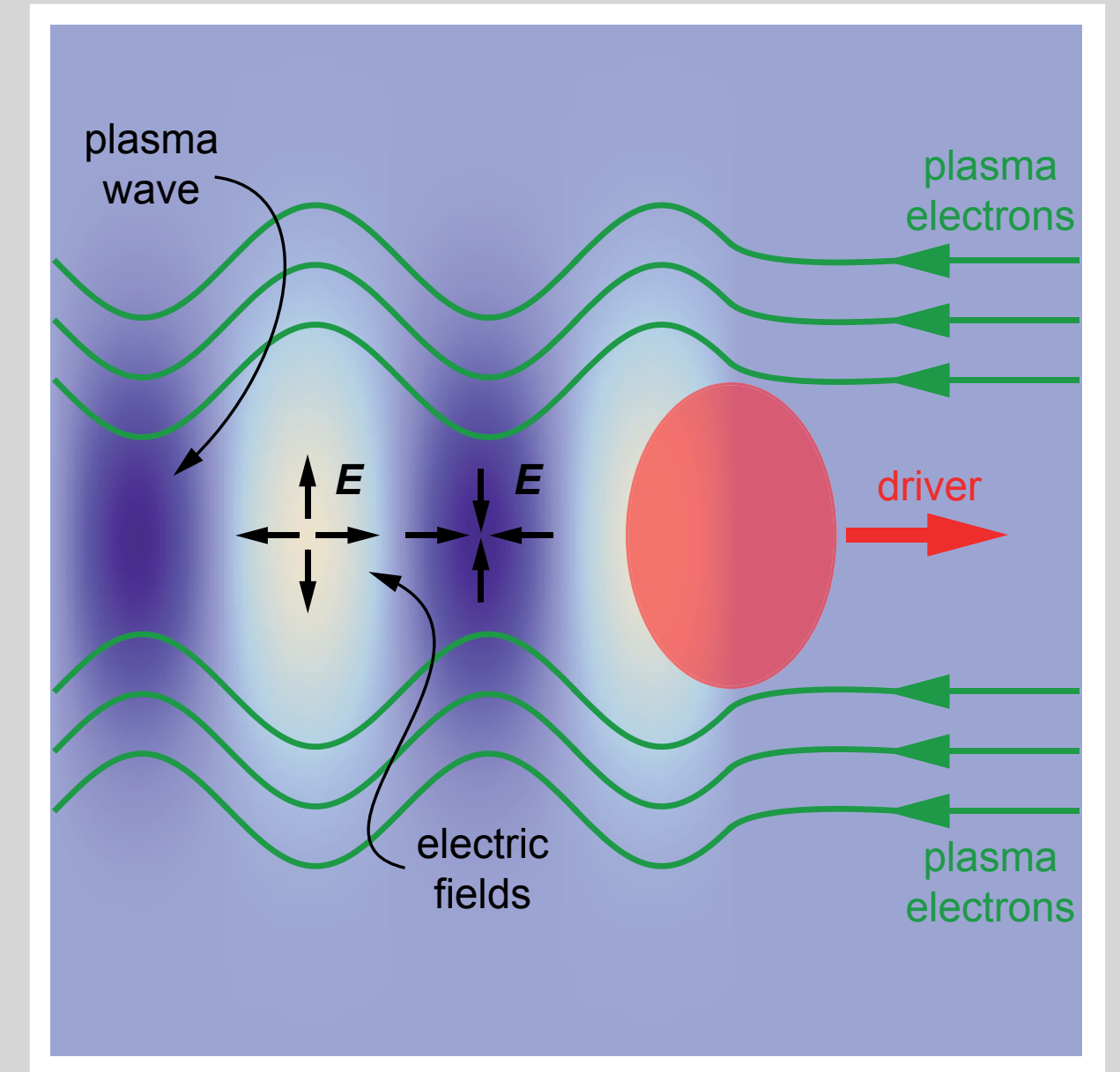
Plasma accelerators: basic concepts

- ▶ Laser & plasma wave propagate at group velocity of laser
- ▶ Plasma oscillates at plasma frequency ω_p
 - Plasma wavelength $\lambda_p \approx \frac{2\pi c}{\omega_p}$
- ▶ Wake amplitude greatest when $\omega_p \tau \approx 1$
- ▶ Electric fields up to order of wave-breaking field E_{wb}

Key parameters

$$\omega_p = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$$

$$E_{wb} = \frac{m_e \omega_p c}{e}$$



		Comment
Laser intensity	$10^{18} \text{ W cm}^{-2}$	1 J, 50 fs, 25 μm
Plasma density	10^{18} cm^{-3}	i.e. 100 mbar
Accel. field	100 GV m^{-1}	10^3 to $10^4 > \text{RF machine}$
Plasma period	100 fs	Need short laser pulses, get short electron bunches
Plasma wavelength	30 μm	

Normalized vector potential

- Eqn of motion of single electron:

$$\frac{d\vec{p}}{dt} = -e \left[\vec{E} + \vec{v} \times \vec{B} \right]$$

$$\vec{E} = -\frac{\partial \vec{A}}{\partial t}$$

$$\vec{B} = \nabla \times \vec{A}$$

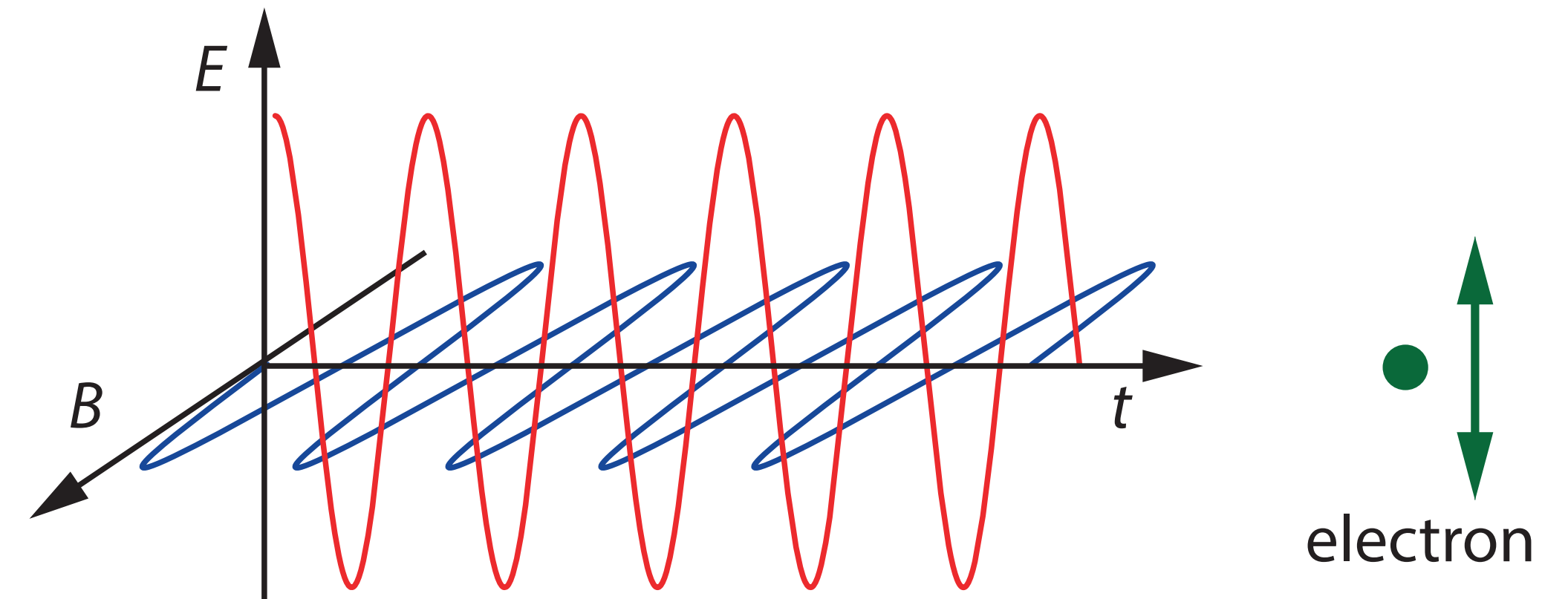
- Can write eqn motion as:

$$\frac{1}{m_e c} \frac{d\vec{p}}{dt} = \frac{\partial}{\partial t} \left(\frac{e}{m_e c} \vec{A} \right) - \vec{v} \times \nabla \times \left(\frac{e}{m_e c} \vec{A} \right)$$

- Hence define normalized vector potential as:

$$\vec{a} = \frac{e\vec{A}}{m_e c}$$

- Note, a_0 is peak value of $\vec{a}$ in laser pulse



For linear poln:

$$a_0^2 \approx 0.73 \times 10^{-18} (\lambda[\mu\text{m}])^2 I_0 [\text{W cm}^{-2}]$$

Electron motion relativistic when $a_0 \approx 1$

Further reading

E. Esarey *et al.* *Rev. Mod. Phys.* **81** 1229 (2009)

P. Gibbon, "Short Pulse Laser Interactions with Matter: An Introduction"

Ponderomotive force

“There are few topics in laser-plasma interactions that have caused such persistent arguments as the curiously named ponderomotive force.”
Paul Gibbon, “Short Pulse Laser Interactions with Matter: An Introduction”

- For non-relativistic case (ignore $\vec{v} \times \vec{B}$ term) write, eqn motion is:

$$m_e \frac{d\vec{v}}{dt} = -e\vec{E}_0 \cos \omega t$$

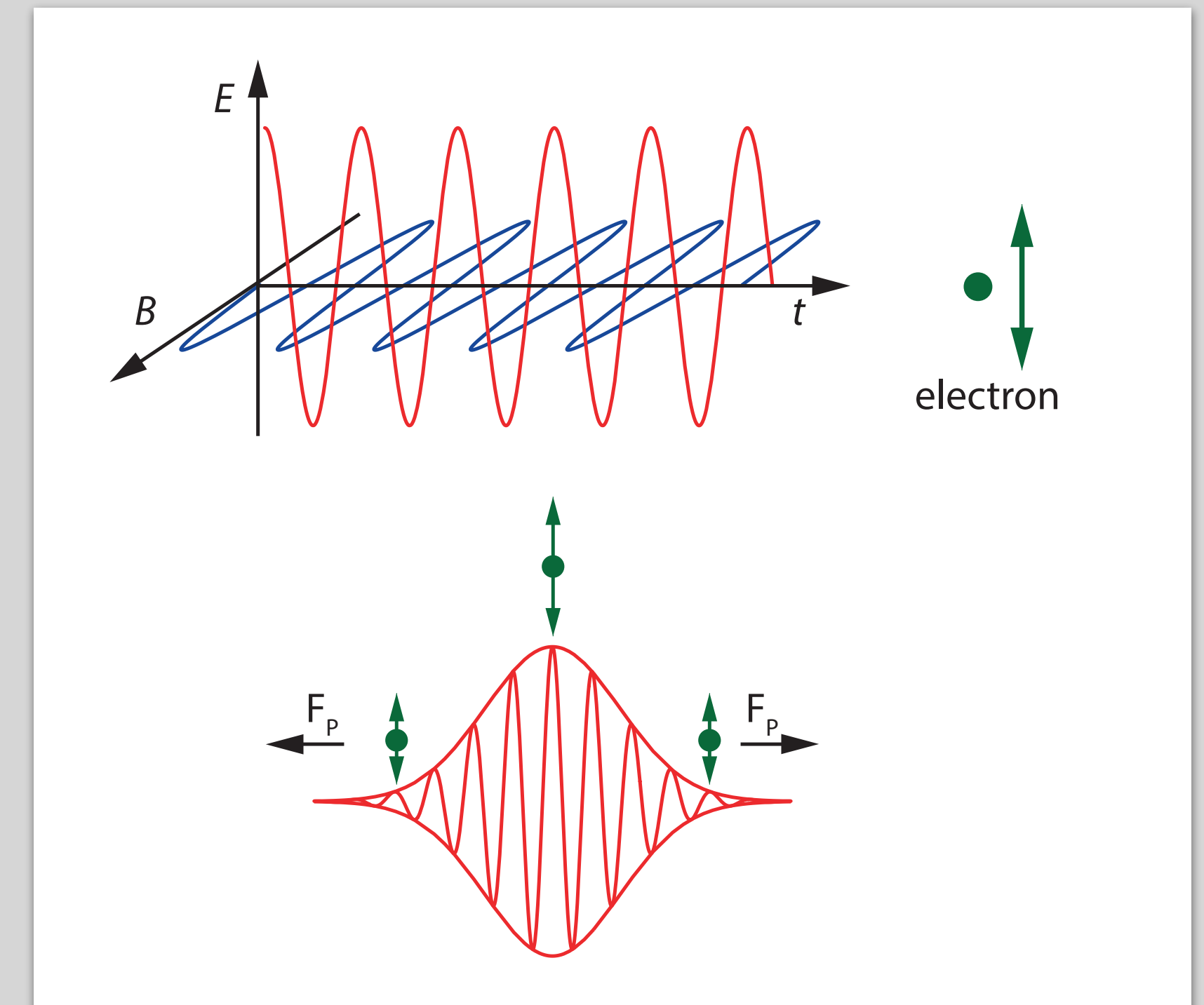
$$\Rightarrow \vec{v}_{\text{osc}} = -\frac{e}{m_e \omega} \vec{E}_0 \sin \omega t$$

- Hence the time-average kinetic energy (the “quiver energy”) is

$$U_p = \left\langle \frac{1}{2} m_e v_{\text{osc}}^2 \right\rangle = \frac{e^2 E_0^2}{4m_e \omega^2}$$

- The ponderomotive force is the derivative of this energy:

$$F_p = -\nabla U_p = -\frac{e^2}{4m_e \omega^2} \nabla E_0^2 = -\frac{1}{2} \frac{e^2}{m_e \epsilon_0 \omega^2} \nabla I$$

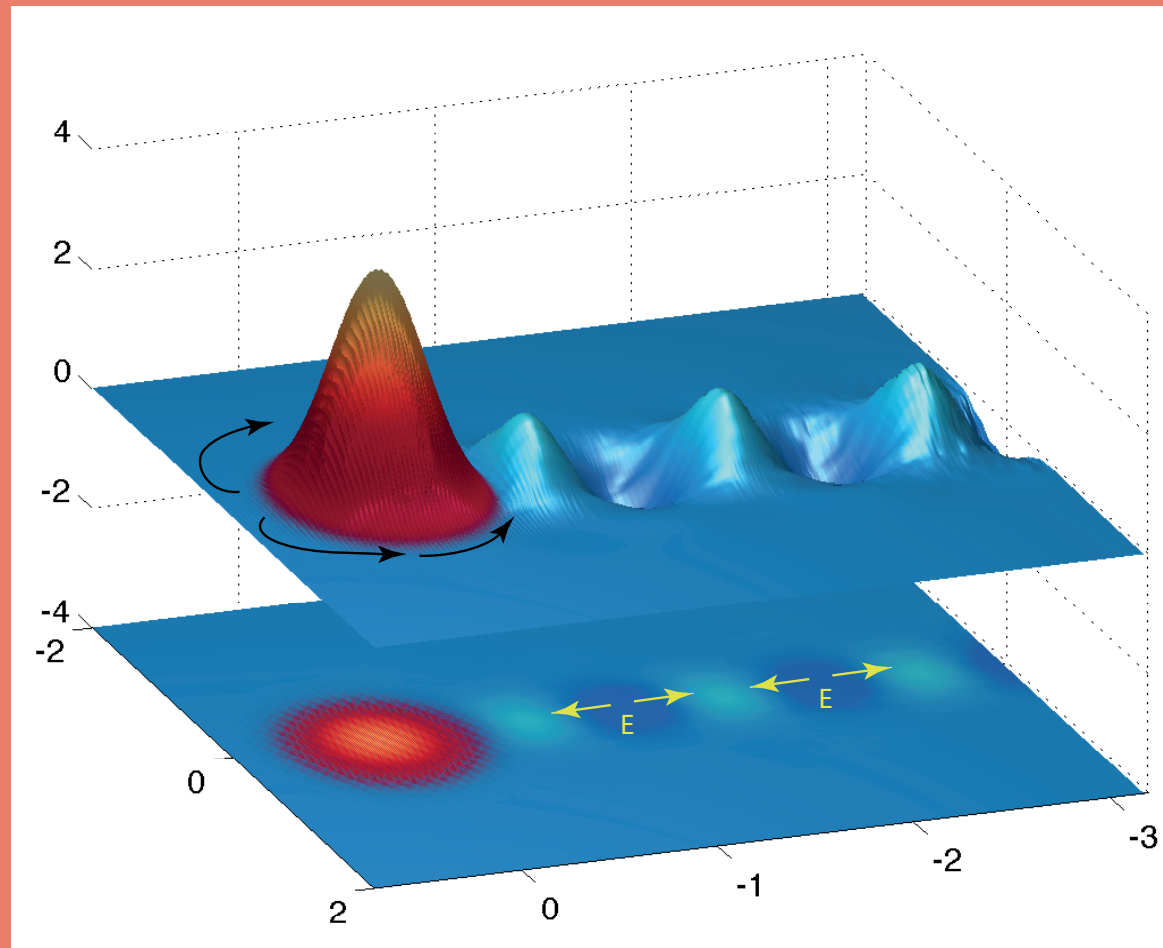


Aside

$$\frac{v_{\text{osc}}}{c} = \frac{eE_0}{m_e \omega c} = a_0$$

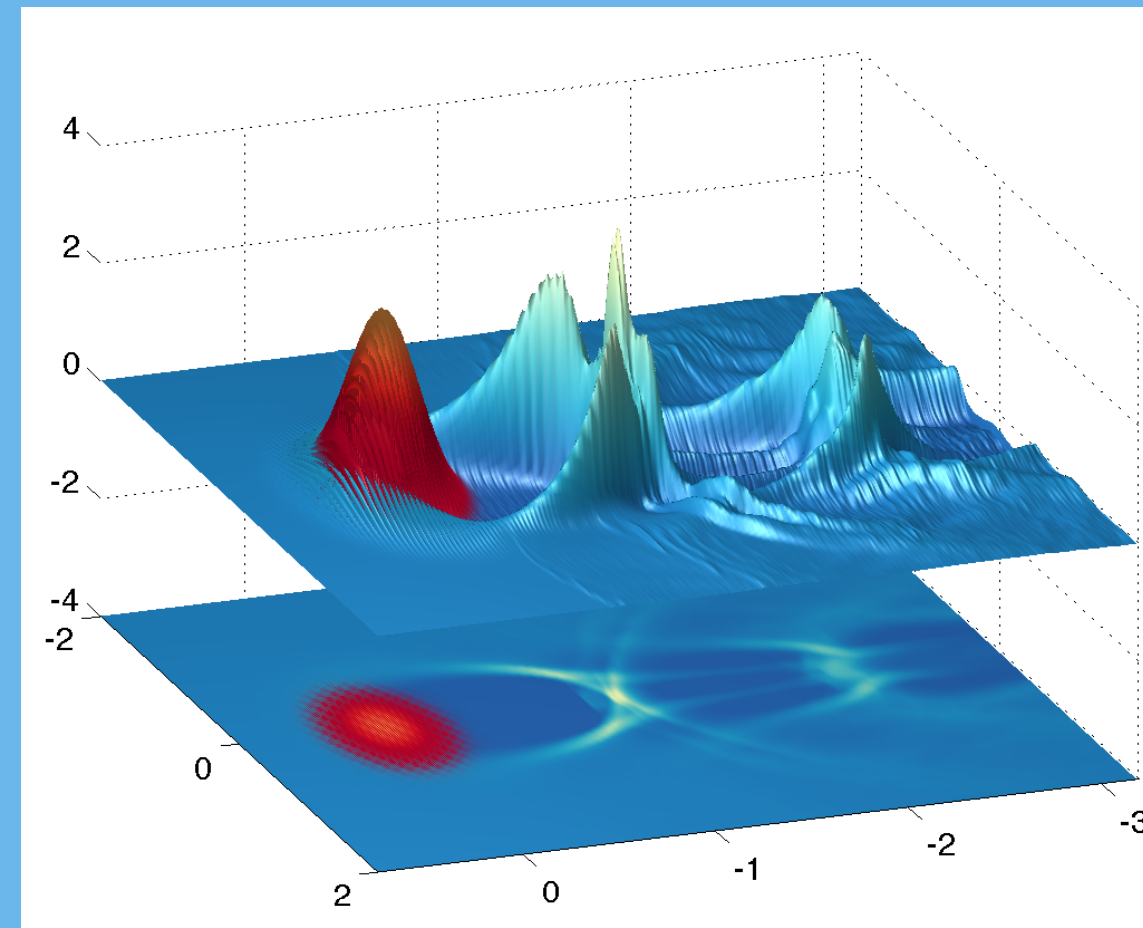
Operating regimes

Linear regime



- $a_0 < 1$
- Sinusoidal wakefield
- Period = λ_p

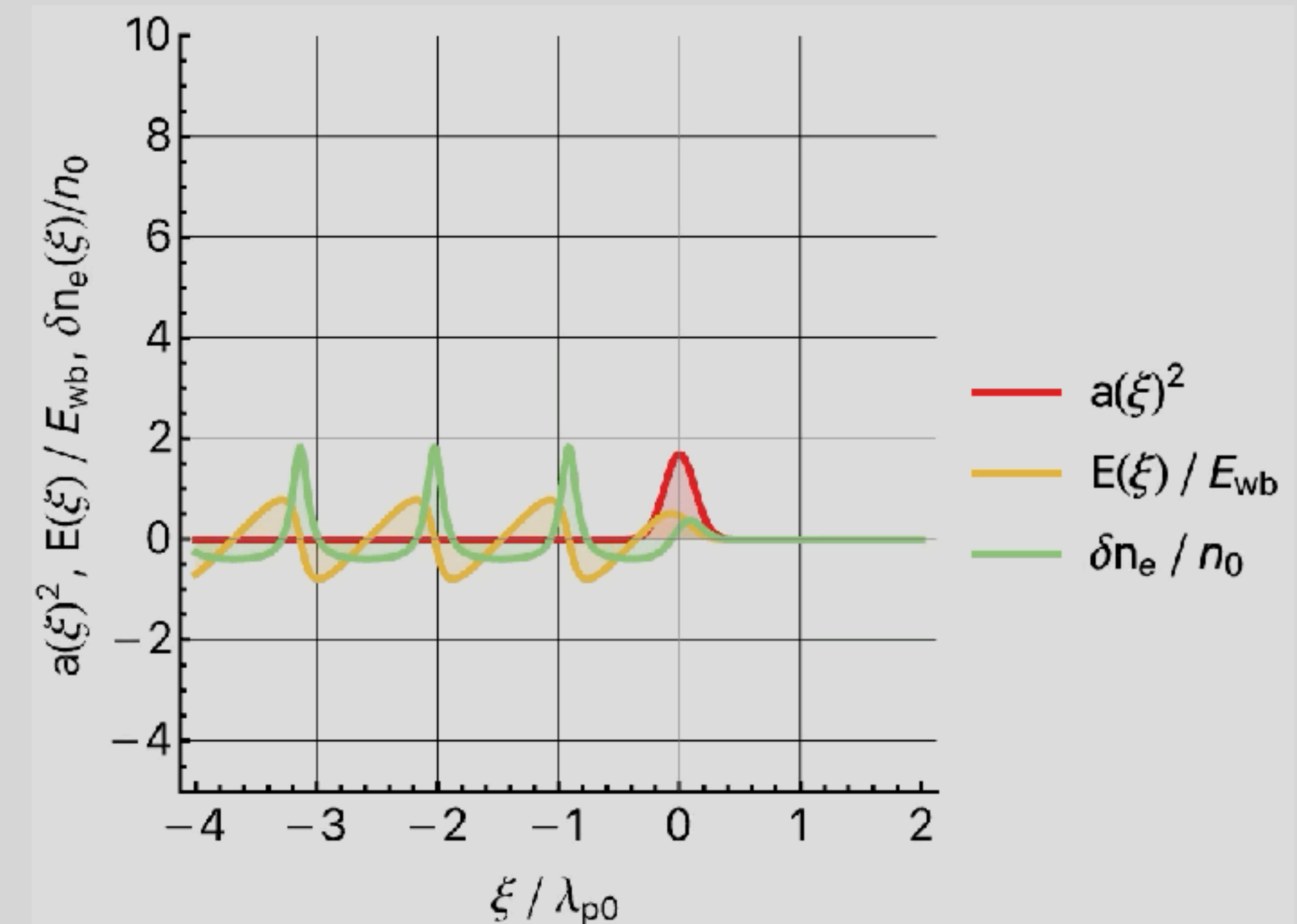
Nonlinear regime



- $a_0 \gg 1$
- Plasma wavelength increases since

$$\omega_p = \sqrt{\frac{n_e e^2}{\gamma m_e \epsilon_0}}$$

- Electron density becomes “spiky”
- Electric field adopts “sawtooth” profile and can exceed E_{wb}



