Beam-beam effects in plasma acceleration-based linear collider

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ICFA Mini-Workshop on Beam-Beam Effects in Circular Colliders
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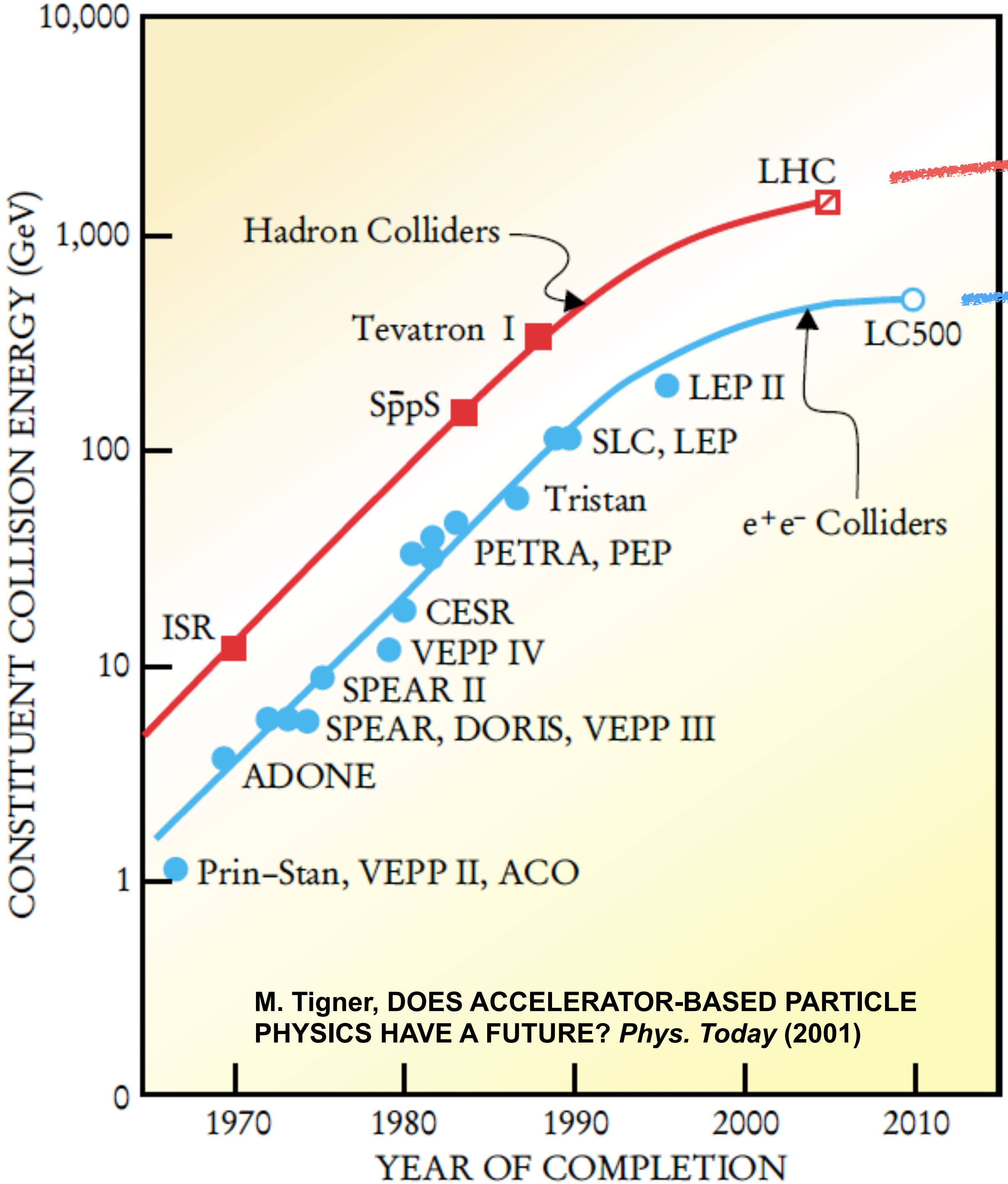
Outline

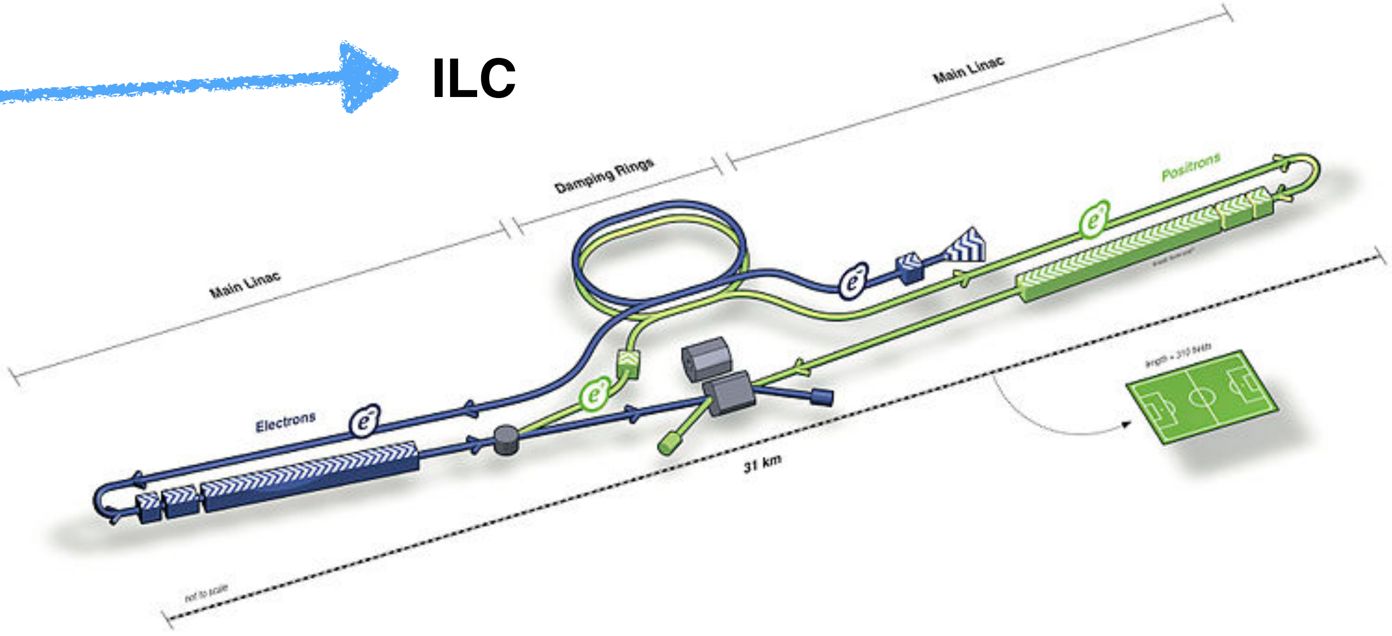
- Laser-driven plasma-based accelerators (LPAs): ultra-high gradient (tens of GV/m) provides compact source of energetic, fs, kA electron beams
  - GeV electron beams in cm-scale plasmas using LPAs
- LPA-based linear collider design considerations
  - operational plasma density
  - beam distribution
  - LPA staging toward high energy
- Beam-beam effects in LPA-based linear colliders
  - Beam-beam interaction effects determine the operational plasma density (determine required laser technology)

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

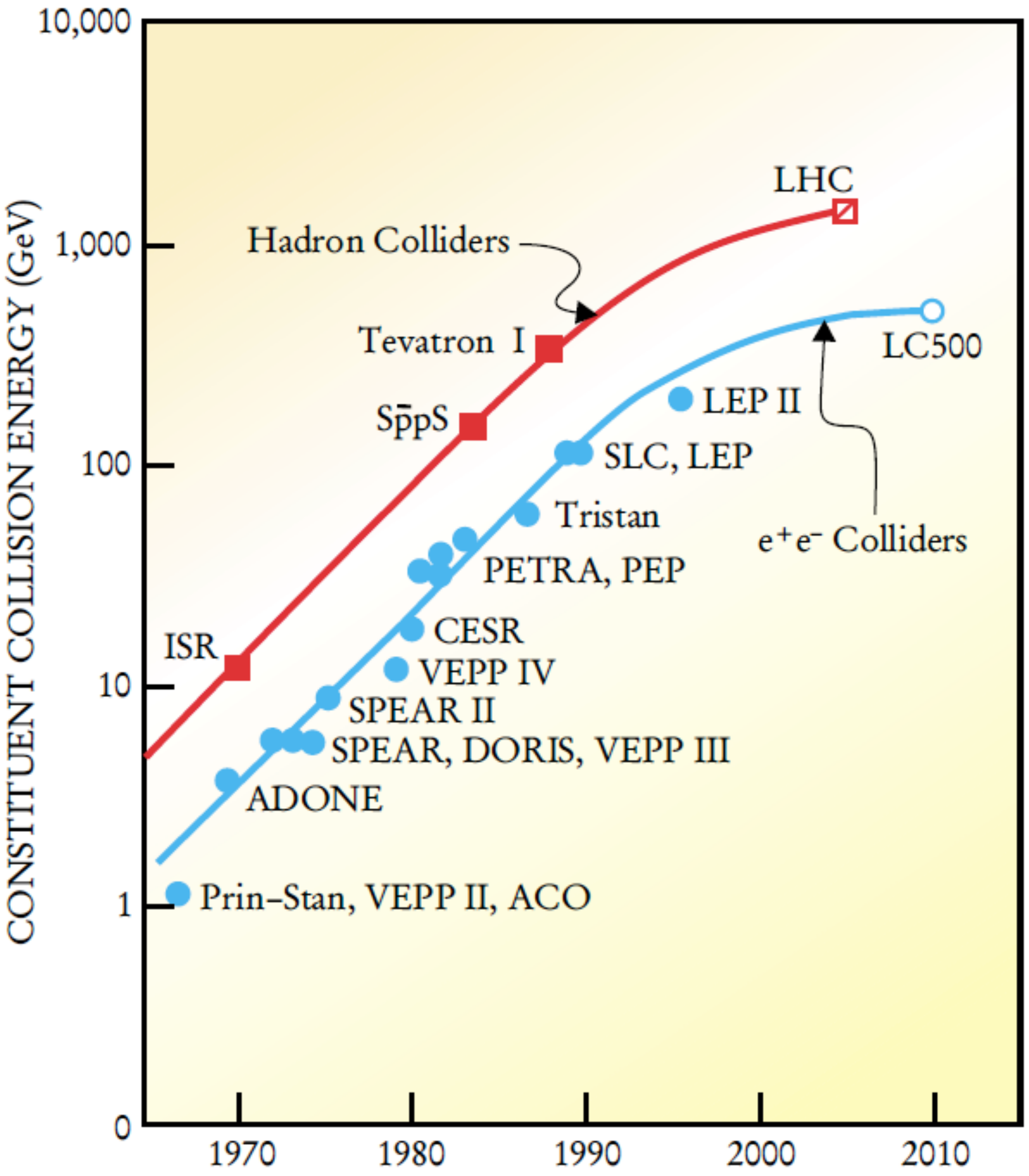


M. Tigner, DOES ACCELERATOR-BASED PARTICLE PHYSICS HAVE A FUTURE? *Phys. Today* (2001)



- 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

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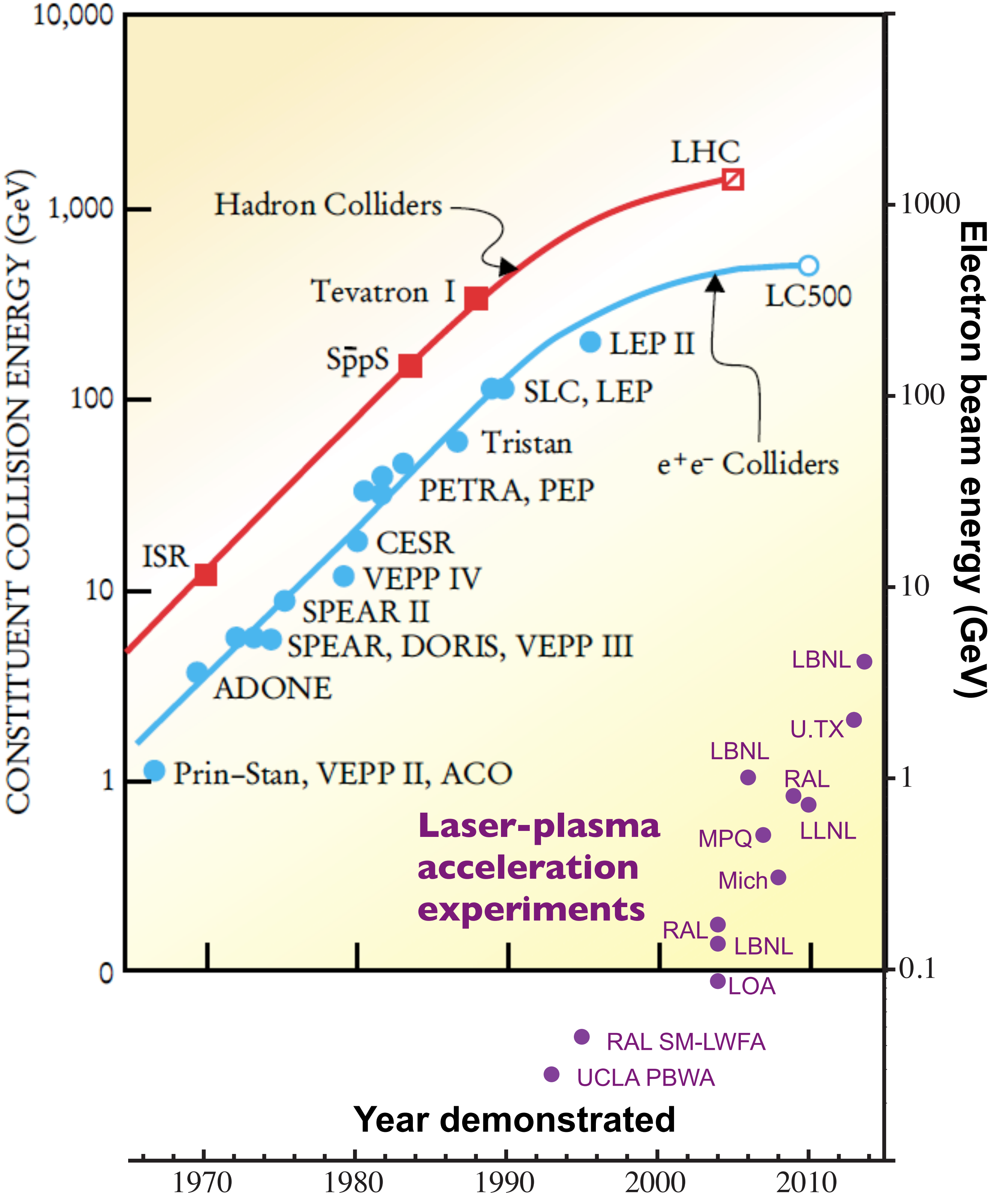

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Laser-plasma accelerators: compact sources (>10 GV/m) of fs e-beams

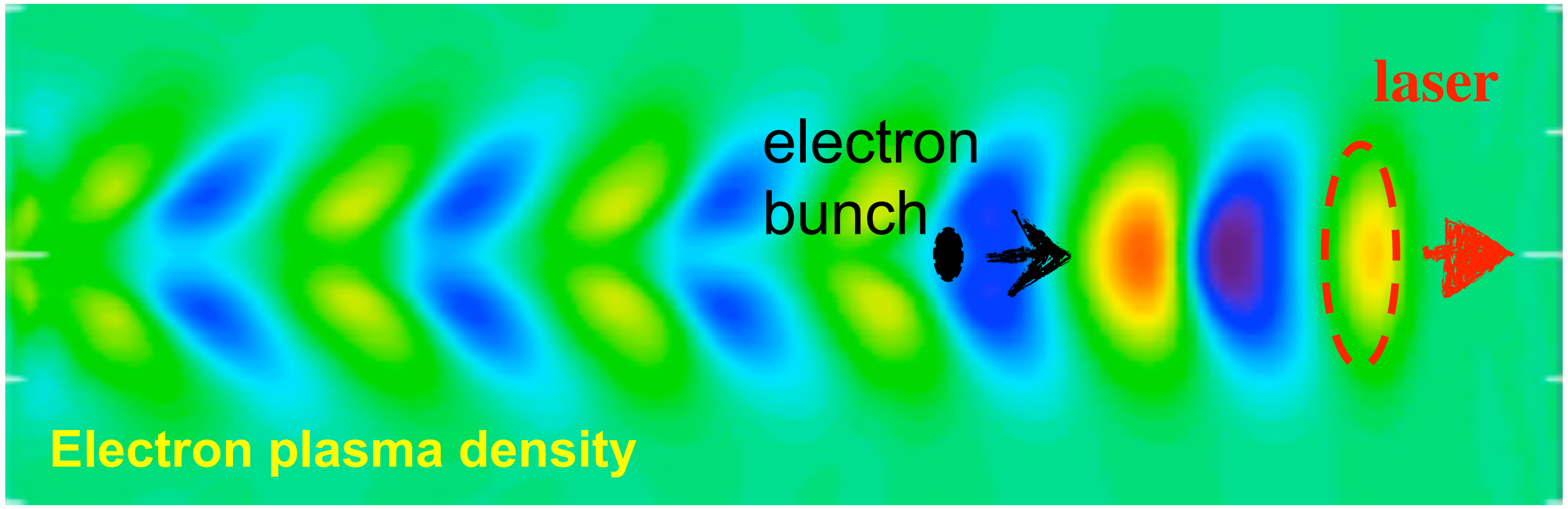
Esarey, Schroeder, Leemans, Rev. Mod. Phys. (2009)

- **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

- **Bunch duration**:
  - Accelerating bucket ~ plasma wavelength

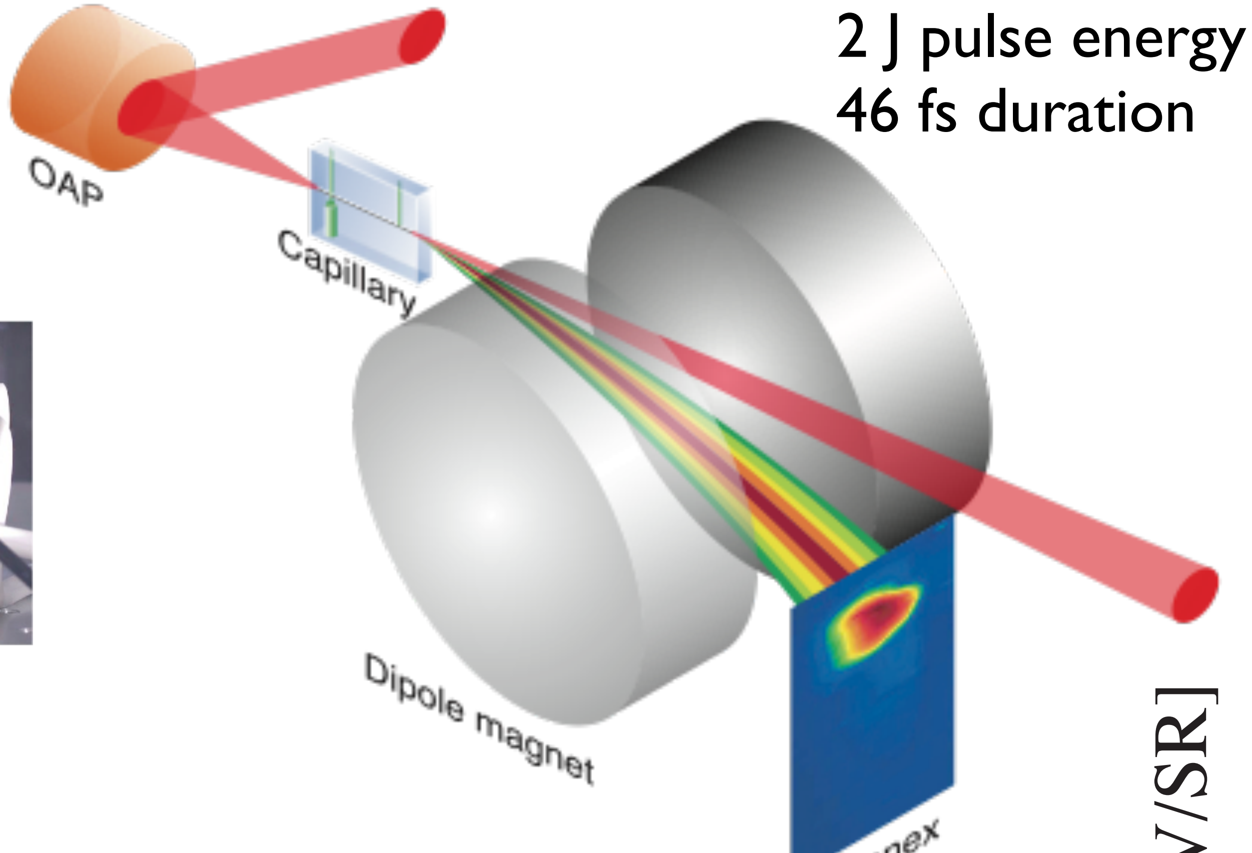


  - Beam charge (set by beam loading, plasma density): ~1-100 pC
  - Beam duration (set by trapping physics and density): ~1-10 fs

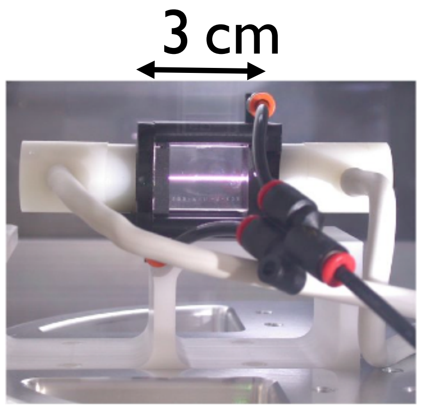
➡ ~1-10 kA peak current

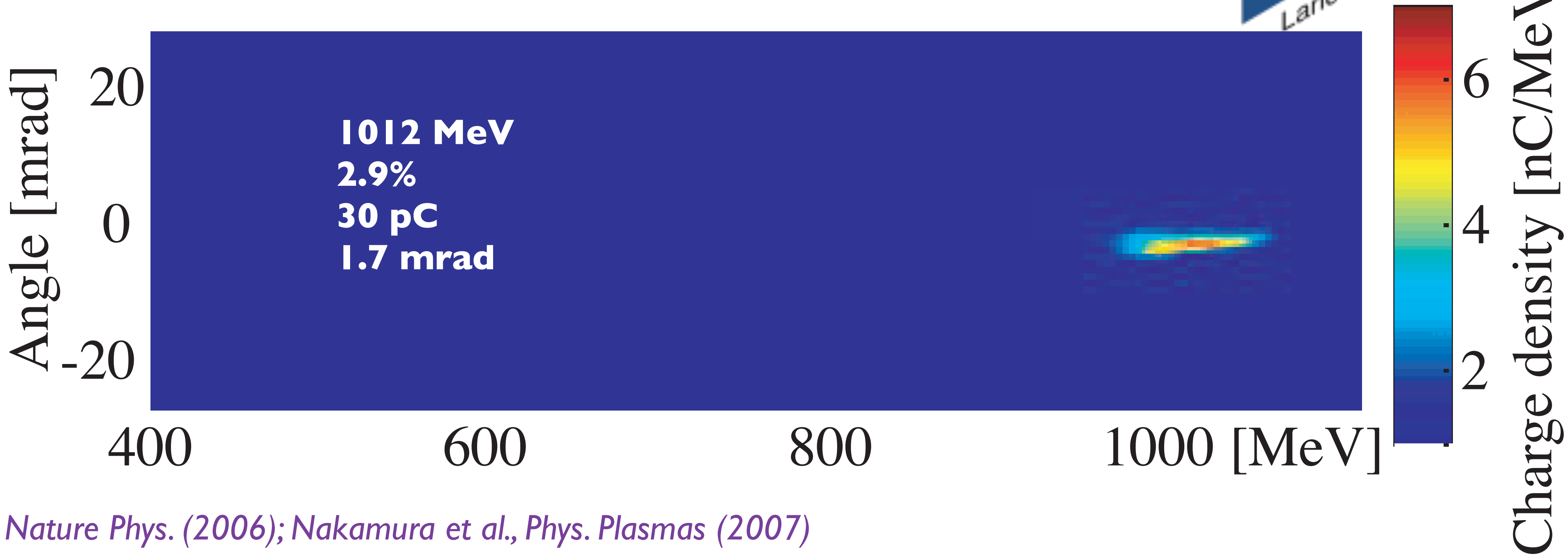
Laser-plasma accelerator (LPA) experimental demonstration of GeV electron beam at LBNL

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



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

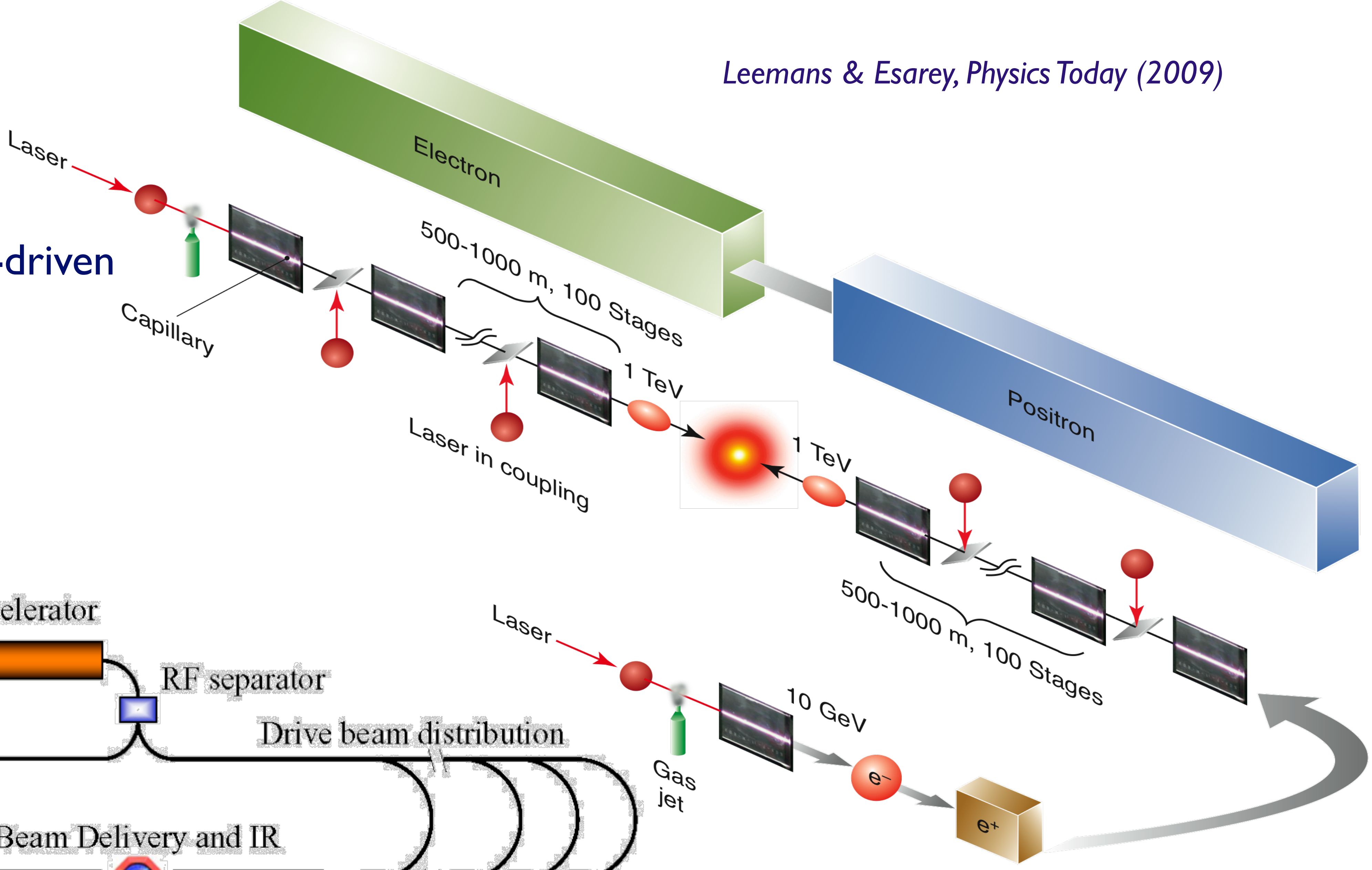




Leemans et al., Nature Phys. (2006); Nakamura et al., Phys. Plasmas (2007)

Plasma-based linear collider concepts

- Collider based on laser-driven plasma acceleration:



Leemans & Esarey, Physics Today (2009)

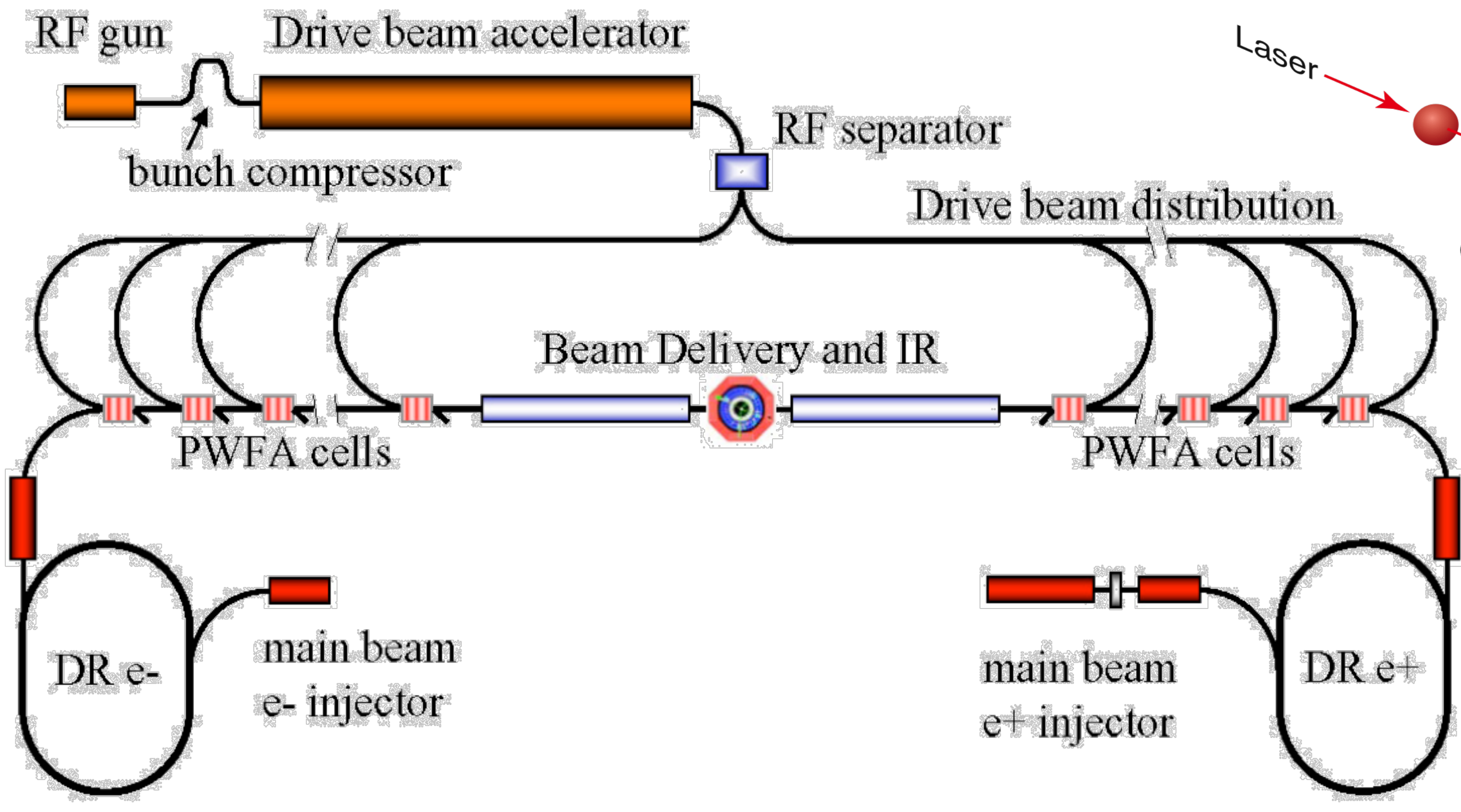
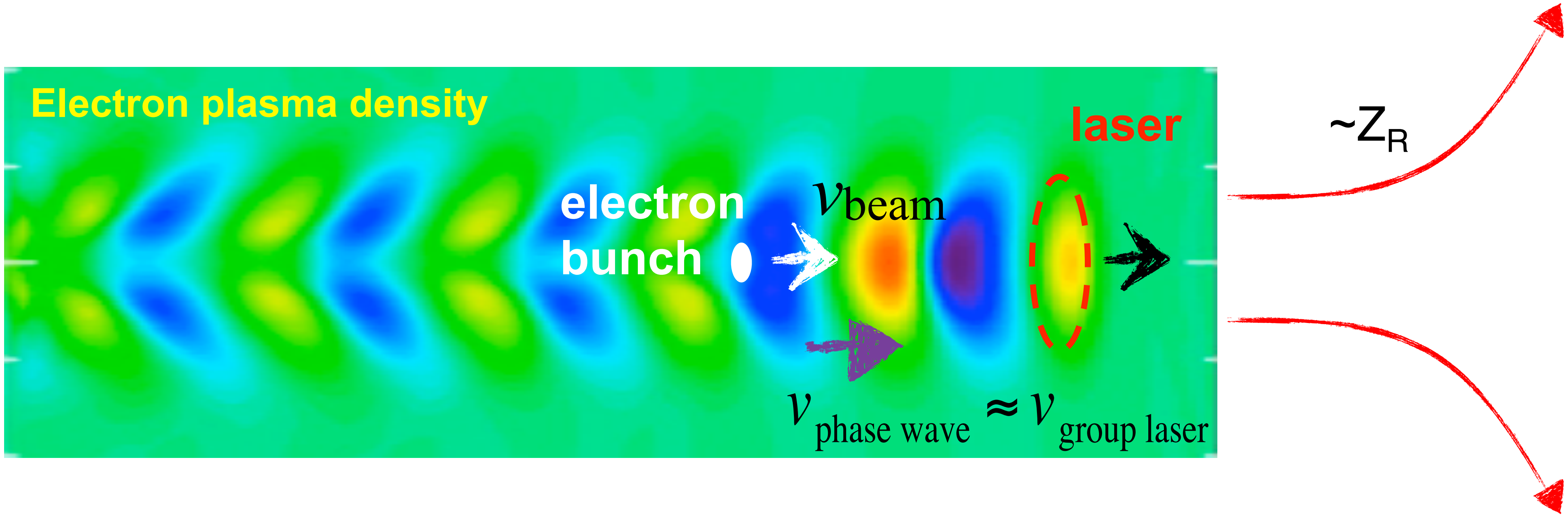


Figure 1: Concept for a multi-stage PWFA-based Linear Collider.

- Collider based on beam-driven plasma acceleration (PWFA):

Seryi et al., PAC Proc (2009)

Limits to energy gain in laser-plasma accelerator (LPA): diffraction, dephasing, depletion



Limits to single stage energy gain: $mc^2\Delta\gamma \sim q(mc\omega_p/e)L_{\text{int}}$

- **Laser Diffraction**: ~ 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
  - Controlled by longitudinal plasma density tailoring (plasma tapering)

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

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

Plasma density scalings

- Laser-plasma interaction (depletion) length:

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

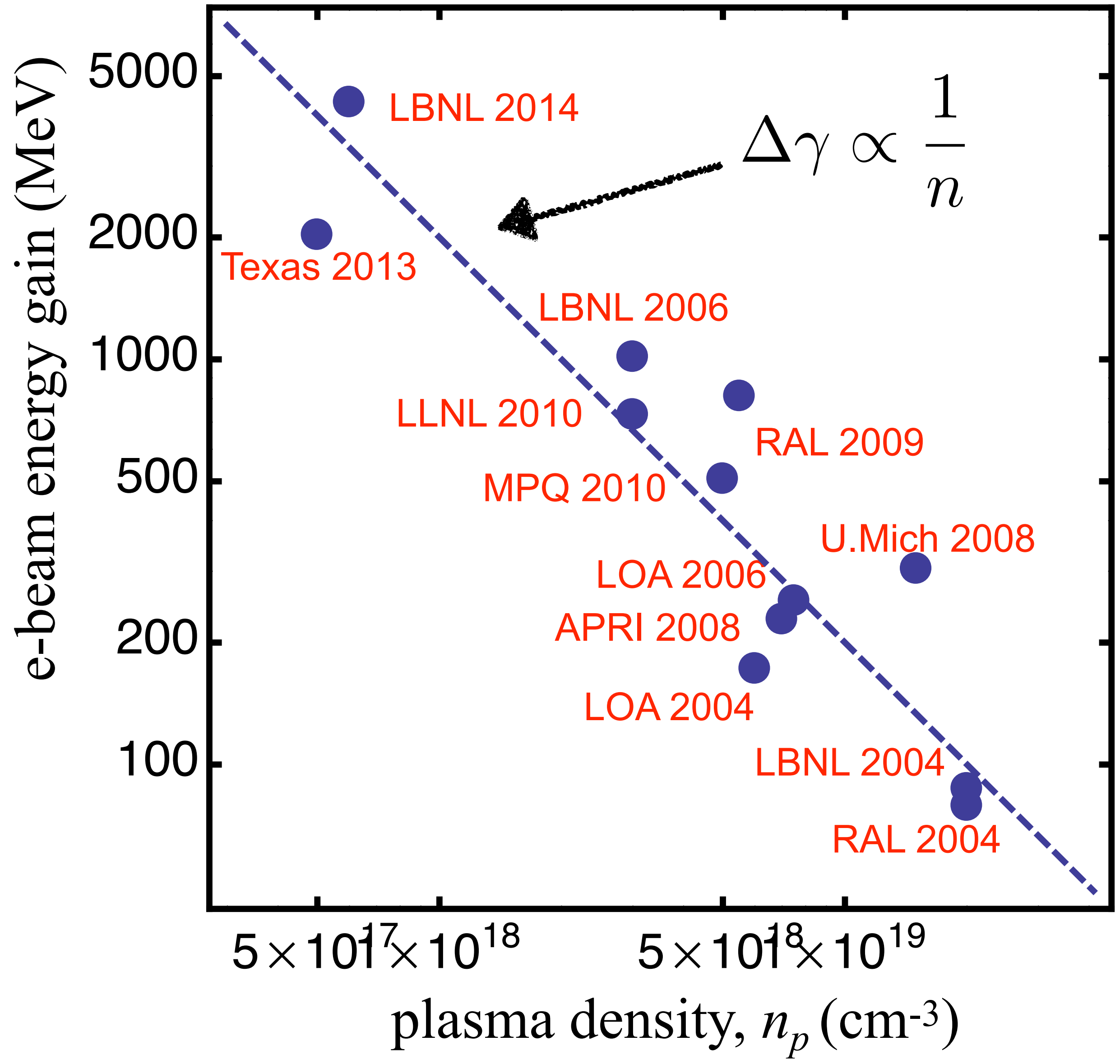
- Accelerating gradient:

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

- Energy gain:

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

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



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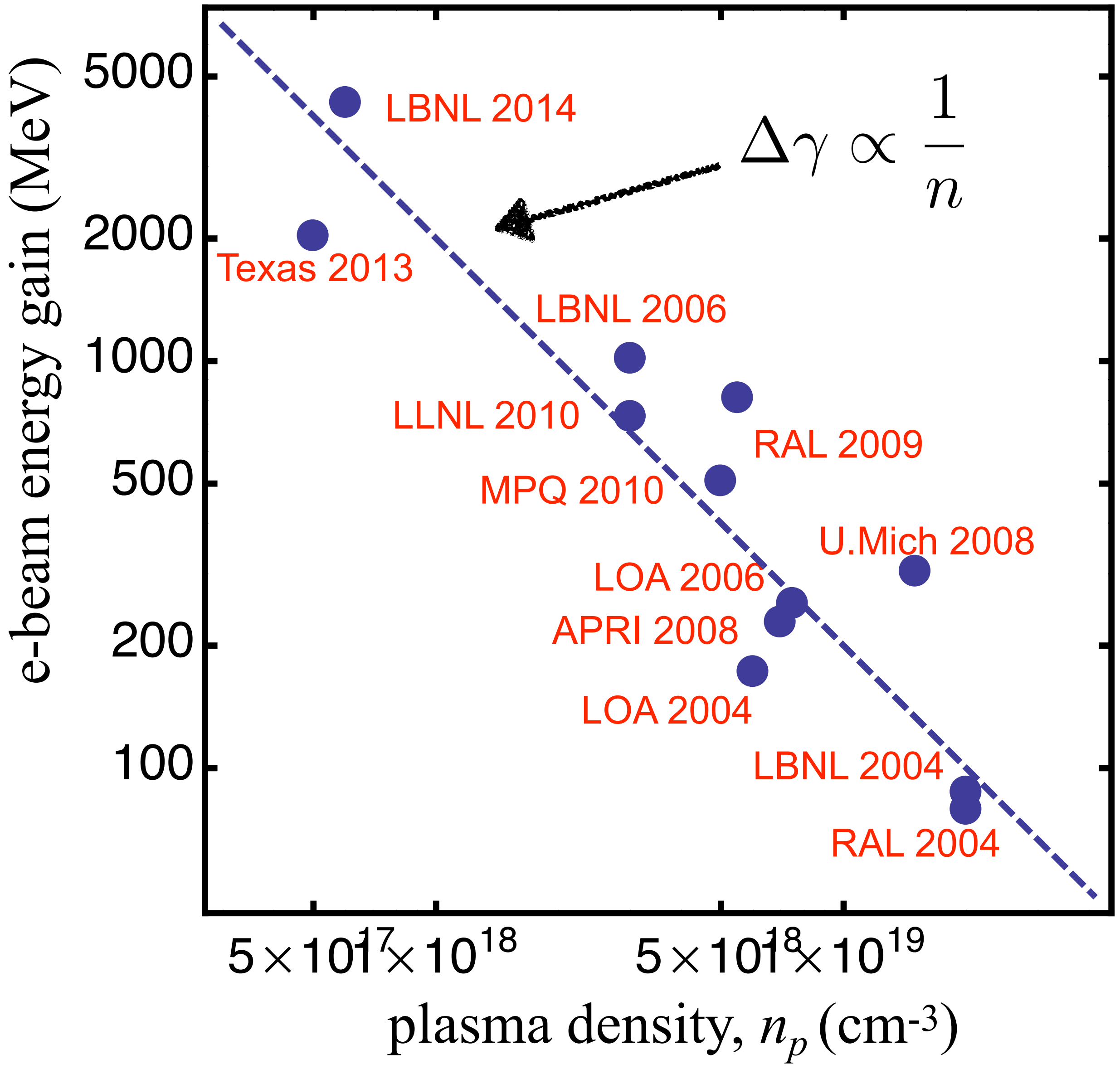

Laser requirements:

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

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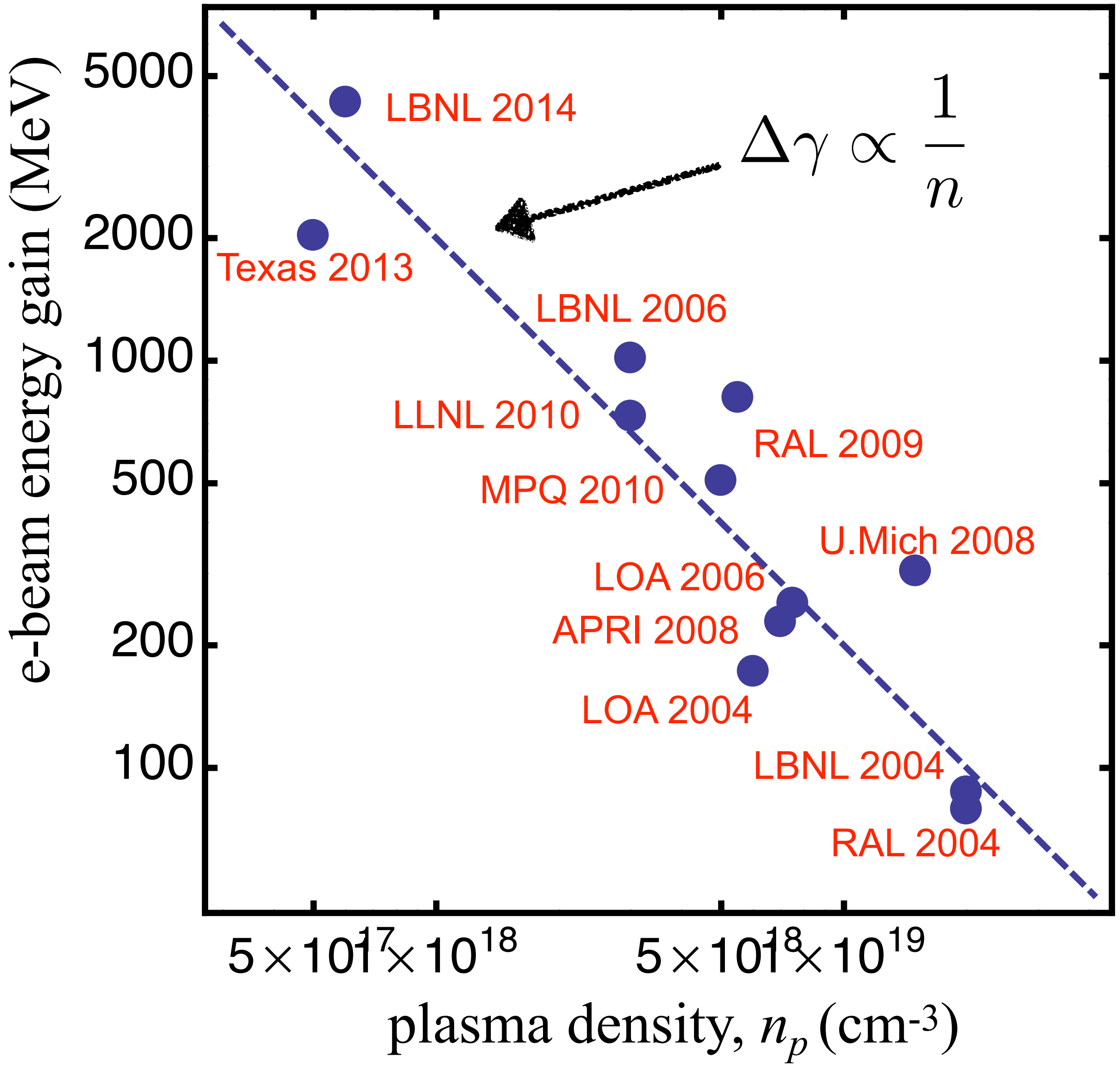

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W~1 GeV
n ~ 3x10^{18} cm^{-3}
L$_{acc}$ ~1 cm
U$_{laser}$ ~2 J
P$_{laser}$ ~100 TW

→

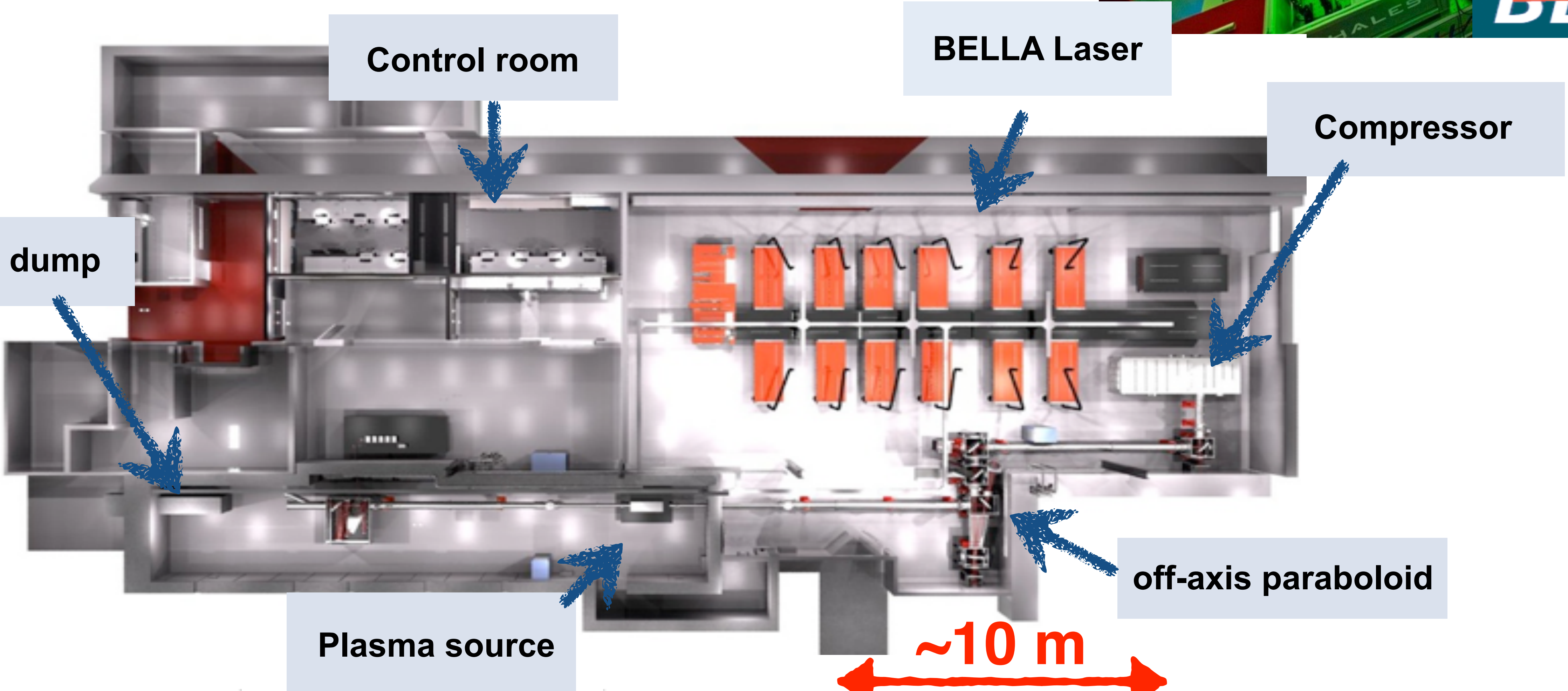
W ~ 4 GeV
n ~ 7x10^{17} cm^{-3}
L$_{acc}$ ~8 cm
U$_{laser}$ ~ 16 J
P$_{laser}$ ~ 0.4 PW

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


Control room

BELLA Laser

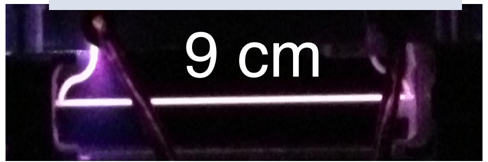
Compressor

Beam dump

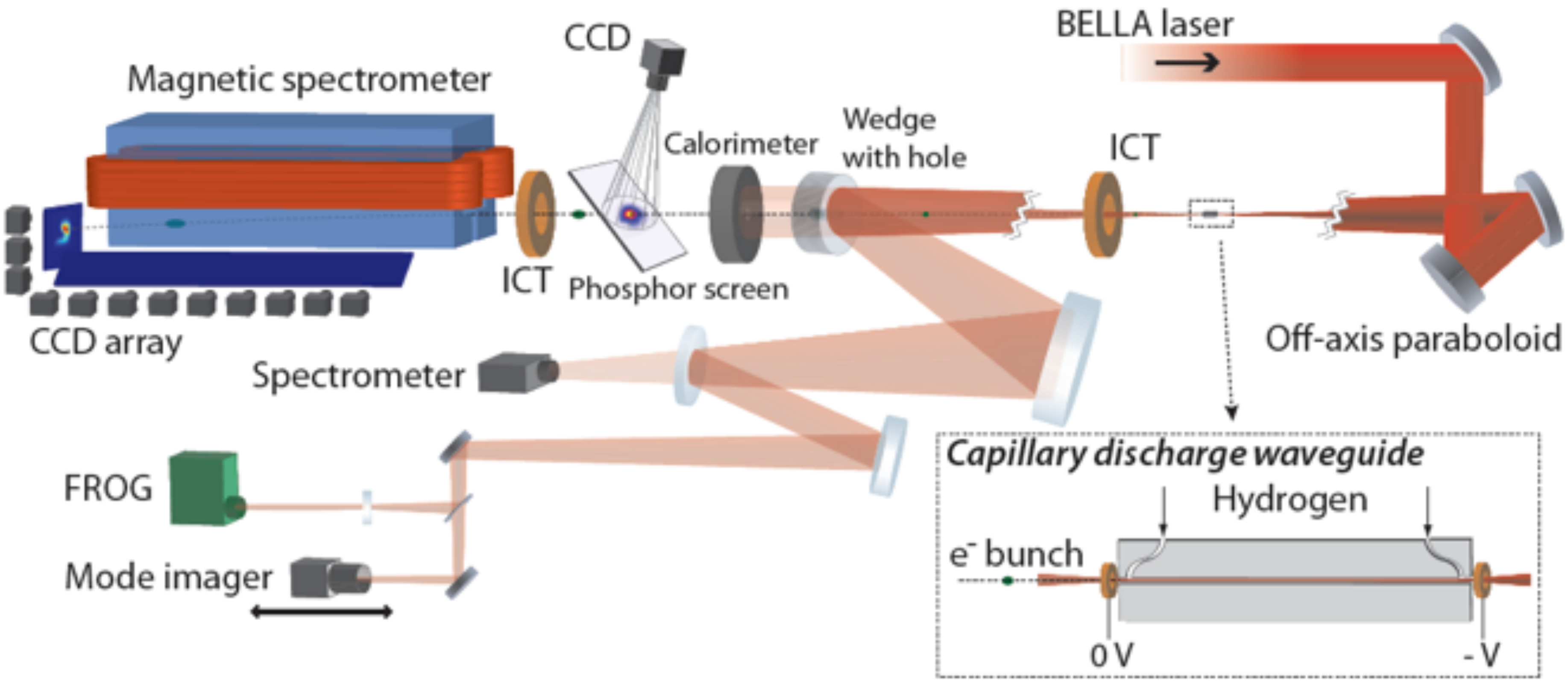
off-axis paraboloid

Plasma source

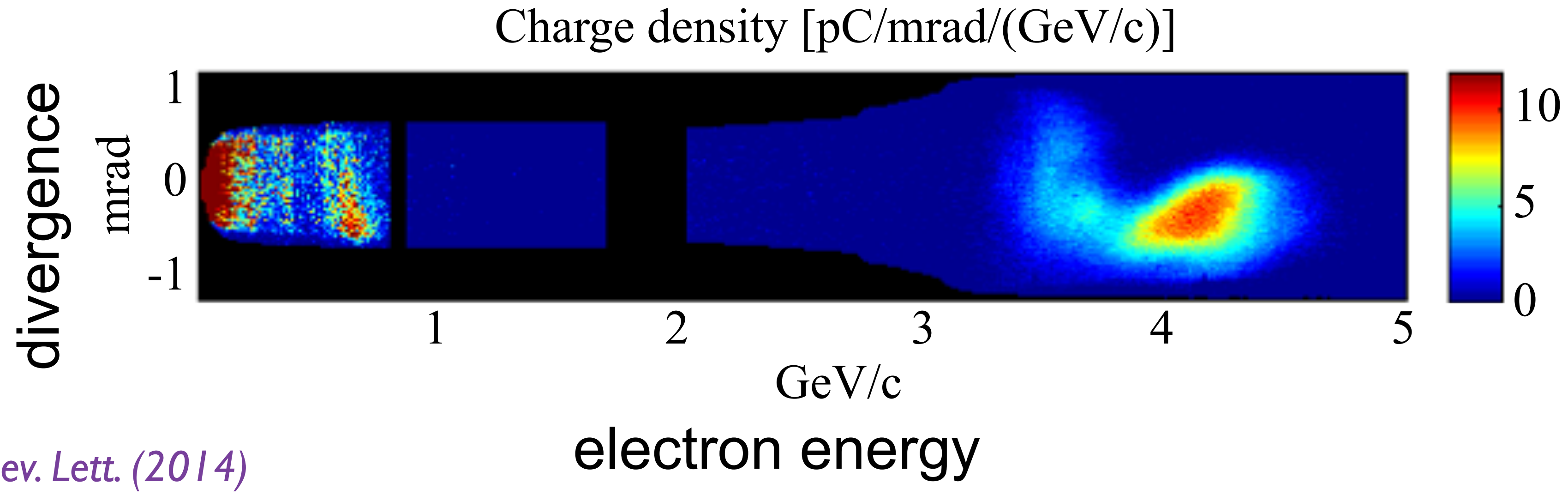
~10 m



Multi-GeV electron acceleration using BELLA



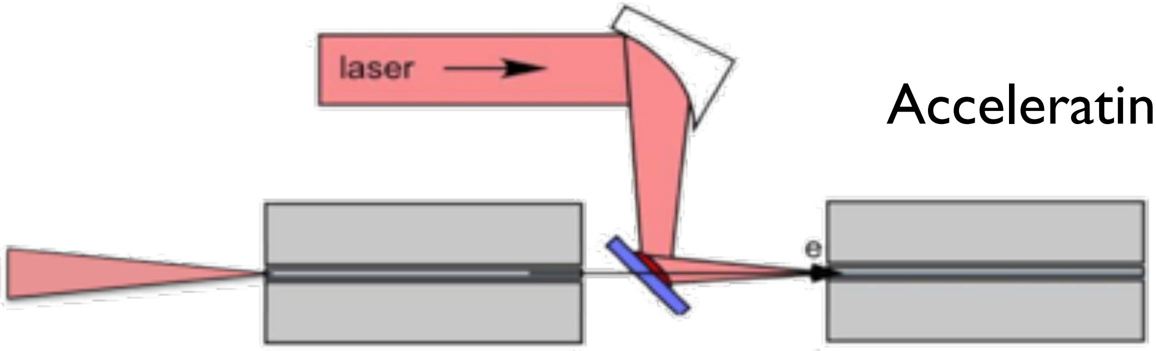
- plasma: 9 cm H-discharge capillary, on-axis density 7x10^{17}/cc
- laser: 16 J, 40 fs
- 4.25 GeV e-beam, 6% energy spread, 0.3 mrad divergence, 10 pC



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

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

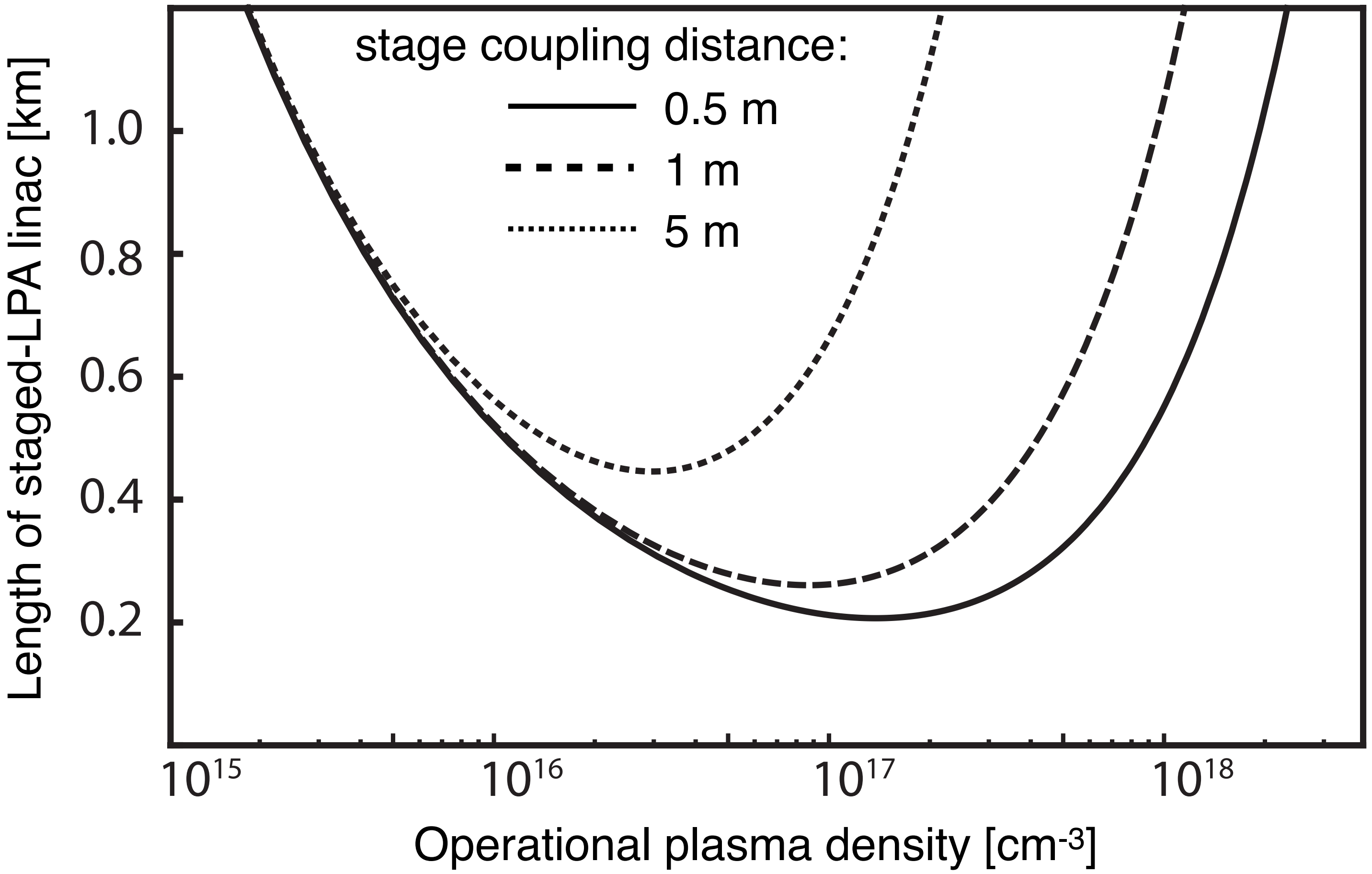
Schroeder et al., PR ST-AB (2010)



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

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

Length of 1 TeV staged-LPA linac



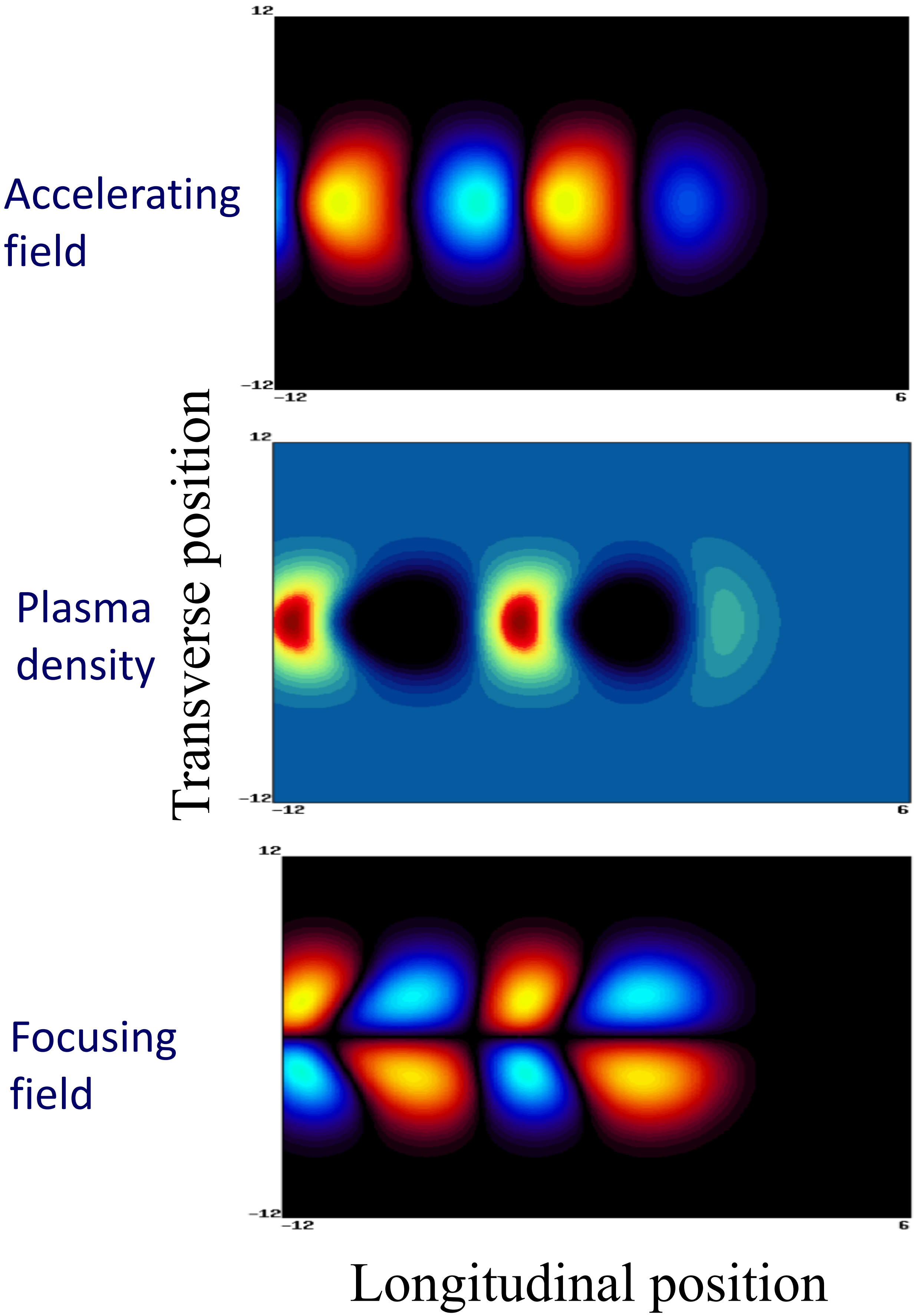
Compact laser in-coupling distance enables high average accelerating gradient:

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

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

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

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

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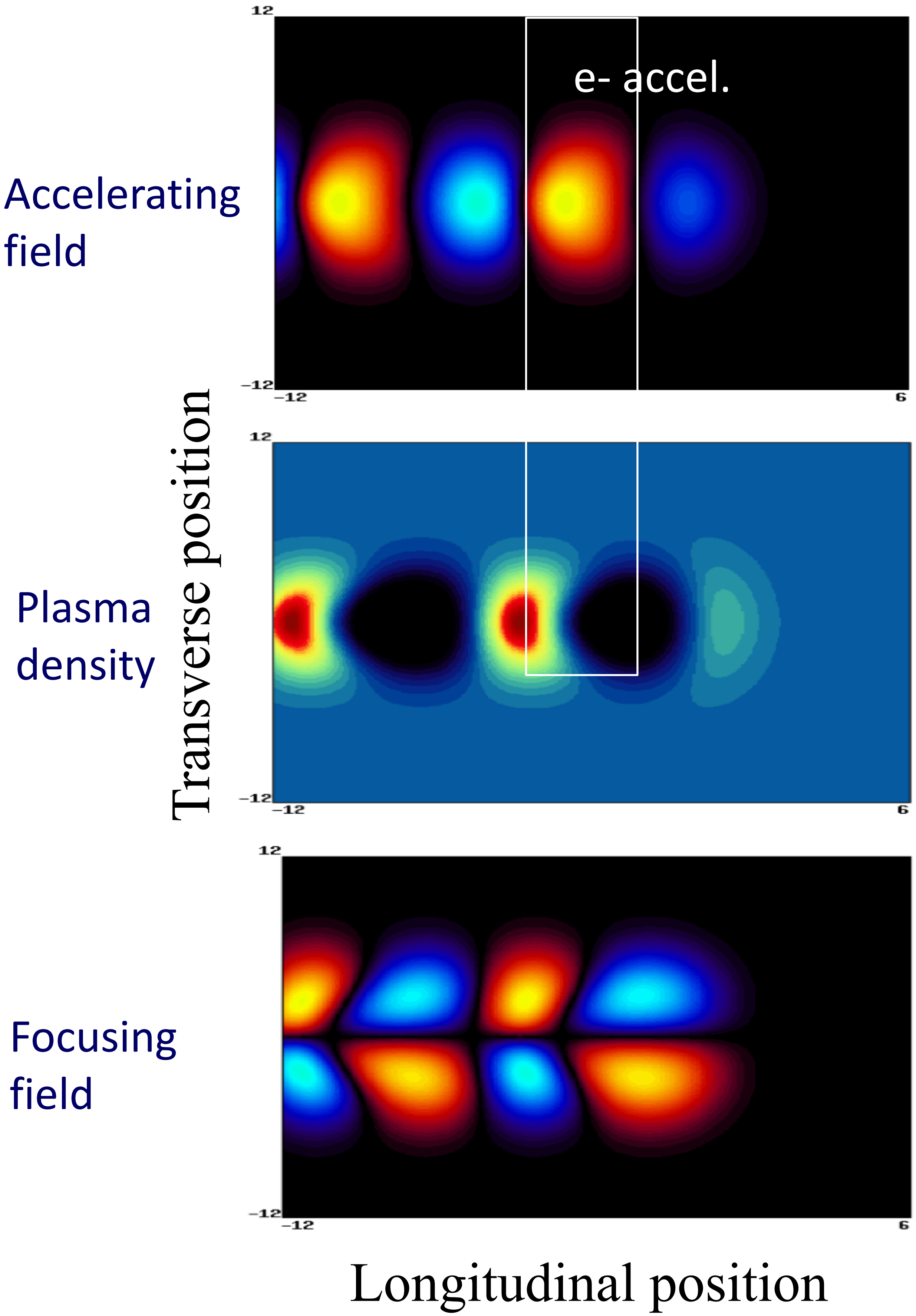

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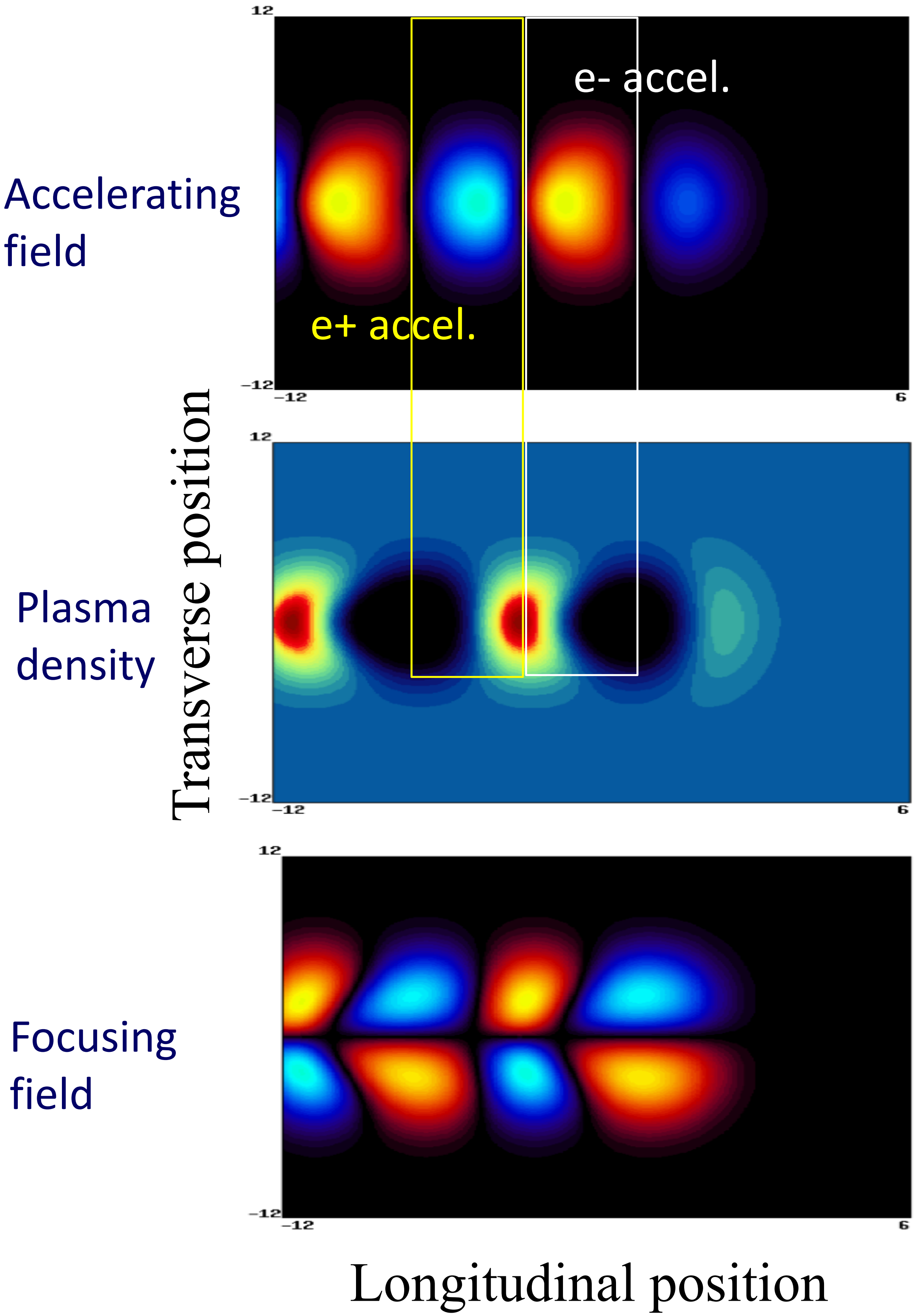

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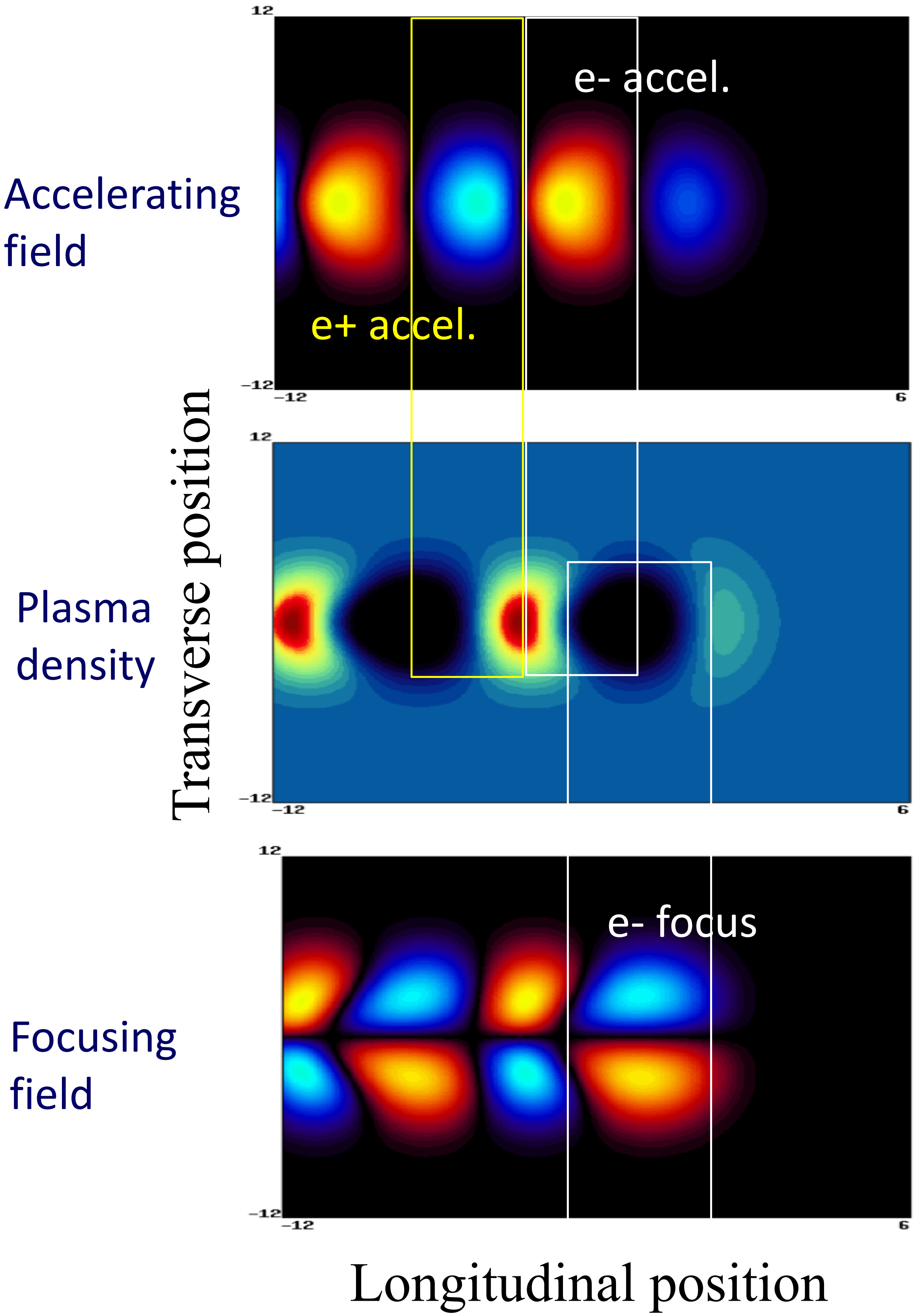

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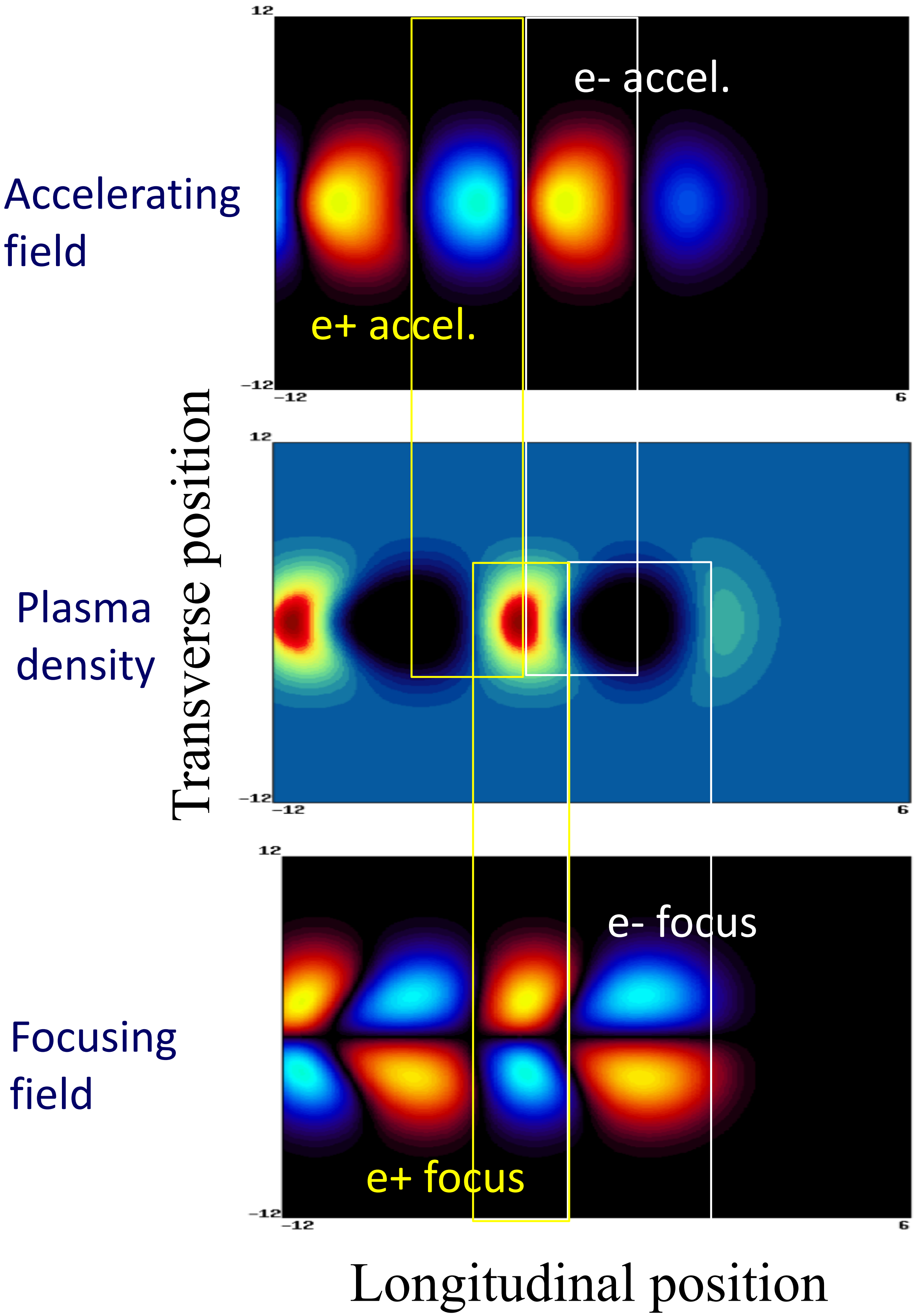

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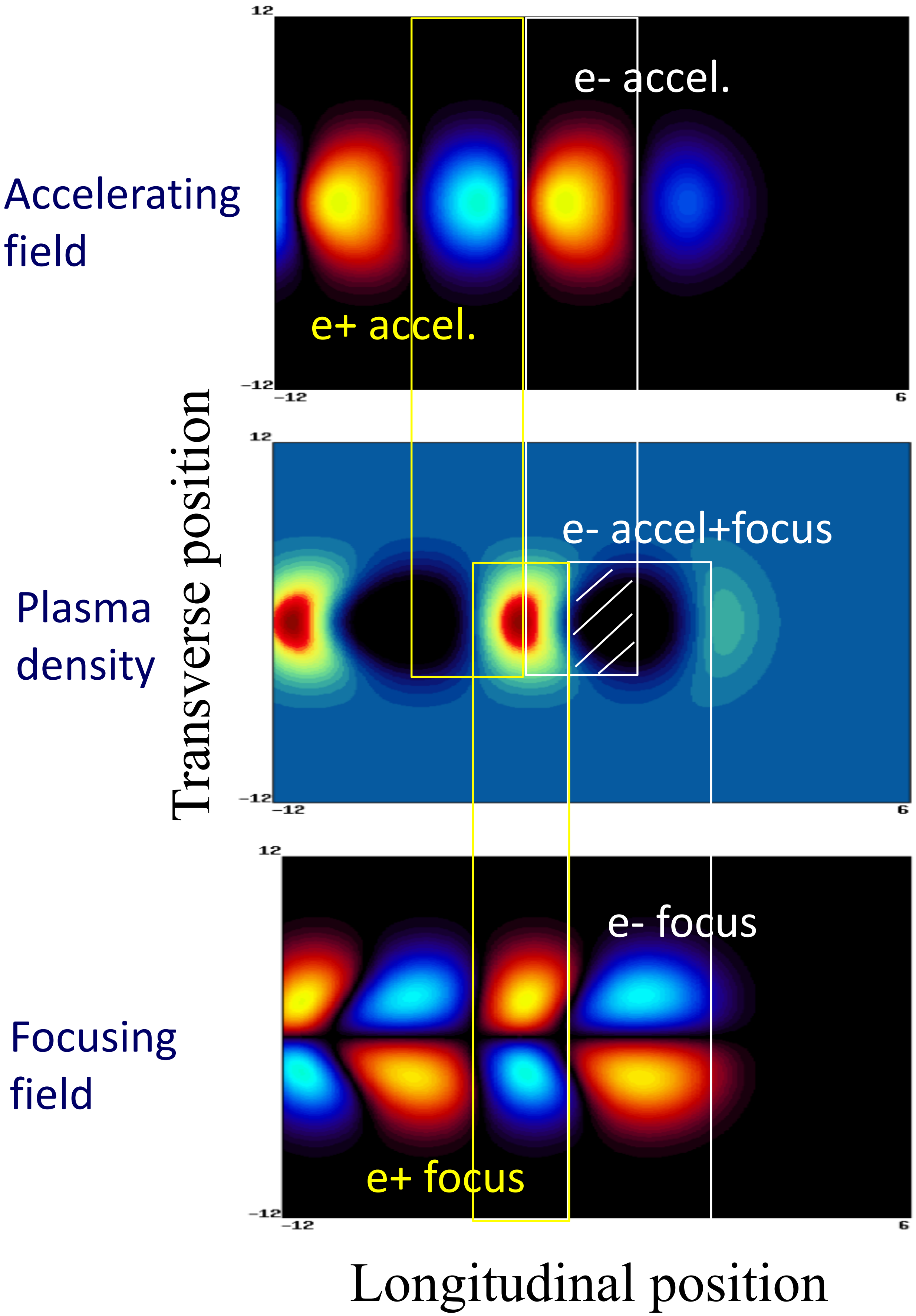

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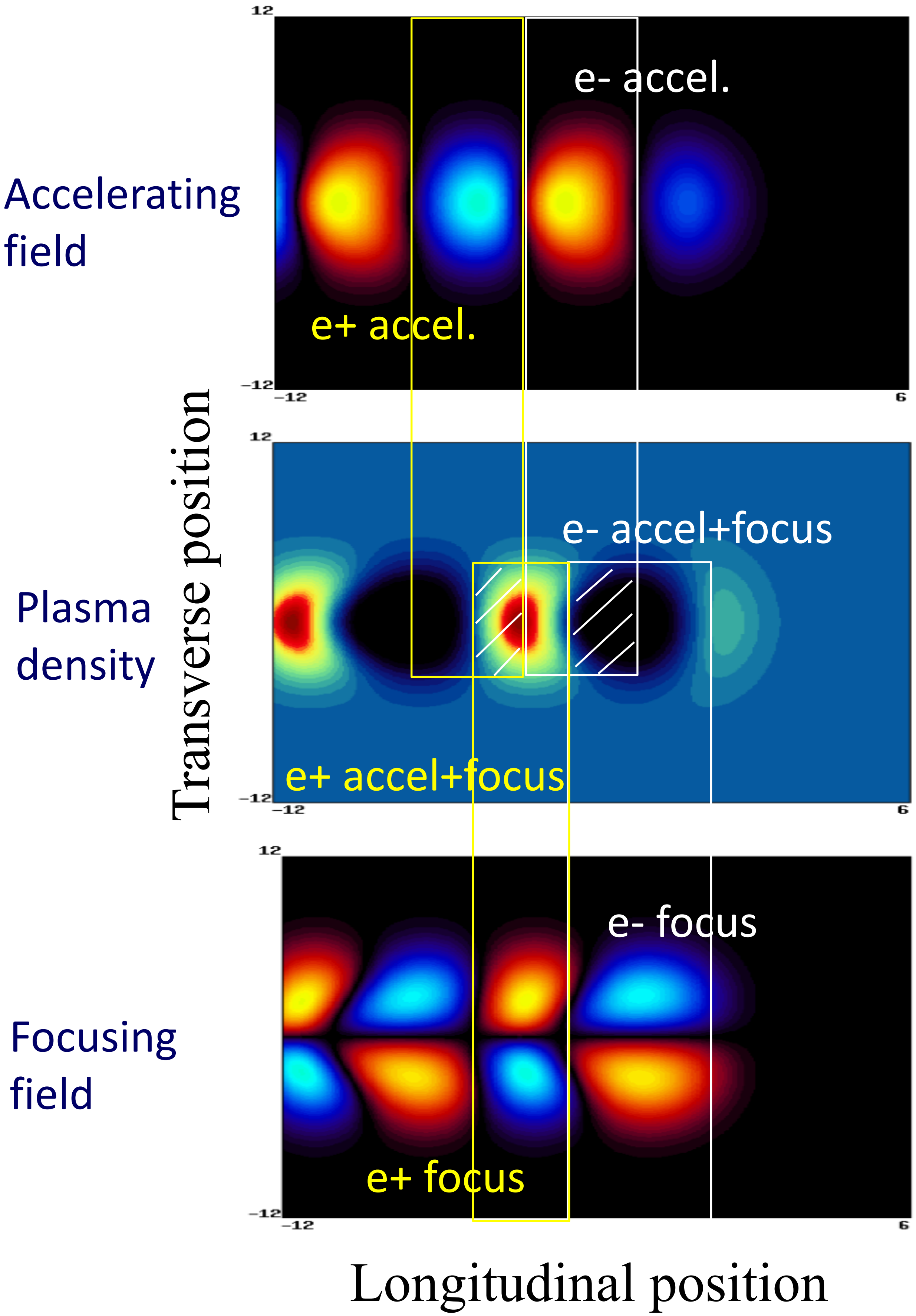

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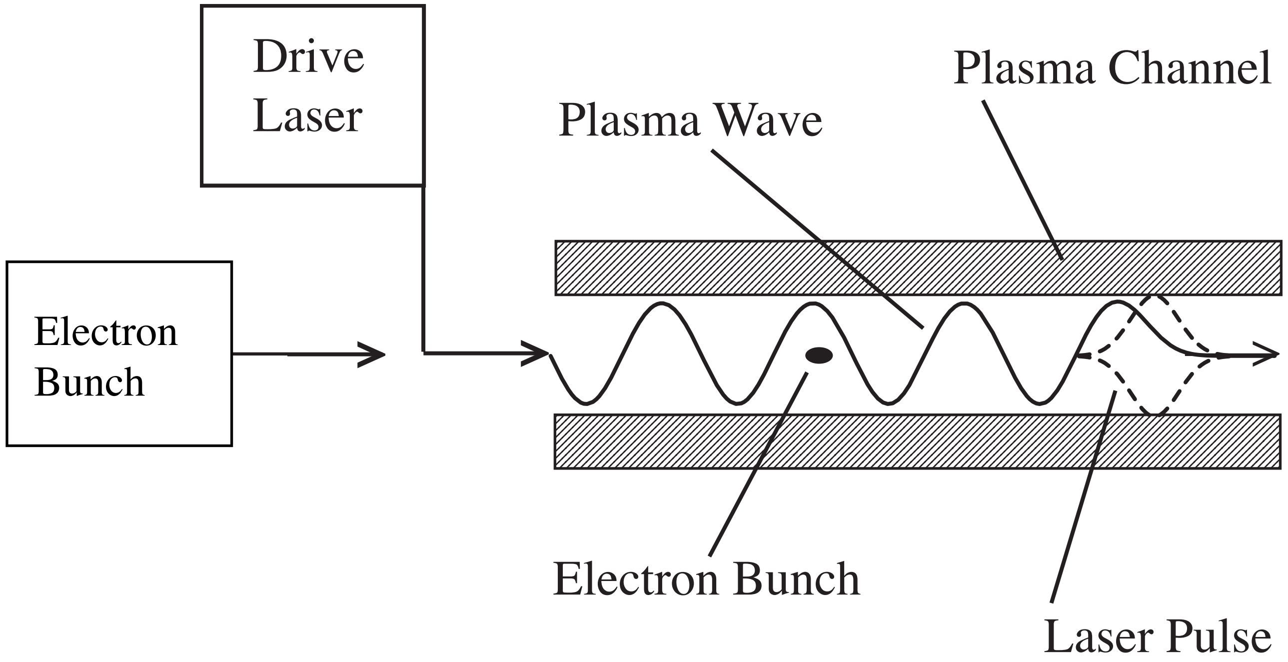
hollow plasma channels: Excellent wakefield properties for ultra-low emittance preservation



- 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
  - Ion motion negligible
  - Mitigates Coulomb scattering

Beam loading in near-hollow plasma channels: use shaped bunches to eliminate energy spread

- Energy spread minimized using shaped beams

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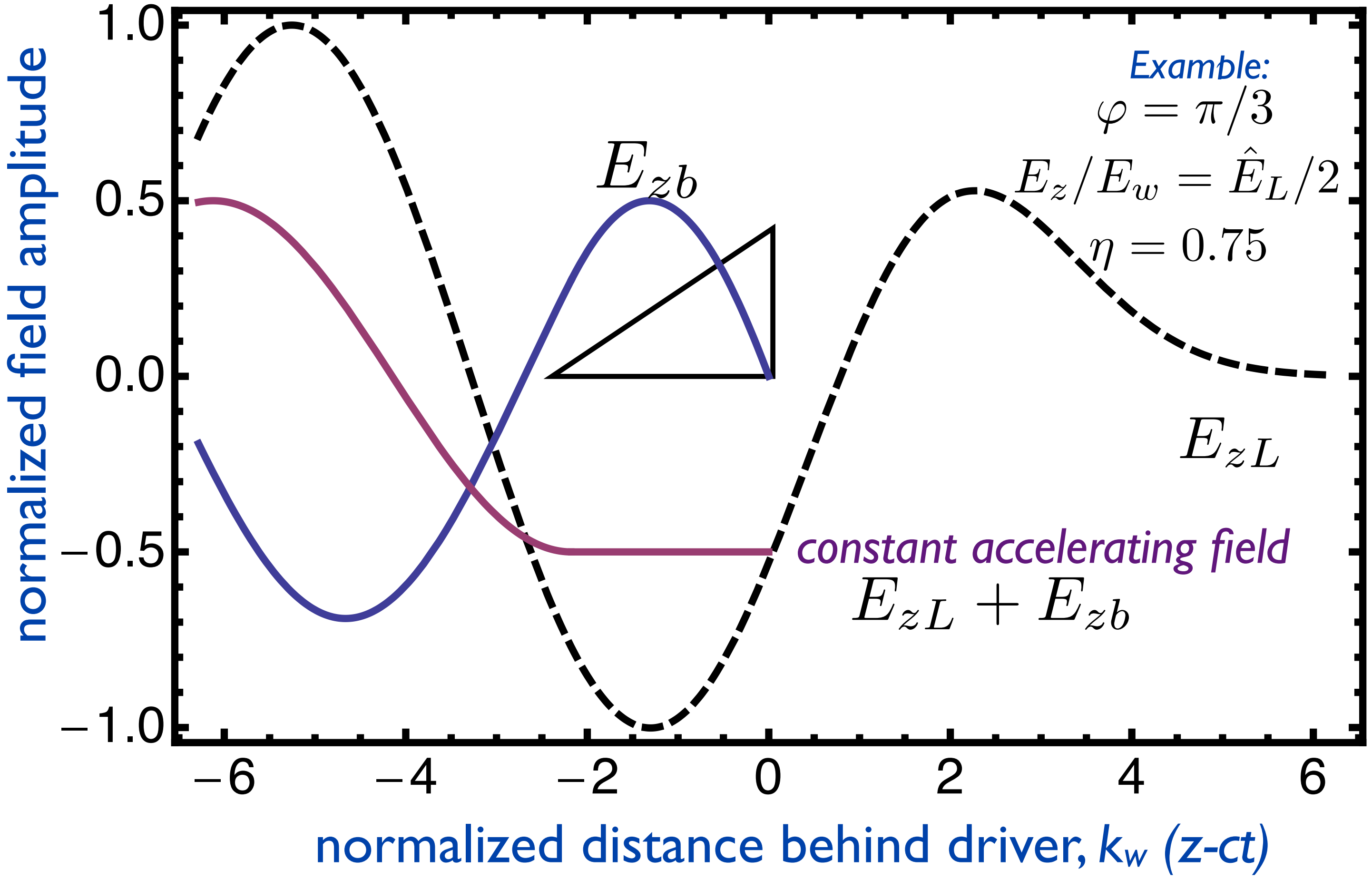
Ramped triangular current distribution :

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



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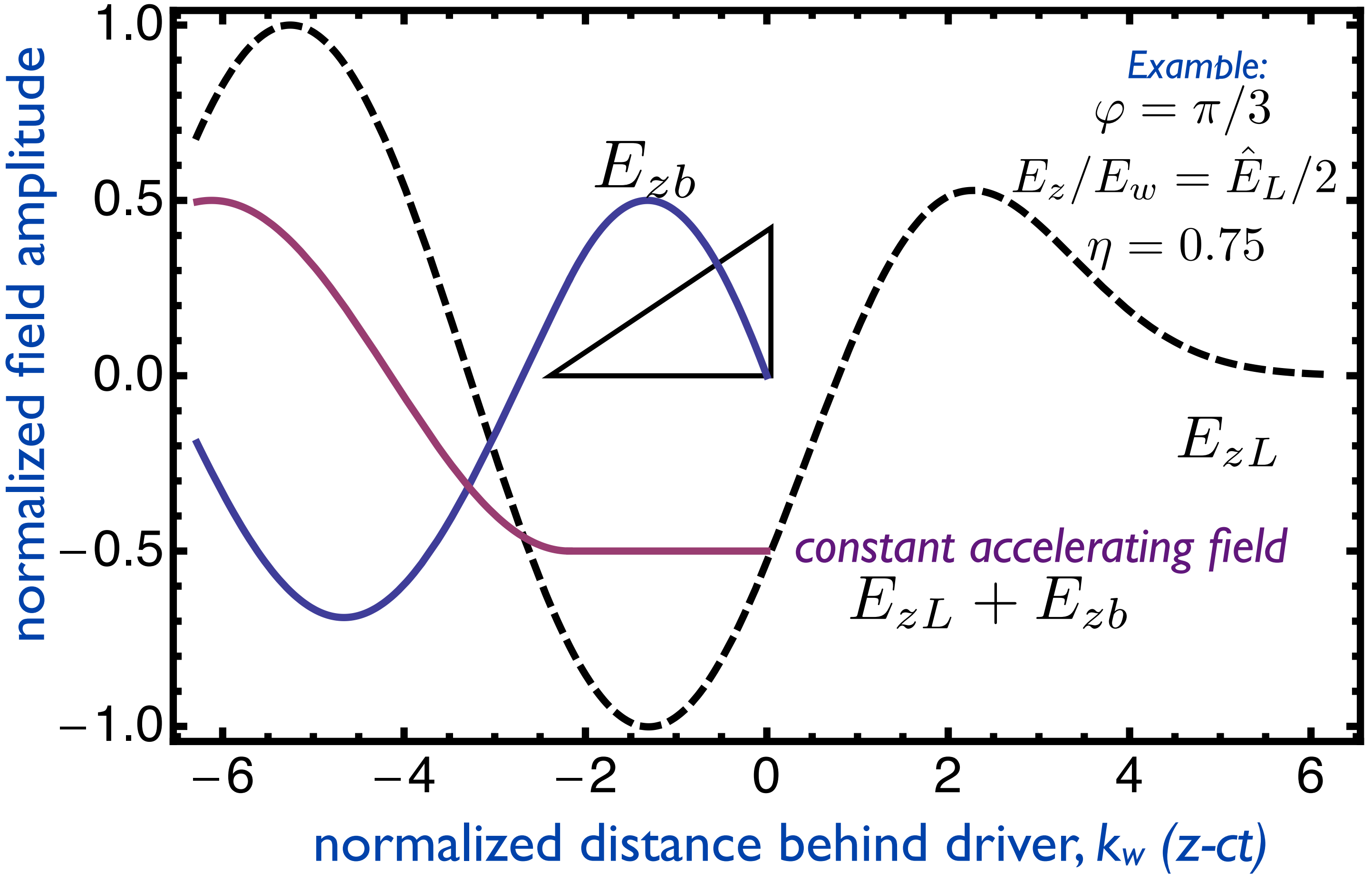
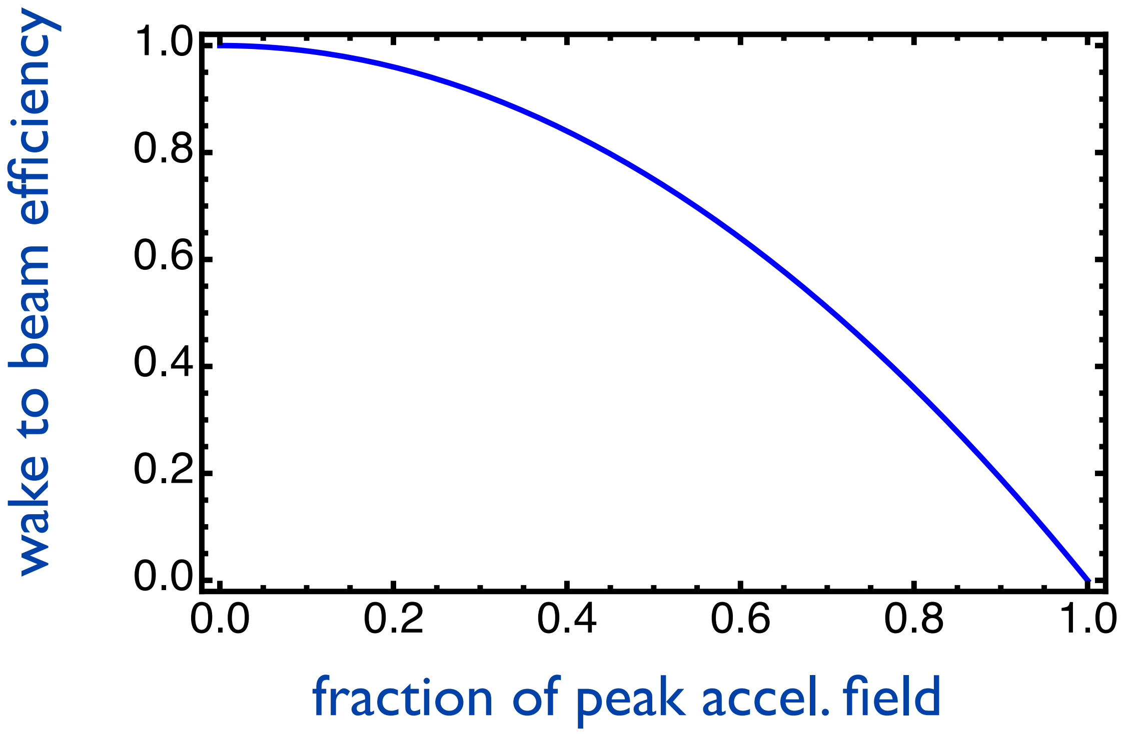


- Trade-off between gradient and efficiency (for no induced energy spread)



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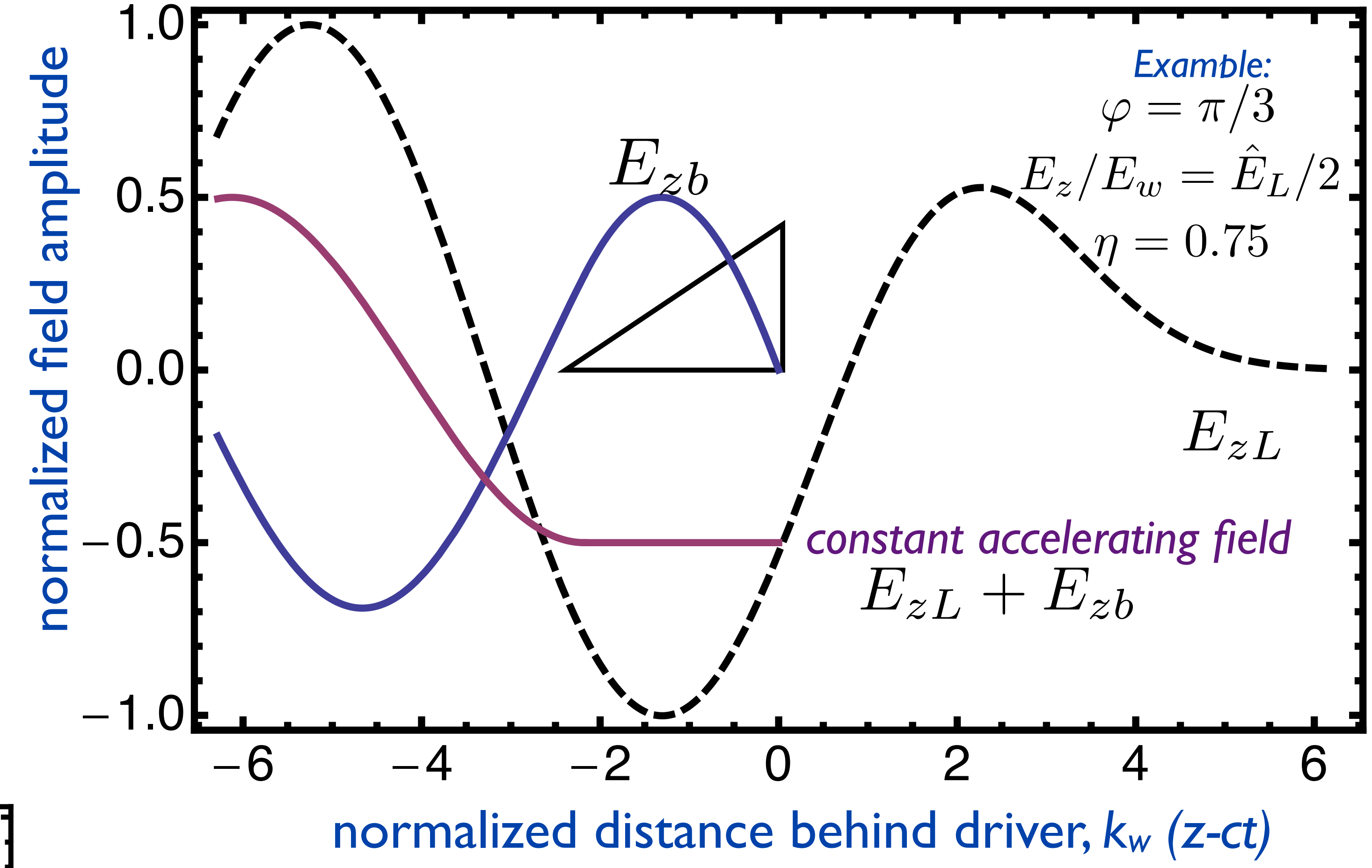

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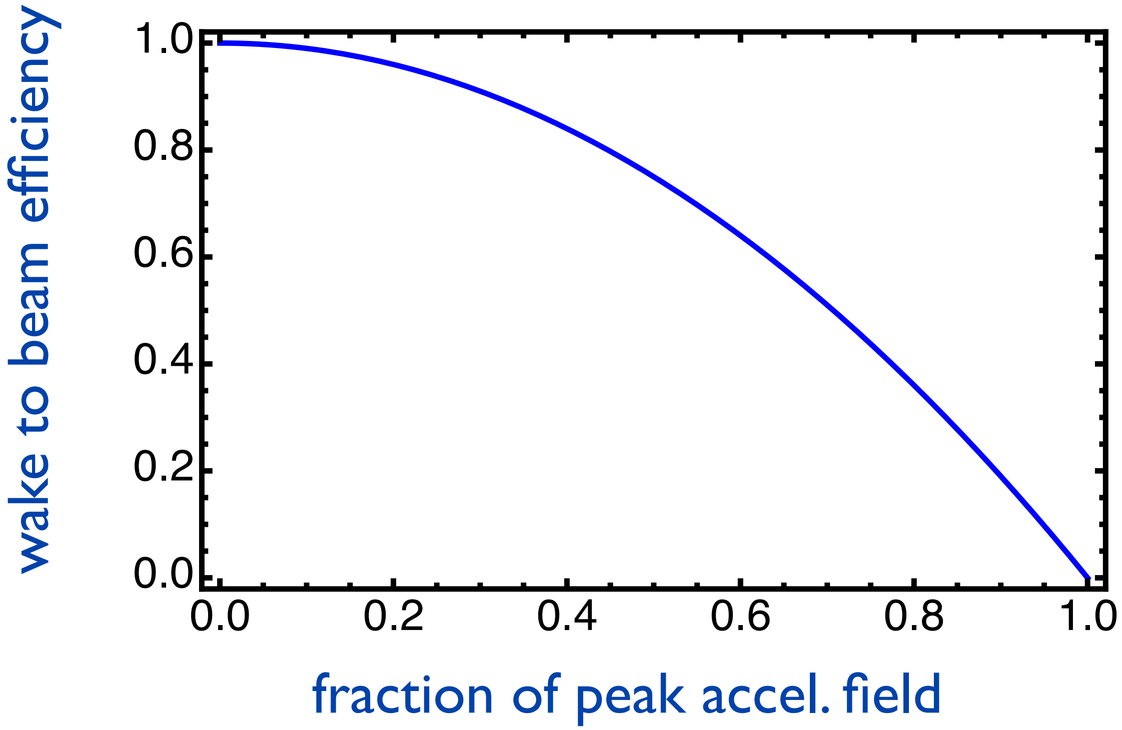
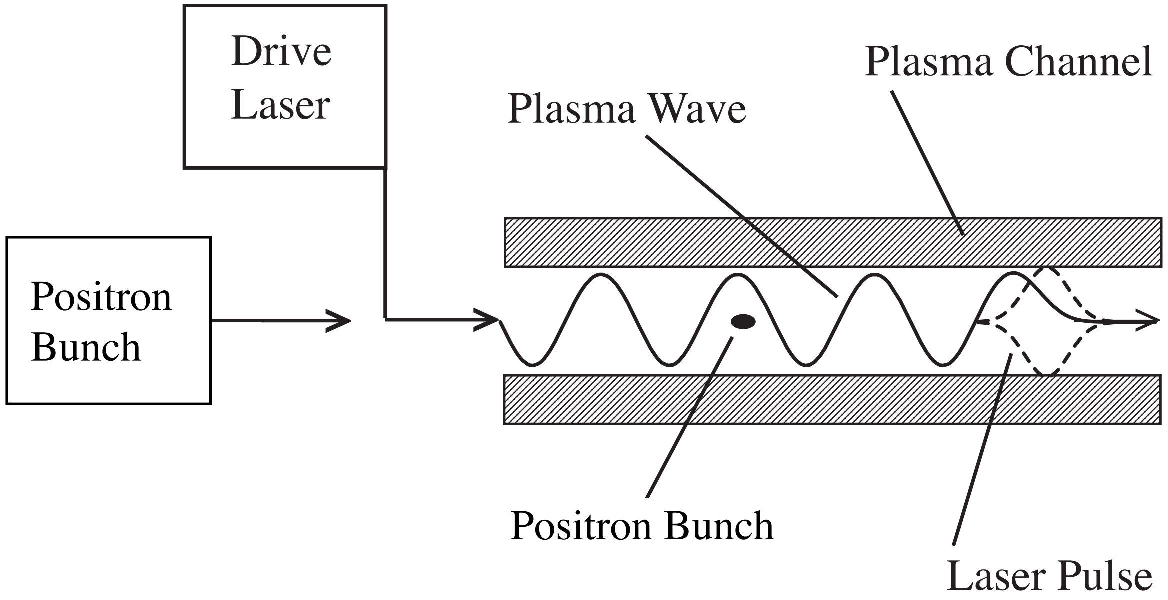


beam charge: $N_b \propto n_w^{-1/2}$

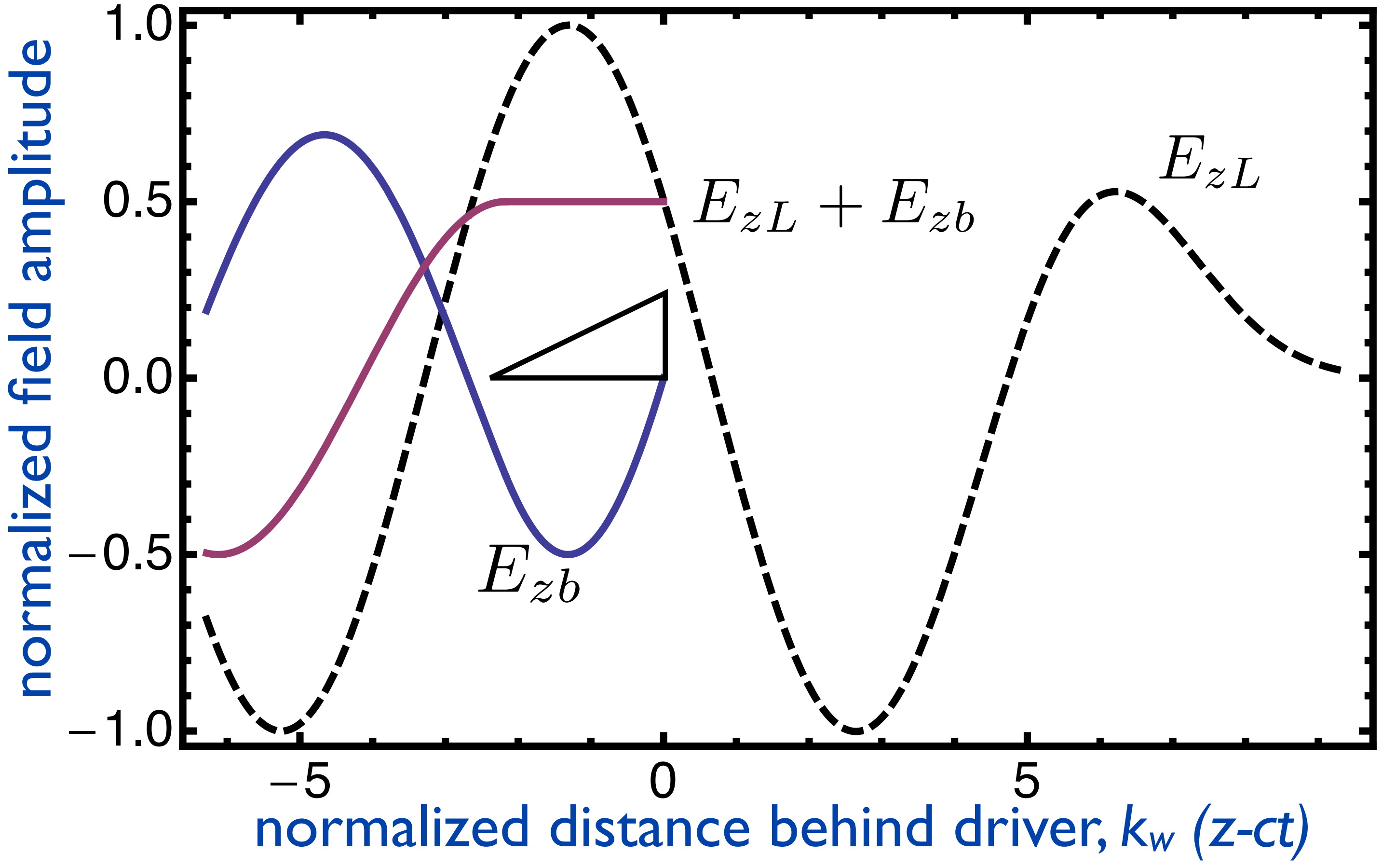
lower plasma density, higher beam charge

beam length: $L_b \sim k_p^{-1} \propto n_w^{-1/2}$

Positron beams accelerated in linear regime in hollow plasma channel



- In quasi-linear regime, acceleration of positrons is symmetric to electrons



Basic scalings indicate disruption small for plasma accelerated (ultra-short) beams

- Disruption parameter:

P. Chen and K. Yokoya, Phys. Rev. D 38, 987 (1988)

$$D_x = \frac{2 r_e N \sigma_z}{\gamma \sigma_x^* (\sigma_x^* + \sigma_y^*)}$$

- Plasma-based accelerators intrinsically produce short (< plasma skin depth) beams

- Luminosity enhancement effects from beam disruption are typically weak D<<1 for LPA-based colliders owing to the ultrashort LPA bunch length (<< beam-beam lens)

Beamstrahlung minimization: basic scalings

- Beamstrahlung parameter: $\Upsilon = \gamma \langle E + B \rangle / E_c \approx \dfrac{5 r_e^2 \gamma}{6\alpha(\sigma_x^* + \sigma_y^*)} \dfrac{N}{\sigma_z}$
- average number of beamstrahlung photons/lepton:

P. Chen and K.Yokoya

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

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- TeV-scale colliders will operate in the high-beamstrahlung regime: Y>>1
- Beamstrahlung suppressed by using short beams (in limit Y>>1):

$$n_\gamma \approx 2.54 \left(\alpha^2 / r_e \gamma\right) \Upsilon^{2/3} \sigma_z$$

$$\delta_\gamma \approx 0.722 \left(\alpha^2 / r_e \gamma\right) \Upsilon^{2/3} \sigma_z$$

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$$\delta_\gamma \approx 0.722 \left(\alpha^2 / r_e \gamma\right) \Upsilon^{2/3} \sigma_z$$

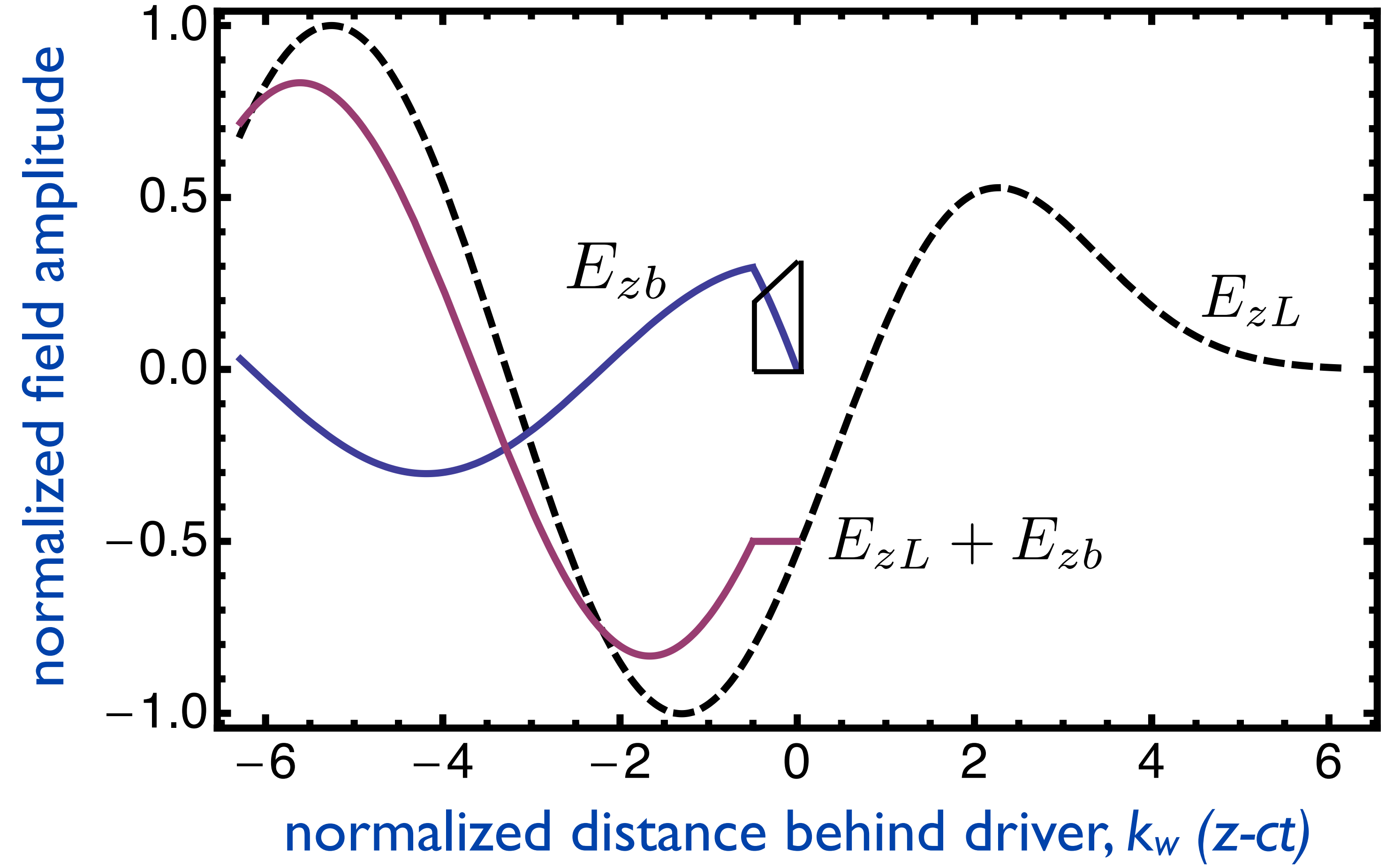
- Short beams save power (Y>>1): $\boxed{\dfrac{\mathcal{L}}{U_{\text{cm}}^2} \propto \dfrac{n_\gamma^{3/2} \eta_{wb} P_{\text{wall}}}{\sigma^* \gamma^{5/2} \sigma_z^{1/2}}}$
- Plasma-based accelerators produce short (< plasma skin depth) beams: $\sigma_z < k_p^{-1}$

Ultra-short beams can be accelerated without energy spread growth

- Ultra-short beams are desirable, e.g., beamstrahlung suppression in colliders.

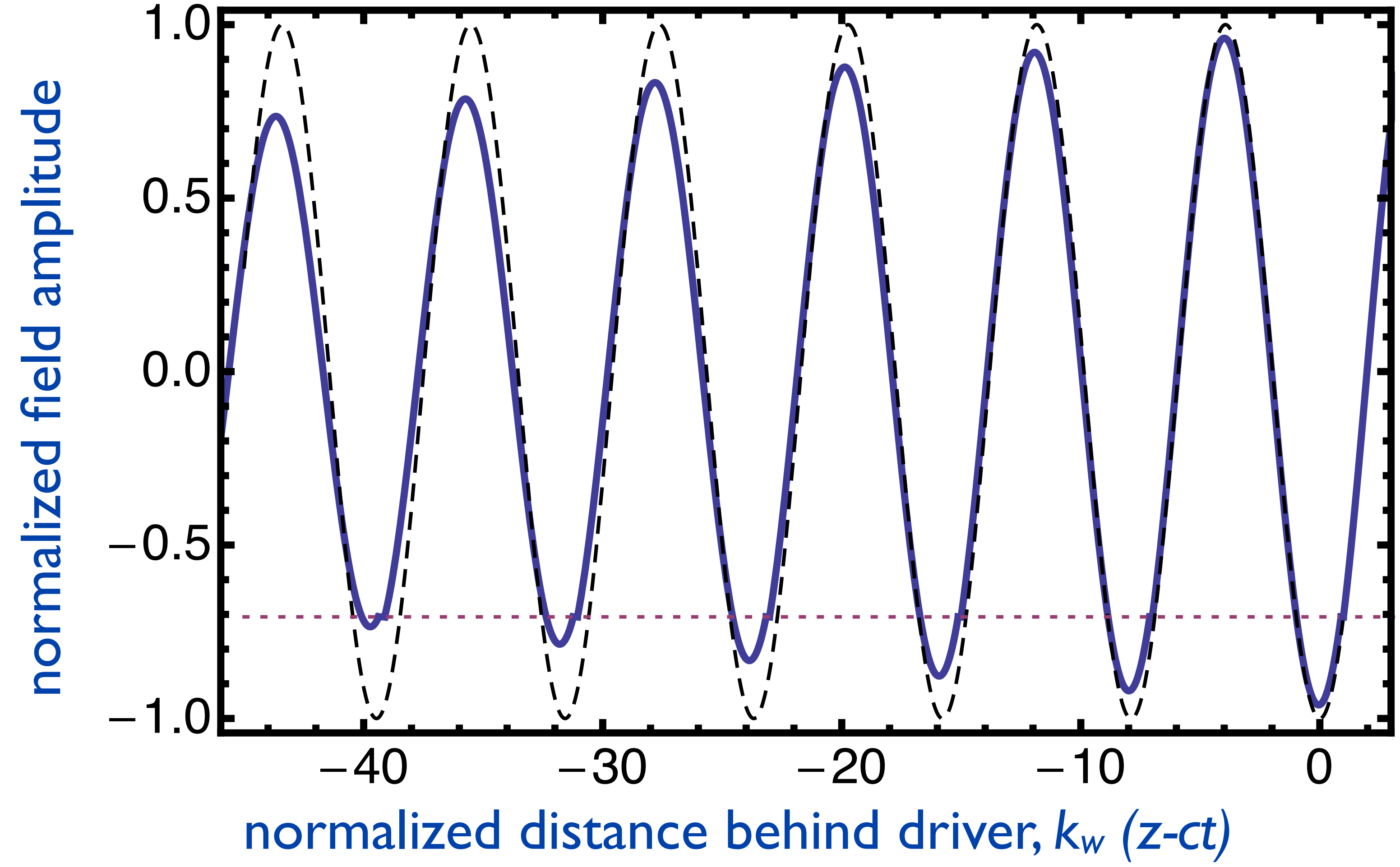
beamstrahlung photons/electron: $n_\gamma \propto \mathcal{L}^{1/3}\sigma_z^{1/3}$

- Trapezoidal current distribution:



- Improved efficiency achieved using bunch trains

Bunch trains allows ultra-short bunches with high efficiency, gradient, and no energy spread



Example:

$$k_w L_1 = 0.1$$

$$\varphi_1 = \pi/4$$

with 1 bunches:

$$\eta_1 \simeq 0.08$$

with 6 bunches:

$$\eta_{\text{total}} \simeq 0.5$$

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

- Improved efficiency achieved using bunch trains:
  - Each bunch has same charge
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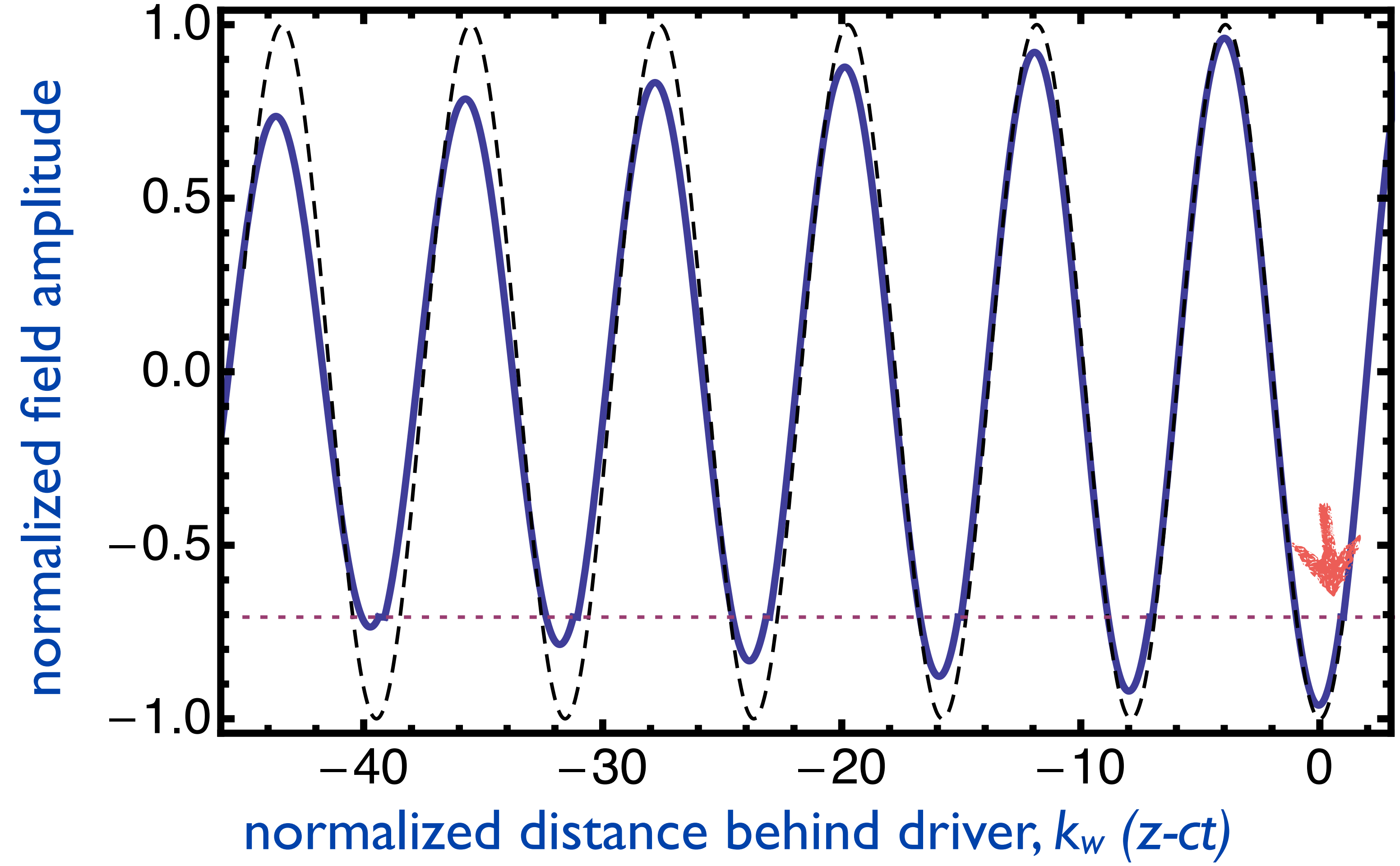

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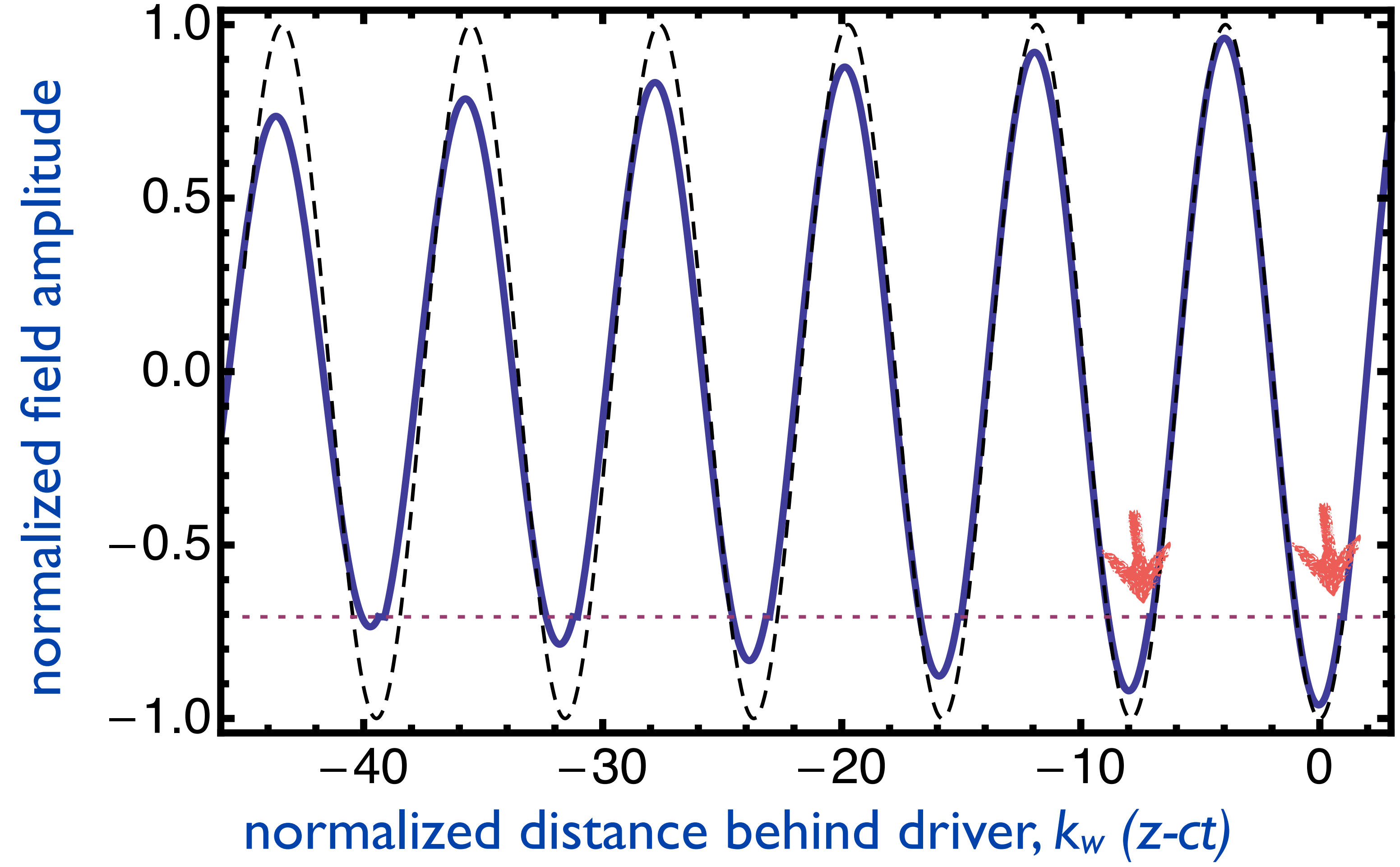

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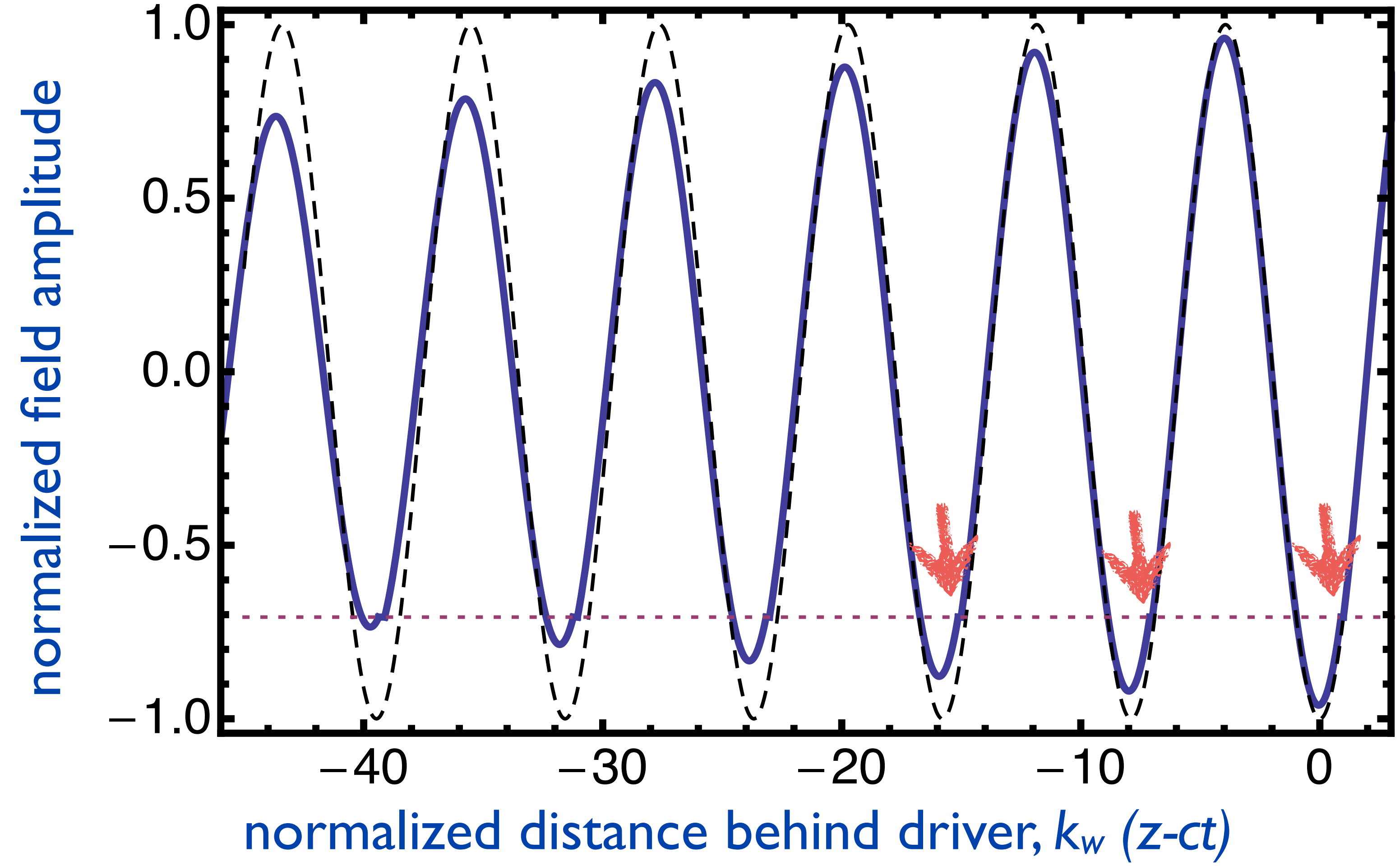

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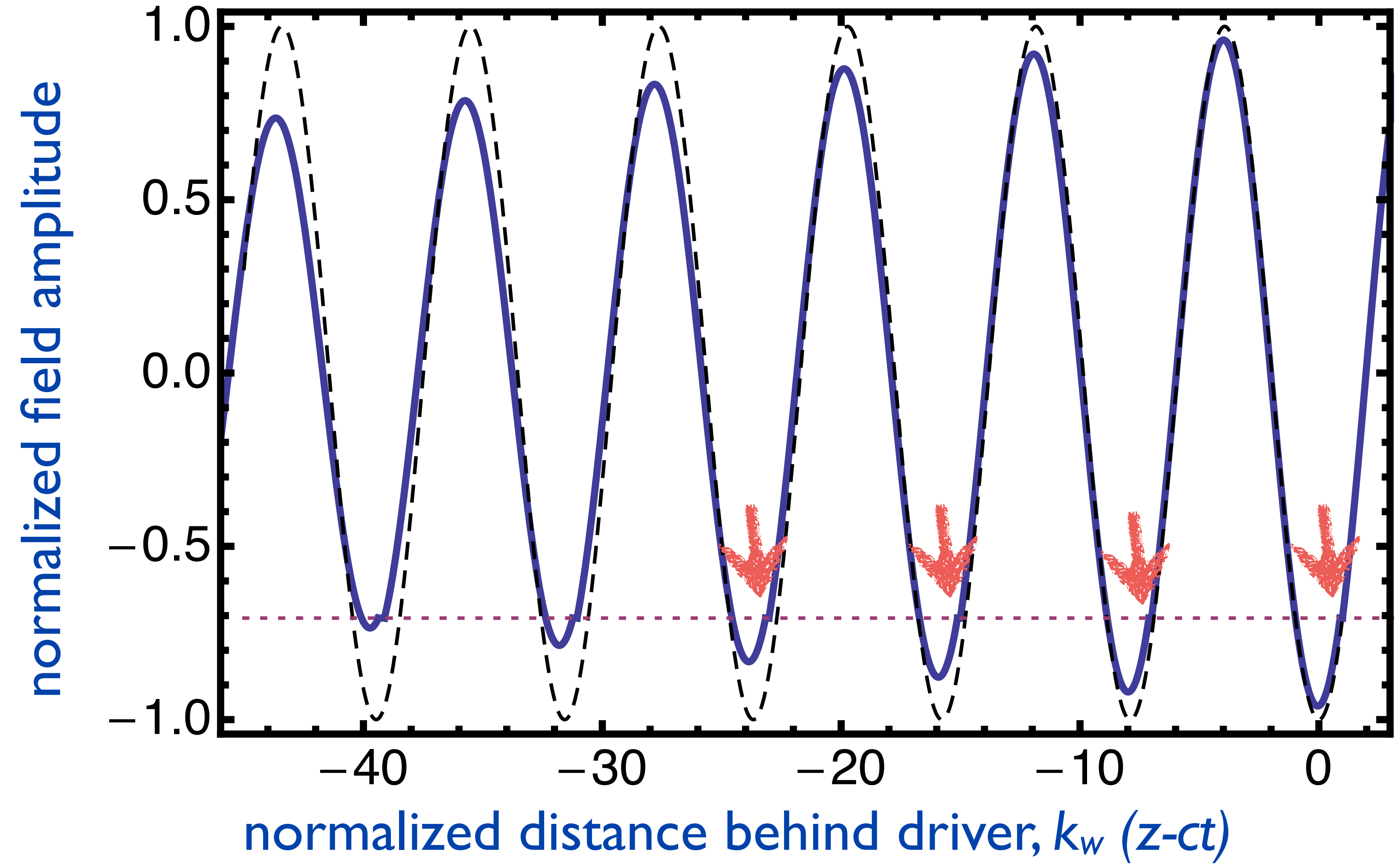

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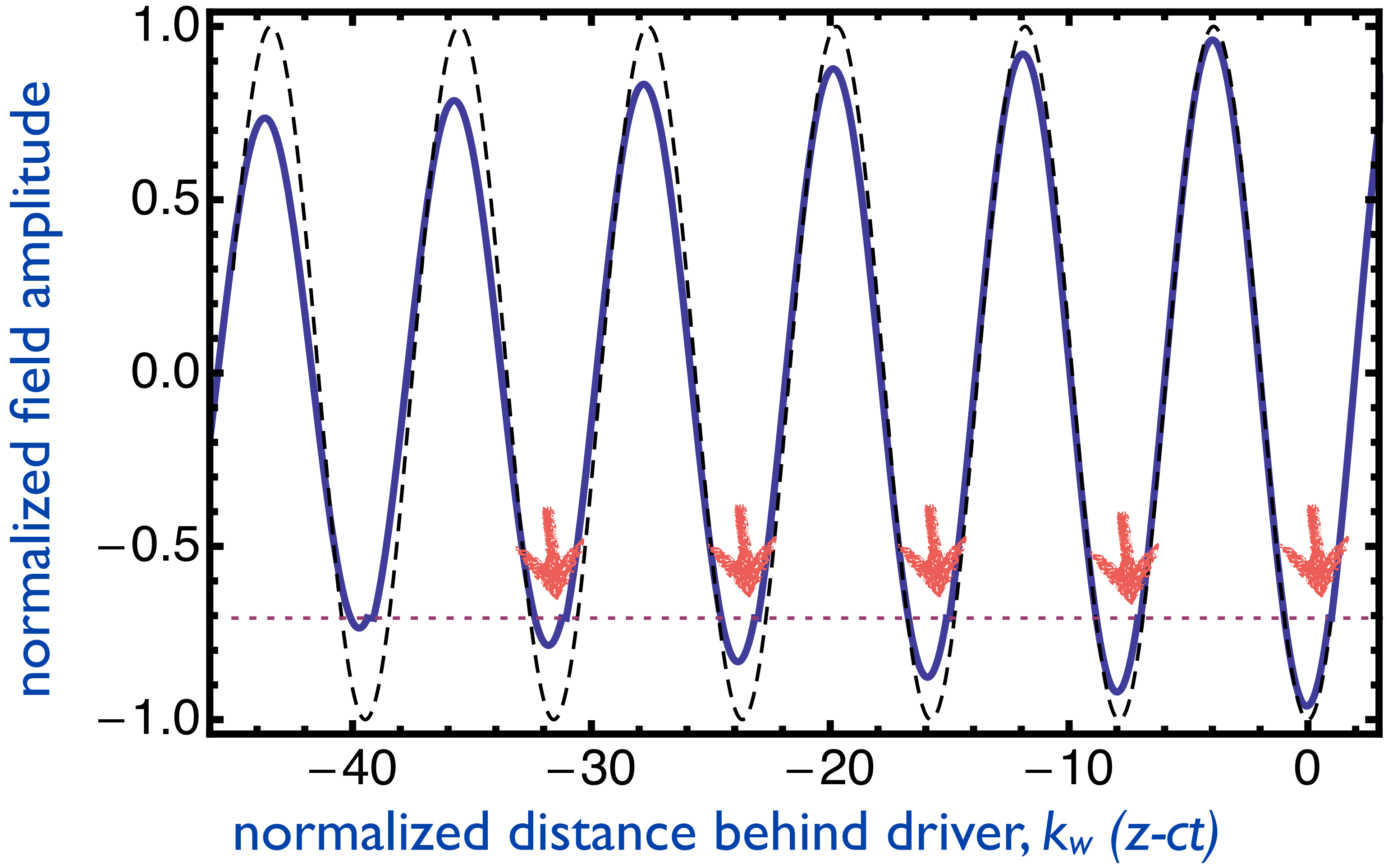

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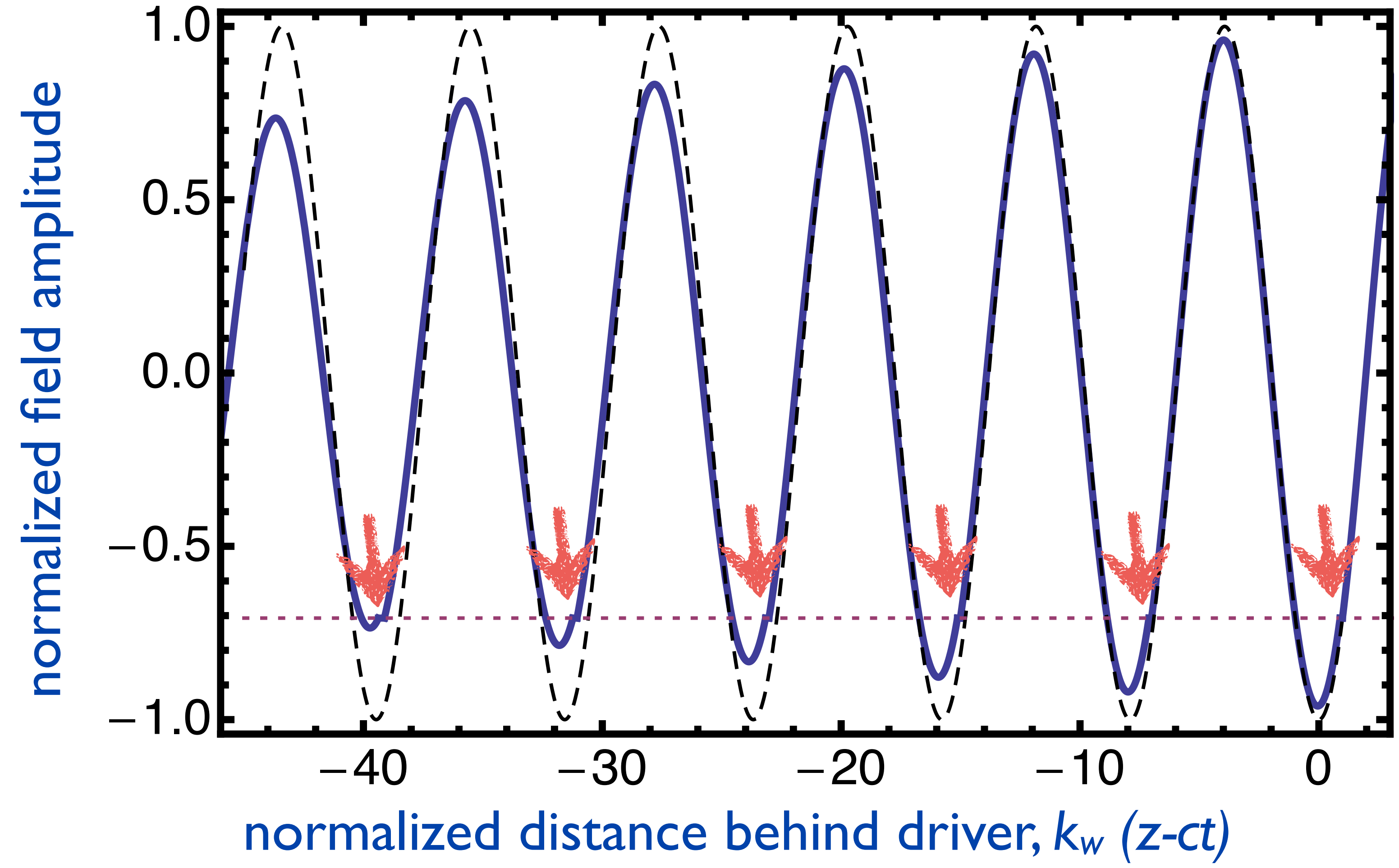

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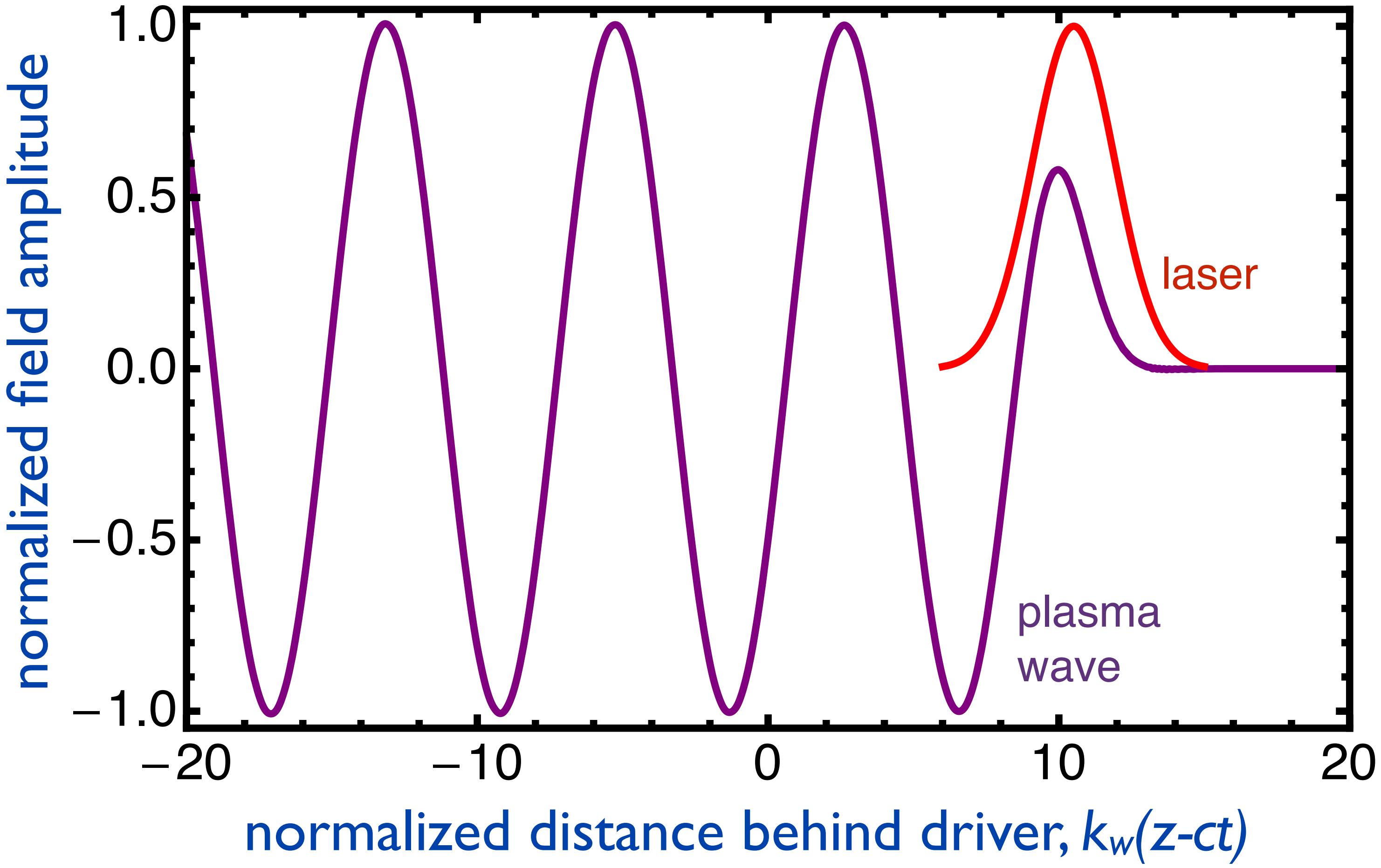
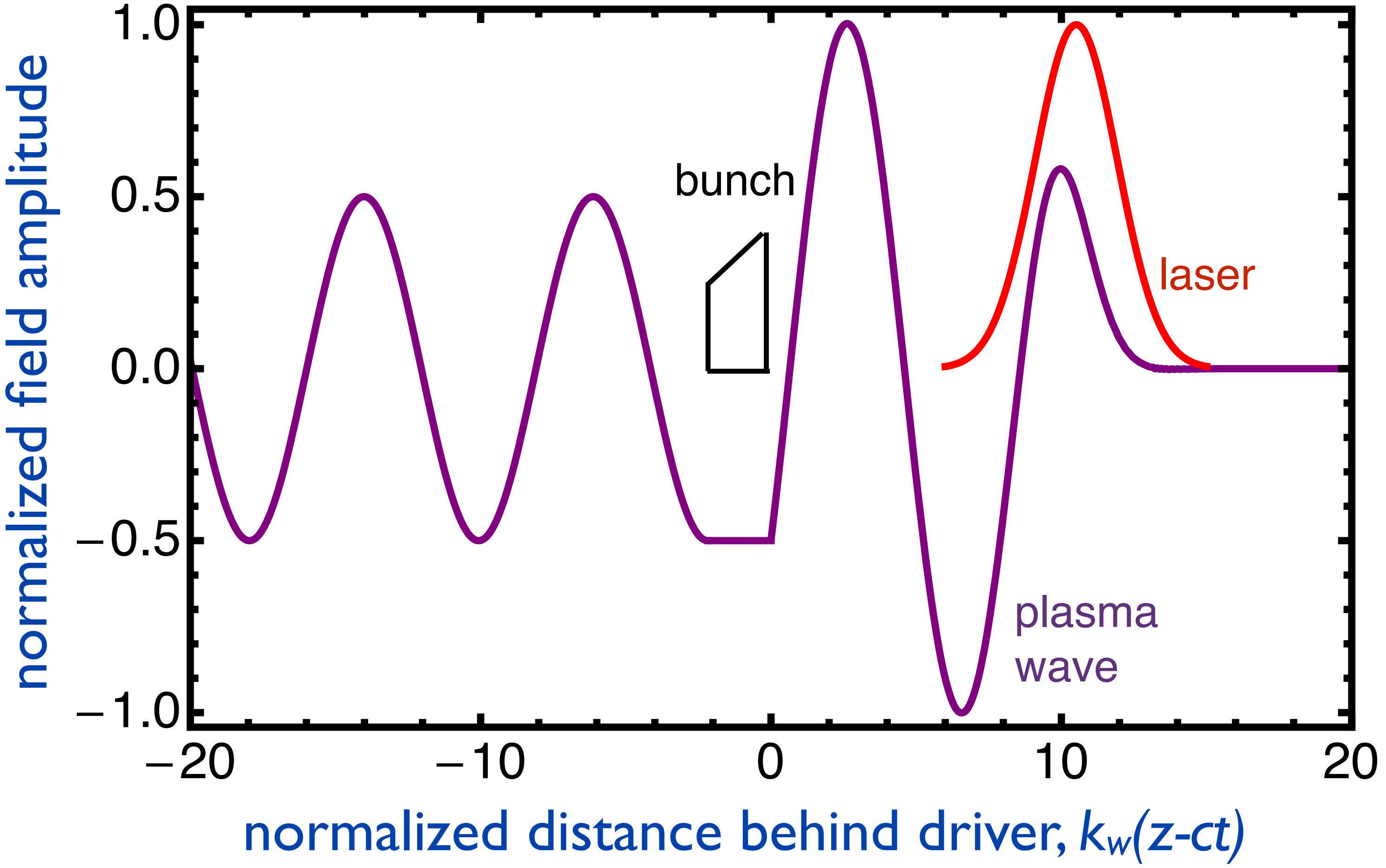
Improved efficiency using additional laser pulses to absorb remaining plasma wave energy



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

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



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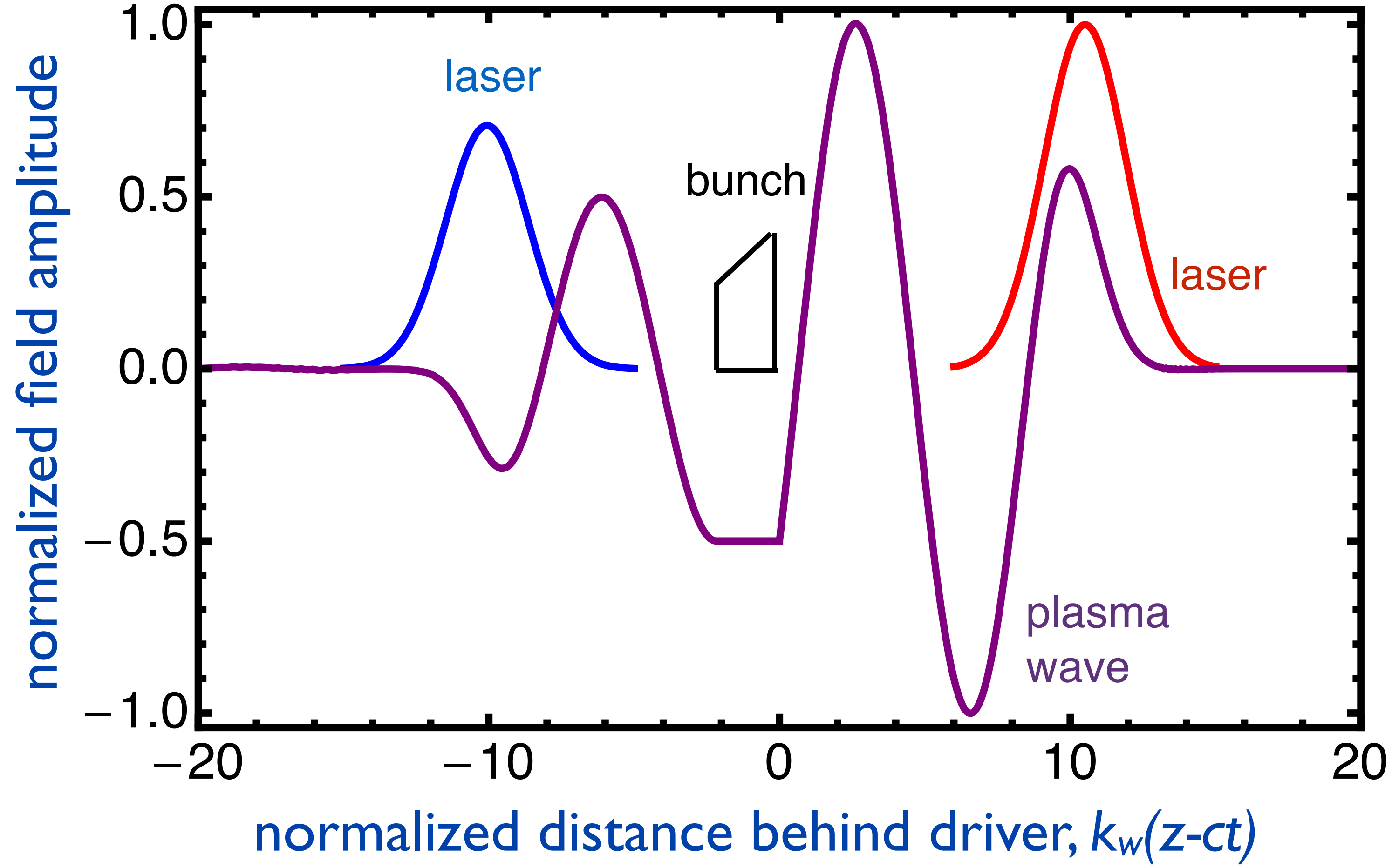

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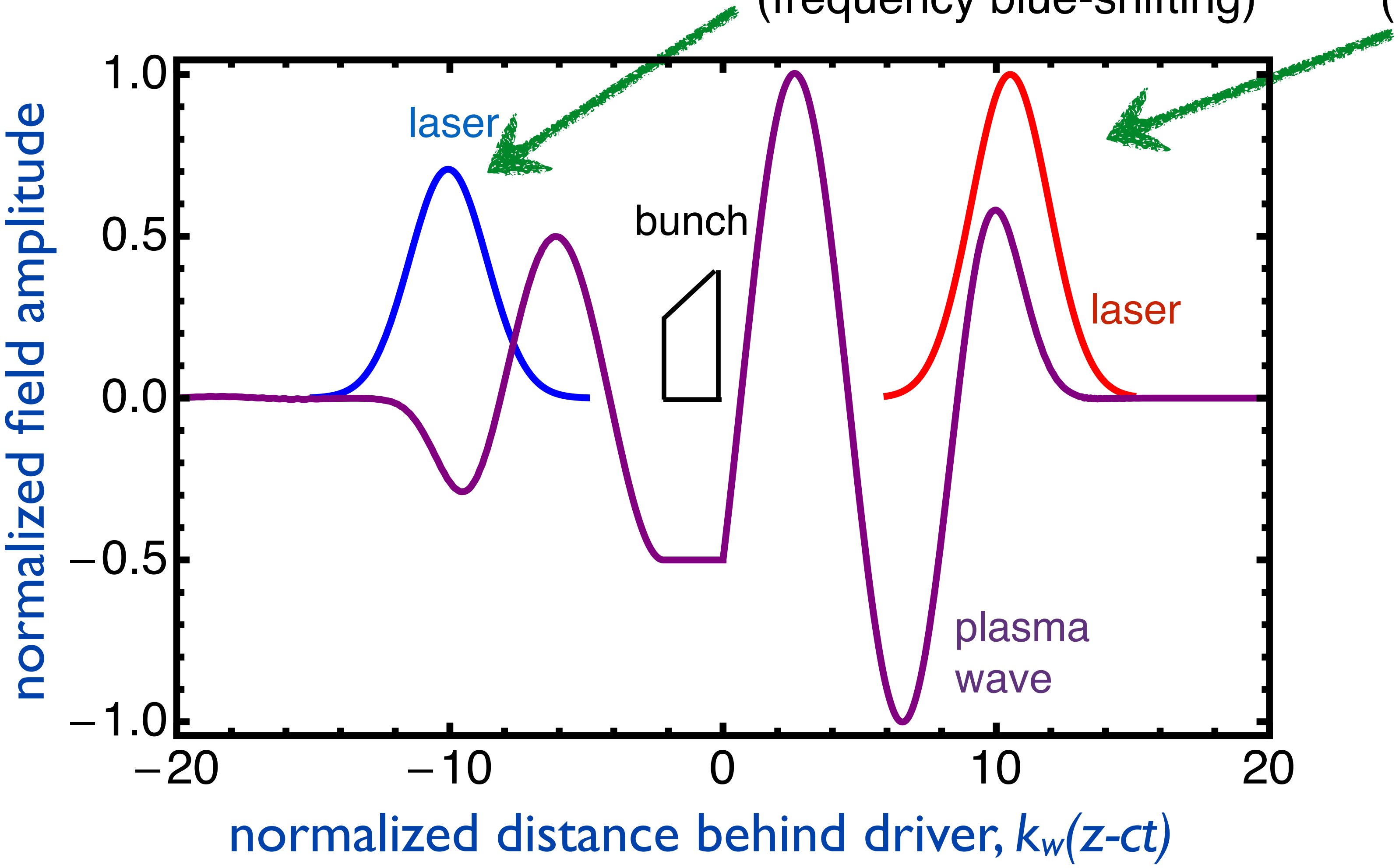


“Energy-recovery” laser absorbing wave energy (frequency blue-shifting)

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

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:

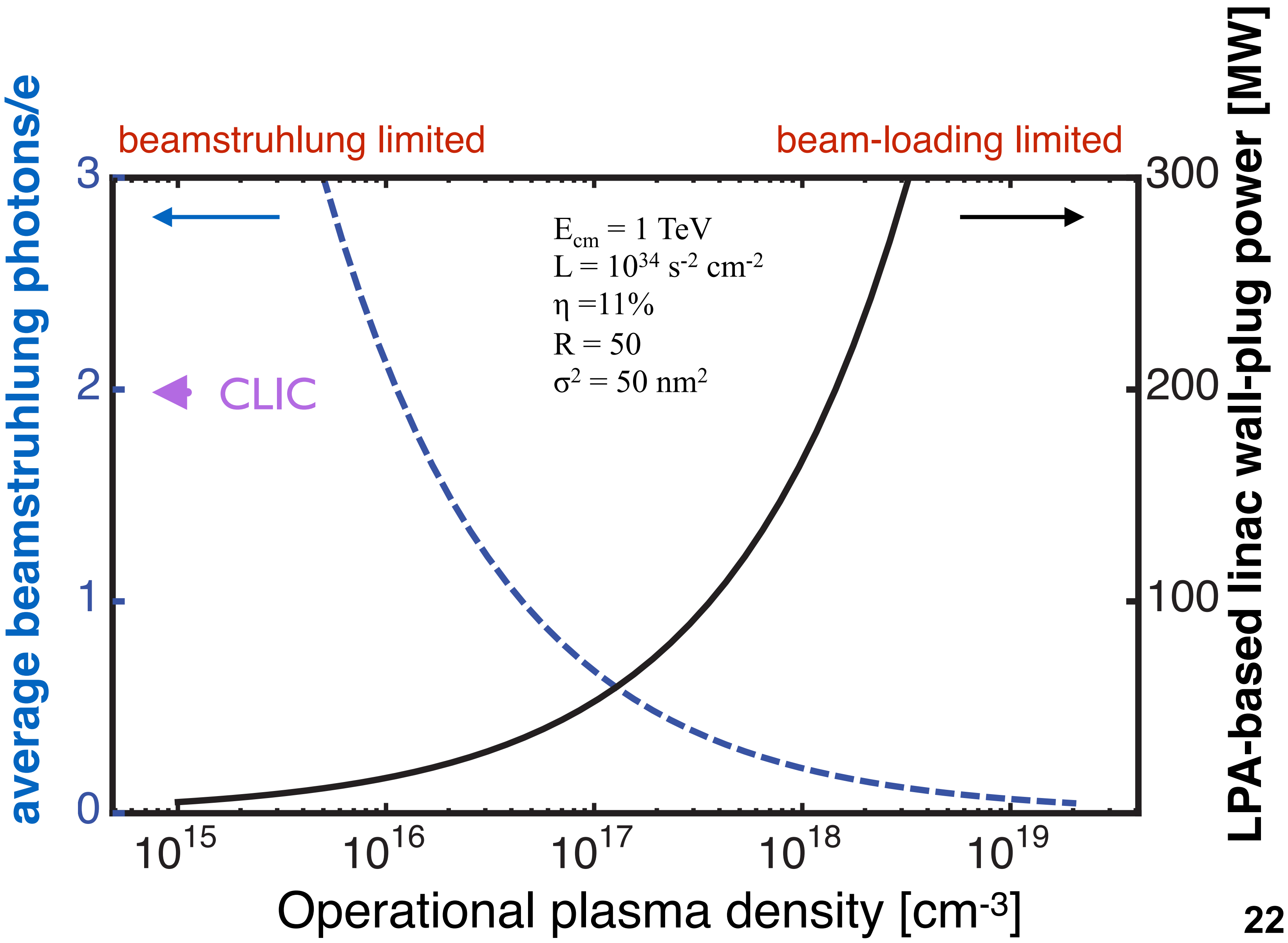
$$P \propto \sqrt{n}$$

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

Average beamstrahlung photons/e at IP:

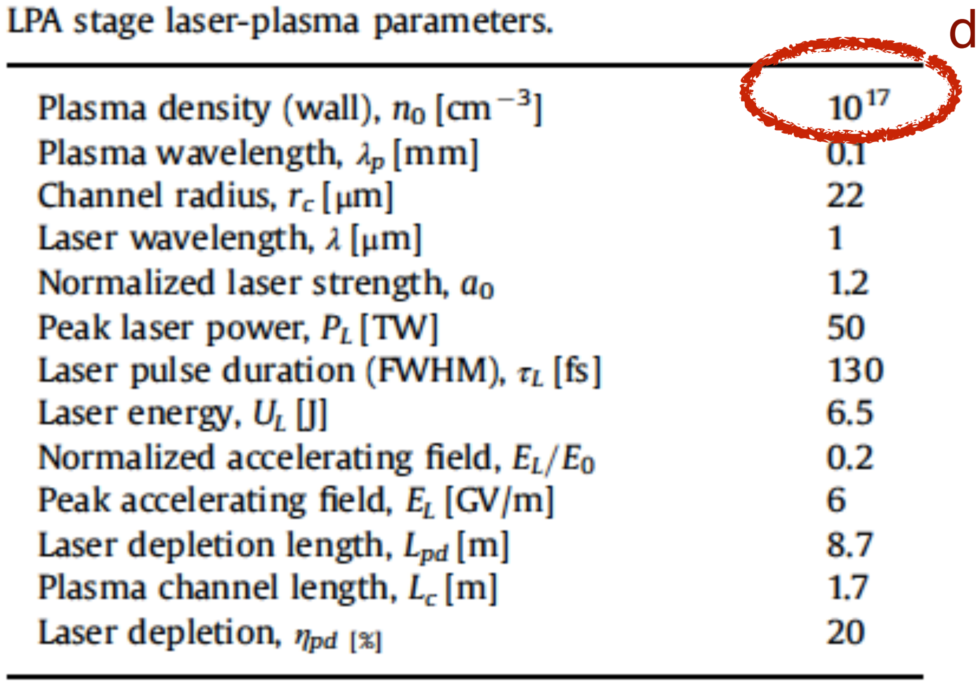
Schroeder et al., PR ST-AB (2012)

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



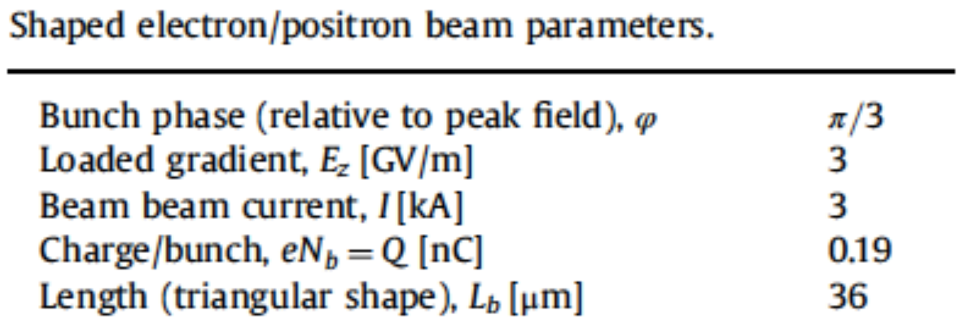
3 TeV laser-plasma collider example

operational plasma density



LPA stage laser-plasma parameters.

Plasma density (wall), n_0 [cm^{-3}]	10^{17}
Plasma wavelength, λ_p [mm]	0.1
Channel radius, r_c [μm]	22
Laser wavelength, λ [μm]	1
Normalized laser strength, a_0	1.2
Peak laser power, P_L [TW]	50
Laser pulse duration (FWHM), τ_L [fs]	130
Laser energy, U_L [J]	6.5
Normalized accelerating field, E_L/E_0	0.2
Peak accelerating field, E_L [GV/m]	6
Laser depletion length, L_{pd} [m]	8.7
Plasma channel length, L_c [m]	1.7
Laser depletion, η_{pd} [%]	20



Shaped electron/positron beam parameters.

Bunch phase (relative to peak field), φ	$\pi/3$
Loaded gradient, E_z [GV/m]	3
Beam beam current, I [kA]	3
Charge/bunch, $eN_b = Q$ [nC]	0.19
Length (triangular shape), L_b [μm]	36

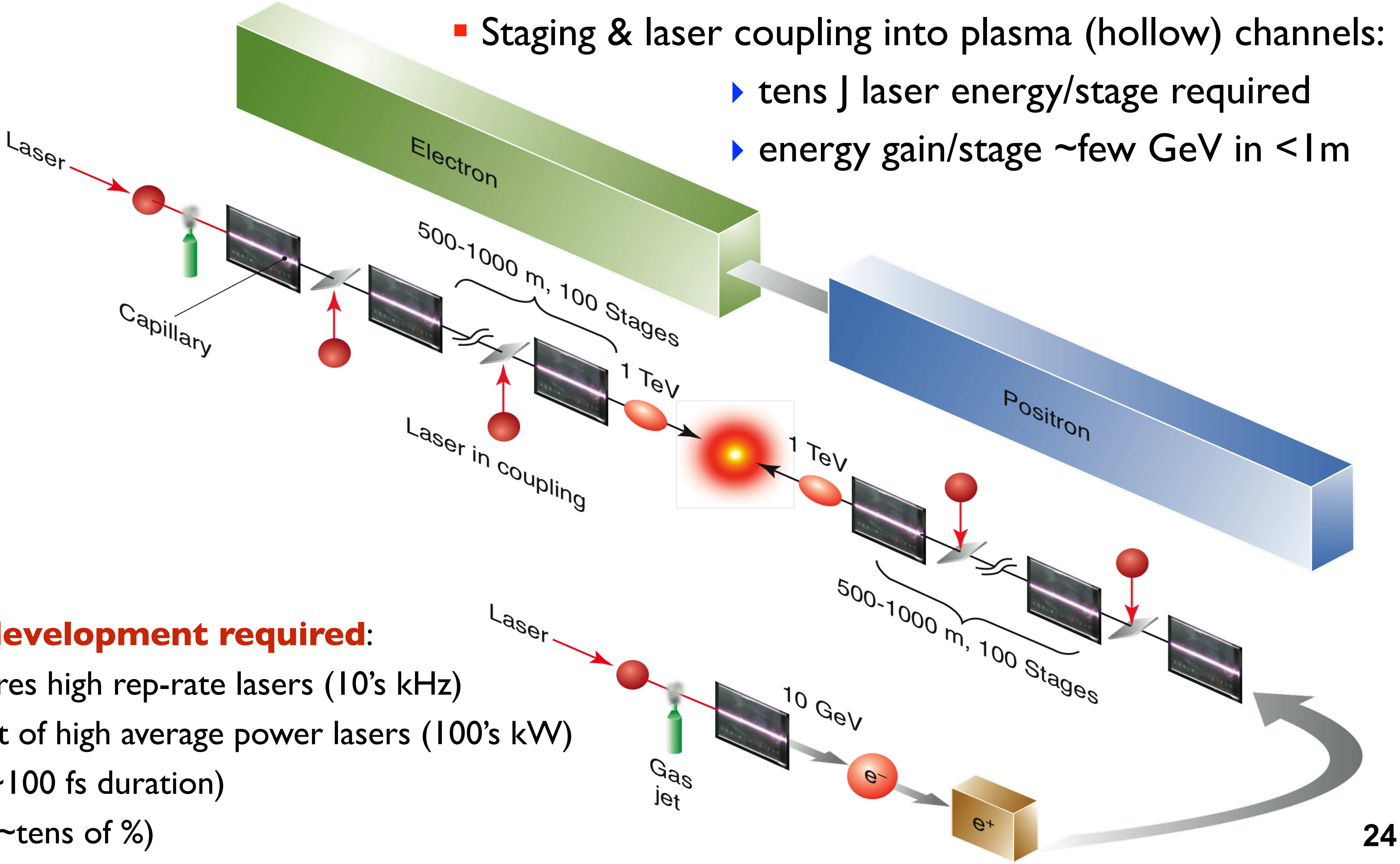
beam energy	1.5 TeV
energy gain/stage	5 GeV
RMS **σ**z[micron]	8.5
σx[nm]/**σ**y[nm]	18 / 0.5
Luminosity [s^{-1}cm^{-2}]	1E+35
laser rep rate [kHz]	84
Beamstrahlung parameter	16
Beamstahlung photons/e	0.81
Beamstrahlung energy spread	0.20
Disruption parameter	0.046
Power (LPA linacs)	407 MW

Laser-plasma accelerator-based collider concept

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

- Plasma density scalings [minimize construction (max. average gradient) and operational (min. wall power) costs] indicates: $n \sim 10^{17}$ cm^{-3}
- Quasi-linear wake ($a \sim 1$): 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)



Laser technology development required:

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

Laser-plasma accelerator-based collider concept

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

- Plasma density scalings [minimize construction (max. average gradient) and operational (min. wall power) costs] indicates: n ~ 10^{17} cm^{-3}
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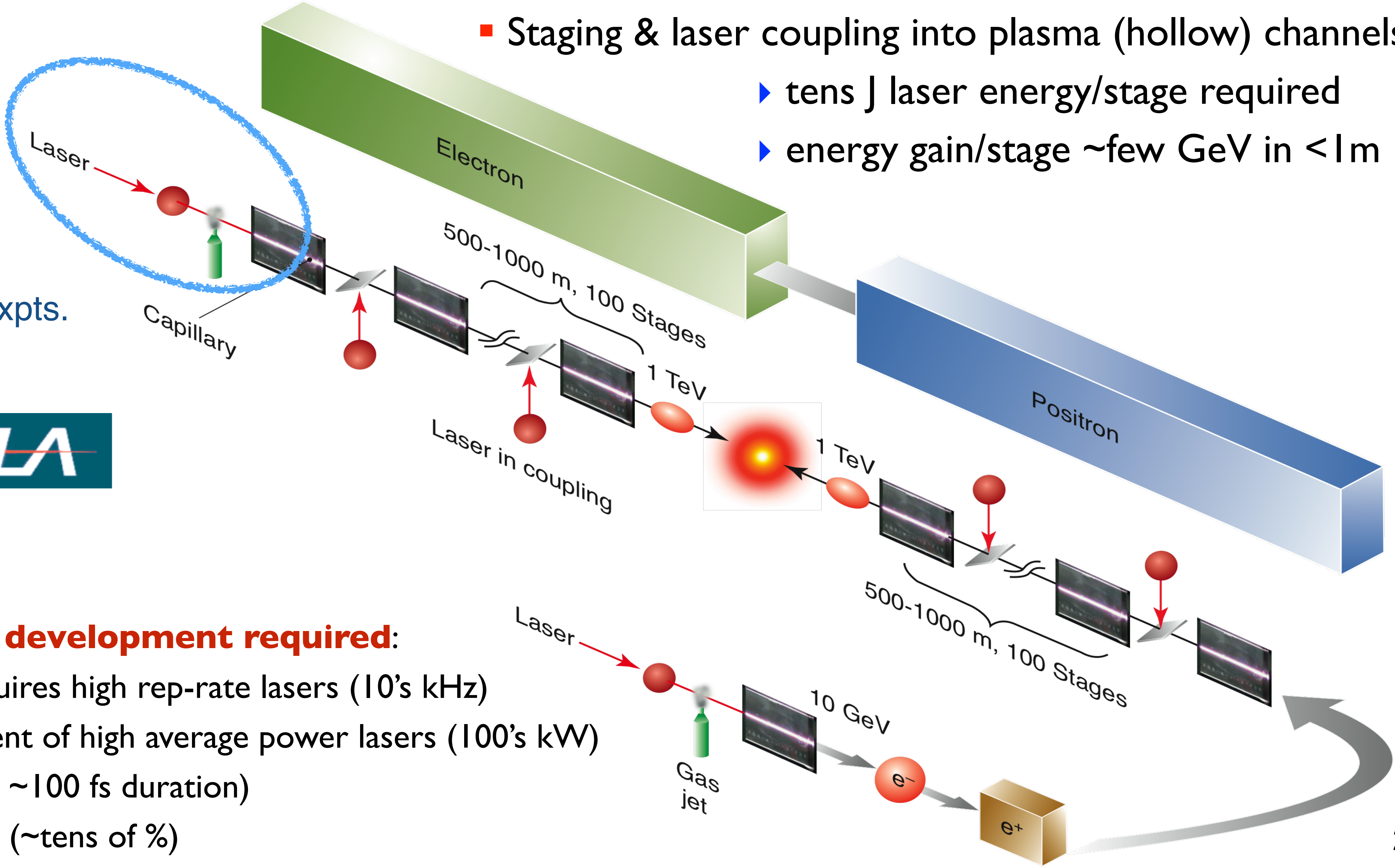

multi-GeV expts.

BELLA

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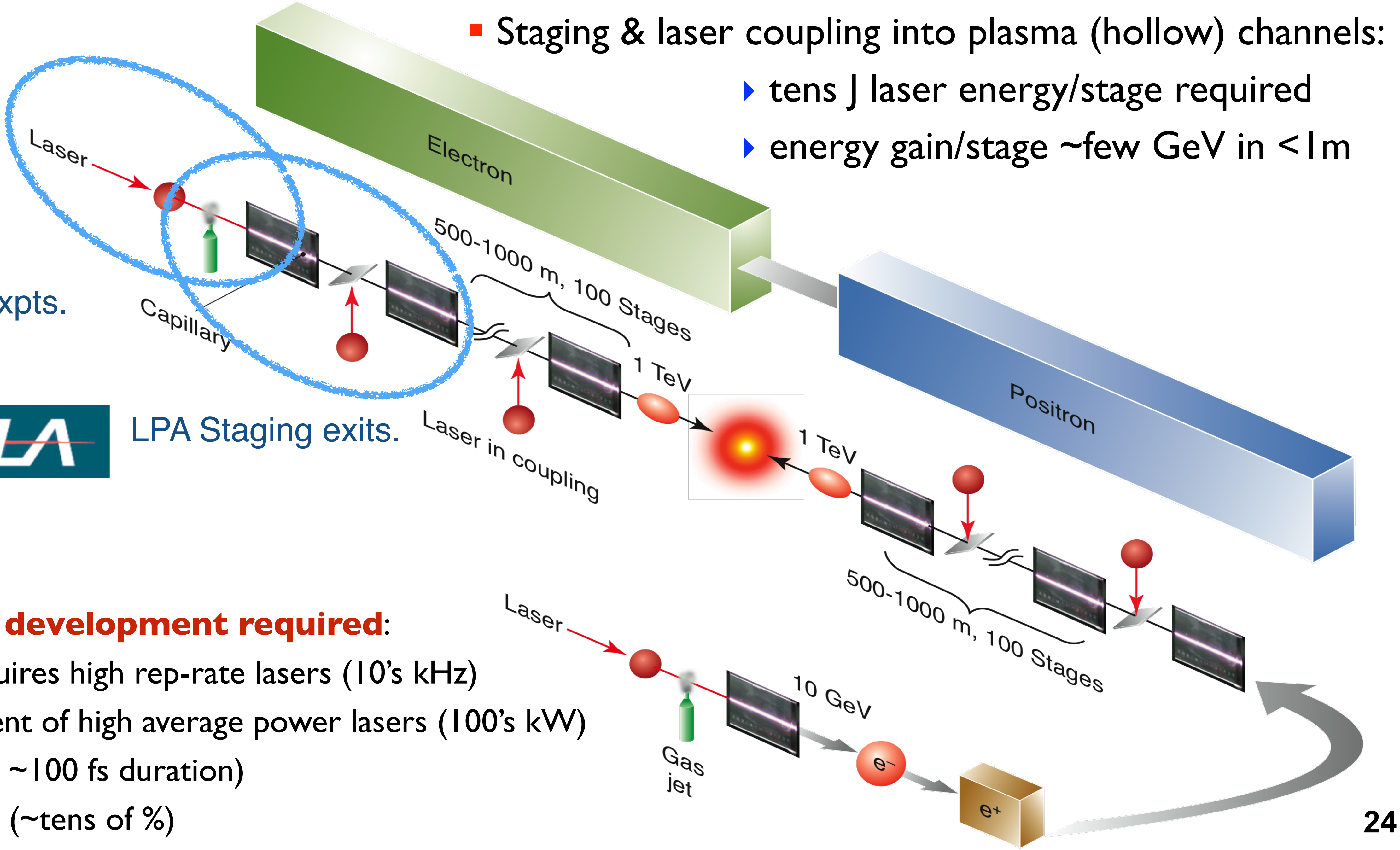

multi-GeV expts.

BELLA

LPA Staging exits.

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- Bandwidth (support ~100 fs duration)
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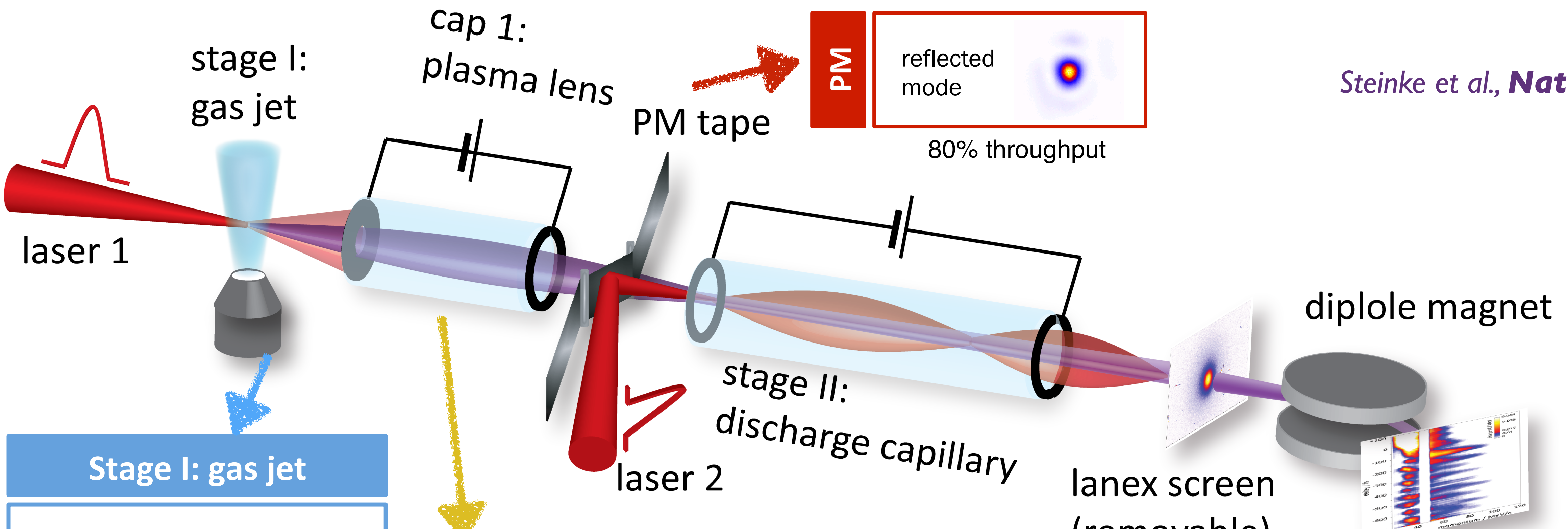
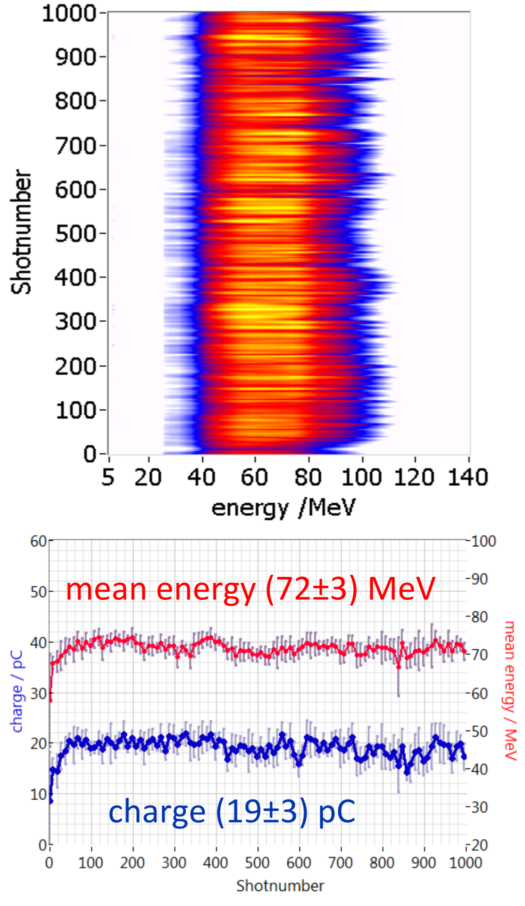
Demonstration of acceleration in second independently-powered laser-plasma accelerator at LBNL



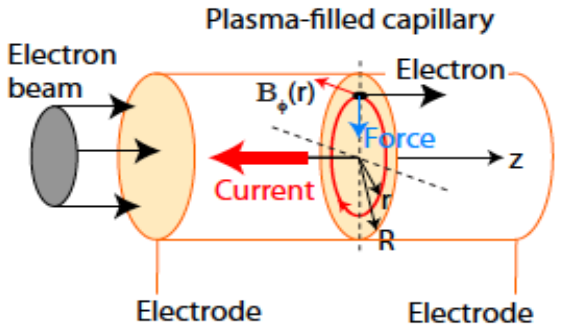
Steinke et al., ***Nature*** *(2016)*

Stage I: gas jet

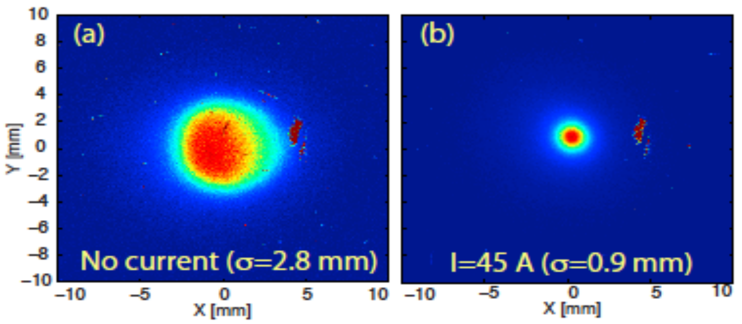


Cap 1: active plasma lens

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)

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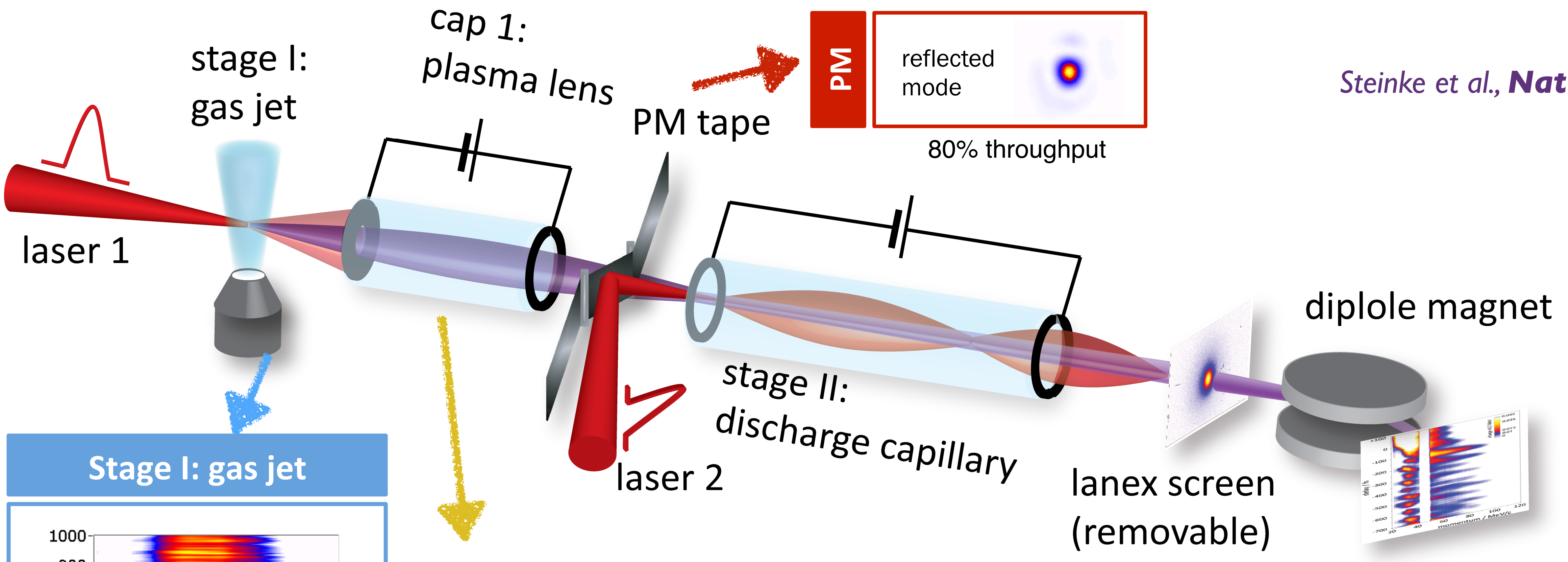

Steinke et al., ***Nature*** *(2016)*

lanex screen

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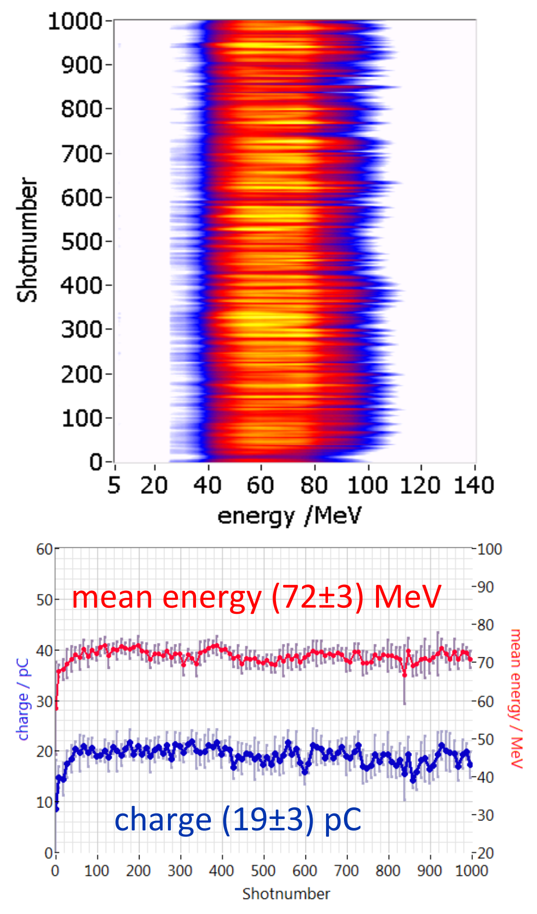

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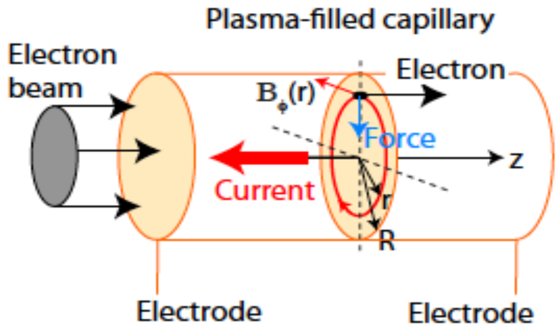

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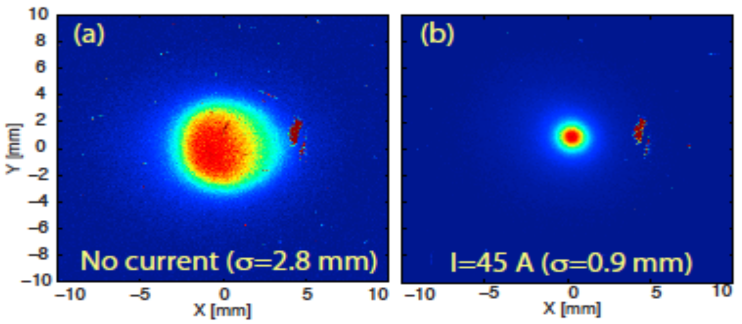
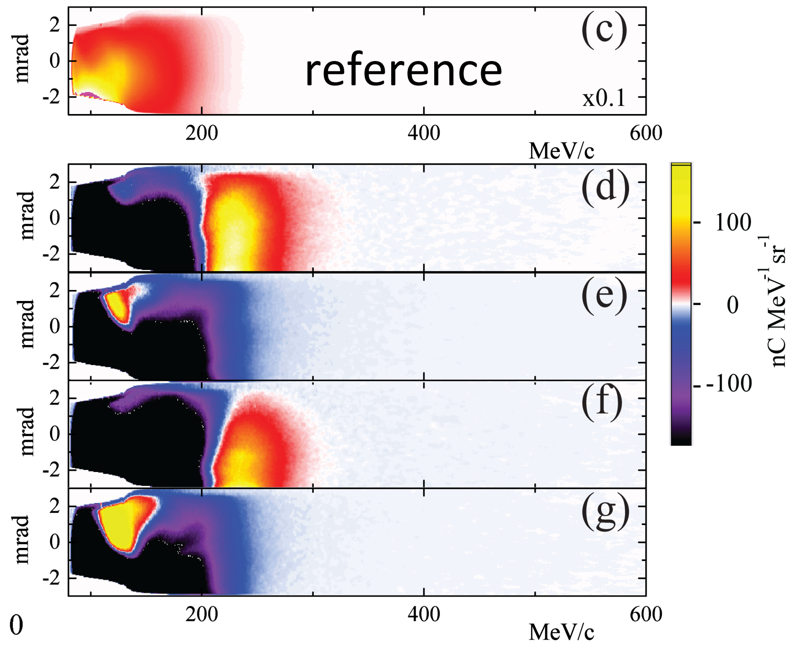


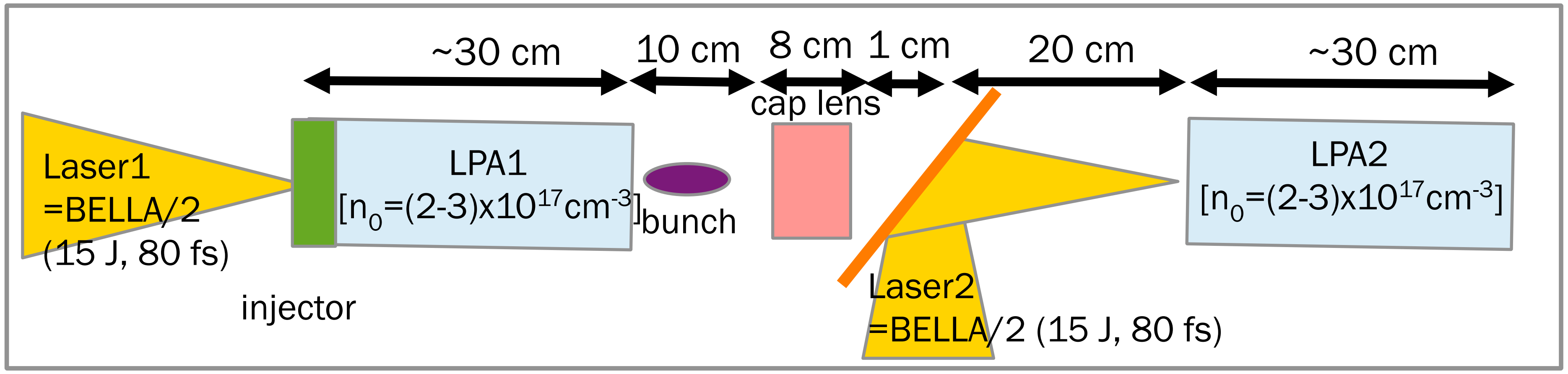
J. van Tilborg et al., PRL (2015)

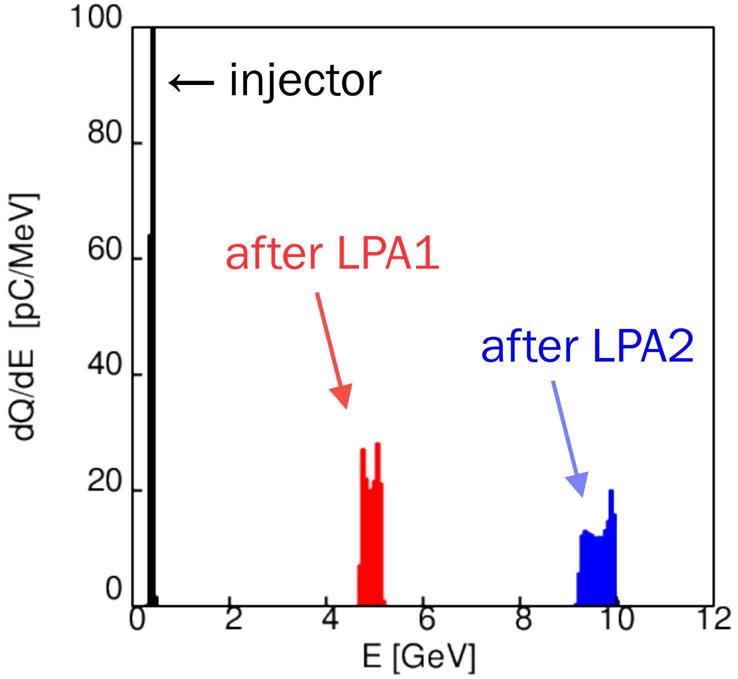
Stage I + II

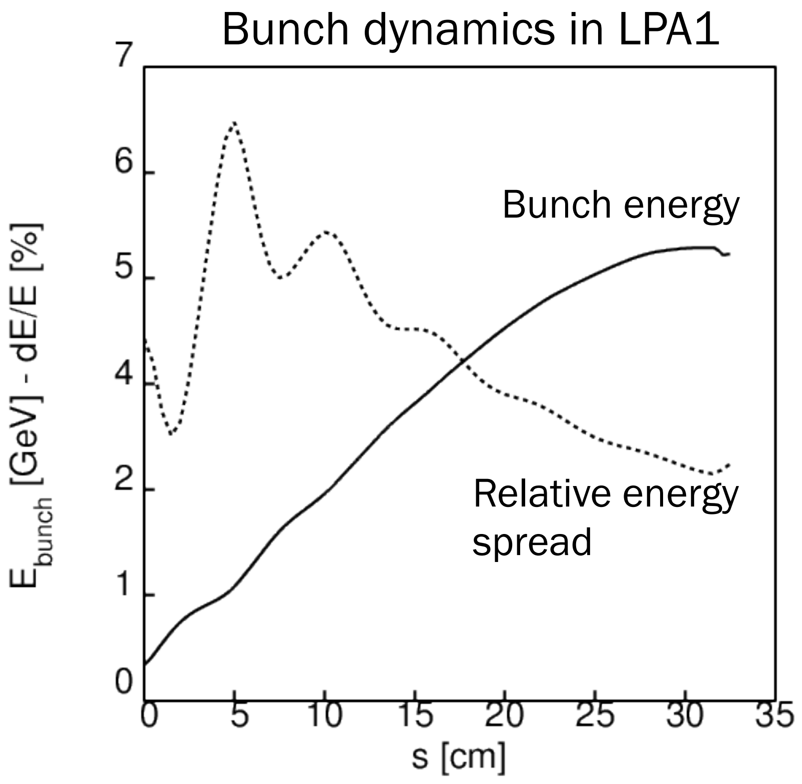


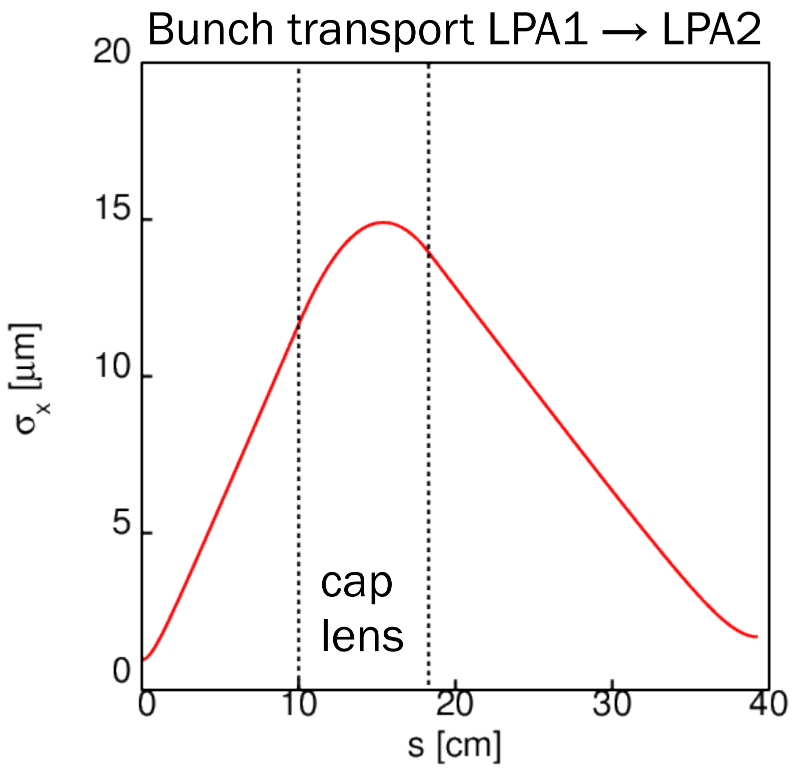
Future LPA staging experiments: 5 GeV + 5 GeV

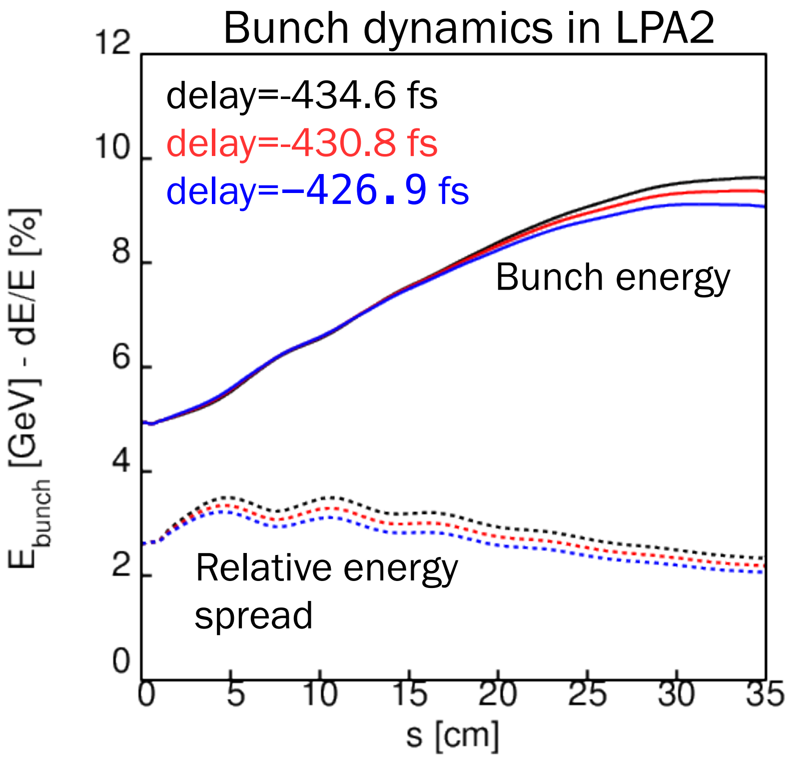
Steinke et al., Phys. Plasmas (2016)











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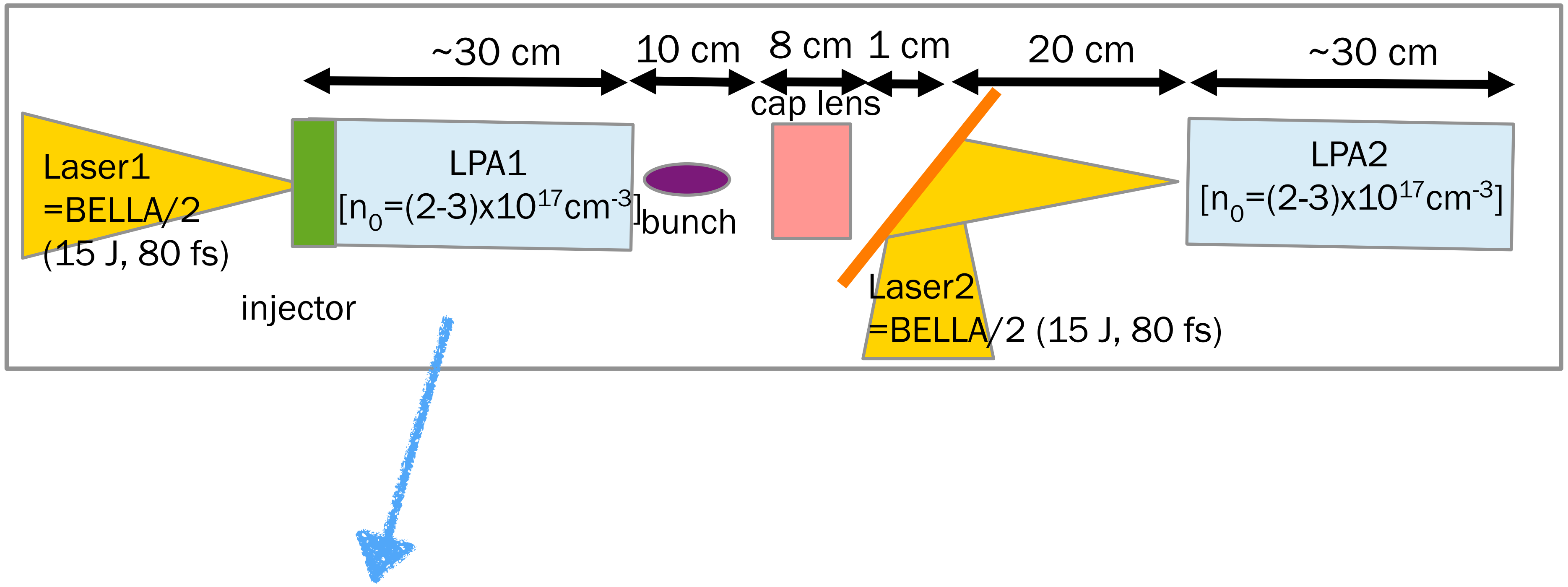


~30 cm

10 cm

8 cm

1 cm

20 cm

~30 cm

cap lens

Laser1 =BELLA/2 (15 J, 80 fs)

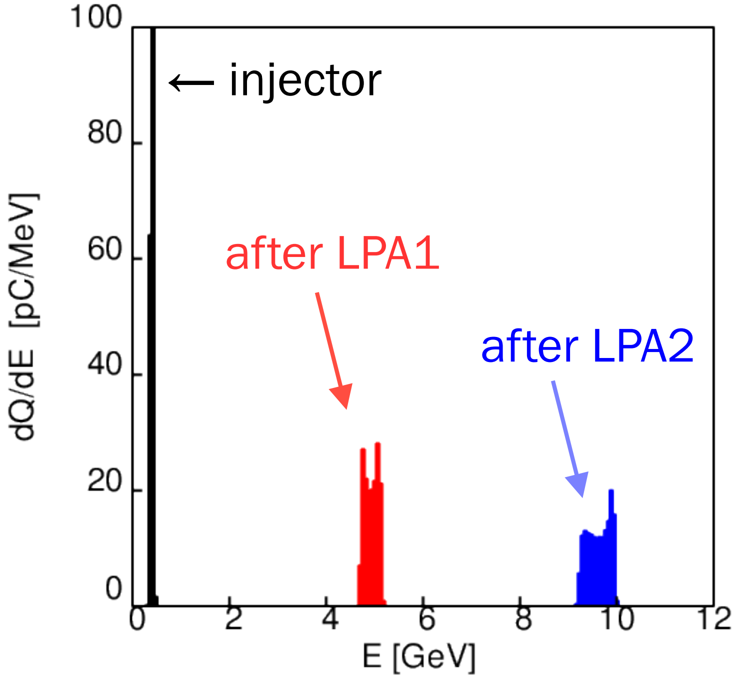
LPA1 [n_0=(2-3)x10^{17}cm^{-3}]

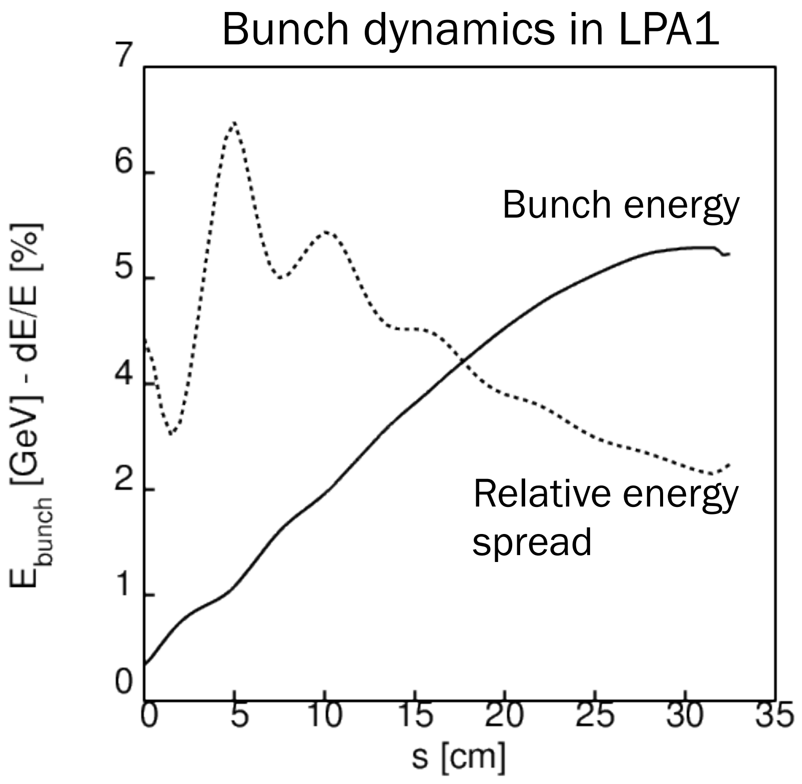
bunch

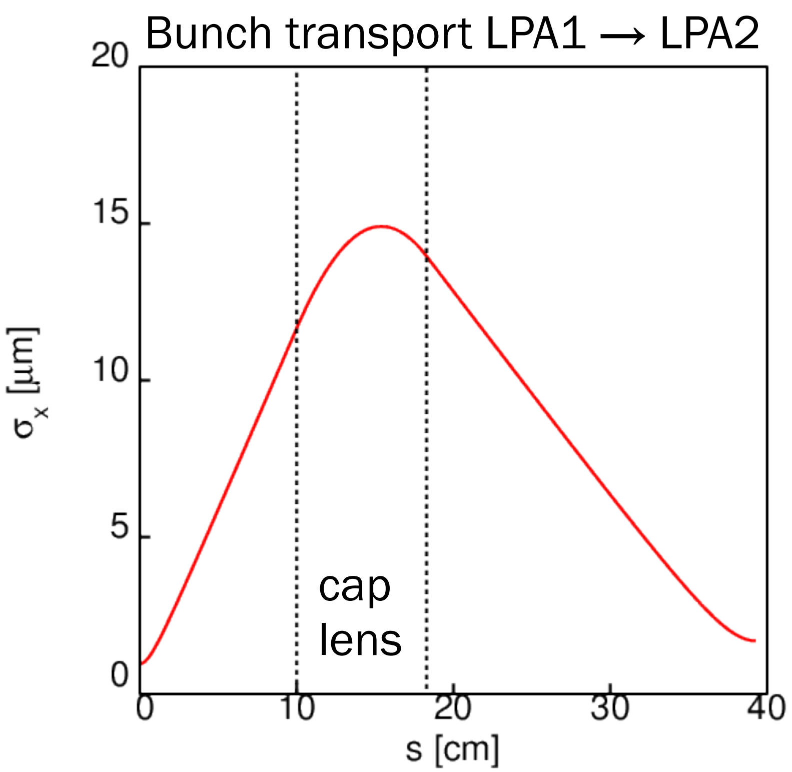
injector

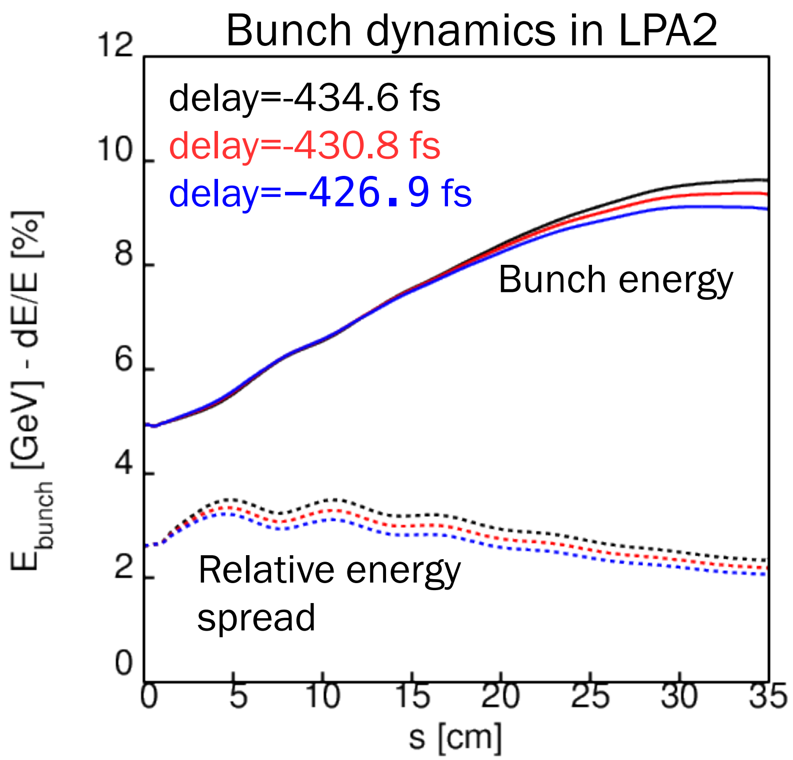
Laser2 =BELLA/2 (15 J, 80 fs)

LPA2 [n_0=(2-3)x10^{17}cm^{-3}]









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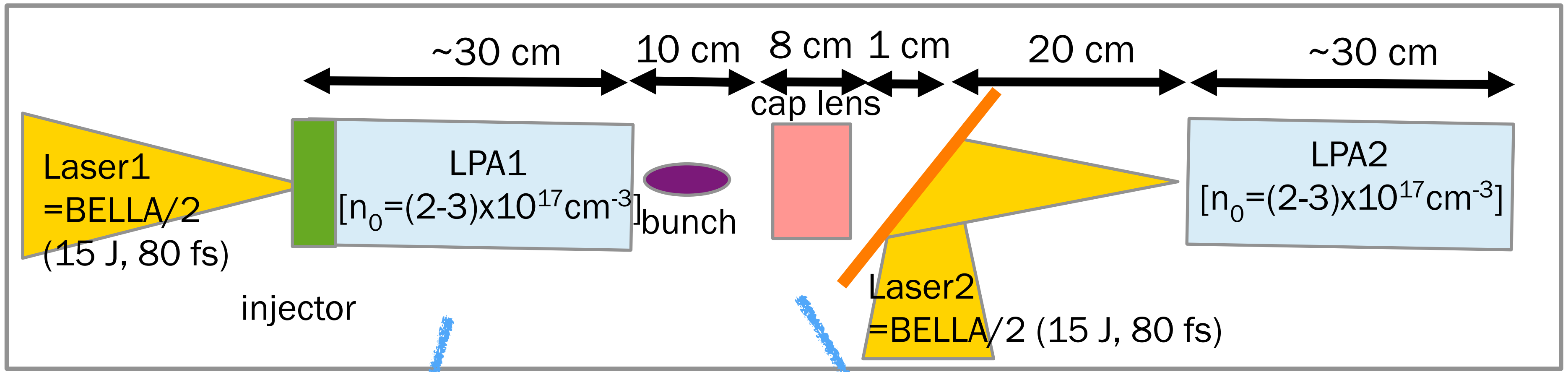

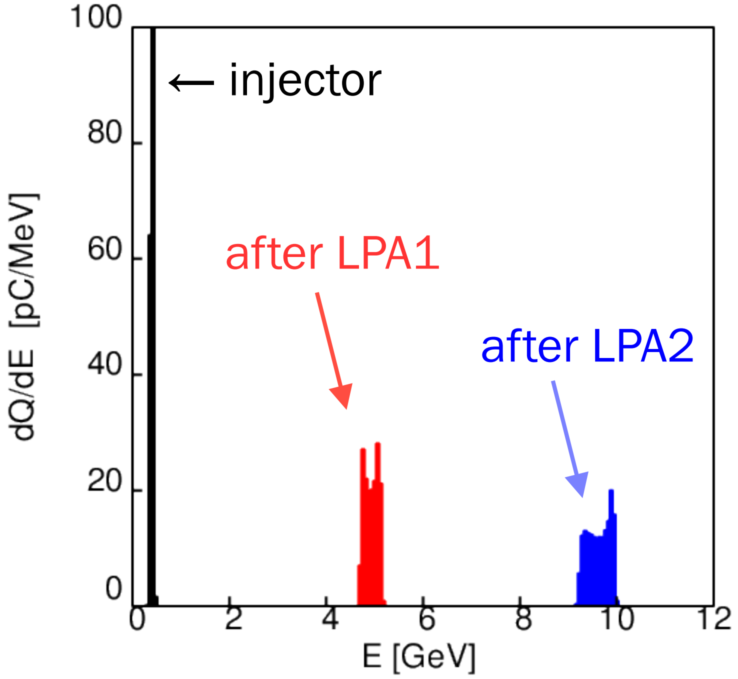

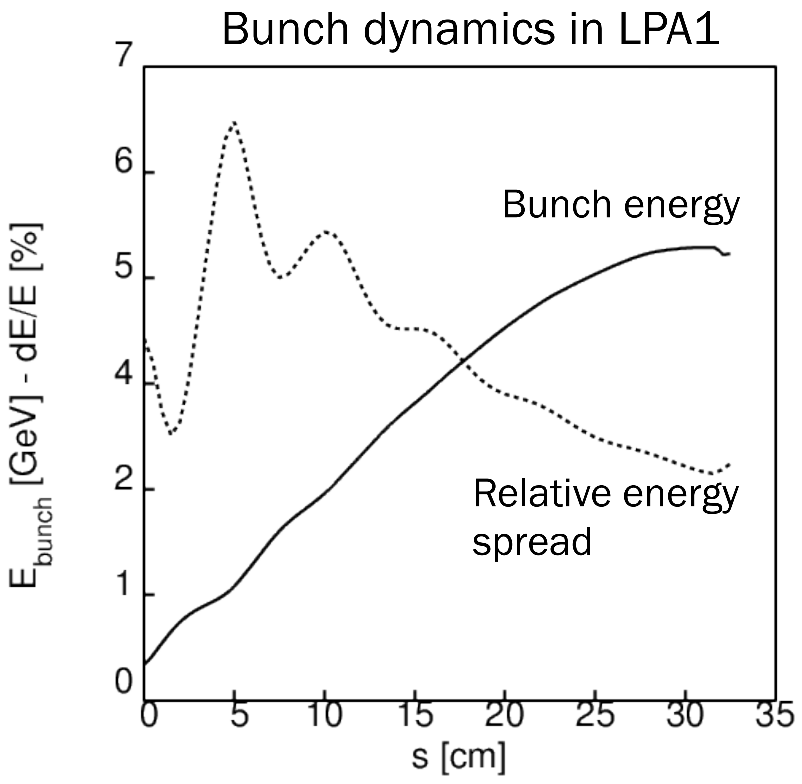

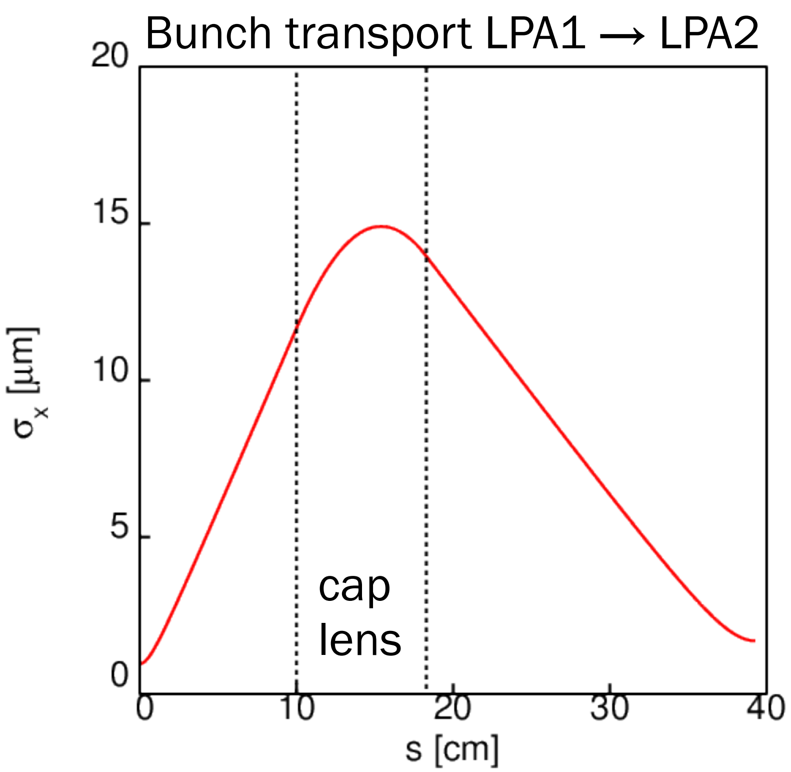

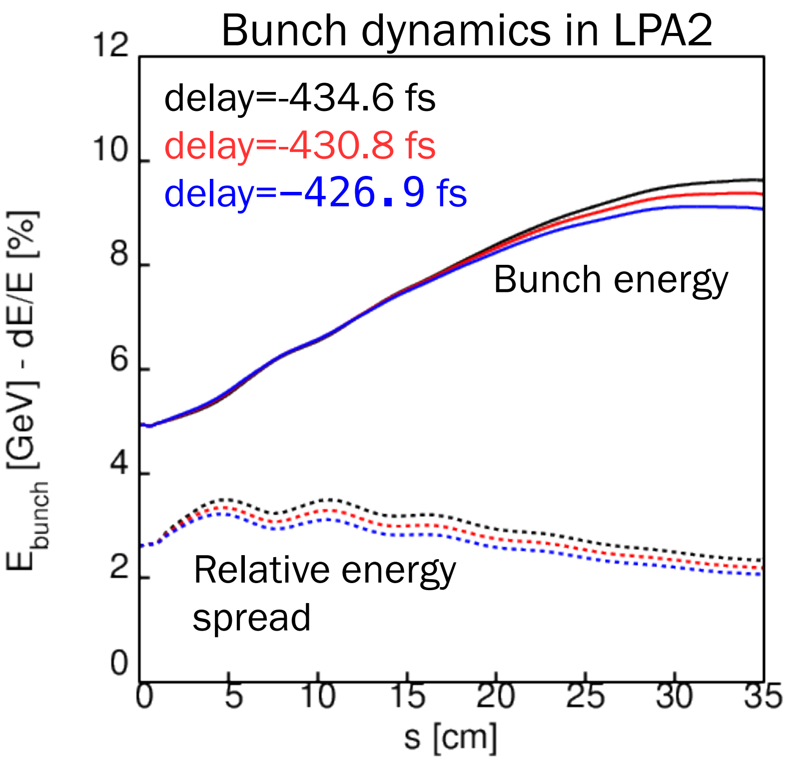

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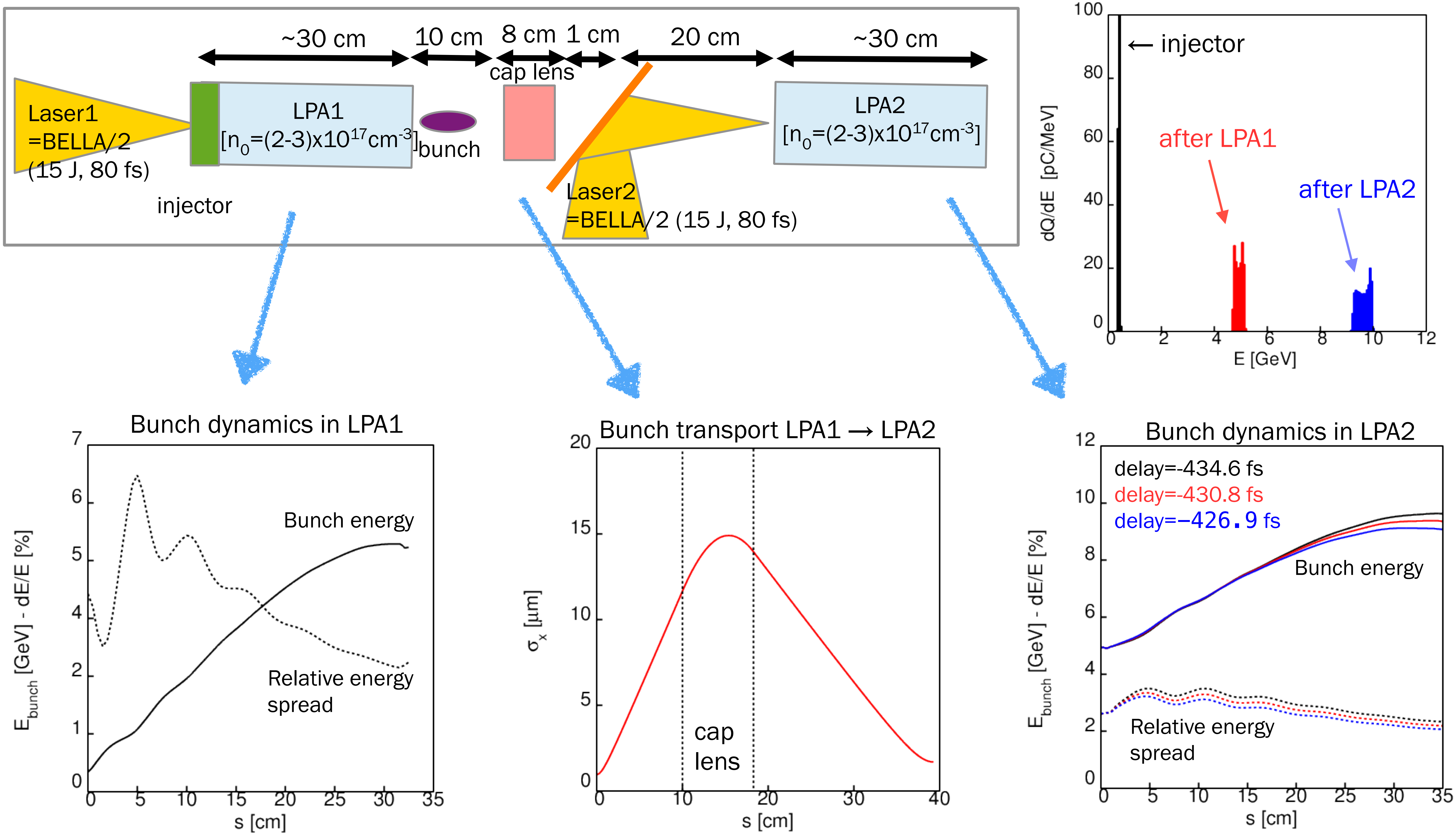

Summary and Conclusions

- 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
- Beam-beam interaction effects modify the basic scalings and determine the operational plasma density (determines required laser technology, etc.)
  - Basic scalings indicate ~1E17/cc operating density.
  - Operating at low plasma density increases beamstrahlung effects (higher bunch charge and longer beams)
  - Bunch charge constrained by beamstrahlung - requiring multi-bunch format or increase repetition frequency (power).
  - Detailed modeling still to be done (including beam shape, delivery system, etc.)
- Laser-plasma accelerator-based linear collider has many technical challenges and R&D for collider application ongoing
  - Staging LPA experiments underway at LBNL
  - High peak & average power laser technology development

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