Laser-plasma accelerators for high-energy physics and light source applications

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Frontiers in Intense Laser-Matter Interaction Theory
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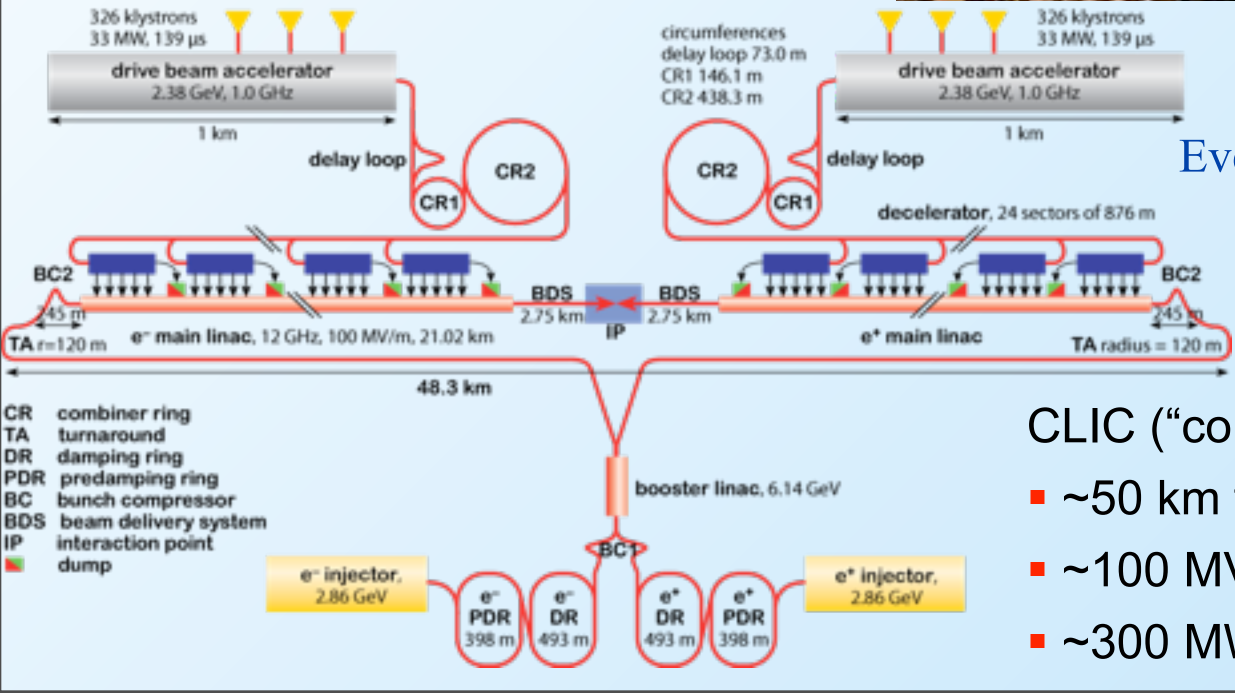
Outline: *long-term and near-term applications of laser-plasma accelerators*

- *Long-term application*: Laser-plasma accelerator (LPA) based linear collider
  - laser intensity requirements
  - limitations on LPA energy gain
  - plasma density and laser wavelength scalings (determine laser requirements)
  - Minimizing linac length (i.e., *construction costs*) and total power requirements (i.e., *operational costs*)
- Development of a single-stage 10 GeV laser-plasma accelerator at LBNL
- *Near-term application*: LPA-driven free-electron laser (FEL)
  - soft-x-ray FEL achievable with today's experimentally demonstrated LPA e-beams

Advanced accelerator concepts needed for future linear colliders

- post-LHC: consensus in physics community for a lepton (e+e-) collider (TeV-scale)
- Increasing energy-frontier requires advanced accelerator concepts



Events = (Luminosity)x(cross-section)

$$\mathcal{L}[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}] \approx U_{\mathrm{cm}}^{2}[\mathrm{TeV}]$$

CLIC (“compact linear collider”)

- ~50 km for 3 TeV CM
- ~100 MV/m gradient
- ~300 MW (~50% total) for RF

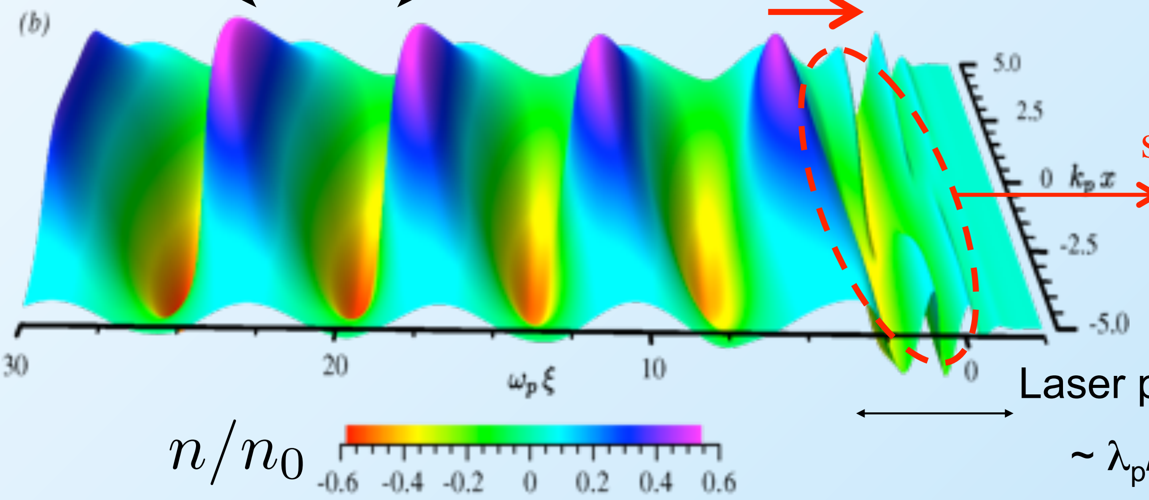
Laser-plasma accelerators (LPAs)

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

$$\underbrace{\left(\partial_t^2 + \omega_p^2\right) n/n_0}_{\text{Plasma wave: electron density perturbation}} = \underbrace{c^2\nabla^2 a^2/4}_{\text{Laser ponderomotive force (radiation pressure)}}$$

$\lambda_p = 2\pi c/\omega_p = (\pi r_e^{-1/2})\, n_p^{-1/2} \sim 10\ \mu\mathrm{m}$

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



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

Laser pulse duration

~ λ_p/c ~ tens fs

n/n_0

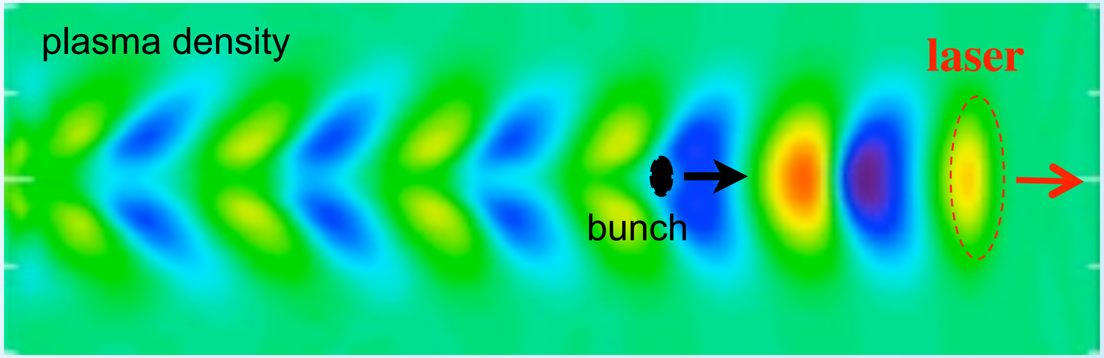
electron plasma density perturbation

Laser-plasma accelerators: 1-100 GV/m accelerating field

$$E \sim \left(\frac{mc\omega_p}{e}\right)\frac{a^2/2}{(1+a^2/2)^{1/2}} \approx (96\ \mathrm{V/m})\sqrt{n_0[\mathrm{cm}^{-3}]}\frac{a^2/2}{(1+a^2/2)^{1/2}}$$

plasma wave (wakefield): E ~100 GV/m (for n~10^{18} cm^{-3} and I~10^{18} W/cm^2)

>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): ~1-100 pC
- Beam duration (set by trapping physics and density): ~1-10 fs

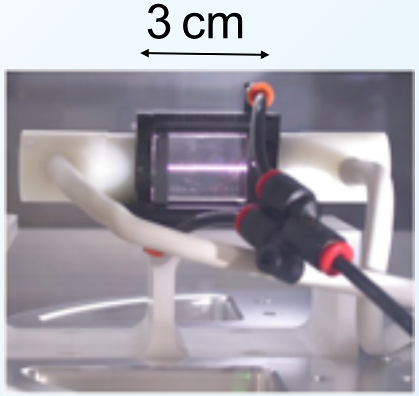
➔ **high peak current**

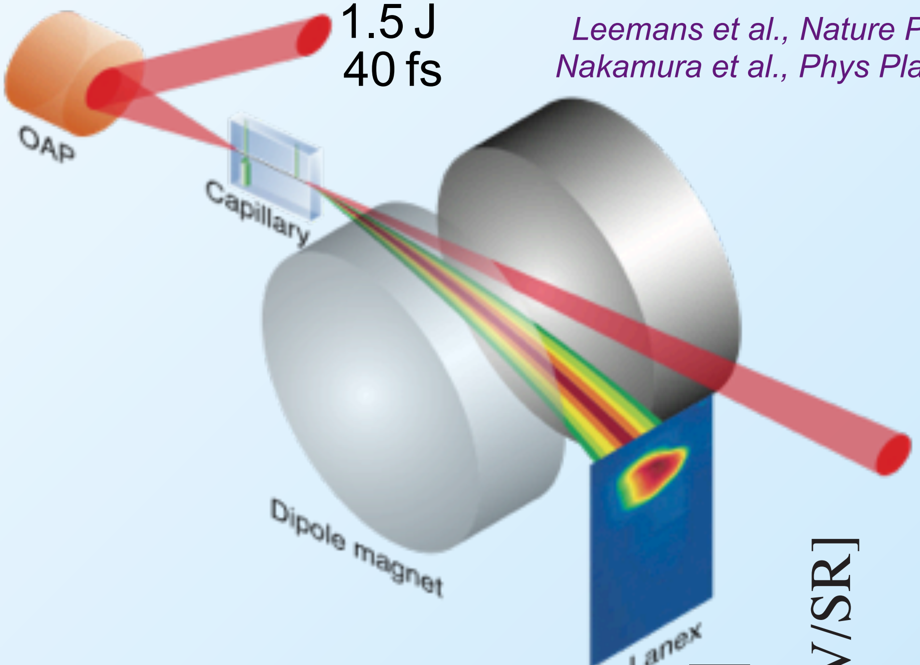
~1-10 kA

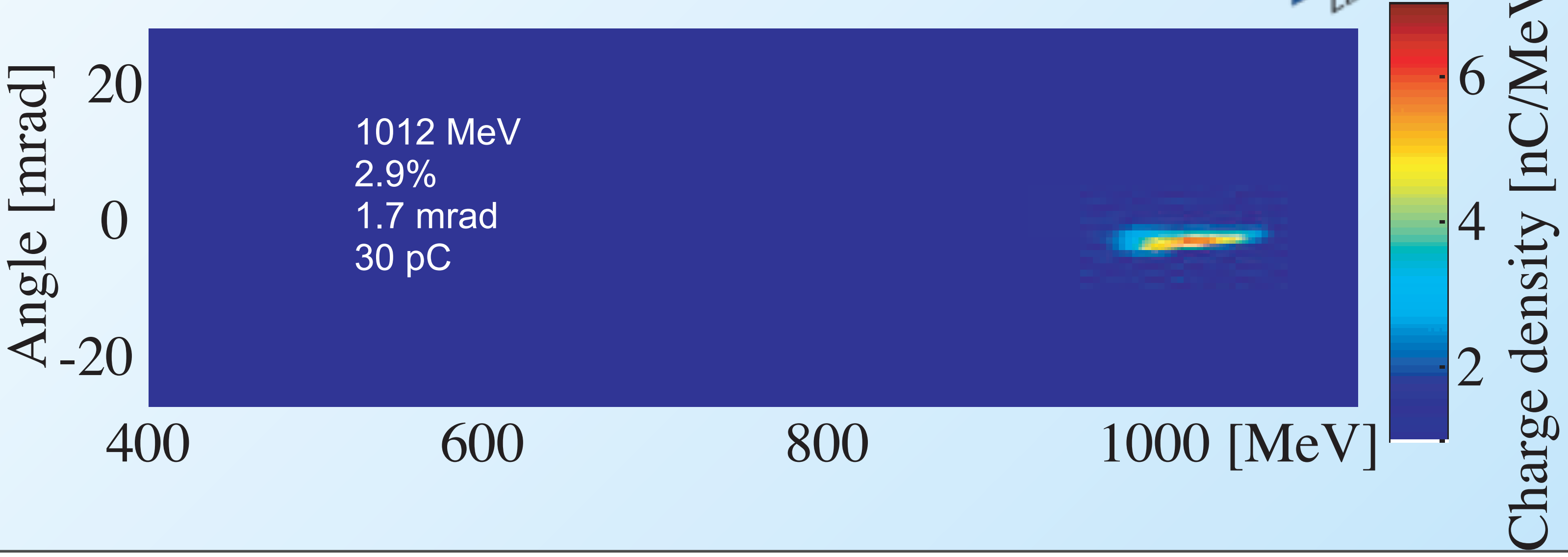
Experimental demonstration: 1 GeV high-quality beam from LPA

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

H-discharge capillary (10^{18} cm^{-3})







1012 MeV
2.9%
1.7 mrad
30 pC

Ultra-high laser intensities: ion cavity formation

condition for cavitation:

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

***a*=3.5**

$k/k_p=20$

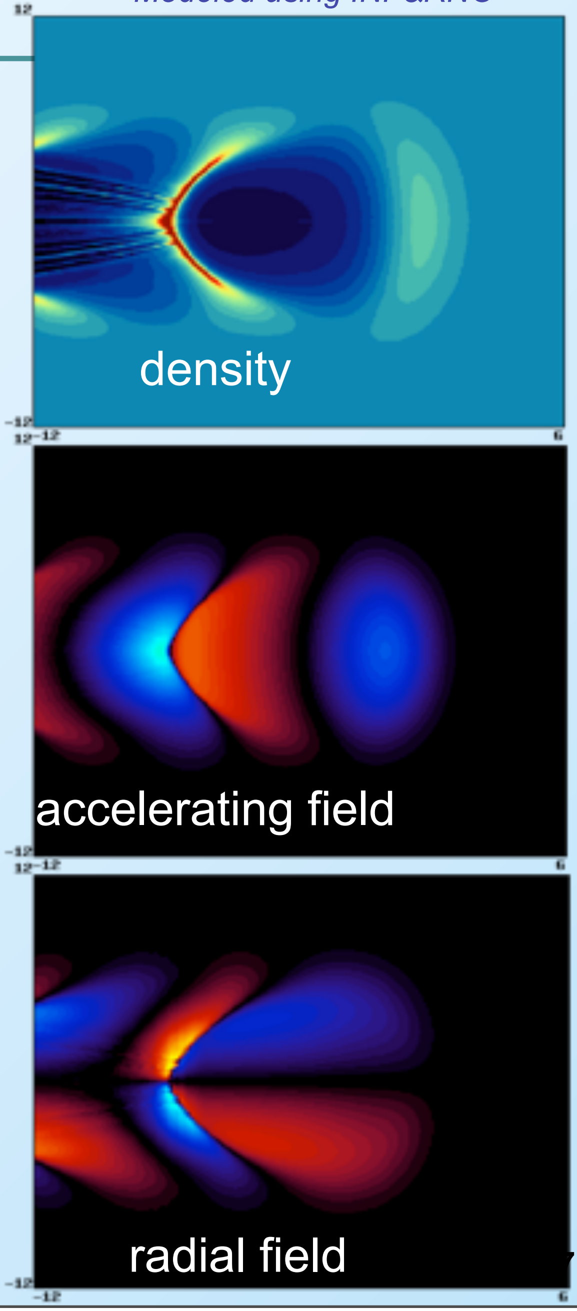
$k_pL=1$

$k_pR=5$

- Bubble regime:
  - High intensity ($a^2 >> 1$)
  - 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 present (staging difficult)
    - strong laser evolution
    - reduced phase velocity (uncontrolled trapping)

Pukhov & Meyer-ter-Vehn, APB (2002)

