Acceleration at the hundred GV/m scale using laser wakefields

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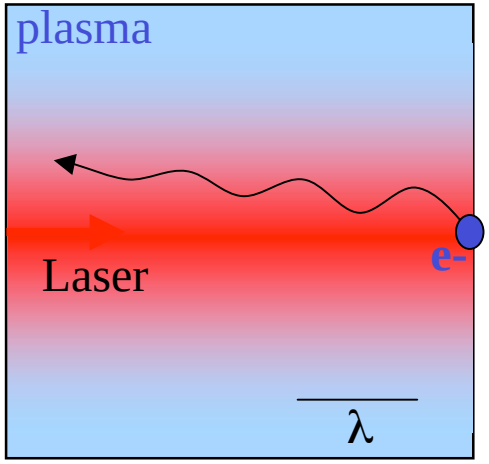
D. Bruhwiler, Tech -X
J. Cary, Tech - X & U. Colorado

SLAC, 2007

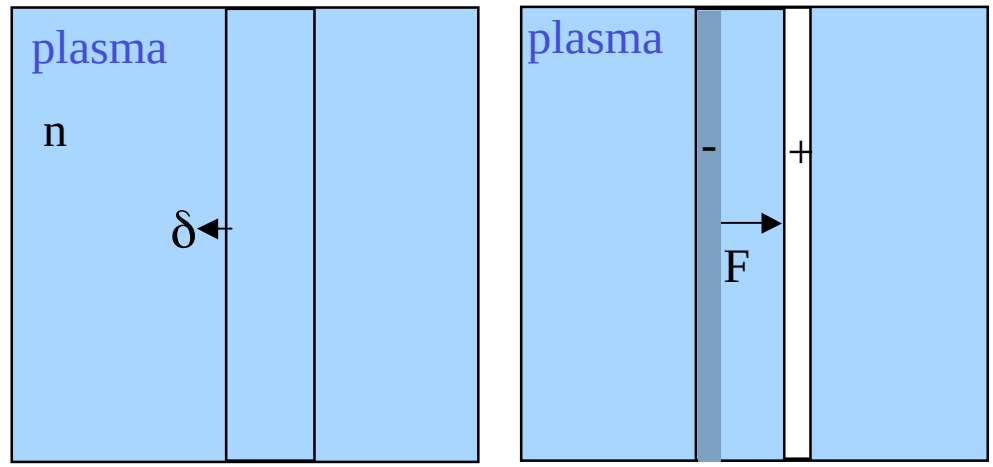
Laser Plasma Interaction for Laser Acceleration

Pondermotive Force



Laser radiation pressure displaces electrons away from laser beam

Plasma Oscillation



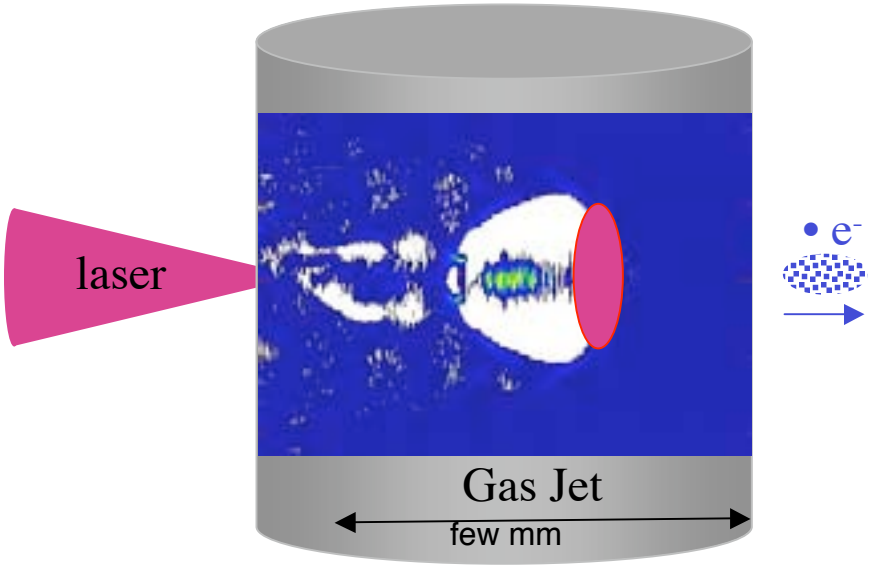
Displacing plasma electrons induces an electric field

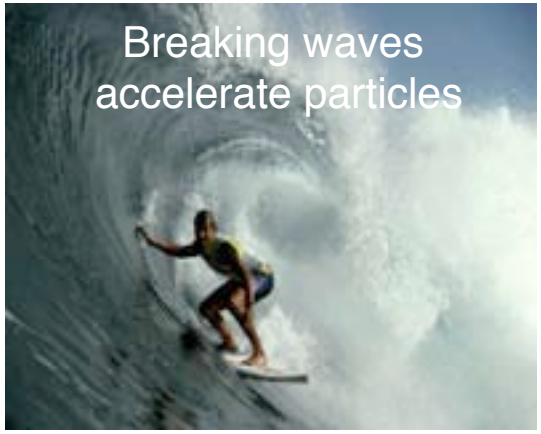
$$E \propto n\delta \longrightarrow F \propto n^2\delta \longrightarrow \omega_p \propto \mathrm{sqrt}(n)$$

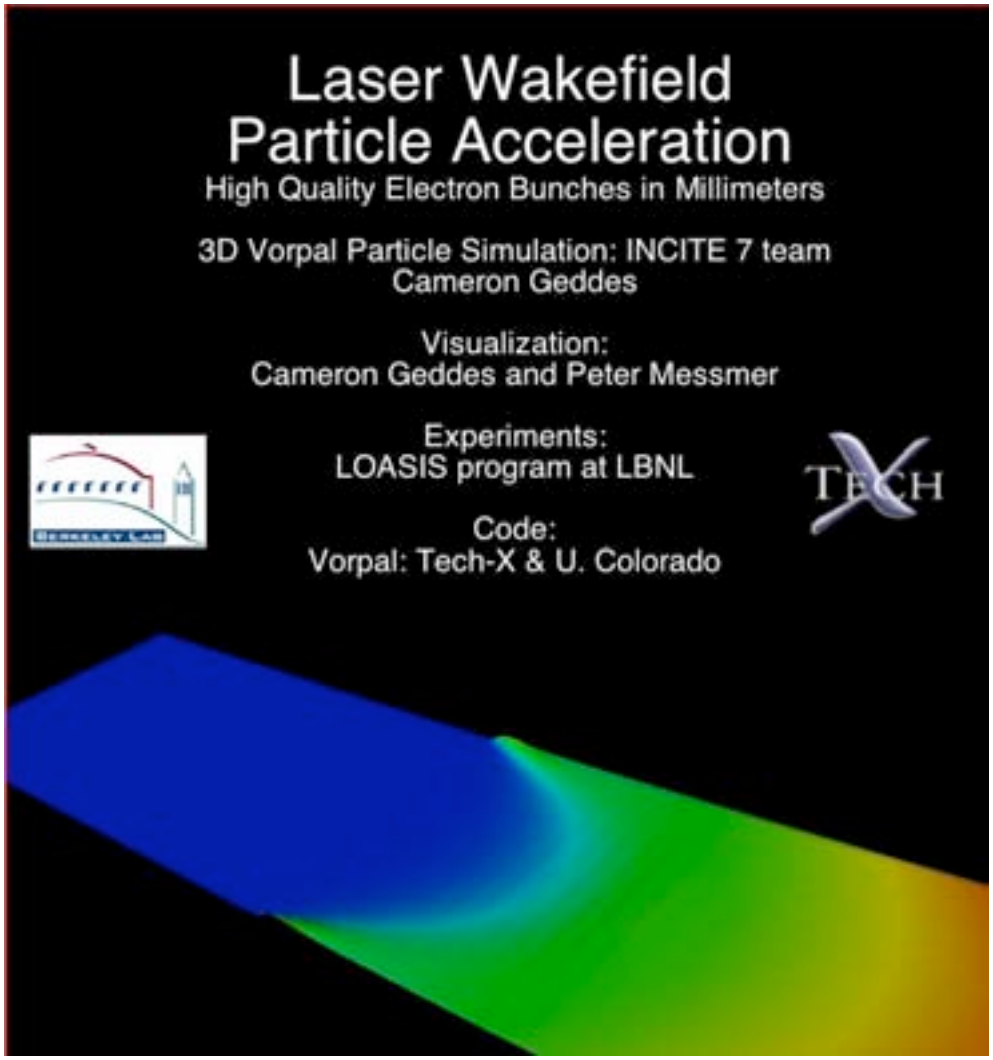
An oscillation of density (and field) results

Laser driven wakefield accelerators offer high gradients, short pulses

Wakefield Acceleration







Fields of 30 - 1000 GV/m

Bunches With % Spread at GeV Now Obtained: Scaling Towards Applications...

-LWFA basics

-Present experiments:

-self modulation & trapping

-guiding

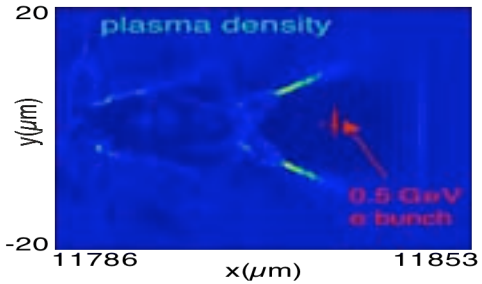
-100 MeV and 1 GeV class experiments

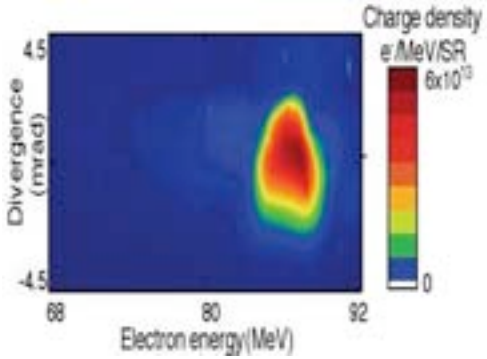
-Physics of narrow energy spread beams

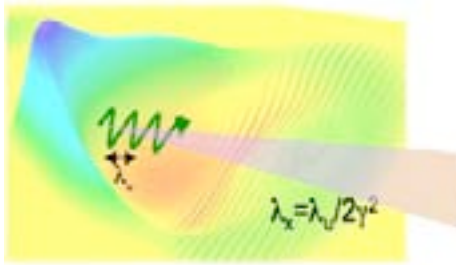
-Staging and scaling to higher energies and stability

-Radiation sources & beam diagnostics

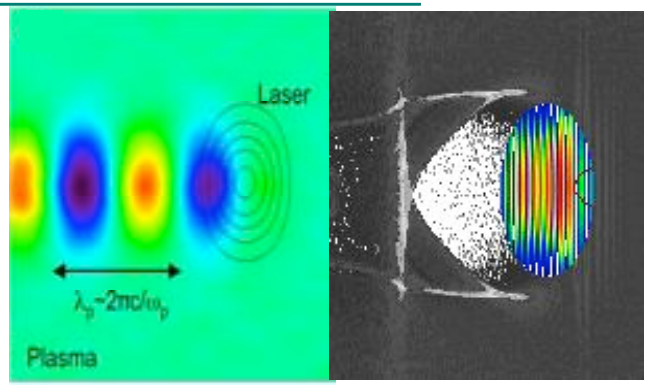
-Future prospects







Wakefield Accelerator Physics: Wave Breaking and Gradient



- Limit on gradient for a cold plasma:

  1D trapping in a wave with v~c approximately for:

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

  E_{WB} ~ 100 GV/m for n~10^{18}, scaling up as sqrt(n)

- Intensity requirement: wake potential is order of ponderomotive potential:

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

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

  ---> a of 1-2 to approach E_{WB} ~ 40 TW for a=2 in an 16μm spot

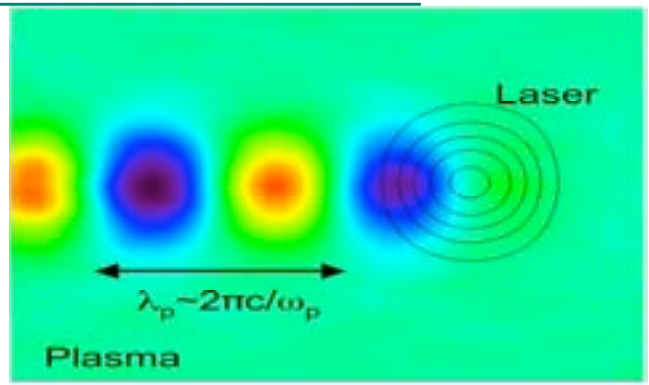
- Pulselength ~ $(1/2)\lambda_p$ -> 50 fs for n ~ 10^{18}

- 3d, nonlinear, & relativistic effects are important: numerics (fluid, PIC, etc.)

