Laser wakefield accelerator simulation requirements

Cameron Geddes

LOASIS Program
Lawrence Berkeley National Laboratory

COMPASS
SCIDAC2

December, 2008

DARPA

Office of Science

National Nuclear Security Administration
NA-22/Nonproliferation R&D

SciDAC Scientific Discovery

TECH X

Collaborators

LOASIS:	C.G.R. Geddes, E. Michel
	E. Esarey, C.B. Schroeder, W.P. Leemans
Tech-X:	D. Bruhwiler, B. Cowan, P. Messmer, P. Mullowney, K.Paul
Tech - X & U. Colorado	J. Cary
ATLAS computing, LLNL:	S. Wilks, A. Kemp
NERSC, visualization:	W. Bethel, J. Jacobsen, Prabhat, O. Rubel,
	D. Ushizima, G. Weber

DOE Scientific Discovery through Advanced Computing:

LBNL AMAC, CBP:	R. Ryne, J.L. Vay, W. Fawley
UCLA:	W.B. Mori, F.S. Tsung, C. Huang, M. Tzoufras, M. Zhou,
	W. Lu, M. Tzoufras, V. Dycek + collaborators at IST
USC/Duke:	T. Katsouleas, X. Wang

Other collaborations include:

LWFA – Nebraska, B.A. Shadwick et al.;

Gas targets - STI Optronics, W. Kimura *et al*; LBNL APDEC, P. Collela *et al*

Laser radiation pressure excites plasma wave to drive compact particle accelerators

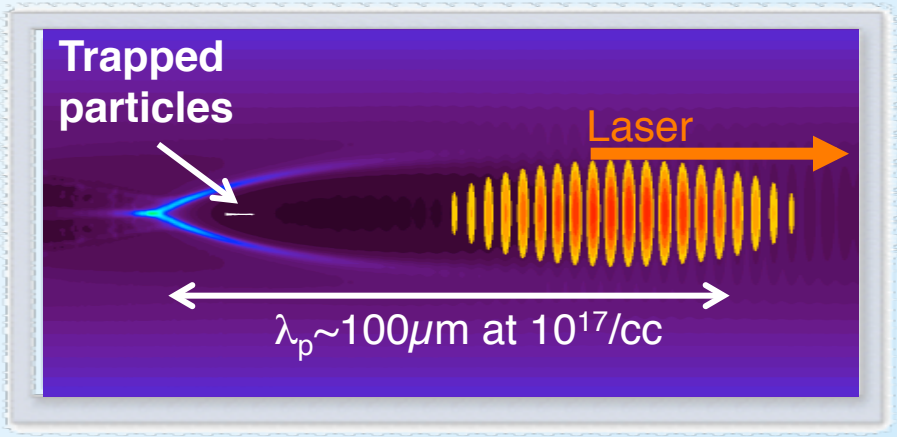
Outline

- Collider sketch – requirements
- Self trapping – narrow $\Delta E/E$, GeV energies, radiation
- Controlled injection – improving beam quality
- HEP stages – 10 GeV with PW lasers + staging

Process: Laser radiation pressure (red) displaces electrons

Space charge causes oscillating density 'wake' moving with the laser (blue-green)

Wake electric fields of of ~ GV/cm accelerate particles (white) (LWFA)



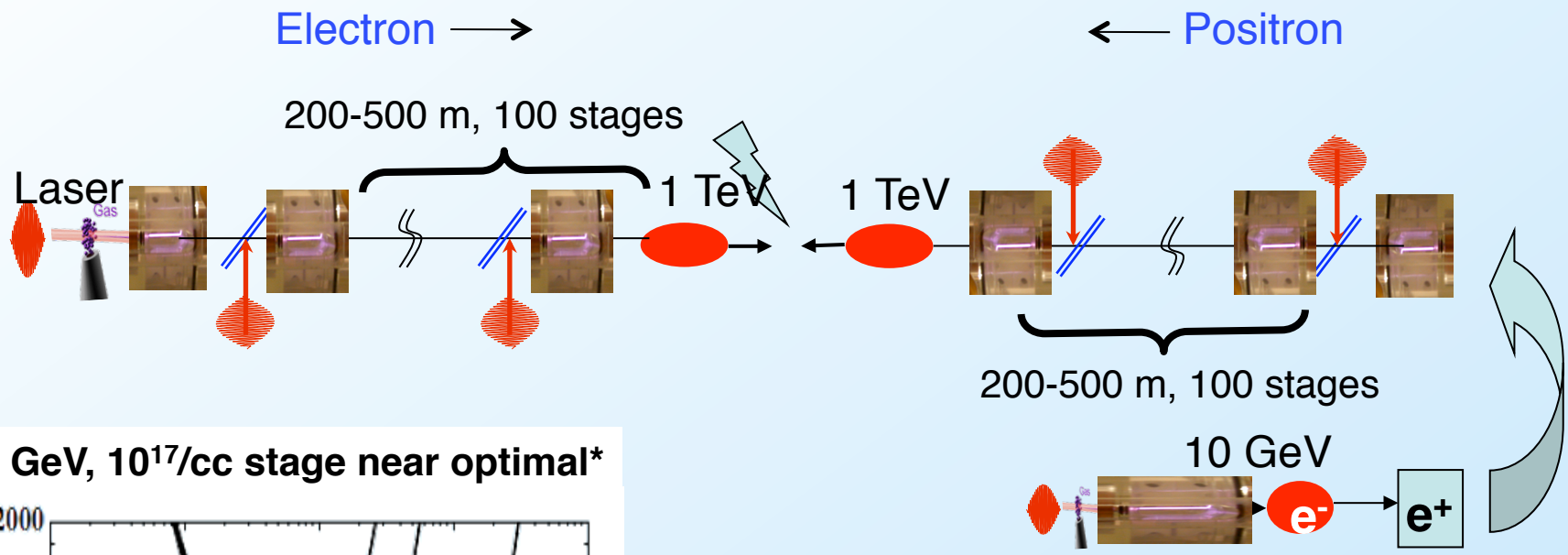
Energy gain ~n^{-1} (10 GV at 10^{17}/cc)
Length ~ $n^{-3/2}$ (1m at 10^{17}/cc)
Gradient ~ $n^{1/2}$ (10 GV/m at 10^{17}/cc)

Laser w_0&L ~ λ_p (100fs at 10^{17}/cc)

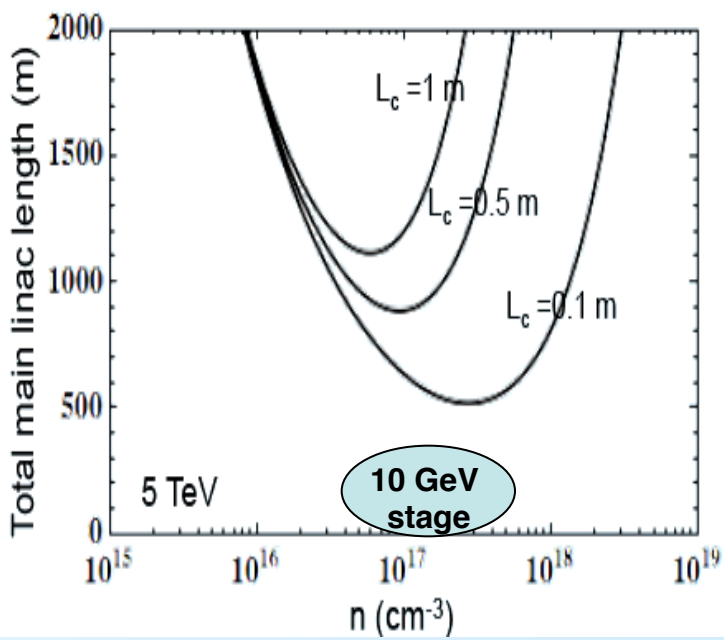
Depletion ~ Dephasing for $a_0 > 1$

Tajima & Dawson PRL 1979;l Esarey et al. TPS 1996; Leemans et al., IEEE Trans. Plasma Science (1996); Phys. Plasmas (1998)