Laser-driven plasma accelerators are limited by the “three Ds”

► Dephasing

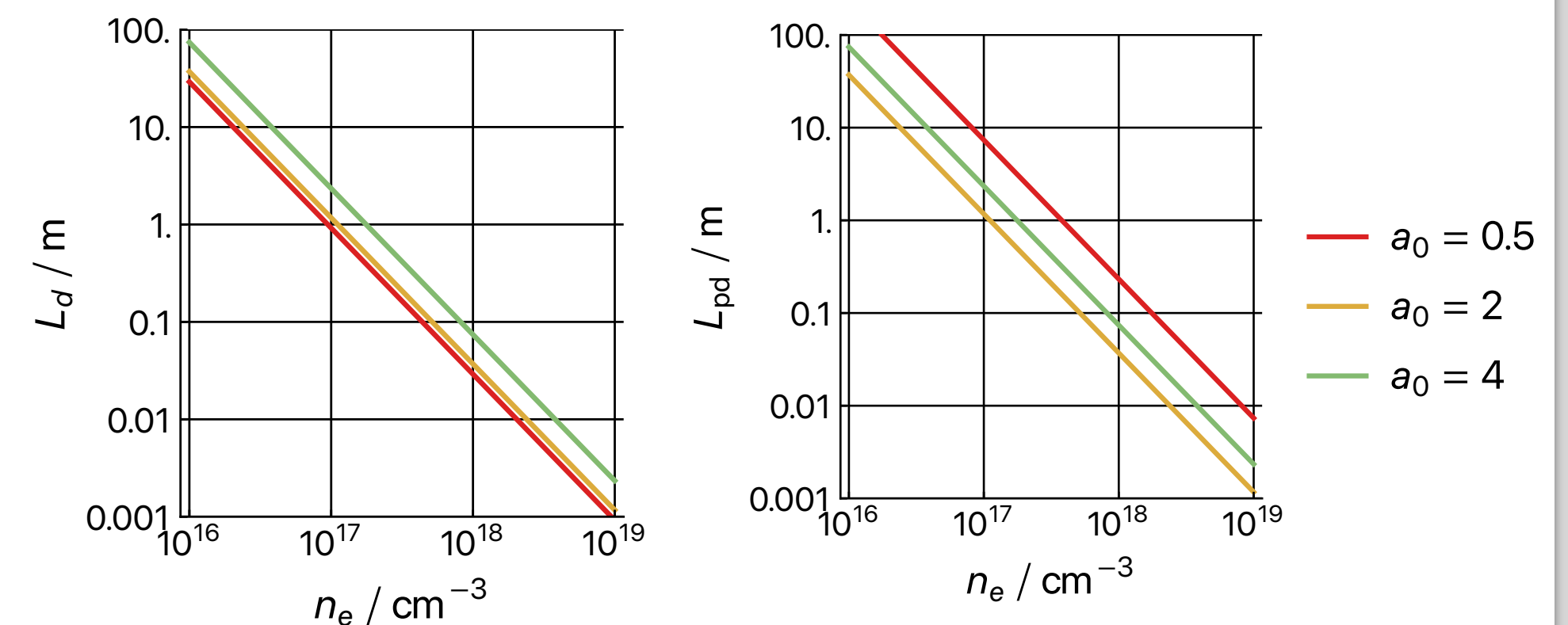
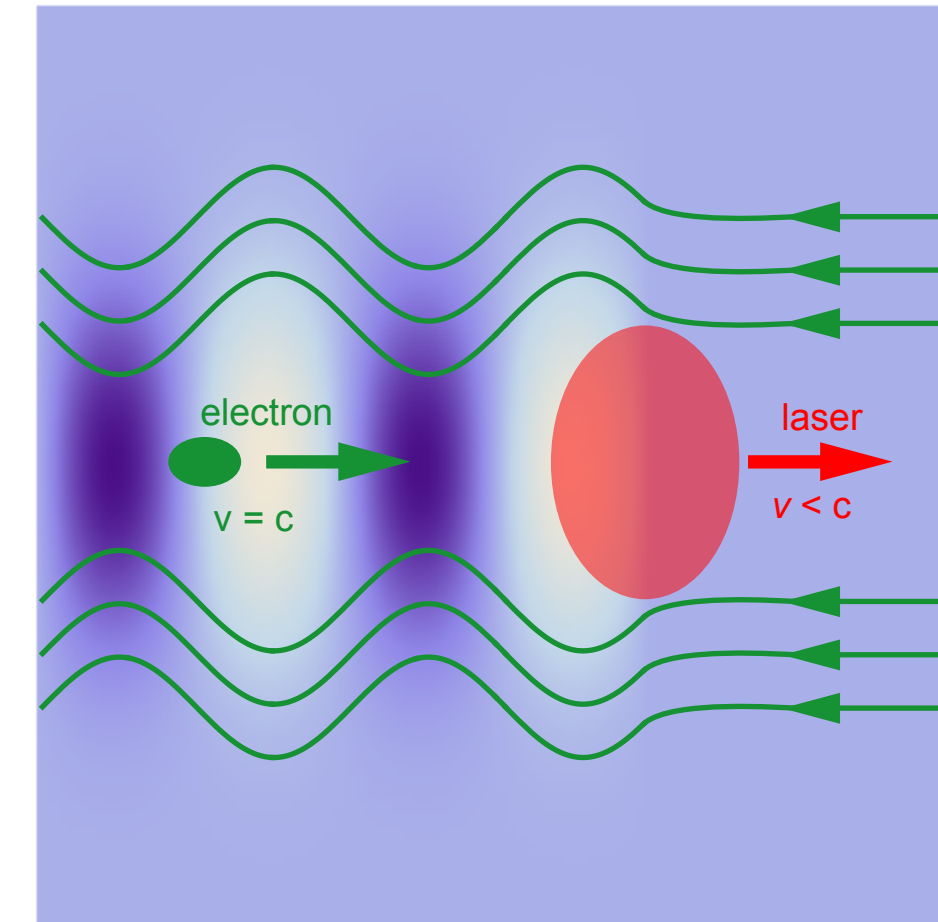
- Electrons move from accelerating to decelerating phase in the **dephasing distance** L_d

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

► Depletion

- Driving laser loses energy in the **pump depletion length** L_{pd}

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



Particle energy gain

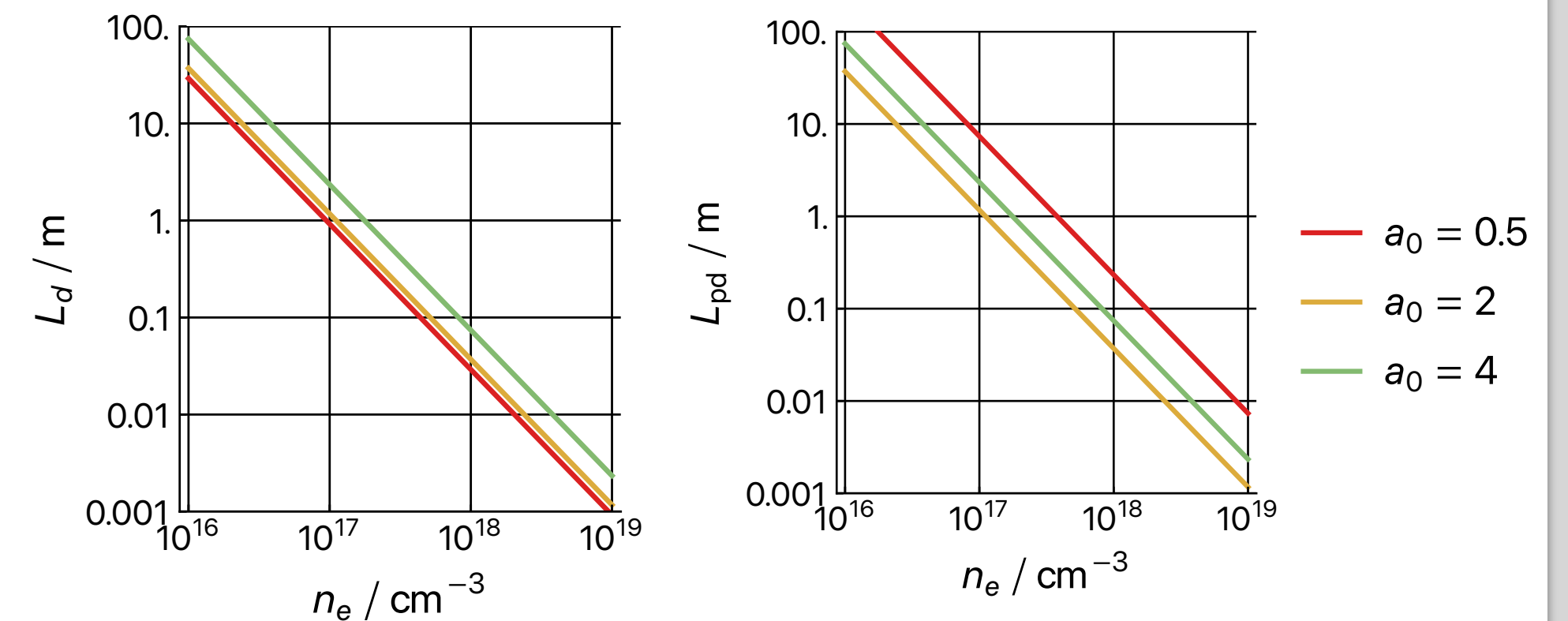
- ▶ In 1D electron energy gain is given by,

$$\Delta W = -e \int_0^{L_{\text{acc}}} E_z(z) dz \approx e \frac{|E_z|_{\text{max}}}{2} L_{\text{acc}}$$

- ▶ If L_{acc} is given by $L_{\text{dephasing}}$ or L_{deplete} .

$$\Delta W \approx \frac{n_c}{n_e} m_e c^2 \begin{cases} \frac{\pi}{2} a_0^2 & a_0 \ll 1 \\ \frac{2}{3} a_0 & a_0 \gg 1 \end{cases} \begin{matrix} \text{1D, linear} \\ \text{3D, nonlinear} \end{matrix}$$

$$n_c = \frac{m_e \epsilon_0}{e^2} \left(\frac{2\pi c}{\lambda_0} \right)^2$$



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

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

Progress in plasma accelerators 1979 - 2004

In the beginning...

VOLUME 43, NUMBER 4

PHYSICAL REVIEW LETTERS

23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson

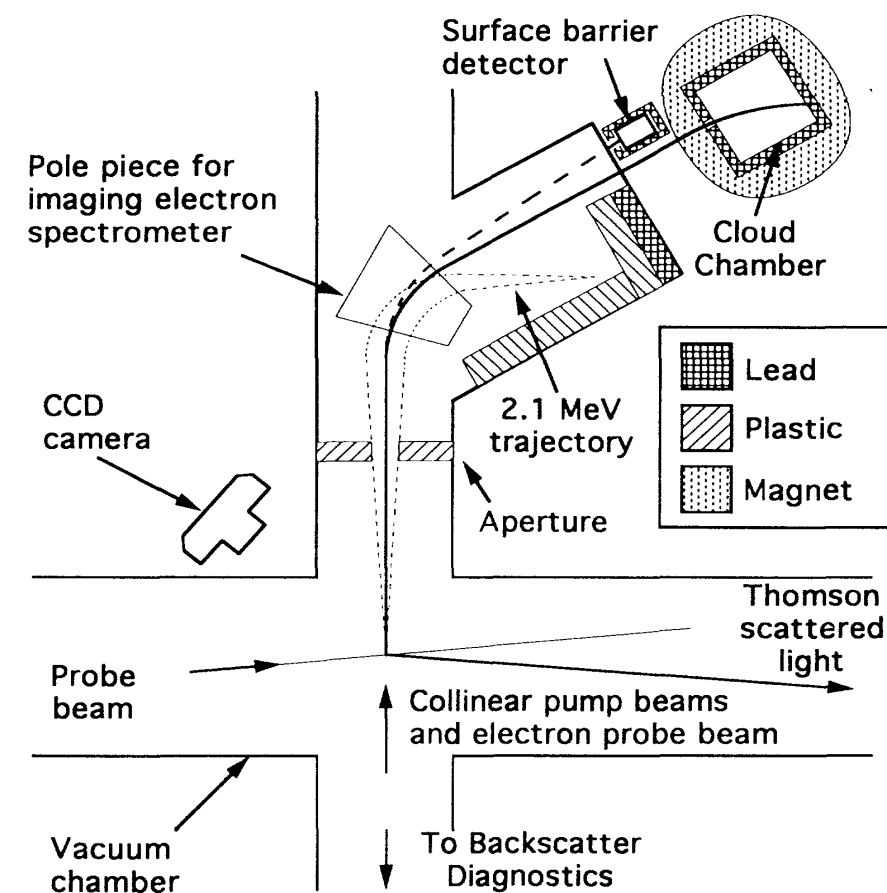
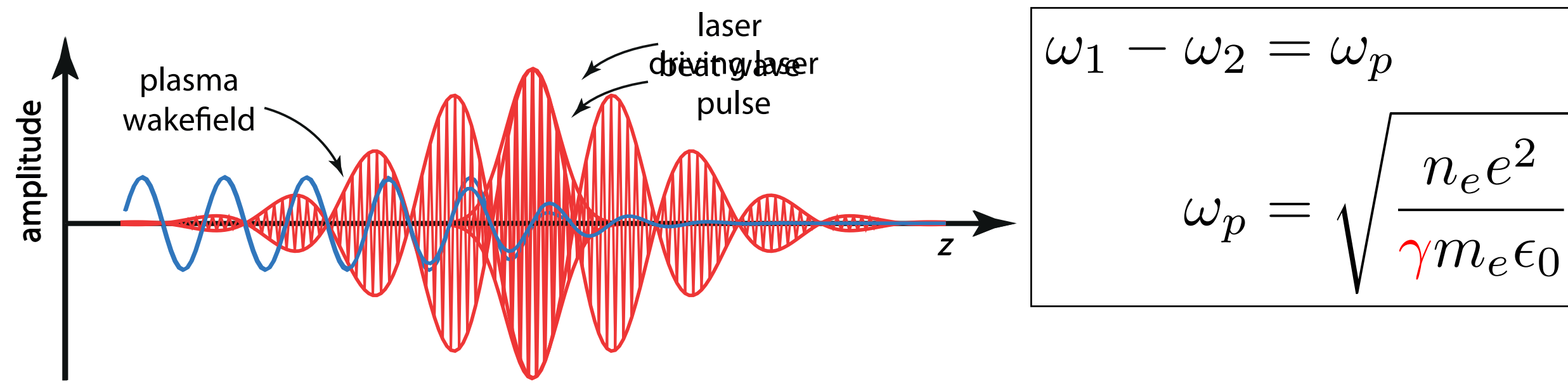
Department of Physics, University of California, Los Angeles, California 90024

(Received 9 March 1979)

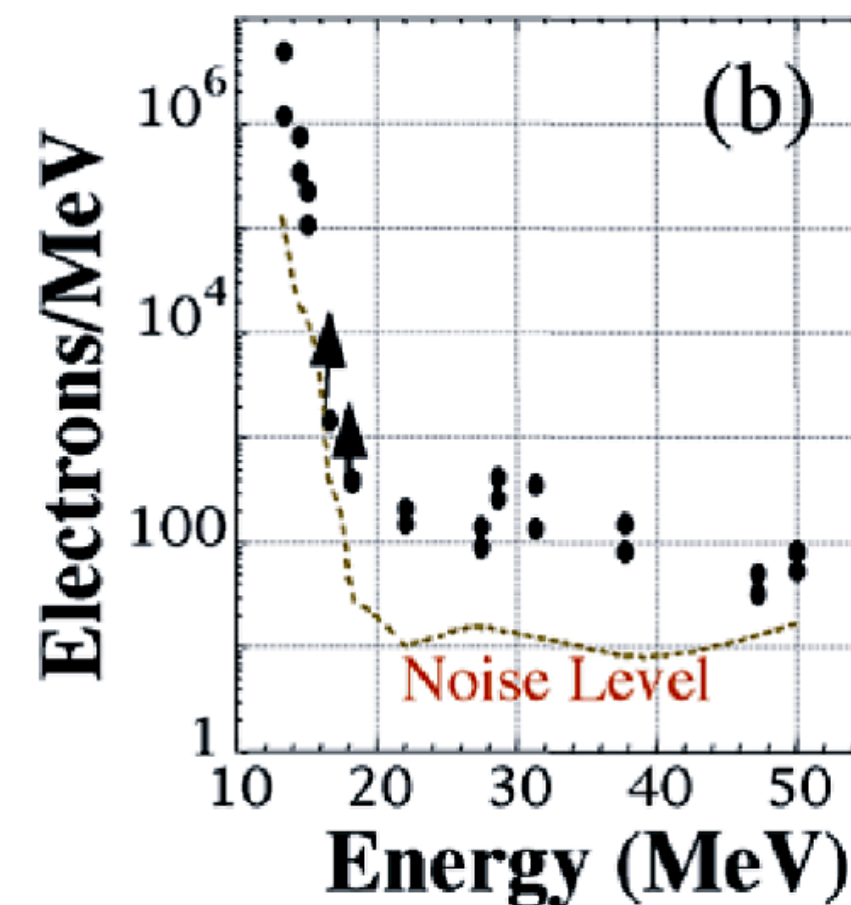
An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18}cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

celerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18}cm^{-3} can yield gigaelectronvolts of electron energy per centimeter

Progress linked to advances in laser technology



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

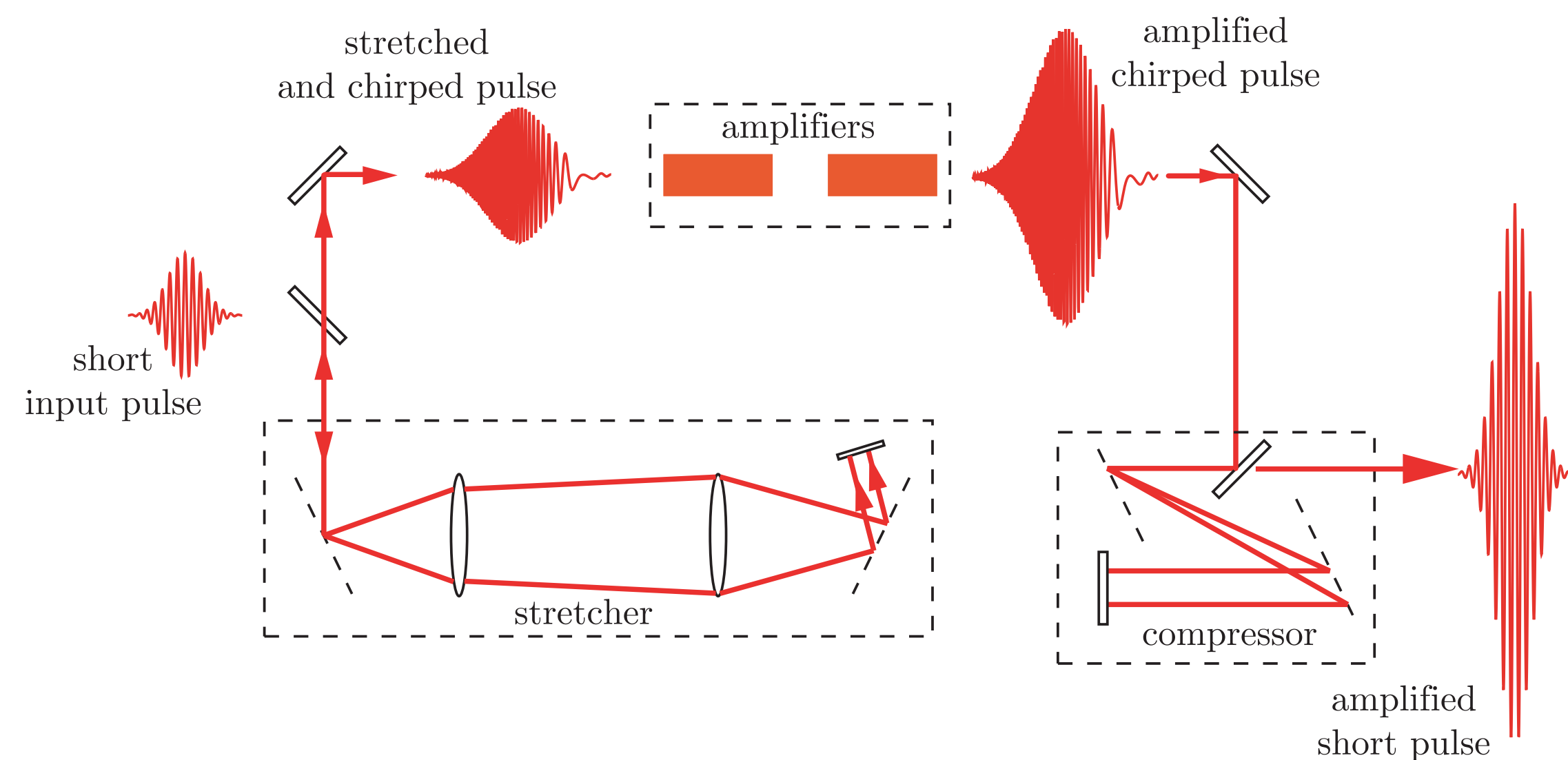


Tochitsky *et al.* *Phys Rev. Lett.* **92** 095004 (2004)
 Laser: 200 J, 400 ps (CO₂)
 Plasma: $n_e \sim 9 \times 10^{15} \text{ cm}^{-3}$
 Injected electrons: 12 MeV