Wakefield Accelerator Physics: Linear Model Pump, Wake, Particle 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: $L_{pump} = 4\ L_d/a^2$

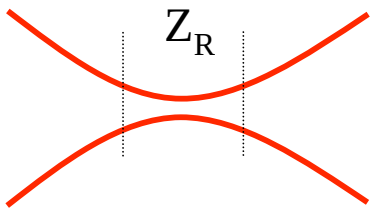
$\Delta W = EL \rightarrow EL_d \sim a^2\ \lambda_p^2/\lambda_0^2$ MeV

Modeling required for detail, but scaling ~ correct.

Densities near 10^{18} and a=1-2 give GeV energies in few cm. $W \sim 1/n$, $L_d \sim 1/n^{3/2}$

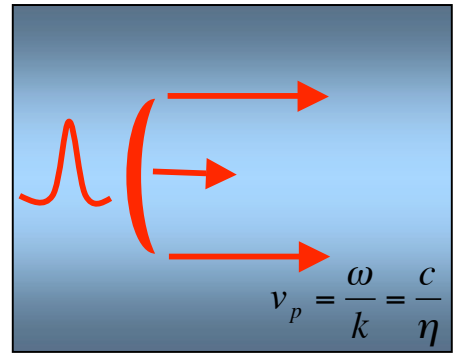
Recent Experiments Extend Acceleration Region: Z_R and Guiding

•High intensity required: $L_{acc} \sim Z_R$ without guiding



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

Guiding



•Guiding from refractive index peak on axis.

for $n \ll n_c$:

$$\eta \approx 1 - \frac{\omega_p^2}{2\gamma_\perp \omega^2} = 1 - \frac{4\pi e^2 n_e(r)/m}{2(1+a^2)^{1/2}\omega^2} \approx 1 - \frac{\omega_{po}^2}{2\omega^2}\left(1 - \frac{a^2}{2} + \frac{\delta n}{n} + \frac{\Delta n}{n}\right) \quad \text{for small a \& } \omega_p$$

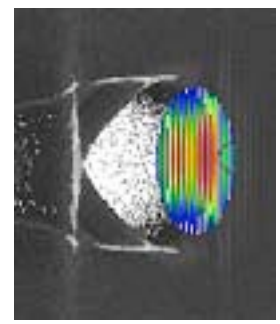
•high density => low η =high v_p, low v_g

•Extend acceleration distance:

1) extend Z_R - expensive, PW for cm scale

2) self guide: a~1 - not effective for short pulses

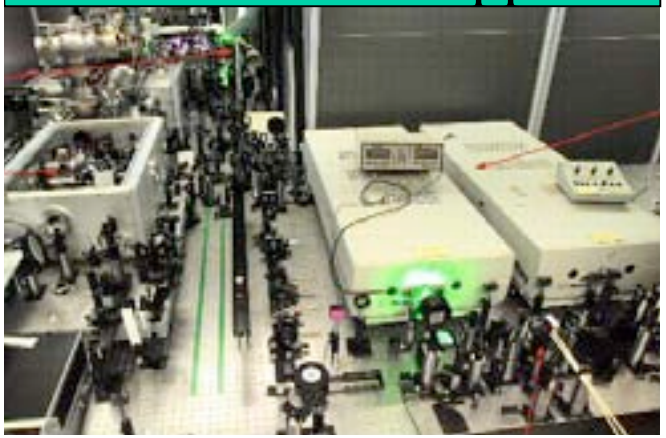
a >> 1 bubble regime - seen in simulation



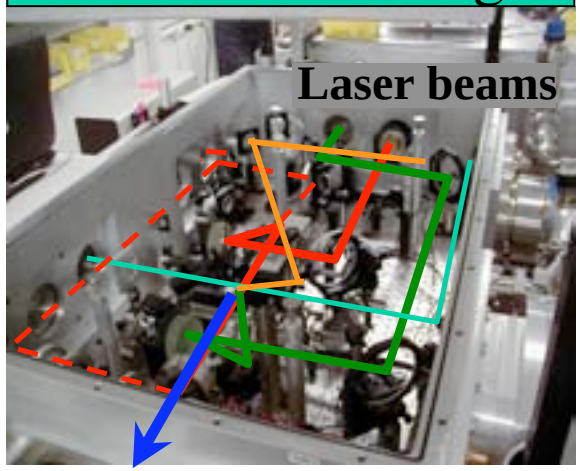
4) **Channel guide with density gradient** - compensate self guide

Laser driven accelerator facility at LOASIS lab: development of GeV accelerators in centimeters

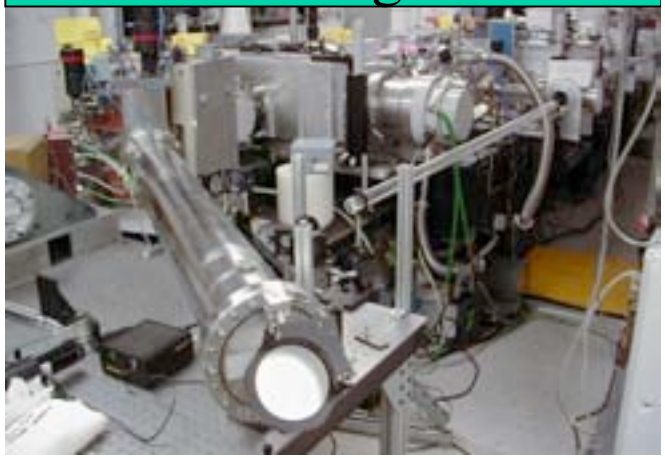
10-100 TW Ti:sapphire



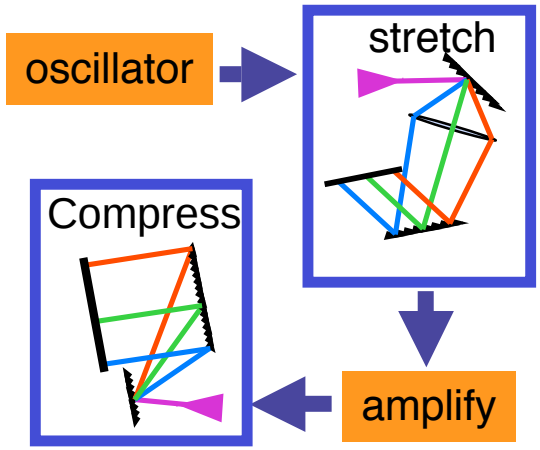
5+ Beams on Target



Shielded target room



Chirped Pulse System



Typical:
10 Hz Ti:S lasers
few J energies
50 fs pulses match ω_p

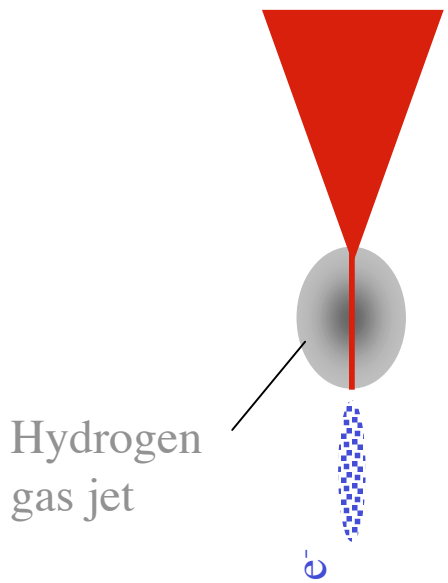
Unique:
Multiple beams, shielded

Control Room

State of the Art 2003- Early 2004: High Gradients, but Low E and large ΔE/E

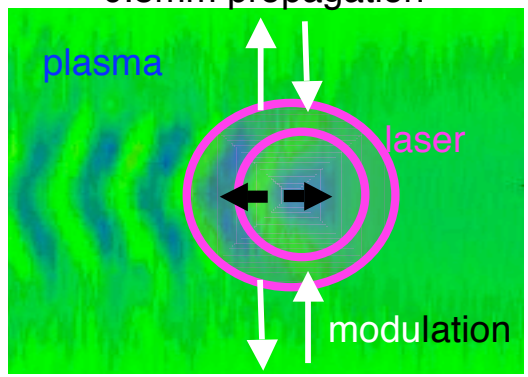
Tightly focused laser ionized gas jet & drove wake

