Laser-Plasma Acceleration Research at Berkeley Lab

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Workshop on Laser-Plasma Accelerators
International Centre for Theoretical Sciences
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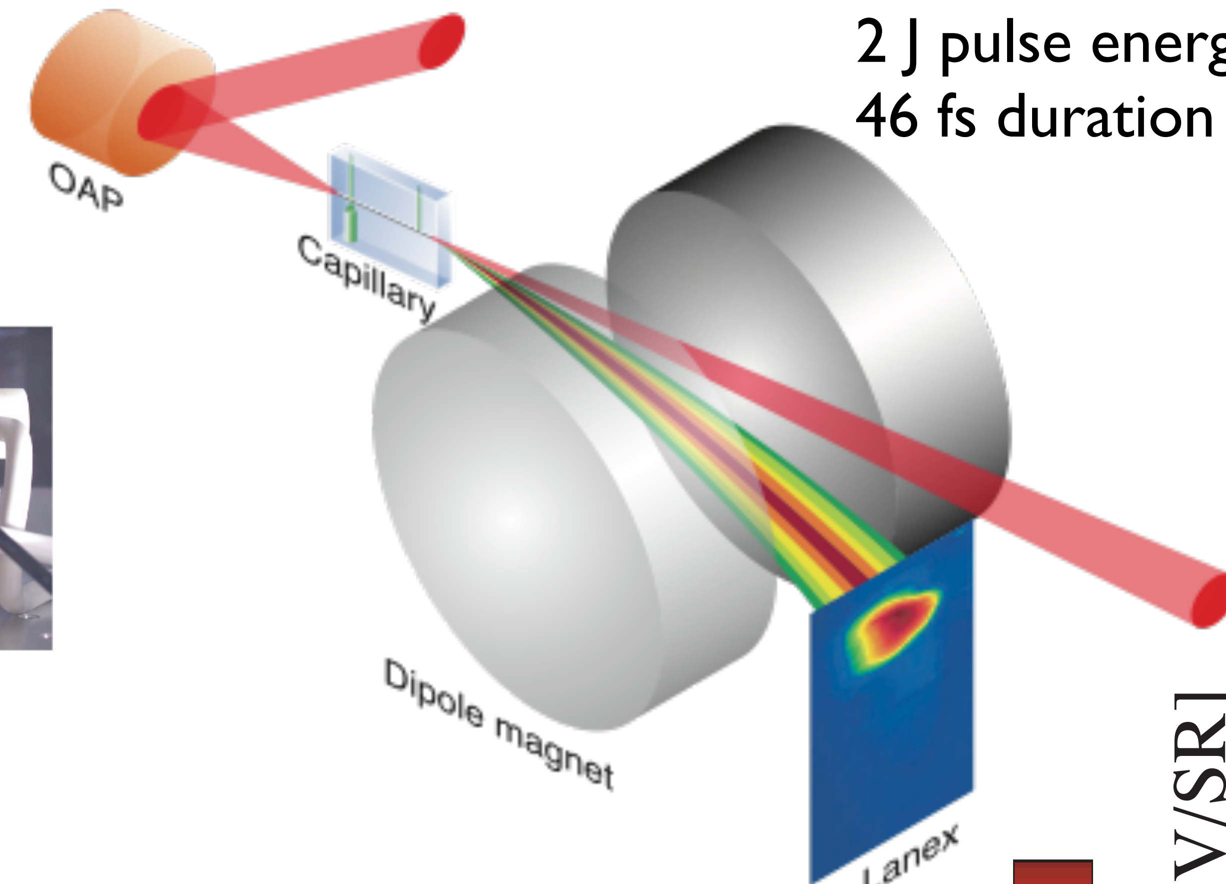
Outline

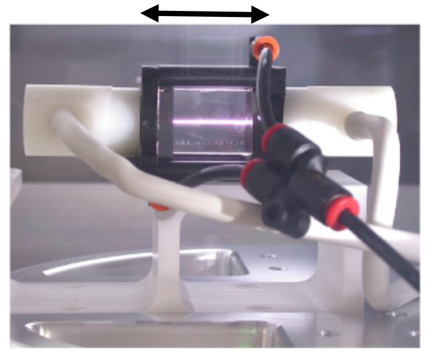
- Laser-driven plasma-based accelerators (LPAs): ultra-high gradient provides compact source of energetic, fs, kA e-beams
  - Experimental results from BErkeley Lab Laser Accelerator (BELLA)
    - GeV beams in cm-scale plasmas available using LPAs
- Improved LPA beam quality, stability using controlled injection techniques
  - Trapping physics and methods (density gradient, ionization)
  - Ultra-low beam emittance generation
- Applications of LPAs:
  - LPA-driven free-electron lasers (FELs)
  - High-energy physics (lepton collider) application of LPAs
    - Experimental results on staging of laser-plasma accelerators

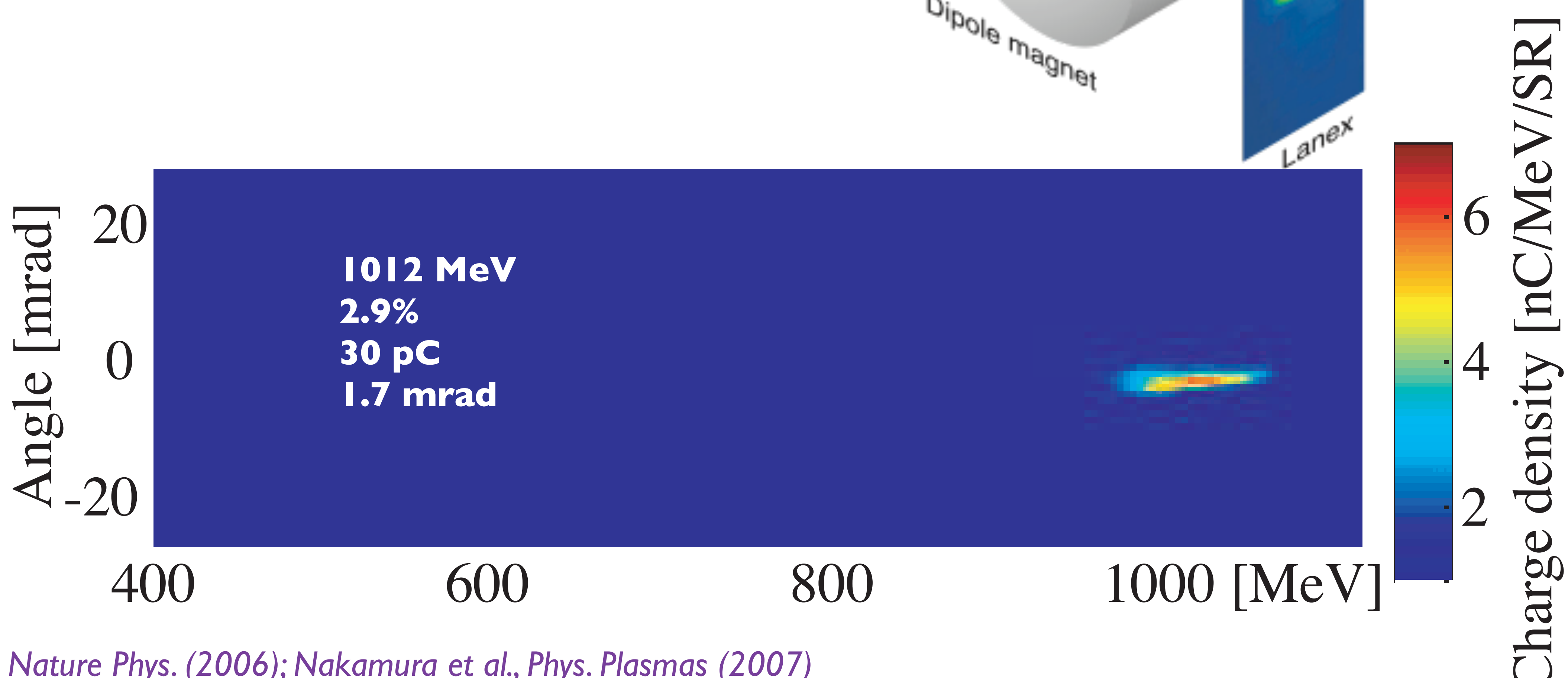
Laser-plasma accelerator (LPA) experimental demonstration of GeV electron beam

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



Plasma source:
H-discharge capillary
number density = 3x10[18] cm[-3]





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

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

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

- **Accelerating field**: characteristic size of plasma wave field, driven by the ponderomotive force of a resonant laser pulse with relativistic intensity (>10^{18} W/cm^2) propagating in underdense plasma:

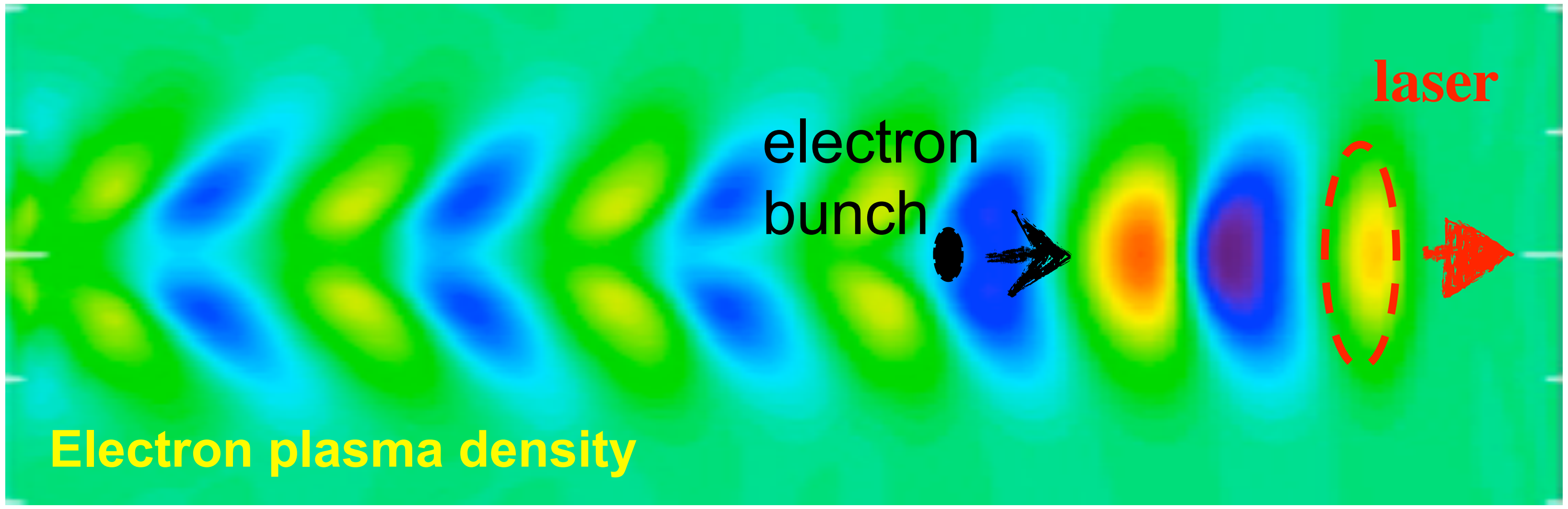
$$E \sim \left(\frac{mc\omega_p}{e}\right) \approx (96\ \mathrm{V/m})\sqrt{n_0[\mathrm{cm}^{-3}]}$$

  - 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

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

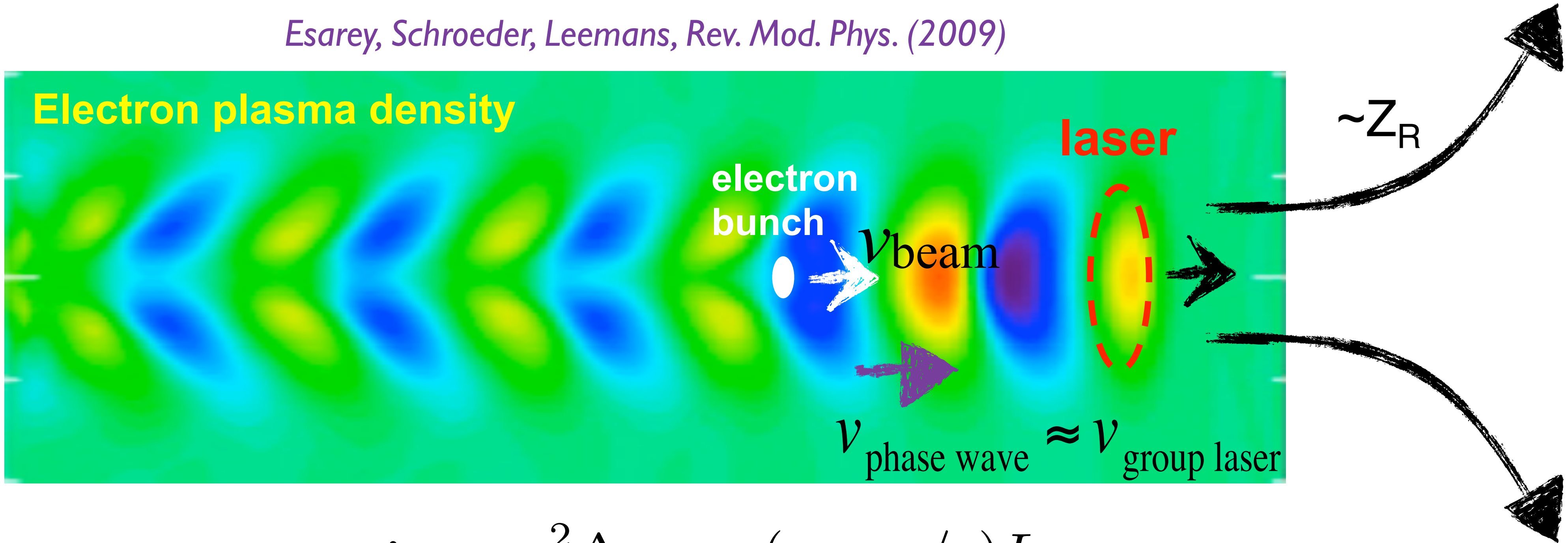


- Beam charge (set by beam loading, plasma density): ~1-100 pC
- Beam duration (set by trapping physics and density): ~1-10 fs

➡ ~1-10 kA peak current

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
- **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) *Schroeder et al., PRL (2011)*
  - Controlled by longitudinal plasma density tailoring (plasma tapering)
- **Laser Energy Depletion**:
  - Rate of laser energy deposition of into plasma wave excitation: $L_{\text{deplete}} \propto n^{-3/2}\lambda^{-2}$

Shadwick, Schroeder, Esarey, Phys. Plasmas (2009)
Benedetti et al., PRE (2015)

Plasma density scalings

- Laser-plasma interaction (depletion) length:

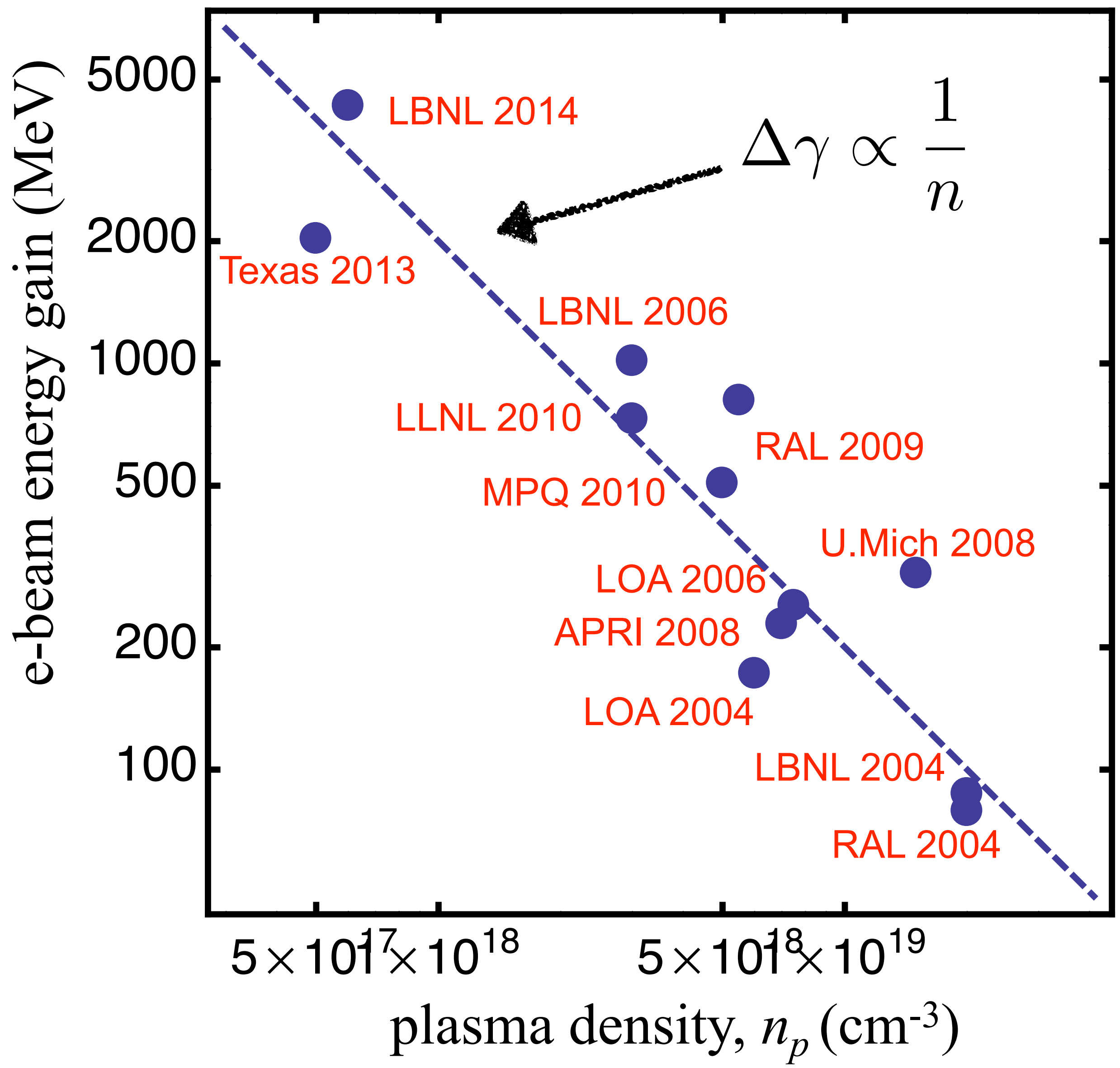
$$L_{\rm acc} \sim \lambda_p^3/\lambda_L^2 \propto n^{-3/2}$$

- Accelerating gradient:

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

- Energy gain:

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



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

Laser requirements:

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

W~1 GeV
n ~ 3x10^{18} cm^{-3}
L_{acc} ~1 cm
U_{laser} ~2 J
P_{laser} ~100 TW

→

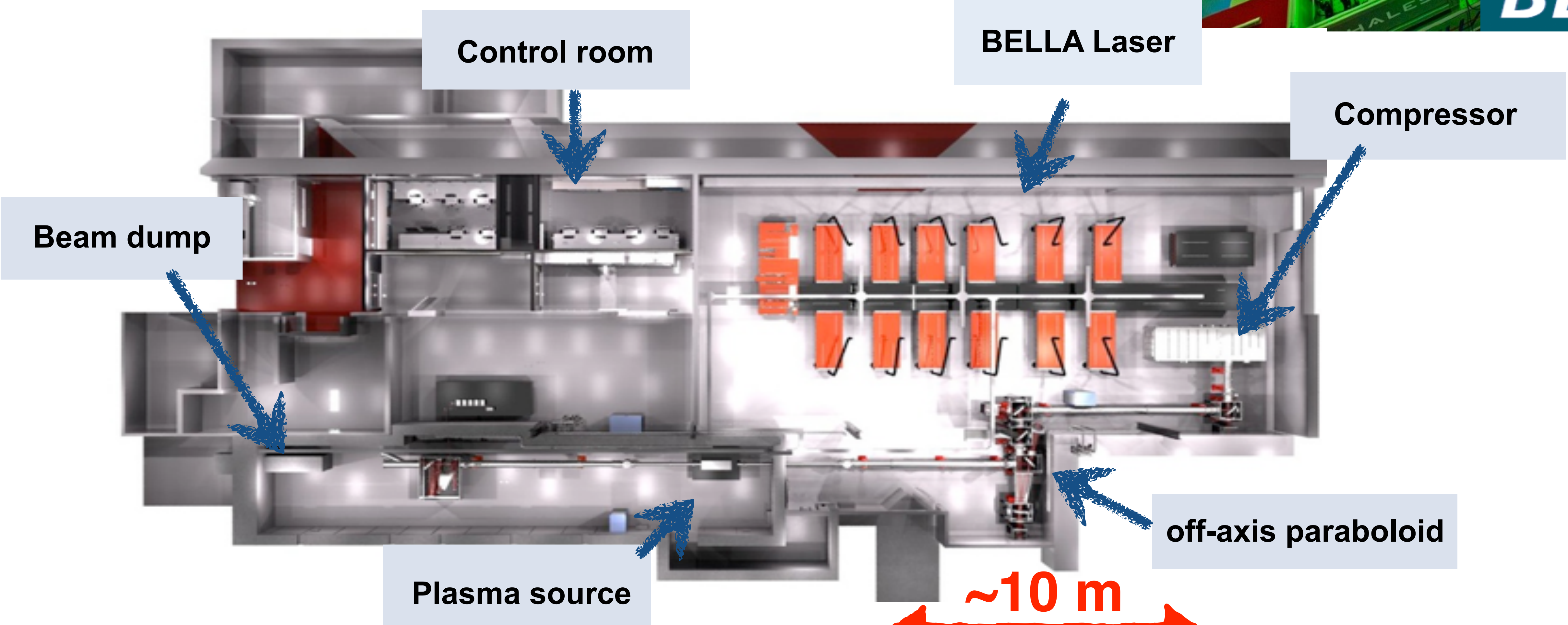
W ~ 4 GeV
n ~ 7x10^{17} cm^{-3}
L_{acc} ~8 cm
U_{laser} ~ 16 J
P_{laser} ~ 0.4 PW

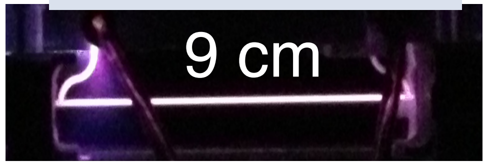
BELLA Laser Facility

Leemans et al., PAC Proc. (2013)

