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U.S. DEPARTMENT OF ENERGY

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Improving laser-plasma accelerator beam quality for FELs

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FEL Conference, Nara Japan, 26-31 Aug 2012

Supported by the U.S. DOE under Contract No. DE-AC02-05CH11231

Outline

- Basics of Laser-Plasma Accelerators (LPAs)
- Measurements of LPA beam properties
  - transverse emittance (~0.1 mm mrad)
  - beam duration (~ 5 fs)
  - correlated energy spread measurements
- Path to improved LPA beam quality (higher brightness)
  - improved quality and stability requires controlled injection
- Prospects for an FEL using LPA electron beams
- Path to higher electron beam energy
  - 10 GeV LPA with BELLA PW laser at LBNL

Laser-plasma accelerators (LPAs)

Tajima & Dawson, Phys. Rev. Lett. (1979); Esarey, Schroeder, Leemans, Rev. Mod. Phys. (2009)

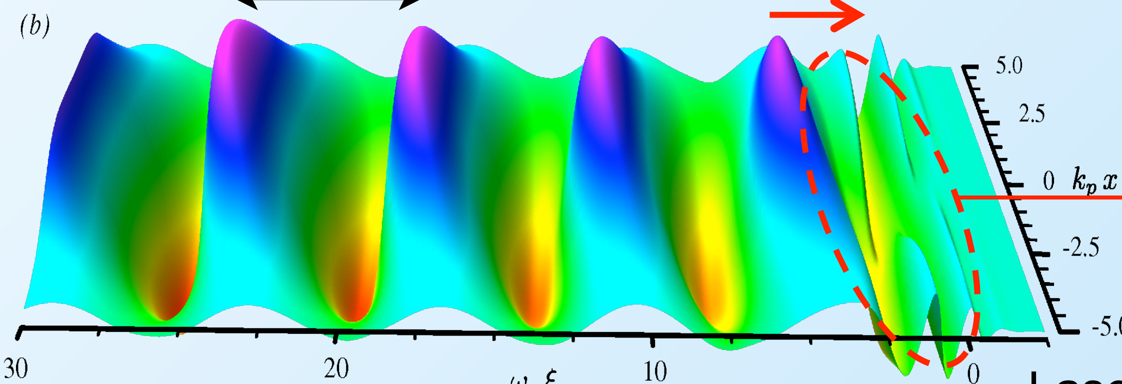
$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_0}=c^2\nabla^2\frac{1}{4}\left(\frac{eE_{\text{laser}}}{mc^2\omega}\right)^2$$

Plasma wave: electron density perturbation

Laser ponderomotive force (radiation pressure)

$\lambda_p = 2\pi c/\omega_p \sim n_p^{-1/2} \sim 10\ \mu\text{m}$

$v_{\text{phase}} \simeq v_{\text{group}} \simeq c$

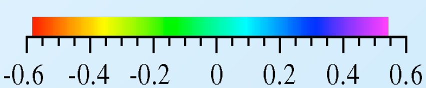


Short pulse, ultra-intense laser: $I \sim 10^{18}$ W/cm^2

Laser pulse duration

$\sim \lambda_p/c \sim$ tens fs

n/n_0



electron plasma density perturbation

Laser-plasma accelerators: >10 GV/m accelerating gradient

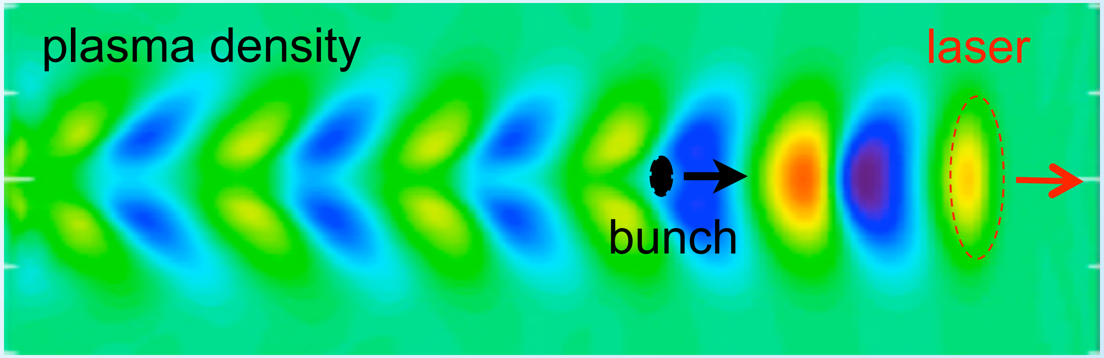
$$E \sim \left(\frac{mc\omega_p}{e}\right) \approx (96\ \mathrm{V/m})\sqrt{n_0[\mathrm{cm}^{-3}]}$$

Plasma wave (wake) field: E ~100 GV/m (for $n \sim 10^{18}$ cm^{-3})

>10^3 larger than conventional RF accelerators ⇒ “>km to <m”

Accelerating bucket ~ plasma wavelength

➔ **ultrashort (fs) bunches (<λ_p/4)**

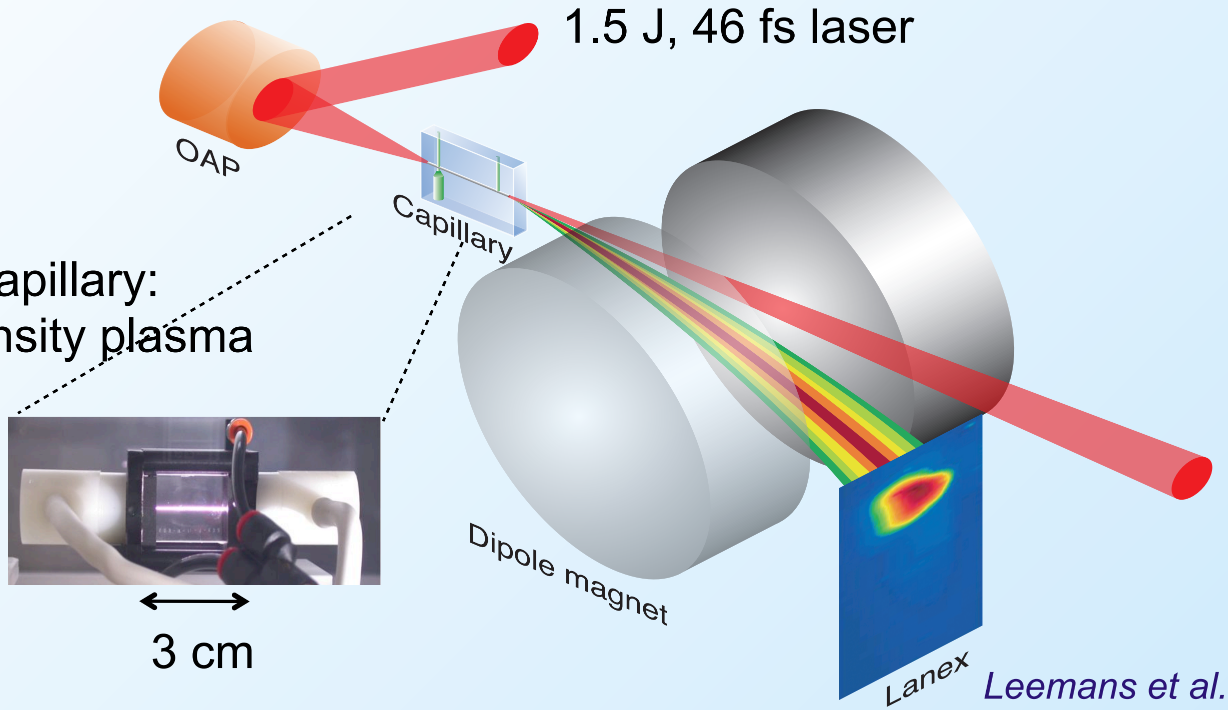


- beam charge (set by beam loading): ~10-100 pC
- beam duration (set by trapping physics and density): <10 fs

