Compact quasi-monoenergetic gamma ray sources based on Laser Plasma Accelerators

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LOASIS program, LBNL

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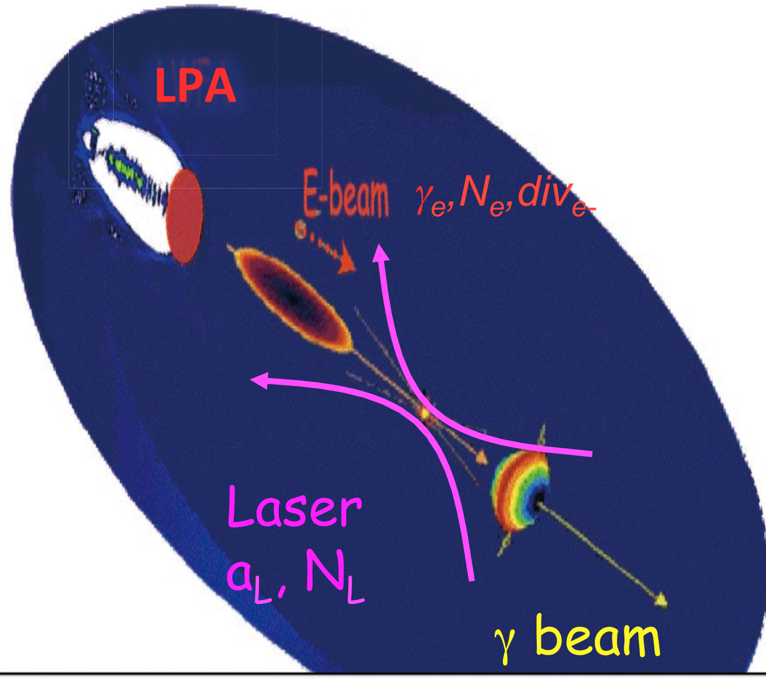
NPNSNP, January 2014

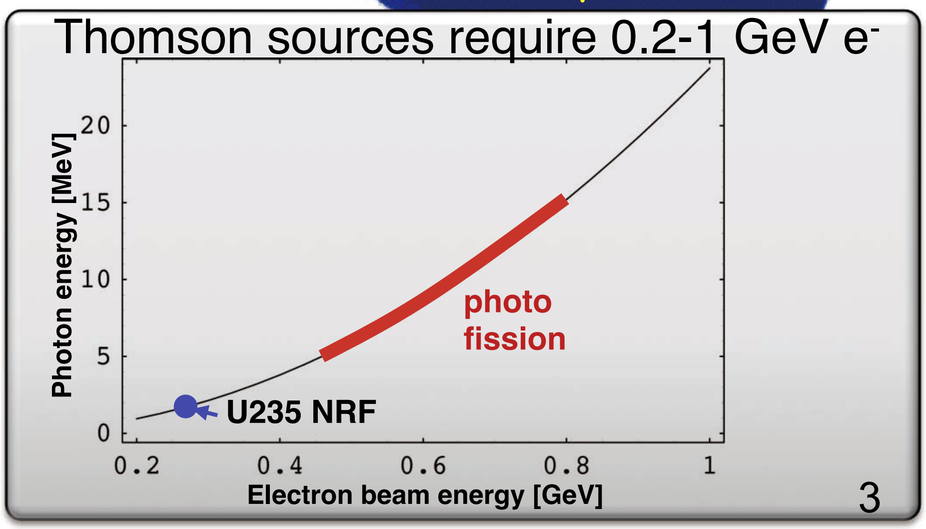
Outline

- Thomson source electron beam requirements
- Laser-plasma accelerator efficiency and beam quality to meet source needs
- Simulations: Thomson scattering of MeV photons from LPA electrons
- BELLA laser and HEP applications

Thomson scattering produces suitable photons
Transportable source needs compact accelerators

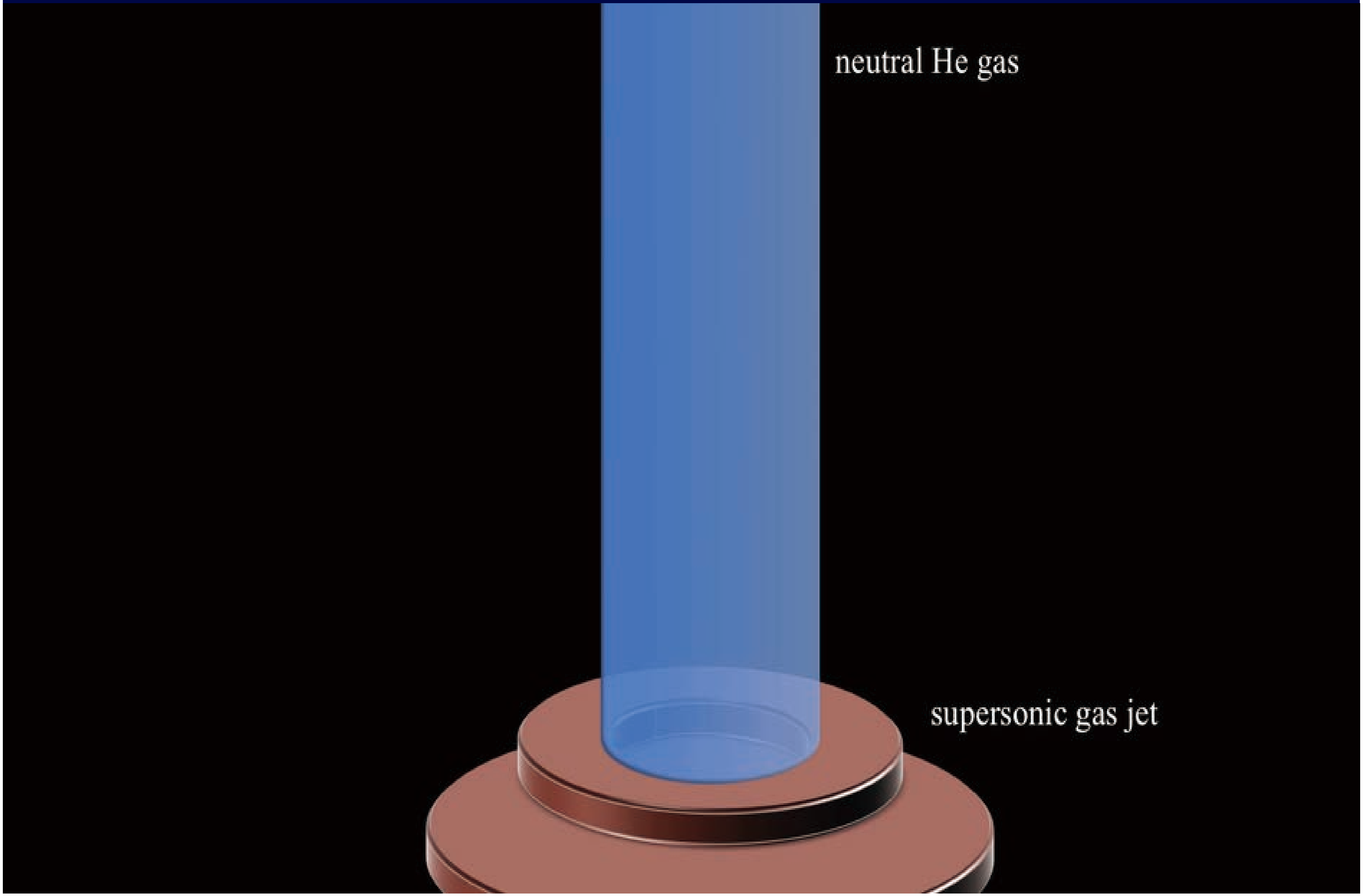
- 1-20 MeV photons from 0.3-1 GeV e-*
  - Mono-energetic: low dose/backgound
  - Low divergence: standoff
- Frequency doubled laser: 0.2-0.7 GeV
- Well proven on conventional accel.
- Compact, efficient solution needed
  - 10^{11}ph/s → 5W e- beam power
  - BW ~ 10 % →e- of 5% DE, ≤ mrad
  - BW ~ 2% →e- of 1% DE, ≤ 0.1 mrad



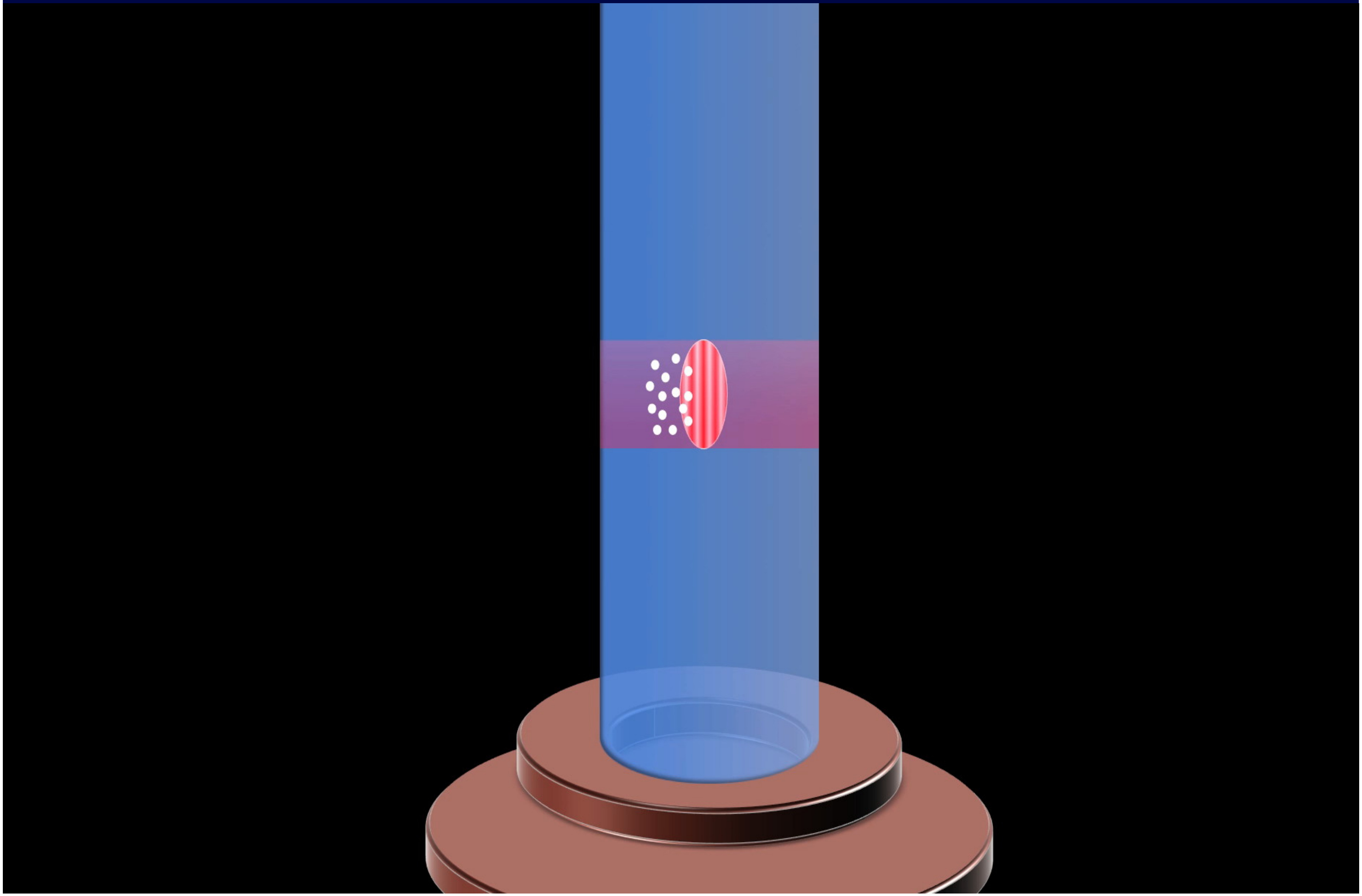


*P. Sprangle et al, J.Appl. Phys 1992,
W.P. Leemans et al., PRL 1996, R.W. Schoenlein et al., Science 1996;
Leemans TPS 2005; Geddes et al., CAARI 2008,
Albert et al PoP2012, Kawase et al, NIMA 2011.
Initial LPA experiments:Chen, PRL 2013 (UNL), Phuoc , Nature Photonics 2012 (LOA)

