Laser-Plasma Accelerators for Future Colliders

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ALEGRO Workshop

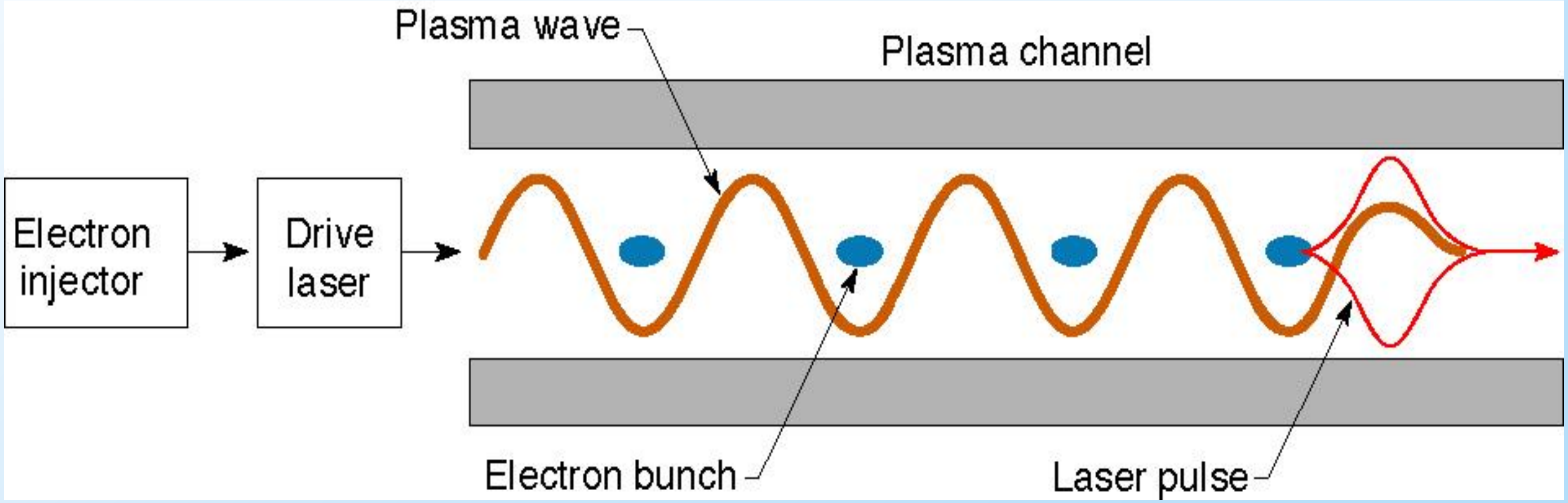
Oxford, UK, 26-29 March 2018

Supported by the U.S. DOE under Contract No. DE-AC02-05CH11231

Outline

- LPA basics
- Scaling laws: Quasi-linear regime
- Zeroth-order picture of LPA collider assuming idealized physics
- Real-world physics that further complicate LPA collider
- Other concepts: multiple pulses

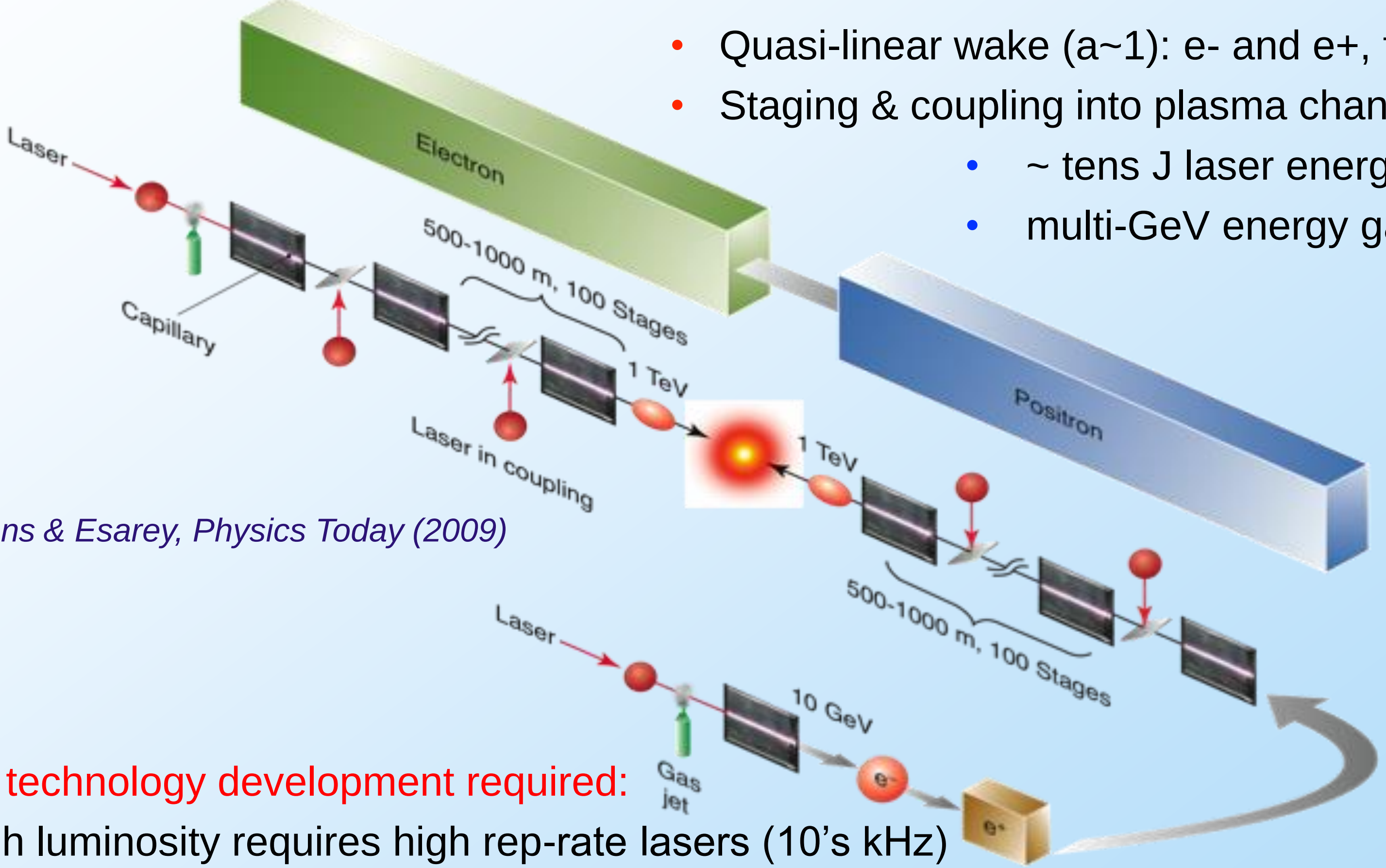
Laser-Plasma Accelerator



Laser-plasma accelerator-based collider concept

Schroeder et al., PR ST-AB (2010); Schroeder et al., PR ST-AB (2012); Schroeder et al., NIMA (2016)

- Plasma density scalings—minimize construction (max. gradient) and operational costs (min. wall power)—indicates: $n \sim 10^{17}$ cm^{-3}
- Quasi-linear wake (a~1): e- and e+, focusing control
- Staging & coupling into plasma channels:
  - ~ tens J laser energy/stage
  - multi-GeV energy gain/stage



Leemans & Esarey, Physics Today (2009)

Laser technology development required:

- High luminosity requires high rep-rate lasers (10’s kHz)
- Requires development of high average power lasers (100’s kW)
- High laser efficiency (~tens of %)

Laser-plasma accelerators (LPAs)

Tajima & Dawson, Phys. Rev. Lett. (1979); Esarey, Schroeder, Leemans, Rev. Mod. Phys. (2009)

$$\underbrace{\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_0}}_{} = \underbrace{c^2\nabla^2\frac{1}{4}\left(\frac{eE_{\text{laser}}}{mc^2\omega}\right)^2}_{}$$

Linear regime

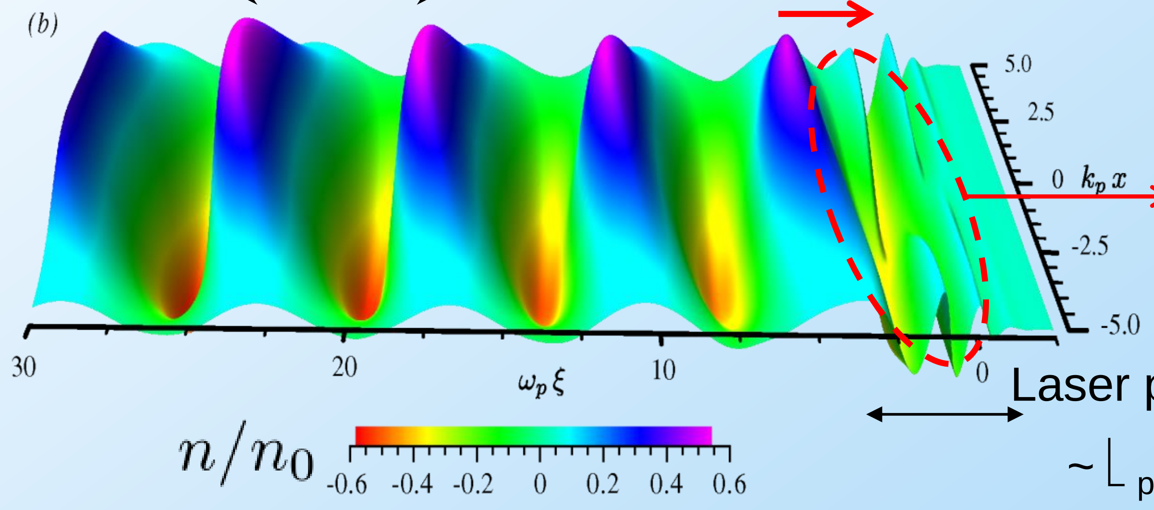
~ a_0^2

Plasma wave: electron density perturbation

Laser ponderomotive force (radiation pressure)

$⎣_p = 2□c/⎤_p = (□r_e^{-1/2})\ n_p^{-1/2}$ ~30 ⌠m

$v_{\text{phase}} \simeq v_{\text{group}} \simeq c$



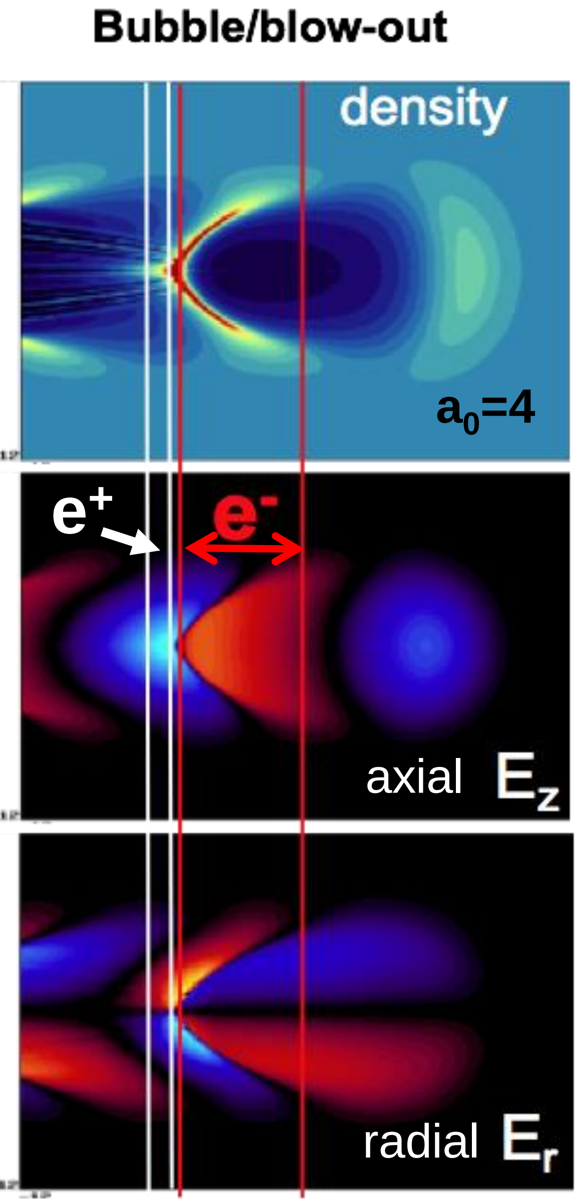
short pulse, ultra-intense laser: I~10^{18} W/cm^2

Laser pulse duration

~$⎣_p$/c ~ tens fs

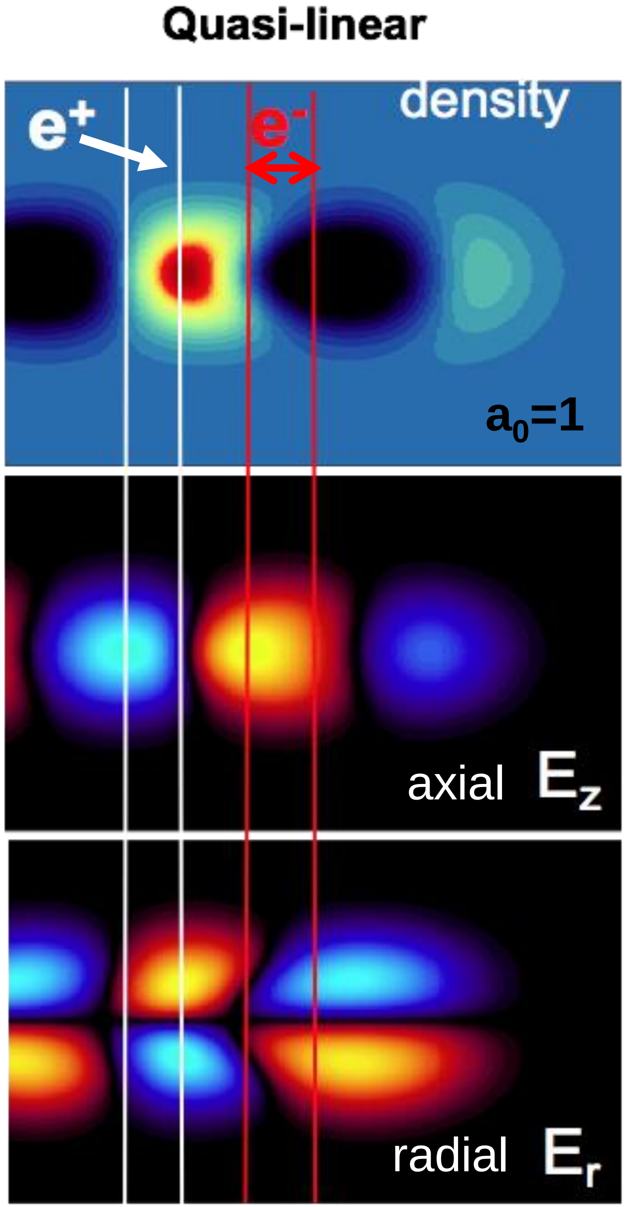
electron plasma density perturbation

Wake structure depends on laser strength



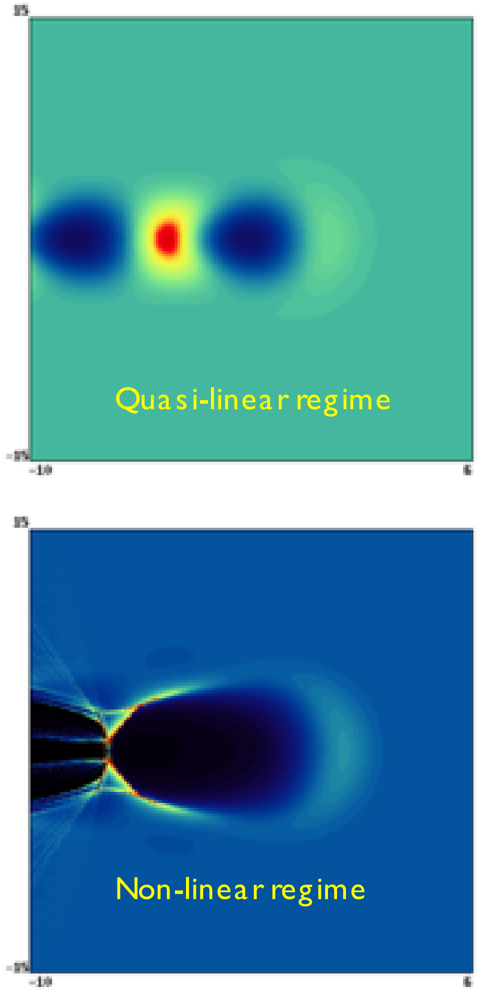
- Blowout regime
  - $a_0 >> 1$
  - very asymmetric
    - focuses e-
    - defocuses e+
  - self-trapping
  - self-guiding

- Quasi-linear
  - $a_0 \sim 1$
  - symmetric e+/e-
  - dark current free
  - channel required
  - tailor focusing forces via laser profile

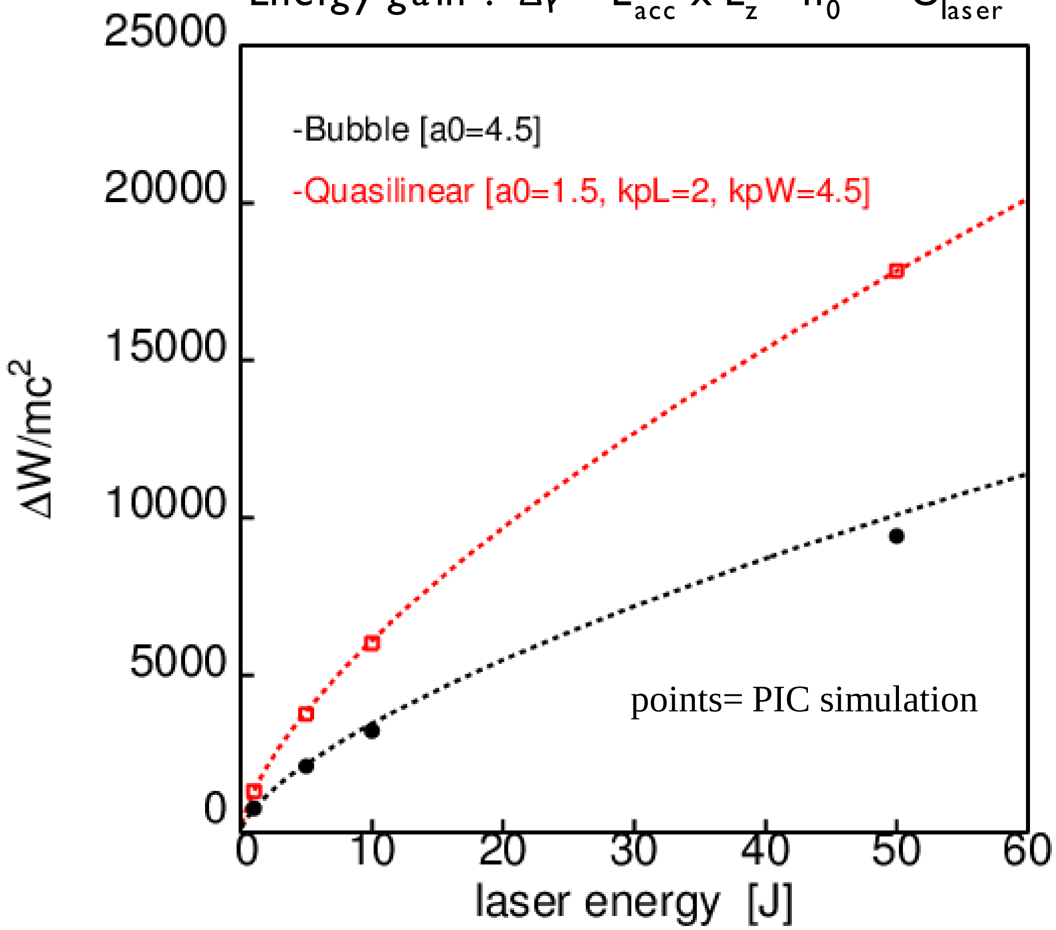


Laser-plasma accelerators can operate in non-linear (bubble) or quasi-linear regimes

electron plasma density



Energy gain*: $\Delta\gamma \sim L_{acc} \times E_z \sim n_0^{-1} \sim U_{laser}^{2/3}$

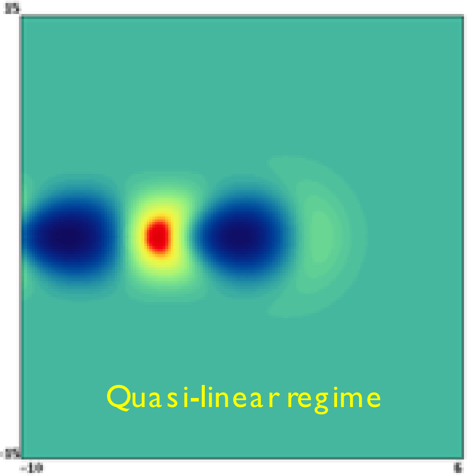


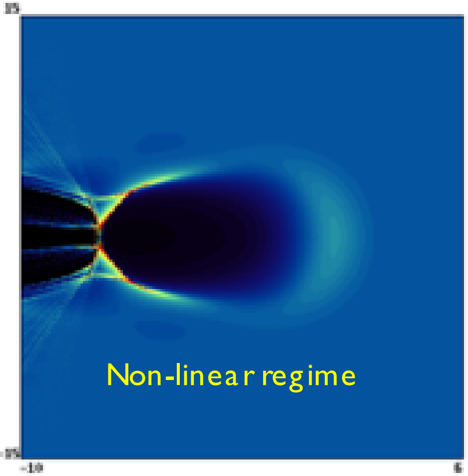
- ➢ Guiding at lower density achieved in quasi-linear regime with channel for fixed laser energy

*Passive (i.e.. no beam loading), short bunch (k_pL_b=0.2)

