Laser-Plasma Accelerators for Future Colliders and Light Sources

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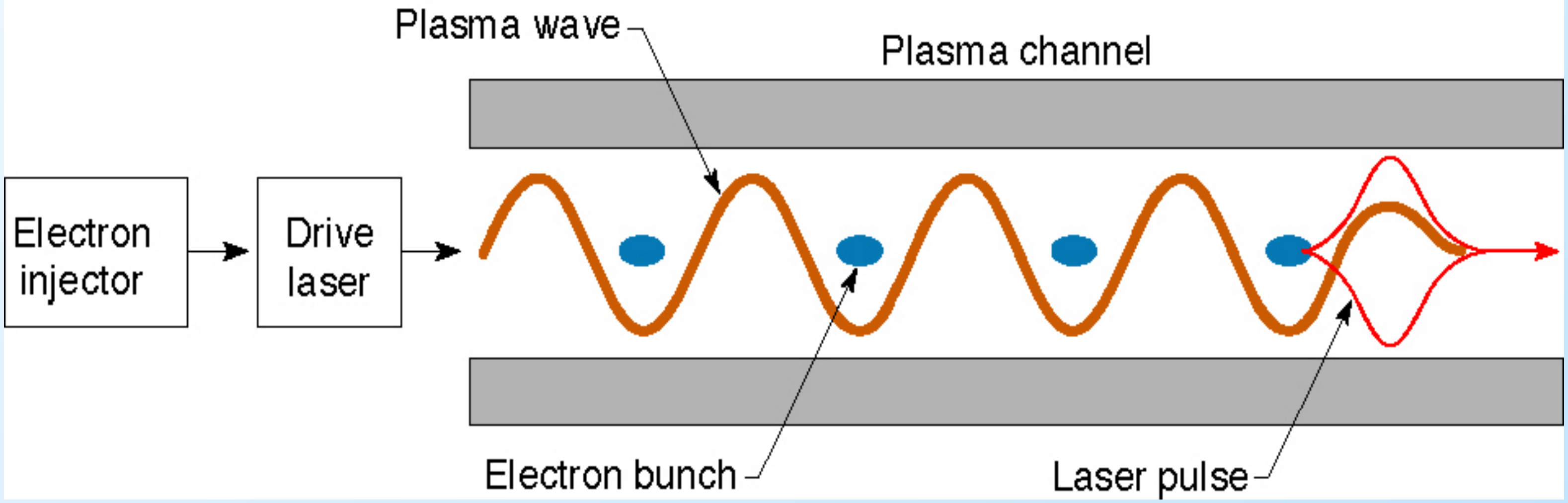
Outline

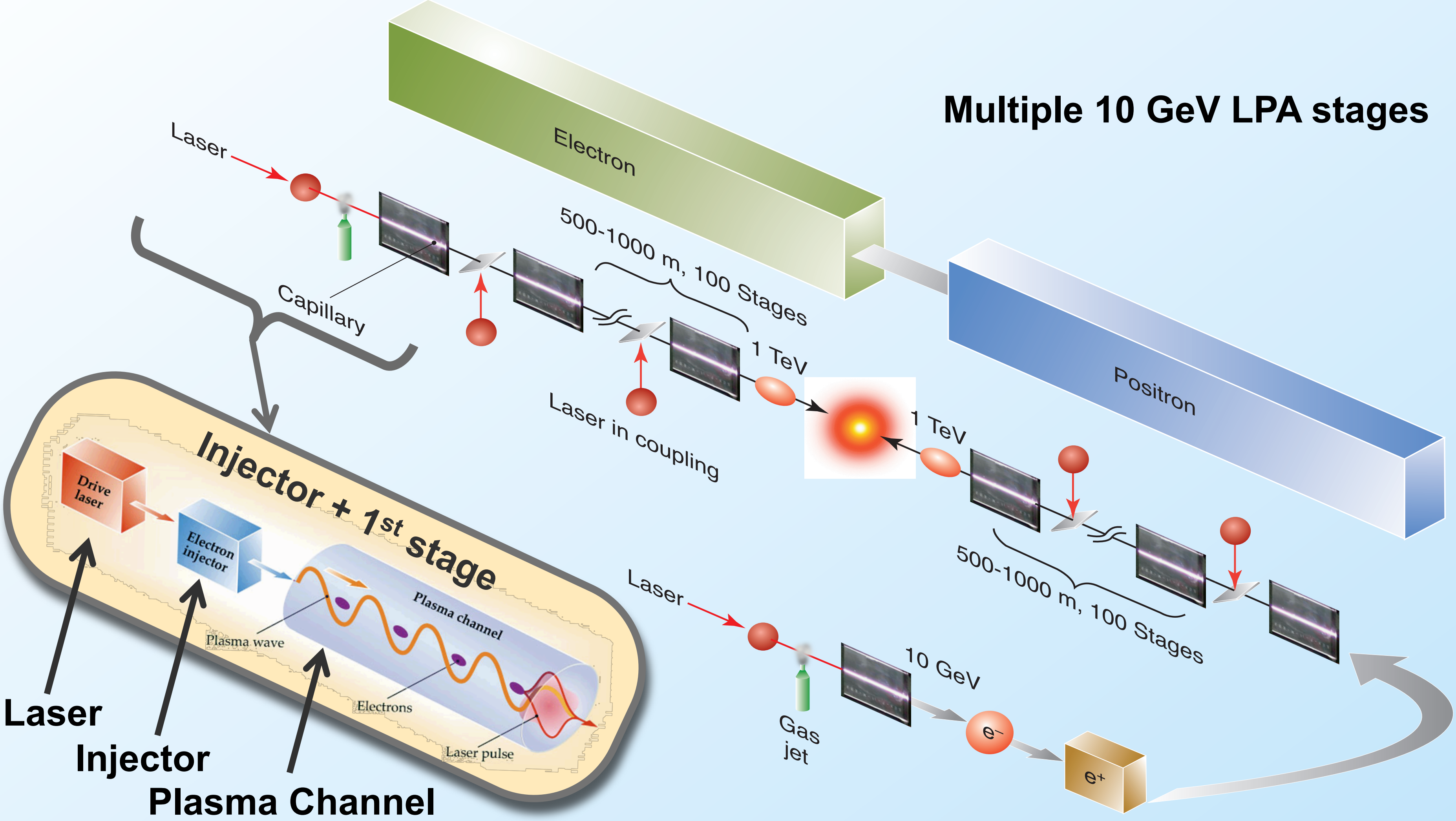
- LPA Basics
- Applications: conceptual designs
  - Electron-positron linear collider
  - XUV/X-ray Free Electron Lasers
- BELLA Project and LBNL

Laser-Plasma Accelerator



Strawman Design of a TeV LPA Collider

Multiple 10 GeV LPA stages



Electron

Positron

Laser

Capillary

500-1000 m, 100 Stages

1 TeV

Laser in coupling

1 TeV

500-1000 m, 100 Stages

Laser

10 GeV

Gas jet

Injector + 1st stage

Laser

Injector

Plasma Channel

Leemans & Esarey, Physics Today, March 2009

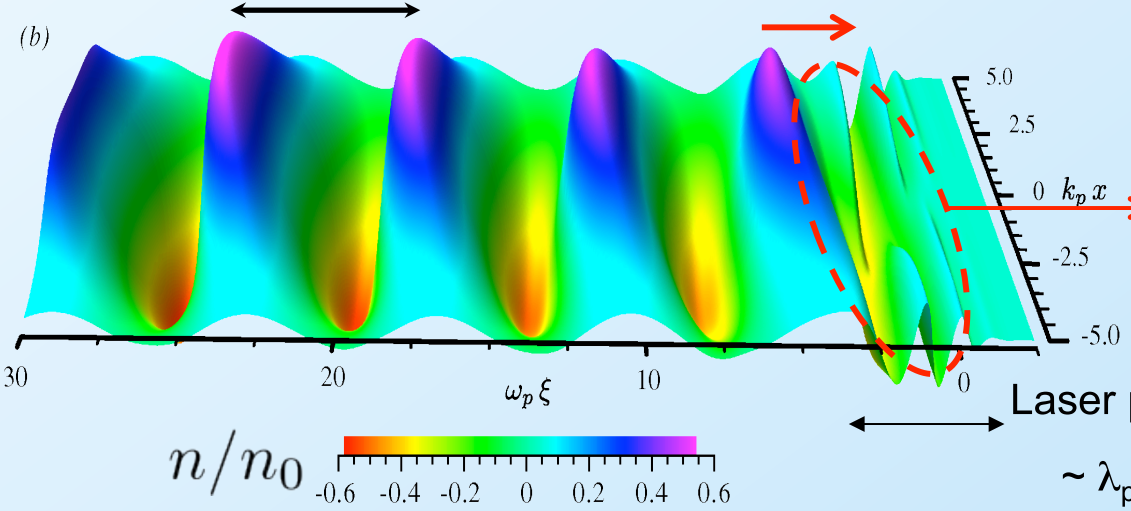
Laser-plasma accelerators (LPAs)

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

$$\underbrace{\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_0}}_{\text{Plasma wave: electron density perturbation}} = \underbrace{c^2\nabla^2\frac{1}{4}\left(\frac{eE_{\text{laser}}}{mc^2\omega}\right)^2}_{\text{Laser ponderomotive force (radiation pressure)}}$$

$\lambda_p = 2\pi c/\omega_p = (\pi r_e^{-1/2})\, n_p^{-1/2} \sim 30\ \mu m$

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



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

Laser pulse duration

~ λ_p/c ~ tens fs

electron plasma density perturbation

Laser-plasma accelerators: >10 GV/m accelerating gradient

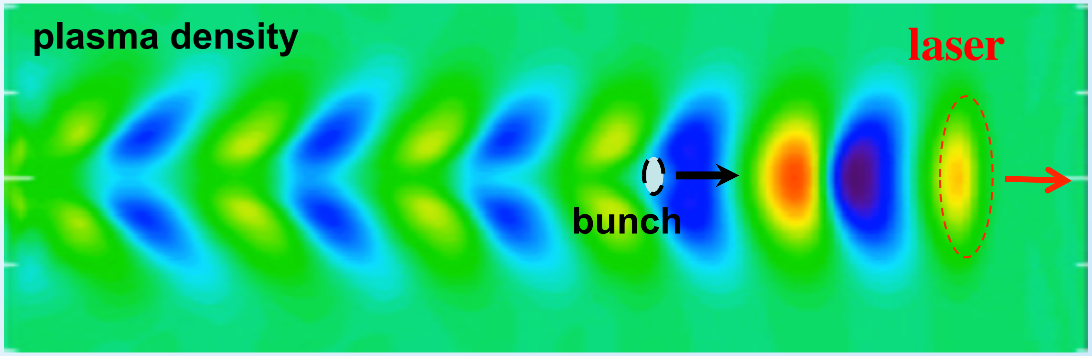
$$E \sim \left(\frac{mc\omega_p}{e}\right) \approx (96\ \mathrm{V/m})\sqrt{n_0[\mathrm{cm}^{-3}]}$$

plasma wave (wakefield) E ~100 GV/m (for n~10^{18} cm^{-3})

>10^3 larger than conventional RF accelerators ⇒ ">km to <m"

Accelerating bucket ~ plasma wavelength

➔ **ultrashort (fs) bunches (<λ_p/4)**

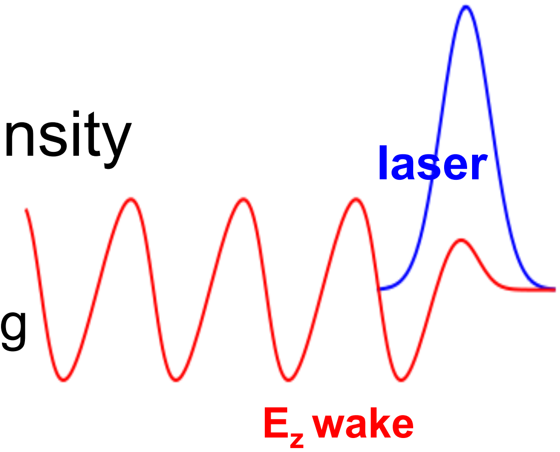


- beam charge (set by beam loading): ~100 pC (for n~10^{18} cm^{-3})
- beam duration (set by trapping physics): <10 fs

