Plasma Photocathode

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Outline

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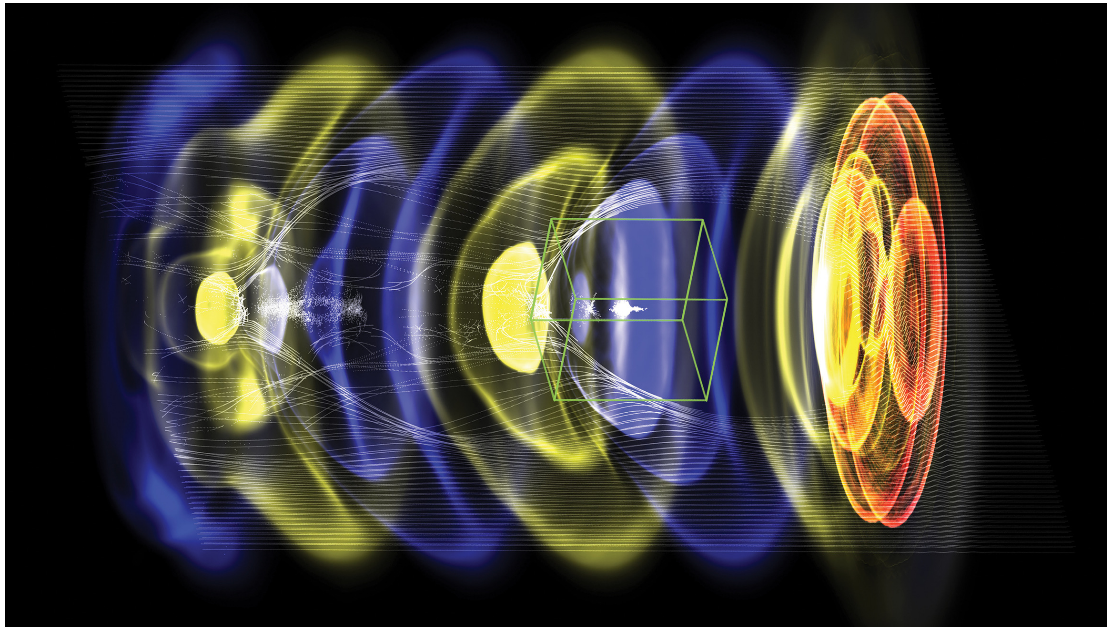
- Plasma-based accelerators (PBAs):
  - Multi-GeV electron beams
  - Femtosecond bunch lengths
  - Sub-micron emittance
  - High-charge bunches

    → PBAs enable high brightness e-beams
- Beam quality depends on injection methods:
  - Self-trapping
  - Plasma density gradient injection
  - Ionization injection



Intense laser (red) drives a density wave (blue to yellow) in plasma, electrons (white) are trapped and accelerated with fields of order 10 GV/m.

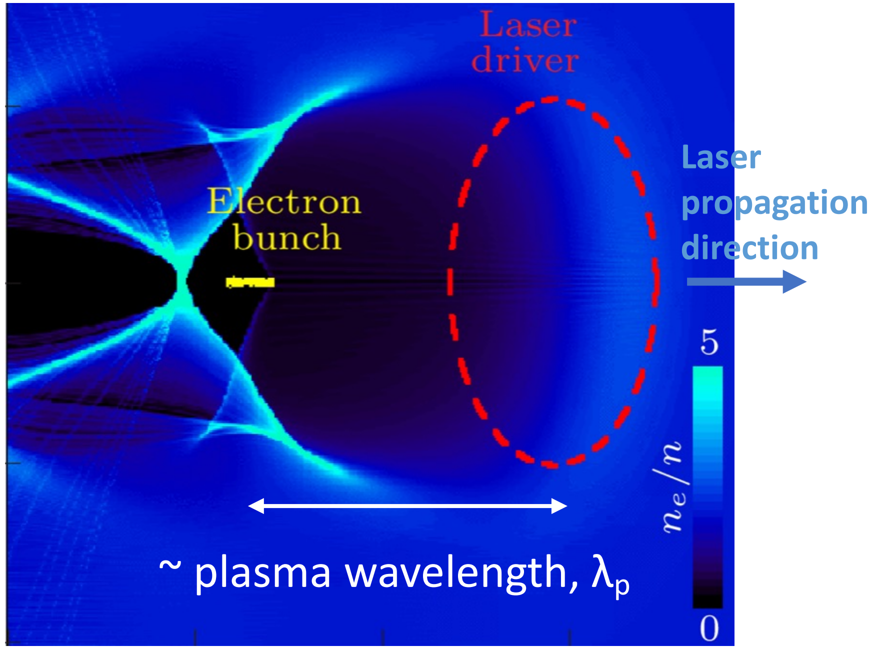
- Path to higher brightness electron beams with the "Plasma photocathode" (relevant for colliders or radiation sources, e.g. x-ray FEL)

Plasma-based acceleration of electron bunches

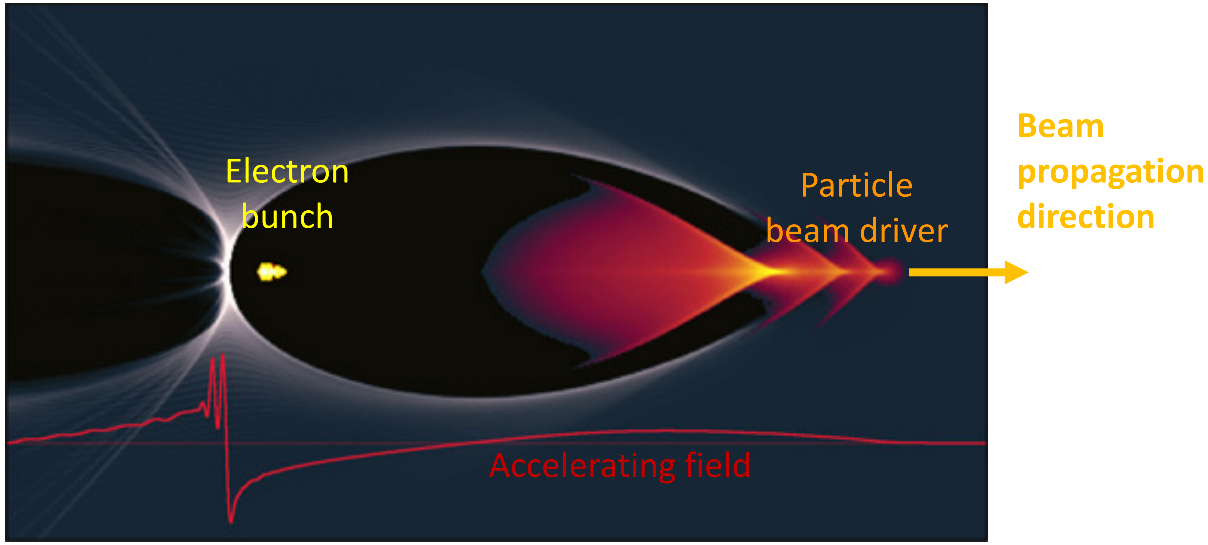
- Plasma wave (wakefield) driven by ponderomotive force of **intense** laser [or space-charge field of particle beam]
- Electron displaced by driver (ions remain stationary) → EM fields from charge separation → plasma oscillations
- Focusing and acceleration provided by plasma wave
- Characteristic size of the plasma wave: λ_p =100 – 10 μm for plasma density 10^{16}–10^{19} cm^{-3}
- Characteristic strength of the wakefields: 10 –100 GV/m for plasma density 10^{16}–10^{19} cm^{-3}

$$E \sim E_0 = m_e c \omega_p / e \simeq 96\sqrt{n_0[\mathrm{cm}^{-3}]}$$

Laser-driven plasma wakefield accelerator (LWFA):



Beam-driven plasma wakefield accelerator (PWFA):



Laser-driven plasma accelerator state-of-the-art: multi-GeV accelerator (~8 GeV in 20 cm)