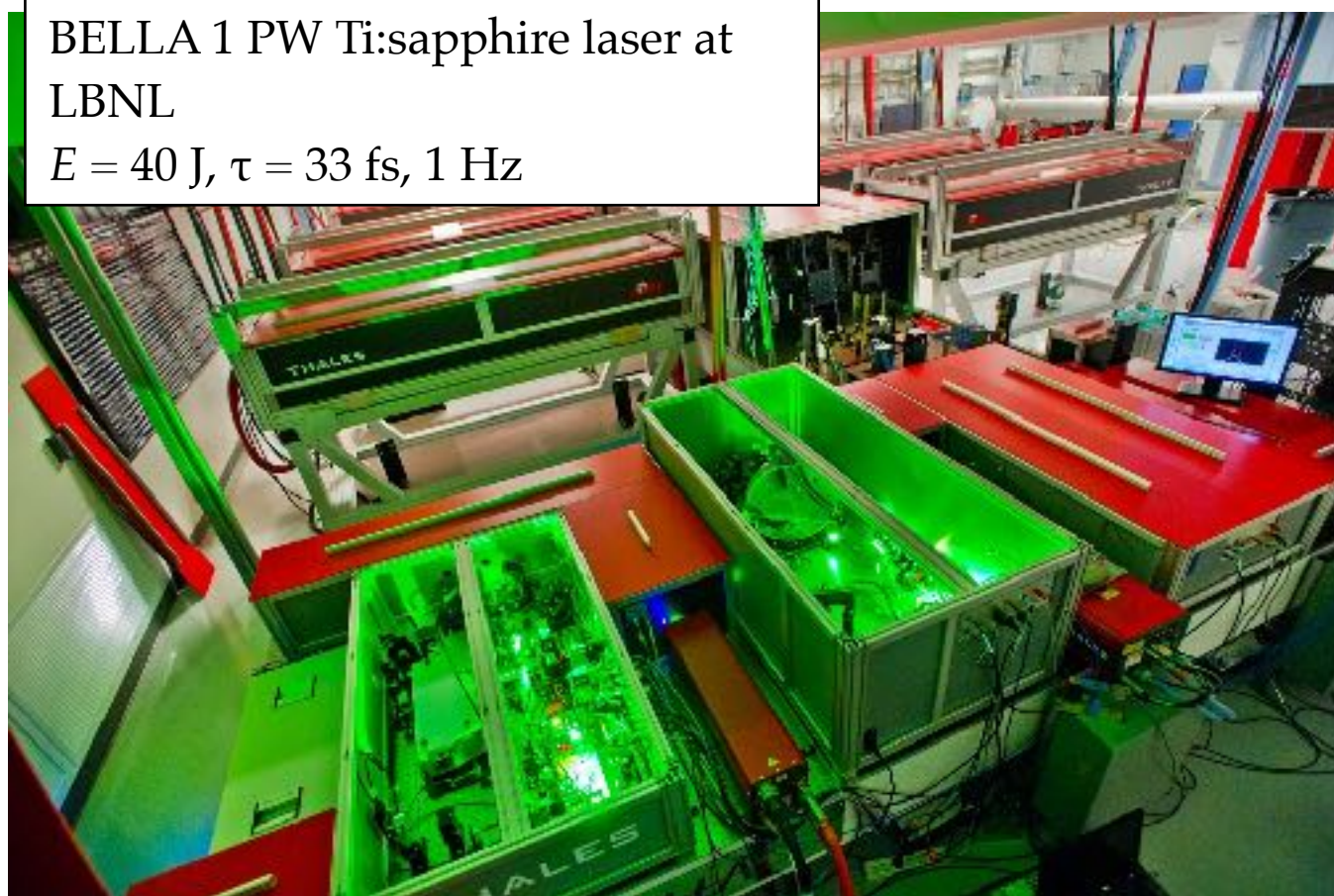
Plasma beat-wave

- ▶ Combine 2 long pulses with freqs ω_1, ω_2
 - Wake amplitudes of 28%
 - $\Delta W = 38 \text{ MeV}$ (external injection)
- ▶ Wakefield saturates due to relativistic increase in electron mass (Rosenbluth-Liu limit)
 - Rosenbluth & Liu, *Phys. Rev. Lett.* **29** 701 (1972)

Chirped-pulse amplification allows the generation of short laser pulses with high energies

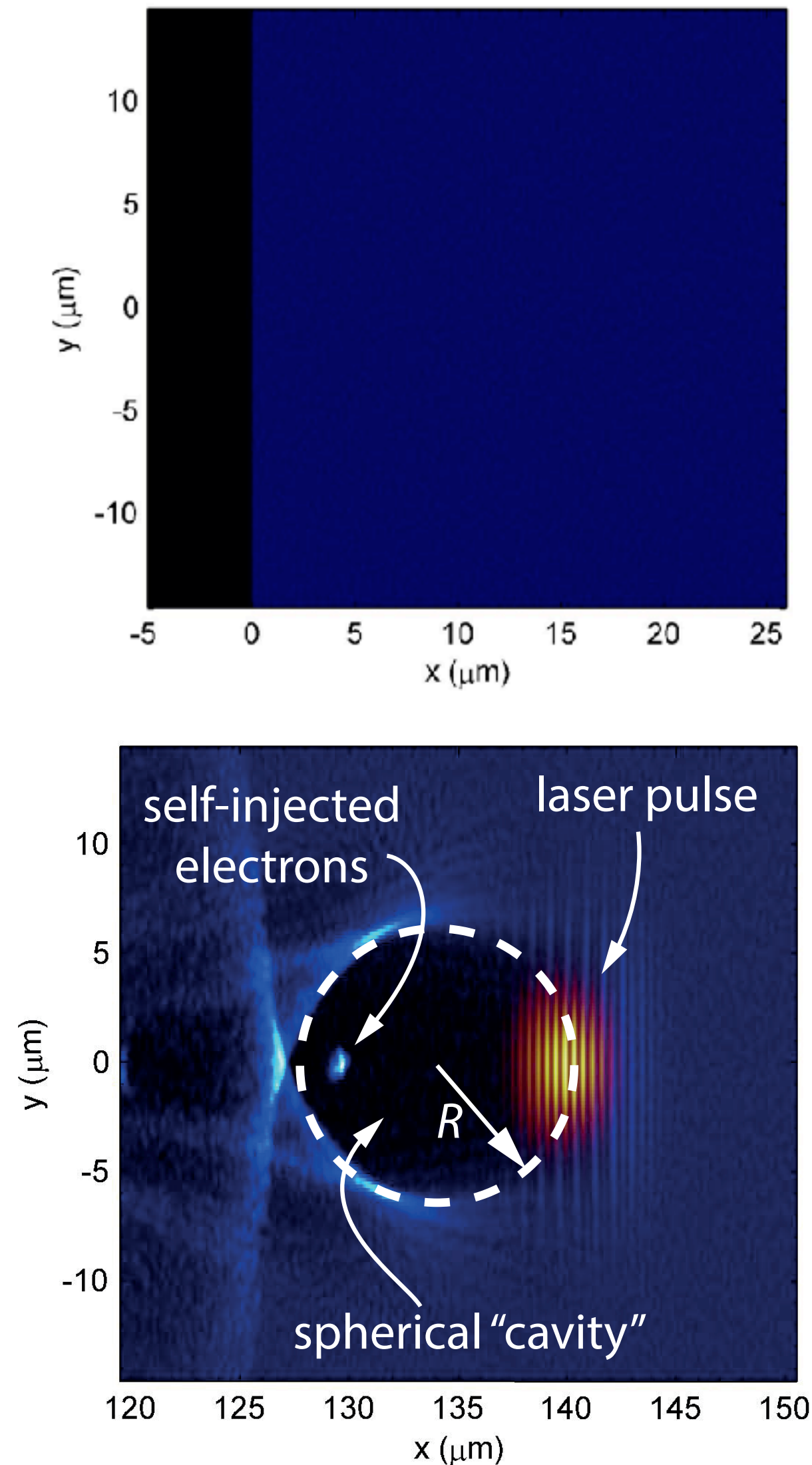


BELLA 1 PW Ti:sapphire laser at LBNL
 $E = 40 \text{ J}$, $\tau = 33 \text{ fs}$, 1 Hz



2018 Nobel Prize in Physics awarded to Donna Strickland and Gérard Mourou for their method of generating high-intensity, ultra-short optical pulses

High-intensity ultrafast lasers: The bubble regime



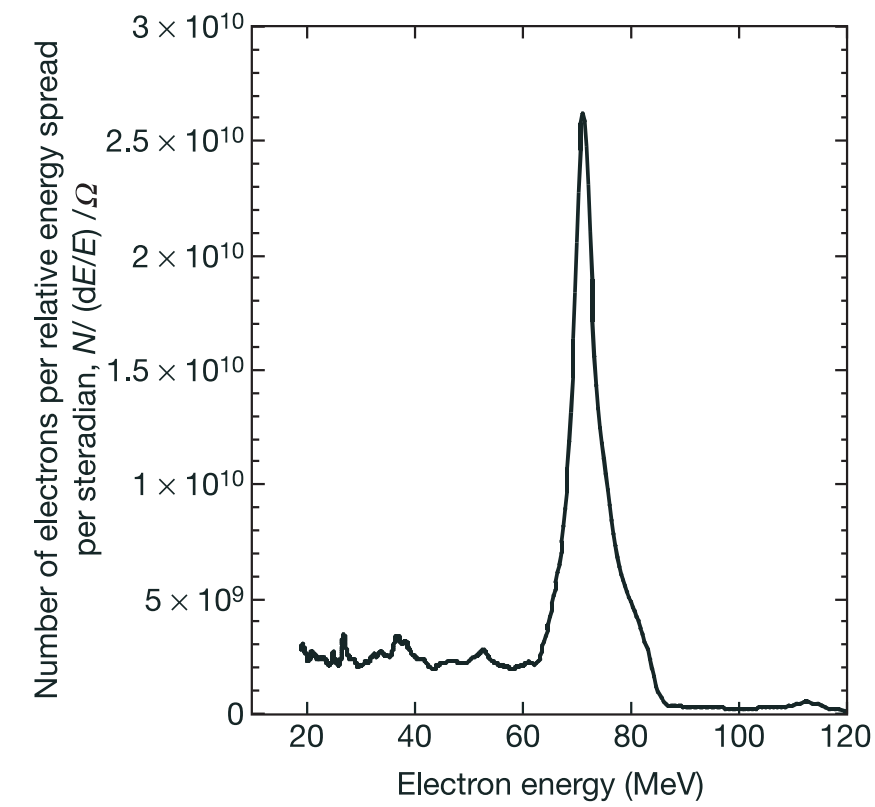
- ▶ For short, high-intensity pulses ponderomotive force can expel all electrons from region behind laser pulse. Requires
 - ⊙ $a_0 > 2$
 - ⊙ $c\tau < w_0 \approx R \approx \frac{\lambda_p}{\pi} \sqrt{a_0}$
- ▶ Approx spherical cavity ("bubble") of radius R formed
 - ⊙ Linear focusing field: preserves emittance
- ▶ Laser pulse relativistically guided over many z_R
- ▶ Electrons self-injected

Further reading

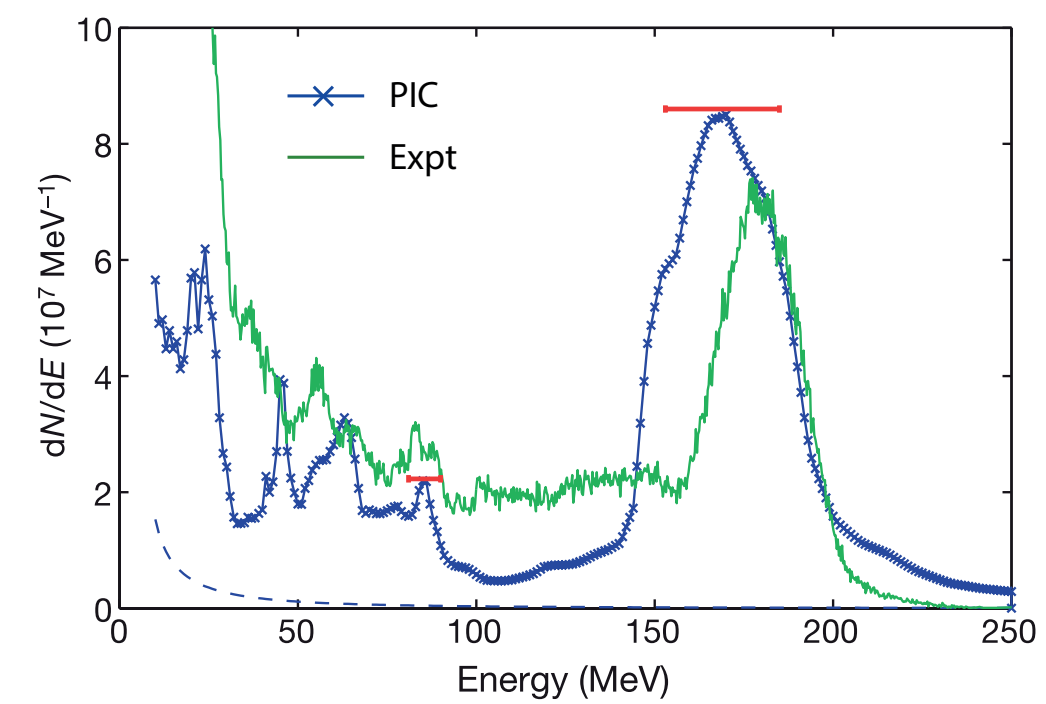
A. Pukhov & J. Meyer-ter-Vehn *Appl. Phys. B* **74** 355 (2002)
W. Lu *et al.* *PRSTAB* **10** 061301 (2007)

Dream beams!

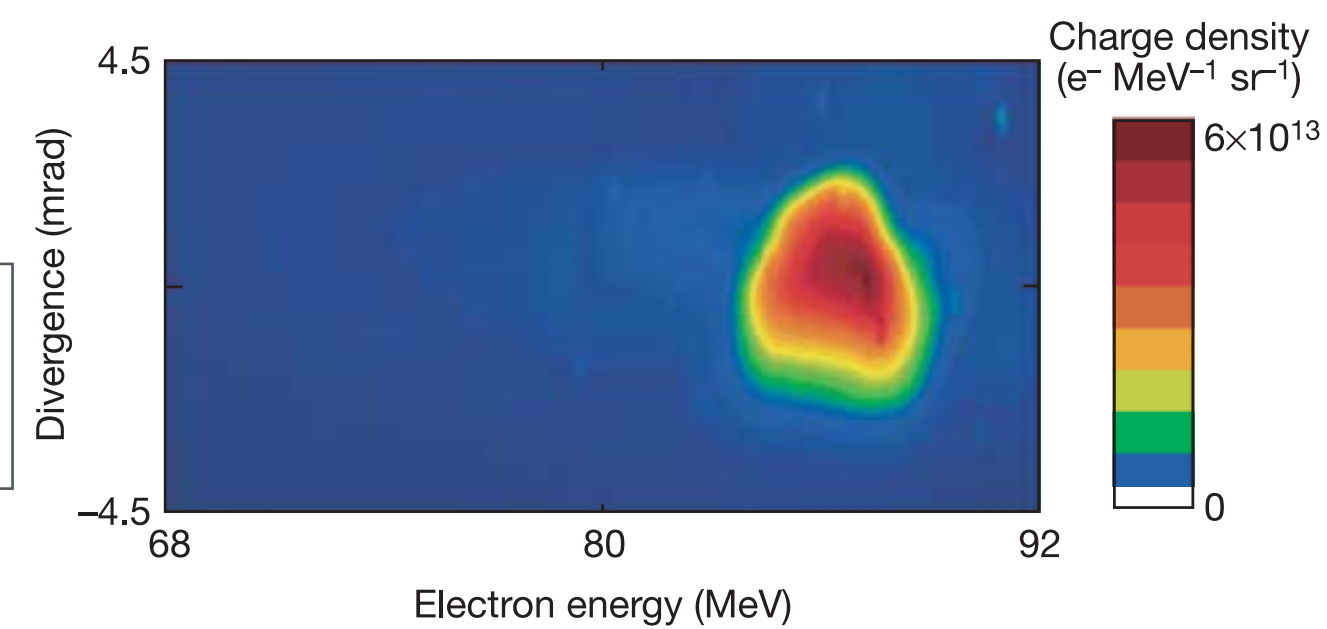
Mangles *et al.* *Nature* **431** 535 (2004)
 $E = 0.5 \text{ J}$, $\tau = 40\text{fs}$, $a_0 \approx 1$
 $n_e = 2 \times 10^{19} \text{ cm}^{-3}$



Faure *et al.* *Nature* **431** 541 (2004)
 $E = 1 \text{ J}$, $\tau = 33\text{fs}$, $a_0 \approx 1.2$
 $n_e = 6 \times 10^{18} \text{ cm}^{-3}$



Geddes *et al.* *Nature* **431** 538 (2004)
 $E = 0.5 \text{ J}$, $\tau = 55 \text{ fs}$, $a_0 \approx 2.3$
 $n_e = 2 \times 10^{19} \text{ cm}^{-3}$



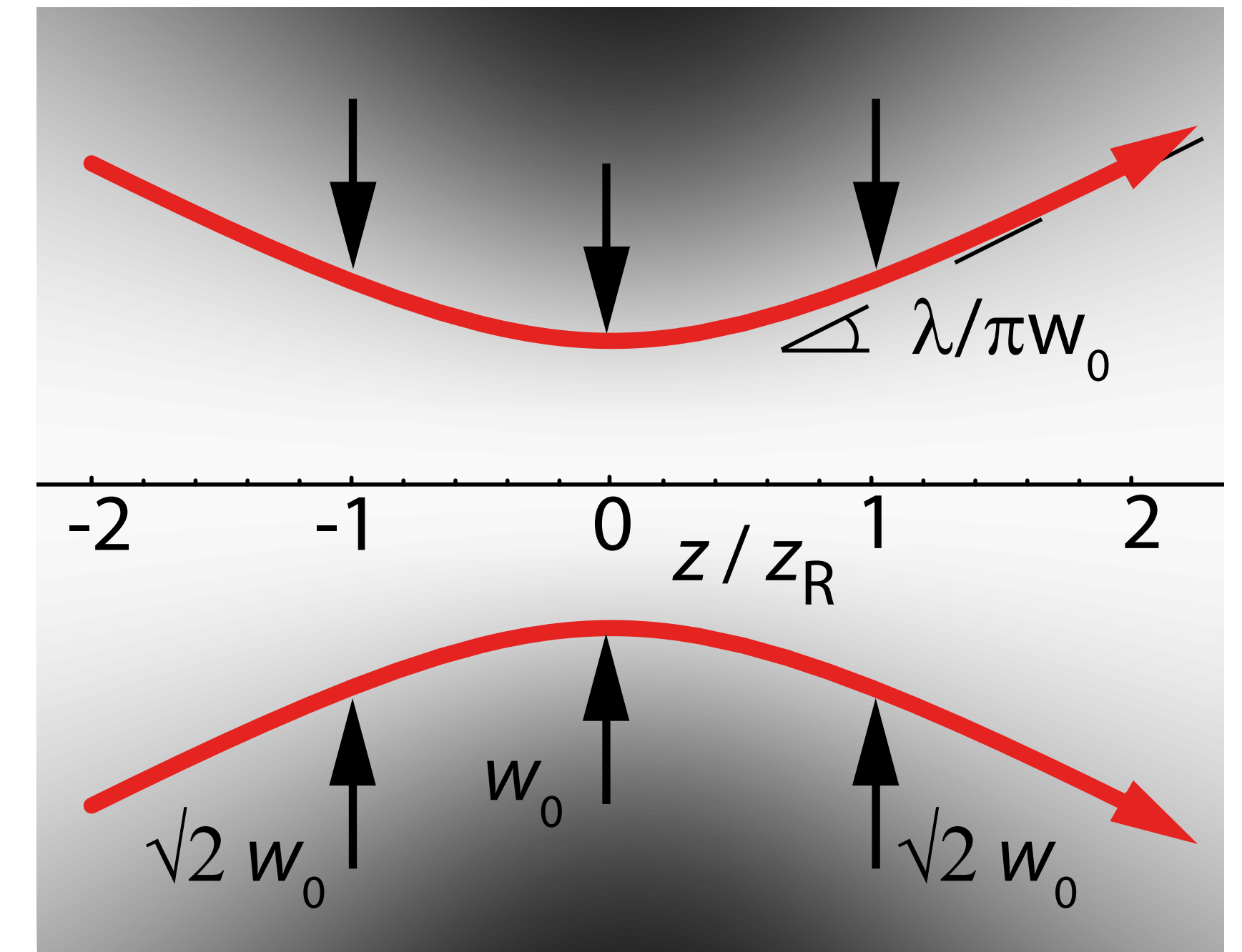
**Increasing the particle energy:
plasma channels**

De-focusing

- ▶ Diffraction limits $L_{\text{acc}} \approx z_R$
- ▶ IF defocusing can be overcome, particle energy gain:

$$\begin{aligned} \Delta W &\propto E_{\text{wb}} \times \min(L_d, L_{\text{pd}}) \\ &\propto \sqrt{n_e} \frac{1}{n_e^{3/2}} \\ &\propto \frac{1}{n_e} \end{aligned}$$

- ▶ Factor 10 increase in energy requires factor 10 decrease in density and factor 30 increase in L_{acc}
- ▶ Reaching GeV-scale energies requires the driving laser pulses to be guided over several cm



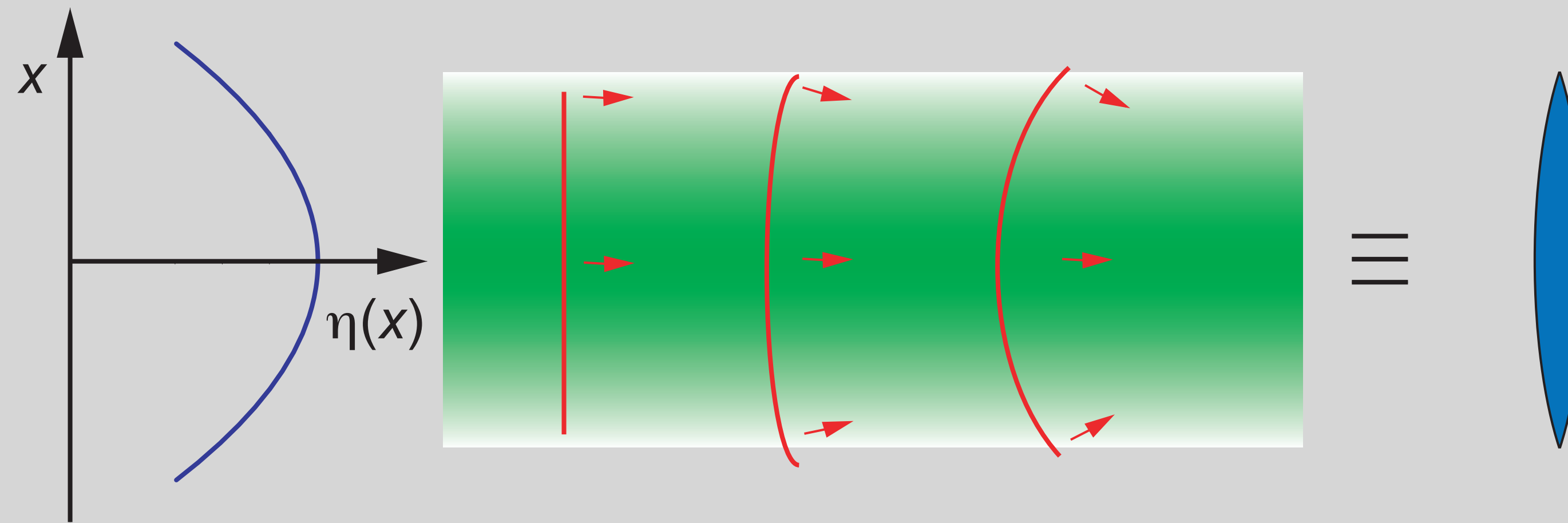
$$Z_R = \frac{\pi w_0^2}{\lambda}$$

Example :

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

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

Gradient refractive index guiding



- ▶ A structure with a radially-decreasing refractive index η will act as a waveguide