➔ **high peak current** $\gtrsim 10\ \mathrm{kA}$

Basic design of a laser-plasma accelerator: single-stage limited by laser energy

- Laser pulse length determined by plasma density
  - $k_p \sigma_z \leq 1, \quad \sigma_z \sim \lambda_p \sim n^{-1/2}$
- Wakefield regime determined by laser intensity
  - Linear (a_0<1) or blowout (a_0>1)
  - Determines bunch parameters via beam loading



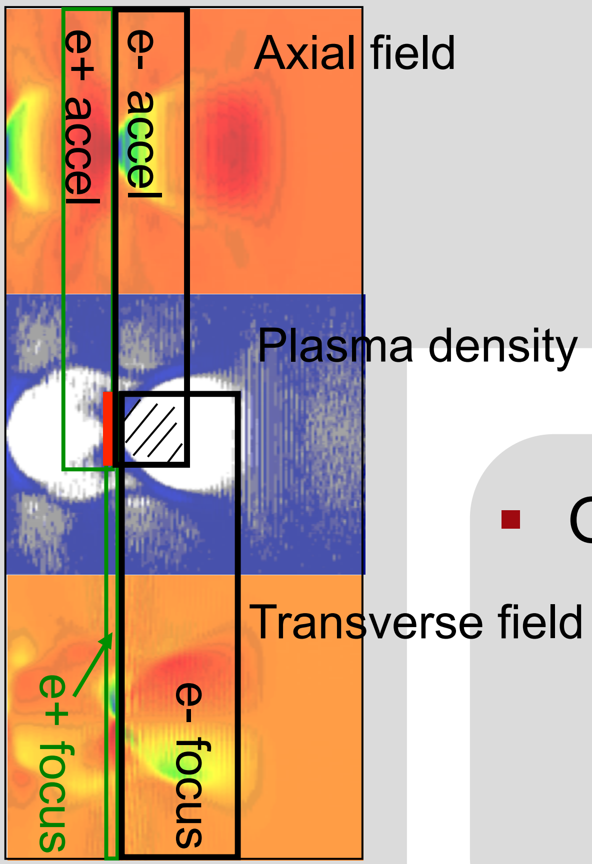
$$a_0^2 \simeq 7.3 \times 10^{-19} [\lambda(\mu\mathrm{m})]^2 I_0(\mathrm{W/cm}^2),$$

  - Ex: $a_0 = 1$ for $I_0 = 2\times10^{18}$ W/cm^2 and $\lambda_0 = 0.8$ μm
- Accelerating field determined by density and laser intensity
  - $E_z \sim (a_0^2/4)(1+a_0^2/2)^{-1/2}\, n^{1/2} \sim 10$ GV/m
- Energy gain determined by laser energy via depletion*
  - Laser: Present CPA technology 10’s J/pulse

*Shadwick, Schroeder, Esarey, Phys. Plasmas (2009)

Linear & blowout regimes: e+/e- acceleration

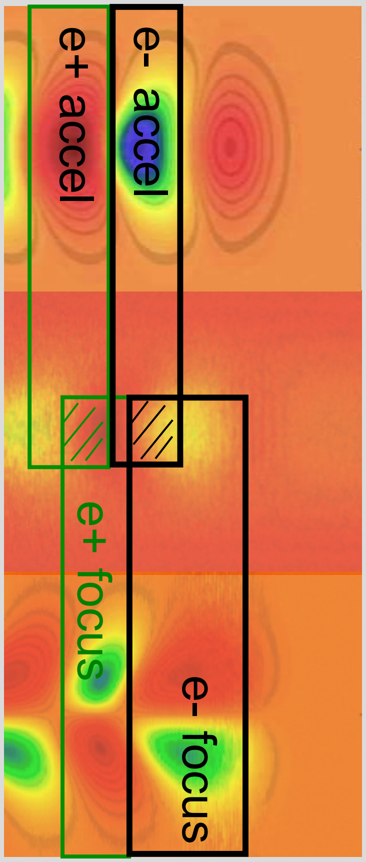
a_0=4



- Blowout regime
  - high field
  - very asymmetric
    - focuses e-
    - defocuses ~~e+~~
  - self-trapping

- Quasilinear
  - linear: symmetric e+/e-
  - high a_0 desired for gradient
    - too high enters bubble
  - a_0 ~1-2 good compromise
  - dark current free

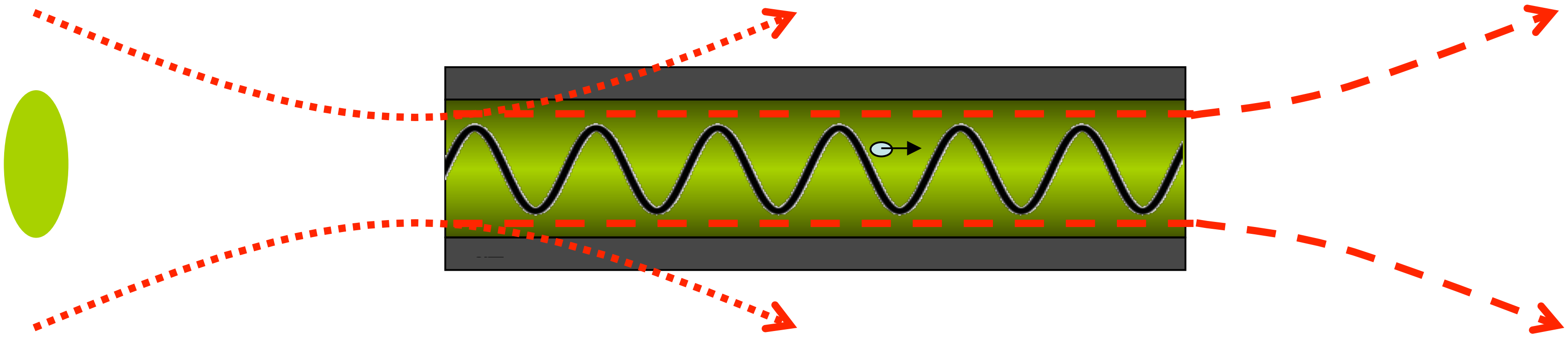
a_0=1



$\Delta W = E_z \,.\, L$

Limits to acceleration length: diffraction

- “3D”: Diffraction, Dephasing, Depletion
- Diffraction of laser pulse
  - $Z_R = \pi\, r_0^2/\lambda_0 \sim 2$ cm, $Z_R \ll L_{dephase} < L_{deplete}$
  - Solution: Density channels



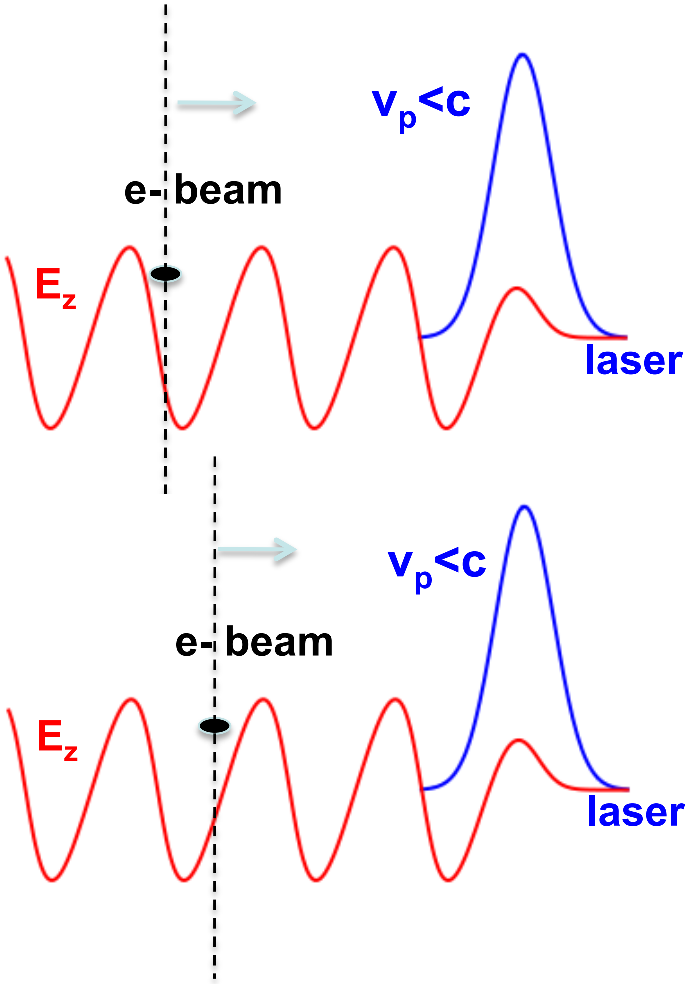
  - Parabolic channel guides gaussian modes
  - Channel depth: $\Delta n\ [\mathrm{cm}^{-3}] = 10^{20} / (r_0[\mu \mathrm{m}])^2 \sim 2\mathrm{x}10^{16}\ \mathrm{cm}^{-3}$

W.P. Leemans et al, *IEEE Trans. Plasmas Sci.* (1996); Esarey et al., *Phys. Fluids* (1993)

$\Delta W = E_z \, . \, L$

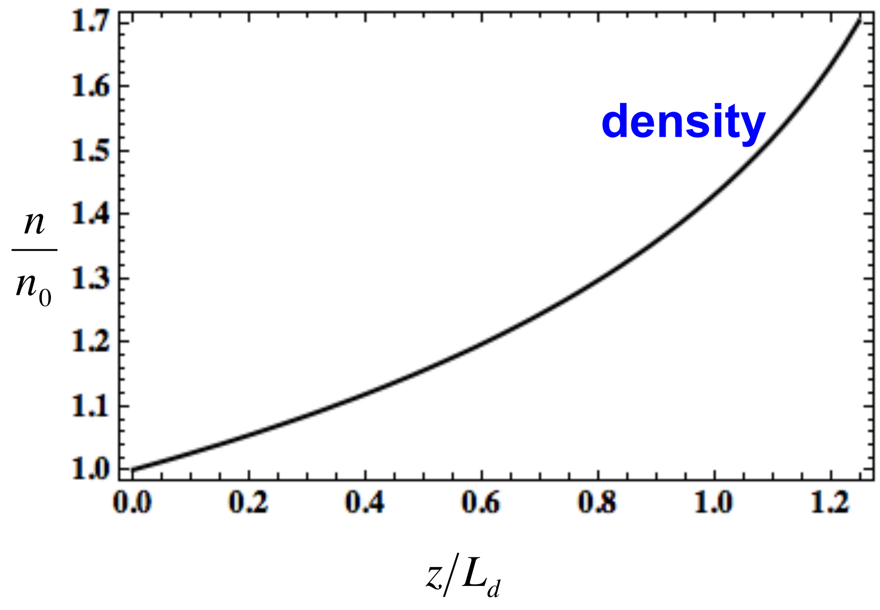
Limits to Acceleration Length: dephasing