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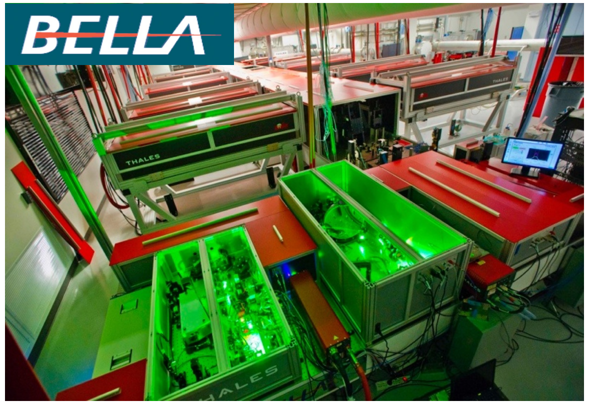
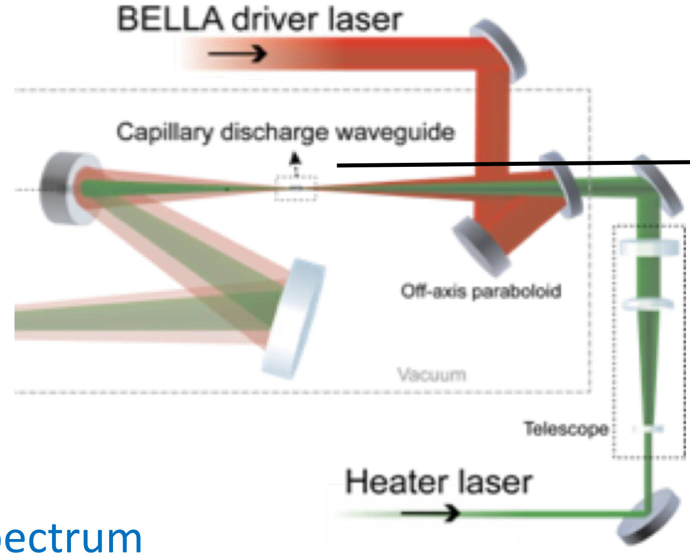


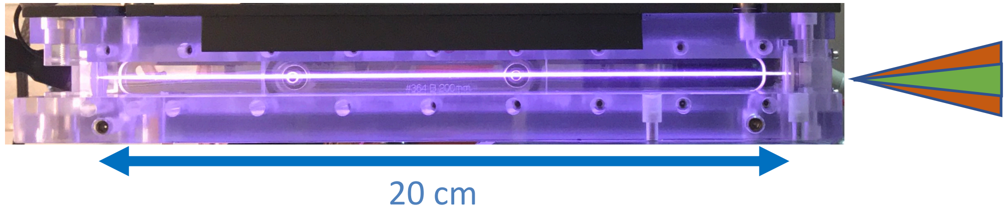
PW (40 J, 30 fs, 1Hz)

Single-stage acceleration: 8 GeV in 20 cm (40 GV/m)

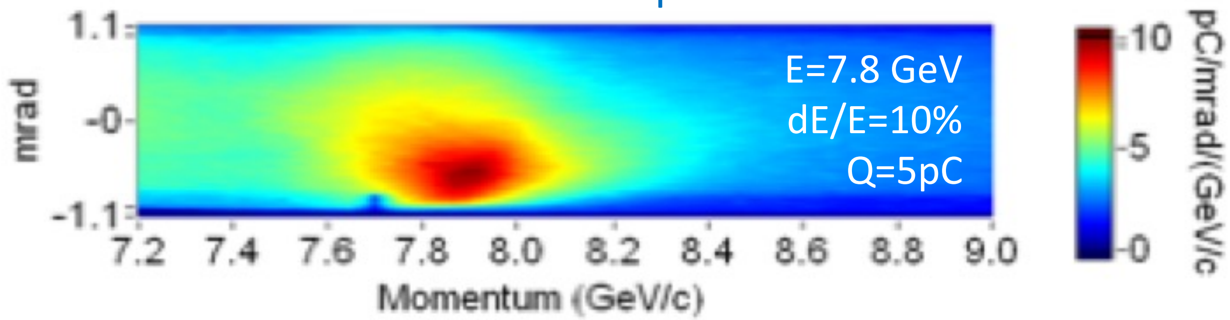
Gonsalves et al. PRL (2019)

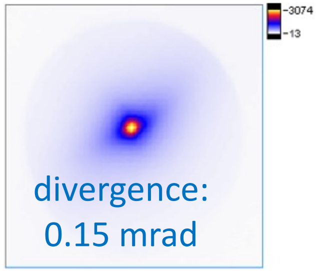


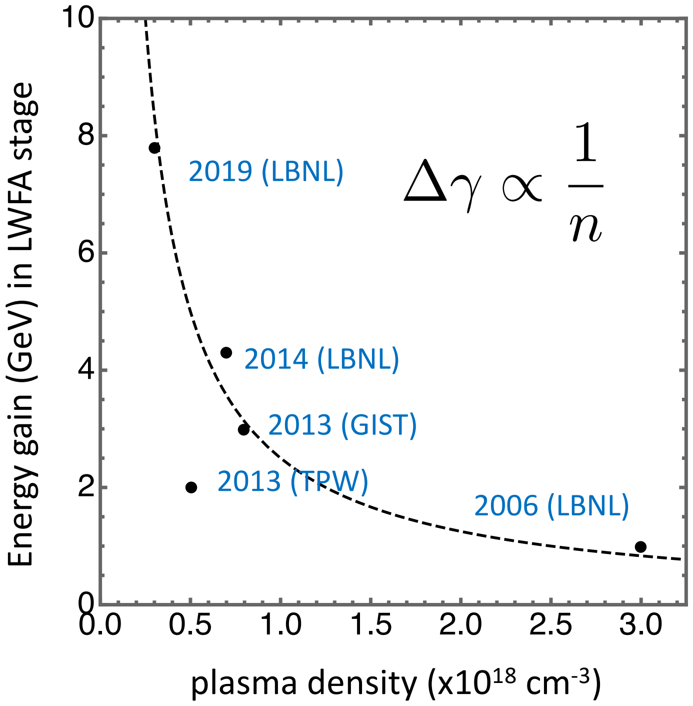
Laser-heater-assisted discharge-capillary plasma waveguide



Electron beam spectrum







- *Key technology*: plasma channel creation for guiding at low density (3×10^{17} cm^{-3})
  – discharge capillary + laser heater
- *New technologies emerging*: hydrodynamic optical-field-ionized plasma channels

Plasma-based accelerators enable high-brightness beams

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- Plasma accelerators have the potential to yield high-brightness beams:
  - Rapid acceleration (>10 GV/m) + shielding from background ions reduce detrimental space-charge effects
  - Ultra-short bunches: $\boldsymbol{\sigma}_z << \boldsymbol{\lambda}_p$ (e.g., $\boldsymbol{\lambda}_p$ ~ 10 μm for 10^{19} cm^{-3}) → 1-10 fs (exp. measured) Buck et al., Nature Phys (2011) Lundh et al., Nature Phys (2011)
  - Low normalized emittances → 0.1 – 1 μm (exp. measured) Weingartner et al., Phys Rev ST AB (2012) Plateau et al., PRL (2012)
  - High charge in a monochromatic peak (< a few %) → 10 -100 pC (exp. measured) Kirchen et al., PRL (2021) Götzfried et al., PRX (2020) Wang et al., PRL (2016)