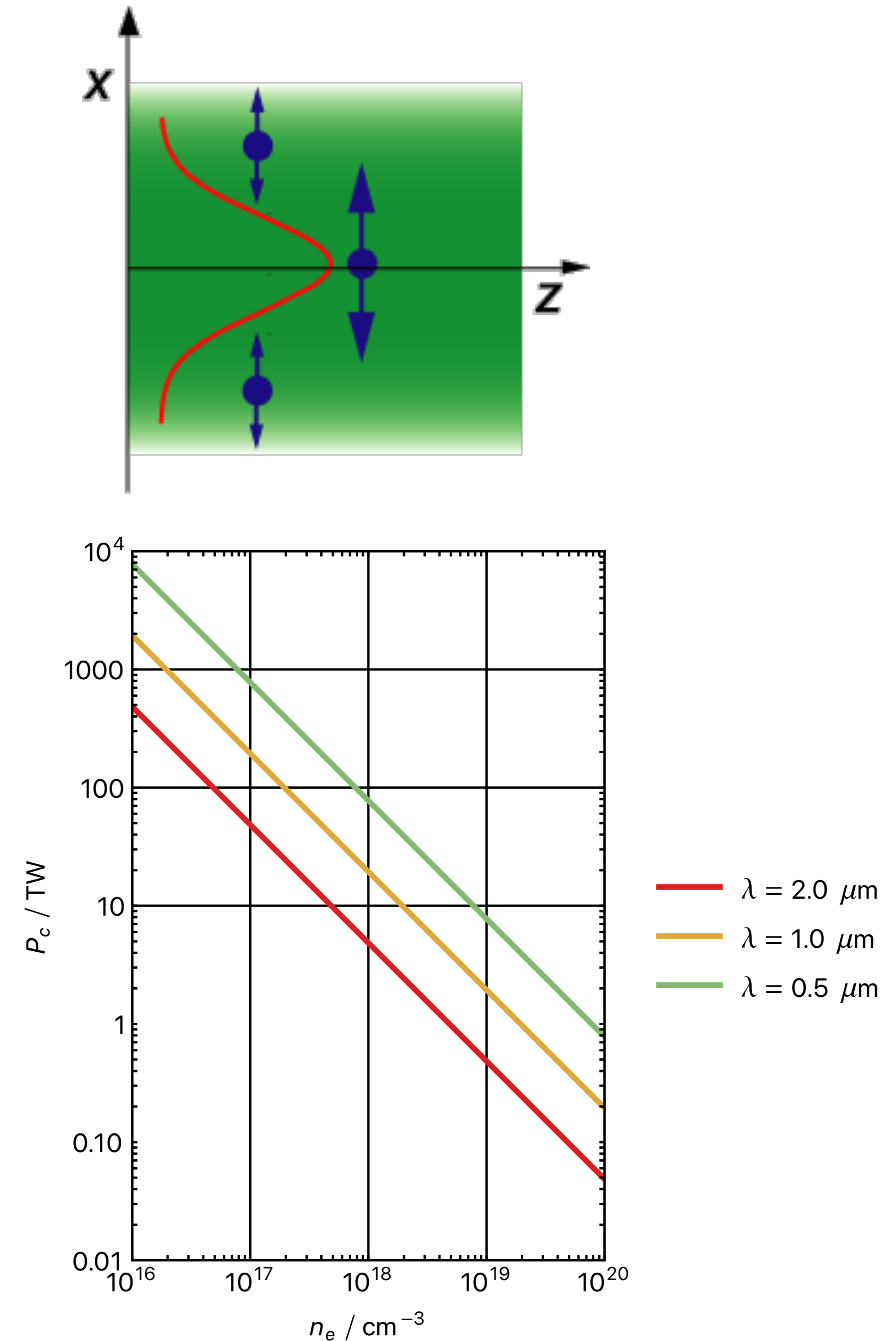
Relativistic self-focusing

- ▶ Refractive index of plasma:

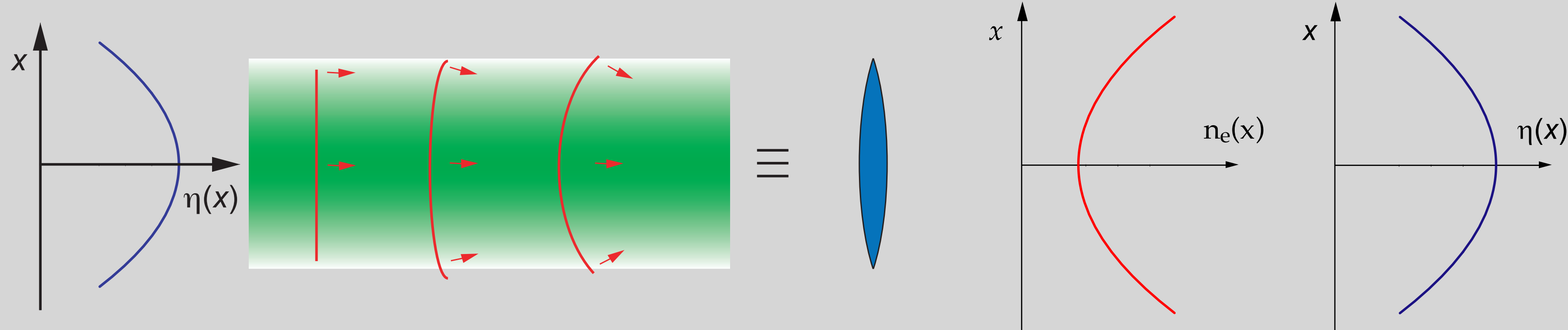
$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \approx 1 - \frac{1}{2} \frac{n_e e^2}{\gamma(r) m_e \epsilon_0 \omega^2}$$

- ▶ **Relativistic self-focusing**: transverse intensity profile forms GRIN structure
- ▶ Critical power for self-focusing given by,

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



Plasma channels



- ▶ Alternatively, we can shape the plasma:

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

- ▶ Gaussian beam of spot size w_M is matched to lowest-order mode of a parabolic plasma channel of form,

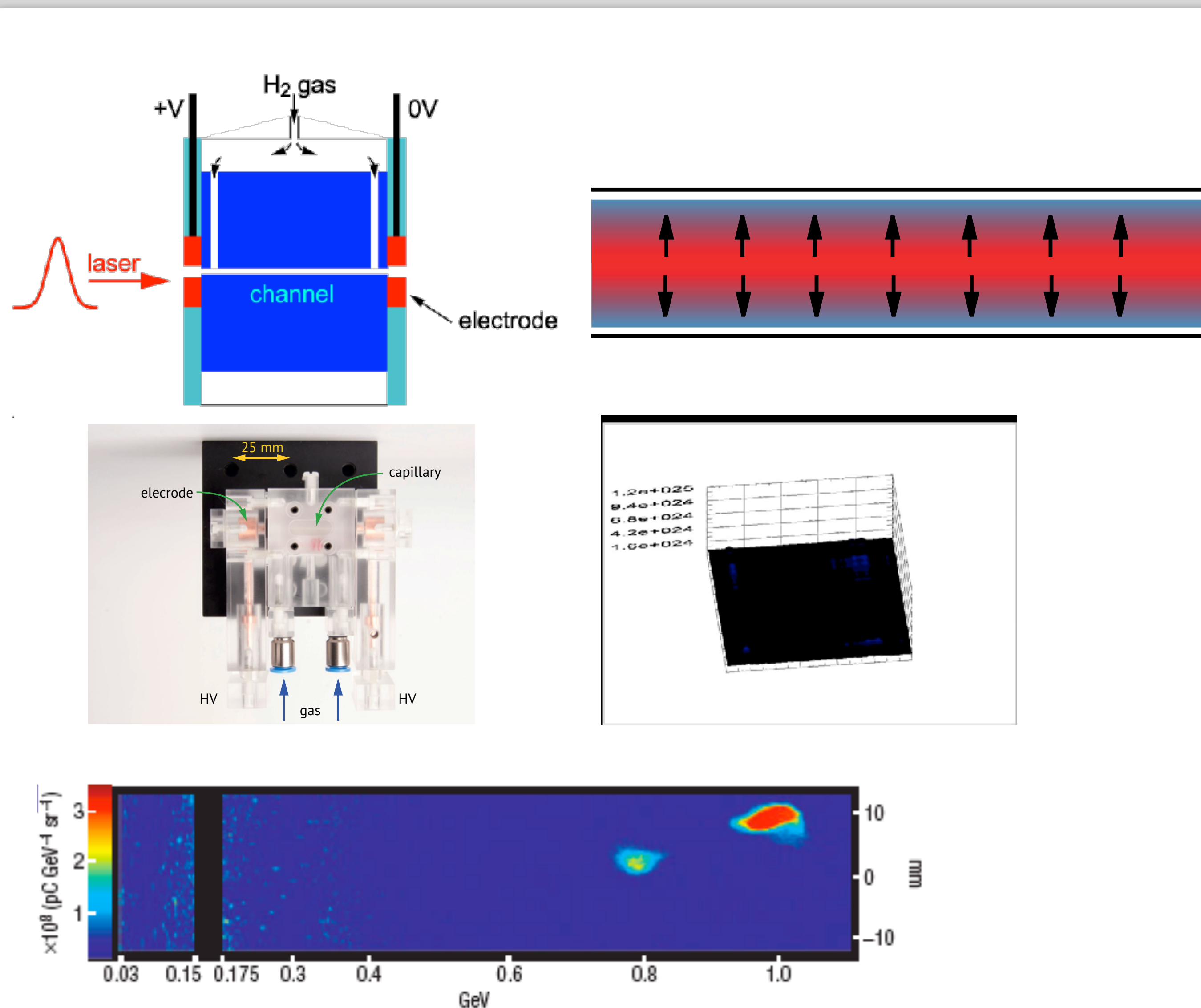
$$n_e(r) = n_e(0) + \frac{1}{\pi r_e w_M^2} \left(\frac{r}{w_M}\right)^2$$

Gas-filled capillary discharge waveguide

- ▶ Pulsed discharge creates plasma in H₂-filled capillary
 - ~300 A peak
 - ~200 ns half-period
- ▶ Heat conduction to wall forms channel
- ▶ Used by Oxford-LBNL collaboration to generate 1 GeV beam for first time in 33 mm long channel

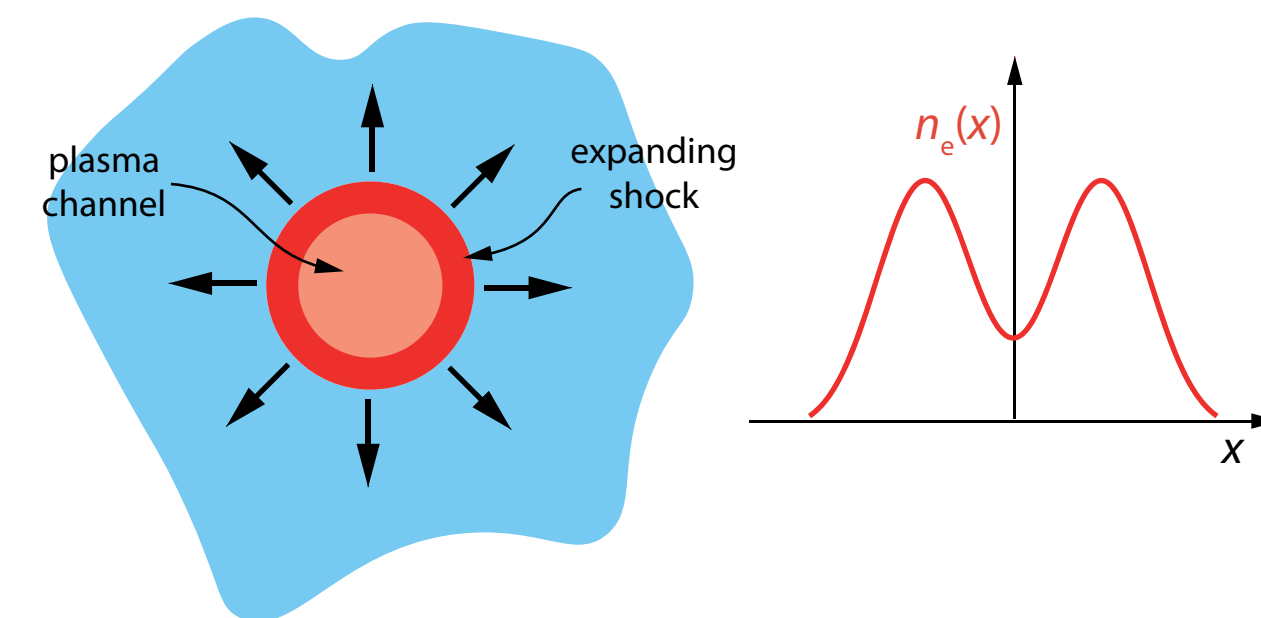
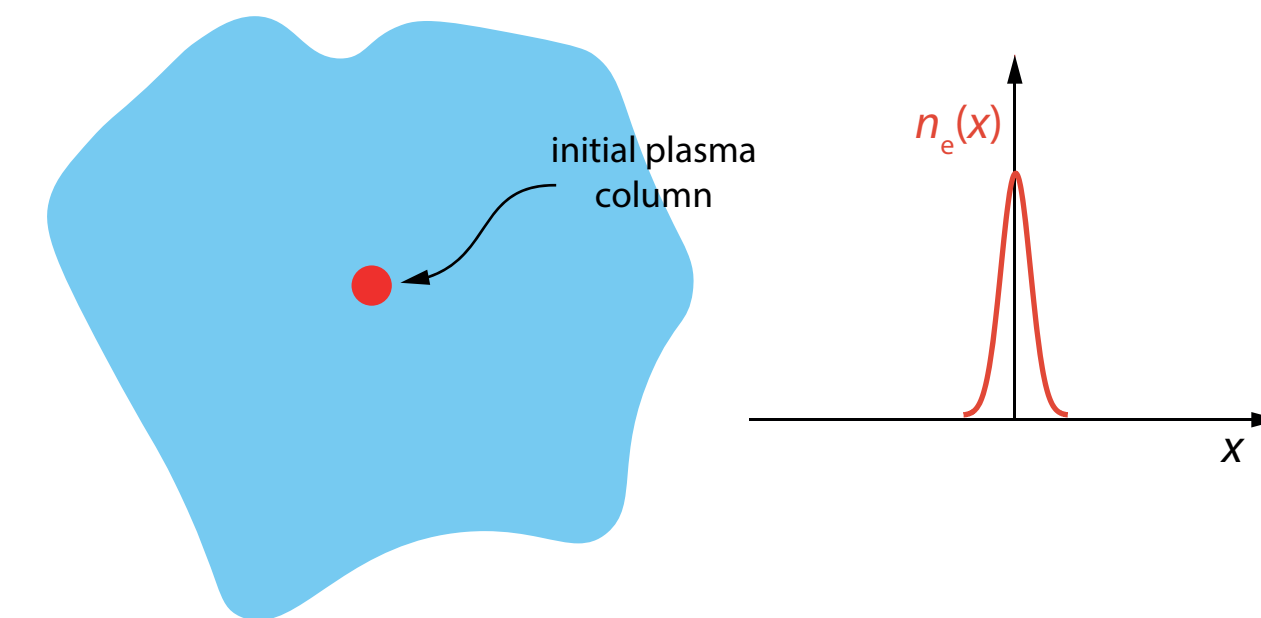
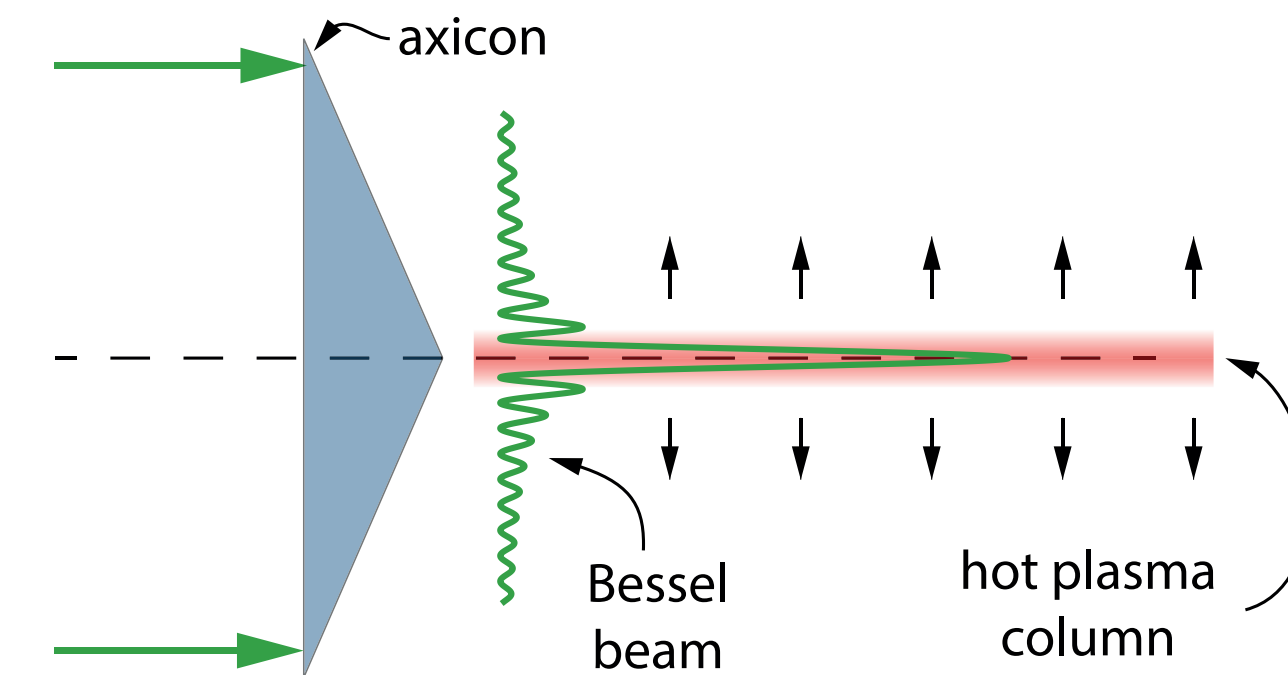
Further reading

Spence *et al.* *Phys. Rev. E* **63** 015401(R) (2001)
 Bobrova *et al.* *Phys. Rev. E* **65** 016407 (2002)
 Butler *et al.* *Phys. Rev. Lett.* **89** 185003 (2002)
 Leemans *et al.* *Nat. Phys.* **2** 696 (2006)
 Gonsalves *et al.* *Phys. Rev. Lett.* **98** 025002 (2007)



Optically generated plasma channels

- ▶ Channels formed by hydrodynamic expansion of collisionally-heated plasma column pioneered by Milchberg et al.
 - Free-standing & “indestructible”
 - Requires high density ($\gtrsim 10^{18} \text{ cm}^{-3}$) for efficient heating
- ▶ Extensively studied by the Milchberg group:
 - Original concept:
 - Durfee & Milchberg, *Phys. Rev. Lett.* 71 2409 (1993)
 - Clark & Milchberg, *Phys. Rev. Lett.* 78, 2373–2376 (1997).
 - Mode properties:
 - T. R. Clark & H. M. Milchberg, *Phys Rev E* 61 1954 (2000).
 - Clustered gases:
 - V. Kumarappan et al. *PRL* 94 205004 (2005)



Hydrodynamic optical-field-ionized (HOFI) plasma channels

- ▶ Optical field ionization occurs when laser field comparable to field binding valance electrons
- ▶ Final energy of electrons depends on laser polarization
 - Linear : “cold” electrons
 - Circular: “hot” electrons
- ▶ Electron energies **independent of density**
- ▶ OFI could generate lower density channels ($\lesssim 10^{17} \text{ cm}^{-3}$)

Lemos *et al.*, *Phys. of Plas.* **20** 063102 (2013)

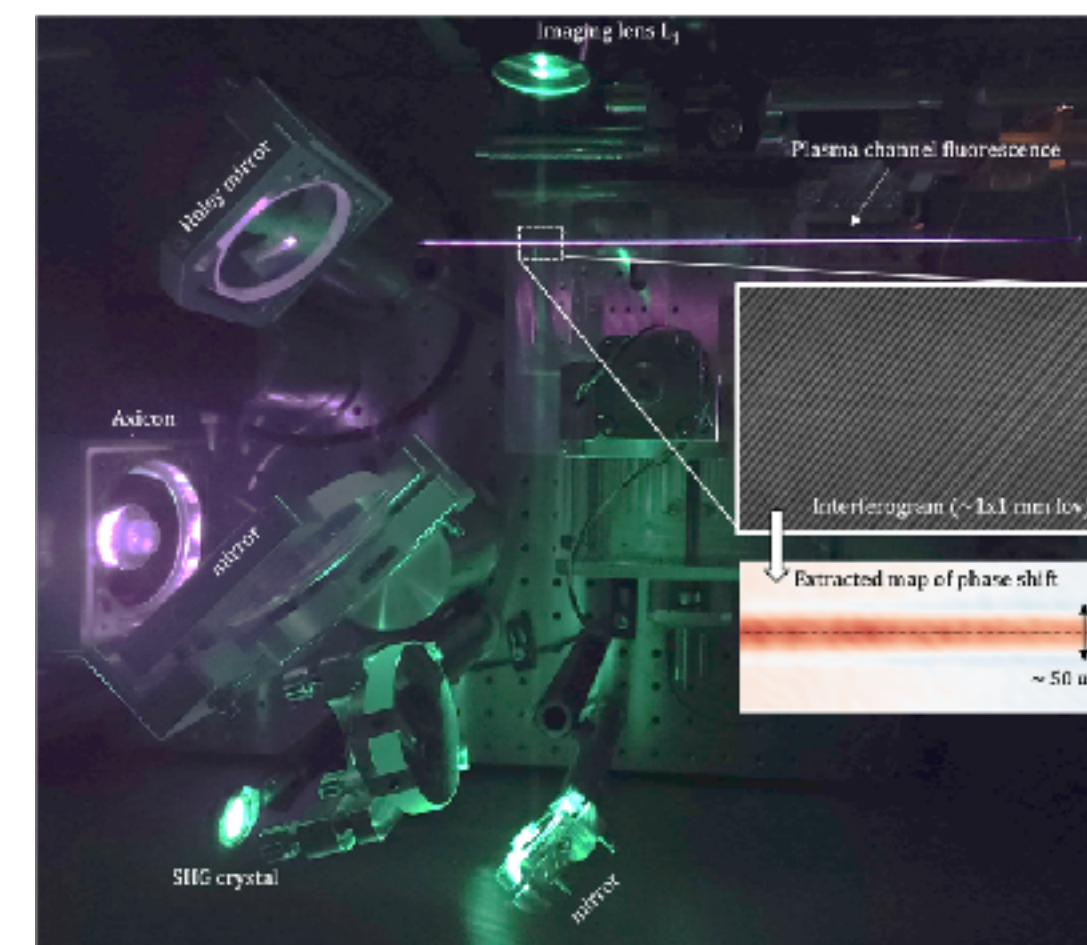
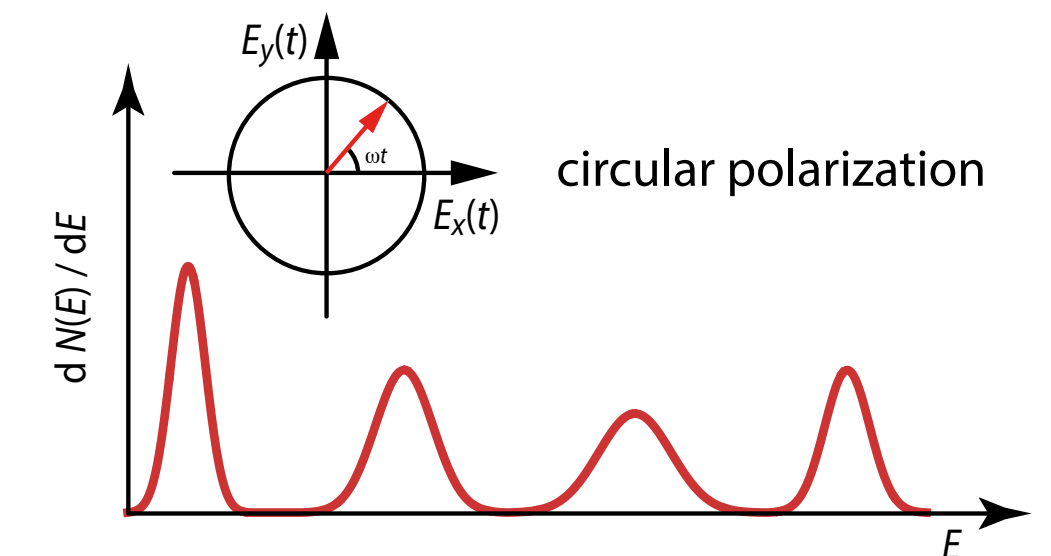
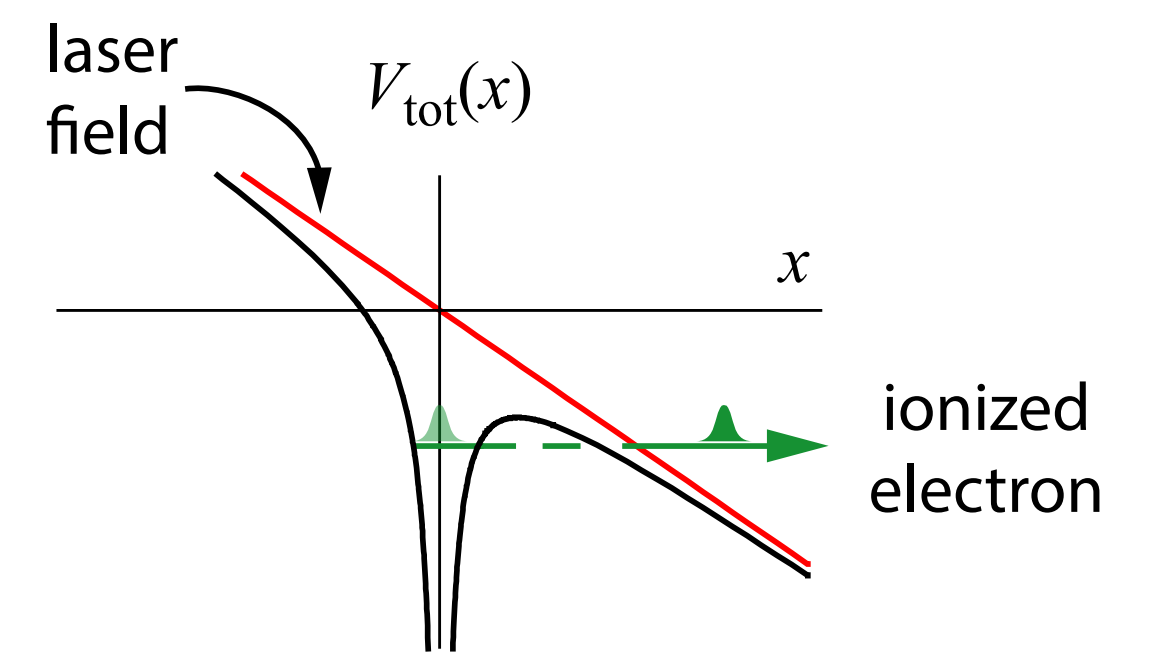
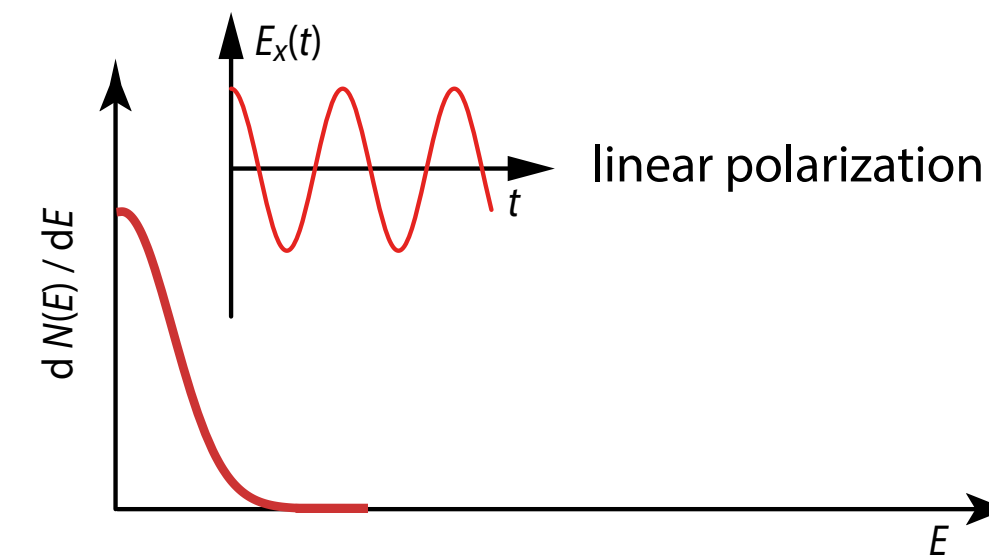
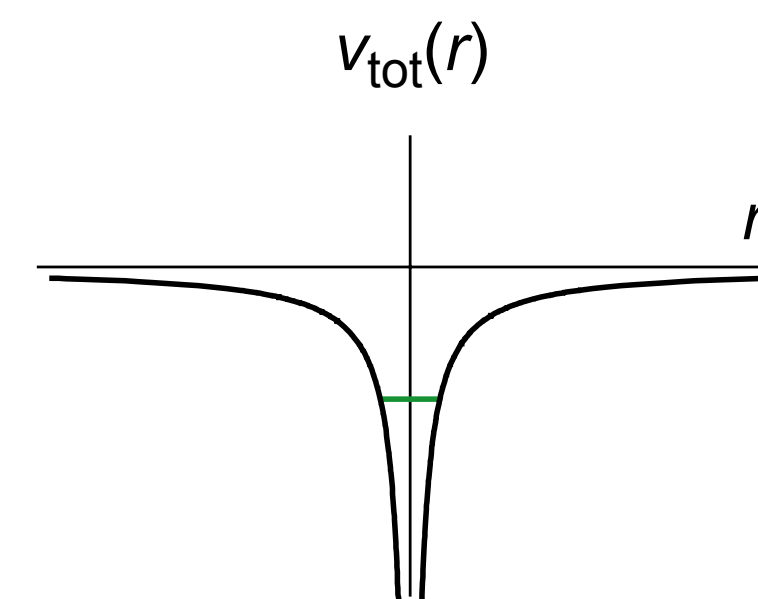
Lemos *et al.*, *Phys. of Plas.* **20** 103109 (2013)