Modeled using INF&RNO



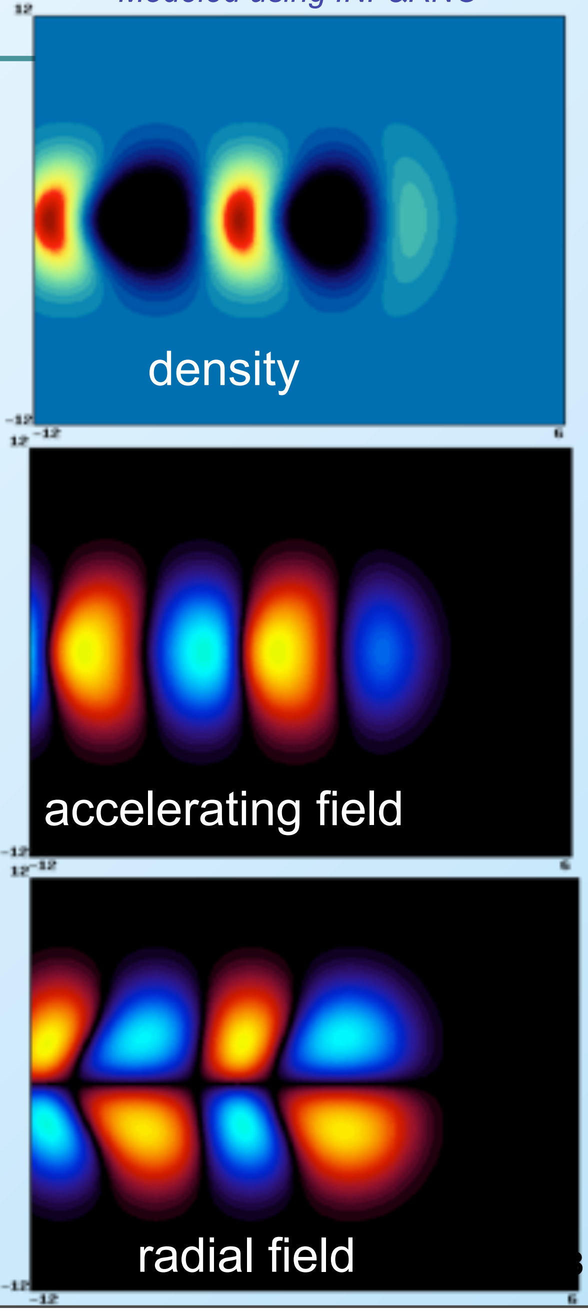
Quasi-linear intensity regime: allows for e⁺ acceleration

$$E \sim \left(\frac{mc\omega_p}{e}\right)\frac{a^2/2}{(1+a^2/2)^{1/2}}$$

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

- Quasi-linear/weakly-relativistic regime
  - a ~ 1, I~10^{18} W/cm^2
  - Nearly-symmetric regions for electron/position acceleration/focusing
  - Dark-current free (no self-trapping)
  - Stable propagation in plasma channel
  - Allows shaping of transverse fields
  - Phase velocity ~ laser group velocity

Modeled using INF&RNO



Matched, ultra-low-emittance beams required

- Collider application requires small beam size at IP for sufficient luminosity:

$$\mathcal{L} = \frac{fN^2}{4\pi\sigma_x^*\sigma_y^*} = \frac{P_b N}{4\pi U_b \sigma_x^*\sigma_y^*}$$

- Focusability of beam (at final focus to IP) limited by synchrotron radiation (***Oide Limit***) - small emittances required:

$$\sigma^*_{\min} = (\gamma\epsilon_n)^{5/7} r_e^{2/7} F$$

- Un-matched beam leads to emittance growth.
  - Matching condition:

$$k_\beta \sigma_x^2 = \epsilon_n/\gamma$$

  - Strong-focusing can lead to small matched beam radius (stringent alignment tolerances):

- In bubble regime $a^2/\gamma_\perp \gg (k_p r_s)^2/4$, focusing force is determined by plasma density and *independent* of laser intensity

$$F_\perp = -eE_0 k_p r/2 \propto n$$

Control of focusing forces by tailoring transverse laser intensity distribution

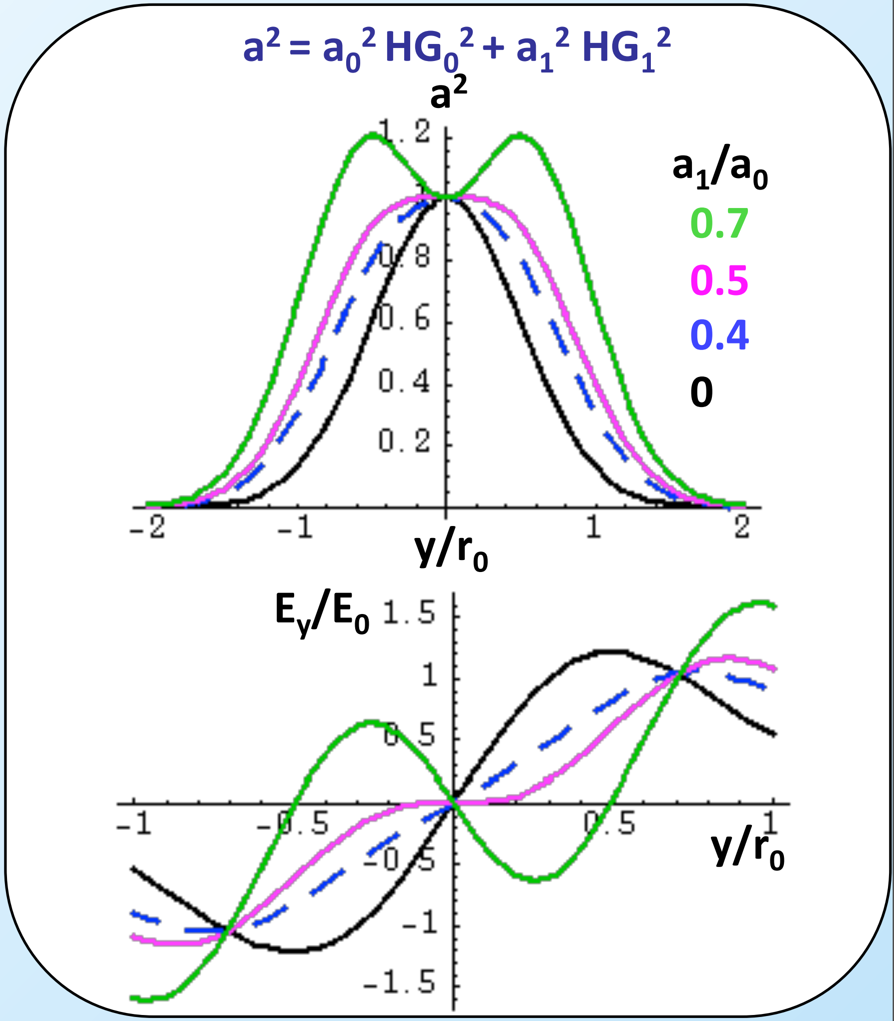
- In weakly-relativistic regime $a^2/\gamma_\perp < (k_p r_s)^2/4$, focusing force is determined by the *local* gradient of the laser intensity

$$\boxed{F_\perp \sim -eE_0 k_p \nabla_\perp a^2}$$

- All Gauss-Laguerre modes guided in parabolic plasma channel

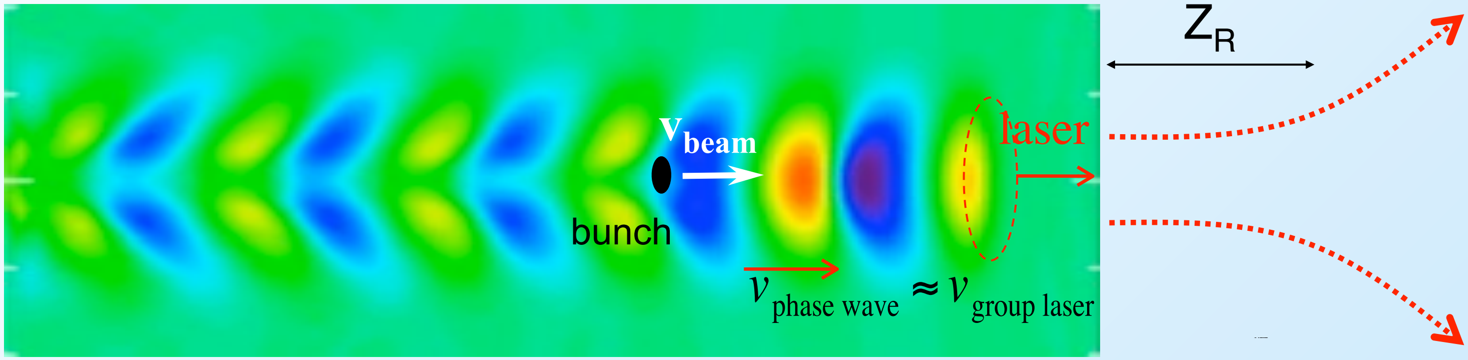
$$n(r) = n_0\left(1 + r^2/R_{ch}^2\right)$$

- Controlling the transverse laser intensity profile, controls the focusing force (independent of the accelerating force)



Cormier-Michel et al., Phys. Rev. ST AB (2011)

Limits to single-stage energy gain: Laser energy depletion necessitates staging



Limits to single stage energy gain:

$$mc^2\Delta\gamma \sim q(mc\omega_p/e)L_{\text{int}}$$

- **Laser Diffraction**
  - Limits laser-plasma interaction length to ~ Rayleigh range (typically most severe)
  - Controlled via transverse plasma density tailoring (plasma channel) and/or relativistic self-guiding and ponderomotive self-channeling

- **Beam-Wave Dephasing**:
  - Slippage between e-beam and plasma wave ($v_{\text{phase}} < v_{\text{beam}} < c$)
  - Determined by plasma wave phase velocity (***approximately*** laser group velocity)

$$L_{\text{dephase}} \propto \lambda_p/\gamma^2_{\text{phase}} \propto n^{-3/2}\lambda^{-2}$$

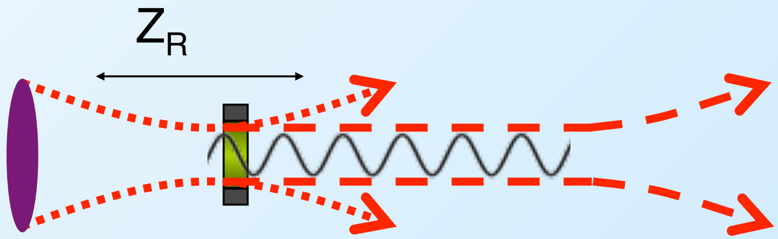
- **Laser Energy Depletion**:
  - Rate of laser energy deposition of into plasma wave excitation

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

Laser diffraction controlled by tailored plasma channel

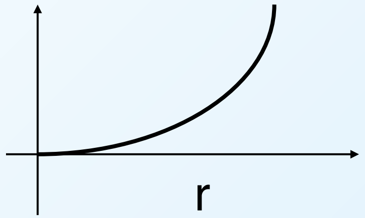
Laser diffraction: ($L \sim Z_R$)

Solution: tailor plasma profile to form plasma channel



Geddes et al., Phys. Rev. Lett. (2005)

Plasma density, n(r)

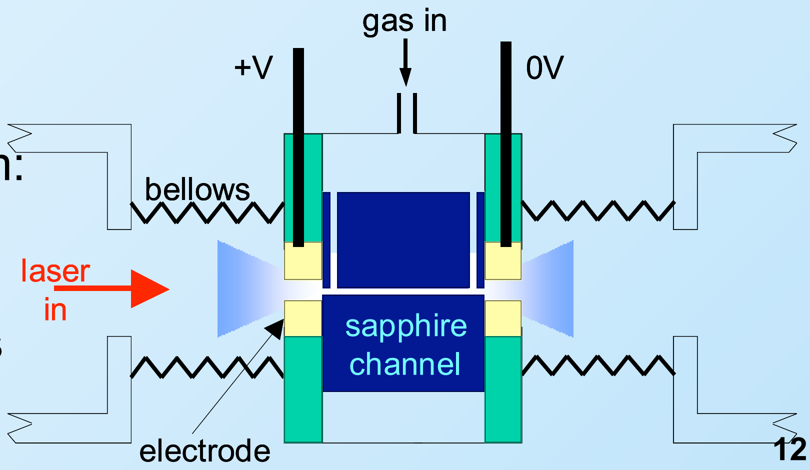


Guiding:
$$\frac{d\eta}{dr} = \frac{d}{dr}\left(1 - \frac{\omega_p^2}{2\omega^2}\right) < 0$$

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: cap. lasts for $>10^6$ shots
- $n_e \sim 10^{17}$ - 10^{19} cm^{-3}

Hooker et al., JOSA (2000)



Laser evolution determines phase velocity (beam dephasing)

Schroeder et al., PRL (2011)

- Laser pulse-steepening increases wavelength
- Laser red-shifting decreases laser velocity

- Nonlinear (a~1) plasma wave phase velocity is a function of laser intensity and not equal to the laser velocity:

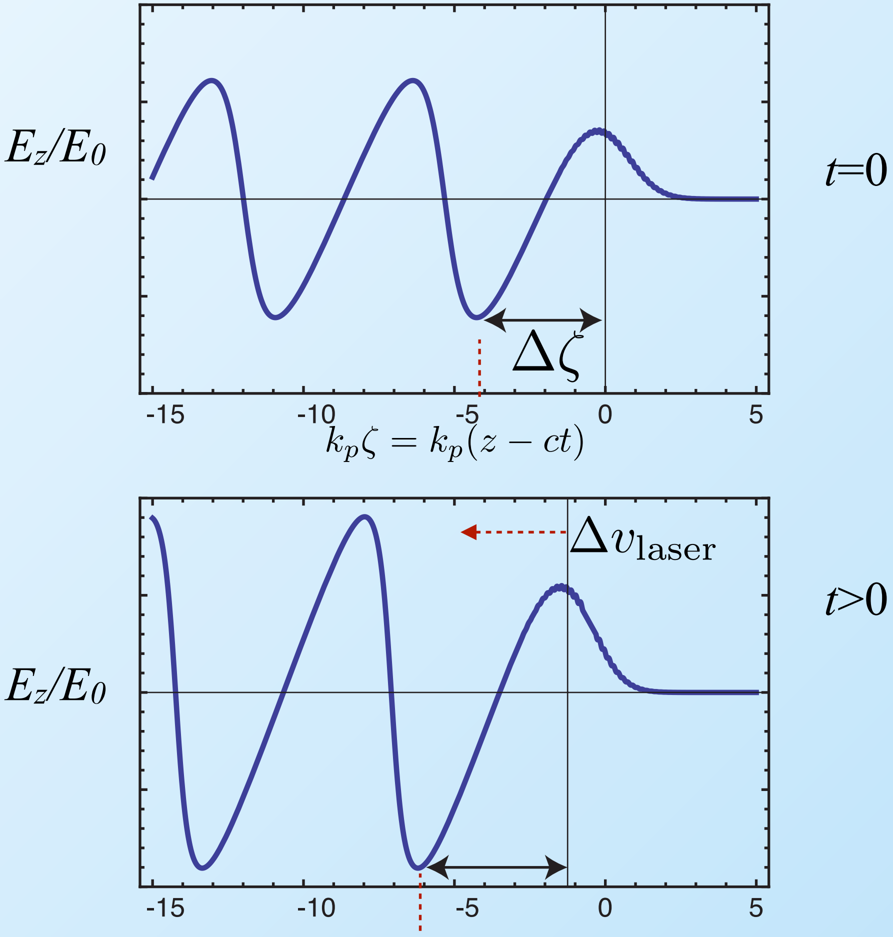
$$\boxed{\gamma_{\text{phase}}(a_0) < \omega_0/\omega_p < \gamma_{\text{group}}(a_0)}$$

- Phase velocity evolves as laser propagates – decreases owing to laser red-shifting and steepening

$$\partial_t \gamma_{\text{phase}} < 0$$

Lower wake phase velocity:

- reduces the trapping threshold
- reduces energy gain and efficiency

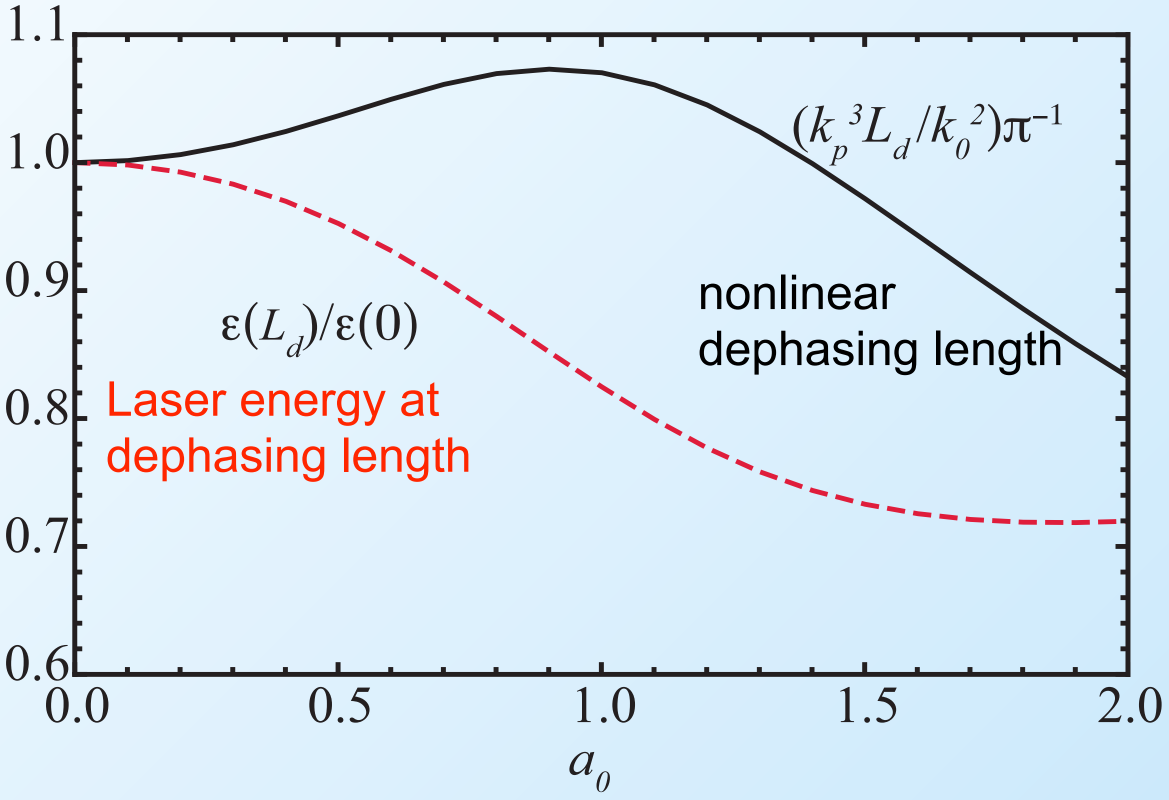


$$\Delta\zeta(t) > \Delta\zeta(0)$$

Energy gain limited by beam-laser dephasing

Schroeder et al., PRL (2011)

$$\boxed{Z_R \ll L_{\rm dephase} < L_{\rm deplete}}$$

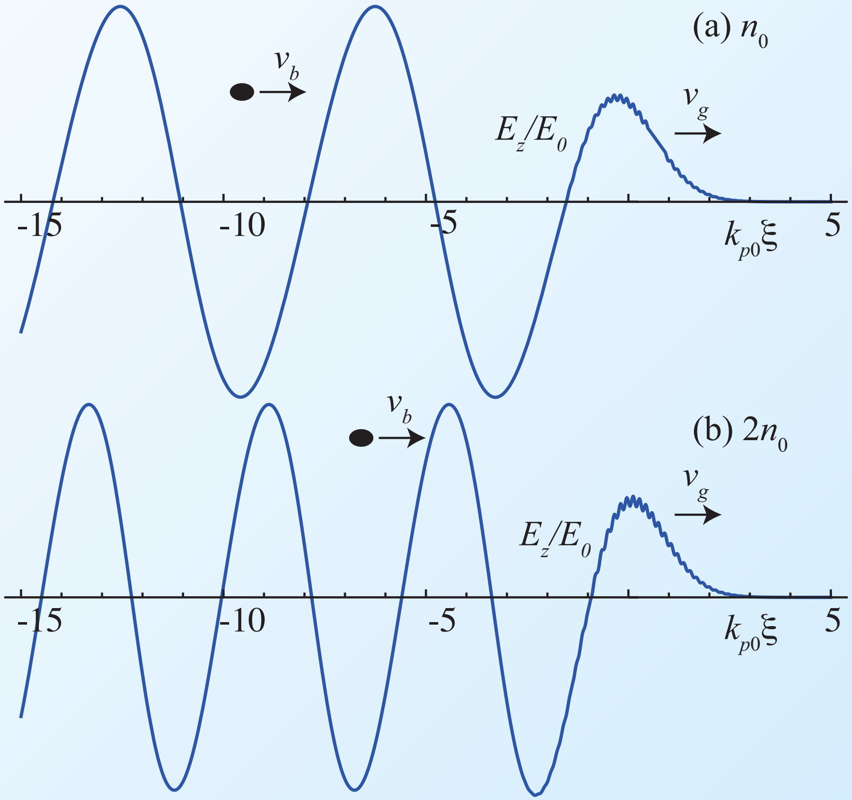


$\propto n^{-3/2}$

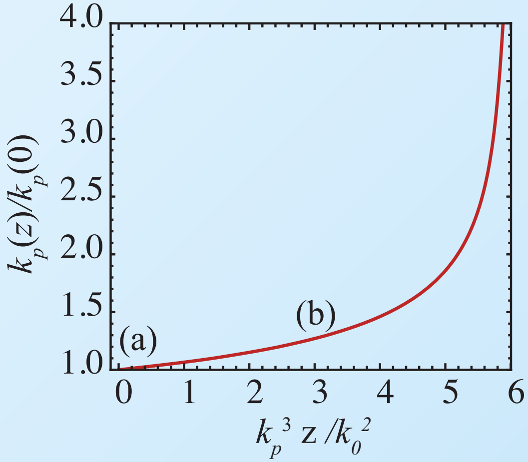
- Significant laser energy remaining at dephasing length in quasi-linear regime
- Energy gain limited by dephasing (in linear and nonlinear regime)
- Plasma tapering required for improved efficiency in nonlinear regime

Slippage controlled via plasma density taper

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



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



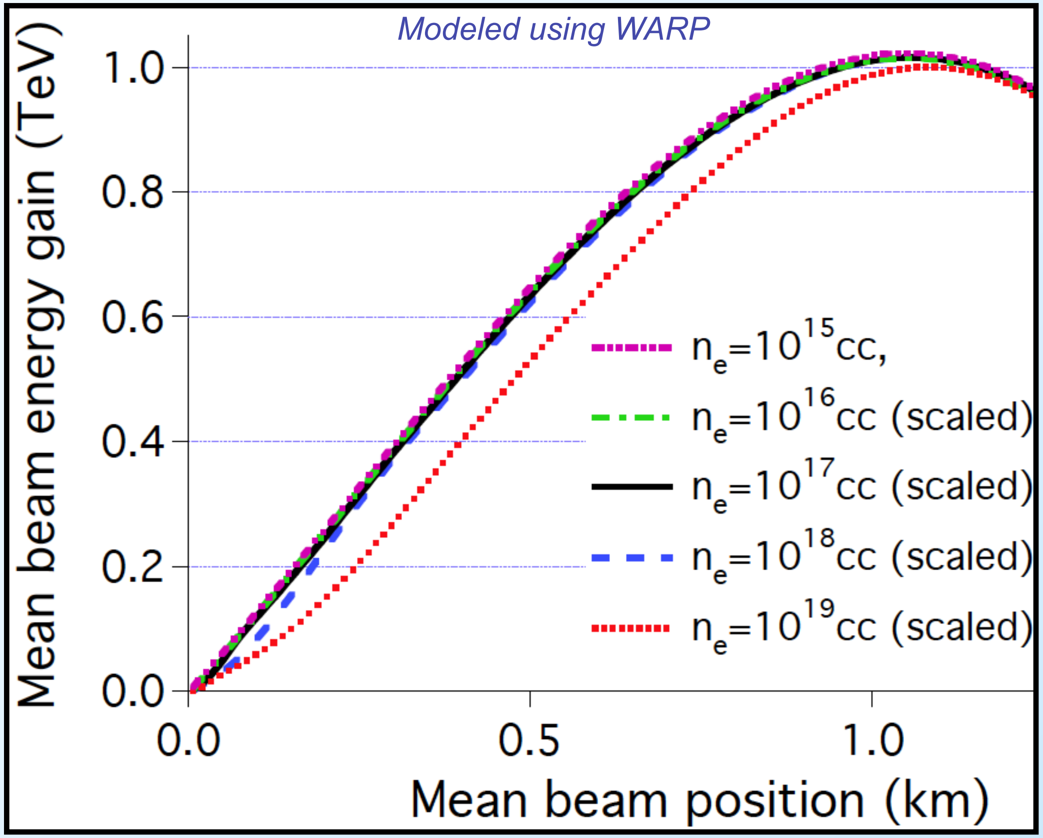
- Channel radius tailored: $R_{\rm ch}(z) = k_{p0}(z) r_0^2/2$
- Phase lock both focusing and accelerating forces

Rittershofer, Schroeder et al., Phys. Plasmas (2010)

Single-stage plasma density scalings verified with PIC simulations

J.-L. Vay et al., Phys. Plasmas (2011)

$\propto n^{-1}$



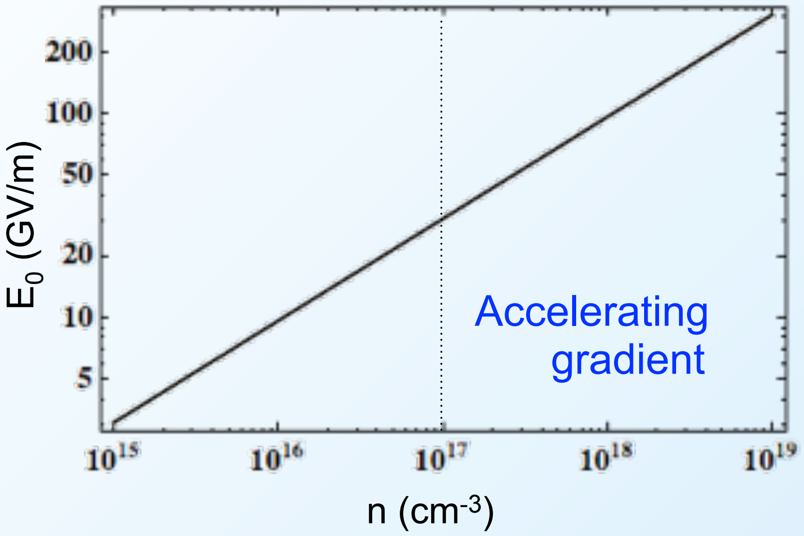
initial laser
inensity: $a_0=1.5$

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

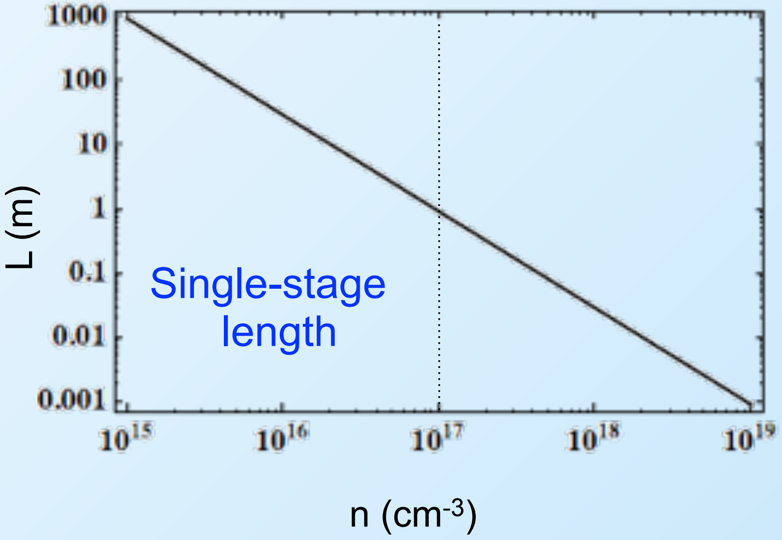
- Single-stage PIC simulations (using WARP with boosted-frame technique) verifying plasma density scaling

LPA single-stage plasma density scalings

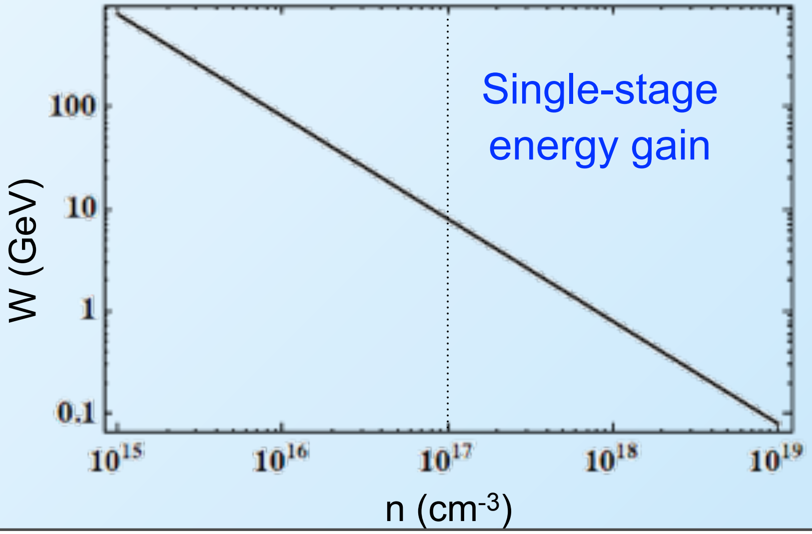
$E_z \sim (m_e c \omega_p / e) \propto n^{1/2}$



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



$W \sim (m c \omega_p / e)\, L_{\mathrm{acc}} \propto n^{-1} \lambda^{-2}$

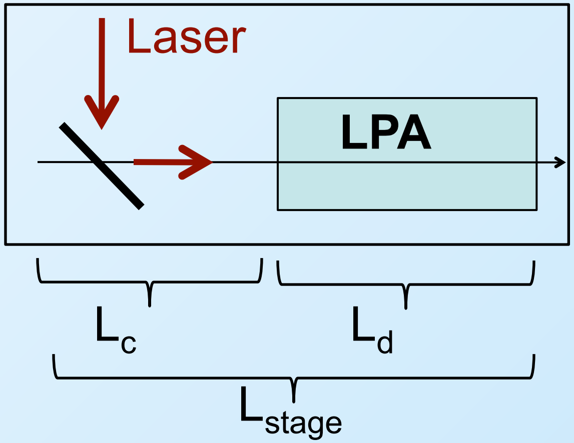


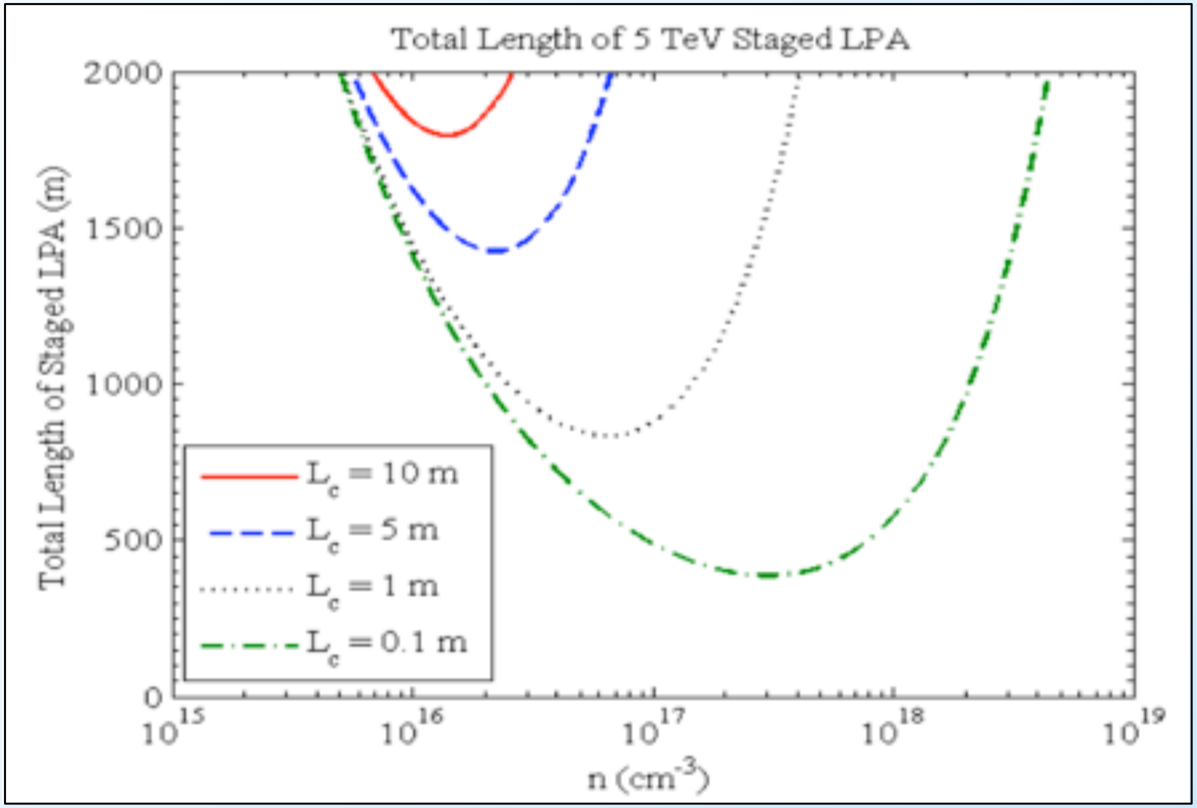
Coefficients determined from simulations of resonant laser with a=1.5

