Plasma accelerators: present status, future developments, and applications

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Future Research Infrastructures: Challenges and Opportunities
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BERKELEY LAB
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U.S. DEPARTMENT OF ENERGY
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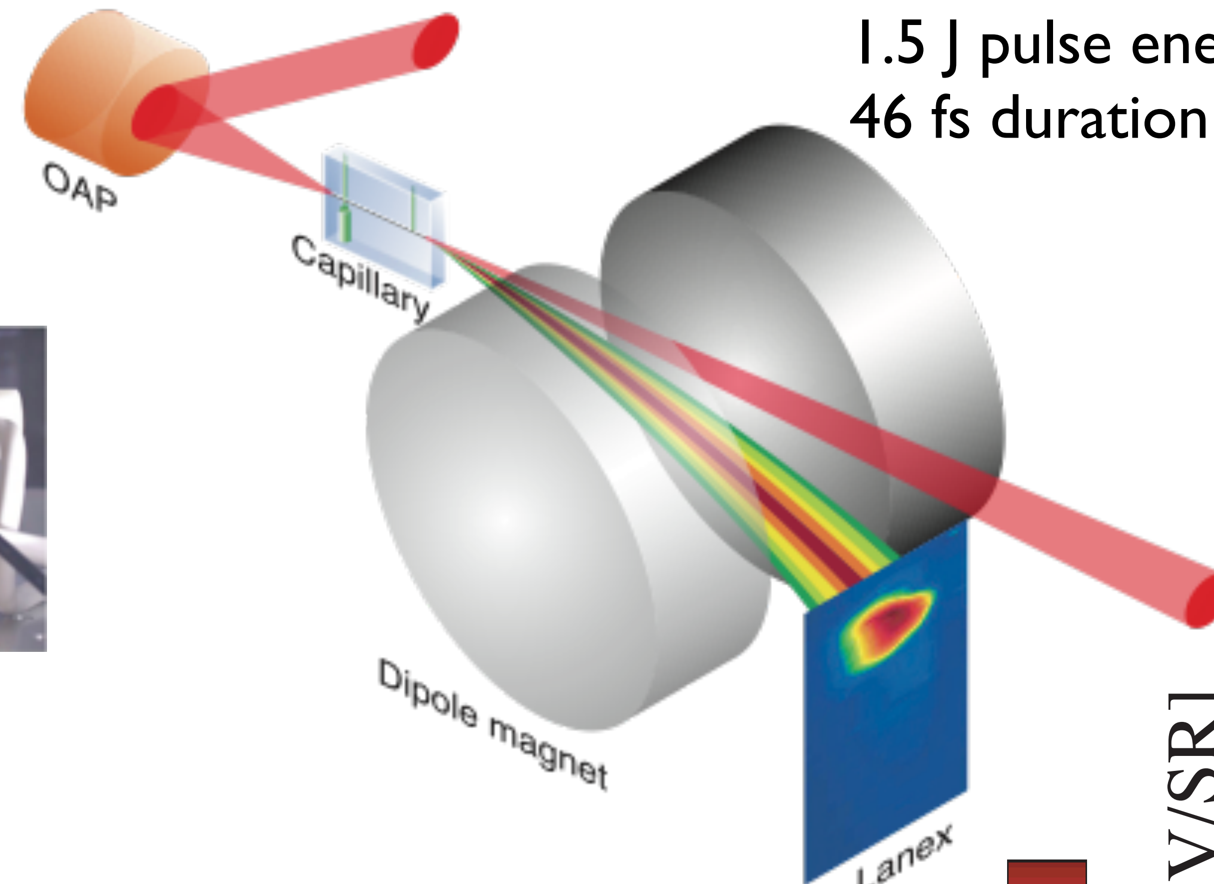
Outline

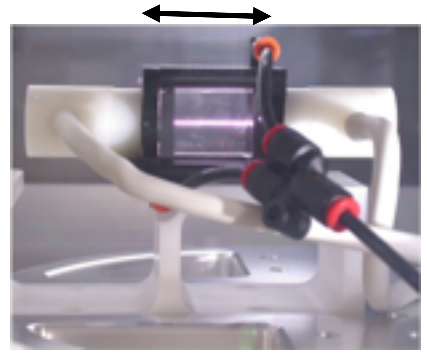
- Laser-driven plasma-based accelerators (LPAs): ultra-high gradient provides compact source of energetic, fs, kA e-beams
  - GeV beams in cm-scale plasmas available using LPAs
  - 6D brightness comparable to conventional sources
- Path to higher energy beams
  - Experimental results from BErkeley Lab Laser Accelerator (BELLA)
- Improved LPA beam quality, stability using controlled injection techniques
  - Ultra-low beam emittance generation
- Applications:
  - LPA-driven free-electron lasers (FELs)
  - High-energy physics (lepton collider) application of LPAs

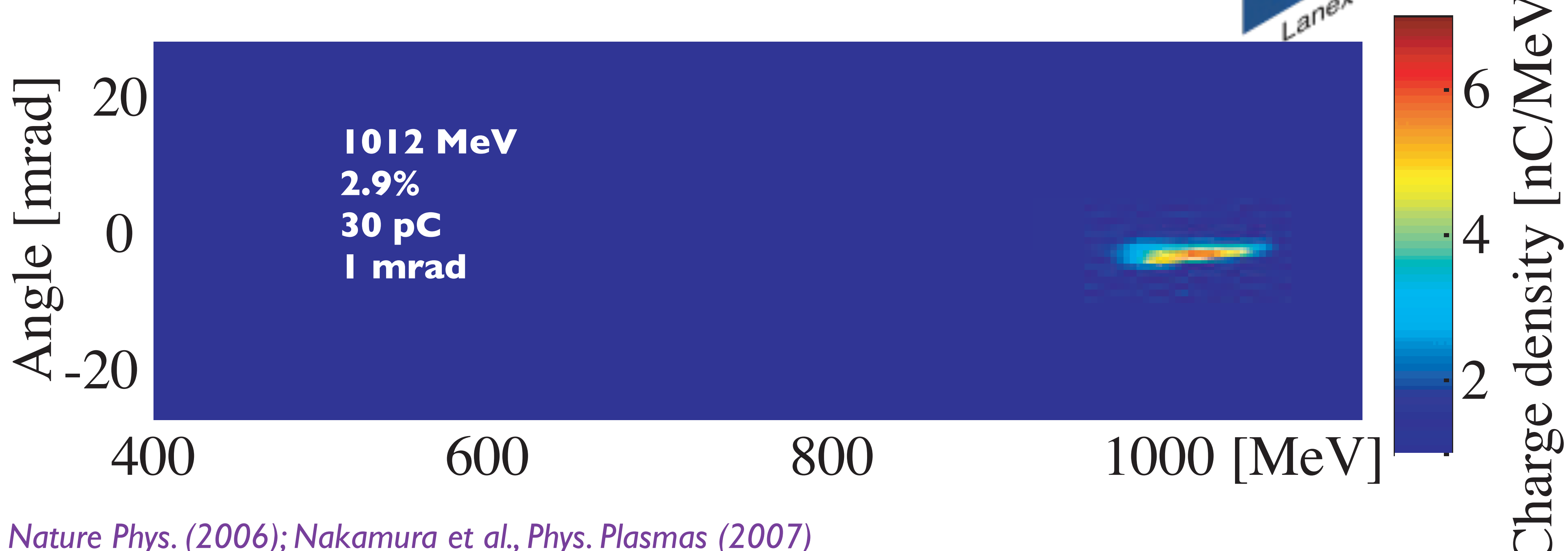
Laser-plasma accelerator (LPA) experimental demonstration of GeV electron beam

Ti:Sapphire laser:
0.8 micron wavelength
1.5 J pulse energy
46 fs duration



Plasma source:
H-discharge capillary
number density = 3×10^{18} cm^{-3}





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

Laser-plasma accelerators:
Laser-driven relativistic electron plasma wave

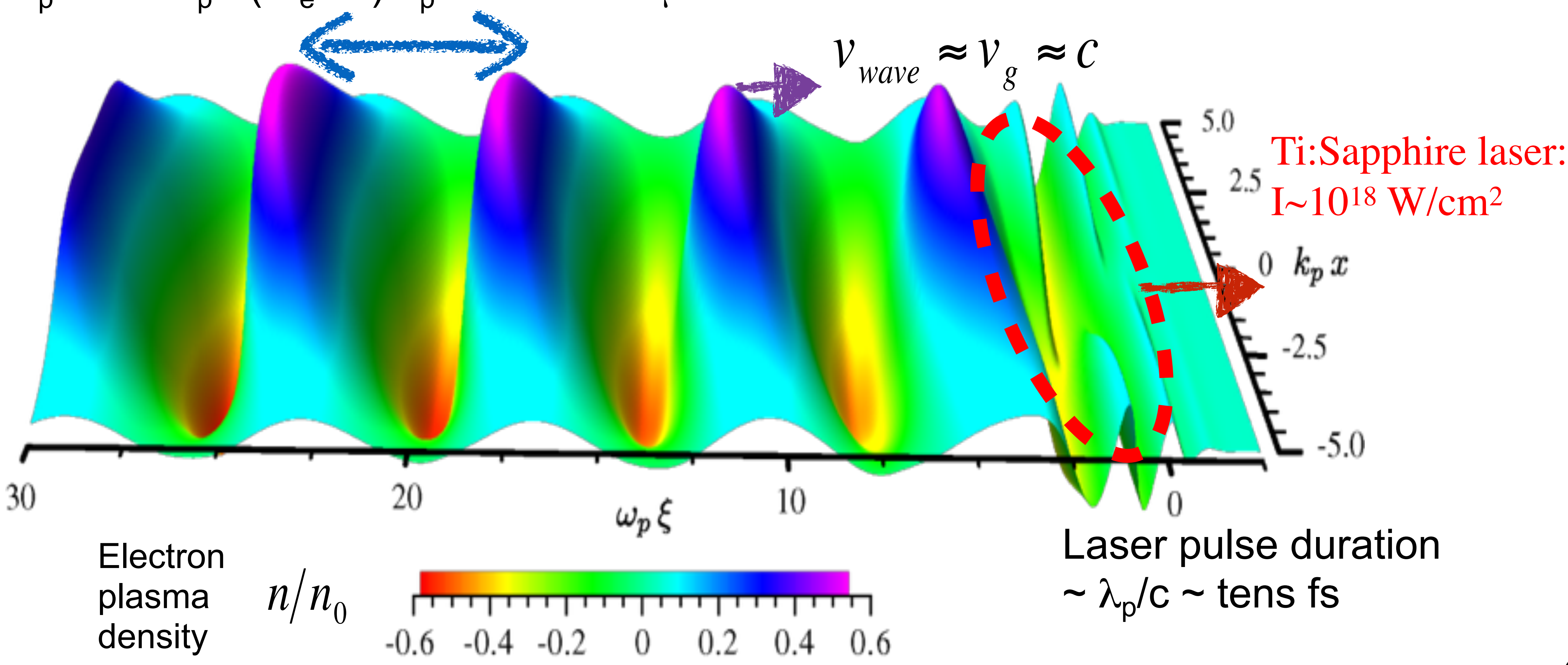
Esarey, Schroeder, Leemans, Rev. Mod. Phys. (2009)

Plasma wave: electron density perturbation

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

Ponderomotive force (radiation pressure)

$\lambda_p = 2\pi c/\omega_p = (\pi r_e^{-1/2})\, n_p^{-1/2} \sim$10-100 μm



Electron plasma density n/n_0

Laser pulse duration ~ λ_p/c ~ tens fs

Laser-plasma accelerators: compact sources (>10 GV/m) of fs e-beams

Esarey, Schroeder, Leemans, Rev. Mod. Phys. (2009)

- **Accelerating field:** with relativistic phase velocity and large density perturbation:

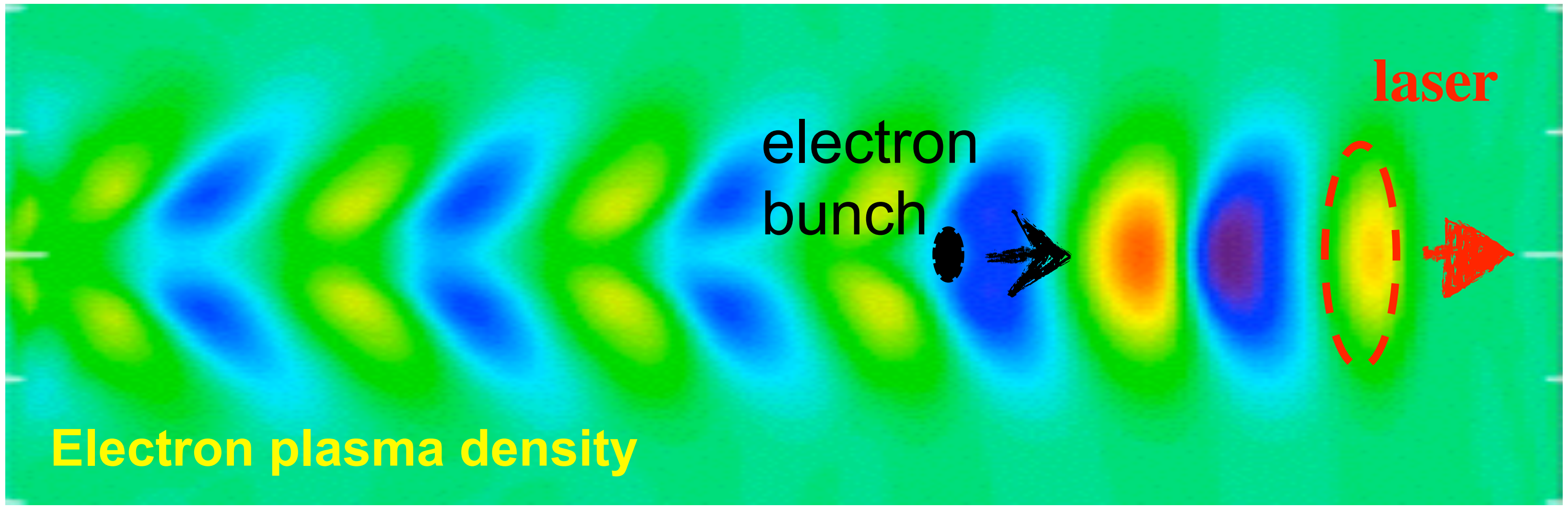
$$E \sim \left(\frac{mc\omega_p}{e}\right) \approx (96\ \mathrm{V/m})\sqrt{n_0[\mathrm{cm}^{-3}]}$$

- E.g., for ~10^{18} cm^{-3} , gradient ~100 GV/m

(~10^3 larger than conventional RF accelerators: from km to m)

- **Bunch duration:**
  - Accelerating bucket ~ plasma wavelength
  - Ultrashort (fs) bunches (<λ_p/4)

Lundh et al., Nature Phys. (2011)
Buck et al., Nature Phys. (2011)



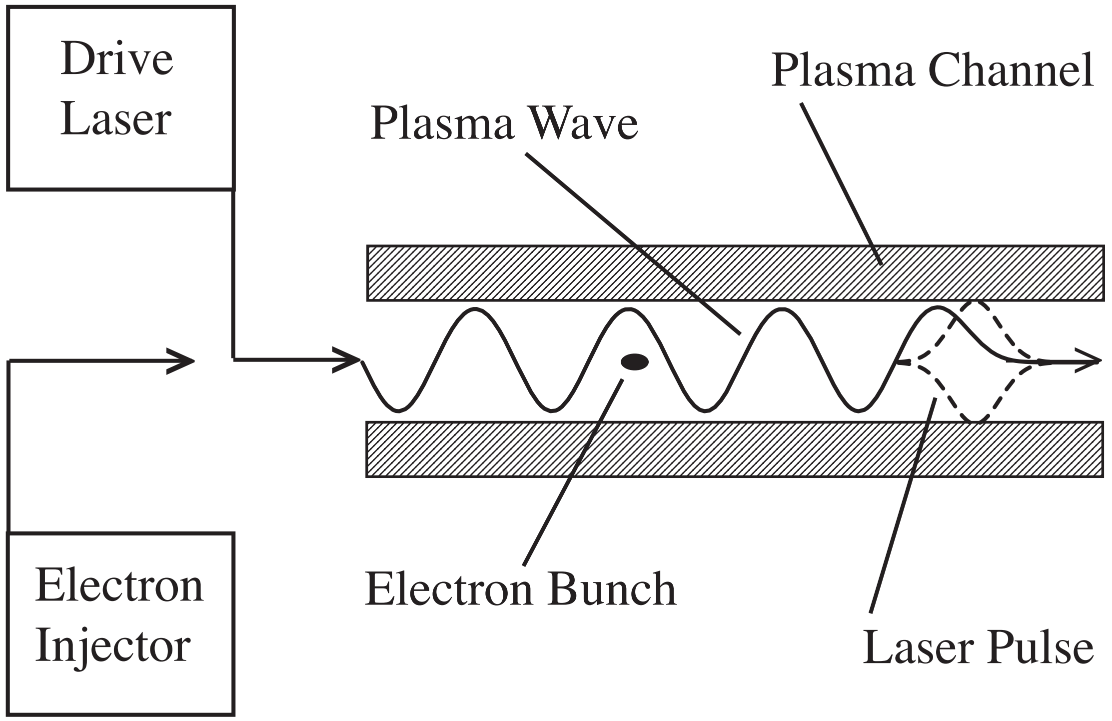
- Beam charge (set by beam loading, plasma density): ~1-100 pC
- Beam duration (set by trapping physics and density): ~1-10 fs

➡ ~1-10 kA

Electron beam injection into plasma wave

- **External injection:**

  - short bunch generation (~fs)
  - beam-laser synchronization

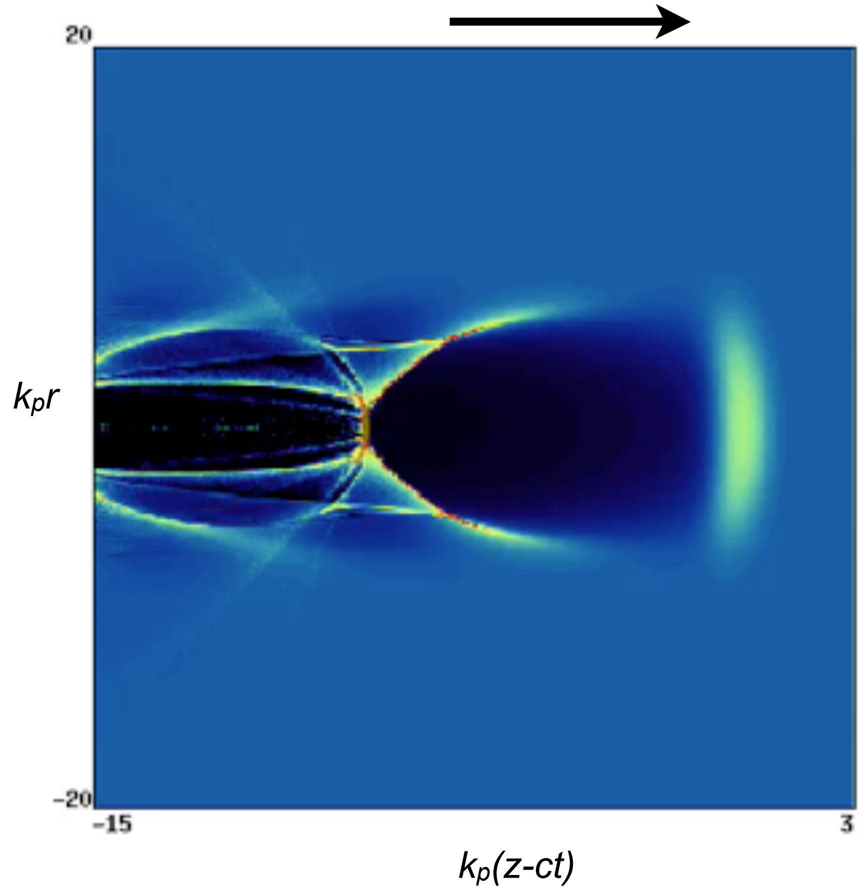


- **Beam generation from trapping background plasma electrons**
- **Trapping process determines beam quality**

  - Self-injection:
    - Relies on nonlinear plasma waves (in "bubble" regime, near wave-breaking)
    - Continuous (uncontrolled) injection, result in large (1-100%) energy spreads, and shot-to-shot fluctuations
    - Requires high plasma density = slow plasma wave phase velocity = lower energy gain
  - Laser-triggered injection
  - Density gradient injection
  - Ionization injection