Hooker *et al.*, *Advanced Accelerators Concepts Workshop* (2016)

R. Shalloo, *D.Phil thesis*, Oxford (2018)

Shalloo *et al.* *Phys. Rev. E* **97** 053203 (2018)

Shalloo *et al.* *Phys. Rev. Accel. Beam* **22** 41302 (2019)



Formation of HOFI channels at CALA

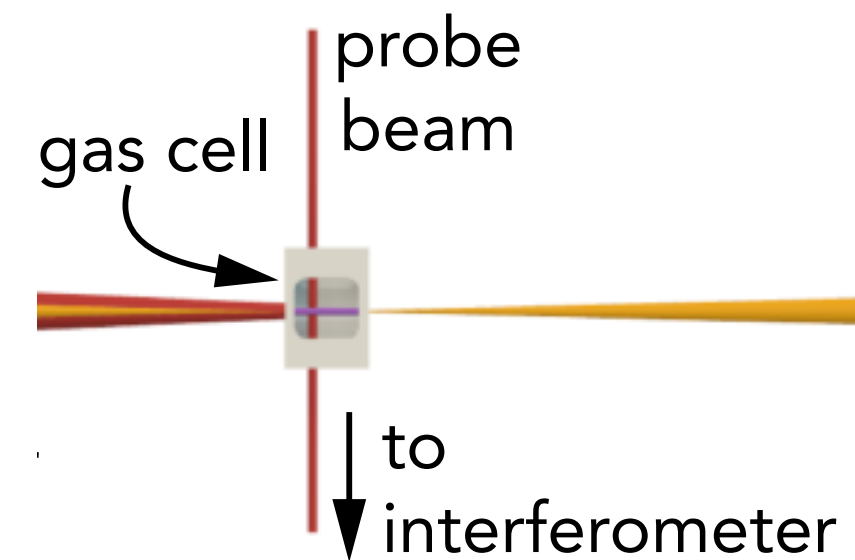
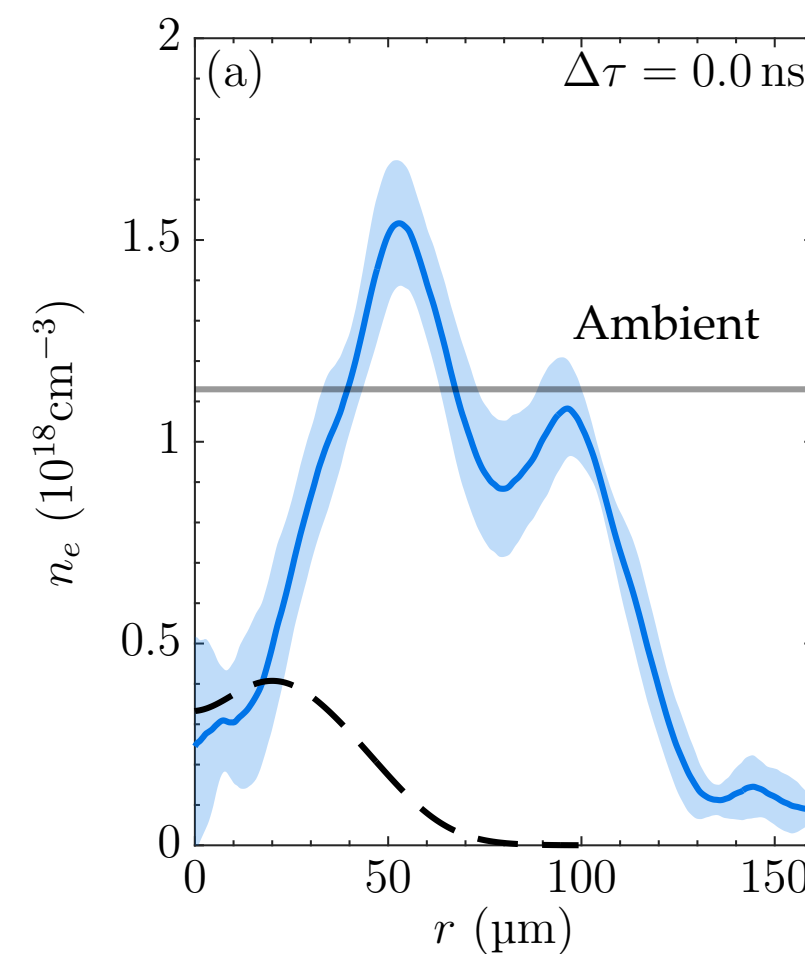
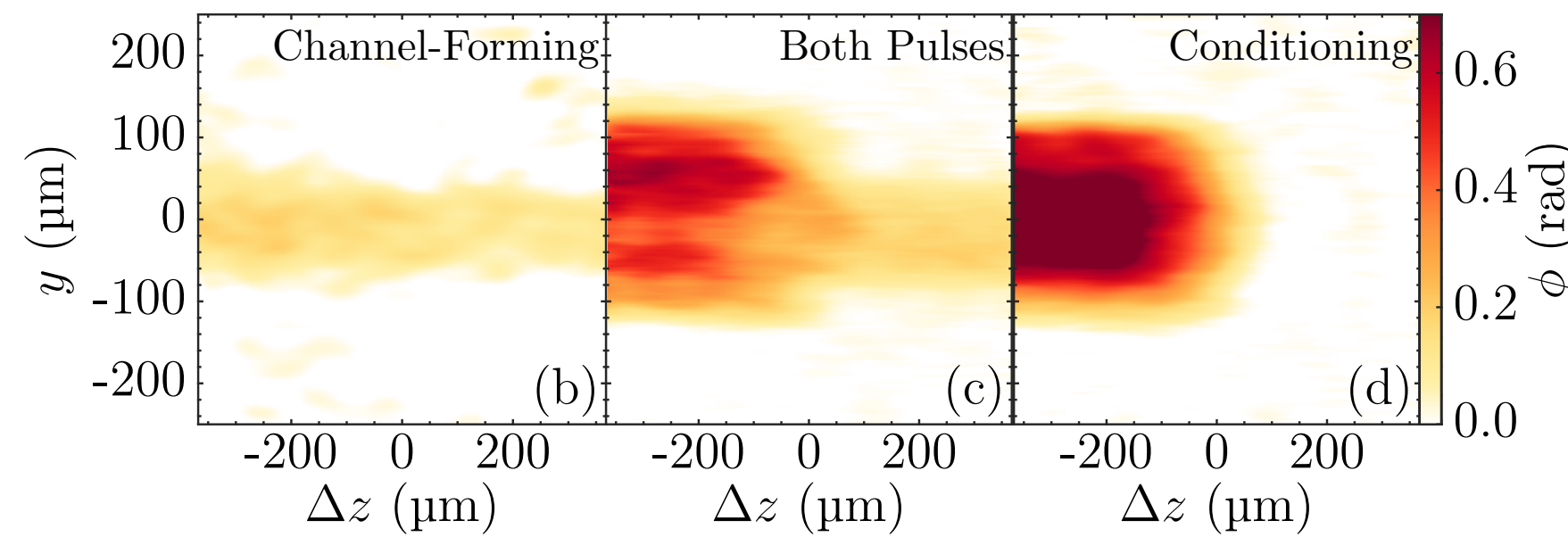
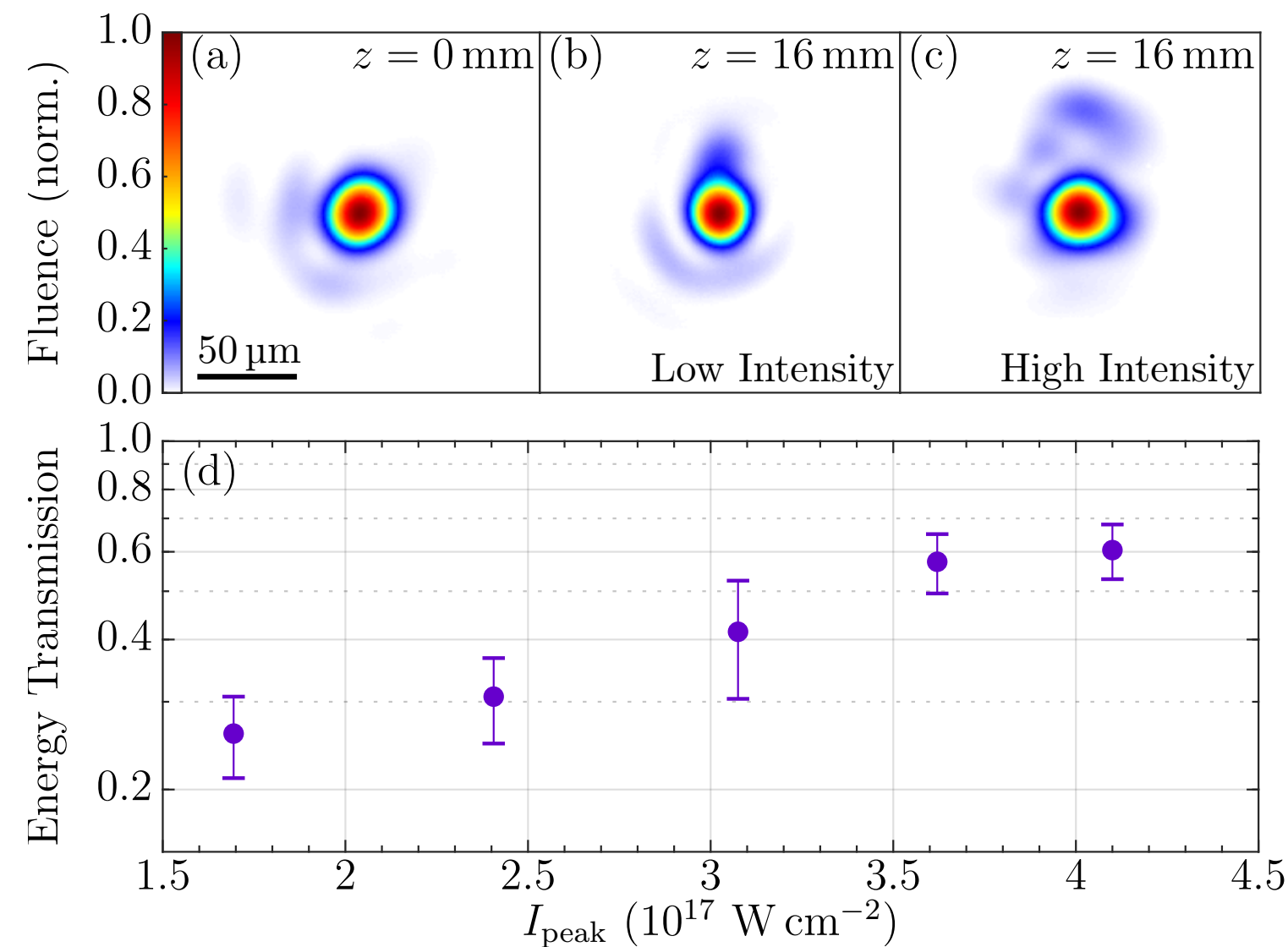
Astra-Gemini TA2 expts 2018

Channel-forming pulse

τ : 45 fs
Poln: Circular
Axicon: 5.6° (base)

Guided pulse

τ : 45 fs
Poln: Linear
 z_R : 1.1 mm
 I_0 : $4 \times 10^{17} \text{ W cm}^{-2}$



R.J. Shalloo *et al.* *Phys Rev Accel. Beam* **22** 41302 (2019)

A. Picksley *et al.* *Phys Rev E* **102** 053201 (2020)

HOFI plasma channels

- ▶ Energy transmission observed to increase with intensity of guided beam
- ▶ Transverse interferometry after guided pulse shows formation of very deep, low loss channels

● $L_{\text{attn}} \gg 1 \text{ m}$

HOFI plasma channels

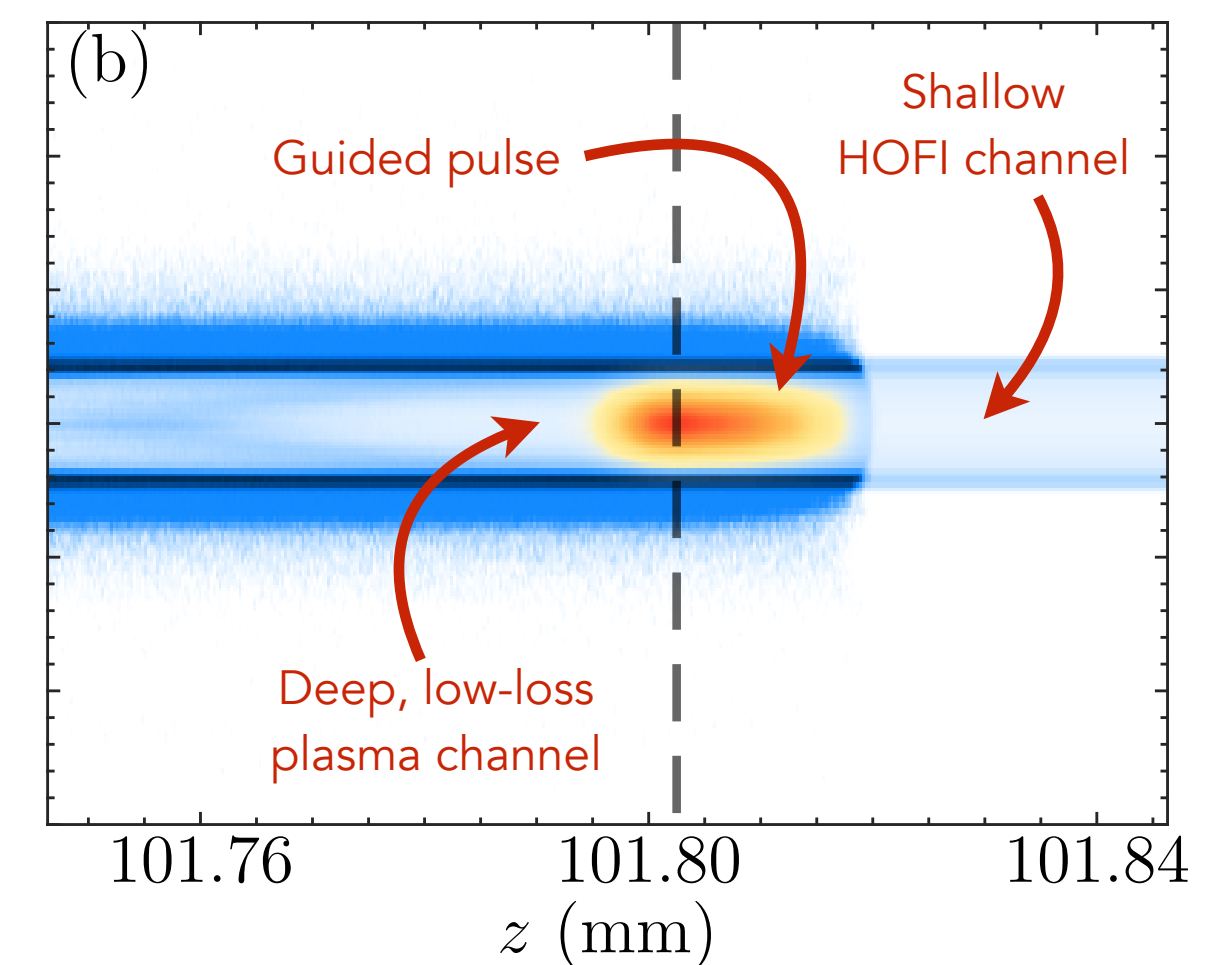
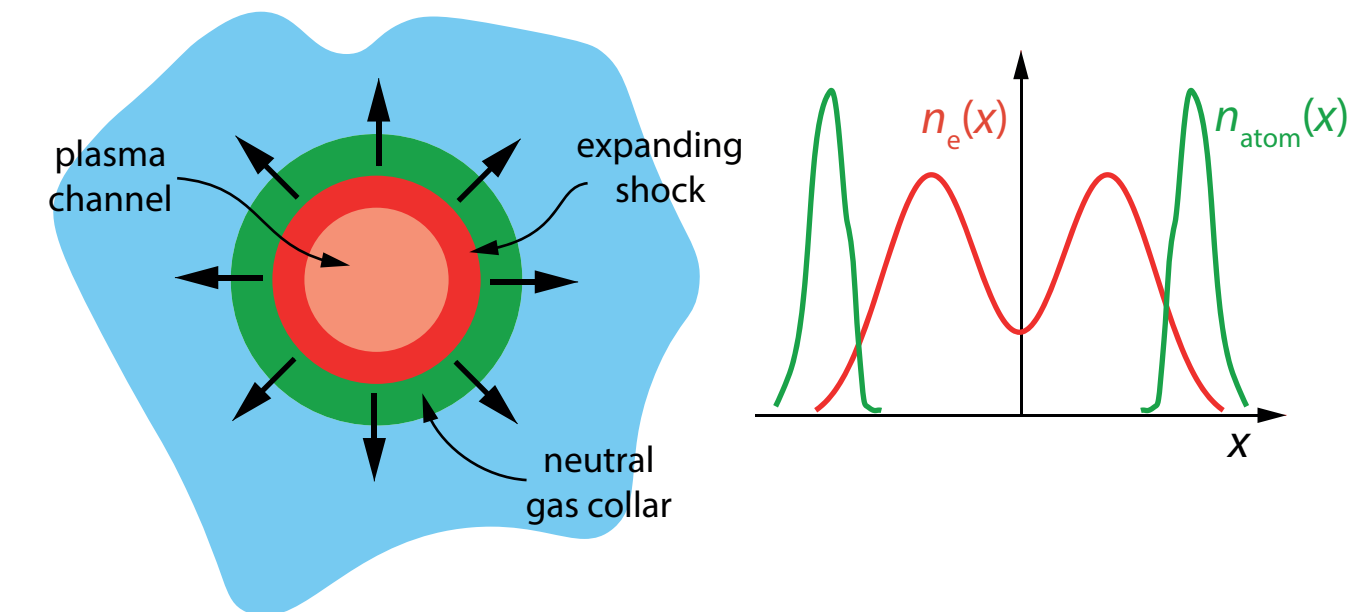
- ▶ Channel formed by two-stage process
 - ⊙ Expansion → weak channel
 - ⊙ Ionization of gas collar → deep, low loss ($L_{\text{attn}} \gg 1$ m) channels

Morozov *et al.* *Phys. of Plas.* **25**, 053110 (2018).