Choice of plasma density and staging determines main linac length

Number of stages:

$$N_{\text{stage}} = \frac{U_b}{W_{\text{stage}}} \propto n\lambda^2$$





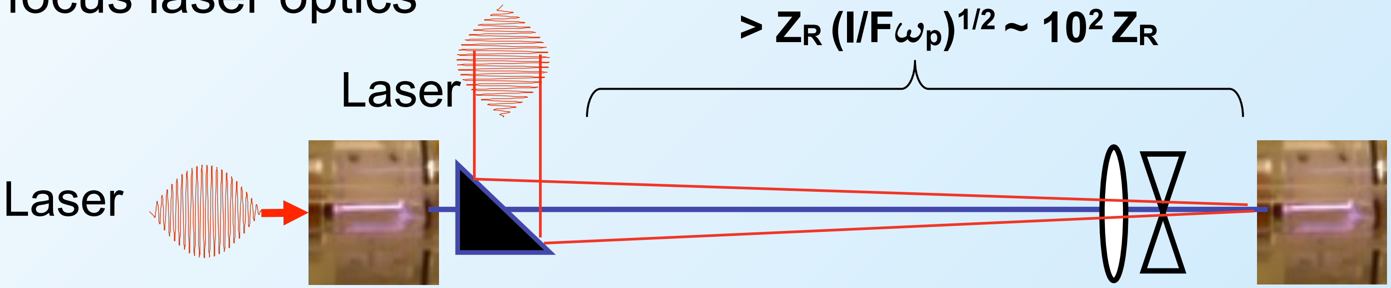
- Total length of linac:

$$L_{\text{linac}} = N_{\text{stage}} L \propto a^{-2} n^{-1/2}$$

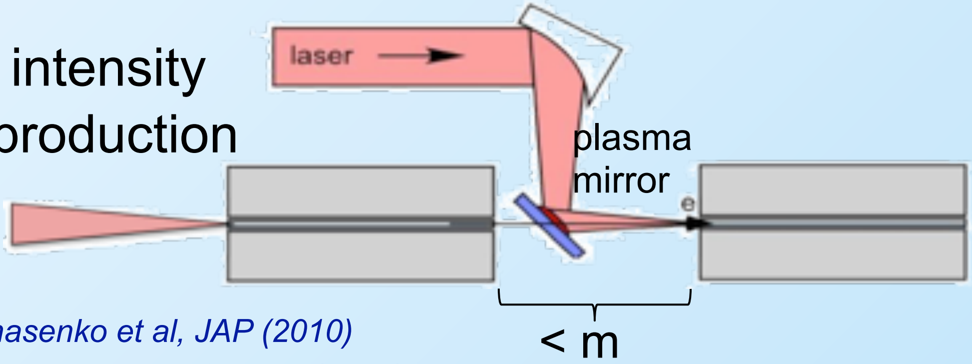
➡ *Total length of linac independent of laser wavelength*

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
  - Laser contrast crucial ($>10^{10}$)



Panasenko et al, JAP (2010)
Sokollik et al., AAC Proc. (2010)

- Advantage of laser-driven plasma waves: short in-coupling distance for plasma wave driver [high average (geometric) gradient]
- Development of staging technology critical to collider application

LPA stage laser energy requirements

- Laser intensity for large accelerating field in quasi-linear regime:

$$E \sim (96\ \mathrm{V/m})\sqrt{n_0[\mathrm{cm}^{-3}]}\,\frac{a^2/2}{(1+a^2/2)^{1/2}}$$ ➡ $a \sim 1$ ➡ $I > 10^{18}$ W/cm^2 for 1 um wavelength

$$a \simeq 8.6\times10^{-10}\lambda[\mu\mathrm{m}]\sqrt{I[\mu\mathrm{m}]}$$

- Laser spot:

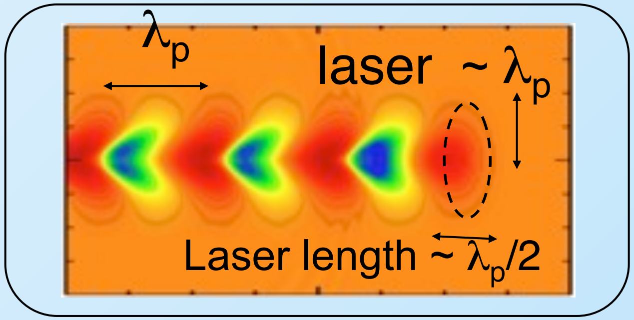
  1. avoid bubble formation
  2. avoid strong self-focusing

$$3 < k_p r_L < 6$$

$$r_L \sim \lambda_p \propto n^{-1/2}$$

- Laser pulse length ~ plasma wavelength

$$L_L \sim \lambda_p/2\pi \propto n^{-1/2}$$



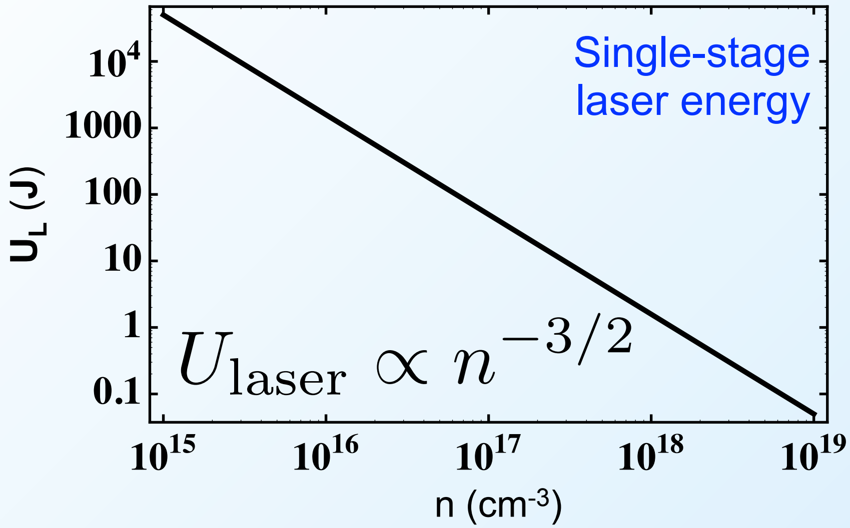
- Laser energy:

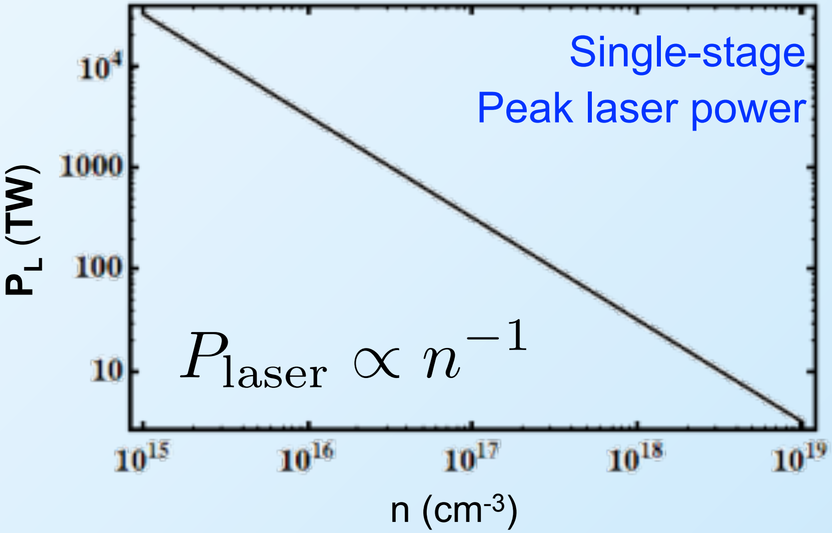
$$U_{\mathrm{laser}} \propto a^2\lambda_p^3/\lambda^2 \propto n^{-3/2}$$

plasma density = $n_0 \sim 10^{17}$ cm^{-3} ➡ $U_{\mathrm{laser}} \sim$ 10's J

$n_0 \sim 10^{15}$ cm^{-3} ➡ $U_{\mathrm{laser}} \sim$ 10's kJ

Collider plasma density scalings: Laser energy and power

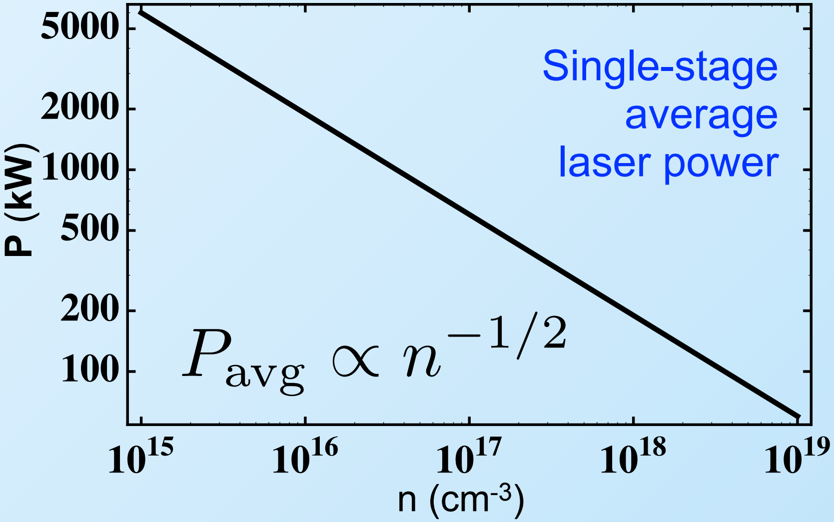




- For fixed luminosity (e.g., $2\text{x}10^{34}$ s^{-1} cm^{-2} for E_{cm} = 1 TeV) and IP size:

Repetition rate: $f_{rep} \propto n$

Beam power: $P_{beam} = fN\gamma mc^2 \propto n^{1/2}$



Collider plasma density scalings: total power requirements

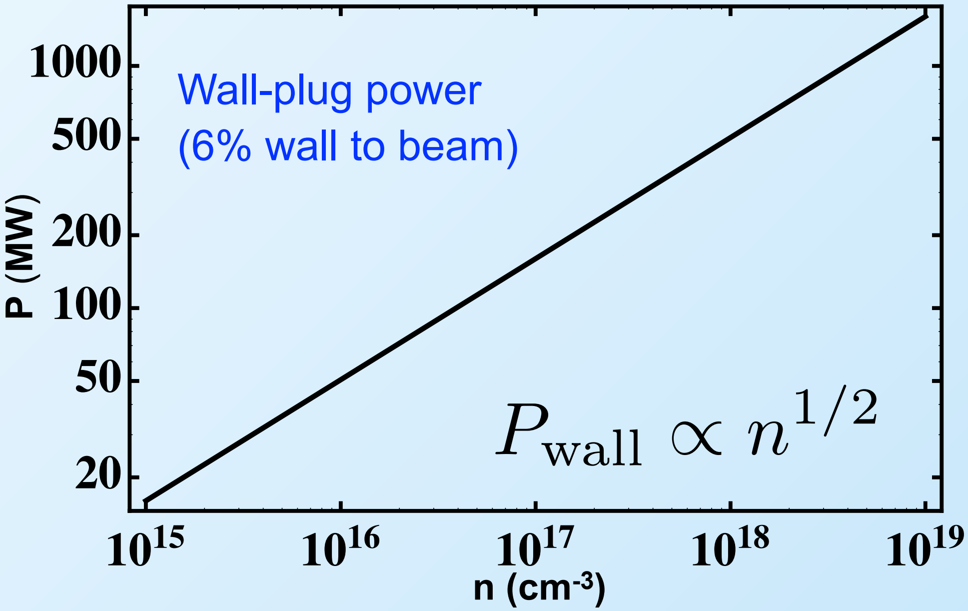
- For fixed luminosity (e.g., 2×10^{34} s^{-1} cm^{-2} for E_{cm} = 1 TeV) and IP size:

Repetition rate: $f_{rep} \propto n$

Beam power: $P_{beam} = fN\gamma mc^2 \propto n^{1/2}$

- Laser to plasma wave efficiency: ~50%
- Plasma wave to beam efficiency: ~40%

~30% wall-plug to laser efficiency (assumed)



Schroeder et al., PR ST-AB (2010)

Particles/bunch (limited by bream loading):

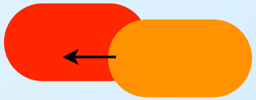
$$N \propto \frac{U_L}{\Delta\gamma} \propto n^{-1/2}$$

Luminosity:

$$\mathcal{L} = \frac{fN^2}{4\pi\sigma_x^*\sigma_y^*} = \frac{P_b N}{4\pi U_b \sigma_x^*\sigma_y^*}$$

Beamstrahlung at IP produces background photons and loss of beam energy

- Beamstrahlung: scattering of beam in field of colliding beam



- Future colliders will be in the quantum beamstrahlung regime: the mean field strength in beam rest frame larger than the Schwinger critical field Y>1

$$\mathcal{L} \propto U_{\rm cm}^2 \quad \longrightarrow \quad \Upsilon \propto U_{\rm cm}^{5/2}$$

- Average number of beamstrahlung photons emitted per electron during collision (using Sokolov-Ternov power spectrum, P. Chen et al.):

$$n_\gamma \approx 2.54 \left(\frac{\alpha^2 \sigma_z}{r_e \gamma} \right) \frac{\Upsilon}{(1+\Upsilon^{2/3})^{1/2}} \propto \sigma_z \Upsilon^{2/3} \propto N^{2/3} \sigma_z^{1/3} \propto n^{-1/2}$$

- Average fractional energy loss (P. Chen et al.):

$$\frac{\delta\gamma}{\gamma} \approx 1.24 \left(\frac{\alpha^2 \sigma_z}{r_e \gamma} \right) \frac{\Upsilon^2}{[1+(3\Upsilon/2)^{2/3}]^2} \approx 0.286\, n_\gamma$$

Beamstrahlung-limited regime: modifies LPA collider scalings at low density

Constraint of fixed beamstrahlung: fixed n_γ (photons per electron):

$$N \leq N_{\text{beam}} = \frac{0.6\, n_\gamma^{3/2}}{\alpha^2 r_e^{1/2}} \frac{\gamma^{1/2}\sigma_*}{\sigma_z^{1/2}} \propto n^{1/4}$$

Schroeder et al., PR ST-AB (2012)

accelerating field:

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

linac length:

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

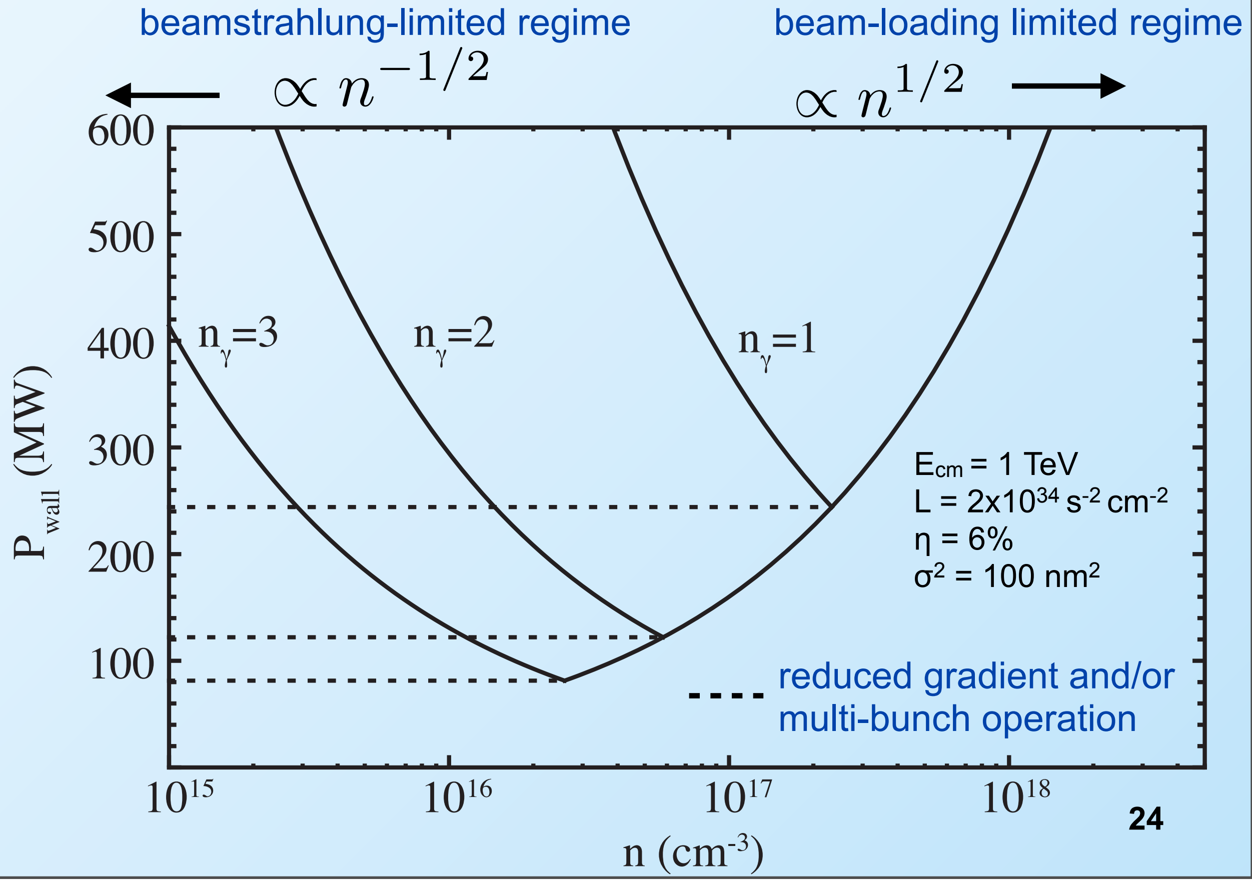
laser energy/stage:

$$U_{\text{laser}} \propto a^2 n^{-3/2}$$

Luminosity per (COM)^2

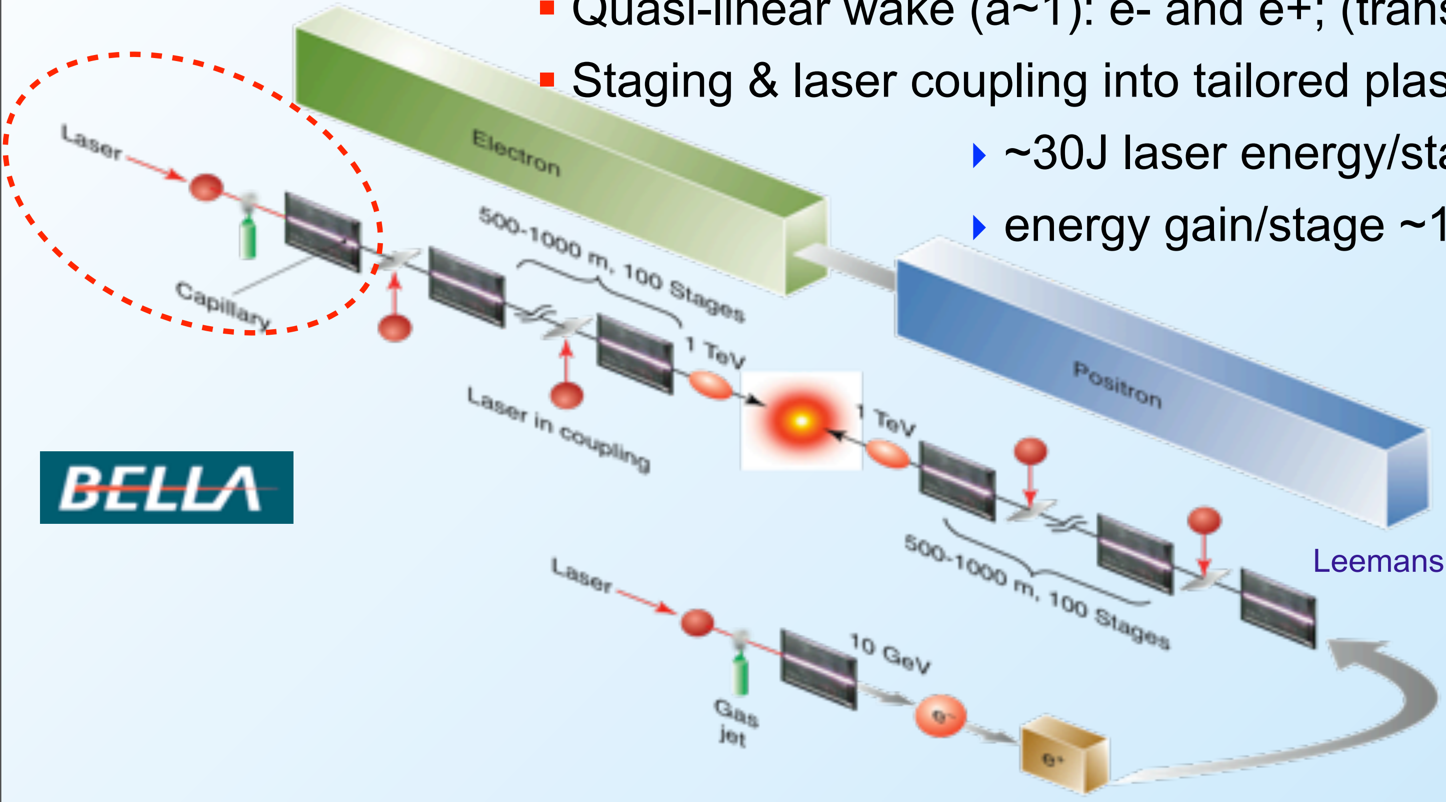
$$\frac{\mathcal{L}}{U_{\text{cm}}^2} \propto \frac{n_\gamma^{3/2} \eta P_{\text{wall}}}{\sigma_* \gamma^{5/2} \sigma_z^{1/2}}$$

Collider wall-plug power:



Conceptual laser-plasma accelerator linear collider

- Plasma density scalings (minimize *construction* and *operational* costs) indicates (independent of λ): $n \sim 10^{17}$ cm^{-3}
- Quasi-linear wake (a~1): e- and e+; (transverse) wake control
- Staging & laser coupling into tailored plasma channels:
  - ~30J laser energy/stage required
  - energy gain/stage ~10 GeV in ~1m



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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 %)

BELLA: BErkeley Lab Laser Accelerator

BELLA Project: >40 J in <40 fs at 1 Hz laser and supporting infrastructure at LBNL

1 PW laser facility

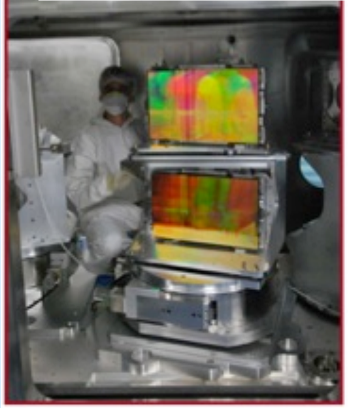
10 GeV electron beam from a meter long plasma accelerator

BELLA Project budget:

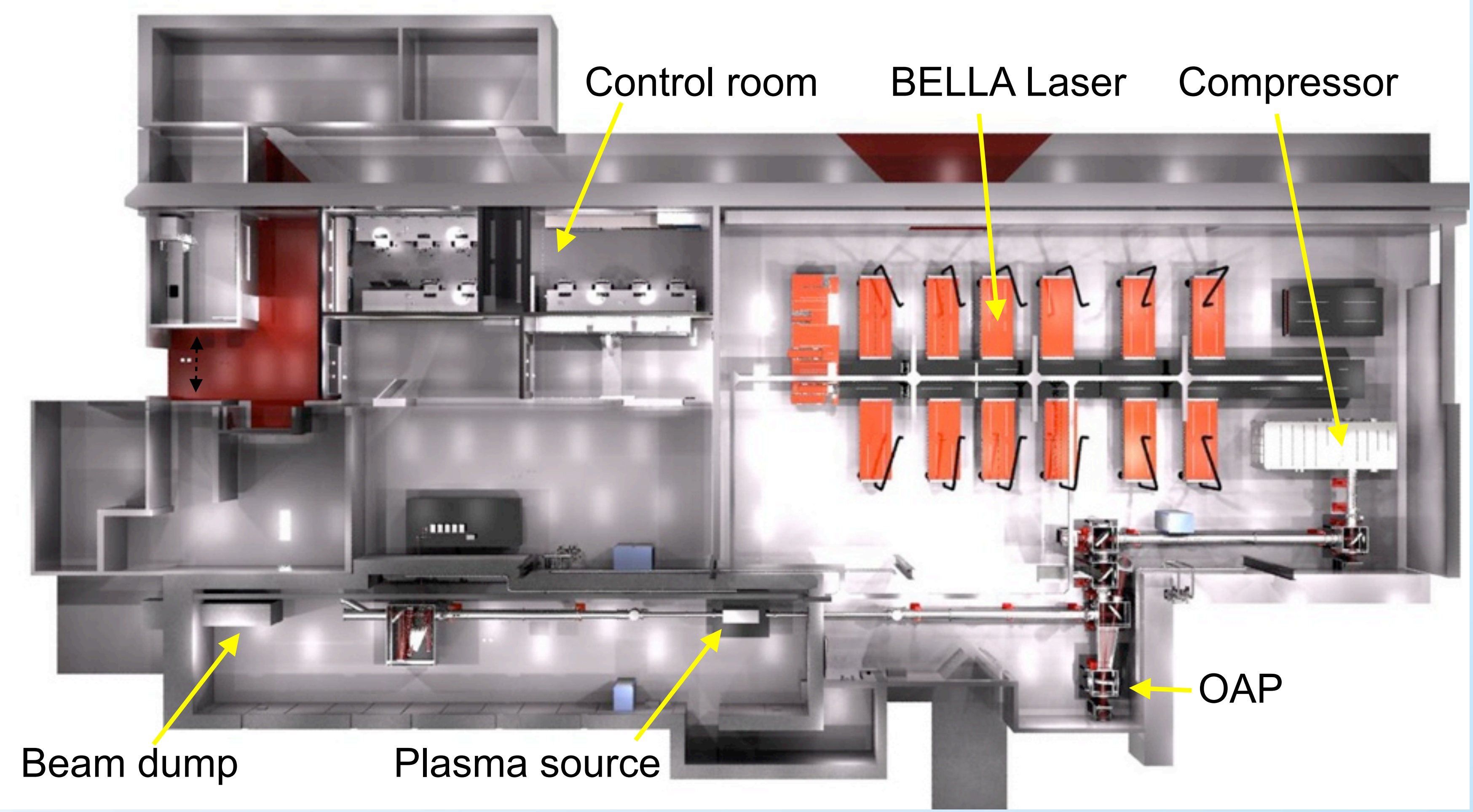
Funded by Office of Science – High Energy Physics

Schedule: laser commissioned mid-2012

first LPA expts.: October 2012



BELLA Facility: state-of-the-art PW-laser for laser accelerator science

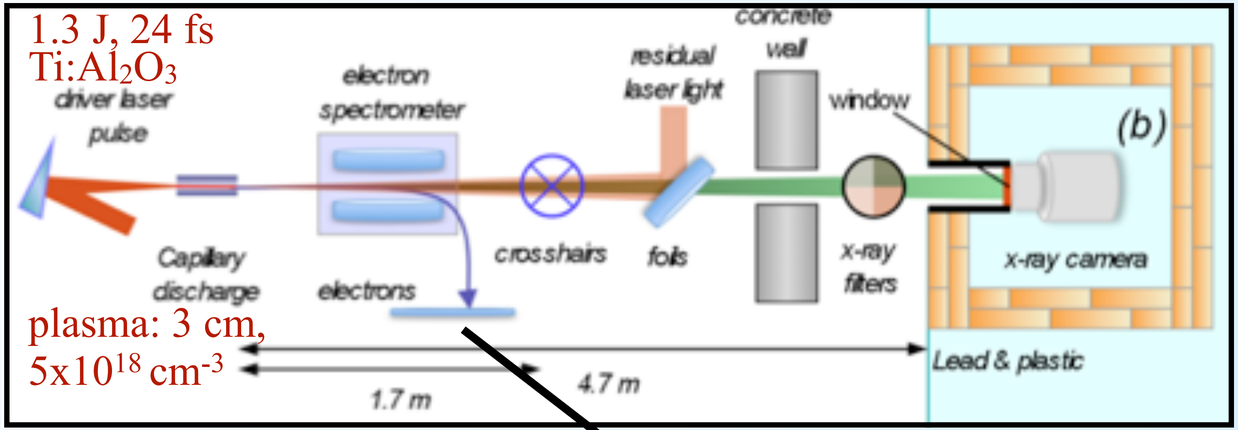


LPA electron beam parameters presently achievable

- Energy: ~ 100 MeV - 1 GeV
  - Obtained with 10-100 TW laser pulses in mm - cm long plasmas
- Charge: ~ 1- 100 pC
  - Depends on tuning, energy spread due to beam loading
- Energy spread: ~ 1 - 10% level
  - Depends on amount of charge, trapping physics
- Normalized Emittance: ~ 0.1 micron
  - Based on divergence measurements (~ 1 mrad) and e-beam spot (~0.1 micron)
  - Improved measurements needed
- Bunch duration: ~ 1 - 10 fs
  - Based on optical probe (*Buck et al., Nature Physics (2011)*), CTR (*Lundh et al., Nature Physics (2011)*), and THz measurements
- Rep. rate (laser system): 1 - 10 Hz
  - limited by availability of high average power lasers
- Foot-print (laser system): ~ (few meter) x (few meter), 10 Hz, 100 TW-peak laser system (30 W-average)

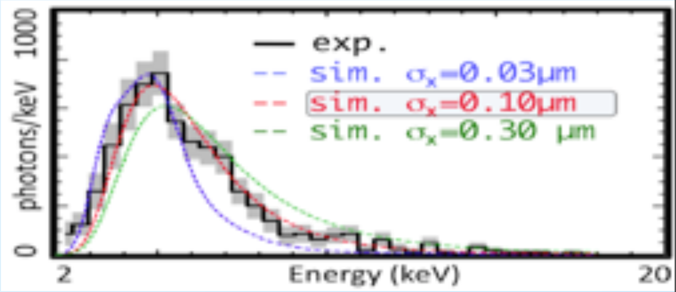
Can today's demonstrated LPA e-beam by used to drive a free-electron laser?

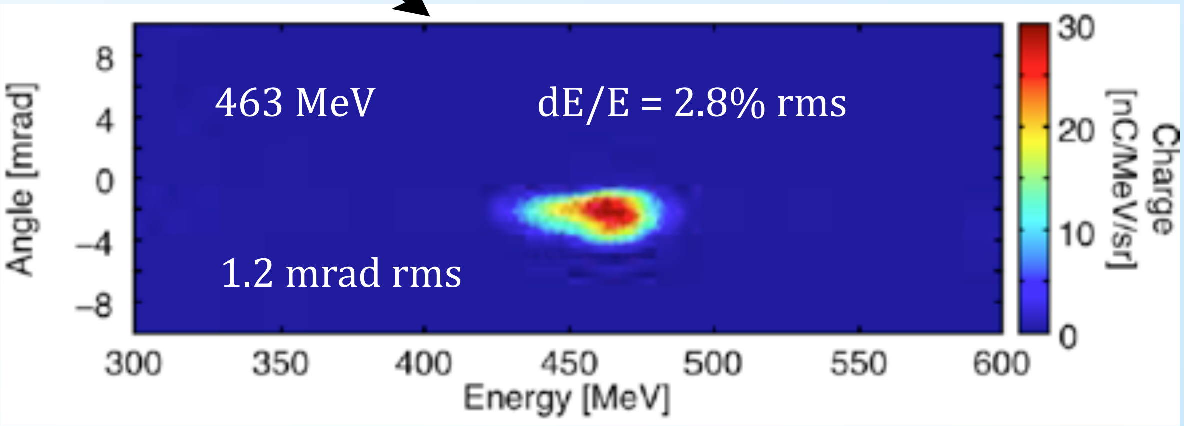
Low transverse emittance estimated from betatron radiation measurement



1.3 J, 24 fs
Ti:Al_2O_3

plasma: 3 cm,
5×10^{18} cm^{-3}





463 MeV

dE/E = 2.8% rms

1.2 mrad rms

➡ beam size, σ_x = 0.1 micron rms

➡ normalized transverse emittance estimate:

$\gamma\ \sigma_x\ \sigma_\theta$ = 0.1 mm mrad

Plateau et al., Phys. Rev. Lett. (2012)

LPA 6D beam brightness comparable to conventional sources

$$B_{6\mathrm{D}} = \frac{N}{\epsilon_{nx}\epsilon_{ny}\epsilon_{nz}} \approx \frac{(I/I_A)}{r_e \epsilon_n^2 \sigma_\gamma} = b_6 \lambda_c^{-3}$$

LPA (LBNL)

$\varepsilon_N = 0.1$ micron
0.5 GeV
3% energy spread
I = 10 kA (5 fs)

$b_6 \sim 4 \times 10^{-11}$

LCLS (SLAC)

$\varepsilon_N = 0.4$ micron
13.6 GeV
0.01% energy spread
I = 3 kA

$b_6 \sim 1 \times 10^{-11}$

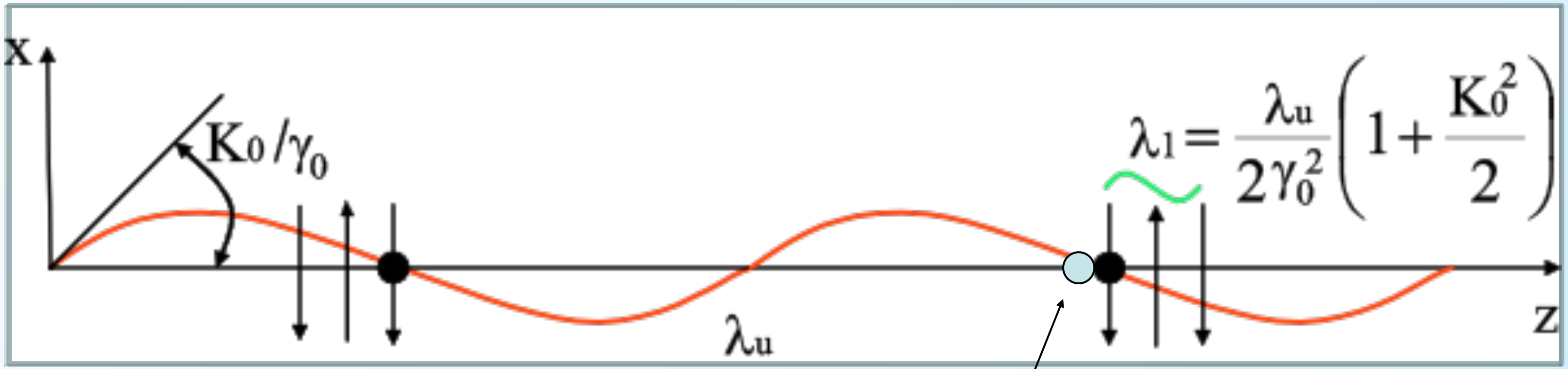
but...