LWFAs for High Energy Physics: Conceptual (strawman) collider lay-out



10 GeV, 10^{17}/cc stage near optimal*



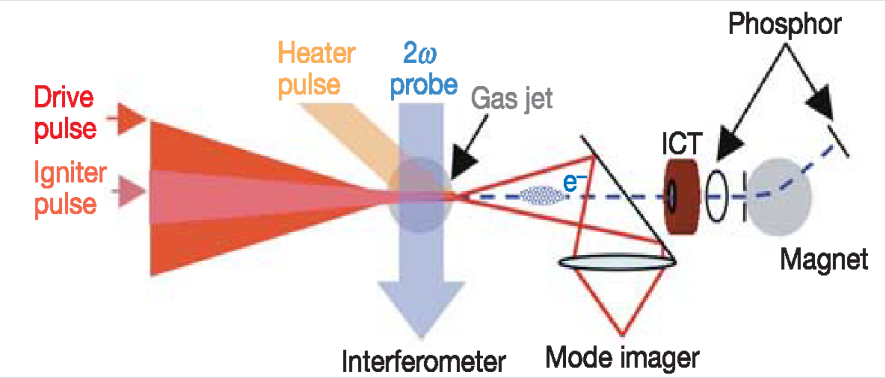
Simulation Challenges:

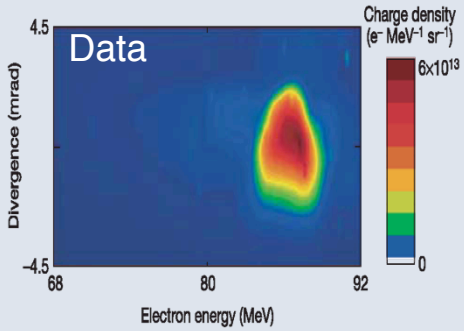
- Source/injector:
  - Energy spread & emittance control
- m-scale stages – reduced/scaled models
  - Efficiency – deep laser depletion
  - Energy spread & emittance preservation – structure, radiation, scattering
- Staging / beam transport**
- Positron & polarized electron sources

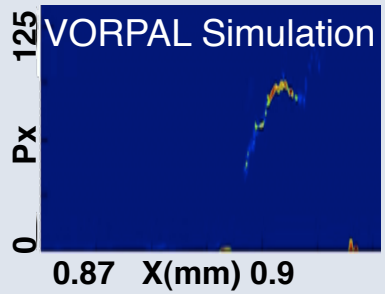
*Schroeder et al., **Panasenko et al., Proc. AAC 2008

Self trapped experiments: percent energy spread, verify scaling

- Laser channeling: first low $\Delta E/E$ beams
  - 10 TW laser, 2mm plasma @ 2×10^{19}/cc



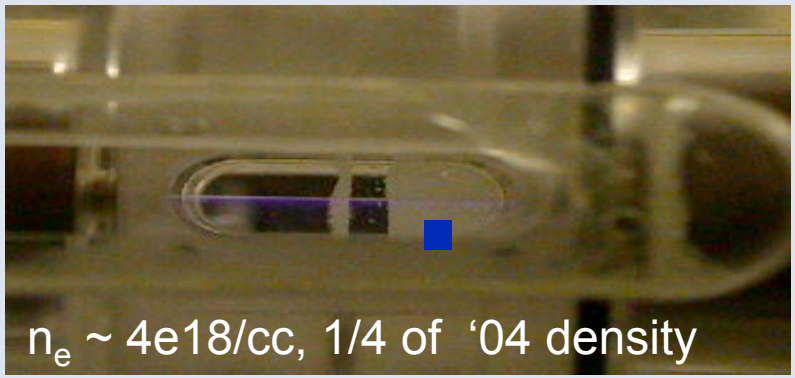


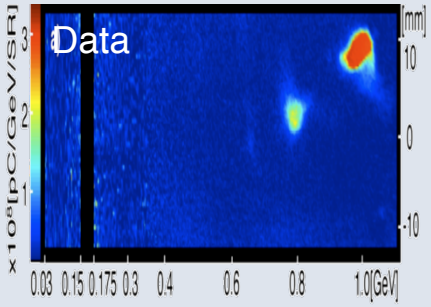


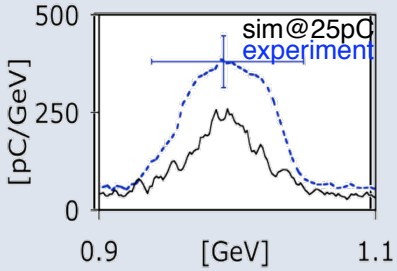
- 3 mrad divergence, $\Delta E/E$ 4%, E_{peak}~170MeV

Geddes et al., Nature 2004*

- Capillary channels+low n_e=GeV in 3 cm
  - 40 TW laser, 3cm plasma@4-5x10^{18}/cc







- 1 GeV beams, stable beams at 0.5 GeV

Leemans et al., Nature Phys 2006

- Simulations show physics of self trapping production of narrow ΔE:
  - beam loading and dephasing – MHour simulations in 3D
  - mrad divergence and % energy spread – momentum accuracy
- Bunch energy scales as expected with laser, plasma

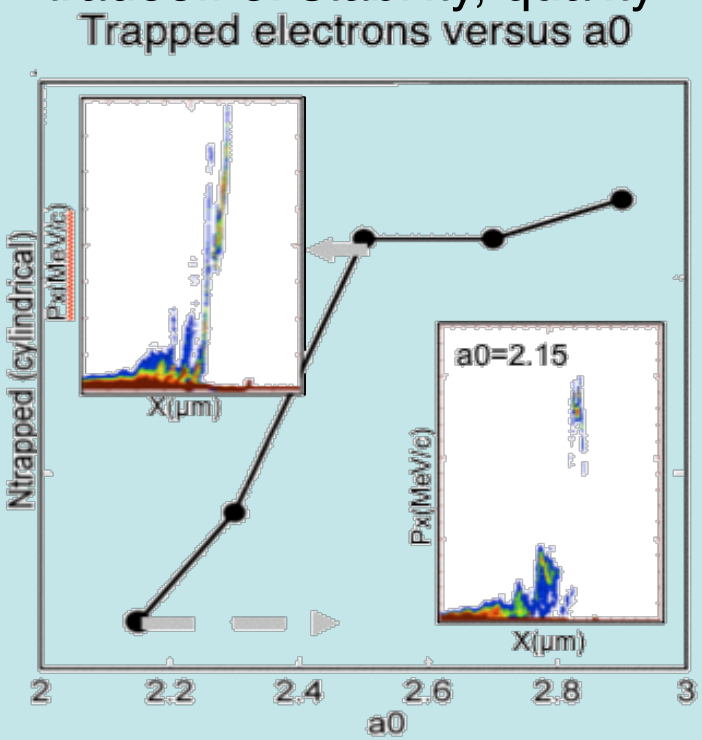
*Also: Faure et al.; Mangles et al. Nature 2004; Tsung et al. PRL 2004

VORPAL : Nieter et al., JCP 2004

Modeling low emittance injectors

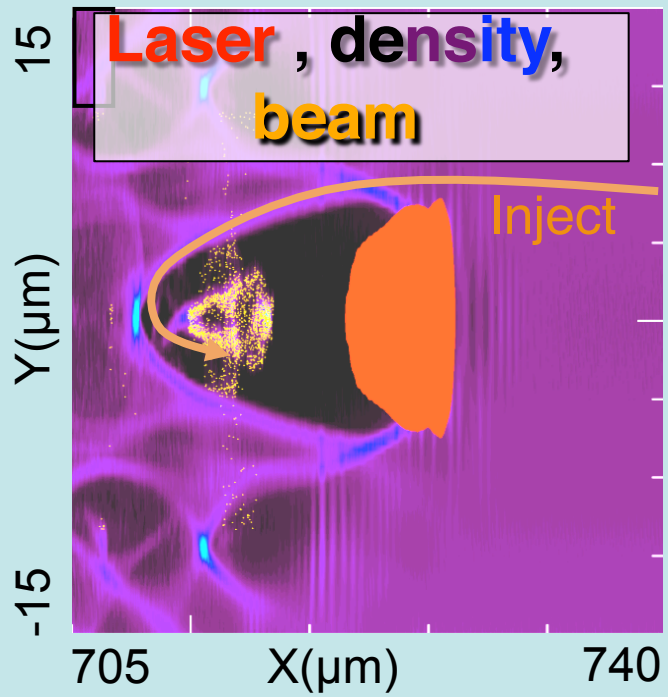
Control injection to improve beam quality and stability