- Typical brightness:

$$B_{5\mathrm{D}} = \frac{2I}{\epsilon_n^2}$$

~ (10-100 pC)/(1-10 fs) ~ 10 kA

~ 10^{18} A/(m-rad)^2

~ 0.1 - 1 um

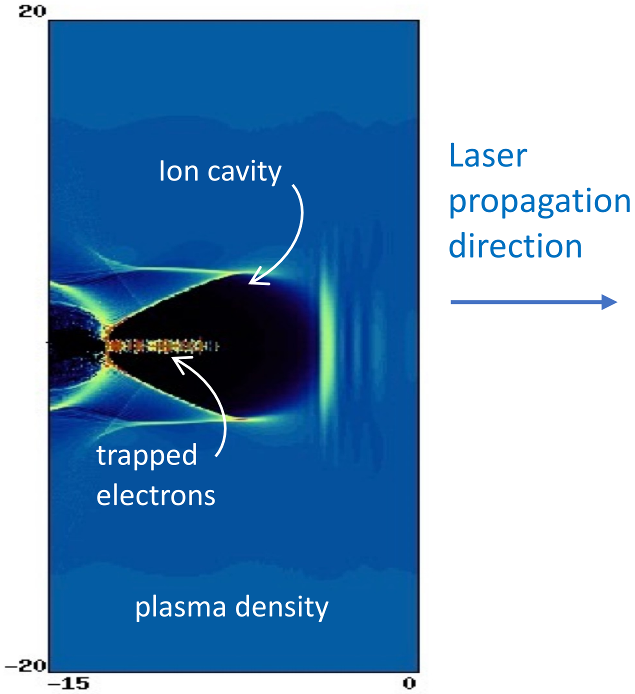
→ Higher quality beam generation (10s nm emittance) possible but requires "controlled / triggered" injection into plasma wave

Injection methods determine electron beam properties and quality

Injection (from background plasma) methods:

- Self-injection
- Triggered injection:
  - Plasma density gradient injection
  - Laser triggered injection
    - Colliding pulse injection
  - Laser ionization injection
    - Single laser pulse
    - Driver + laser injector ("plasma photocathode")

Self-injection



- Requires large amplitude wakefield → high laser intensity

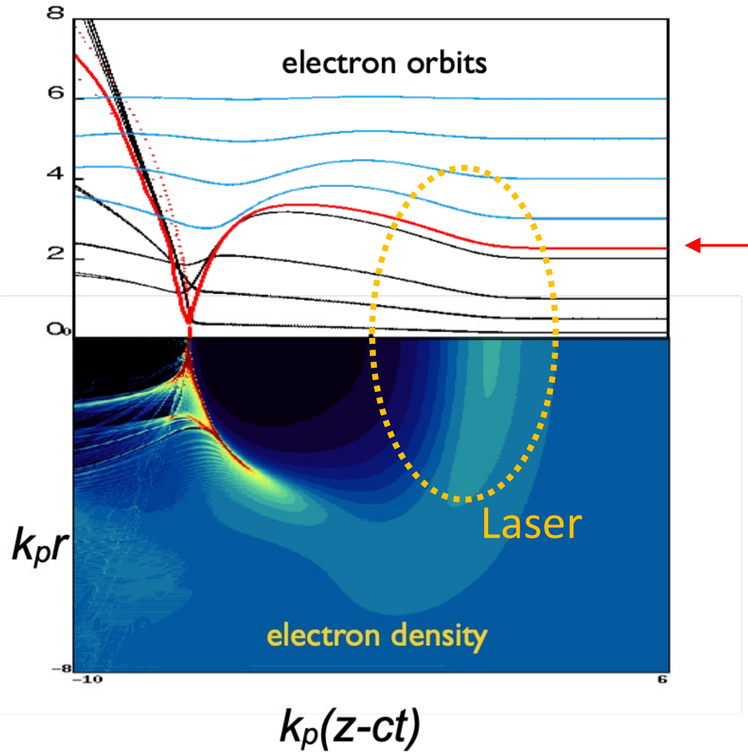
Laser strength: $$a_0 = 0.85\lambda[\mu\mathrm{m}]\left(I[10^{18}\mathrm{W/cm}^2]\right)^{1/2}$$

- Requires slow plasma wave velocity → high plasma density

Wake velocity: $$\gamma_p \sim \frac{\omega_L}{\omega_p} \propto n^{-1/2}$$

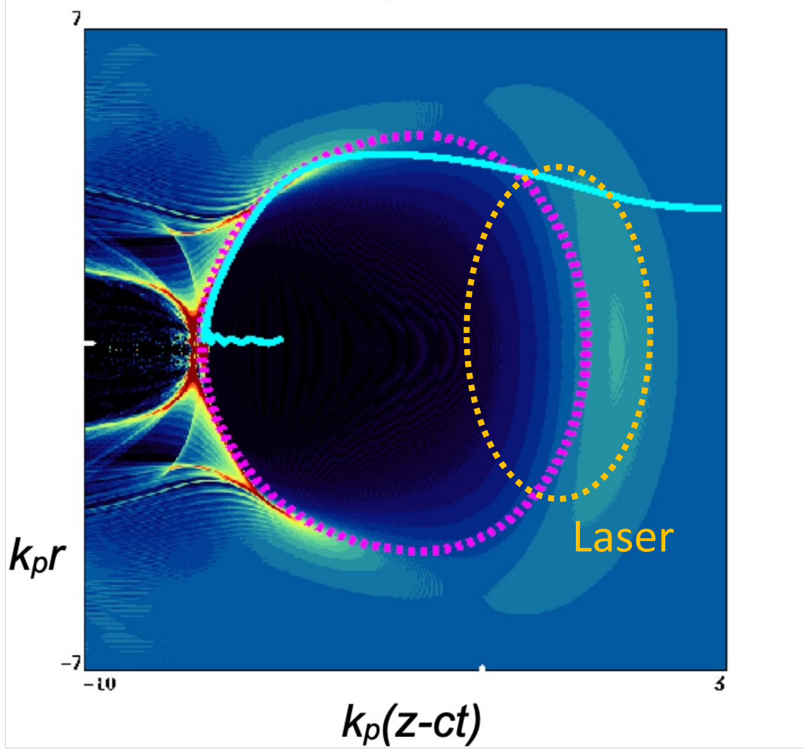
Electron orbits in a laser-produced wakefield