} ➔ **high peak current** ~10 kA

Experimental demonstration: GeV Beam in 3 cm using LPA

H-discharge capillary:
~10^{18} cm^{-3} density plasma

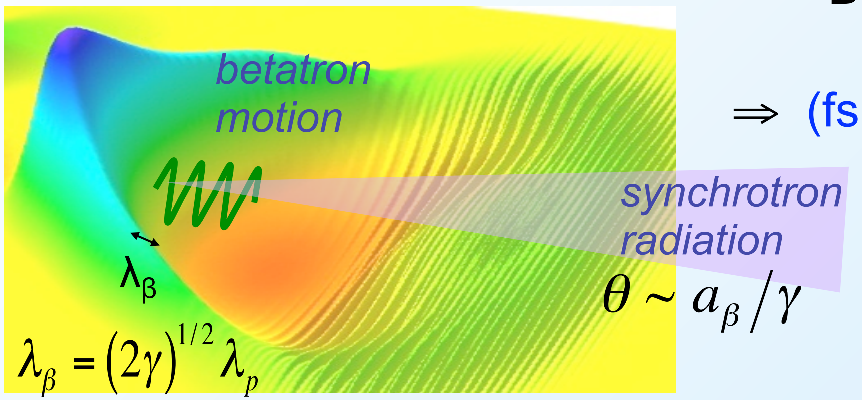


Leemans et al., Nature Phys. (2006)

Strong focusing forces in plasma wave produces synchrotron radiation

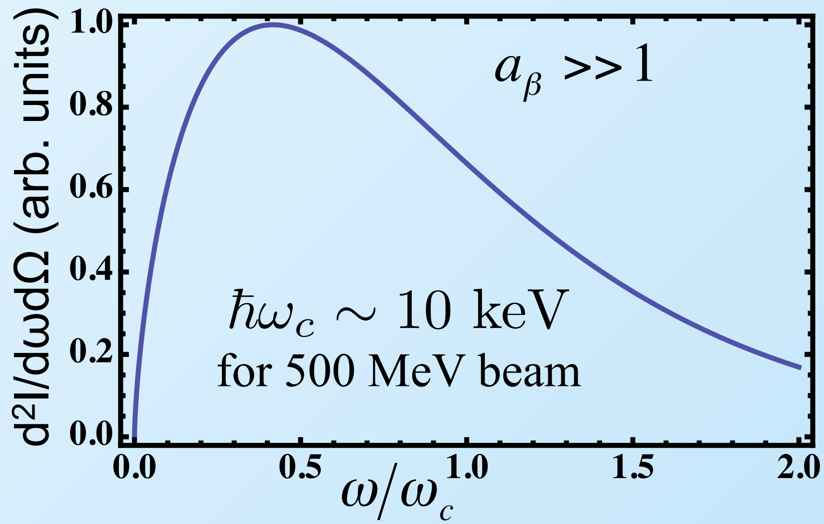
Strong focusing of plasma wave:

Betatron motion: $E_\perp \sim E_0 k_p r$



Esarey et al., PRE (2002)

$\Rightarrow$ (fs, broadband, hard x-ray) synchrotron radiation



wiggler parameter:

$$a_\beta \approx 0.13\sqrt{\gamma\, n[10^{18}\mathrm{cm}^{-3}]}\, r_\beta[\mu m]$$

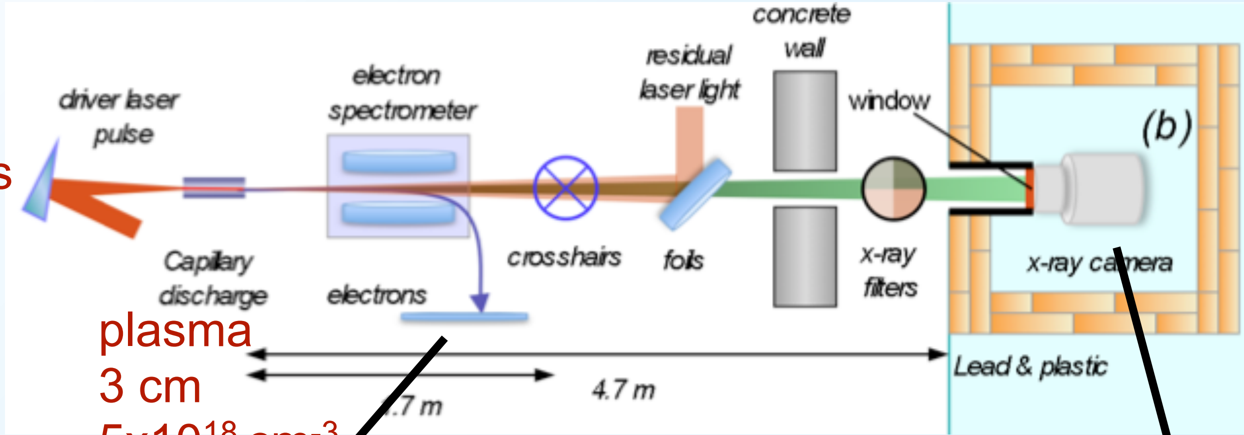
critical frequency:

$$\hbar\omega_c[\mathrm{keV}] \approx 1.1\times 10^{-5}\gamma^2 n[10^{18}\mathrm{cm}^{-3}]\, r_\beta[\mu m]$$

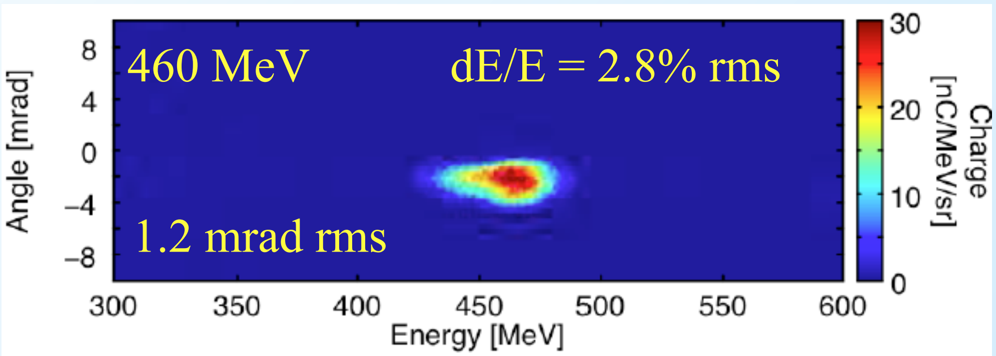
➡ X-ray spectra non-invasive, in situ, single-shot measurement of beam size

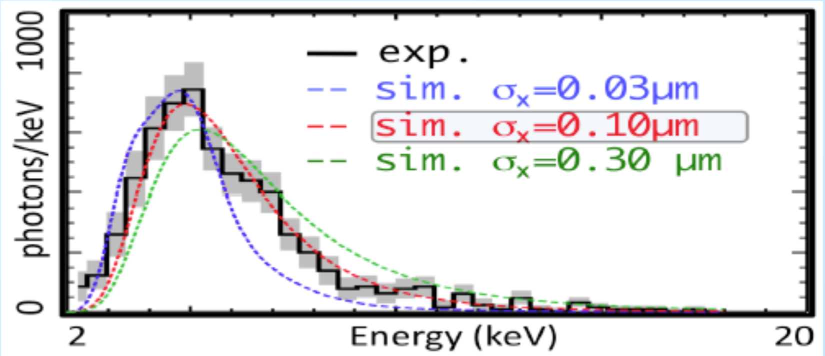
Synchrotron radiation spectrum yields in situ measurement of beam size ~ 0.1 micron