Self trapping control of phase* → tradeoff of stability, quality



⇒ Separately control trapping, acceleration for precision, stability

Self trapping transversely** → MeV $p_{transverse,}$ degrades emittance

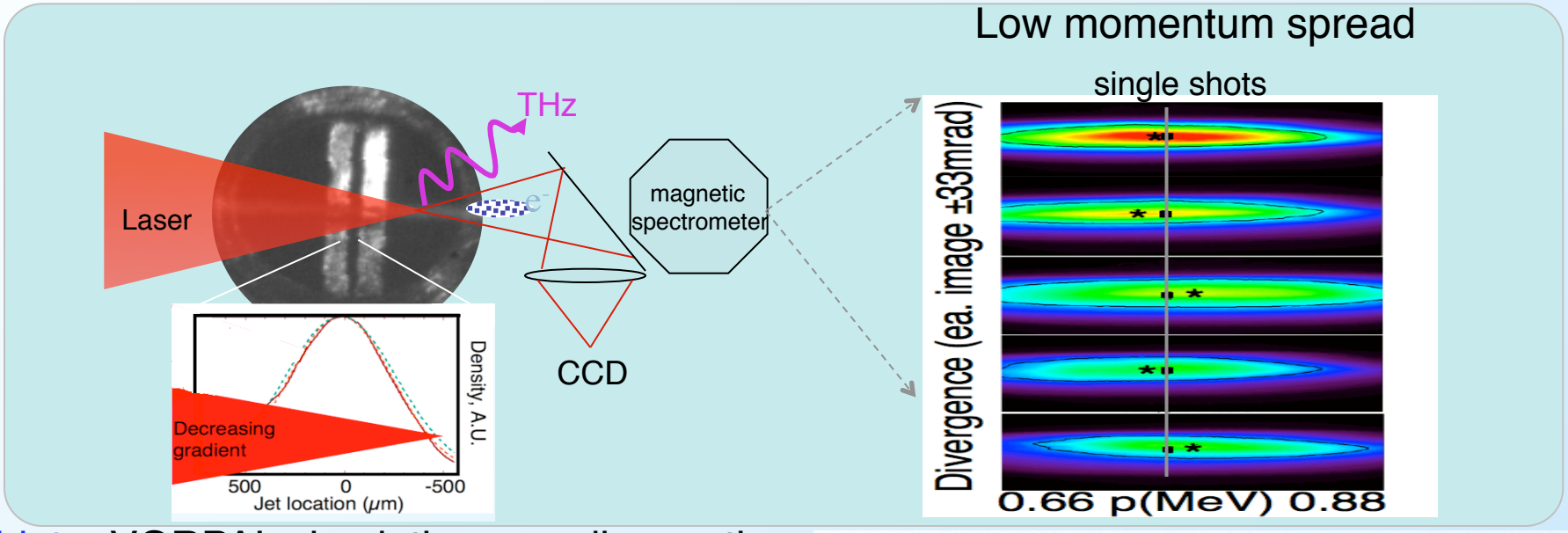


⇒ Controlled trapping at low wake amplitude

Requires injection of fs bunch with μm precision – all optical injectors

*Expt's: Leemans et al. Nature Physics 2006, Nakamura et al. PoP 2007 **Geddes Ph.D dissertation 2005, Tsung et al. PRL 2004

Plasma downramp trapping: all-optical low-ΔE, low-ε injector



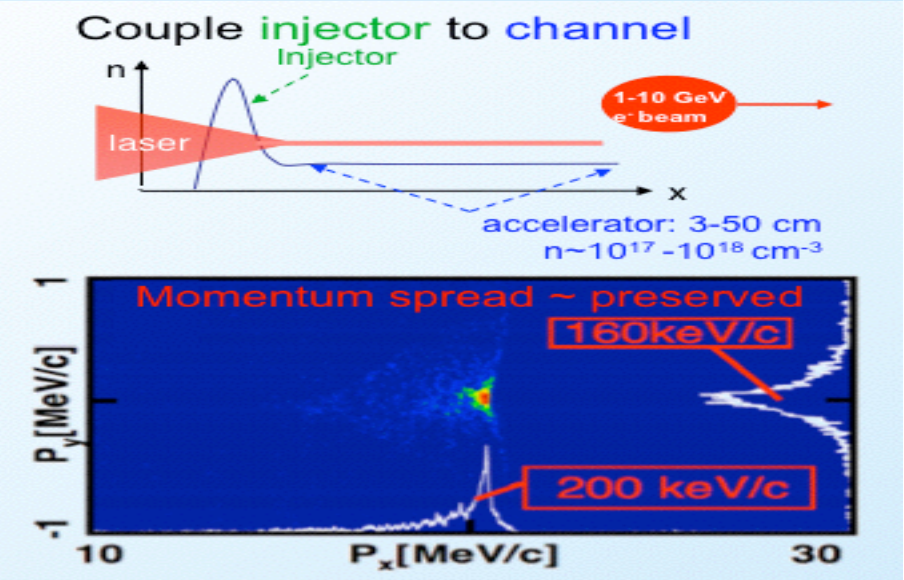
Validate: VORPAL simulations vs. diagnostics

- MeV momentum, $\Delta p \sim 200$ keV/c
- 20-50 keV/c transverse momentum
- 70% laser transmission
- Ultrashort bunch – THz diagnostics

Physics: ramp controlled trapping threshold

Ramp → channel: low ΔE at high E

experiments in progress

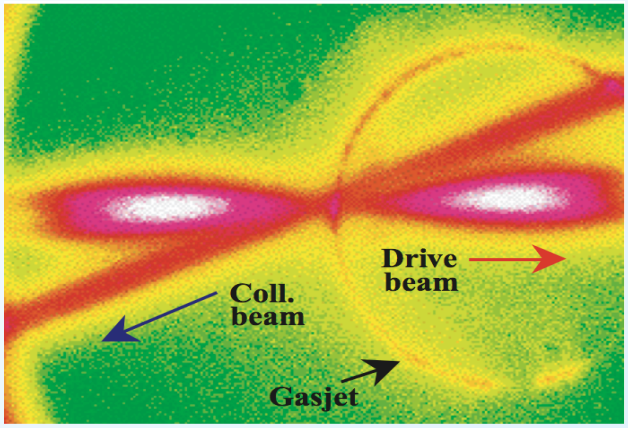


Geddes et al, PRL 2008, JPCS 2008.; G. Plateau, proceedings PAC 2007; Concept: Bulanov PRE 1998

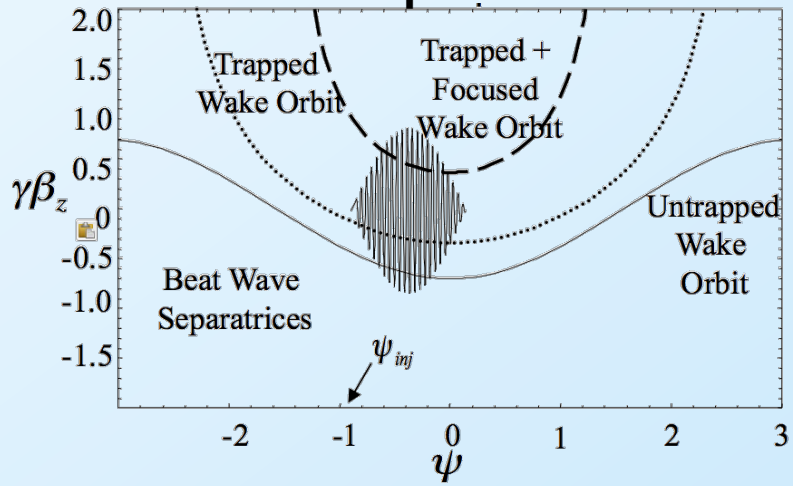
Detailed control over phase space using colliding pulse injection