Drive beam
10 TW, 500mJ 50fs, 10^{19}W/cm^2

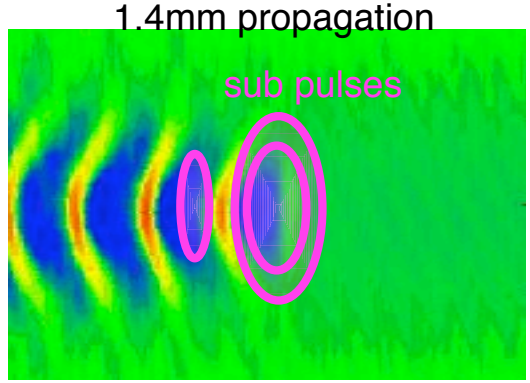


Laser self modulation to plasma period drives wake to trapping

0.5mm propagation

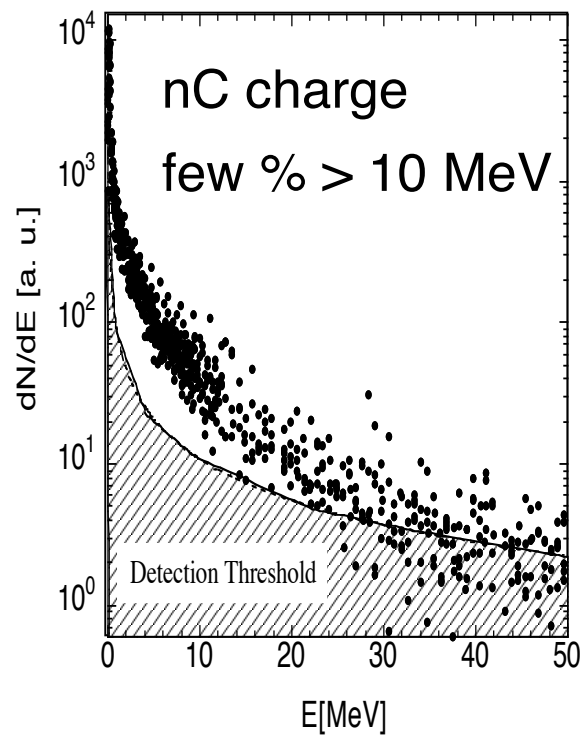


1.4mm propagation

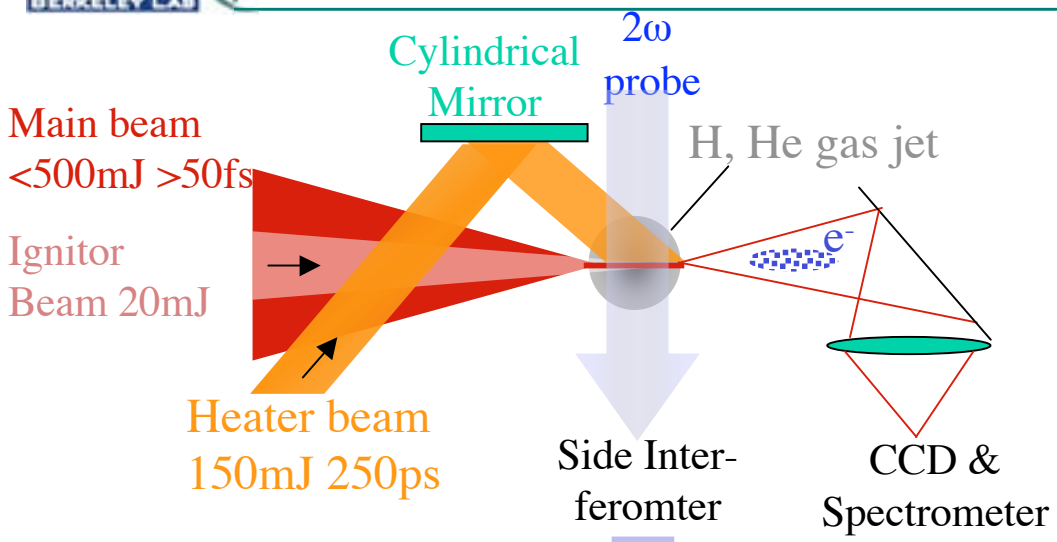


Enlarged wake

Acceleration to 50 MeV in ~1 mm



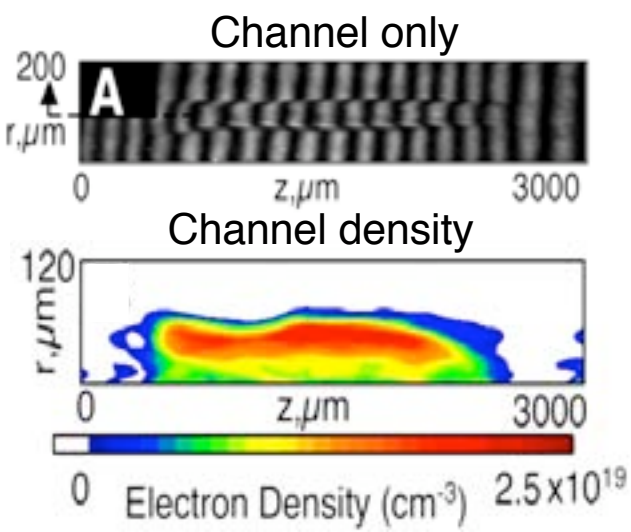
Hydrodynamic Channels Guided Unaberrated Modes at Relativistic Intensity



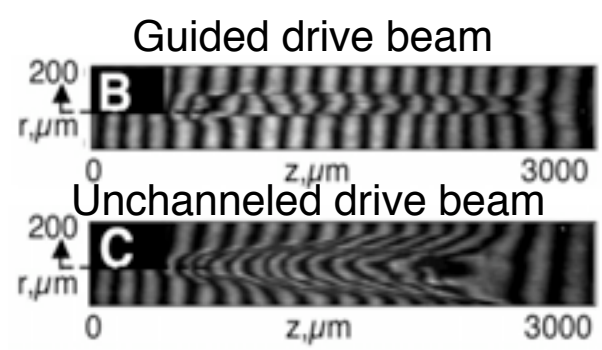
Plasma ionized by ignitor heated by heater

Expansion shock yields guiding profile

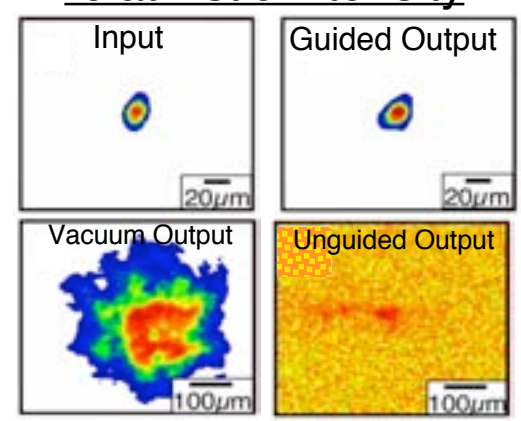
Channel profile



No channel leakage



Guiding over > 10 ZR ~ 2mm relativistic intensity



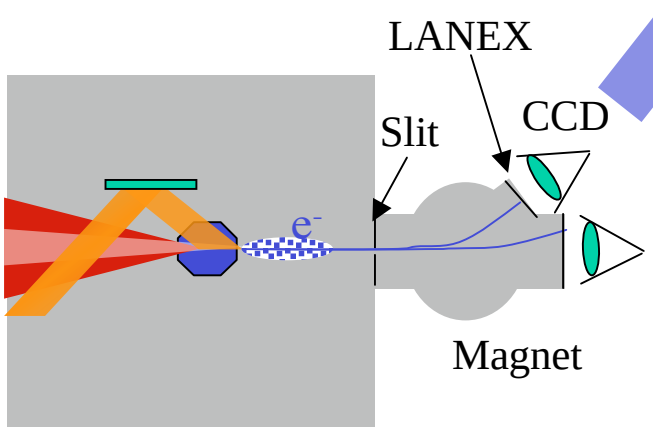
High quality guiding up to 4TW

C.G.R. Geddes et al, PRL, 2005

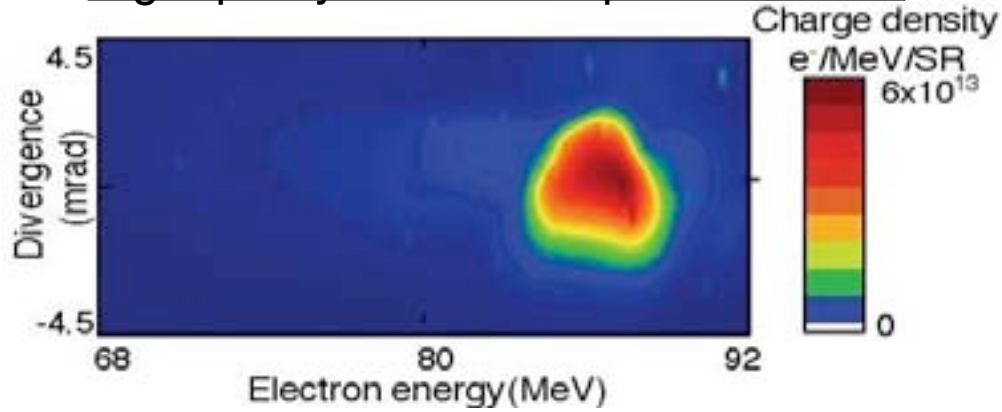
Intense Beams with Low Energy Spread and High Energy from Channeled Accelerator

Laser = 9TW, 50 fs, Z_R=200μm **Plasma = 1.8e19cm^{-3}, 1.7mm**

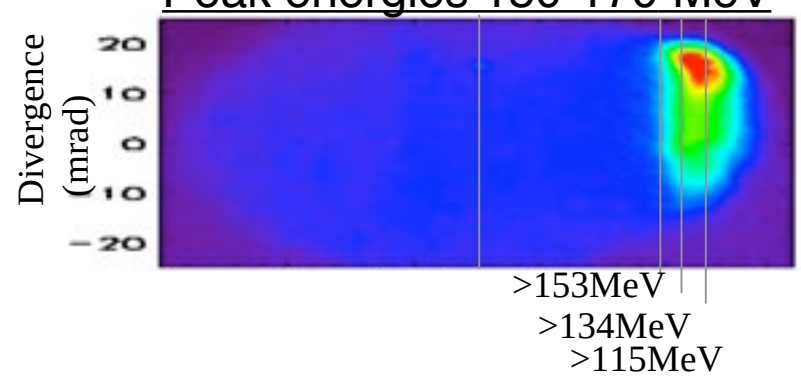
Magnetic Spectrometer



High quality beams: 300pC @ 86 MeV



Peak energies 150-170 MeV



High quality, intense beams*

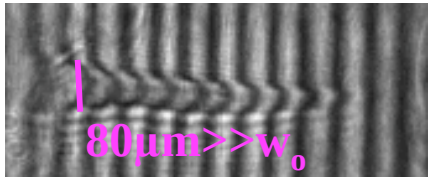
2e9 electrons Divergence 3mrad

Energy Spread<4MeV Normalized Geometric Emittance 2π mm-mrad

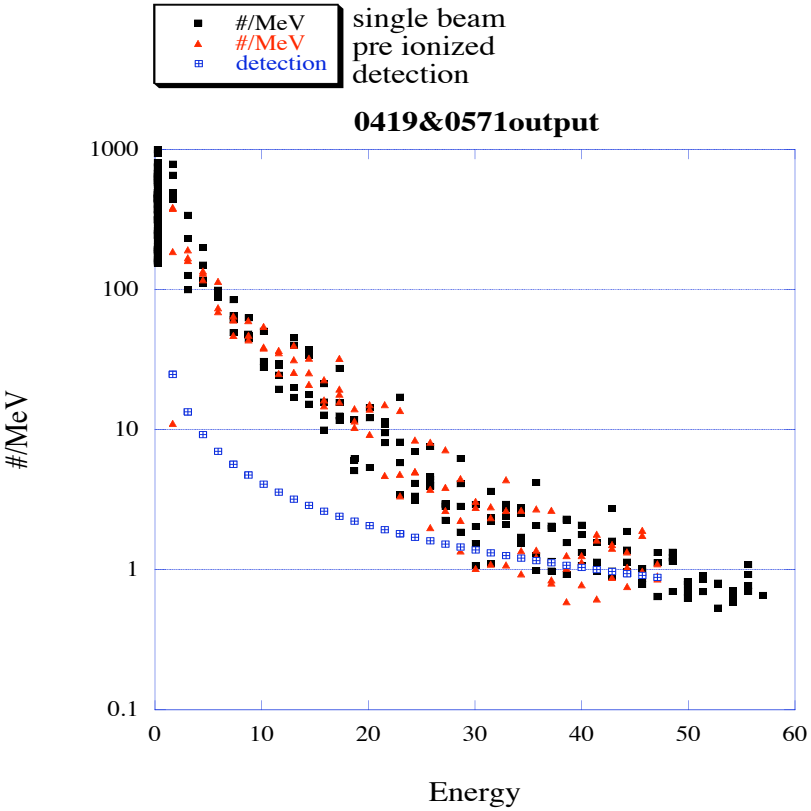
*C.G.R Geddes *et al*, Nature, Sept 30 2004; Related: Faure, Mangles, Katsouleas, same issue;Kitagawa, PRL, 2004, Tsung PRL 2004