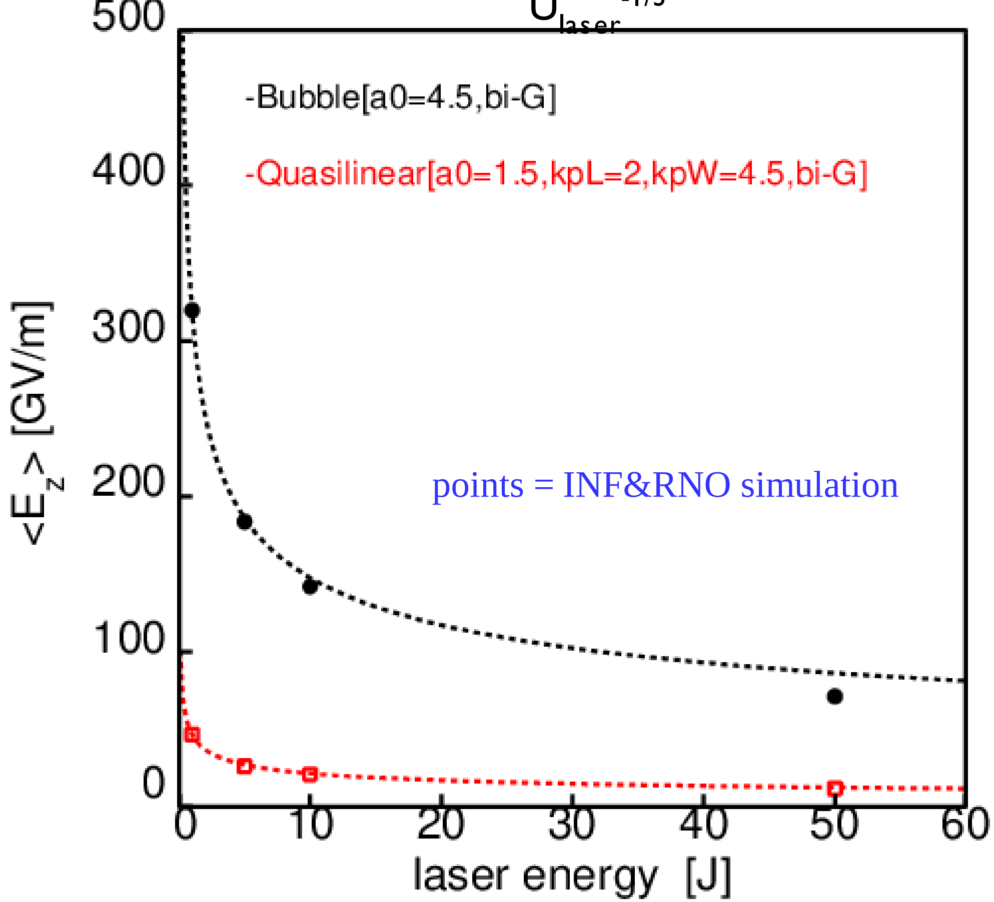
Laser-plasma accelerators can operate in non-linear (bubble) or quasi-linear regimes

electron plasma density





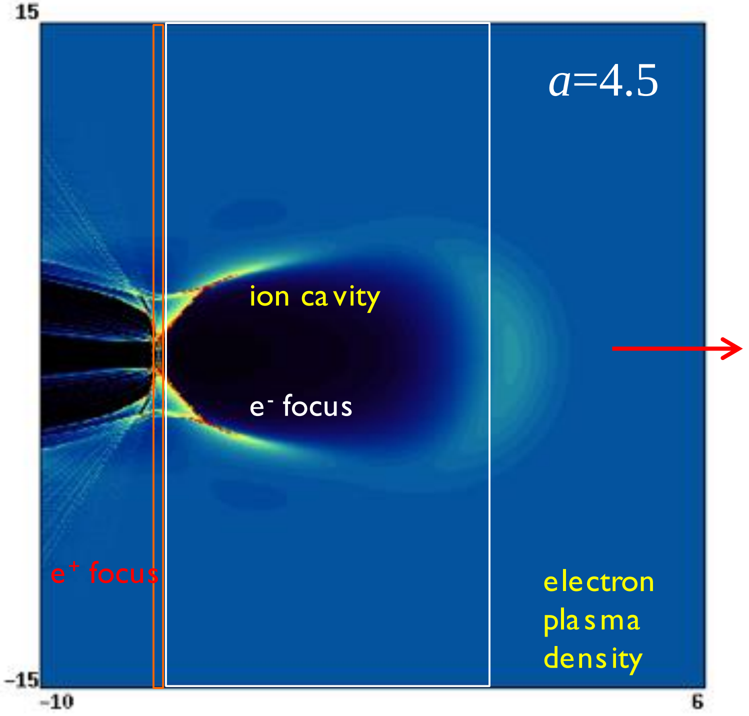
Accelerating gradient: $E_z \sim E_0 \sim n_0^{1/2} \sim U_{laser}^{-1/3}$



- ➢ Quasilinear regime operates at lower density:
- ➢ Higher bunch charge, higher efficiency

Positron beam quality preservation in highly-nonlinear regime difficult

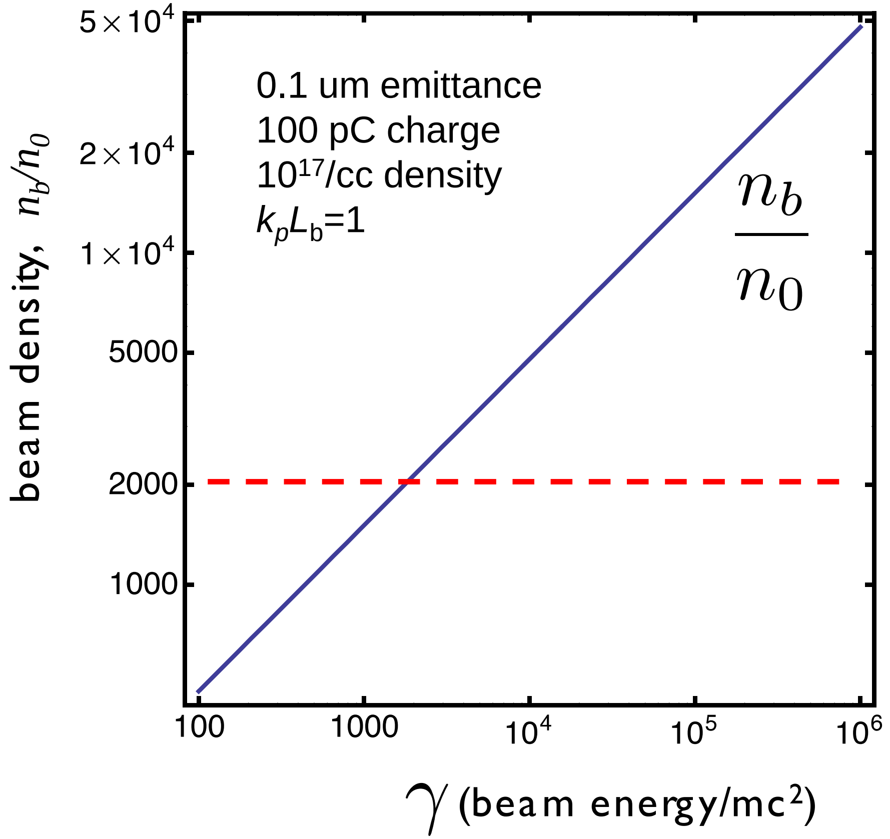
- In nonlinear regime, laser can self-guide in plasma and generate large accelerating fields
  - Condition for guiding: $a \sim (k_p w_L)^2/4$
  - Peak field: $E_z \approx (mc\omega_p/e)\, a^{1/2}$



- High intensity (a^2>>1)
- Forms ion cavity
- Self-trapping present (staging difficult)
- Strong laser evolution
- Electron focusing determined by background ion density
- Positron acceleration and focusing (with high beam quality preservation) difficult (nonlinear accelerating and focusing fields)

Independent control of beam focusing required: Strong focusing from plasma yields ion motion

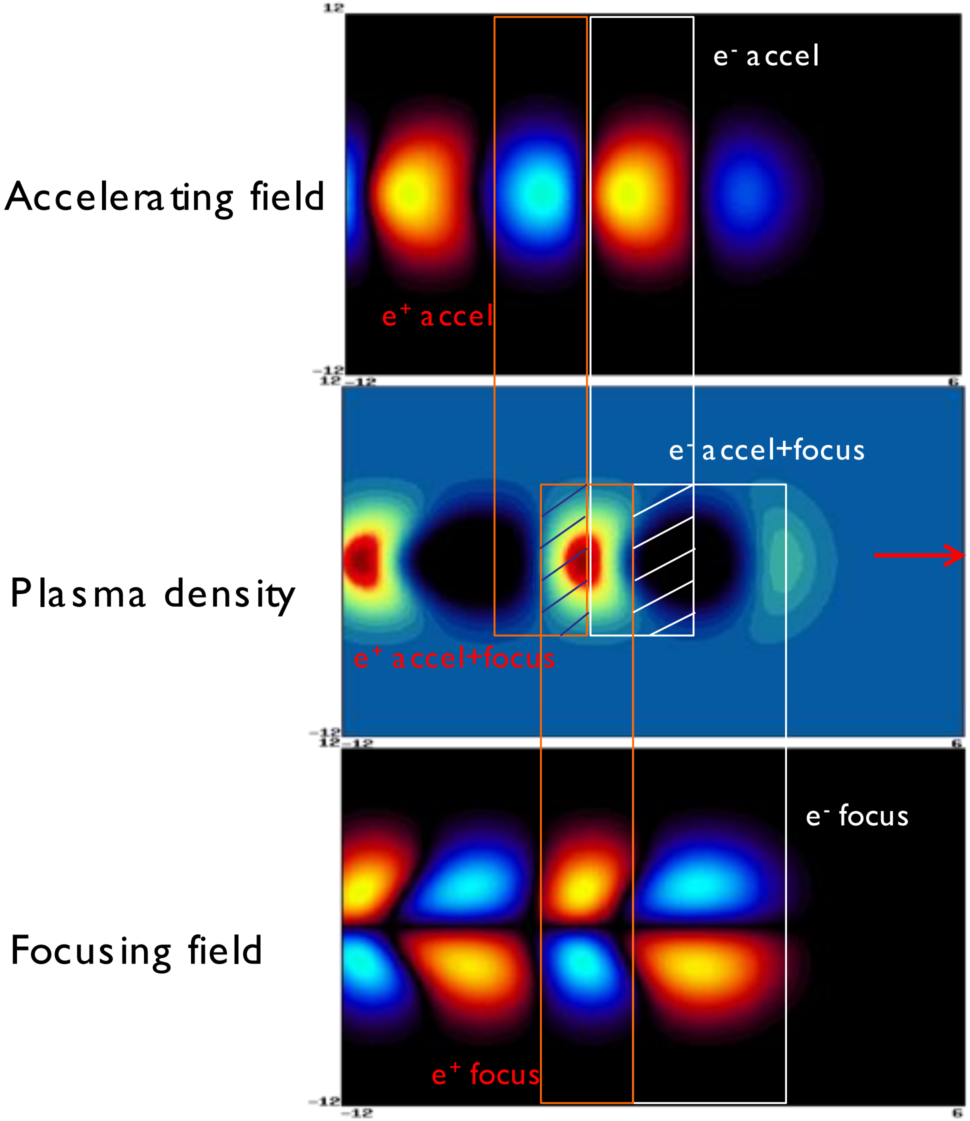
- Focusing due to background plasma ions: $\sigma_x^2 = \frac{\epsilon_n}{\gamma k_\beta} = \sqrt{\frac{2}{\gamma}}\frac{\epsilon_n}{k_p}$



Rosenzweig et al., PRL (2005)

← Ion motion (non-linear focusing head-to-tail; emittance growth) $\frac{n_b}{n_0} \gtrsim \frac{2M_i}{Zm_e}$

Quasilinear regime: e+ focus and acceleration, Independent control of focus and acceleration



- Quiver momentum weakly-relativistic (*a*~1)
- Region of accelerating/focusing for both electrons and positrons
- Stable laser propagation
- Independent control of accelerating and focusing forces:
  - Driver transverse profile

$$F_\perp \propto \nabla_\perp a^2$$

Cormier-Michel et al., PRST-AB (2011)

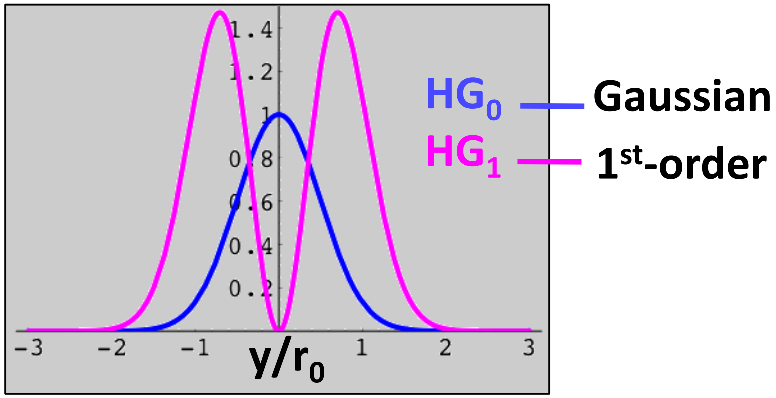
  - Plasma channel profile

Schroeder et al., Phys. Plasmas (2013)

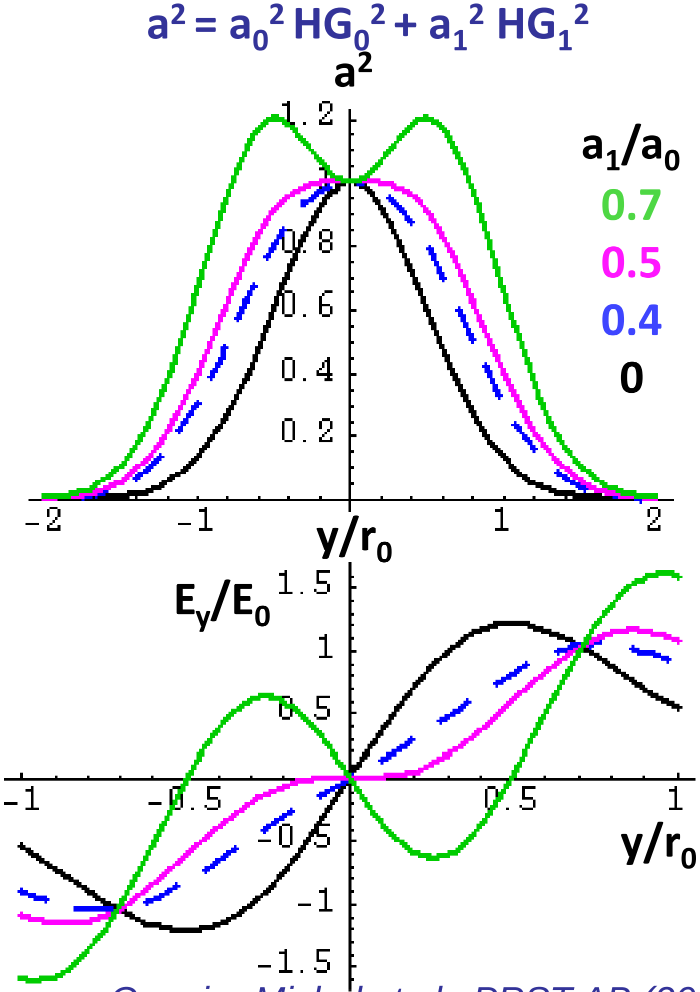
Quasilinear regime: shape transverse laser intensity for control of transverse wake

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

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

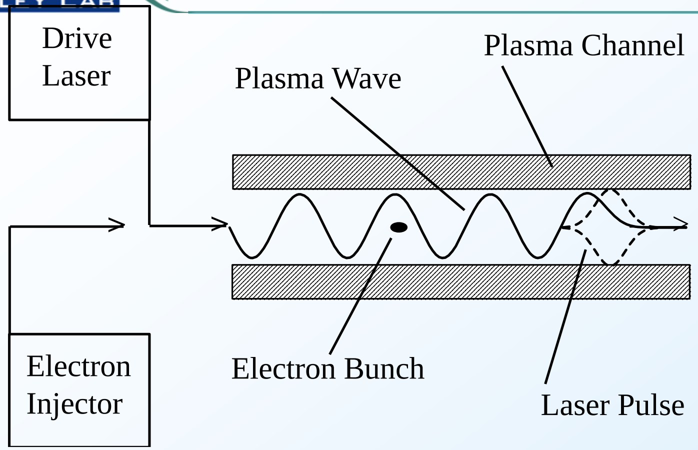


- Allows additional (independent) control of focusing forces (and matched beam spot)



Cormier-Michel et al., PRST-AB (2011)

(near-) Hollow plasma channels: ultra-low emittance preservation



- Provides structure for laser guiding (determined by channel depth not on-axis density)
- Excellent wakefield properties in plasma channel and *independent* control over accelerating and focusing forces
  - Accelerating wakefield transversely uniform
  - Focusing wakefield linear in radial position and uniform longitudinally

- (Near-) hollow plasma channel geometry provides emittance preservation
  - Mitigates Coulomb scattering

Schroeder et al., Phys. Plasmas (2013)

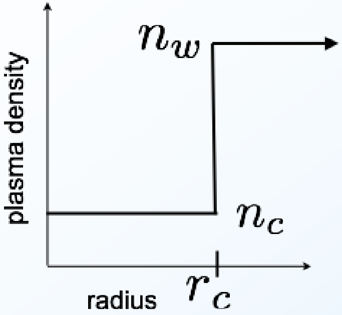
$$\epsilon_{nf} = \left[\epsilon_{ni}^2 + \frac{\sigma_x^2 r_e Z_w \beta_{\rm th}}{(E_z/E_w) r_c}(\gamma_f - \gamma_i)\right]^{1/2} \sim \left(\frac{r_e \beta_{\rm th} \gamma_f}{k_p}\right)^{1/2}$$

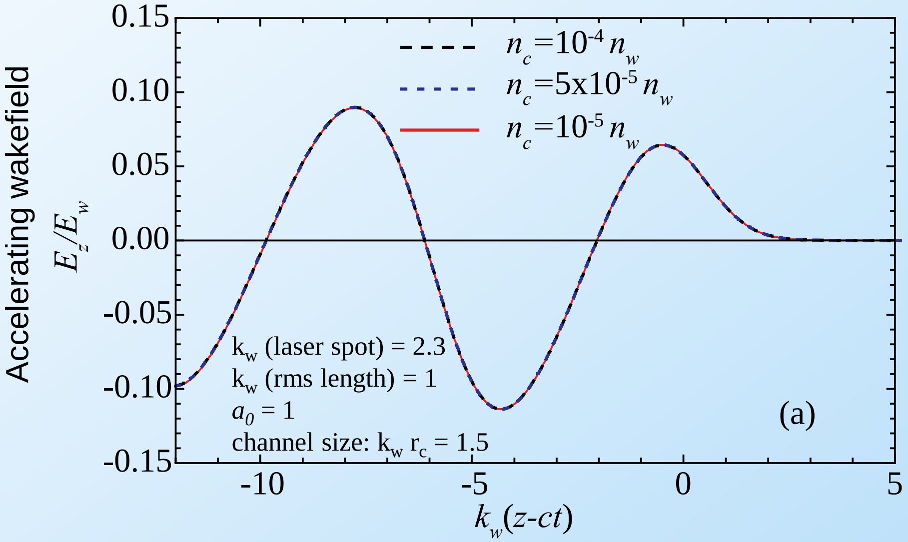
For relevant 1 TeV collider parameters: $\epsilon_{nf} \sim 10^{-9}$ m

- Control of focusing force and beam density – prevents ion motion

Ion motion negligible if ratio of beam density to wall density is less than ion-electron mass ratio $(n_b/n_w) < M_i/m_e$

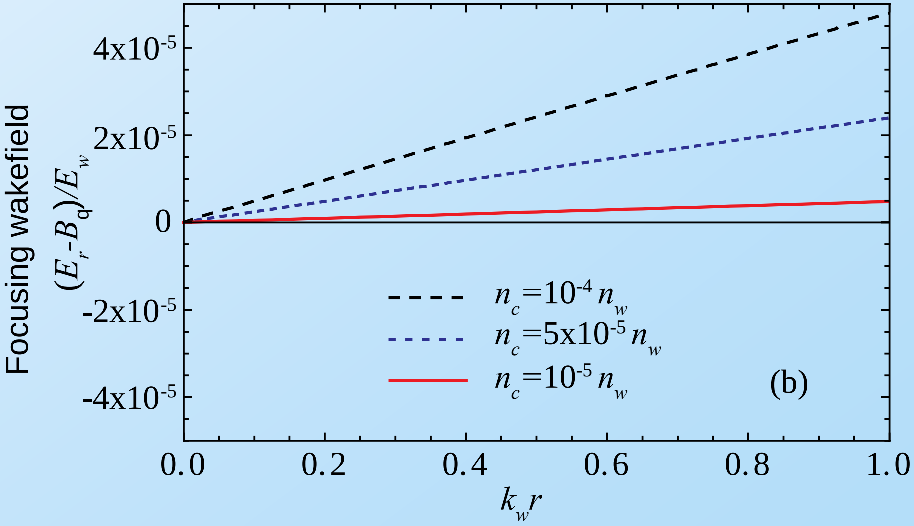
Near-hollow plasma channel: Independent control of acceleration and focusing





- Accelerating wakefield set by wall density

$$E_z \sim E_w = m_e c^2 k_w / e \propto \sqrt{n_w}$$



- Focusing (for electrons) wakefield set by channel density

$$E_r - \beta B_\theta = E_c k_c r / 2 \propto n_c$$

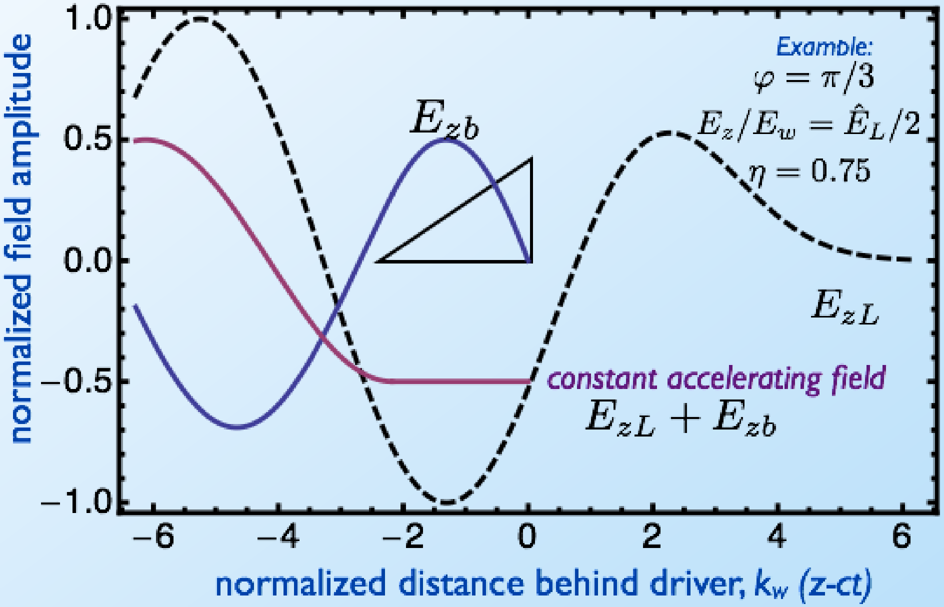
Modeled with PIC code INF&RNO

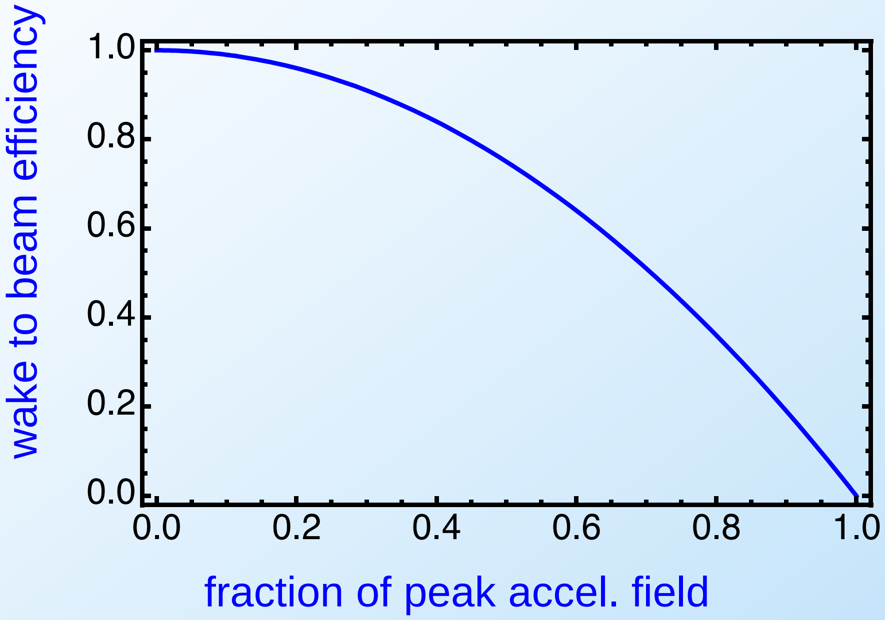
Shaped beams required for high-efficiency acceleration