Beat between two counter-propagating lasers controls phase space

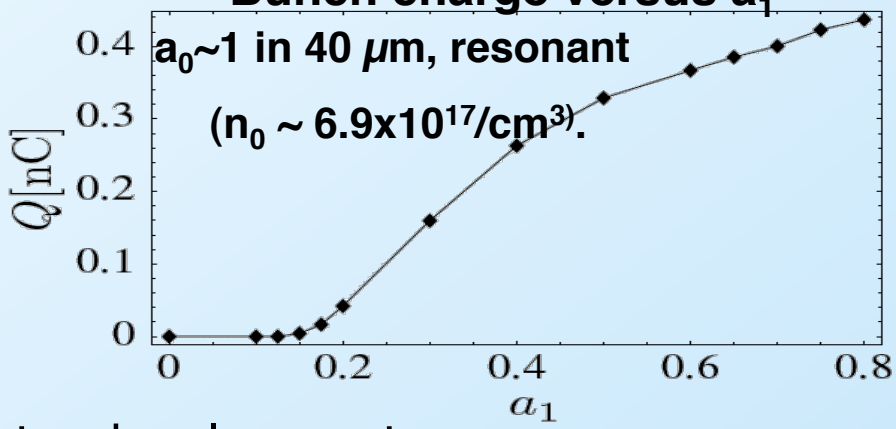
Laser intersection



Phase space control



Bunch charge versus a_1



Theory: Esarey et al., PRL (97); Schroeder et al., PRE (99), Fubiani et al. (04);

Expt: Faure et al., Nature 2006, Toth et al., PAC 2007, Kotaki et al., JPCS 2008

- Low emittance injector development:
  - Explicit and envelope simulations to resolve trapping,
  - Key development: Momentum accuracy, launchers.

Staging to HEP energies

Scaling to 10 GeV

- Guiding : Channel
- Dephasing: Electrons outrun wakefield

Dephasing Length: $L_D \propto \frac{1}{n_e^{3/2}}$

Energy gain: $\Delta W_D \propto \frac{I}{n_e}$

- Efficiency: depletion ~ dephasing

$a_0 \geq 1$

- Spot size ~ pulselength ~ 0.5 λp

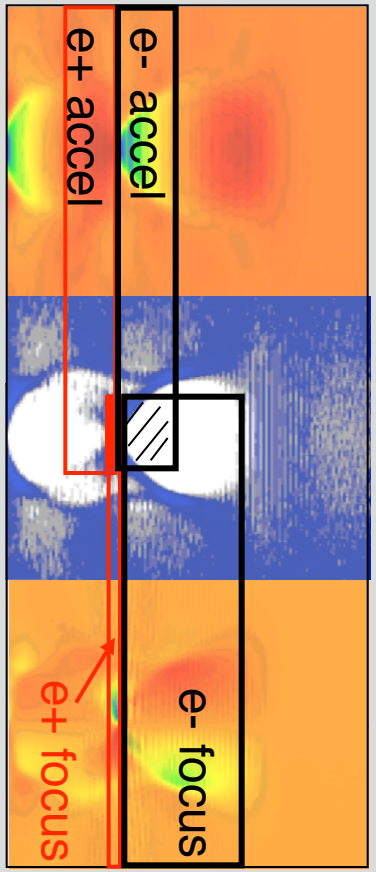
10 GeV
n_e~10^{17}/cc
40 J laser

BELLA proposal – LBNL
40J, PW, high rep rate

10 GeV
injection
staging
diagnostics

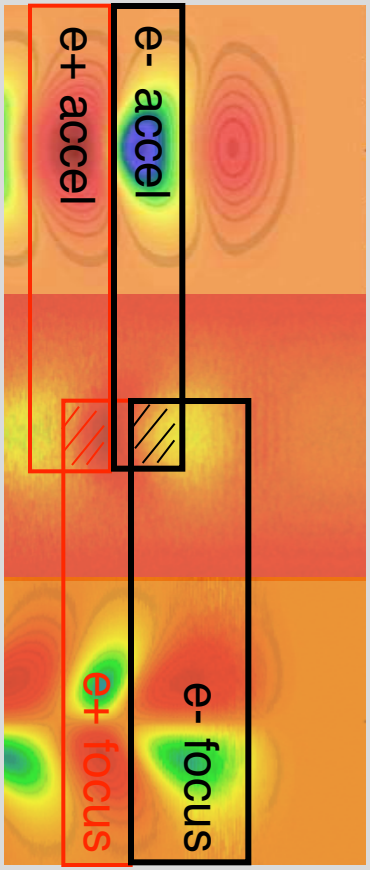
Quasilinear regime optimizes e+/e- acceleration

a_0=4



- Bubble regime
  - high field, loading
  - wake curvature
    - focuses e-
    - defocuses e+

a_0=1



- Quasilinear
  - linear: symmetric e+/e-
  - mildly nonlinear a_0 ~1-2
    - near symmetric, high gradient
  - Beam loading via shaped field

Linear, nonlinear scalings are of same order

Scaling with density used to simulate 10 GeV stages

- Full 3D, explicit 10 GeV simulation not yet practical
  - Key problems: plasma size, m-scale length, v_{group}
- Scaled explicit simulation – use + verify:
  - Self focusing ~ $\mathbf{a_0^2(w_0/\lambda_p)^2}$
  - Energy gain ~ λ_p^2 for const. $\mathbf{a_0}$ & $\mathbf{(L_{laser}/\lambda_p)}$
  - Fill theory gaps - scaled stage design

    2D/3D structure, a_0 dependence, etc.

Resolve depletion, broadening

- Use with reduced simulations at full scale
  - Envelope, Quasistatic
  - Lorentz

Resolve Betatron oscillation

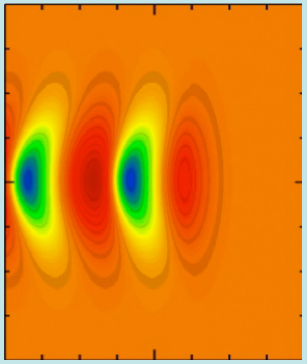
- Scale simulations w/ constant:
  - L_{laser}/λ_p
  - w_0/λ_p
  - a_0

Wake scales with density

Scaled simulations at a=1

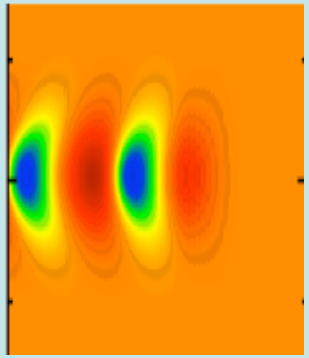
$n_e=10^{18}$ cm^{-3}

E_x - max 40 GV/m



$n_e=10^{19}$ cm^{-3}

E_x - max 120 GV/m

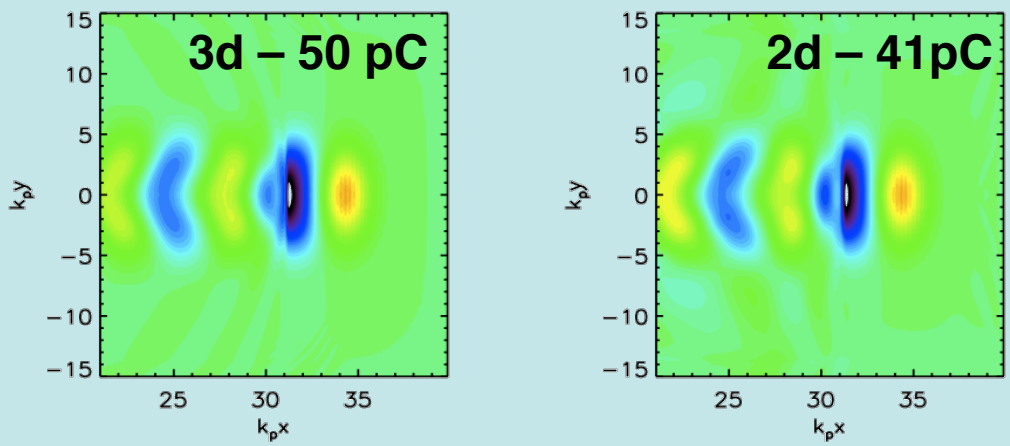


energy gain~ λ_p^2

Beam loading demonstrates regime for efficient accelerator operation

- Beam loading characterized:
  - scaling with $k_p\sigma_r$, a_0, density, and in 2 & 3D
- Field structure scales