no self-trapping:
a_0=3.5
ω/ω_p=20



electrons orbits along bubble "border" can reach back of bubble and be trapped

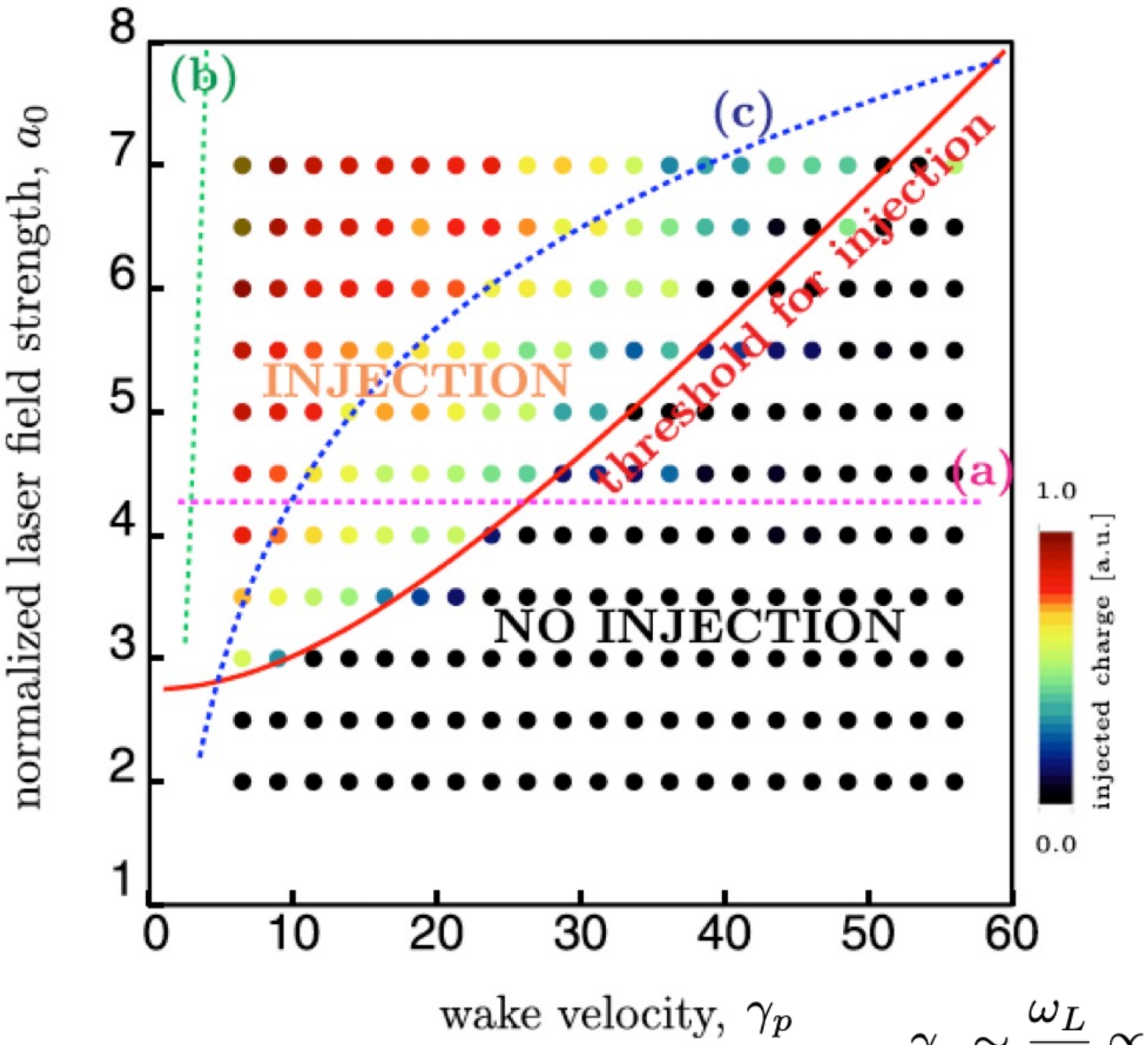
self-trapping:
a_0=4
ω/ω_p=20



- Trapping determined by the strength of the accelerating wakefield (laser strength) + wake velocity (plasma density)

Self-injection trapping threshold

Benedetti et al., Phys Plasmas (2013)



$$\gamma_p \sim \frac{\omega_L}{\omega_p} \propto n^{-1/2}$$

- Trapping threshold a function of amplitude of the accelerating wake field (laser strength) and wake phase velocity (plasma density)
- Sub-micron emittance observed from self-trapping

Density gradient injection (downramp injection)

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- Reduce phase velocity by exciting plasma wave on a density gradient

S. V. Bulanov, PRE (1998)
C. G. R. Geddes, PRL (2008)
X. L. Xu, PRAB (2017)

Plasma wave:

$$E \sim \cos[k_p(z)(z - \beta_g t)] = \cos\psi$$

Phase velocity:

$$\beta_p = \frac{\omega}{k} = \frac{-\partial_t \psi}{\partial_z \psi}$$

$$\beta_p \simeq \beta_g \left[1 - |\zeta| k_p^{-1} dk_p/dz\right]^{-1}$$

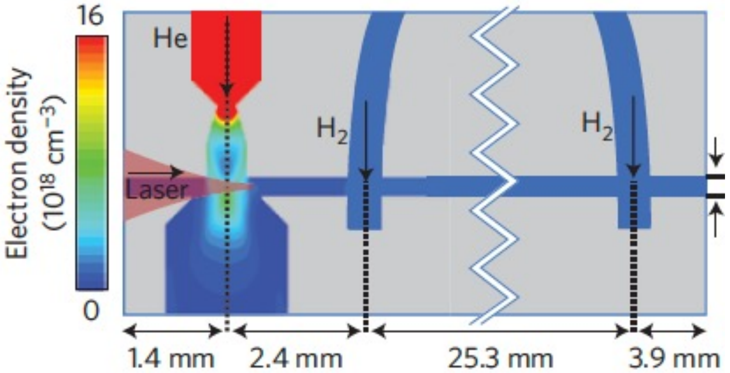
Laser velocity

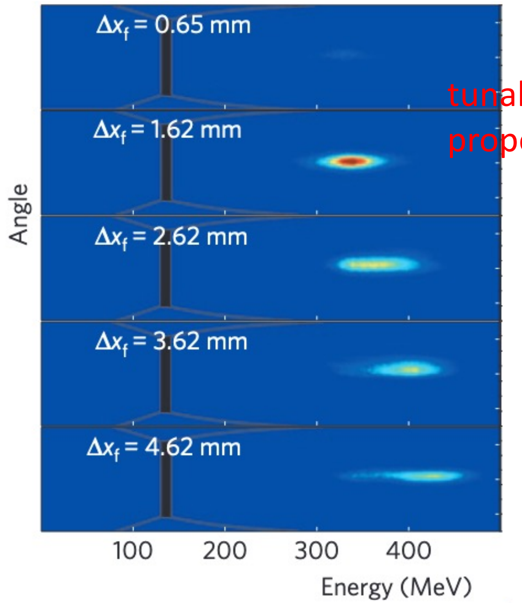
Control phase velocity using density variation and laser evolution:

$$\frac{1}{k_p}\frac{dk_p}{dz} = \frac{1}{2n}\frac{dn}{dz} - \frac{1}{\lambda}\frac{d\lambda}{da}\frac{da}{dz}$$