Schroeder et al., Phys. Plasmas (2013)

- Energy spread minimized using shaped beams
  - Ramped/triangular current distribution:

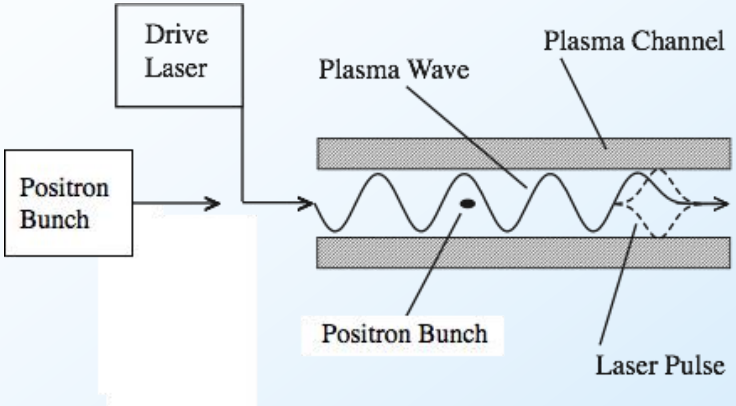
$$I = (1 + \zeta/L_b)I_b$$



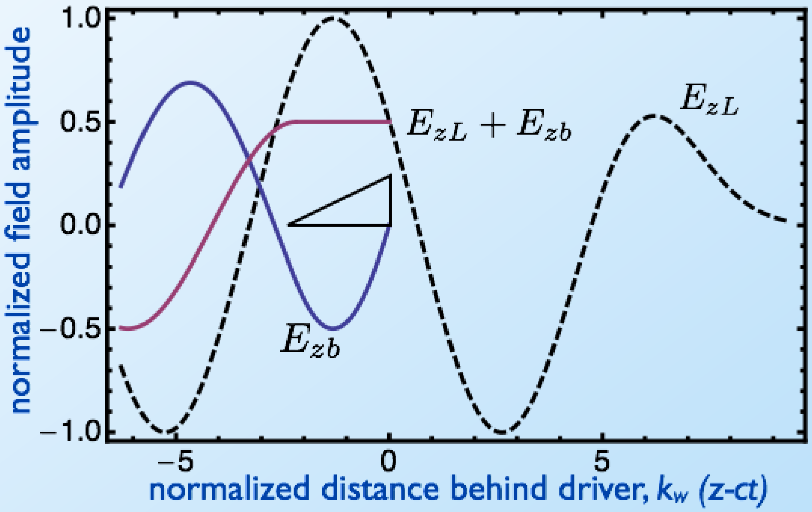


- Beam charge: $N_b \propto n_w^{-1/2}$
  - Lower plasma density, higher bunch charge

Positron beams accelerated in hollow plasma channel with external focusing



- Acceleration of positron beam in quasi-linear regime in hollow plasma channel:

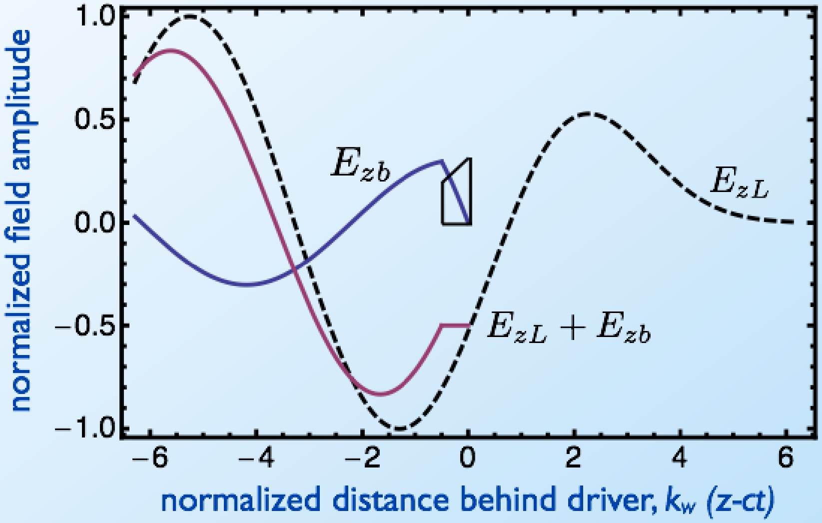


- Provide external focusing for positrons

Bunch trains allow ultra-short bunch accel. with high efficiency, without energy spread growth

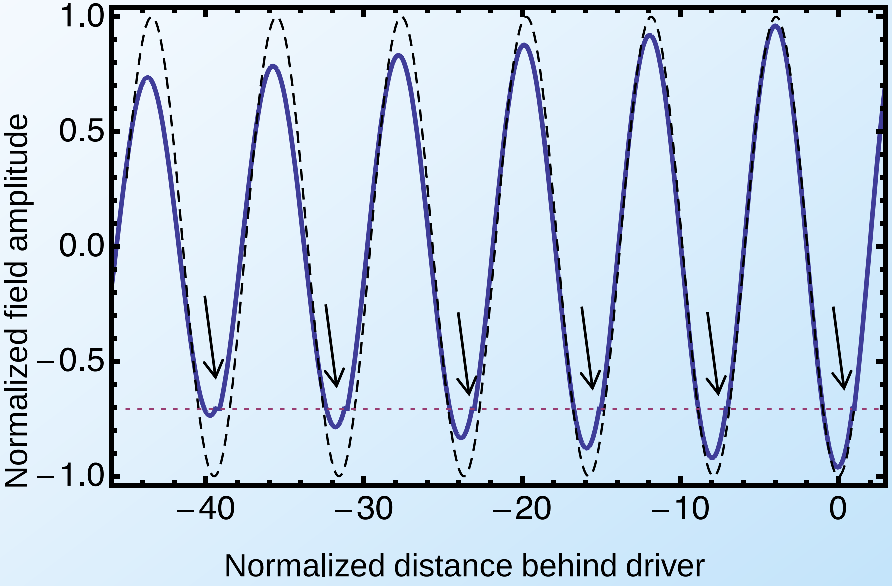
- Ultra-short beams suppress beamstrahlung
  - Beamstrahlung photons/electron

$$n_\gamma \propto \mathcal{L}^{1/3}\sigma_z^{1/3}$$



- Improved efficiency using bunch trains

$$k_w L_1 = 0.1$$



1 bunch:
$$\eta_1 \simeq 0.08$$

6 bunches:
$$\eta_{\text{total}} \simeq 0.5$$

$$E_z = E_L \cos(\pi/4) = E_L/\sqrt{2}$$

- Using bunch trains, trade-off between efficiency and gradient, with no energy spread growth

LPA plasma density scalings: Staging required

- Laser-plasma interaction (depletion) length:

$$L_{\rm acc} \sim \lambda_p^3/\lambda_L^2 \propto n^{-3/2}$$

- Accelerating gradient:

$$E \sim E_0 = (m_e c\omega_p/e) \propto \sqrt{n}$$

- Energy gain:

$$W \sim (mc\omega_p/e)\, L_{\rm acc} \propto 1/n$$

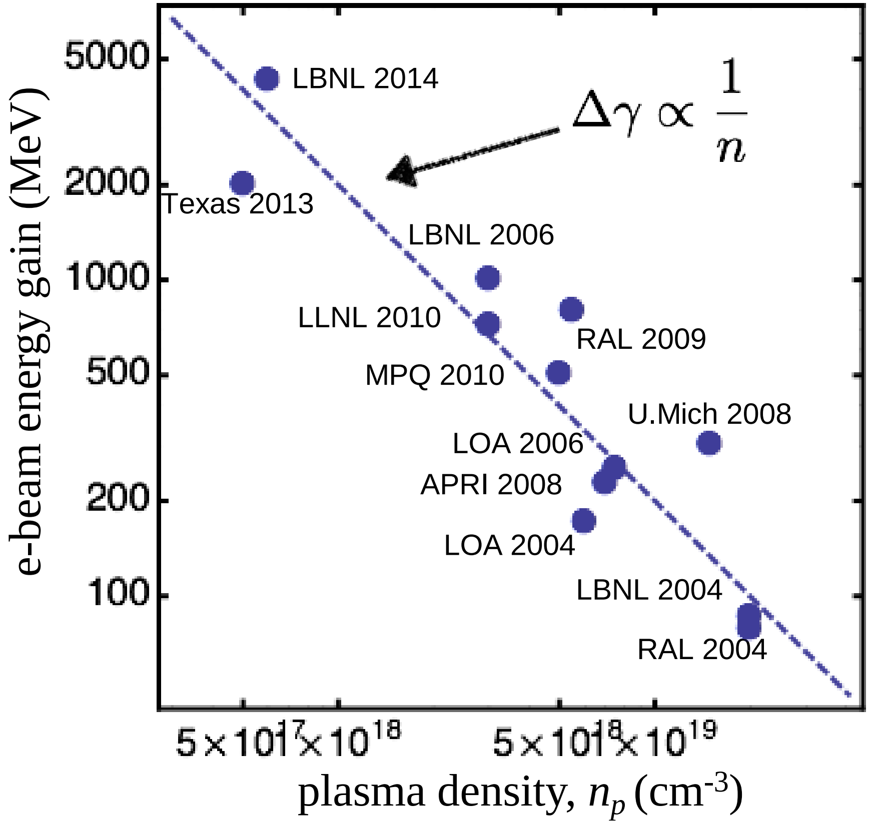
For high-energy applications, laser depletion (and reasonable gradient) necessitates staging

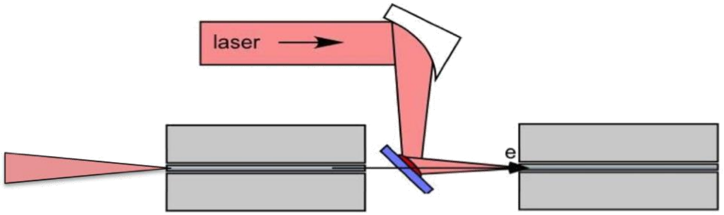
Scalings verified with simulations

LPA Examples (single stage):

W ~ 1 GeV	W ~ 10 GeV
n ~ 10^{18} cm^{-3}	n ~ 10^{17} cm^{-3}
L_{acc} ~ 3 cm	L_{acc} ~ 1 m
U_{laser} ~ 1 J	U_{laser} ~ 40 J
P_{laser} ~ 100 TW	P_{laser} ~ 1 PW (eg,BELLA)

LPA Experiments (single stage)





Beam loading simulations predicts 300-500 pC for 10 GeV stages

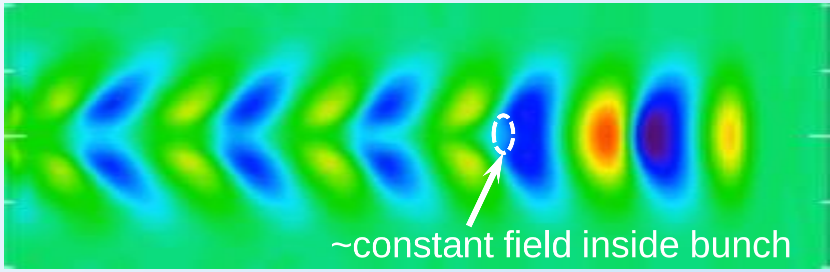
- Beam loading theoretical limit
  - e-bunch wake = laser wake
  - Linear theory , $k_p \sigma_z < 1$, $k_p \sigma_r \sim 1$
  - $N_b \sim 9\mathrm{x}10^9 (n_0/10^{16}\,\mathrm{cm}^{-3})^{-1/2} (E_z/E_0)$
  - Ex.: $N_b = 3\mathrm{x}10^9$ (0.5 nC) for $n_0 = 10^{17}$ cm^{-3} and $E_z/E_0=1$

- VORPAL PIC simulations

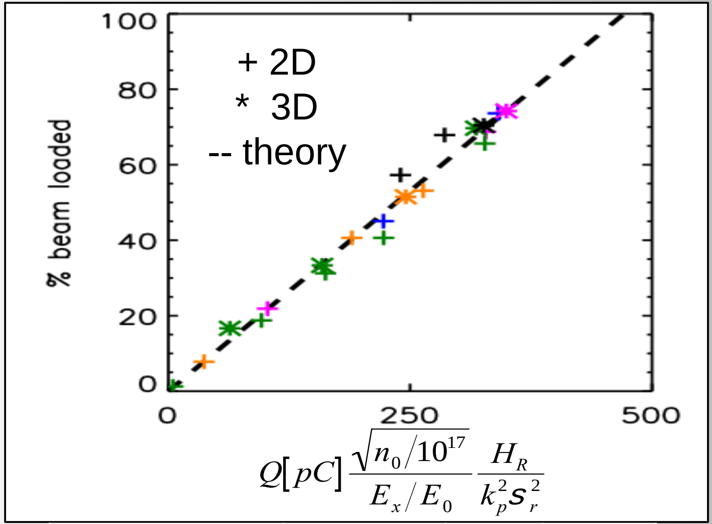
- 500 pC at 10^{17} cm^{-3} for $k_pL=2$, $k_p\sigma_r \sim 2$
  - 10% of laser energy to electrons

- Bunch length & profile alters field inside bunch
  - flatten field across bunch – reduces ΔE
  - focusing must be matched for emittance

- Ongoing: precise control w/shaped bunches



Quasi-linear beam loading matches linear theory



density & k_pL:	$k_p\sigma_r$ = 0.3	1	1.8
k_pL =2, a_0=1 $n_0 = 10^{18}$ cm^{-3}			+*
k_pL =2, a_0=1 $n_0 = 10^{19}$ cm^{-3}	+*	+*	+*
k_pL =1, a_0=1.4 $n_0 = 10^{19}$ cm^{-3}	+		

* Cormier-Michel et al, Proc. AAC 2008, **Katsouleas PRA 1986

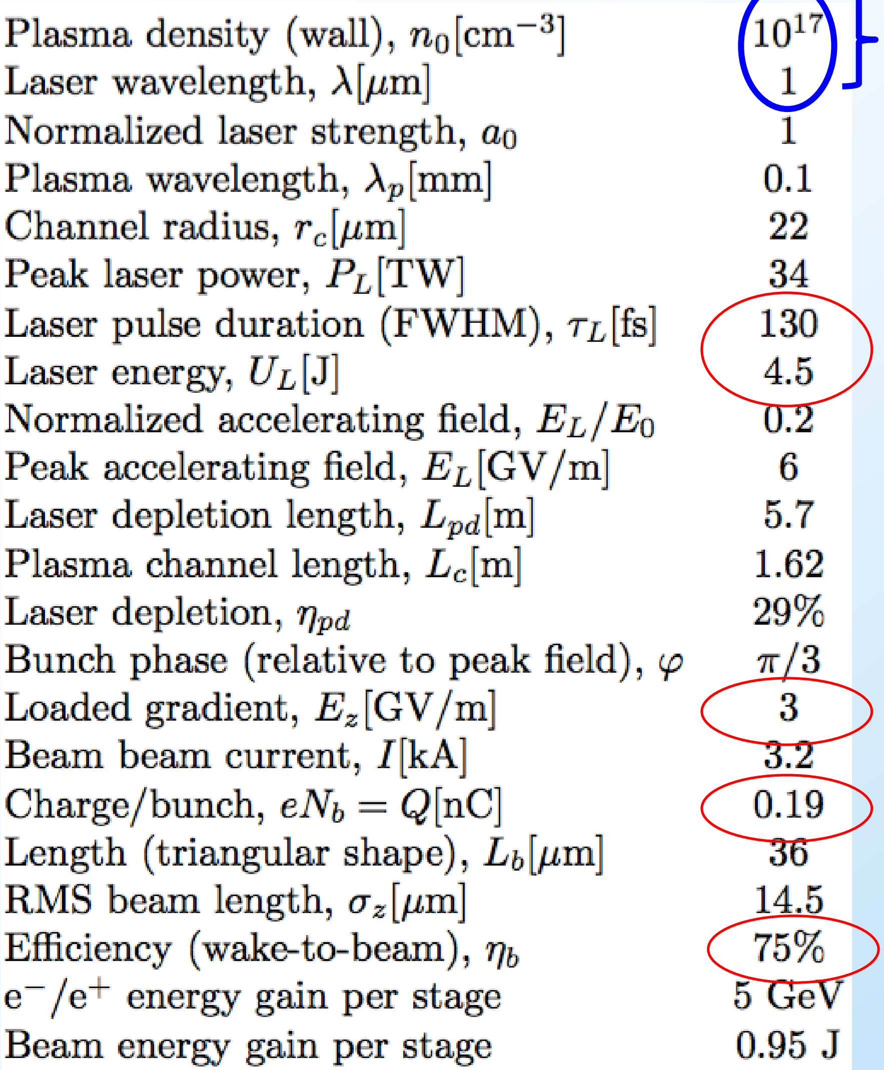
Collider Requirements: Luminosity

- Rate of events: (luminosity) x (collision cross-section)
- Luminosity: cross-section $\mu\ g^{-2}$ ➔ $L[10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}] \gg \left(E_{cm}[\mathrm{TeV}]\right)^2$

$$L = \frac{fN^2}{4ps_x s_y} = \frac{P_b}{4pE_{cm}} \frac{N}{s_x s_y}$$

  - For fixed beam power, $P_b=2f\,N_b(\gamma mc^2)$, transverse beam density must be increased
- Limitations:
  - Achievable beam emittance
  - Final focus optics to IP: adiabatic plasma lens
  - Beam-beam interaction (beamstrahlung)
  - Emittance growth in main linacs (beam scattering in plasma)

Example set of LPA stage parameters for collider



Plasma density (wall), $n_0[\mathrm{cm}^{-3}]$	10^{17}
Laser wavelength, $\lambda[\mu\mathrm{m}]$	1
Normalized laser strength, a_0	1
Plasma wavelength, $\lambda_p[\mathrm{mm}]$	0.1
Channel radius, $r_c[\mu\mathrm{m}]$	22
Peak laser power, $P_L[\mathrm{TW}]$	34
Laser pulse duration (FWHM), $\tau_L[\mathrm{fs}]$	130
Laser energy, $U_L[\mathrm{J}]$	4.5
Normalized accelerating field, E_L/E_0	0.2
Peak accelerating field, $E_L[\mathrm{GV/m}]$	6
Laser depletion length, $L_{pd}[\mathrm{m}]$	5.7
Plasma channel length, $L_c[\mathrm{m}]$	1.62
Laser depletion, η_{pd}	29%
Bunch phase (relative to peak field), φ	$\pi/3$
Loaded gradient, $E_z[\mathrm{GV/m}]$	3
Beam beam current, $I[\mathrm{kA}]$	3.2
Charge/bunch, $eN_b = Q[\mathrm{nC}]$	0.19
Length (triangular shape), $L_b[\mu\mathrm{m}]$	36
RMS beam length, $\sigma_z[\mu\mathrm{m}]$	14.5
Efficiency (wake-to-beam), η_b	75%
$\mathrm{e}^-/\mathrm{e}^+$ energy gain per stage	5 GeV
Beam energy gain per stage	0.95 J

- LPA stage density and wavelength scalings:

$$E_z \propto n^{1/2}$$

$$L_{\mathrm{stage}} \propto n^{-3/2}\lambda^{-2}$$

$$U_{\mathrm{stage}} \propto n^{-1}\lambda^{-2}$$

$$\tau_{\mathrm{laser}} \propto n^{-1/2}$$

$$U_{\mathrm{laser}} \propto n^{-3/2}\lambda^{-2}$$

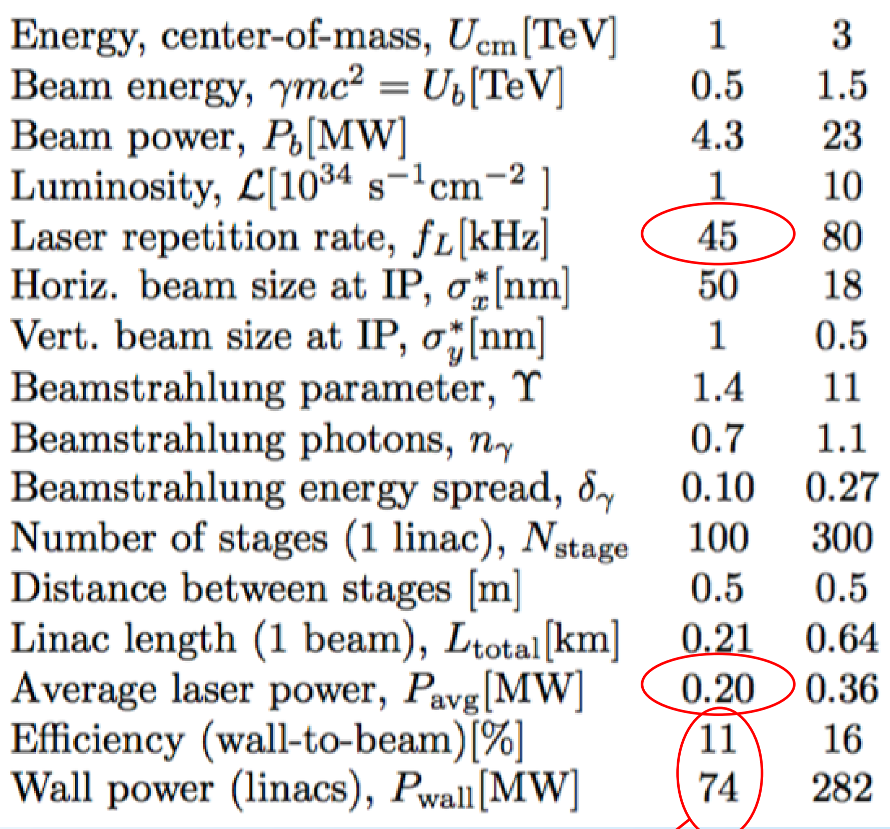
$$P_{\mathrm{laser}} \propto n^{-1}\lambda^{-2}$$

$$\sigma_z \propto n^{-1/2}$$

$$N_b \propto n^{-1/2}$$

Schroeder et al., NIMA (2016)