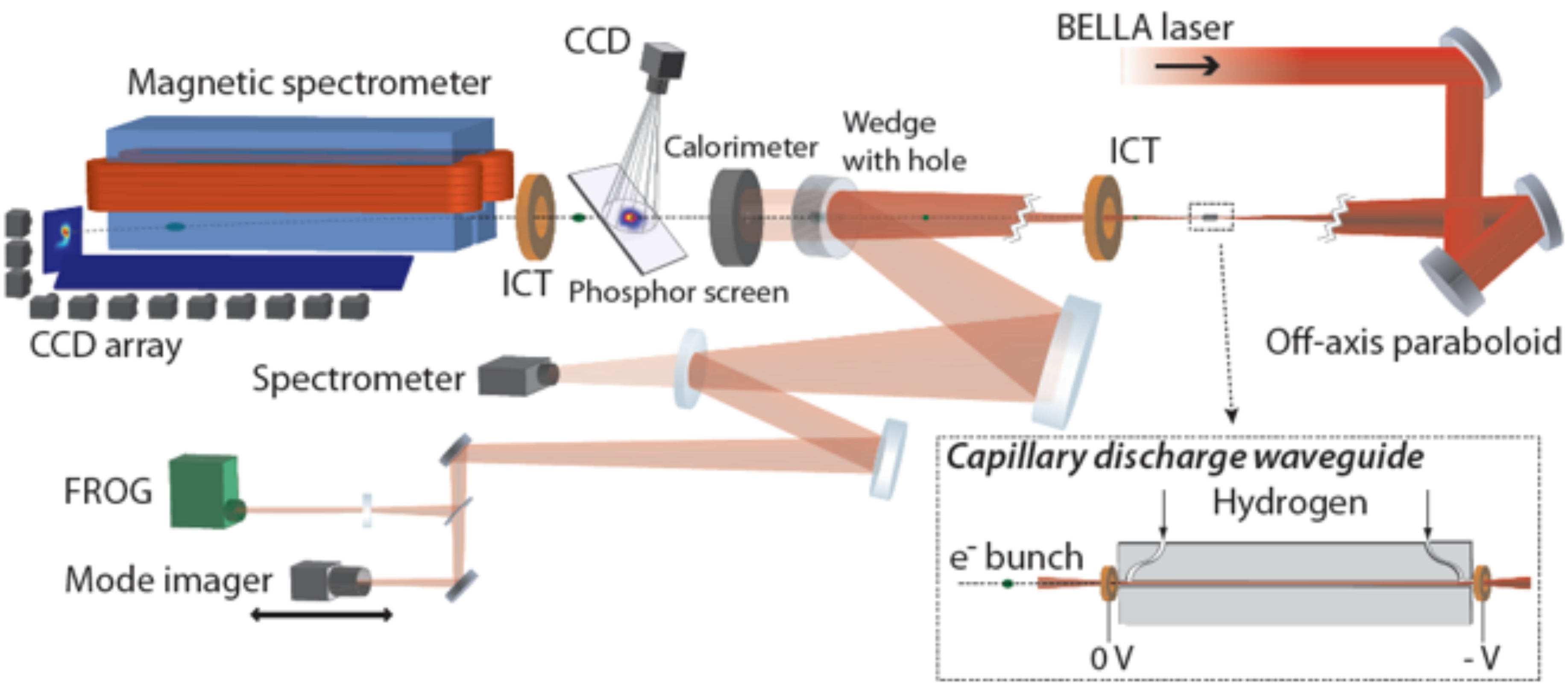
BELLA (BErkeley Lab Laser Accelerator) Facility:

- PW-laser for laser-accelerator science
- >42 J in <40 fs (> 1PW) at 1 Hz laser and supporting infrastructure at LBNL
- commissioned in 2013

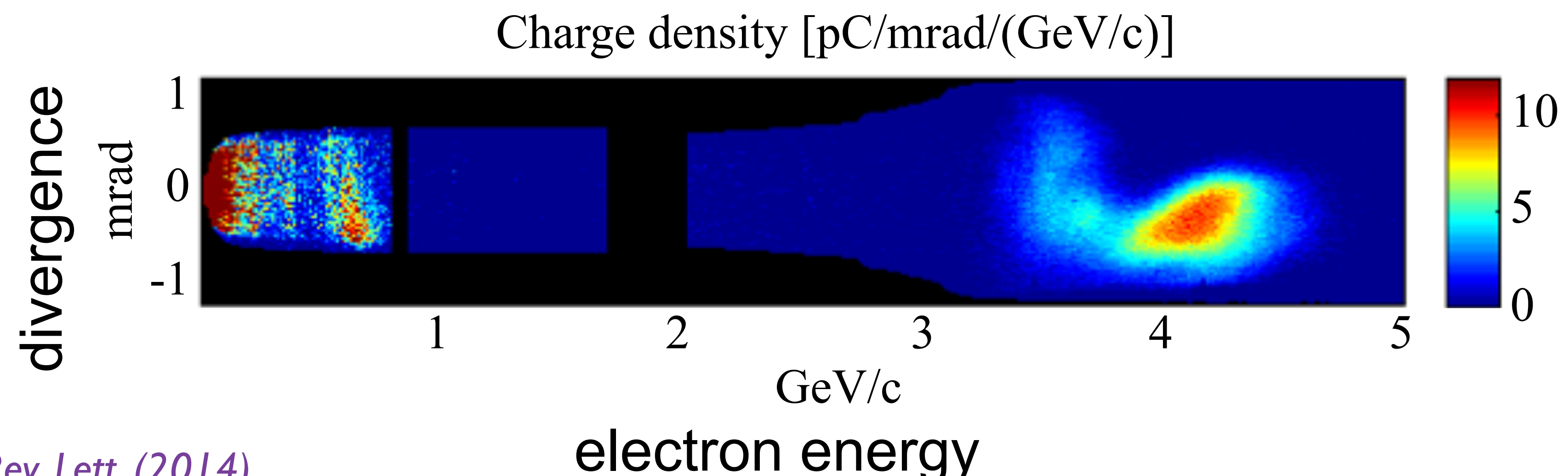




Multi-GeV electron acceleration using BELLA

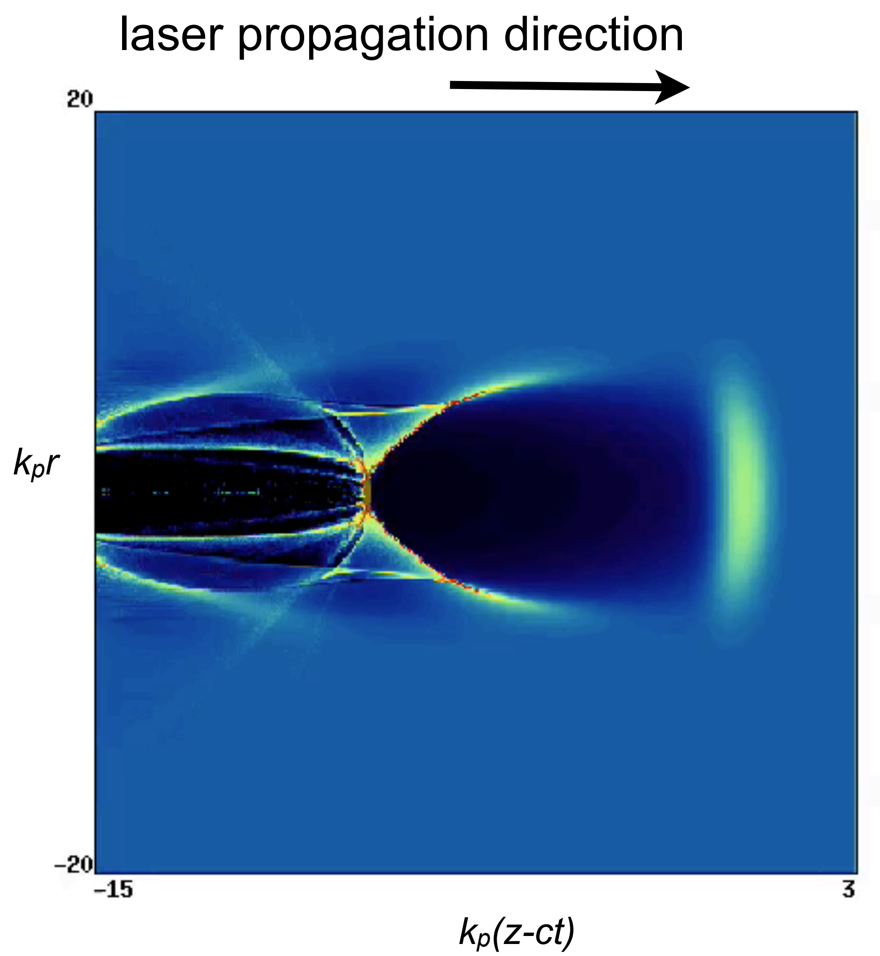


- plasma: 9 cm H-discharge capillary, on-axis density 7×10^{17}/cc
- laser:16 J, 40 fs
- 4.25 GeV e-beam, 6% energy spread, 0.3 mrad divergence, 10 pC



Leemans et al., Phys. Rev. Lett. (2014)

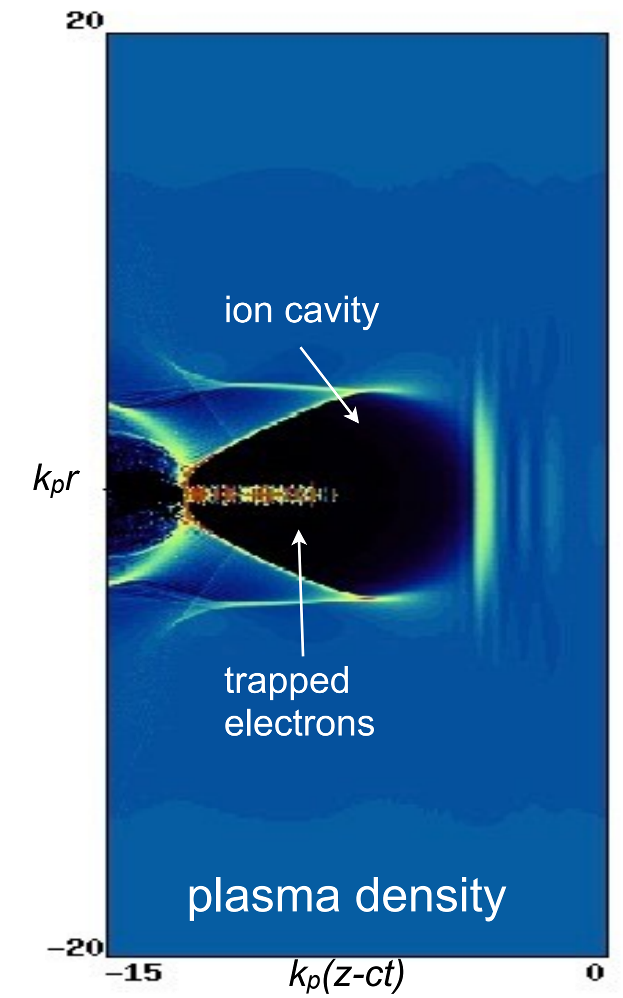
Self-injection from background plasma — determines beam quality



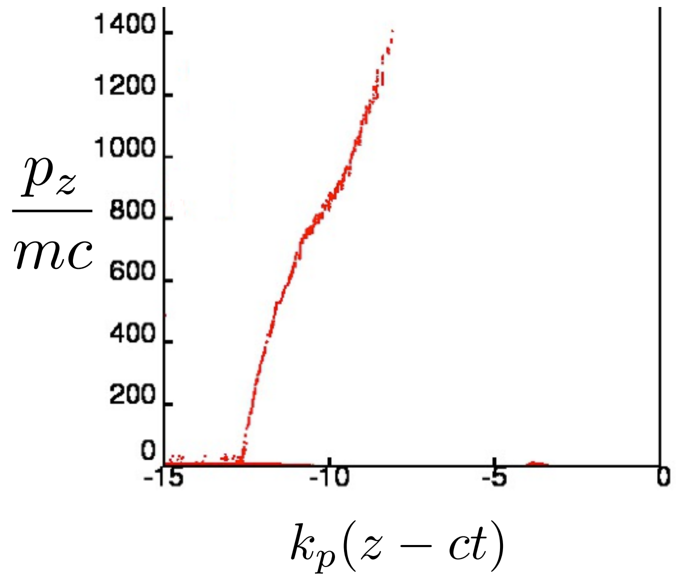
Benedetti, Schroeder et al., Phys Plasmas (2013)

- Requires high intensity laser (*a*>3, depends on wave phase velocity, plasma temperature, etc.)
- Requires high plasma density (slow plasma wave phase velocity)

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



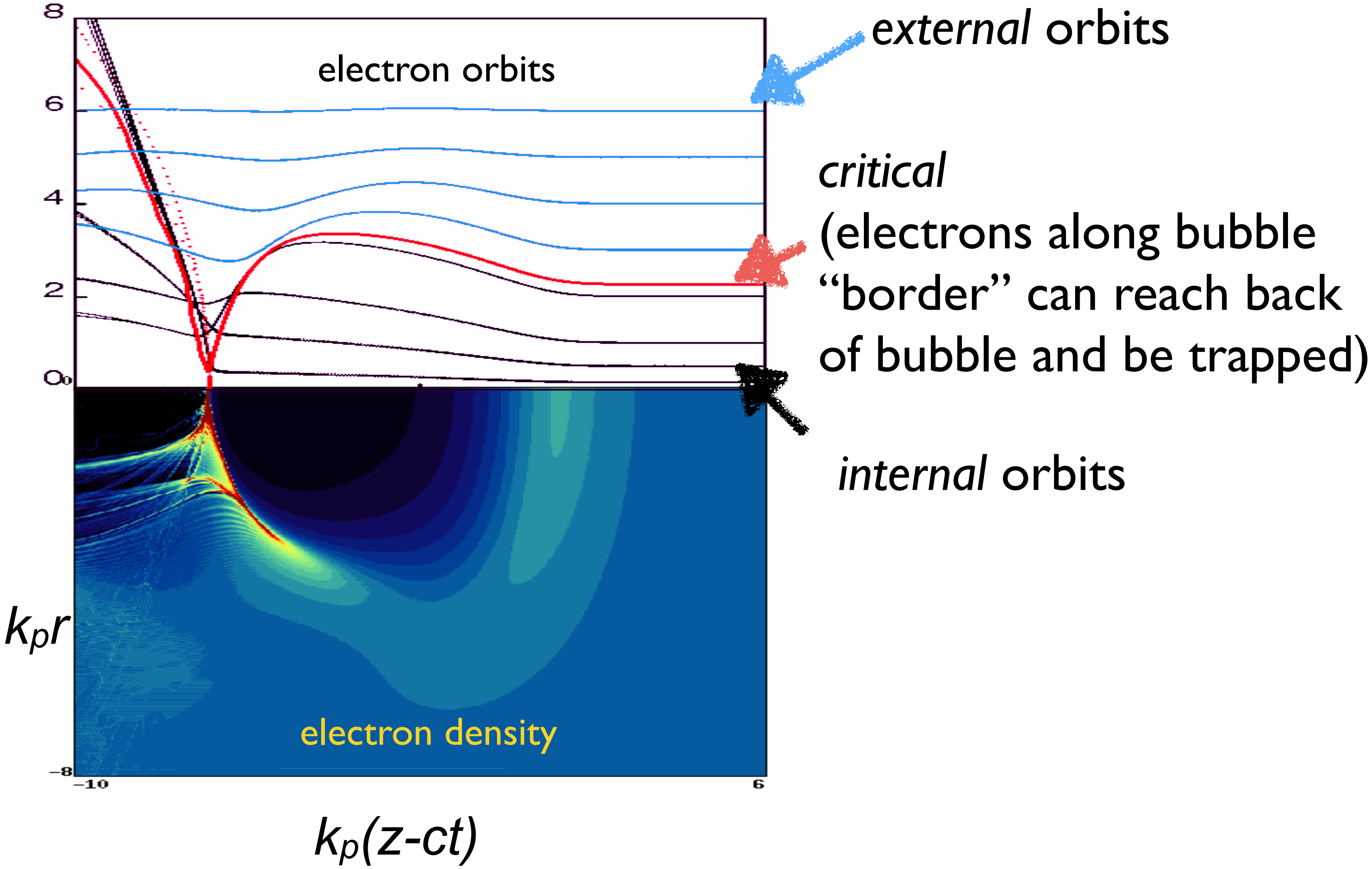
- continuous (uncontrolled) injection can result in large (1-100%) energy spreads
- energy gain proportional to injection time; chirped energy distribution
- controlled (triggered) injection: improve stability, reduced shot-to-shot fluctuations, and reduced energy spread



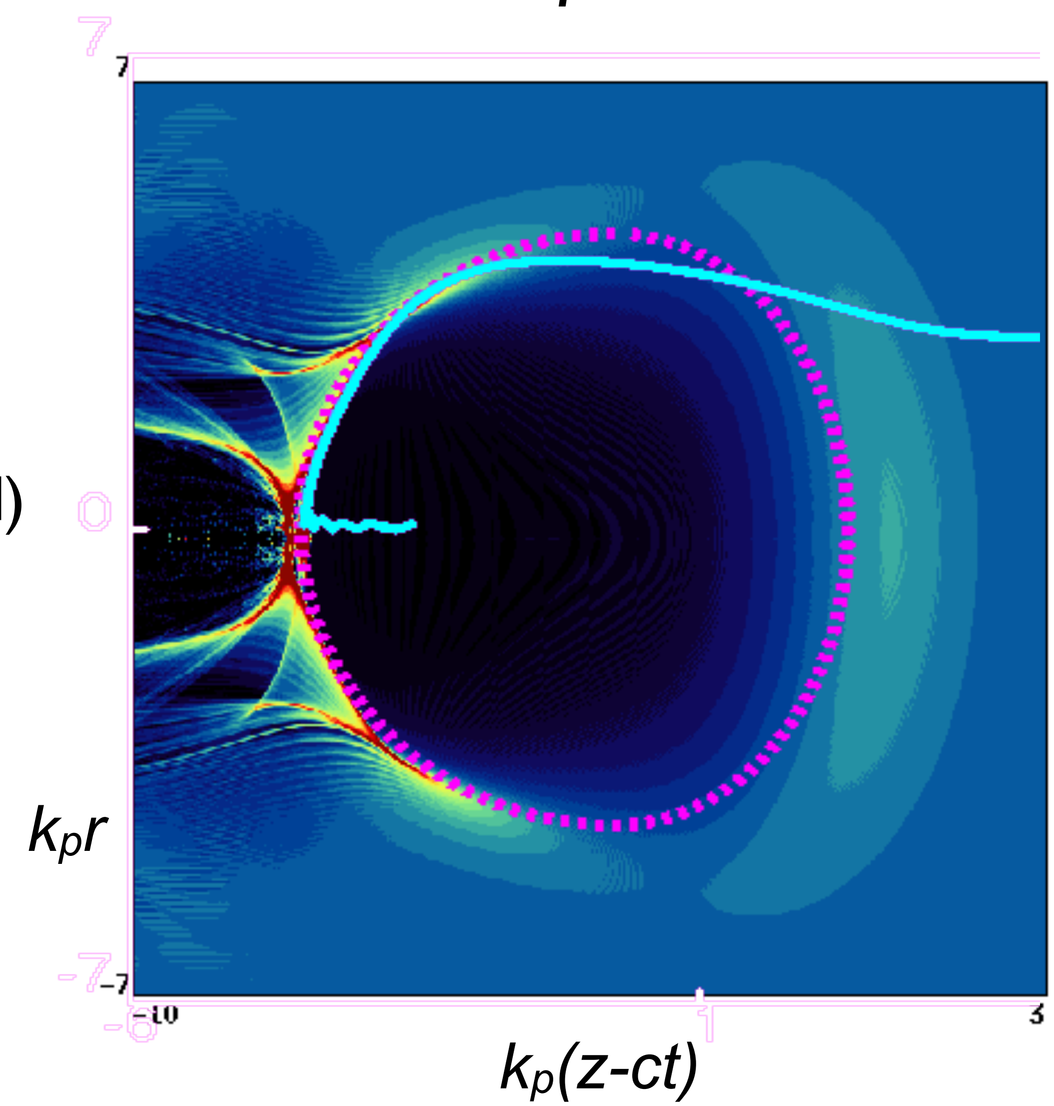
Self-injection from background plasma

Modeled using PIC (INF&RNO)