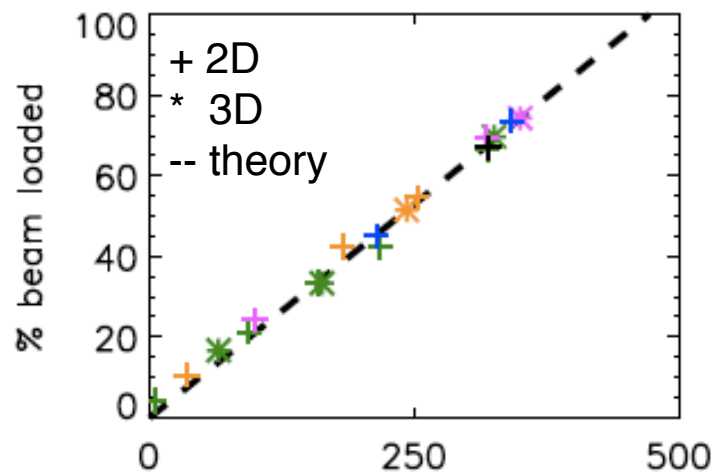
Beam loading at 10^{19} density



Geometric factor connects charge in 2 / 3D ~1 at $k_p\sigma_r$ =2

- $k_p\sigma_r$~ 2 → 500pC 10^{17} cm^{-3}
  - 10 % of laser energy into electrons

Beam loading scaling allows prediction of stage charge



$$Q[pC]\frac{\sqrt{n_0/10^{17}}}{E_x/E_0}\frac{H_R}{k_p^2\sigma_r^2}$$

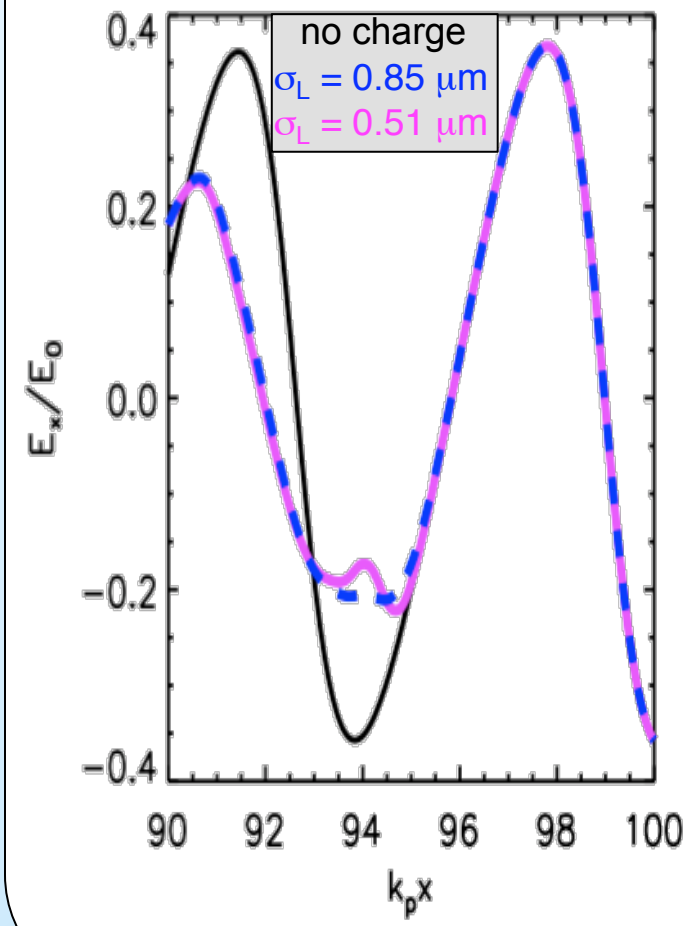
density & k_pL:	$k_p\sigma_r$ = 0.3	1	1.8
k_pL =2, a_0=1 n_0 = 10^{18} cm^{-3}			+
k_pL =2, a_0=1 n_0 = 10^{19} cm^{-3}	+*	+*	+*
k_pL =1, a_0=1.4 n_0 = 10^{19} cm^{-3}	+		

Cormier-Michel et al., Proc. AAC 2008

Adjusting charge and length flattens field for minimum energy spread

- Beam length adjusts wake loading
  - Flattens field across bunch
  - Reduces ΔE
- Bunch & laser wake nearly balanced
  - Symmetric bunches
  - Shaped bunch can further reduce ΔE*
- Phase bunch to optimize energy

Beam loading versus bunch length



Cormier-Michel et al., Proc. AAC 2008

* Katsouleas et al Part. Accel 1987

Taper allows optimization of beam phase and energy spread

- Increasing density taper locks phase*
  - Easiest for buckets far behind laser
- Linear taper
  - 60% n_e change over dephasing
  - 4 x gain energy, 30% depletion, $k_pL=2$
  - Percent energy spread
- Positron acceleration nearly symmetric
  - Wake is mildly nonlinear
  - Slightly reduced phase (positron gain 80% of electron gain)

Spectrum at dephasing (10^{19} cm^{-3})

<u>electrons</u>

$k_p \sigma_r = 1$

$k_p \sigma_L = 0.5$

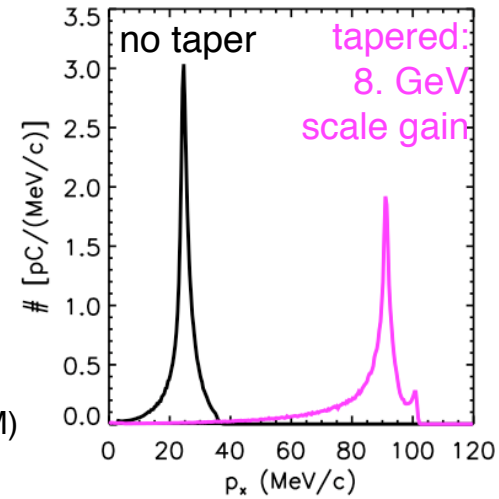
50% beam loaded

3D charge: 22.5pC

→**225pC** at 10^{17} cm^{-3}

8 GeV energy gain

3% energy spread (FWHM)