Examples for 1 TeV and 3 TeV CM colliders



Energy, center-of-mass, $U_{\rm cm}$[TeV]	1	3
Beam energy, $\gamma mc^2 = U_b$[TeV]	0.5	1.5
Beam power, P_b[MW]	4.3	23
Luminosity, $\mathcal{L}[10^{34}\ \mathrm{s}^{-1}\mathrm{cm}^{-2}]$	1	10
Laser repetition rate, f_L[kHz]	45	80
Horiz. beam size at IP, σ_x^*[nm]	50	18
Vert. beam size at IP, σ_y^*[nm]	1	0.5
Beamstrahlung parameter, Υ	1.4	11
Beamstrahlung photons, n_γ	0.7	1.1
Beamstrahlung energy spread, δ_γ	0.10	0.27
Number of stages (1 linac), $N_{\rm stage}$	100	300
Distance between stages [m]	0.5	0.5
Linac length (1 beam), $L_{\rm total}$[km]	0.21	0.64
Average laser power, $P_{\rm avg}$[MW]	0.20	0.36
Efficiency (wall-to-beam)[%]	11	16
Wall power (linacs), $P_{\rm wall}$[MW]	74	282

Assumed $\eta_{\rm laser}$ = 0.4 and $\eta_{\rm recovery}$=0.9

- Density and wavelength scalings (fixed Luminosity and laser efficiency):

$$N_{\rm stages} \propto n\lambda^2$$

$$L_{\rm linac} \propto n^{-1/2}$$

$$f_{\rm rep} \propto n$$

$$P_b \propto n^{1/2}$$

$$P_{\rm avg\ laser} \propto n^{-1/2}\lambda^{-2}$$

$$P_{\rm wall} \propto n^{1/2}$$

$$n_\gamma \propto n^{-1/2}$$

- Total efficiency:

$$\eta_{\rm total} = \frac{\eta_{\rm beam}\eta_{\rm pd}}{[1/\eta_{\rm laser} - (1-\eta_{\rm pd})\eta_{\rm recovery}]}$$

- Electrical-to-optical of diode-pumped lasers = 55%
- Optical-to-optical of fibers = 90%
- Combining/stacking fibers = 80%

Schroeder et al., NIMA (2016)

Short beams from LPA help control beamstrahlung

- Plasma-based accelerators accelerate ultra-short beams (~plasma skin depth)
- Plasma-based accelerators compatible with asymmetric (flat) beams

CLIC CONCEPTUAL DESIGN REPORT (2012)

	CLIC	**LPA**
CMS energy [TeV]	3	3
Luminosity [x10^{34} cm^{-2} s^{-1}]	6	10
Particle/bunch [x10^9]	3.7	1.2
Bunch length, rms [um]	44	14.5
IP beam size ratio, σ_x/σ_y	45	36
$\sigma_x\sigma_y$ at IP, [nm^2]	45	18
Beamstrahlung parameter	4.9	12
Photons/lepton, n_γ	2.1	1.1
Energy loss [%], δ_γ	0.29	0.27
Coherent pairs/BX [x10^8]	6.8	0.8

P. Chen and Telnov PRL (1989)

$$n_{\mathrm{coh}} \approx \frac{4\sqrt{3}}{25\pi}\left(\frac{\alpha^2\sigma_z\Upsilon}{r_e\gamma}\right)^2 \Xi(\Upsilon)$$

- Better IP background can be achieved with plasma accelerators owing to the short bunches
- Re-design damping/cooling system to be compatible with short beams

Power requirements reduced at lower density (Beamstrahlung limits charge/bunch)

Charge/bunch:

$$N \propto \frac{U_L}{\Delta\gamma} \propto n^{-1/2}$$

⇨

Laser rep. rate (for fixed luminosity):

$$f \propto n$$

⇨

Wall-plug power:

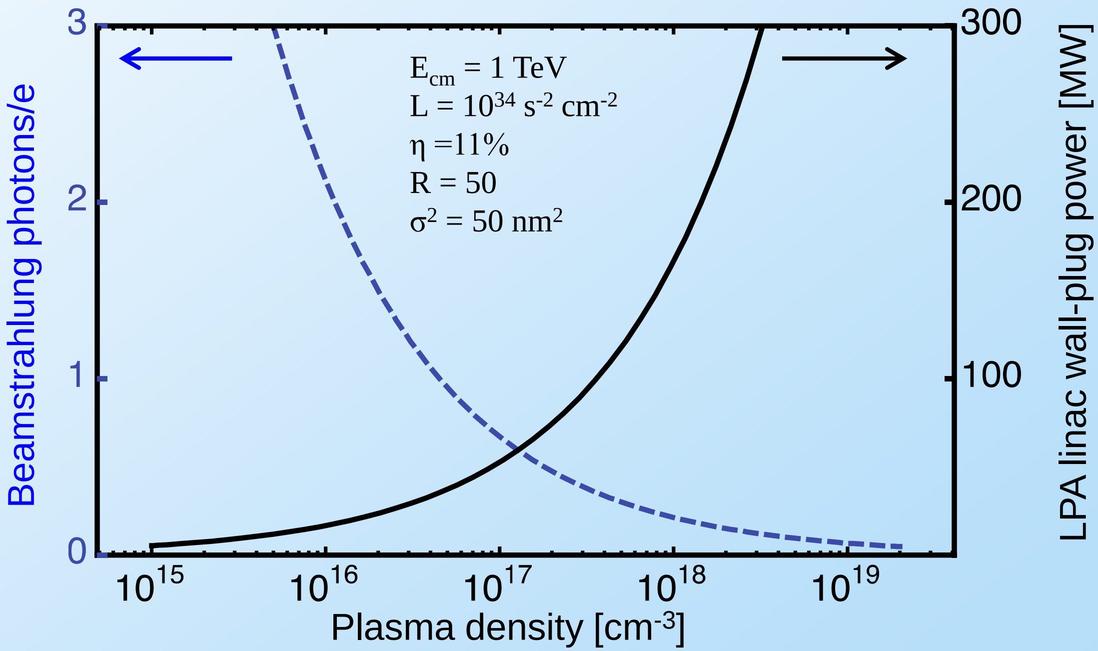
$$P \propto \sqrt{n}$$

Schroeder et al., PRST-AB (2010)

Charge/bunch limited by beamstrahlung:

$$n_\gamma \propto N^{2/3}\sigma_z^{1/3} \propto n^{-1/2}$$

Schroeder et al., PRST-AB (2012)



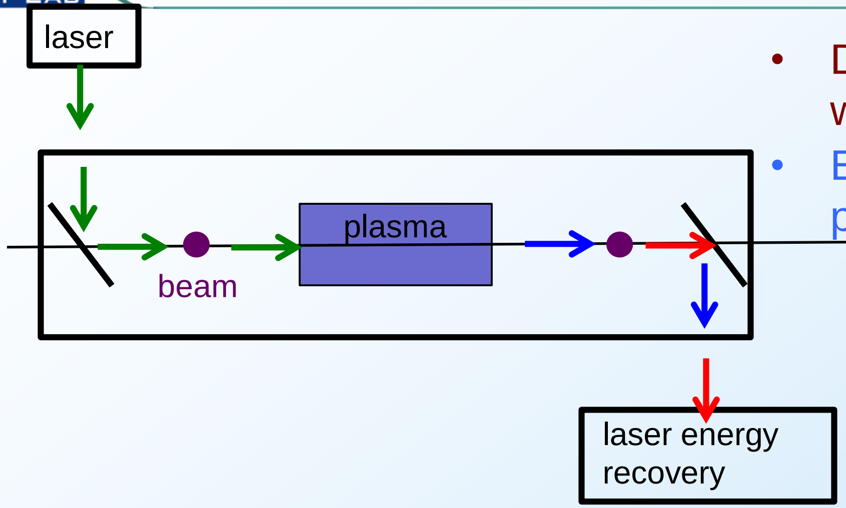
Beamstrahlung limited

Beam loading limited

Power scalings:

$$\frac{\mathcal{L}}{U_{\mathrm{cm}}^2} \propto \frac{n_\gamma^{3/2}\eta P_{\mathrm{wall}}}{\sigma_* \gamma^{5/2}\sigma_z^{1/2}}$$

Improved efficiency using laser energy recovery


laser

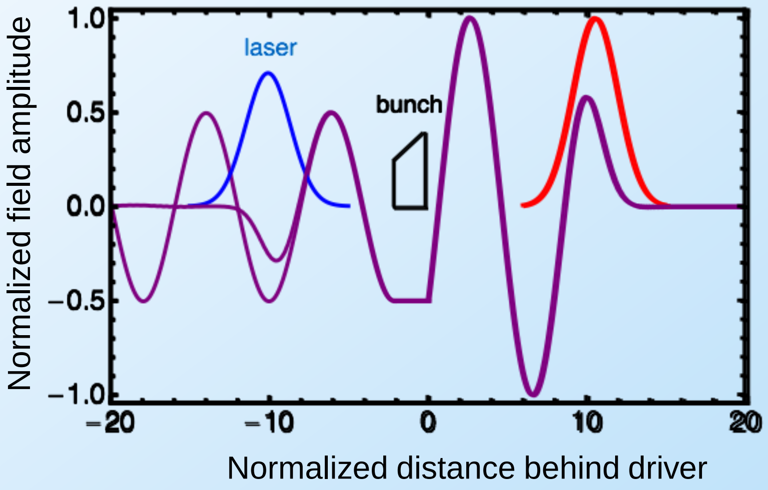
plasma

beam

laser energy recovery

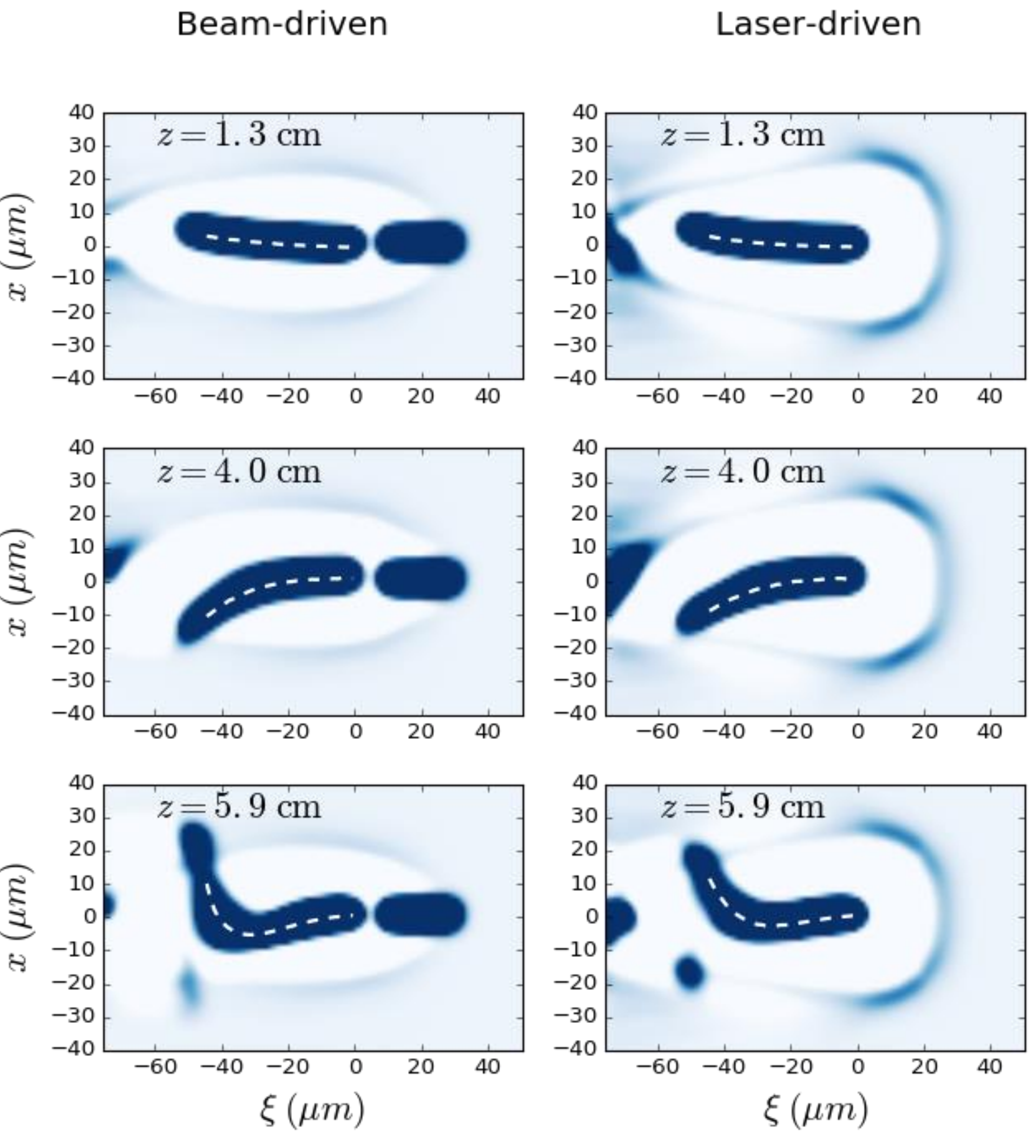
- Drive laser deposits energy into plasma wave (frequency red-shifts)
- Energy-recovery laser absorbs energy from plasma wave (frequency blue-shifts)

- Re-use laser in another LPA stage
- Send to photovoltaic (targeted to laser wavelength) – energy recovery



- Additional energy-recovery laser pulse allows for no energy to remain in coherent plasma oscillations after energy transfer to beam – heat management

BBU/Hosing: Similar behavior for similar wakes independent of driver



Parameters:

- Plasma density: 2e17 cm-3
- Beam density: 50e17 cm-3
  (~ 800 pC)
- Laser a0: 3
- Laser waist: 16 microns
- Laser duration: 30 fs

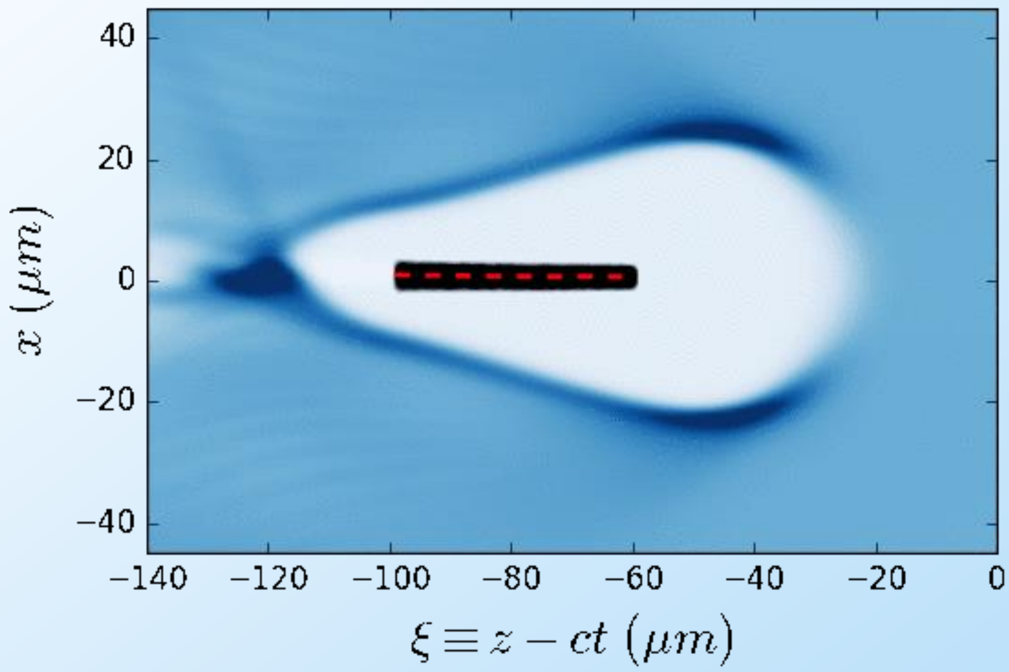
Ponderomotive implementation of laser envelope in Warp:

$$\vec{F} = -\frac{mc^2}{2(1+\vec{u}^2+\langle\vec{a}^2\rangle)^{1/2}}\vec{\nabla}\langle\vec{a}^2\rangle$$

- Driver (Beam/Laser) is not evolving

Beam hosing (BBU instability): Transverse bunch oscillation in wake

Growth of centroid oscillations owing to resonance with wakefield



simulation using WARP

Hosing limits plasma accelerator length

- Centroid oscillation evolution equation:

wakefield mode wavenumber

$$\partial_z^2 x_c(\xi, z) + k_\beta^2\, x_c(\xi, z) = k_c^2 \int_\xi^0 \sin(\kappa_p(\xi' - \xi))x_c(\xi', z)\ \kappa_p d\xi'$$

centriod offest

betatron motion

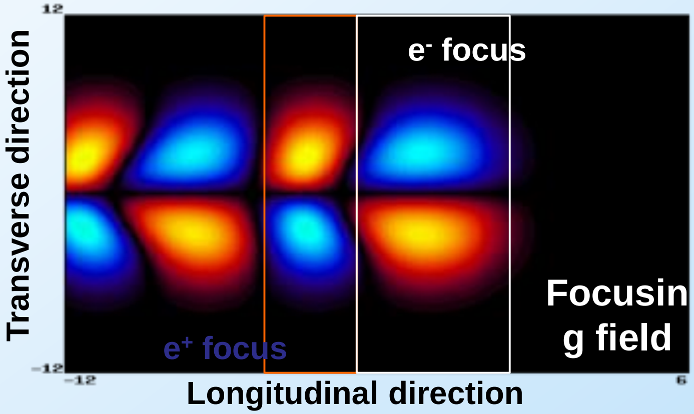
wake coupling

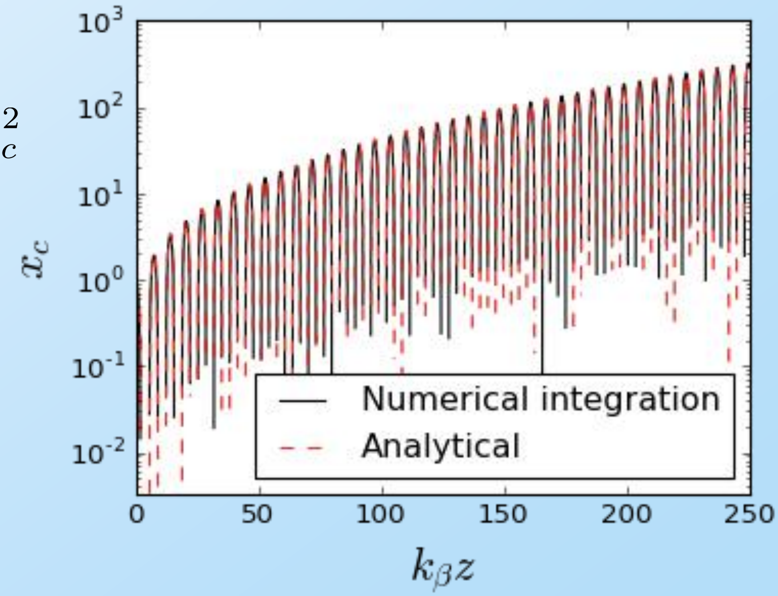
- Long beam, weakly coupled [Whittum et al., PRA (1992)]
- Short beam, weak focusing [Schroeder et al., PRL (1999)]: $k_\beta^2 \ll k_c^2$
- Bubble/blowout regime [Huang et al., PRL (2007)]: $k_\beta = k_c = k_p/\sqrt{2\gamma}$
- Short beam, strongly coupled regime in quasi-linear LPA [this work]: $k_\beta^2 \sim k_c^2$

Number of betatron periods

Length of bunch

$$x_c \sim e^{N(k_\beta z, k_p \zeta)}$$





Transverse alignment tolerance: Beam break-up (BBU) instability (i.e., beam hosing)

- Can be a in regime where (BBU growth length) < (accelerator stage length)
  - Focusing required: (betatron length) < (BBU growth length)

centroid off-set growth: $x_c/x_0 \sim A^{-1/2}\exp(A)$

exponentiation: $A = C_g\left[(k_\beta z)(k_p\zeta)^2\right]^{1/3}$

bunch length

Constant (determined mainly by geometry)

Plasma accelerator length

- For a hollow plasma channel: [from theory of Schroeder et al., PRL (1999)]

$$C_g = \frac{3^{3/2}}{2^{5/3}}\left[2\frac{I}{I_A}\frac{\kappa_1(k_w r_c)}{(k_w r_c)^2}\right]^{1/3} \simeq 0.4$$

- In bubble/blow-out regime: [estimate from theory of Huang et al., PRL (2007); note, < Whittum theory for adiabatic ion channel]

$$C_g = 1.3\,(c_r c_\psi)^{1/3} \sim 0.6$$

Possible BBU instability cures: Staggered tuning and betatron frequency spread

- In hollow plasma channel fundamental (accelerating) and dipole (BBU) modes have different frequencies:

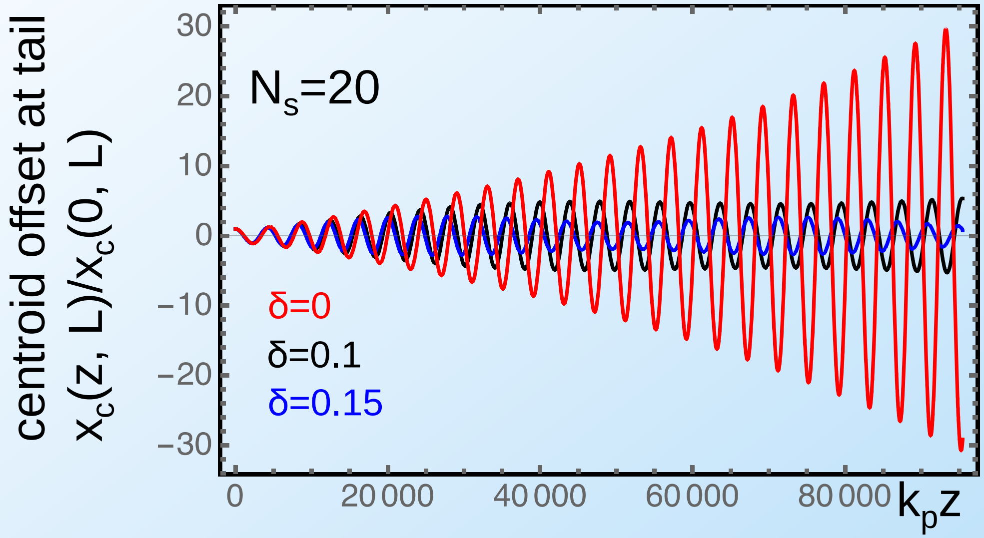
Fundamental wakefield: $$W_{\parallel} \sim \exp\left[\omega_0(k_p, r_c)(t - z/c)\right]$$