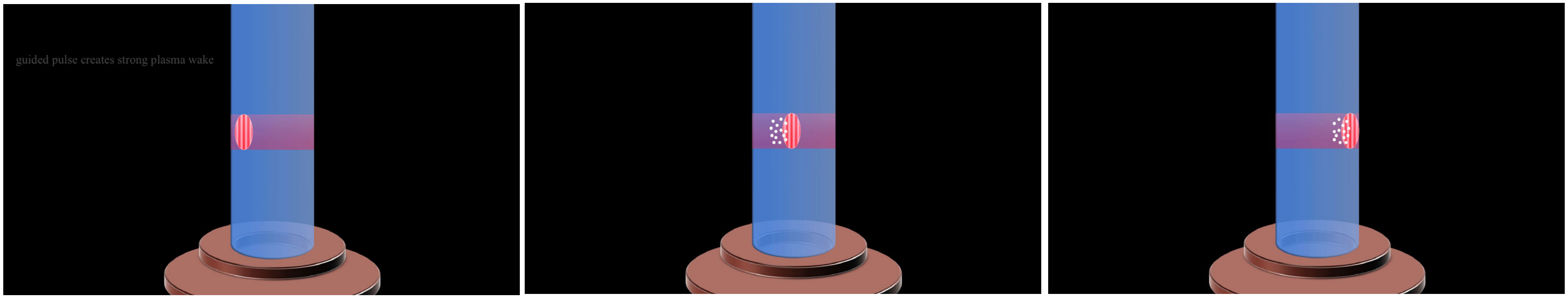
Intense femtosecond laser drives a plasma for Laser Plasma Acceleration (LPA)

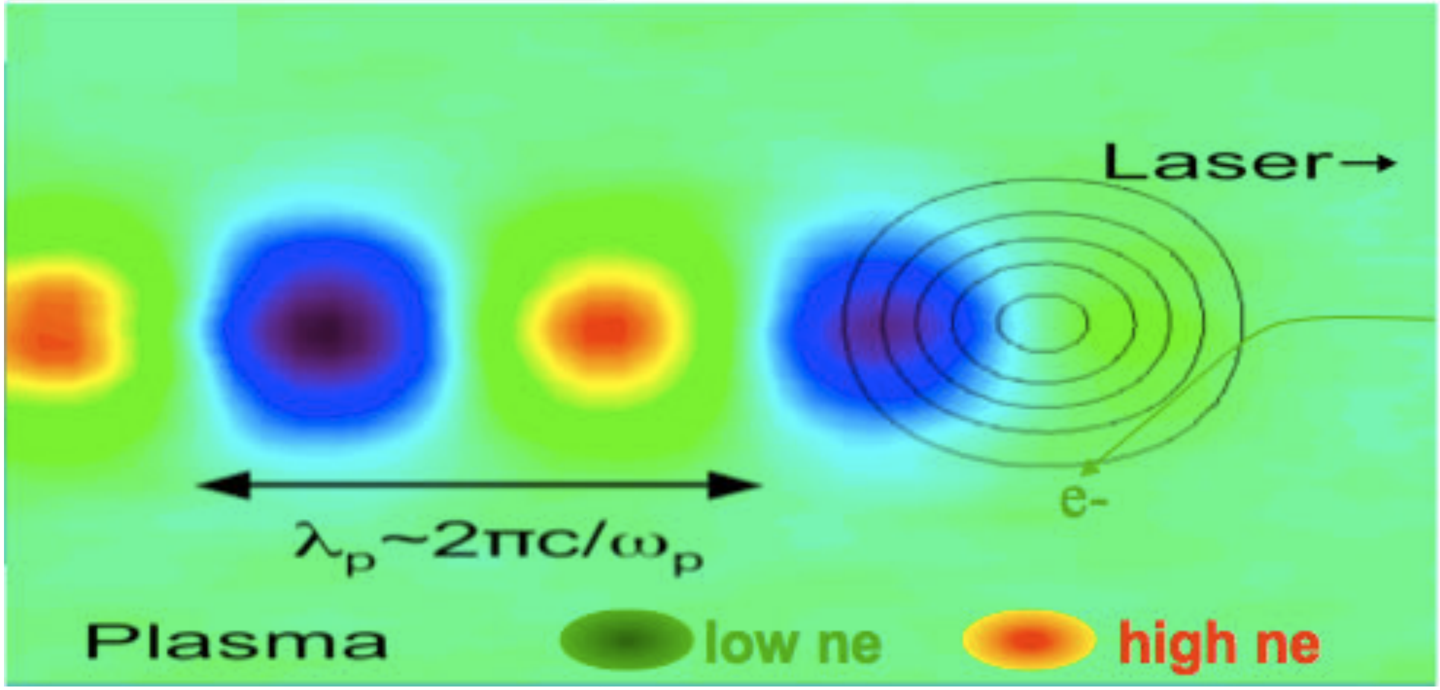


Intense femtosecond laser drives a plasma for Laser Plasma Acceleration (LPA)



Laser ponderomotive force + plasma oscillation create LPA structure

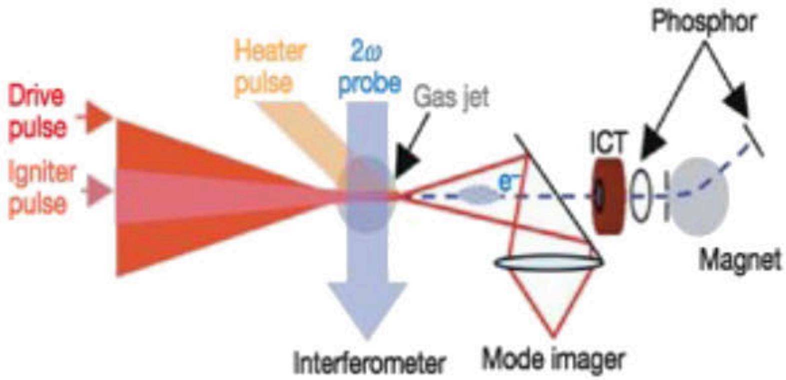


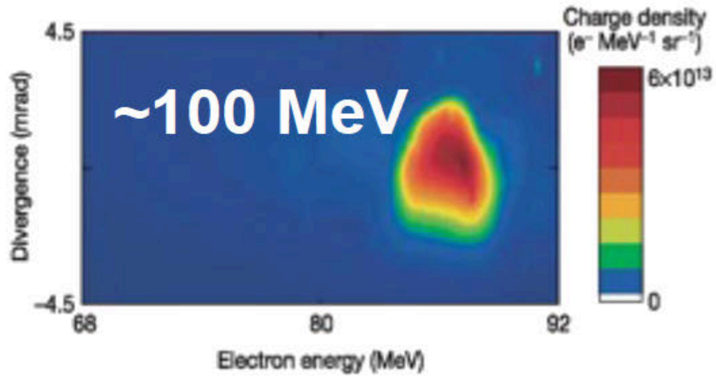


Concept: Tajima and Dawson, PRL 1979. Review articles: E. Esarey, Rev. Modern Physics 2009; Trans. Plasma Sci 1996.

Self injected experiments produce high quality beams but limited tuning

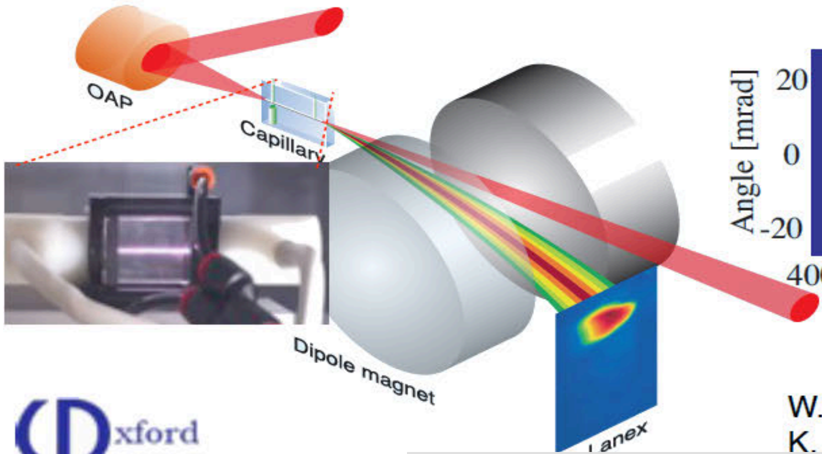
2004 result: 10 TW laser, mm-scale plasma

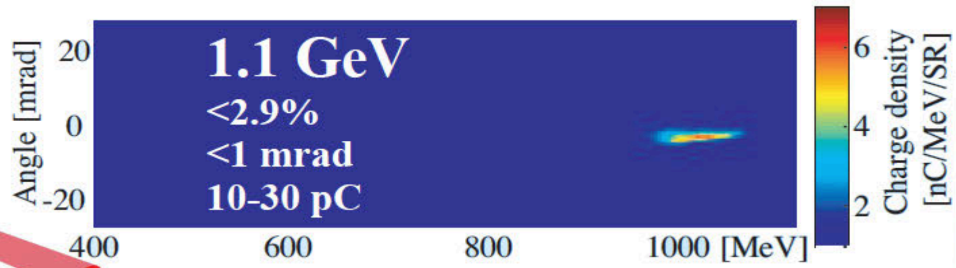


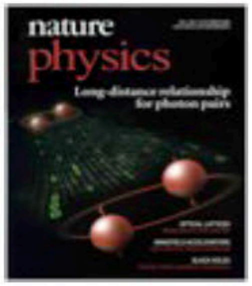


C. G. R. Geddes,et al, Nature,**431**, p538 (2004)
S. Mangles et al., Nature **431**, p535 (2004)
J. Faure et al., Nature **431**, p541 (2004)

2006 result: 40 TW laser, cm-scale plasma







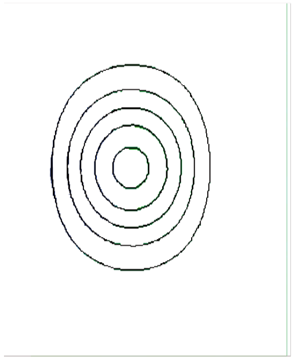
W.P. Leemans et. al, *Nature Physics* **2**, p696 (2006)
K. Nakamura et al., Phys. Plasmas **14**, 056708 (2007)

Oxford Physics

Current LPA Thomson sources limited to near-100% bandwidth and low yield by e-beam and laser

Control is required for reliable acceleration

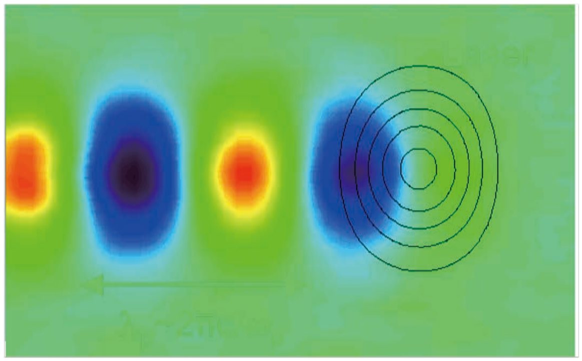
Separate controls of laser, stage, injector for efficient LPA



- Laser control – approach pure Gaussian mode

Concept: Tajima and Dawson, PRL 1979. Review articles: E. Esarey, Rev. Modern Physics 2009; Trans. Plasma Sci 1996.