Energy enhancement is due to channeling not pre ionization

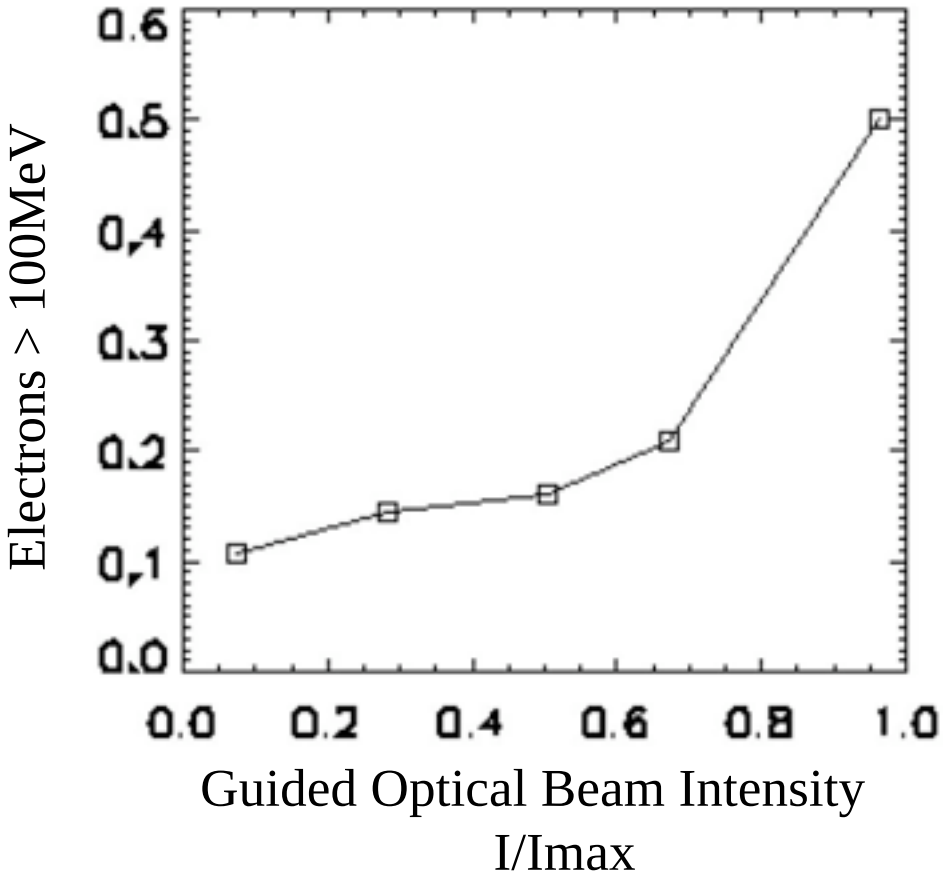
Pre ionized plasma: ignitor @t_0-80ps



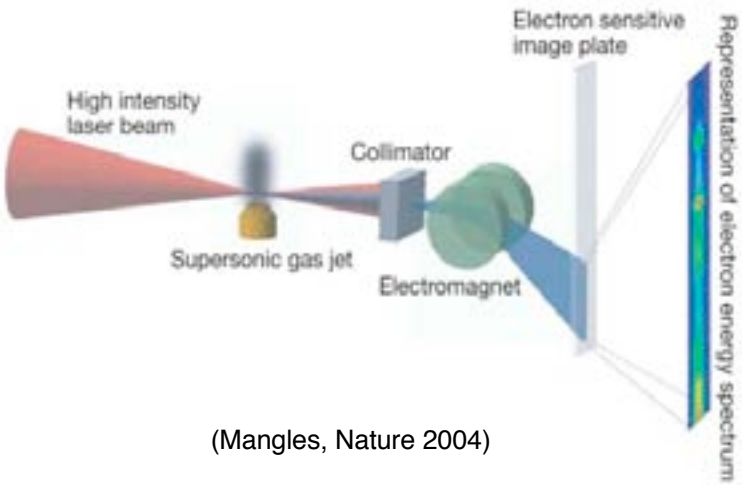
Magnetic Spectrum:
Single Beam same as Pre Ionized



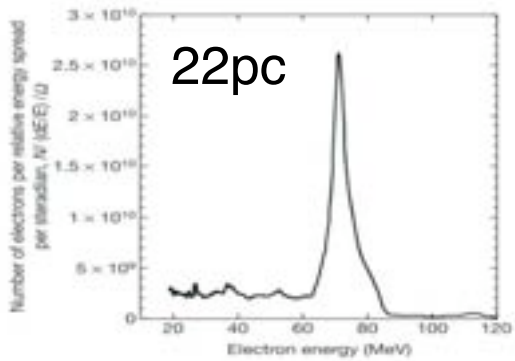
Well Guided Optical Beams Correlated to Highest Energy Electrons



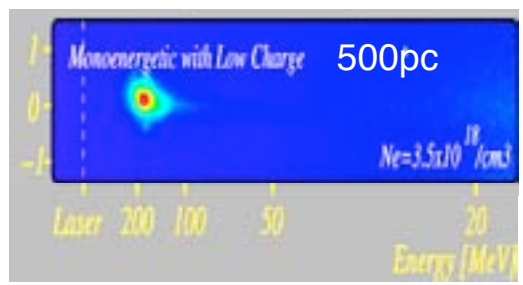
Several groups observed
Mononoenergetic beams from unchanneled accelerators



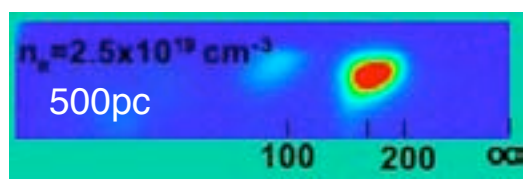
(Mangles, Nature 2004)



RAL:
12 TW, 40fs, Z_R~ 1mm
Plasma n ~ 2e19, 2mm
(Mangles, Nature 2004)



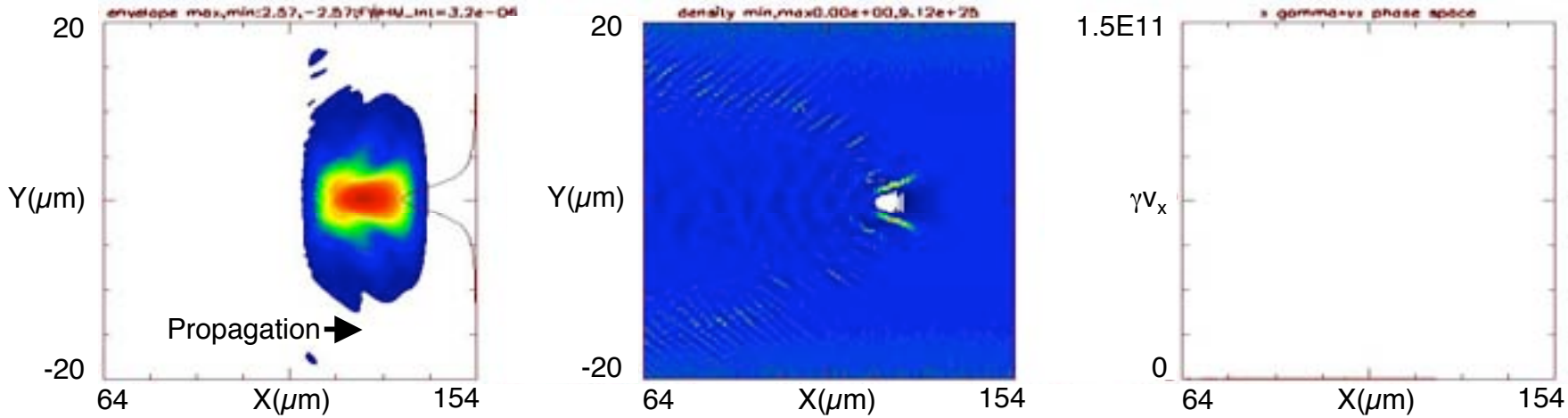
LOA:
30 TW, 33fs, Z_R~ 1mm
Plasma n ~ 3.5e18, 3mm
(Faure et al, Nature 2004)



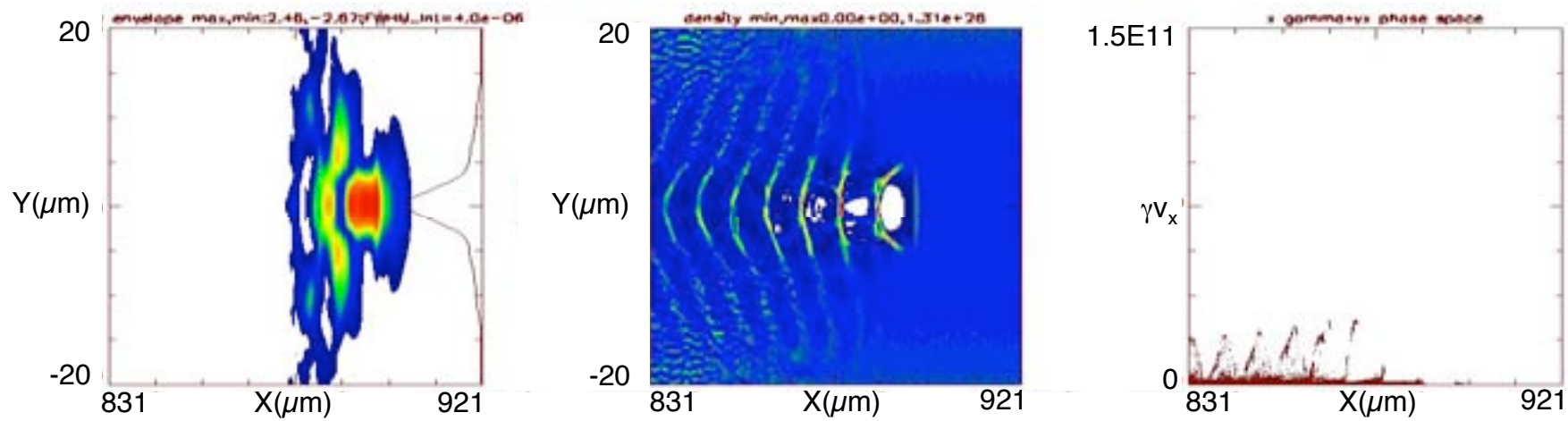
Michigan:
40 TW, 30fs, Z_R~ 1mm
Plasma n ~ 2.5e19, 2mm
(Maksimchuk et al, submitted)

Simulations show laser evolution and electron acceleration:VORPAL particle in cell code

Start: Laser un-modulated and ~ 1.5 times λp, small wake



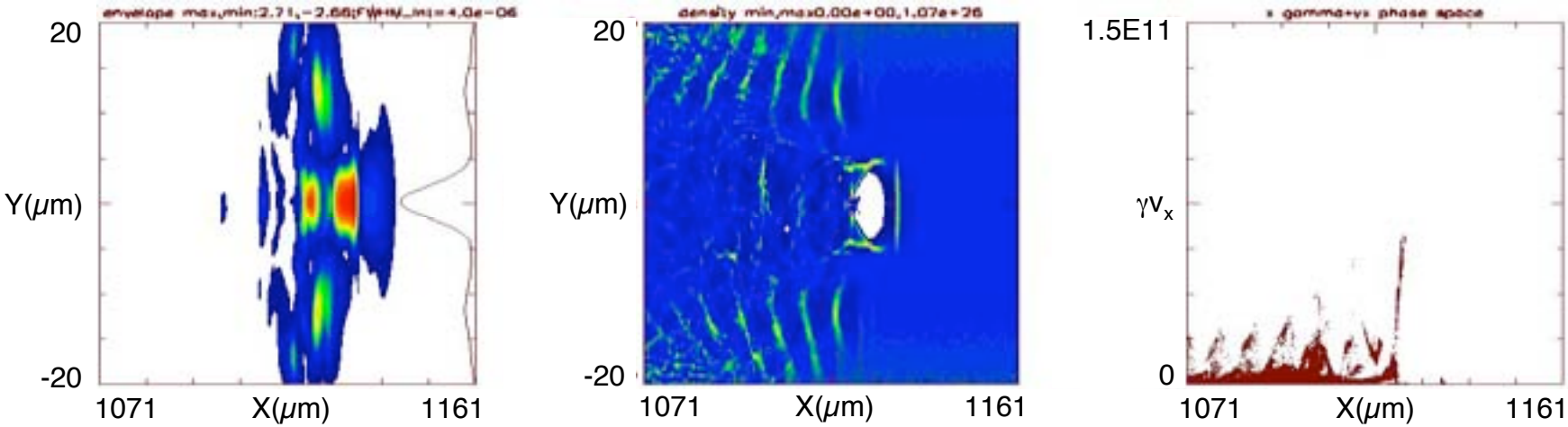
900μm: Laser modulated, large wake excited