Dipole wakefield: $$W_{\perp} \sim \exp\left[\omega_1(k_p, r_c)(t - z/c)\right]$$

  - Stagger tuning: dipole frequency is varied and fundamental is constant, stage-to-stage

- Head-to-tail betatron frequency spread effective in suppressing BBU is single stage, but requires large energy spreads:

$$\frac{\Delta\gamma}{\gamma} \approx \frac{I}{I_A}(k_w L_b)\left[\frac{2K_1(k_w r_c)\Omega_1(k_w r_c)}{(k_w r_c)^3 K_2(k_w r_c)}\right] \sim 0.1$$



- Linear head-tail energy chirp:

$$\gamma(\zeta) = \gamma_0\left[1 - \delta(\zeta/L_b)\right]$$

Head-to-tail betatron detuning leads to suppression of hosing instability

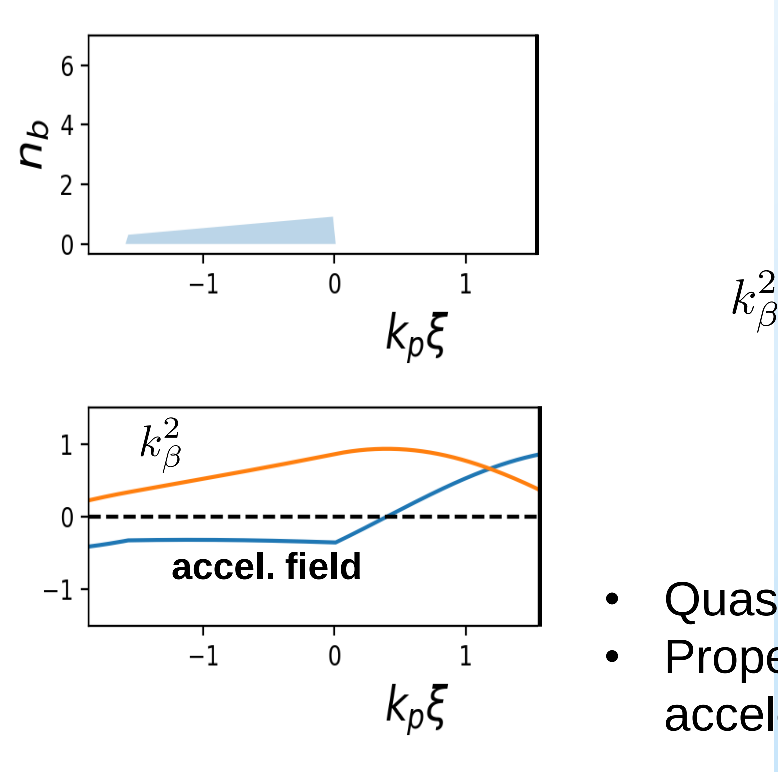
R. Lehe et al., PRL (2017)

- Head-to-tail spread in betatron frequency:

$$k_\beta(\xi) = k_{\beta,0} + \Delta k_\beta\, \kappa_p \xi$$

- Energy spread (BNS damping)
  - Requires 1-10% energy chirp

- Focusing force spread (e.g., from finite bunch length in quasi-linear wakefield)



$$k_\beta^2 = \frac{k_p^2}{2\gamma}\left[\underbrace{A_L \sin\left(k_p\xi\right)}_{\text{laser driver}} + \underbrace{\frac{n_b}{n_0}\int_\xi^0 \sin(k_p(\xi'-\xi))k_p d\xi'}_{\text{beam loading}}\right]$$

- Quasi-linear wakefield regime:
- Proper beam-loaded wake can have constant acceleration and linear focusing chirp (Panofsky-Wenzel)

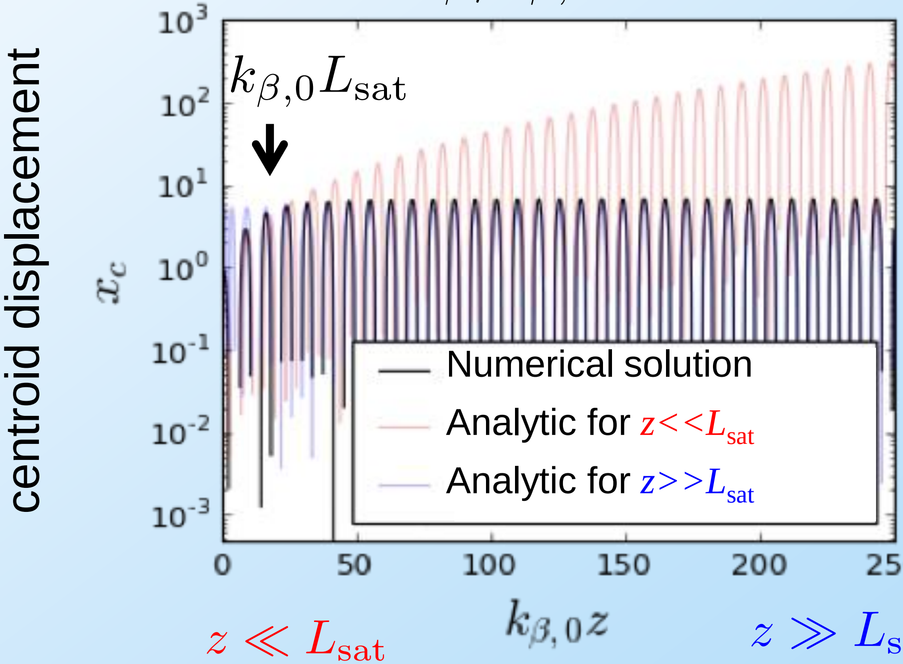
Wakefield spread in focusing force leads to saturation of hosing instability

New result: (quasi-linear wakefields)

Saturation of instability in strongly-coupled, short beam regime

- Analysis predicts saturation after distance: $$L_{sat} = \left(\frac{k_c^2}{k_{\beta,0} \Delta k_\beta^3 (\kappa_p |\xi|)} \right)^{1/2}$$
- Exponential growth for $z \ll L_{\mathrm{sat}}$
- Saturation for $z \gg L_{\mathrm{sat}}$

$$\Delta k_\beta / k_{\beta,0} = 0.2$$



$$N(z) = \left(\frac{k_c^2 z (\kappa_p |\xi|)^2}{k_{\beta,0}} \right)^{1/3}$$

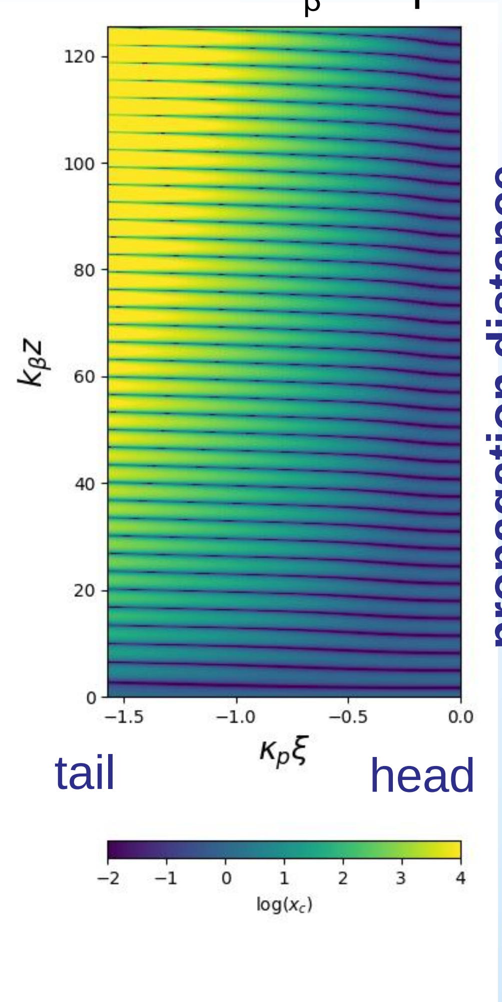
N_{sat}

$z \ll L_{\mathrm{sat}}$ $z \gg L_{\mathrm{sat}}$

R. Lehe et al., PRL (2017)

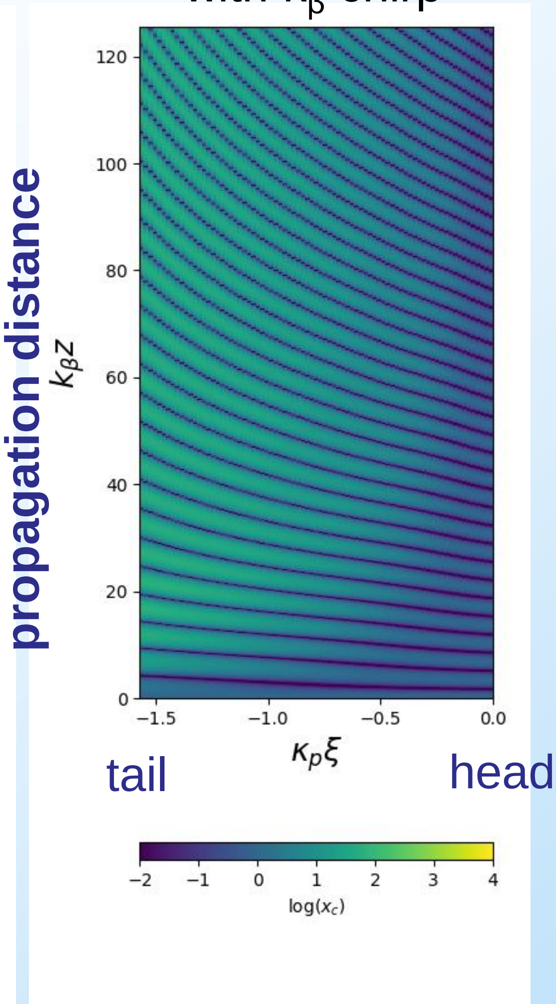
Wakefield spread in focusing force leads to saturation of hosing instability

without k_β chirp



propagation distance

with k_β chirp



- Heuristically, N_{sat} is growth after detuning distance:

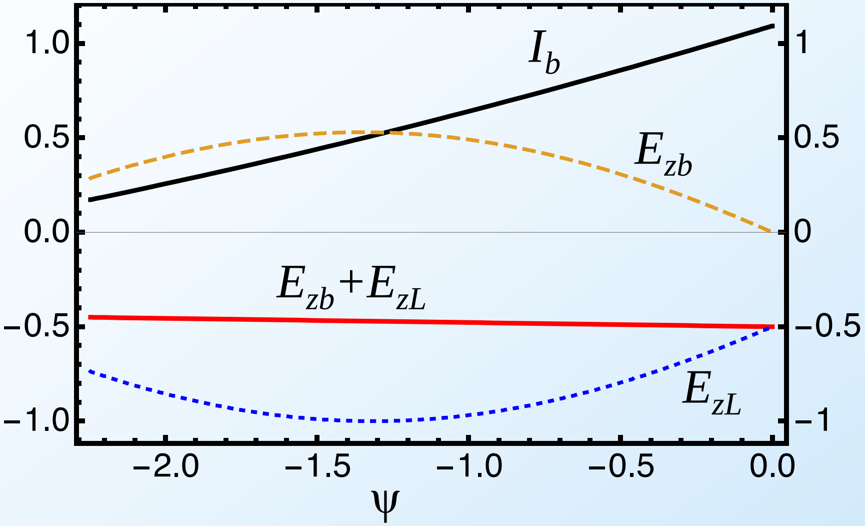
$$\Delta k_\beta z k_p |\xi| \sim 1$$

- Saturation length decreases with chirp and head-to-tail distance
- Saturation amplitude decreases with chirp and increases with head-to-tail distance

R. Lehe et al., (in prep.)

BBU cures: energy chirp requires final focus using adiabatic plasma lens

- Shape bunch for δ~0.1 chirp throughout accelerator:



- Linear head-tail energy chirp:

$$\gamma(\zeta) = \gamma_0\left[1 - \delta(\zeta/L_b)\right]$$

- Re-design beam-delivery system (BDS) – Adiabatic (plasma) focusing:
  - mismatched beta-function (amplitude of lower-energy particles never exceeds highest):

$$\tilde{\beta}(s) = \beta(s)\left[1 - \delta\sin^2\left(\psi(s)/\sqrt{1-\delta}\right)\right] \leq \beta(s)$$

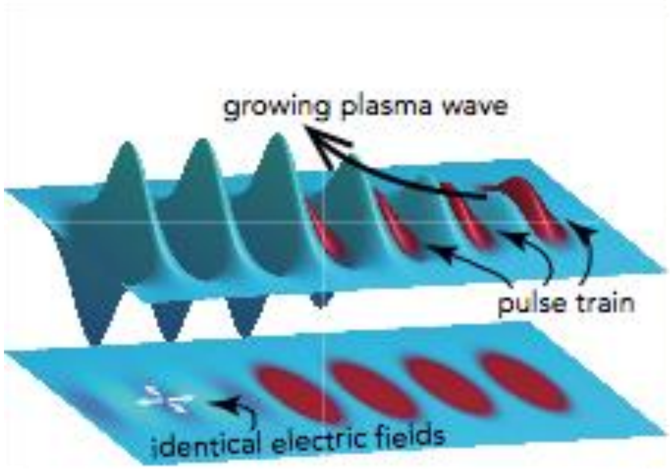
Chen, Oide, Sessler, Yu, PRL (1990)

  - In principle, allows focusing system to overcome Oide limit (due to synchrotron rad.)

Multi-pulse laser wakefield acceleration

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

- Drive wakefield with train of low-energy laser pulses
- Resonant excitation allows driving laser energy to be delivered over many plasma periods
- Enables use of different laser technologies capable of **high-rep-rate operation** and with **high wall-plug efficiency**
- Fibre lasers: 5.7 mJ, 200 fs @ 40 kHz [Klenke *et al.* Opt. Lett. **39** 6875 (2014)]
- Thin-disk Nd:YAG: 0.2 - 1 J, 1 ps at 5 kHz commercially available
- Potential for additional control over wake excitation
- Natural architecture for “energy recovery”
- Not a new idea
- Many theory papers published in 1990s

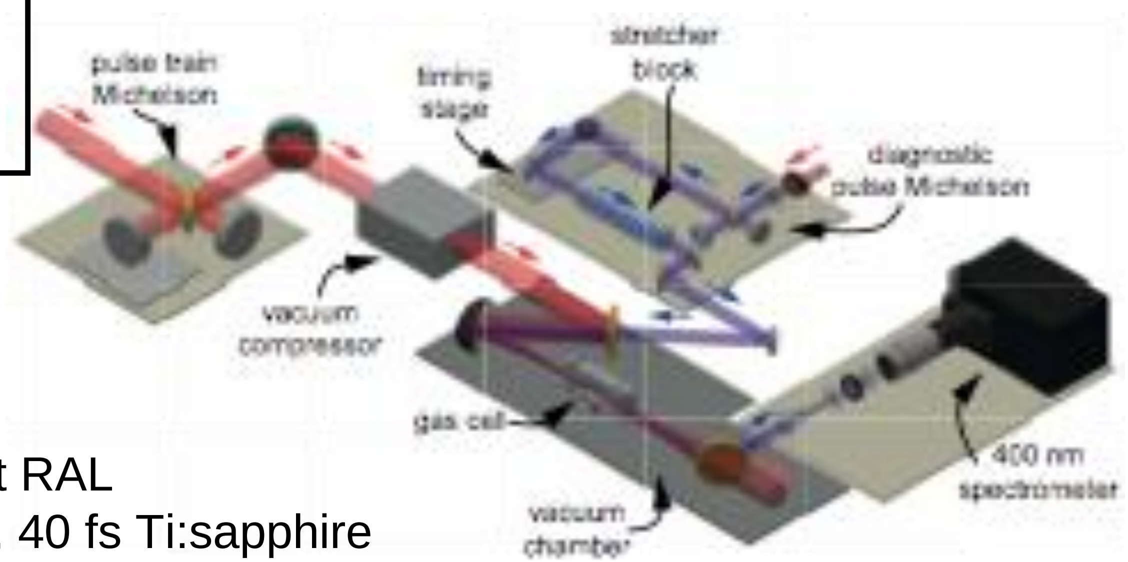


Multi-pulse LWFA Only 4 laser pulses shown. In reality would use 10 - 100!

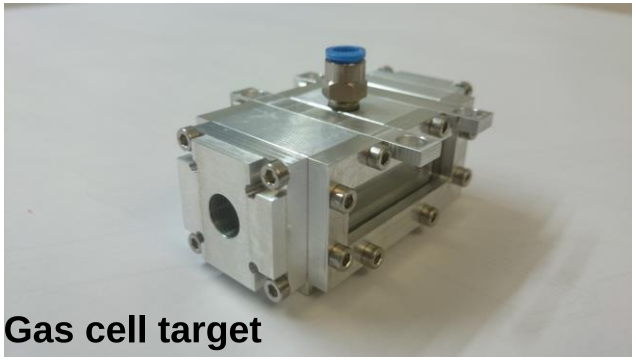
Proof-of-principle demonstration

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

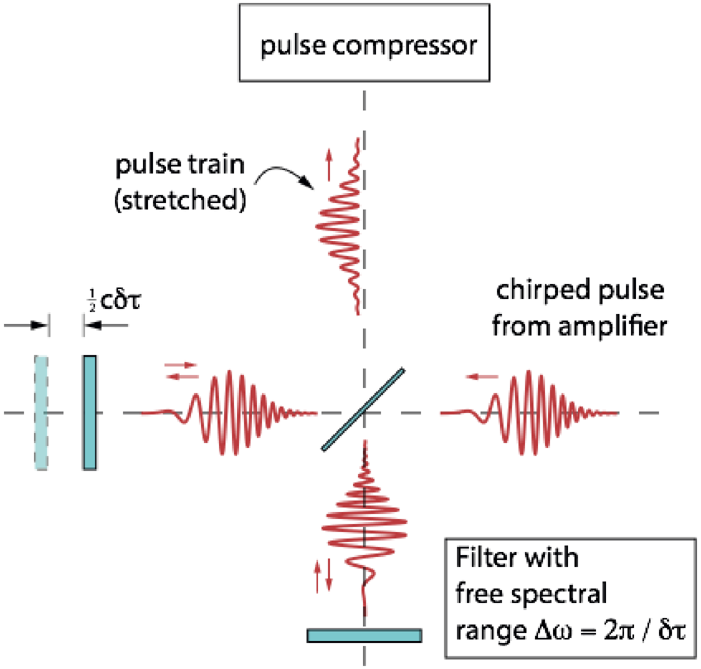
E_L: 160 - 270 mJ
w_0: (35 ± 5) μm
L_{cell}: 3 mm

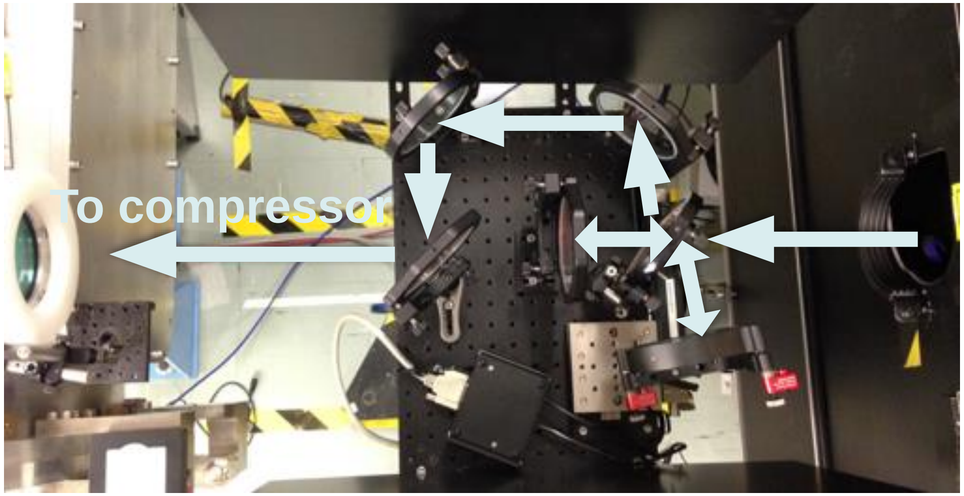


- Expts with Astra TA2 laser at RAL
- Astra delivers single 500 mJ, 40 fs Ti:sapphire pulses
- Converted single pulses into train of *N* = 1 - 7 pulses
- Wakefield measured by frequency-domain holography & TESS


Gas cell target

Pulse train generation



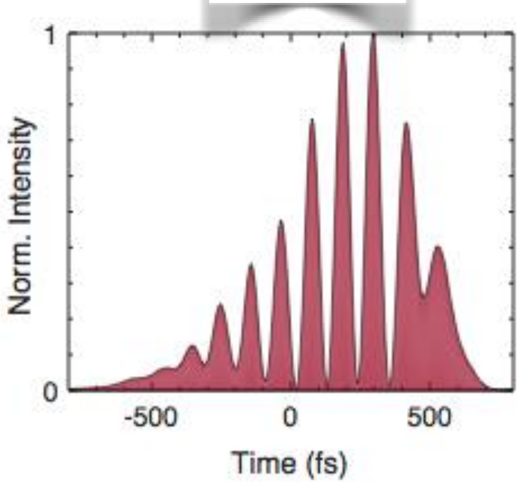


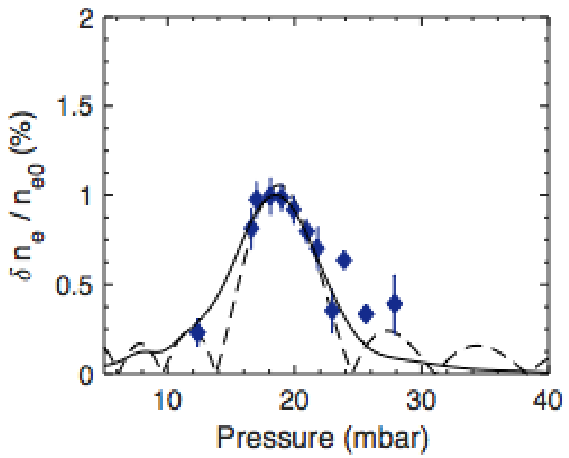
- Michelson interferometer inserted prior to compressor
- If total path delay is cδτ then free spectral range of Michelson is $\Delta\omega = 2\pi / \delta\tau$
- Partial compression
- modulated chirped pulse (pulse train)
- Full compression:
- pair of pulses of separation δτ
- Alternatively, can think of this as **chirped beat-wave**