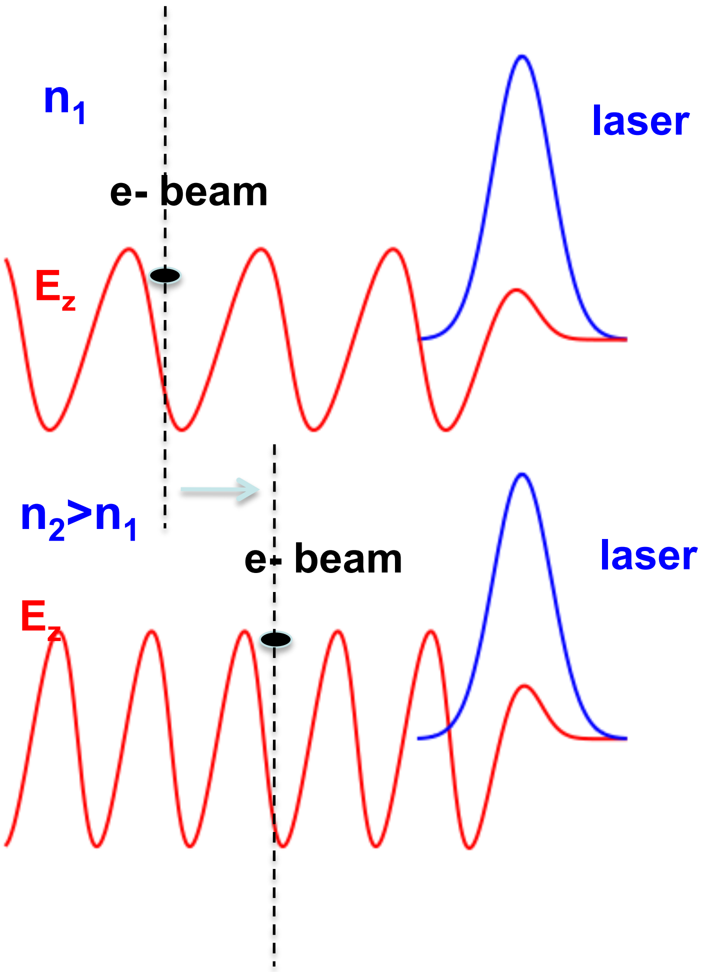
- Dephasing: e^- outrun wake,
  - Phase velocity: $v_p/c \approx v_g/c = 1 - \lambda_0^2/2\lambda_p^2$
  - $L_{dephase}(1-v_g/c) = \lambda_p/2$,
  - $L_{dephase} = \lambda_p^3/\lambda_0^2 \sim n^{-3/2} \sim 1.6$ m
- Solution: density tapering



Density Tapering: Phase Lock e-

- For $a_0 \sim 1$, $L_{dephase}$ may be < $L_{deplete}$
- Phase velocity depends on density
  - Phase position ~ $\lambda_p \sim n^{-1/2}$
- Taper density to tune wake velocity
- Depletion then limits e^- energy gain

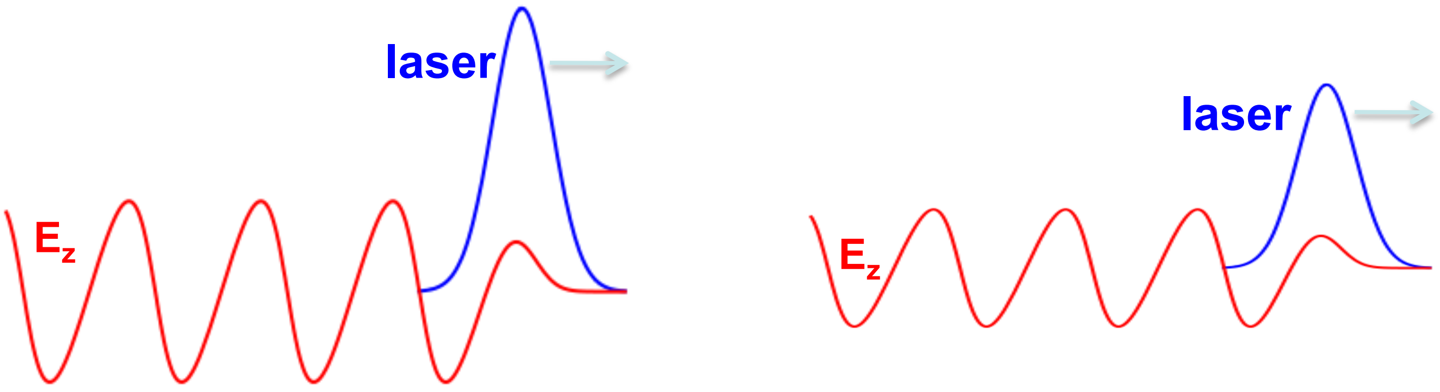




Katsouleas, PRA (1986); Rittershofer et al, PP (2010)

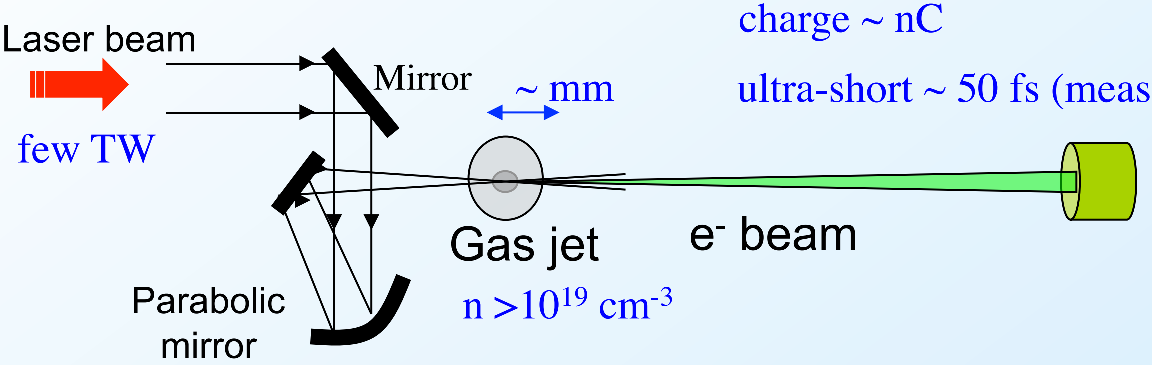
$\Delta W = E_z \, . \, L$
Limits to acceleration length: depletion

- Depletion: laser loses energy to wake
  - Energy balance: $E_L{}^2 \, \sigma_z = E_z{}^2 \, L_{deplete}$
  - Linear limit $a_0{}^2 << 1$: $L_{deplete} = a_0{}^{-2} \, L_{dephase} >> L_{dephase}$
  - Nonlinear limit $a_0{}^2 >> 1$: $L_{deplete} \sim L_{dephase}$



Solution: staging

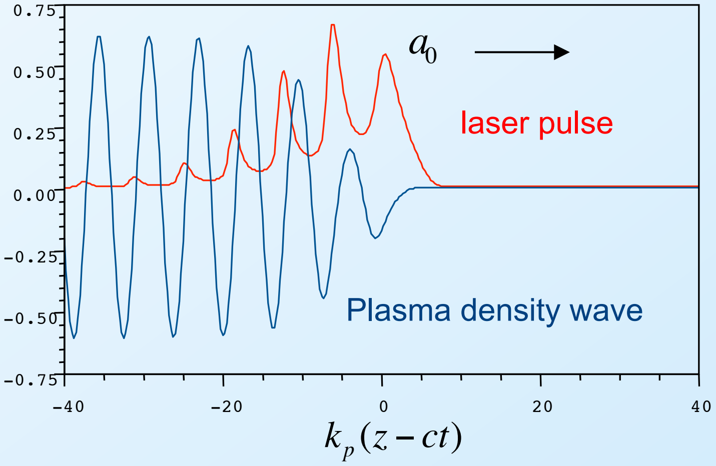
Prior to 2004: Self-modulated laser-plasma accelerator experiments



charge ~ nC

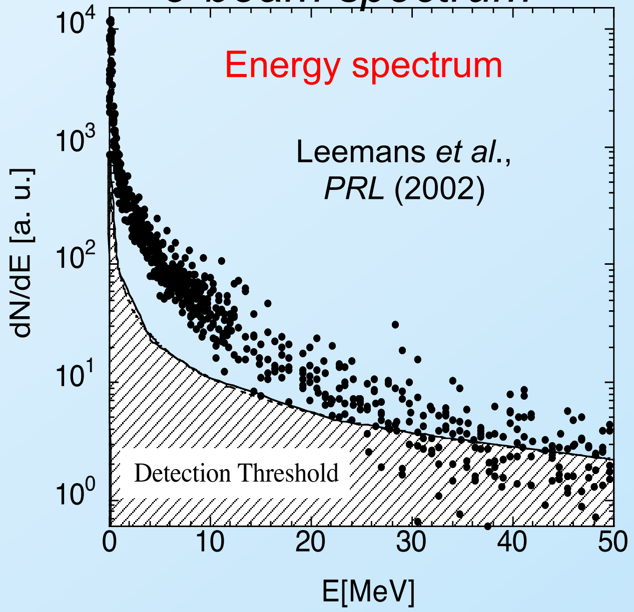
ultra-short ~ 50 fs (measured CTR THz)

- Plasma wave generated via Raman scattering instability (modulation of a long laser pulse)



Schroeder *et al.*, *Phys. Plasmas* (2003)

e-beam spectrum



Leemans *et al.*, *PRL* (2002)

Exponential distribution:

(1) Raman instability results in continued electron trapping

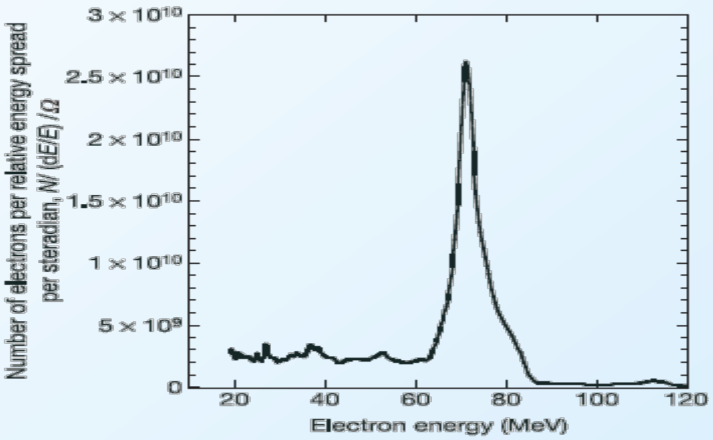
(2) High density ⇒ $L_{dephase} << L_{gas\text{-}jet}$ ⇒ electrons accelerated and deccelerated

2004 Experimental Results: High-quality 100 MeV beams

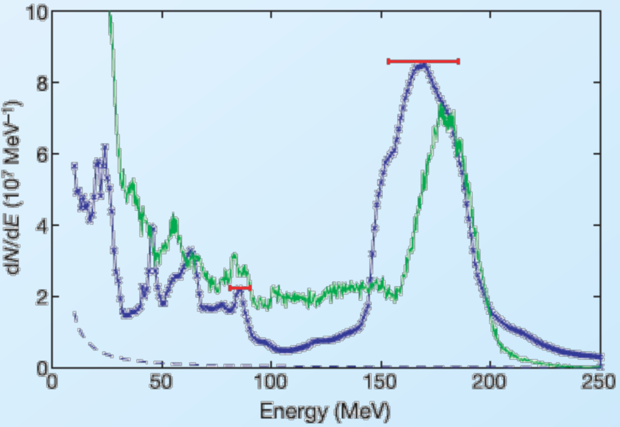
Extend interaction length and lower plasma density to match interaction length to dephasing length: $L_{\text{int}} \sim L_{\text{dephase}} \sim L_{\text{deplete}}$

- Approach 1: bigger laser spot (more laser energy)

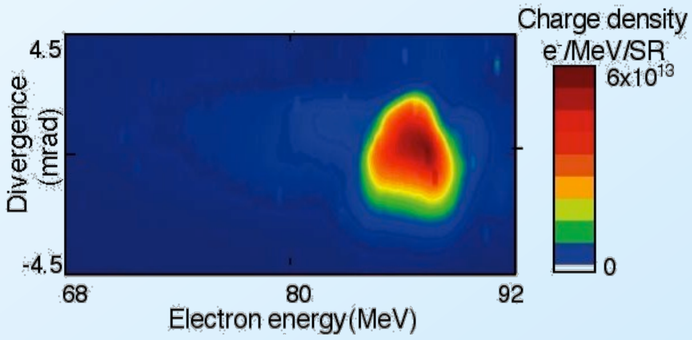
RAL (UK):
Mangles et al,
Nature (2004)



LOA (France):
Faure et al,
Nature (2004)



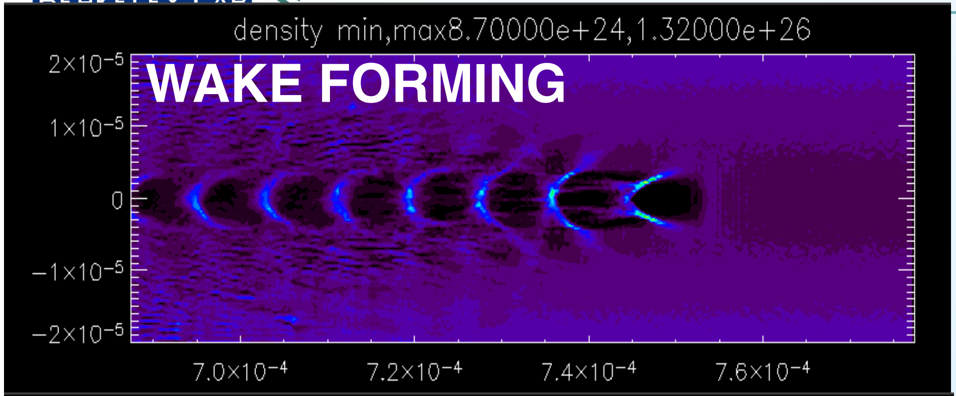
- Approach 2: preformed channel guided: LBNL expt.