Self-injection from background plasma

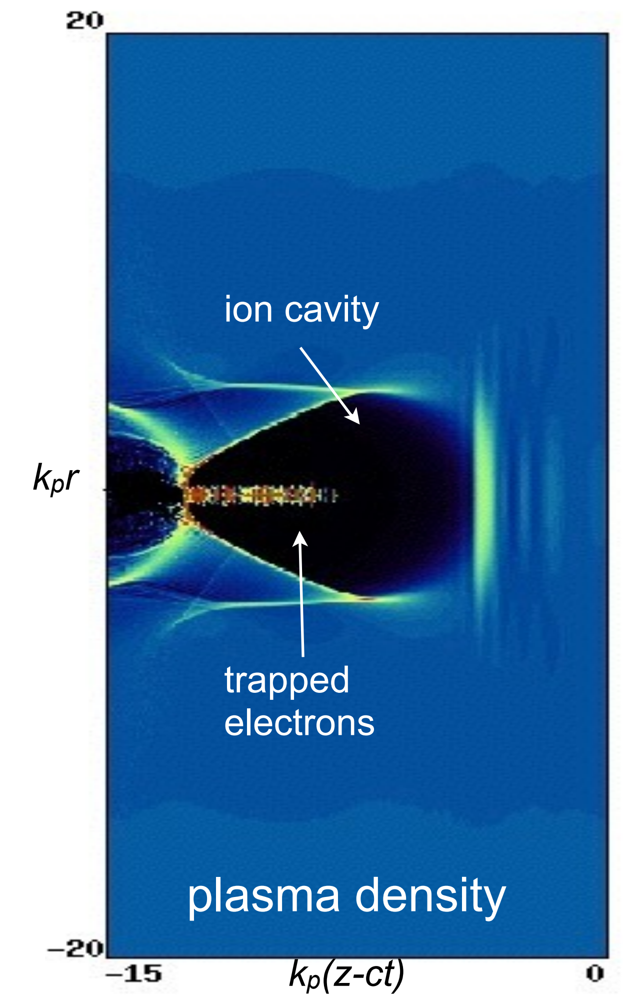
laser propagation direction

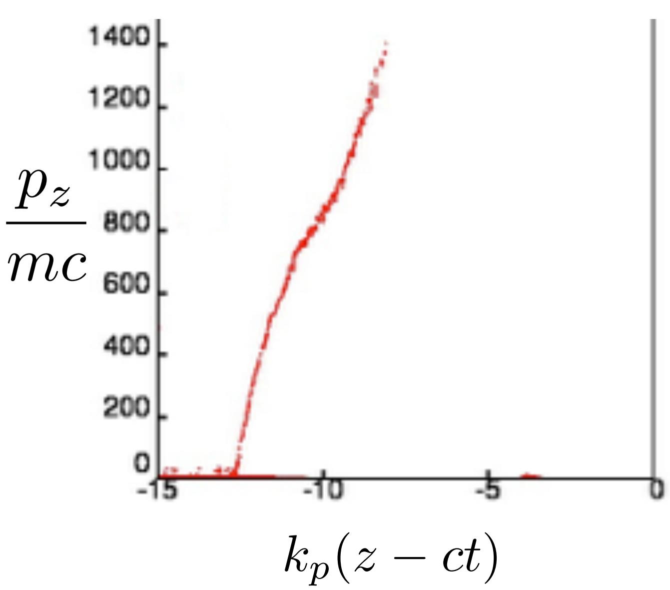


Benedetti, Schroeder et al., Phys Plasmas (2013)

- Requires high intensity laser (a>3)
- Requires high plasma density (slow plasma wave phase velocity)

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



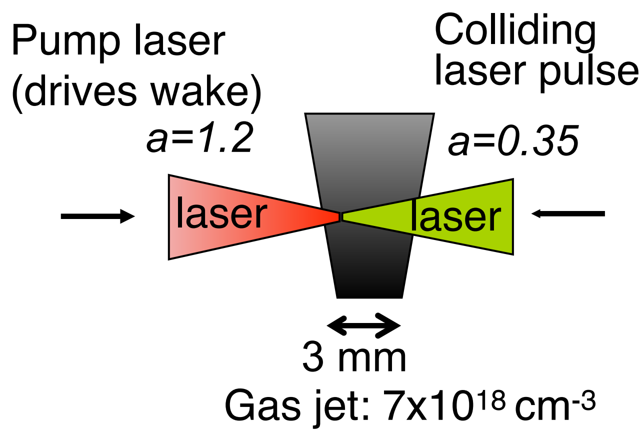


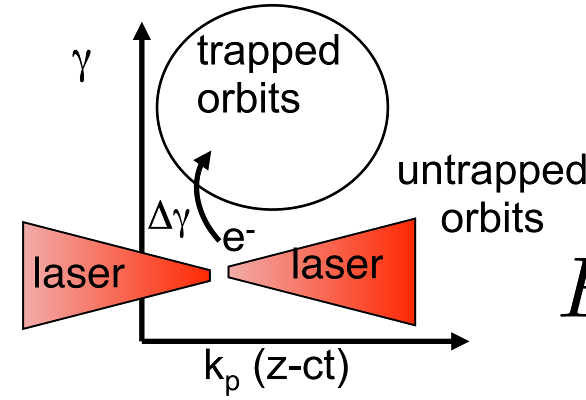
- continuous (uncontrolled) injection result in large (1-100%) energy spreads
- energy gain proportional to injection time chirped energy distribution
- controlled (triggered) injection ➡ improve stability and reduced energy spread

Laser-triggered injection: colliding-pulse injection

- **Colliding pulse injection:** beating of two laser pulses generates a slow phase velocity beat wave that provides a ponderomotive force, kicking electrons into trapped orbits of plasma wave

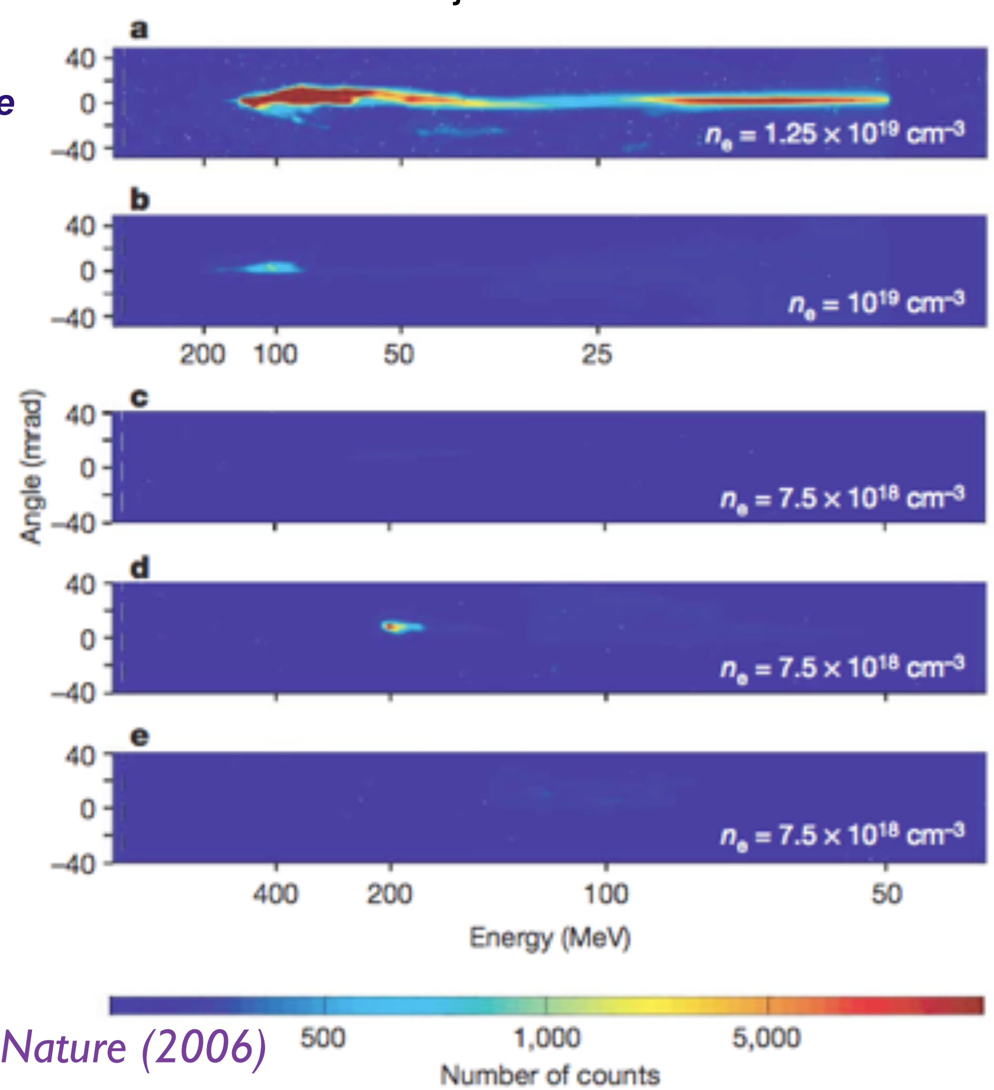
Esarey et al. PRL (1997)
Schroeder et al., PRE (1999)





$$F_{\text{beat}} \sim mc^2(2k_L)a_1a_2$$

Laboratoire d'Optique Appliquée



high density

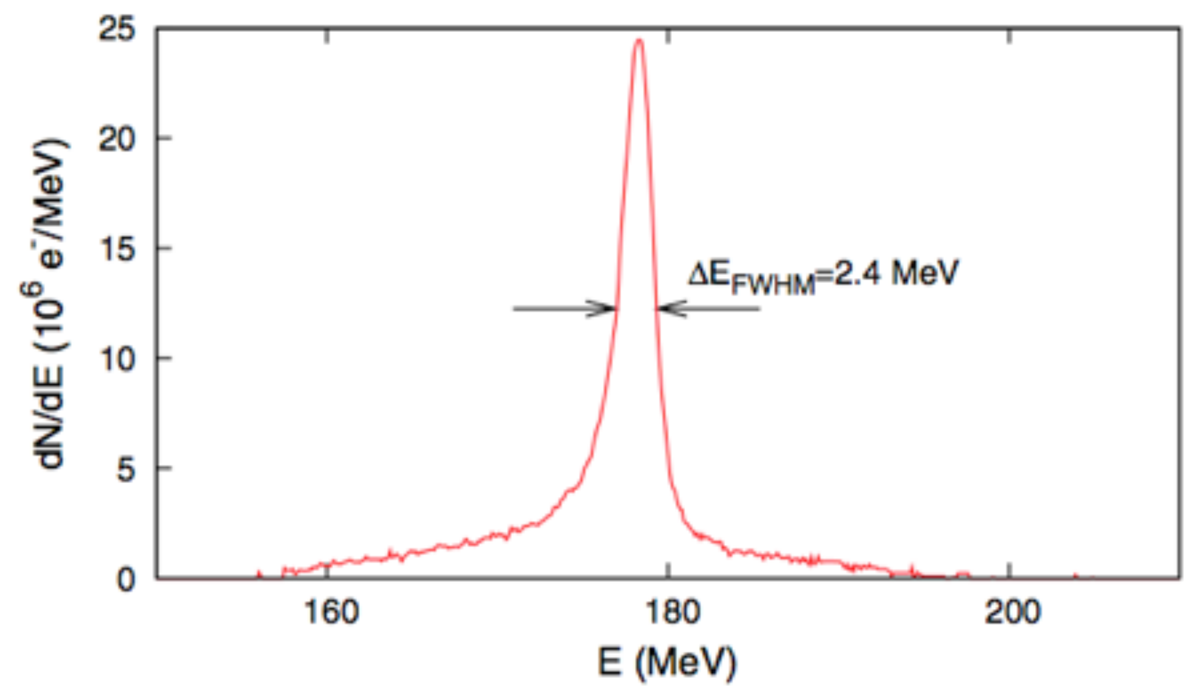
low density

colliding pulse

colliding pulse (orthogonal polarization)

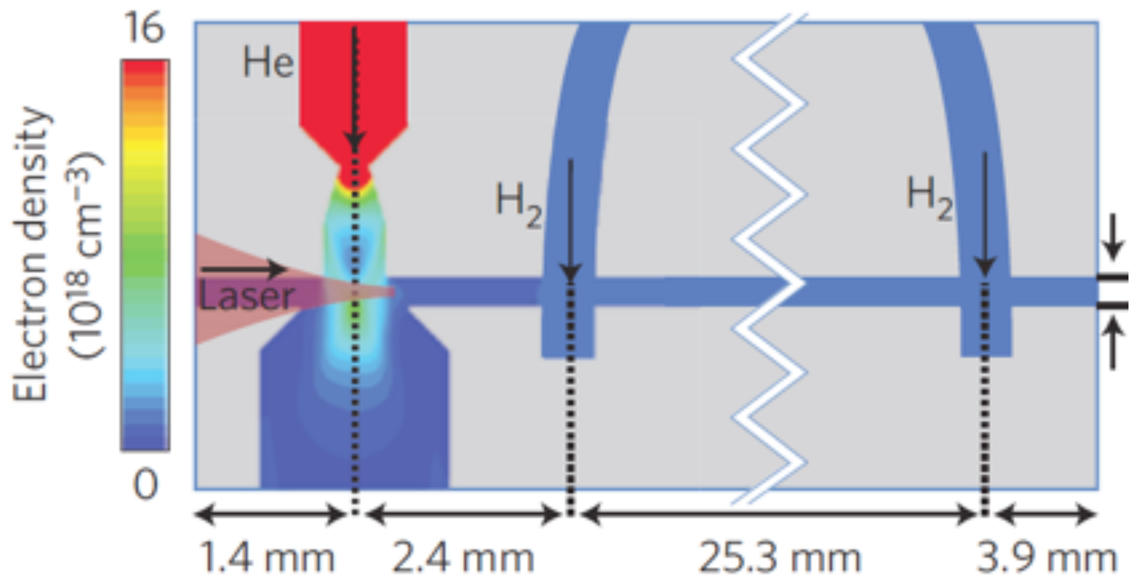
Faure et al. Nature (2006)

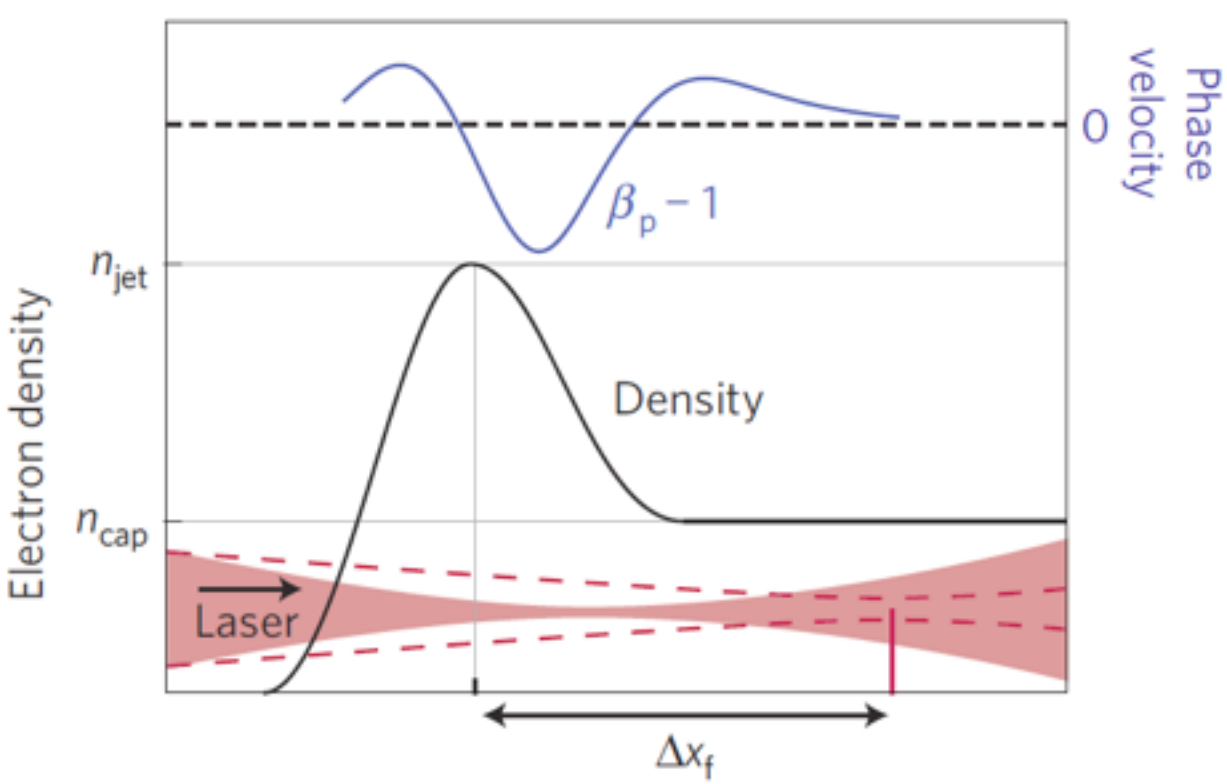
Rechatin et al., PRL (2009)

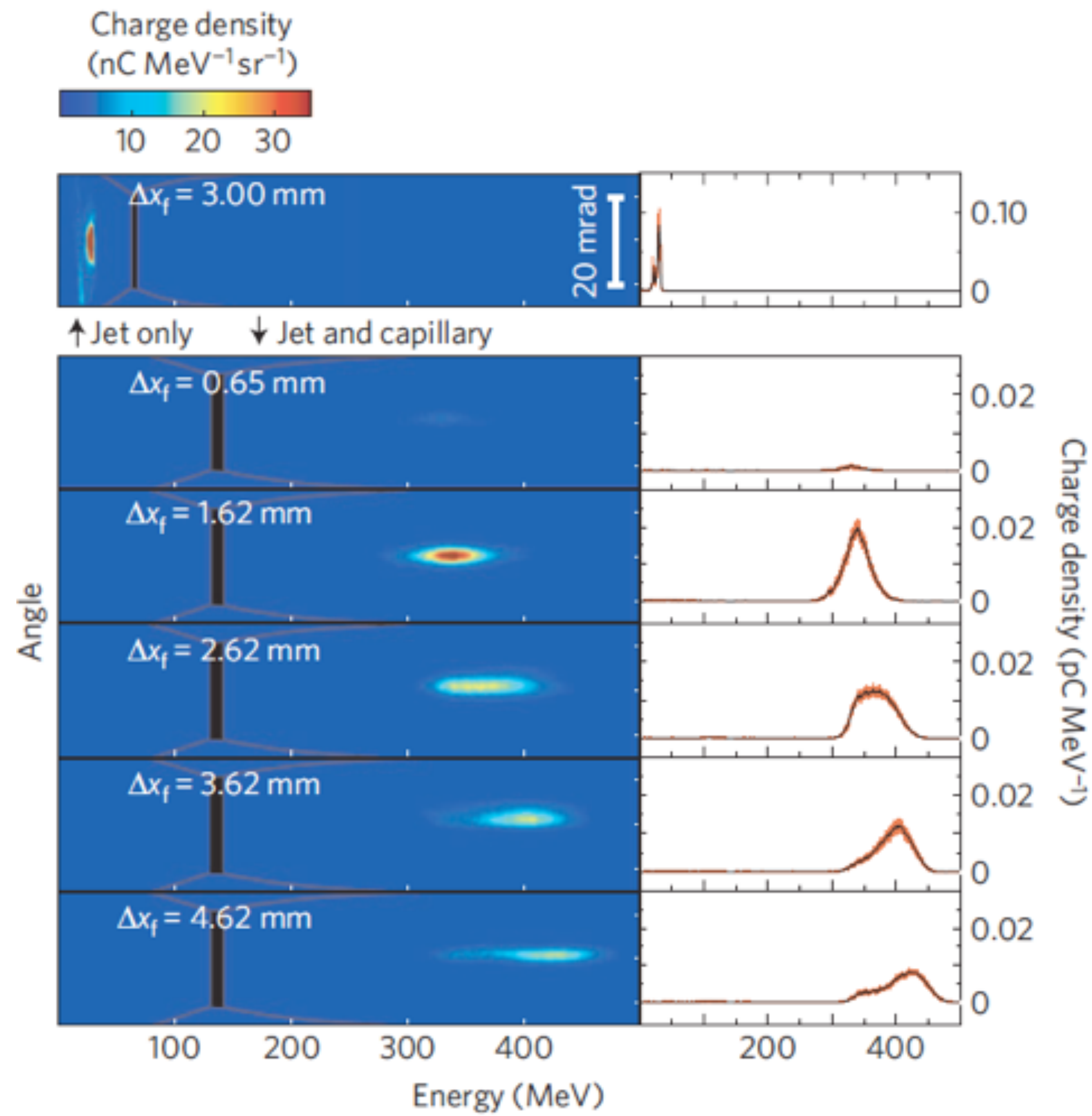


Injection: phase velocity control with density gradients

- Control phase velocity using density variation and laser evolution:







Gonsalves et al., Nature Phys. (2011)

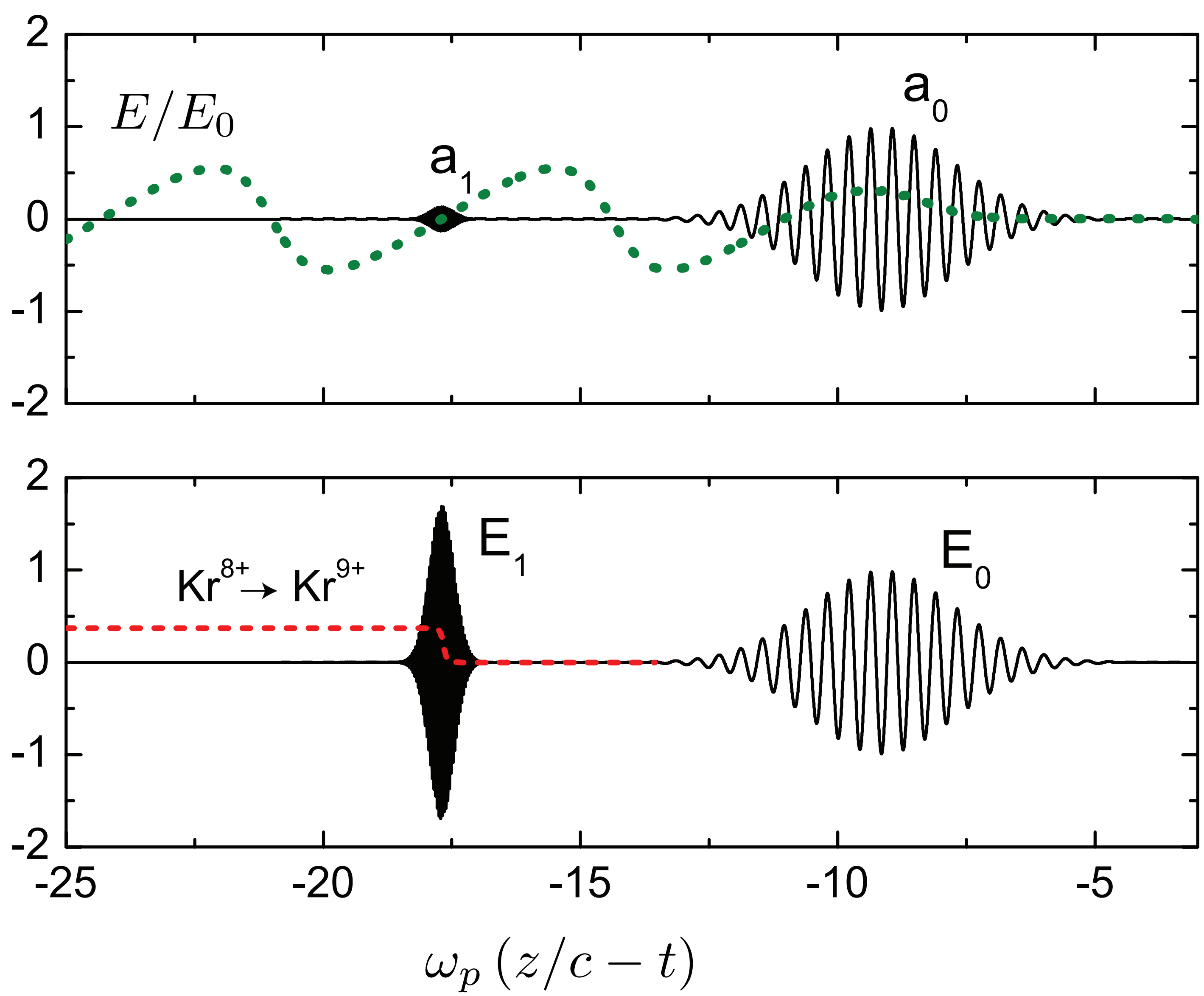
- Trapping occurs when wave phase velocity < plasma fluid velocity