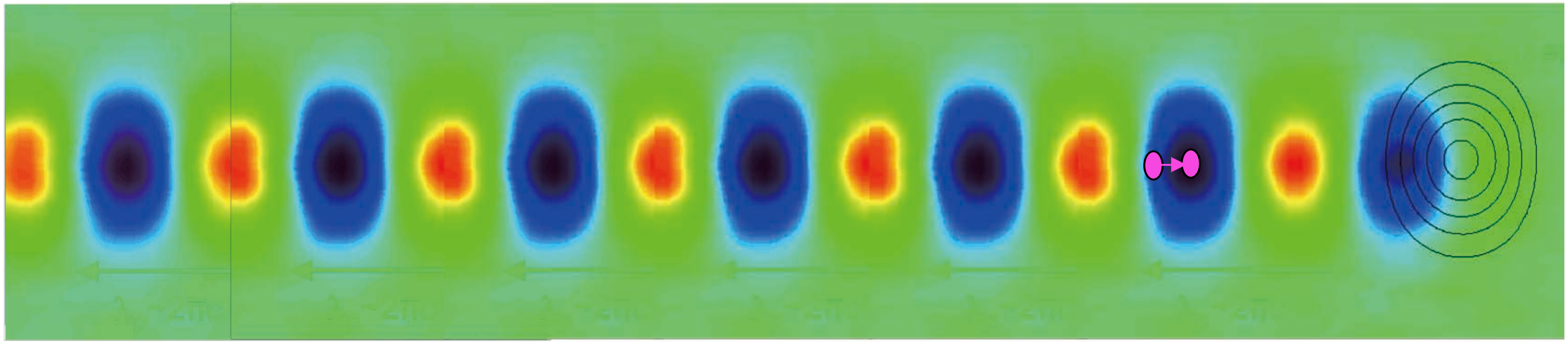
Injector + accelerator stage
separate controls for efficient LPA



- Laser control – approach pure Gaussian mode
- Structure control via laser, plasma

Concept: Tajima and Dawson, PRL 1979. Review articles: E. Esarey, Rev. Modern Physics 2009; Trans. Plasma Sci 1996.

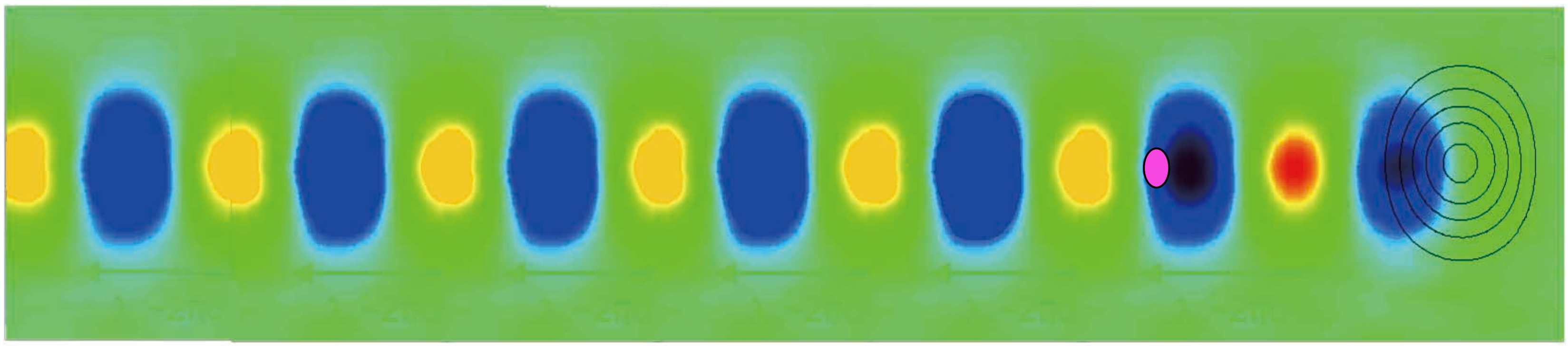
Injector + accelerator stage
separate controls for efficient LPA



- Laser control – approach pure Gaussian mode
- Structure control via laser, plasma
    - Self and channel guiding – to length of laser depletion/ electron dephasing

Concept: Tajima and Dawson, PRL 1979. Review articles: E. Esarey, Rev. Modern Physics 2009; Trans. Plasma Sci 1996.

Injector + accelerator stage
separate controls for efficient LPA



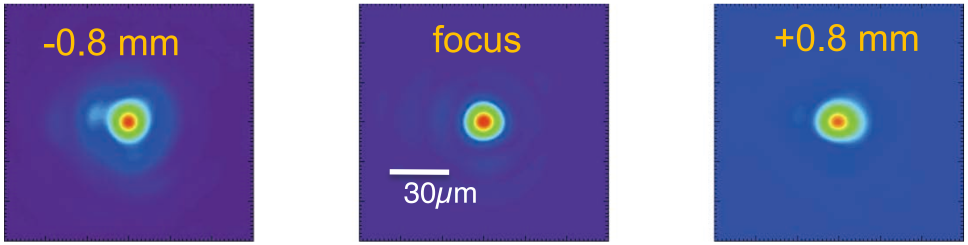
- Laser control – approach pure Gaussian mode
- Structure control via laser, plasma
  - Self and channel guiding – to length of laser depletion/electron dephasing
- Injection control: high quality stable beams

Concept: Tajima and Dawson, PRL 1979. Review articles: E. Esarey, Rev. Modern Physics 2009; Trans. Plasma Sci 1996.

Long interaction length via laser & plasma control

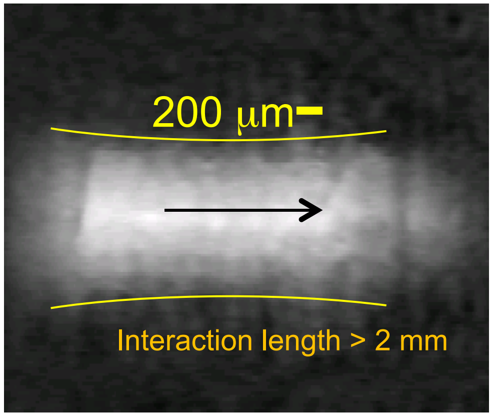
- Laser phase front control
  - Deformable mirror
  - Strehl > 0.9

High-quality laser mode over full focal depth



- Interaction over L_{jet} ~2mm
- Plasma density controls dephasing
  - Fluctuations tuned by jet contour

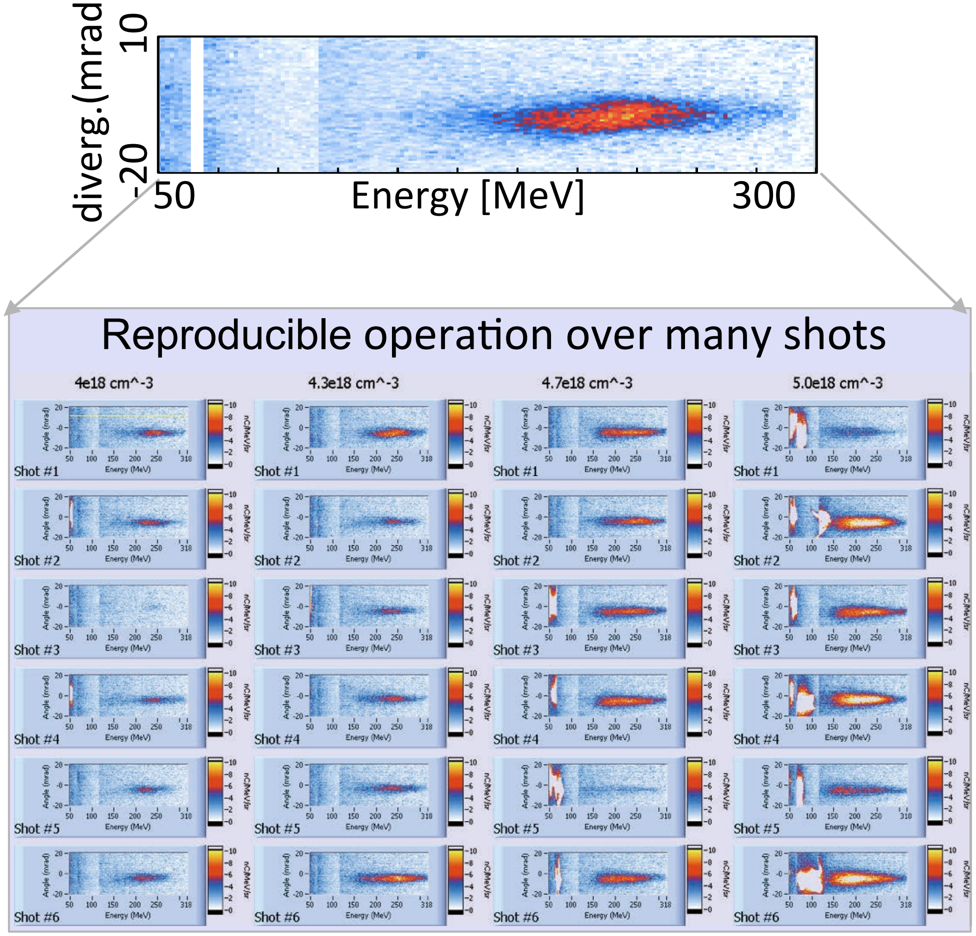
Uniform gas jet plasma & propagation



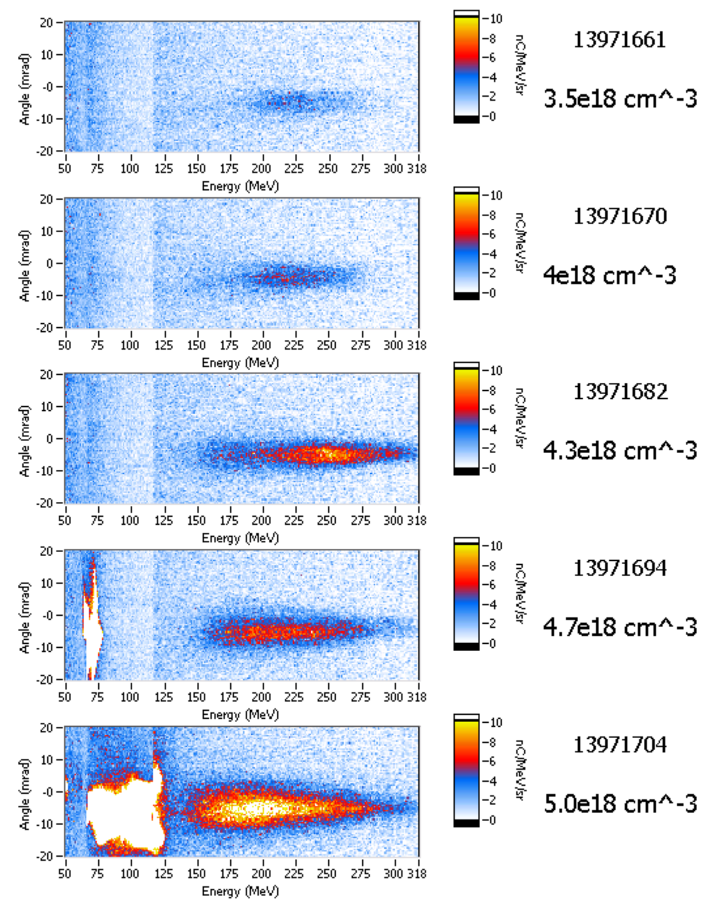
N.H. Matlis et al., Proc. AAC 2012.

Self trapping produces > 200 MeV at 10 TW

Electron spectrum



Self trapped tuning is limited



N.H. Matlis et al., Proc. AAC 2012.

Control LPA injection

- Limit on gradient for a cold 1D nonrelativistic wave:

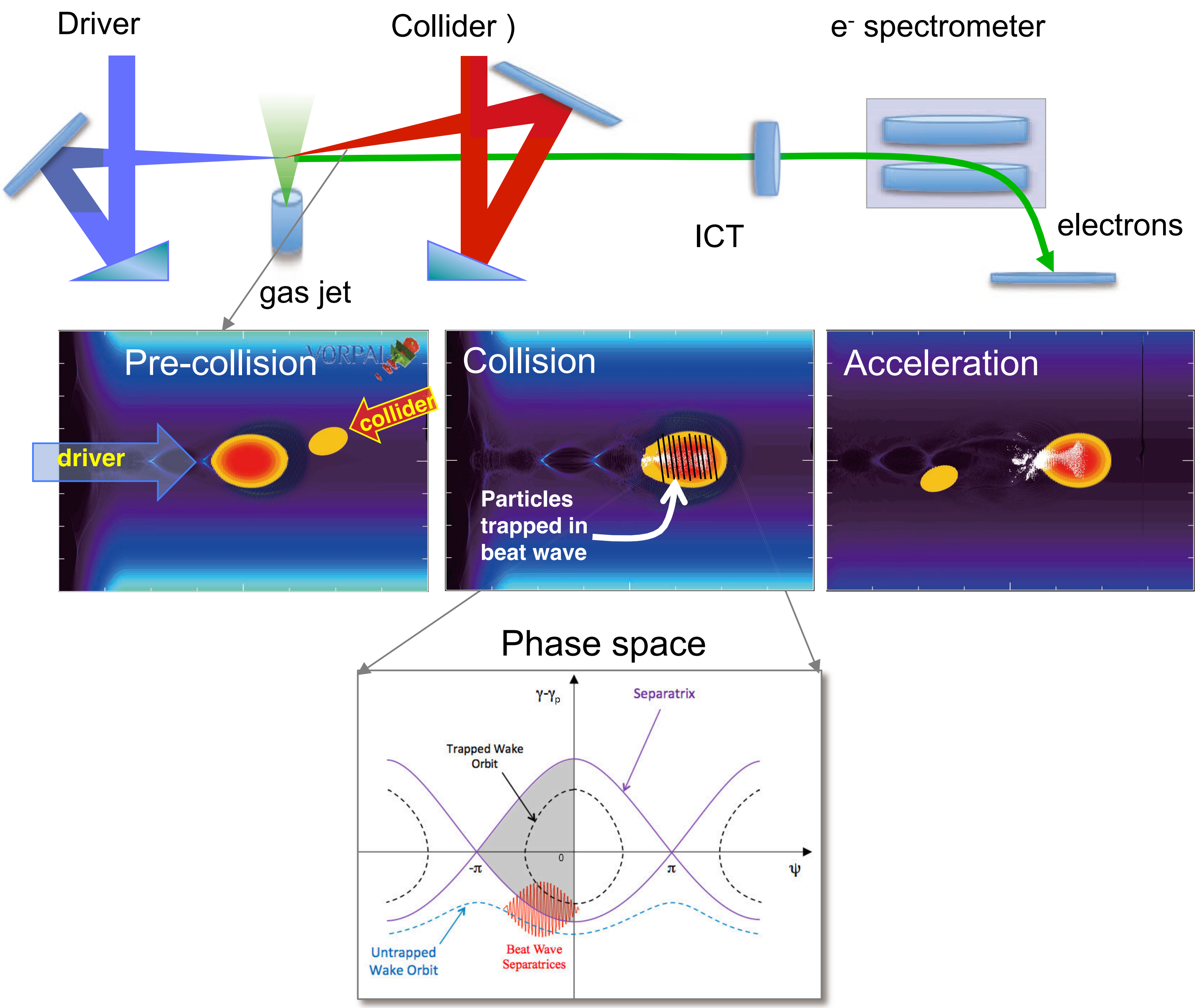
$(E_{WB}e/m)*(1/\omega_p) = \Delta v \sim v_{wake} \sim c$

→ to control injection:

a) change initial particle velocity

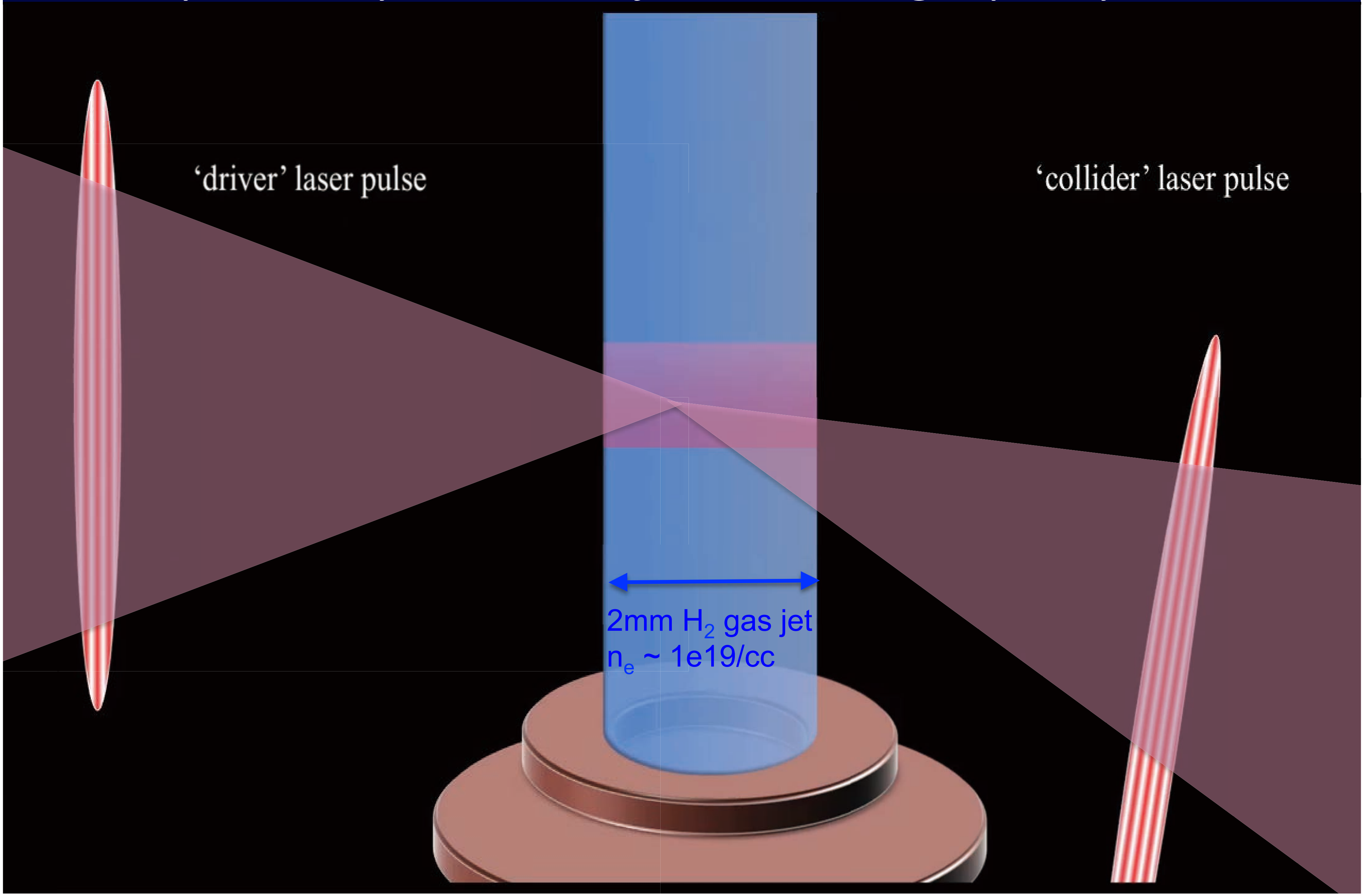
b) modulate wake velocity

Colliding pulse beat wave controls injection

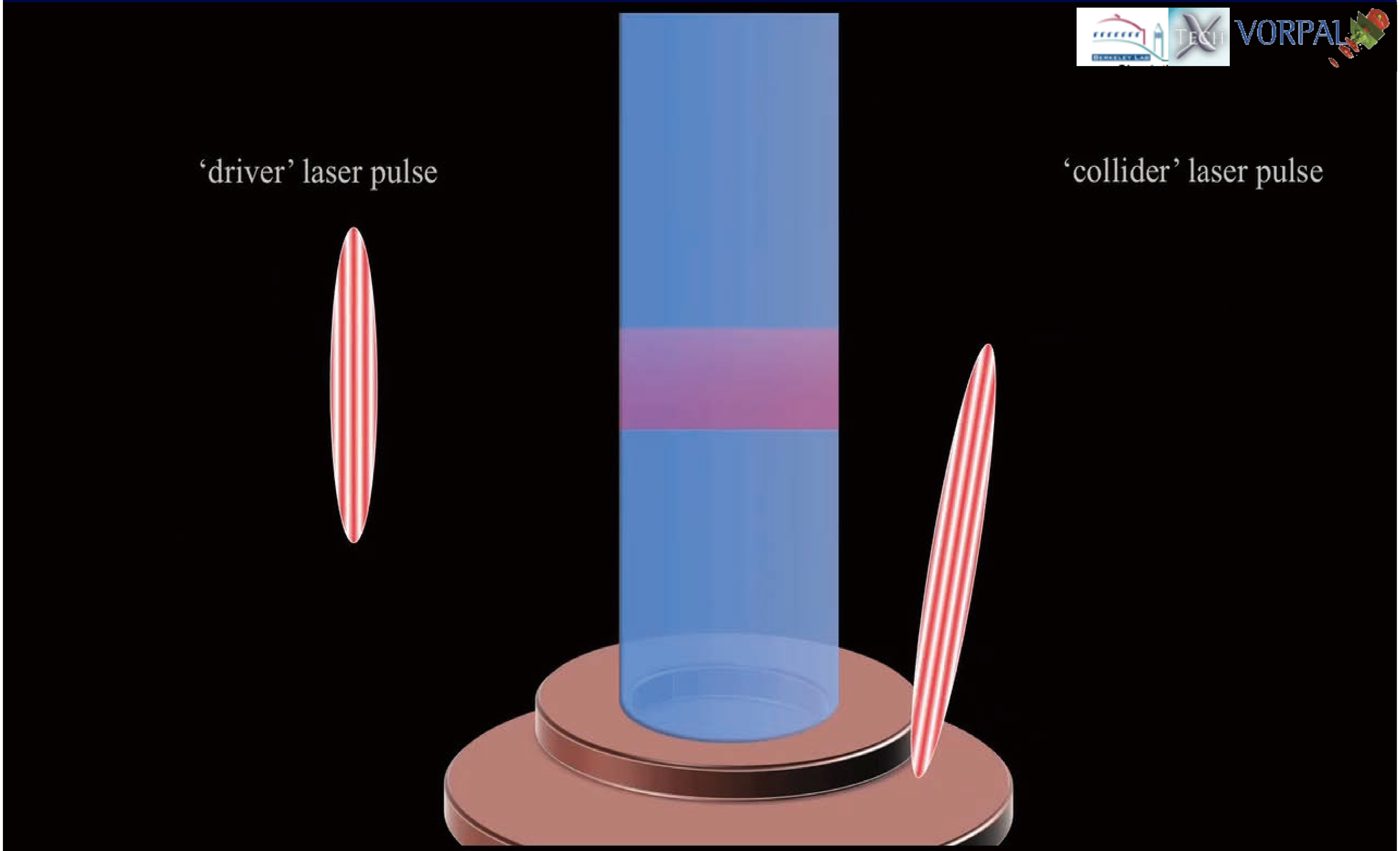


Theory: Esarey PRL 97; ^ Fubiani PRE06; Related exp: Faure et al. Nature 2006, Kotaki et al PRL 2009, Toth et al, PAC 2007.

Injection control via two colliding pulses independently controls injection for high quality beams

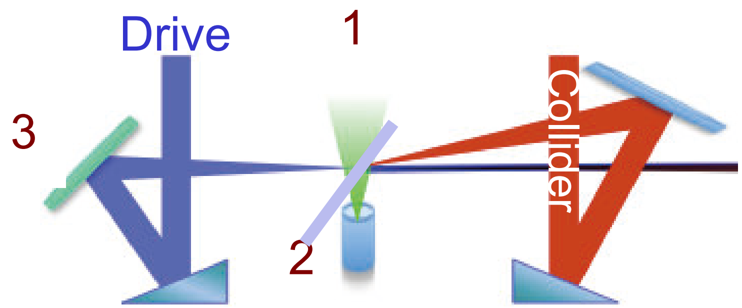


Colliding pulse injection: kick selected electrons to inject



Movie courtesy Cormier-Michel; SciDAC visualization award winner.
Theory: Esarey PRL 97; Fubiani PRE06, VORPAL code Nieter JCP 2004

Colliding pulse overlap stabilized



1

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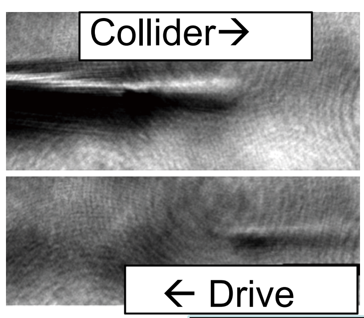

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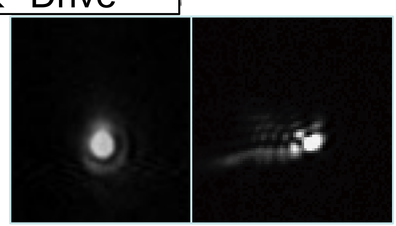
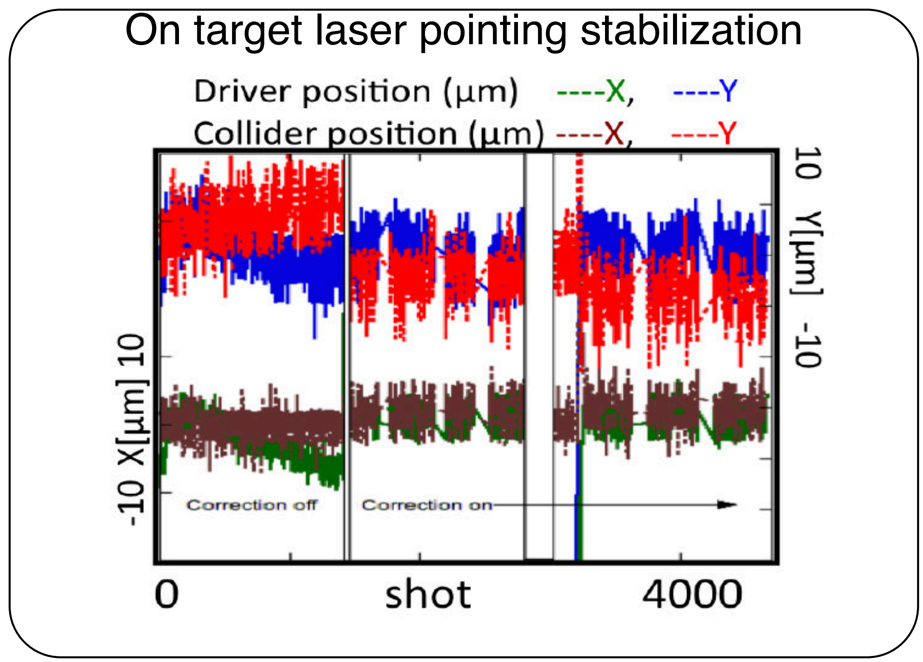


* L. Rabely – Masters' project

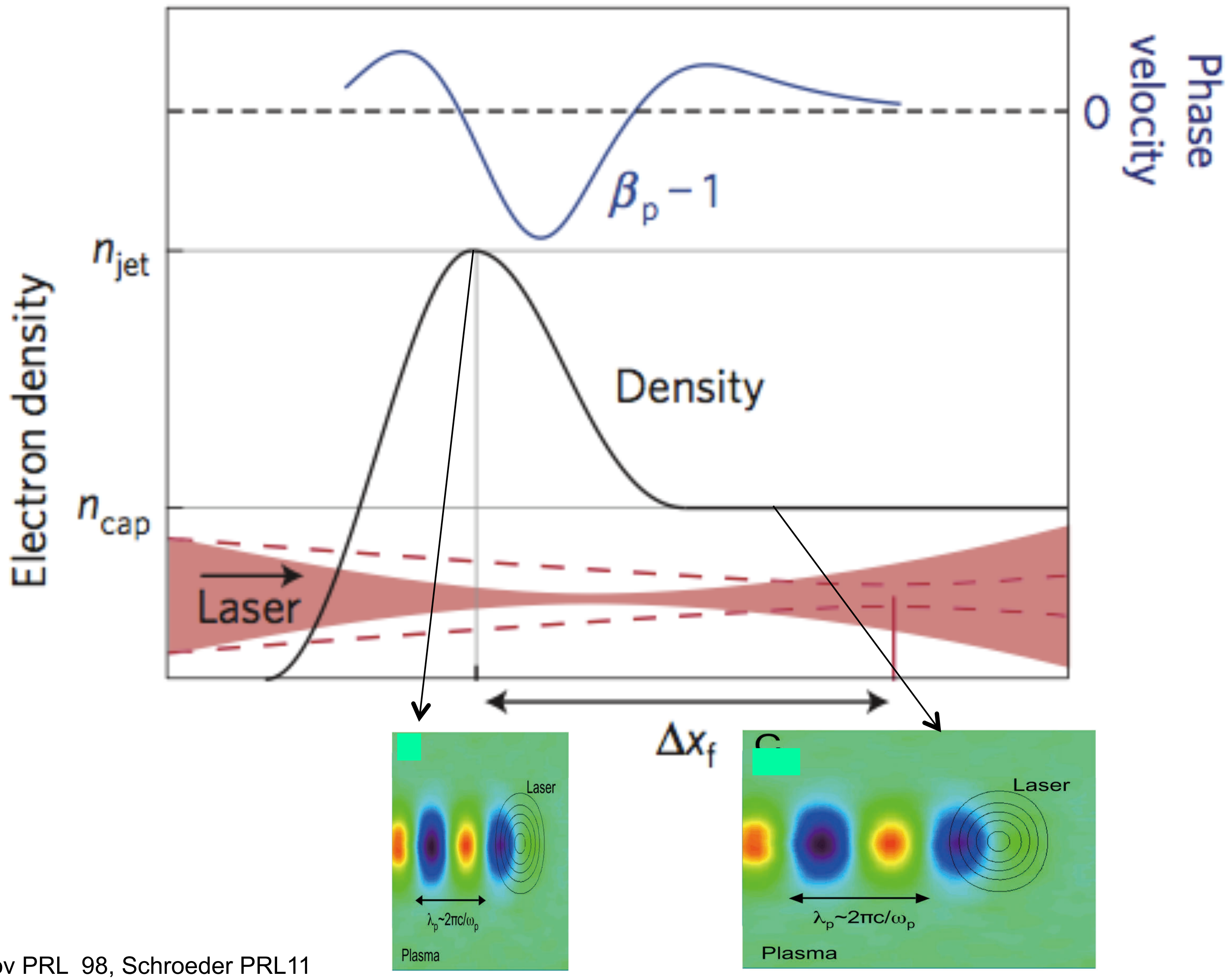
Controls for repeatable accelerator:

1. Top view establishes intersection
2. Shadowgram sets vertical alignment & timing
3. Automatic beam pointing maintains overlap



1; Geddes et al., PAC 2011

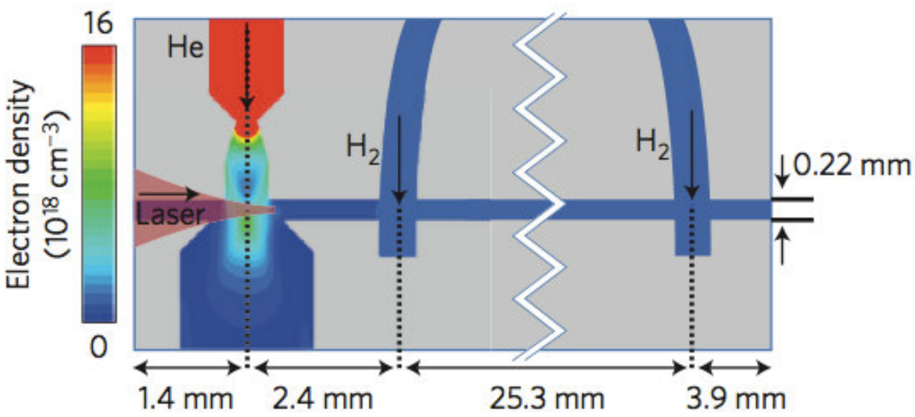
Injection control via wake phase velocity modulation



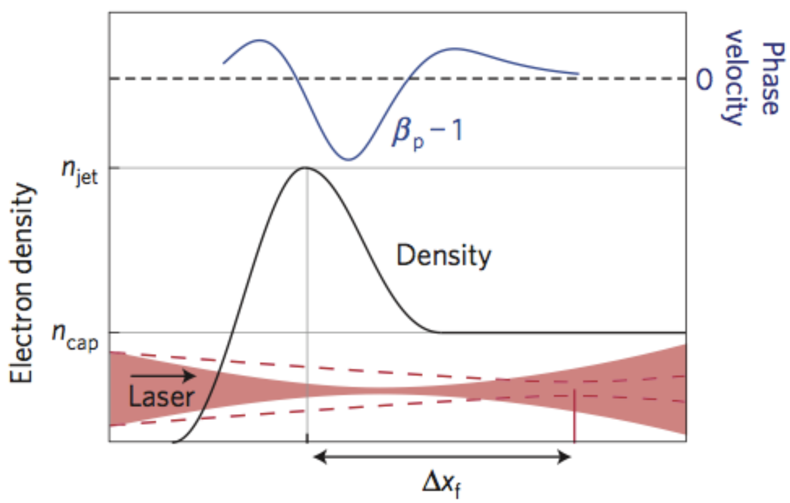
Theory: Bulanov PRL 98, Schroeder PRL11

Injection control via wake phase velocity modulation: Stable & tunable near 0.5 GeV – suitable for 10 MeV photons

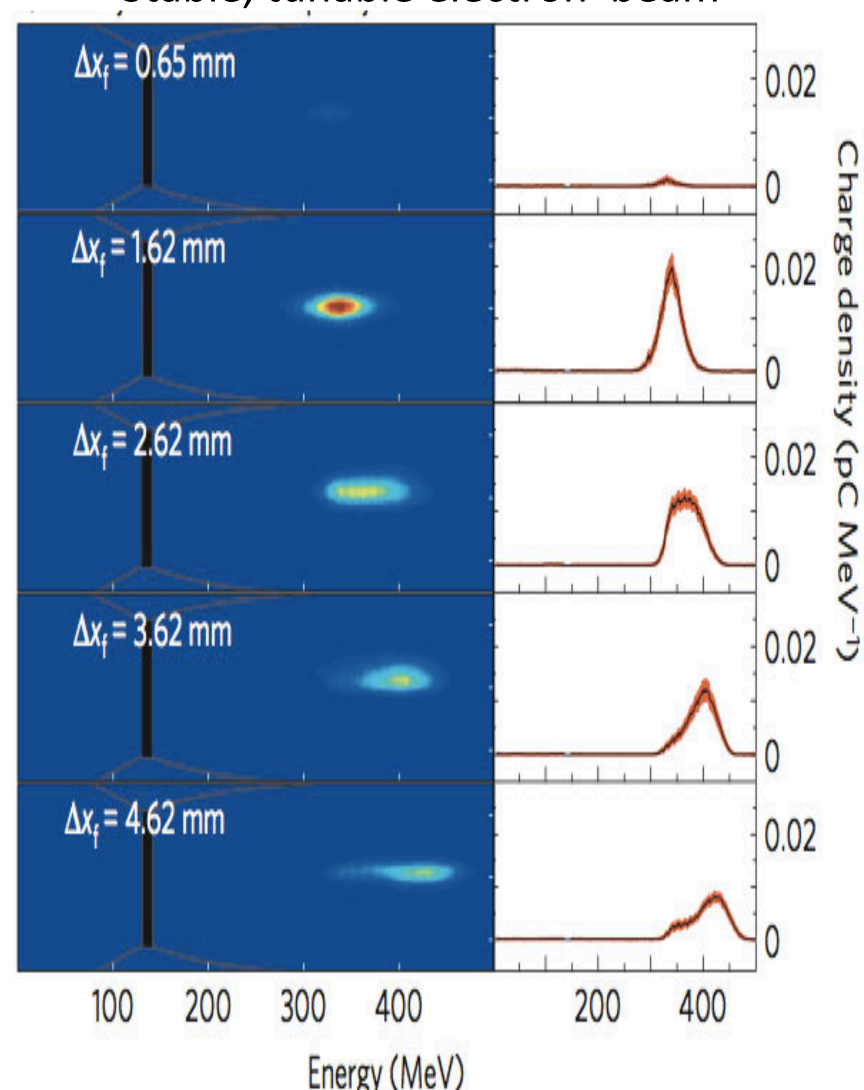
Gas jet in capillary creates density 'bump'



Density change reduces wake velocity controlling trapping



Stable, tunable electron beam



Gonsalves et al, 2011. Earlier experiments Geddes et al PRL 08, Hosokai PRE03; Theory: Bulanov PRL 98, Schroeder PRL11

Betatron x-rays used to measure beam size
Determine emittance → photon energy spread from Δθ

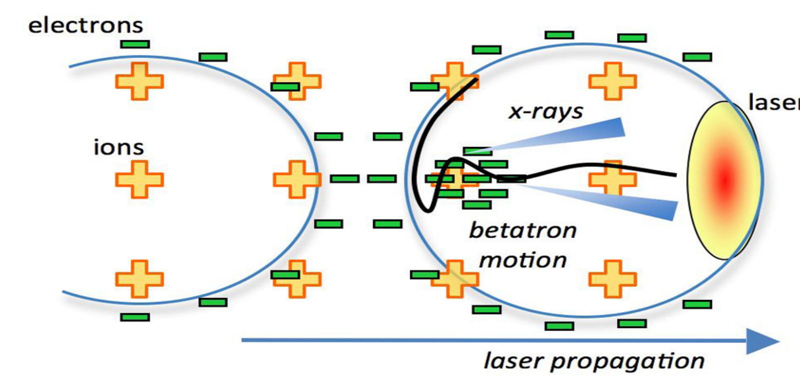
- Motivation: mrad divergence → sub-µm size if matched: $\sigma_x = \sigma_\theta(\lambda_p/\pi)\sqrt{\gamma/2}$

- Infer beam size from spectral form
  - Depends on $a_\beta \propto r_\beta \sqrt{\gamma\, n_e}$
  - γ from electron spectrometer

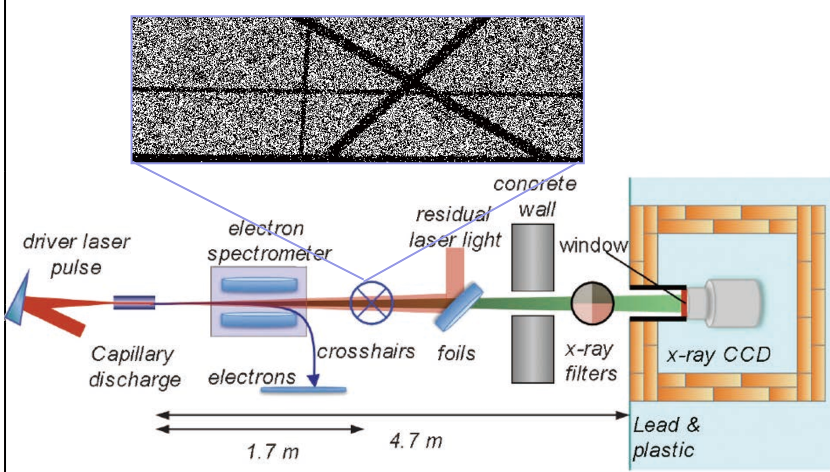
- CCD camera records spectrum
  - photon counting w/ charge sharing

- Simulations with endpoint corrected integrals allow small oscillation number[1]
  - Quantitative matching of experiments

Electron oscillation in focusing field causes betatron X-ray emission



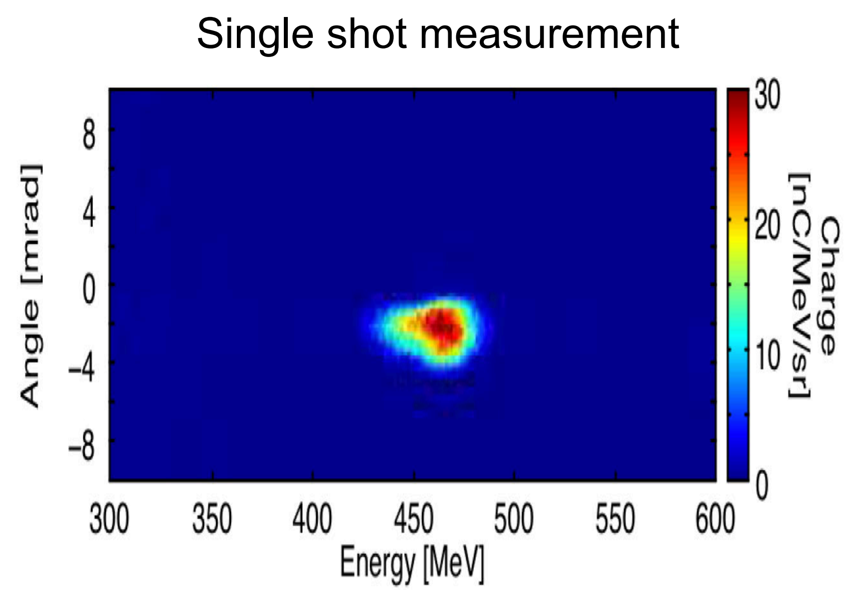
Measurement on TREX self injected LPA



1; Chen et al, PRST-AB 2013, Rykovanov et al. AAC 2012

X-ray spectra indicate 0.1 mm-mrad emittance Comparable to state of the art RF accelerators

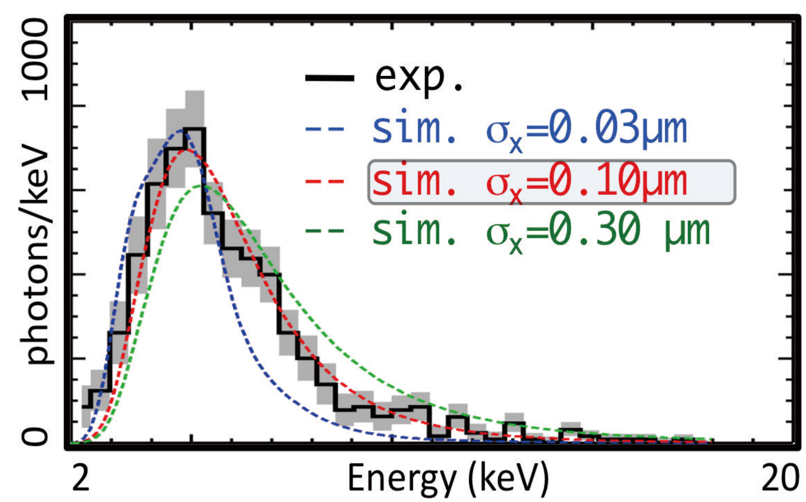
- Single shot spectra
  - 463 MeV, ΔE ~ 6.6%, σ_θ ~ 1.2 mrad



- Quantitative fitting of experiment & simulated spectra
  - Infer 0.1 µm radius
  - consistent with matched beam

- Indicates normalized emittance[1]

$$\epsilon_x \approx \gamma\sigma_x\sigma_\theta \approx$$ 0.1 mm-mrad



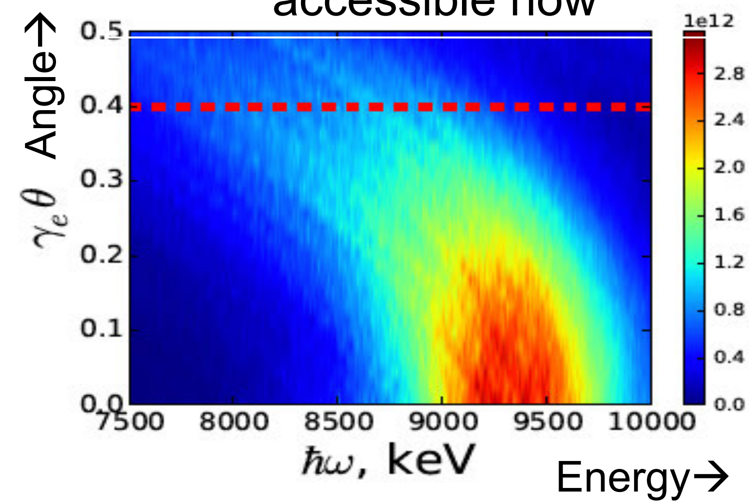
1; Plateau et al., PRL 2012, Thorn et al. RSI 2010

Related: Weingartner et al, PRSTAB 2012, Quad scan, measured similar emittance

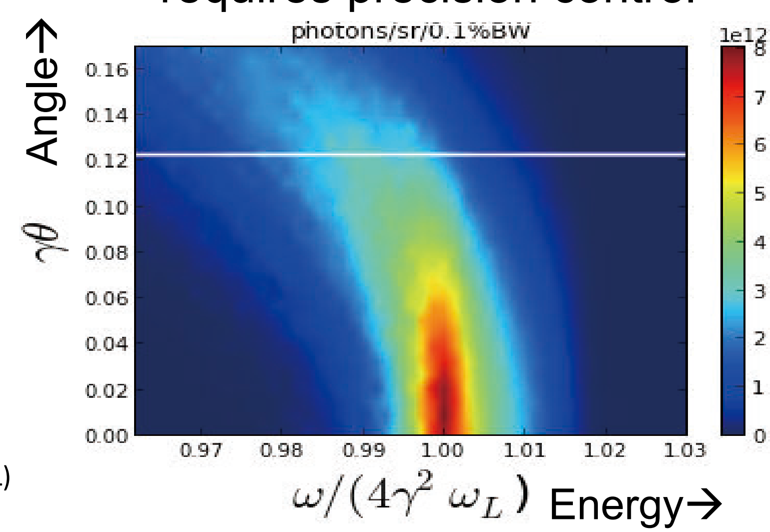
Thomson photon sources require high quality LPA and scattering laser

- Simulations & conventional accelerator data:
  - Photons of 1.7-9 MeV from 0.2-0.6 GeV e-
  - Photon Band Width (BW) from e- ΔE and Δθ:
- BW ~ 10 % → e- of 5% ΔE, ≤ mrad diverg.
- BW ~ 2% → e- of 1% ΔE, ≤ 0.1 mrad diverg.
  - Photon bandwidth ~ 2% FWHM achievable w/ LPA e-bunch DE
- Low emittance e- reduces Δθ contribution
  - Beam radius ~ 1μm for 2% BW (expanded)
  - Scattering in plasma for 10% BW

Ten-percent bandwidth accessible now



Percent-level bandwidth requires precision control



Rykovanov et al., AAC 2012, Chen et al., PR ST-AB 2013, Leemans et al. PRL 1996.
Related A.G.R. Thomas et al PRST-AB 2010 (U. Michigan); Ghebregziabher PRSTAB 2013 (UNL)
P. Chen, et al., a, NIMA 355 (1995) 107. (CAIN code)

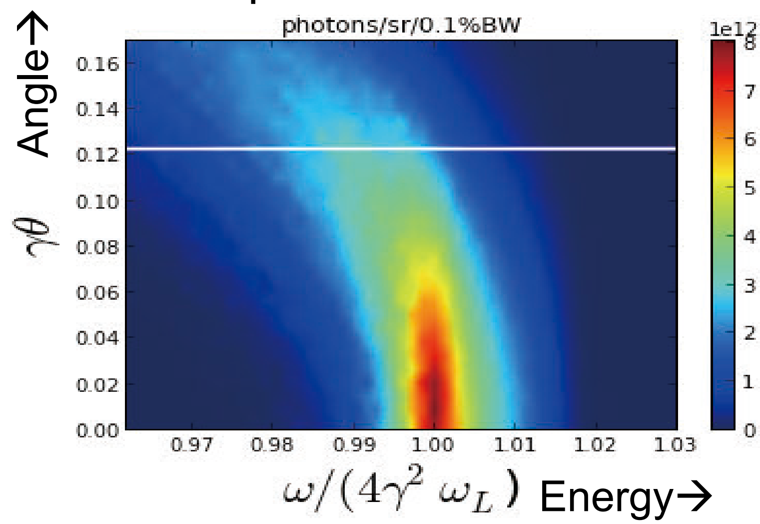
Thomson scattering from LPA-like e-beam produces tunable high quality photon beam

- Fluxes of 10^{10}-10^{12}/sec require high efficiency and rep rate.

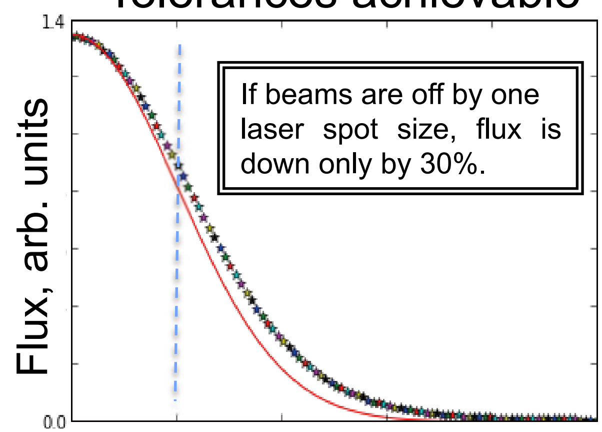
- For 10^{11}ph/sec at 10^{8}e-/shot:
  - Photon fraction in BW~ BW (2% in 2% BW).
  - 10% BW → kHz and 10 ph/electron
  - 2% BW → 10 kHz and 5 ph/electron

- Beam stability acceptable

Percent-level gamma energy spread acheivable



Key effects parameterized
Tolerances achievable



Rykovanov et al., AAC 2012, Chen et al., PR ST-AB 2013
Related A.G.R. Thomas et al PRST-AB 2010 (U. Michigan); Ghebregziabher PRSTAB 2013 (UNL)
P. Chen, et al., a, NIMA 355 (1995) 107. (CAIN code)

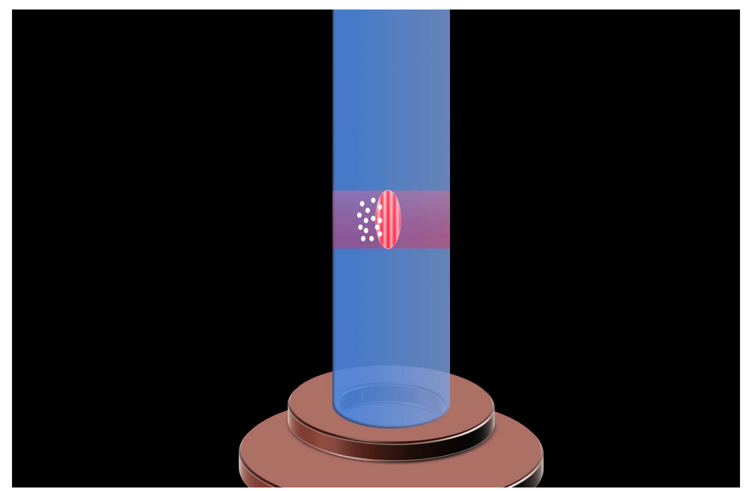
Photon source drivers: Joule-class, kHz, 30 fs-ps pulse lasers

- Drive: 10-20 TW fs lasers at 0.5 -2J
  - $1 M range, $\leq 6m^2$ → rapidly dropping
  - 10 Hz typical

→Adequate for demonstration

- Scatter 1-10 ph/e-: 1-10 ps, 2-40 J laser
  - Depends on scattering geometry

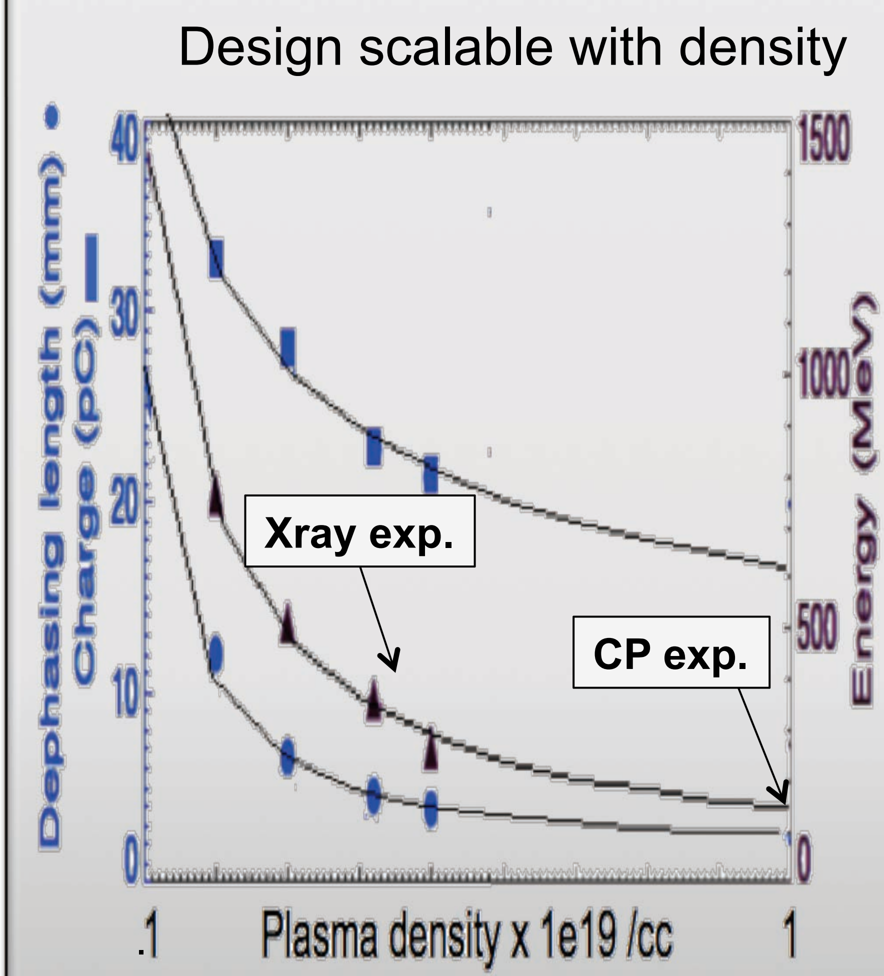
- High flux sources: ≥ kHz laser at >1% efficiency[1]
  - Diode pumping, Efficient materials, Fiber combination?
  - Single pulse, or pulse train at plasma duration



1 http://www-bd.fnal.gov/icfabd/Newsletter56.pdf

Scalable simulations allow design for future source

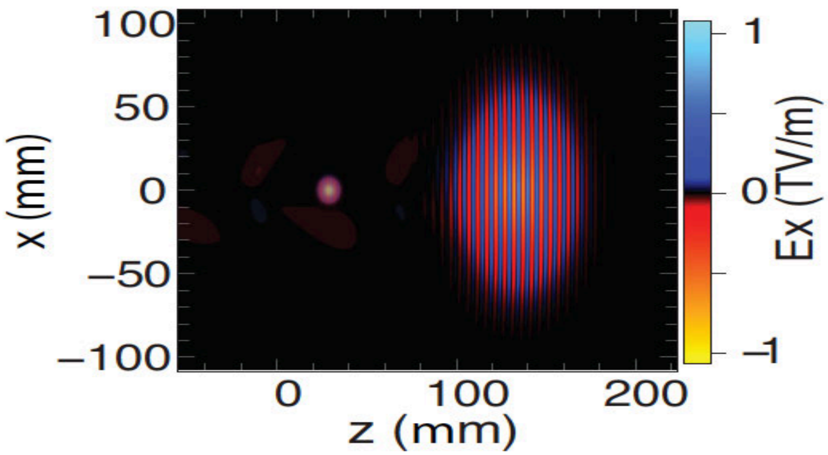
- Control beam energy via plasma density $E_e \sim 1/n$
  - ~ 10^8 e-/shot
- Laser scales with plasma wavelength
  - $E_{Laser} \sim E_e^{3/2}$
  - $L_{plasma} \sim E_e^{3/2}$
- Access 0.2 -1 GeV energies
  - Gammas at 1.7 -20MeV
  - Simulation + experiment agree



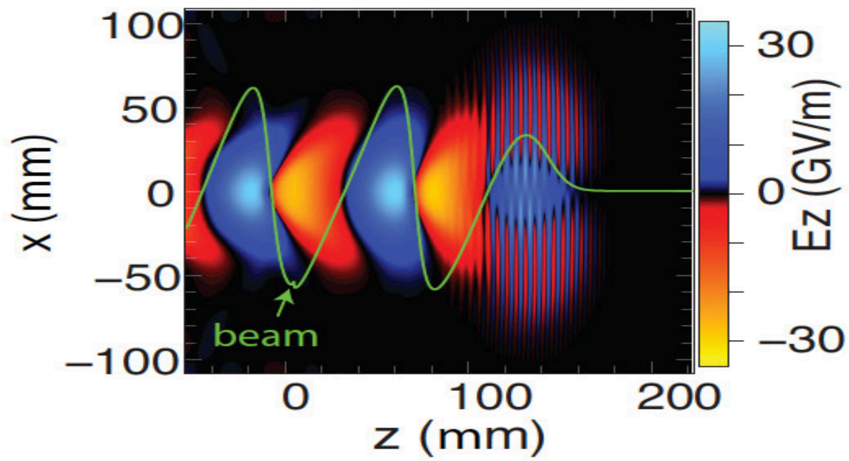
E. Cormier-Michel, In prep.

Novel methods for future experiments simulated: Very low emittance via two-color ionization

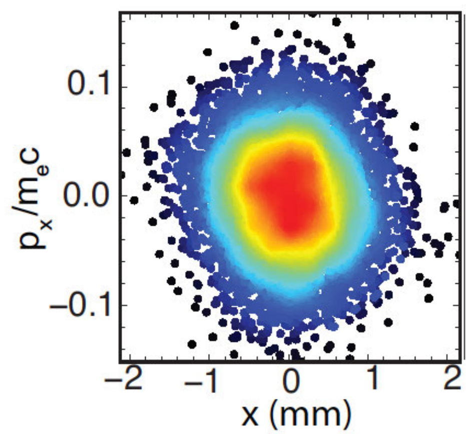
Short-wavelength trailing pulse



Injects beam into wake of driver



Creating low emittance beam due to small a_0, diameter



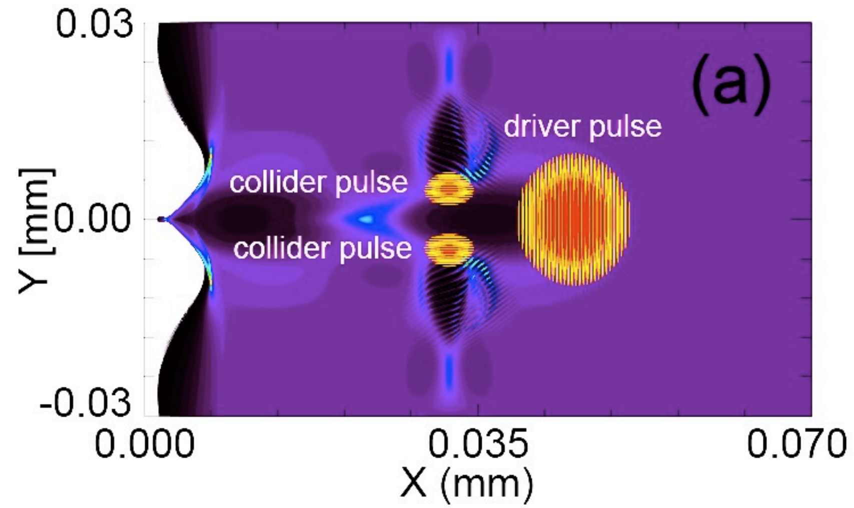
- Emittance < 0.03 mm-mrad
  - percent level bandwidth without expansion
  - sub-percent bandwidth with expansion

Min Chen, Proc AAC 2012 and submitted

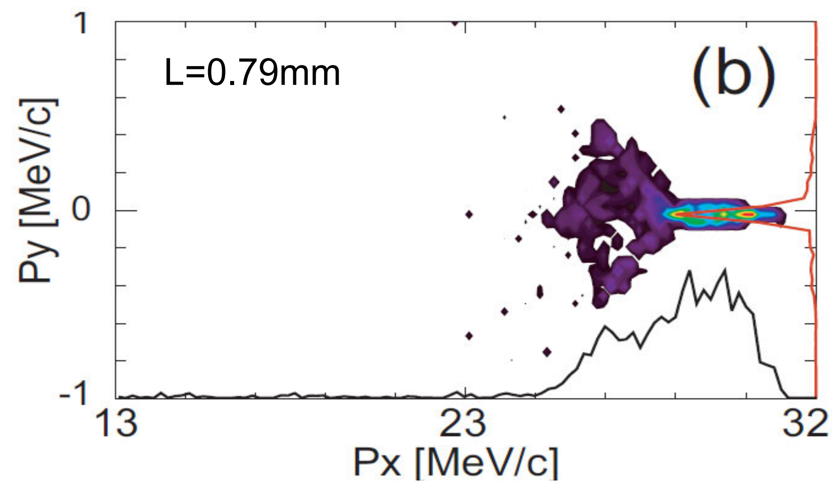
Novel methods for future experiments simulated: Low emittance via transverse colliding pulses

- Three pulse geometry with driver at right angles to collision
  - Beat wave kick transverse
  - Selects transverse position
- Emittance < 0.1 mm-mrad
- Charge control via addition of N2 gas and ionization

Transverse collision diagram



Low transverse momentum selected

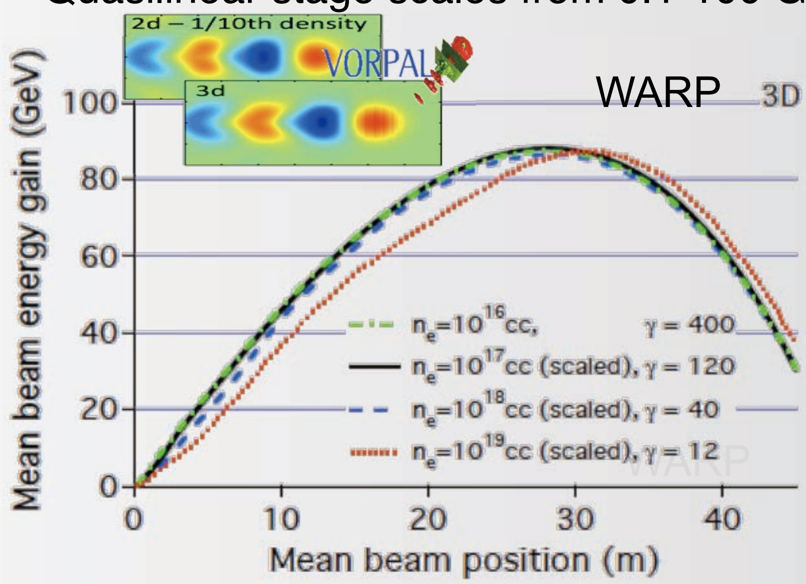


Min Chen, Proc AAC 2012 and submitted

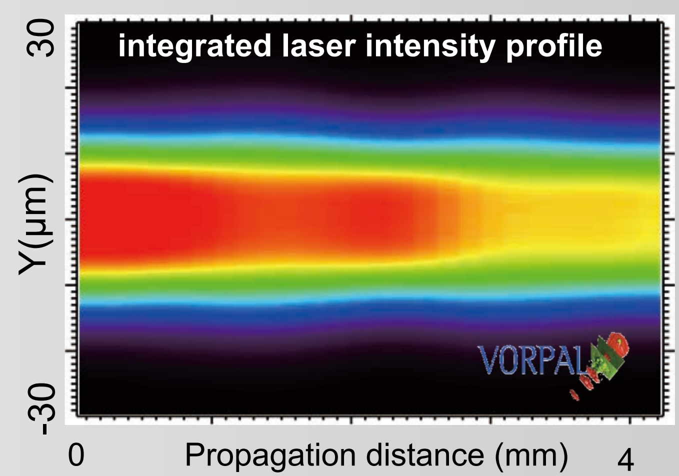
Scalable LPA designs towards future FELs and Colliders

- LPA scaling with laser & plasma parameters established
  - Designs for 100 MeV – 100 + GeV allow evaluation of collider scalings
- Beam manipulation by controlling beam loading & shaping of laser pulse
  - Allows reduced divergence for Thomson source

Quasilinear stage scales from 0.1-100 GeV



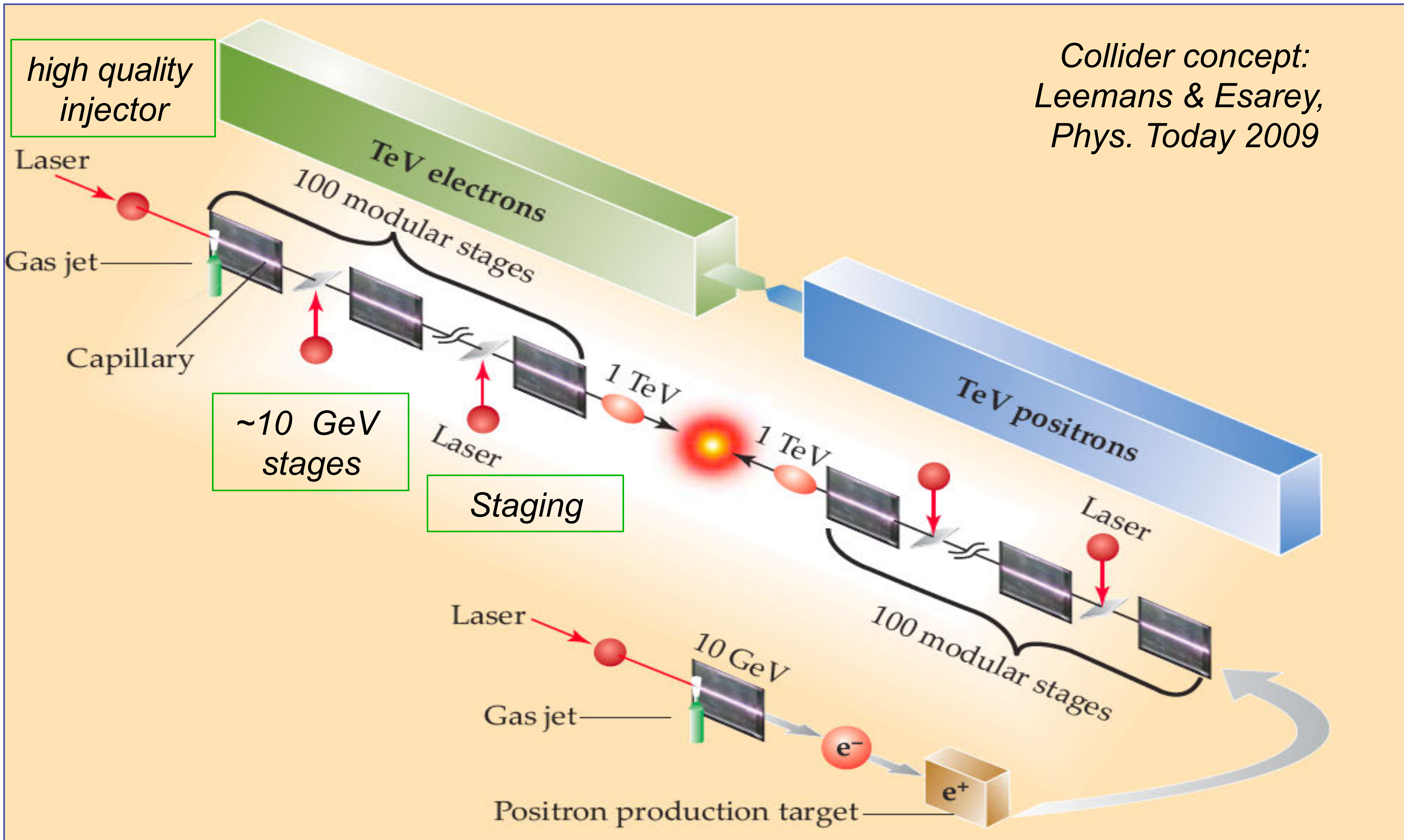
Laser mode control in a channel for high charge at low emittance



Vorpal; Cormier-Michel AAC 2008, Geddes SciDAC Review 2009 .
WARP; Vay, PoP 11, JCP11

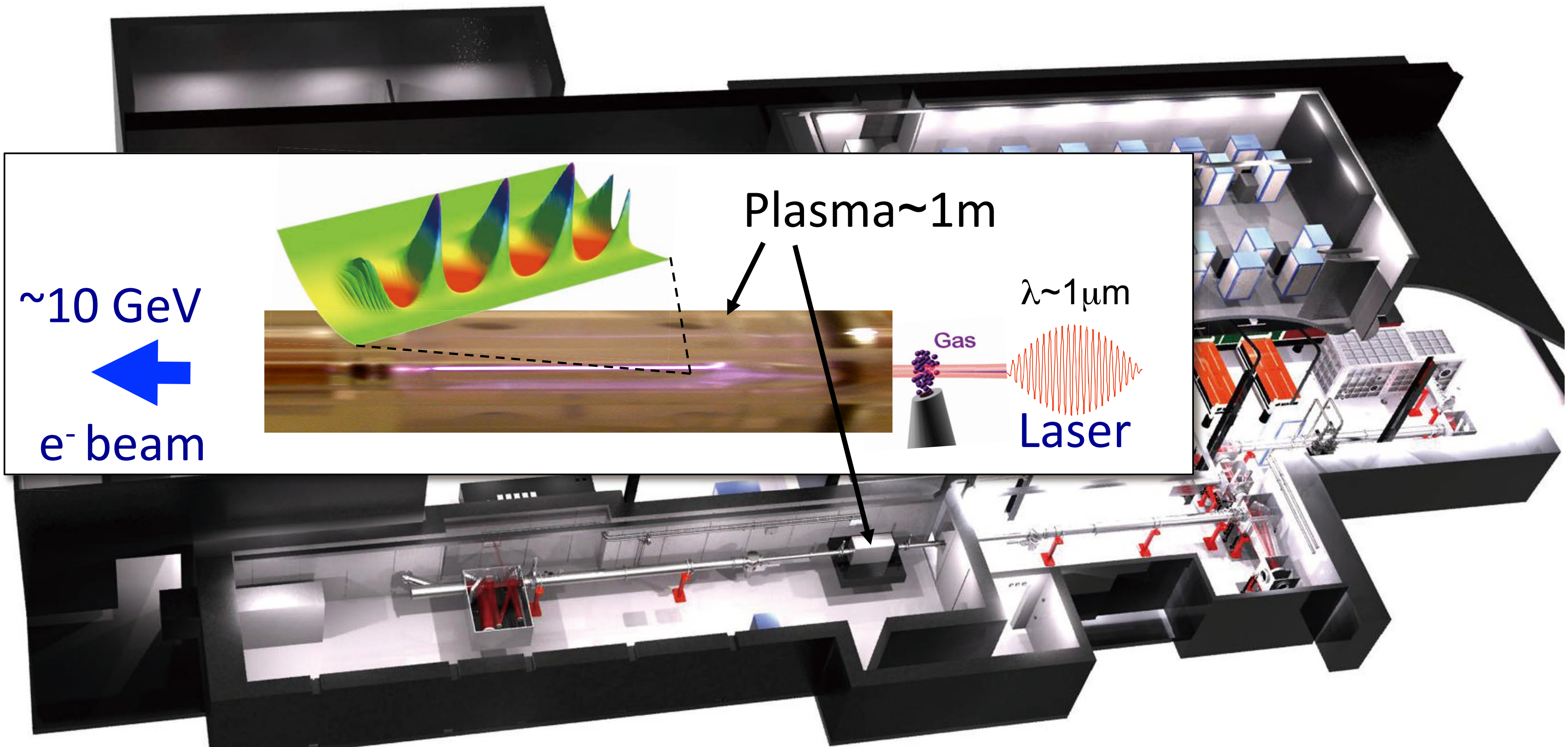
Cormier-Michel, PRSTAB 2011

Scalable LPA designs towards future FELs and Colliders



BELLA laser in operation at LBNL : 10 GeV Collider relevant module

- State of the art 1 PW, 1Hz, 40 fs
  - Commercial system with Strehl > 0.9
- Simulations show 10 GeV in 0.1-0.5 m – experiments in progress



Leemans, Proc. Adv. Accel. Concepts Workshop 2010

Summary

- LPAs produce GeV in centimeters: compact drivers for Thomson sources
  - Tunable, 1% level energy spread
  - State of the art emittance

- Radiography, photofission accessible now
  - Integrate high quality LPA, scattering

- ≤ Percent level FWHM bandwidth achievable
  - Beam manipulation or advanced injector

- kHz lasers needed for applications