Multi-pulse driver

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

***N* ≈ 7**





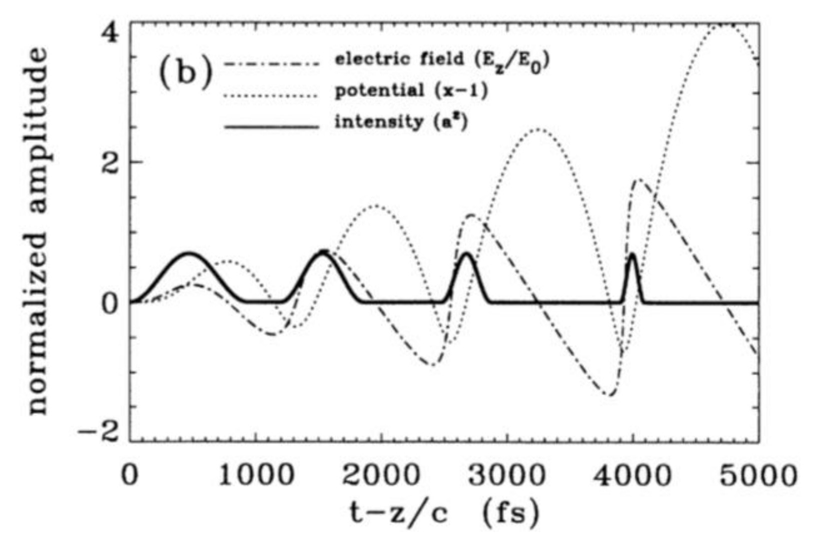
$$\frac{\delta n_e}{n_{e0}} = \left[\frac{\delta n_e}{n_{e0}}\right]_{N=1} \times \left|\frac{\sin\left(\frac{1}{2}N\omega_{p0}\delta\tau\right)}{\sin\left(\frac{1}{2}\omega_{p0}\delta\tau\right)}\right|$$

- Excellent fit to analytic expression for *N* = 7
  - $\delta\tau = (116 \pm 2)$ fs,
  - SSA: $\delta\tau = (112 \pm 6)$ fs
- Excellent agreement with fit of wake calculated from measured pulse train with $\zeta \rightarrow \alpha\zeta$
- Find $\alpha = 1.04 \pm 0.02$

Wakefield maximized using optimized pulse trains

- As wake amplitude grows nonlinear plasma wavelength increases
- To maintain resonance, optimize pulse train parameters
- Pulse separation increases
- Pulse duration decreases

Umstadter, Esarey, Kim, PRL (94)



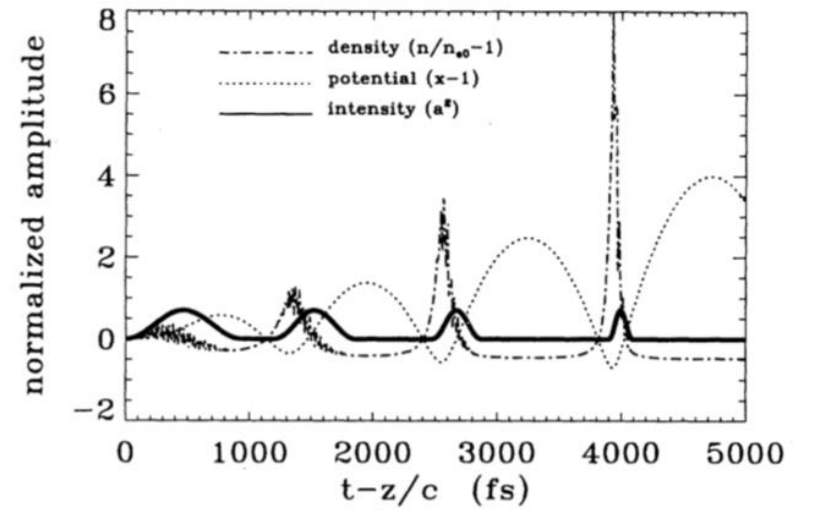


FIG. 6. Numerical solutions for the RLPA with sine-shaped pulses at $n_e = 10^{16}$ cm^{-3} and $a_0 = 1.2$, showing plasma-wave density instead of electric field.

Coherent laser combining: new laser technology provides a path for high average power

- Coherent combination of diode-pumped fiber lasers: path to high-peak power, high-average power, high-efficiency lasers:
  - Fiber lasers: sub-ps pulses, ~mJ energy, ~10 kHz, ~10% wall-plug efficiency
  - Coherent combination of fiber lasers is proposed to achieve high peak power (energy)
  - *Challenge*: Requires combining (control of all laser phases, group velocity delays, dispersion) ~10^4 fiber lasers

ICAN =
"International Coherent Amplification Network"

G. Mourou et al., Nature Photonics (2013)

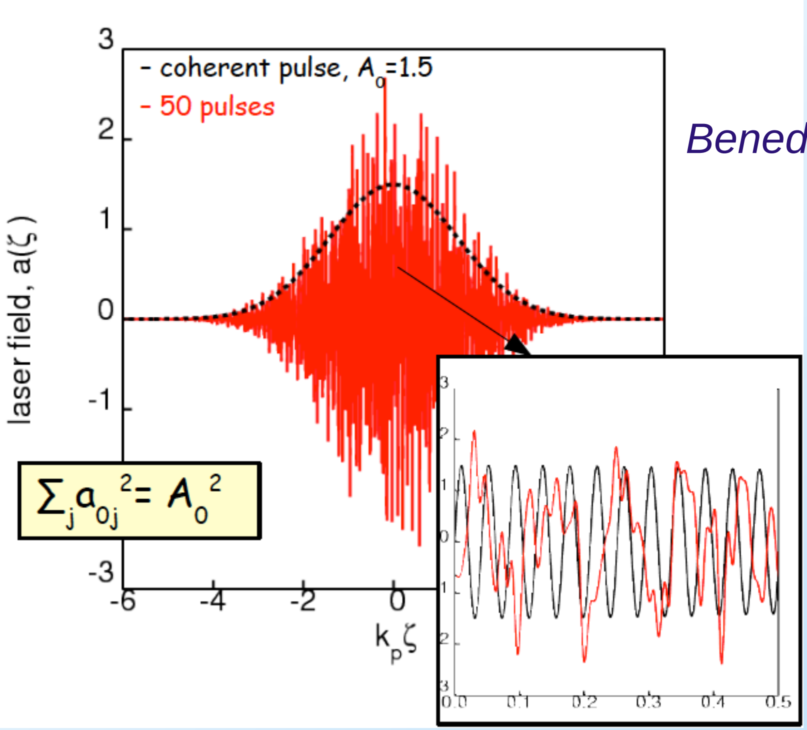
Figure 1 | Principle of a coherent amplifier network. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of ~1 mJ at a high repetition rate (4). All the channels are combined coherently, compressed (5) and focused (6) to produce a pulse with an energy of >10 J at a repetition rate of ~10 kHz (7).

Wakefield excitation by incoherently combined lasers: path to high-average power

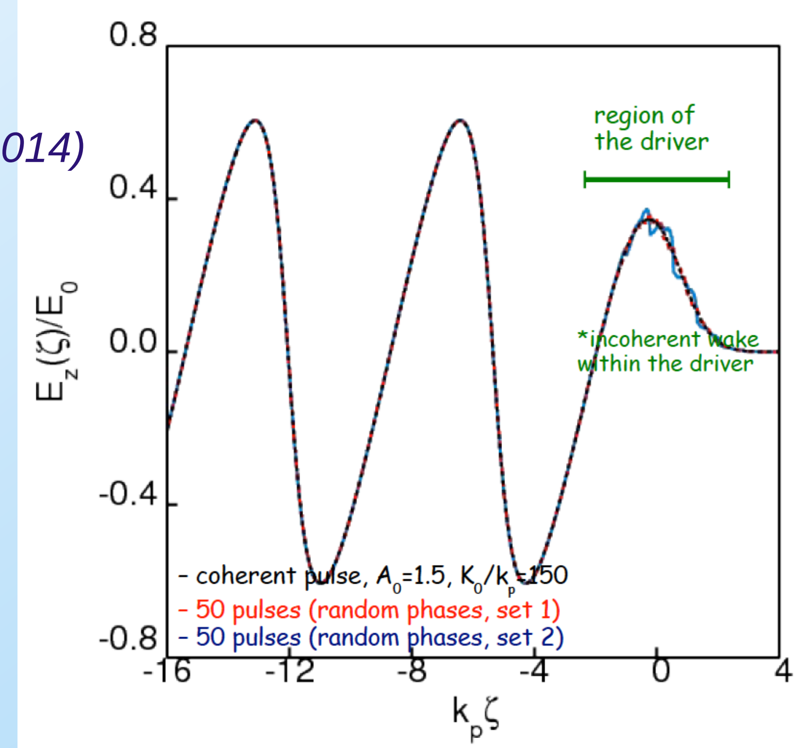
- Wakefield driven by time-integrated gradient of electromagnetic energy density: depends on the average properties of the radiation in the volume (~λ_p^3)

$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{E}{E_0}=-\omega_p^2\frac{1}{2}\nabla\left(\frac{eE_\text{laser}}{mc^2\omega}\right)^2 \longrightarrow \frac{E}{E_0}=-c\int_0^t dt'\,\sin[\omega_p(t-t')]\frac{1}{2}\nabla\left(\frac{eE_\text{laser}}{mc^2\omega}\right)^2$$

- Wakefield excitation does not require coherence, only energy density
- Incoherent combination (of many low energy) lasers for wakefield excitation:
  - Require only sufficient energy deposited in ~λ_p^3 volume



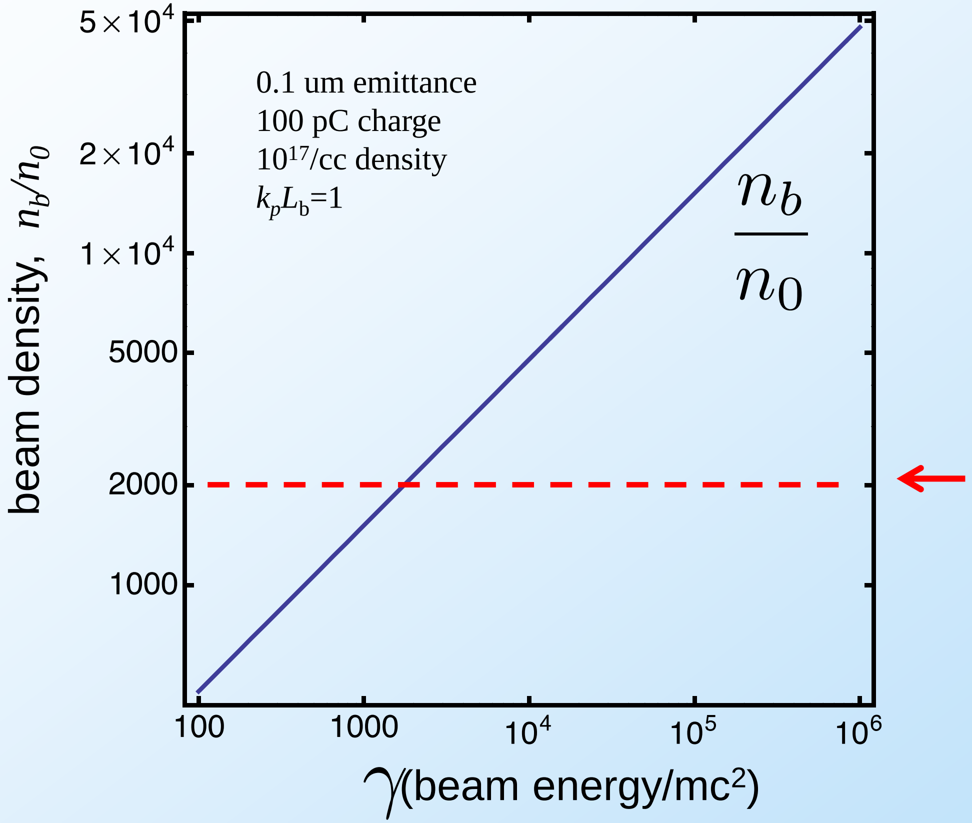
Benedetti et al., PoP (2014)



- Incoherent summation easier than coherent (requires no phase control)

Beam self-focusing in plasma results in dense bunches

- Matched beam spot decreases with energy gain: $\sigma_x^2 = \frac{\epsilon_n}{\gamma k_\beta} = \sqrt{\frac{2}{\gamma}}\frac{\epsilon_n}{k_p}$



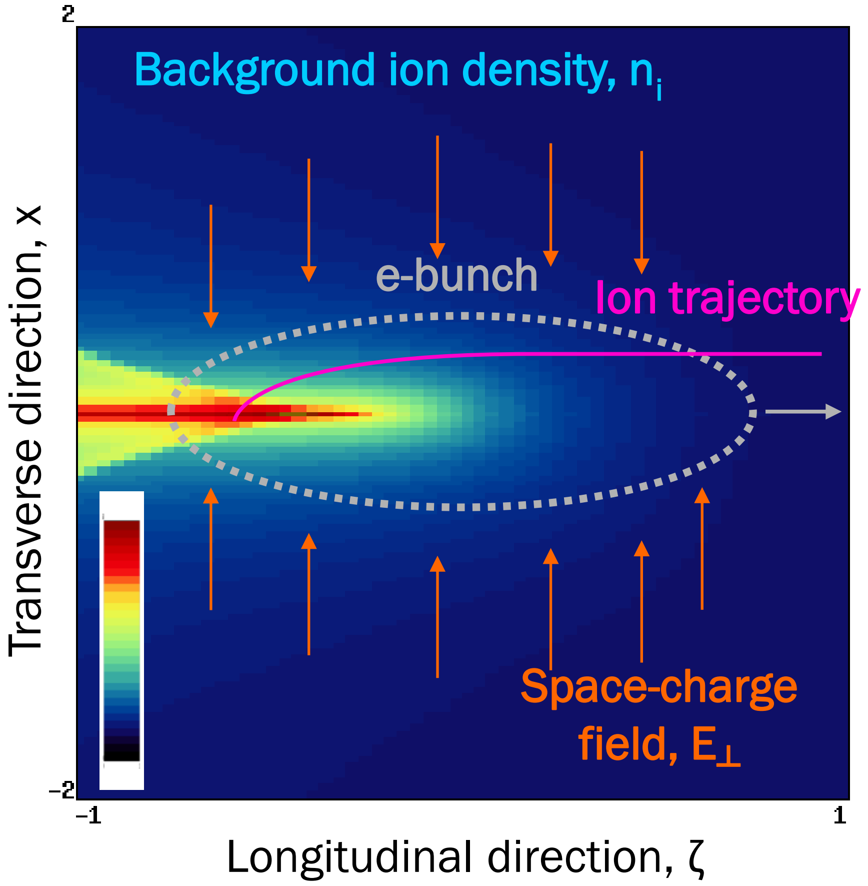
Ion motion
(non-linear focusing head-to-tail;
emittance growth) $\frac{n_b}{n_0} \gtrsim \frac{M_i}{m_e}$

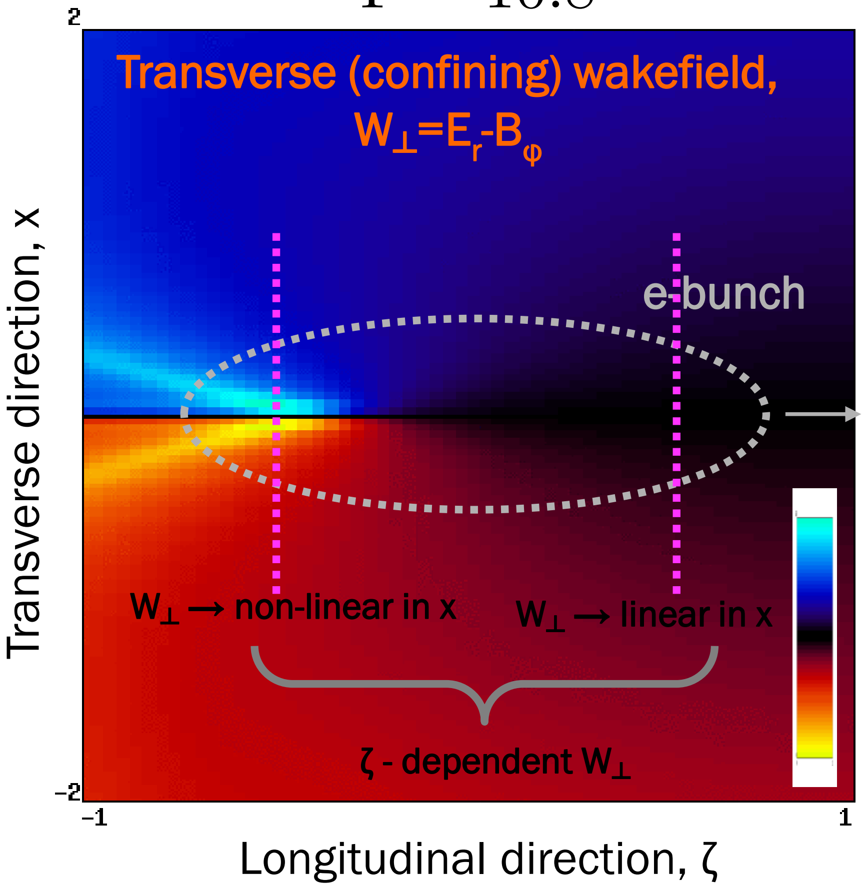
Rosenzweig et al., PRL (2005)

Space-charge field of dense beam: ion motion and nonlinear wakefield

simulations using INF&RNO

$\Gamma = 10.8$

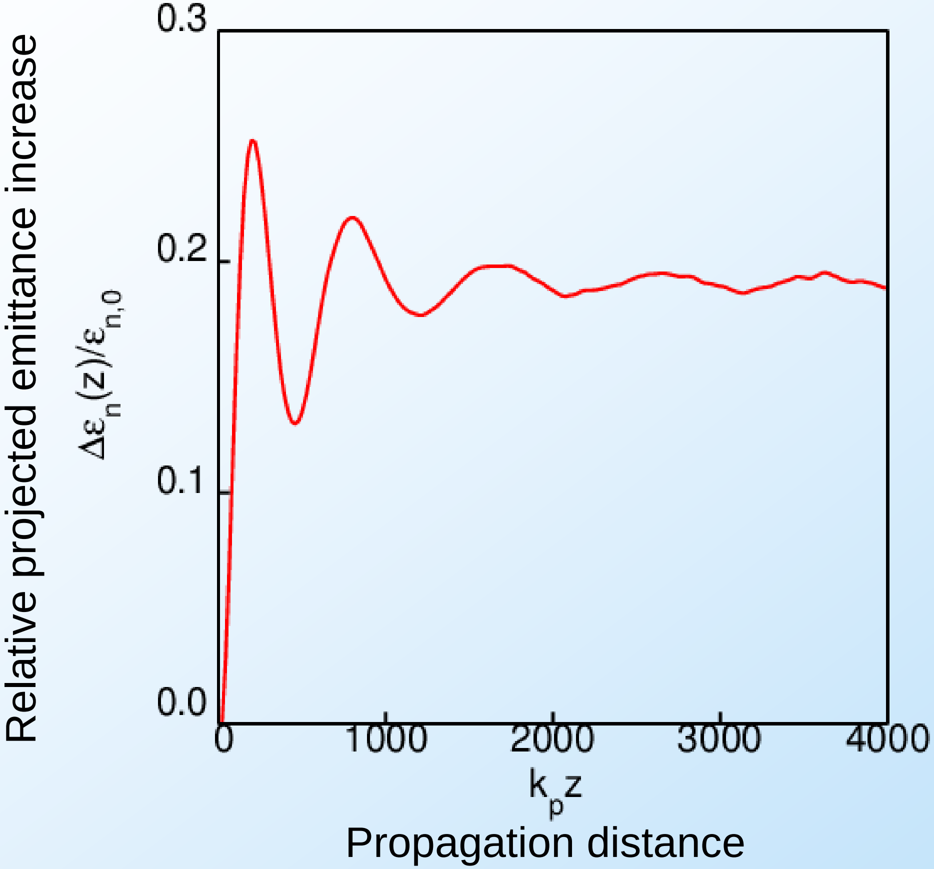


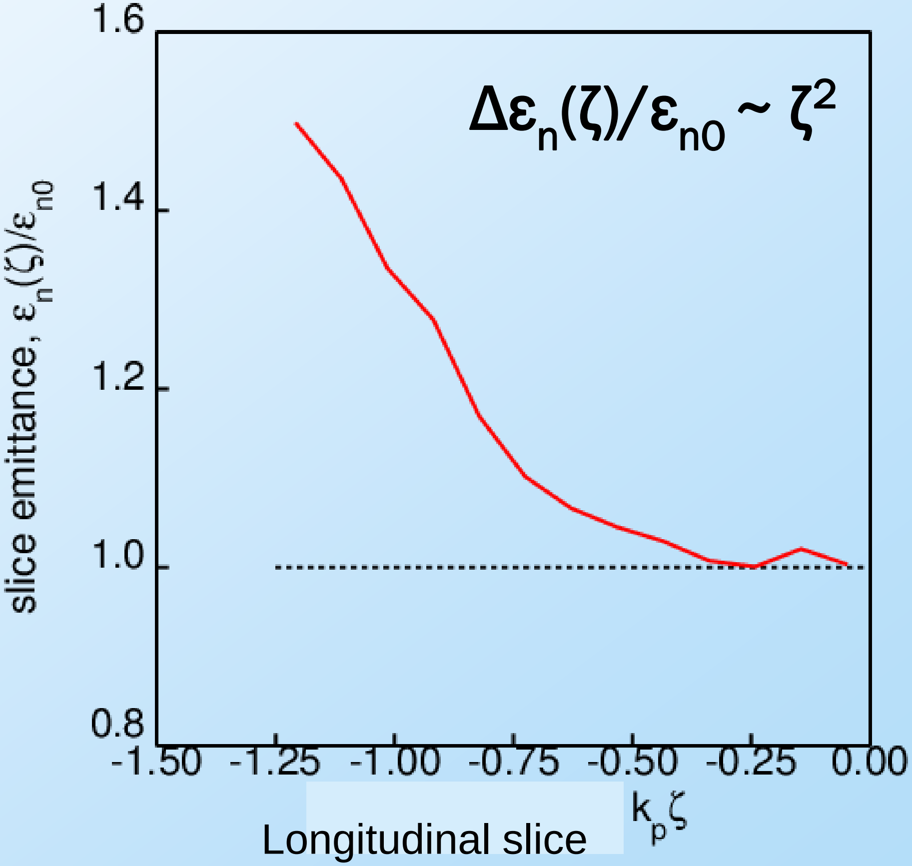


Condition for ion motion: $\Gamma = Z_i(m/M_i)(n_{b,0}/n_0)(k_pL_b)^2 \gtrsim 1$

Ion motion results in emittance growth

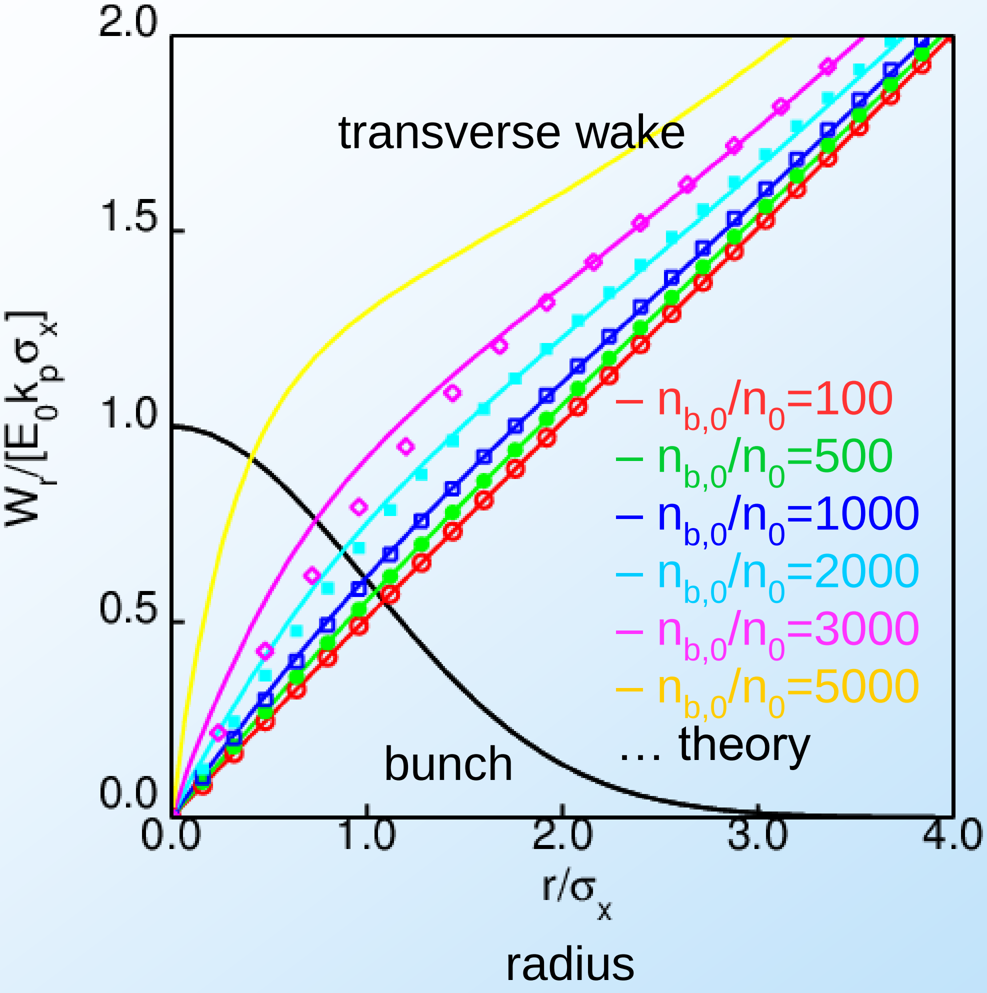
e-beam: E=25 GeV, $\varepsilon_{n,0}=(\varepsilon_{n,x}\varepsilon_{n,y})^{1/2}=0.6$ um, $L_b=20$ um, $N_b=10^{10}$ particles, $n_{b,0}/n_0=12000$
plasma: Hydrogen ions, $n_0=10^{17}$ cm^{-3}



