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Physics of laser-driven and beam-driven plasma accelerators

(similarities & differences, comparable & contrasting features, lasers or beams?)

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Hampton, VA

U.S. DEPARTMENT OF ENERGY | Office of Science

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Plasma-based accelerators for future colliders

- PWFA-linear collider:
- two-beam accelerator geometry
- 25 GeV drive beams
- 19 plasma stages (1 TeV)
- n=10^{17} cm^{-3} (set by 30 um driver bunch length)

Seryi et al., Proc. PAC (2009)

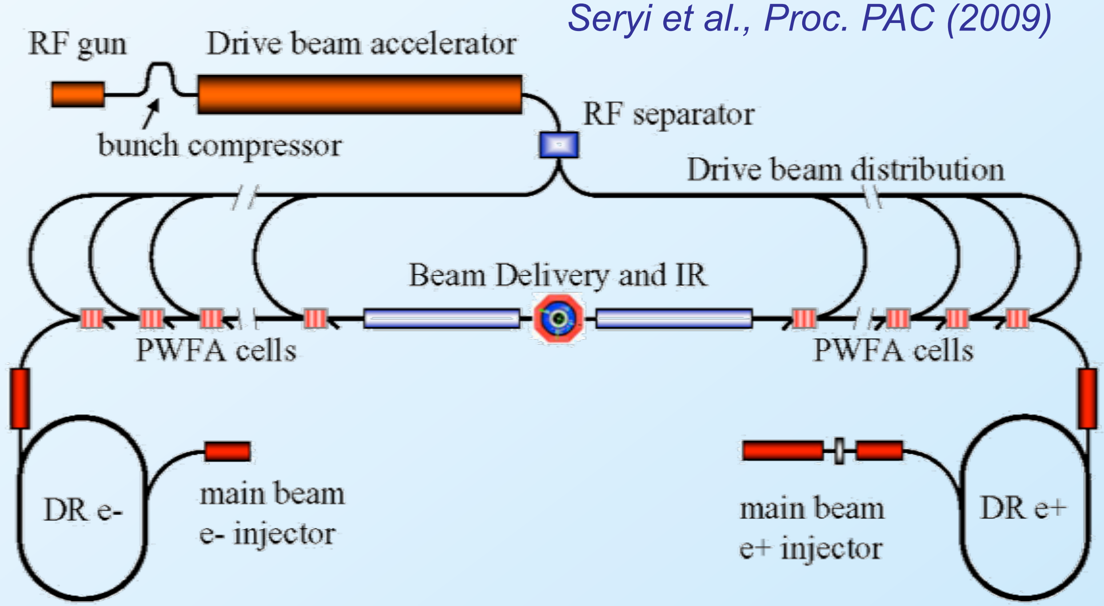
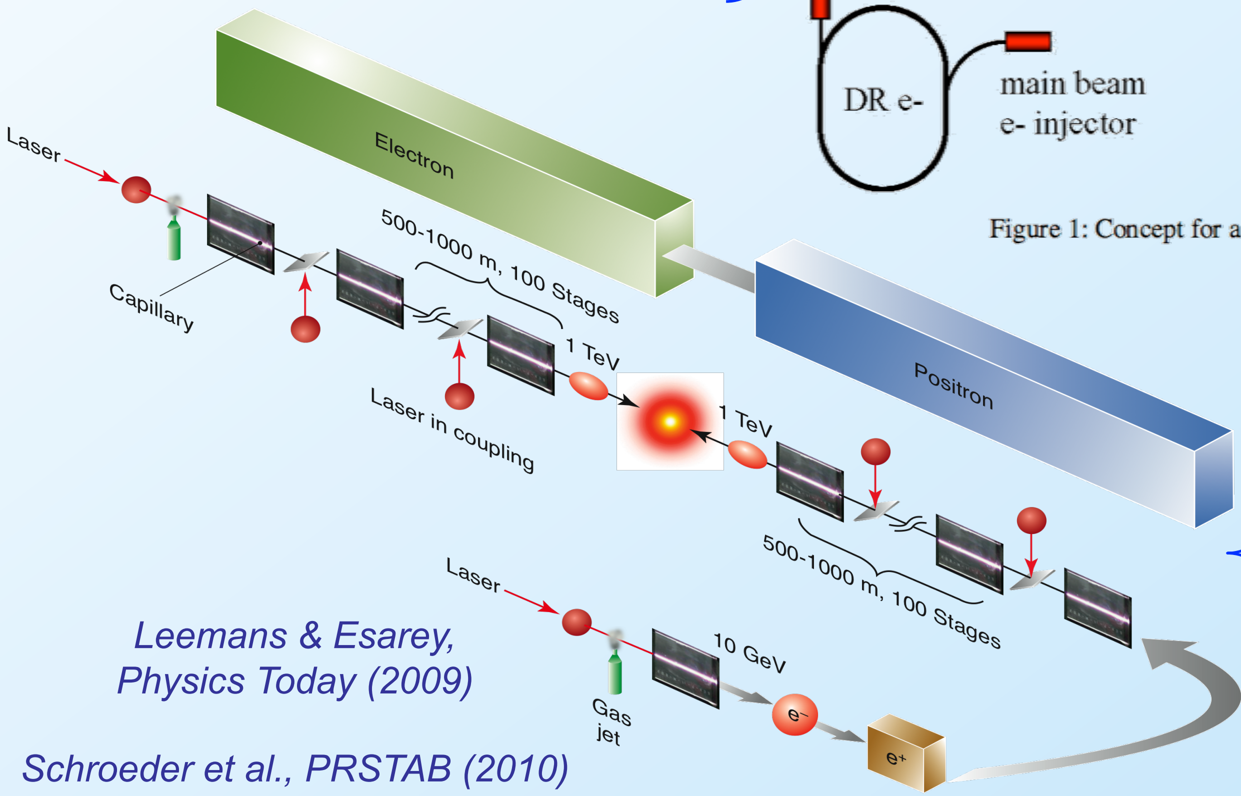


Figure 1: Concept for a multi-stage PWFA-based Linear Collider.



Leemans & Esarey, Physics Today (2009)

Schroeder et al., PRSTAB (2010)

- LPA-linear collider:
- 50 stages (1 TeV collider)
- 10 GeV/stage
- requires ~10 J laser (at tens of kHz, hundreds of kW)
- n=10^{17} cm^{-3} (set by laser depletion)

Outline

- Plasma wave excitation
  - Transverse wake structure
    - Beam-driver - space-charge fields: extends plasma skin depth
    - Laser-driver - local ponderomotive force: extends laser spot size
  - Regimes of operation: quasi-linear and non-linear
  - Energy gain: operational plasma density
- Driver propagation in plasma
  - Driver diffraction/divergence, self-guiding, and head-erosion
  - Plasma wave phase velocity ~ driver propagation velocity
    - Slippage - taper for laser-driven plasma waves
    - Self-trapping for low phase velocities
- Driver-plasma coupling
  - Staging for high-energy physics

Plasma acceleration: ultrahigh accelerating gradients

Tajima & Dawson, PRL (1979)
Chen et al., PRL (1985)

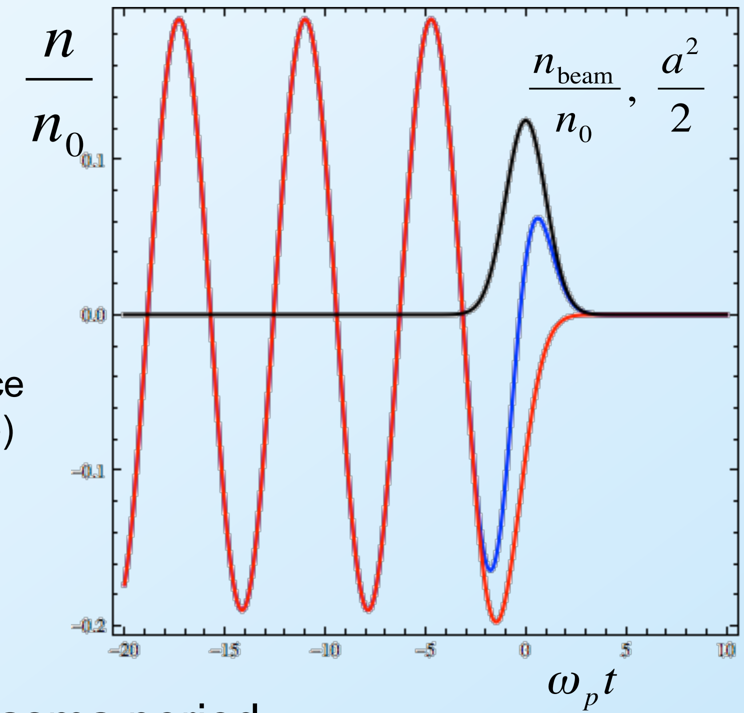
$$\left(\frac{\partial^2}{\partial t^2} + \omega_p^2\right)\frac{n}{n_0} = -\omega_p^2 \frac{n_{\rm beam}}{n_0} + c^2 \nabla^2 \frac{a^2}{2}$$

Plasma wave: electron density perturbation

Space-charge force of particle beam

Ponderomotive force (radiation pressure)

$$a = \frac{eA}{mc^2} \propto \lambda I^{1/2}$$



Common features:

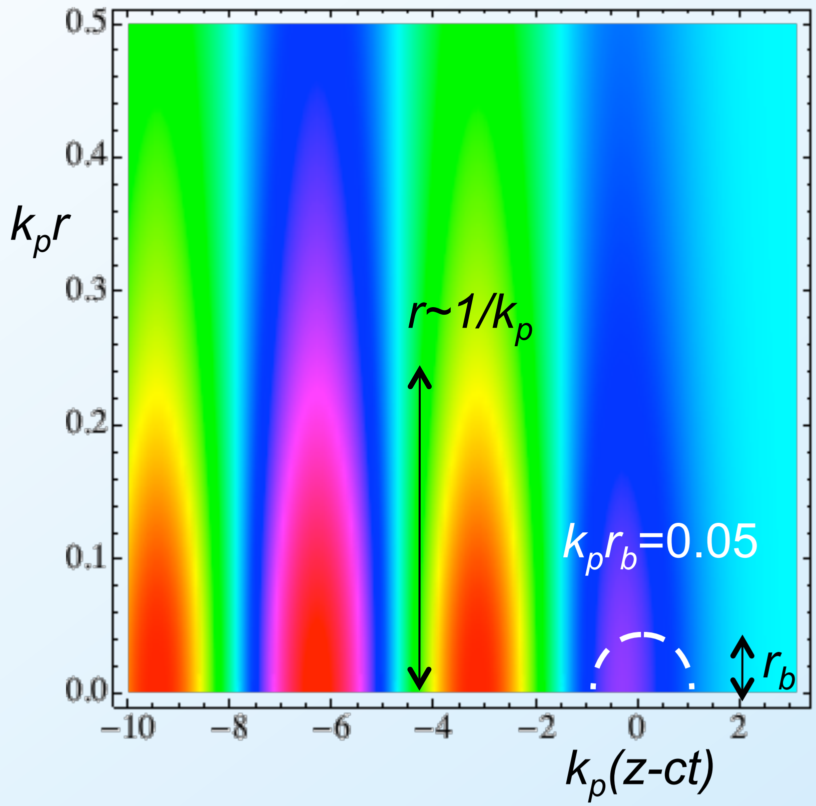
- Wave excitation efficient for driver duration ~ plasma period
- Bucket size ~ plasma wavelength: $\lambda_p = 2\pi c/\omega_p = (\pi r_e^{-1/2})\, n_p^{-1/2}$ ~10-100 μm
- Large waves excited for $n_{beam}/n_0 \sim 1$ or $a \sim 1$
- Characteristic accelerating field: $E \sim \left(\frac{mc\omega_p}{e}\right) \approx (96\,\mathrm{V/m})\sqrt{n_0[\mathrm{cm}^{-3}]}$
- Phase velocity of wave determined by driver velocity

Transverse wakefield structure

Beam driver (a=0)

$$\frac{E_z}{E_0} = -k_p^3 \int d\xi' \cos\left[k_p(\xi - \xi')\right] \int r' \, dr' I_0(k_p r_<) K_0(k_p r_>) \frac{n_b}{n_0}$$

Keinigs & Jones, Phys. Fluids, (1987)