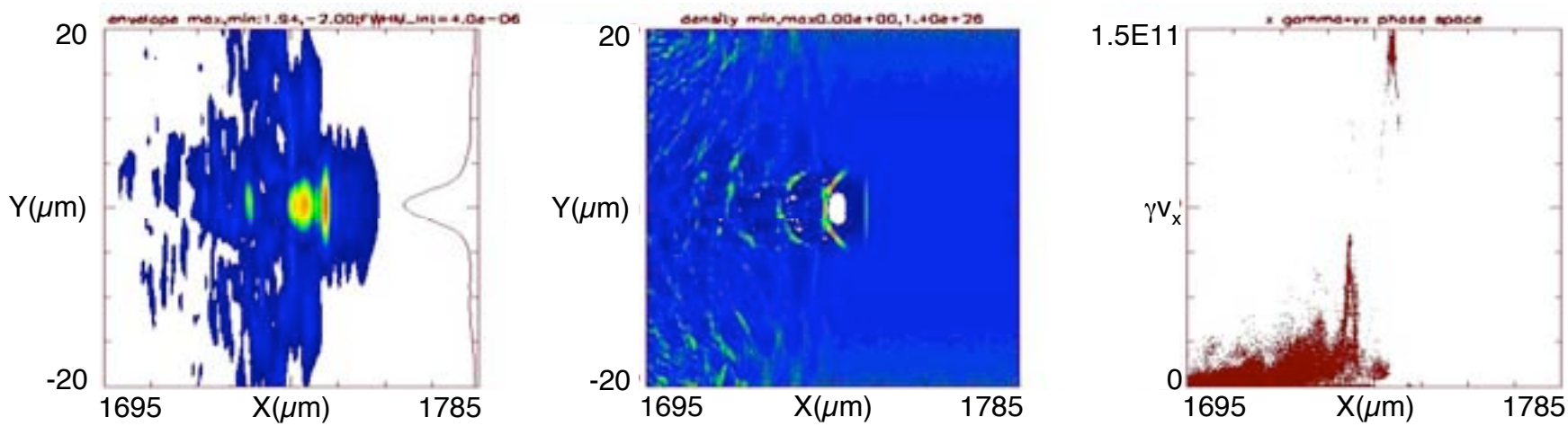
Simulations grid space, deposit current from particles, finite difference Maxwell

Wake Evolution and Dephasing Yield Low Energy Spread Beams

1150μm: particles trapped, wake damped preventing further trapping



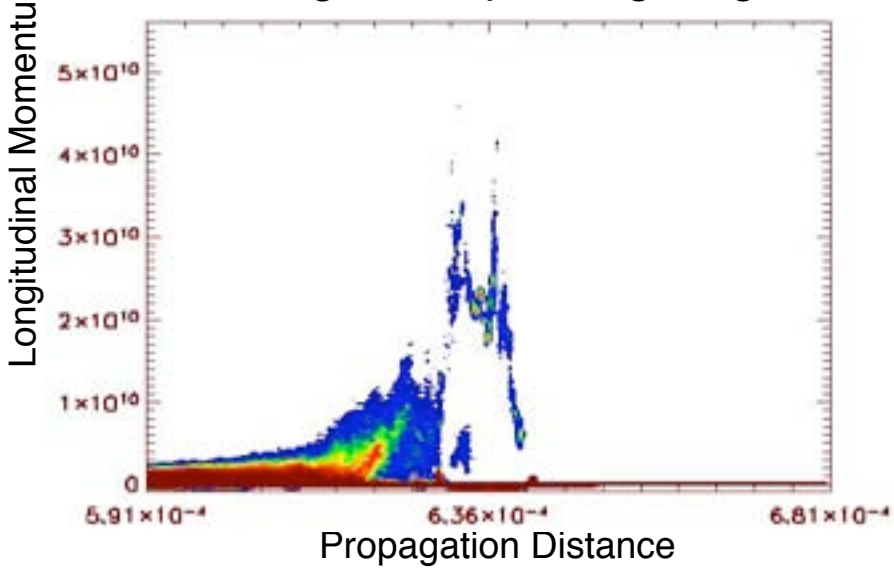
1750μm: particles dephase, minimizing energy spread



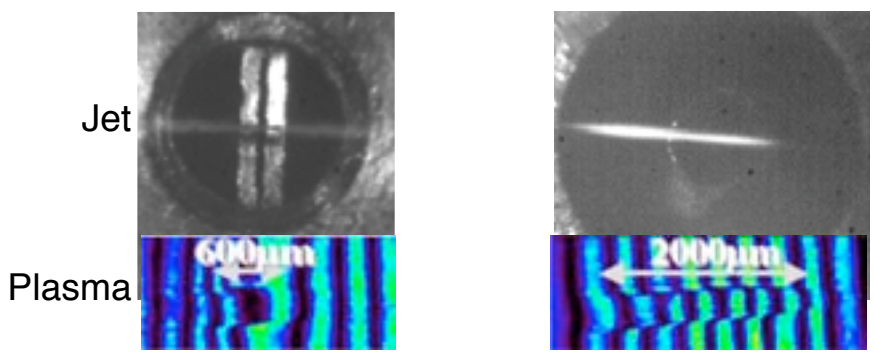
Related: Pukhov AP-B 2002, Tsung PRL 2004

Matching Plasma Length to Dephasing & Depletion Optimizes Performance

Simulation:optimal acceleration at length = dephasing length

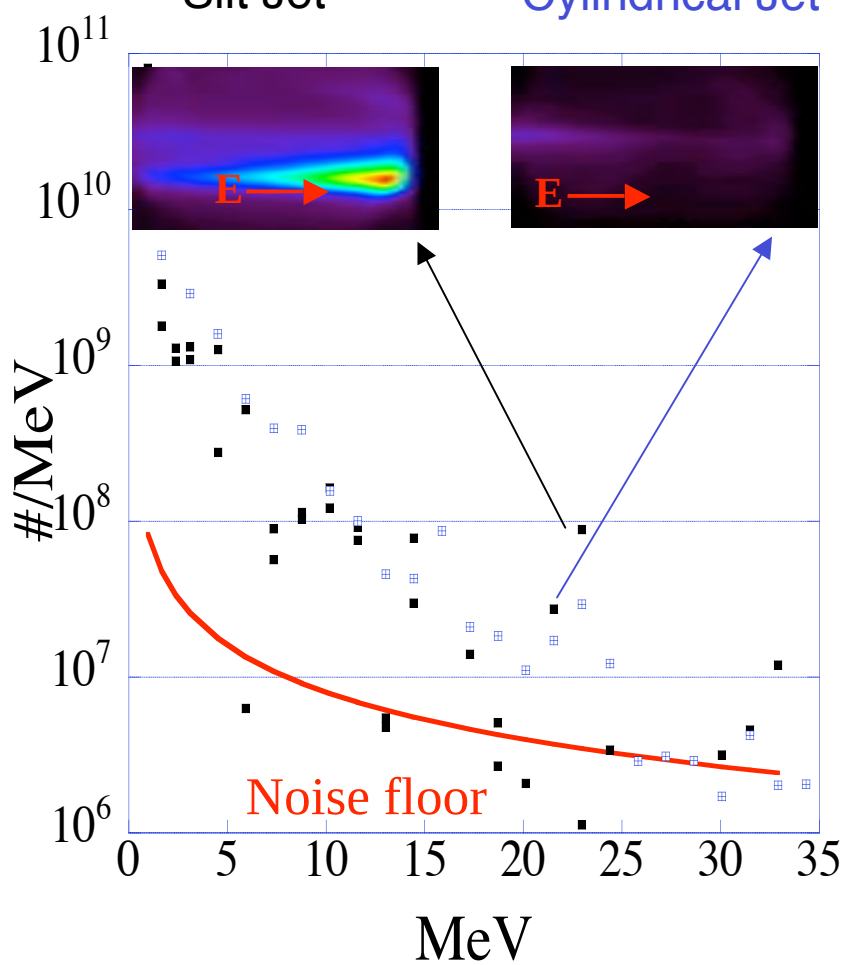


Experiment: plasma length variation confirms optimal performance at dephasing



Multi Shot Experimental Energy Spectra

n_e = 4e19/cm^3



Geddes et al, PoP 2004; related: Hsieh et al PRL 2006

GeV laser accelerator: channeling over cm-scale

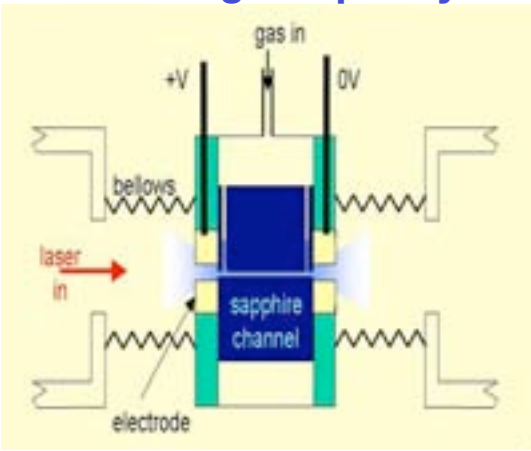
- Increasing beam energy requires increased dephasing length and power:

$$\Delta W_d[\mathrm{GeV}] \sim a^2 \lambda_p^2 \sim I[\mathrm{W/cm^2}]/n[\mathrm{cm^{-3}}]$$

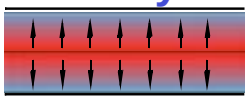
- Scalings indicate cm-scale guide at ~ 10^{18} cm^{-3} and 40-100 TW laser for GeV
- Laser heated channel formation inefficient at low density
- Use capillary channels for cm-scale guides driven by upgraded laser

3 cm capillary channels at reduced density: increased laser v_{group} produces GeV ebeams