Picksley *et al.* *Phys. Rev. E* **102**, 053201 (2020)

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

Miao *et al.* *Phys. Rev. Accel. Beams* **27** 081302 (2024)

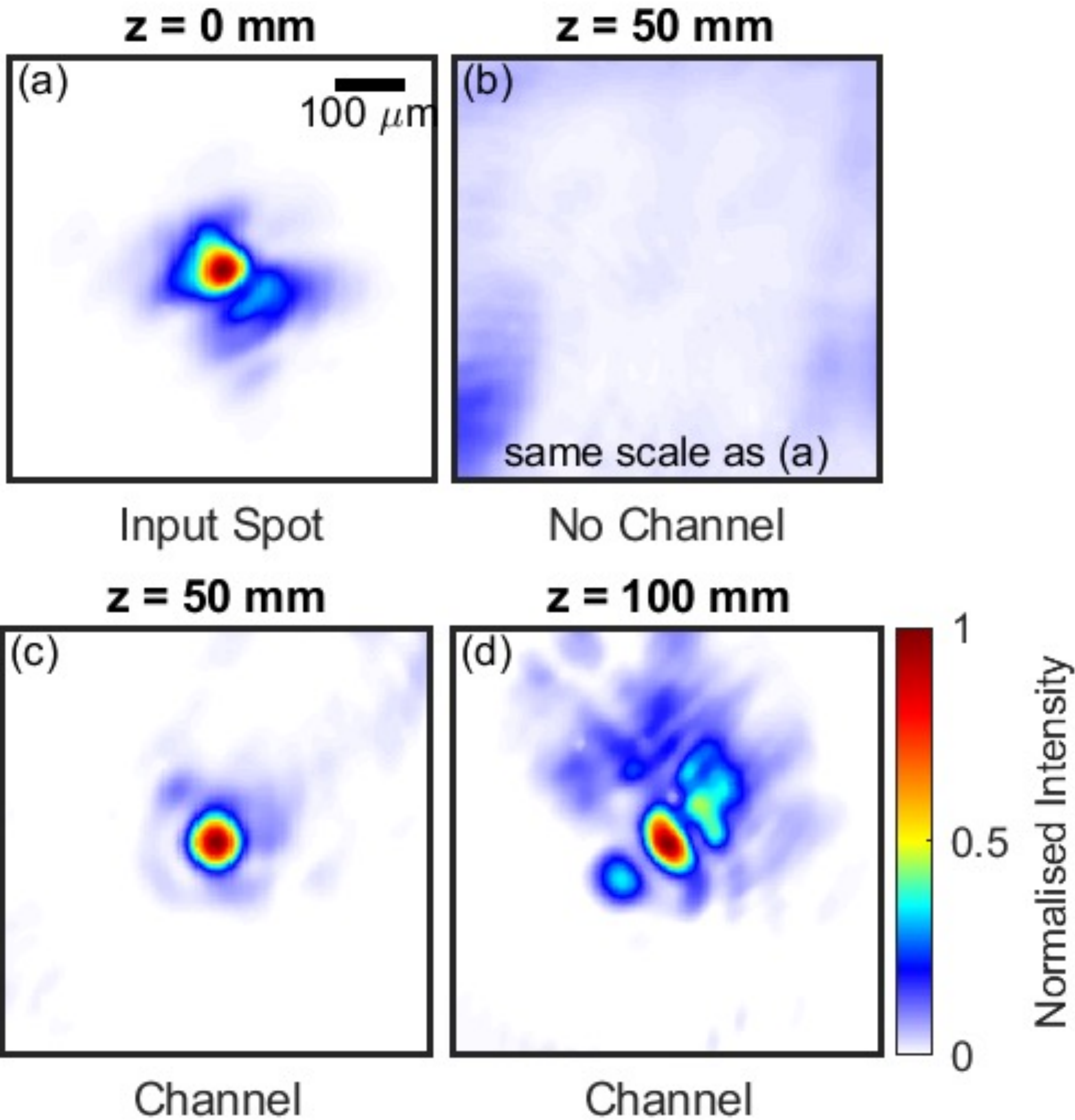
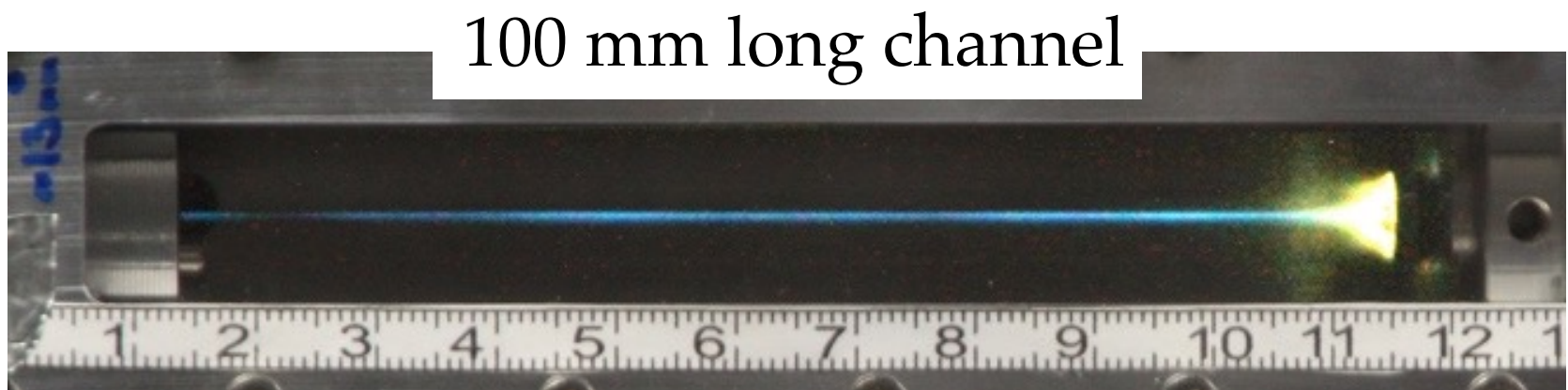
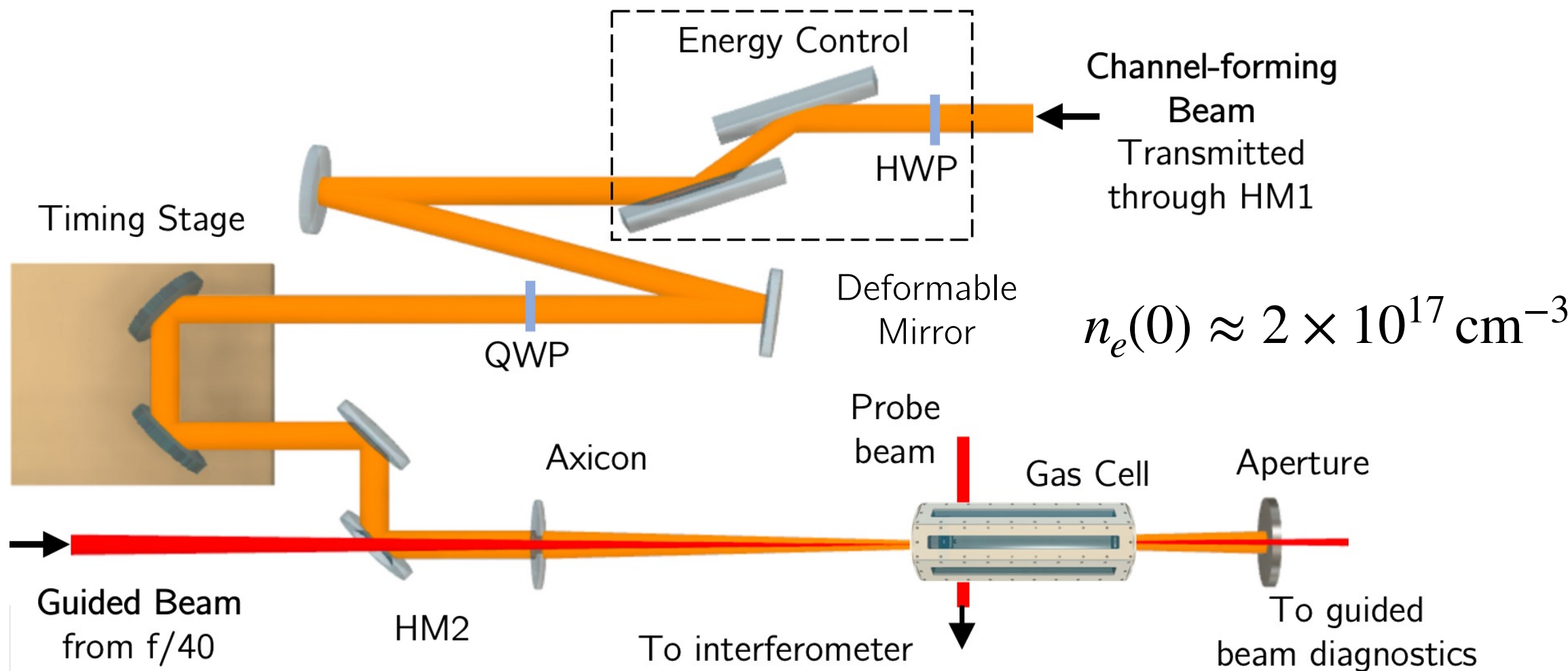


Guiding over 100 mm

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

Astra-Gemini TA3 expts 2019

Channel-forming pulse	Guided pulse
τ : 45 fs	τ : 40 fs
Poln: Circular	Poln: Linear
Axicon: 5.6° (base)	w_0 : 38 μm
I_{ax} : $6 \times 10^{15} \text{ Wcm}^{-2}$	I_0 : $6 \times 10^{17} \text{ W cm}^{-2}$



HOFI channels are becoming the channel of choice!

► Demonstration of kHz capability

- Operation at 0.4 kHz over 6.5 hours with no change in guiding properties

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

► Generation of metre-scale channels

Shrock et al., *Phys Plasmas* **29**, 073101 (2022).

Miao et al., *Rev. Sci. Instrum.* **96**, 043003 (2025).

Tripathi et al., *Opt. Lett.* **50**, 3441 (2025).

► Electron acceleration in HOFI channels

Miao et al., *Phys Rev X* **12**, 031038 (2022).

Oubrierie et al. *Light Sci. Appl.* **11**, 180 (2022).

Picksley et al., *Phys. Rev. Lett.* **131**, 245001 (2023).

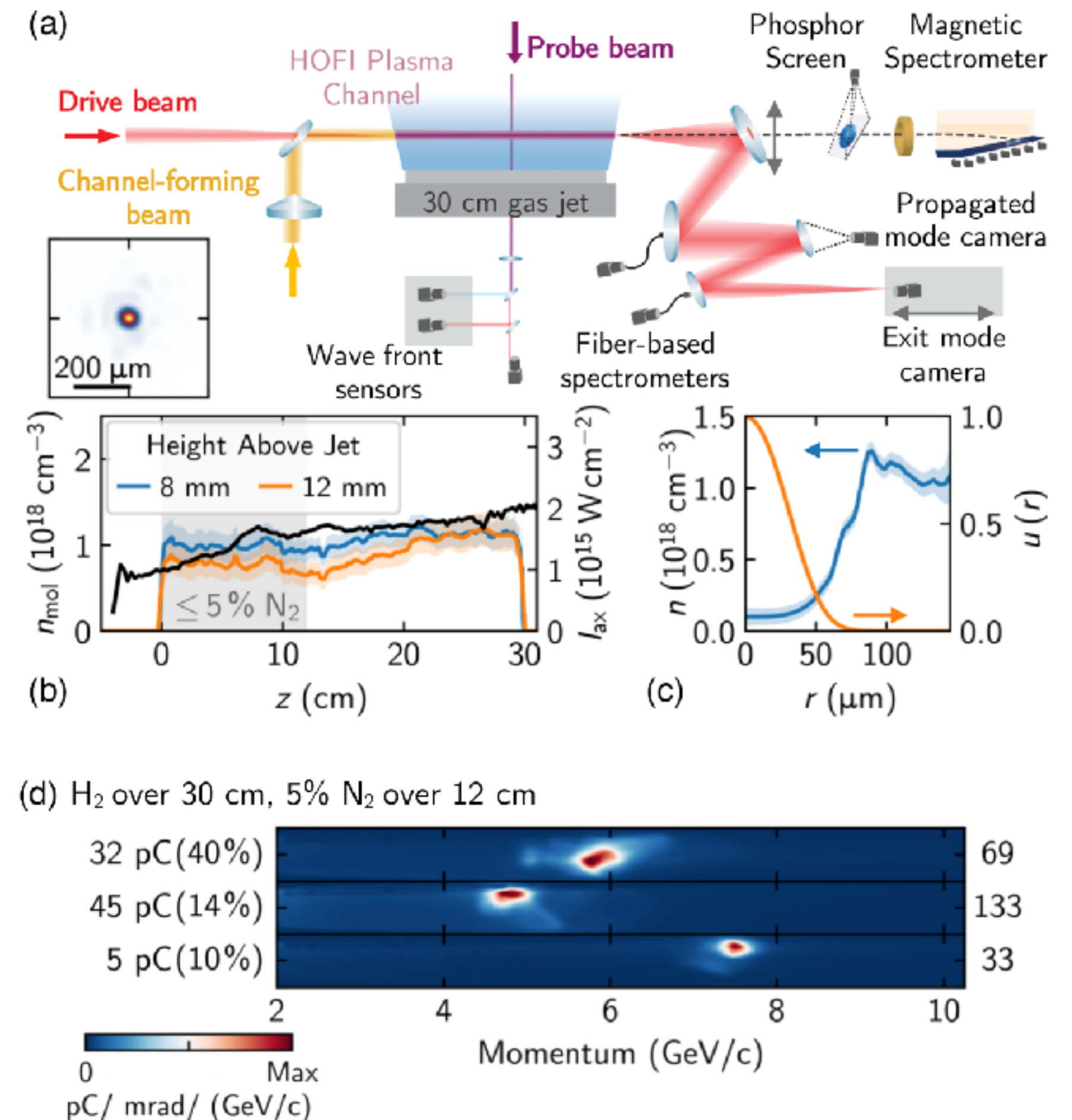
Picksley et al., *Phys. Rev. Lett.* **133**, 255001 (2024).

Shrock et al., *Phys. Rev. Lett.* **133**, 045002 (2024).

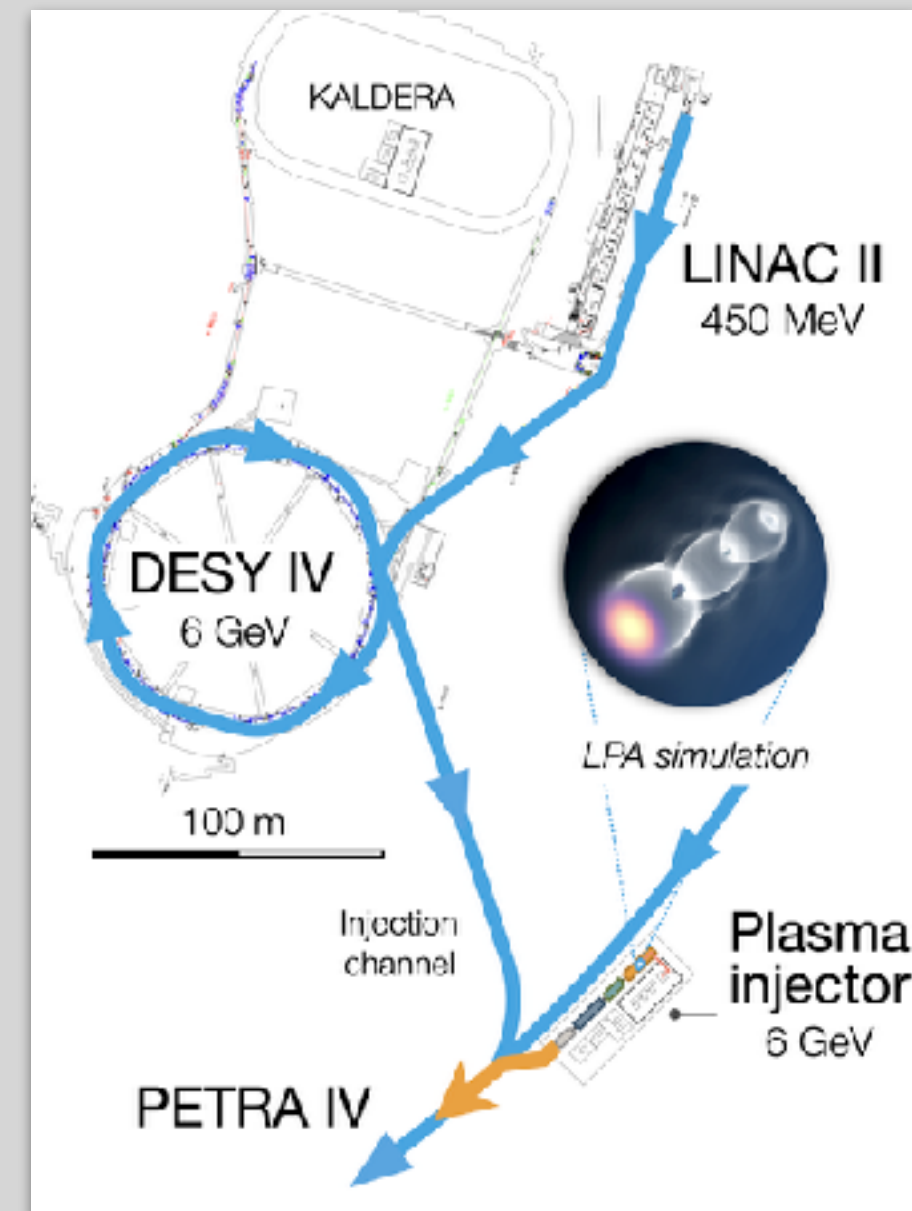
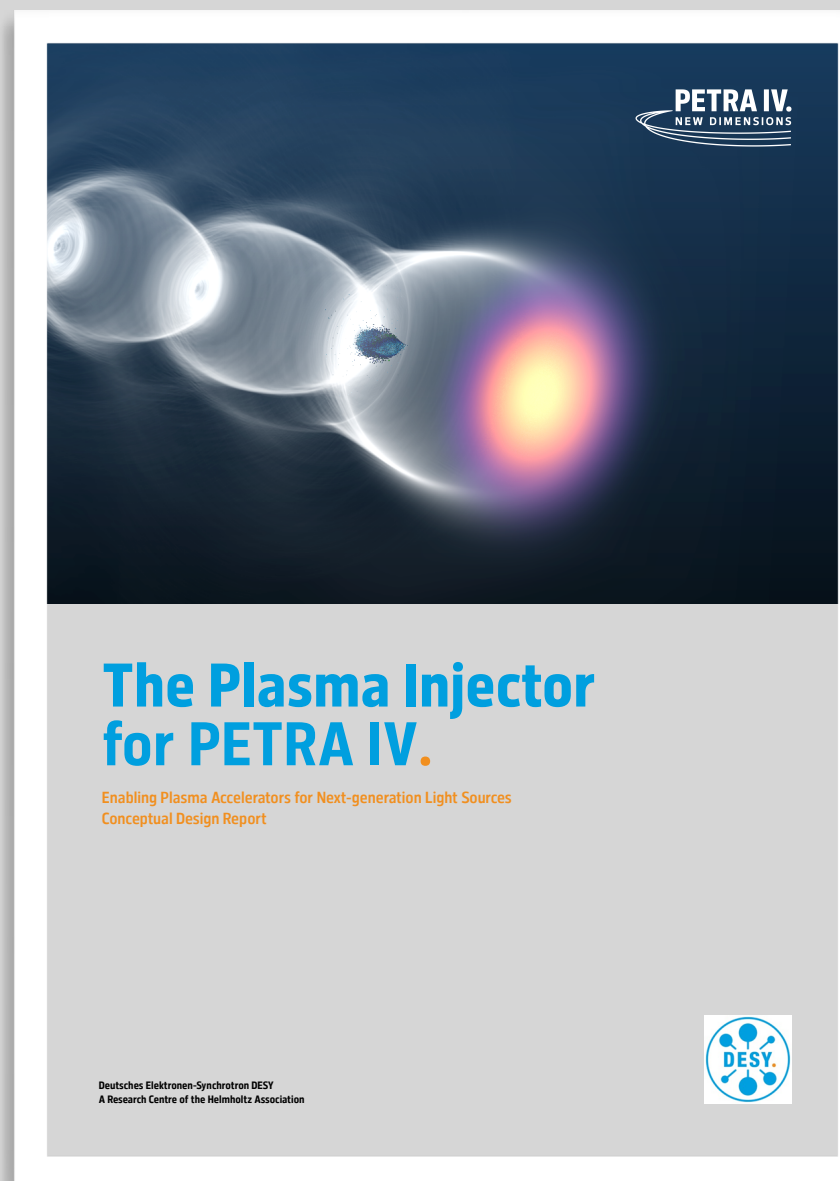
Rockafellow et al. *Phys. Plasmas* **32**, 053102 (2025).

Lahaye et al., *Phys. Rev. Accel. Beams* **28**, 091301 (2025).

Picksley et al., *Phys. Rev. Lett.* **133**, 255001 (2024).



HOFI channels are becoming the channel of choice!

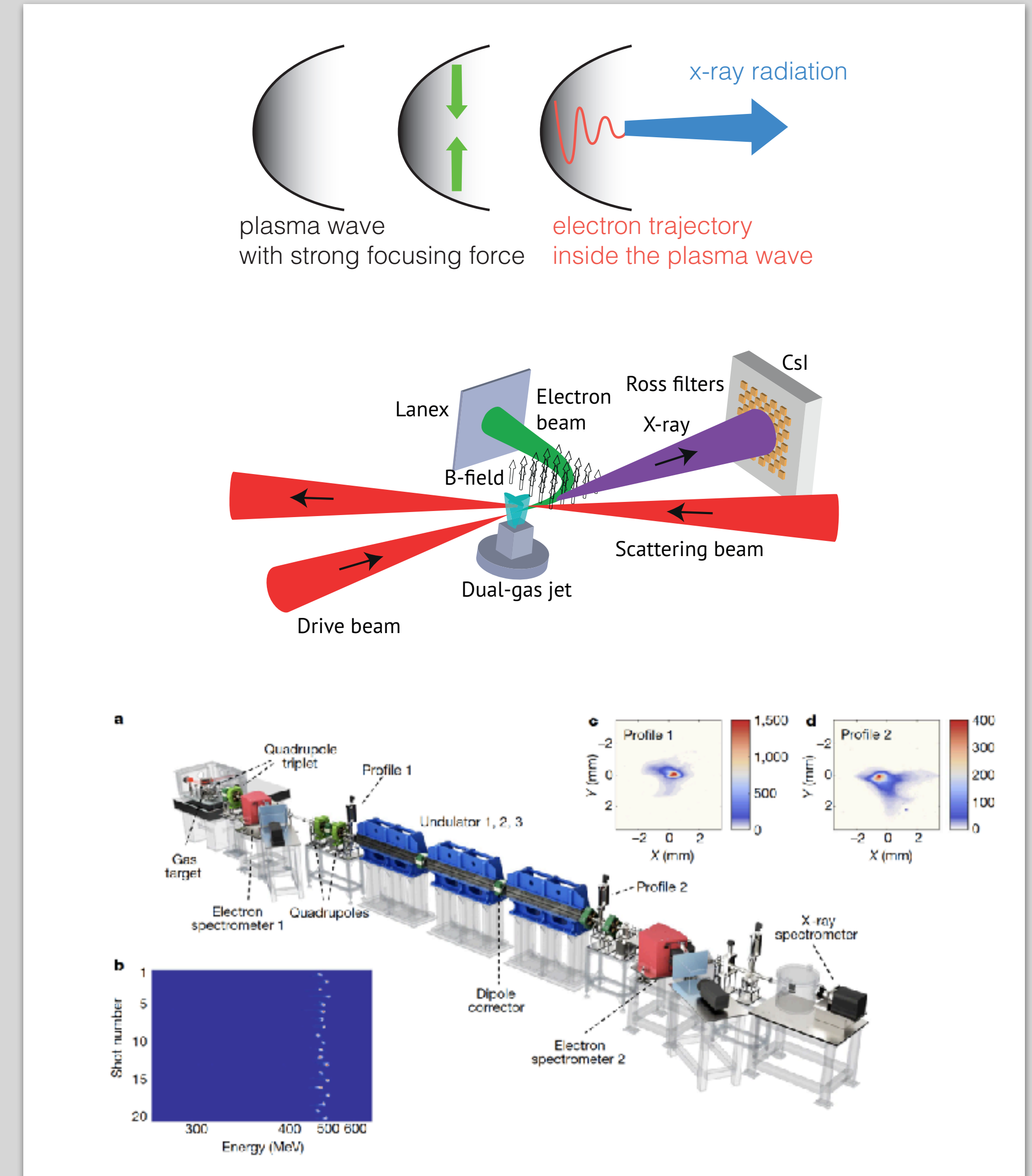


- “...[HOFI channels] are advantageous since their structure is immune to damage...”
- “... HOFI waveguides offer the ability to generate plasma channels with relatively small matched spot sizes at low plasma densities, consistent with the required multi-GeV acceleration.”