Wakefields of a narrow bunch ($k_p r_b \ll 1$) will extend to skin depth $\sim k_p^{-1}$

Transverse wakefield structure

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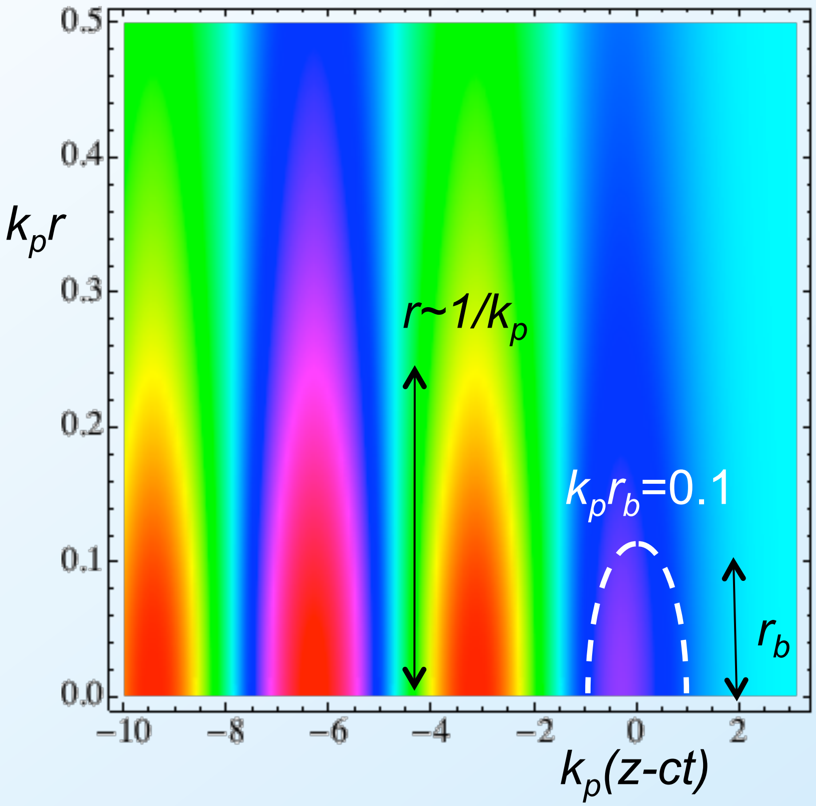
Keinigs & Jones, Phys. Fluids, (1987)

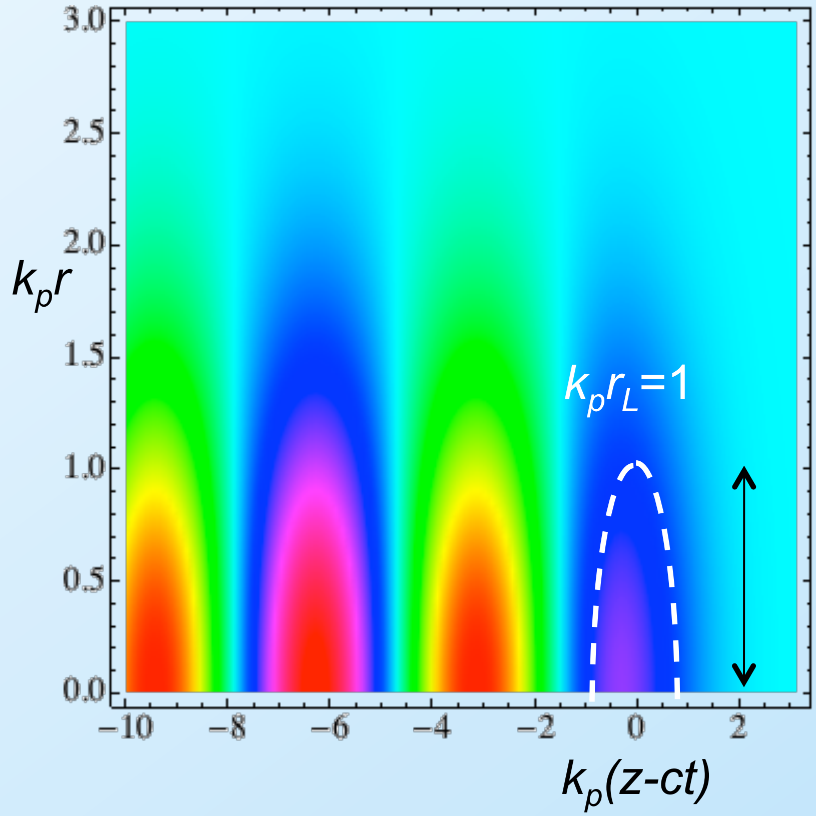


Wakefields of a narrow bunch ($k_p r_b << 1$) will extend to skin depth $\sim k_p^{-1}$

Laser driver (n_b=0)

$$\frac{E_z}{E_0} = -k_p^3 \int d\xi' \cos\left[k_p(\xi-\xi')\right] \frac{\partial_\xi a^2}{2}$$

Sprangle et al., APL (1988)



Wakefields determined by local laser intensity gradient: extend to laser spot $\sim r_L$

Transverse wakefield structure

Beam driver (a=0)

$$\frac{E_z}{E_0} = -k_p^3 \int d\xi' \cos\left[k_p(\xi-\xi')\right] \int r'\,dr' I_0(k_p r_<) K_0(k_p r_>) \frac{n_b}{n_0}$$

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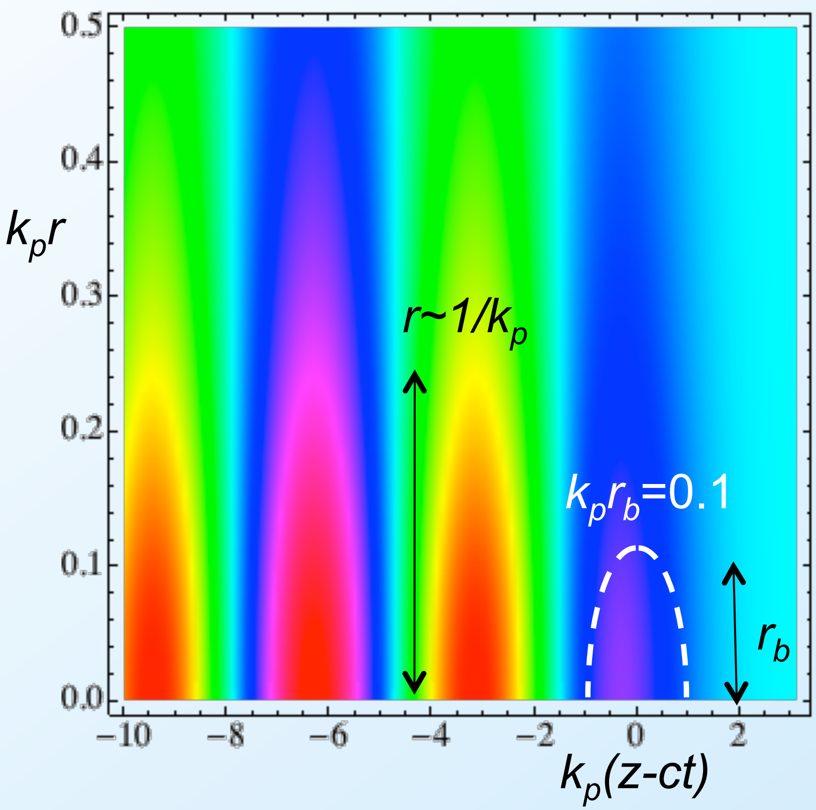

Wakefields of a narrow bunch ($k_p r_b \ll 1$) will extend to skin depth $\sim k_p^{-1}$

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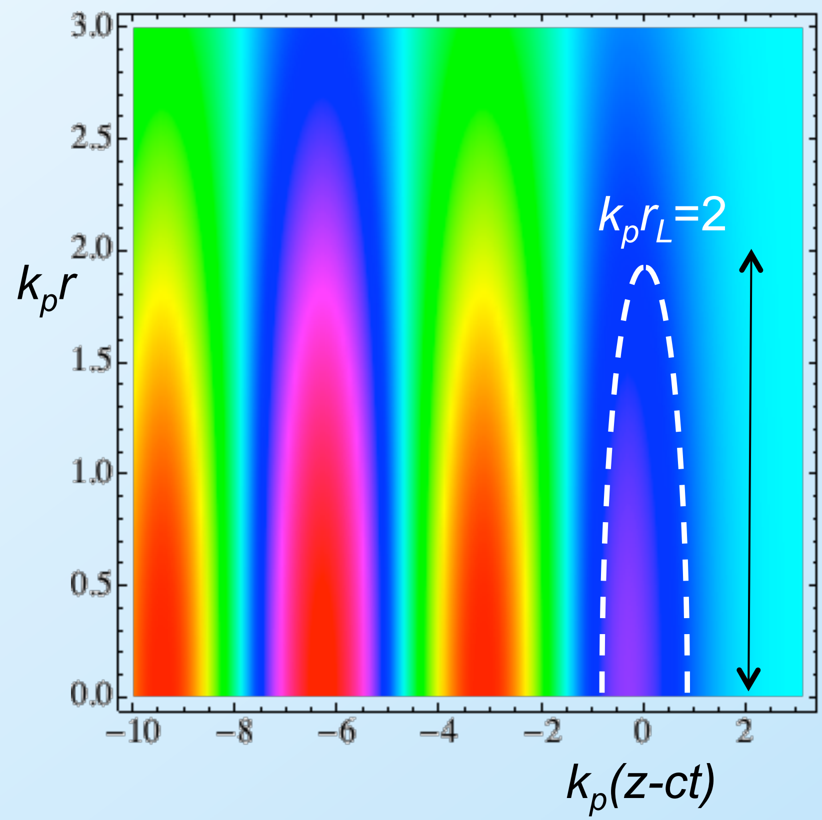
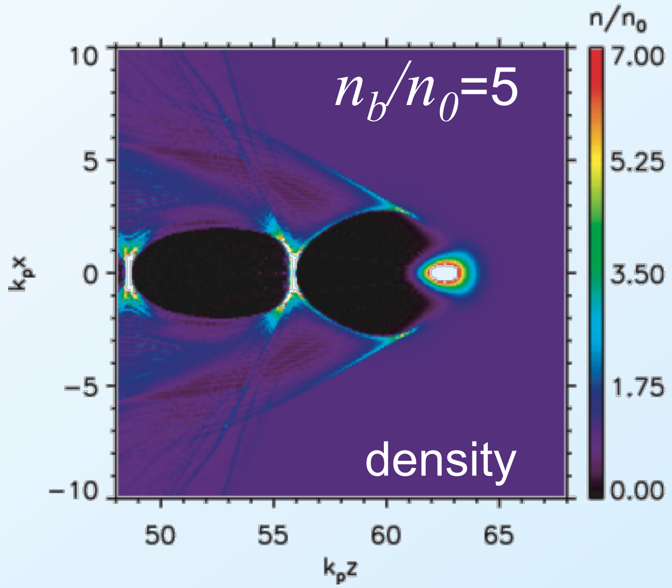


Wakefields determined by local laser intensity gradient: extend to laser spot $\sim r_L$

Nonlinear regime: ion cavity formation

- **Blow-out/Bubble/Cavitated regime:**
  - Highly nonlinear
  - Expulsion of plasma electrons and formation of co-moving ion cavity:
    - Focusing forces for electrons linear (determined by ion density)
    - Accelerating fields for electrons transversely uniform

Beam driver: *Rosenzweig et al., PRA (1991)*
Lu et al., PRL (2006)

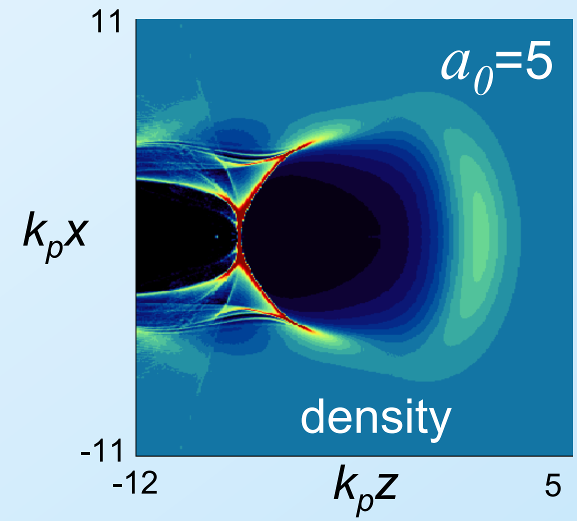


conditions for cavitation: $n_b > n_0$

$k_p L < 1$

$k_p R_b < 1$

Laser driver: *Mora & Antonsen PRE (1996)*
Pukhov & Meyer-ter-Vehn APB (2002)