no self-trapping:
a_0=3.5
ω/ω_p=20



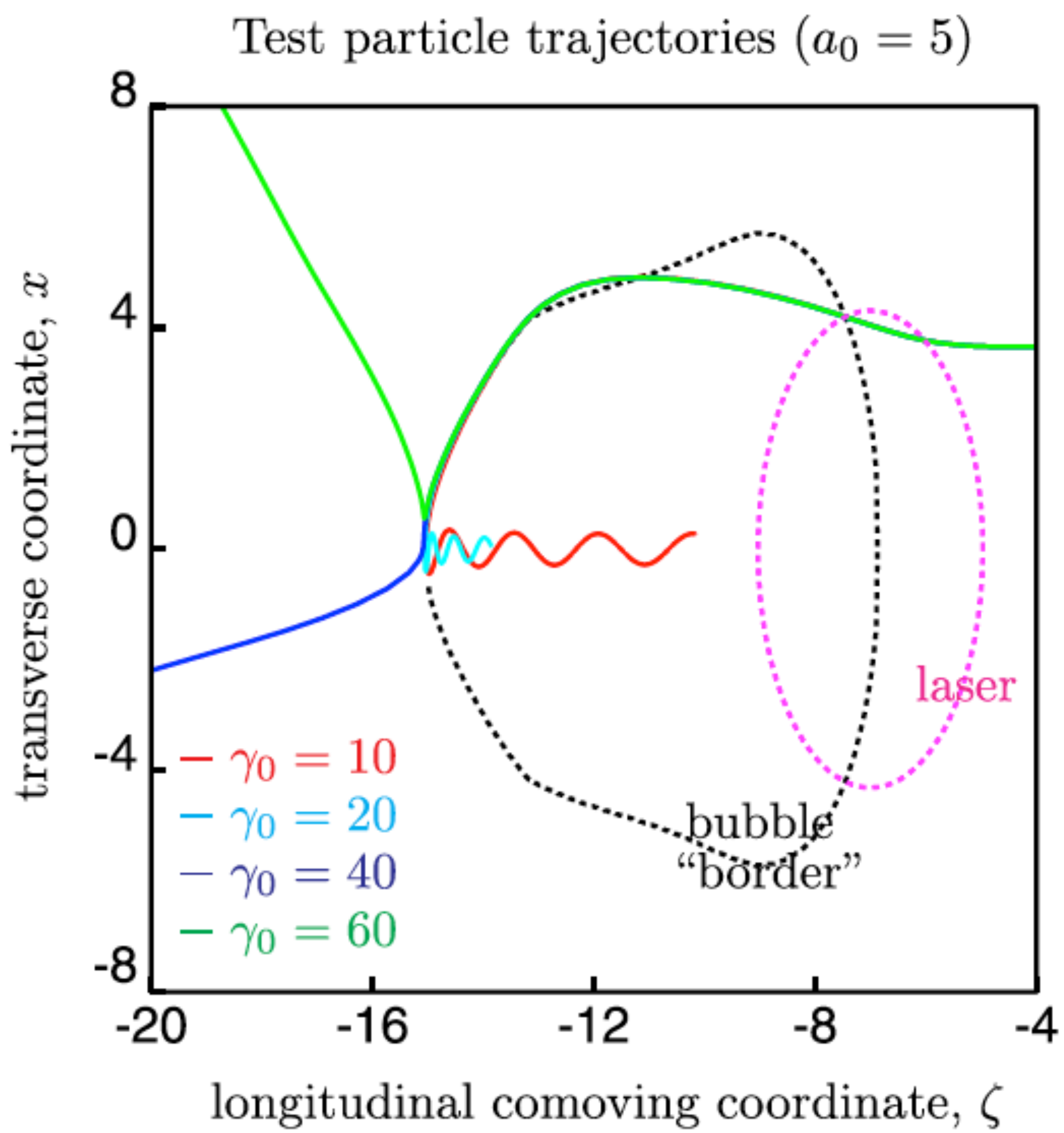
self-trapping:
a_0=4
ω/ω_p=20

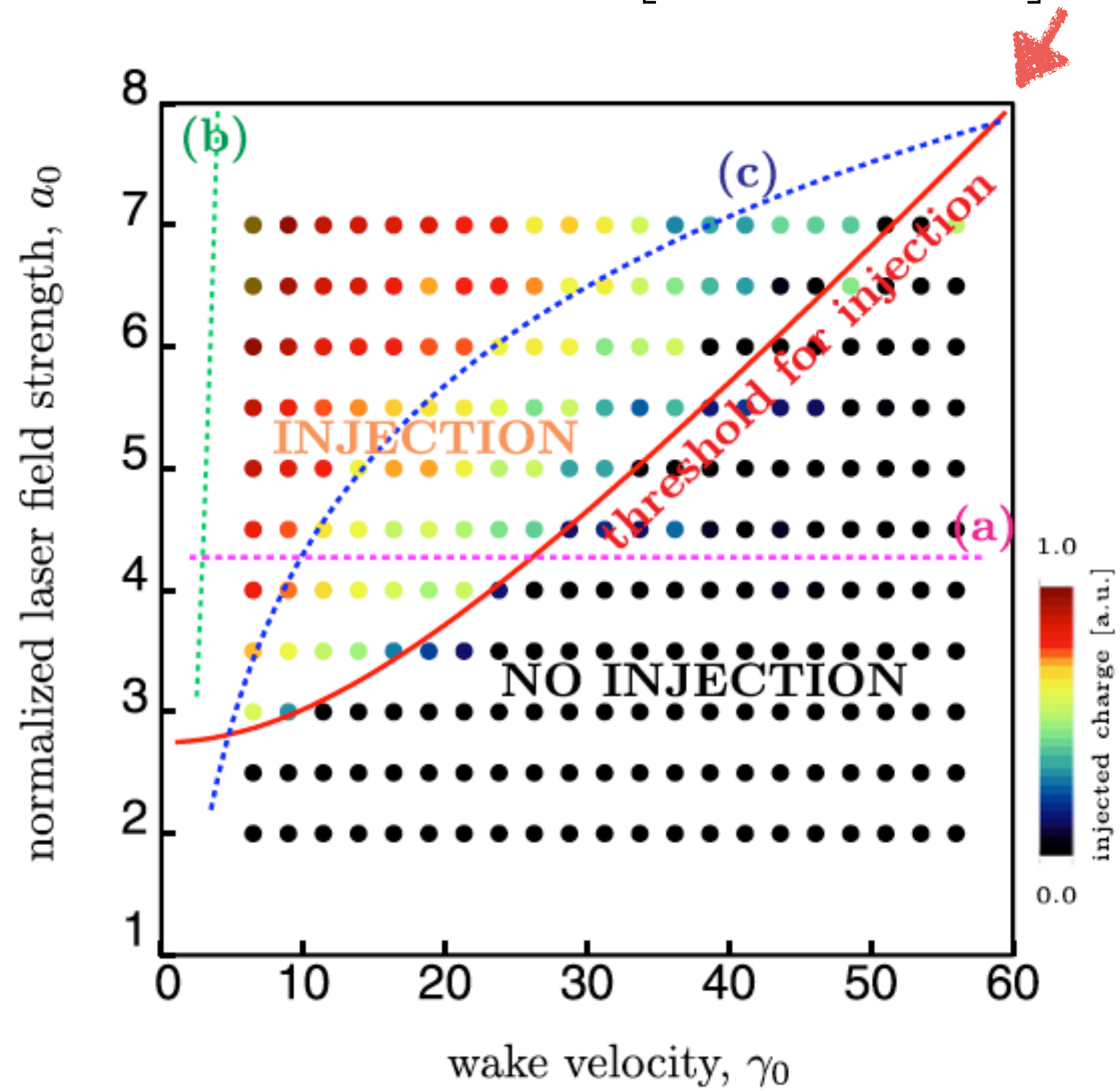


Self-injection from background plasma

Benedetti, Schroeder, Esarey, Leemans, Phys Plasmas (2013)

empirical (numerical) threshold: $a_{\text{th}} = 2.75\left[1 + (\gamma_p/22)^2\right]^{1/2}$





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

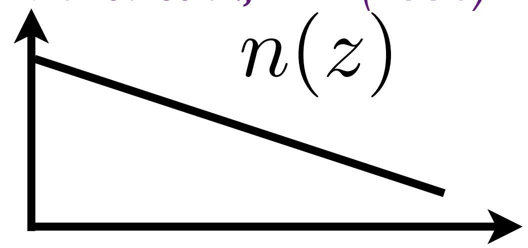
Injection: phase velocity control with density gradients

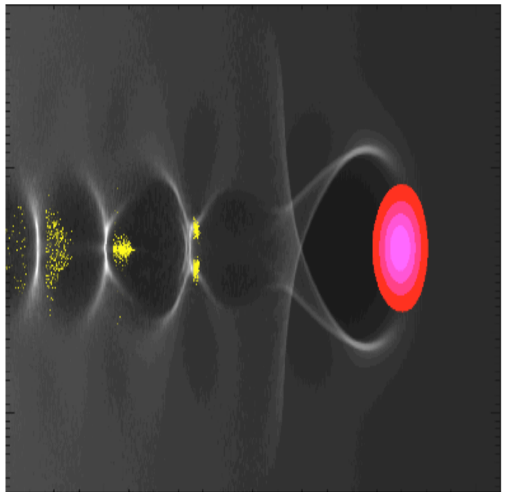
- Plasma wave: $$E \sim \cos[k_p(z)(z-\beta_g t)] = \cos\psi$$
- Phase velocity: $$\beta_p = \frac{\omega}{k} = \frac{-\partial_t \psi}{\partial_z \psi}$$

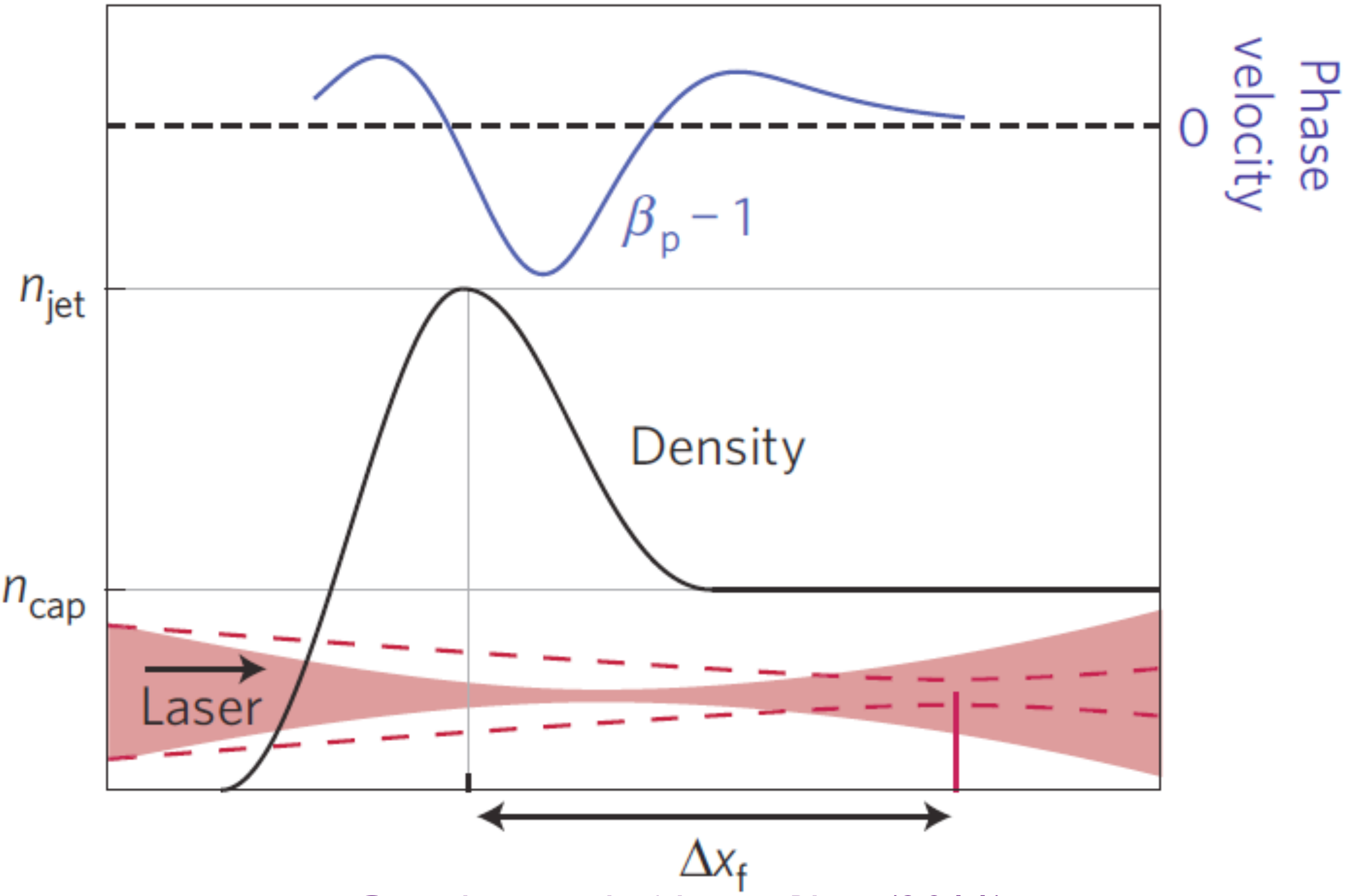
$$\beta_p \simeq \beta_g \left[1 - |\zeta| k_p^{-1} dk_p/dz\right]^{-1}$$

driver velocity
(laser group vel.)

Bulanov et al., PRE (1998)







Gonsalves et al., Nature Phys. (2011)

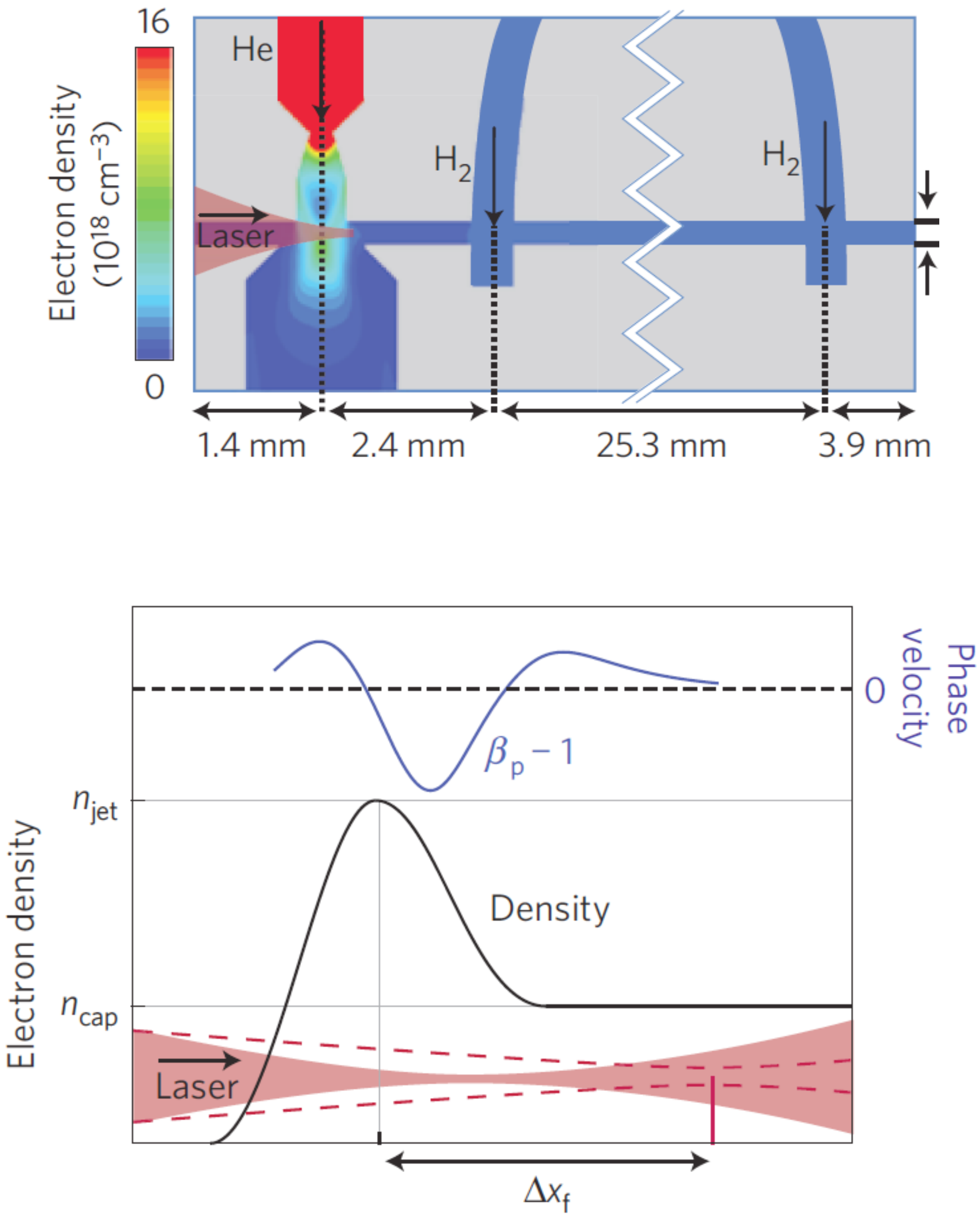
- Control phase velocity using density variation and laser evolution:

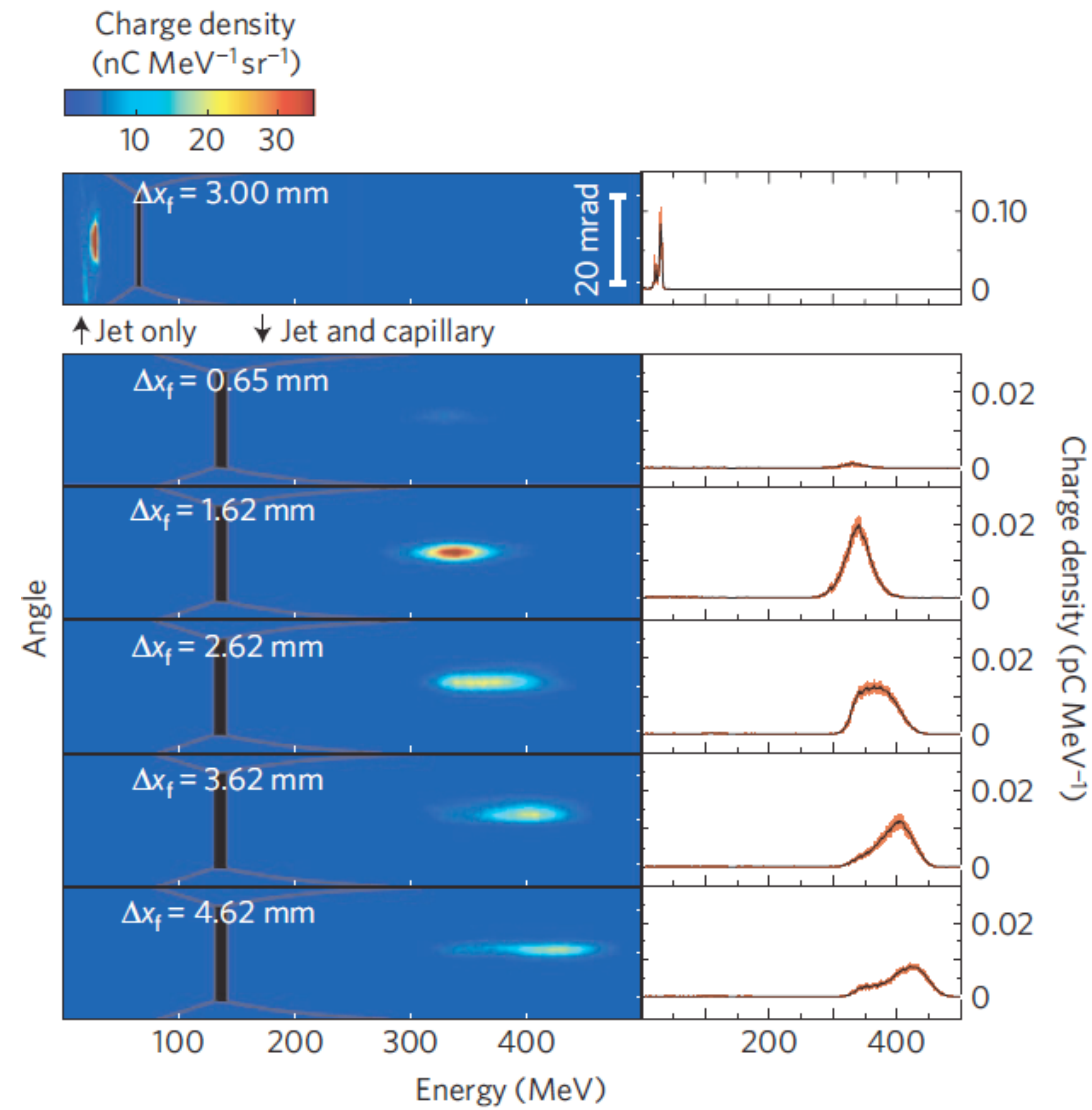
$$\frac{1}{k_p}\frac{dk_p}{dz} = \underbrace{\frac{1}{2n}\frac{dn}{dz}}_{\text{plasma density evolution}} - \underbrace{\frac{1}{\lambda}\frac{d\lambda}{da}\frac{da}{dz}}_{\text{laser evolution: self-focusing}}$$

- Trapping occurs when wave phase velocity < plasma fluid velocity

Injection: phase velocity control with density gradients

- Control phase velocity using density variation and laser evolution:





Gonsalves et al., Nature Phys. (2011)

Ionization injection

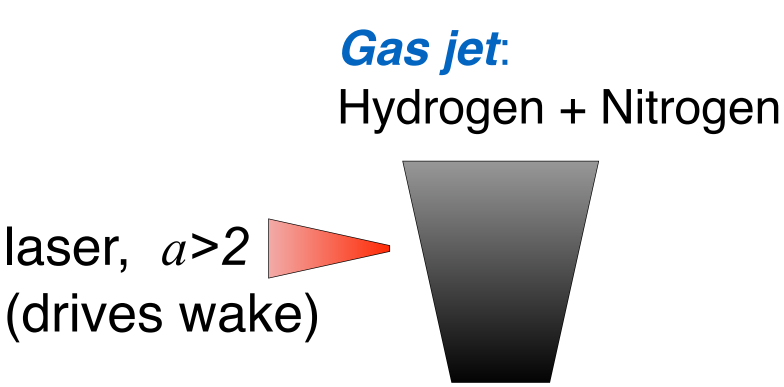
- Larger energy gain achieved at lower plasma density:

$$\Delta\gamma \propto E_0 L_d \propto \left(m_e c^2 \omega_p / e\right)\left(\lambda_p \gamma_p^2\right) \propto n^{-1}$$

- lower density ➤ higher plasma wave phase velocity ➤ more difficult to self-inject

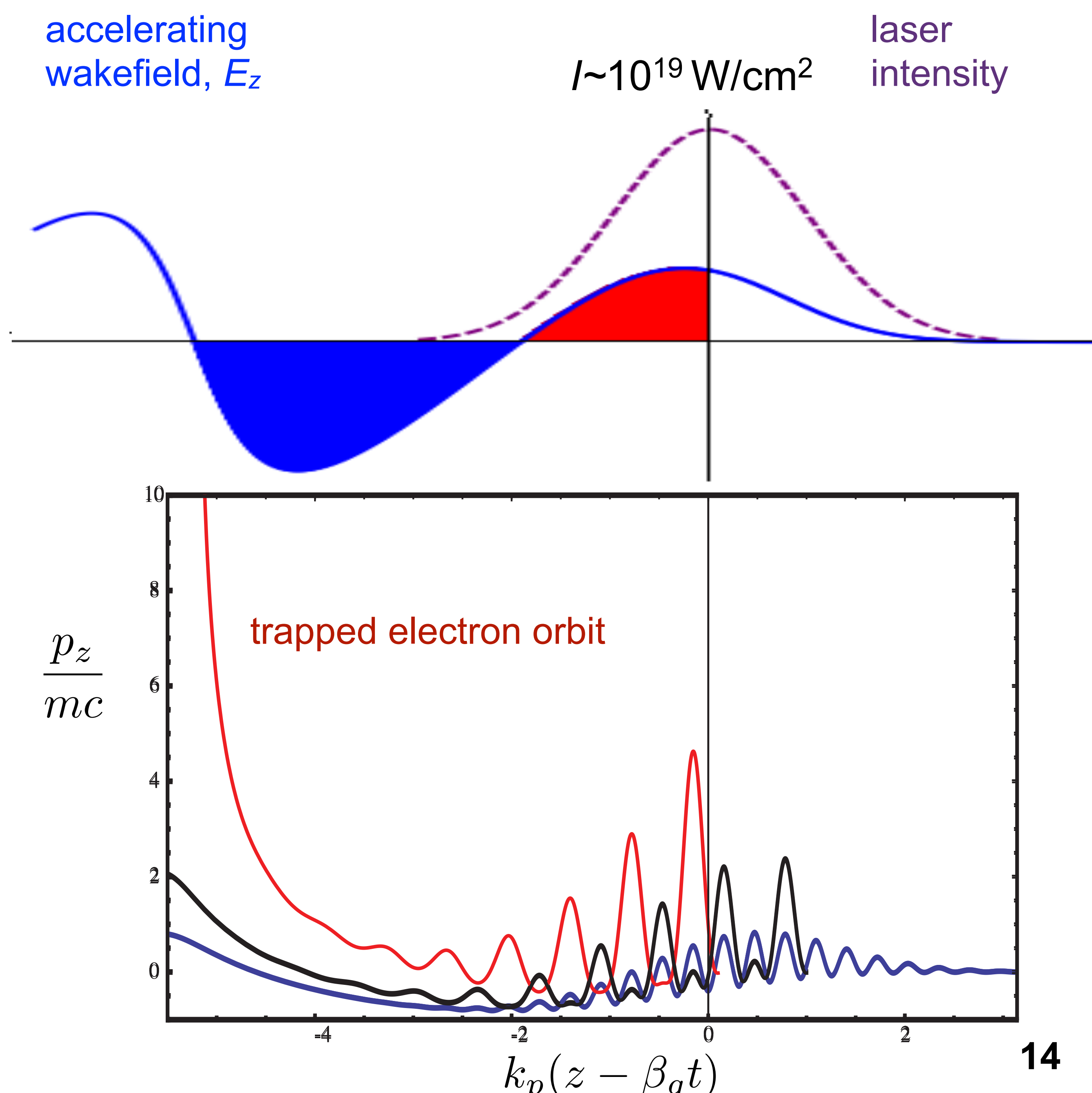
- ***Ionization injection*** enables trapping at lower laser intensity (allowing operation at lower plasma densities and higher energy gains).