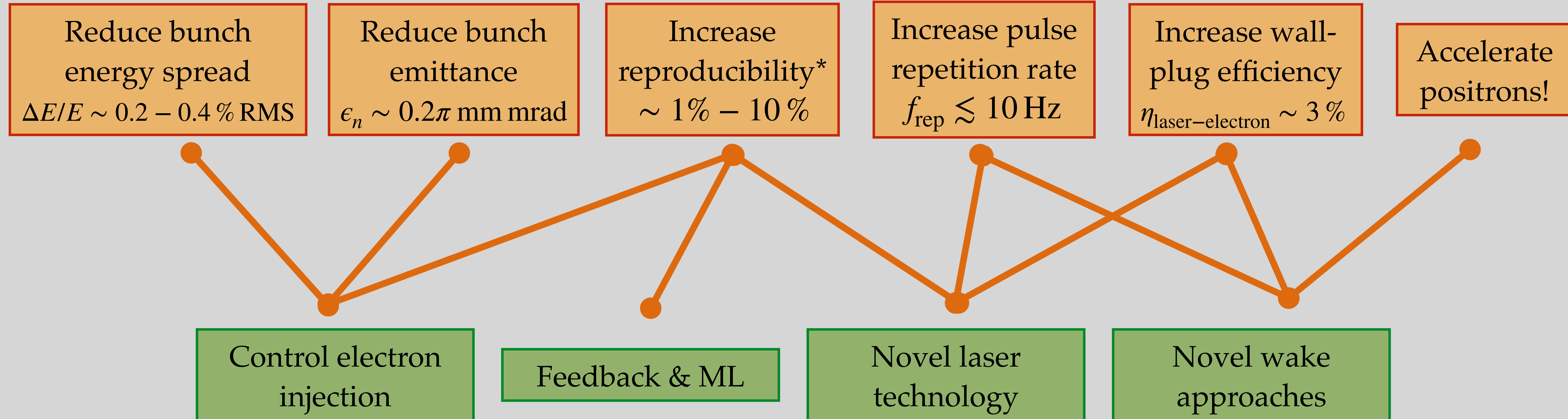
Status & Challenges

GeV-scale beams are “routine” & are starting to drive applications

- ▶ 100 eV radiation from undulators
 - *Fuchs et al. Nat. Phys. 5 826 (2009)*
- ▶ 10 - 150 keV radiation from betatron motion
 - *Kneip et al. Nat. Phys. 6 980 (2010)*
 - *Cippiccia et al. Nat. Phys. 7 861 (2011)*
- ▶ 1 - 100s MeV from Thomson / Compton scattering
 - *Powers et al. Nat. Photon. 8 28 (2013)*
 - *Khrennikov et al. Phys. Rev. Lett. 114 195003 (2015)*
- ▶ FEL gain demonstrated!
 - 27 nm : *Wang et al Nature 595 516 (2021)*
 - 800 nm: *Pompili et al. Nature 605 659 (2022)*
- ▶ First user facilities being planned & developed
 - EPAC, Harwell : under construction, first expts in 2026
 - EuPRAXIA : laser- and beam-driven FELs being developed at 2 sites.



Challenges ... and possible solutions



- Parameters from

M. Fuchs *et al.*, "Snowmass whitepaper AF6: Plasma-based particle sources," arXiv:2203.08379v2

- * My estimate

Increasing stability: 24 hour beam generation

► DESY LUX beamline

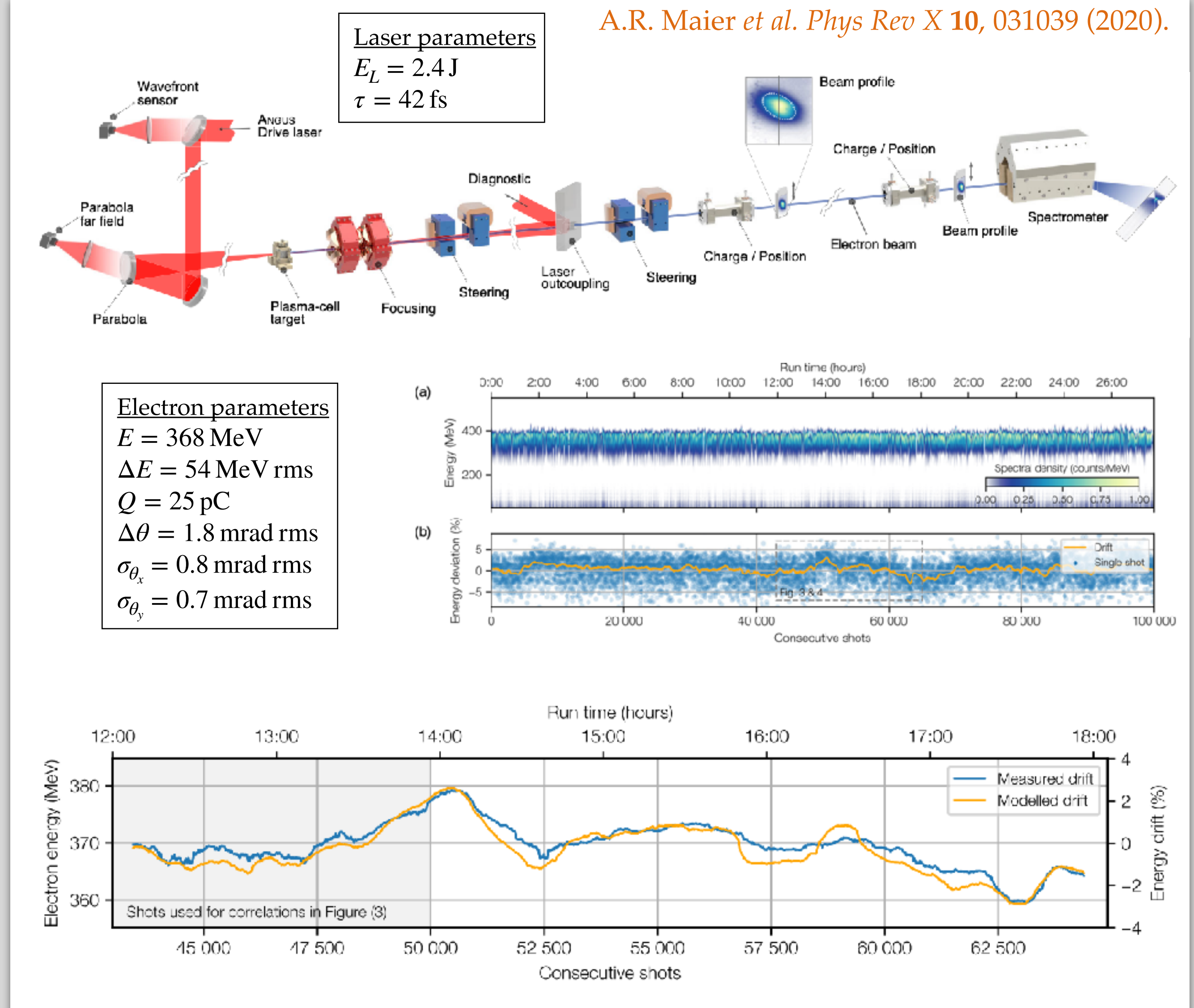
- 1 Hz rep. rate
- 24 hour operation demonstrated
- Laser spectrum, energy, beam profile monitored at each stage of beam line

► Large data set allowed correlations to be determined

- Correlations measured over 2 hours could predict electron energy for next 6 hours

$$\Delta E_e = \frac{\partial E_e}{\partial E_L} \Delta E_L + \frac{\partial E_e}{\partial z_{\text{focus}}} \Delta z_{\text{focus}} + \frac{\partial E_e}{\partial \theta_x} \Delta \theta_x + \frac{\partial E_e}{\partial \theta_y} \Delta \theta_y$$

A.R. Maier *et al. Phys Rev X* 10, 031039 (2020).



Increasing stability: Active energy stabilization

► Active energy stabilization

- Magnetic chicane imprints linear energy-time correlation

1% energy spread beams stretched by factor of ~ 1000

- Dechirper cavity: 5 m long S-band RF cavity

► Improved energy stability

- Energy spread: 1.8% $\rightarrow$ 0.097%
- Energy jitter: 3.5% $\rightarrow$ 0.048%
- Fractional charge within $\pm 1\%$ window: 18.1% $\rightarrow$ 99.9%

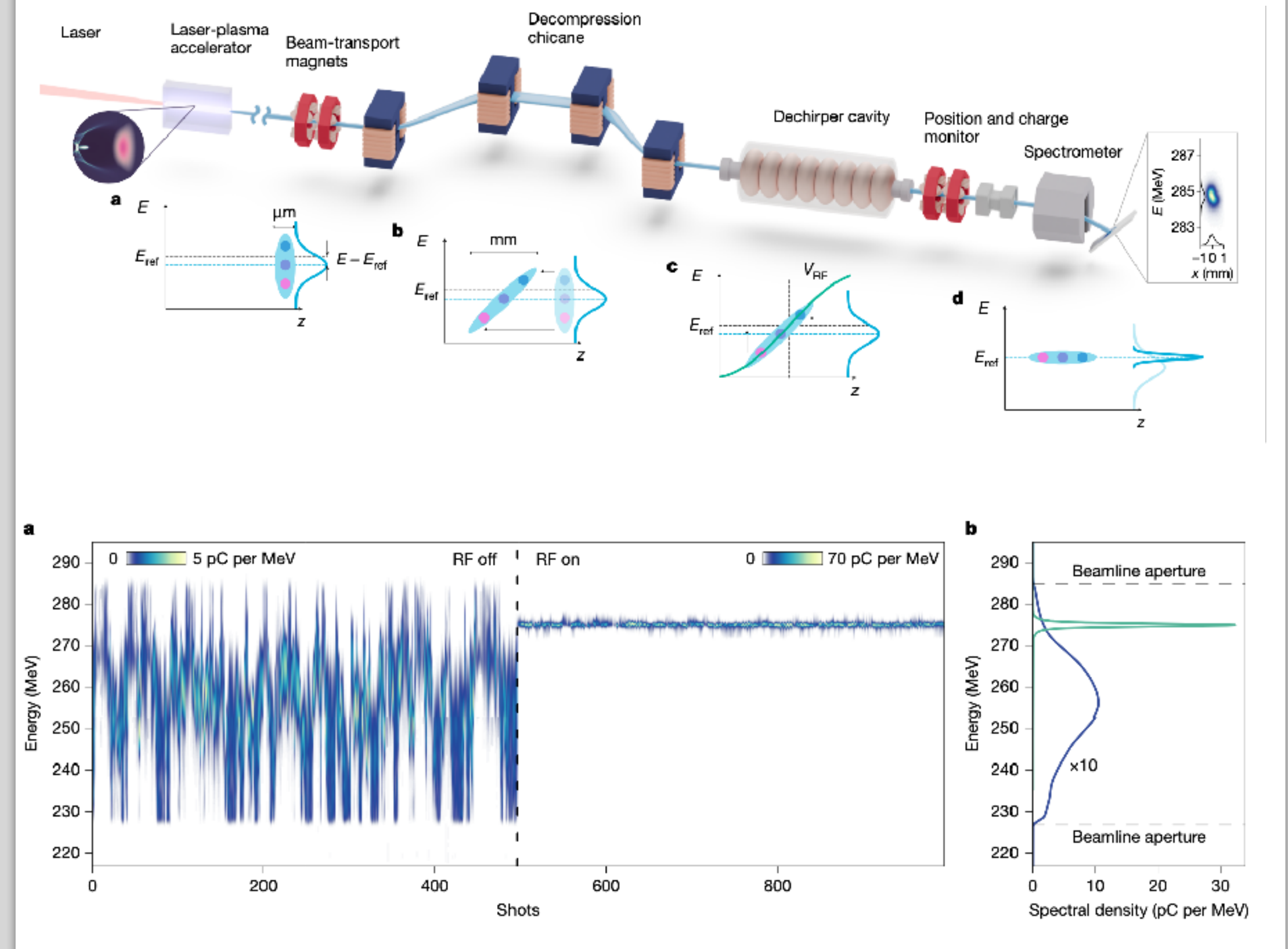
► Future:

- Extend to higher energy electron beams

Use X-band for de-chirper cavity to prevent increase in footprint

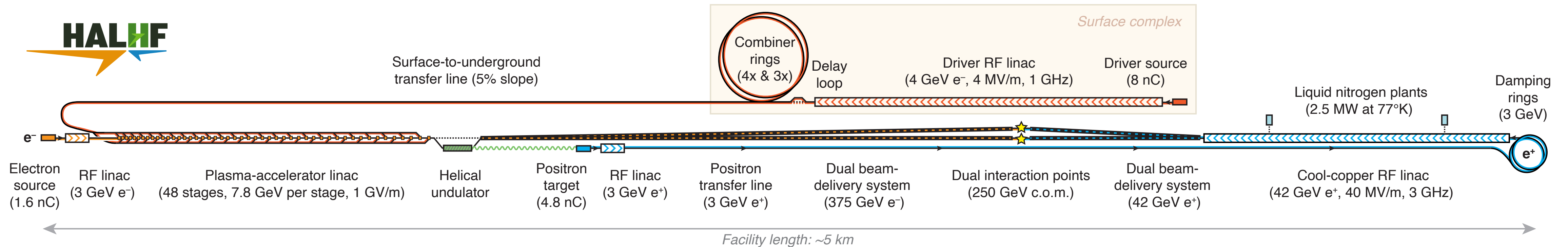
- Extend to plasma-based dechirper

P. Winkler *et al.* *Nature* 640, 907–910 (2025)



HALHF: A Hybrid, Asymmetric, Linear Higgs Factory

A smaller, cheaper, greener, and (possibly) quicker Higgs factory in Europe

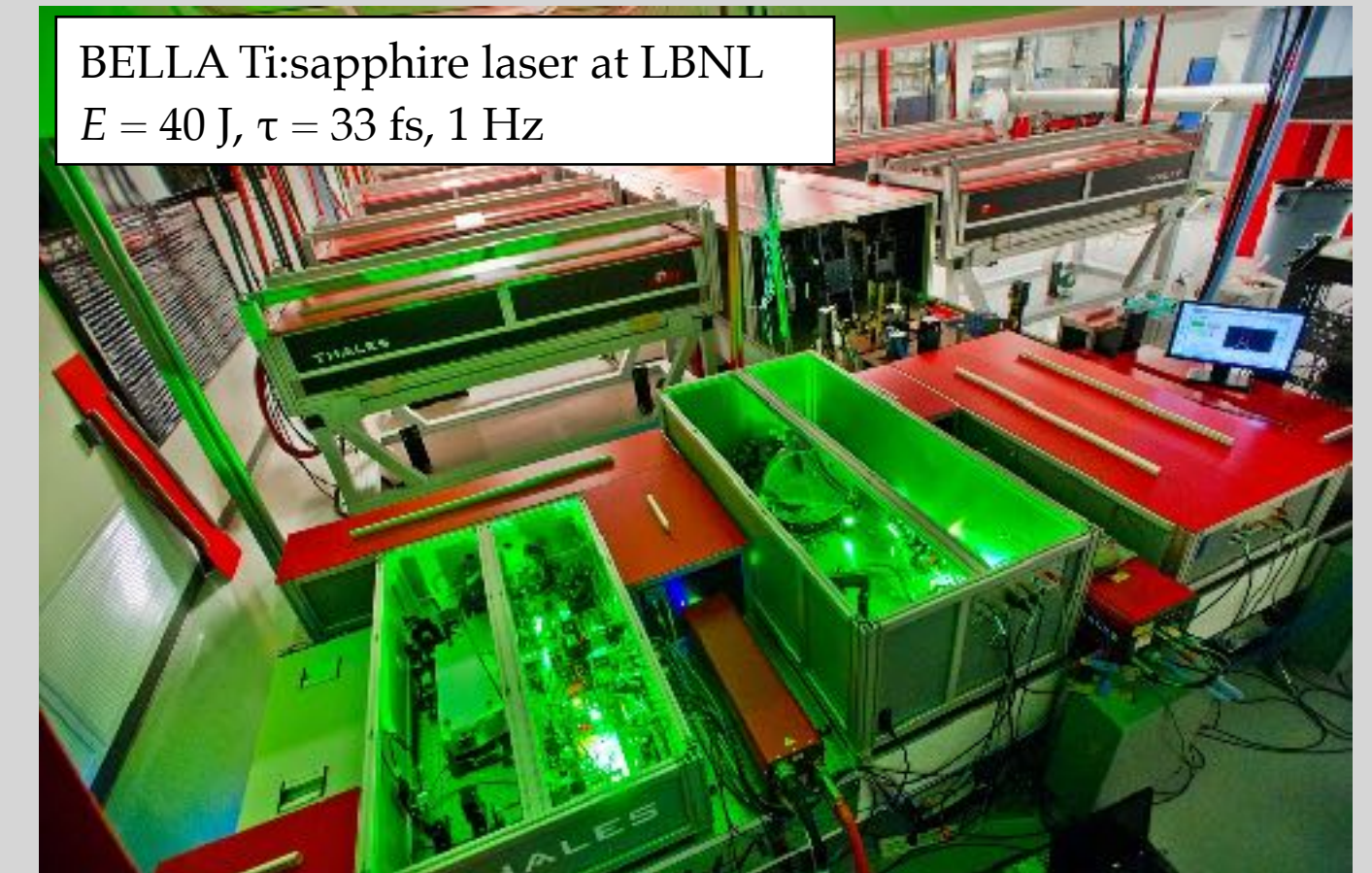


Source: [Foster et al., Phys. Open 23, 100261 \(2025\)](#)

- > Sidesteps the 'positron problem' in plasma (arising due to charge asymmetry of plasma)
- > Positrons accelerated in Cool-Copper RF (40 MV/m) and electrons in plasma (1 GV/m)
- > **Luminosity** (250 GeV com) — $1.2 \times 10^{24} \text{ cm}^{-2}\text{s}^{-1}$ (53% in top 1%) → similar to ILC (by design)
- > **Cost** (250 GeV com) — 3.8B CHF → ~50% of the cost of CLIC and ILC
- > Also performed for 380 and 550 GeV (presented in the ESPPU submission arXiv:2503.19880v2)
- > Much targeted (plasma & RF) R&D still required (staging, repetition rate, stability, polarisation, etc.)

Increasing repetition rate

- ▶ Driving laser of choice is Ti:sapphire (> 1 J, < 50 fs)
 - High-energy systems limited to low rep rate ($f_{\text{rep}} \lesssim 10$ Hz)
 - Low wall-plug efficiency
- ▶ But many applications require $f_{\text{rep}} \gtrsim 1$ kHz ...



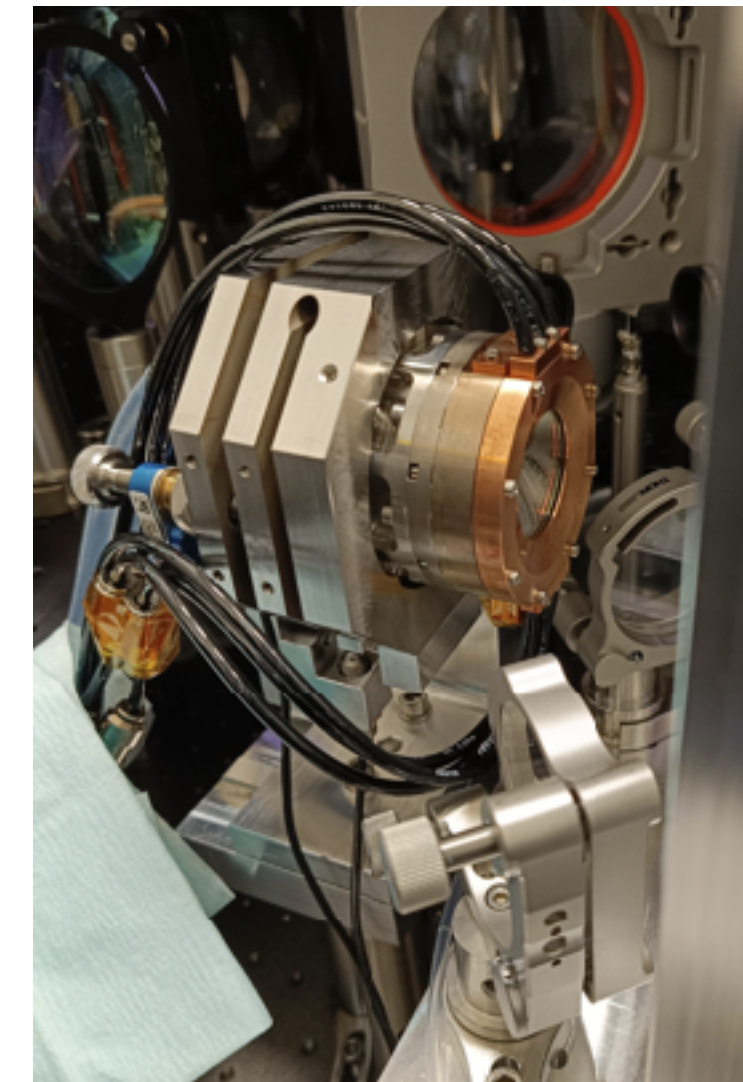
Increasing the repetition rate: Plasma-Modulated Plasma Accelerators

- ▶ Commercially-available Yb:YAG thin-disk lasers (TDLs) can generate ~ 1 J, ~ 1 ps, 1 kHz pulses:

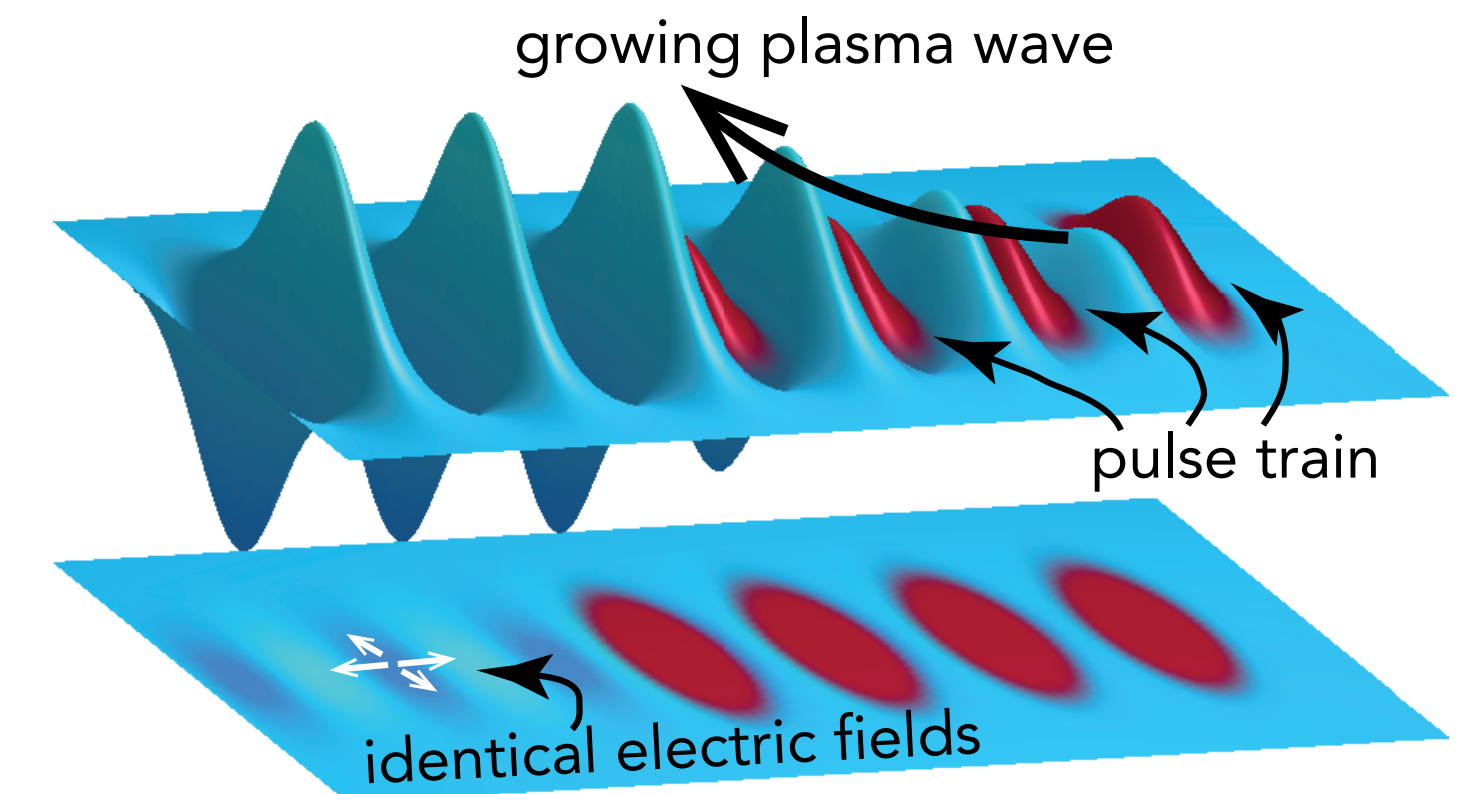
Y. Wang et al. Opt. Lett. 45 6615 (2020)

Herkommer et al. Opt. Exp. 28 30164 (2020): 0.72 J, 0.9 ps, 1 kHz

- ▶ Could we drive LWFAs with these lasers?
- ▶ TDL pulses too long to drive wake directly ...
 - ... but could resonantly excite wakefield if modulate pulse at plasma period
 - ... but no second freq. laser available ...