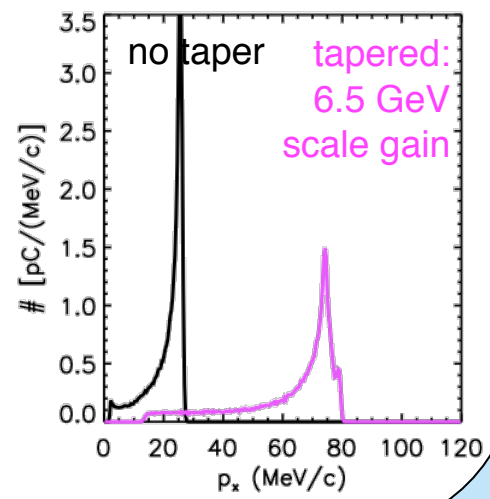
<u>positrons</u>

same beam parameters

→**225pC** at 10^{17} cm^{-3}

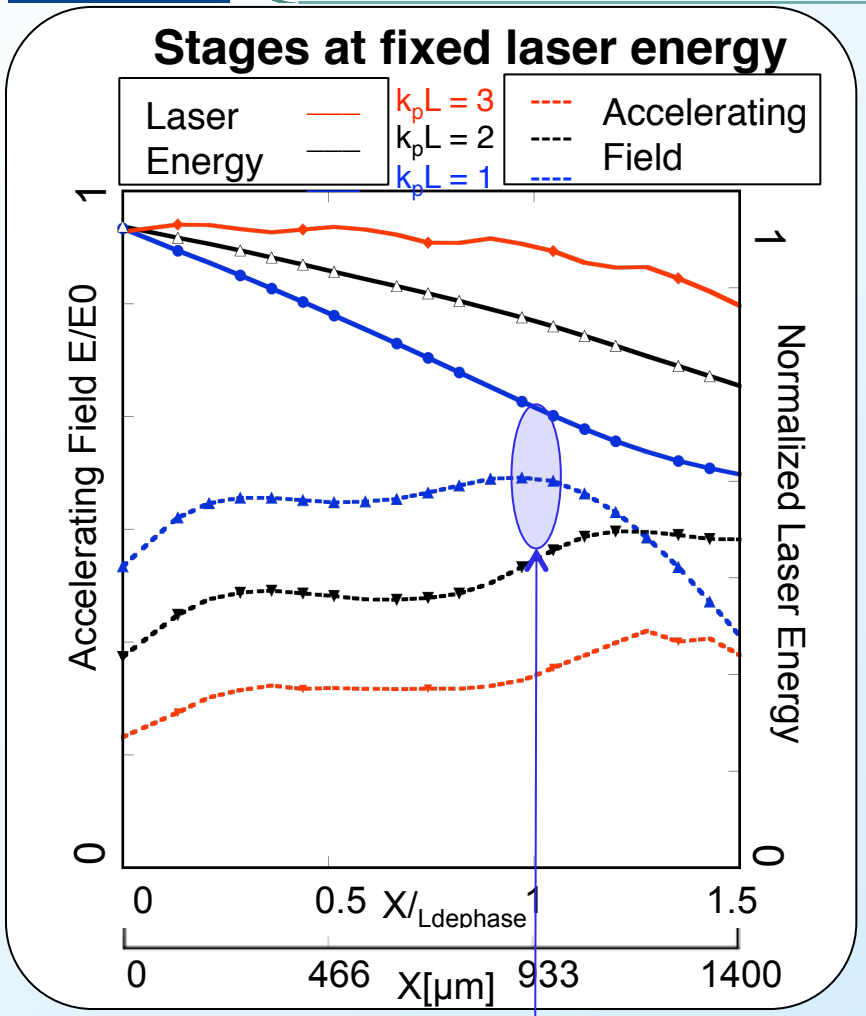
6.5 GeV energy gain

5% energy spread (FWHM)