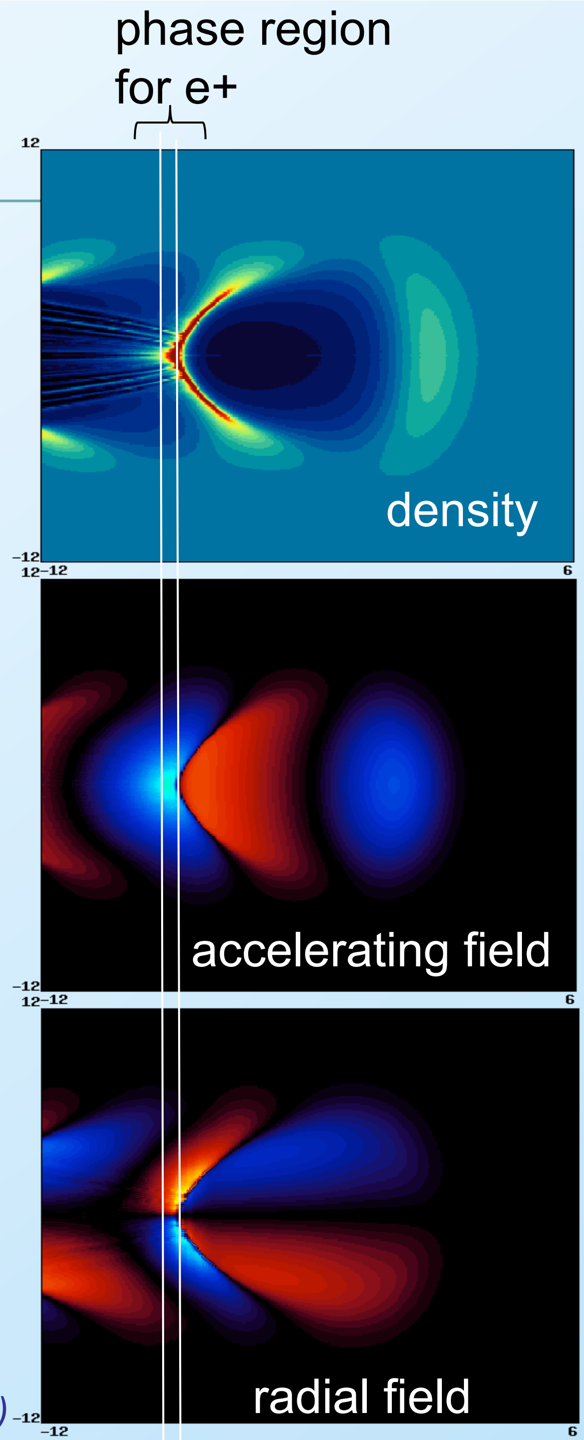


condition for cavitation:

$$k_p^{-2}\nabla_\perp^2\left(1+a^2/2\right)^{-1/2} \sim k_p^{-2}\nabla_\perp^2\phi \sim n/n_0 - 1$$

$$k_p r_L < \sqrt{a}$$

Ultra-high laser intensity: ion cavity formation



a=3.5
k/k_p=20
k_pL=1
k_pR=5

- Bubble/Blow-out/Cavitated regime:
  - High field (a^2>>1)
  - Highly asymmetric and nonlinear
    - Increasing intensity increases asymmetry
  - ion cavity:
    - Focuses electrons
    - Defocuses positrons
  - positron acceleration on density spike
    - Nonlinear focusing forces
    - Non-uniform accelerating forces
  - Self-trapping may be present for laser driver (low phase velocity of wake) with a>4
    ➔ staging difficult

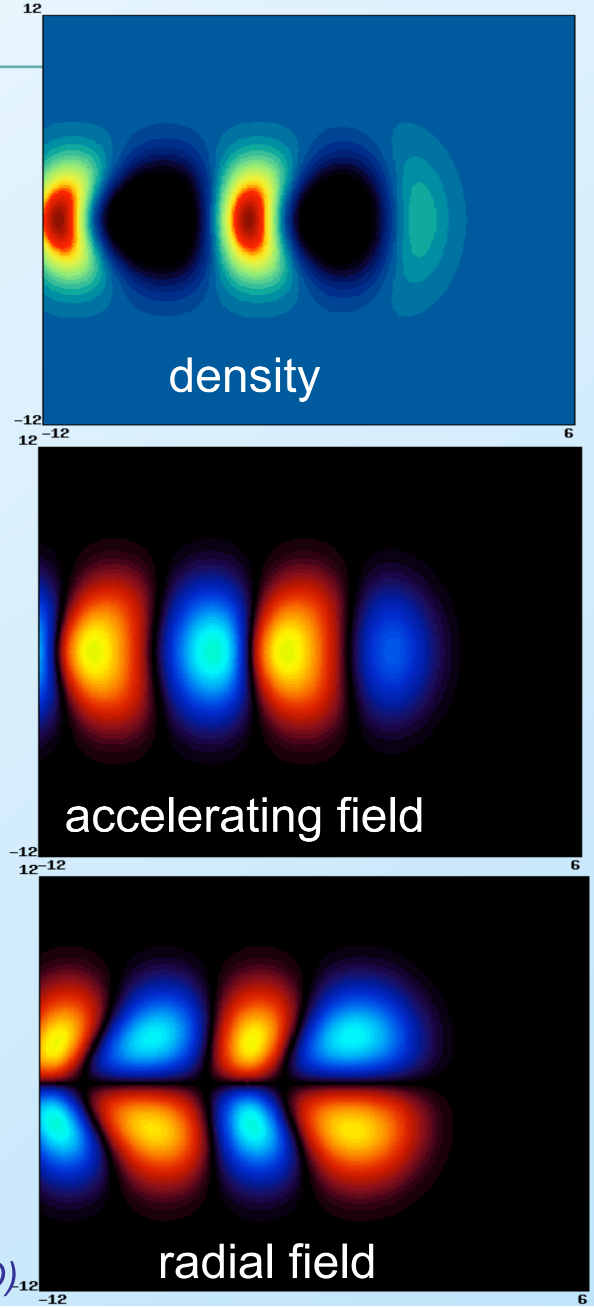
C. Benedetti (INF&RNO)

Quasi-linear laser intensity regime: allows for e^+ acceleration

condition for quasi-linear regime:

$$a^2\left(1+a^2/2\right)^{-1/2} << k_p^2 r^2/4$$

***a*=1**
k/k_p=20
k_pL=1
k_pR=5



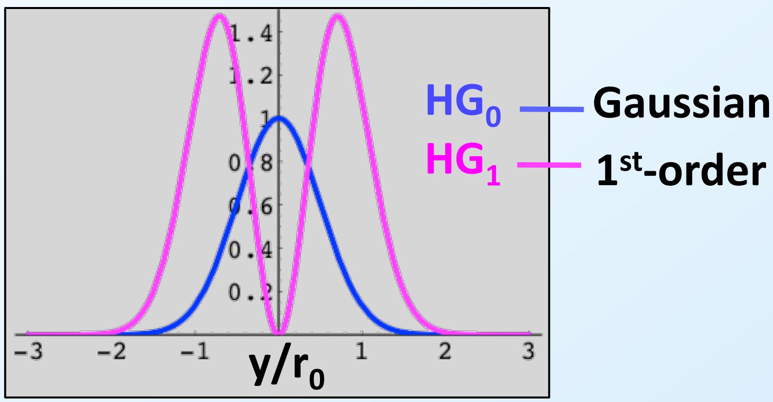
- Quasi-linear/weakly-relativistic regime
  - a ~ 1
  - Nearly-symmetric regions for electron/position acceleration/focusing
  - Dark-current free (no self-trapping)
  - Stable propagation in plasma channel
  - Allows shaping of transverse fields

C. Benedetti (INF&RNO)

Shaping transverse laser intensity allows tailored transverse wakefield (focusing force)

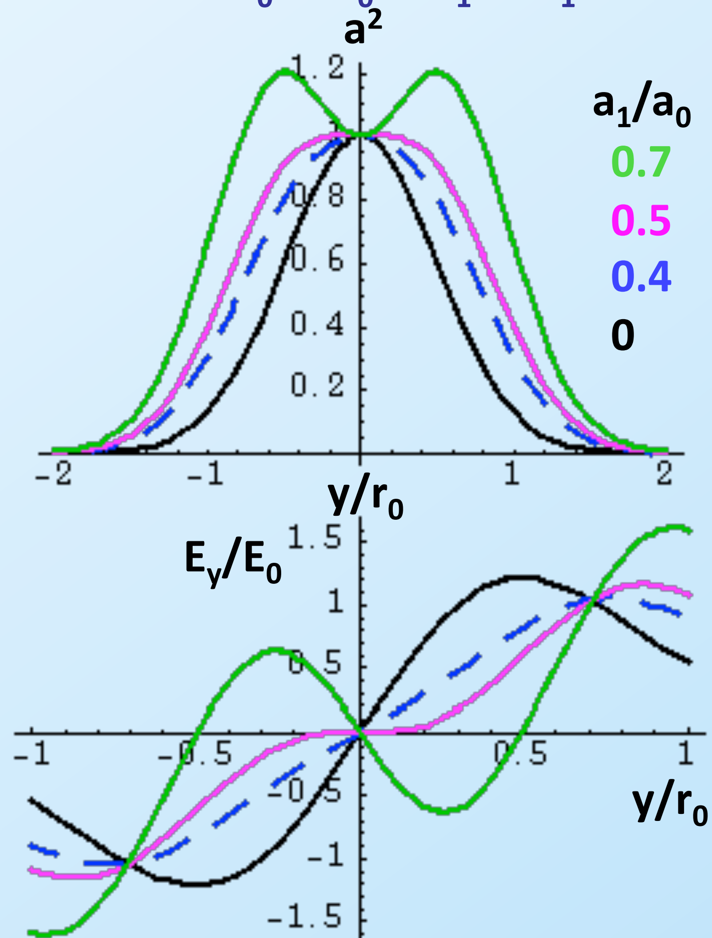
$$\frac{E_r}{E_0} = -k_p^3 \int d\xi' \cos\left(k_p(\xi - \xi')\right)\partial_r a^2/2 \propto \nabla_\perp a^2$$

Add Gaussian modes:
(all modes guided in parabolic plasma channel)



- Allows additional (independent) control of focusing forces (and matched beam spot)