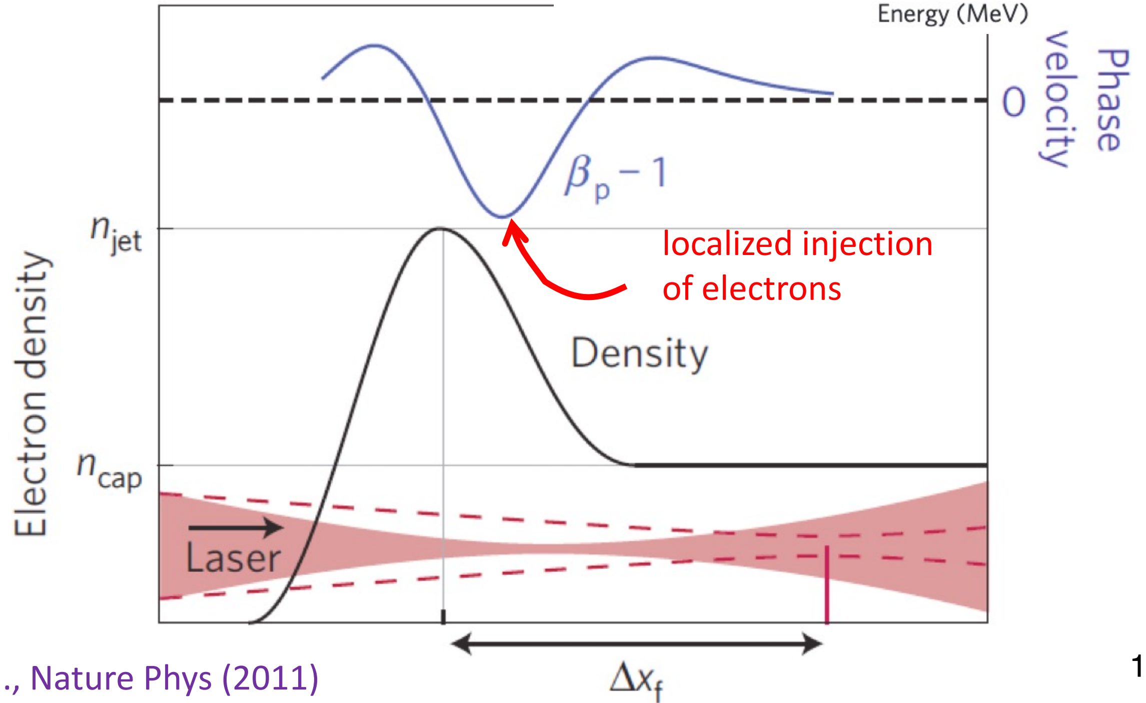
Density gradient

Laser evolution





tunable bunch properties

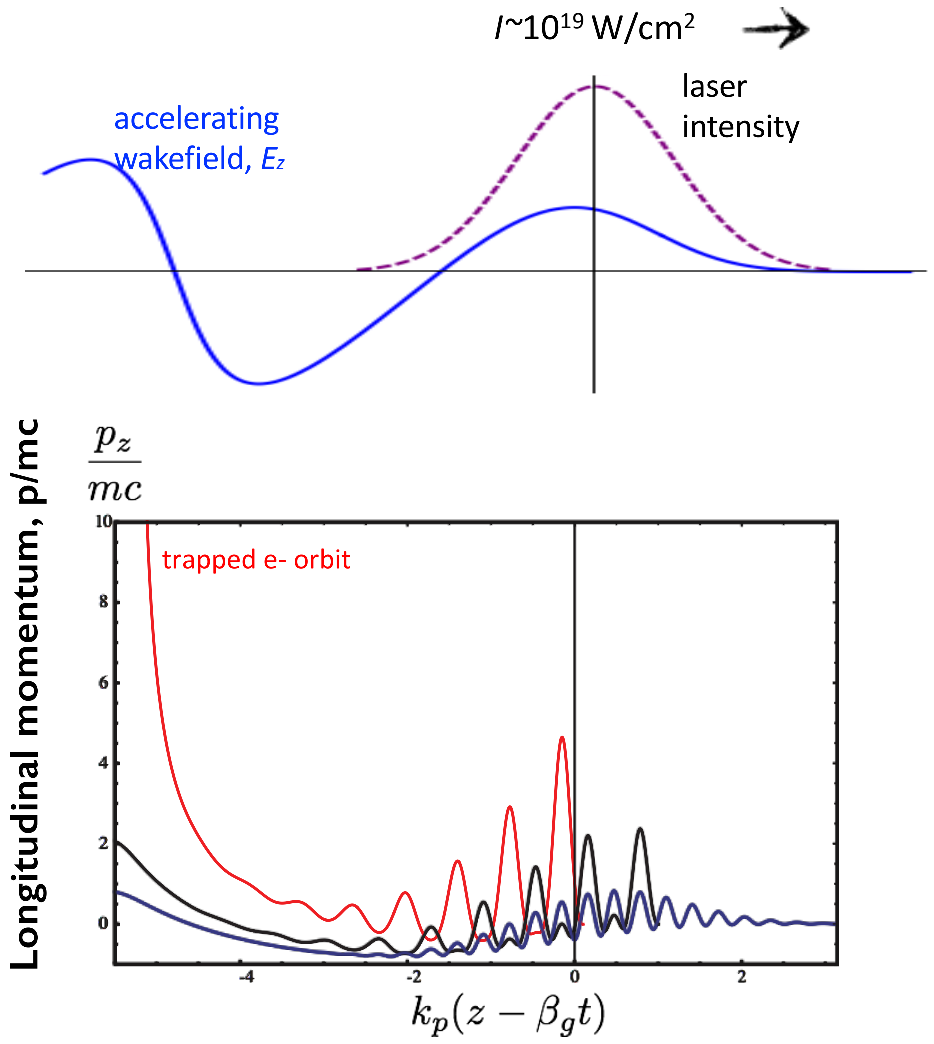


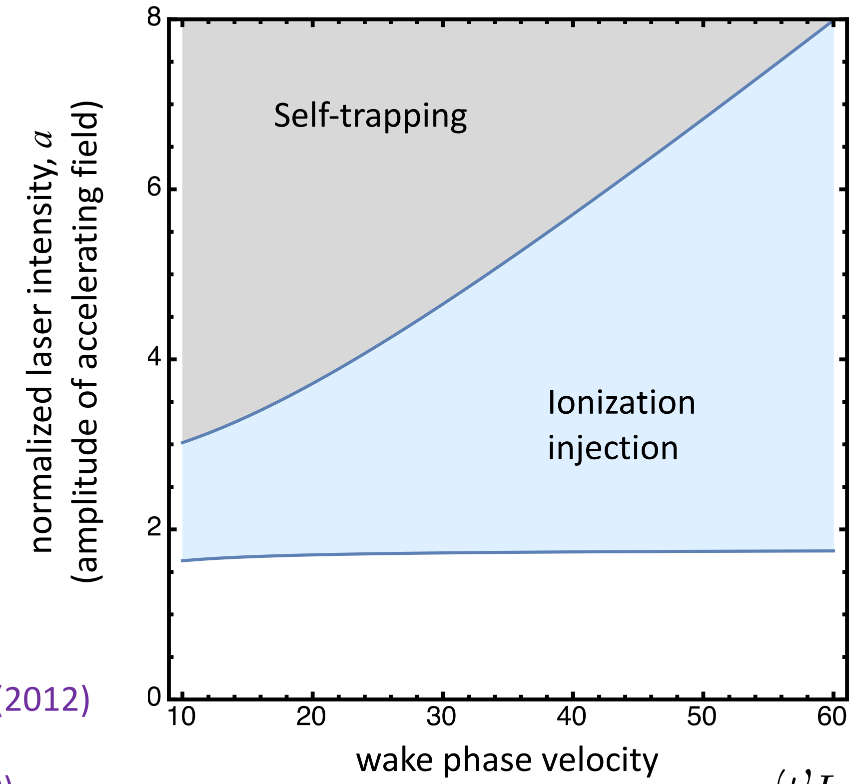
localized injection of electrons

Gonsalves et al., Nature Phys (2011)

Ionization injection

Ionization injection: ionize bound electron (at rest) in trapped orbit of plasma wave using high-Z gas (e.g., Hydrogen doped with Nitrogen)





$$\gamma_p \sim \frac{\omega_L}{\omega_p} \propto n^{-1/2}$$

Chen et al., Phys. Plasmas (2012)
Pak et al., PRL(2010)
McGuffey et al., PRL (2010)

- Weak dependence on density (wake velocity)
- Amplitude for trapping reduced: a>1.7
  - → enables trapping at lower laser intensity and lower plasma densities
- Large energy gains achieved operating at low density

Emittance dependence on injection method

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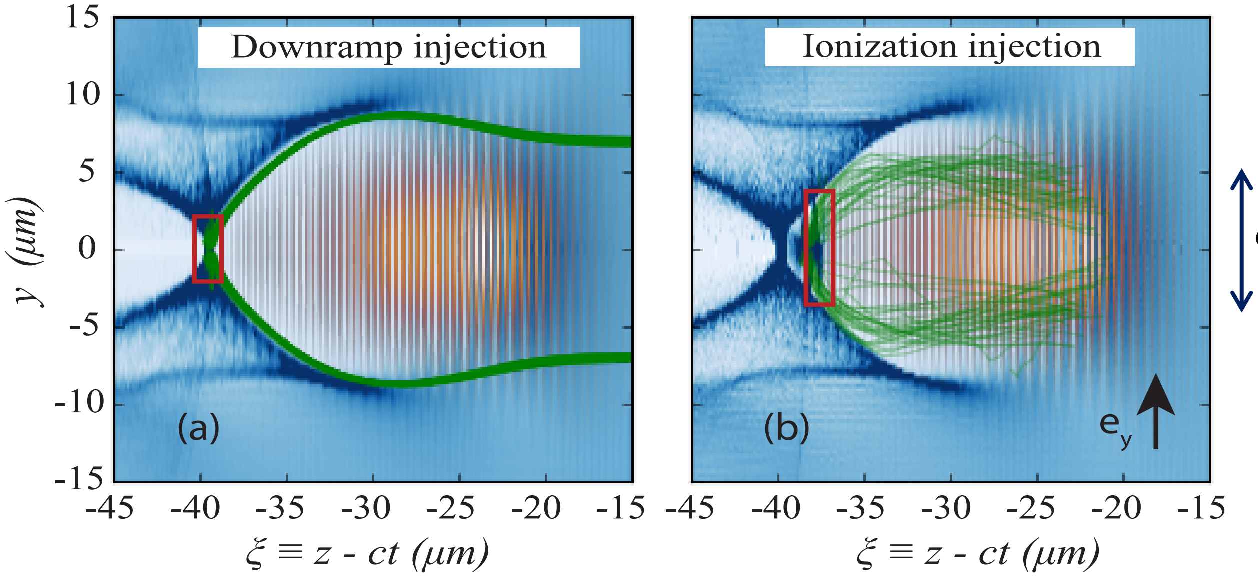
- Characteristics of trapped e-beam determined by initial distribution of injected electrons (injection method)