Two-color ionization injection

L.-L. Yu, Esarey, Schroeder et al., PRL (2014)

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

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



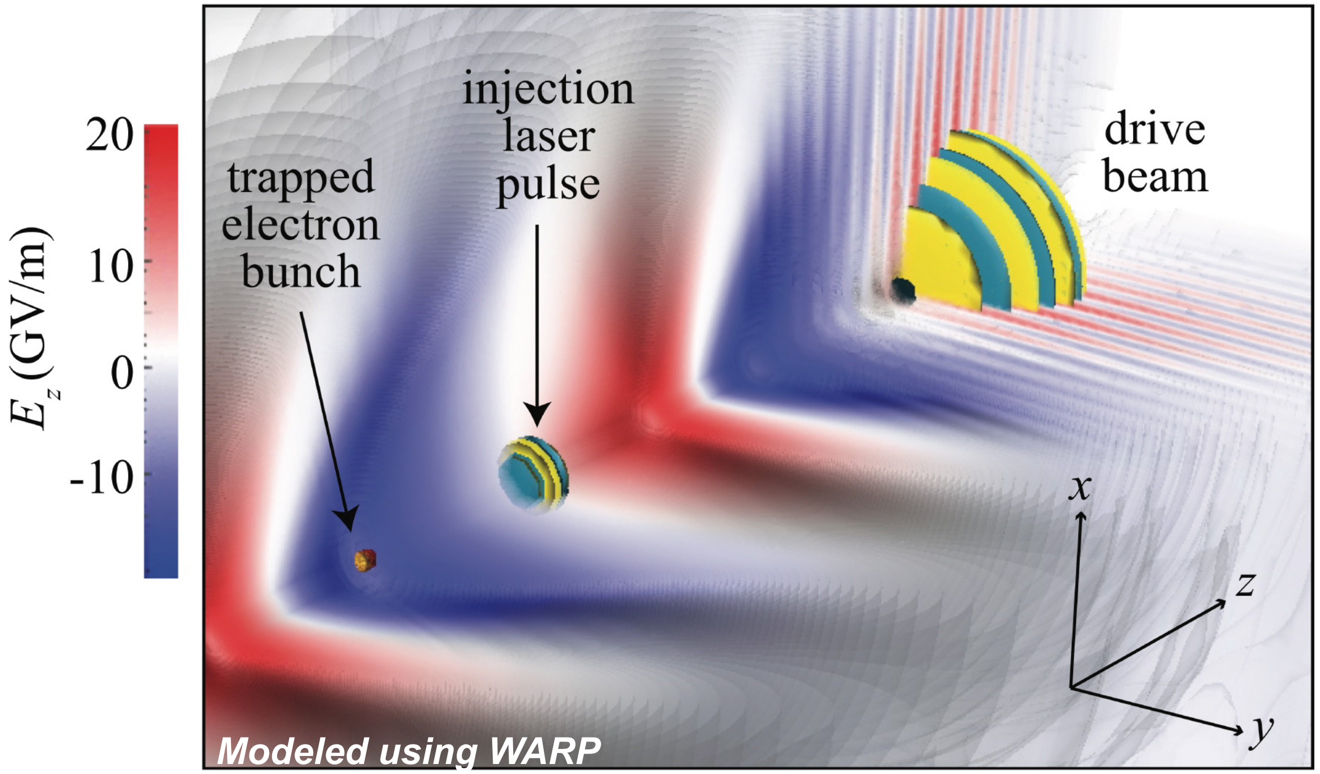
- Ponderomotive force drives plasma wave:

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

- Ionization determined by peak laser electric field:

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

Increased e-beam brightness using two-color ionization injection

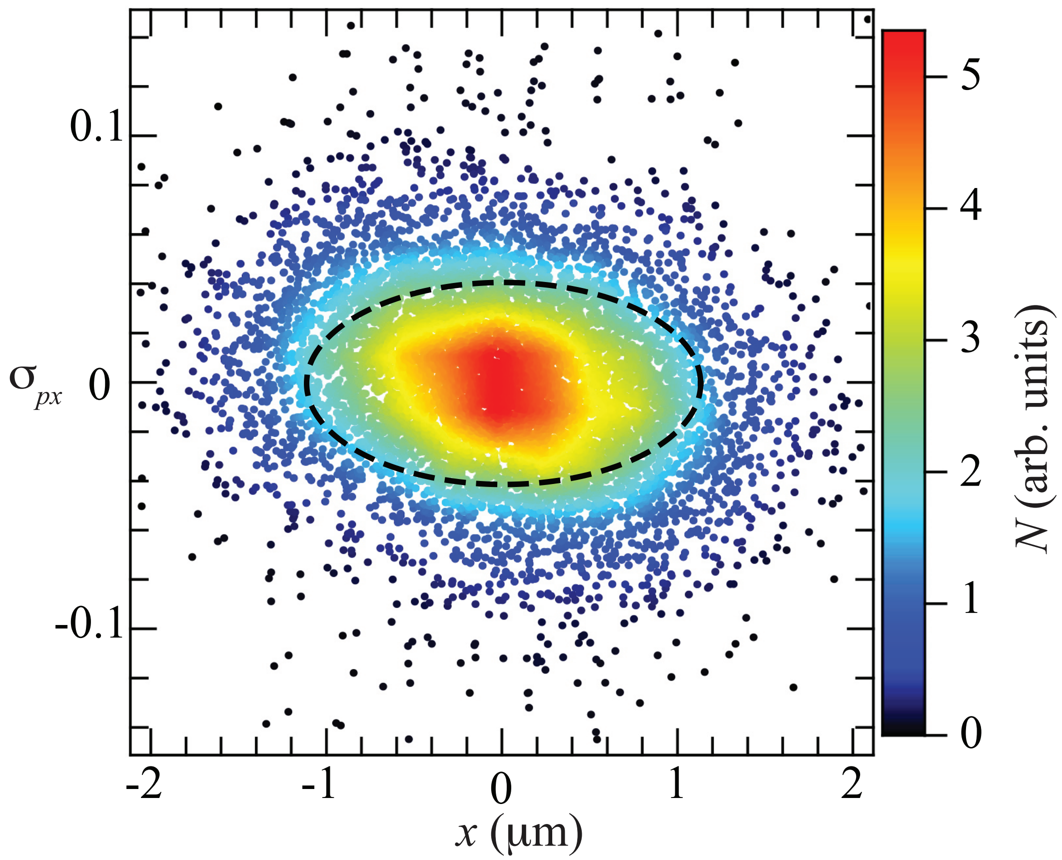


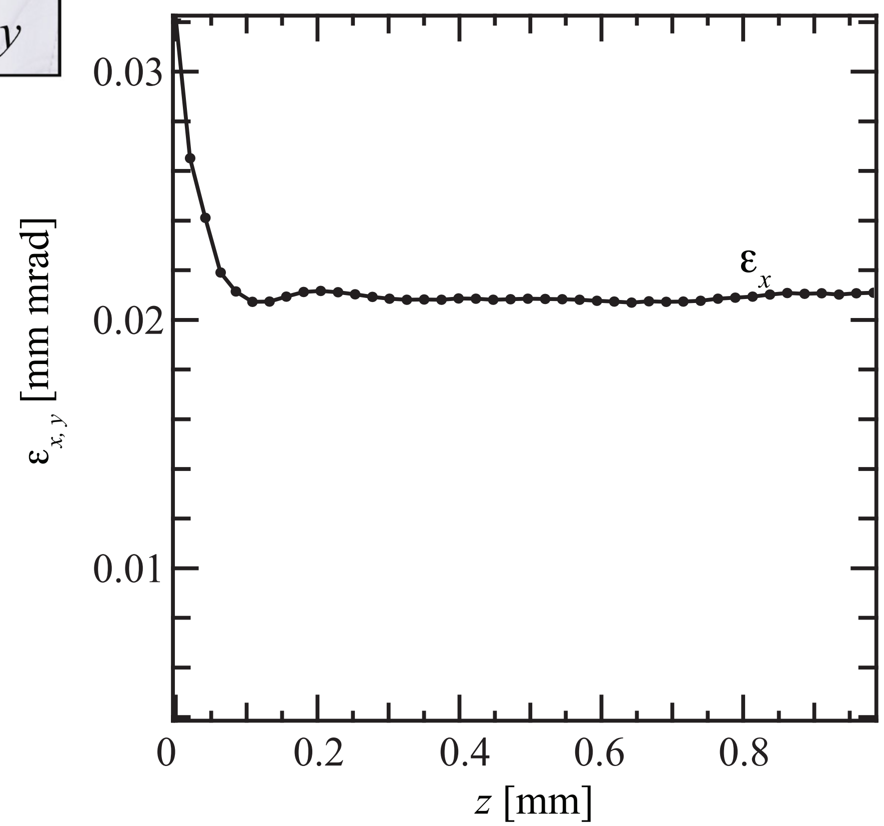
Schroeder et al., PRST-AB (2014)

Pump laser pulse:
a=1.2, 5 um wavelength
92 fs, 36 um spot
Injection laser pulse:
a=0.1, 0.4 um wavelength
16 fs, 5 um spot
plasma:
Krypton gas (230 eV)
2×10^{17} cm^{-3}

matched injection:

$$\sqrt{2}a_i/w_i \approx k_\beta$$



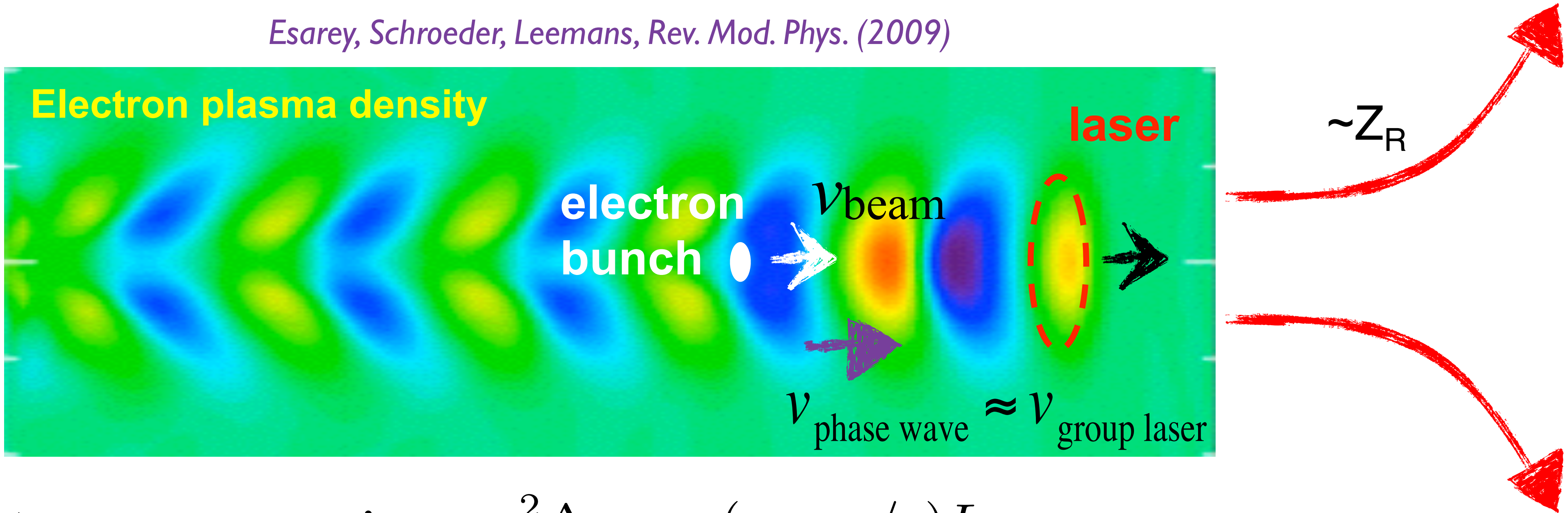


$$\epsilon \simeq a_i w_i \Delta^2/\sqrt{2}$$
$$\approx 0.02\ \mu m$$

- Two-color ionization injection yields order of magnitude improvement in transverse emittance

Limits to energy gain: Diffraction, Dephasing, Depletion

Esarey, Schroeder, Leemans, Rev. Mod. Phys. (2009)



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 by transverse plasma density tailoring (plasma channel) and/or relativistic self-guiding and ponderomotive self-channeling

Schroeder et al., PRL (2011)

- **Beam-Wave Dephasing**:
  - Slippage between e-beam and plasma wave: $L_{\text{dephase}} = \lambda_p/2(1-\beta_p) \approx \lambda_p^3/\lambda^2$
  - Determined by plasma wave phase velocity (approximately laser group velocity)
  - Controlled by longitudinal plasma density tailoring (plasma tapering)

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

- **Laser Energy Depletion**:
  - Rate of laser energy deposition of into plasma wave excitation: $L_{\text{deplete}} \propto n^{-3/2}\lambda^{-2}$

LPA plasma density scalings

- Laser-plasma interaction (depletion) length:

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

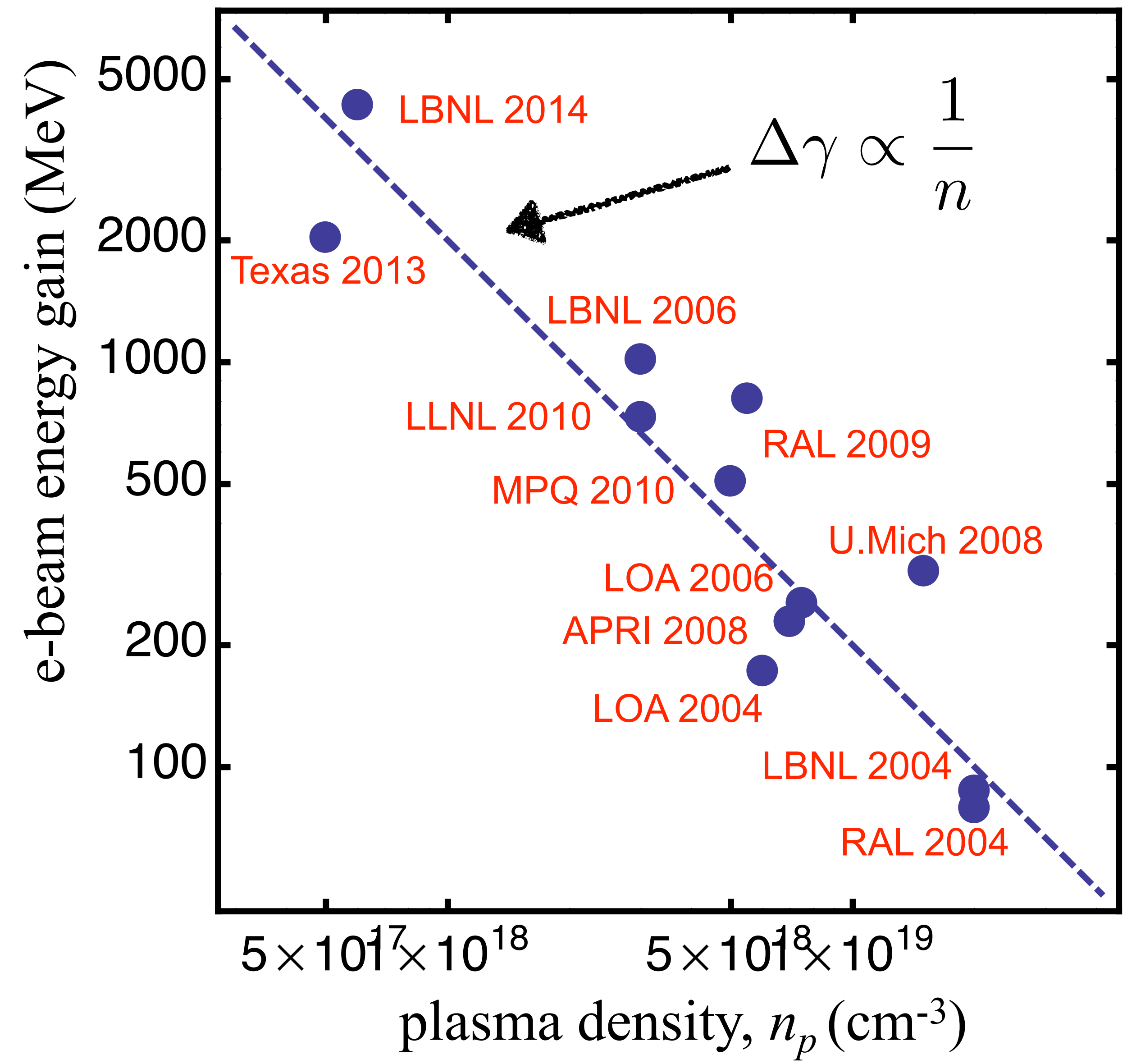
- Accelerating gradient:

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

- Energy gain:

$$W \sim (m c \omega_p / e)\, L_{\text{acc}} \propto 1/n$$

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



Laser requirements:

- Laser energy: $U_{\text{laser}} \propto \lambda_p^3 \propto n^{-3/2}$
- Laser duration: $\tau_{\text{laser}} \propto \lambda_p \propto n^{-1/2}$
- Laser peak power: $P_{\text{laser}} \propto n^{-1}$

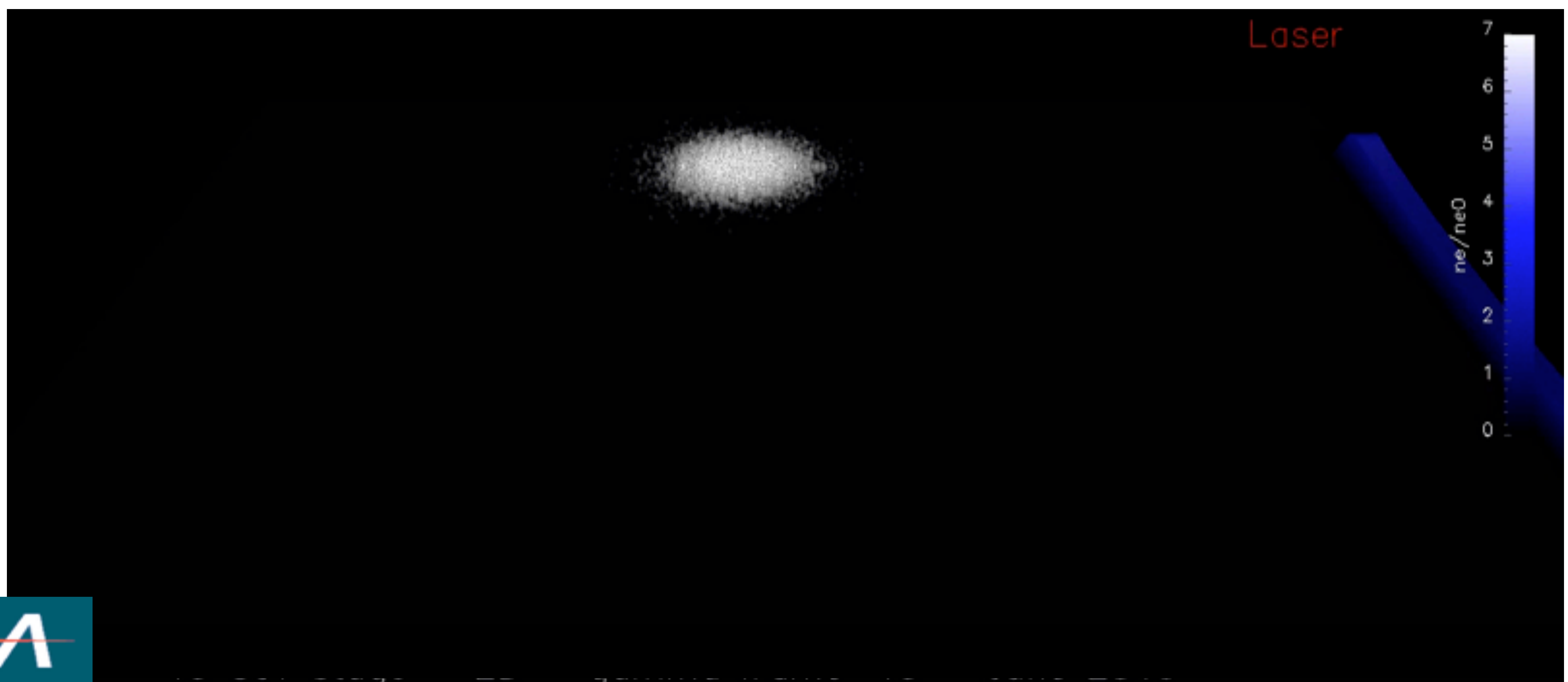
W~1 GeV	W ~ 10 GeV
n ~ 10^{18} cm^{-3}	n ~ 10^{17} cm^{-3}
L_{acc} ~3 cm	L_{acc} ~1 m
U_{laser} ~1 J	U_{laser} ~ 40 J
P_{laser} ~100 TW	P_{laser} ~ 1 PW