$a^2 = a_0^2 HG_0^2 + a_1^2 HG_1^2$

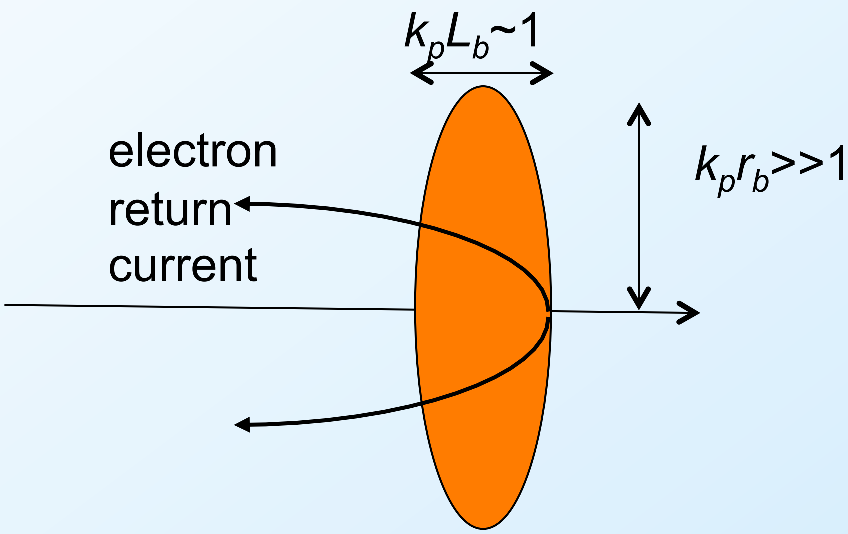


Cormier-Michel et al., submitted for publication

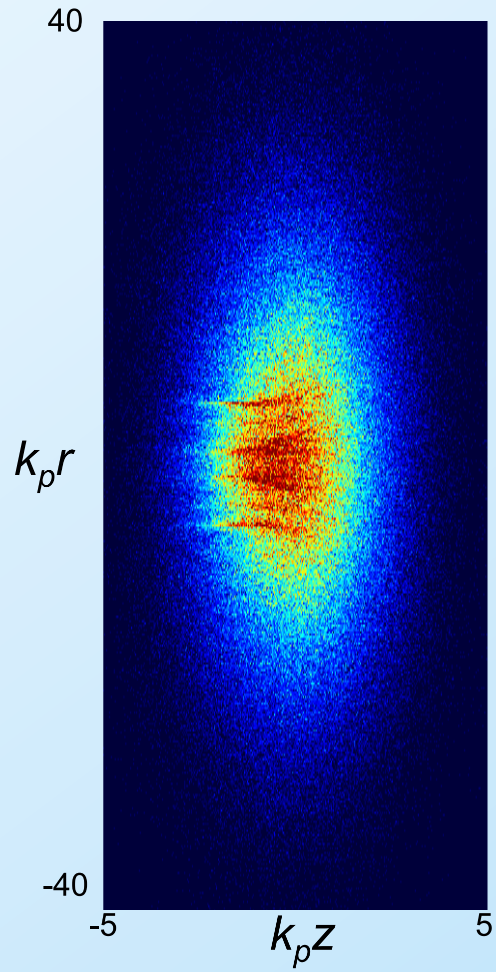
Broad beam-driver allows shaping transverse fields of beam-driven wake

- Shaping transverse field of beam driver requires beam transverse size to be many plasma skin depths: $k_p r_b >> 1$

- Return current flows in beam:



- Subject to filamentation instability:
  - Growth rate: $$k_p\Gamma \sim \left(\frac{n_b}{n_0\gamma_b}\right)^{1/2}$$



$k_p r_b = 2\pi$
$k_p L_b = 2^{1/2}$

$$\omega_p t = \gamma_b n_0 / n_p$$

Keinigs & Jones, Phys. Fluids, (1987); Bret (2009)

C. Benedetti (INF&RNO)

Operational plasma density for nonlinear PWFA

- For large accelerating gradient, operate in the nonlinear blow-out regime:

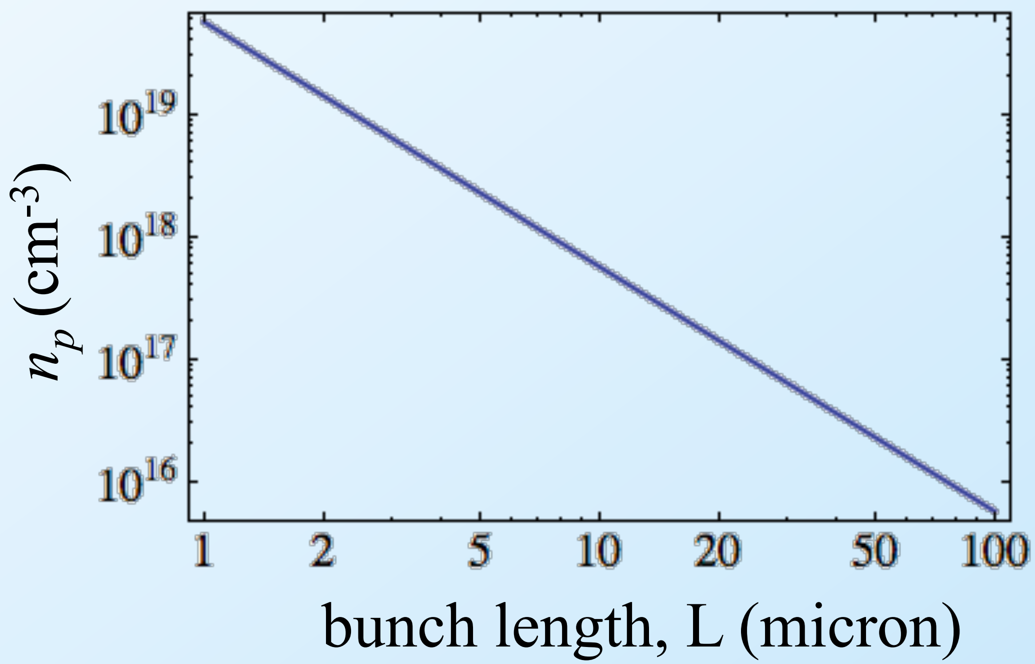
$$n_b/n_0 >> 1, \quad k_p R_b < 1$$

$$E_z \propto \frac{N_b}{L^2} \propto N_b n$$

Lu et al., PRL (2006)
Lotov (2005)

- Operational density determined by length of (unshaped) bunch (for fixed charge):

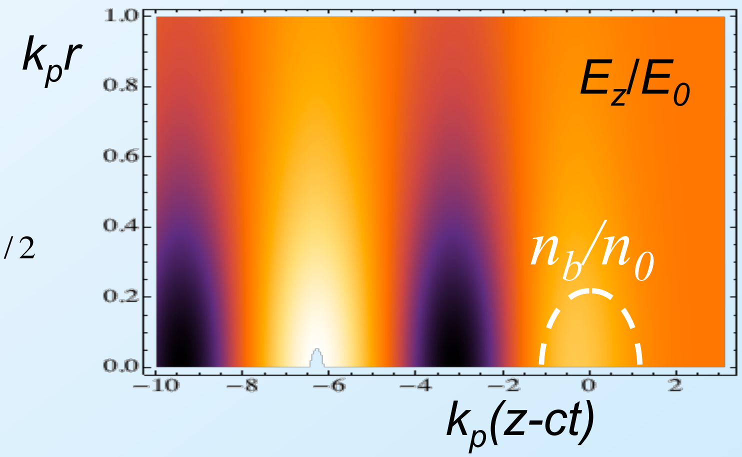
$$k_p L_b \sim \sqrt{2}$$



- Higher gradient achieved for ultra-short drive bunches (operating at higher plasma densities).

Linear regime of beam-driven wakefields

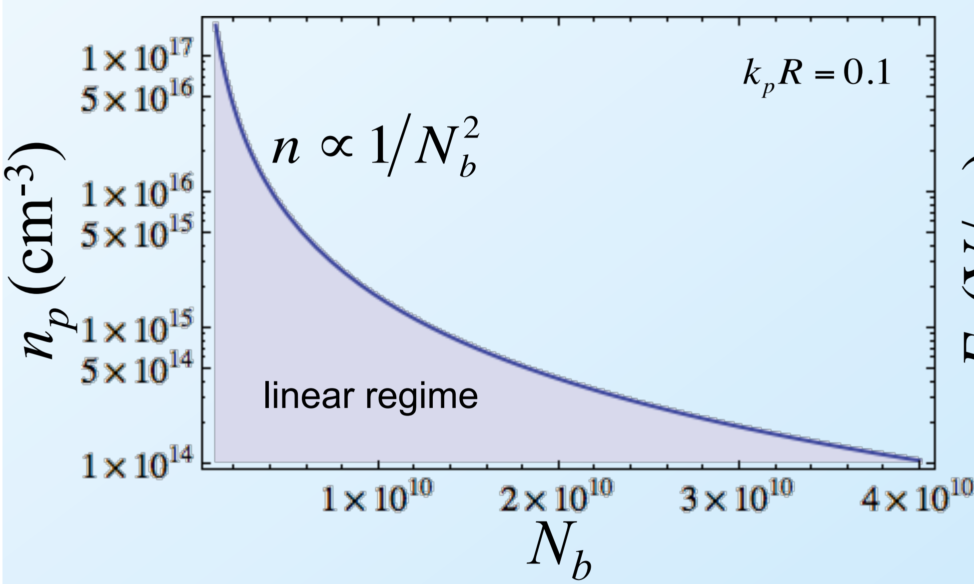
Conditions for linear regime: $k_p L < 1 \quad k_p R_b < 1$

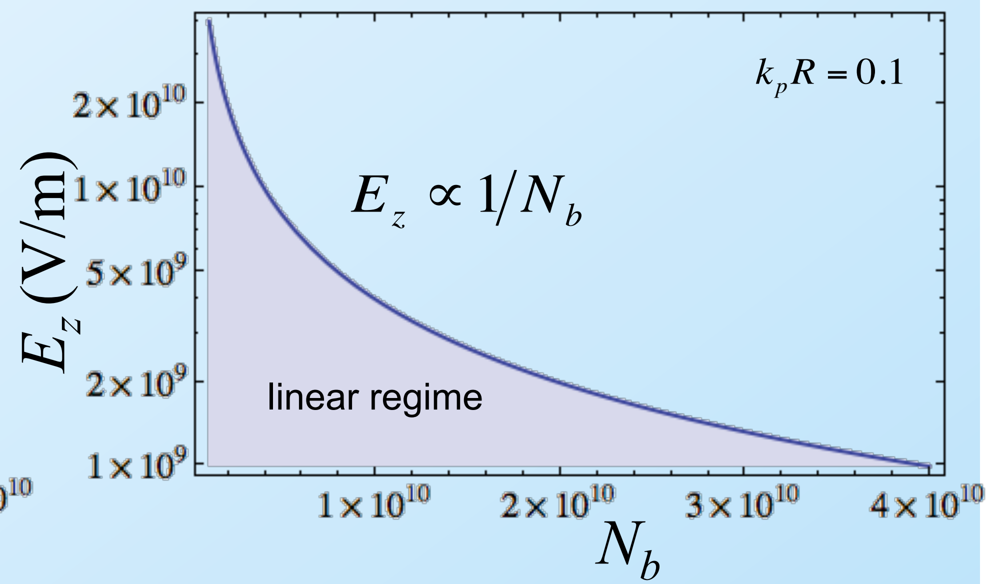


$$1 \geq \frac{E_z}{E_0} = \sqrt{2\pi}\,\frac{n_b}{n_0}(k_p L)(k_p R)^2\left[\ln(1/k_p R)\right] \propto N_b n^{1/2}$$

- Linear regime accessible for low plasma density (for fixed bunch charge)

$$E_z = 2E_0(k_p r_e)N_b\left[\ln(1/k_p R)\right] \propto \frac{N_b}{L^2} \propto N_b n \propto \frac{1}{N_b}$$





PWFA: Energy gain and transformer ratio

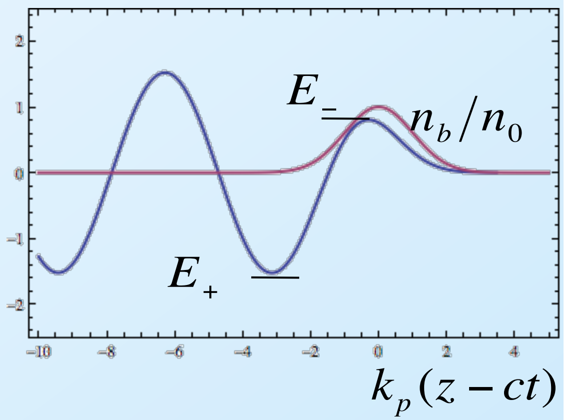
- Energy gain in beam-driven plasma wave given by transformer ratio: $R = E_+ / E_-$
  - Drive beam losses energy after distance:

$$L_d \sim \gamma_b mc^2 / eE_-$$

  - Energy gain of witness bunch:

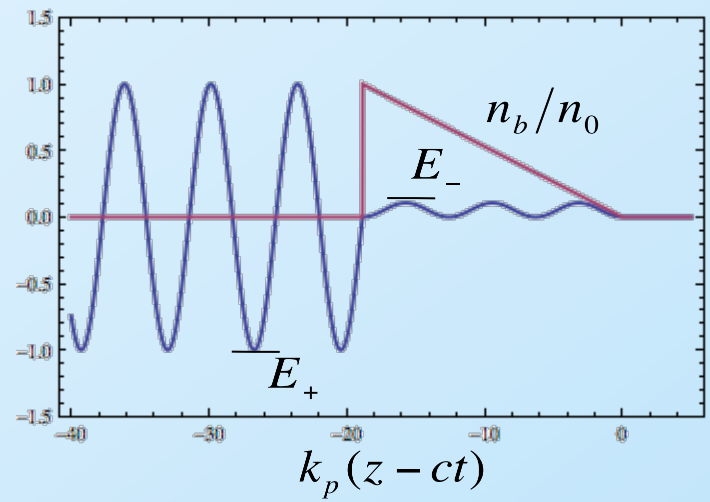
Chen et al., PRL (1986)

$$\Delta\gamma mc^2 \sim eE_+ L_d \sim R\left(\gamma_b mc^2\right)$$



- General considerations (e.g., symmetric bunches): $R \leq 2$

- Higher transformer ratios can be achieved using shaped (asymmetric bunches)
  - Triangular longitudinal bunch
  - Ramped bunch train
  - Nonlinear blow-out regime: ramped bunches for high R

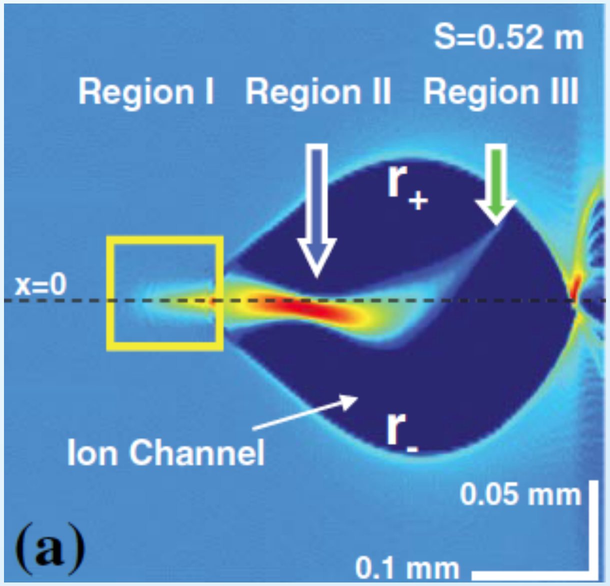


Lu et al., PAC (2009) $R \sim \frac{L_b}{R_b}\sqrt{\frac{n_0}{n_b}}$

Drive beam hose instability

- Hose instability:

Huang et al., PRL (2007)



Instability growth: $$\Gamma_{\text{hose}} \sim c_{\text{hose}} \gamma_b^{-1/6} \left(\omega_p t\right)^{1/3} \left(k_p L\right)^{2/3}$$

- Long bunches (or train of bunches) subject to electron-hose instability

Operational plasma density for laser-driven plasma accelerators

- Laser-plasma interaction length limited by laser depletion length:

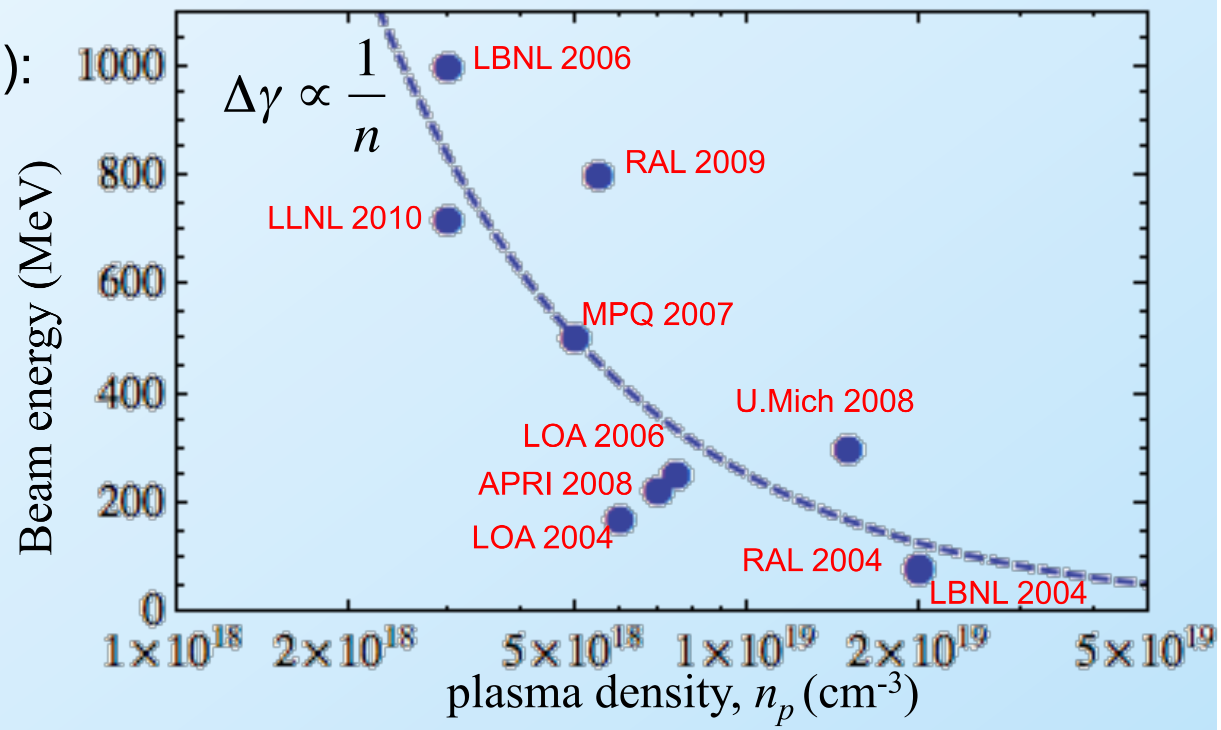
Shadwick et al., Phys. Plasmas (2009)

$$L_d = \left[2.8\left(\frac{1+a^2/2}{a^2}\right)\right]\frac{\lambda_p^3}{\lambda_L^2} \propto n^{-3/2}$$

- Excited wake: $E_z = \left[0.38\left(\frac{a^2}{\sqrt{1+a^2/2}}\right)\right]E_0 \propto n^{1/2}$

- Energy gain (single-stage):

$$\Delta\gamma mc^2 \sim L_d E_z \propto 1/n$$



Laser-driven plasma accelerators: triggered-injection for low densites

- Phase velocity of laser-driven plasma wave function of density: $v_p \approx v_g = c\left(1-\omega_p^2/\omega_0^2\right)^{1/2}$

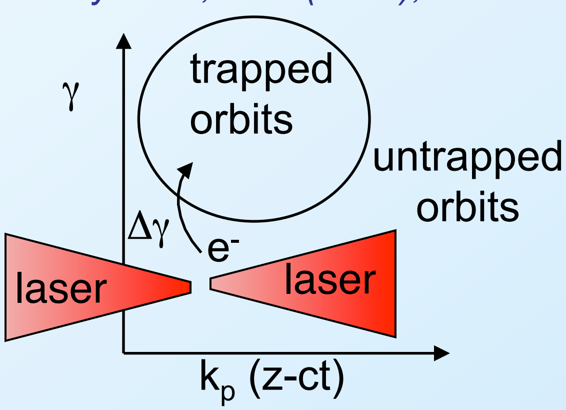
$$\gamma_p \approx \lambda_p/\lambda_0 \propto 1/\sqrt{n}$$

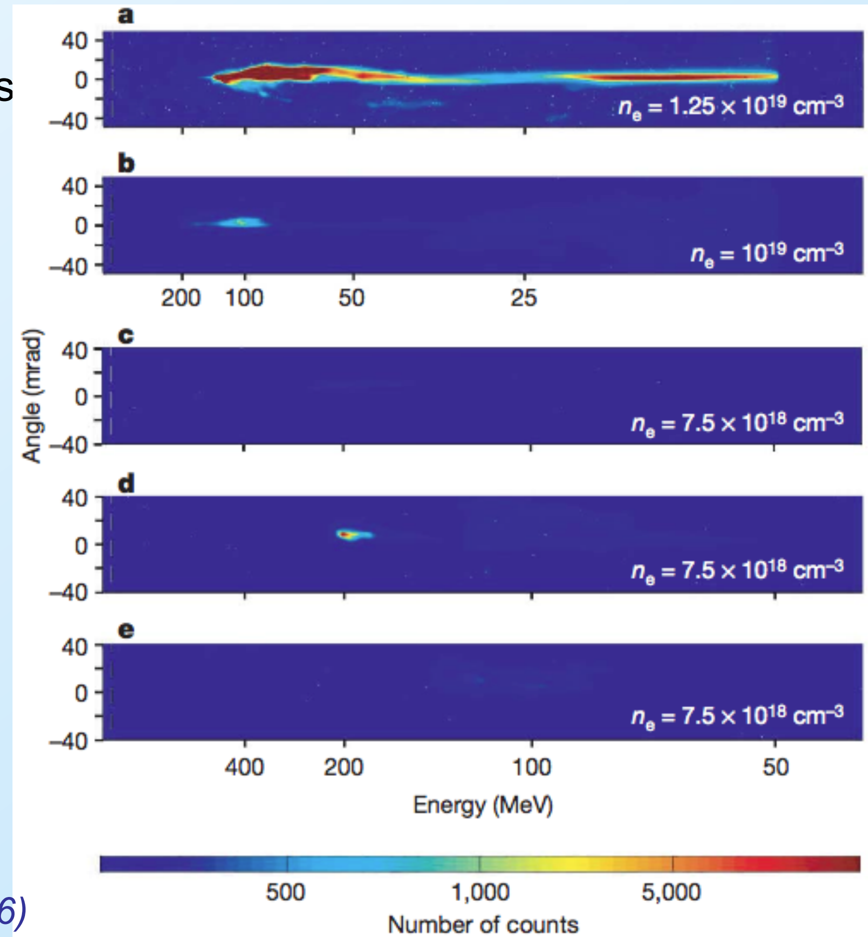
- Plasma electron self-trapping threshold increases as plasma wave phase velocity increases

- Low densities require triggered-injection techniques
  - ➢ Density gradient injection
  - ➢ Ionization injection
  - ➢ Colliding pulse injection

- generate ultra-short (fs) bunches

Esarey et al., PRL (1997); Schroeder et al., PRE (1999)





Faure et al., Nature (2006)

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- Plasma wave excitation
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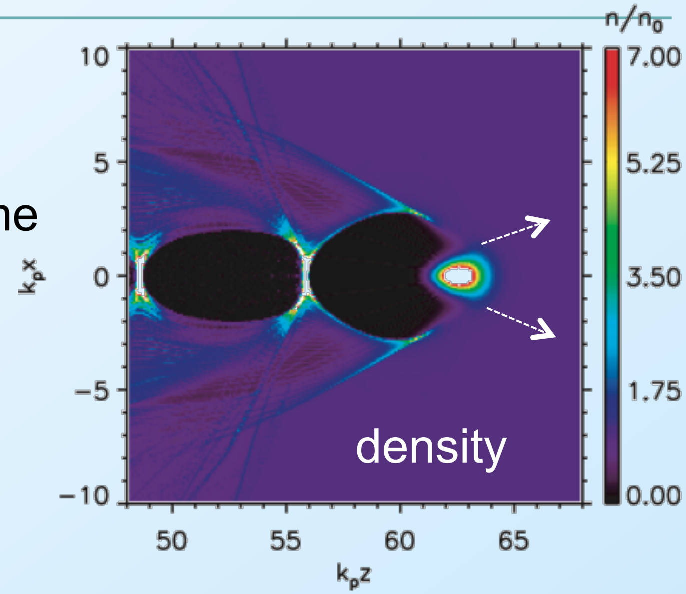
    - Beam-driver driven by space-charge fields: extends plasma skin depth
    - Laser-driver driven by local ponderomotive force: extends laser spot size
  - Regimes of operation: quasi-linear and non-linear
  - Energy gain: operational plasma density
- **Driver propagation in plasma**
  - Driver diffraction/divergence, self-guiding and head-erosion
  - Plasma wave phase velocity ~ driver propagation velocity
    - Slippage - taper for laser-driven plasma waves
    - Self-trapping for low phase velocities
- Driver-plasma coupling
  - Staging for high-energy physics