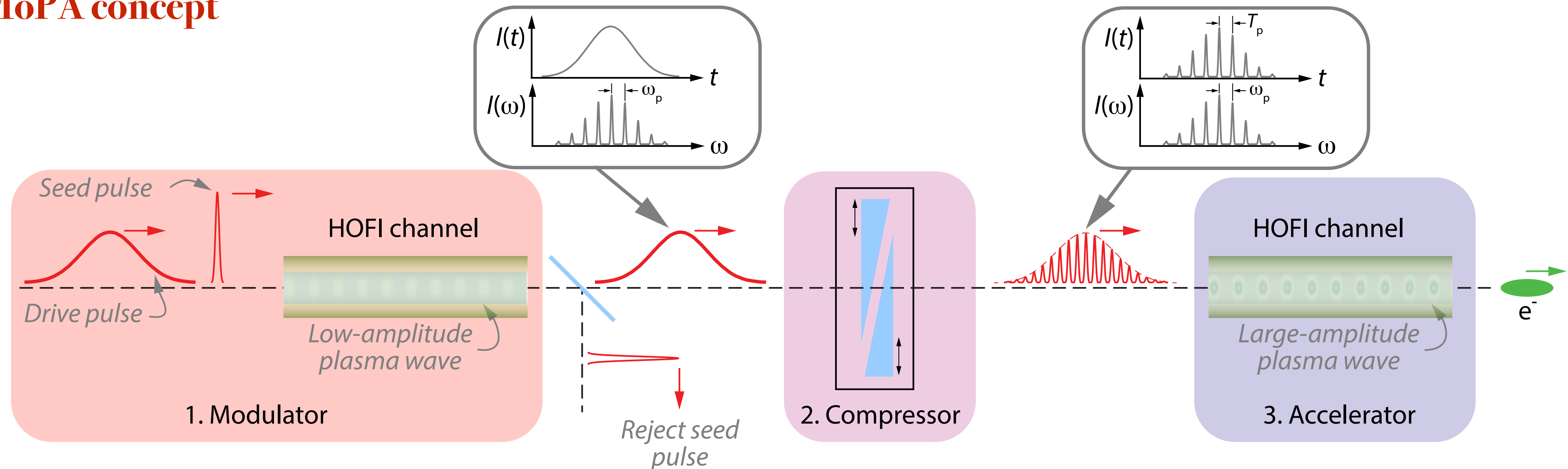
Yb:YAG TDL at CALA, Munich.
 $E = 10$ J, $\tau \sim 1$ ps, 10 Hz
 (currently), $\lambda = 1030$ nm



P-MoPA : Plasma-modulated plasma accelerator

The P-MoPA concept

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



Step 1: Modulator:

- Co-propagate long (1 ps), high-energy “drive” pulse with low-amplitude wake driven by short (< 100 fs), low-energy “seed” pulse
- Drive develops sidebands at $\omega = \omega_0 \pm m\omega_p$

Step 2: Compressor:

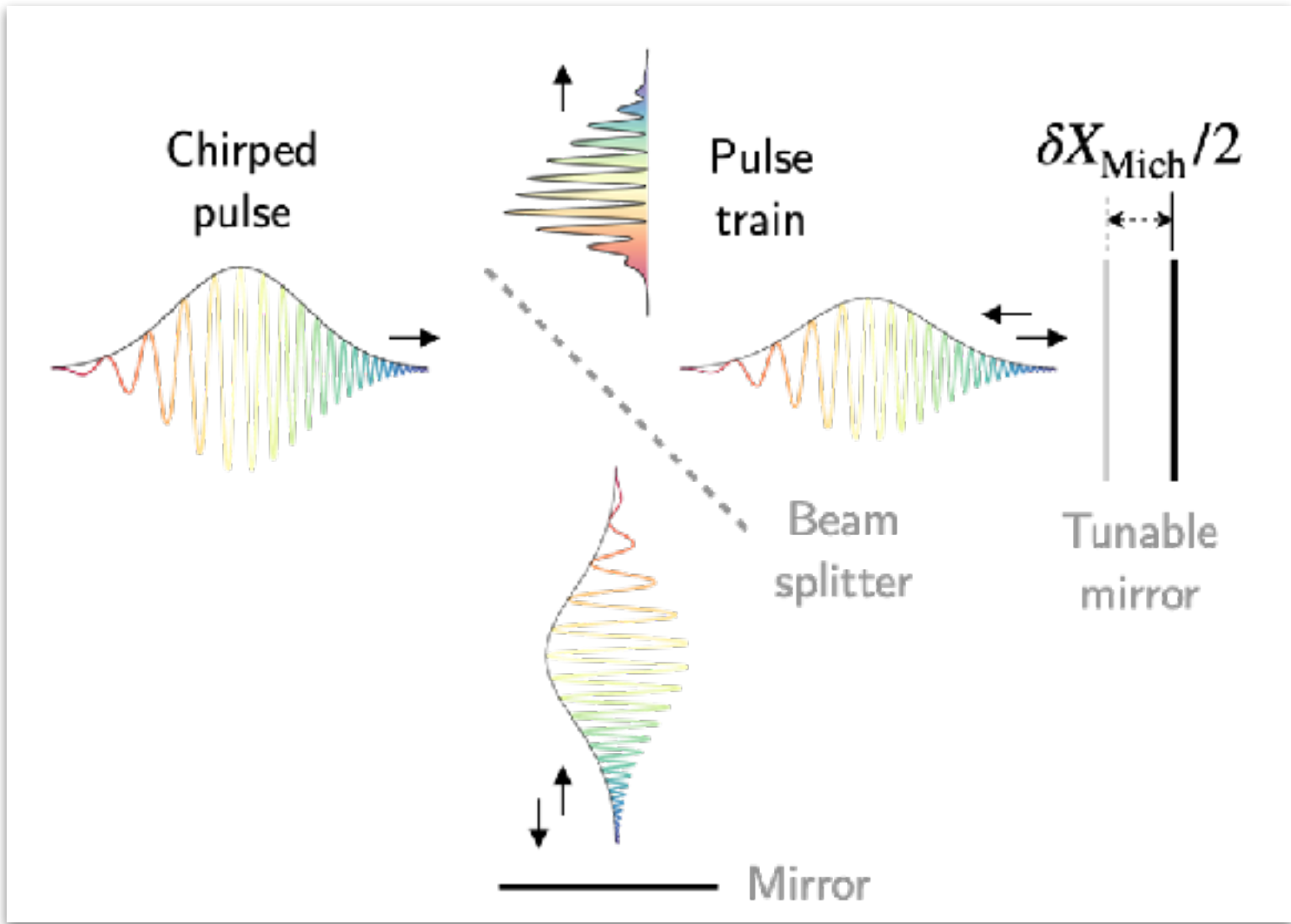
- Remove spectral phase of spectrally-modulated drive
- Forms a train of short pulses spaced by $\Delta t = 2\pi/\omega_p$

Step 3: Accelerator:

- Train resonantly excites a large-amplitude wakefield

Demonstration of Step 3

Ross *et al.* *Phys. Rev. Res.* **6** L022001 (2024)



Pulse train

$$E = (2.5 \pm 0.5) \text{ J}$$

$$w_0 = (45.5 \pm 3.4) \mu\text{m}$$

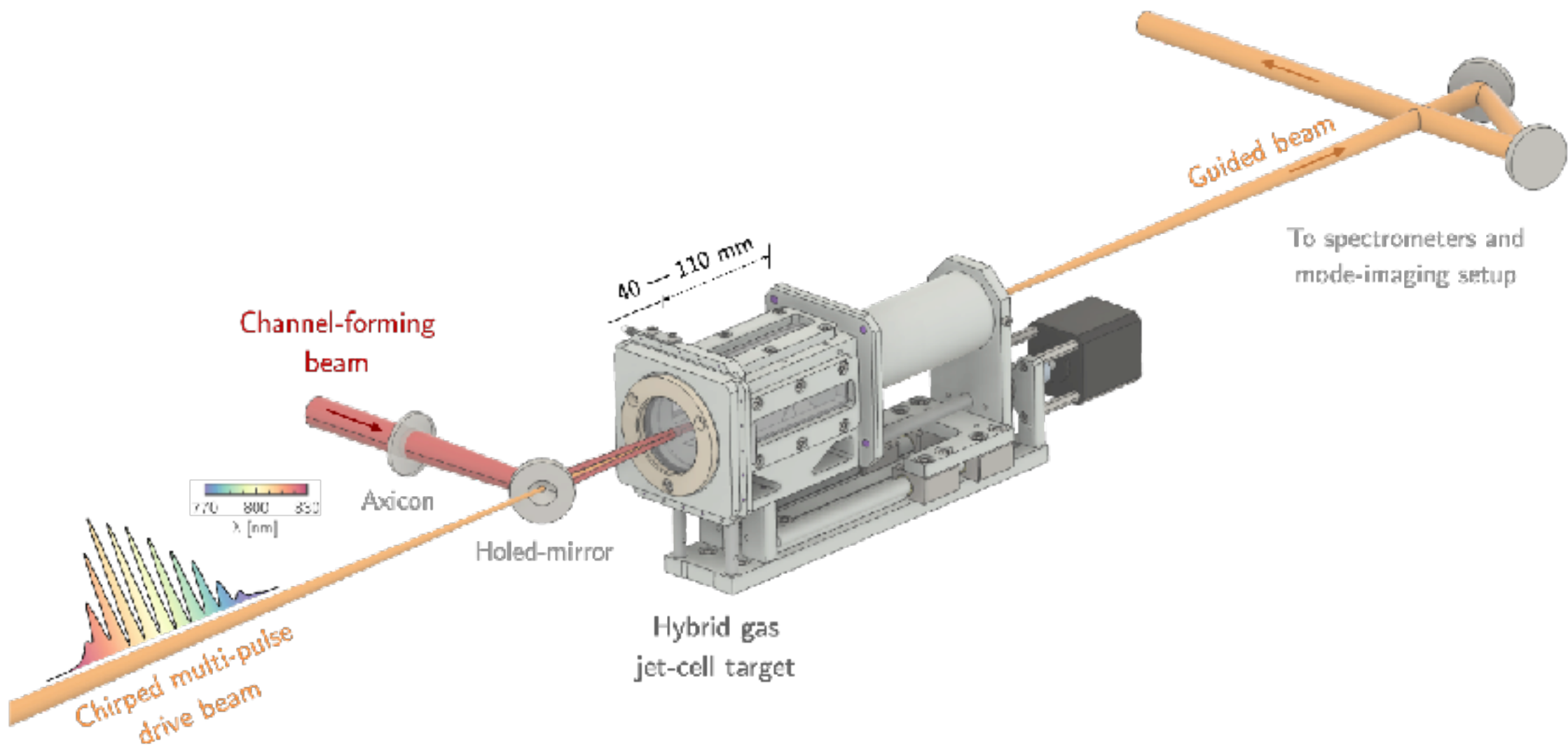
$$z_R = (7.9 \pm 0.7) \text{ mm}$$

Channel-forming beam

$$\tau = 80 \text{ fs}$$

$$E \sim 100 \text{ mJ}$$

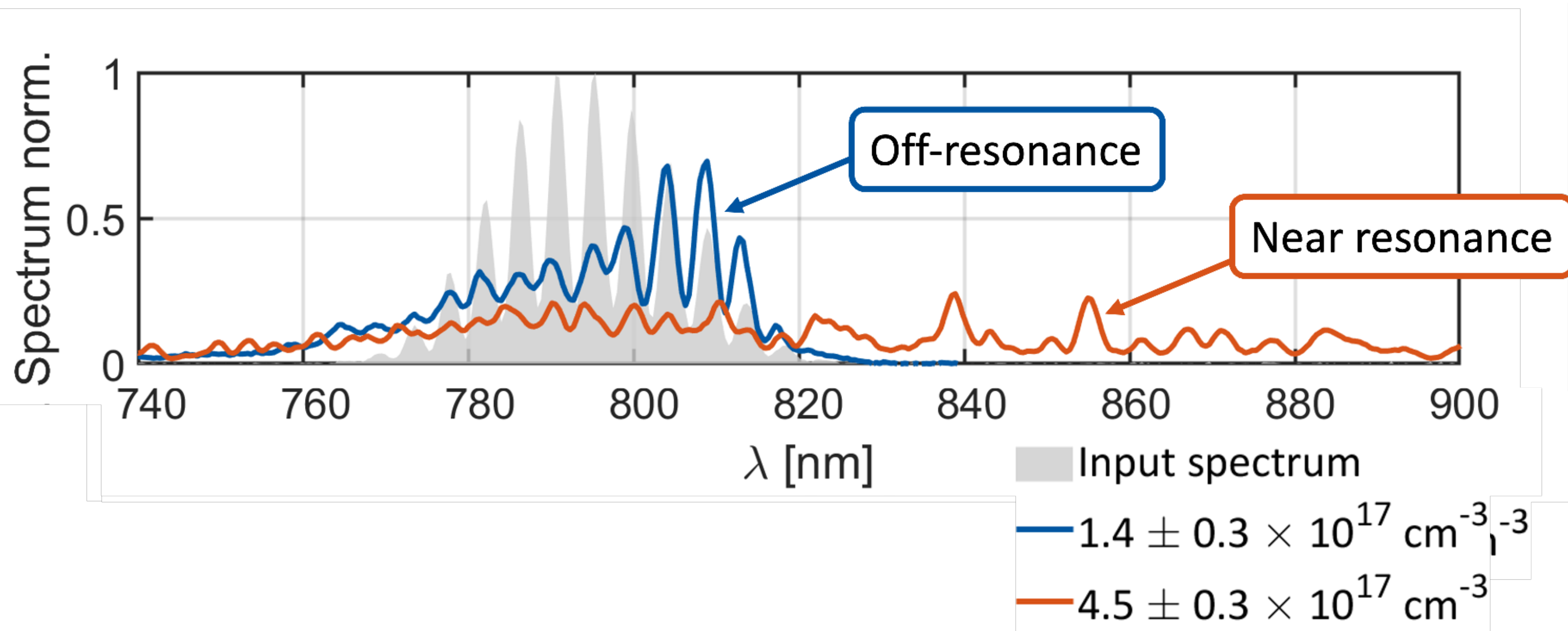
$$\theta_{\text{axicon base}} = 3.6^\circ$$



Astra-Gemini Laser, RAL

Pulse train spectra demonstrate resonant excitation

Ross et al. *Phys. Rev. Res.* 6 L022001 (2024)

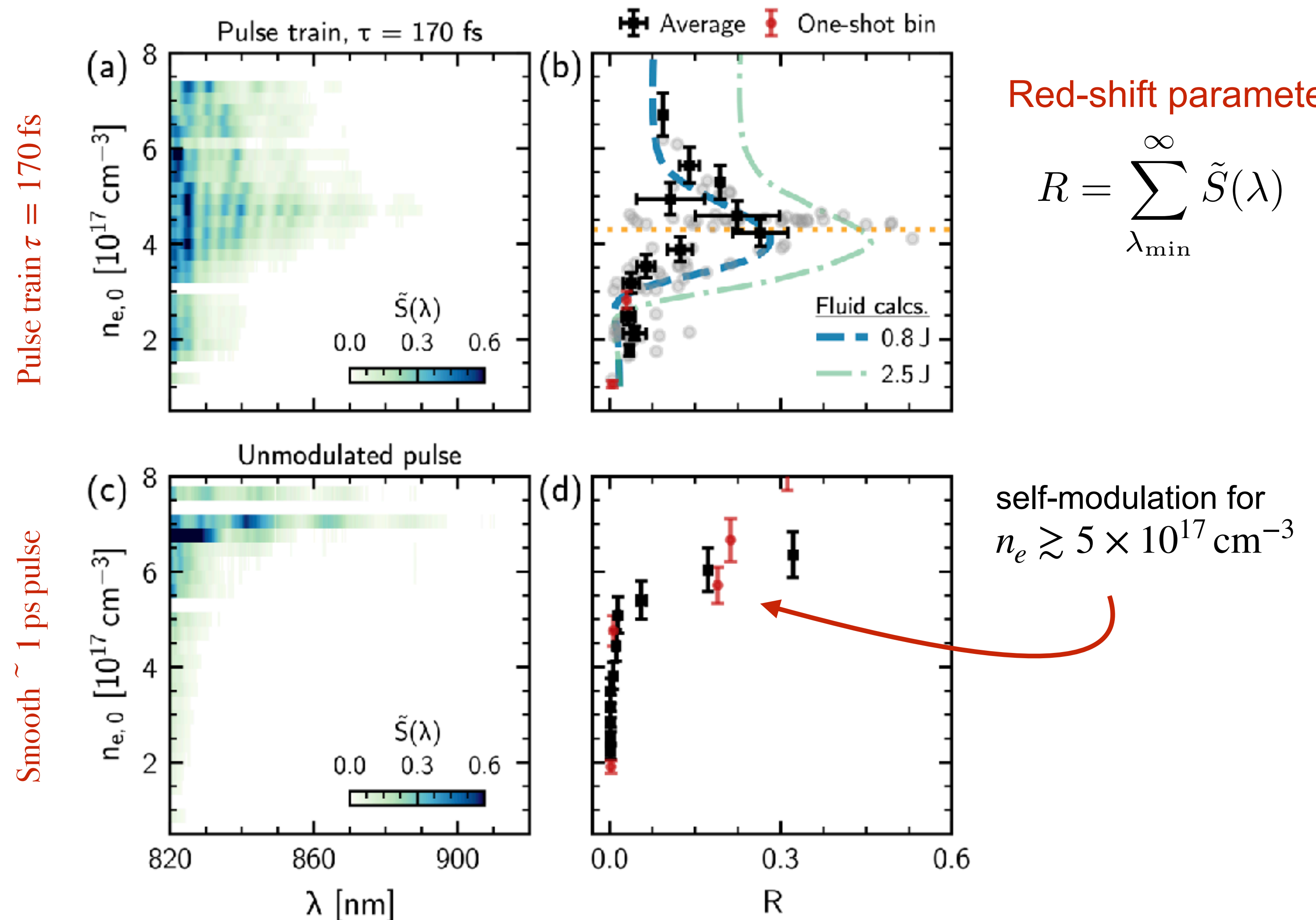


Clear resonance observed for pulse trains, but not for smooth pulses

► Comparison with simulations

- 2D cylindrical fluid benchmarked against PIC
- Largest shifts agree well with calcn for perfect coupling
- Average shifts consistent with ~ 0.8 J coupled into channel
- Accel. gradient 3 - 10 GeV / m, i.e. **(0.3 - 1) GeV over the stage**

Ross *et al.* *Phys. Rev. Res.* **6** L022001 (2024)



P-MoPAs : Summary of progress

Technologies

Drive laser

- ✓ Industrial-class
- ✓ Multi-joule
- ✓ Multi kilohertz
- ✓ Optical efficiency ~ 40%

Seed laser

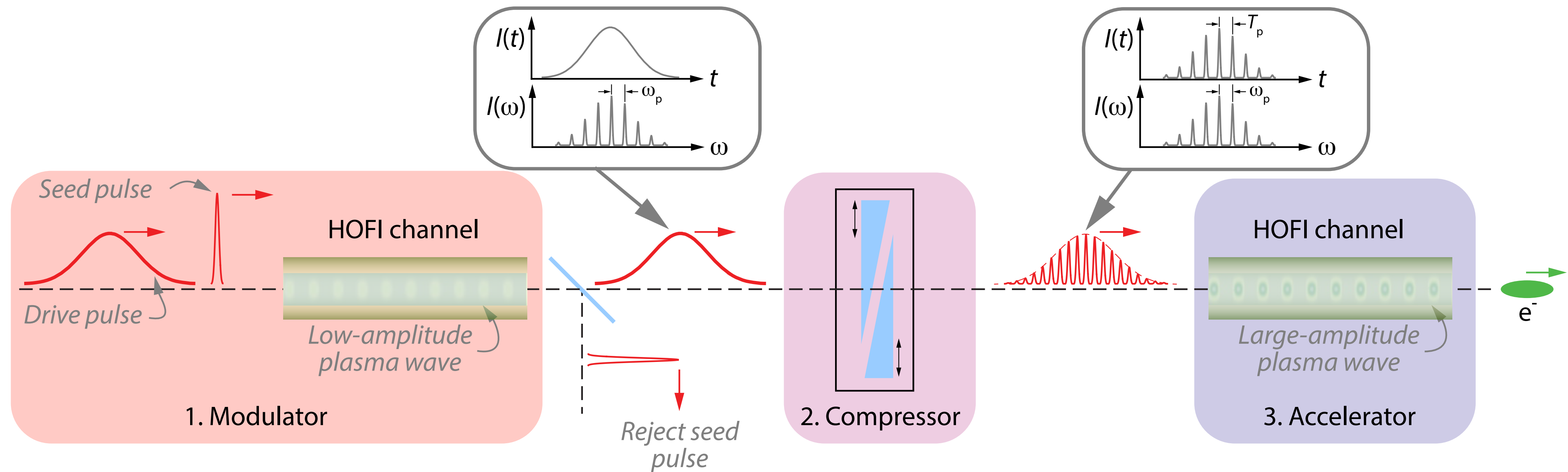
- ✓ Industrial-class
- ✓ ~ 100 mJ
- ✓ Multi kilohertz

HOFI plasma channel

- ✓ Low loss
- ✓ > 100 mm guiding
- ✓ kHz rep. rate

Key

- ✓ Concept demonstrated
- To be demonstrated



Step 1: Plasma modulator

- ✓ Drive & seed pulses guided in HOFI channel
- Spectrum of drive pulse modulated by wake driven by seed pulse

Step 2: Train generation

- Spectrally-modulated drive pulse converted to pulse train by dispersive system

Step 3: Accelerator

- ✓ Resonant wake excitation by pulse train guided in HOFI channel
- Acceleration of injected electrons to multi-GeV energies @ kHz rep. rate

Summary

- ▶ Laser-plasma accelerators can produce acceleration gradients $1000 \times$ that of RF accelerators
- ▶ GeV-scale beams “routine” & first applications are starting to emerge:
 - Compact sources of bright, ultrafast, incoherent X- & gamma-radiation
 - Generation of FEL gain (at long wavelengths)
 - Concepts for injectors to conventional accelerators
- ▶ Further advances still required for the most demanding applications:
 - Reduced shot-to-shot jitter of bunch parameters
 - Long-term reliability
 - Increased bunch quality (energy spread, emittance, ...)
 - Increased pulse repetition rates

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