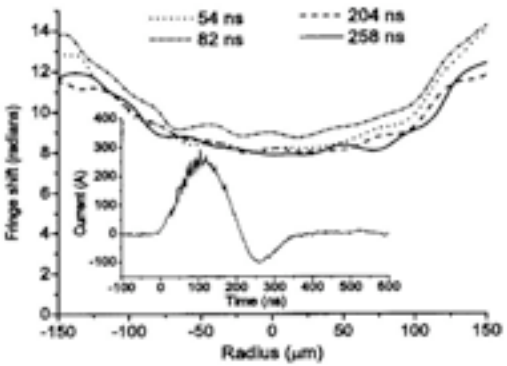
Discharge Capillary



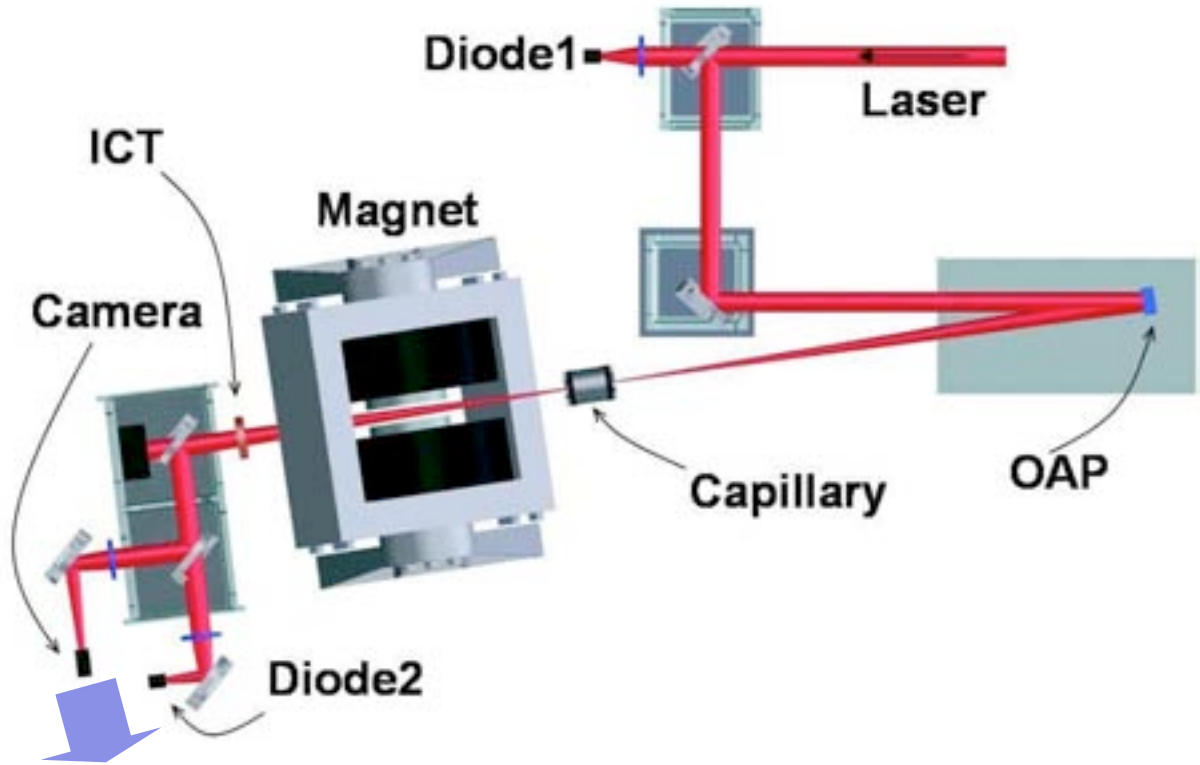
Pressure Balance-> low density on axis



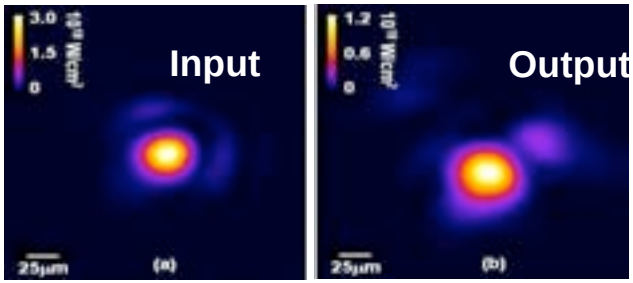
Channel Profile



From: Spence et al, JOSA-B, **20**,p138, 2003



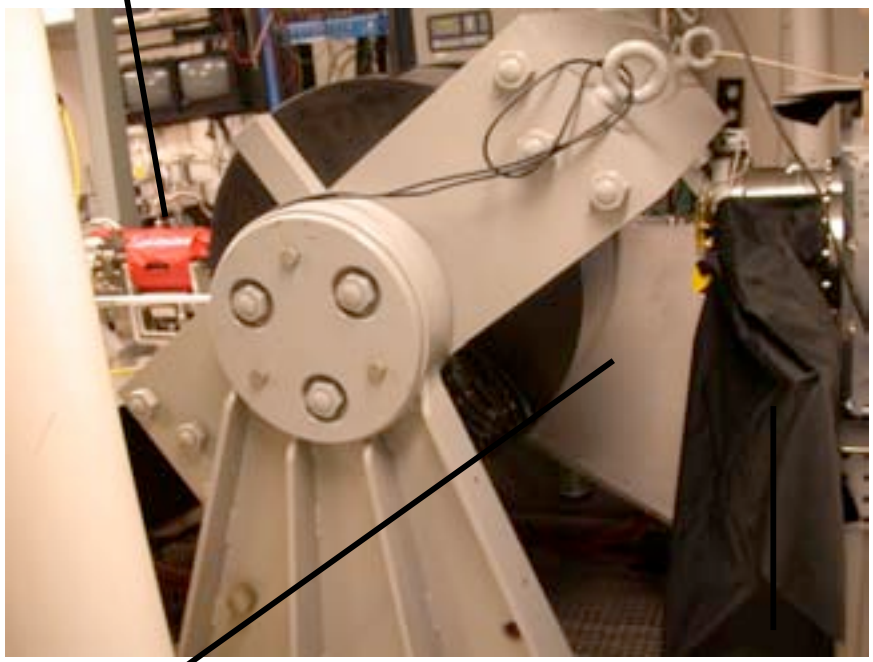
Guiding over > 10 ZR ~ 3 cm relativistic intensity



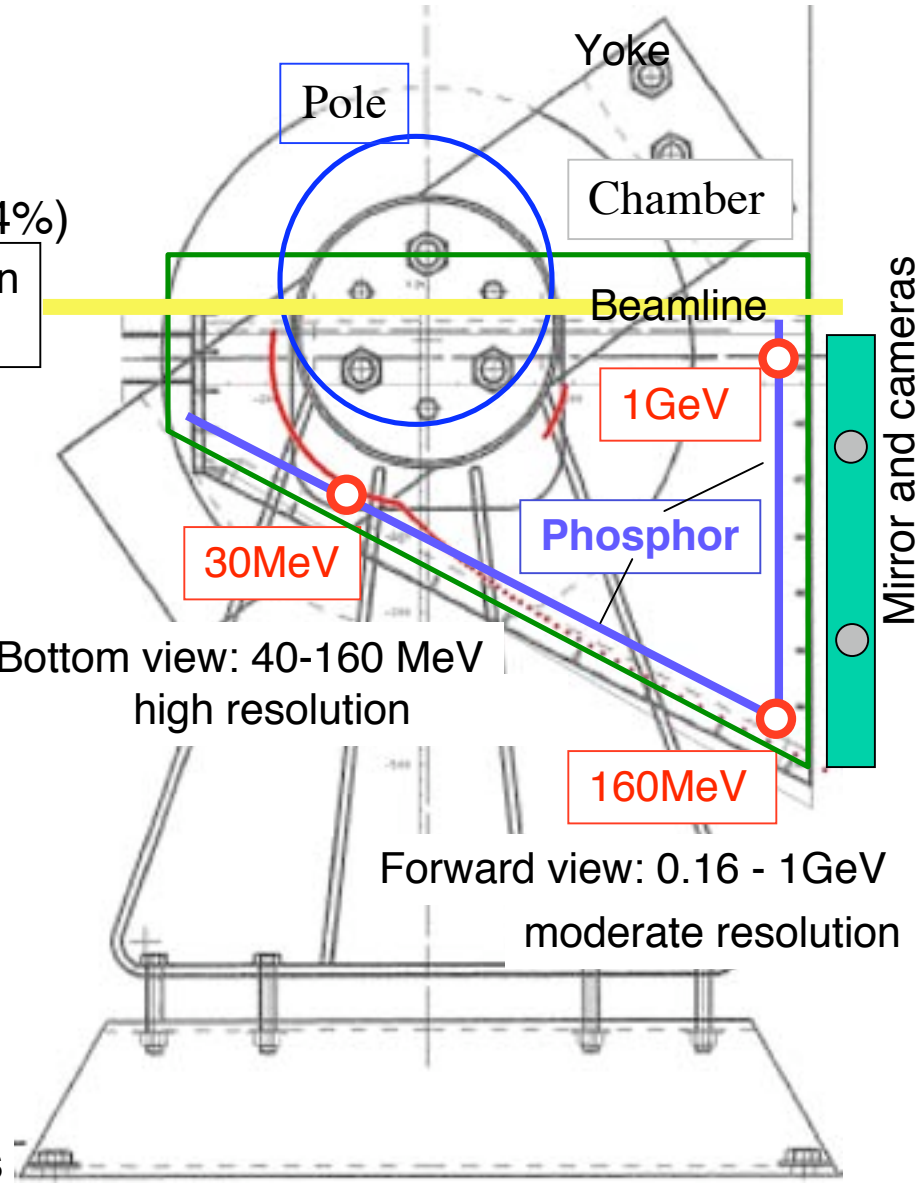
Leemans et al, Nature physics,2006

LOASIS GeV Spectrometer

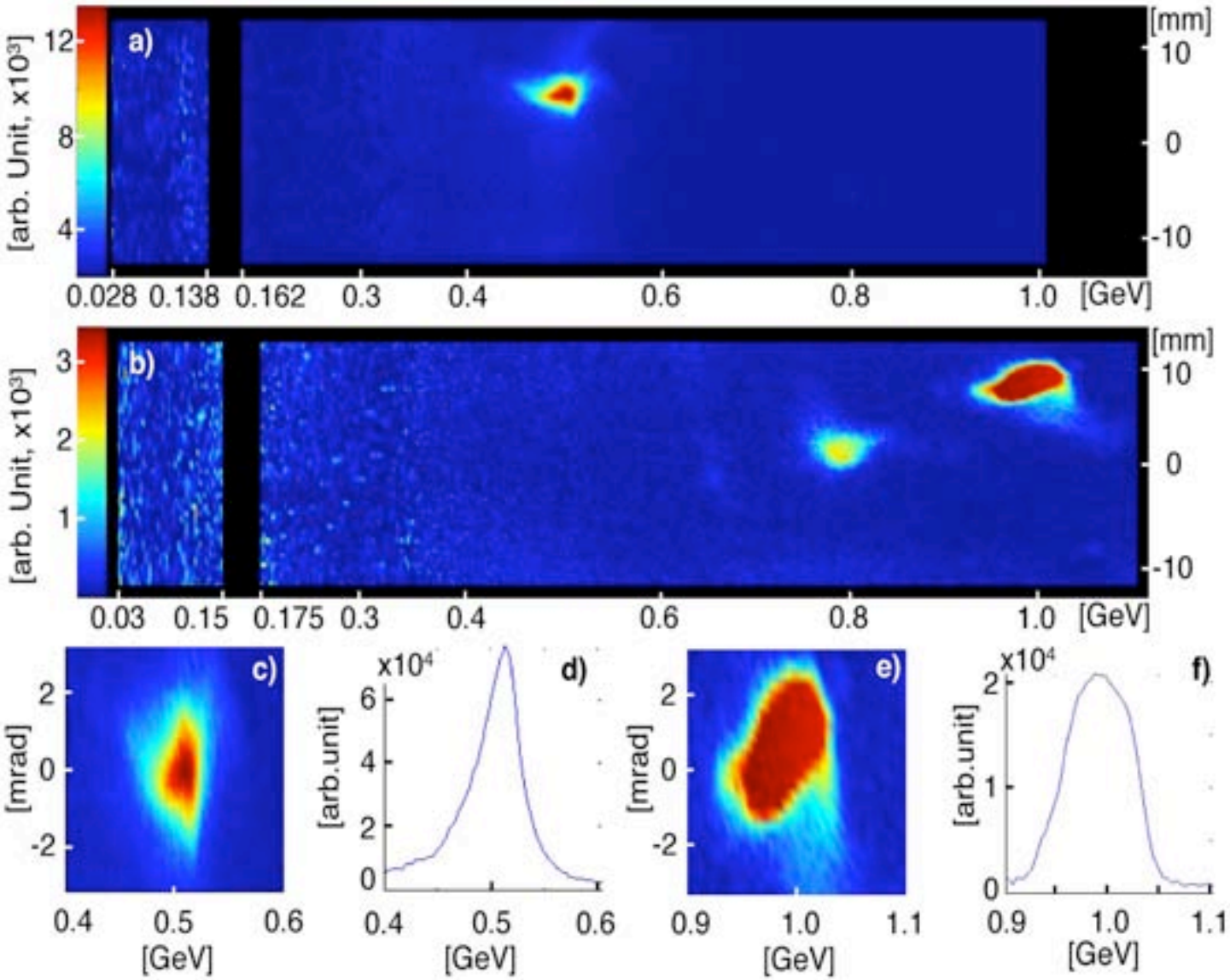
- Maximum resolving energy: ~1.1 GeV
- Large momentum acceptance (>factor 35)
- High resolution (bottom: <1%, forward: 2~4%)