Driver propagation

- Focused e-beam diverges
  - Characteristic distance ~β
  - Beam body may be self-guided in blow-out regime
    - Head of beam outside cavity, continues to diverge ➔ beam head erosion: $\text{rate} \propto \varepsilon_n$
  - Solution: Low emittance beam:

    long beta-function ~ beam-plasma interaction length:

$$\beta = \sigma_r^2 / \varepsilon$$

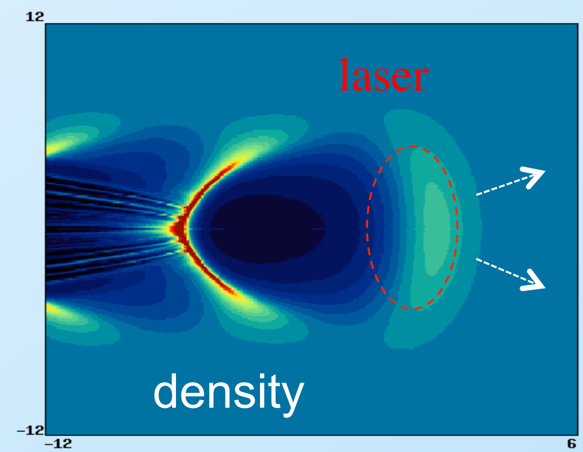


e.g., β=1 m for $\varepsilon = 10^{-10}$ m and σ_r=10 um

- Focused laser diffracts
  - Characteristic distance ~ Rayleigh range:

$$Z_R = \pi \sigma_r^2 / \lambda$$

  - Beam body may be self-guided in ion-cavity
    - Head of beam outside cavity, continues to diffract ➔ laser head erosion
  - Emittance fixed by laser wavelength

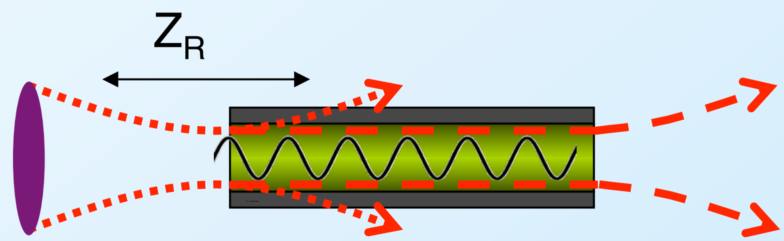


e.g., Z_R = 2 mm for λ=1 um and σ_r=25 um

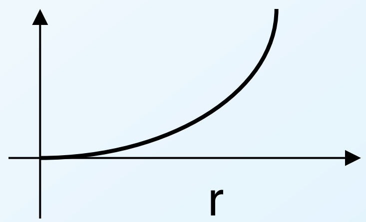
Laser diffraction controlled by plasma channel

Laser diffraction: (L ~Z_R)

Solution: tailor plasma profile to form plasma channel



Plasma density, n(r)



Guiding:

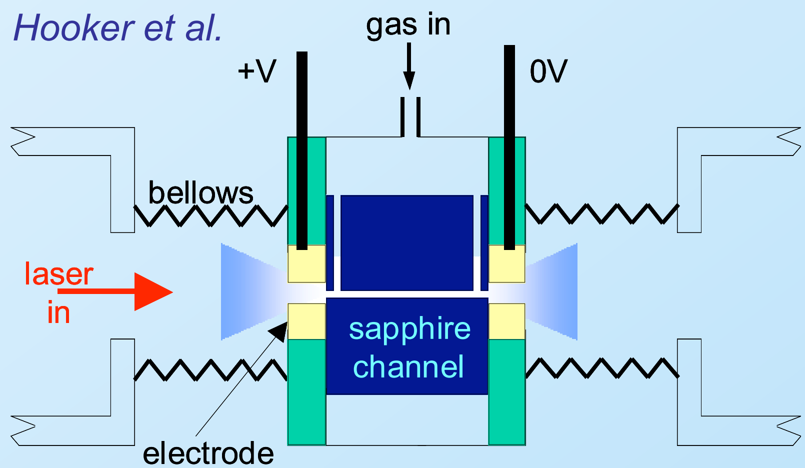
$$\frac{d\eta}{dr} = \frac{d}{dr}\left(1 - \frac{\omega_p^2}{2\omega_L^2}\right) < 0$$

Durfee & Milchberg PRL (1993)
Geddes et al., PRL (2005)

Capillary discharge plasma waveguides:

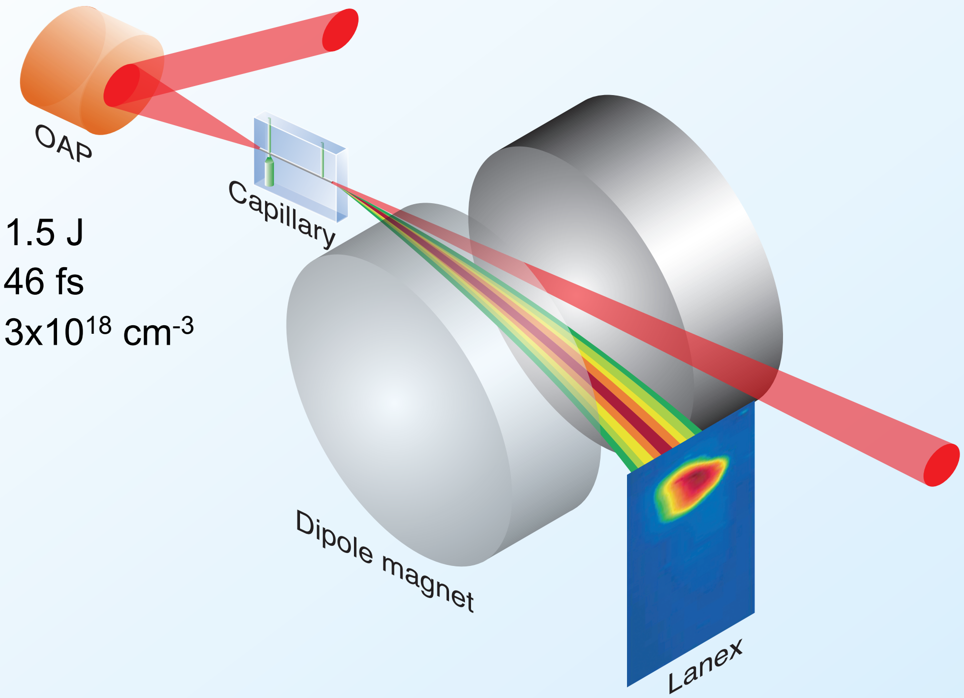
- Plasma fully ionized for t > 50 ns
- After t ~ 80 ns plasma is in quasi-equilibrium: Ohmic heating is balanced by conduction of heat to wall
- Ablation rate small
- n_e ~ 10^{17} - 10^{19} cm^{-3}

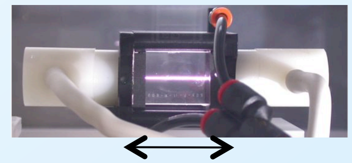
Hooker et al.



Experimental demonstration: 1 GeV beam using Laser Plasma Accelerator

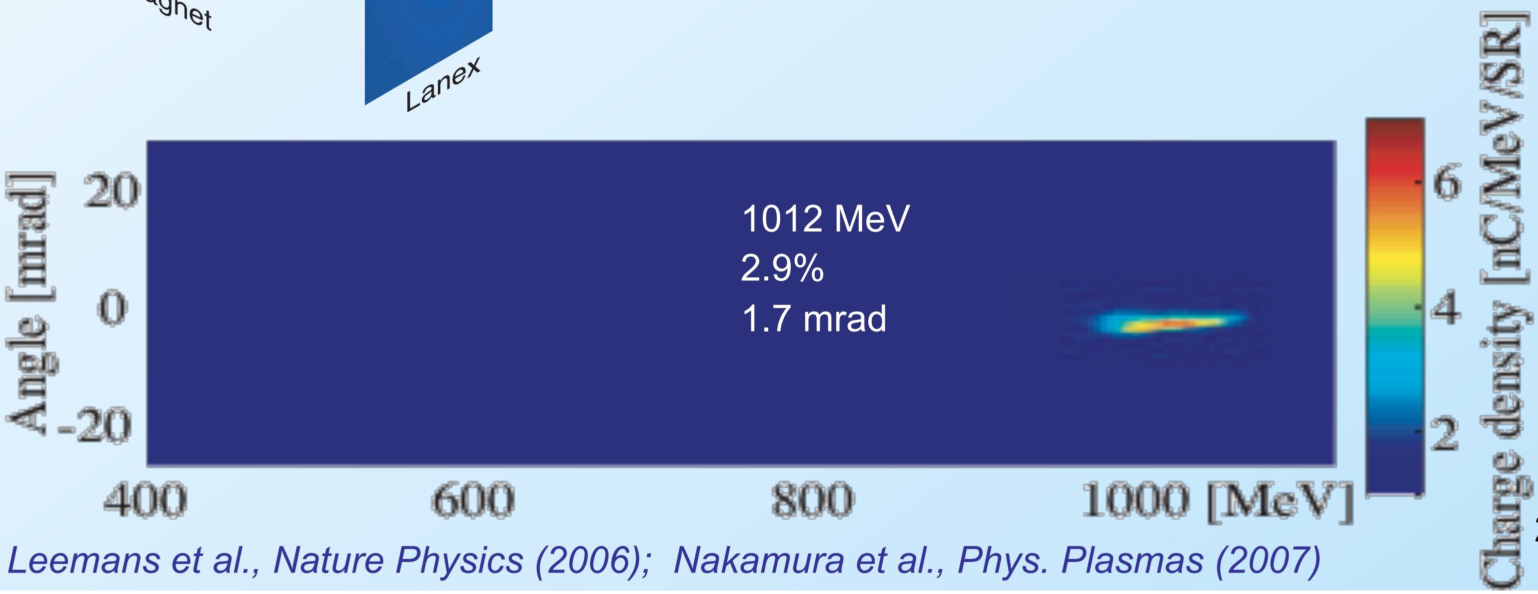
1.5 J
46 fs
3×10^{18} cm^{-3}





3cm

H-discharge capillary technology:
plasma channel production (~10^{18} cm^{-3})

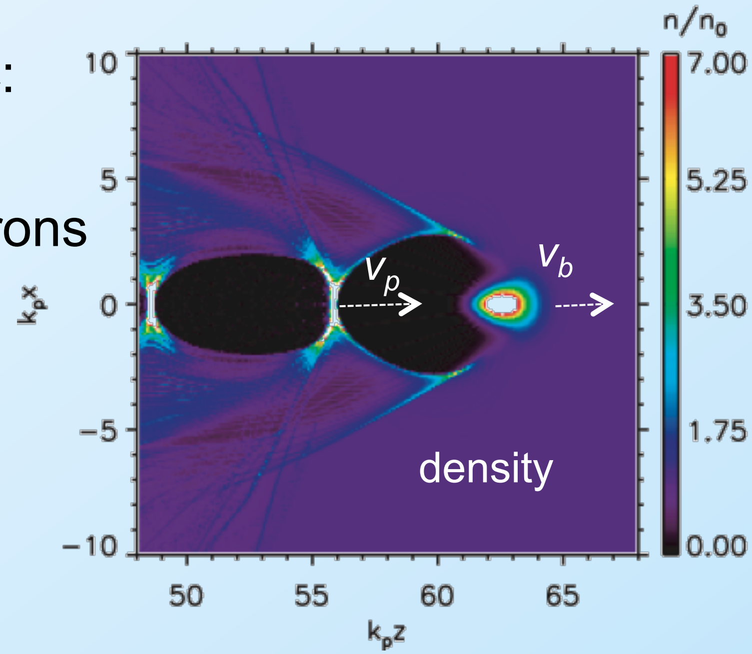


Leemans et al., Nature Physics (2006); Nakamura et al., Phys. Plasmas (2007)

Beam driver propagation velocity

- Phase velocity of the wake approximately driver propagation velocity

- Beam driver velocity typically ultra-relativistic:
  - Eg. 10 GeV, $\gamma_b = \gamma_p \sim 10^4$
  - No trapping of background plasma electrons (dark current free)
  - Negligible slippage between drive and witness bunch
  - Stiff driver ➔ stable propagation