- transverse size ~ laser waist

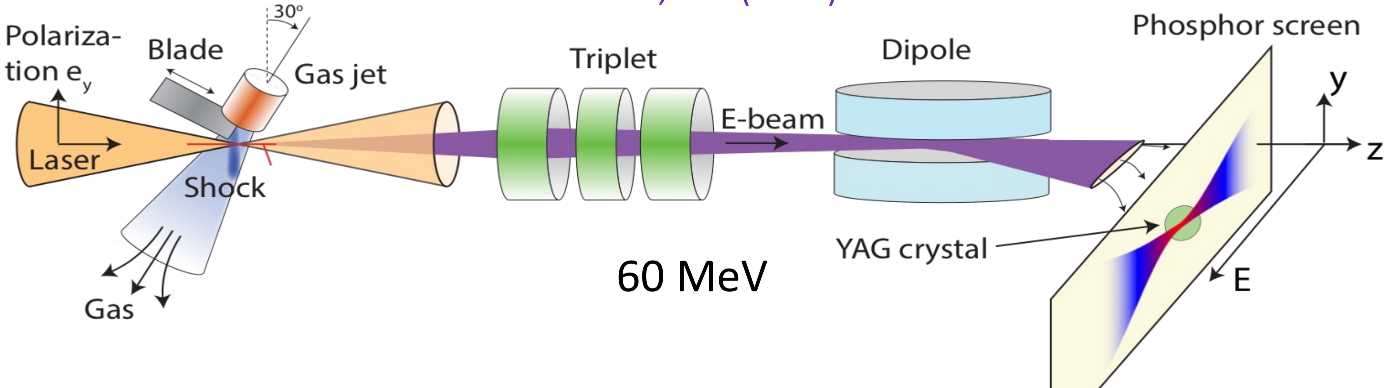
$$\sigma_x \propto w_0 \sim 2k_p^{-1}\sqrt{a_0}$$

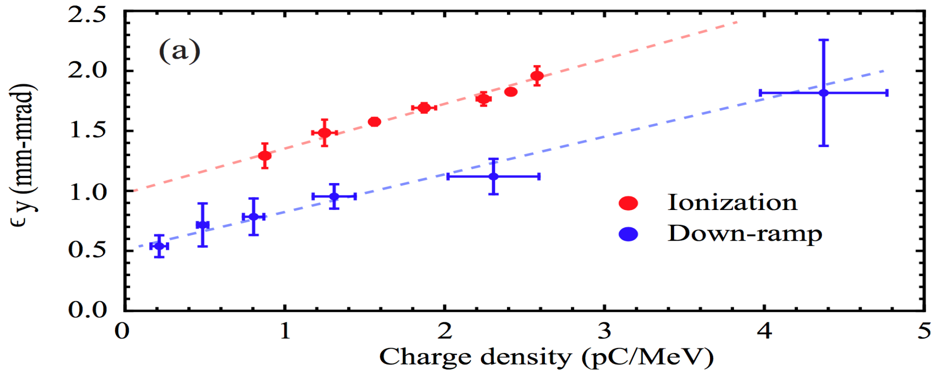
- transverse momentum: $\sigma_p = \left[\sigma^2_{\text{quiver}} + \sigma^2_{\text{PMF}}\right]^{1/2}$

$$\sigma_{\text{quiver}} \propto a_0$$

$$\sigma_{\text{PMF}} \propto \frac{a_0^2}{\sqrt{1 + a_0^2/2}}$$

Barber et al., PRL (2017)

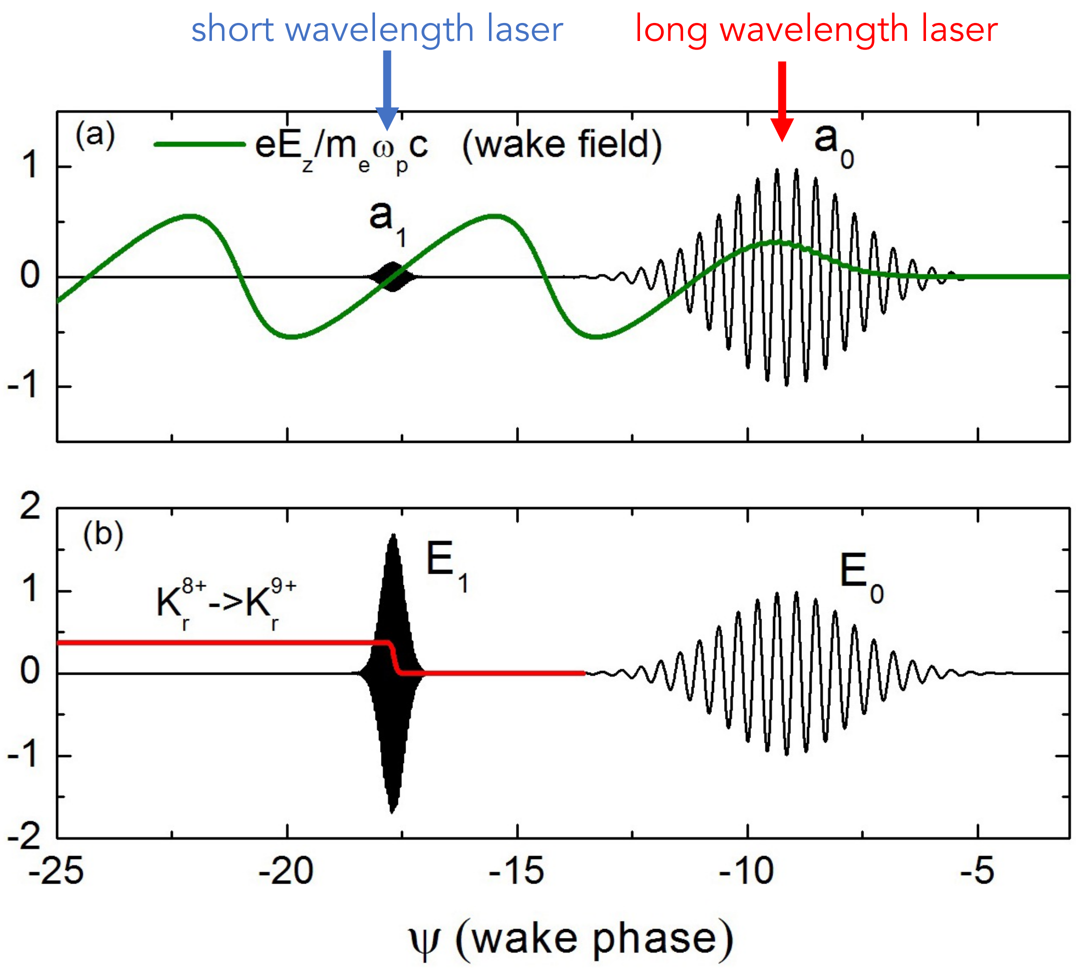




→ Emittance from single-pulse ionization injection larger than that from downramp injection due large spread in initial transverse momenta

Plasma photocathode: higher brightness e-beams from two-color laser ionization injection

- **Two-color, two-pulse laser-ionization injection:** use two lasers of different wavelengths to separate plasma wave excitation (long wavelength) and ionization injection (short wavelength)



Laser electric field: $E = (2\pi m_e c^2/e)\dfrac{a}{\lambda}$

→ Long wavelength laser for large ponderomotive force and plasma wave excitation

ponderomotive force: $F_{\mathrm{PMF}} = m_e c^2 \nabla a^2/2$

→ Short wavelength laser for large peak electric field and ionization

Ionization rate: $w \propto \dfrac{E_a}{E}\exp\left[-\dfrac{2}{3}\dfrac{E_a}{E}\left(\dfrac{U_{\mathrm{ion}}}{U_{\mathrm{H}}}\right)^{3/2}\right]$

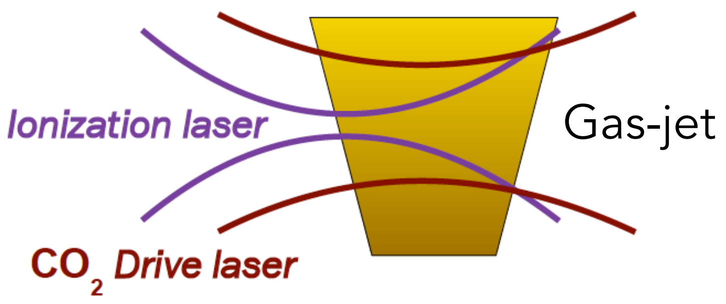
- Requires: $a_i > \left(\dfrac{\lambda_i}{\lambda_0}\right) a_0$

Yu et al., PRL (2014)

Two-color ionization injection: charge vs emittance

Two-color ionization injection using CO2 drive laser can achieve 10s nm emittance with 10s pc charge.