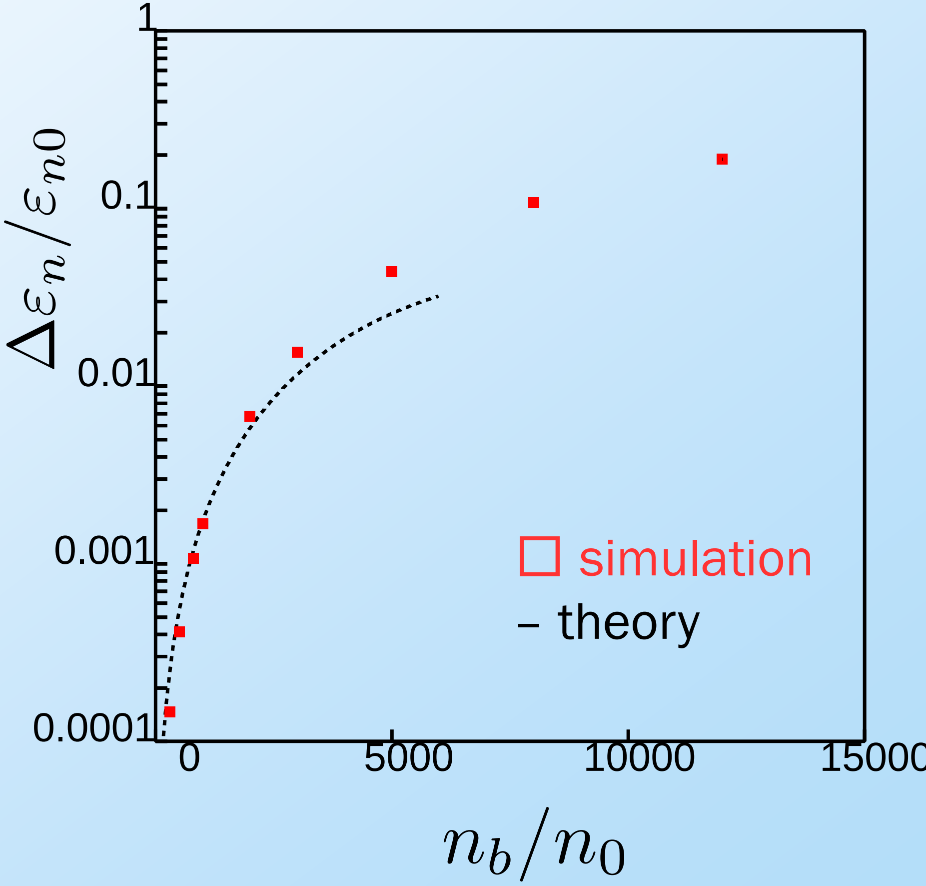


Analytical expression for the perturbed wakefield with ion motion derived

e-beam: long. flat-top (k_pL_b=1); trans. Gaussian
plasma: Hydrogen ions



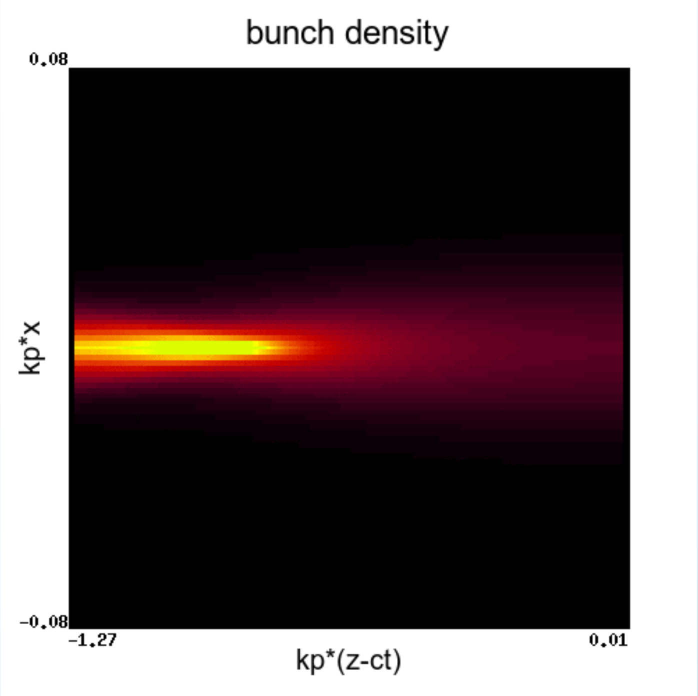
Emittance growth (saturated)

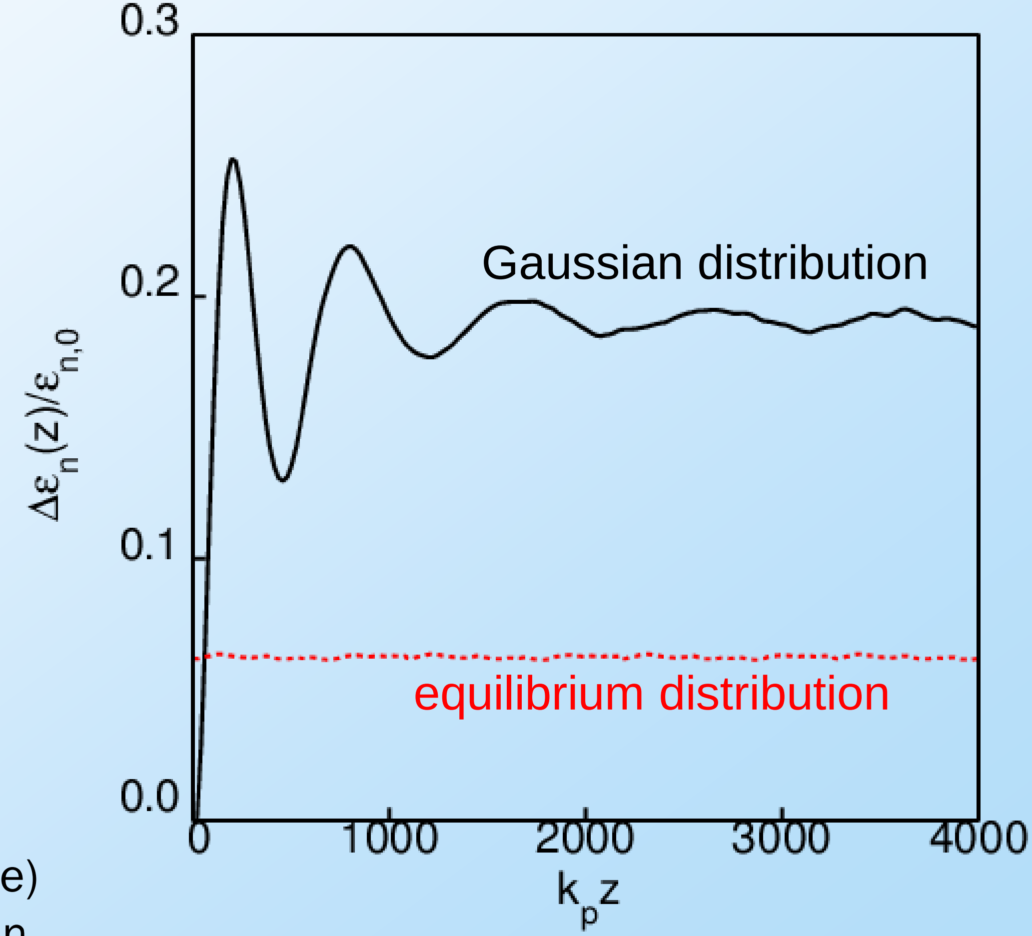


Equilibrium beam distribution -- Bunch propagation without emittance growth

e-beam: E=25 GeV, $\varepsilon_{n,0}=(\varepsilon_{n,x}\varepsilon_{n,y})^{1/2}$=0.6 um, L_b=20 um, $N_b=10^{10}$ particles, $n_{b,0}/n_0$=12000, uniform current

plasma: Hydrogen ions, $n_0=10^{17}$ cm^{-3}



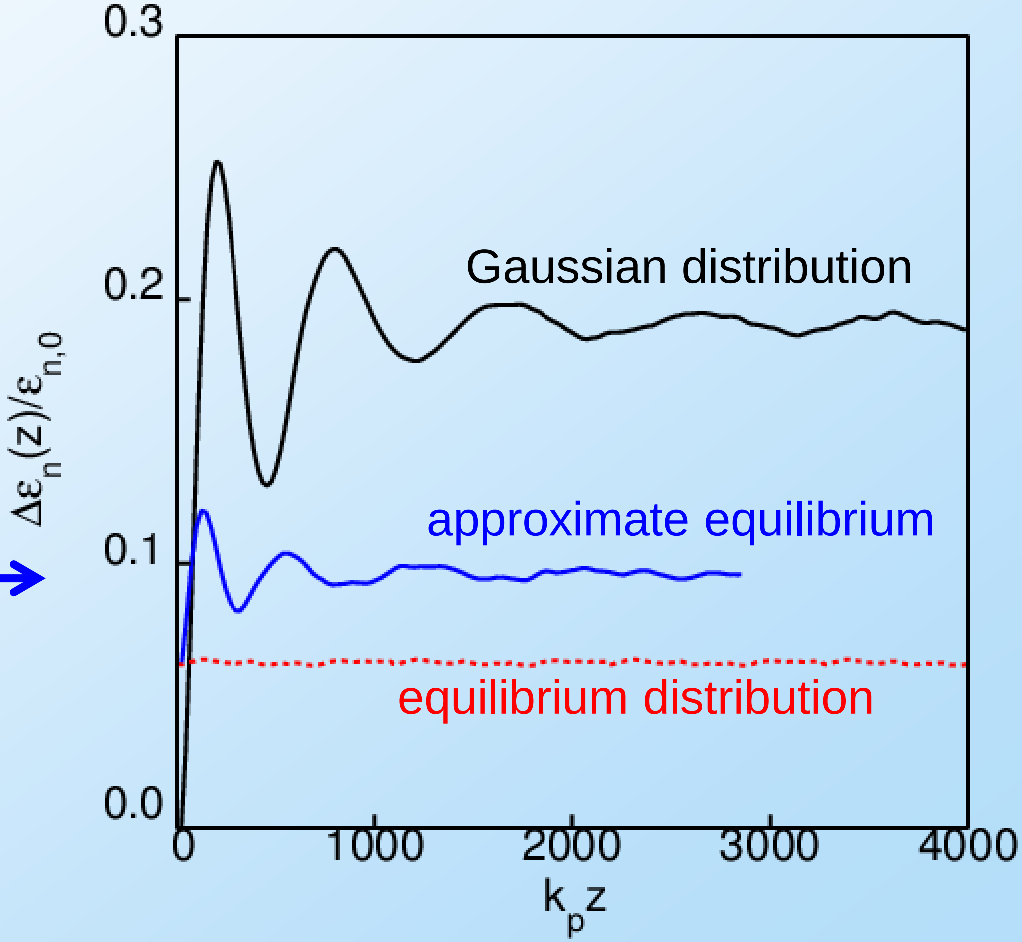


- Requires exact preparation of initial 4D phase-space (non-Gaussian in space)
- Arbitrary longitudinal current distribution

Approximate equilibrium distribution shows moderate emittance growth

e-beam: E=25 GeV, $\varepsilon_{n,0}=(\varepsilon_{n,x}\varepsilon_{n,y})^{1/2}=0.6$ um, $L_b=20$ um, $N_b=10^{10}$ particles, $n_{b,0}/n_0=12000$
plasma: Hydrogen ions, $n_0=10^{17}$ cm^{-3}

Approximate equilibrium distribution = Gaussian having the same slice-by-slice rms properties as exact distribution →



LPA-based collider challenges and potential solutions (requiring R&D)

- Laser diffraction
  - Self-guiding in nonlinear regime
  - Guiding in pre-formed plasma channel
- Laser - particle beam dephasing
  - Plasma tapering
- Laser energy depletion (with high accelerating gradient)
  - LPA staging
  - Compact driver in-coupling
- Positron focusing and acceleration (maintaining high beam quality)
  - Operate in linear regime
- High laser to beam efficiency (without energy spread growth)
  - Shaped particle beams
  - Laser energy recovery
- Heating of plasma
  - Use "energy recovery" pulse
- High average laser power
  - Laser beam combining

LPA-based collider challenges and potential solutions (requiring R&D)

- Scattering in plasma
  - Strong plasma focusing
  - Use (near-) hollow channels
- Emittance growth via ion motion
  - Quasi-linear regime: Control particle beam density via focusing
- Beamstrahlung mitigation
  - Short bunches
  - Flat beams
- Synchronization
  - ~fs laser-driver timing required
- Beam break-up
  - De-tune dipole mode (stagger tuning)
  - Strong focusing
- Compatibility with other (non-linac) collider subsystems
  - Most, if not all, collider sub-systems would need to be re-designed
- Alignment tolerances
  - …

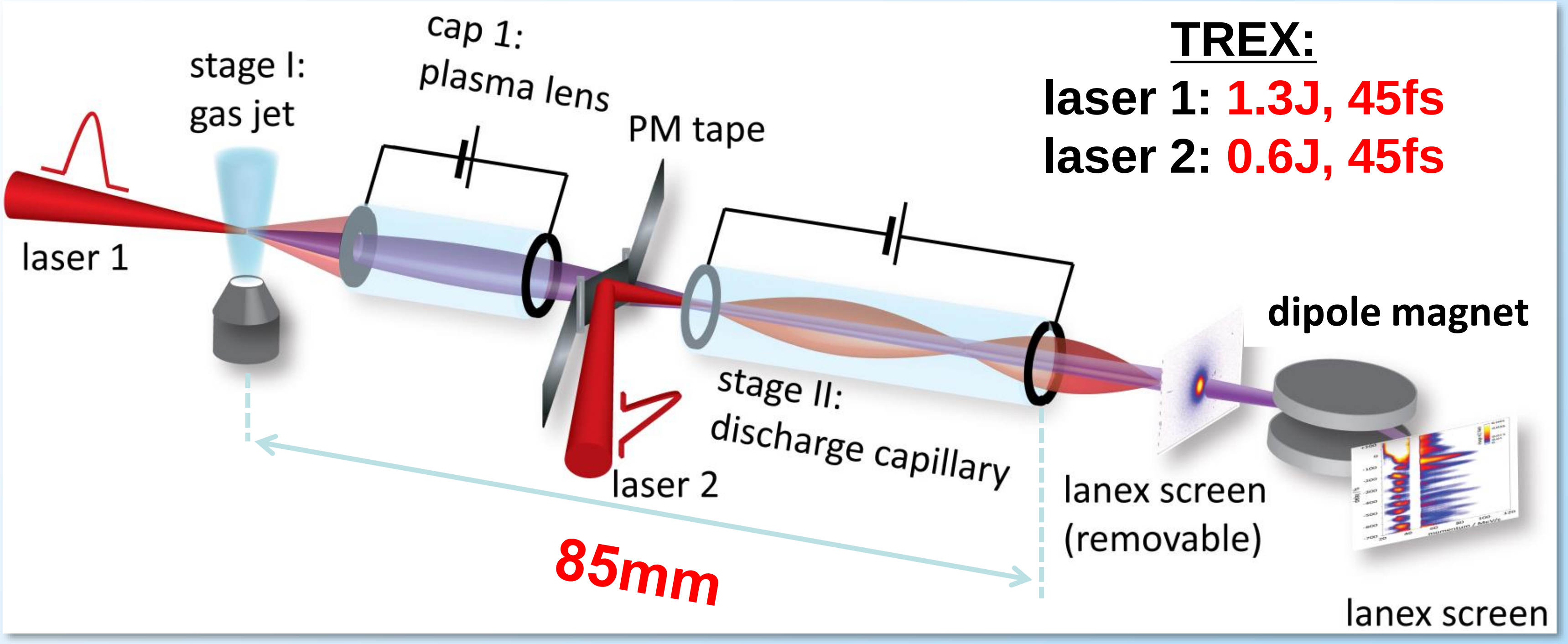
Multistage Coupling of two independent LPAs

Stage I: gas jet - injector

Coupling II (laser): tape-driven plasma mirror

Coupling I (e-beam): active plasma lens

Stage II: discharge capillary - accelerator



TREX:

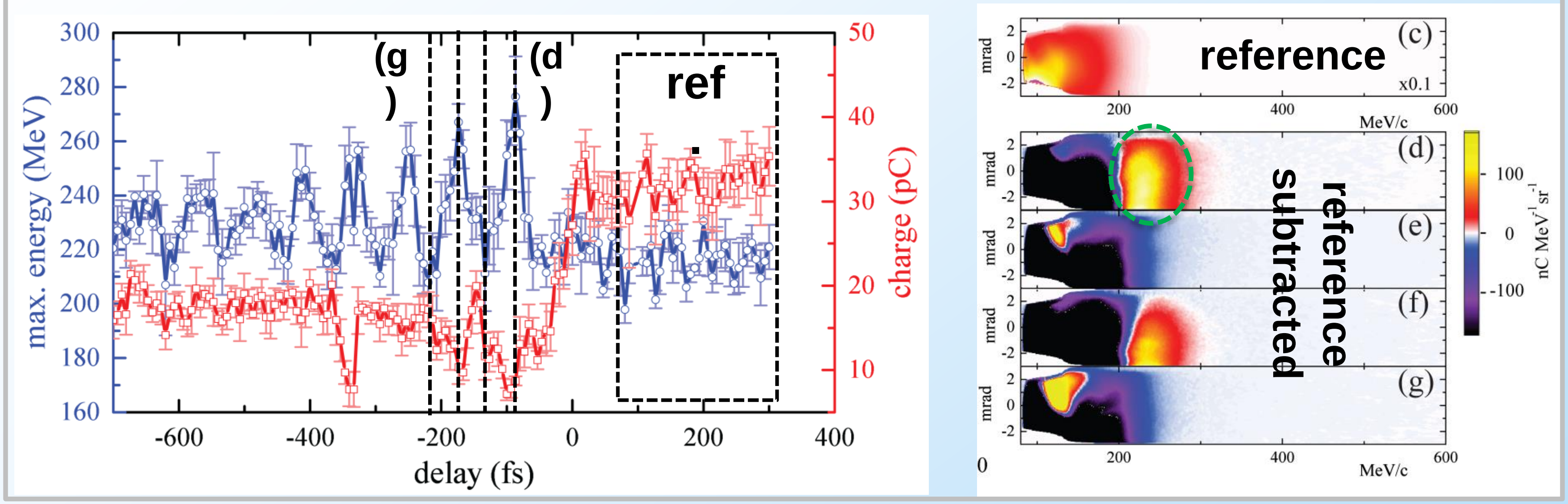
laser 1: 1.3J, 45fs

laser 2: 0.6J, 45fs

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

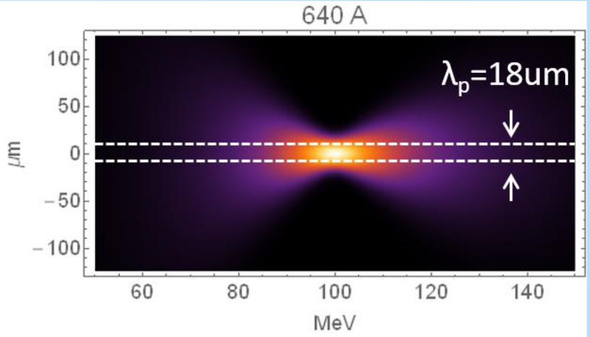
Staging Experiment: Energy gain of witness beam by timing of second laser (wake phase)

Modulation period of 80 fs consistent with a plasma frequency at a density of 2x10^{18} cm^{-3}