- Energy spread order of magnitude too large (for soft-x-ray FEL; $\rho \sim 5 \times 10^{-3}$)
- Bunch duration < slippage length (for soft x-ray FEL)

solutions:

- Emittance exchange
- Phase-space redistribution/manipulation:
  - collimation
  - decompression
  - introduce transverse position-energy correlation (use transverse gradient undulator)

Narrow beam energy spread required for FEL resonance



- For efficient FEL interaction, the resonant wavelength spread caused by the energy spread over a gain length << 1

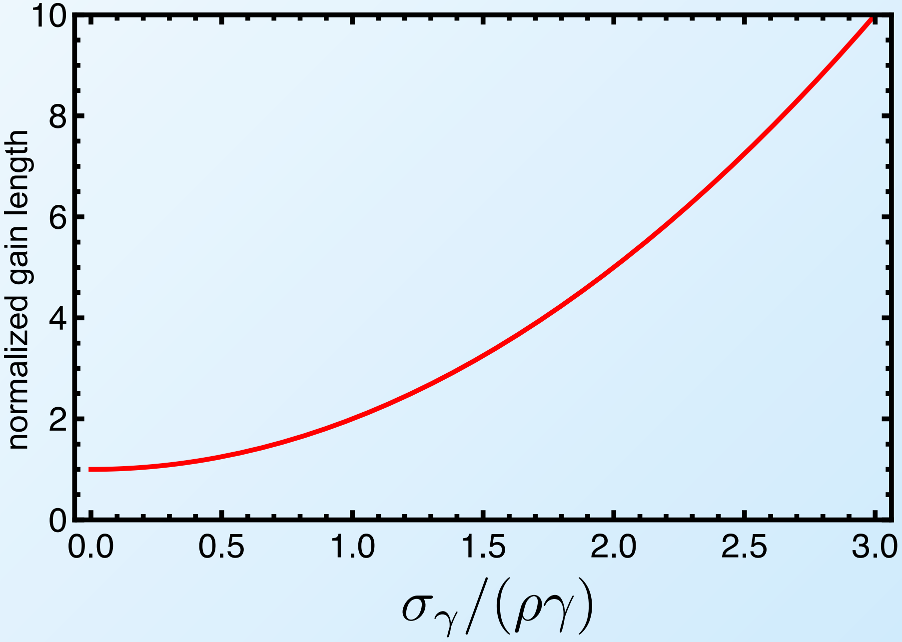
$$\frac{\Delta\gamma}{\gamma} = \frac{\Delta\lambda}{2\lambda} \ll \frac{\lambda_u}{2L_g} \approx 4\pi\rho$$

➔ $\sigma_\delta < \rho \sim 10^{-3}$ for short-wavelength FELs

- This is a local energy spread requirement not projected (for LPA, bunch length < slippage, local ~ projected)

FEL radiation gain length

- FEL radiation power grows exponentially: $P \propto \exp(z/L_g)$
- Gain length: $$L_g \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho}\left[1+\left(\frac{\sigma_\gamma}{\gamma\rho}\right)^2\right]$$



requires beam energy spread < FEL parameter:

$$\frac{\sigma_\gamma}{\gamma} < \rho$$

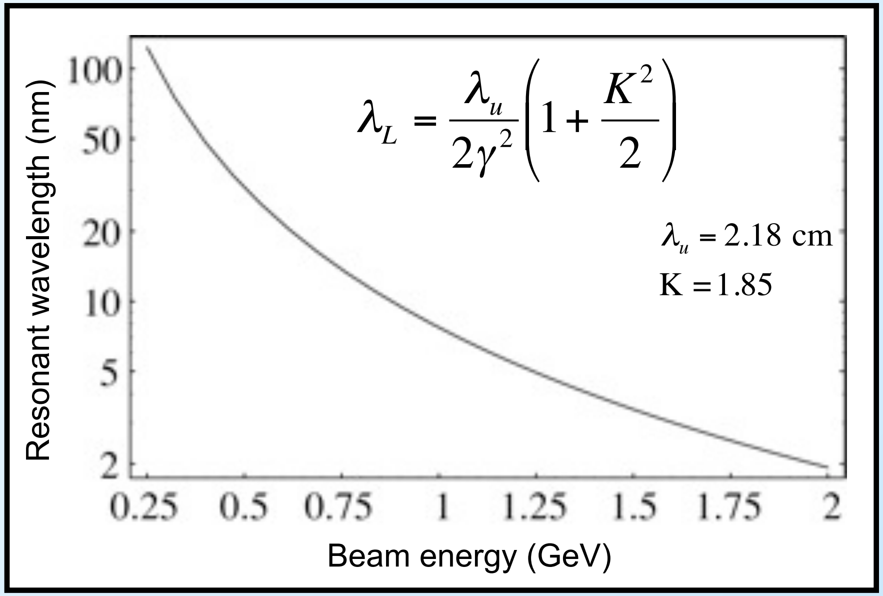
- FEL parameter: $$\rho = \frac{1}{4\gamma}\left[\frac{I}{I_\mathrm{A}}\left(\frac{K[JJ]\lambda_u}{\pi\sigma_x}\right)^2\right]^{1/3}$$

ρ~few x 10^{-3}

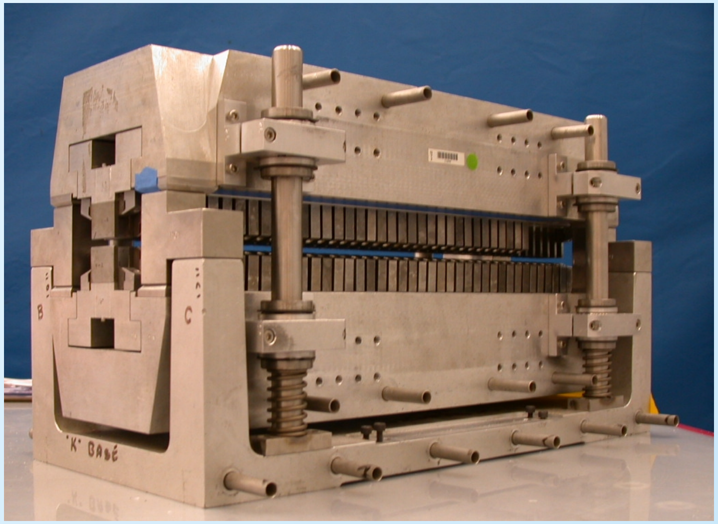
THUNDER undulator at LBNL

THUNDER (*Tapered Hybrid Undulator*) on-loan to LBNL from Boeing Corp.

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

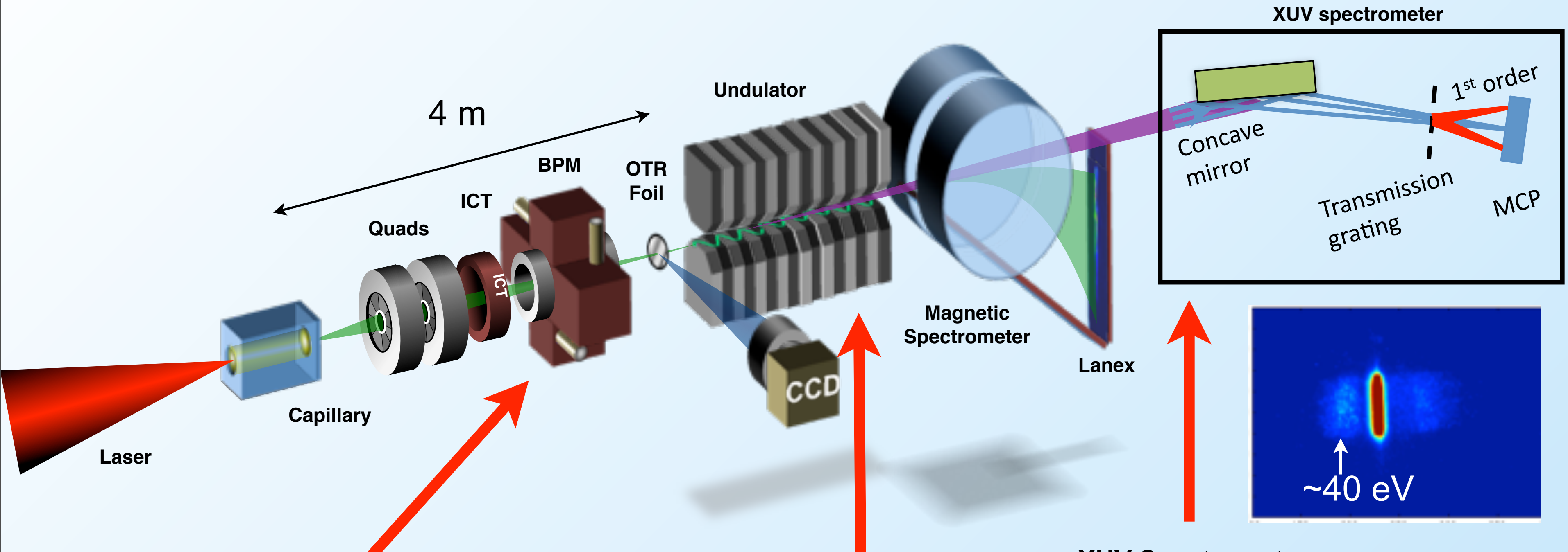


Undulator type	planar
Undulator period	2.18 cm
Number of periods	220
Peak Field	1.02 T
Magnetic gap	4.8 mm
Undulator parameter,	K=1.85
Canted-pole focusing, beta-function (0.5 GeV)	3.6 m

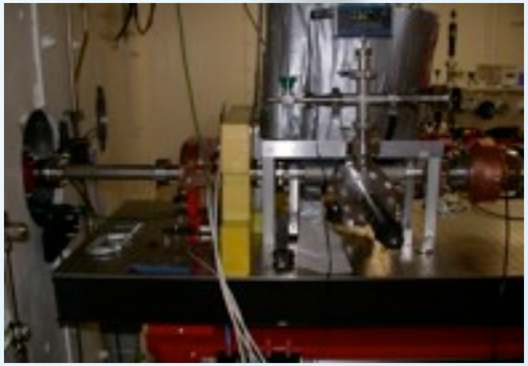


- ten (22 period, 50 cm) undulator sections = 5 m

Coupling LPA electron beam to undulator at LBNL

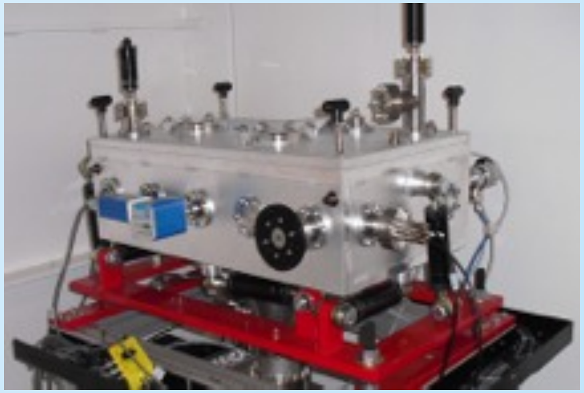


BPM & OTR



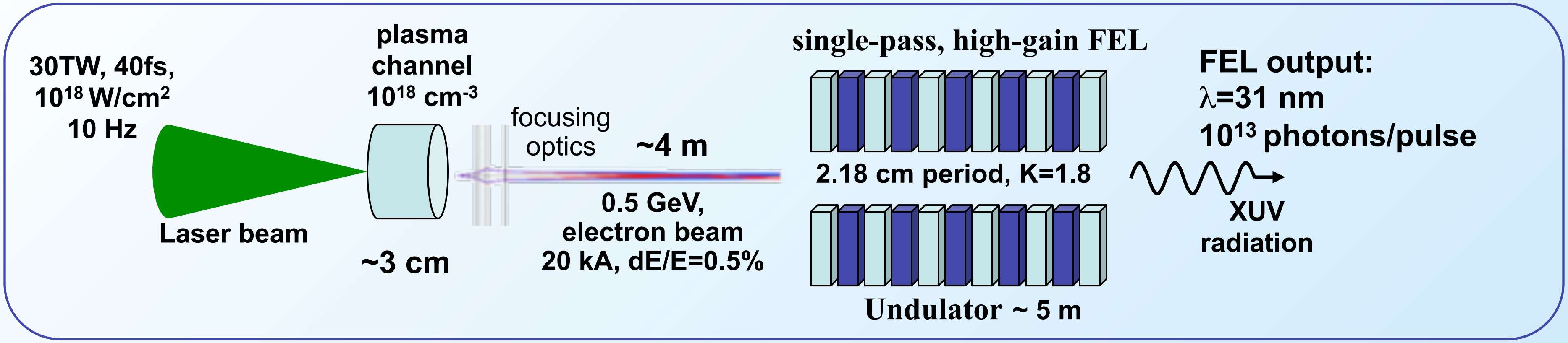
THUNDER Undulator

XUV Spectrometer



- Diagnostic of electron beam (emittance and energy spread)

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

~4 m

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

single-pass, high-gain FEL

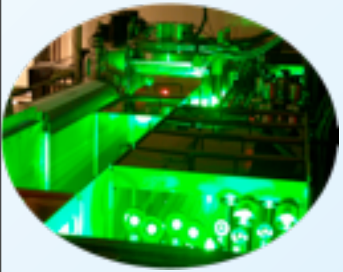
2.18 cm period, K=1.8

Undulator ~ 5 m

FEL output:
λ=31 nm
10^{13} photons/pulse

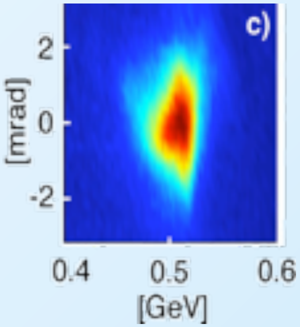
XUV
radiation

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



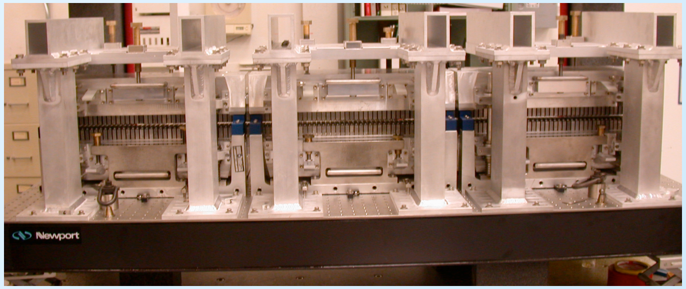
Plasma
capillary
technology

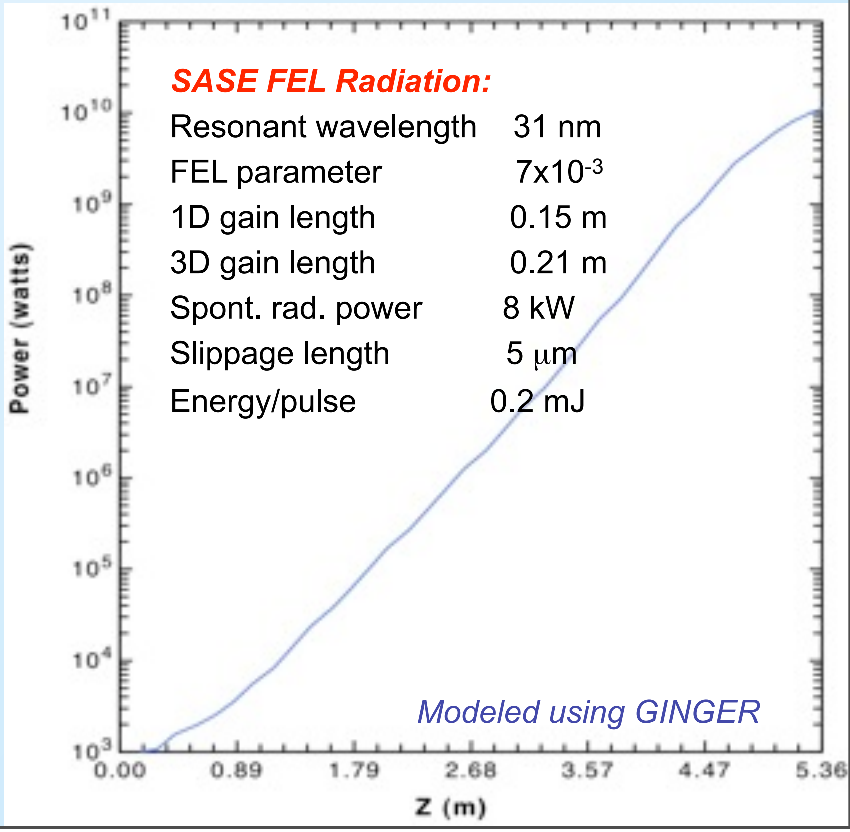
LPA e-beam



conventional
undulator
(THUNDER)