BELLA Laser Facility at Berkeley Lab

Leemans et al., AAC (2010)

BELLA (BErkeley Lab Laser Accelerator) Facility:

- *state-of-the-art PW-laser for laser-accelerator science*
- >42 J in <40 fs (> 1PW) at 1 Hz laser and supporting infrastructure at LBNL
- Key experiment: demonstrate 10 GeV acceleration



WARP simulation *(J.-L. Vay)*

BELLA Laser Facility at Berkeley Lab

Leemans et al., AAC (2010)

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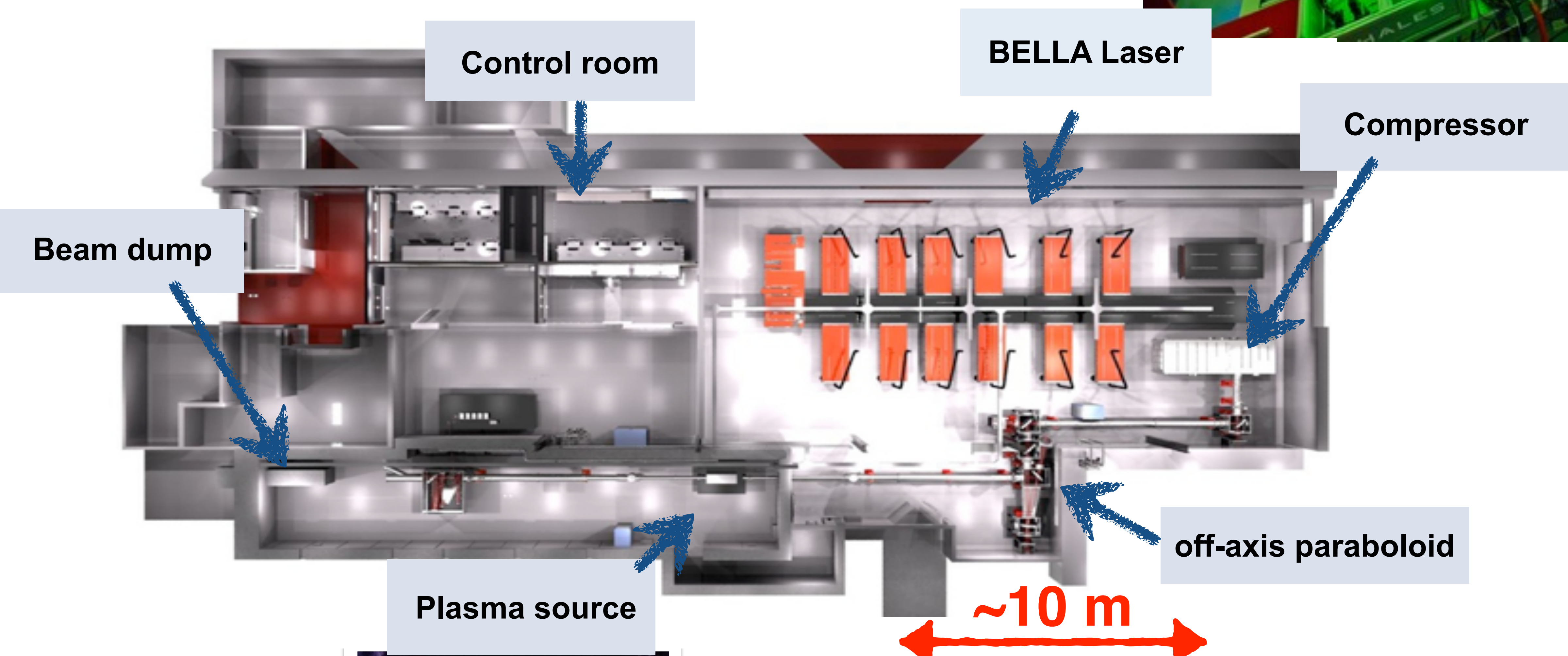
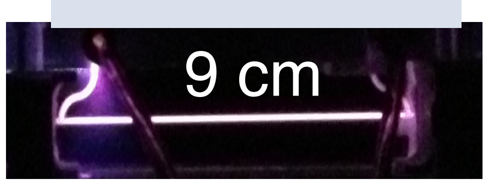
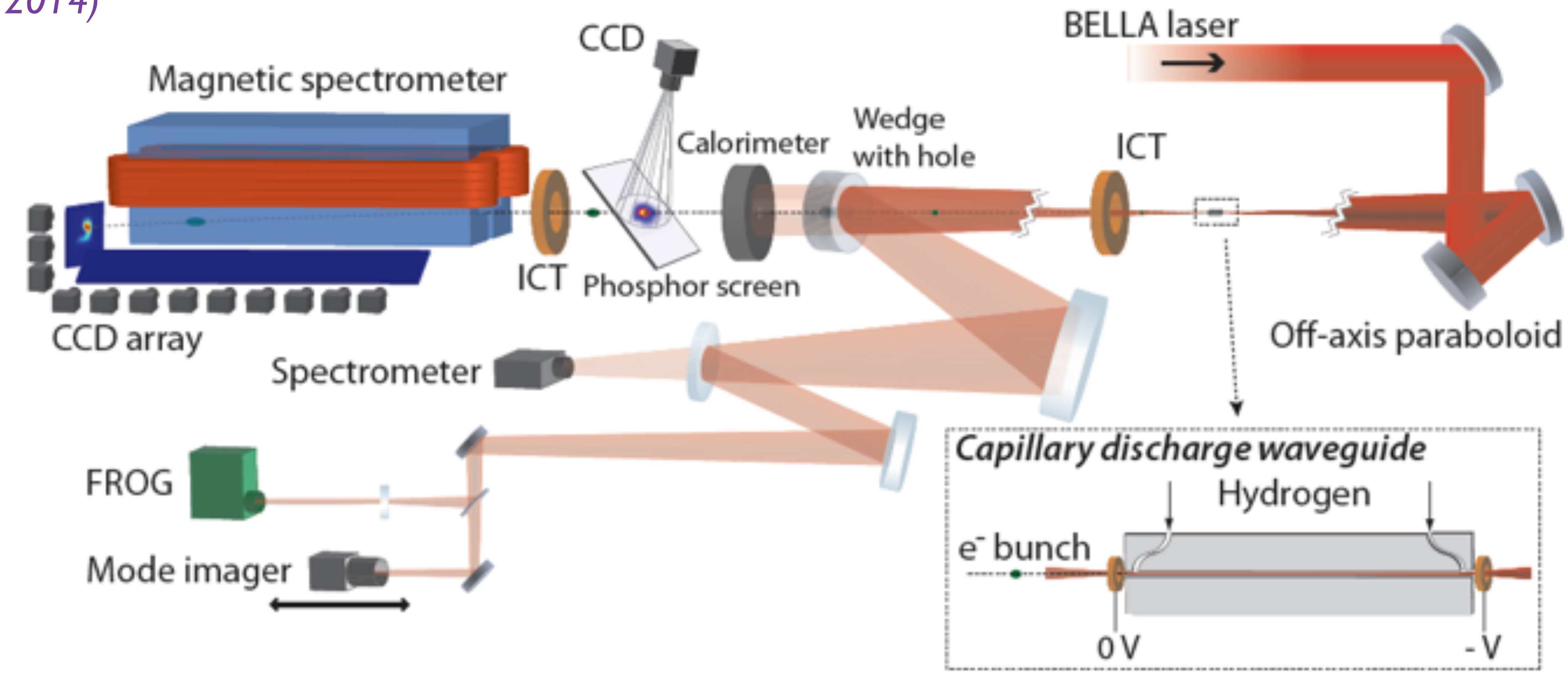


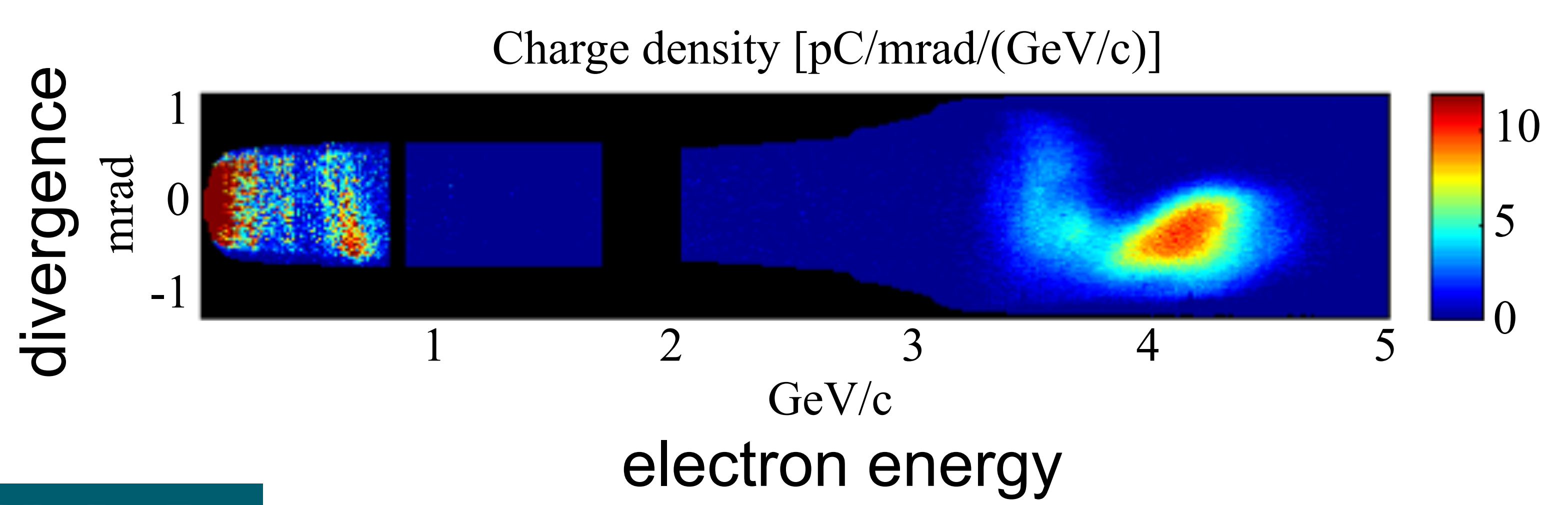


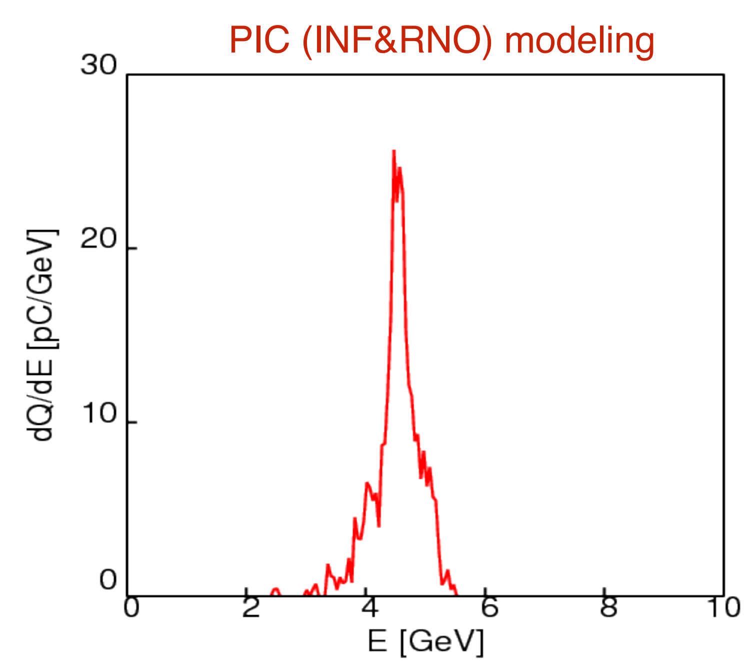
Multi-GeV electron acceleration using BELLA

Leemans et al., PRL (2014)



- 4.25 GeV e-beam, 10 pC
- using 9 cm H-discharge capillary



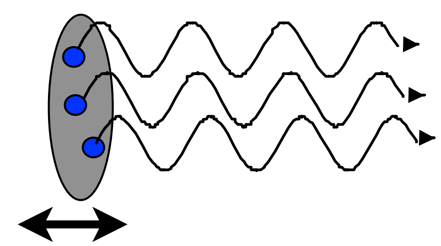


BELLA

LPA applications: Radiation generation

- Applications take advantage of
  - high gradient (compact devices)
  - short bunch structure
  - laser-particle beam synchronization

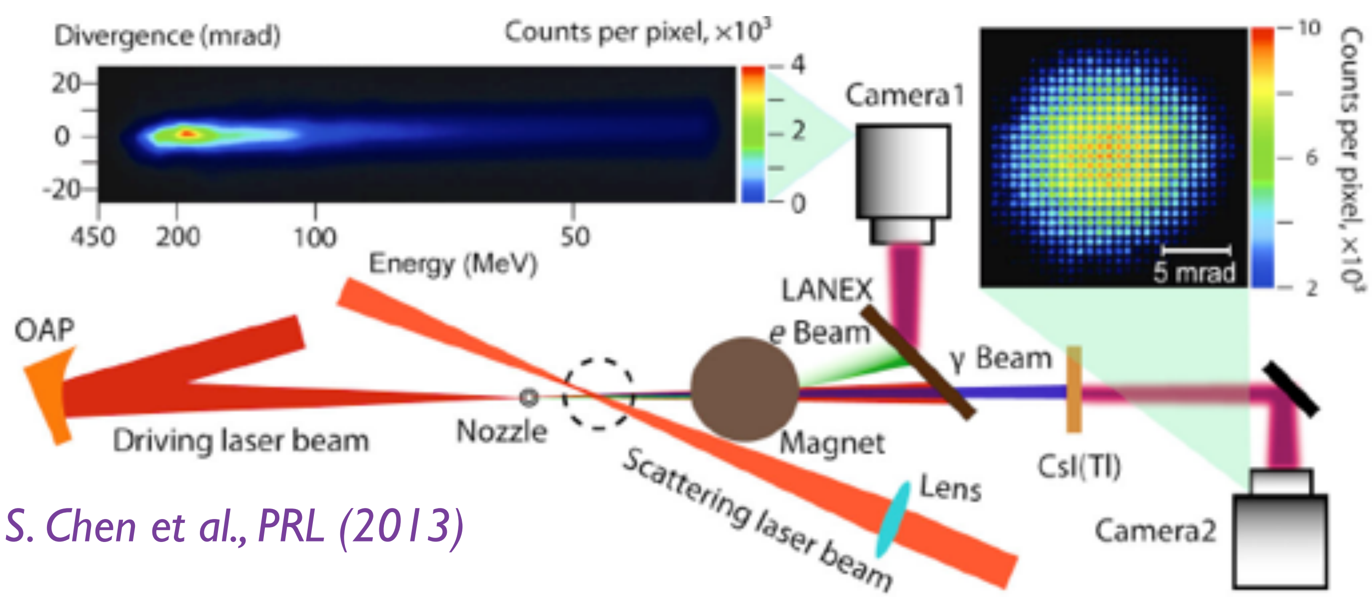
- **high-field THz generation** -- Coherent transition/diffraction radiation of short bunches



CTR = single-cycle (broadband 0-6THz)
~0.4 MV/cm

van Tilborg, Schroeder et al., Opt. Lett. (2007)

- **Thomson scattering** -- scattering electron bunch from laser -- compact gamma-rays



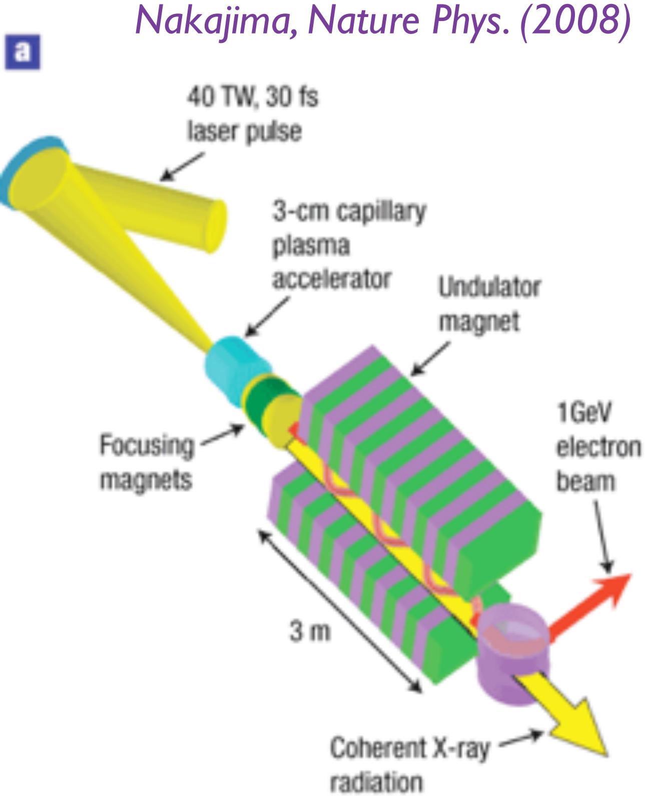
S. Chen et al., PRL (2013)

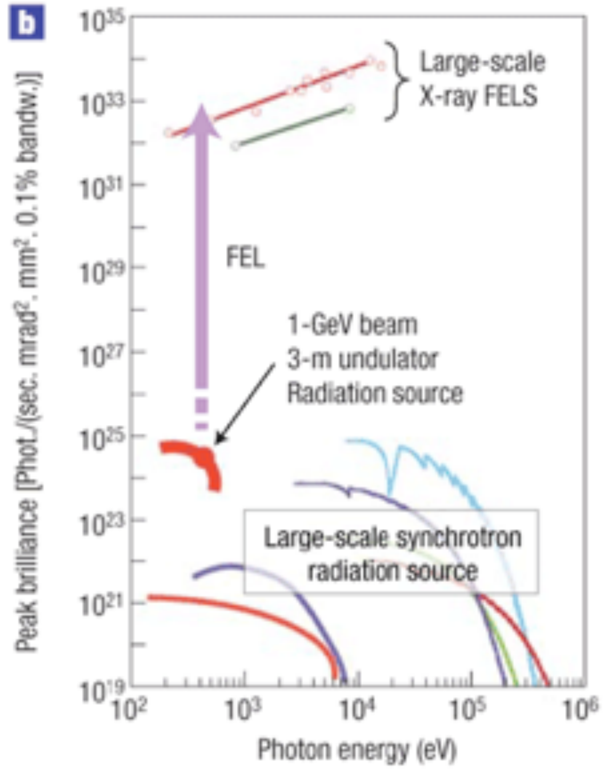
~MeV photons

- **Betatron radiation** -- synch. rad. from beam in trans. wakefield -- fs, broadband, hard x-rays
- **Undulator radiation** -- fs source of soft x-rays
- **LPA-driven FEL** -- compact source of high-peak power, coherent radiation

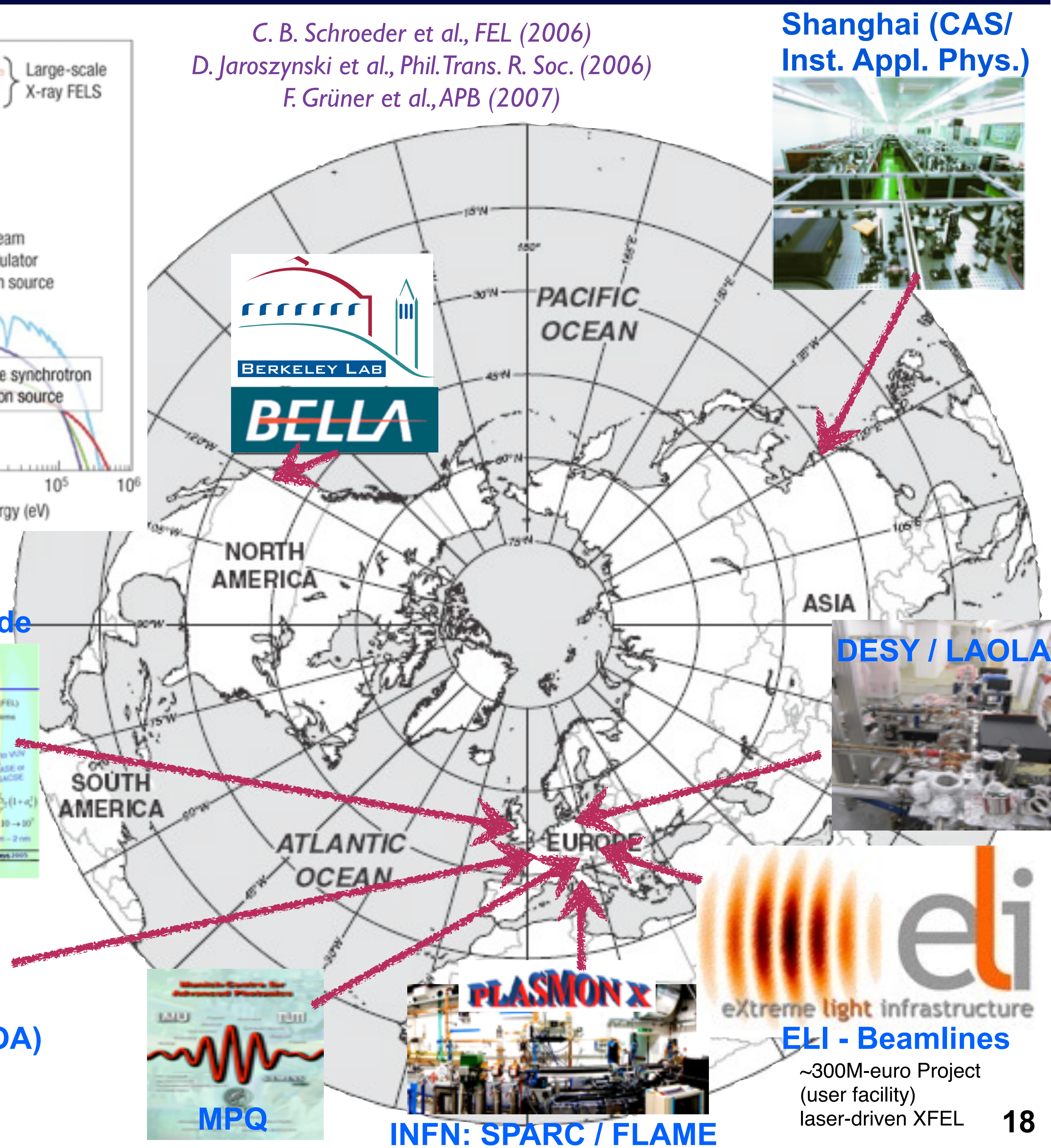
Application: Free-electron laser

Nakajima, Nature Phys. (2008)