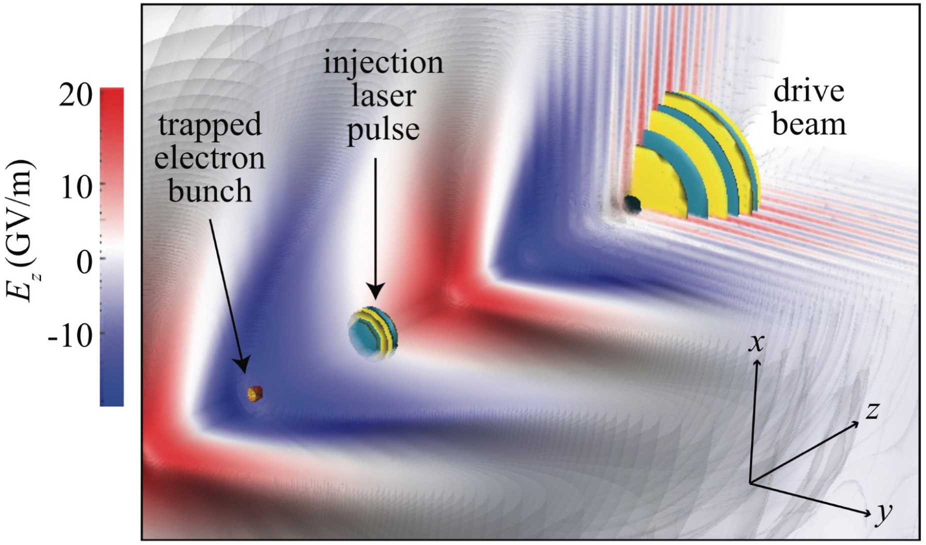
(L~5 mm) Kr

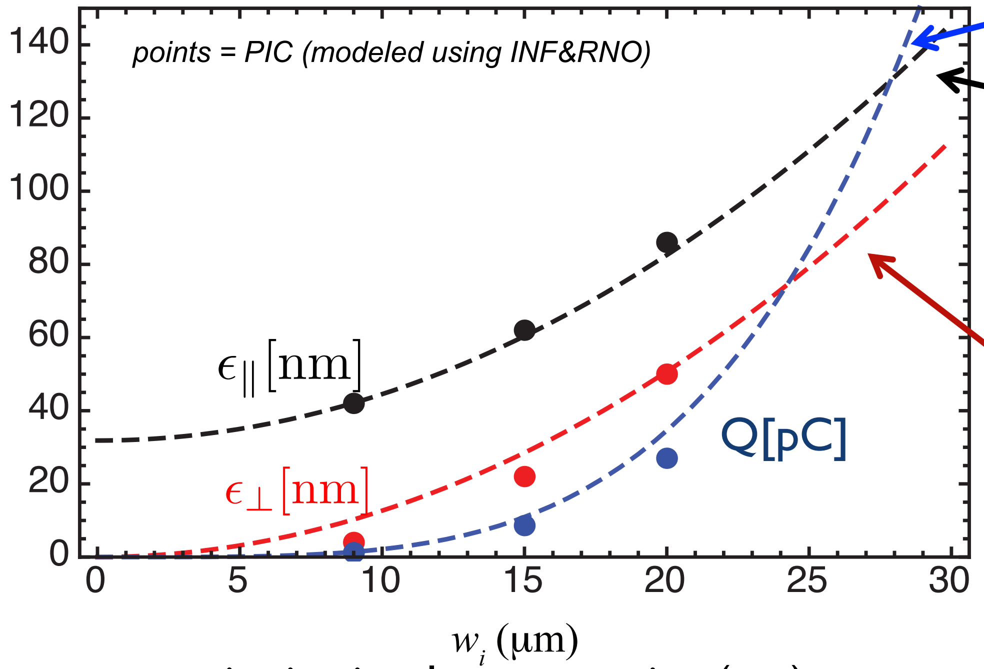


$n_e = 10^{16}$ cm^{-3}

CO2 pump laser pulse:
a=2
10 um wavelength
470 fs (FWHM intensity)
155 um spot (ZR = 7.5 mm)
10 J

Frequency-doubled Ti:Sa injection pulse:
a=0.13
0.4 um wavelength
50 fs
20 um spot (ZR = 3 mm)
120 mJ
→ ionizes Kr^{+8} → Kr^{+9}





ionization laser spot size (um)

charge:

$$Q = eN_t = en_g(\pi w_i^2 \Delta^2) Z_{Ri} \propto w_i^4$$

normalized emittance (in laser pol. plane):

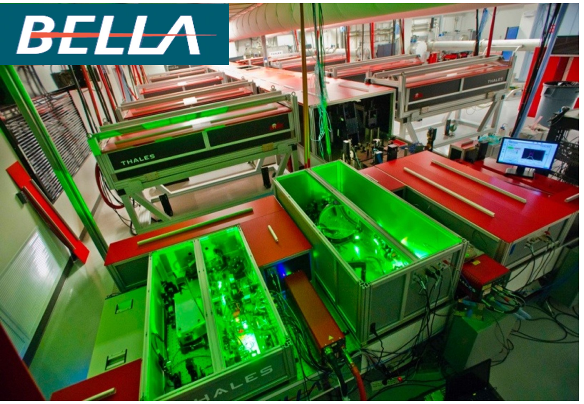
$$\epsilon_\parallel = \left[1 + \left(\frac{2a_i}{k_p w_i}\right)^2\right] \frac{k_p w_i^2}{4\sqrt{2}} \Delta^2$$

normalized emittance (out of pol. plane):

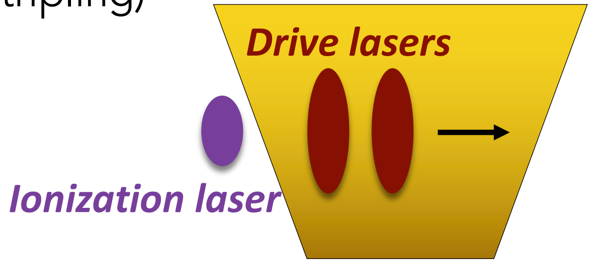
$$\epsilon_\perp = \frac{k_p w_i^2}{4\sqrt{2}} \Delta^2 \propto w_i^2$$

Schroeder et al., PRAB (2014)
Schroeder et al., SPIE(2015)