Laser driver propagation velocity

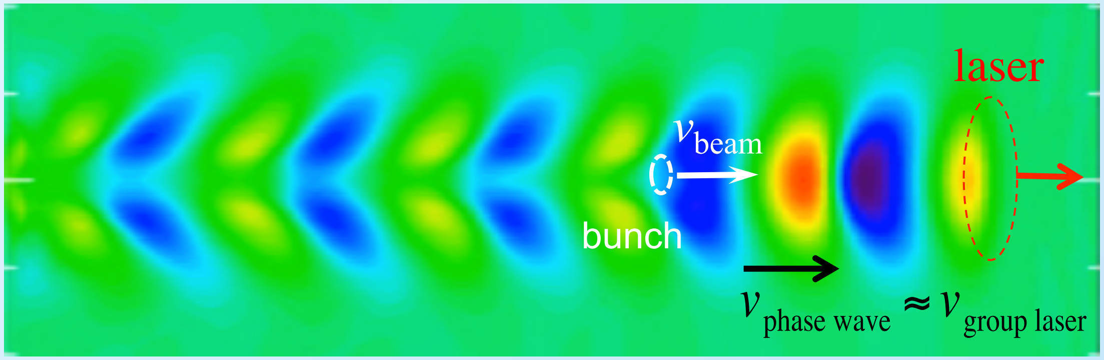
- Laser driver velocity approximately the laser group velocity (function of plasma density):

$$v_g = c\left(1 - \omega_p^2/\omega_0^2\right)^{1/2}$$

  - For typical underdense plasmas using 1-micron laser:

$$\gamma_p \sim \gamma_g = \omega_0/\omega_p \sim 10 - 100$$

  - Trapping of background plasma electrons (beam generation) present for sufficiently large plasma waves:
    - 1D theory: $E_z/E_0 \sim a > \sqrt{2\gamma_p}$
    - Bubble regime: $a > \gamma_p^2/2$ *Kostykov et al., PRL (2009)*
  - Slippage (between beam and wake) can limit energy gain: $\Delta\gamma \propto \gamma_p^2$

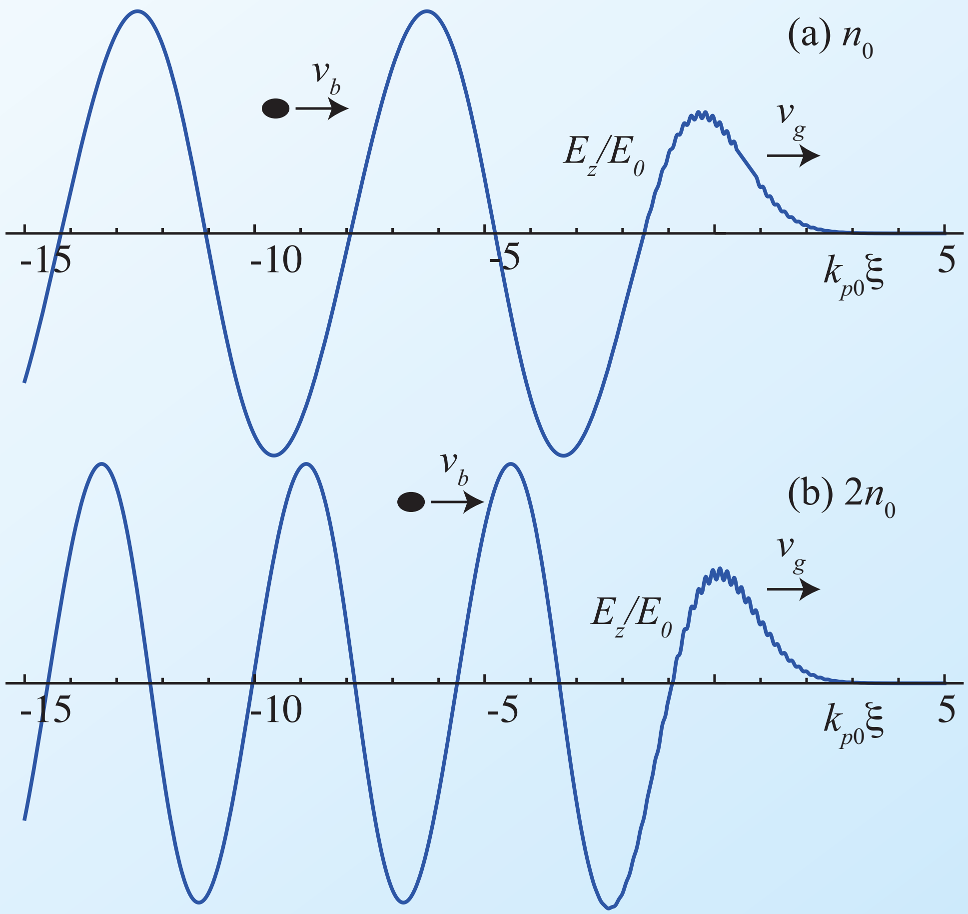


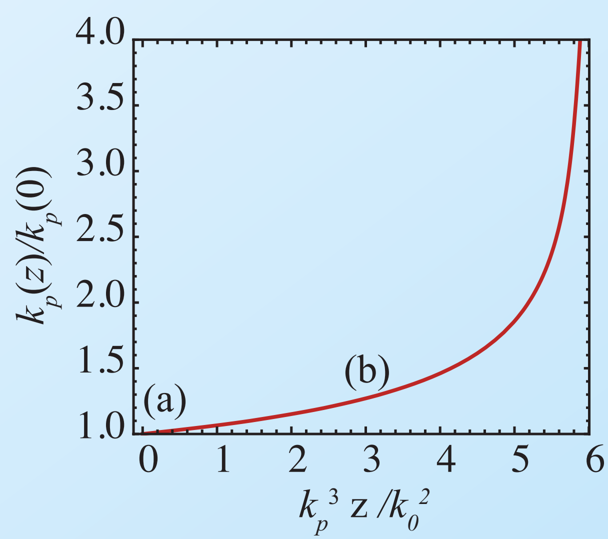
Taper to phase-lock beam to wake

- To lock phase of accelerating field, plasma density must increase (plasma wavelength decrease) as beam slips with respect to driver:

$$\lambda_p \propto 1/\sqrt{n}$$

Katsouleas, PRA (1986)
Bulanov et al., (1997)
Sprangle et al., PRE (2001)
Rittershofer et al., Phys. Plasmas (2010)

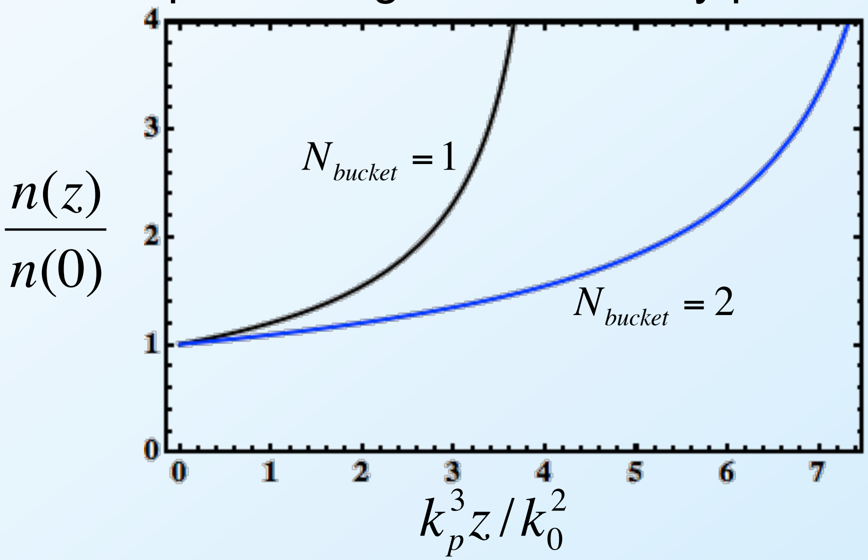




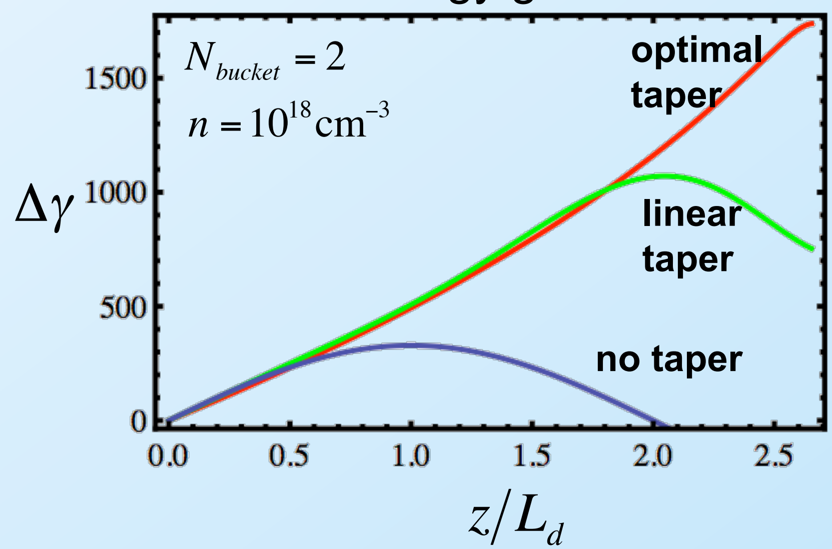
Tapering yields enhanced energy gain and efficiency in weakly-relativistic regime

- In weakly-relativistic regime: $a^2 << 1$
  - dephasing length << depletion length: $L_{\text{dephase}} \sim \frac{\lambda_p^3}{\lambda_0^2} << L_{\text{deplete}} \sim \frac{\lambda_p^3}{a^2 \lambda_0^2}$
  - Significant energy gains can be realized with plasma tapering:

Optimal longitudinal density profile:



Energy gain:



- In plasma channel, focusing and accelerating wakes have different phase velocities: varying density and channel radius to phase lock both.

Rittershofer et al., Phys. Plasmas (2010)

Outline

- Plasma wave excitation
  - Transverse wake structure
    - Beam-driver driven by space-charge fields: extends plasma skin depth
    - Laser-driver driven by local ponderomotive force: extends laser spot size
  - Regimes of operation: quasi-linear and non-linear
  - Energy gain: operational plasma density
- Driver propagation in plasma
  - Driver diffraction/divergence, self-guiding and head-erosion
  - Plasma wave phase velocity ~ driver propagation velocity
    - Slippage - taper for laser-driven plasma waves
    - Self-trapping for low phase velocities
- **Driver-plasma coupling**
  - Staging for high-energy physics

Plasma-based accelerators for future colliders

- PWFA-linear collider:
- two-beam accelerator geometry
- 25 GeV drive beams
- 20 stages (1 TeV collider)
- 10^{17} cm^{-3} (set by 30 um driver bunch length)

Seryi et al., PAC09 (2009)