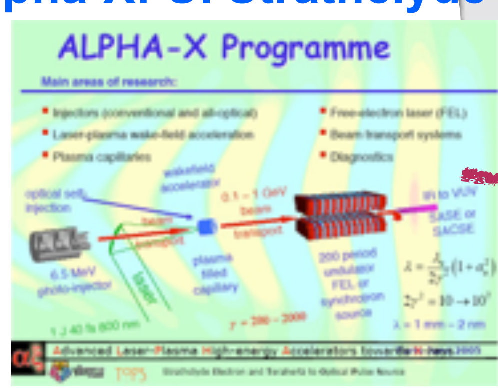




C. B. Schroeder et al., FEL (2006)
D. Jaroszynski et al., Phil.Trans. R. Soc. (2006)
F. Grüner et al., APB (2007)



Alpha-X: U. Strathclyde



LUNEX5 (SOLEIL / LOA)

~300M-euro Project
(user facility)
laser-driven XFEL

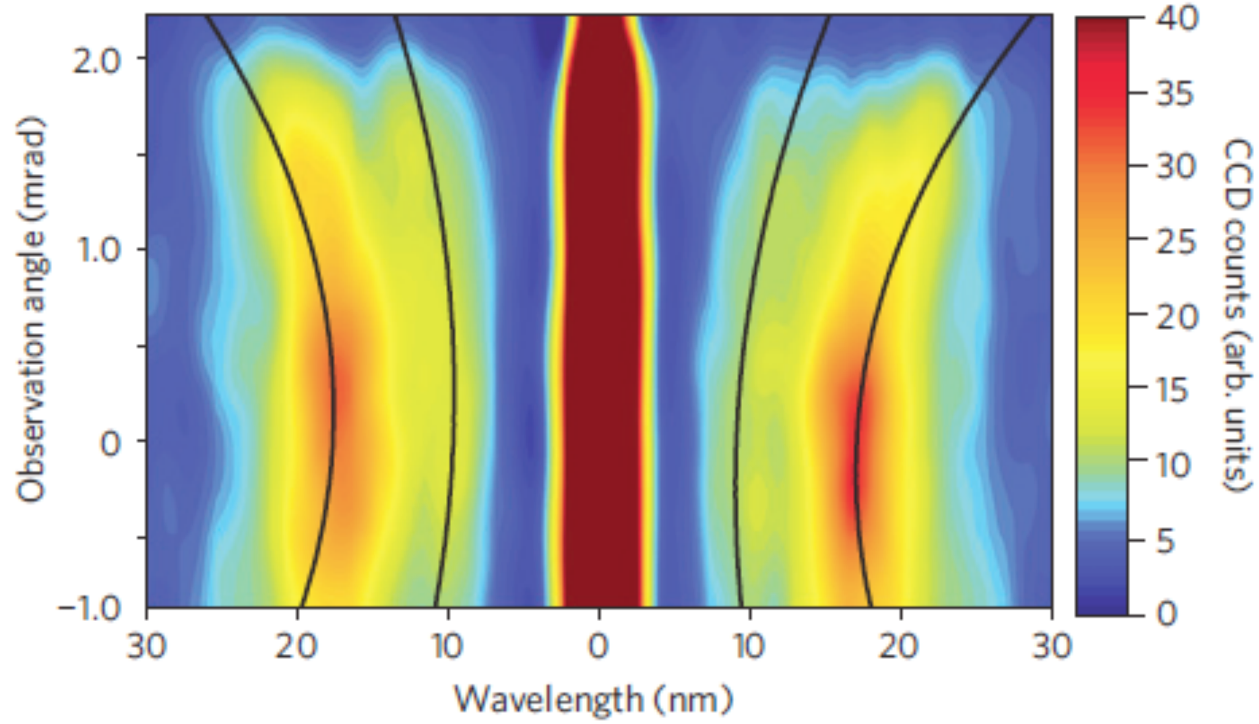
a sampling of active programs....

Experimental measurement of LPA-driven undulator radiation

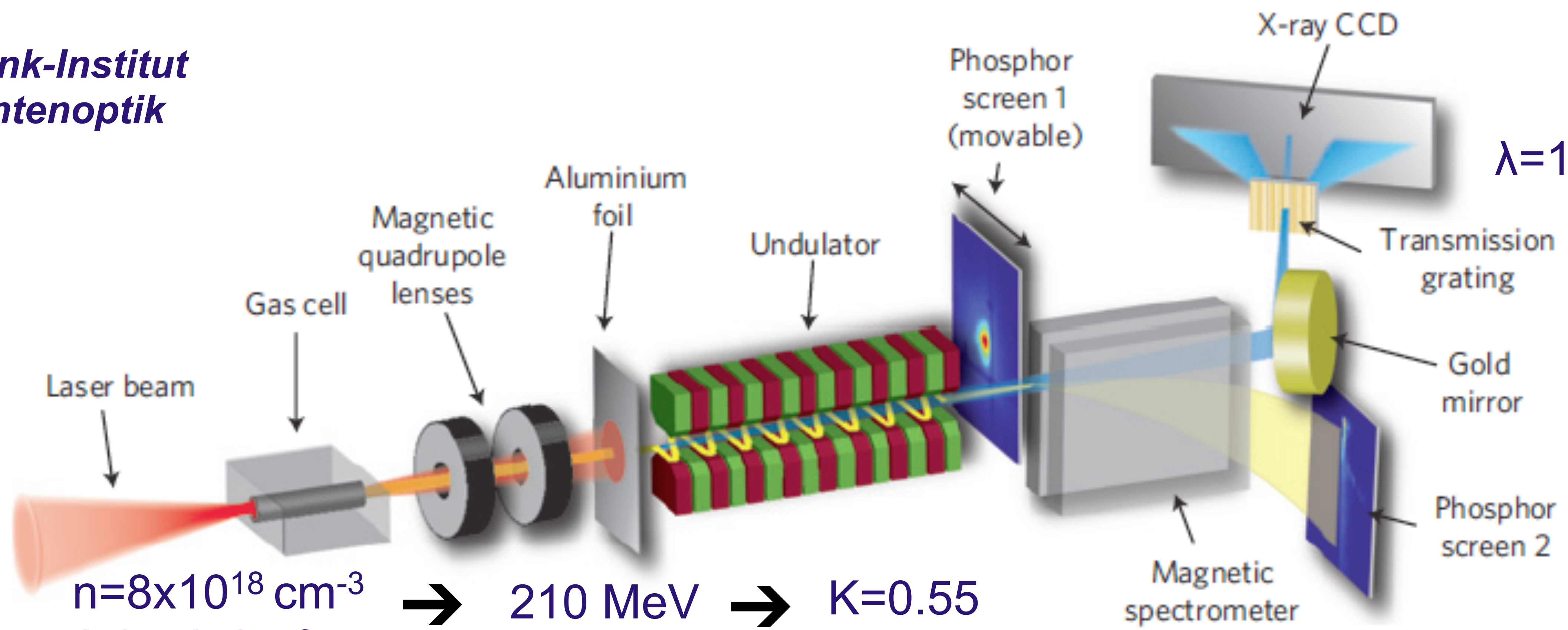
M. Fuchs et al., Nature Physics (2009)

- Measured 1st and 2nd harmonic:

$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$



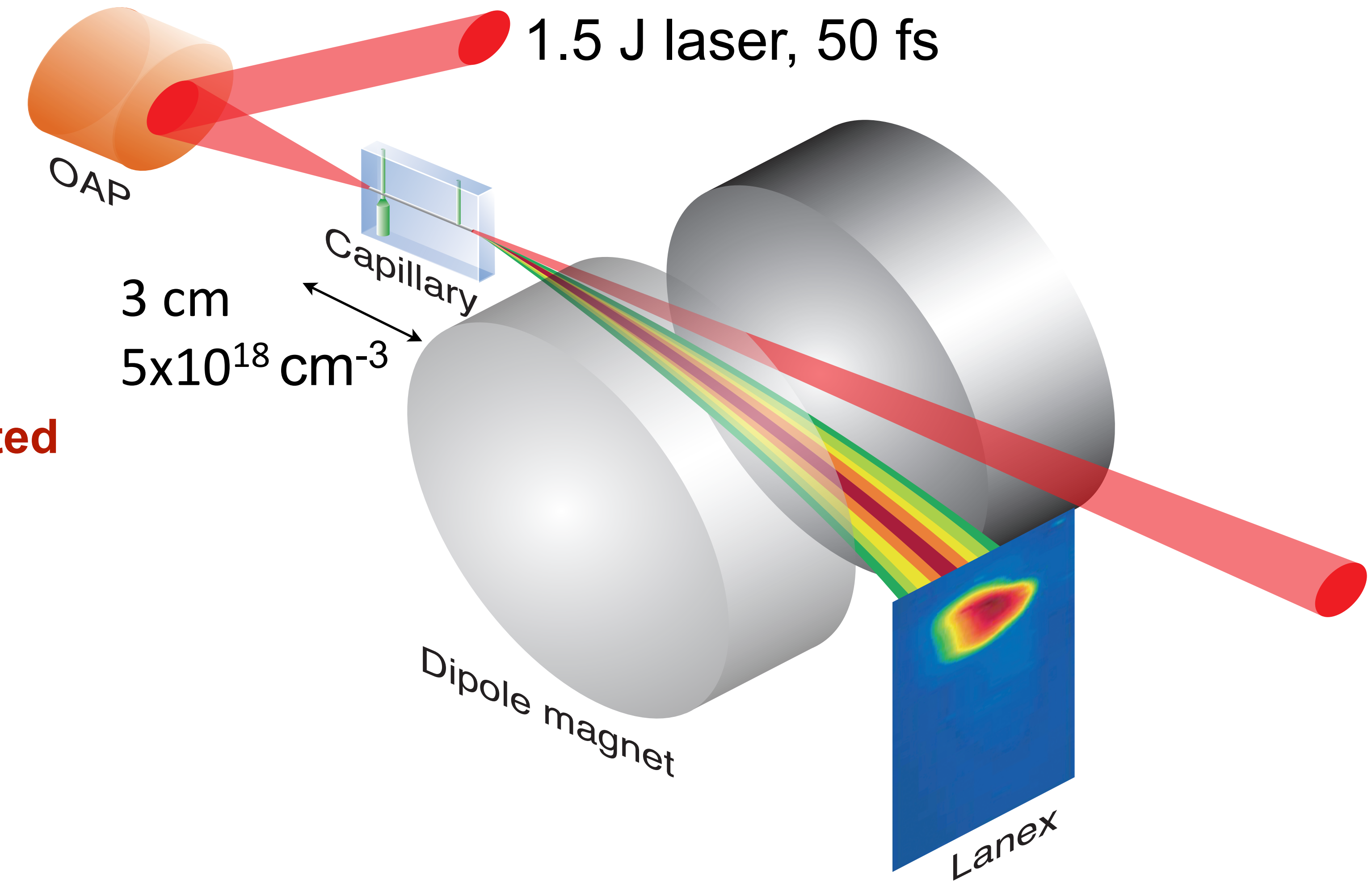
Max-Plank-Institut für Quantenoptik



λ=17 nm

$n=8\times10^{18}$ cm^{-3}
0.85 J, 37 fs → 210 MeV ~10 pC → K=0.55 λu=5 mm

Laser-plasma accelerator beam characteristics

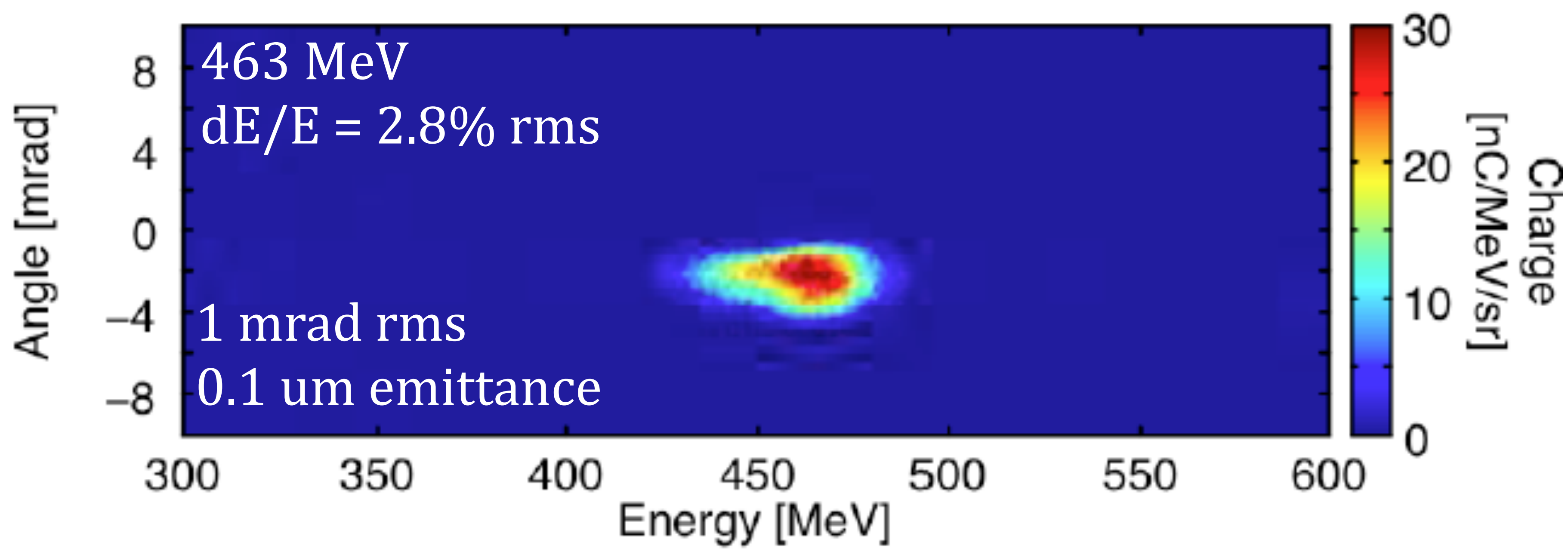


Experimentally-demonstrated LPA beam parameters:

0.1-1 GeV energy
1-10% energy spread
1-100 pC charge
0.1-1 micron emttance
1-10 fs duration
1-10 Hz

Laser foot-print:

(few m)x(few m)
for 100 TW peak power
(10 Hz) laser system



LPA 6D brightness comparable to conventional sources: consider phase-space manipulation

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

LPA

ε_N = 0.1 micron
0.5 GeV
4% energy spread
I = 3 kA (~5 fs)

$b_6 \sim 9 \times 10^{-12}$

LCLS

ε_N = 0.4 micron
13.6 GeV
0.01% energy spread
I = 3 kA

$b_6 \sim 9 \times 10^{-12}$

- Energy spread order of magnitude too large (for soft-x-ray FEL):

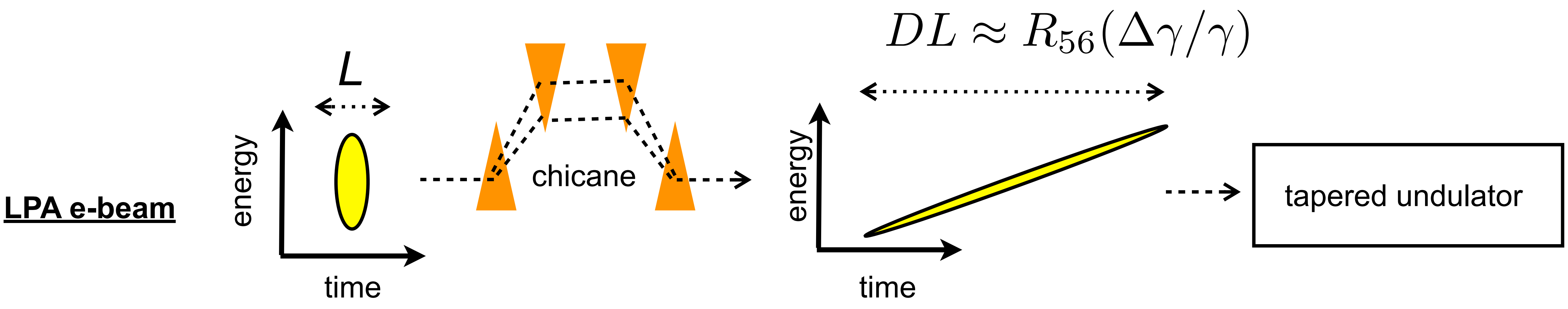
- FEL realized with post-LPA e-beam phase space manipulation (redistribution)
  - Emittance exchange
  - Collimation
  - Phase-space redistribution:
    - Longitudinal decompression (with tapered undulator)
    - Transverse dispersion (with transverse gradient undulator)

C. Schroeder et al., FEL (2012)

FEL with present LPA performance: Beam decompression

Maier, Messeck, Reiche, Schroeder, Grüner, Phys. Rev. X. (2012)

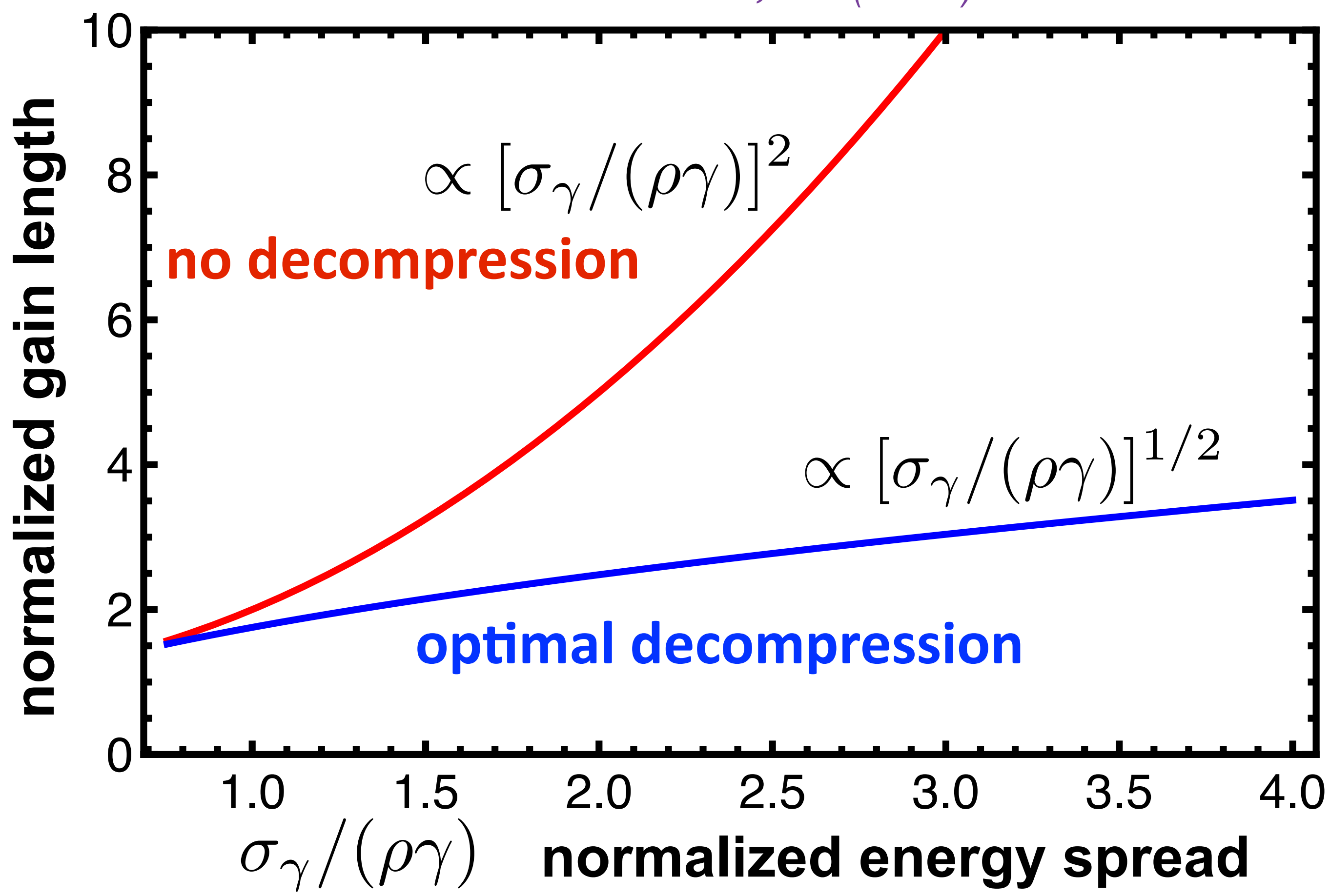
- **Beam decompression:** reduced slice energy spread



Decompression:

- slice energy spread < FEL bandwidth ρ
- reduced current: $\rho \propto I^{1/3}$