McGuffey et al., PRL (2010)
Pak et al., PRL (2010)
Clayton et al., PRL (2010)
Liu et al., Phys Rev Lett (2011)

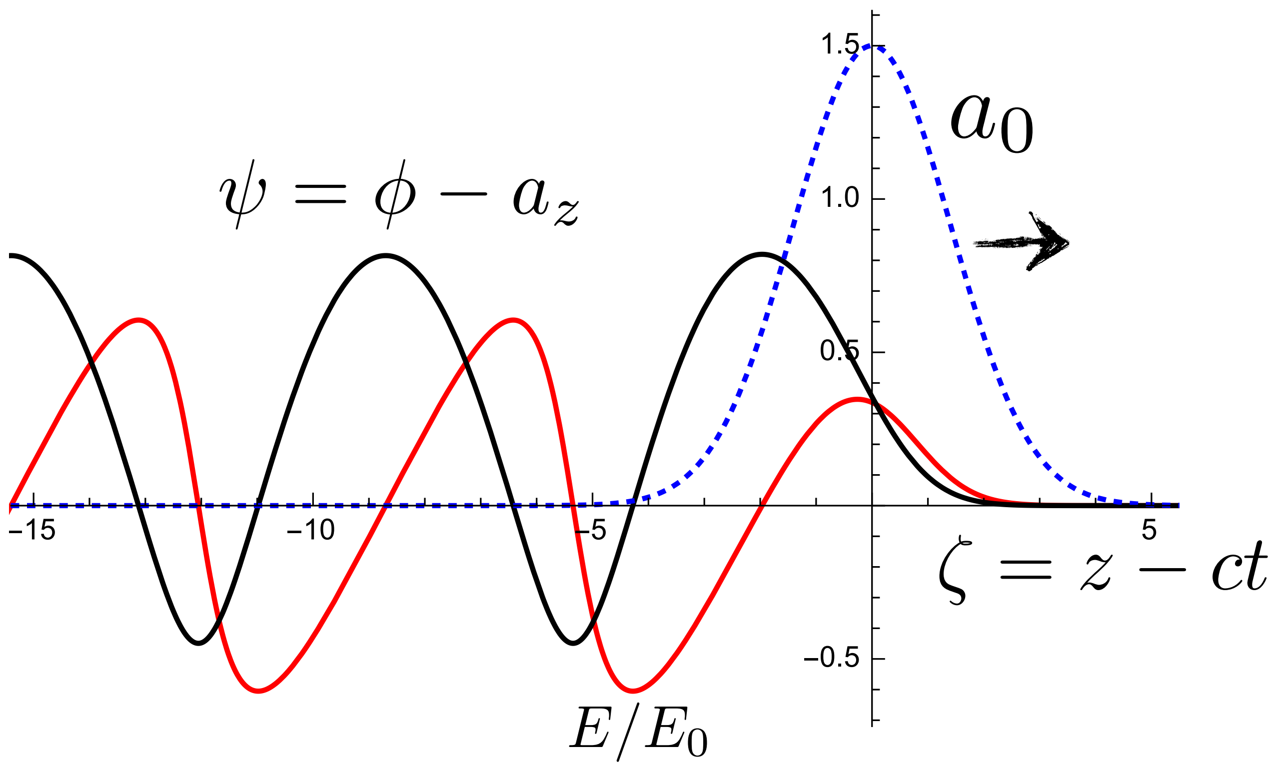


▸ **Ionization injection:** ionize electron (at rest) in trapped orbit of plasma wave using high-Z gas

M. Chen et al., Phys. Plasmas (2012)



Wakefield amplitude required for ionization trapping

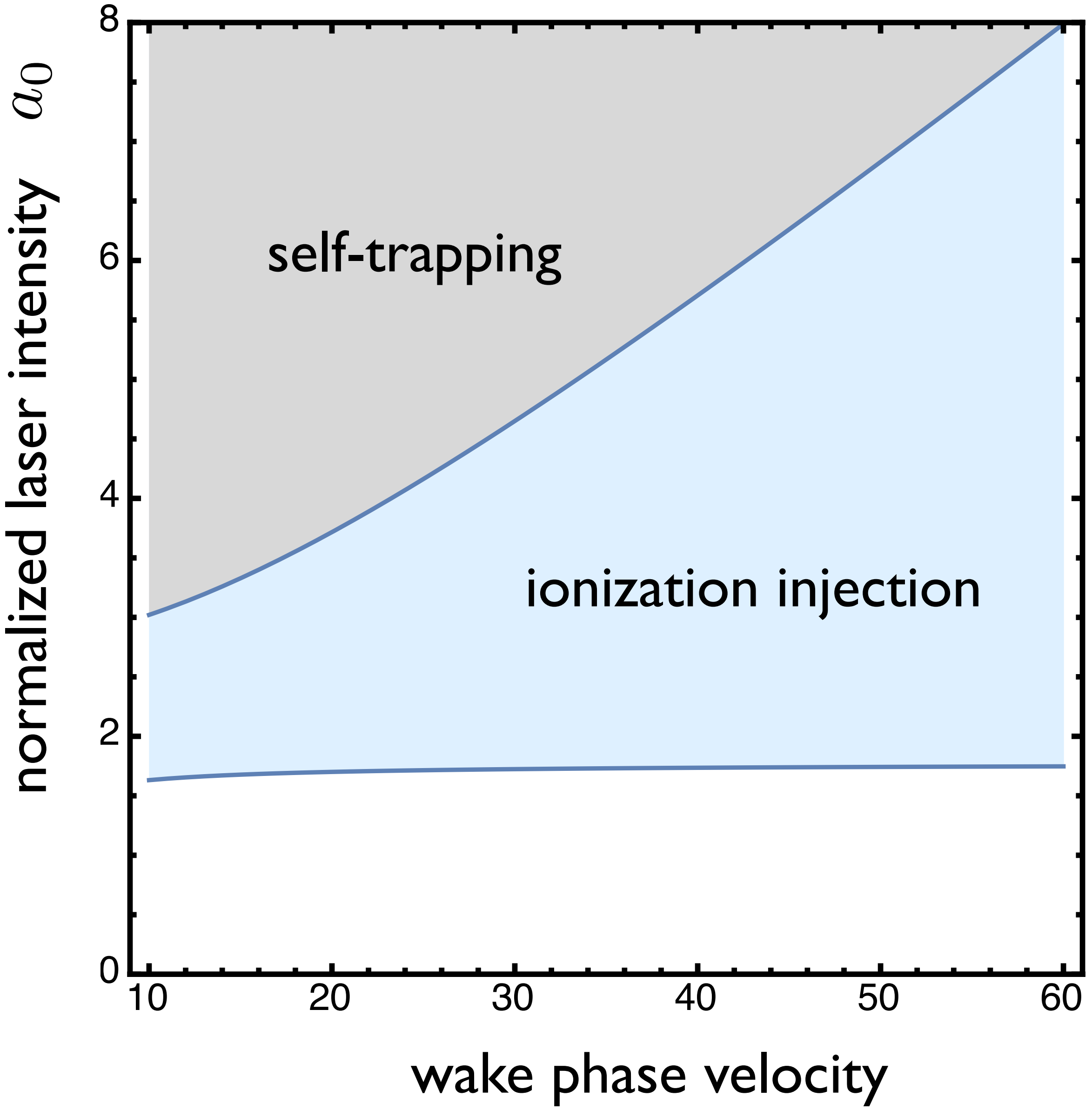


Trapping for e- ionized at laser peak: $\zeta_i = 0$

Trapping condition:

$$1 + \psi_{\min} - \psi(\zeta_i) \le \gamma_p^{-1}\left(1 + p_\perp^2\right)^{1/2}$$

Esarey & Pillof Phys Plasmas (1995)
Pak et al., PRL (2010)
M. Chen et al., Phys Plasmas (2012)



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

Ionization injection:

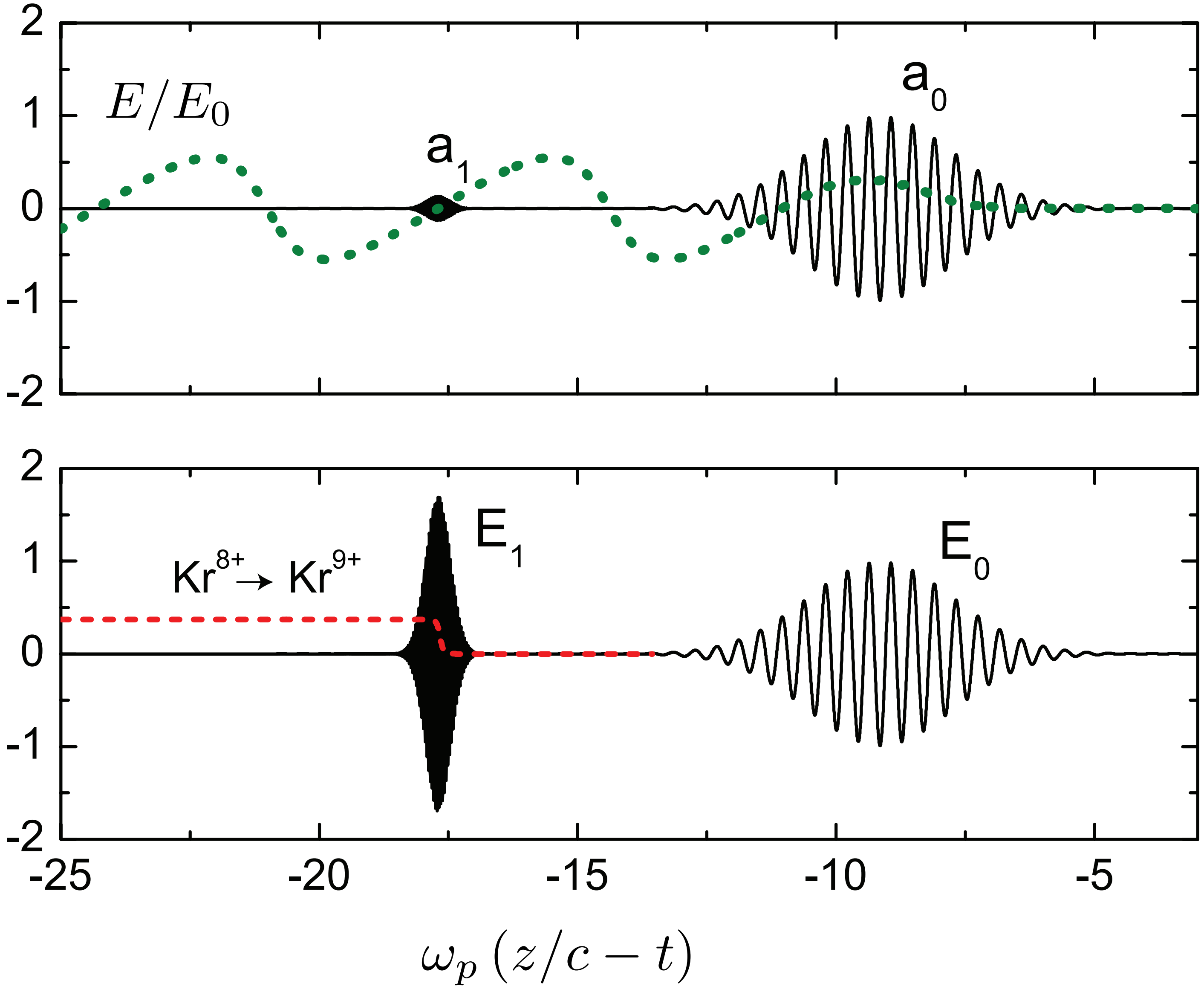
- single-pulse ionization injection requires *a*>2
- weak dependence on plasma density

Two-color ionization injection

L.-L. Yu, Esarey, Schroeder et al., PRL (2014); Schroeder et al., PR ST-AB (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)



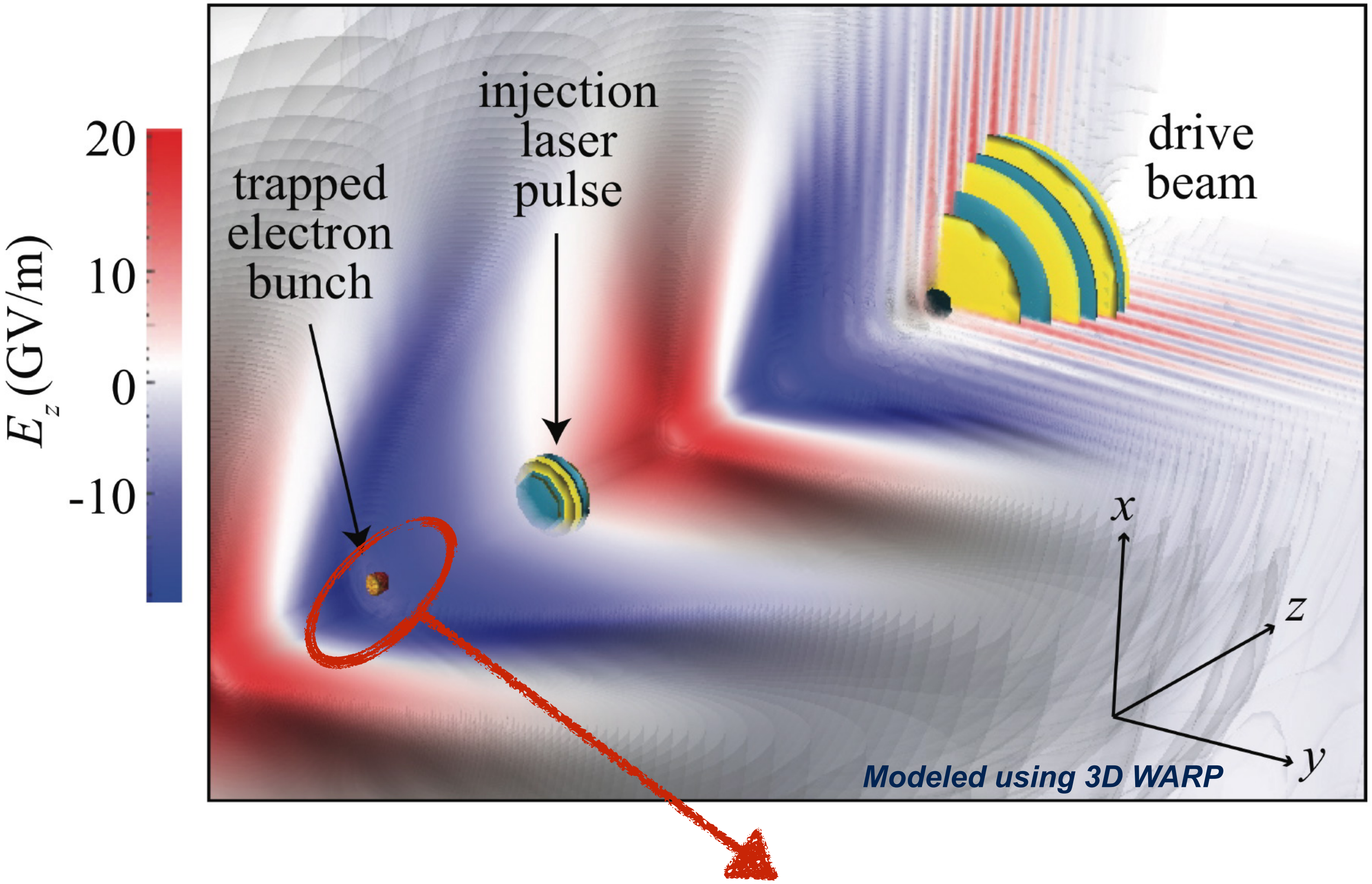
- Ponderomotive force drives plasma wave:

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

- Ionization determined by peak laser electric field:

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

Two-color ionization injection: method to generate ultra-low emittance beams

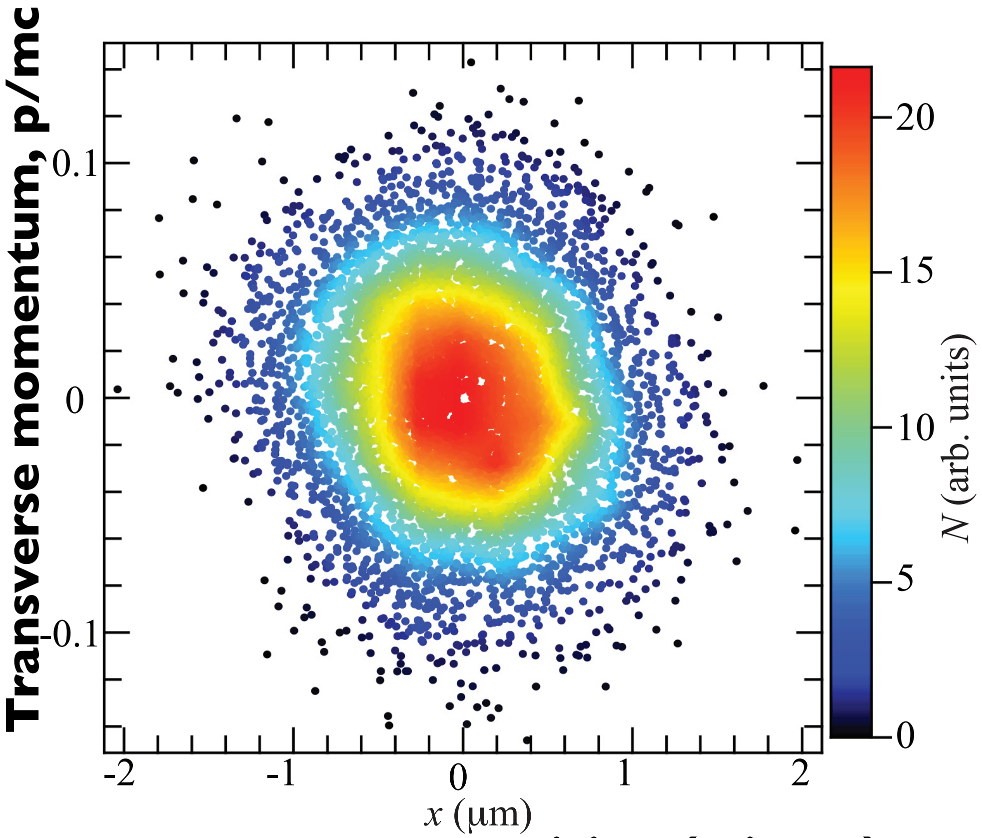


Pump laser pulse (circular-polarization):
a=1.2, 5 um wavelength
92 fs, 36 um spot

Injection laser pulse (linear-polarization):
a=0.1, 0.4 um wavelength
16 fs, 5 um spot

plasma:
Krypton gas, $2\text{x}10^{17}$ cm^{-3}

transverse phase space (in laser polarization plane):
normalized emittance = 20 nm



➡ Ultra-low normalized emittance:

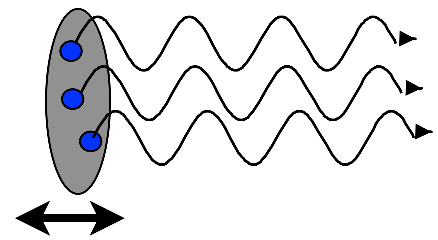
$$\epsilon_y \simeq \epsilon_x = k_p w_i^2 a_i \left(\frac{3\pi r_e}{4\sqrt{2}\alpha^4 \lambda_i} \right) \left(\frac{U_H}{U_I} \right)^{3/2}$$

C. Schroeder et al., PR ST Accel. Beams. (2014); C. Schroeder et al. SPIE (2015)

Laser-plasma accelerator applications: Radiation generation

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

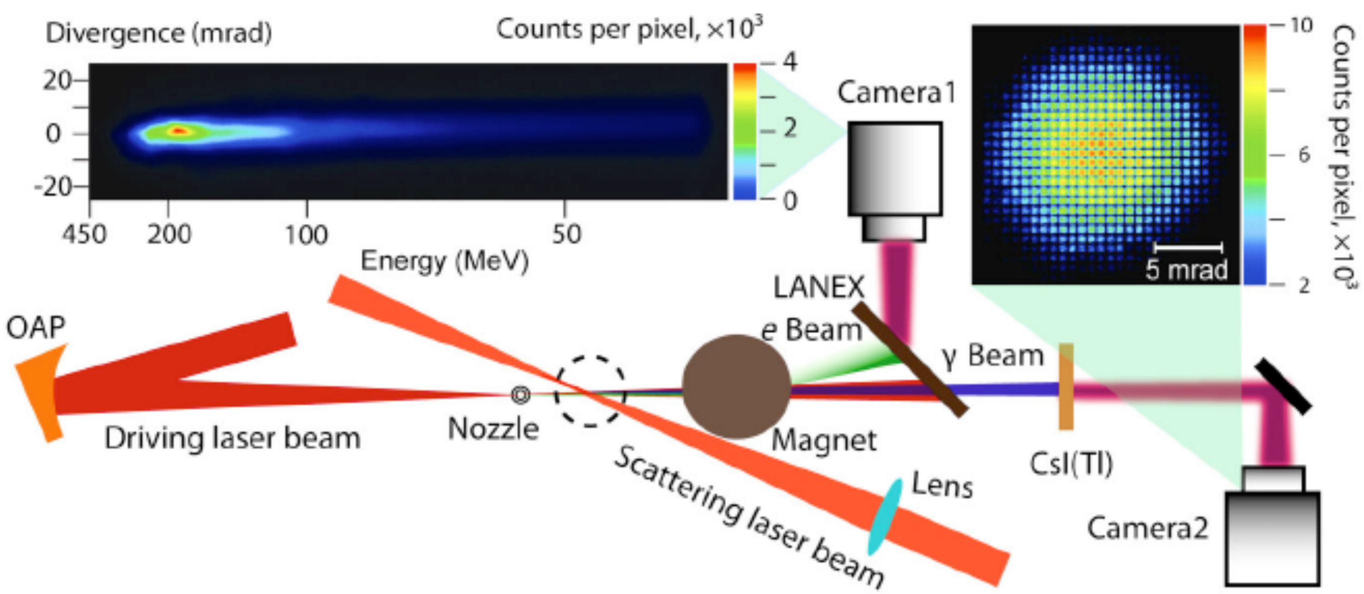
- **high-field THz generation** -- Coherent transition/diffraction radiation of short bunches



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)