Shielded mirror and cameras



1 GeV bunches with narrow energy spread achieved with 40 TW laser pulses



25 TW

E<0.6 GeV,stable

Q~50-300 pC

40 TW

E< 1.1 GeV

Q~36 pC

Energy spread at spectrometer resolution

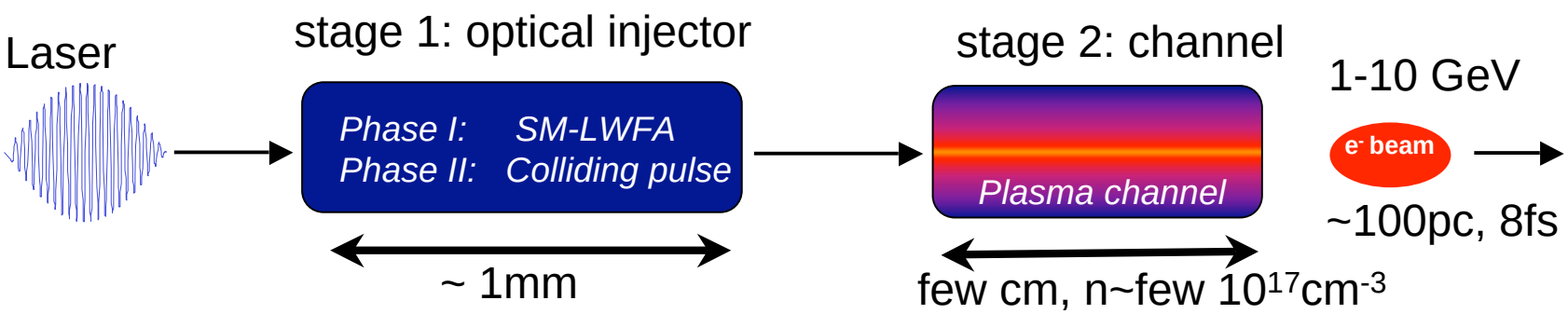
Leemans et al, Nature Physics 2006

Staging and controlled injection for next generation accelerators

- GeV experiments close to predicted energy

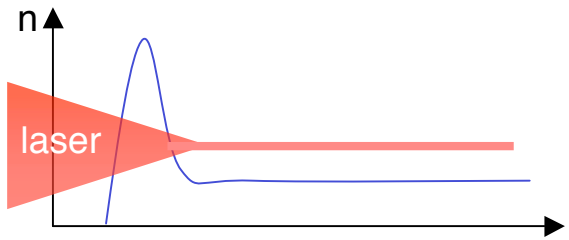
$$\Delta W_d[\mathrm{GeV}] \sim a^2 \lambda_p^2 \sim I[\mathrm{W/cm^2}]/n[\mathrm{cm^{-3}}]$$

- Energy spread limited measurement
- Bunches may be percent energy spread
- Staging ~ preserves ΔE
  - stage a low energy injector injector and 1-10 GV accelerator modules
  - 10 GeV using ~ PW of laser energy and m-scale plasma

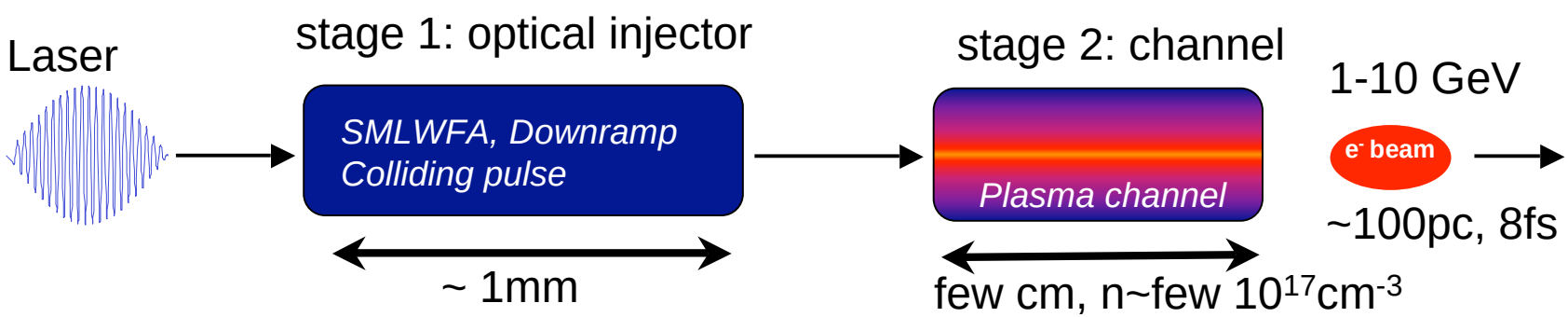


Staging and controlled injection for next generation accelerators

- Couple downramp to capillary channel

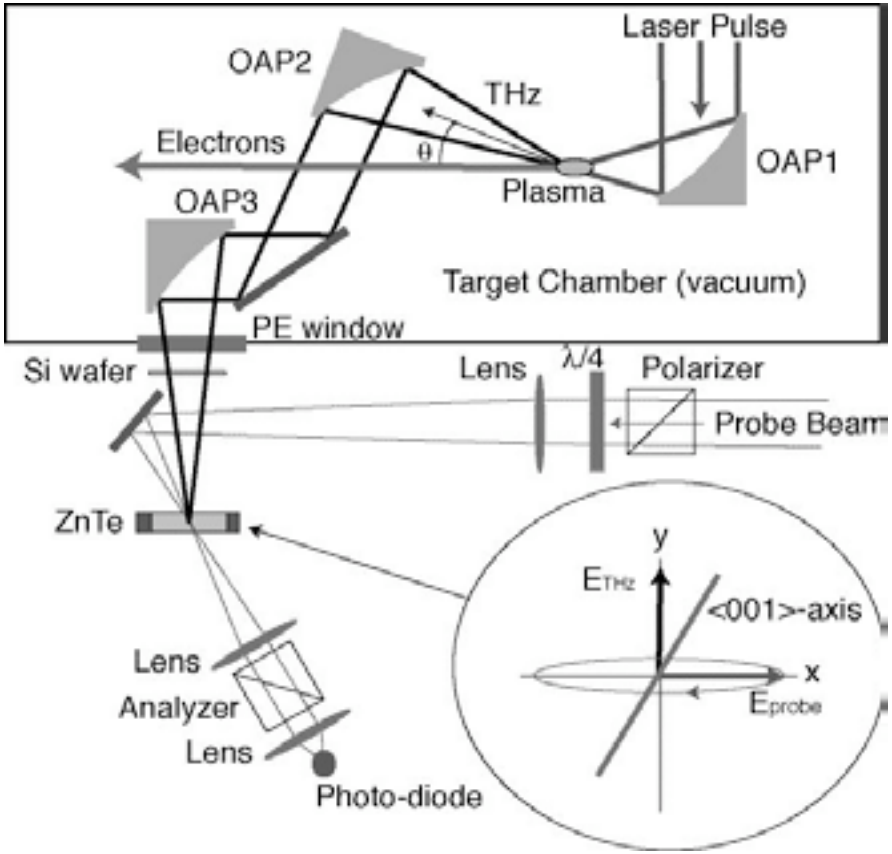


- Staging
  - GeV experiments close to expected energy
  - stage low energy injector and 1-10 GV accelerator modules
  - 10 GeV using ~ PW of laser energy and meter-scale plasma
  - Gain in emittance, stability, efficiency by separating injection, acceleration



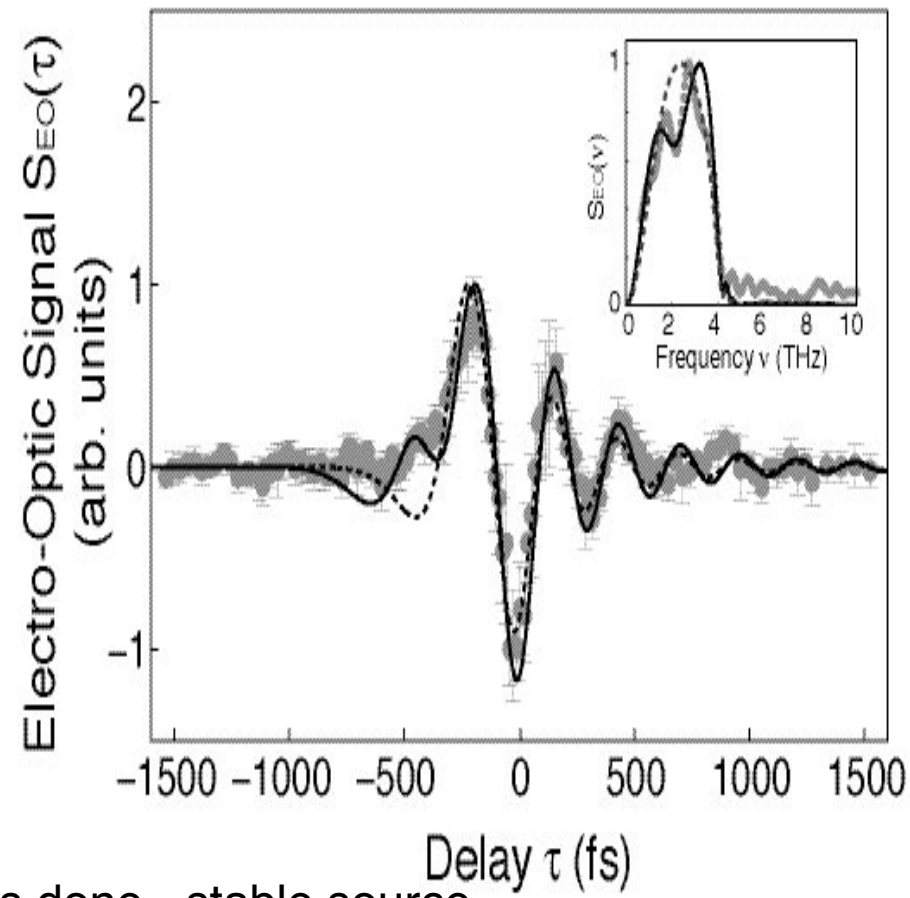
THz radiation from the Laser-Wakefield Accelerator: Intense THz source, and ultra-fast bunch diagnostic