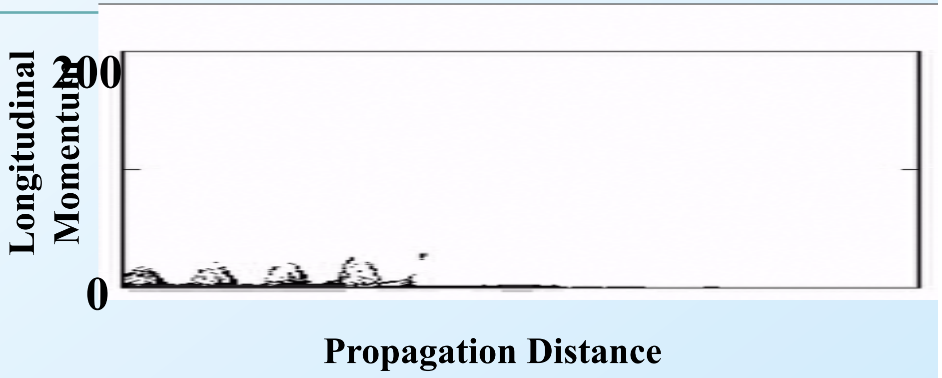


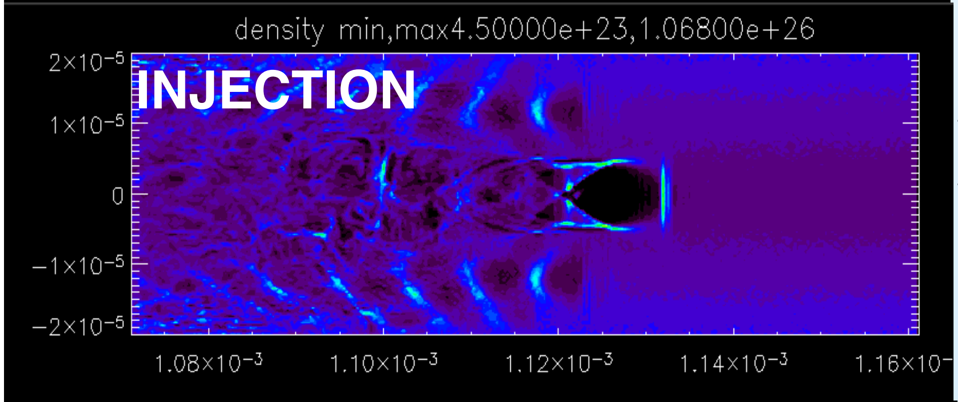
Geddes et al, Nature 431 (2004)

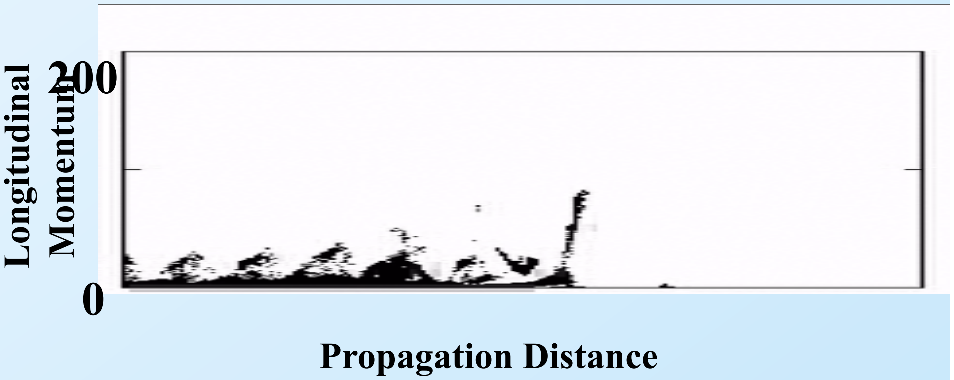
PIC Simulation of LBNL Expt.

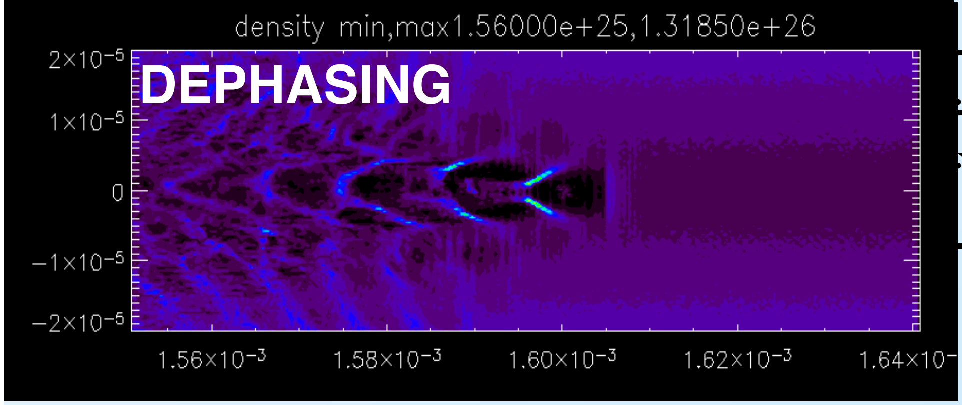
Wake Evolution and Dephasing Yield Low Energy Spread Beams in PIC Simulations

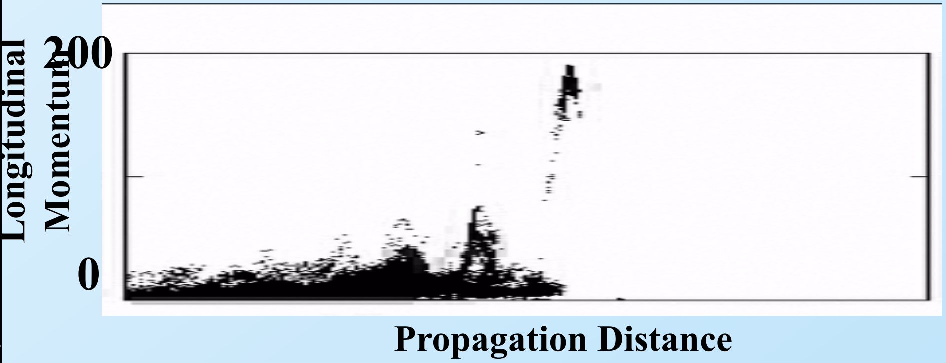












Geddes et al., Nature (2004) & Phys. Plasmas (2005)

LWFA: Production of a Monoenergetic Beam

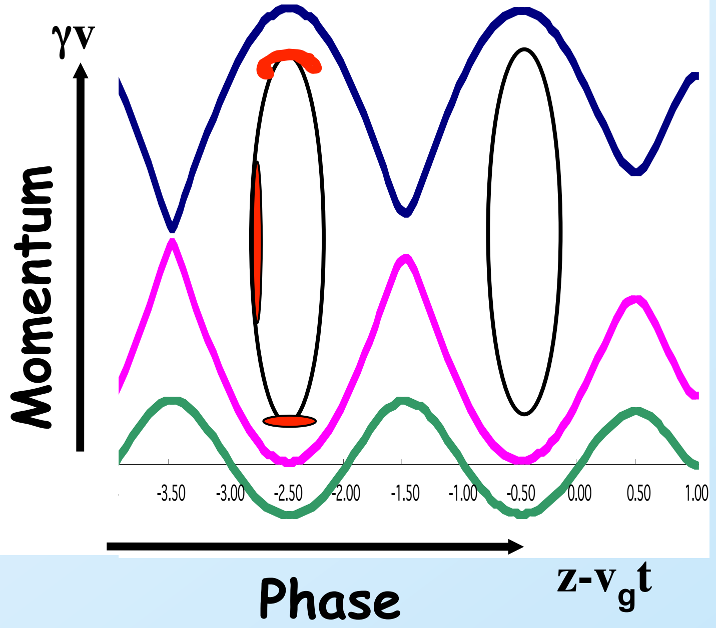
1. Excitation of wake (e.g., self-modulation of laser)
2. Onset of self-trapping (e.g., wavebreaking)
3. Termination of trapping (e.g., beam loading)
4. Acceleration

   If > dephasing length: large energy spread

   If ≈ dephasing length: monoenergetic

- **Dephasing distance:**

$$L_{dph} \approx \left(\lambda_p^3 / \lambda^2\right) \propto n_e^{-3/2}$$



1
Wake Excitation

2-3
Trapping

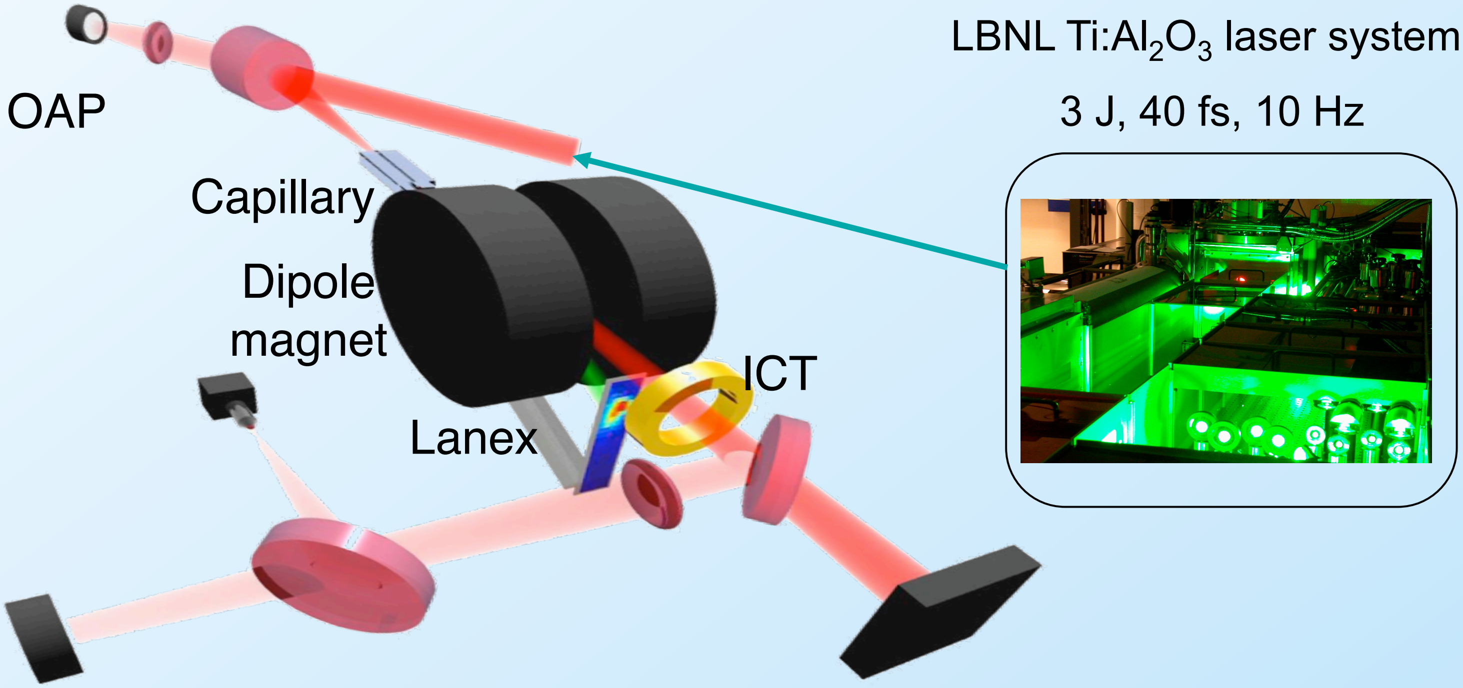
4
Acceleration: $L_{accel} \sim L_{dephase}$