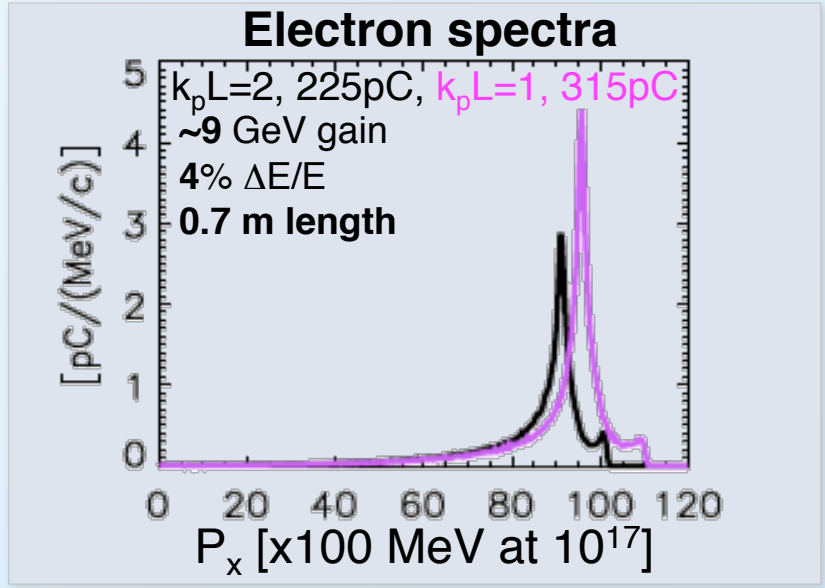


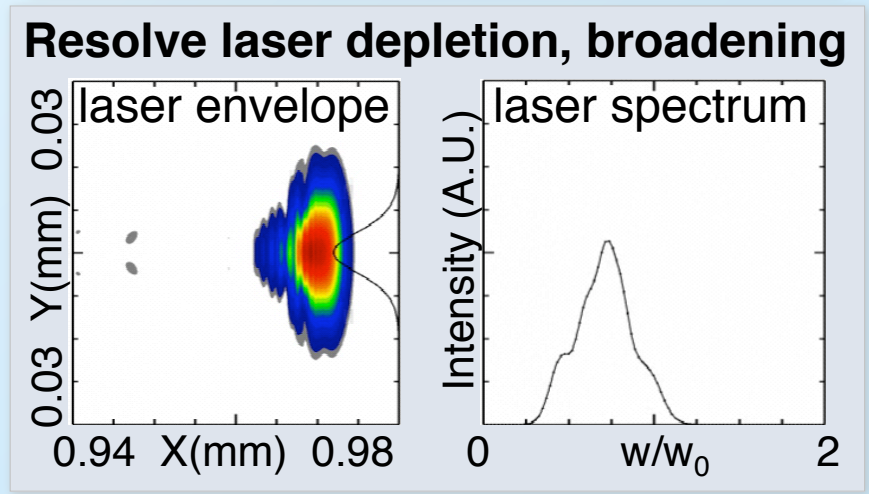
*Katsouleas PRA 1986

Tune laser pulselength: Efficient stage near k_pL =1



At kpL =1: 16 GV/m for 10 GeV, efficient depletion at dephasing

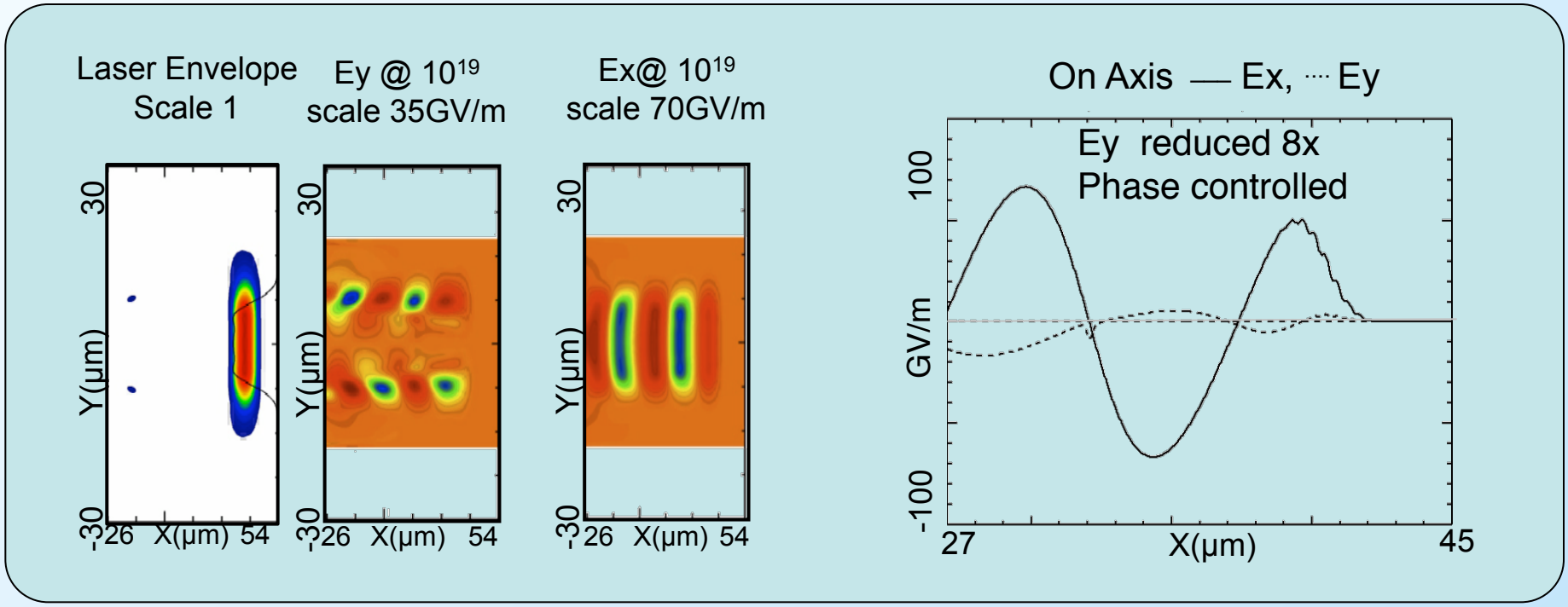




- Increase efficiency – shaped bunches, laser pulses

Transverse field structure control for emittance control

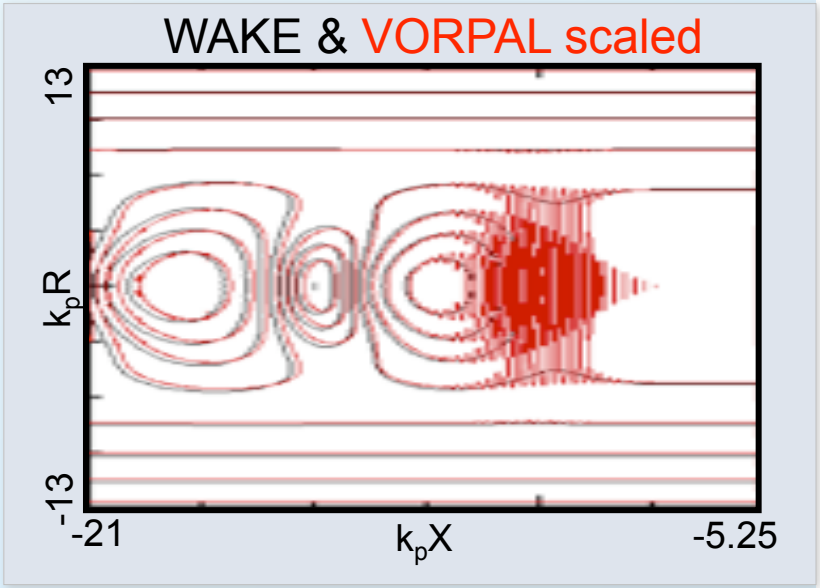
- Emittance matched bunch radius << λ_p for nonlinear & Gaussian-laser linear
  - Mesh refinement may be needed – especially for reduced codes
- Laser mode shaping regulates emittance matched bunch radius, loading



- Detailed emittance – integrate momentum accuracy, radiation, scattering

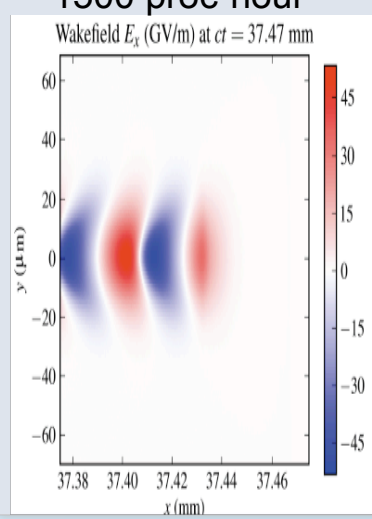
Envelope and Quasistatic simulations verify stage design at 10 GeV density & r-z

- Axisymmetric 2D quasistatic (WAKE**)
  - 10 GeV density of 10^{17}
  - Wake structure matches scaled sim.
  - Scaled simulation fields valid
  - No significant ion motion

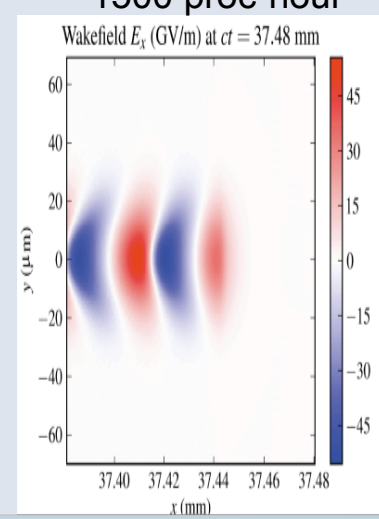


- Envelope simulations*:
  - Resolve only λ_p
  - Improved laser dispersion
  - Resolve wave breaking

VORPAL Explicit
1500 proc-hour



VORPAL Envelope
1500 proc-hour



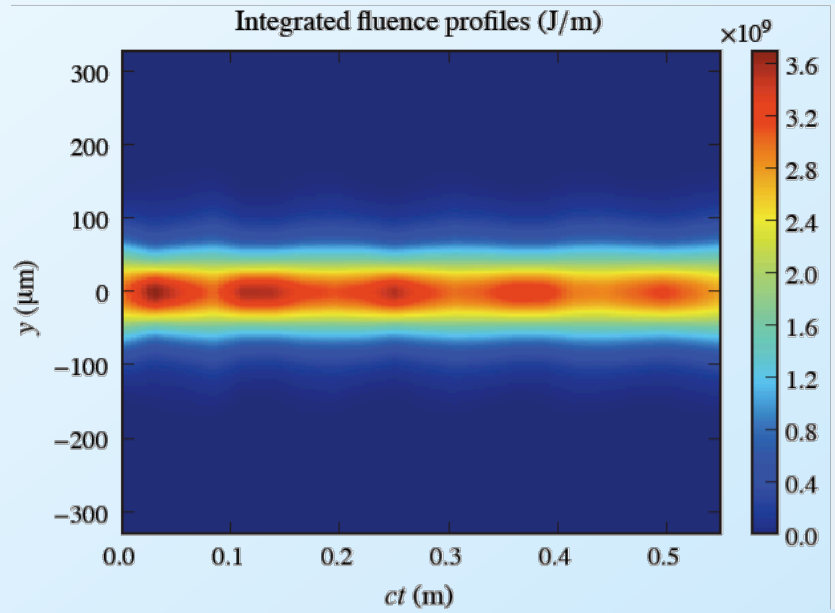
*B.Cowan, et al., Proc AAC 2008; **Antonsen & Mora, Phys. Plasmas **4**, 217 (1997)

Envelope and Quasistatic simulation depletion and bunch considerations

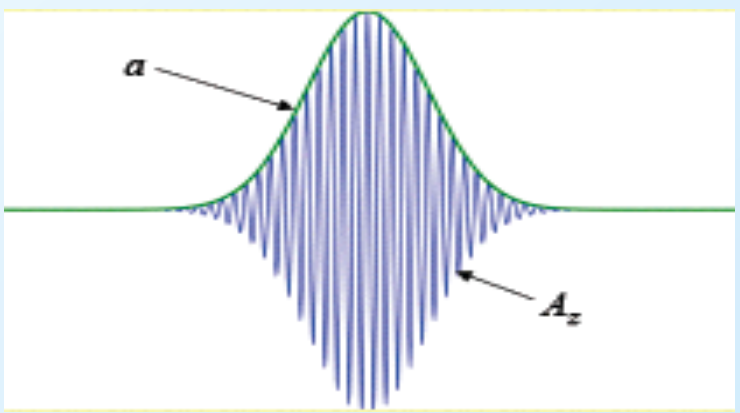
- Model 10 GeV stages at full scale

  Correct Betatron period

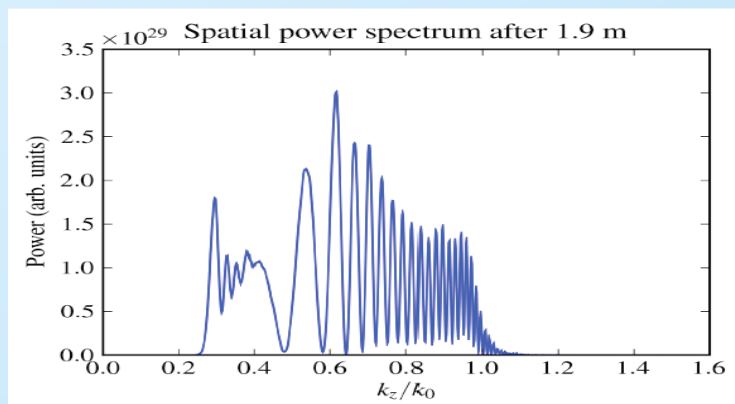
- Envelope model challenges:
  - Deep depletion – fast oscillating term
  - Small bunches
- Increased resolution requirement or ?