Electro-optic sampling for THz detection



THz profile

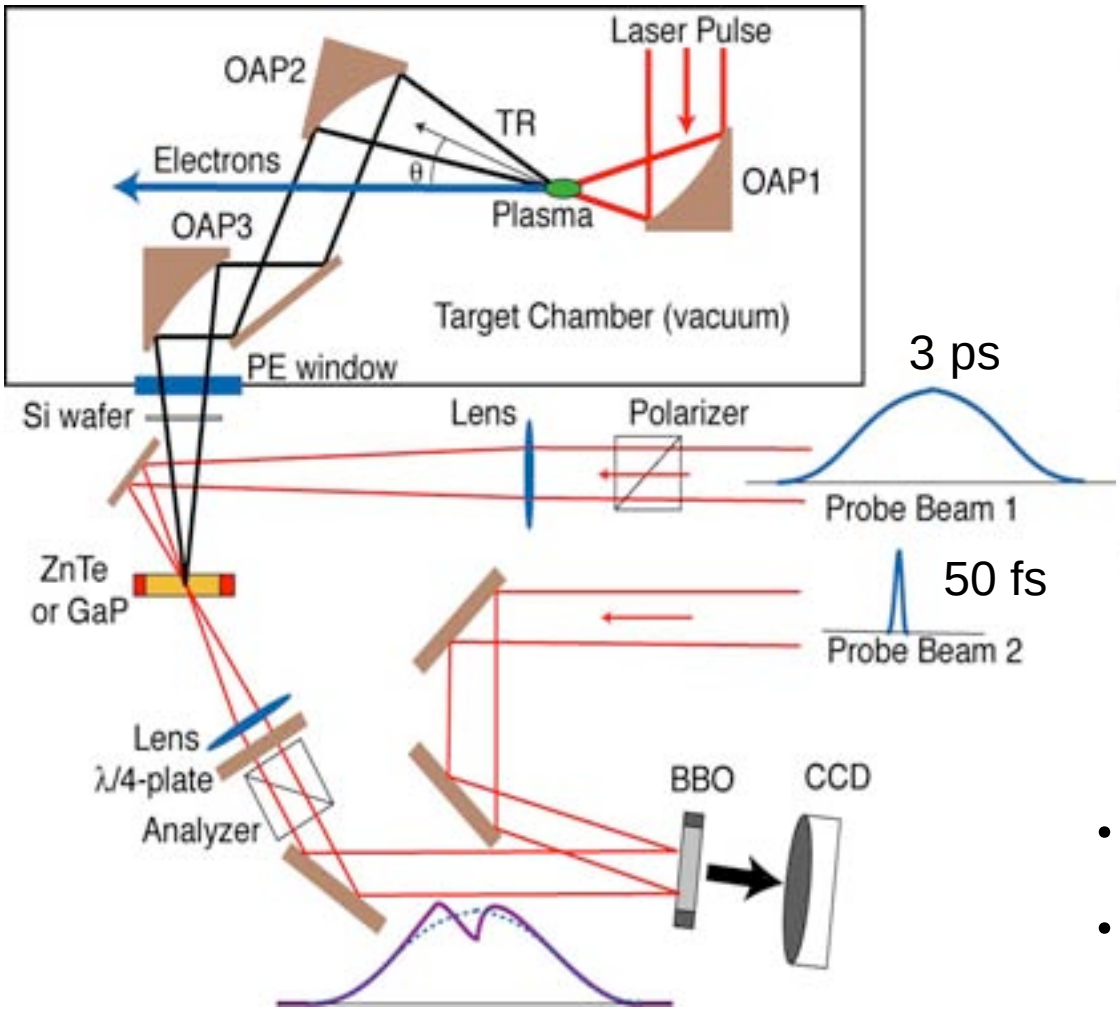
Dashed fit: Single 50 fs Gaussian e-beam
Solid fit: double pulse- possibly due to geometry

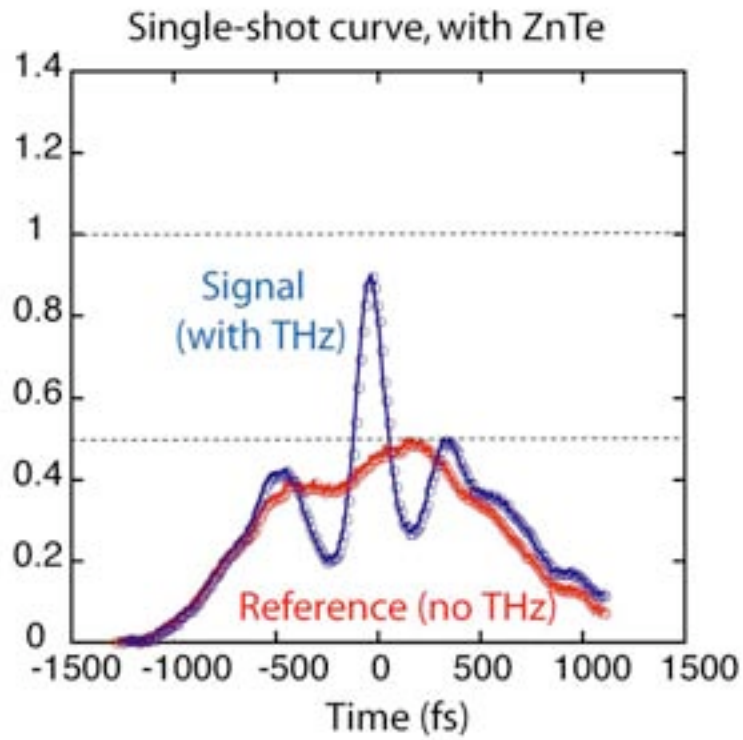


Scanning and single shot measurements done - stable source
Sample using downstream foils -> understand beam expansion

J. van Tilborg et al., PRL 2006

Single-Shot THz technique
Information on every bunch



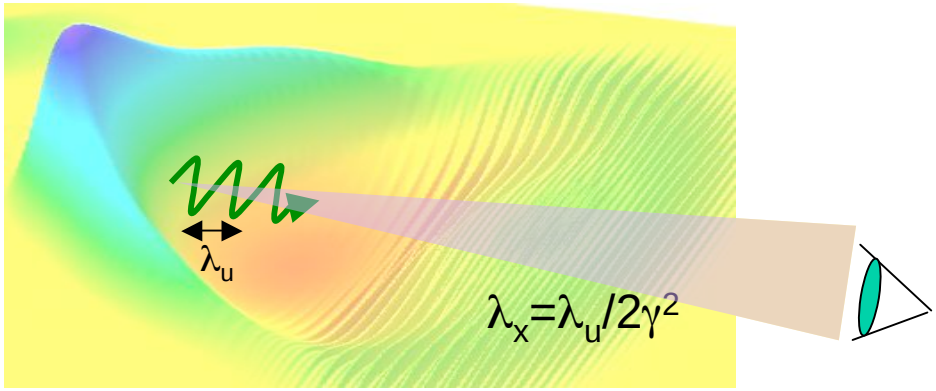


- < 50 fs bunches
- peak E-field of $E_{CTR} \approx 400$ kV/cm

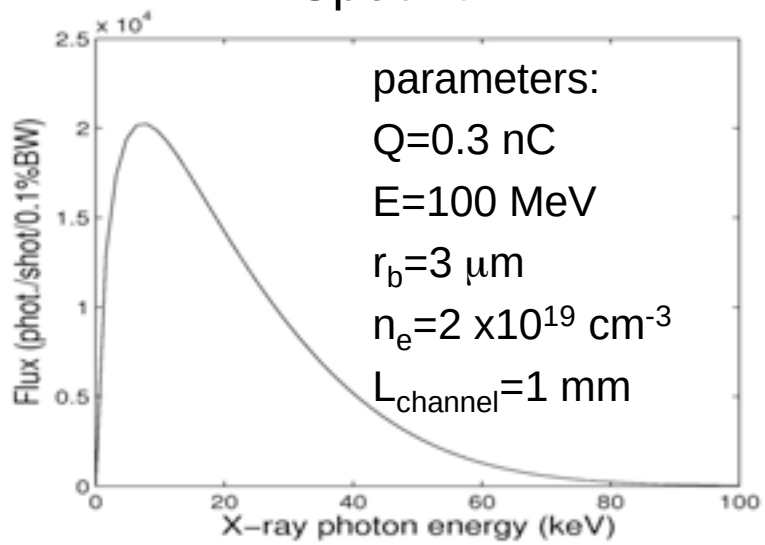
G. Berden et al., Phys. Rev. Lett. 93, 114802 (2004)

J. van Tilborg et al., OL 2007

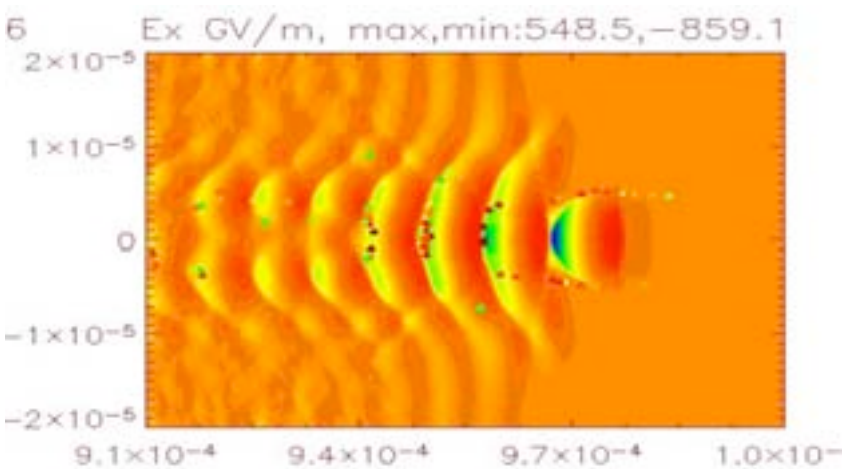
Betatron X-rays
Diagnostic of Electron Motion, Broadband source



Spectrum



- Betatron (synchrotron) emission:
- Transverse dynamics diagnostic



Material courtesy of Pierre Michel and collaboration with UNR and LLNL, see also: E. Esarey et al., PRE 2002, A. Rousse et al., PRL 2004

Channeled Laser Accelerators Produce Intense High Quality Electron Beams

•Demonstrated high quality beams from compact accelerators

-Channel guided relativistic intensities

- Low energy spread low divergence electron beams

- Tuning by dephasing

•Physics is self trapping limited by beam loading, then dephasing concentration of particles in energy space (simulations)

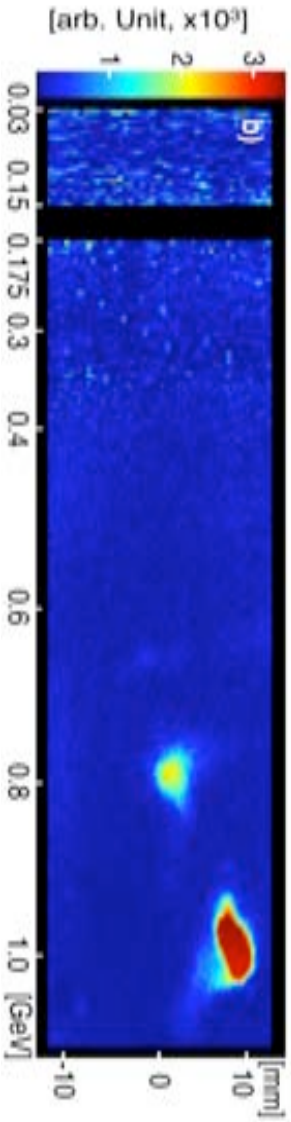
•GeV energies demonstrated, consistent with predictions

•Simulations indicate stable sources possible at higher densities/powers but with tradeoff in energy spread

• Low energy low absolute energy spread beams demonstrated

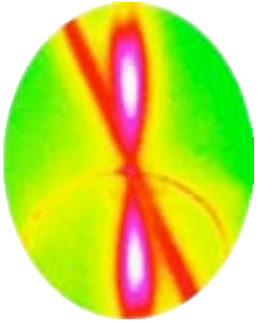
- Staged experiments for improved stability, quality

•Radiation sources used as diagnostics



Scaling to Future Laser Driven Accelerators

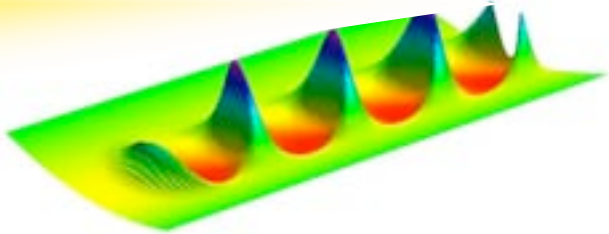
Lasers at > 300 TW, > 300 W



Staging of modules: ΔE, phase
Stable injection

Challenges

10 GeV, low energy spread & emittance
Guiding over meter scale



One-to-one, 3-D modeling
Improved algorithms

Understanding of:

-Laser evolution, shaping, depletion, spectral shifting

-Bubble guiding experiments

-Beam dynamics, applications, optimization (THZ, X-rays, FEL's)