Laser-plasma accelerator for GeV beams

Energy gain: $W \sim (mc\omega_p/e)L_{acc} \propto n^{-1}$ ➡ low density plasmas (~10^{18} cm^{-3})

Accelerator length: $L_{acc} \sim \lambda_p^3/\lambda_L^2 \propto n^{-3/2}$ ➡ long plasma channels (~cm)

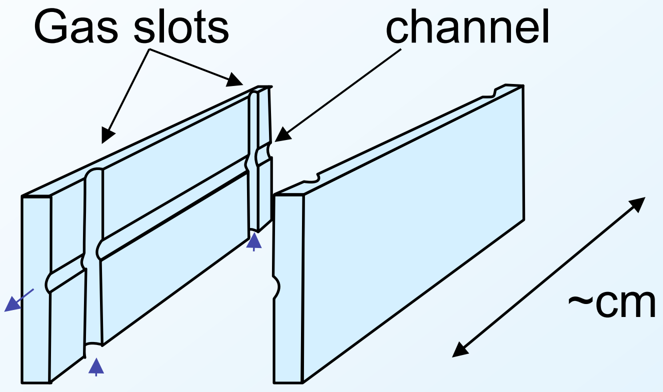
Laser energy/power: $\left.\begin{array}{l} U_{laser} \propto n^{-3/2} \\ P_{laser} \propto n^{-1} \end{array}\right\}$ ➡ more laser energy (power)

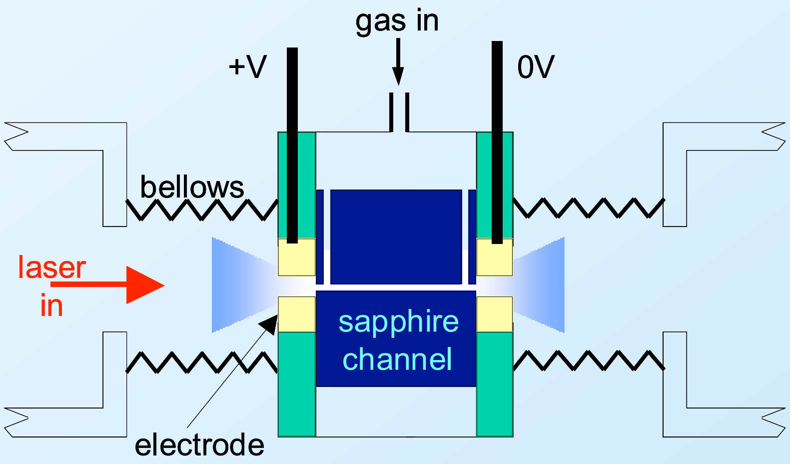


LBNL Ti:Al$_2$O$_3$ laser system:

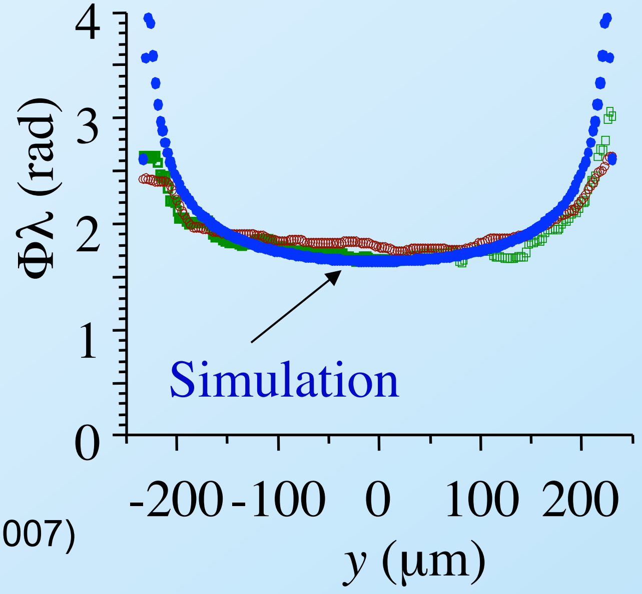
3 J, 40 fs, 10 Hz

Capillary discharge plasma waveguides



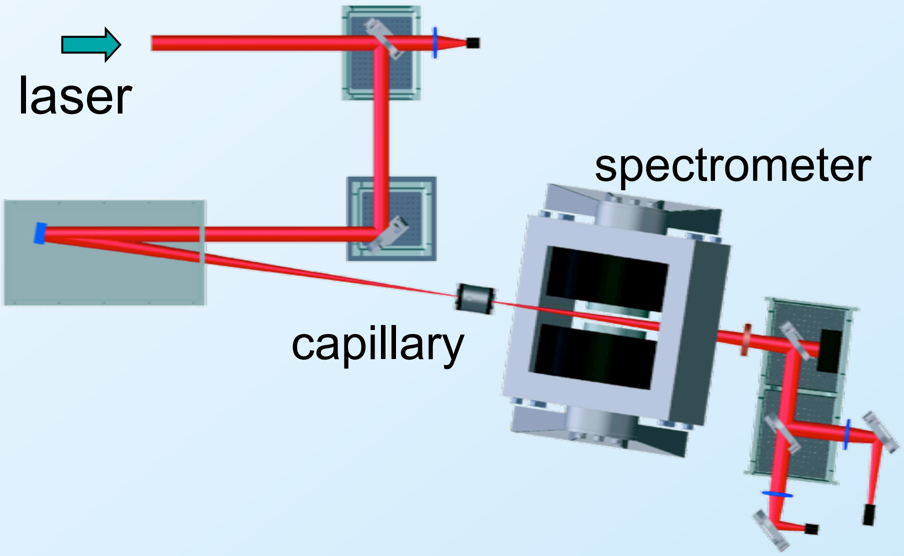


- Ionized by pulse discharge (200-500A, ~100ns)
- Plasma fully ionized for t > 50 ns
- After t ~ 80 ns plasma is in quasi-equilibrium: Ohmic heating is balanced by conduction of heat to wall
- Ablation rate small: cap. lasts for $>10^6$ shots
- $n_e \sim 10^{17} - 10^{19}\ \text{cm}^{-3}$

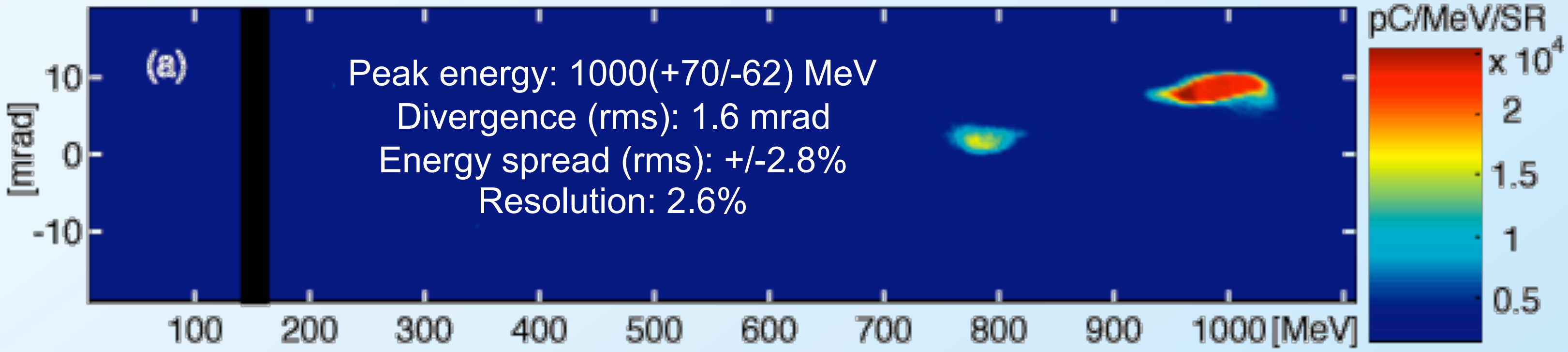


Spence & Hooker, Phys. Rev. E (2001); Gonsalves et al. PRL (2007)

GeV electron beam from laser-plasma accelerator demonstrated



- a_0 ~ 1.46 (40 TW, 37 fs)
- n_e ~ 4×10^{18} cm^{-3}
- capillary: 33 mm length



Peak energy: 1000(+70/-62) MeV
Divergence (rms): 1.6 mrad
Energy spread (rms): +/-2.8%
Resolution: 2.6%

Leemans et al., Nature Physics (2006)

Challenge: Controlled injection for improved beam quality and stability

- In regime of beam self-trapped from background plasma, beam quality determined by self-trapping physics.

- Controlled injection (charge and location) of electrons into plasma wave to improve beam stability and quality

  - External injection (from conventional RF gun)
    - problematic: coupling to plasma-wavelength-scale and synchronization

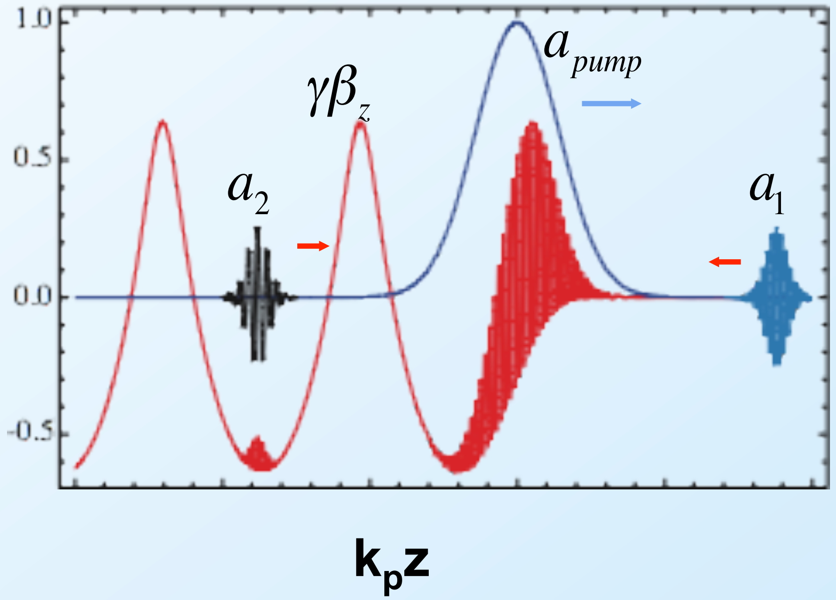
  - Triggered trapping (injection) of plasma electrons:
    1. Laser-triggered injection (colliding pulse injection)
    2. Plasma density gradient injection