laser
1.3 J, 24 fs
$Ti:Al_2O_3$



plasma
3 cm
$5x10^{18}$ cm^{-3}





➡ beam size, σ_x = 0.1 micron rms

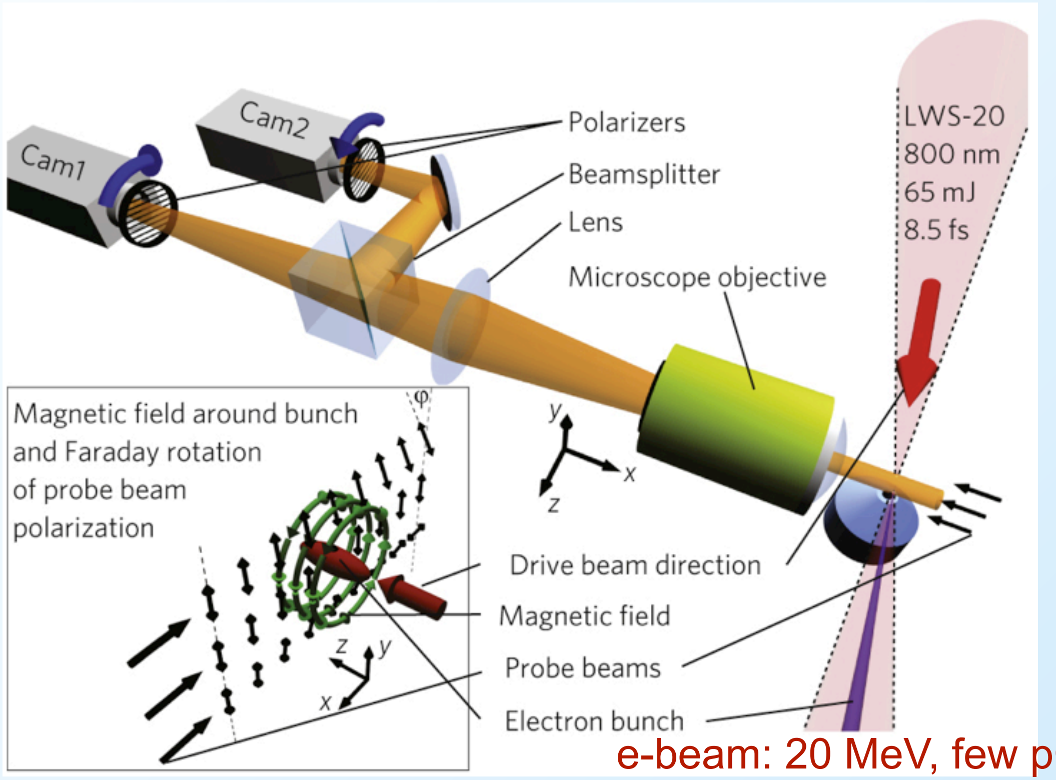
➡ normalized transverse emittance estimate:

$\gamma\, \sigma_x\, \sigma_\theta$ = 0.1 mm mrad

Faraday rotation used to measure bunch length: ~5 fs

A. Buck et al. *Nature Physics* (2011)

Max-Plank-Institut für Quantenoptik



e-beam: 20 MeV, few pC

Ultra-short (few cycle) laser used to measure e-beam magnetic field using time-resolved polarimetry

Faraday (polarization) rotation:

R- and L-wave along direction of B in plasma have different phase velocities

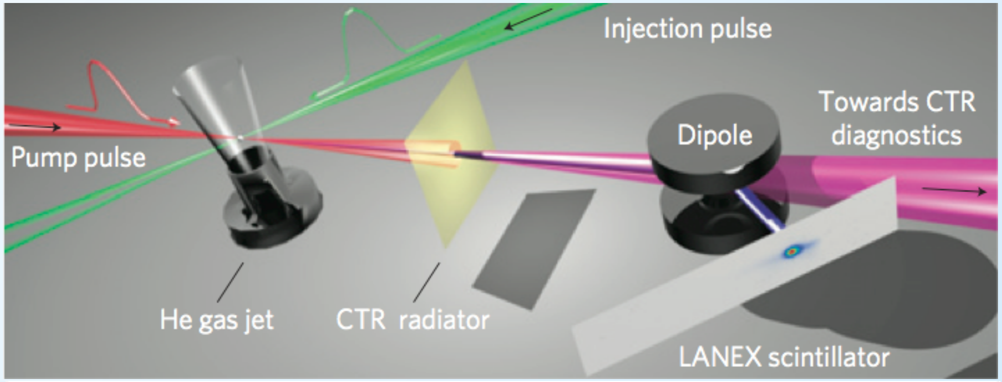
e-beam generates azimuthal B-field and rays of probe beam pass above and below beam are rotated in opposite directions

➡ single-shot, in situ, non-destructive measurement of e-bunch duration:
τ = 5.8 fs FWHM

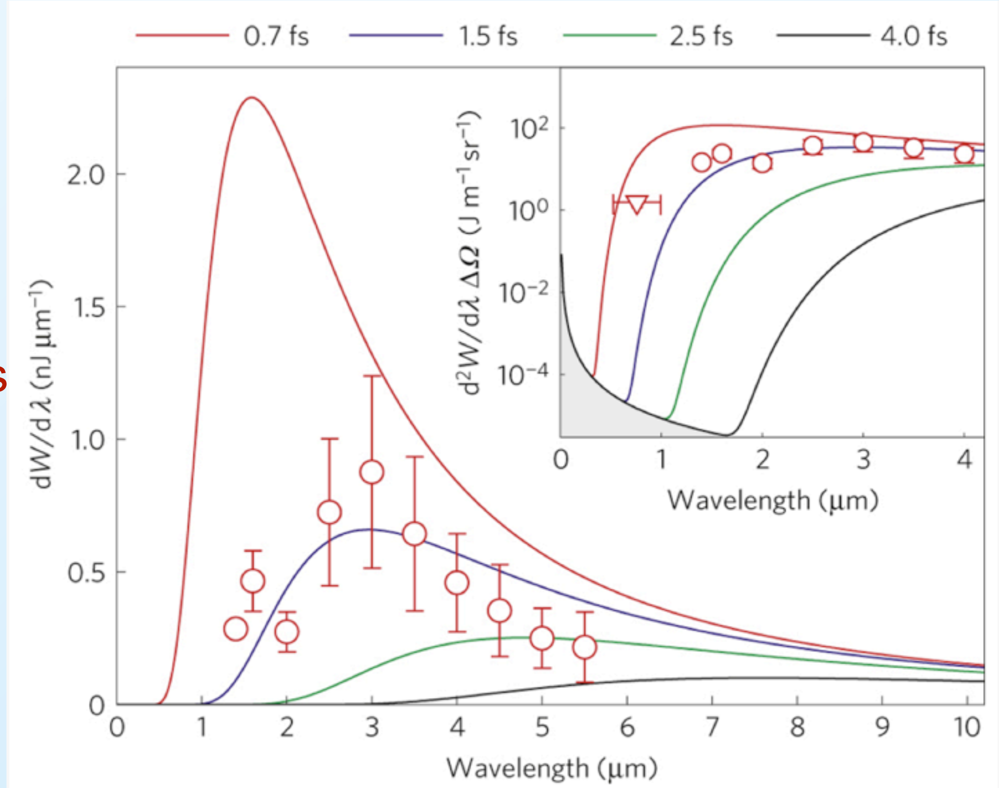
CTR spectrum used to determine bunch length: ~few fs

Lundh et al. Nature Physics (2011)

Laboratoire d'Optique Appliquée



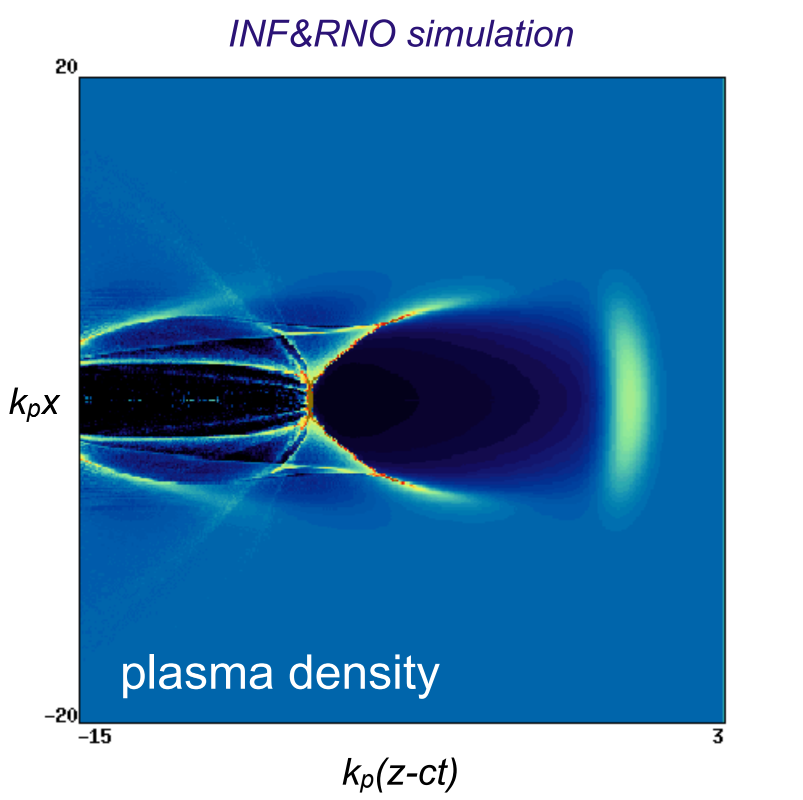
e-beam:
85 MeV, 15 pC



RMS beam duration 1.4 fs
peak current 4 kA

"Bubble regime": uncontrolled trapping

Laser propagation direction →



- Ultra-high intensity laser (a>2):

$$\sqrt{a} > k_p r_L/2$$

- Drives large amplitude density wake and formation of co-moving electron-free cavity