C. Schroeder et al., FEL (2012)

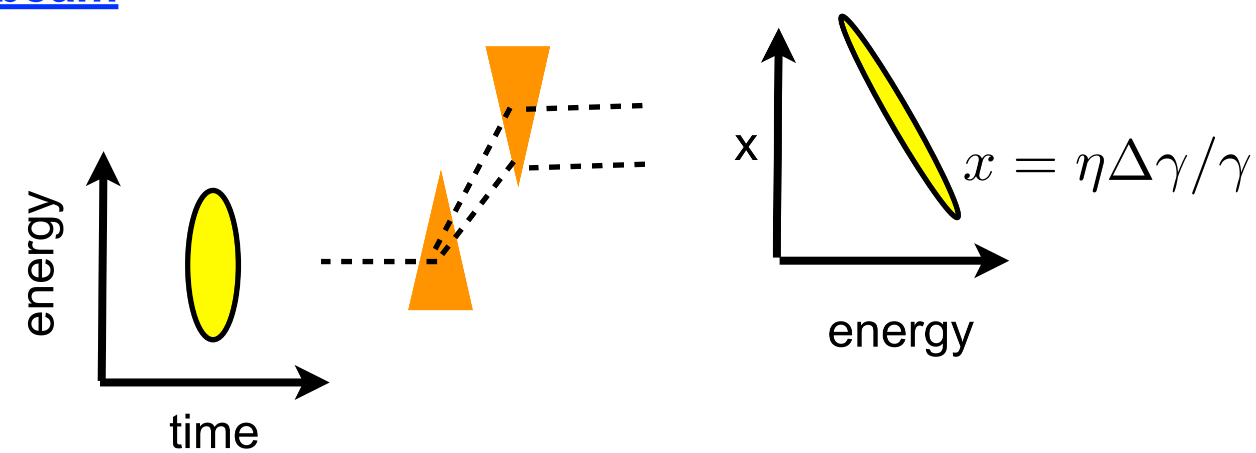


Beam Dispersion and transverse gradient undulator for large energy spread acceptance

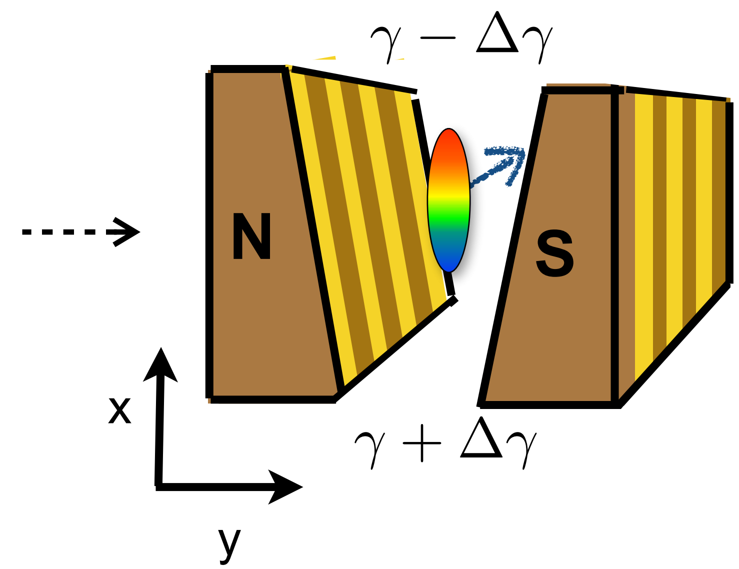
Huang, Ding, Schroeder, PRL (2012)

Transverse gradient undulator (TGU):

LPA e-beam



canted-pole undulator



$$\frac{\Delta K}{K} = \alpha x$$

- Resonant condition:

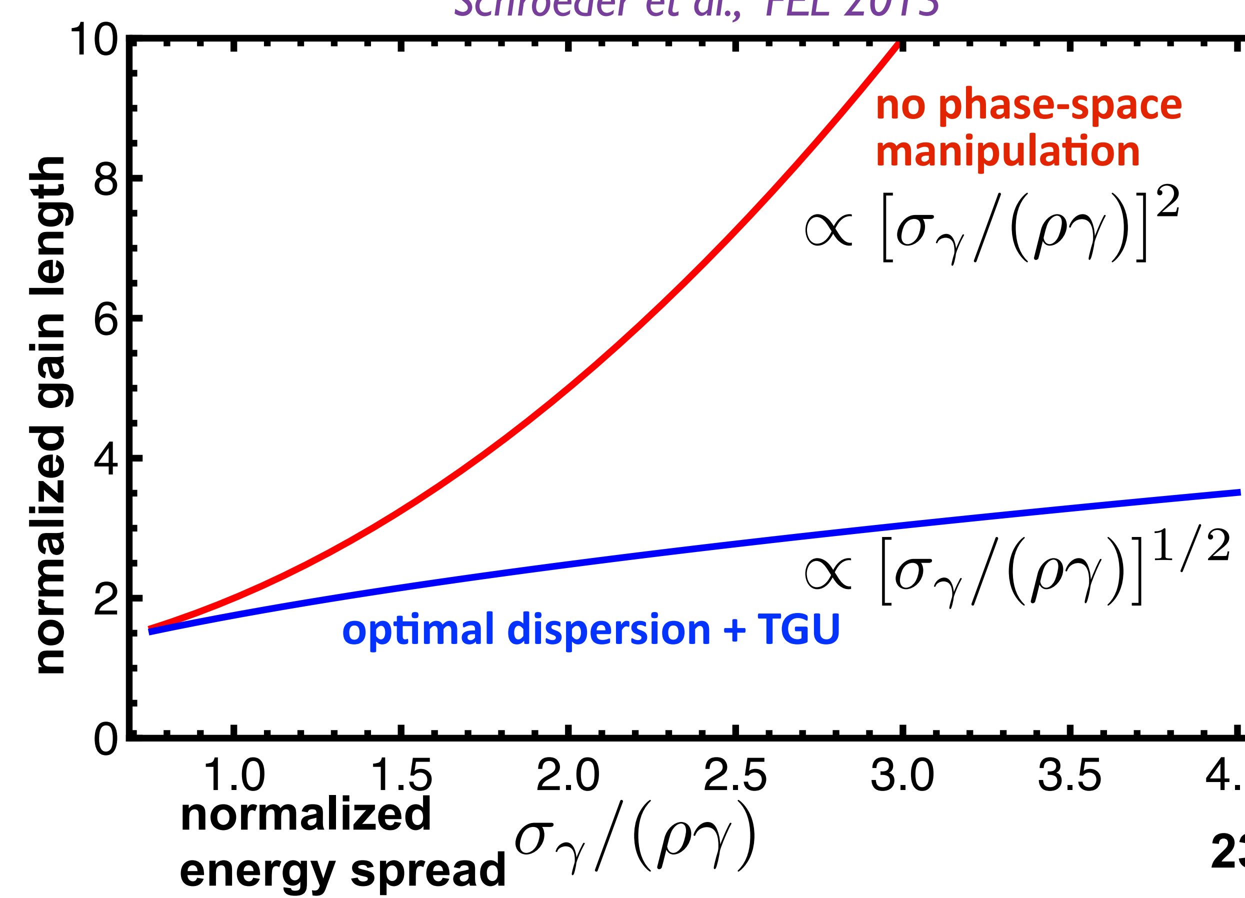
$$\lambda = \frac{\lambda_u}{2\gamma^2(x)}\left[1 + K(x)^2/2\right]$$

- Sort e-beam energies, couple to TGU to satisfy resonant condition:

$$\eta = \frac{2 + K^2}{\alpha K^2}$$

- Dispersion reduces the beam density
- effective energy spread (at transverse slice) reduced

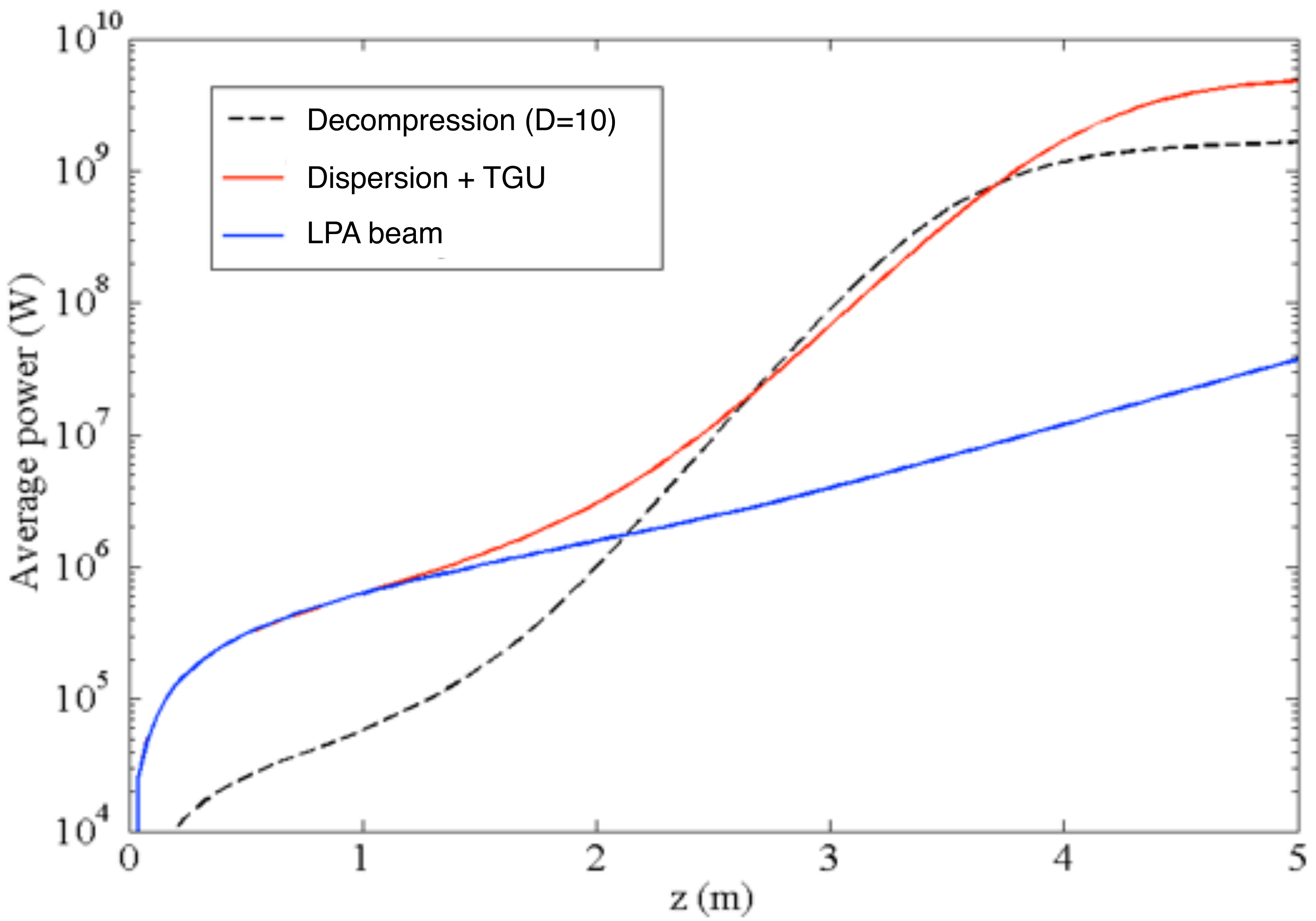
Schroeder et al., FEL 2013

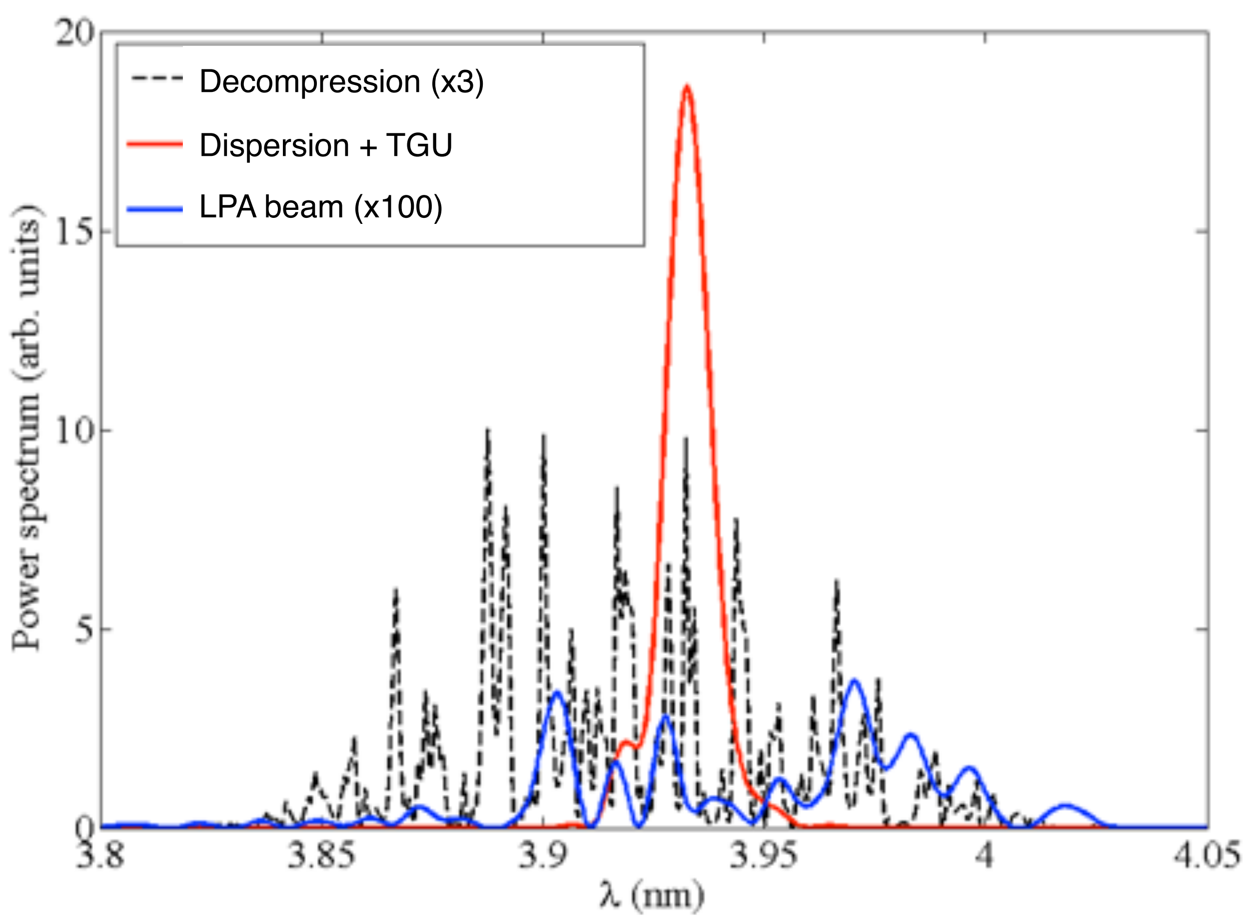


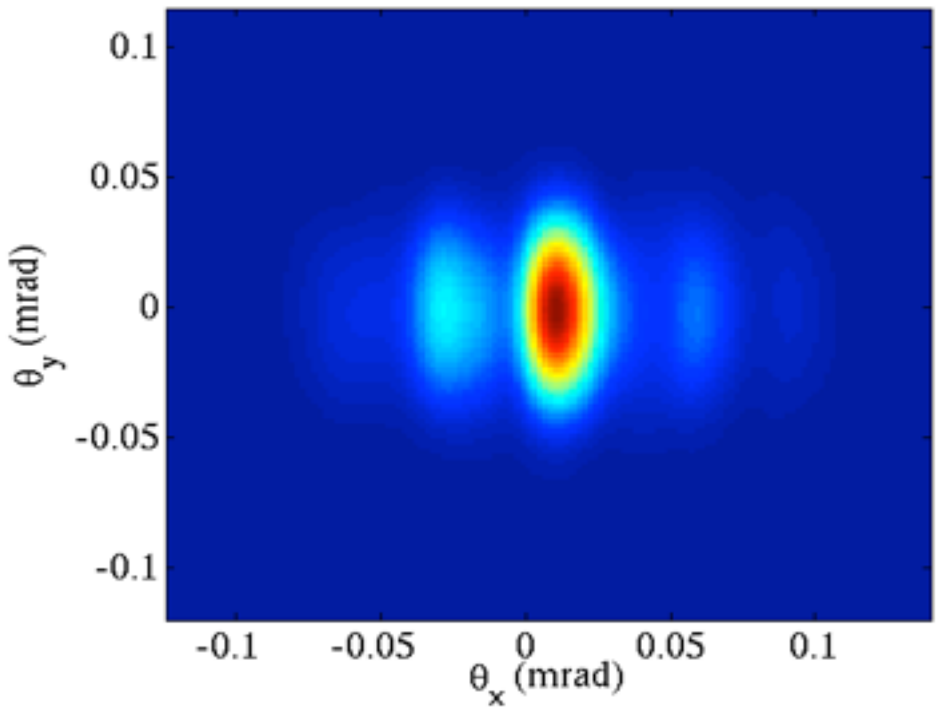
LPA-driven 4-nm FEL using e-beam phase space manipulation

- 1 GeV, 10 kA, 1% rms energy spread
- 0.1 um 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 = 0.0 m; beam size 100um x 15um

Huang, Ding, Schroeder, PRL (2012)

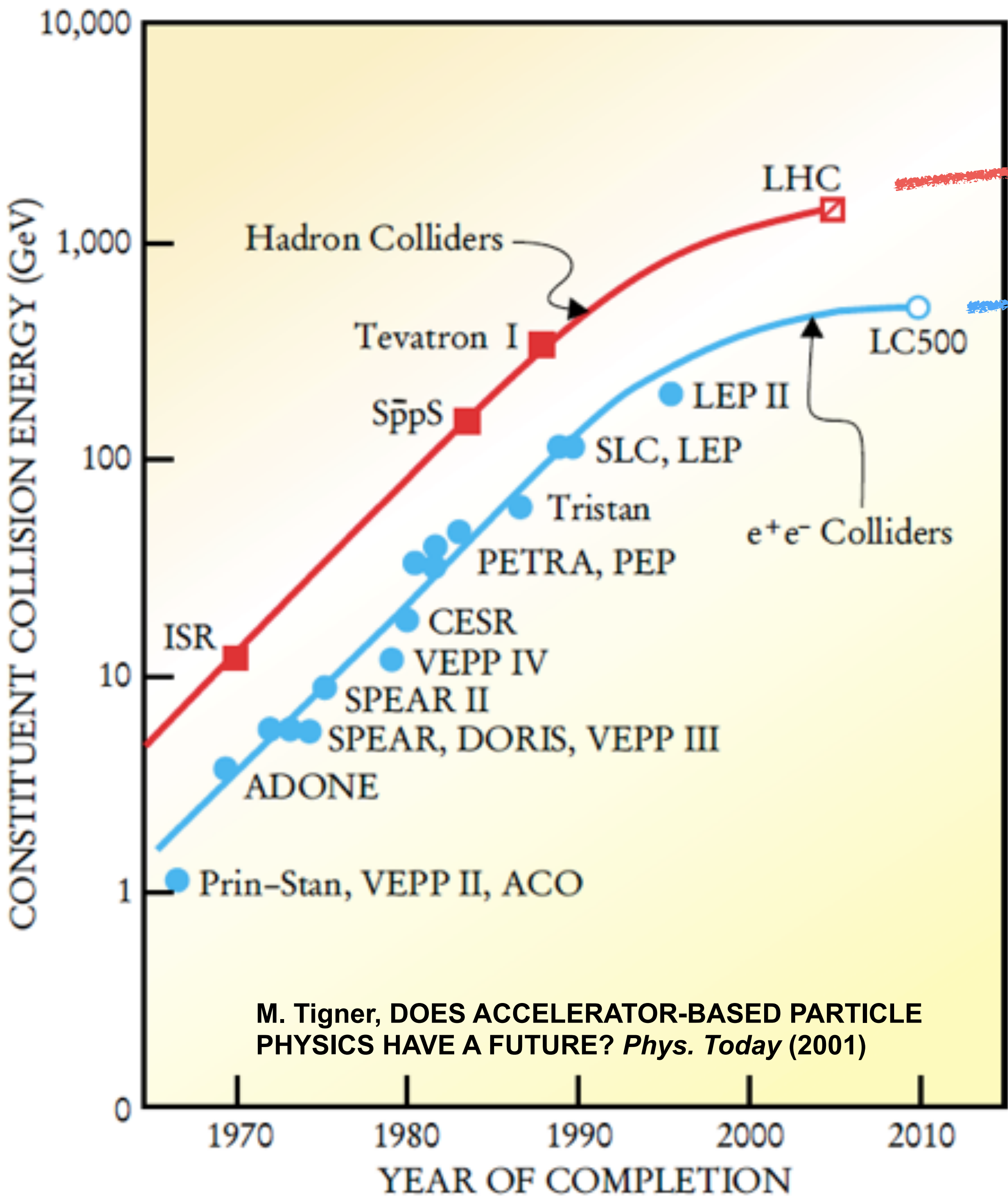




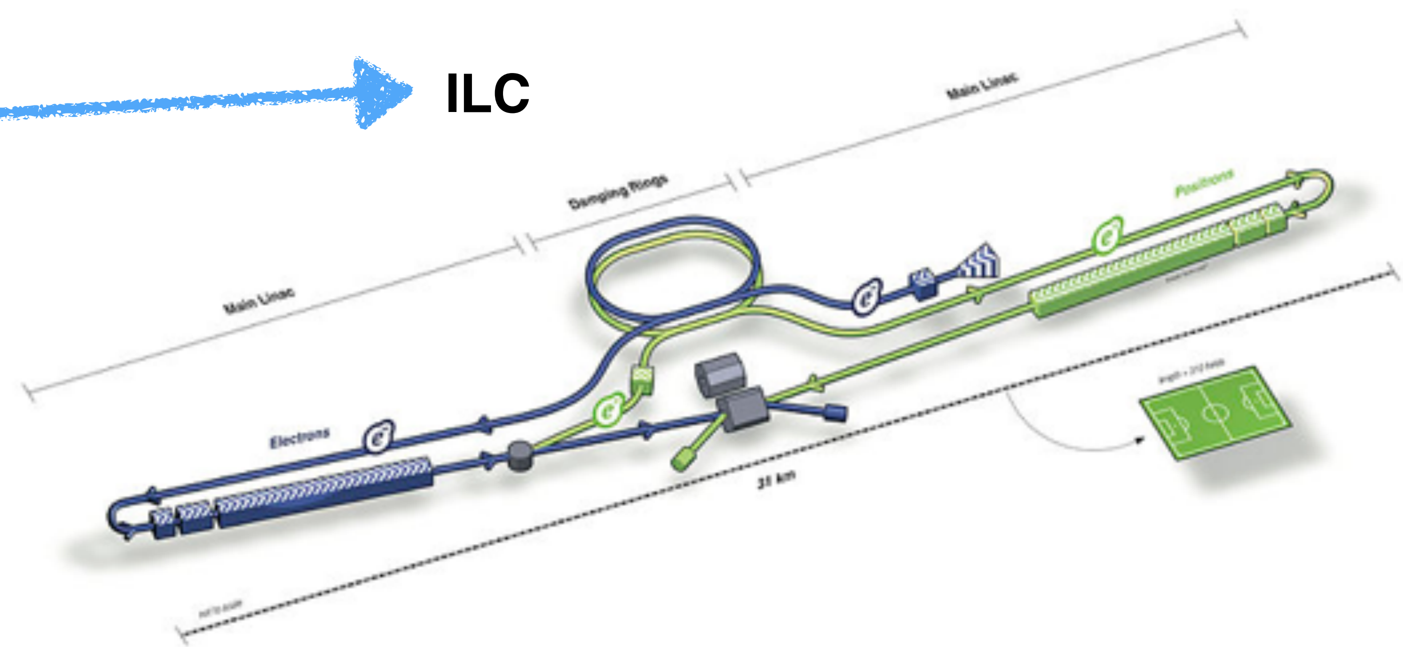


High-energy physics application of LPAs

- "Livingston Plot" Saturation of accelerator tech.
  - Practical limit reached for conventional accelerator technology (RF metallic structures)
  - Gradient limited by material breakdown
    - e.g., X-band demonstration ~100 MV/m