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



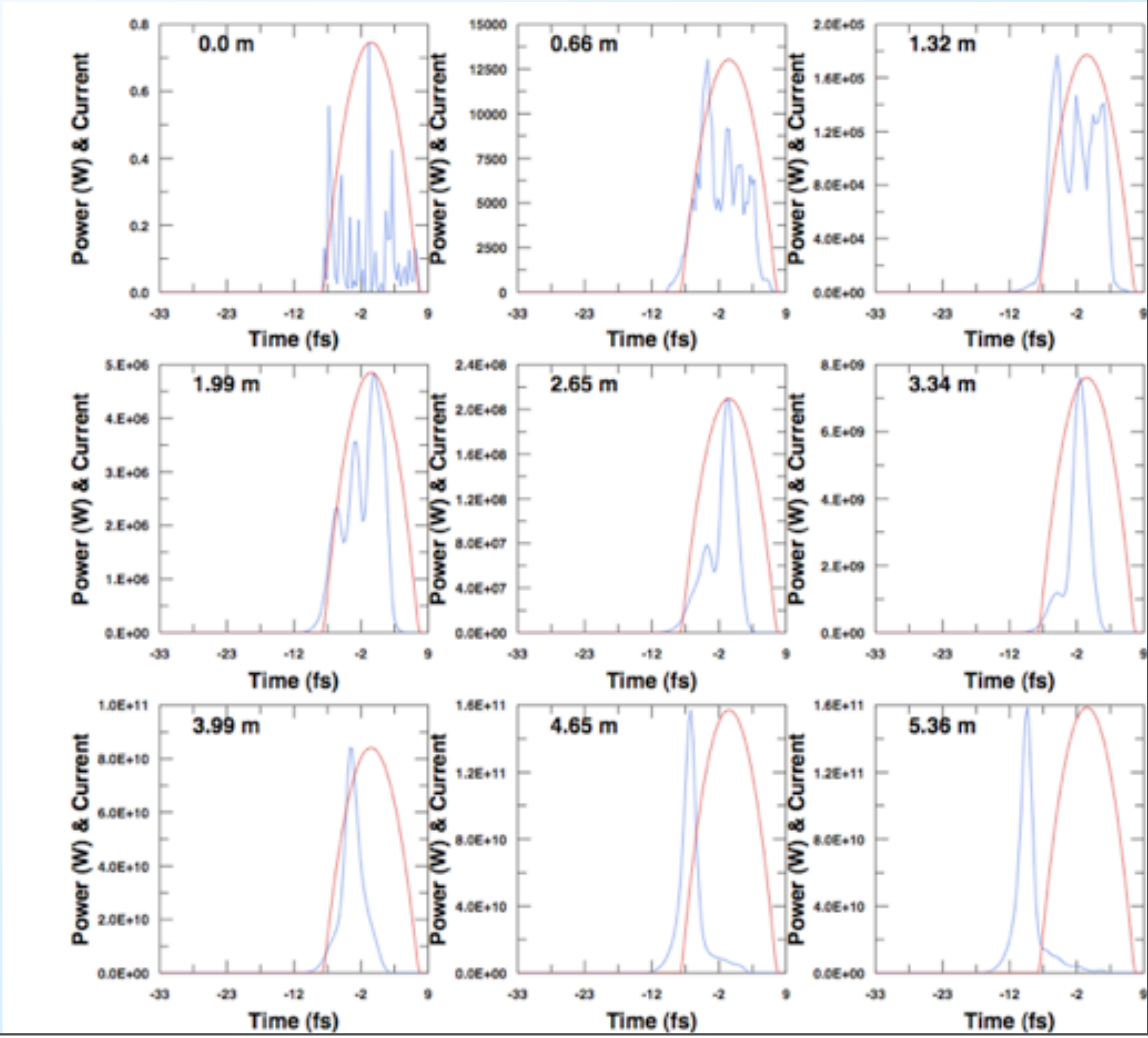


SASE FEL Radiation:

Resonant wavelength	31 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

Modeled using GINGER

Slippage dominant effect for fs LPA beams



bunch length < slippage

$$L_b < N_u\lambda \sim \frac{\lambda}{\rho}$$

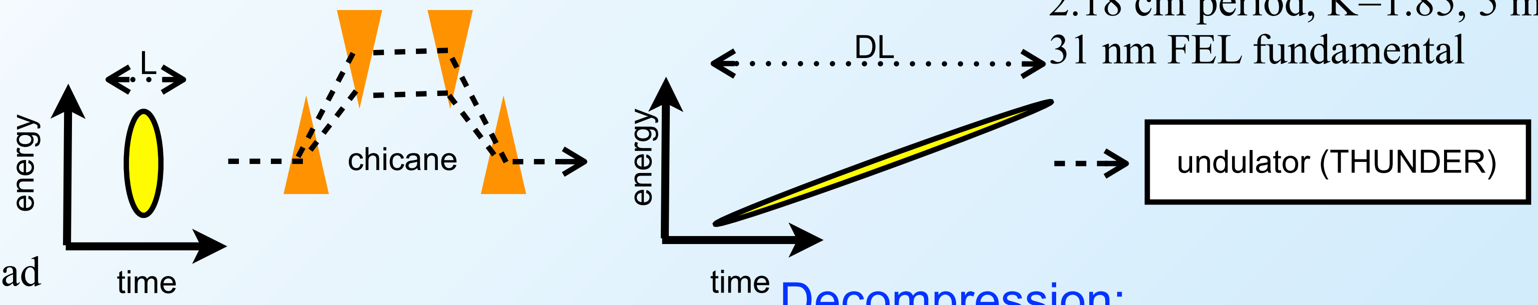
single-spike operation:

$$L_b \sim L_c = \frac{\lambda}{4\pi\rho}$$

LPA beam decompression for FEL lasing

LPA e-beam

$\varepsilon_N = 0.1$ micron
500 MeV
4% (rms) energy spread
I = 10 kA (5 fs)



2.18 cm period, K=1.85, 5 m
31 nm FEL fundamental

Decompression:

- slice energy spread << ρ
- bunch length > slippage length
- reduced beam density: $\rho \sim n_b^{1/3}$

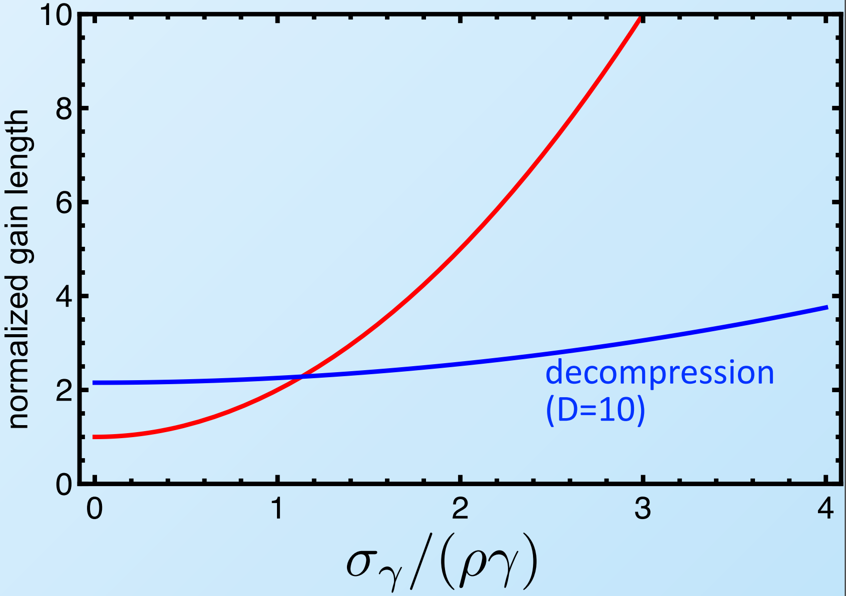
For decompression factor D>>1:
[e.g., $D \sim (\Delta\gamma/\gamma) R_{56}/L$]

$$L_g \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho} D^{1/3} \left[1 + D^{-4/3} \left(\frac{\sigma_\gamma}{\gamma\rho} \right)^2 \right]$$

with minimum at

$$D = 3^{3/4} (\sigma_\gamma / \gamma\rho)^{3/2}$$

$$L_{g,\min} = \frac{4}{3^{3/4}} \left(\frac{\sigma_\gamma}{\gamma\rho} \right)^{1/2} \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

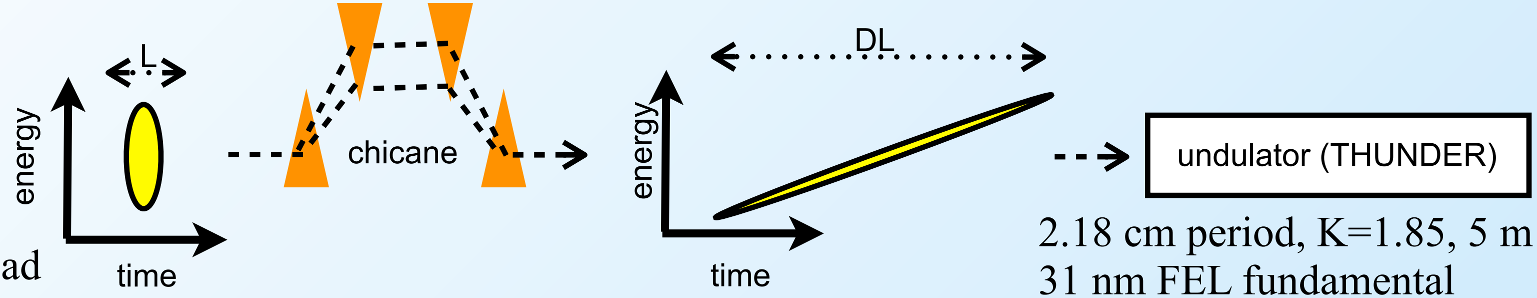


Schroeder et al., Proc. FEL (2012)

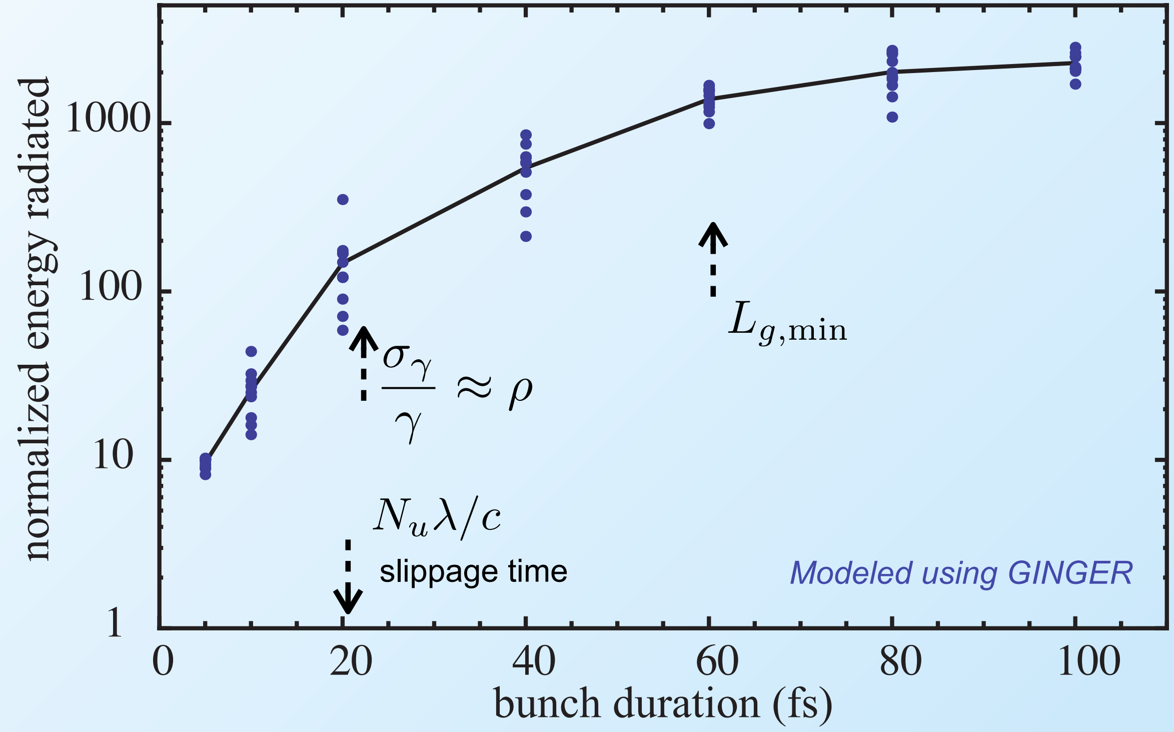
>2 orders of magnitude enhancement using LPA beam decompression

LPA e-beam

$\varepsilon_N = 0.1$ micron
500 MeV
4% (rms) energy spread
I = 10 kA (5 fs)

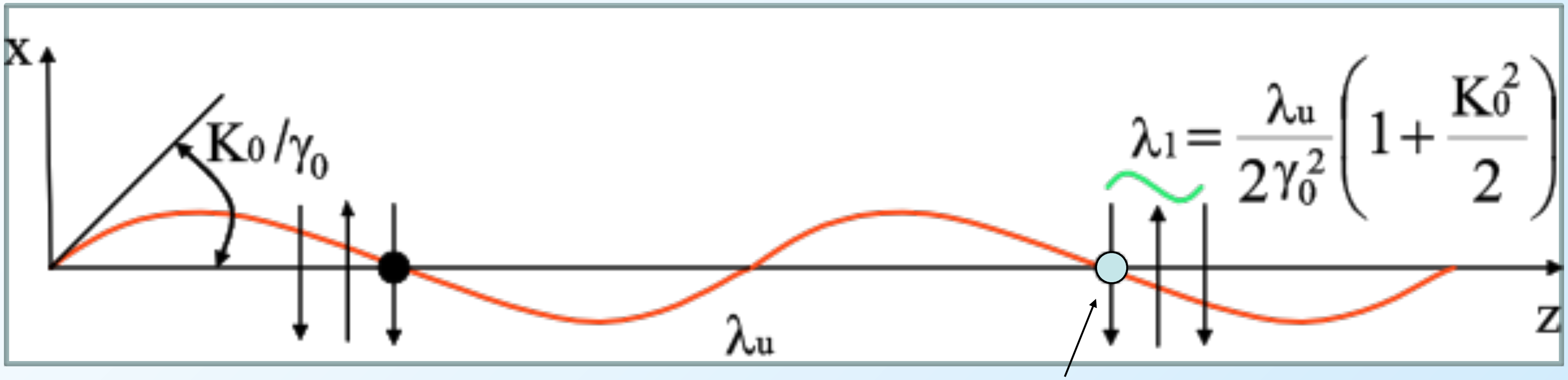


2.18 cm period, K=1.85, 5 m
31 nm FEL fundamental



Decompression by factor ~10 ➔ >2 orders of magnitude enhancement

Transverse gradient undulaor (TGU) to compensate for large energy spread



off-energy particle in TGU

- ➢ Resonance condition:

$$\boxed{\lambda = \frac{\lambda_u}{2\gamma^2(x)}\left[1 + K(x)^2/2\right]}$$

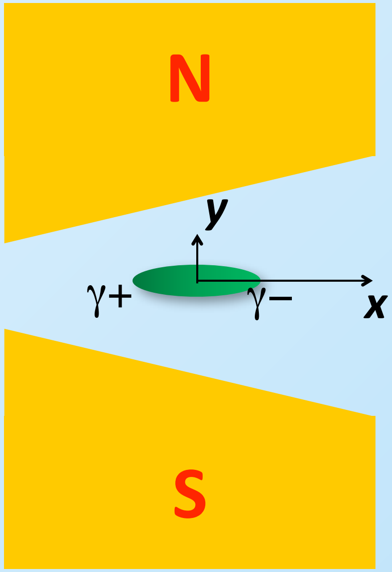
- ➢ Sort e-beam with dispersion: $x = \eta\Delta\gamma/\gamma$

- ➢ Canting the undulator poles, generate a linear field gradient: $\frac{\Delta K}{K} = \alpha x$

- ➢ Resonance condition can be satisfied for all energies: $\boxed{\eta = \frac{2+K^2}{\alpha K^2}}$

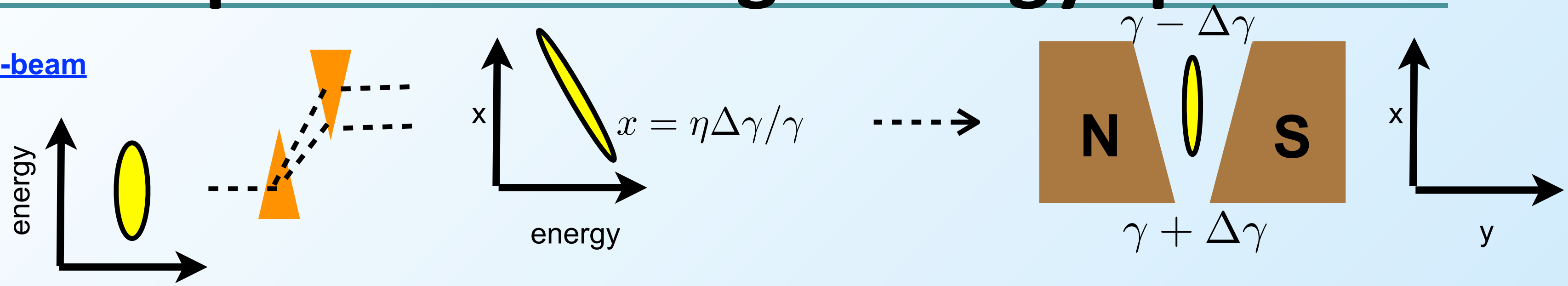
Transverse gradient undulator (TGU):