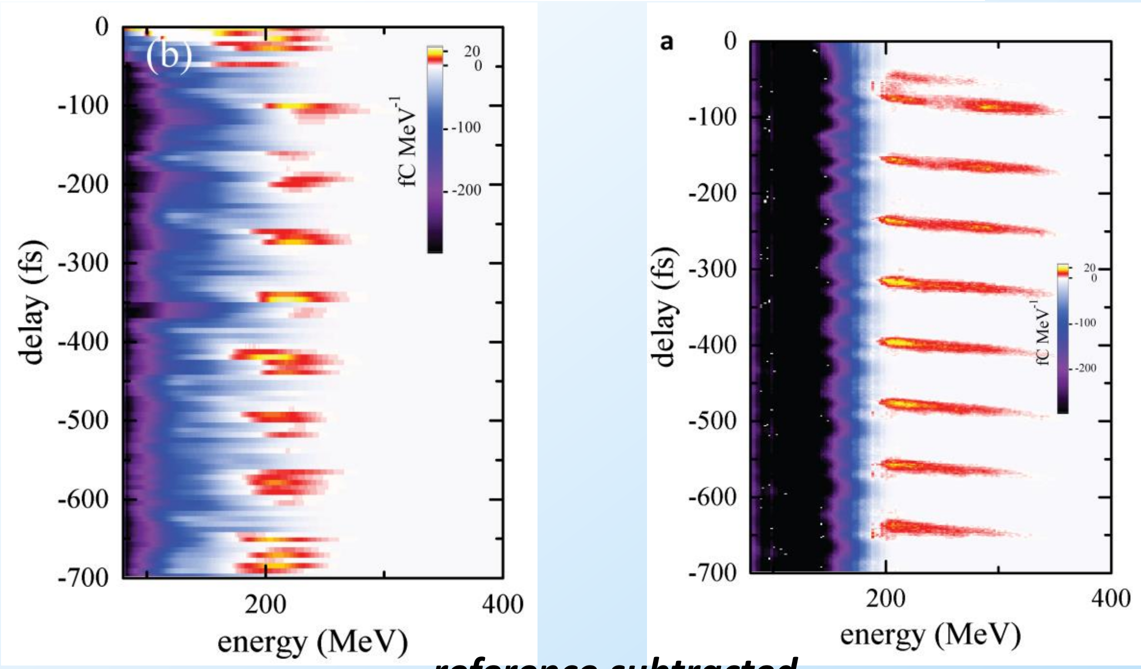
S. Steinke et al., Nature 530, 190 (2016)

Previous plasma lens calculation suggest that 1.2pC of trapped charge corresponds to a wake trapping efficiency of 30%,
but it's not that easy (unfortunately)



Simulation reproduce staging signatures at correct magnitude

Comparison of experiment and simulation

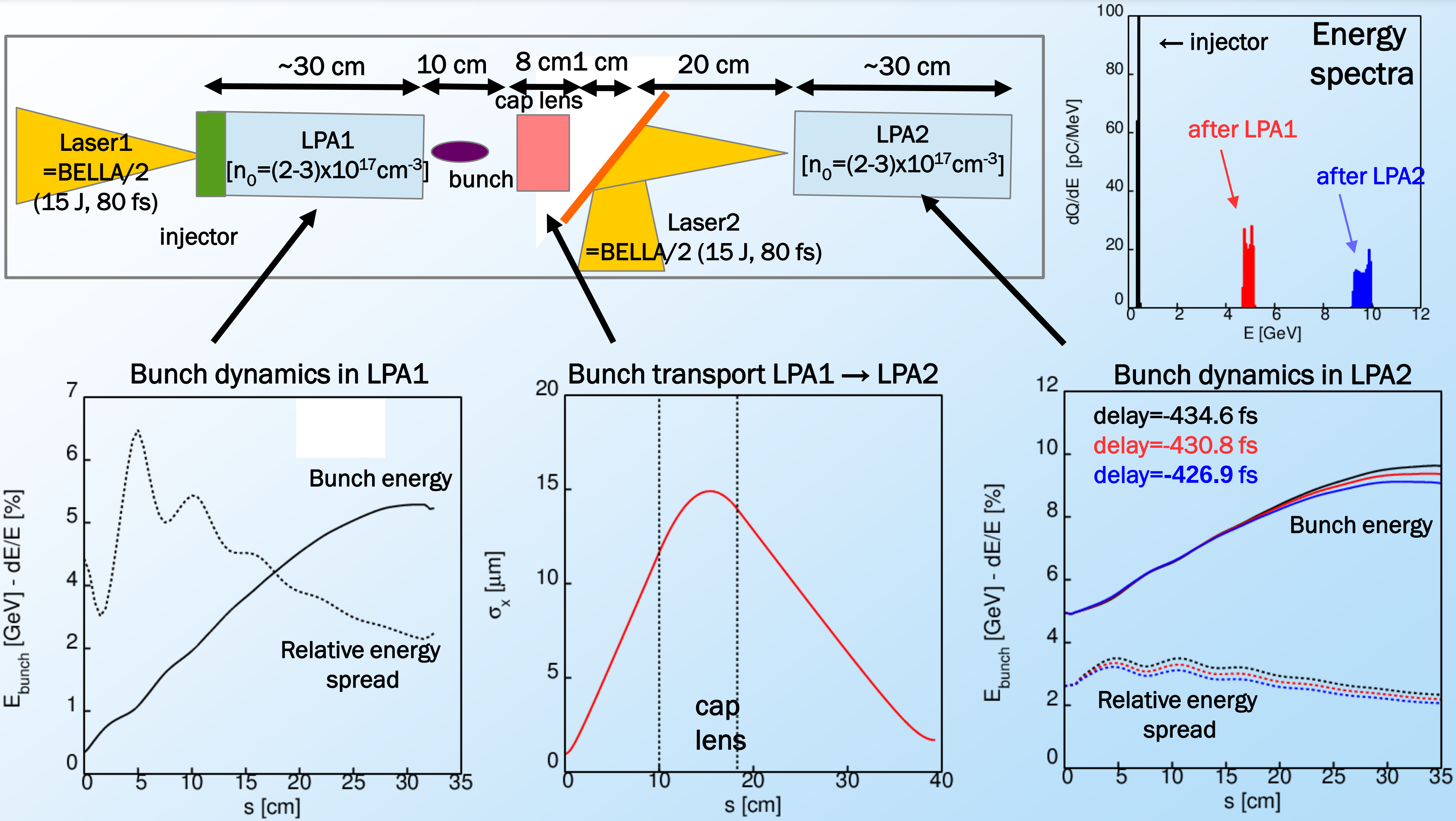


reference subtracted

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

- Recurring post acceleration (100 MeV) at the plasma frequency
- ~ 1 pC of charge at energies > 200 MeV
- Analysis of simulation results unravels details of the acceleration/ deceleration

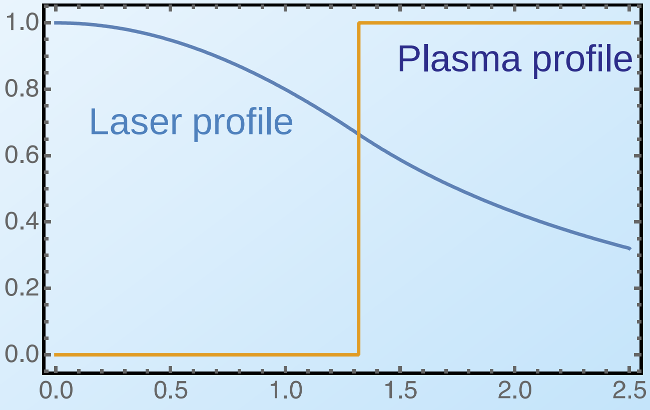
~10 GeV electron beams from STAGING experiment using BELLA: simulations show high efficiency capturing and acceleration in LPA2 of the bunch produced by LPA1



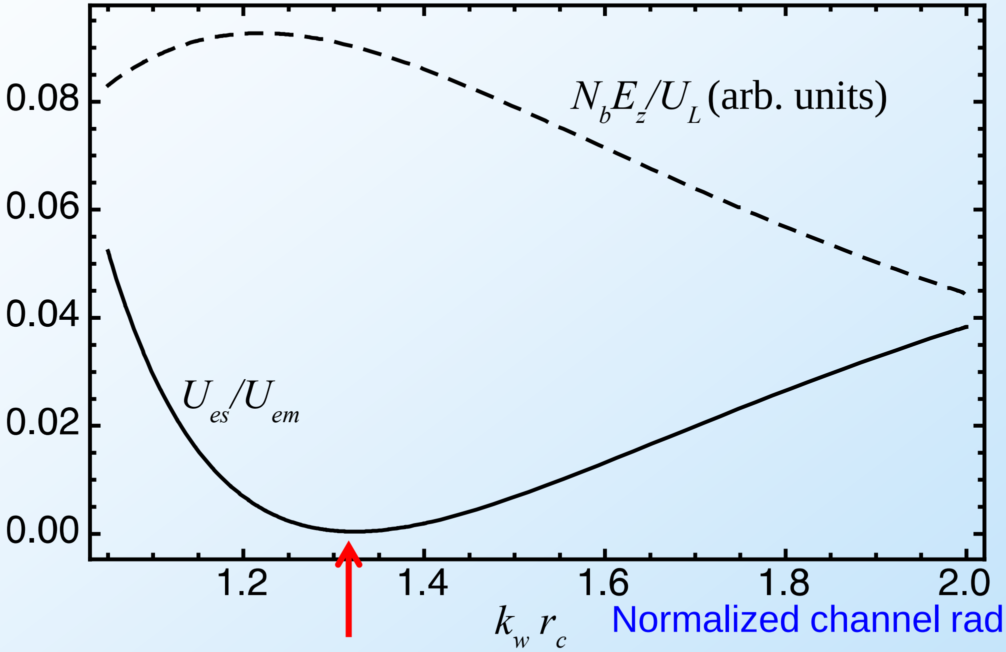
Energy in electrostatic plasma mode is a small fraction of total wake energy

- Assumes matched laser profile:

(exact linear guiding is achieved using a linearly-polarized LP_{01}mode)



Normalized radius

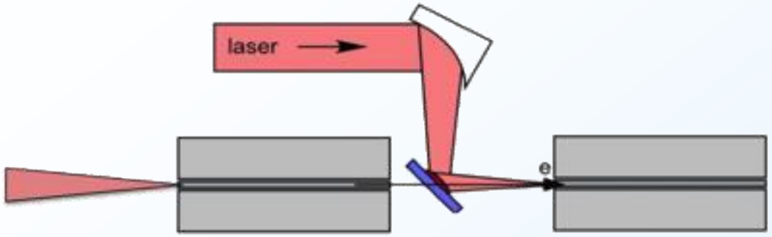


Normalized channel radius

0.04% at $k_w r_c = 1.32$

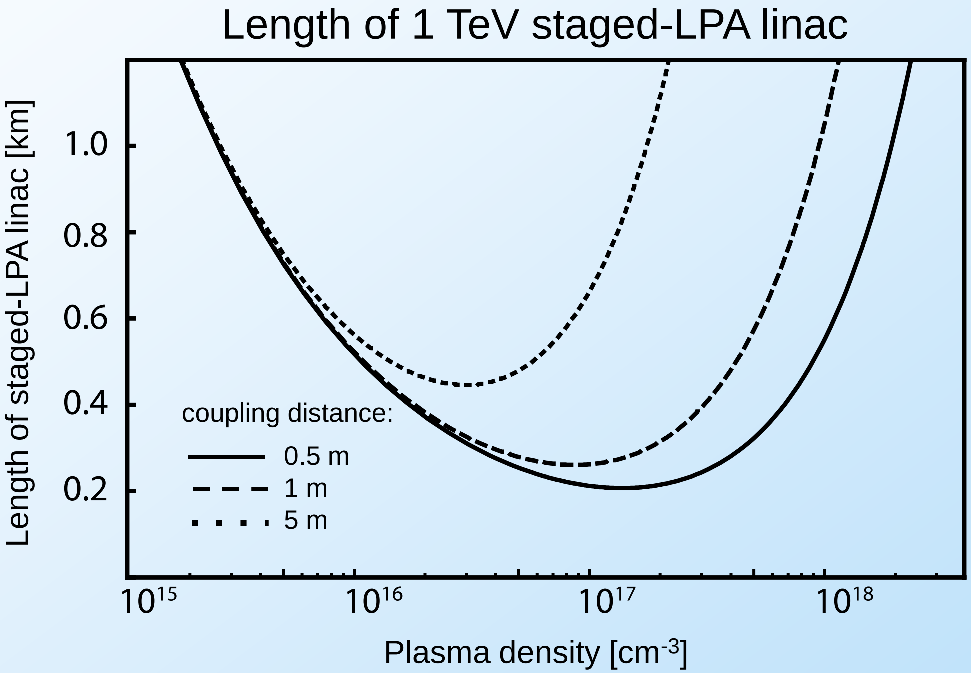
- Fraction of energy in electrostatic mode can be <1%

Staged LPAs: average gradient determined by driver in-coupling distance



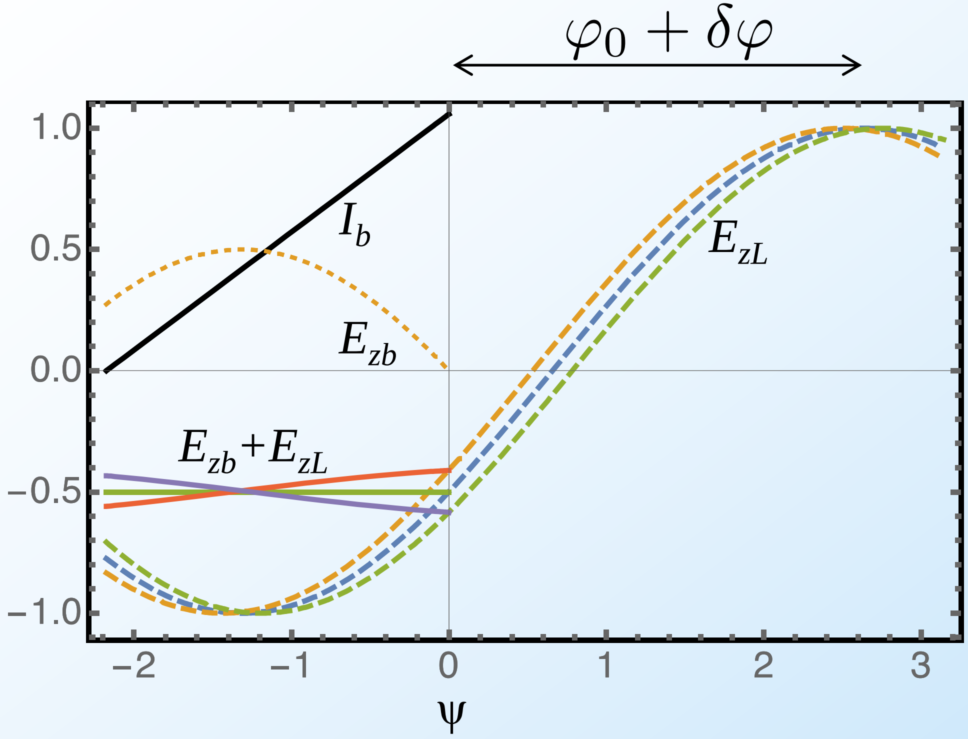
- Number of stages:

$$N_{\text{stage}} \propto n\lambda^2$$



- Compact laser in-coupling distance (enables high average gradient)
  - Conventional optics: requires many Rayleigh ranges to reduce fluence on optic (avoid damage) $L_{\text{coupling}} \propto n^{-5/4}\lambda^{-1}$
  - Plasma mirror: relies on critical density plasma production (high laser intensity): coupling <1 m

Timing jitter tolerances achievable with present technology



- RMS beam energy spread induced per phase error:

$$\frac{(\sigma_\gamma/\gamma)}{\delta\varphi} = f(\varphi_0)$$

For beam loading at ½ peak field

$$f(\pi/3) \simeq 1.1$$

- RMS laser-beam timing jitter required:

energy spread goal at end of linac

$$\sigma_{(\delta t)} = [\omega_p \Omega(k_p r_c)]^{-1} \frac{\sqrt{N_s}}{f(\varphi_0)} \overbrace{\left(\frac{\sigma_\gamma}{\bar{\gamma}}\right)}$$

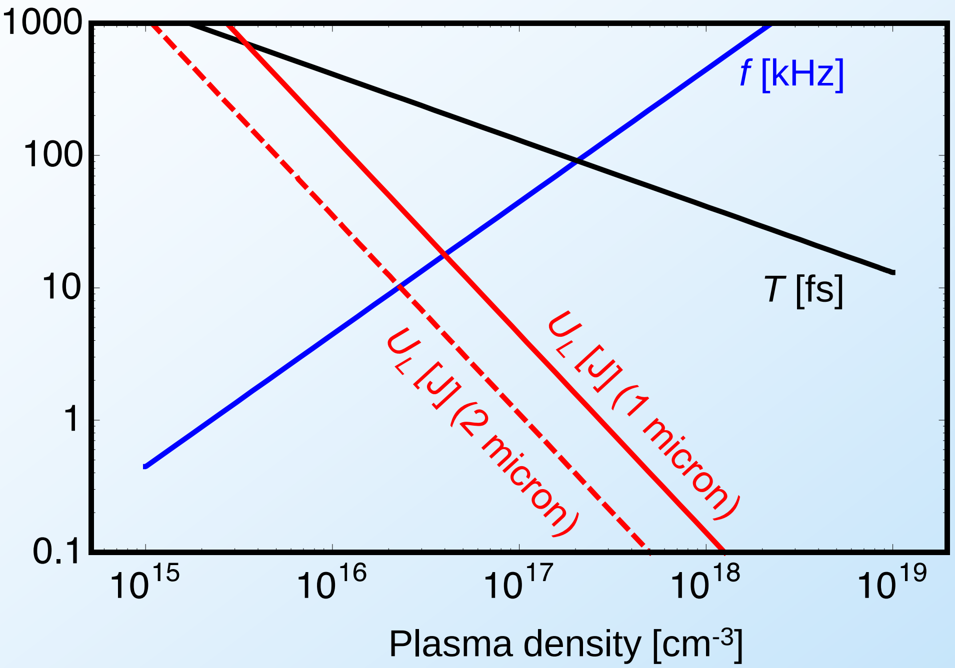
0.5% energy spread at end of linac (100 stages) requires <3.2 fs timing synchronization required

- fs timing demonstrated in LPA staging experiments at LBNL

Steinke et al., Nature (in press, 2016)

Collider requires high efficiency laser technology compatible with LPA density range

- Different operational plasma densities require different laser parameters (laser technologies) with varying efficiency



- Laser duration (bandwidth) requirements:

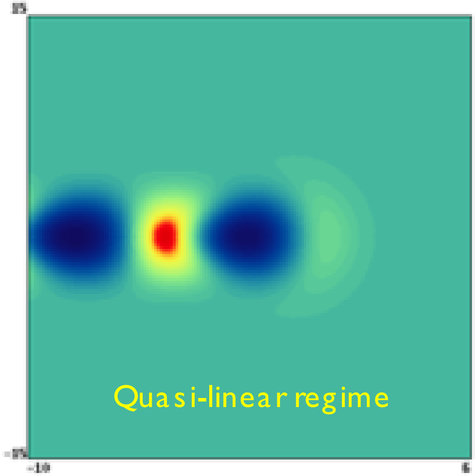
$$\tau_L \propto n^{-1/2}$$

- Laser average power requirements:

$$P_{\mathrm{avg}} \propto n^{-1/2}\lambda^{-2}$$

Laser-plasma accelerators can operate in non-linear (bubble) or quasi-linear regimes

electron plasma density



Laser driver w/ given energy: a_0=1.5, k_pL=2 (resonant), k_pw_0=4.5 , λ_0=0.8

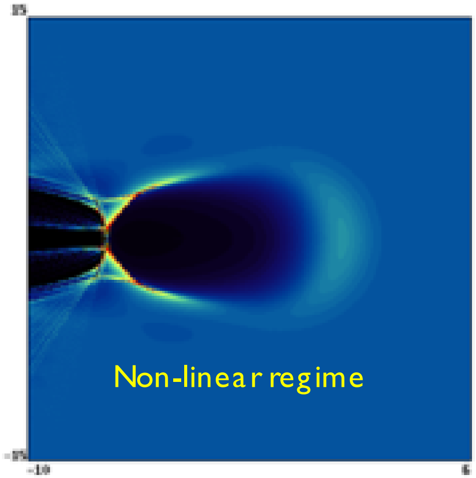
→ density: $n_0[10^{18}\ \mathrm{cm}^{-3}] = 1.5 \times (U_{laser}[\mathrm{J}])^{-2/3}$

→ guiding provided by parabolic plasma channel

→ accelerating gradient: $E_z \sim E_0 \sim n_0^{1/2}$

→ accelerating length: $k_pL_{acc} \sim n_0^{-1}$ (dephasing/depletion)

→ Energy gain → $\Delta\gamma \sim L_{acc} \times E_z \sim n_0^{-1} \sim U_{laser}^{\ 2/3}$



Laser driver w/ given energy: a_0=4.5, $k_pL_{fwhm}=(4/3)\sqrt{a_0}$, $k_pw_0=2\sqrt{a_0}$, λ_0=0.
(optimal pulse duration and spot chosen according to theory by
Lu et. al PRSTAB 2007, assuming etching length = dephasing length)

→ density: $n_0[10^{18}\ \mathrm{cm}^{-3}] = 6.9 \times (U_{laser}[\mathrm{J}])^{-2/3}$

→ self-guiding

→ accelerating gradient: $E_z \sim \sqrt{a_0}E_0 \sim \sqrt{a_0}n_0^{1/2}$

→ accelerating length: $k_pL_{acc} \sim \sqrt{a_0}n_0^{-1}$ (etching length=dephasin

→ Energy gain → $\Delta\gamma \sim L_{acc} \times E_z \sim a_0n_0^{-1} \sim a_0U_{laser}^{\ 2/3}$

Future R&D to address challenges for laser-plasma-based linear collider

- LPAs have made tremendous progress over the last decade (demonstration of high gradient, multi-GeV acceleration, improved stability, etc.), but require significant R&D to realize LPLC:

- Beam quality preservation
  - Plasma target design
    - Plasma channels to mitigate scattering and control focusing (ion motion)
  - Particle beam injection
    - Shaped beam currents enables high efficiency without induced energy spread
- Coupling of laser and witness beams between stages
  - Compact transport of witness beam with emittance preservation
  - Compact delivery of drive laser beam (for high average gradient)
- Laser technology development
  - High average power lasers (beam combining)
  - High efficiency (fiber lasers)
- Development of other collider systems compatible with LPAs
  - Novel methods for generation and cooling electron and positron beams (replace damping rings)
  - Novel final focus concepts (plasma-based adiabatic focusing)
  - Development of novel alignment instrumentation and techniques required