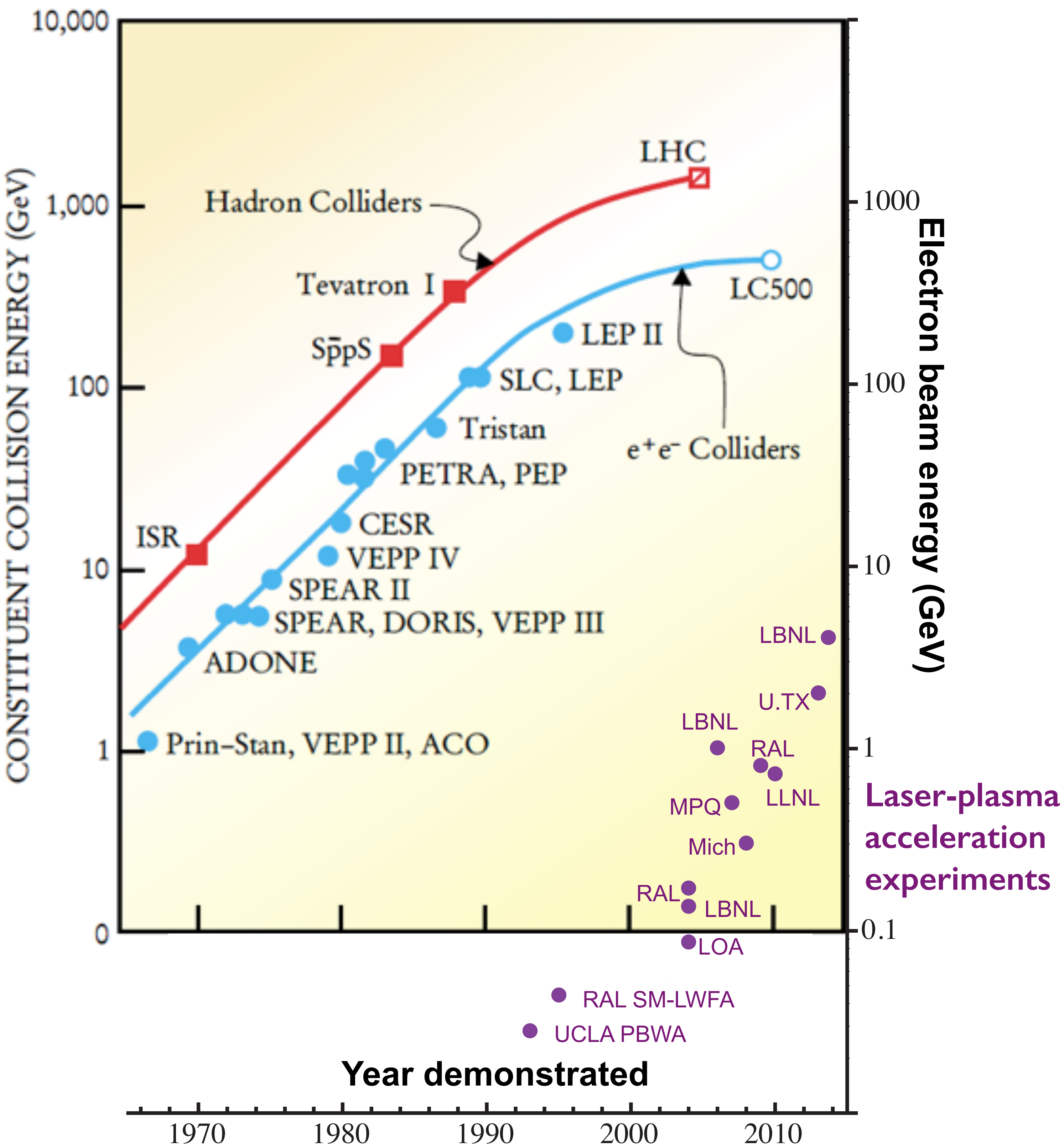


M. Tigner, DOES ACCELERATOR-BASED PARTICLE PHYSICS HAVE A FUTURE? *Phys. Today* (2001)



- Largest cost driver is acceleration
  - ~50 MV/m implies ~20 km/TeV
  - Facility costs scale roughly with facility size (and power consumption)
  - >50% cost in main linacs (e.g., ILC)

LPA application: Lepton Collider



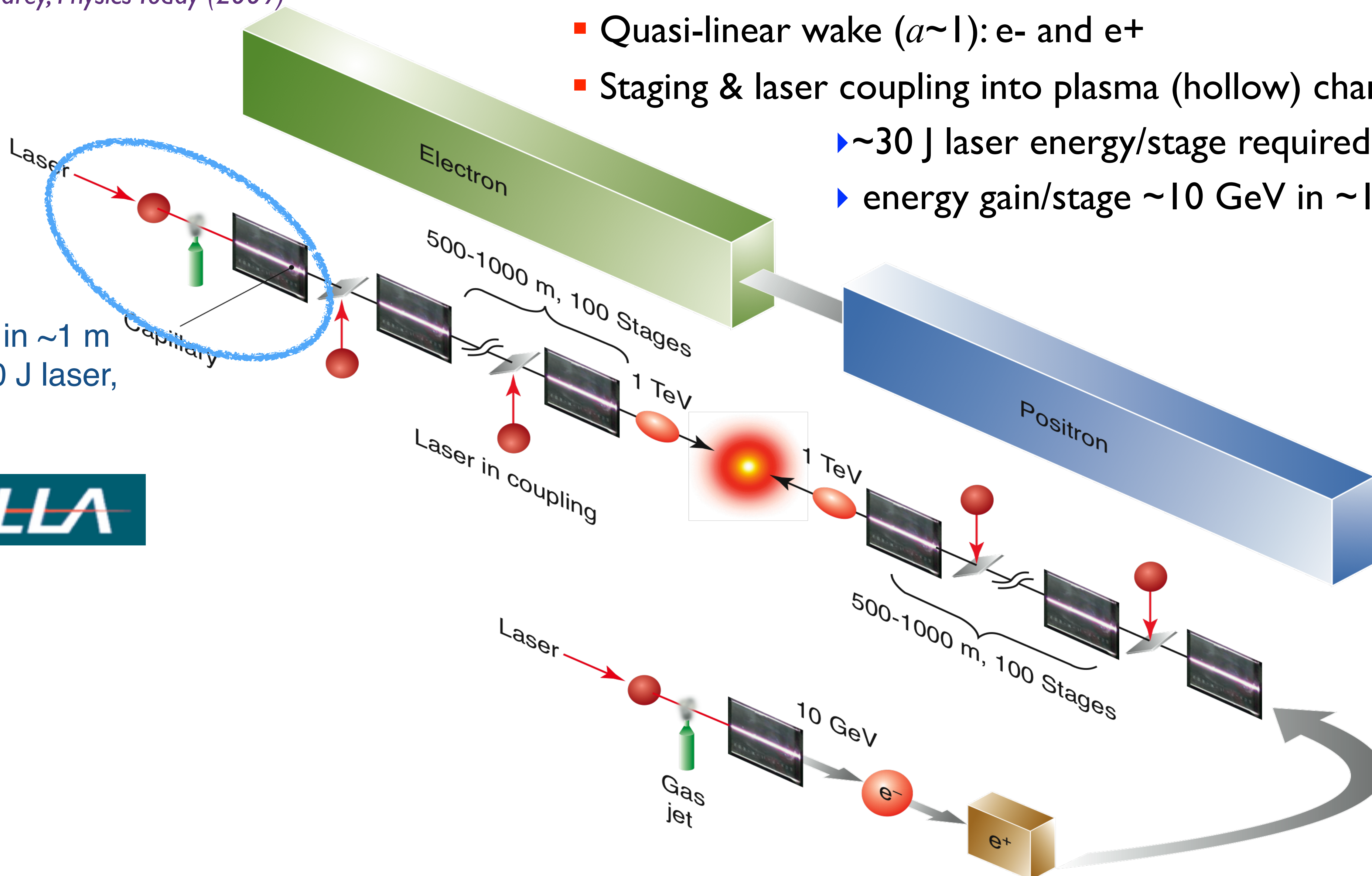
- Any future linear TeV (>TeV) collider is a massive (ultra-massive) project
  - require >order of magnitude increase in acceleration gradient
- Ultra-high gradient requires structures to sustain high fields:
  - Dielectric structures: ~1 GV/m
  - Plasmas: ~10 GV/m
- High gradients require high peak power:
  - Beam driven
  - Laser driven
- Significant progress worldwide in LPAs in the last 20+ years
- Critical developments:
  - Better understanding of LPA physics
  - Development of laser technology (CPA) for high peak power delivery

Laser-plasma accelerator-based collider concept

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

- Plasma density scalings [minimize construction (max. average gradient) and operational (min. wall power) costs] indicates: $n \sim 10^{17}\ \mathrm{cm}^{-3}$
- Quasi-linear wake (a~1): e- and e+
- Staging & laser coupling into plasma (hollow) channels:
  - ~30 J laser energy/stage required
  - energy gain/stage ~10 GeV in ~1m

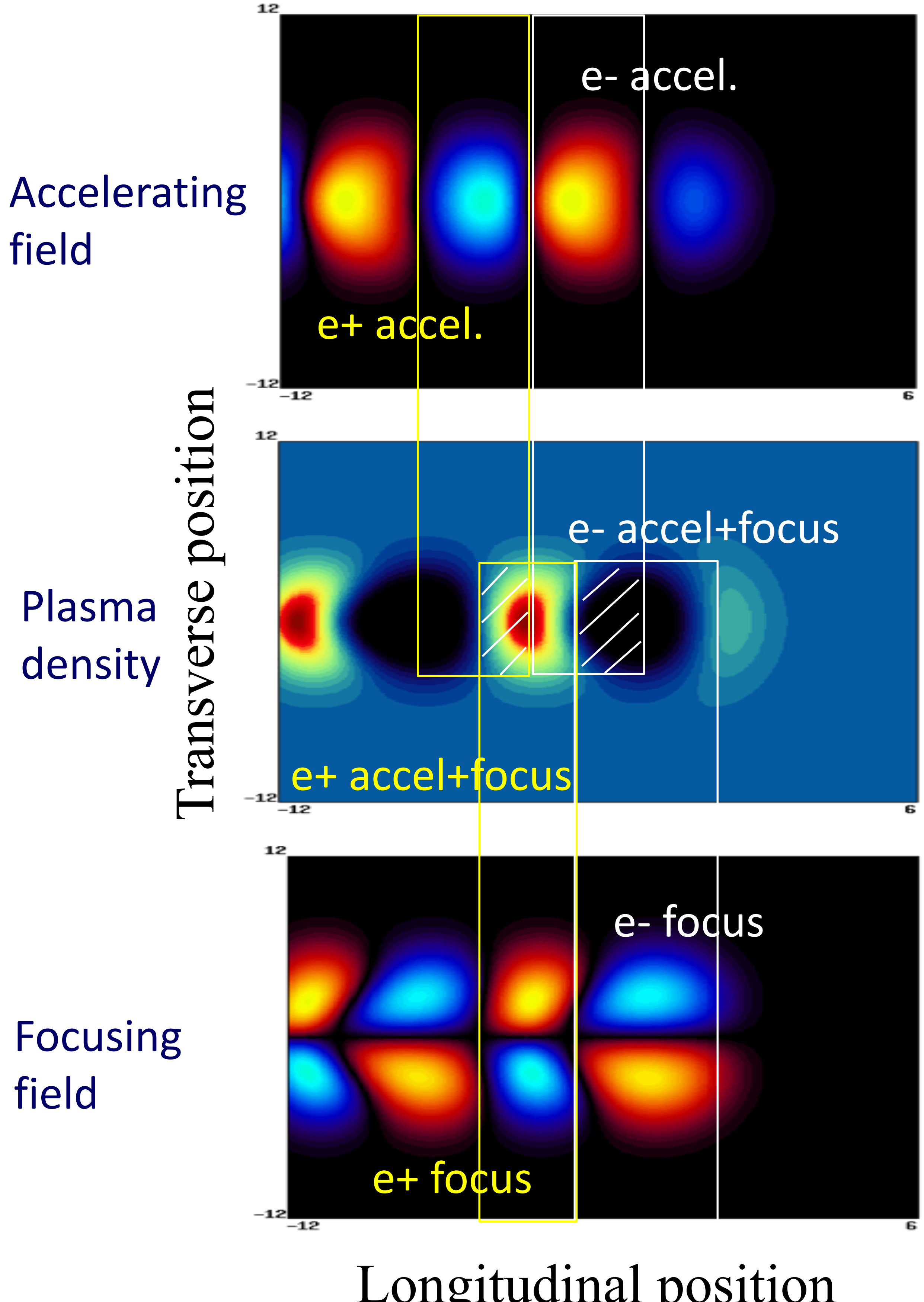
Leemans & Esarey, Physics Today (2009)



~10 GeV in ~1 m using ~30 J laser, ~100 fs

BELLA

Quasi-linear regime: positron focusing & independent control of acceleration and focusing



- Operate in "quasi-linear" regime:
  - Quiver momentum weakly-relativistic $a \sim 1$ (Intensity ~ 10^{18} W/cm^2)
  - Region of acceleration/focusing for both electrons and positrons
  - Stable laser propagation in plasma channel
  - Independent control of accelerating and focusing forces

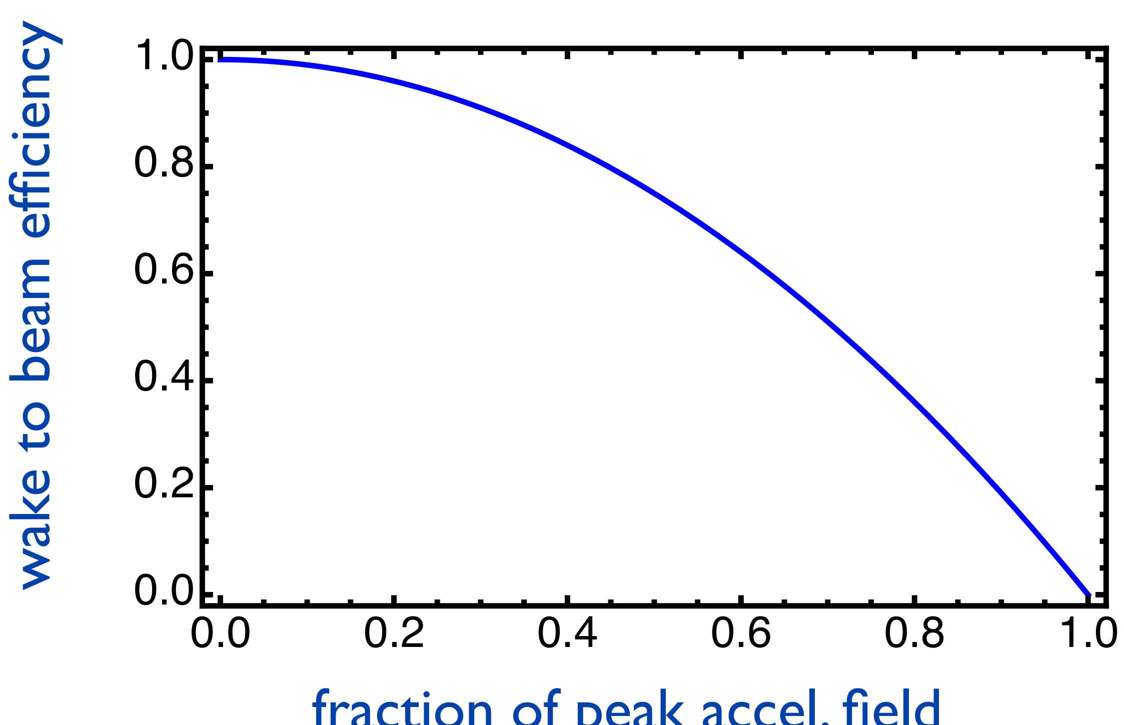
Use shaped bunches to eliminate energy spread

- Energy spread minimized using shaped beams
  S. van der Meer (1985)

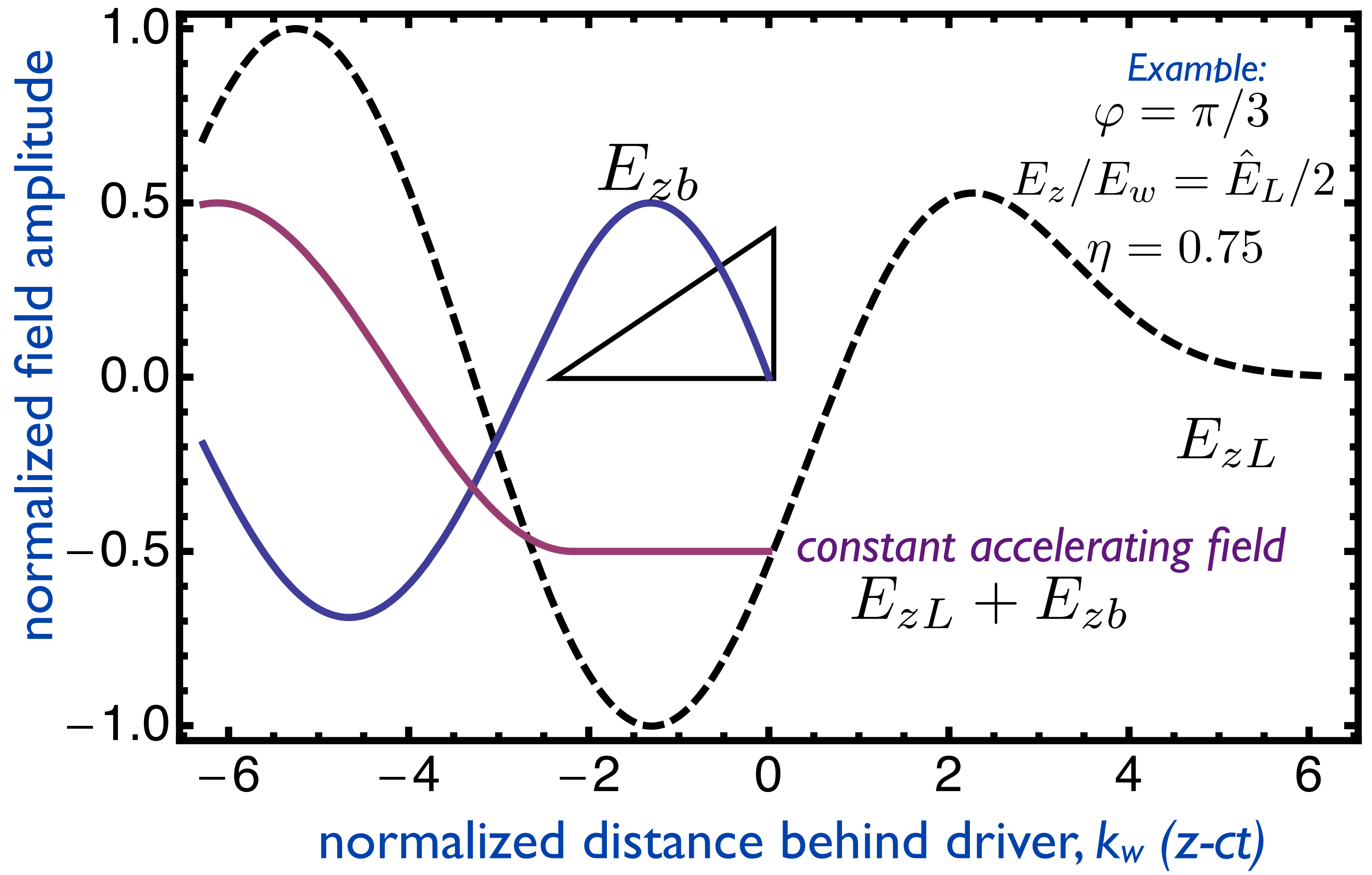
Ramped triangular current distribution :

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

- Trade-off between gradient and efficiency (for no induced energy spread)