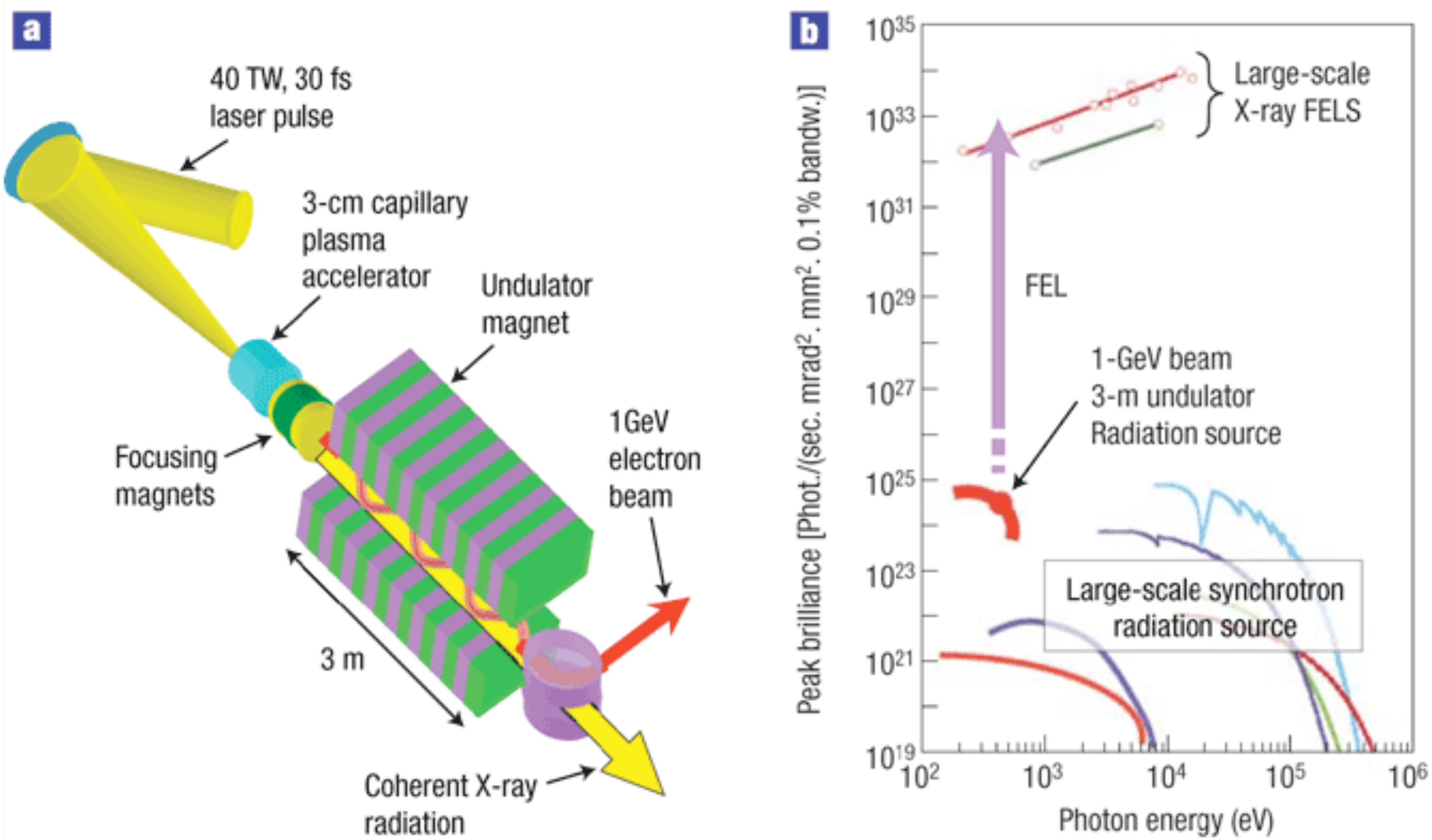
~MeV photons

- **Betatron radiation** -- synch. rad. from beam in trans. wakefield -- fs, broadband, hard x-rays
- **Undulator radiation** -- fs source of soft x-rays *M. Fuchs et al., Nature Physics (2009)*
- **LPA-driven FEL** -- compact source of high-peak power, coherent radiation

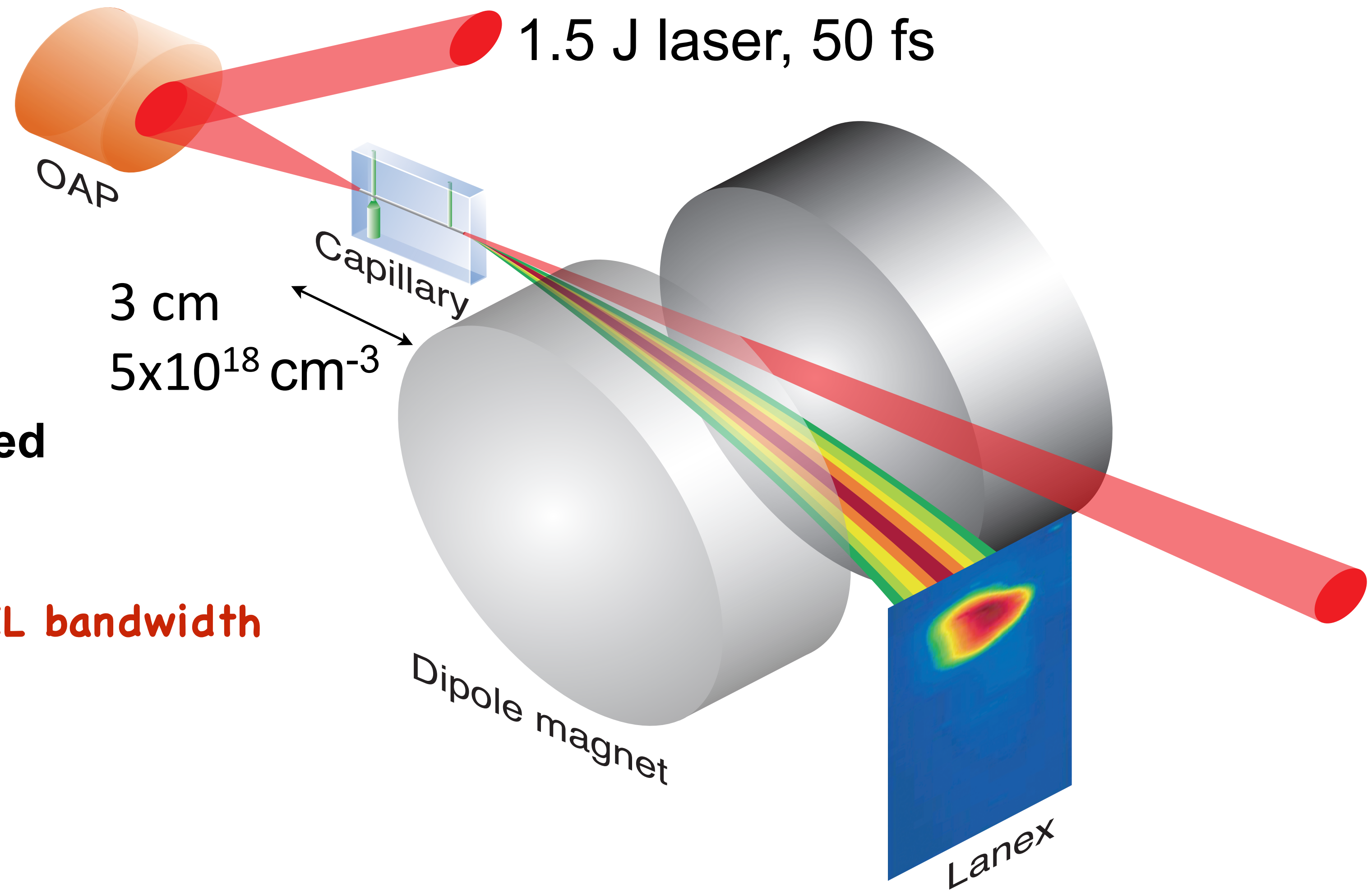
Application: Free-electron laser (FEL)

Schroeder et al., FEL (2006)
Jaroszynski et al., Phil.Trans. R. Soc.(2006)
Grüner et al., APB (2007)
A. Maier et al., PRX (2012)
Huang et al., PRL (2012)
Schroeder et al., FEL (2013)
Couprie et al., PPCF (2016)
T. Liu et al., PRAB (2017)

Nakajima, Nature Phys. (2008)



Laser-plasma accelerator beam characteristics



Experimentally-demonstrated LPA beam parameters:

0.1-1 GeV energy

1-10% energy spread > FEL bandwidth

1-100 pC charge

1-10 fs duration >1 kA

0.1-1 micron emttance

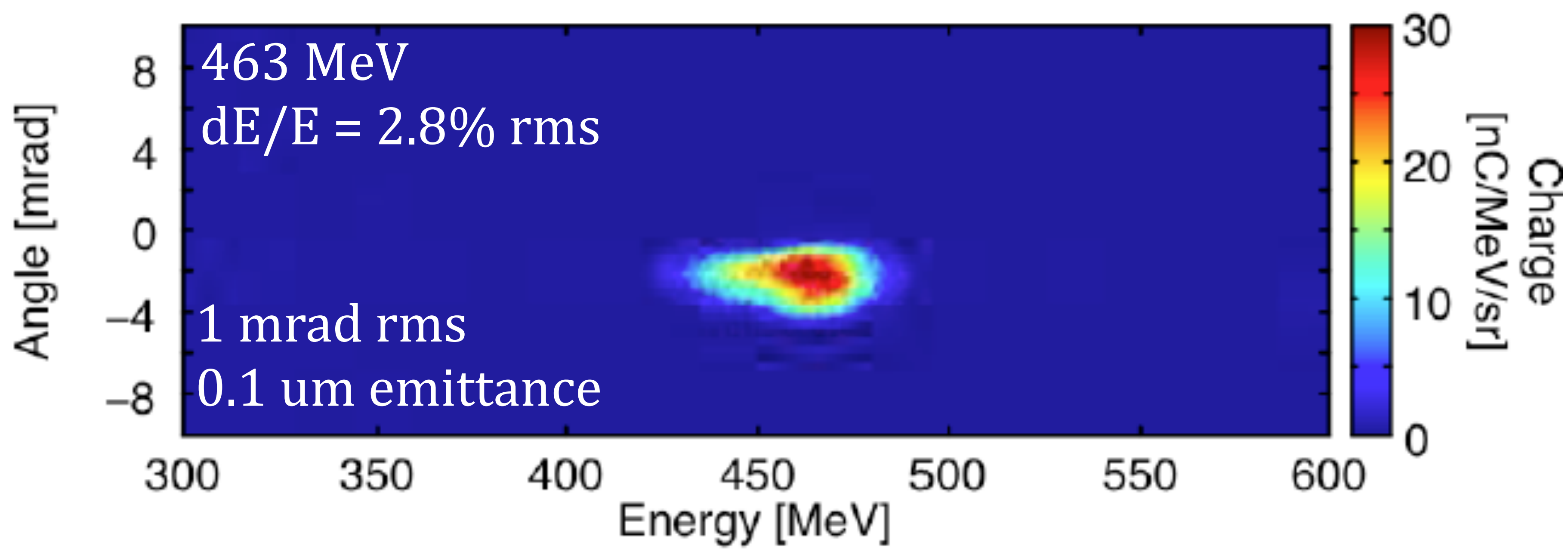
1-10 Hz

Laser foot-print:

(few m)x(few m)

for 100 TW peak power

(10 Hz) laser system



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

- Energy spread order of magnitude too large (for soft-x-ray FEL)
  - Required beam energy spread < FEL bandwidth ~ FEL parameter ~ 10^{-3}
- Beam brightness:

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

LPA

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

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

LCLS (SLAC)

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

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

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

      C. Schroeder et al., FEL (2012); Maier et al., PRX (2012)
    - Transverse dispersion (with transverse gradient undulator)

      Huang et al,. PRL (2012); C. Schroeder et al., FEL (2013)

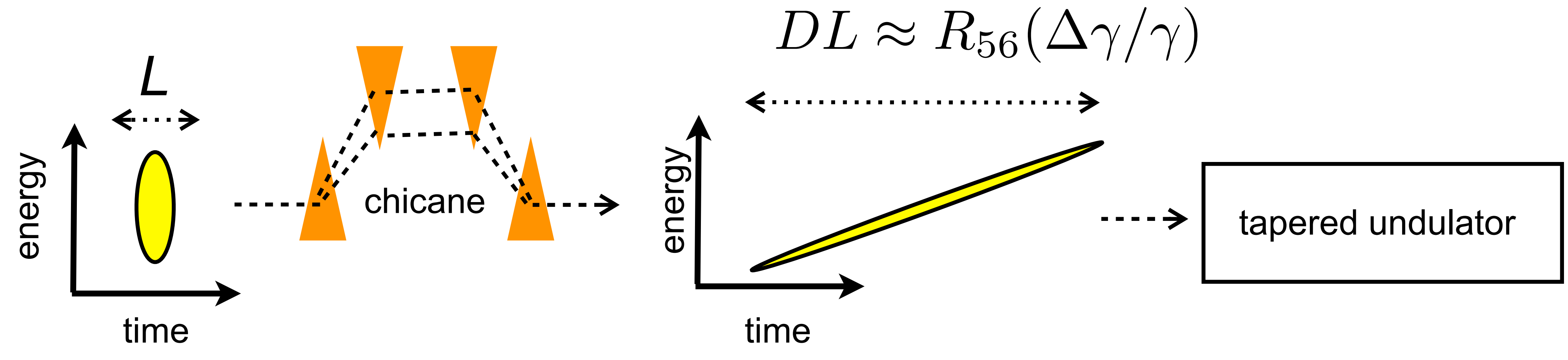
FEL with present LPA performance: Beam decompression

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

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

$$DL \approx R_{56}(\Delta\gamma/\gamma)$$

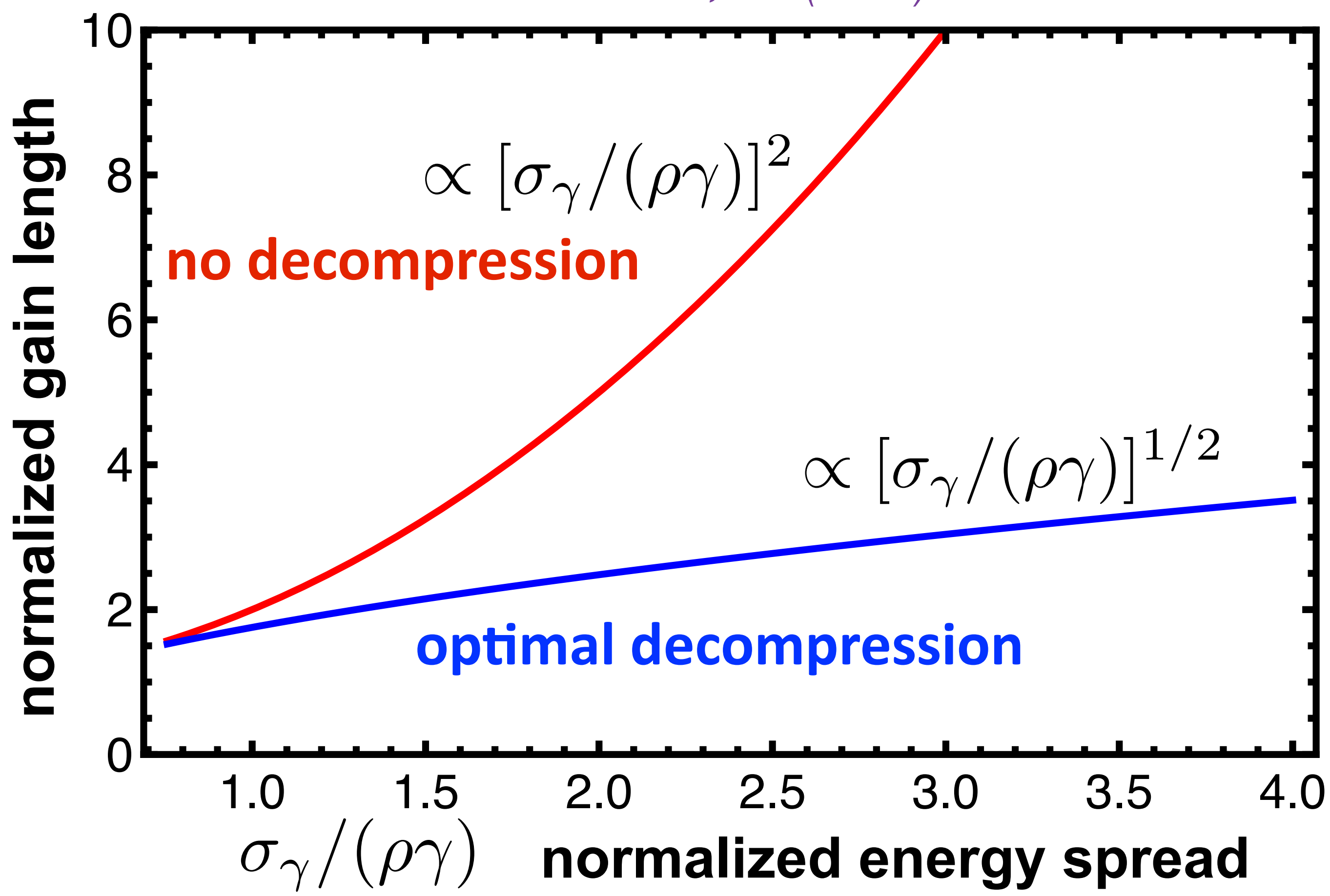
LPA e-beam



Schroeder et al., FEL (2012)

Decompression:

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



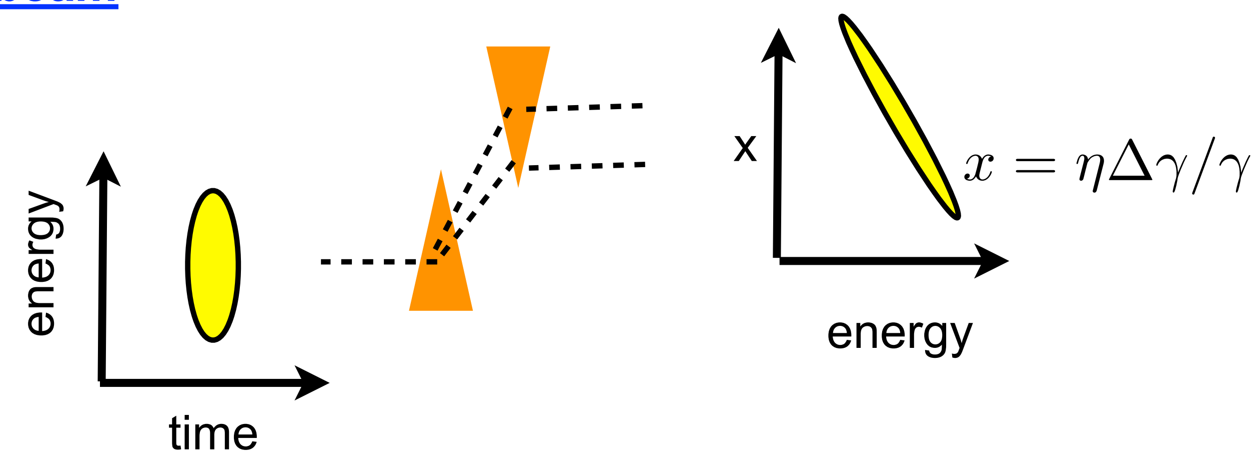
Beam Dispersion and transverse gradient undulator for large energy spread acceptance

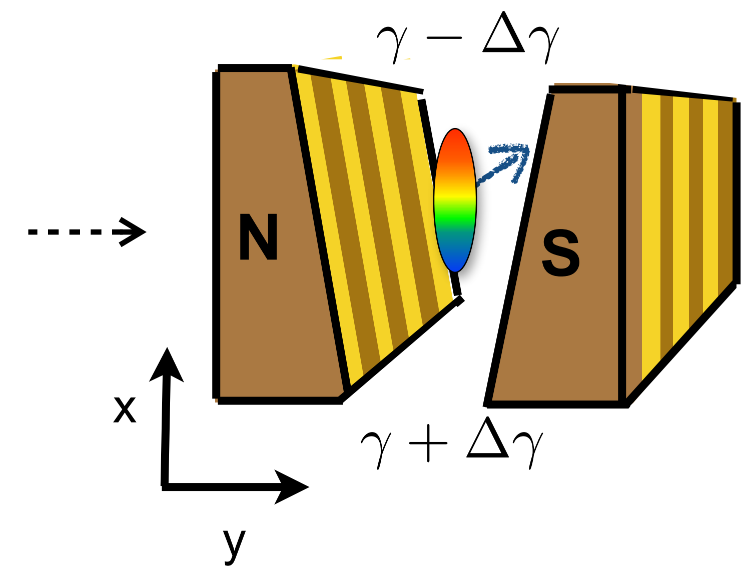
Transverse gradient undulator (TGU):

Huang, Ding, Schroeder, PRL (2012)

canted-pole undulator

LPA e-beam





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

- Resonant condition:

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

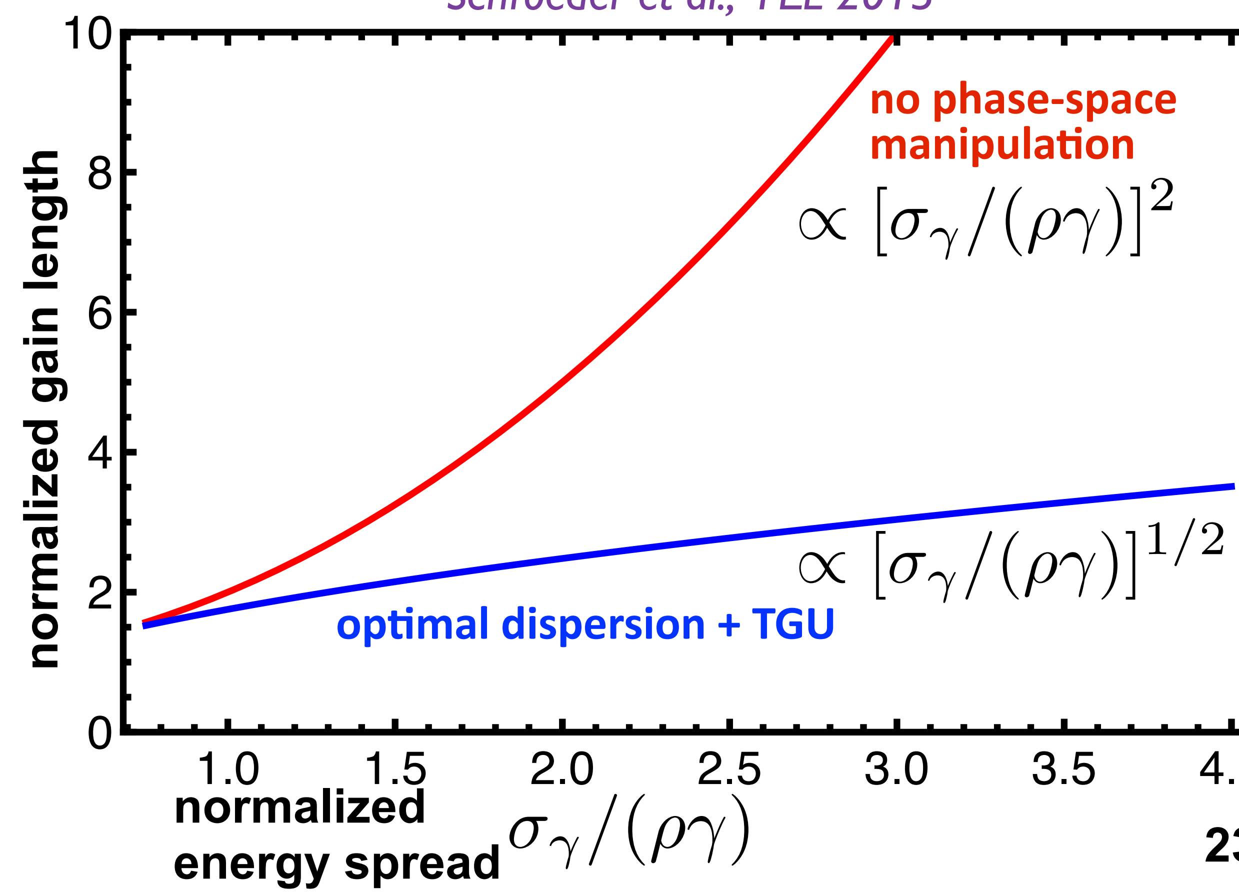
- Sort e-beam energies, couple to TGU to satisfy resonant condition:

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

- Dispersion reduces the beam density

- effective energy spread (at transverse slice) reduced

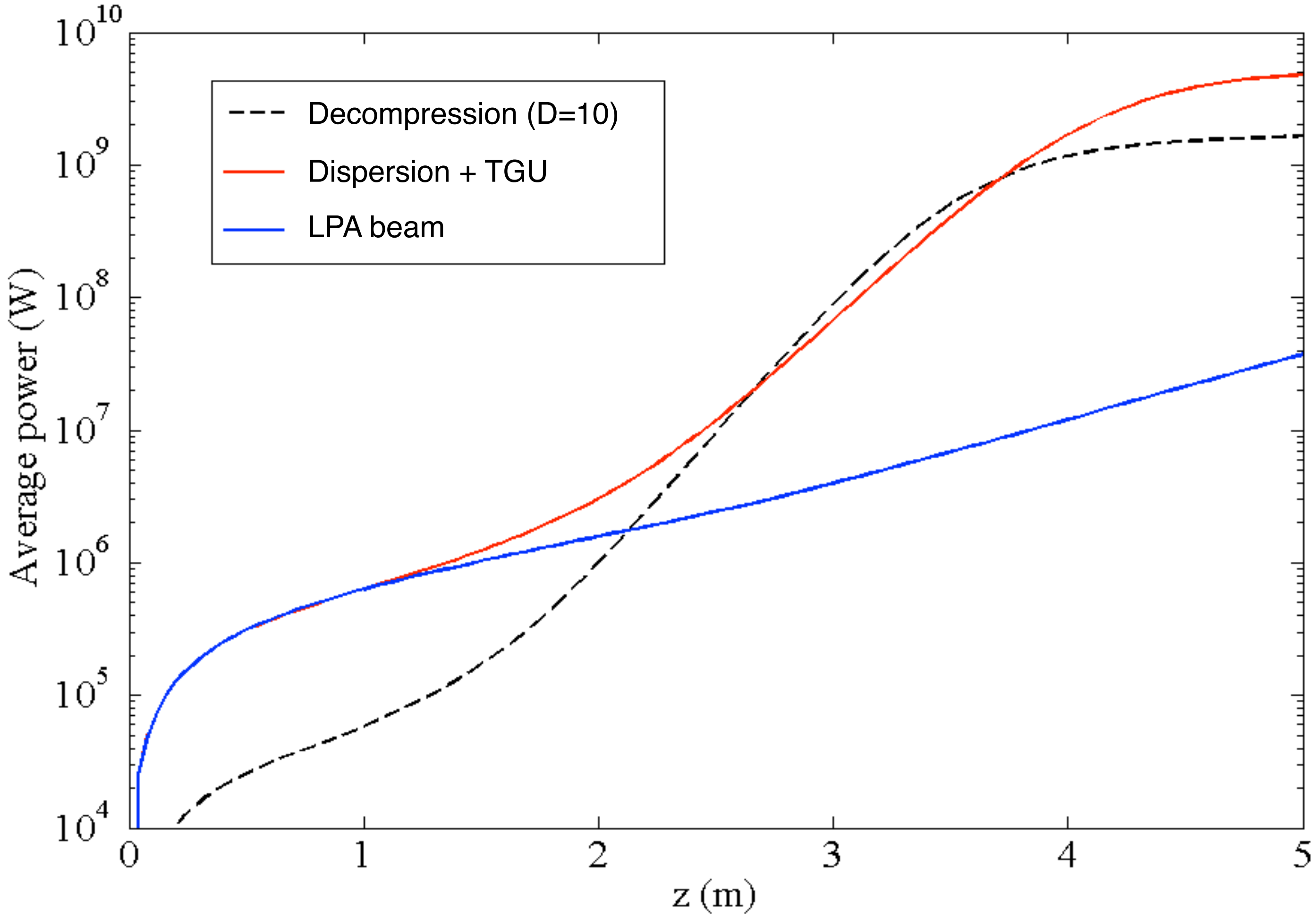
Schroeder et al., FEL 2013

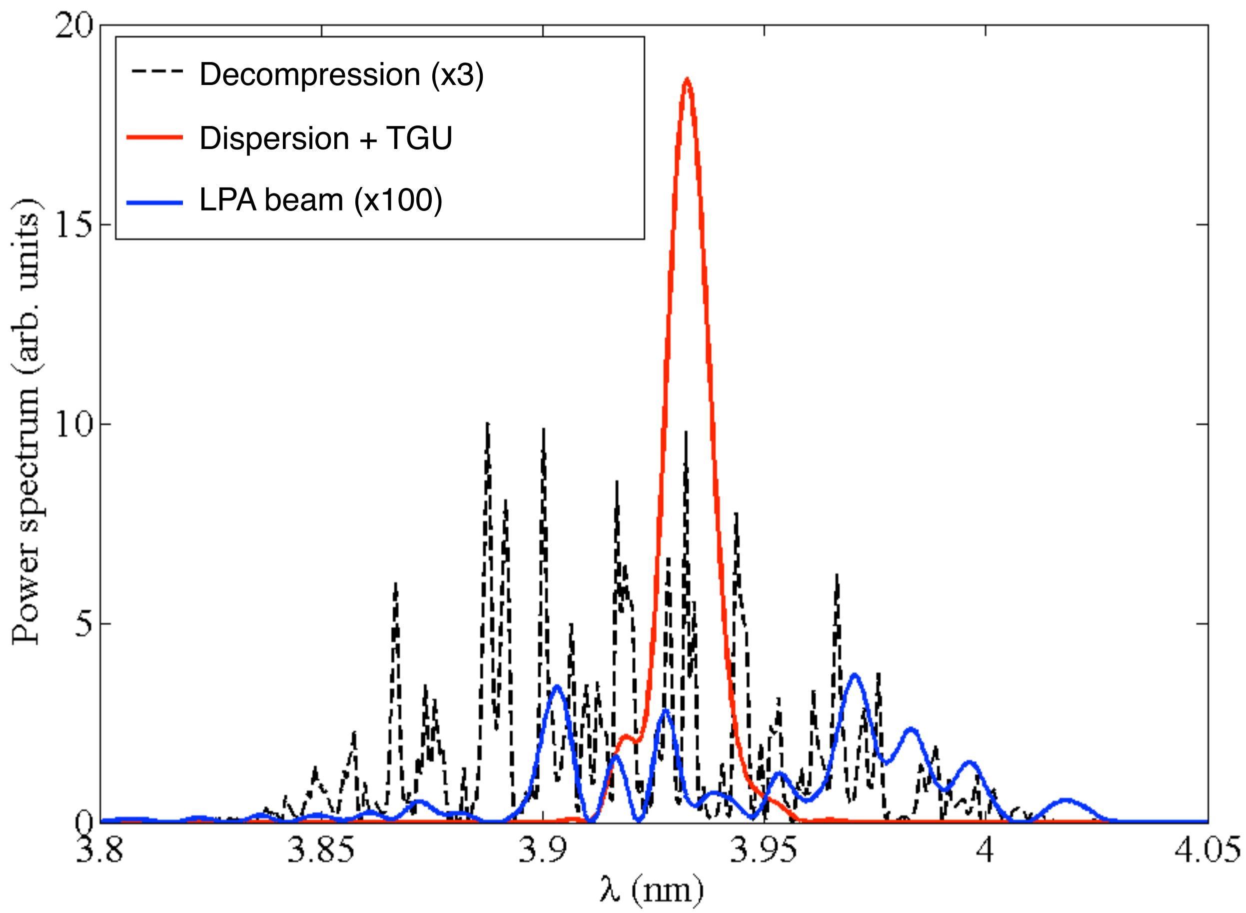


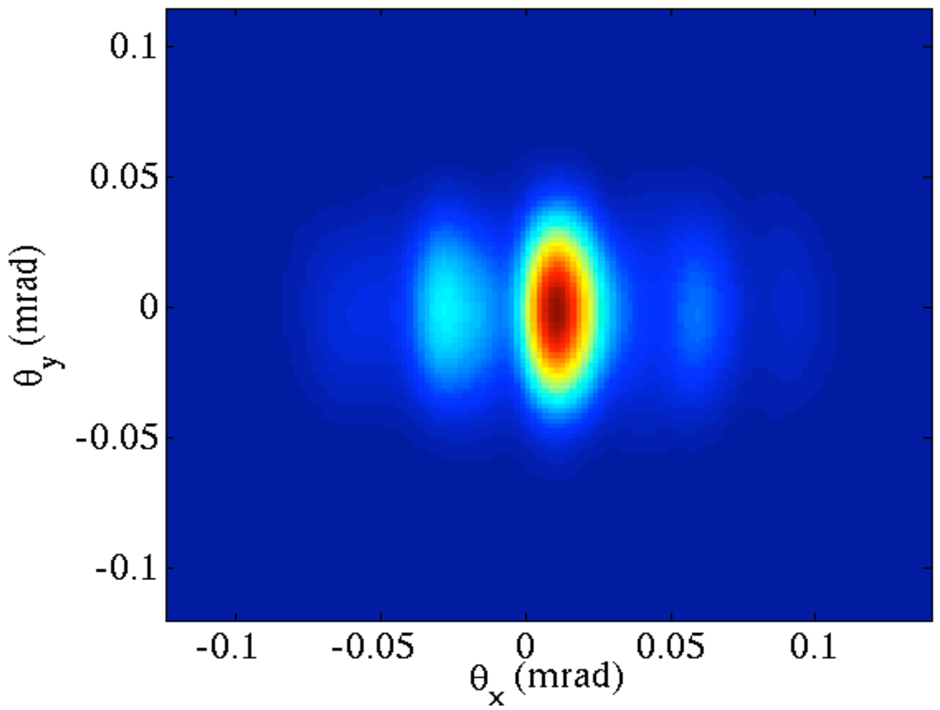
LPA-driven 4-nm FEL using electron-beam phase space manipulation

- 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)

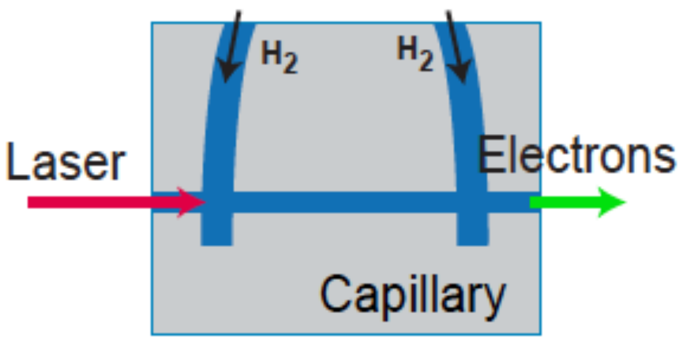


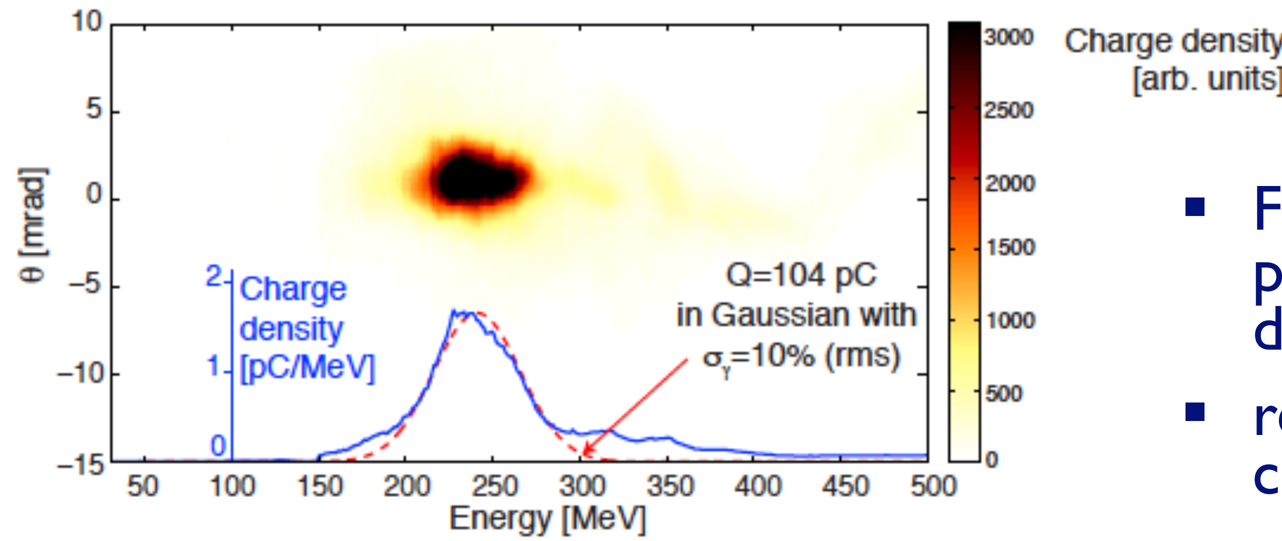




LBNL experimental path to FEL lasing: electron beam decompression

J. van Tilborg et al., AAC (2017)

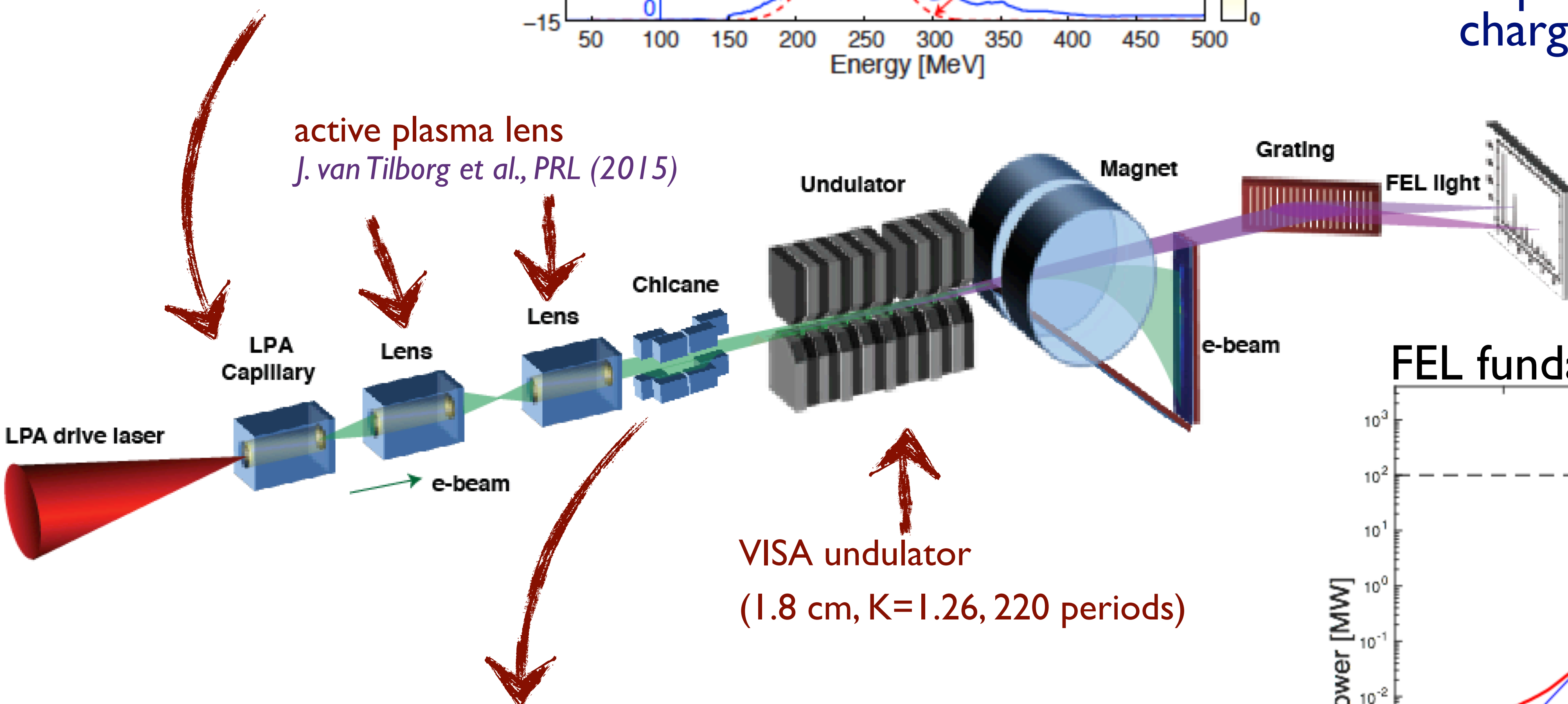




- FEL lasing requires sufficient peak current following decompression
- requires sufficient spectral charge density following LPA

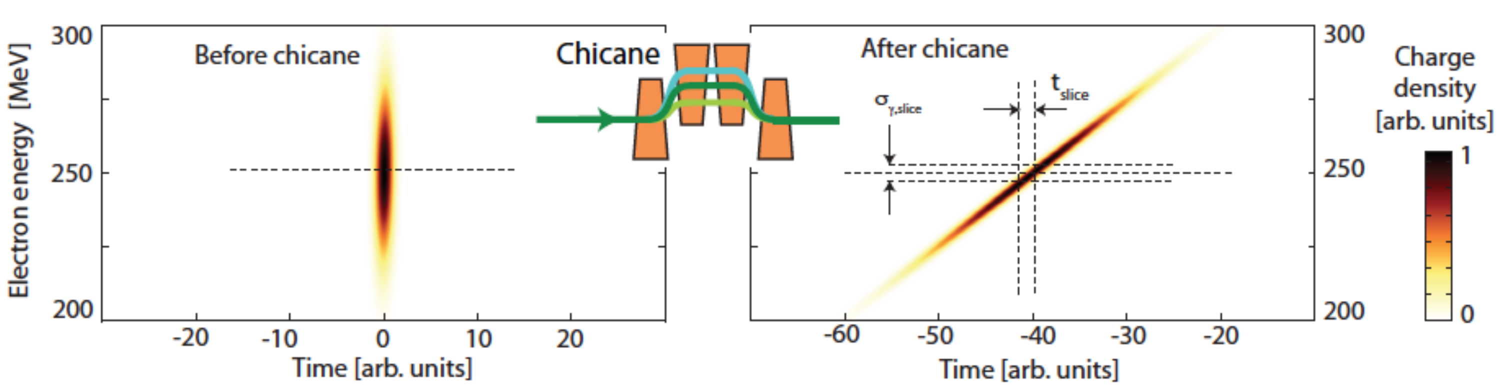
active plasma lens

J. van Tilborg et al., PRL (2015)

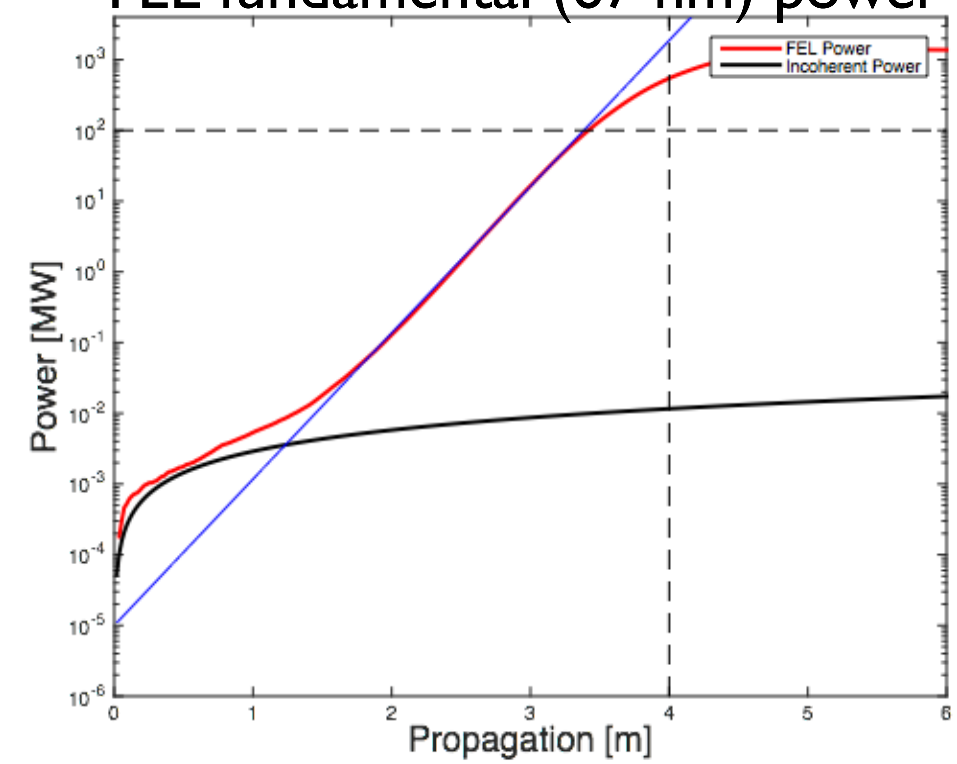


VISA undulator

(1.8 cm, K=1.26, 220 periods)

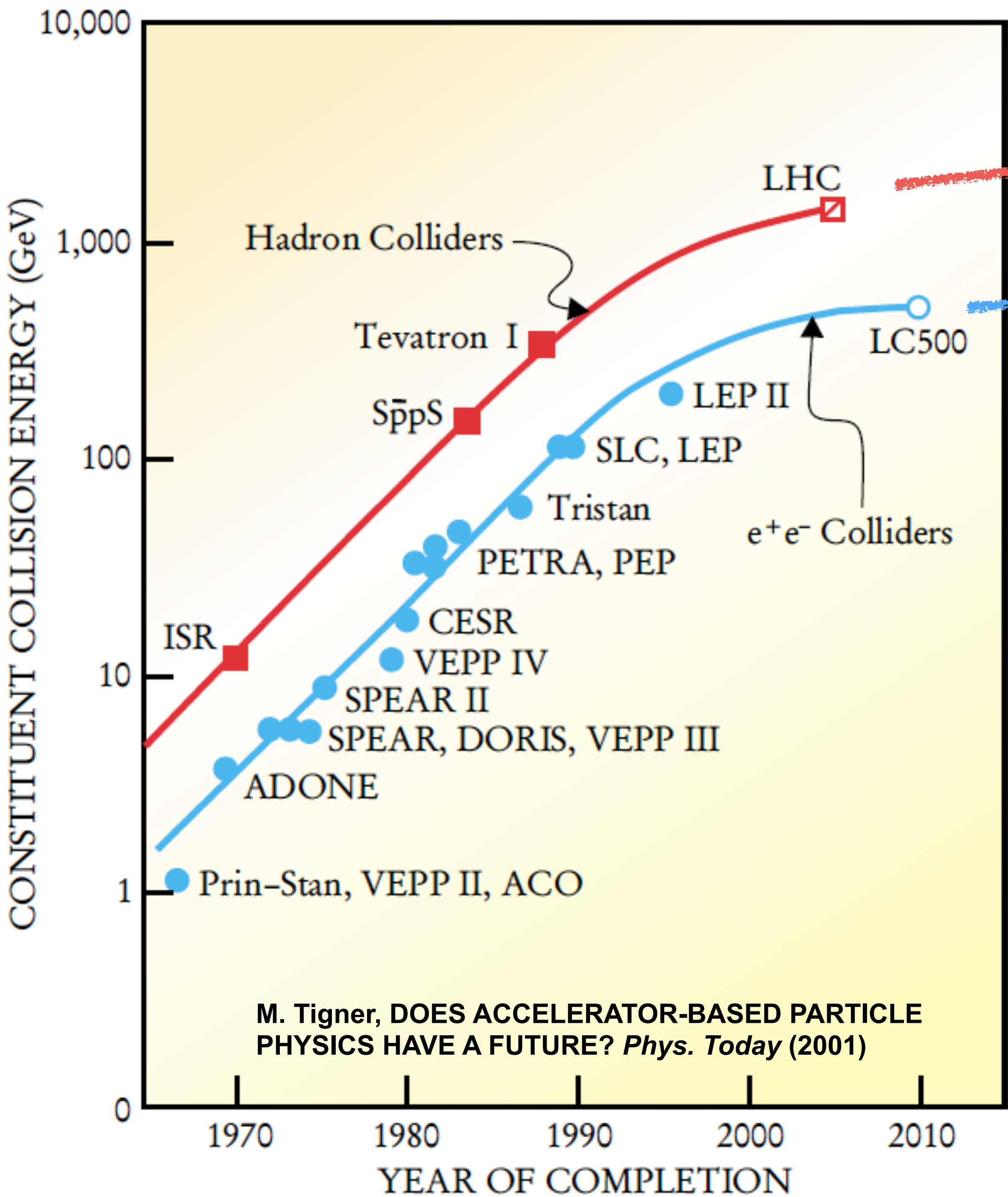


FEL fundamental (67 nm) power

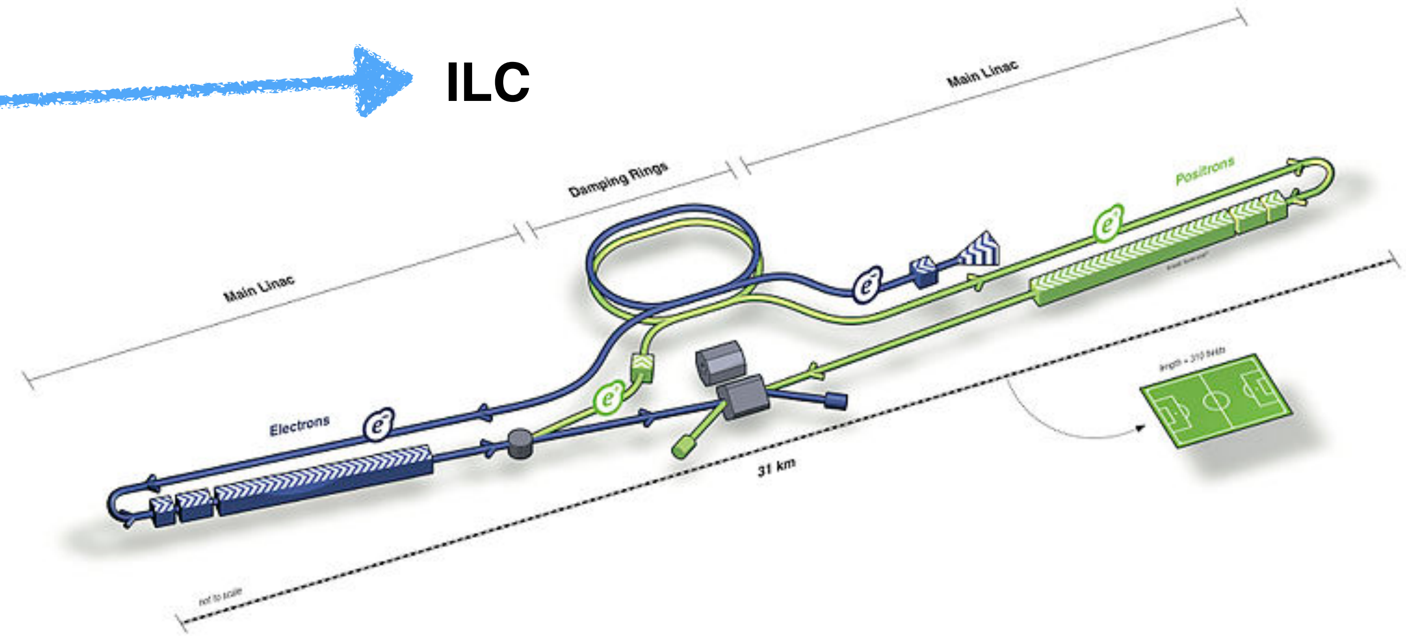


High-energy physics application of LPAs

- “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

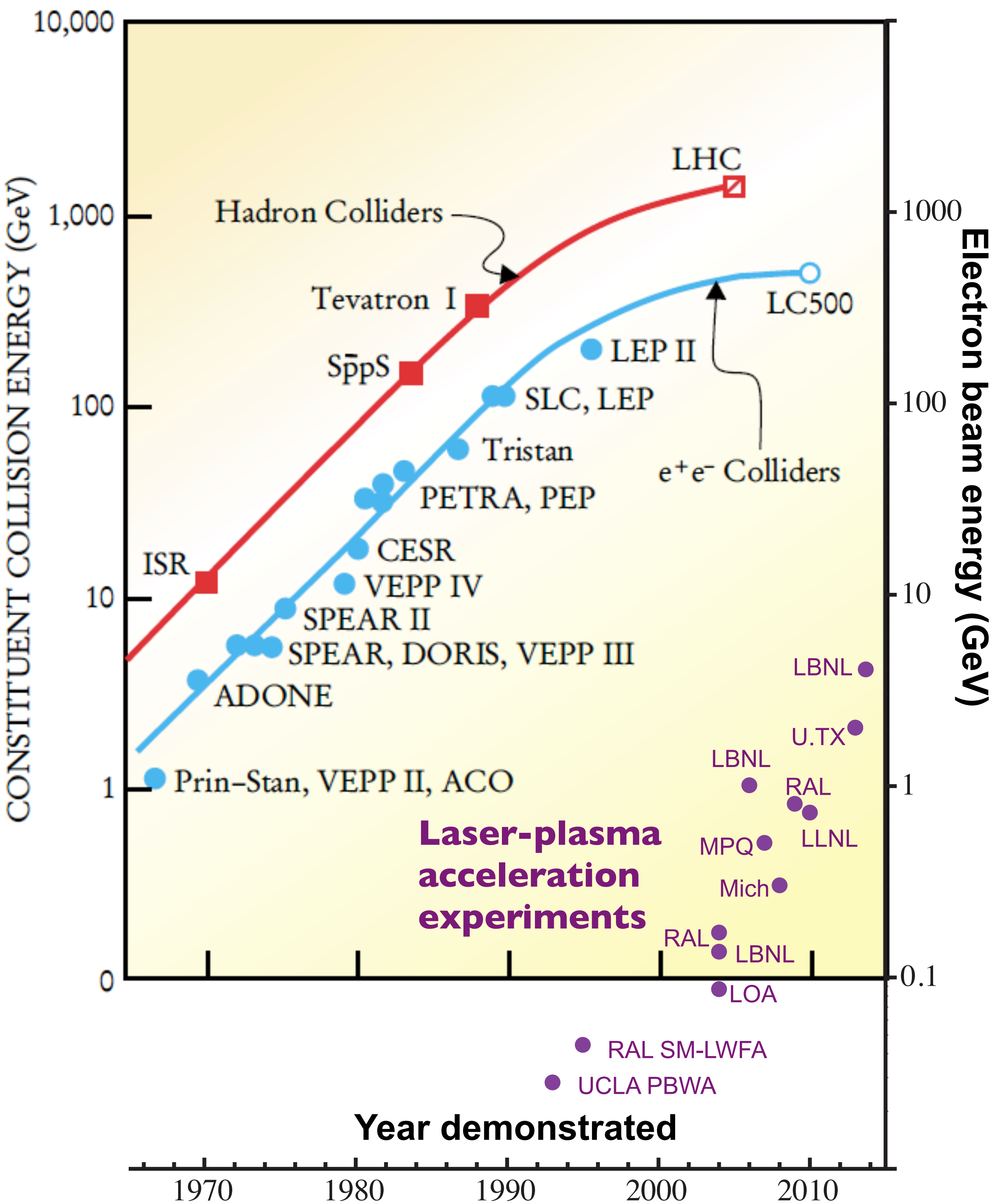


M. Tigner, DOES ACCELERATOR-BASED PARTICLE PHYSICS HAVE A FUTURE? *Phys. Today* (2001)



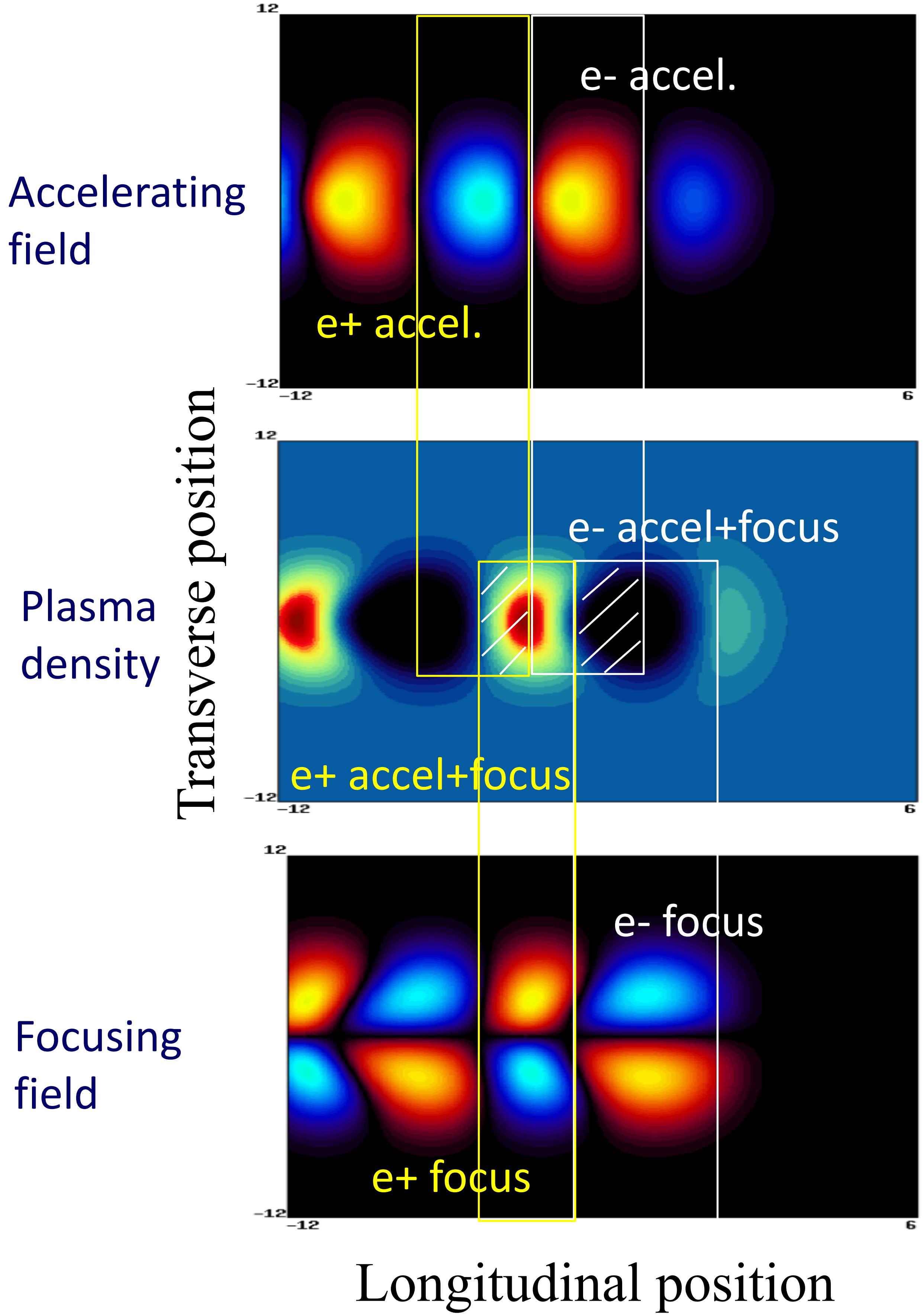
- Largest cost driver is acceleration
  - ~50 MV/m implies ~20 km/TeV
  - Facility costs scale roughly with facility size (and power consumption)
  - >50% cost in main linacs (e.g., ILC)

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

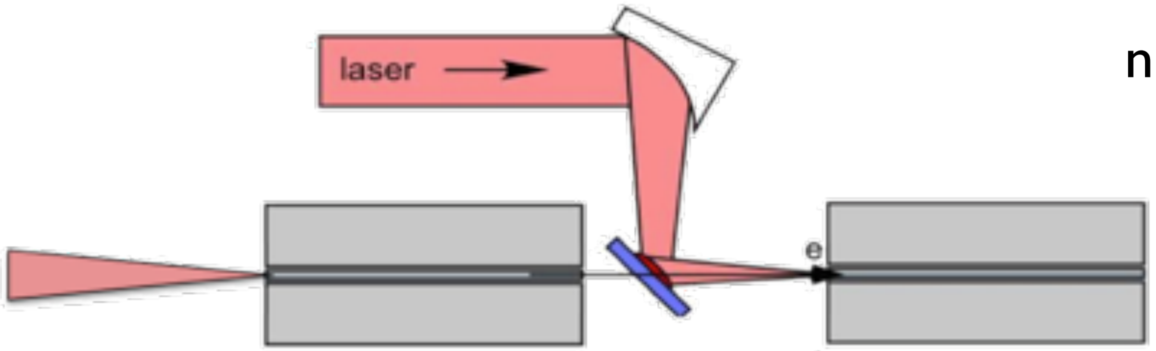
Quasi-linear regime: positron focusing & independent control of acceleration and focusing



- 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

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

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



number of stages: $N_{\rm stage} \propto n\lambda^2$

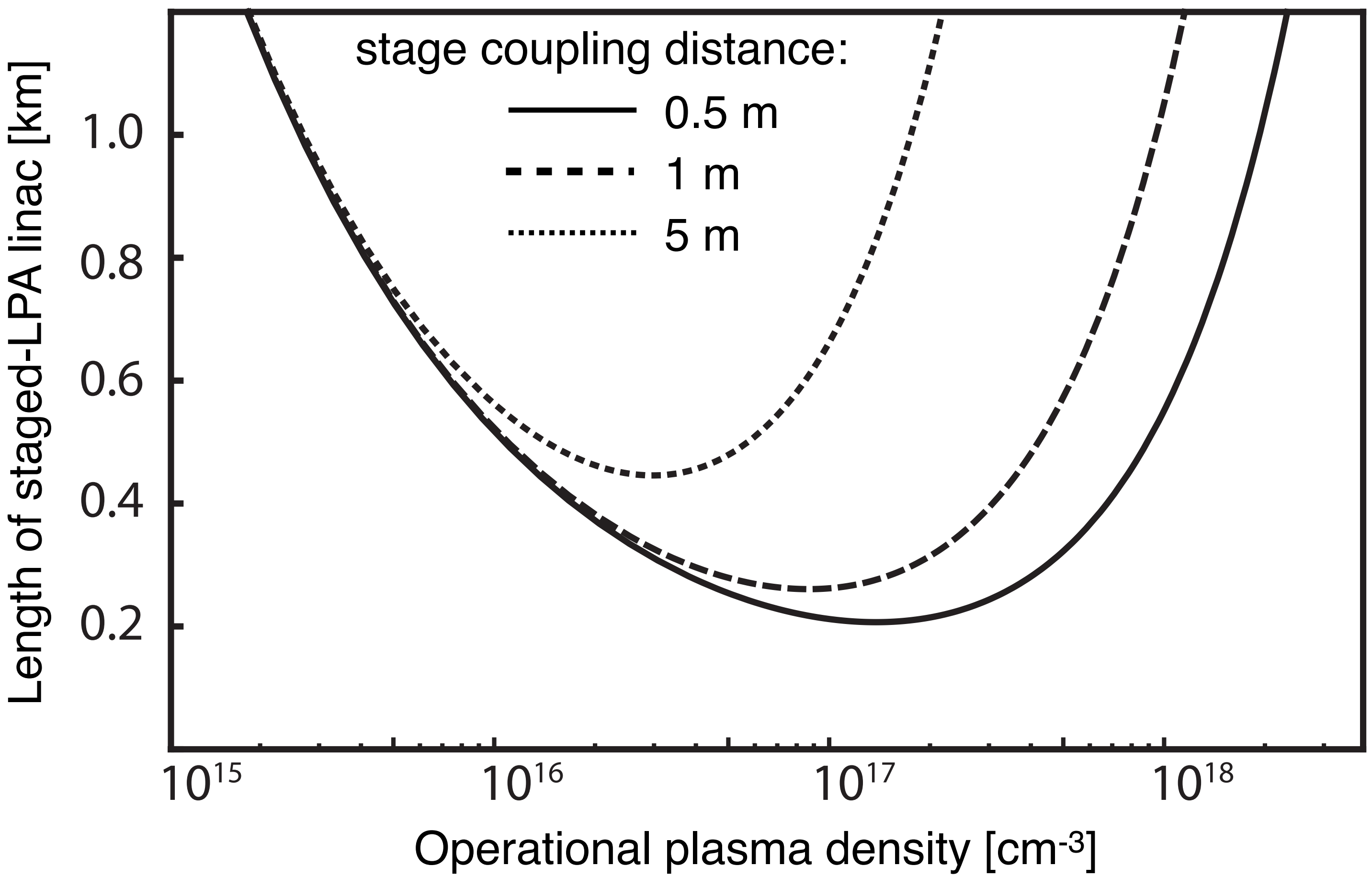
Compact laser in-coupling distance enables high average accelerating gradient:

- Conventional laser optics: requires many Rayleigh ranges to reduce fluency on optic (avoid damage)

$$L_{\rm coupling} \propto n^{-5/4}\lambda^{-1}$$

- Plasma mirror: relies on critical density plasma production (high laser intensity): laser coupling <1 m

Length of 1 TeV staged-LPA linac



Average power reduced at lower plasma density (Beamstrahlung limits charge/bunch)

Charge/bunch:

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

→ Laser rep rate (for fixed luminosity goal):

$$f \propto n$$

→ Wall-plug power:

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

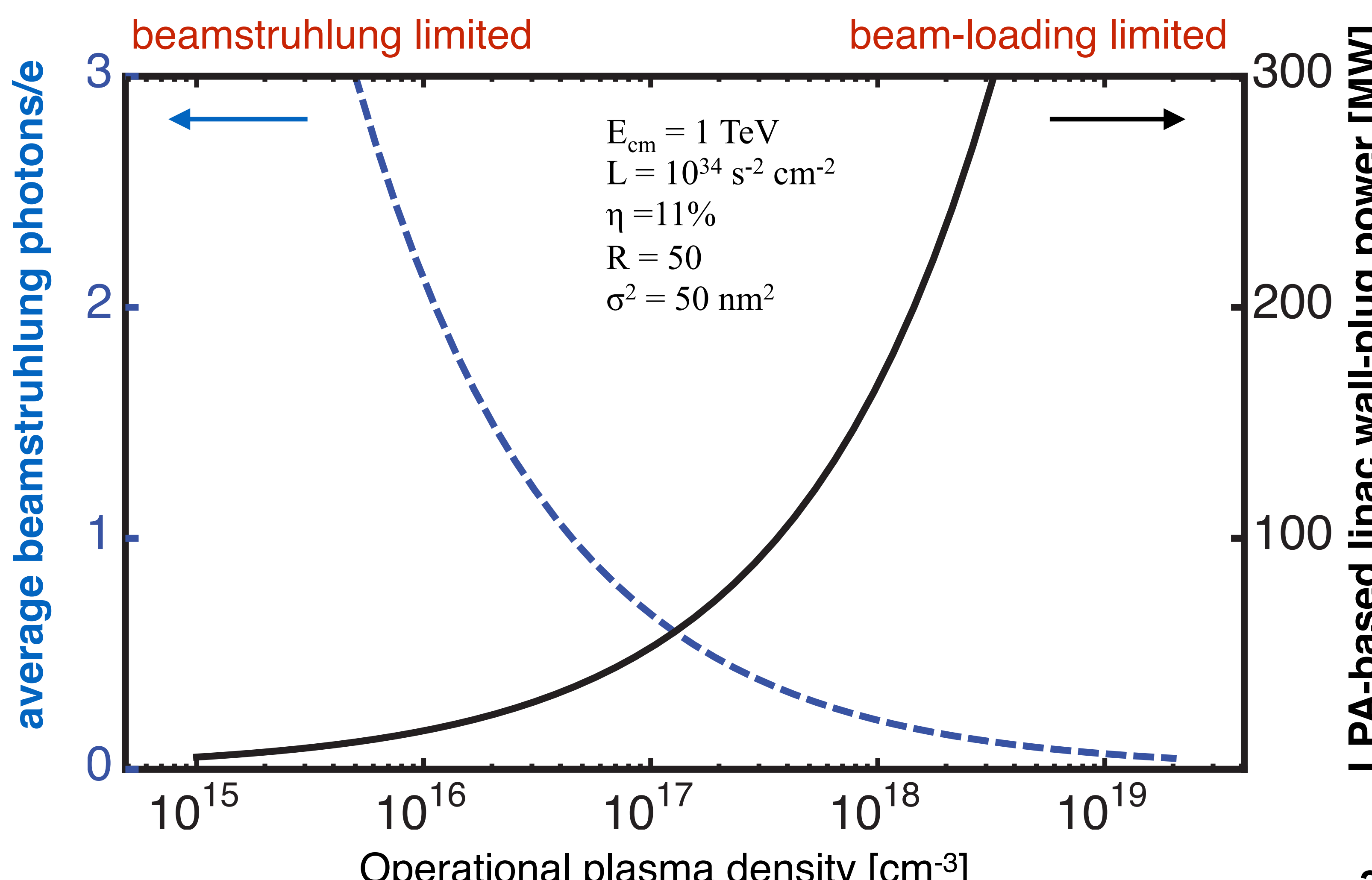
Schroeder et al., PR ST-AB (2010)

Average beamstrahlung photons/e at IP: $$n_\gamma \propto N^{2/3}\sigma_z^{1/3} \propto n^{-1/2}$$

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

Power scalings:

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

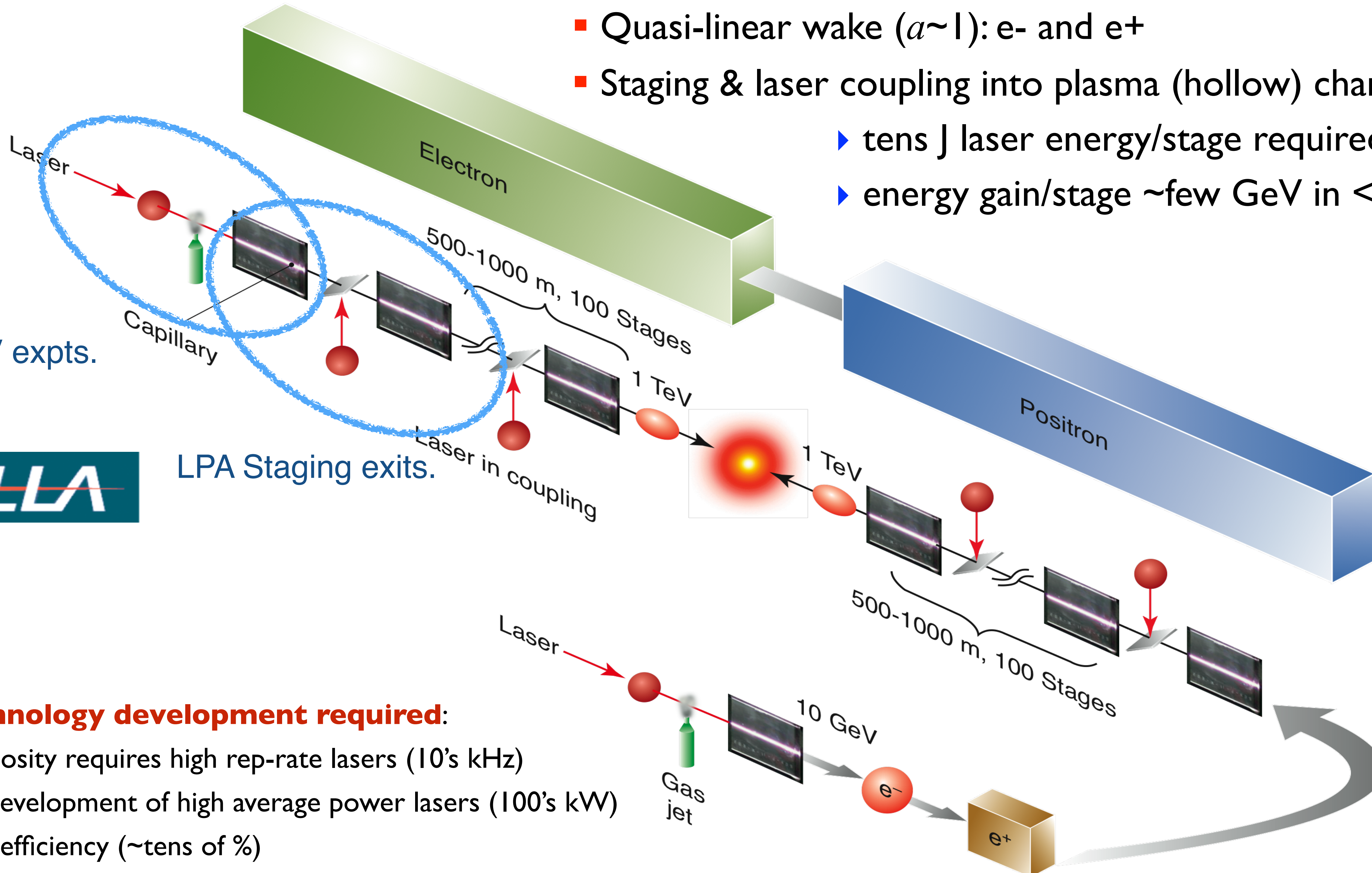


Laser-plasma accelerator-based collider concept

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: $n \sim 10^{17}$ cm^{-3}
- Quasi-linear wake (a~1): e- and e+
- Staging & laser coupling into plasma (hollow) channels:
  - tens J laser energy/stage required
  - energy gain/stage ~few GeV in <1m

Leemans & Esarey, Physics Today (2009)



multi-GeV expts.

BELLA

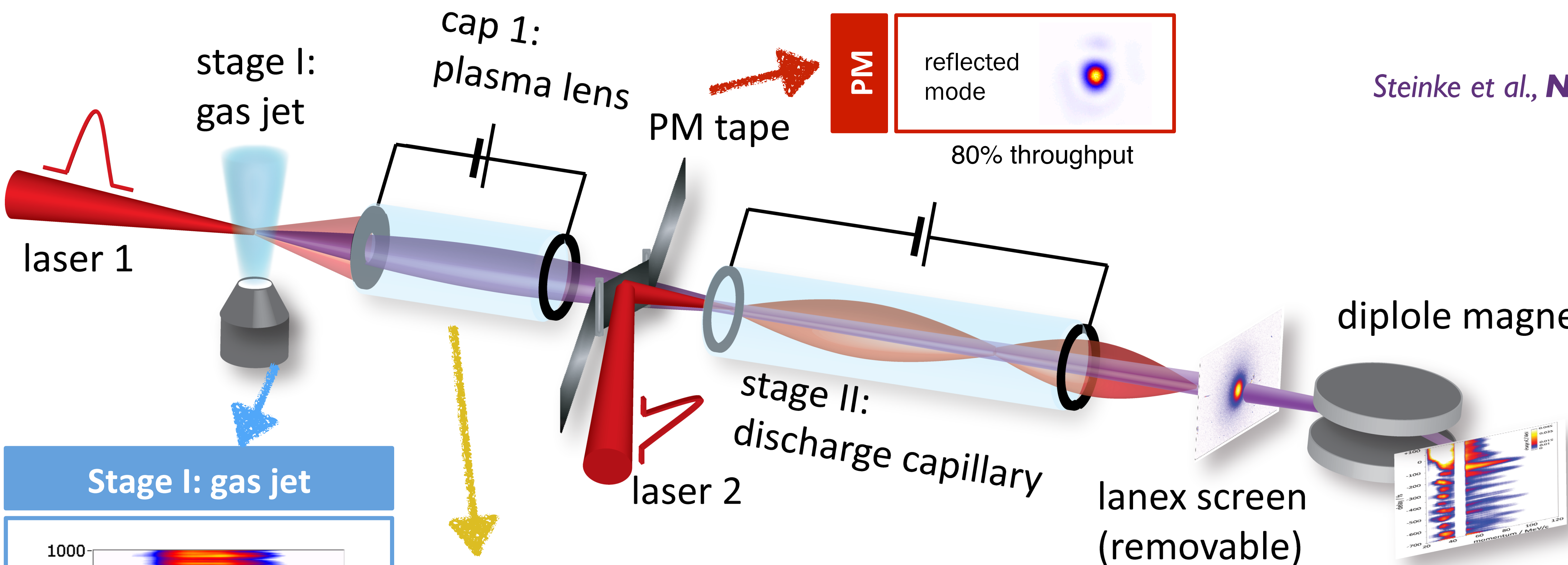
LPA Staging exits.

Laser technology development required:

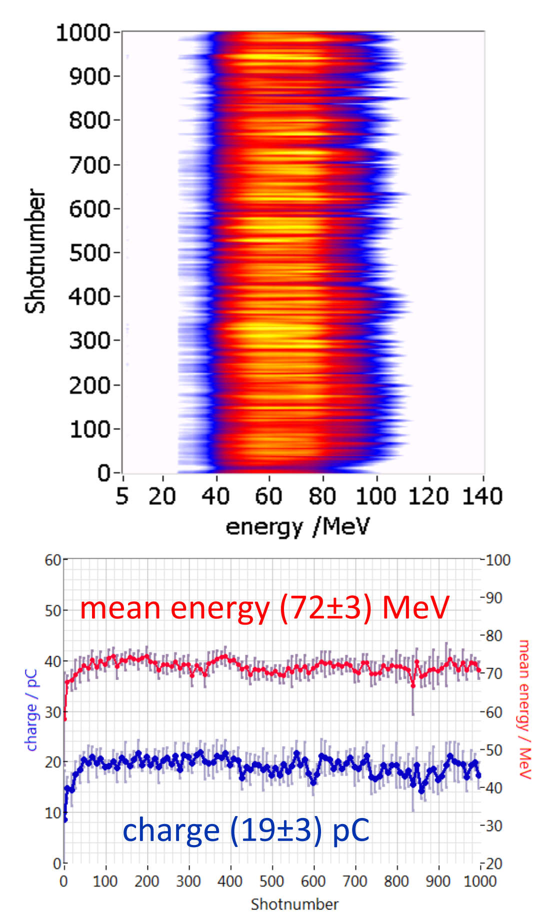
- High luminosity requires high rep-rate lasers (10's kHz)
- Requires development of high average power lasers (100's kW)
- High laser efficiency (~tens of %)

Demonstration of acceleration in second independently-powered laser-plasma accelerator at LBNL

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

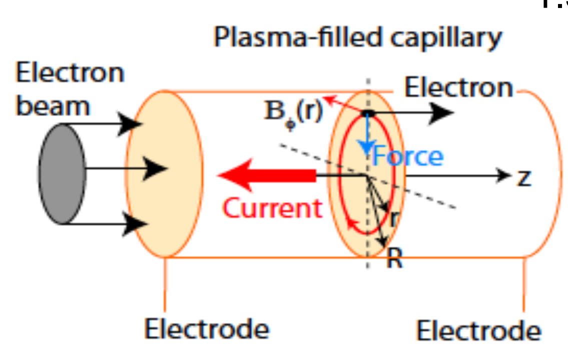


Stage I: gas jet

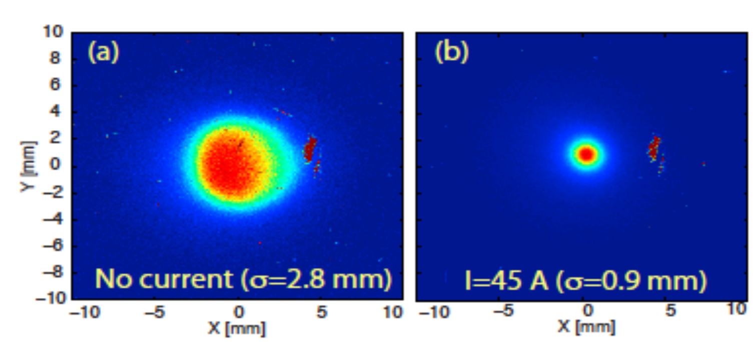


Cap 1: active plasma lens

1.5 cm, up to 3000 T/m



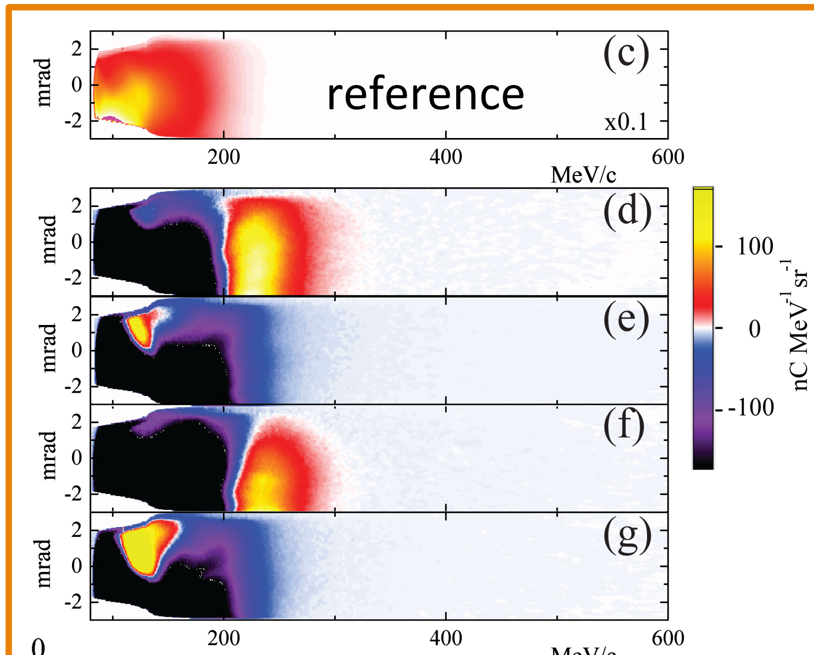
$$\frac{\partial B_\varphi}{\partial r} = \frac{\mu_0 I_0}{2\pi R_{\mathrm{cap}}^2}$$



J. van Tilborg et al., PRL (2015)

lanex screen

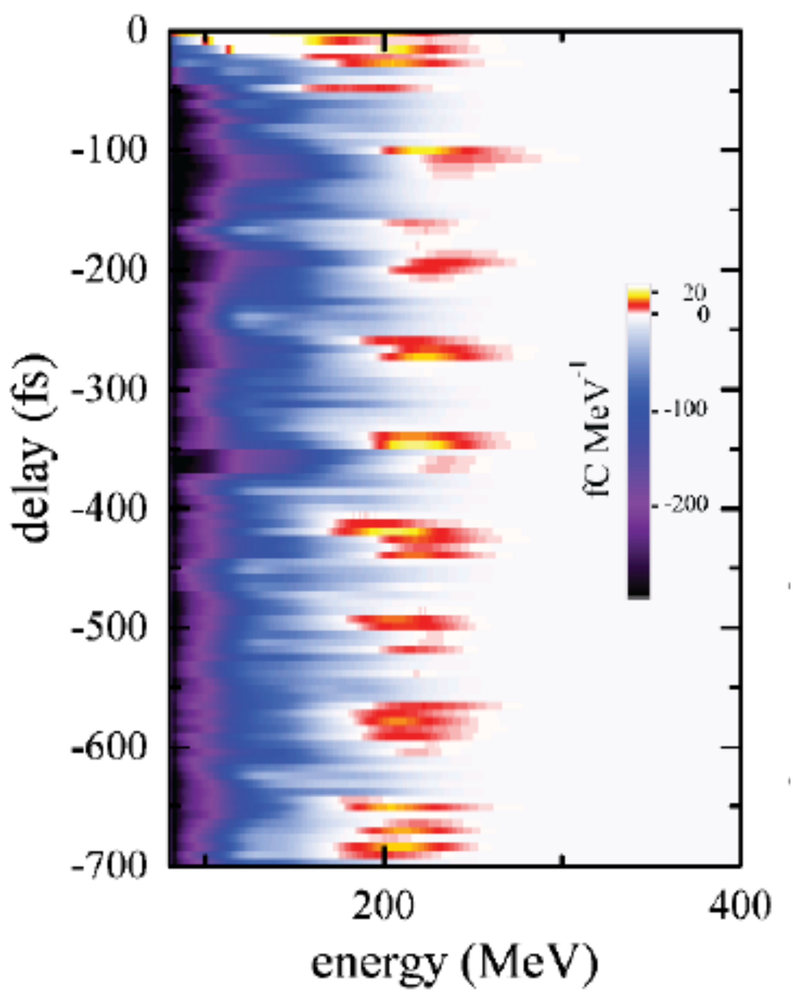
Stage I + II



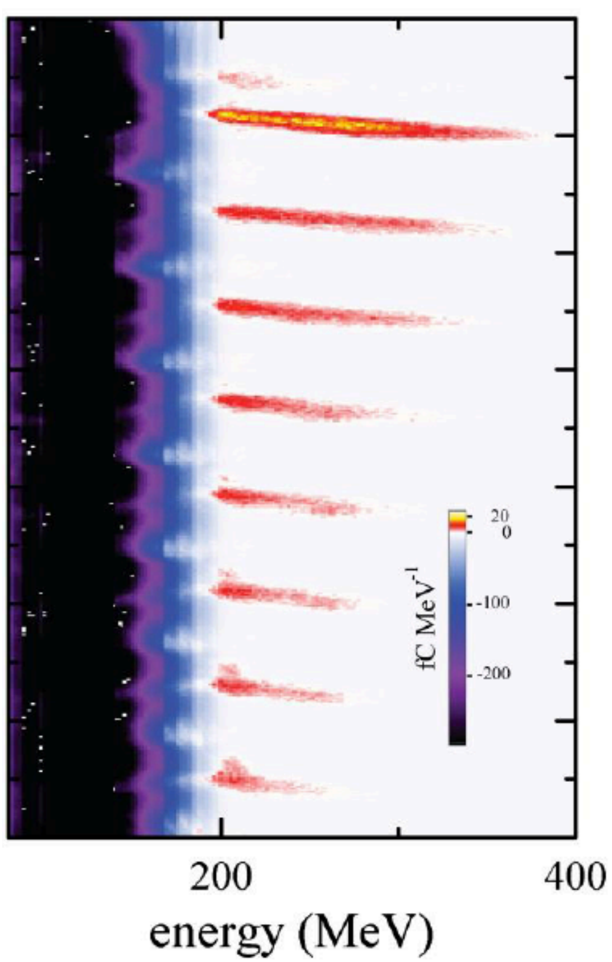
Staged LPA: electron spectra vs laser delay

Electron spectra as a function of delay between Laser/1 (electron beam) and Laser/2

Experiment



(start-to-end) Simulation (using INF&RNO)



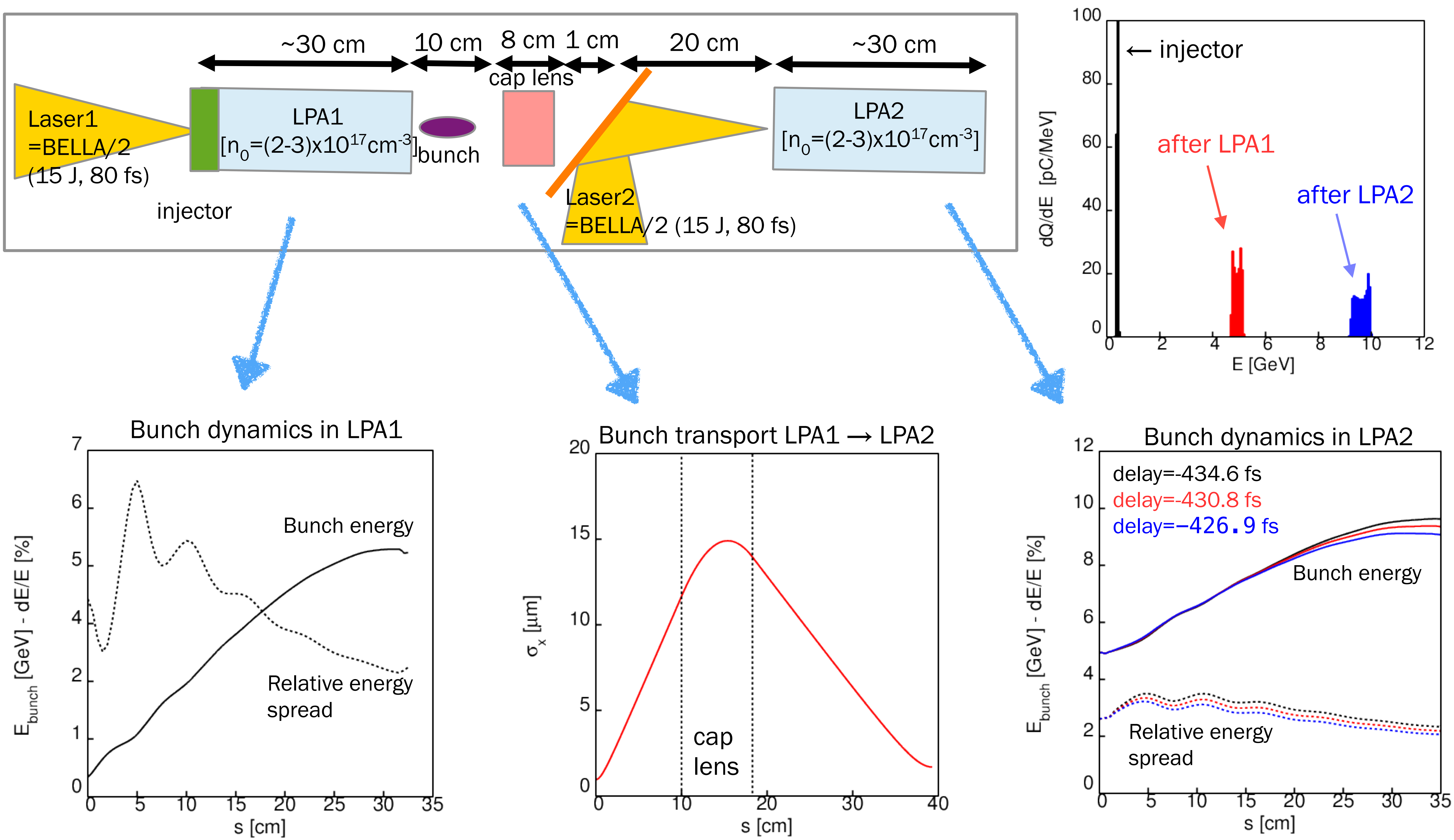
Steinke et al., ***Nature*** *(2016)*

Periodic regions of acceleration (approx. +100 MeV) in the 2nd LPA stage:

- multiple accelerating buckets
- 80 fs modulation period (24 micron plasma wavelength; consistent with 1.9×10^{18} /cc)
- quasi-linear wakefield regime (consistent with laser-plasma parameters, $I_2 = 1.4 \times 10^{18}$ W/cm2)
- bunch length < $\lambda_p/4$

Future LPA staging experiments: 5 GeV + 5 GeV

Steinke et al., Phys. Plasmas (2016)



Conclusions and future directions

- 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 (2-color ionization inj.) — source of ultra-cold beams (emittance~10 nm)
- 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; …
  - Practical application to TeV colliders have many technical challenges
    - Staging LPA experiments underway
    - High peak & average power laser technology development required
- 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

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Wim Leemans

Jean-Luc Vay

and the members of the *BELLA Center*

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