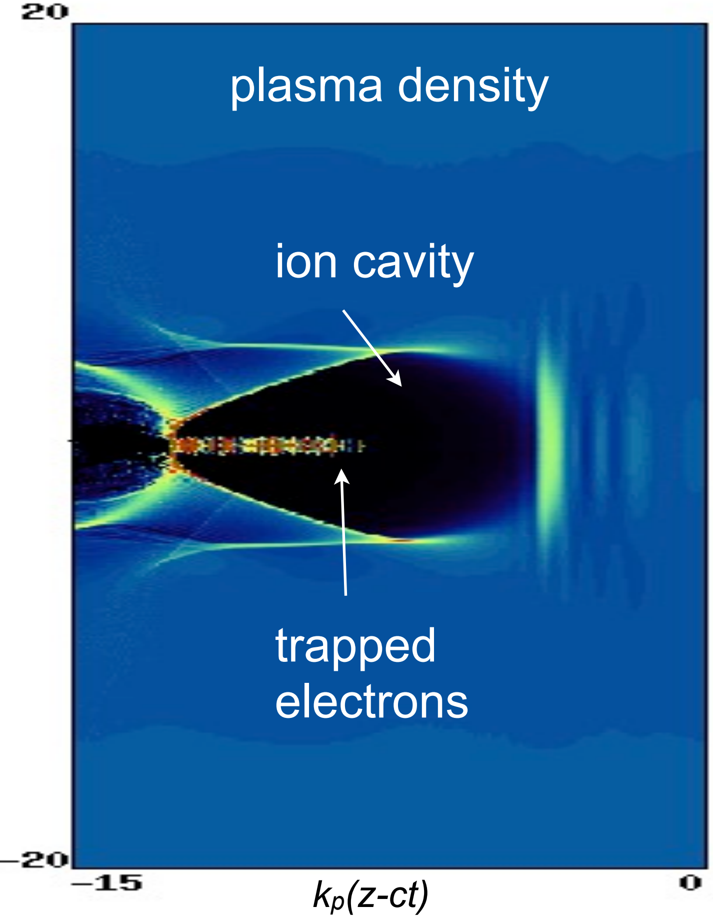
- Low wake phase velocity (and large wake amplitude) allow self-trapping of plasma electrons

$$\gamma_p \propto 1/\sqrt{n}$$

- Continuous (uncontrolled) injection result in large (1-10%) energy spreads
- Energy gain proportional to injection time ➡ *chirped* energy distribution

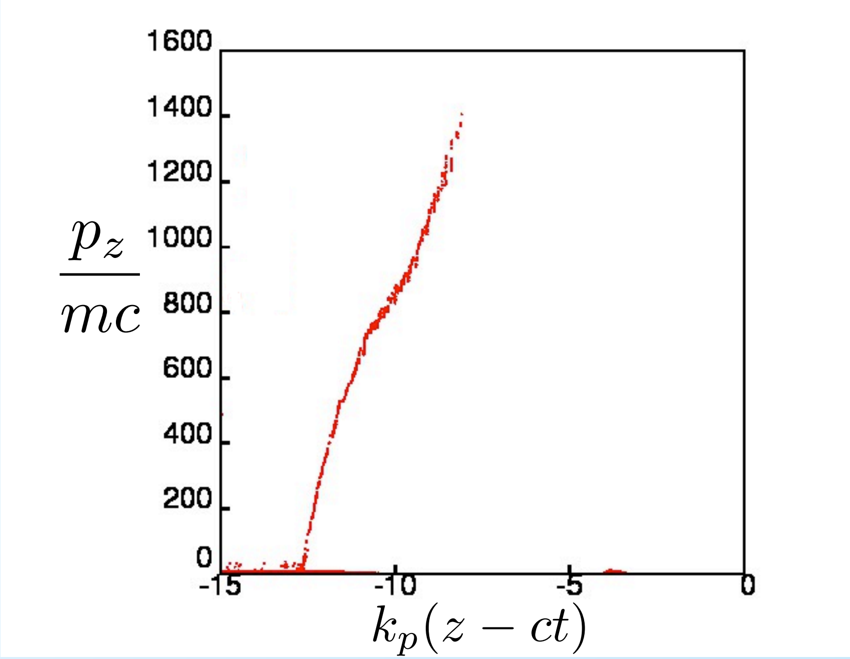
Trapping physics results in large energy spread, chirped energy distribution

- Continuous (uncontrolled) injection result in large energy spreads
- Energy gain proportional to injection time ➡ *chirped* energy distribution



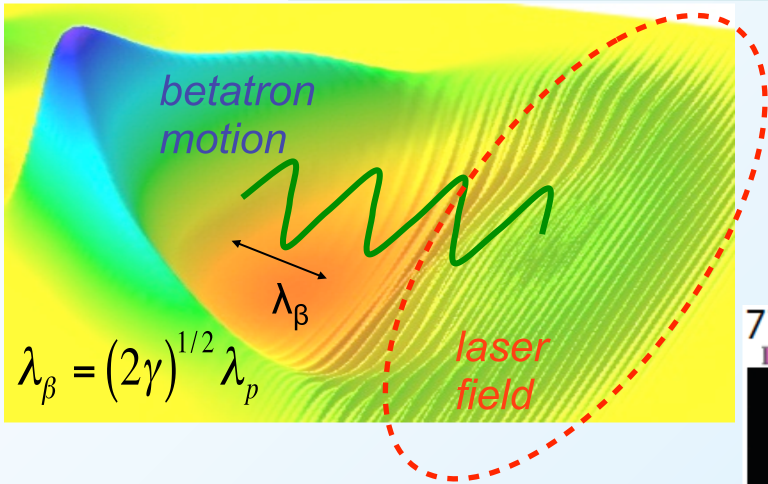
INF&RNO simulation

longitudinal phase space



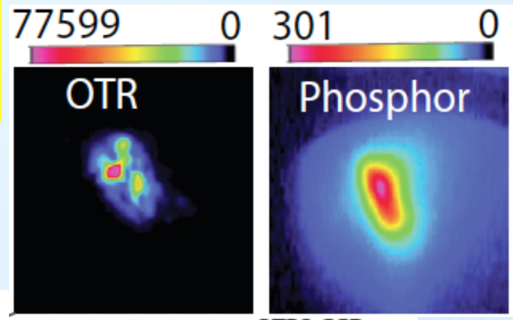
- Controlled (triggered) trapping ➡ improve stability and energy spread