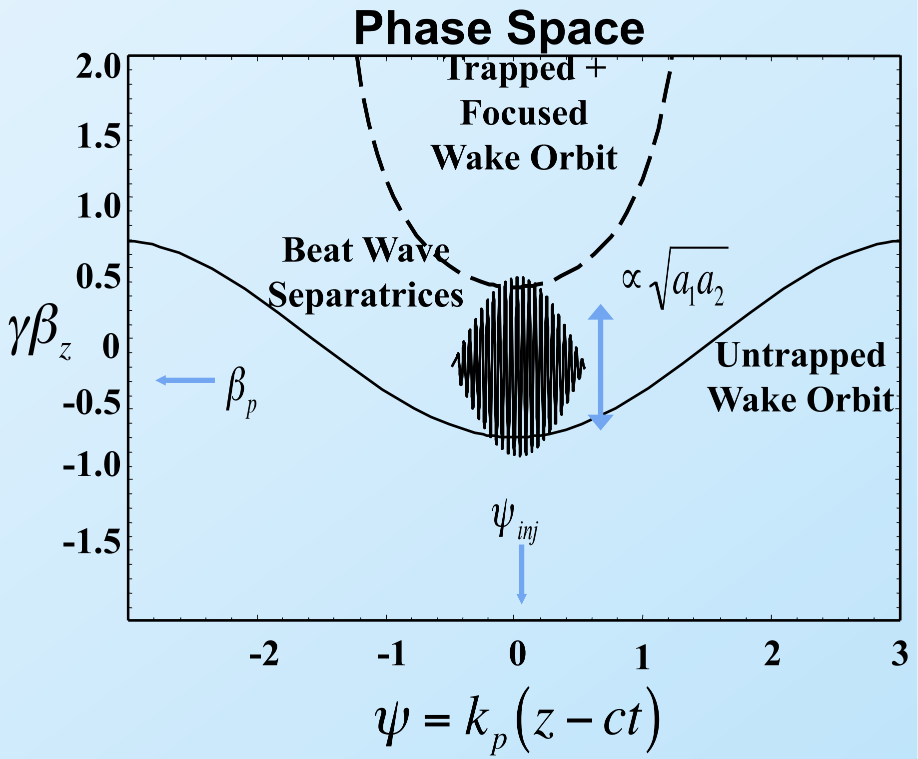
- In principle, triggered injection in a plasma wave could achieve beam quality (low emittance) beyond state-of-the-art photocathodes (space-charge shielding provided by ions, rapid acceleration)

Controlled pulse injection enables detailed control of injection phase space via laser

Room for improvement:

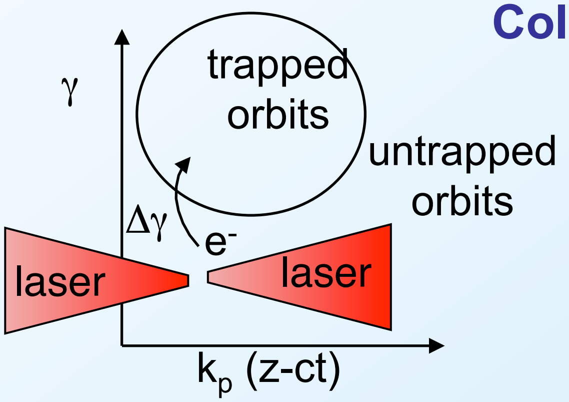
- *3-pulse* colliding pulse:
    1. control of injection position (by delay between pump and trailing pulses)
    2. lower colliding laser pulse intensity (less wake distrubiton)
- Phase velocity of beat separatrices controlled by using different frequency laser pulses





Controlled injection via colliding laser pulses improves beam quality

Theoretical development:

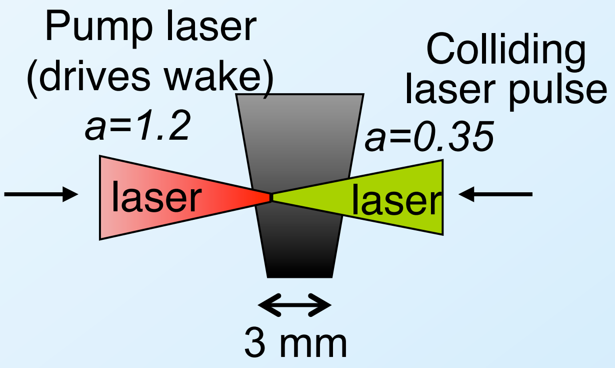


Colliding pulse injection:

Esarey et al. PRL (1997);
Schroeder et al. PRE (1999);
Fubiani et al. PRE (2004)

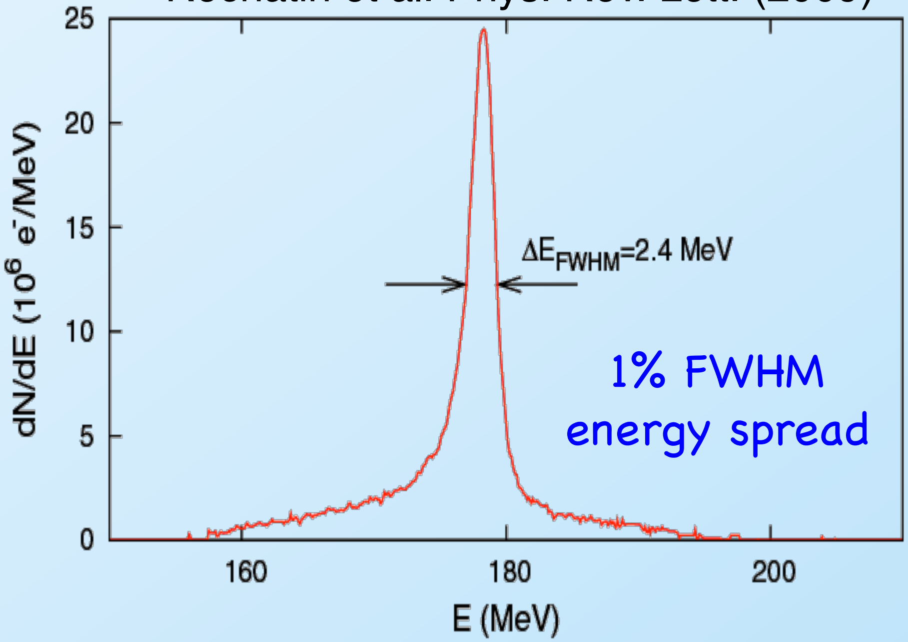
Experimental demonstration:

LOA (France): Faure et al., Nature (2006)



Gas jet: 7×10^{18} cm^{-3}

Rechatin et al. Phys. Rev. Lett. (2009)



Depletion: necessitates multiple stages

- Single stage energy gain limited by laser energy depletion
  - Diffraction limitation: mitigated by transverse plasma density tailoring
  - Dephasing limitation: mitigated by longitudinal plasma density tailoring

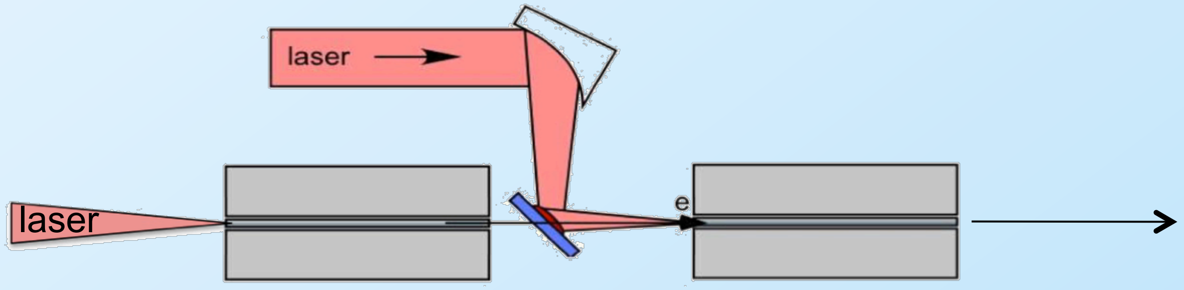
Depletion Length: $L_D \propto \frac{1}{n_e^{3/2}}$

Accelerating field: $E_0[\mathrm{V/m}] \approx 100\sqrt{n[\mathrm{cm}^{-3}]}$

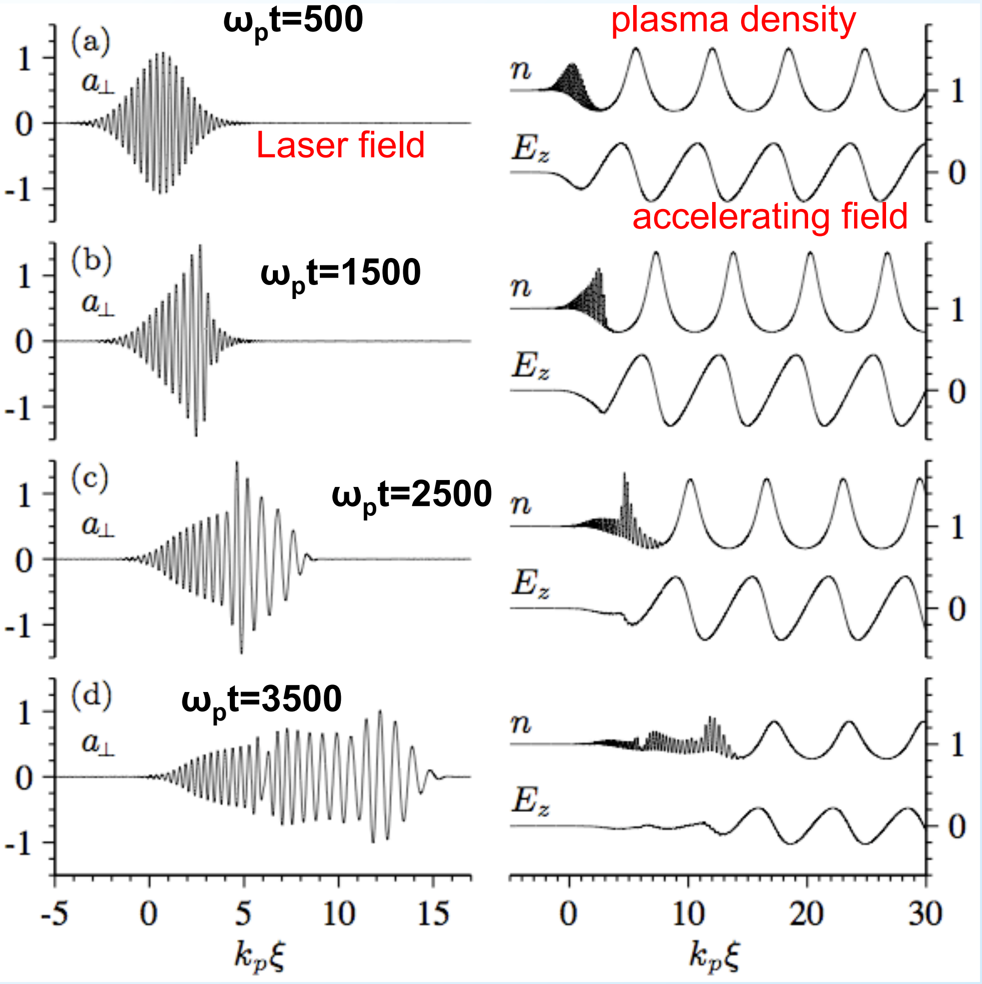
Energy gain (linear regime): $W_{\mathrm{stage}}[\mathrm{GeV}] \approx \frac{I[\mathrm{W/cm}^2]}{n[\mathrm{cm}^{-3}]}$

- Ex: W_{stage} = 10 GeV for I = 10^{18} W/cm^2 and n = 10^{17} cm^{-3}

- Multiple-stages for controlled acceleration to high energy:

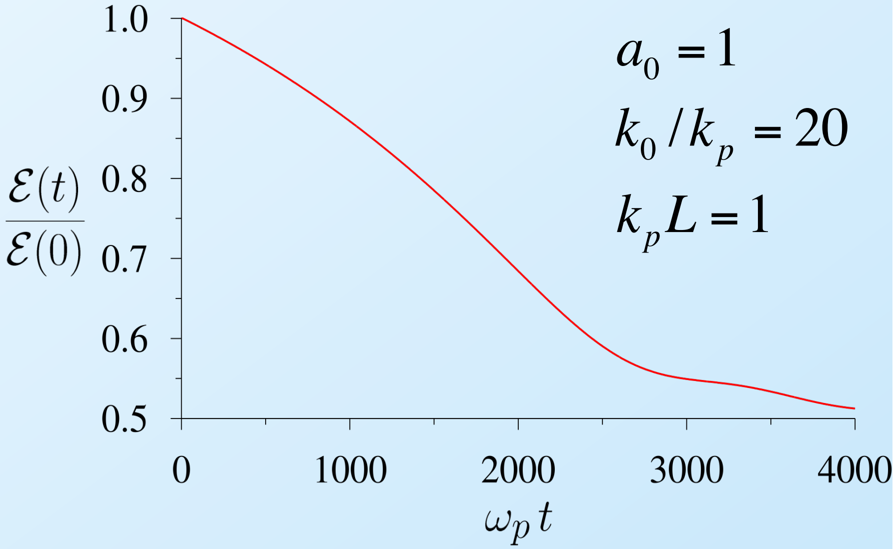


Laser pulse evolution



$$a_0 = 8.6\times10^{-10}\,\lambda[\mu\text{m}]I^{1/2}[\text{W/cm}^{-2}]$$

Laser energy evolution:

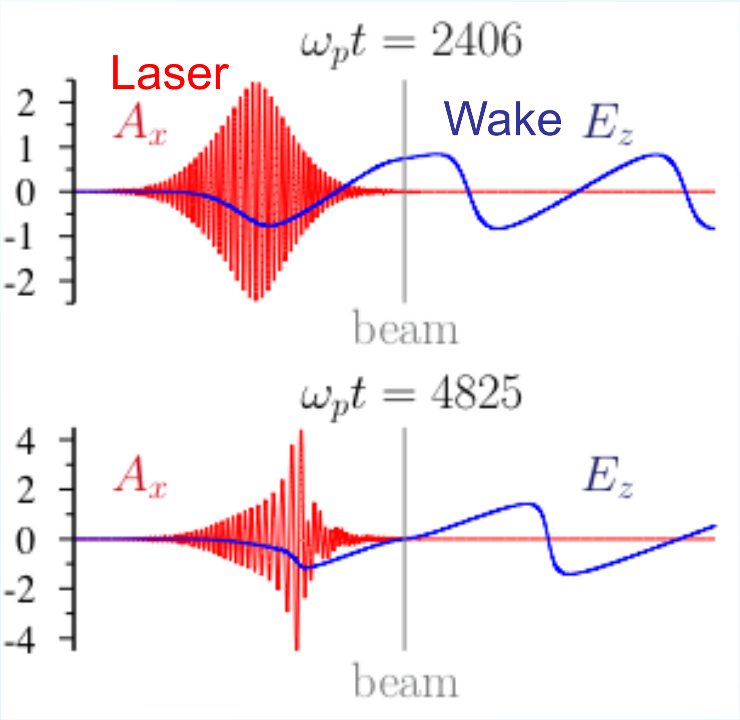


- Laser evolution interplay between laser intensity steepening, laser frequency red-shifting, energy depletion

Shadwick, Schroeder, Esarey, Physics of Plasmas (2009)

Longitudinal e-bunch dynamics:
energy spread minimum near dephasing

Fluid plasma + e-bunch described by moments (includes beam loading)



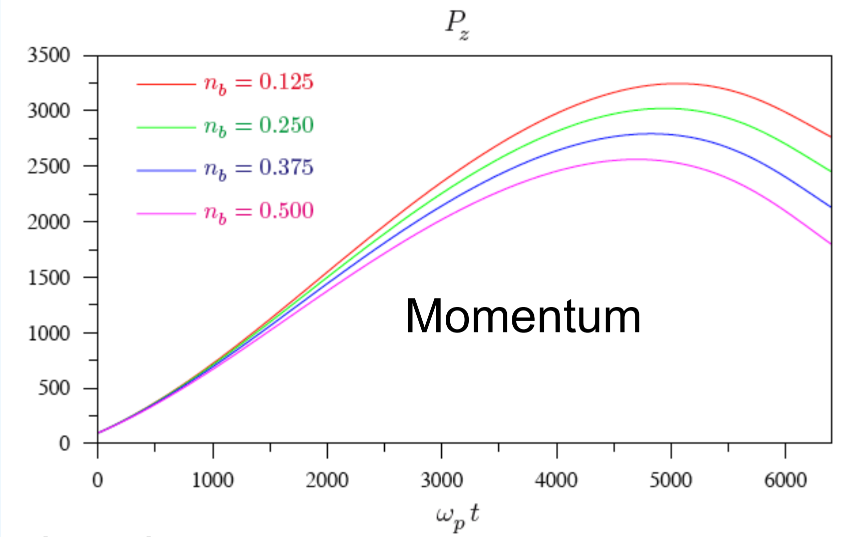
Position, $k_p(z\text{-}ct)$

Energy spread

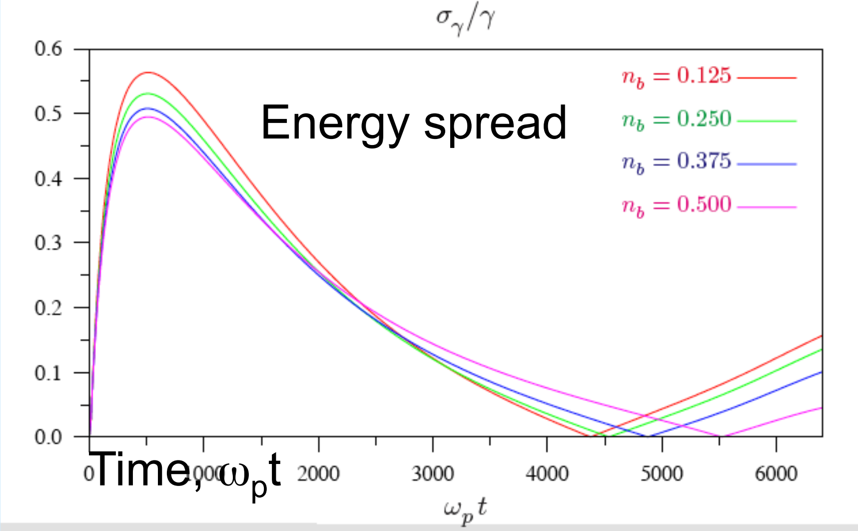
Initial: σ_γ/γ = 0.3% at γ = 100

Final: σ_γ/γ = 0.01% at γ = 3000

B.A. Shadwick et al.

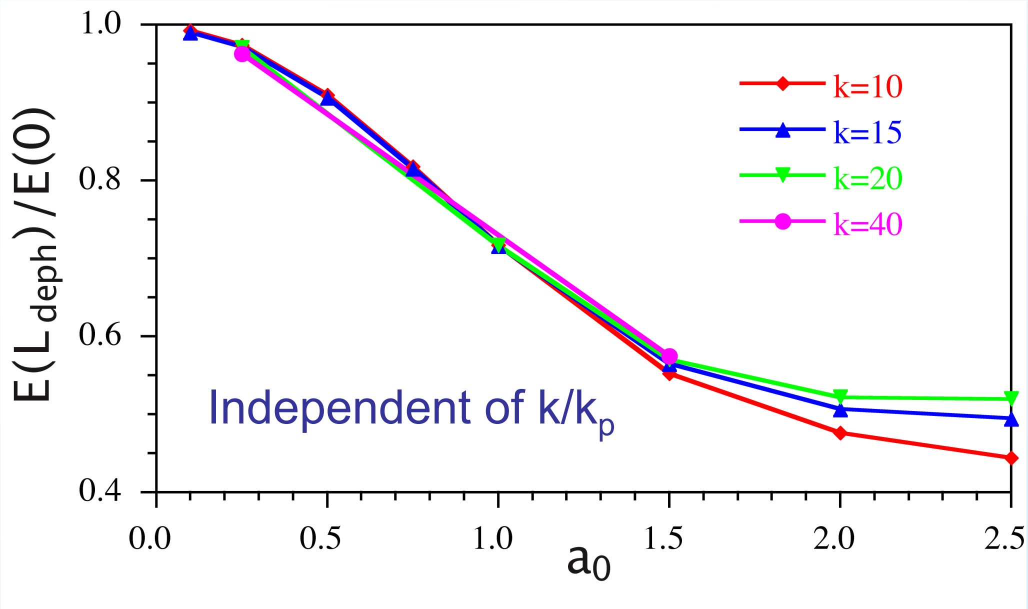


e-bunch



Scaling laws from fluid code: dephasing/depletion lengths & energy gain

Fraction of laser energy at dephasing length



- Quasi-linear: $a_0 \sim 1$
  - Dephasing ~ depletion
  - Good efficiency
- Fix laser parameters (a_0, k_pL_0, k_pr_0), increase (k/k_p) to increase energy

Point designs: 10 and 100 GeV

a_0	P/P_c	P(PW)	W_L	t_0(fs)	r_0(μm)	λ_p(μm)	n_0(cm^{-3})	L_{dp}	W_e (GeV)
2	2.2	0.38	40 J	98	53	80	1.7×10^{17}	38 cm	10
1.5	1.1	0.30	40 J	130	63	99	1.1×10^{17}	79 cm	10
1	0.45	0.22	40 J	170	82	140	6.0×10^{16}	2.4 m	10
2	2.2	3.8	1.3 kJ	310	170	250	1.7×10^{16}	12 m	100
1.5	1.1	3.0	1.3 kJ	390	200	310	1.1×10^{16}	25 m	100
1	0.45	2.2	1.3 kJ	550	260	430	6.0×10^{15}	78 m	100

Laser power: $P[\mathrm{GW}] = 21.5(a_0 r_0/\lambda)^2$, Critical power: $P_c[\mathrm{GW}] = 17(k/k_p)^2$, $P/P_c = (a_0 k_p r_0)^2/32$.

All assume: $k_p L_0 = 2$, $\lambda = 0.8$ μm

Collider Requirements: Luminosity

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

$$L = \frac{fN^2}{4\pi\sigma_x\sigma_y} = \frac{P_b}{4\pi E_{cm}}\frac{N}{\sigma_x\sigma_y}$$

  - 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)

1 TeV LPA Collider Parameters

Plasma density scalings:

Stage density scalings:

$$E_0 \propto n^{1/2}$$

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

$$W_{\text{stage}} \propto n^{-1}$$

$$U_L \propto n^{-3/2}$$

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

Collider density scalings (for fixed luminosity):