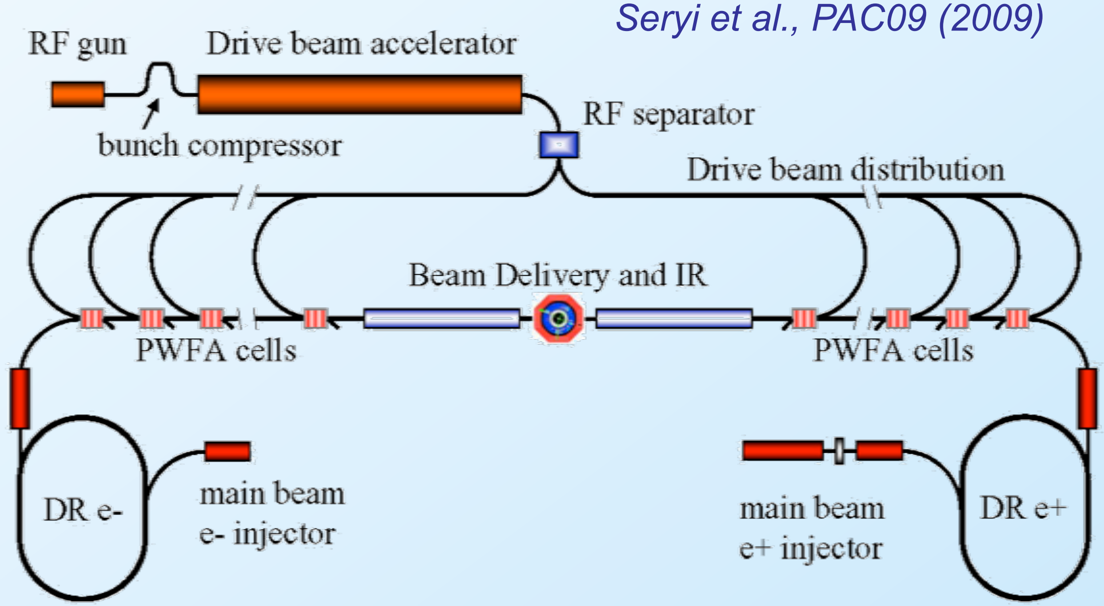
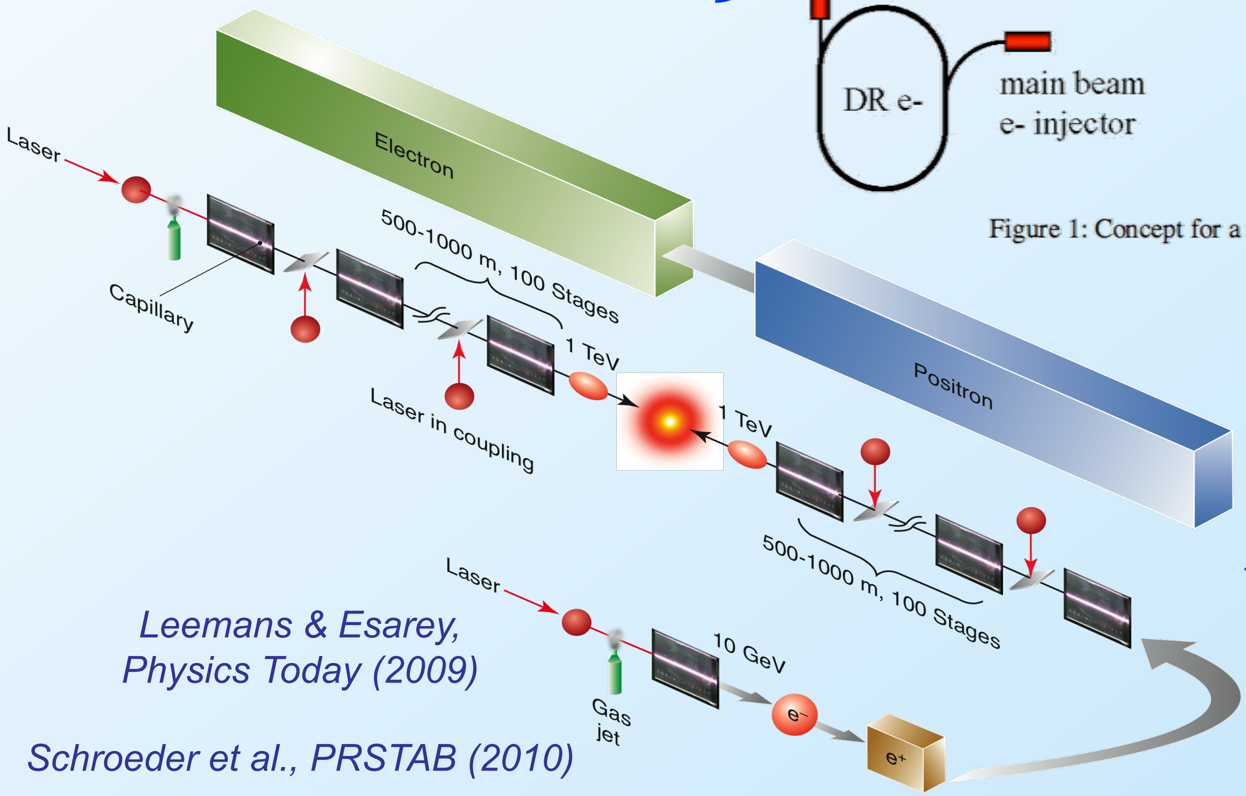


Figure 1: Concept for a multi-stage PWFA-based Linear Collider.



Leemans & Esarey, Physics Today (2009)

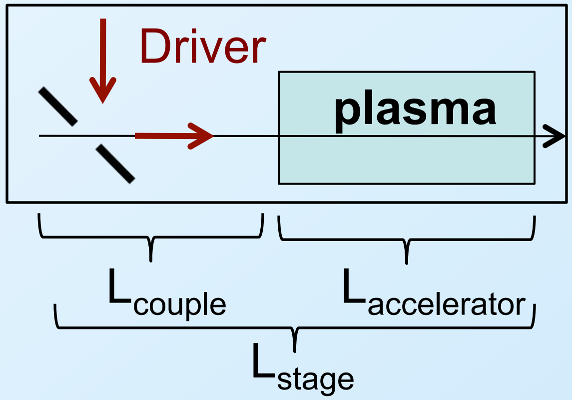
Schroeder et al., PRSTAB (2010)

- LPA-linear collider:
- 50 stages (1 TeV collider)
- 10 GeV/stage
- requires 10 J laser (tens of kHz, hundreds of kW)
- 10^{17} cm^{-3} (set by laser depletion)

High-energy physics applications: Staging plasma-based accelerators

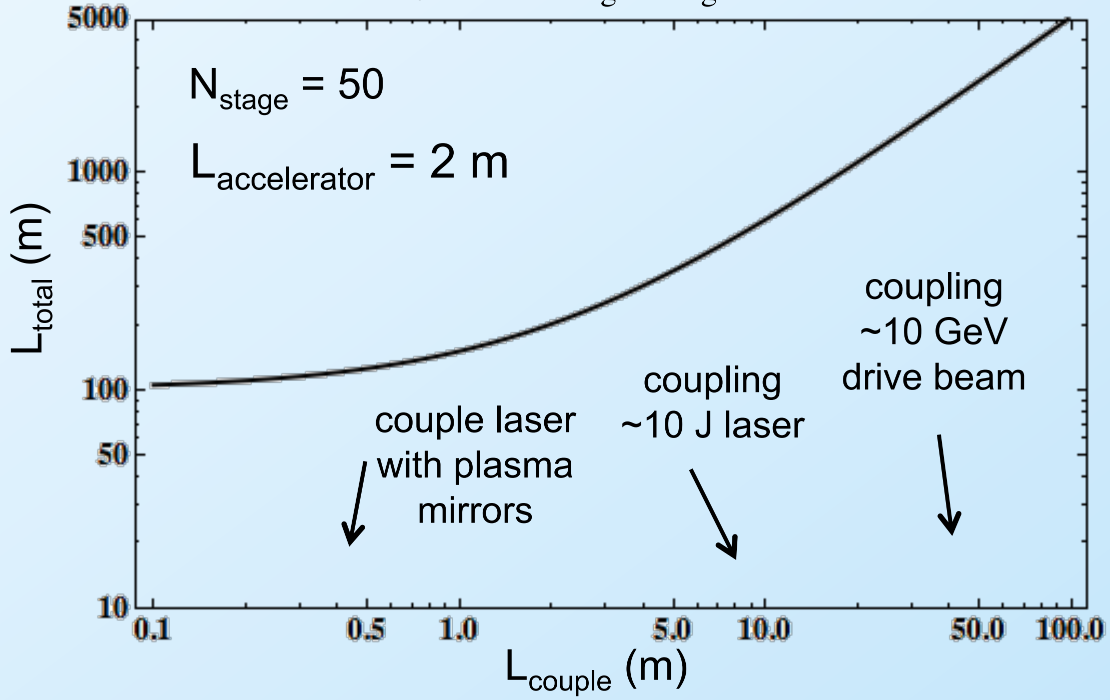
- For fixed driver energy, increasing beam energy will require staging

  Number of stages: $N_{stage} \sim W_{final} / W_{driver}$



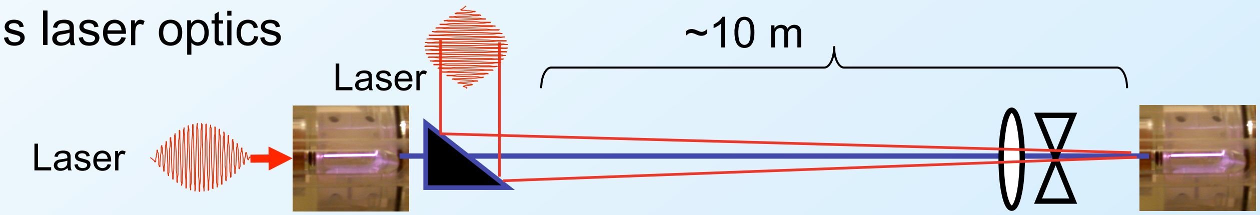
- Accelerator length will be determined by staging distance (technology)

$$L_{total} = N_{stage} L_{stage}$$

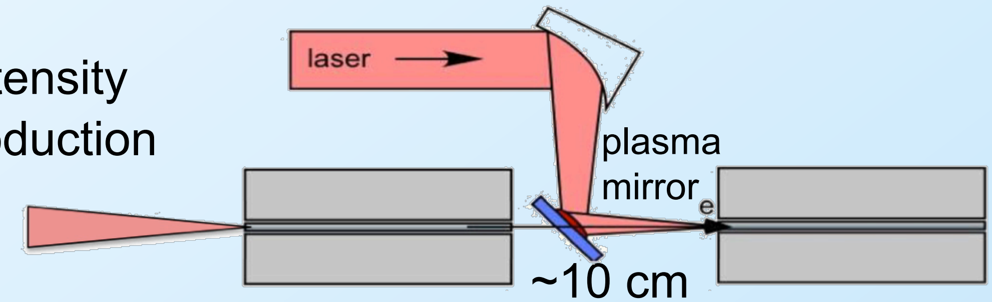


Laser in-coupling using plasma mirrors allows compact staging

- Conventional optics approach: stage length determined by damage on conventional final focus laser optics

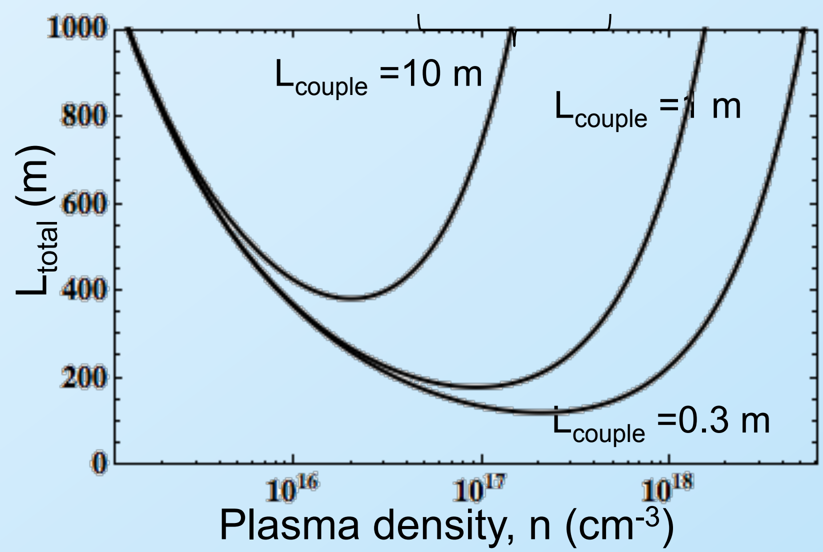


- Plasma mirror in-coupling:
  - “Renewable” mirror for high laser intensity
  - Relies on critical density plasma production
  - Thin liquid jet or foil (tape)
  - Laser contrast crucial (>10^{10})



- Short in-coupling distance for plasma wave driver [high average (geometric) gradient]

Laser driver: $L_{accelerator} \sim n^{-3/2}$



Summary

- Laser or beams use different excitation mechanisms
  - Transverse field structure
  - Access to linear/non-linear regimes
  - Wake phase velocity
- Driver propagation:
  - Driver divergence
  - Driver-plasma interaction length and coupling length
- Driver technology:
  - High power, high efficiency, high rep rate beam-drivers available.
  - High average laser drivers under development
  - Laser footprint small: <10mx10m for 10's J delivering 1-10GeV beams
  - Beam-driver footprint potentially small: e.g., use X-band technology with high transformer ratio (asymmetric bunch)
- Many of these physics issues will be addressed at existing and future facilities: