Laser-Plasma Accelerators and Quasi-Monoenergetic Photon Sources

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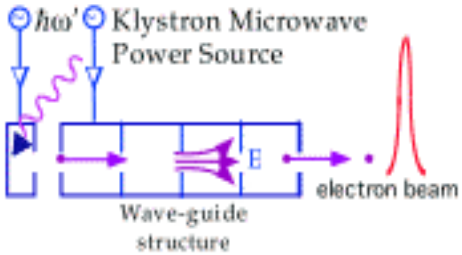
Particle accelerators drive science from the energy frontier to nanoscience

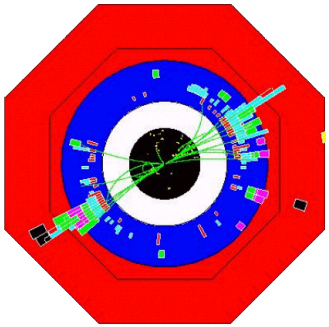


RF technology very successful - but:

•limited gradient - machines are large

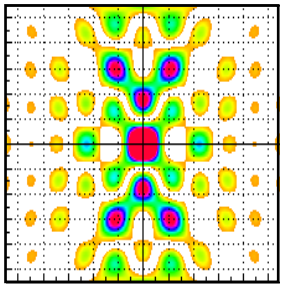
•fs pulses difficult

What's needed?



•High energy physics:

higher gradients for increased energy, low emittance



•Radiation sources:

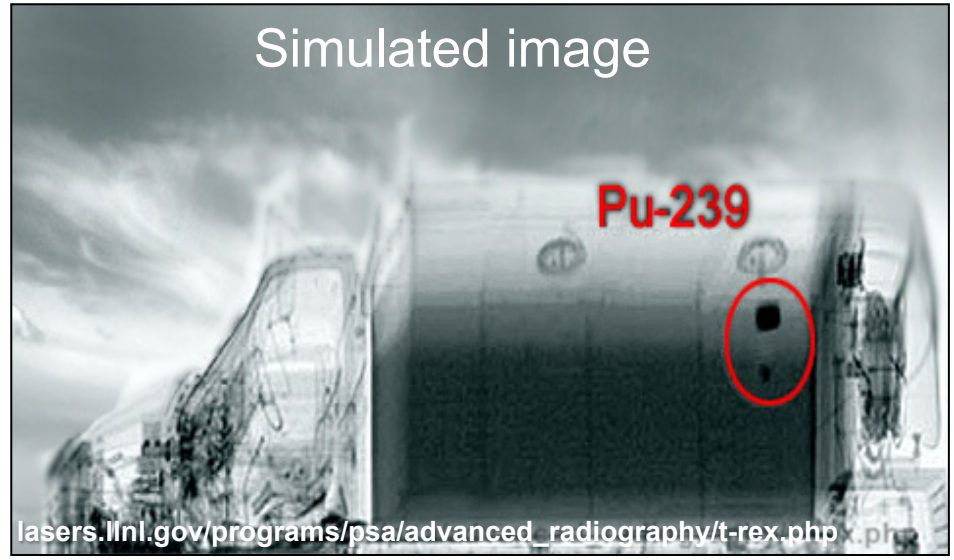
ultrafast tunable sources for dynamics

•Detection/imaging:

compact tunable sources

Transportable MeV photon probe important to detection and characterization of nuclear material

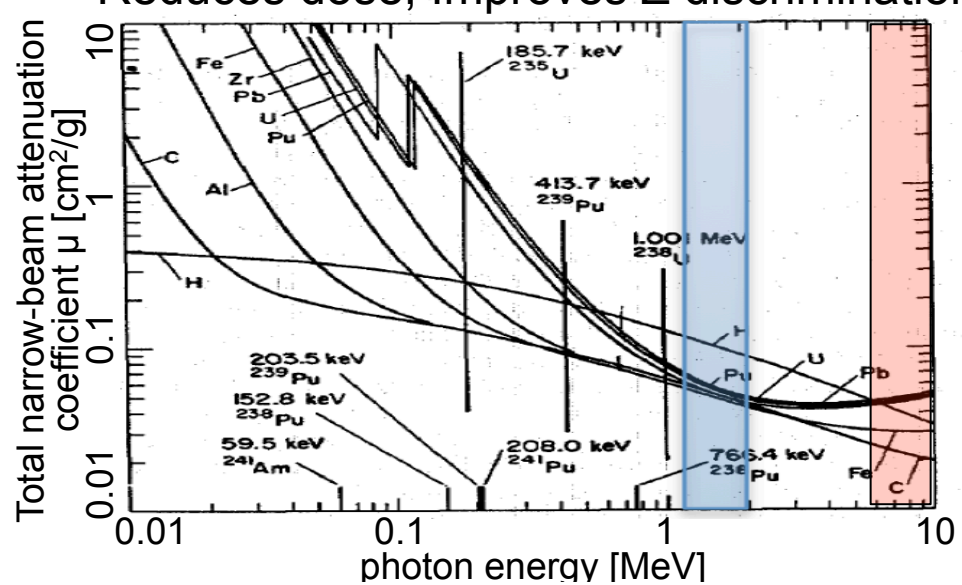
- Increase resolution via:
  - Narrow bandwidth, mrad divergence
  - Tunable energy
- Ports, interdiction, fuel assay
  - Transportable source advantageous



- Penetration sets base photon need
  - 10^8 ph for 40 cm, 10^6 for 20 cm steel
  - Allows typical dose < mrem
- 20cm steel at 80cm/s resolving 1 cm
  - Linear scan 10^8ph/sec, 100Hz
  - Container 10^{10}/s, 10kHz

Radiography[2]: Selecting energy

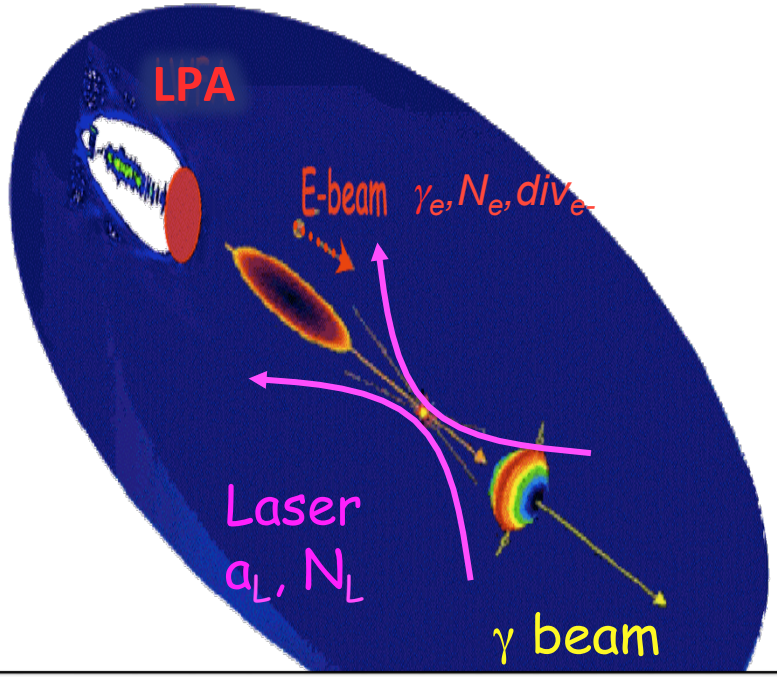
Reduces dose, Improves Z discrimination

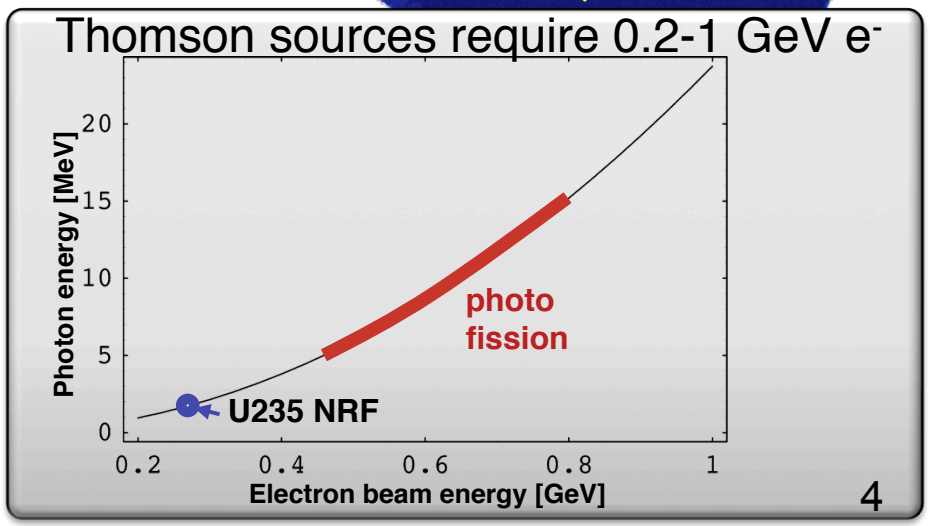


1) W. Bertozzi, et al. Phys. Rev. C 78 (2008) 041601 (R).
2) B.J. Quiter et al, J. Appl. Phys. **103**, 064910 (2008)

MeV photon sources enabled by Thomson scattering + 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
- Compact, efficient solution needed
  - 10^{11}ph/s → 10^{8} e-/sh @ ≥ kHz



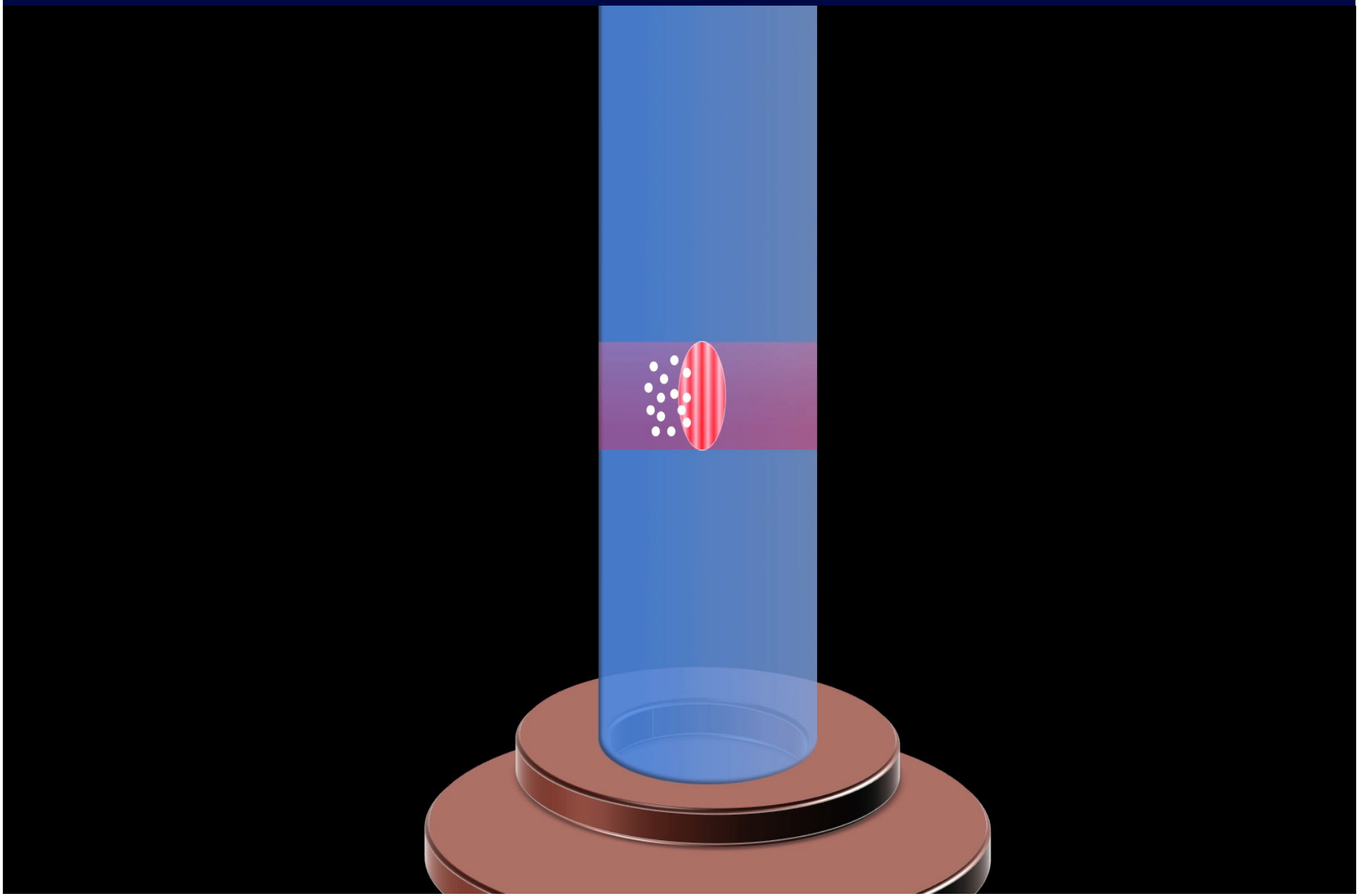


*P. Sprangle et al, J.Appl. Phys 1992,
W.P. Leemans et al., PRL 1996, R.W. Schoenlein et al., Science 1996;
Leemans TPS 2005; Geddes et al., CAARI 2008,
Albert et al PoP2012, Kawase et al, NIMA 2011.
Initial LPA experiments:Chen, PRL 2013 (UNL), Phuoc , Nature Photonics 2012 (LOA)

Outline

- Laser Plasma Accelerators – physics and scaling
- LPA efficiency and beam quality
- 0.2-1 GeV class LPAs
  - Application to Thomson scattering photon sources
- High energy physics and advanced photon sources
  - High energy LPA and very low emittance
  - Repetition rate and efficiency

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



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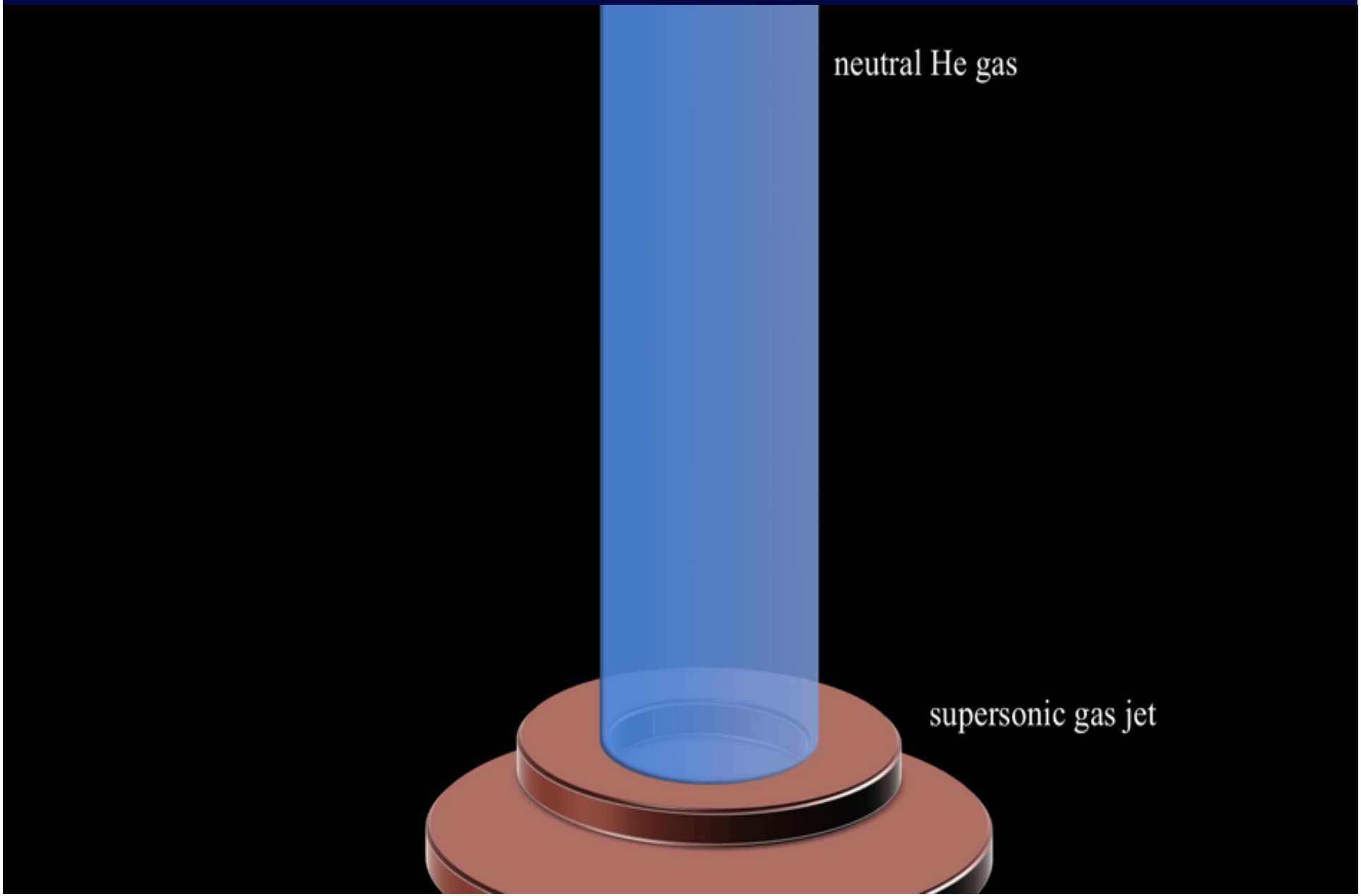
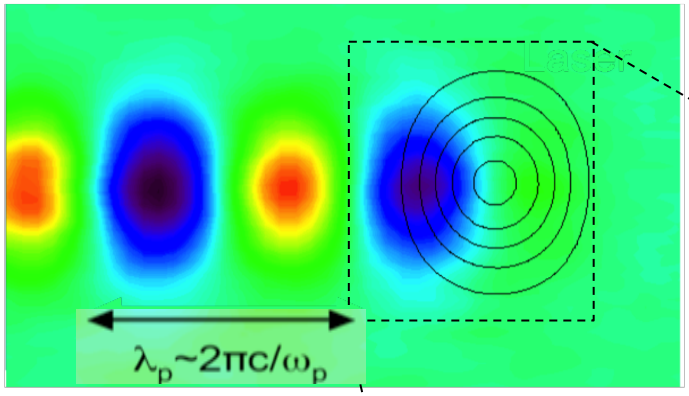
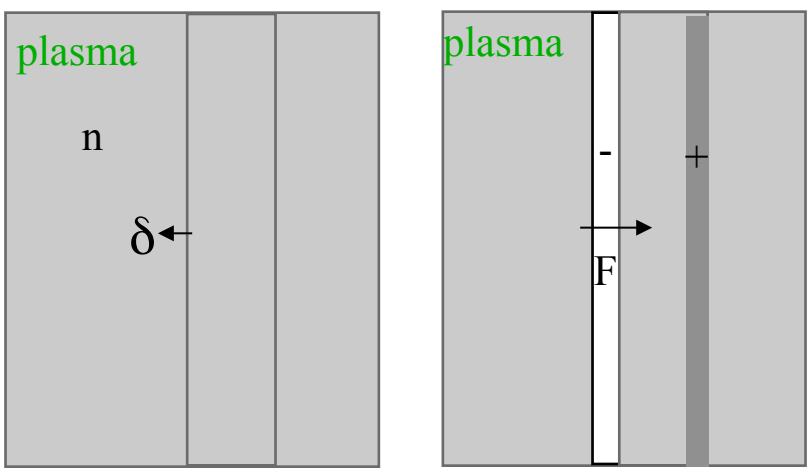


Laser ponderomotive force + plasma oscillation create LPA structure

Wake



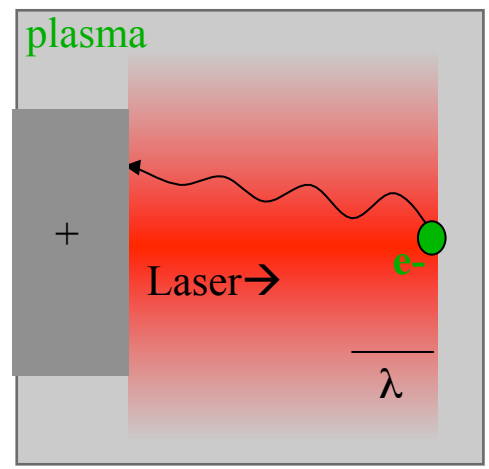
Plasma Oscillation



Displaced electrons induce electric field

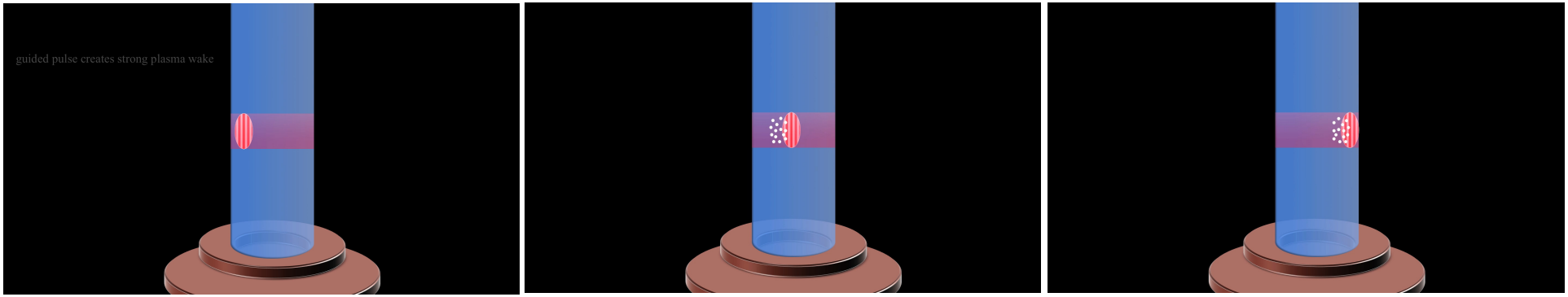
$E \propto n\delta \longrightarrow F \propto n^2\delta \longrightarrow \omega_p \propto \mathrm{sqrt}(n)$

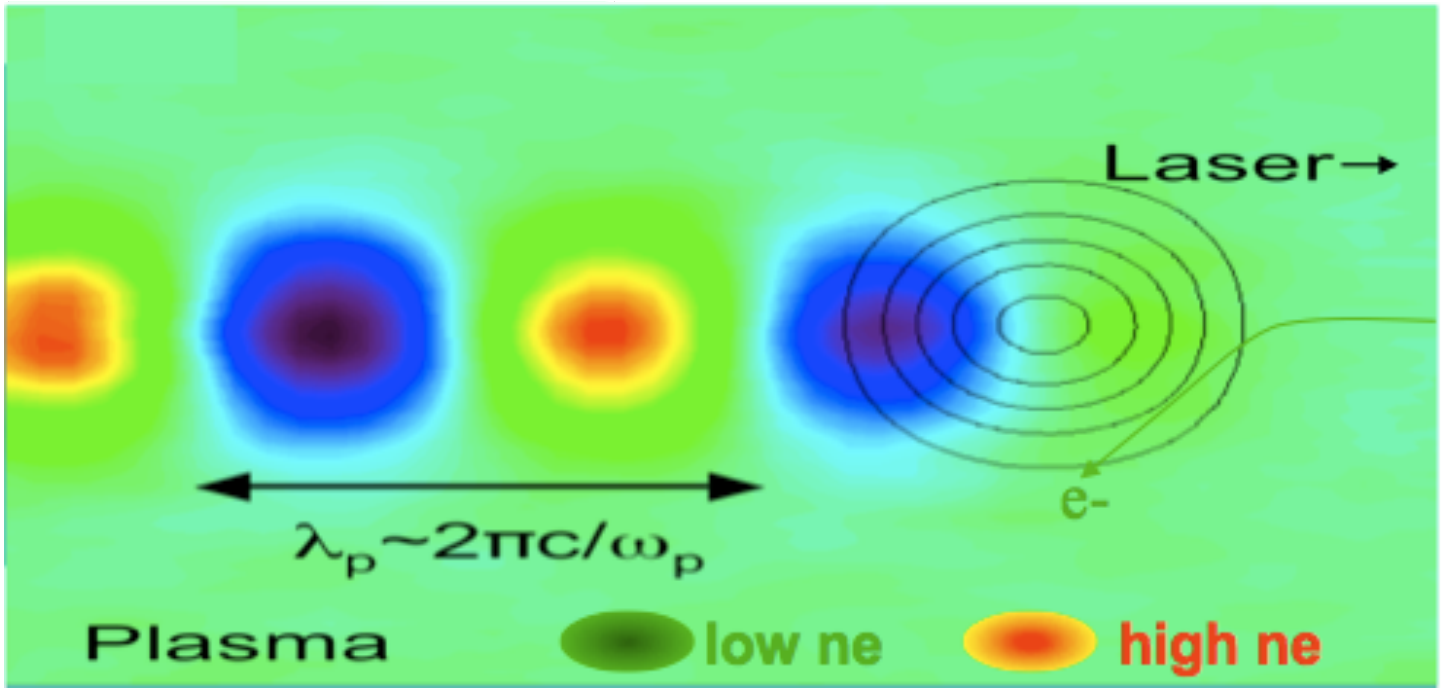
Ponderomotive Force



Laser radiation pressure displaces electrons

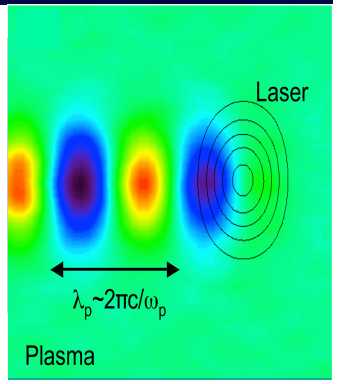
Laser ponderomotive force + plasma oscillation create LPA structure





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

LPA structure gradient and laser



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

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

  $\rightarrow E_{WB} \sim 100$ GV/m at $n \sim 10^{18}$, proportional to $n^{1/2}$

- Laser intensity : wake potential is order of ponderomotive potential:

  $\Phi_p = mc^2a^2/4e$ with $a = eE/\omega mc$

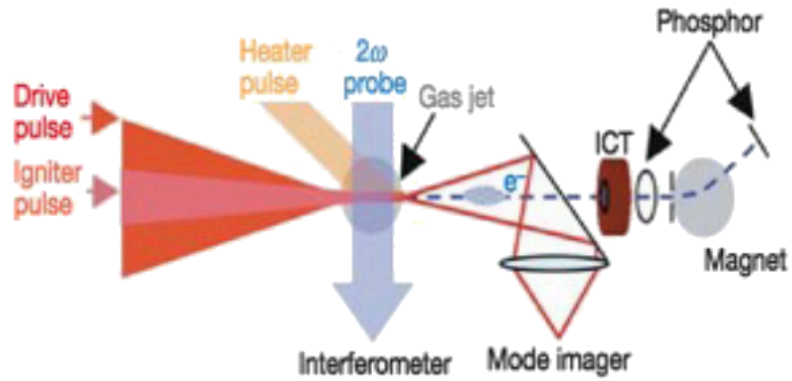
  $E_{wake} \sim \Phi_p/(0.25\lambda_p) \sim mc^2a^2/e\lambda_p \sim 0.5\, a^2\, E_{WB}$

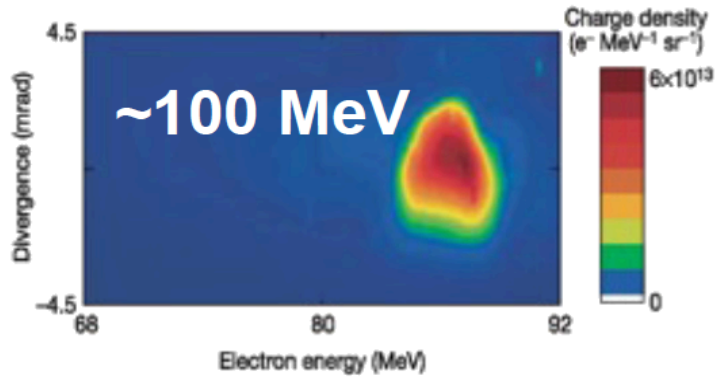
  $\rightarrow$ a ~ >1 to approach E_{WB}

- Pulselength ~ $(1/3)\lambda_p$ -> 30 fs for $n \sim 10^{18}$

Self injected experiments produce high quality beams but limited tuning

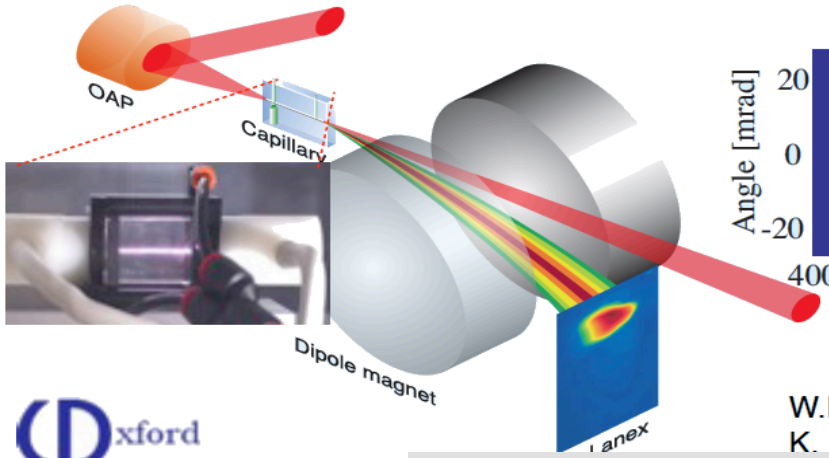
2004 result: 10 TW laser, mm-scale plasma

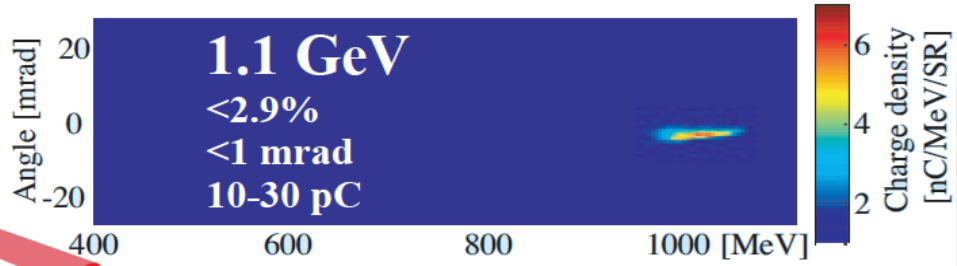


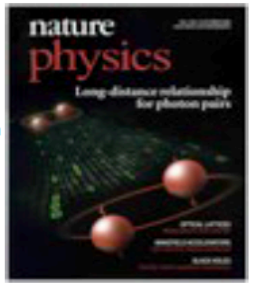


C. G. R. Geddes,et al, Nature,**431**, p538 (2004)
S. Mangles et al., Nature **431**, p535 (2004)
J. Faure et al., Nature **431**, p541 (2004)

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)

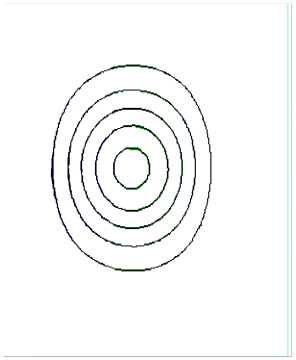
Oxford Physics

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

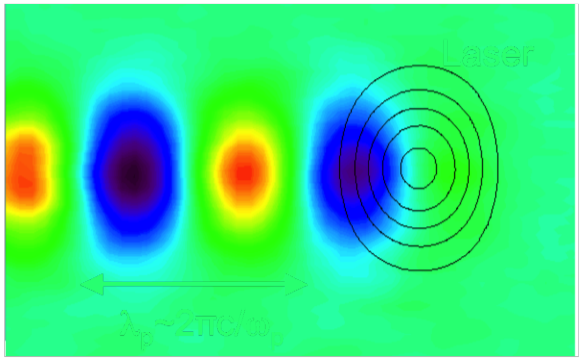
- Laser control – approach pure Gaussian mode



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

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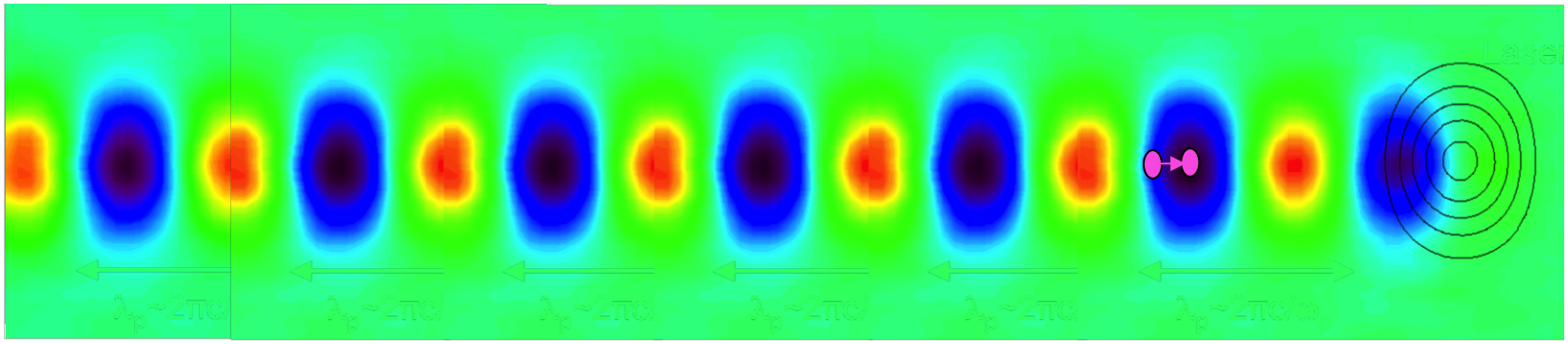
Injector + accelerator stage separate controls for efficient LPA

- Laser control – approach pure Gaussian mode

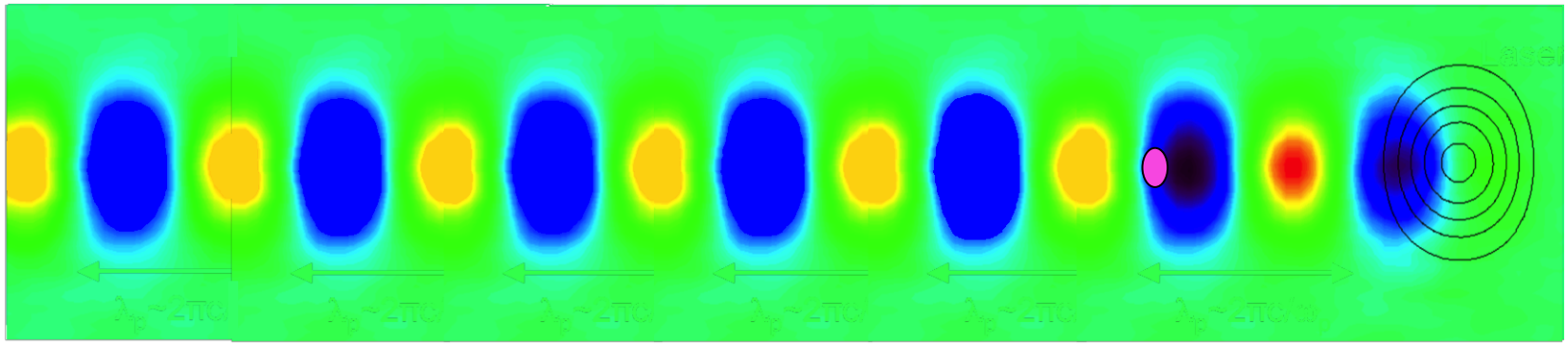


- Structure control via laser, plasma
  - Self and channel guiding – to length of laser depletion/ electron dephasing

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



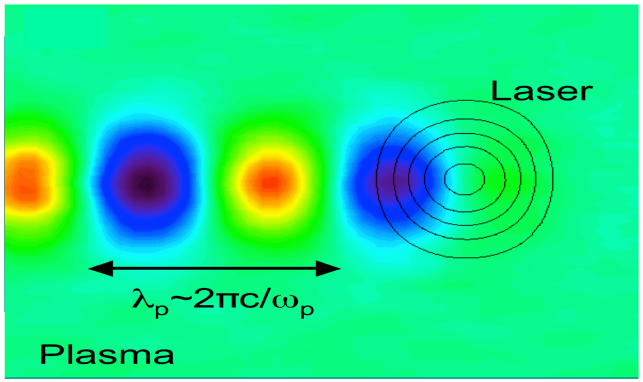
- Structure control via laser, plasma
  - Self and channel guiding – to length of laser depletion/electron dephasing
- Injection control: high quality stable beams
- Diagnostics, Thomson scattering

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

LPA energy scalings

- Laser velocity

$$\eta = \sqrt{1-\left(\frac{\omega_p}{\omega}\right)^2} \qquad v_p = \frac{\omega}{k} = \frac{c}{\eta} \qquad v_g = \frac{d\omega}{dk} = c\eta$$

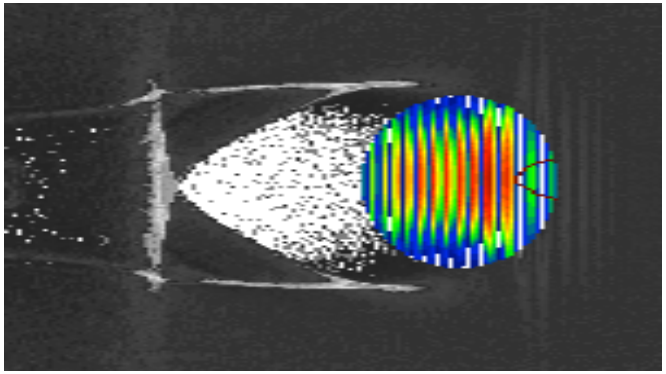


- Acceleration limitations (1D linear):
  - Dephasing: $L_d = \lambda_p^3/\lambda_0^2$
  - Depletion: $L_{pump} = 4\, L_d/a^2$ → a ~ 1-2 efficient
  - Energy: $E\, L_d \sim a^2\, \lambda_p^2/\lambda_0^2$

- GeV energies in few cm at 10^{18}/cc with a=1-2

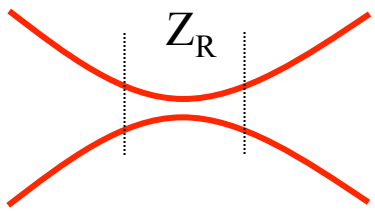
- Charge: $< e\, N_e$ (wake period) $\sim e\, \lambda_p^3 n_e \sim \lambda_p$

- Nonlinear regime scales similarly



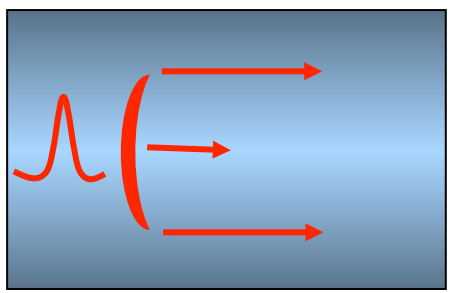
Laser guiding for high energy LPAs

- cm-scale acceleration > Z_R at P <1 PW



$Z_R = \pi w_0^2/\lambda$
a=2→ 200μm @10 TW
2cm @ 1 PW

- Guiding due to refractive index peaked on axis



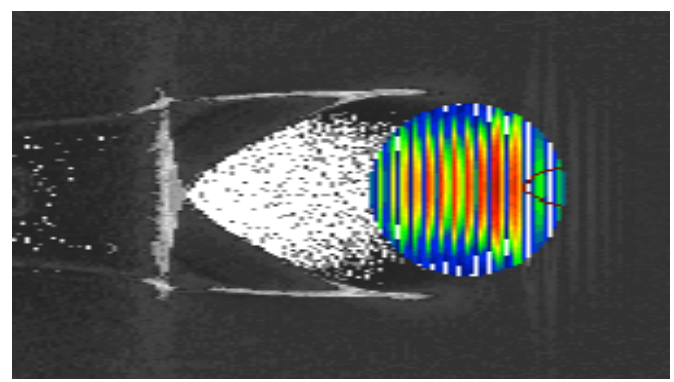
$$\eta \approx 1 - \frac{\omega_p^2}{2\gamma_\perp \omega^2} = 1 - \frac{4\pi e^2 n_e(r)/m}{2(1+a^2)^{1/2}\omega^2}$$

for small a & ω_p

$$- \approx 1 - \frac{\omega_{po}^2}{2\omega^2}\left(1 + \frac{\Delta n}{n} - \frac{a^2}{2} + \frac{\delta n}{n}\right)$$

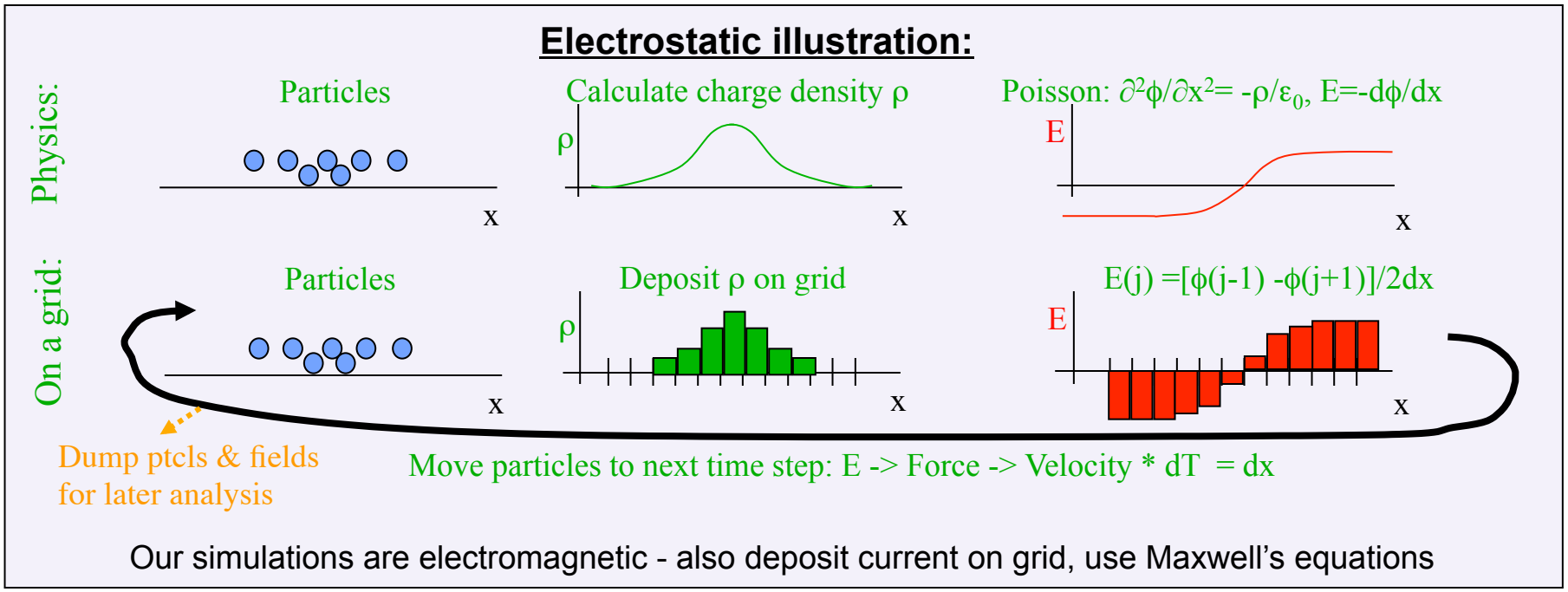
•high density → low η =high v_p, low v_g

- Guiding due to
  - channel guide with density gradient
  - self guide a >> 1 bubble regime (low a0 part erodes)



Particle in cell plasma simulations capture kinetics – at high computational cost

- Plasma is charged particles: electrons and ions. No nonlinear 3D analytic theory.
  - Fluid treatment does not resolve particle trapping
  - Calculating field of each particle on others $O(N^2)$
- Particle in cell method - O(N * log(N)):
  - many electrons represented by simulation 'macro' particles
  - deposit charge and current on a 'grid'

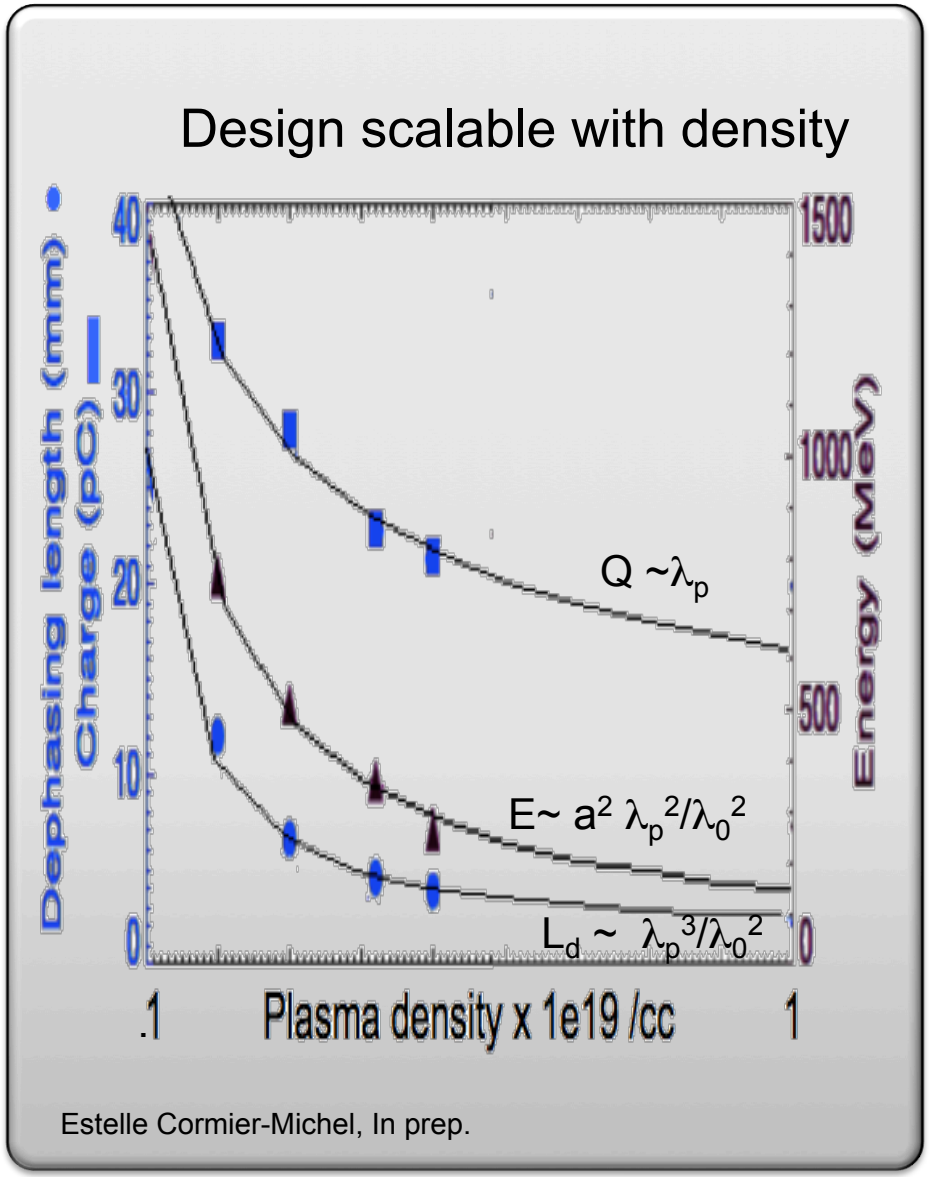


Our simulations are electromagnetic - also deposit current on grid, use Maxwell's equations

See Birdsall & Langdon: "Plasma Physics via Computer Simulation"

Scalable simulations allow design for future source

- Control beam energy via plasma density $E_e \sim 1/n$
  - $\sim 10^8$ e-/shot
- Laser scales with plasma wavelength
  - $E_{Laser} \sim E_e^{3/2} \rightarrow$ 10 TW @250-300 MeV
  - $L_{plasma} \sim E_e^{3/2}$
- Access 0.2 -1 GeV energies
  - Gammas at 1.7 -20MeV

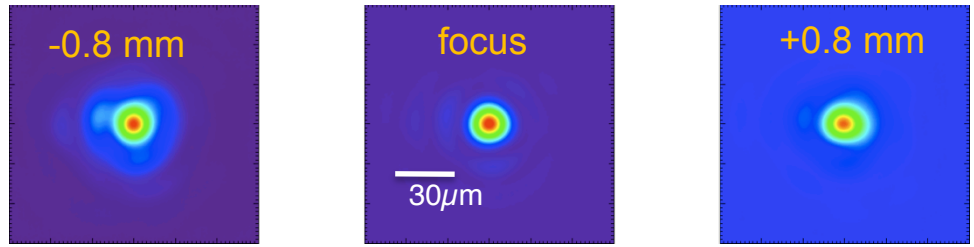


Estelle Cormier-Michel, In prep.

Long interaction length via laser & plasma control

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

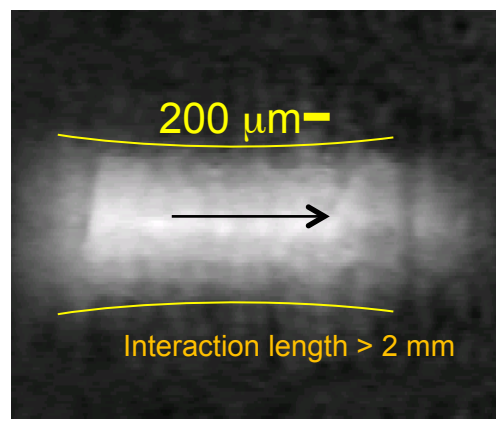
High-quality laser mode over full focal depth



- Interaction over L_{jet} ~2mm

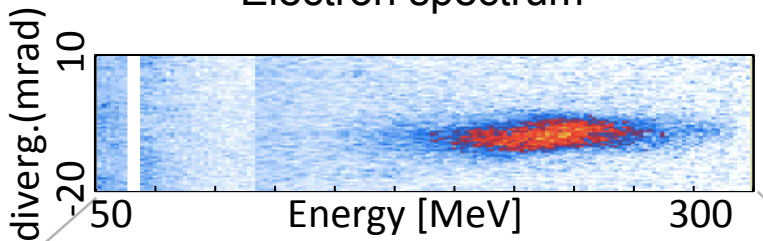
- Plasma density controls dephasing
  - Fluctuations tuned by jet contour

Uniform gas jet plasma & propagation

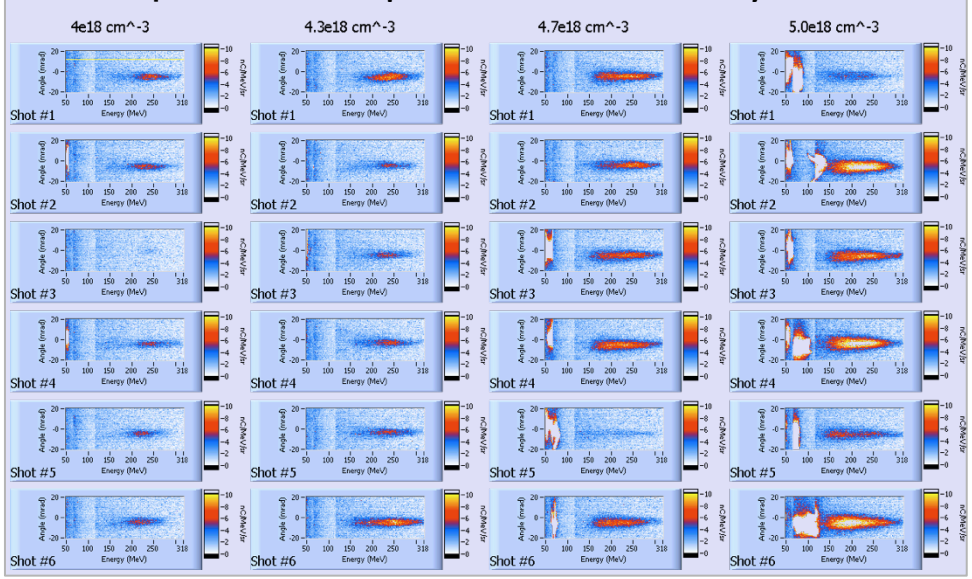


Self trapping produces > 200 MeV at 10 TW

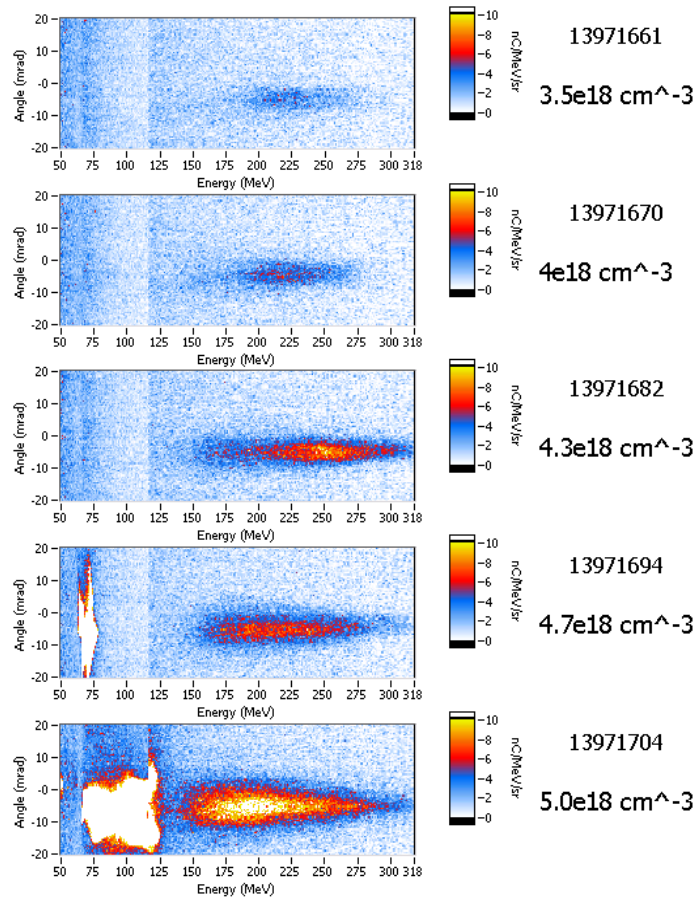
Electron spectrum[1]



Reproducible operation over many shots



Self trapped tuning is limited



Related experiments show self trapped normalized emittance of 0.1 mm-mrad[2]

1: Matlis et al., proc. Adv. Accel. Concepts Wkshp 201. 2: Plateau et al., PRL 2012

Control LPA injection

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

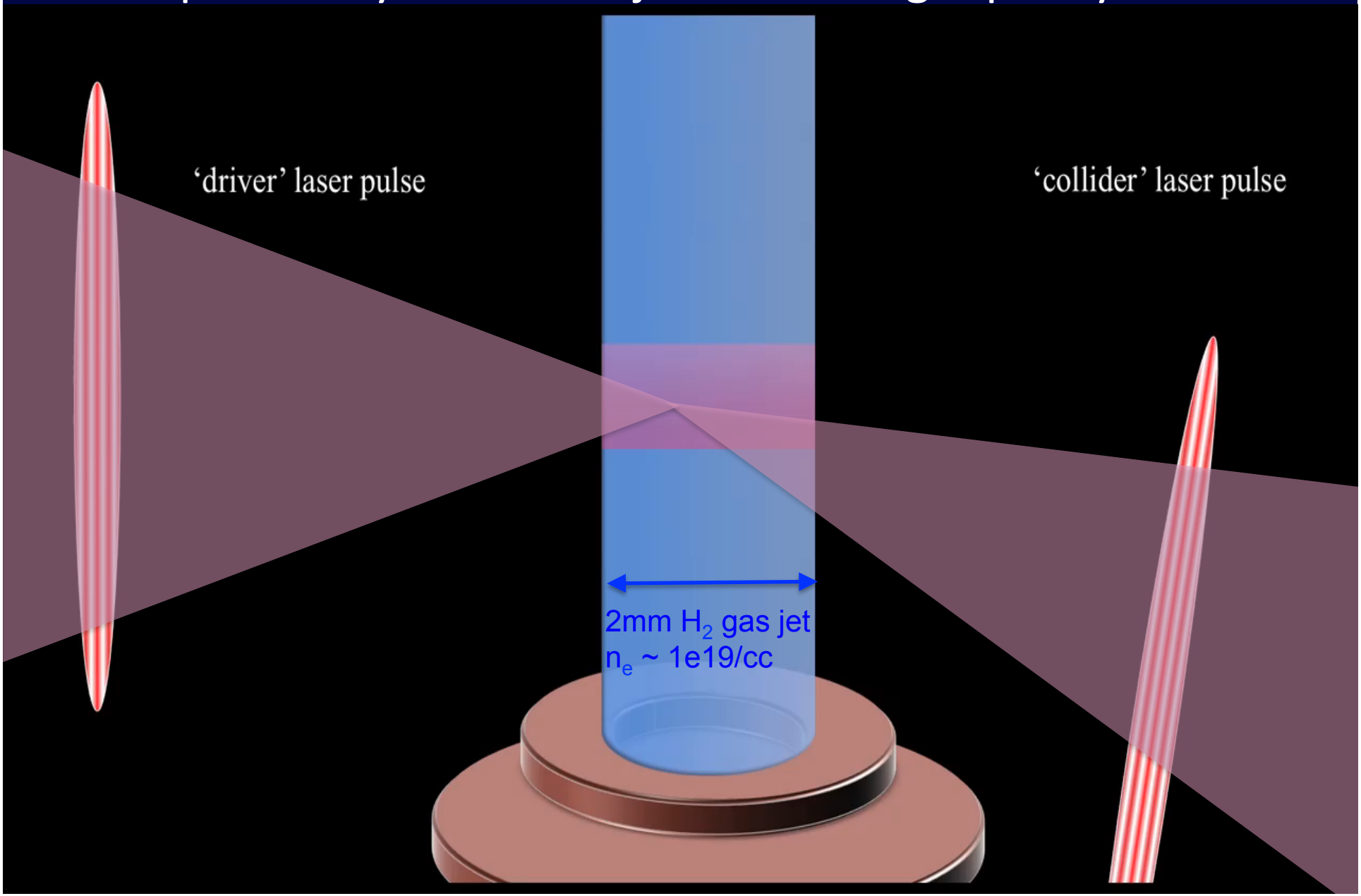
  $(E_{WB}e/m)*(1/\omega_p) = \Delta v \sim v_{wake} \sim c$

  → to control injection:

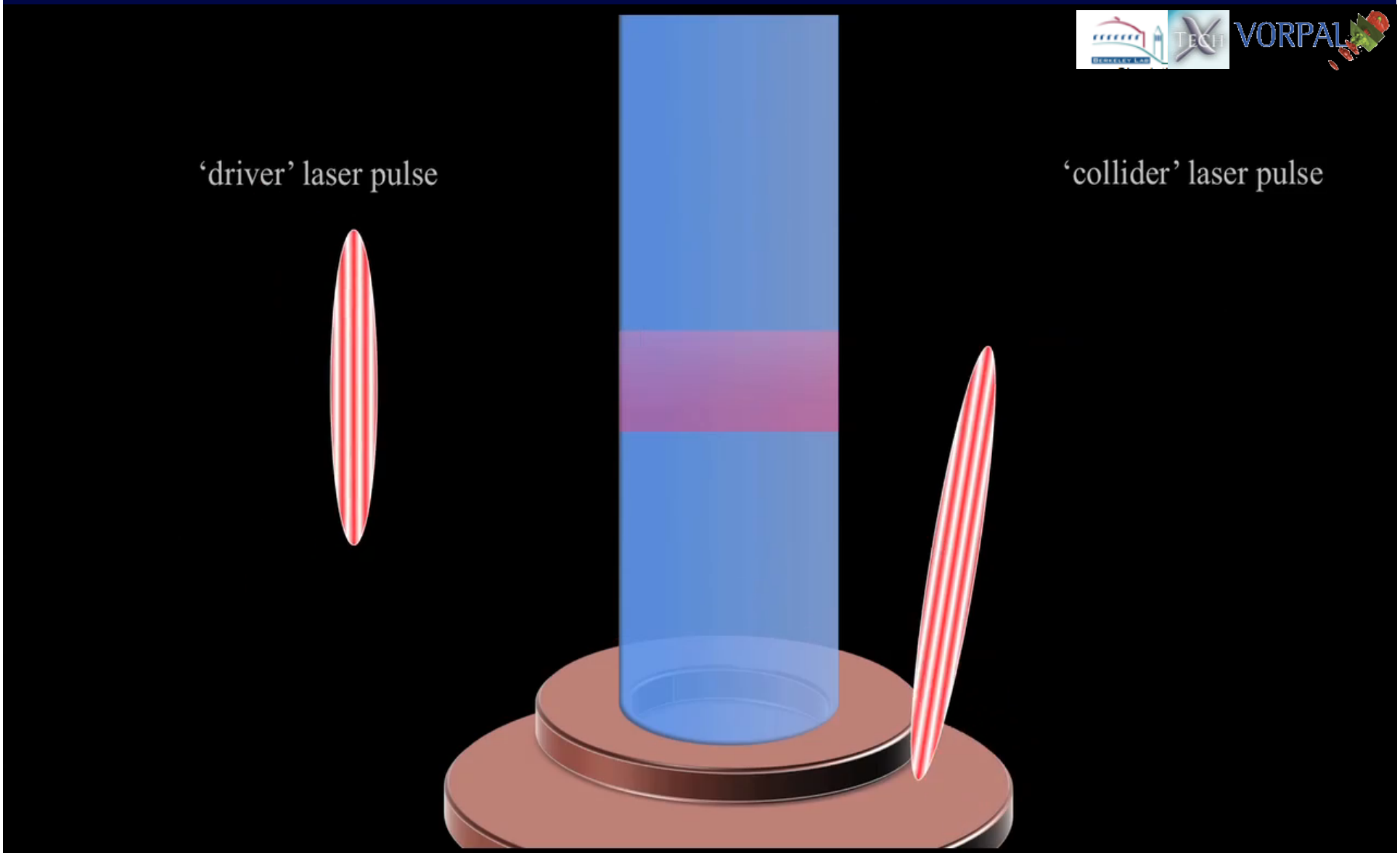
  a) change initial particle velocity

  b) modulate wake velocity

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



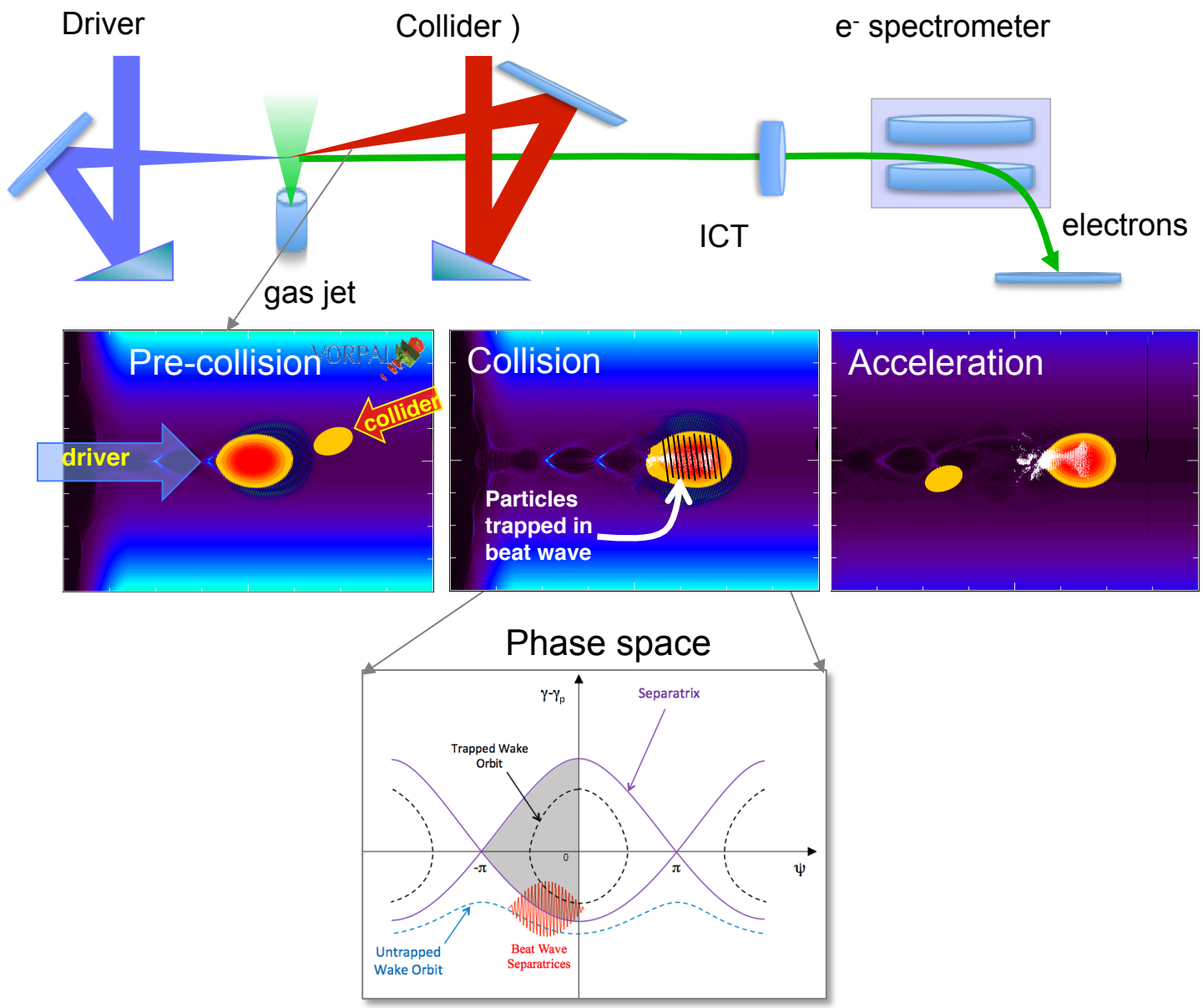
Colliding pulse injection: kick selected electrons to inject



Movie courtesy Cormier-Michel; SciDAC visualization award winner.

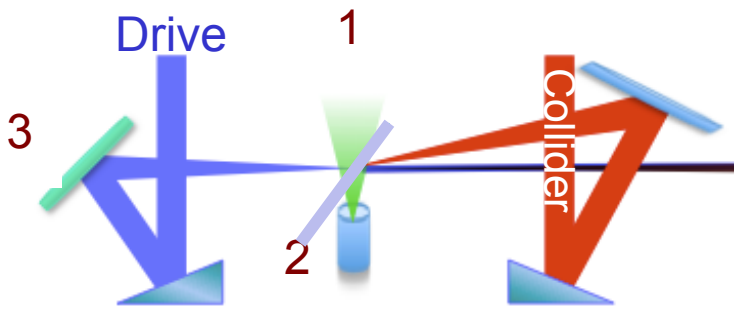
Theory: Esarey PRL 97; Fubiani PRE06, VORPAL code Nieter JCP 2004

Colliding pulse 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.

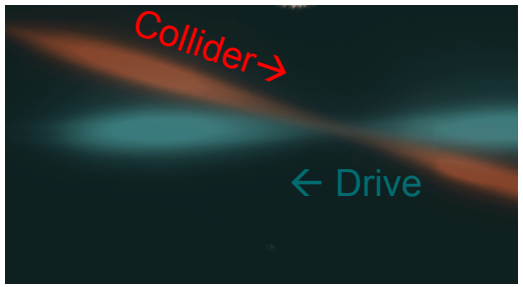
Colliding pulse overlap stabilized



Controls for repeatable accelerator:

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

1



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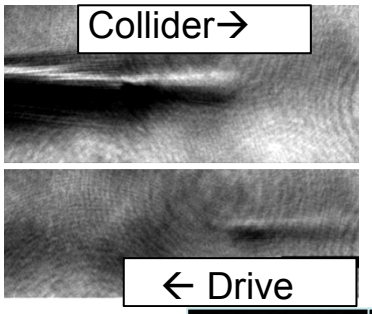
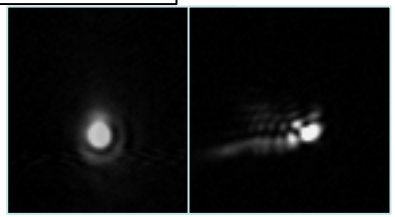
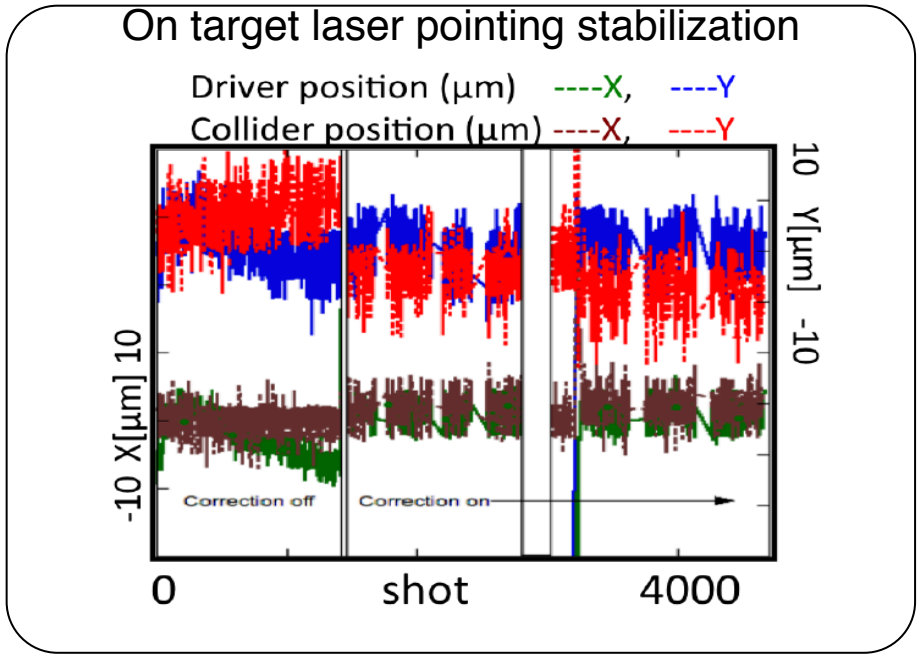


3



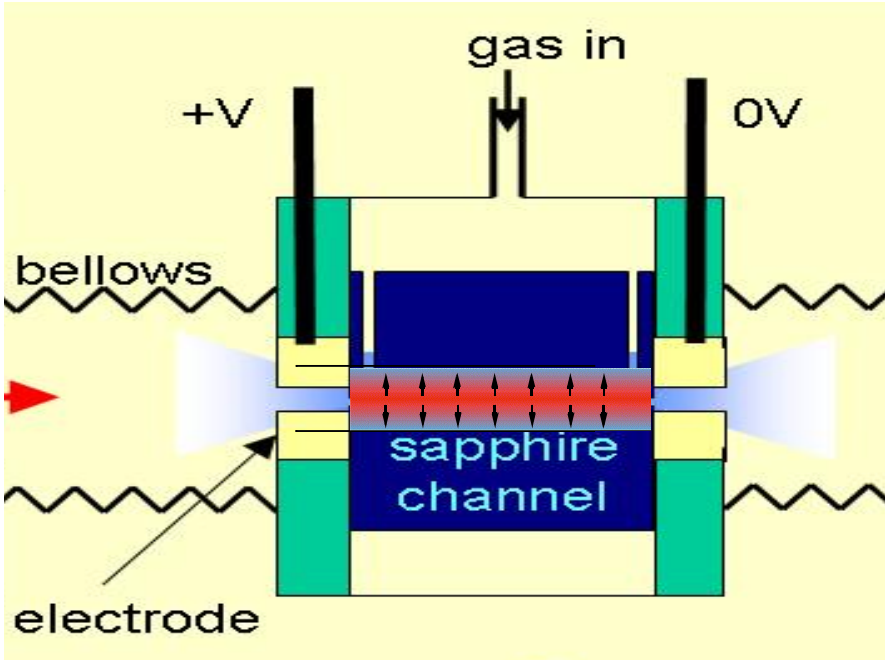
* L. Rabely – Masters' project



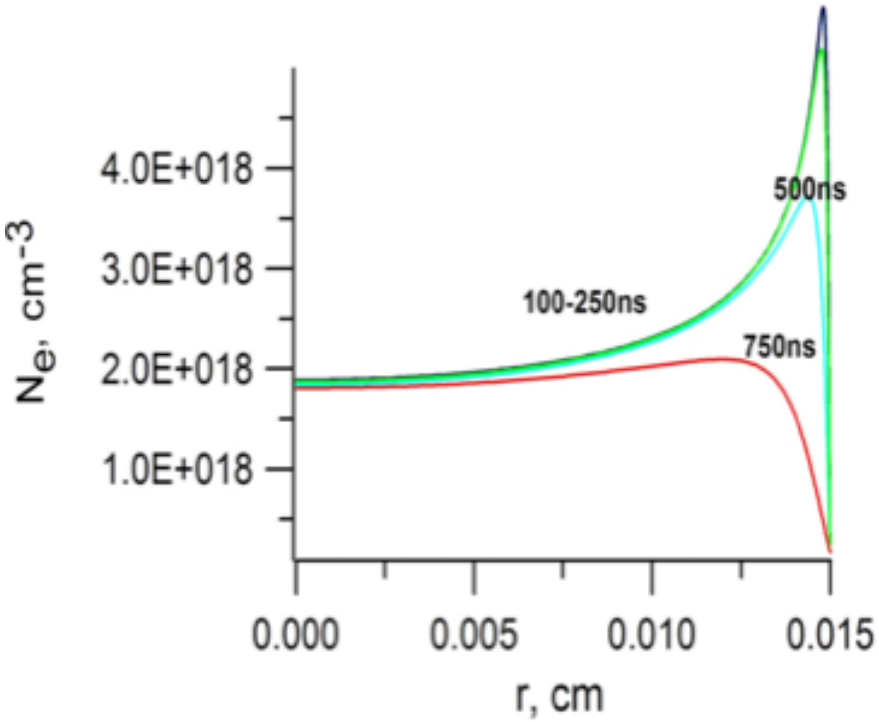
1; Geddes et al., PAC 2011

Capillary channels scale guide laser to > cm scale

Discharge heat conduction forms channel



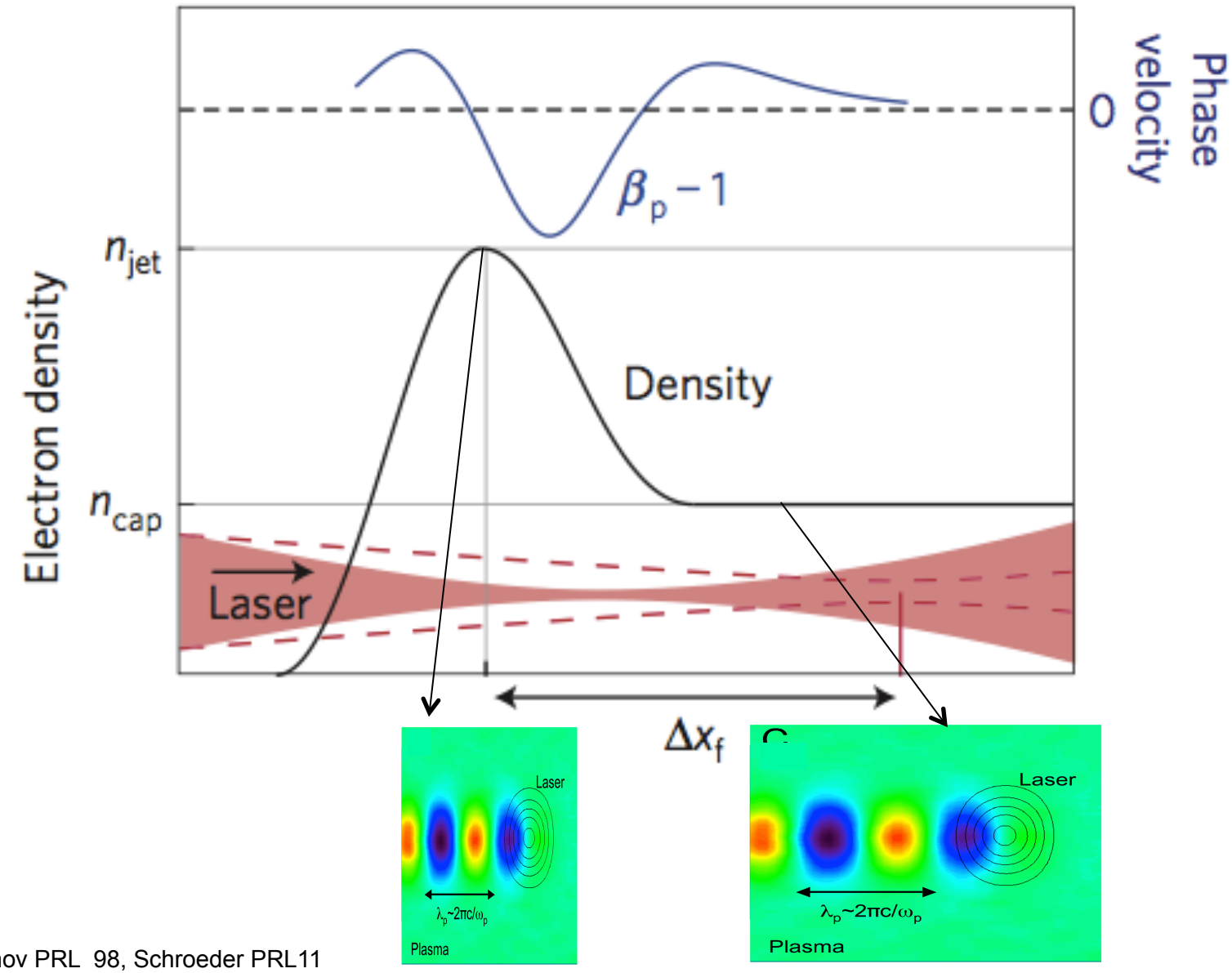
Hydro simulation of capillary characterizes guiding



A. Butler, DJ. Spence, S.M. Hooker, PRL 2002

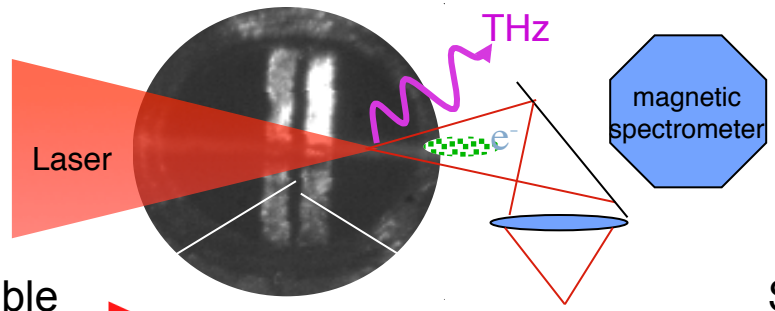
Simulation courtesy N. Bobrova, S. Bulanov

Injection control via wake phase velocity modulation



Theory: Bulanov PRL 98, Schroeder PRL11

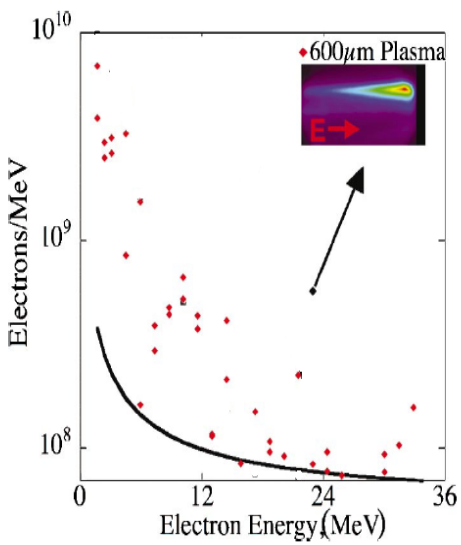
Plasma ramp injection in gas jet produced low momentum spread stable over many days

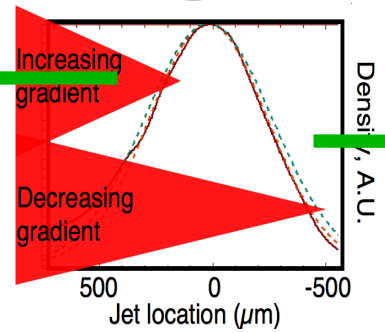


Injection control by

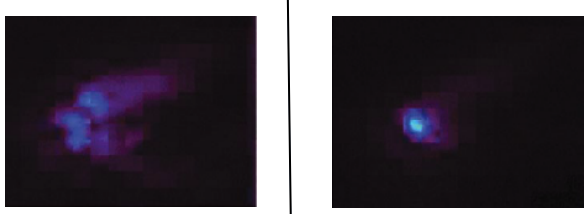
plasma gradient

<u>Self modulated – not stable</u>
Exponential with quasimonenergetic bunches





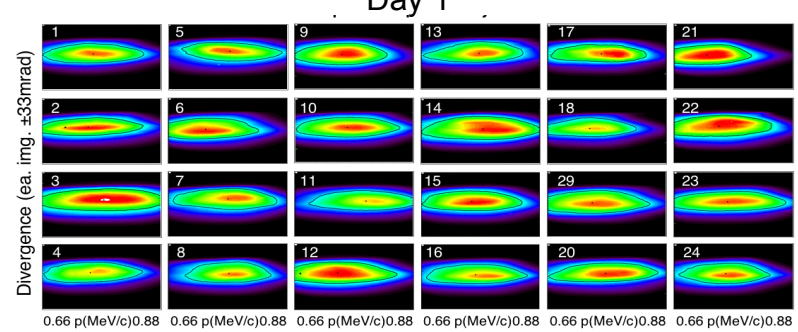
<u>Mode CCD</u>



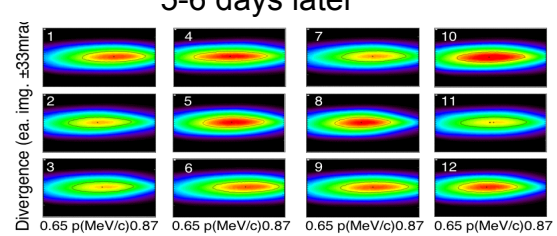
<u>Stable day after day*</u>
E = 0.77MeV±0.03MeV
DE/E = 0.16-0.19

Sequential spectra each ±0.11MeV/c, 33mrad

Day 1



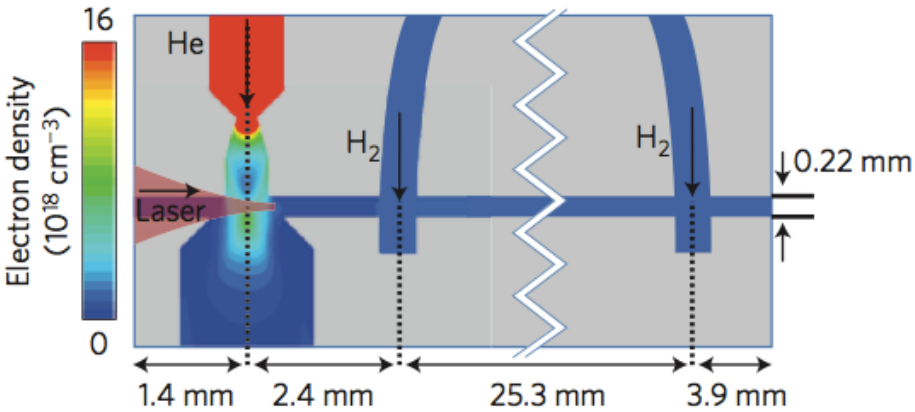
5-6 days later



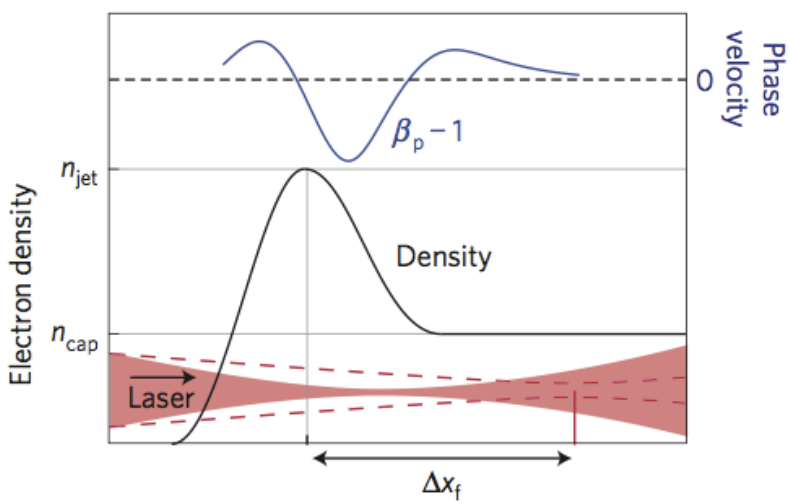
* Geddes et al., PRL 2008; Gonsalves et al., in preparation

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

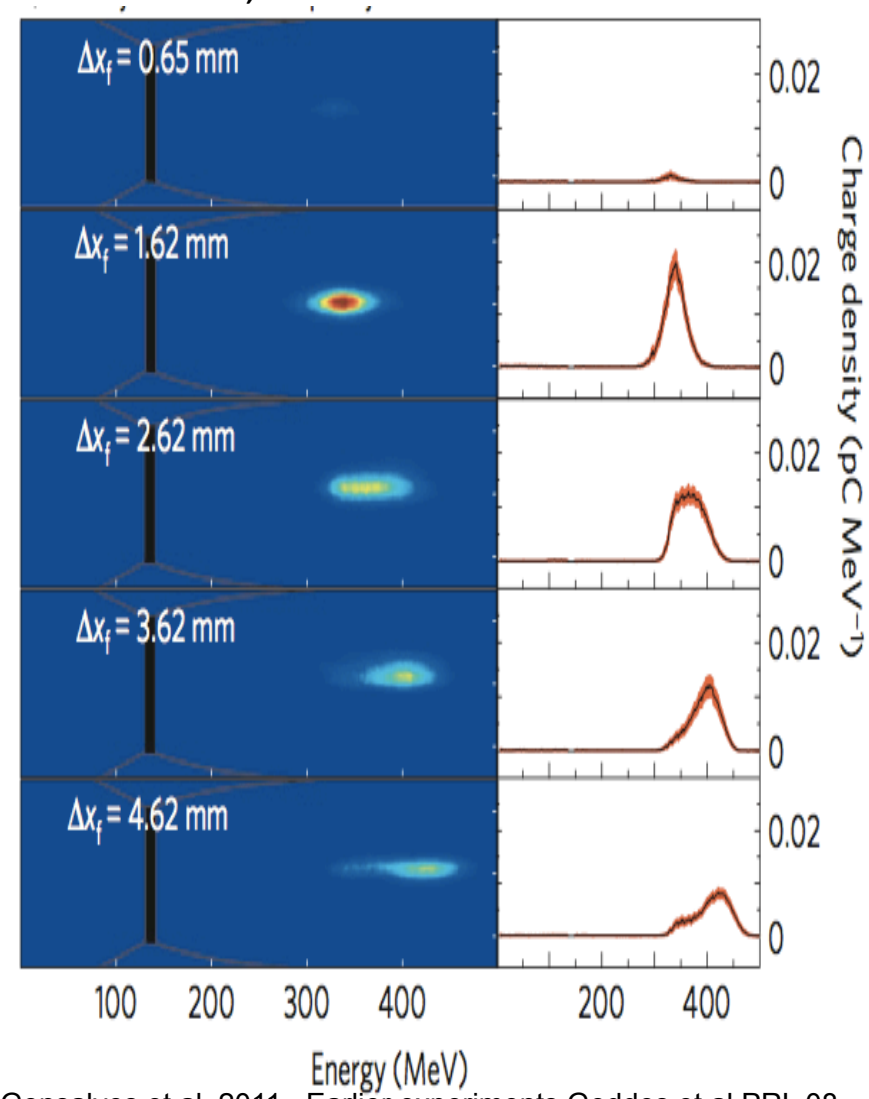
Gas jet in capillary creates density 'bump'



Density change reduces wake velocity controlling trapping



Stable, tunable electron beam

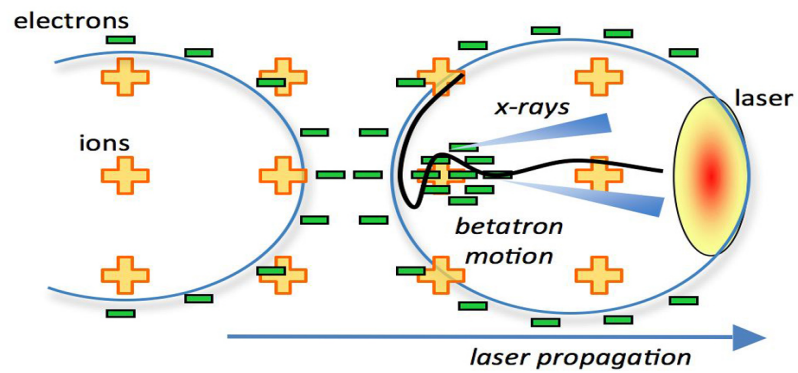


Gonsalves et al, 2011. Earlier experiments Geddes et al PRL 08, Hosokai PRE03; Theory: Bulanov PRL 98, Schroeder PRL11

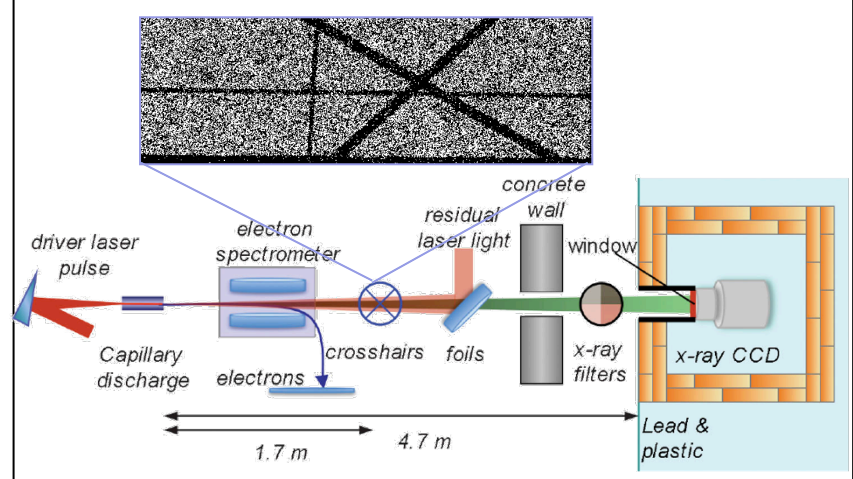
Betatron x-rays used to measure beam size
Determine emittance → photon energy spread from $\Delta\theta$

- 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



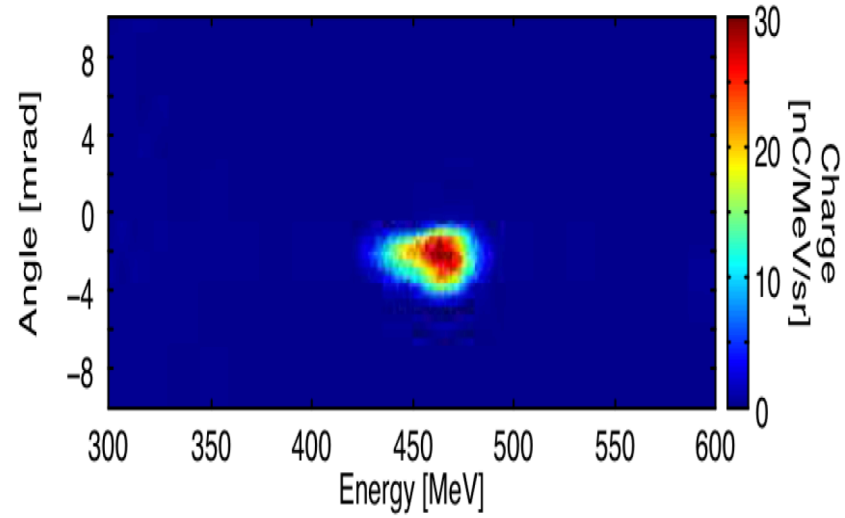
1; Chen et al, PRST-AB 2013, Rykovanov et al. AAC 2012
Related: Thoma et al., Phys. Plasmas 2009. Kneip APL 2011

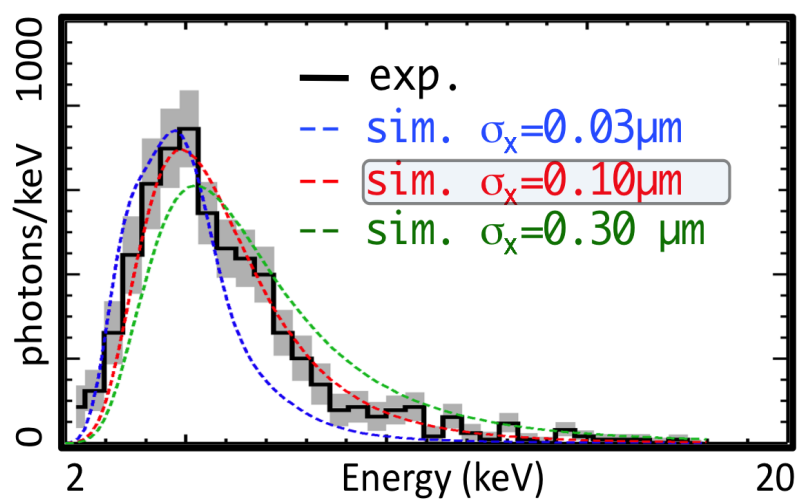
X-ray spectra indicate 0.1 mm-mrad emittance
Comparable to state of the art RF accelerators

- Single shot spectra
  - 463 MeV, $\Delta E \sim 6.6\%$, $\sigma_\theta \sim 1.2$ 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

Single shot measurement



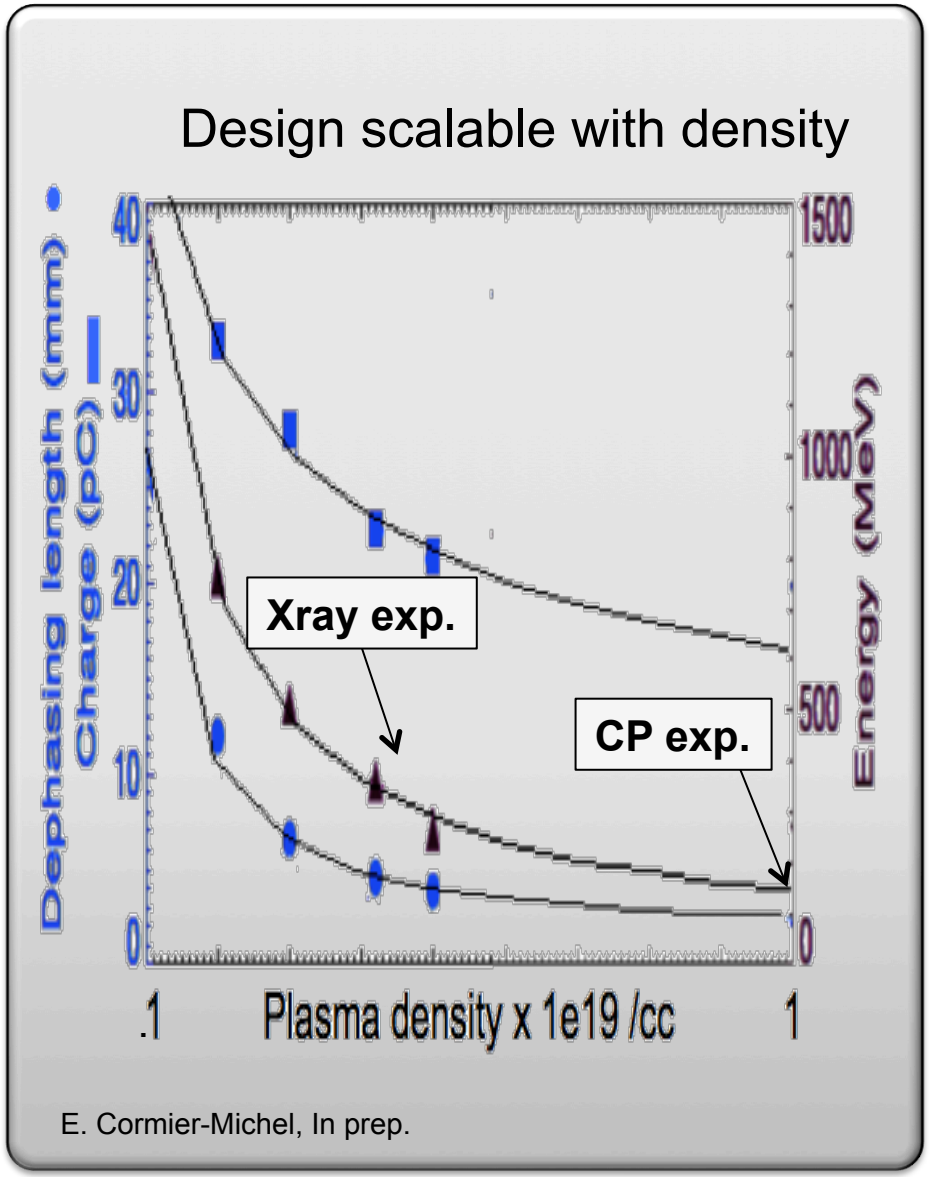


1; Plateau et al., PRL 2012, Thorn et al. RSI 2010

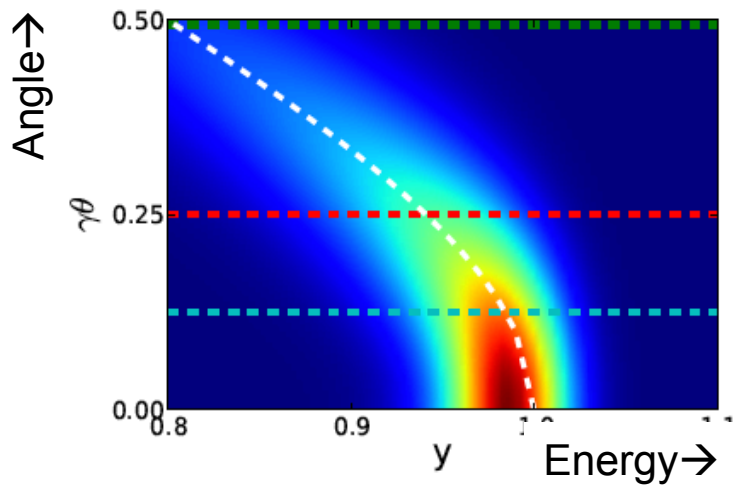
Related: Weingartner et al, PRSTAB 2012, Quad scan, measured similar emittance

Scalable simulations allow design for future source

- Control beam energy via plasma density $E_e \sim 1/n$
  - $\sim 10^8$ 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



Thomson photon sources produce quasi-monoenergetic gamma rays



Beam quality drives on-axis source bandwidth

laser bandwidth usually negligible if ≥ ps

$$\sqrt{\frac{\gamma_e^4\sigma_{\theta,\mathrm{FWHM}}^4}{16}+\frac{4\sigma_{\gamma_e,\mathrm{FWHM}}^2}{\gamma_e^2}+\frac{a_0^4}{4}+\left[N_{sc}\cdot 2\gamma_e\frac{\hbar\omega_L}{m_ec^2}\right]^2}<\kappa.$$

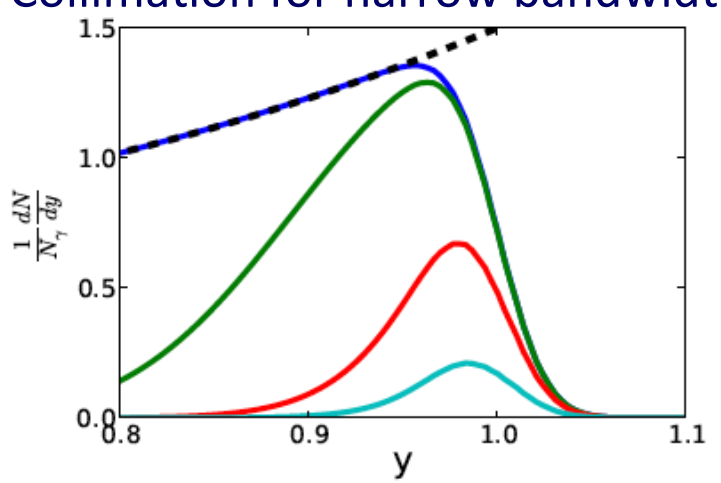
e- energy spread

e- divergence

laser amplitude

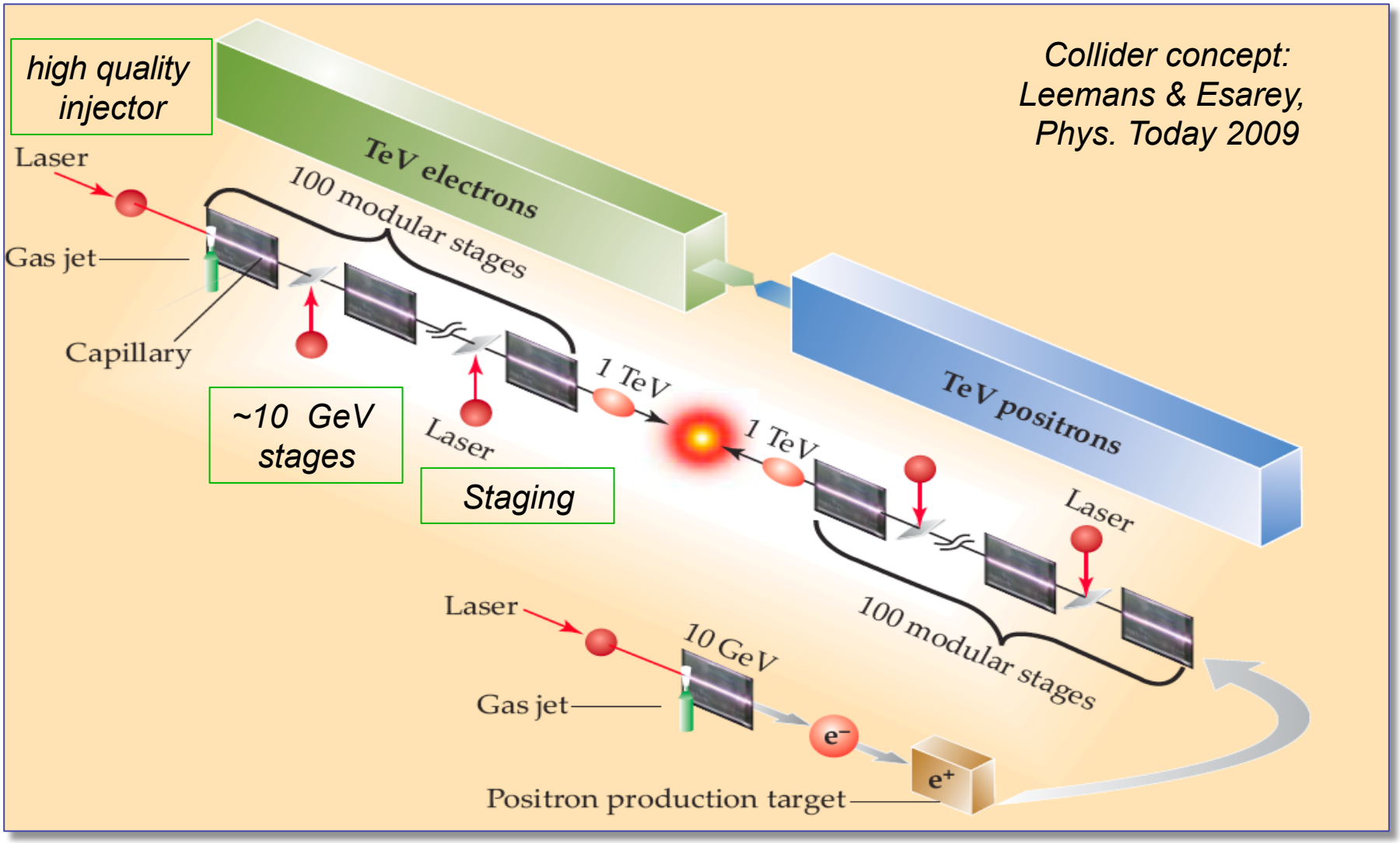
multiple scatter

Collimation for narrow bandwidth



- BW ~ 10 % →e- of 5% DE, ≤ mrad
- BW ~ 2% →e- of 1% DE, ≤ 0.1 mrad

LPA designs towards future FELs and Colliders



Conceptual design of an LPLC

- Linac length set by tradeoff of gradient vs. staging

- Required luminosity L[10^{34} cm^{-2} s^{-2}] ~ (E_{cm}[TeV])^2 (cross section ~γ^{-2})

$$L = \frac{fN^2}{4\pi\sigma_x\sigma_y} = \frac{P_b}{4\pi E_{cm}}\frac{N}{\sigma_x\sigma_y}$$

- Beam power: $P_b = fNE_{cm}$

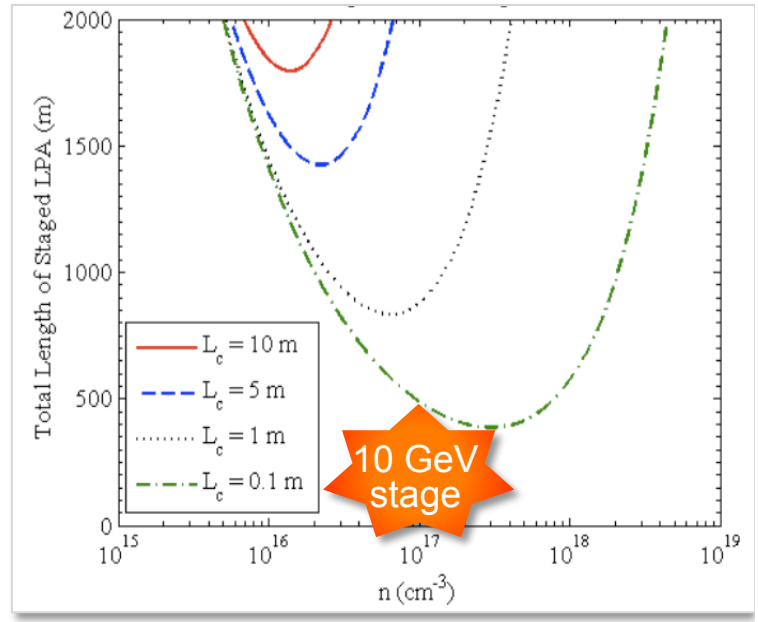
$N \sim 3\text{x}10^9$
$f \sim 15$ kHz
$E_{cm} \sim 1$ TeV

$P_b \sim 4$ MW

- AC wall-plug power: ~ 200 MW ➔2% efficiency
  ➔~10% laser to beam
  ~20% wall-plug to laser
  ➔laser and accelerator development

- Additional options include gamma-gamma collider**

5TeV LPA length vs stage density*



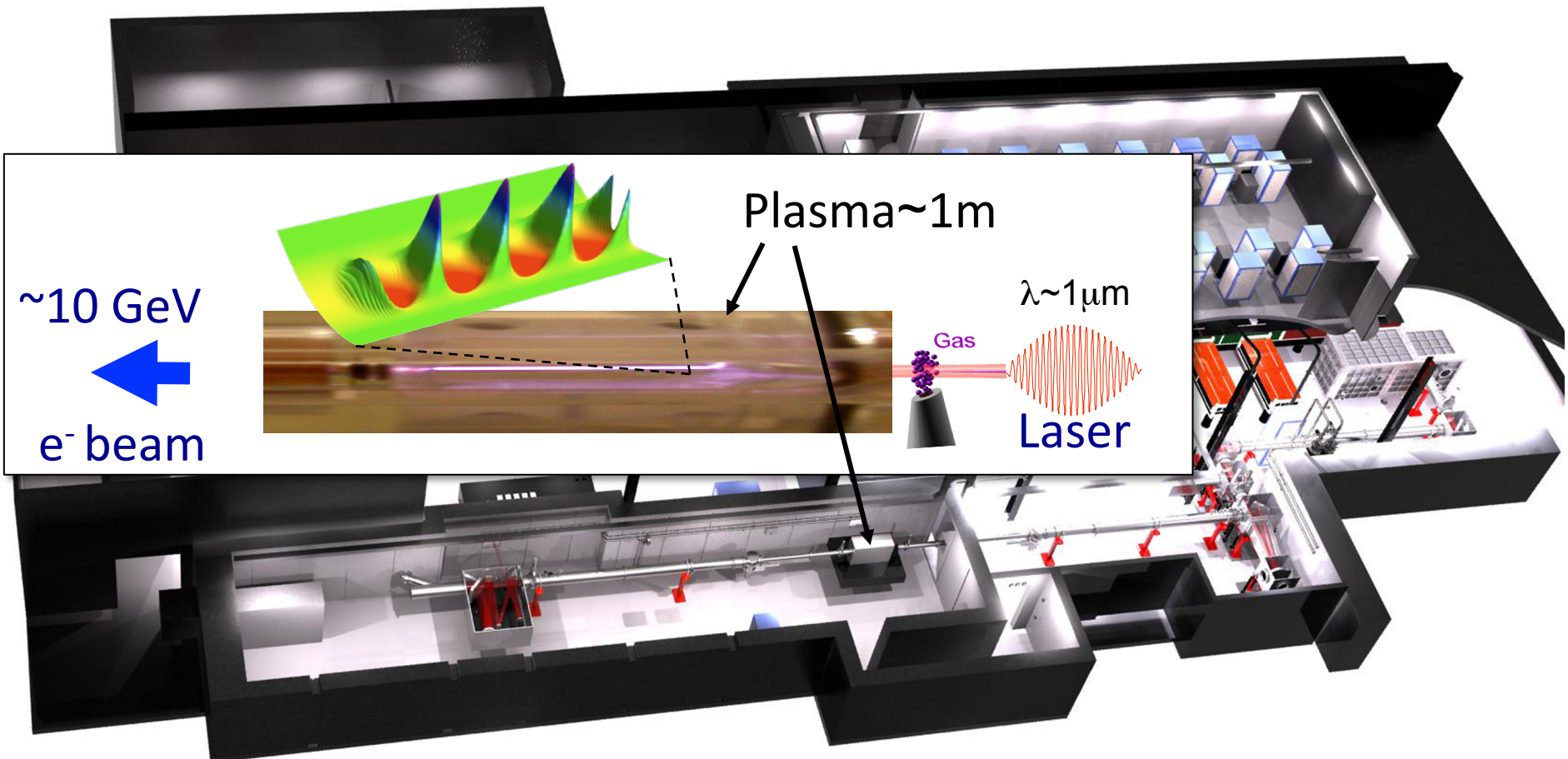
LPLC Concept at 10^{17} /cc*

Plasma number density, n_0	10^{17} cm^{-3}
Energy, center of mass, E_{cm}	1 TeV
Beam energy, γmc^2	0.5 TeV
Number per bunch, N	3×10^9
Collision rate, f	15 kHz
Beam Power, $P_b = fN\gamma mc^2$	3.5 MW
Luminosity, $\mathscr{L}$	10^{34} s^{-1} cm^{-2}

Staging - Panasenko et al, AAC 2008
*Collider Details – Schroeder et al, AAC 2008; Leemans & Esarey Phys. Today 2009 **Schroeder et al, PAC 2009

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

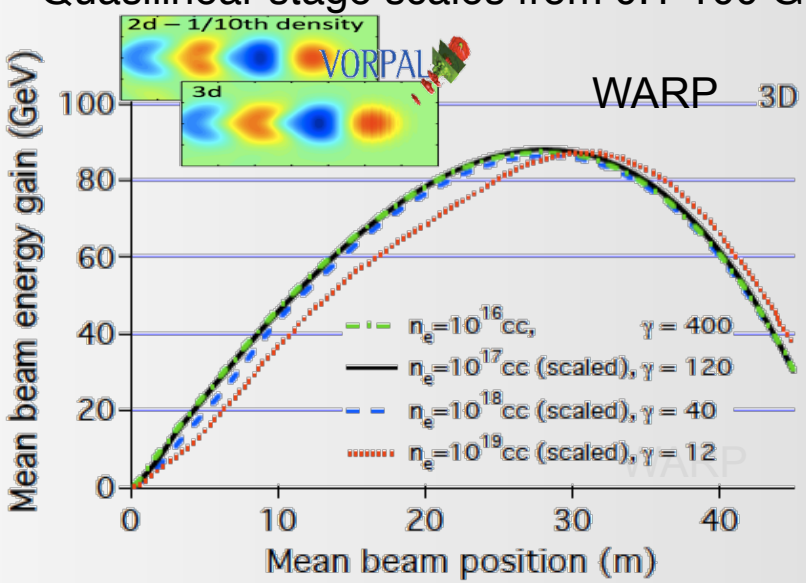


Leemans, Proc. Adv. Accel. Concepts Workshop 2010

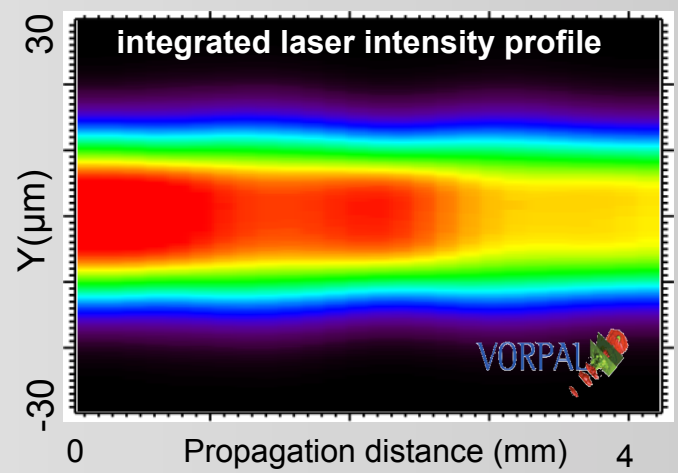
Scalable LPAs with beam size/divergence control

- 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



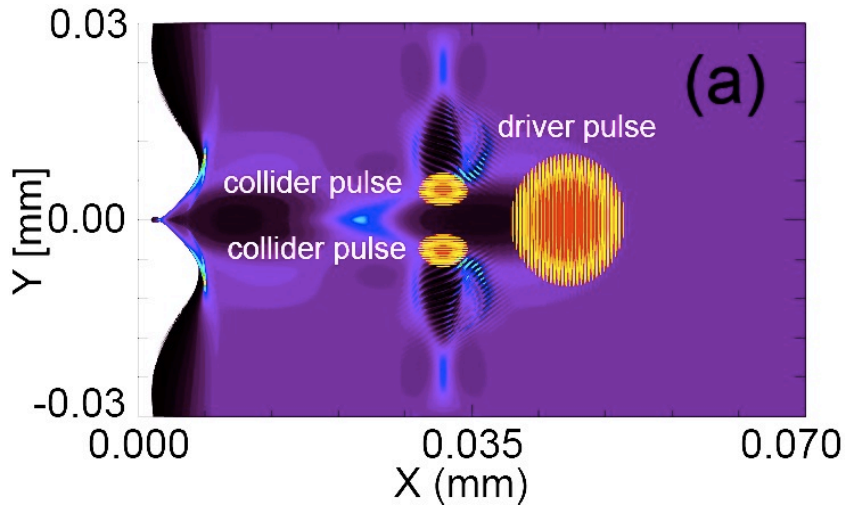
Vorpal; Cormier-Michel AAC 2008, Geddes SciDAC Review 2009 .
WARP; Vay, PoP 11, JCP11

Cormier-Michel, PRSTAB 2011

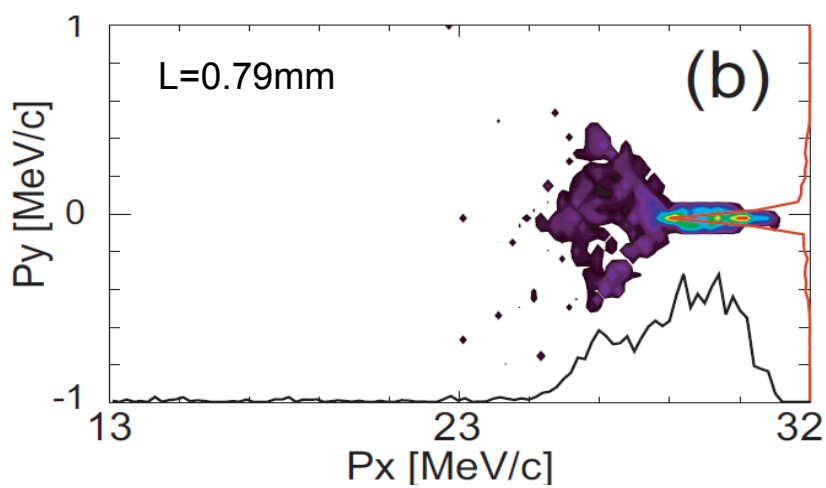
Novel methods for future experiments simulated: Low emittance via transverse colliding pulses

- 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



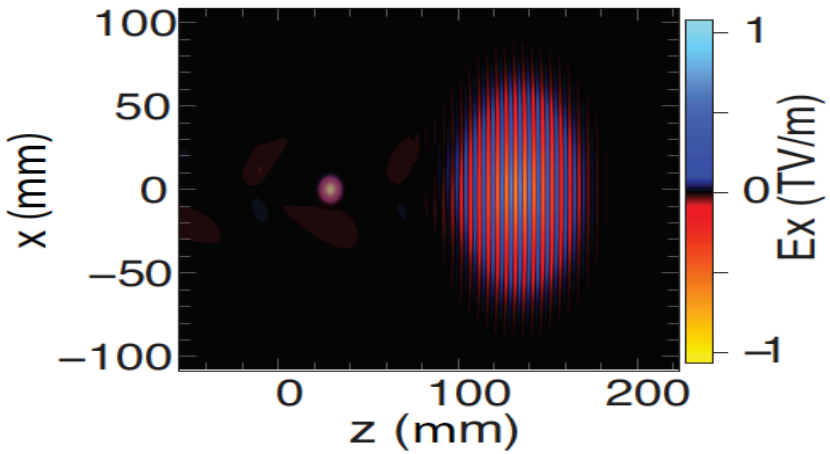
Low transverse momentum selected



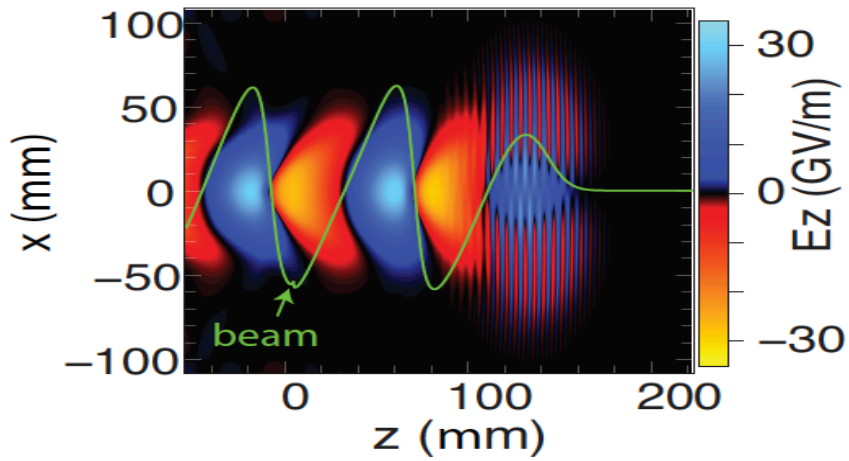
Min Chen, Proc AAC 2012 and submitted

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

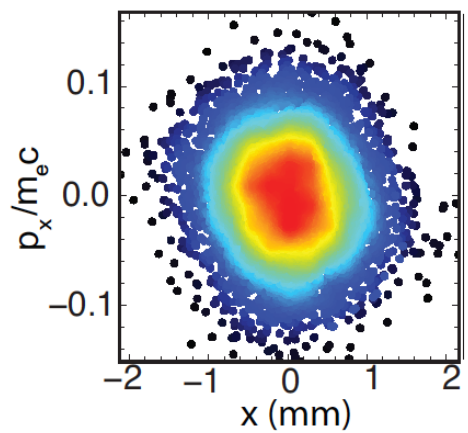
Short-wavelength trailing pulse



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

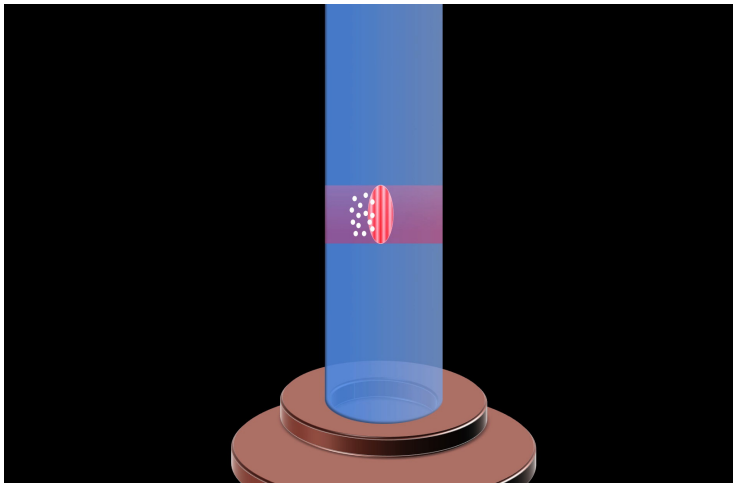
Min Chen, Proc AAC 2012 and submitted

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

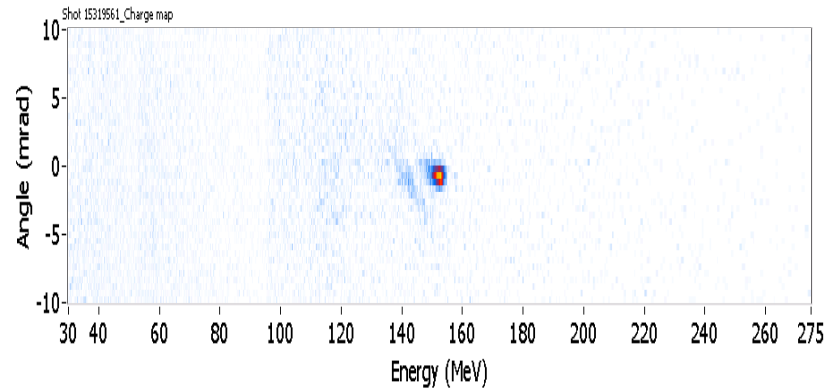
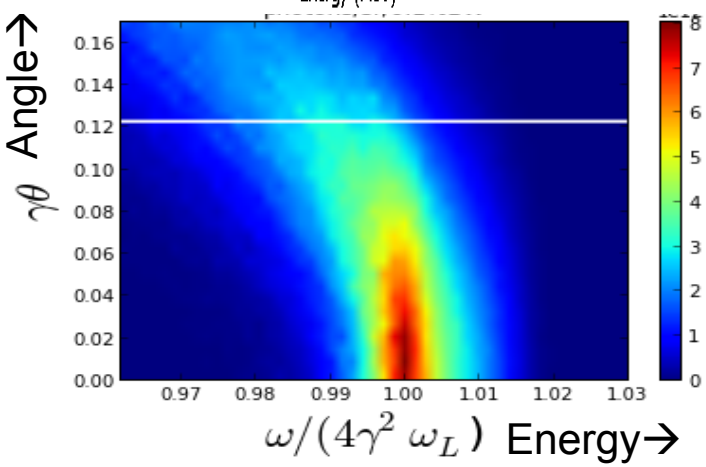
- Drive: 10-20 TW fs lasers at 0.5 -2J
  - $1 M range, ≤ 6m^2 → rapidly dropping
  - 10 Hz typical

→Adequate for demonstration

- 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

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