Two-color ionization injection: proof-of-principle demo planned at LBNL



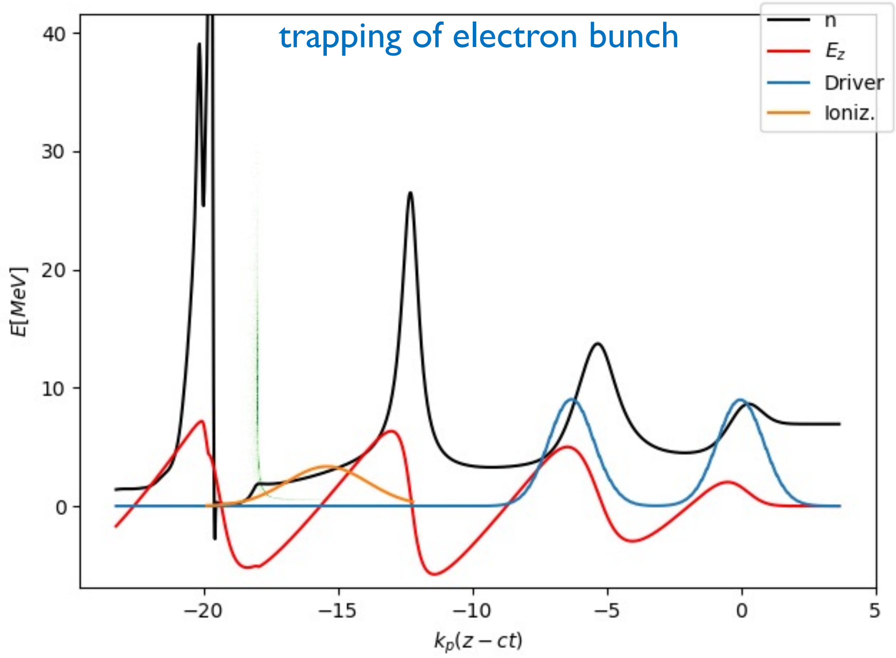
Ionization laser pulse - frequency tripled Ti:Sa
- E = 1.9 J (before frequency tripling)
- Tripling efficiency = 15%
- w_0 = 7 um
- T_{FWHM}=70 fs
- a_0 = 0.51



Gas jet:
(L~10 mm)
n_e = 3x0^{17} cm^{-3}

Laser wake drivers:
- E = 13 J (total for both pulses)
- w_0=52 um
- a_0 = 0.92
- T_{FWHM}= 40 fs
- P = 153 TW (single pulse)

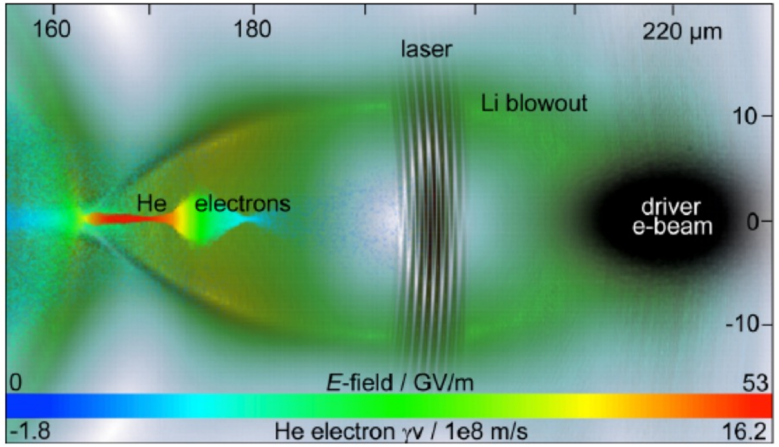
Plasma
- n_0=3e17 cm^{-3}
- P_{crit}=100 TW
- L ~1cm (driver Rayleigh range)
- Nitrogen



Electron beam after 1cm
- emittance: 0.08 μm / 0.35 μm
- 15 pC
- 400 MeV (dE/E < 3%)

PIC simulation using INF&RNO (D.Terzani)

Plasma photocathode in a PWFA: experiments ongoing at SLAC

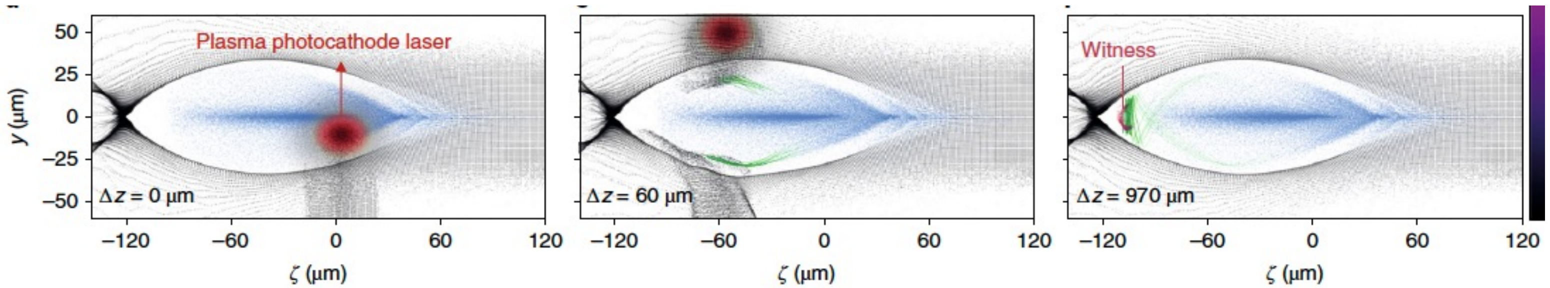


B. Hidding et al., PRL (2012)

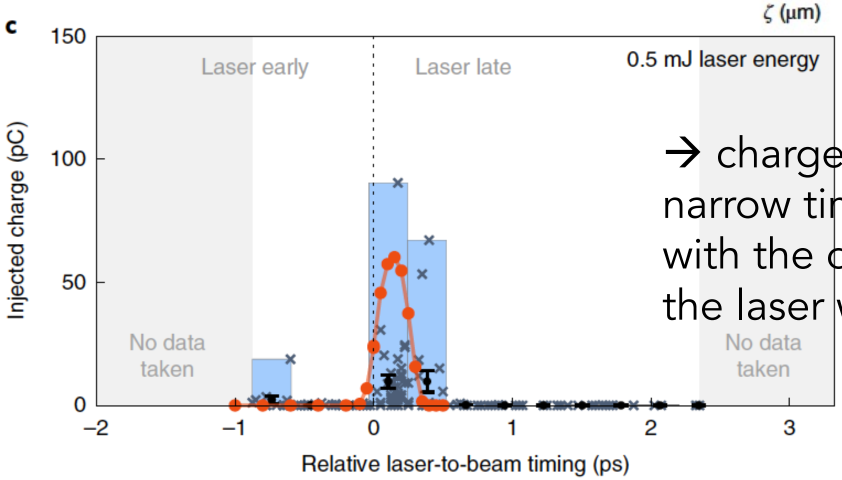
- Use beam diver to excite plasma wave + ionization laser behind driver at low laser intensities resulting in lower beam transverse emittance (“Trojan horse” scheme)

- 10s of nm emittance observed in PIC simulations

Experiments ongoing at SLAC – FACET (completed) & II (planned)

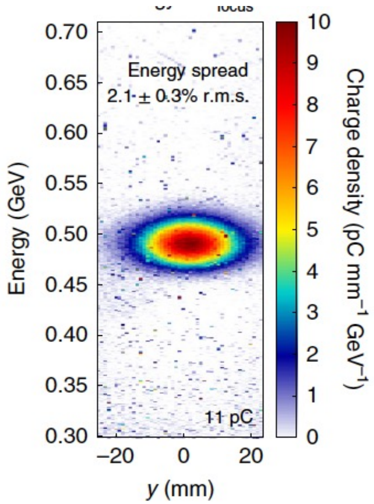


Deng et al., Nature Phys. (2019)



→ charge observed only in a narrow time window, consistent with the duration of the overlap of the laser with the plasma wave

0.5 GeV beams with 2% energy spread and ~1 µm emittance →



Conclusions

- Plasma-based acceleration of electron beams:
  - Compact (>10 GV/m) source of 100 MeV to multi-GeV electron beams
  - Bunch length: ~few fs
  - Sub-micron emittance
  - Brightness: $B_{5D} \sim 10^{18}$ A/(m-rad)^2

- Injection method enables control of initial beam phase space

- Path to higher brightness – plasma accelerators using laser-triggered injection (plasma photocathode):

  10s pC charge + 10s nm emittance and potential to reach $B_{5D} \sim 10^{20}$ A/(m-rad)^2

Thank you for the attention!