Separates envelope & oscillation



Depletion – high frequency oscillation



B.Cowan, et al., Proc AAC 2008

10 GeV Nonlinear stages accessible at 40J

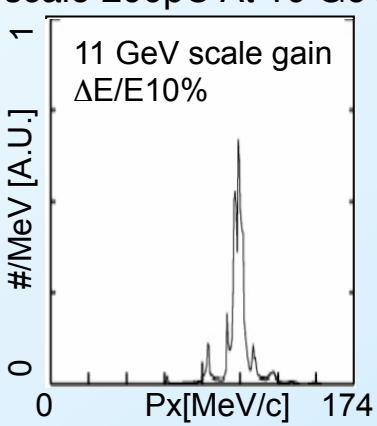
- Nonlinear scalings similar*- coeficients differ
  - $E_{electron\text{-}bunch} \sim 1/n$
  - $P \sim 1/n$
  - $E_{laser} \sim 1/n^{1.5}$
- For $a_0=2$:
  - $n_e = 1.3e17$
  - $k_pL=k_pw_0 = 2a_0^{0.5} \sim 2.8 \rightarrow 41\mu m$
  - $E_{laser} \sim 40J$
  - 10 GeV

Near-linear focusing for e^-
Restricted phase for e^+

Separate envelope & oscillation

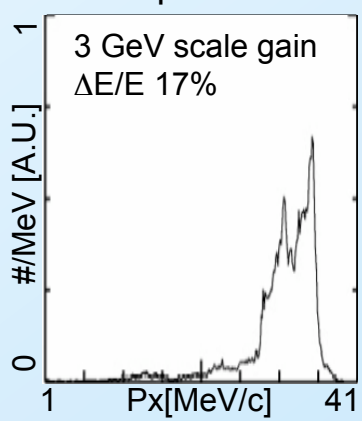
Electrons

scale 200pC At 10 GeV



Positrons

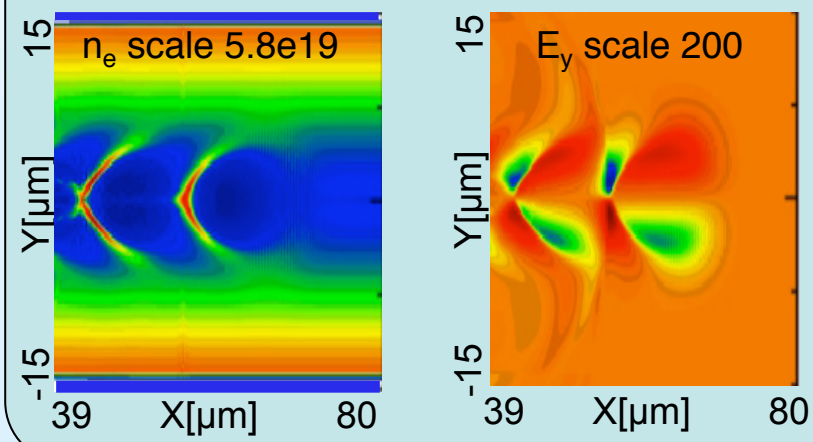
scale 200pC at 3 GeV



a_0=2 nonlinear

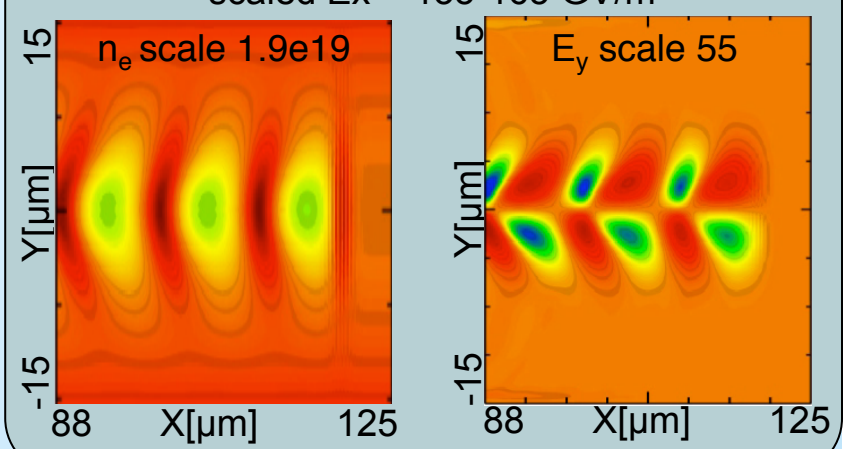
scaled Ex = 230-550 GV/m

10 GeV stage Ex = 23-55 GV/m



a_0=1 quasilinear

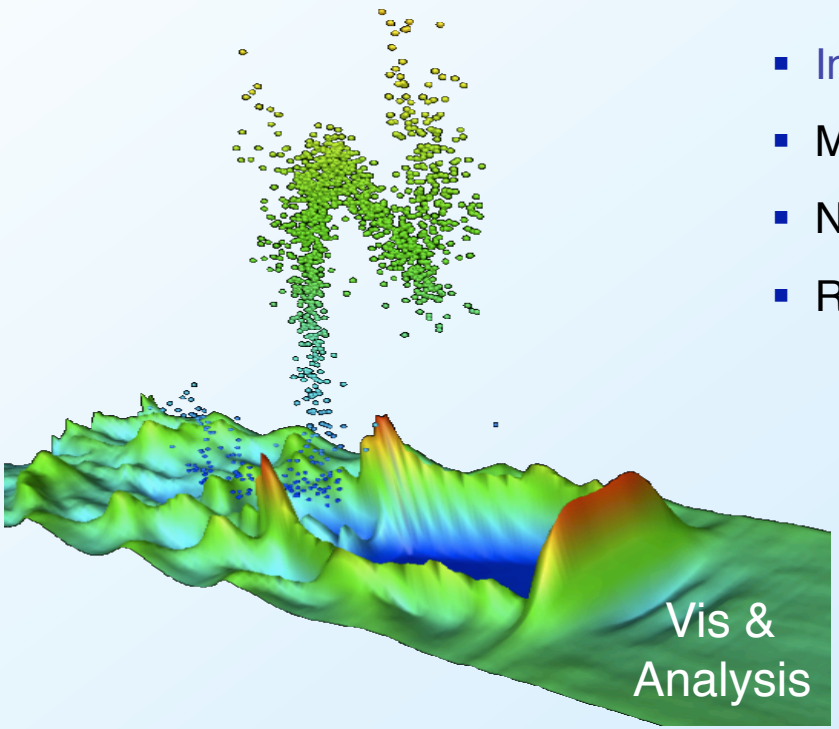
scaled Ex = 135-165 GV/m



* Lu et al, PRL 96, 0165002 (2006).

Simulation challenges for LWFA development

- Accurate kinetics and bunch emittance
  - Improve accuracy in momentum advance
  - Mesh refinement at particle bunch
  - Noise control – fluids, smoothing, EM dispersion
  - Radiation & scattering



- Key model development
  - Explicit PIC, Fluid, hybrid

    Long stage scaling, EM dispersion, Momentum accuracy
  - Laser Envelope model, Quasistatic

    Resolve depletion/wavelength shift, Small bunch
  - Optimal Lorentz Frame

    Diagnostics (simultaneity), Noise control, Backward waves

- Meter scale structures
  - Accurate reduced, scaled models
  - EM dispersion (laser propagation)
  - Error accumulation, Scaling