T. Smith et al, J. Appl. Phys. (1979)



Transverse gradient undulaor (TGU) to compensate for large energy spread

LPA e-beam

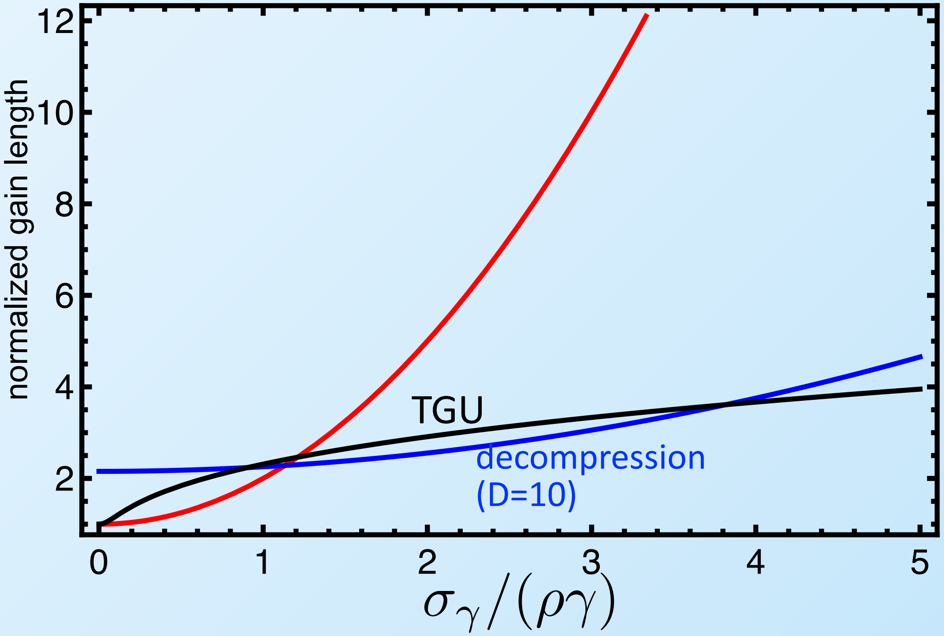


Gain length in TGU
(dispersion reduces beam density):

$$L_g \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho}\left[1+\left(\frac{\eta\sigma_\gamma}{\sigma_x\gamma}\right)^2\right]^{1/6}$$

Advantages of TGU:

- shorter radiation pulse durations
- higher peak FEL power
- smaller FEL bandwidth
- seeding possible
- stabilization of wavelength to beam central energy jitter (energy jitter -> transverse position jitter); enables seeding



Huang, Ding, Schroeder (submitted)

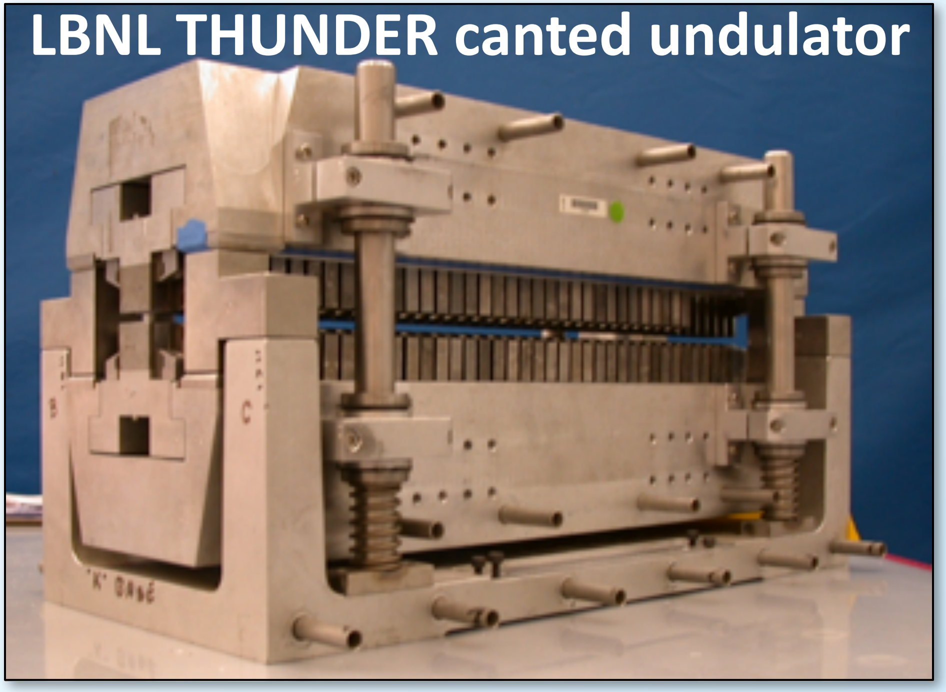
- Depending on beam parameters (bunch length, FEL wavelength, ...), may want to **combine** TGU with decompression

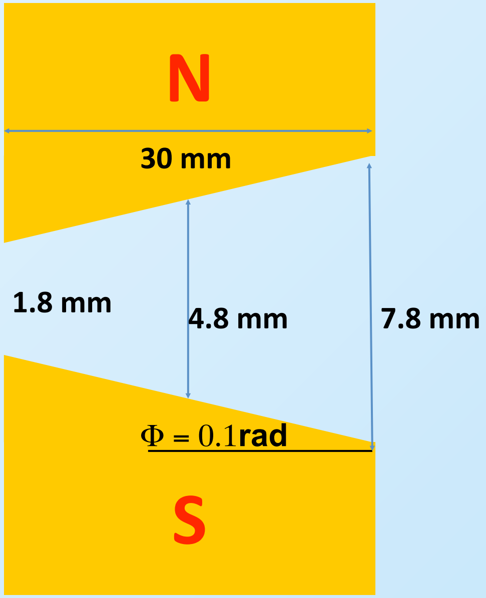
THUNDER: canted pole undulator

Halbach formula for Hybrid undulator:

$$\alpha = 2\phi \frac{1}{K_0}\frac{\partial K_0}{\partial y} = 2\phi\left(\frac{5.47}{\lambda_u} - 3.6\frac{g}{\lambda_u^2}\right)$$

LBNL THUNDER canted undulator





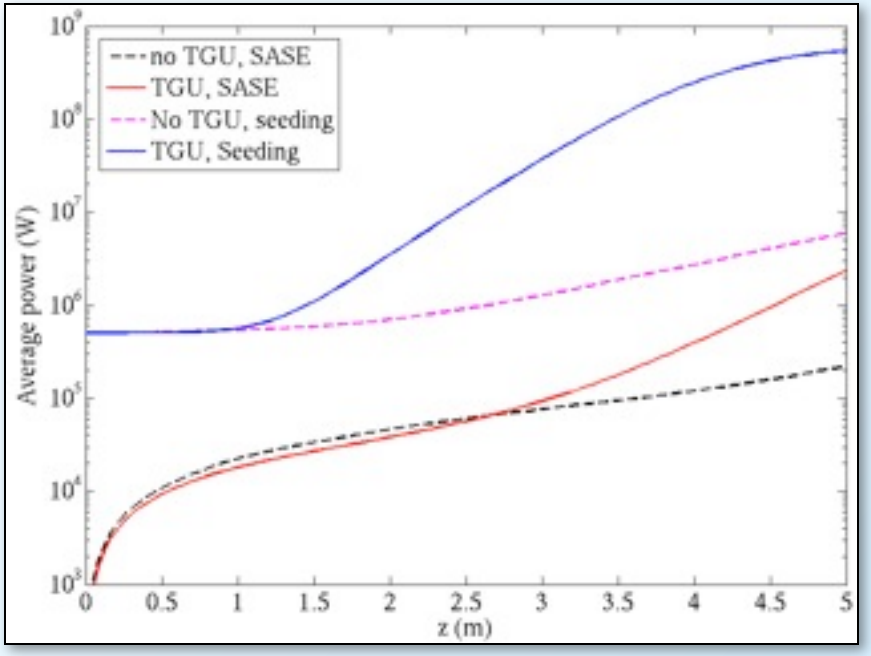
e.g., $2\phi = 0.2$ rad, $\lambda_u = 2.18$ cm, $g = 4.8$ mm ➔ $\alpha = 43\ \mathrm{m}^{-1}$

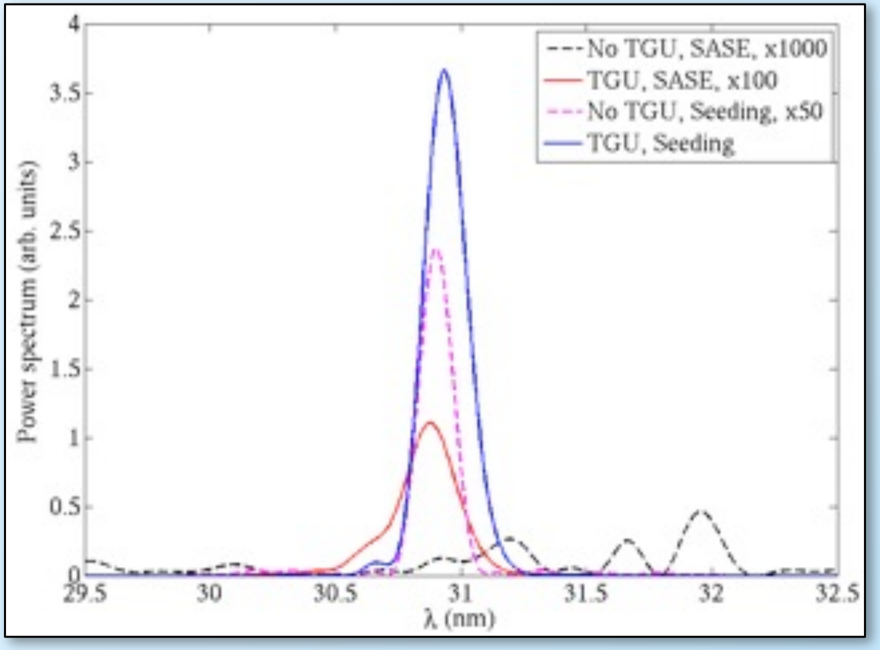
FEL Enhancement using flat beam in TGU

500 MeV beam with 2% energy spread (rms)
5kA, 0.1 um emittance, 10 fs
5-m (THUNDER) undulator, λ_u = 2.18 cm, K = 1.85

Radiation wavelength λ_r = 31 nm

For TGU, dispersion η = 3.7 cm, trans. e-beam size: 790um x 20um

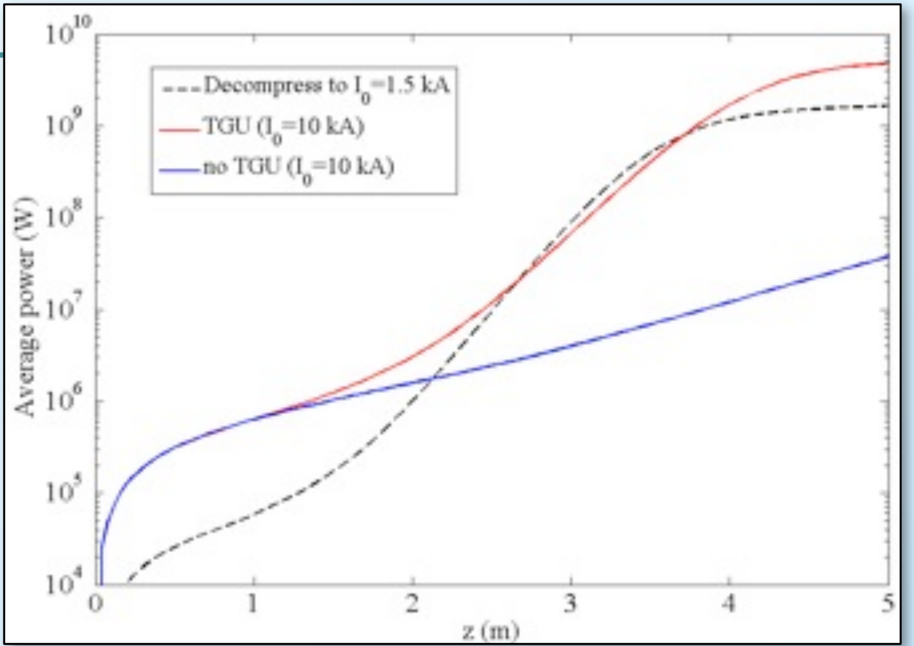




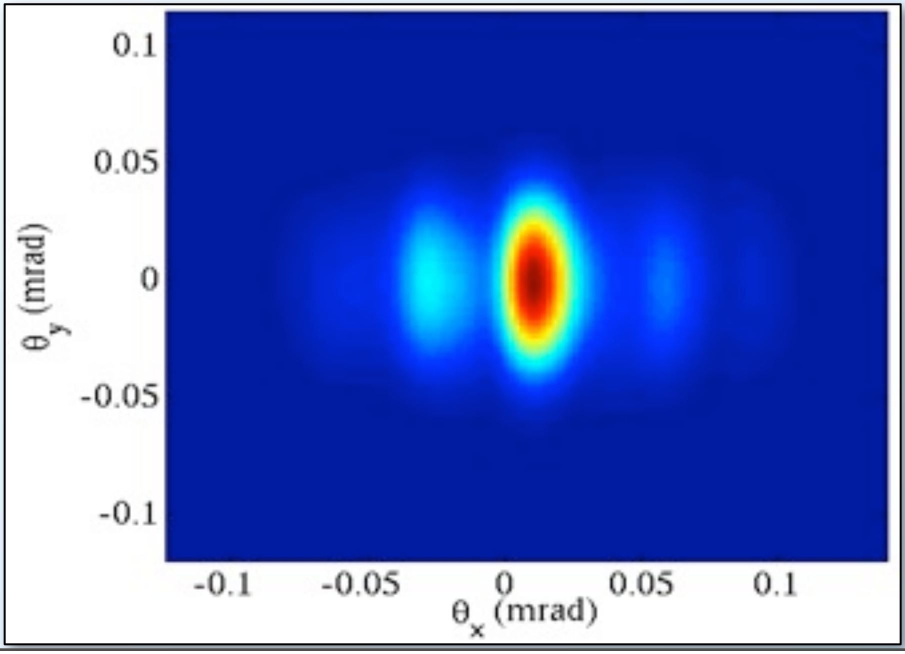
Huang, Ding, Schroeder (submitted)

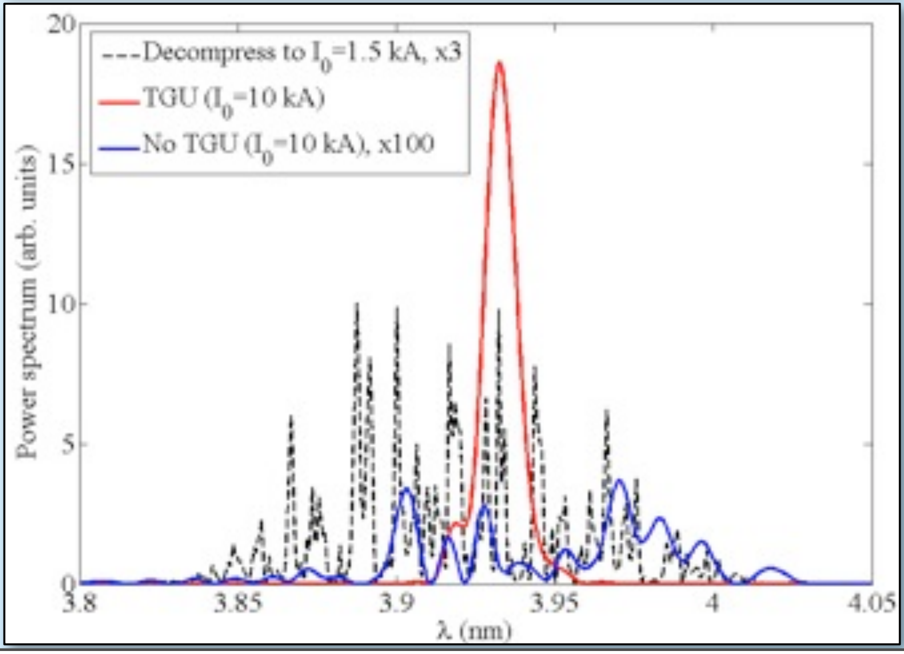
Soft x-ray LPA-driven FEL at 3.9 nm

- 1 GeV, 10kA, 1% energy spread;
- 0.1um emittance; 5 fs (50 pC)
- **5-m (SC) undulator λ_u = 1 cm, *K* = 2;**
- Transverse gradient α **= 150 m^{-1}**
- Radiation wavelength λ_r = 3.9 nm
- TGU, dispersion η = 0.01 m: trans. beam size 100um x 15um



Huang, Ding, Schroeder (submitted)





Summary

- Laser-plasma accelerators considered for future linear collider:
  - Operation in quasi-linear regime (a~1): e+ acceleration, control of focusing forces
  - Laser depletion and beam dephasing; staging with tapered plasma channels
  - High luminosity required ➔ ultra-low beam emittance; Beamstrahlung at IP limits charge/bunch
- Plasma density scalings - determine required laser technology
  - Minimizing construction and operating costs ➔ operating at $10^{16} < n[\mathrm{cm}^{-3}] < 10^{18}$
  - ~10 GeV stages (operating at $n=10^{17}$ cm^{-3}): requires laser pulse (at 1 micron), ~30 J, a~1, ~100 fs, ~15 kHz, ~30% efficiency

- **BELLA** ➔ PW (>40 J, <40 fs) laser for demonstration of 10 GeV LPA

- LPA-driven Free-electron laser is a promising near-term application of LPA
  - LPA 6D brightness comparable to conventional sources; FEL application hindered by relative energy spread and slippage.
  - soft x-ray FEL realizable using demonstrated LPA e-beam parameters:
    - Beam decompression
    - Beam dispersion coupled with transverse gradient undulator

Acknowledgements

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SLAC:
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Z. Huang