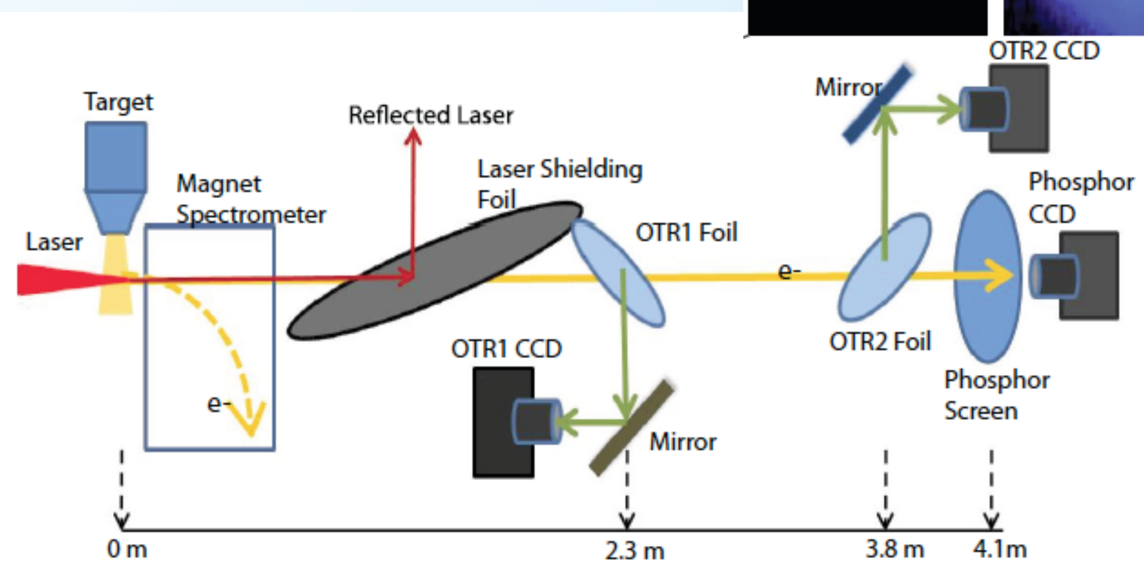
CTR of laser-plasma generated microbunching indicates small slice energy spread

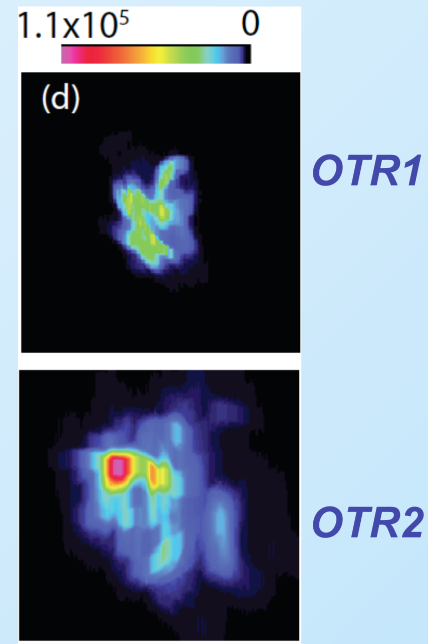


- Operate plasma at high density (~10^{19} cm^{-3})
  - ➡ λ_p short, laser group velocity slow
- Beam interacts with drive laser
  - ➡ momentum modulations (~laser period)

C. Lin et al., PRL (2012)







Coherent enhancement observed in spectral range 0.4 - 0.9 micron

➡ Observed coherence implies slice energy spread of ~0.5%.

Electron injection methods for laser plasma accelerators

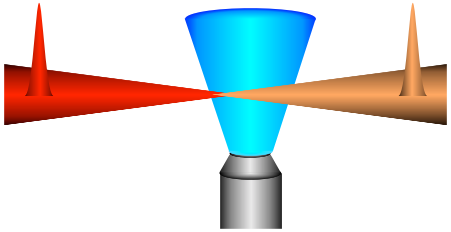
Ponderomotive injection

D. Umstadter et al. PRL (1996) …

Colliding pulse injection

E. Esarey et al. PRL (1997)
C.B. Schroeder et al. PRE (1999)
J. Faure et al. Nature (2006) …

Boost electron momentum



Density down ramp injection

S.V. Bulanov et al. PRE (1998)
C.G.R. Geddes et al. PRL (2008)…

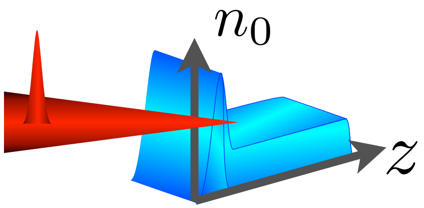
Density transition injection

H. Suk et al. PRL (2001)…

Plasma lens injection

A. Gonsalves et al., Nature Phys. (2011)

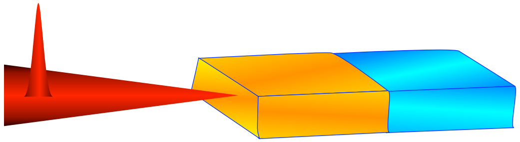
Reduce plasma wave velocity



Ionization injection

M. Chen et al. J. Appl. Phys. (2006)
A. Pak et al. PRL (2010)
B. C. McGuffey et al. PRL (2010)
C.E. Clayton et al. PRL (2010)
M. Chen et al. Phys. Plasmas (2012);…

Produce electrons at proper phase



Trapping and wake phase velocity controlled via plasma profile

Trapping: high wake amplitude + low phase velocity

Plasma wave phase velocity ⇒ $$\beta_p = \frac{\omega}{ck} = \beta_g \left(1 + |\zeta| \frac{1}{\lambda_p} \frac{d\lambda_p}{dz}\right)^{-1}$$