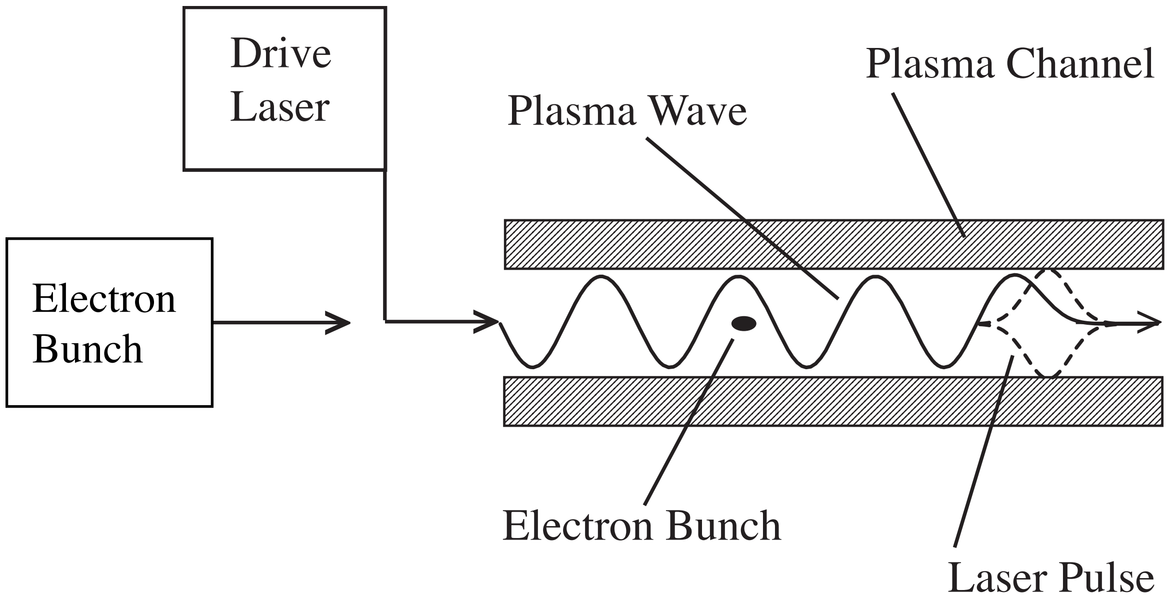
Schroeder et al., Phys. Plasmas (2013)



beam charge: $N_b \propto n_w^{-1/2}$

lower plasma density, higher beam charge

Near-hollow plasma channels: Excellent wakefield properties for ultra-low emittance preservation



- Excellent wakefield properties in plasma channel and *independent* control over accelerating and focusing forces:
  - Accelerating wakefield uniform in radial position
  - Focusing wakefield uniform in longitudinal position (no head-to-tail variation in focusing force) and linear in radial position

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

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

for relevant (1 TeV) parameters: $\epsilon_{nf} \sim 10^{-9}\ \mathrm{m}$ *Schroeder et al., Phys. Plasmas (2013)*

  - Control of focusing force and beam density — prevents ion motion:

Ion motion in channel negligible if ratio of beam density to wall density less than ion-electron mass ratio:

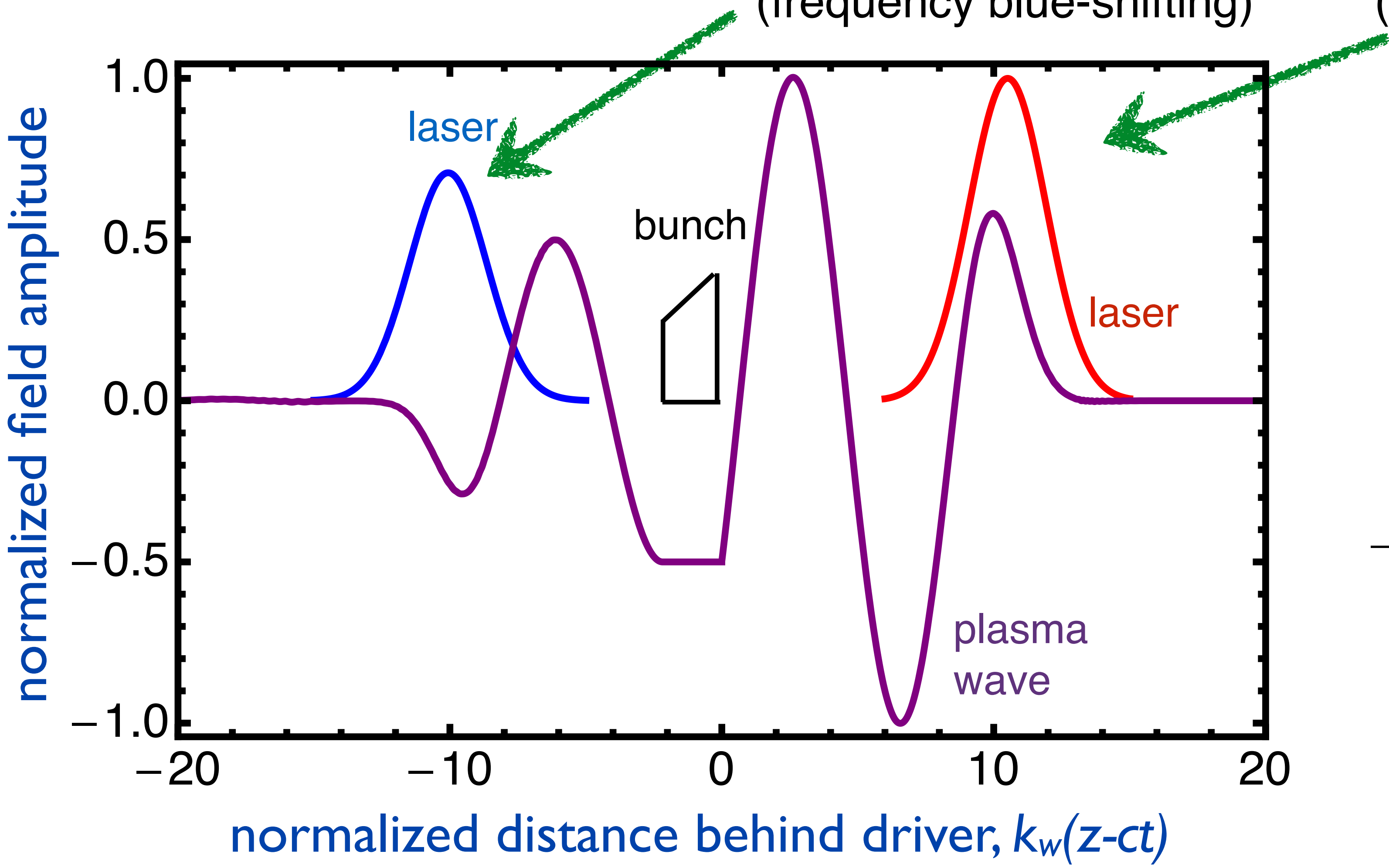
$$(n_b/n_w) < M_i/m_e$$

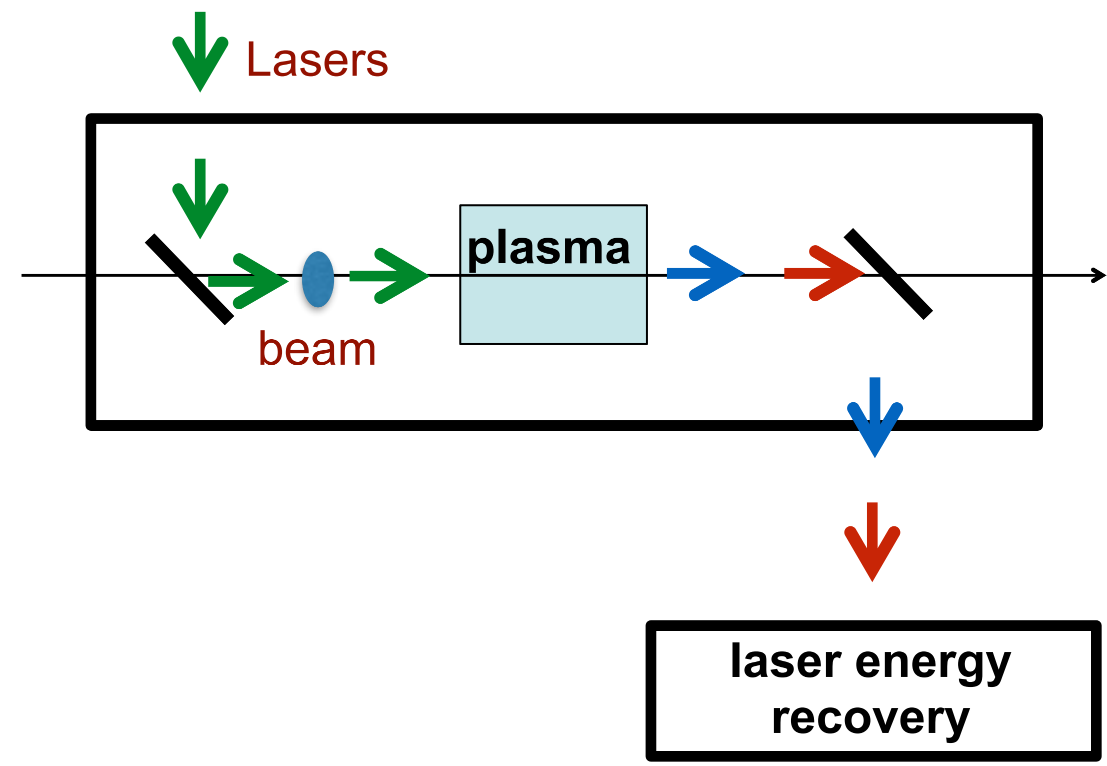
Improved efficiency using additional laser pulses to absorb remaining plasma wave energy

η(plasma to beam)= 0.75
gradient = 0.5 (peak field)

"Energy-recovery" laser absorbing wave energy (frequency blue-shifting)

Drive laser depositing energy into wave (frequency red-shifting)





- Additional laser pulse allows for no energy to remain in coherent plasma oscillations after energy transferred to particle beam

- Re-use in another LPA stage
- Sent to photovoltaic (energy back to grid)

Schroeder et al., Proc. AAC (2014)

Laser-plasma accelerator-based collider concept requires laser technology development

- Plasma density scalings: $n \sim 10^{17}$ cm^{-3}
- Quasi-linear wake (a~1): e- and e+
- Staging & laser coupling into plasma (hollow) channels:
  - ~30 J laser energy/stage required
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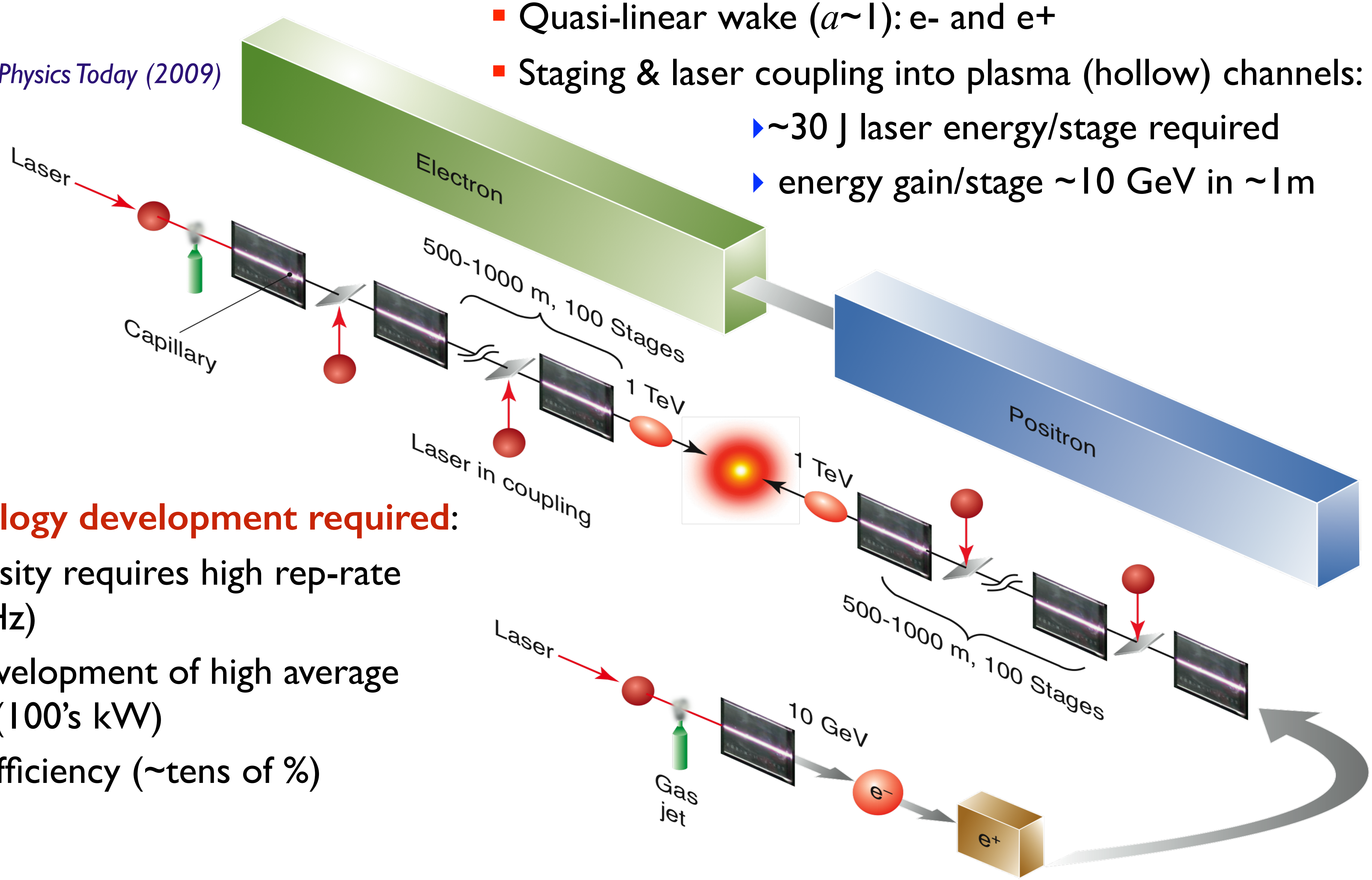
Leemans & Esarey, Physics Today (2009)

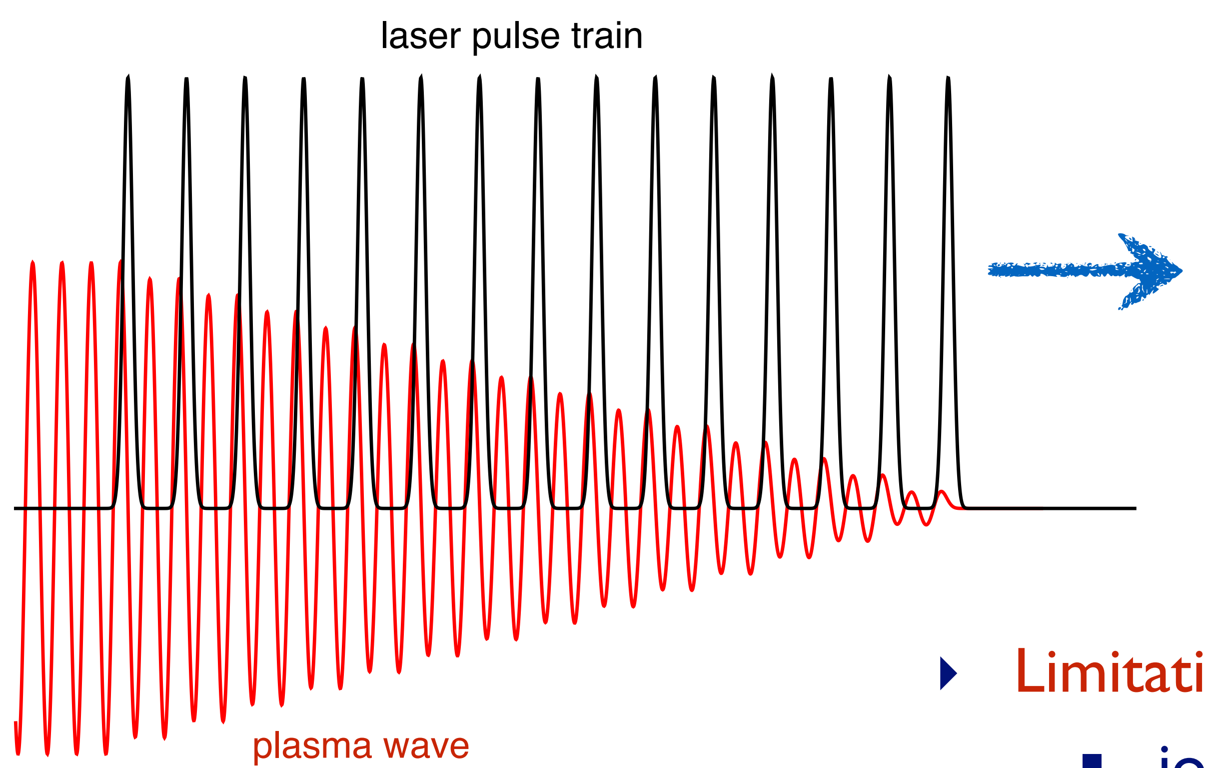


Laser technology development required:

- 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 %)

High-energy physics application using LPA requires new laser technology for high average power

- BELLA PW Laser operates at ~40 W average power
- Development of a kHz, ~0.5 J (~500 W) short-pulse laser system underway at **MPQ** (and high peak and average laser power system planned at **ELI-Beamlines**)
- ~100 kW average power/beam required for HEP application
- New concepts emerging to solve this technical challenge
  - Drive wake fields with train of laser pulses (low energy, high rep rate, high efficiency):
    - Reduce required energy/pulse by 1-2 orders of magnitude
    - Investigated experimentally at Oxford *S. Hooker et al., (2013)*



- Limitations of pulse trains:
  - ion motion $\omega_p \tau < (M_i/m_e)^{1/2}$
  - laser-plasma instabilities ("beam break-up")

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

- Coherent combination of diode-pumped fiber lasers has been proposed as a possible path to high-peak power, high-average power, high-efficiency lasers:
  - Fiber lasers can provide sub-ps pulses with ~mJ energy at ~10 kHz and ~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) $\sim 10^4$ fiber lasers

ICAN = “International Coherent Amplification Network”

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

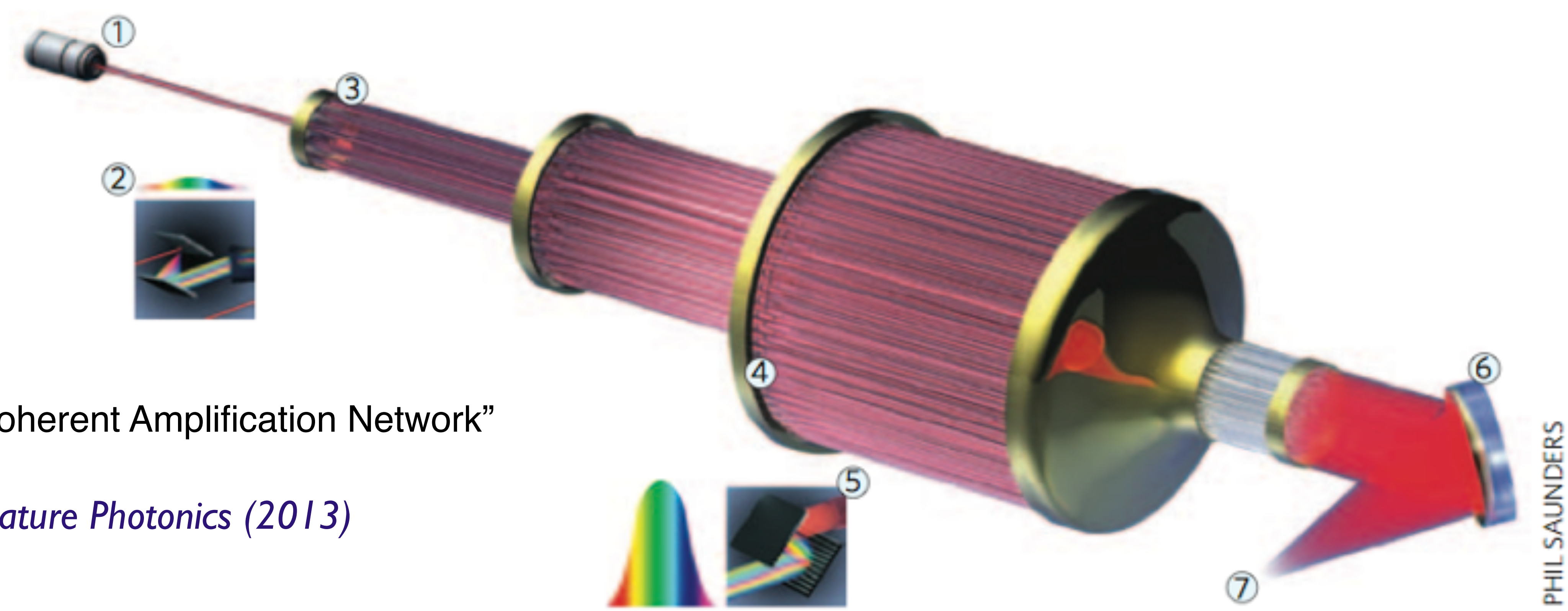


Figure 1 | Principle of a coherent amplifier network. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of ~1 mJ at a high repetition rate (4). All the channels are combined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

Plasma acceleration promising compact accelerator technology for many applications

- Laser-pasma accelerators provide ultra-high gradients (compact accelerators) generating short (fs) beams (high peak current)
  - 4 GeV beams in 9-cm plasma using LPA at BELLA
    - 10 GeV beams in <1m will be available in next (few) years
  - 6D brightness comparable to conventional sources
- Improved LPA beam quality using controlled injection from background plasma
  - novel injection concepts — source of ultra-cold beams (~10 nm emittance)
- Many applications possible for compact LPAs, delivering ultra-short, high-peak-current e-beams (improved beam stability and quality required as well as LPA technology maturity)
  - FEL achievable with demonstrated LPA beams using beam phase-space manipulation
  - Compact gamma-ray Thomson sources; Ultrafast science applications; High-intensity particle-photon interactions; …
- Laser technology is rapidly advancing, driving experimental progress
  - 1 PW (1 Hz) laser systems available; 10 PW (1 Hz) systems under construction
  - 1 J (100 TW), 1 kHz laser systems will be available in next few years
- Practical application to TeV colliders have many technical challenges
  - Techniques for bunch & plasma tailoring required for high efficiency and beam quality preservation
  - High peak & average power laser technology development required

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