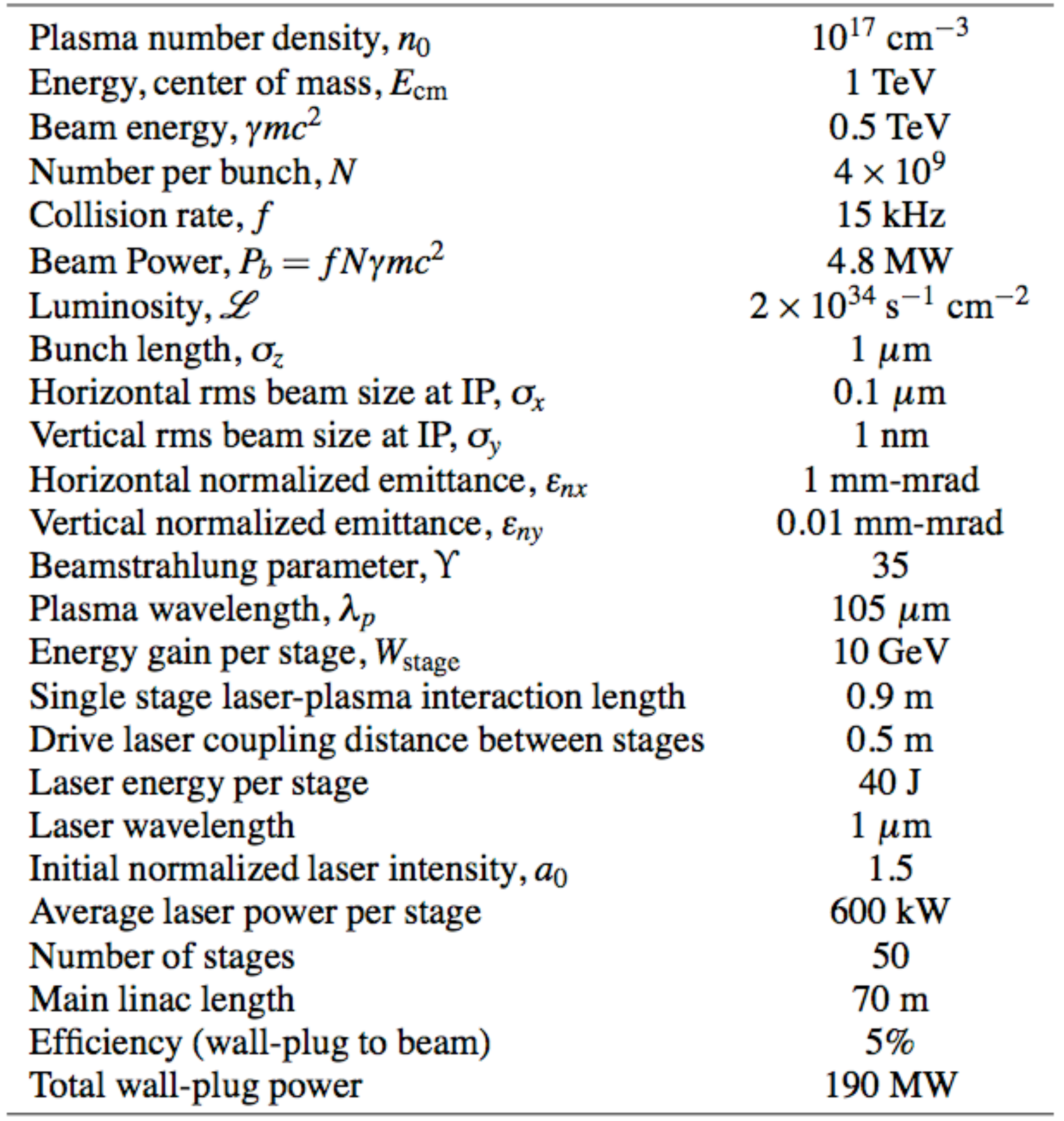
$$f \propto n$$

$$N_{\text{stage}} \propto n$$

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

$$P_{\text{laser}} \propto n^{-1/2}$$

Schroeder et al., AAC08



Plasma number density, n_0	10^{17} cm^{-3}
Energy, center of mass, E_{cm}	1 TeV
Beam energy, γmc^2	0.5 TeV
Number per bunch, N	4×10^9
Collision rate, f	15 kHz
Beam Power, $P_b = fN\gamma mc^2$	4.8 MW
Luminosity, $\mathscr{L}$	2×10^{34} s^{-1} cm^{-2}
Bunch length, σ_z	1 μm
Horizontal rms beam size at IP, σ_x	0.1 μm
Vertical rms beam size at IP, σ_y	1 nm
Horizontal normalized emittance, ε_{nx}	1 mm-mrad
Vertical normalized emittance, ε_{ny}	0.01 mm-mrad
Beamstrahlung parameter, Υ	35
Plasma wavelength, λ_p	105 μm
Energy gain per stage, W_{stage}	10 GeV
Single stage laser-plasma interaction length	0.9 m
Drive laser coupling distance between stages	0.5 m
Laser energy per stage	40 J
Laser wavelength	1 μm
Initial normalized laser intensity, a_0	1.5
Average laser power per stage	600 kW
Number of stages	50
Main linac length	70 m
Efficiency (wall-plug to beam)	5%
Total wall-plug power	190 MW

Collider power and efficiency requirements: High average power laser

- Beam power: $P_b = fNE_{cm}$

$$\left.\begin{array}{r} N \sim 4\text{x}10^9 \\ f \sim 15\ \text{kHz} \\ E_{cm} \sim 1\ \text{TeV} \end{array}\right\} \quad P_b \sim 5\ \text{MW}$$

- AC wall-plug power: ~ 200 MW ➔ 5% efficiency

- Laser to plasma wave efficiency: ~50%
- Plasma wave to beam efficiency: ~30%

➔~15% laser to beam efficiency
➔~33% wall-plug to laser efficiency

- Collider based on 10-GeV stages:
  - (total beam energy ~300 J)/(50 stages) = ~6 J/stage
  - ~40 J/laser at 15 kHz = ~600 kW average power laser

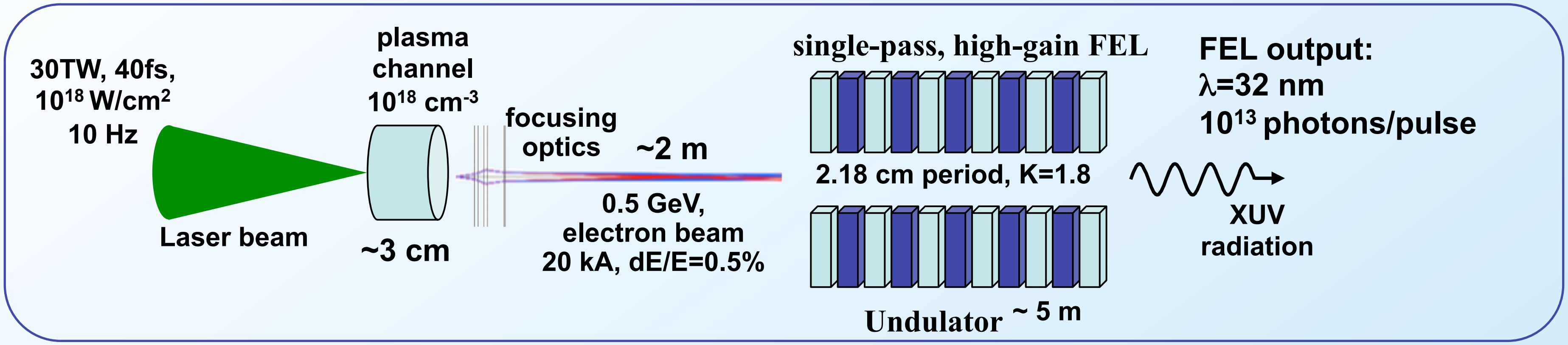
beyond state-of-the-art laser technology
➔ Laser technology development required

- Energy remaining in plasma-based accelerator (damped plasma wave)
  - ~10J/stage remains in plasma ➔ >100 kW/m

BELLA: BErkeley Lab Laser Accelerator

- 1 PW laser facility
- 10 GeV electron beam from a meter long accelerator
- BELLA Project budget:
  - Funded by Office of Science – High Energy Physics
- Located in Bldg. 71 – old SUPERHILAC location
- Schedule: early finish mid 2012, CD-4 date: Dec. 2014
- CD-3 approval, ESAB signed: July 2010

Laser-plasma accelerator driven XUV FEL at LBNL



30TW, 40fs,
10^{18} W/cm^2
10 Hz

Laser beam

plasma channel
10^{18} cm^{-3}

~3 cm

focusing optics

~2 m

0.5 GeV, electron beam
20 kA, dE/E=0.5%

single-pass, high-gain FEL

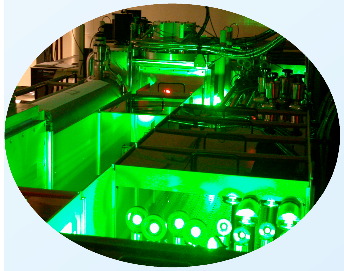
2.18 cm period, K=1.8

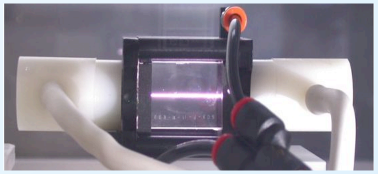
Undulator ~ 5 m

FEL output:
λ=32 nm
10^{13} photons/pulse

XUV radiation

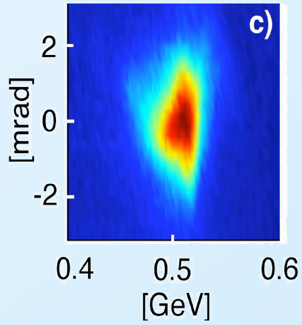
Ti:Al$_2$O$_3$ laser system

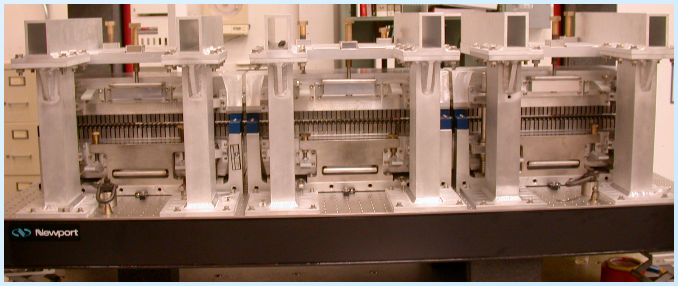




Plasma capillary technology

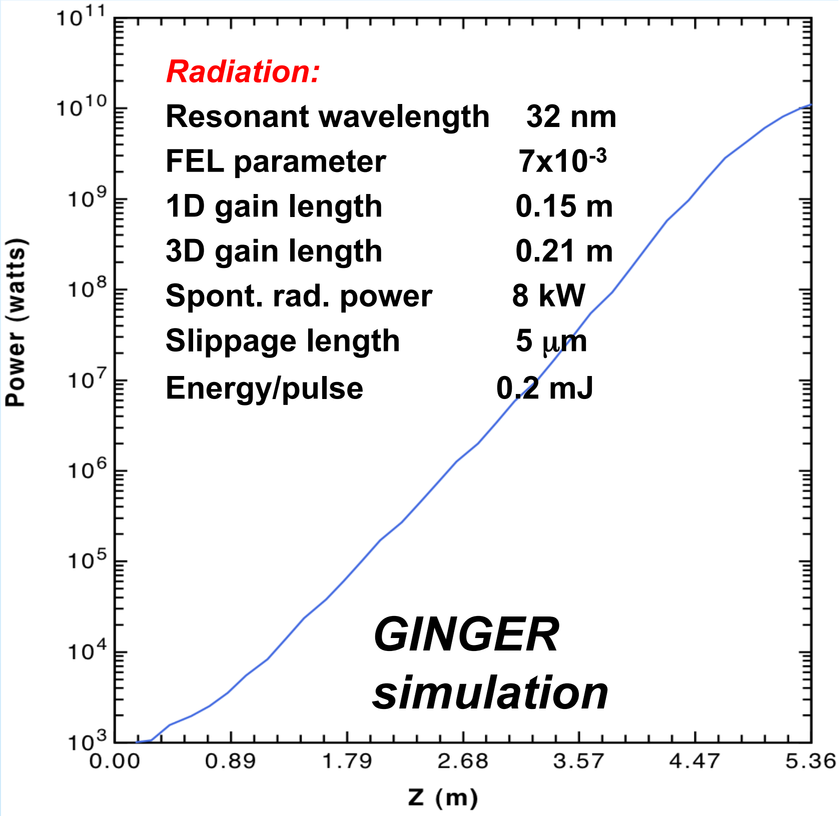
LPA electron beam





conventional undulator (THUNDER)

K. Robinson et al., IEEE QE (1987)



Radiation:

Resonant wavelength	32 nm
FEL parameter	7x10^{-3}
1D gain length	0.15 m
3D gain length	0.21 m
Spont. rad. power	8 kW
Slippage length	5 μm
Energy/pulse	0.2 mJ

GINGER simulation

Summary

- Laser plasma accelerators:
  - 1 GeV in < 3 cm
  - BELLA Project will allow 10 GeV in < 1 m
  - Developing techniques for beam control
  - Laser technology maturing rapidly
- Applications:
  - Compact accelerator for basic science
    - Collider based on 10 GeV LPA stages
  - Medical, homeland security
  - Compact light source based on Berkeley’s LPA technology
    - 5th generation light source: LPA-FEL
- Students and postdocs from all over the world:
  - Award winning dissertations, more than 15 PhD’s through program and ~ 80 students (MS and undergrad)