λ_p

Snapshots of wake ⇒

$d\lambda_\mathrm{p}/dz > 0$

Trapping enabled

$d\lambda_\mathrm{p}/dz < 0$

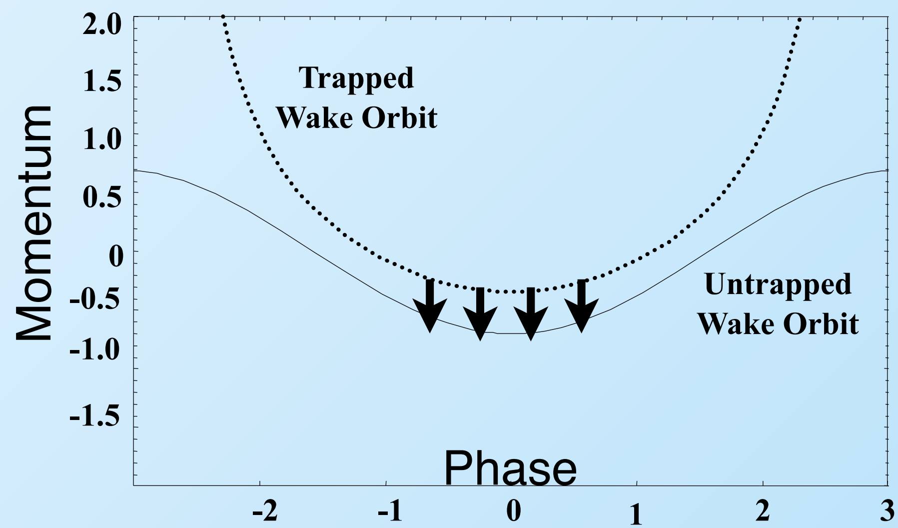
Trapping terminated

Phase velocity reduced by

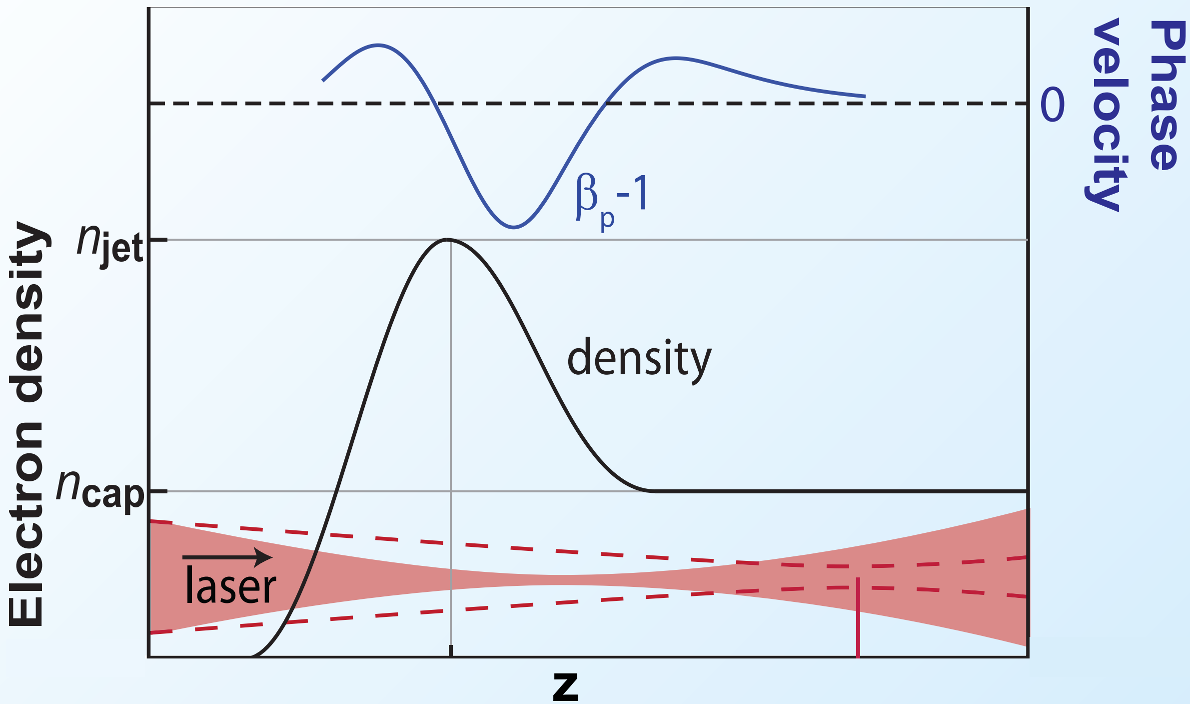
- Negative plasma density gradient
  - Theory: Bulanov et al. PRL 1997
  - Experiment: Geddes et al., PRL 2008

$$dn_\mathrm{e}/dz < 0 \Rightarrow d\lambda_\mathrm{p}/dz > 0$$

Since $\lambda_p \propto \frac{1}{\sqrt{n_e}}$



Trapping, wake amplitude and phase velocity controlled via laser focusing with plasma lens



Focusing laser:

$$da_0/dz > 0$$

$$\Downarrow$$

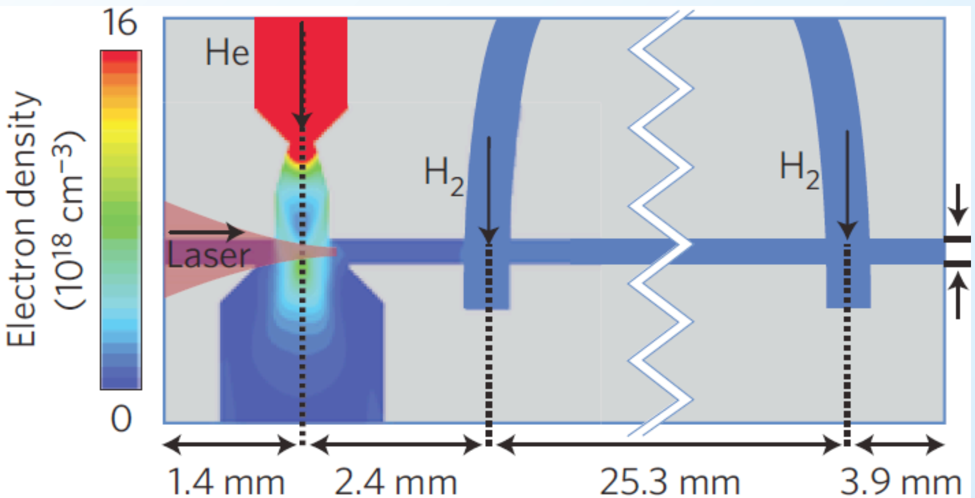
$$d\lambda_{\rm p}/dz > 0$$

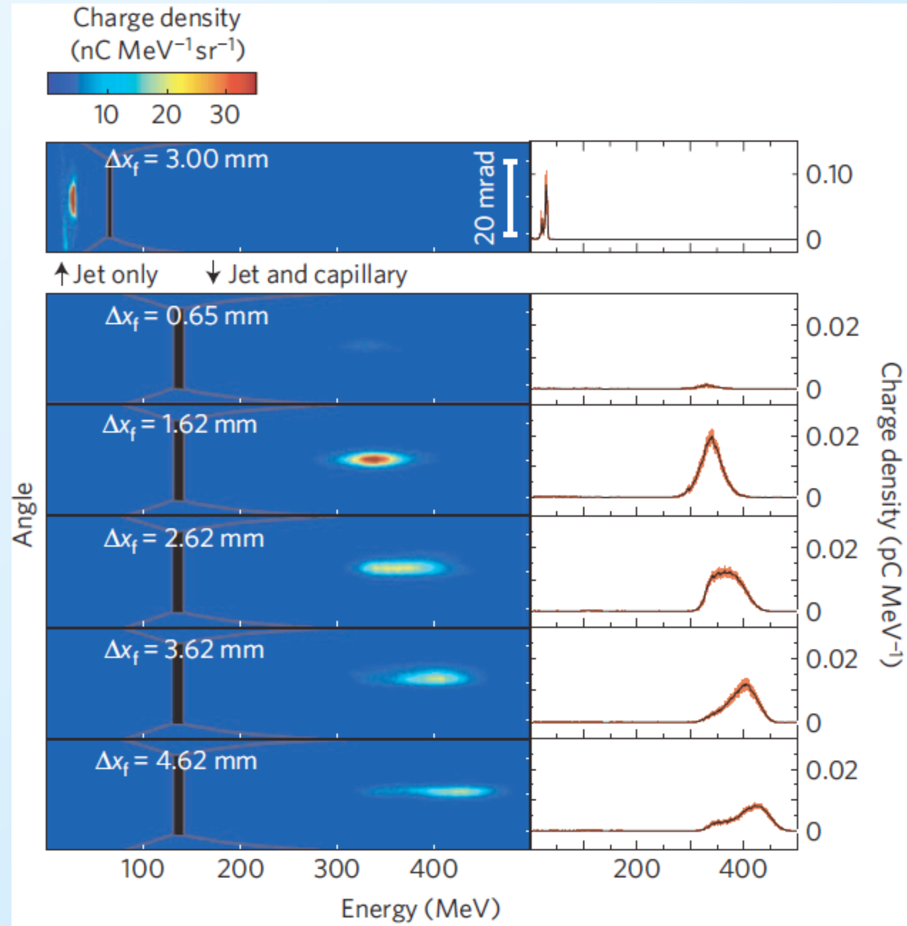
- Increasing laser intensity lowers phase velocity through increase in non-linear plasma wavelength (enables trapping)
- Decreasing laser intensity (after focus) can terminate trapping
- Density can control effect via self-focusing (plasma lens)

Experiment: Gonsalves et al., Nature Physics (2011)
Theory: Schroeder et al., Phys. Rev. Lett. (2011)

Integrated injector and accelerator demonstrates improved stability

Gonsalves et al., Nature Physics (2011)





- Electron trapping and energy gain was controlled by varying the
  - (1) gas jet density
  - (2) laser focal position

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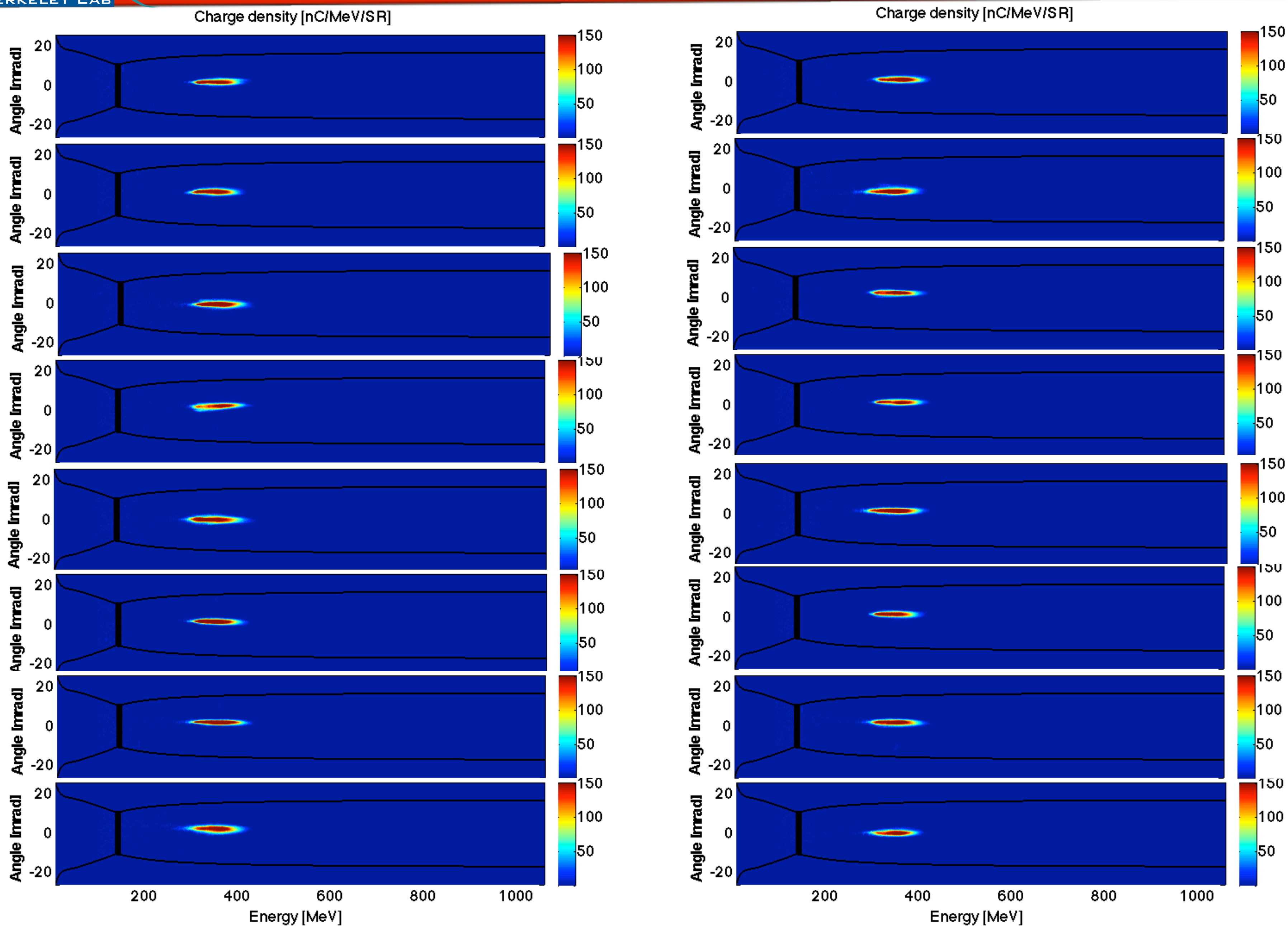
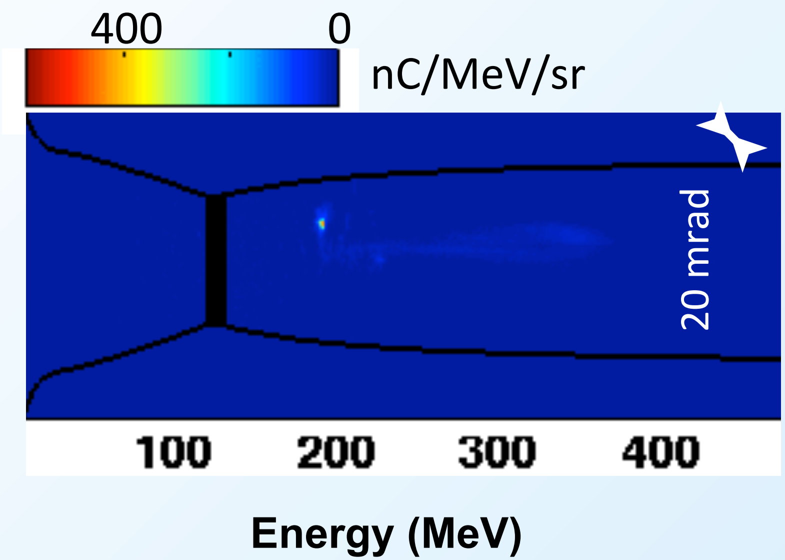
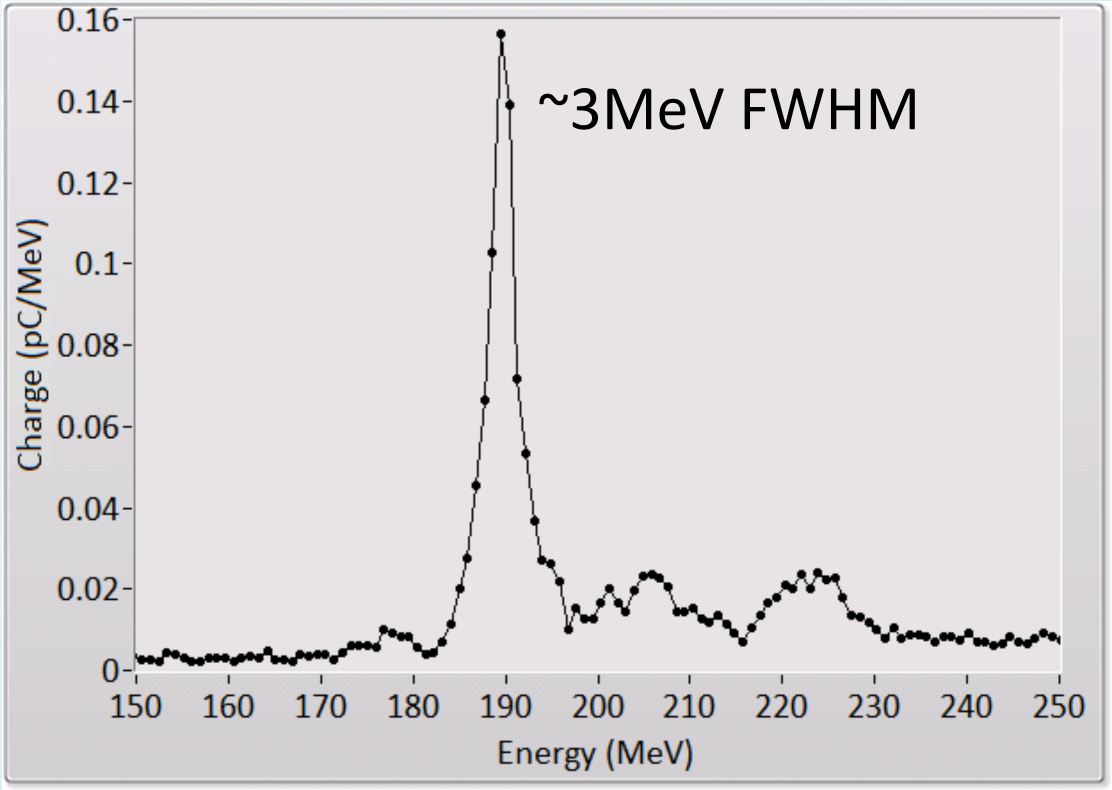
Stable e-beams from jet+capillary: 2% energy variation; 6% charge variation



Percent-level energy spread also observed from jet+capillary

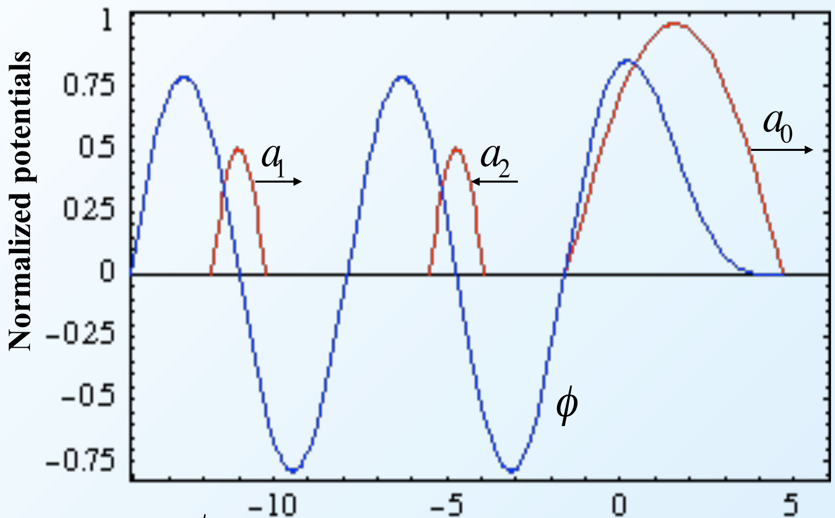




Slow beat wave of colliding pulses: boost momentum into trapped orbit

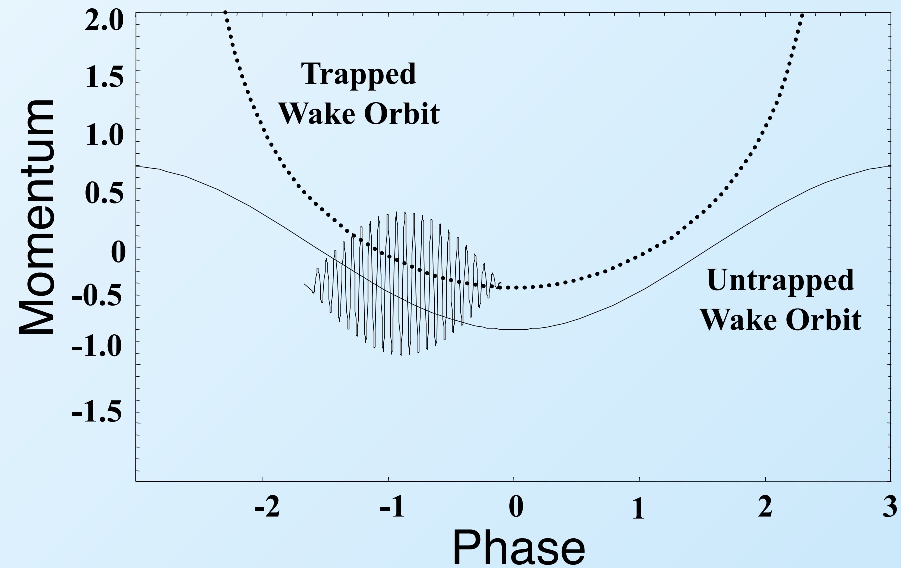
Colliding pulse injection: 3 pulses

Concept

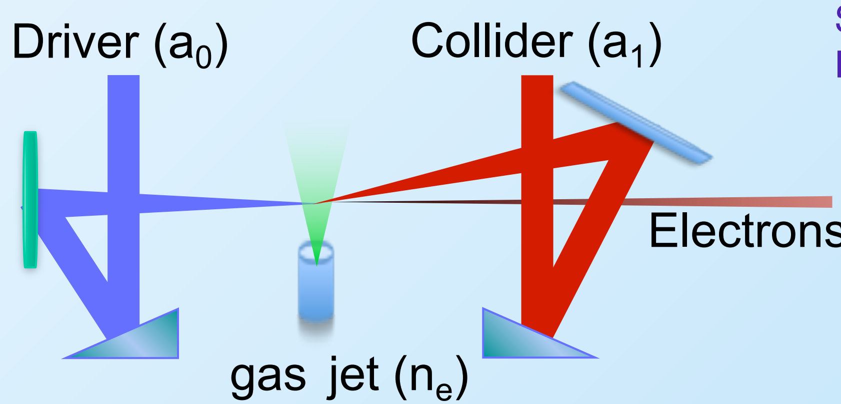


ψ = plasma wake phase = $k_p z - \omega_p t$

Phase Space

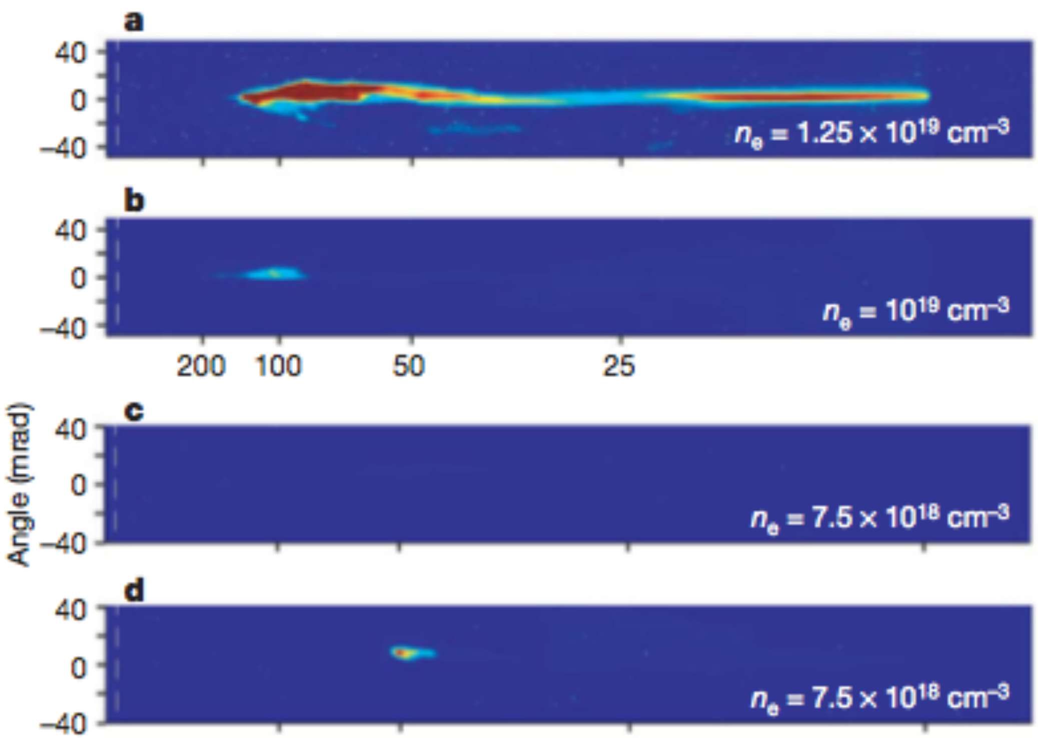


Experiments: 2 pulses

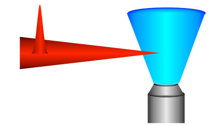


Esarey et al. PRL (1997);
Schroeder et al. PRE (1999);
Fubiani et al. PRE (2004)

Colliding Pulse Showed Injection At Low Density

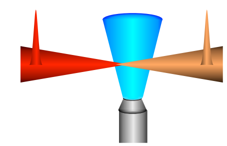


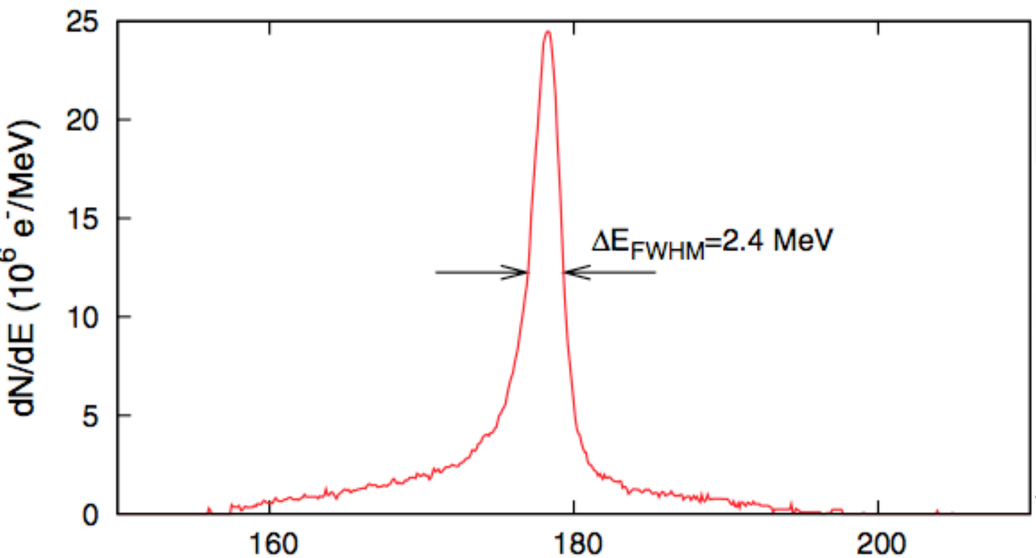
Single pulse injection at high density



Density too low for injection

Colliding pulse enables injection



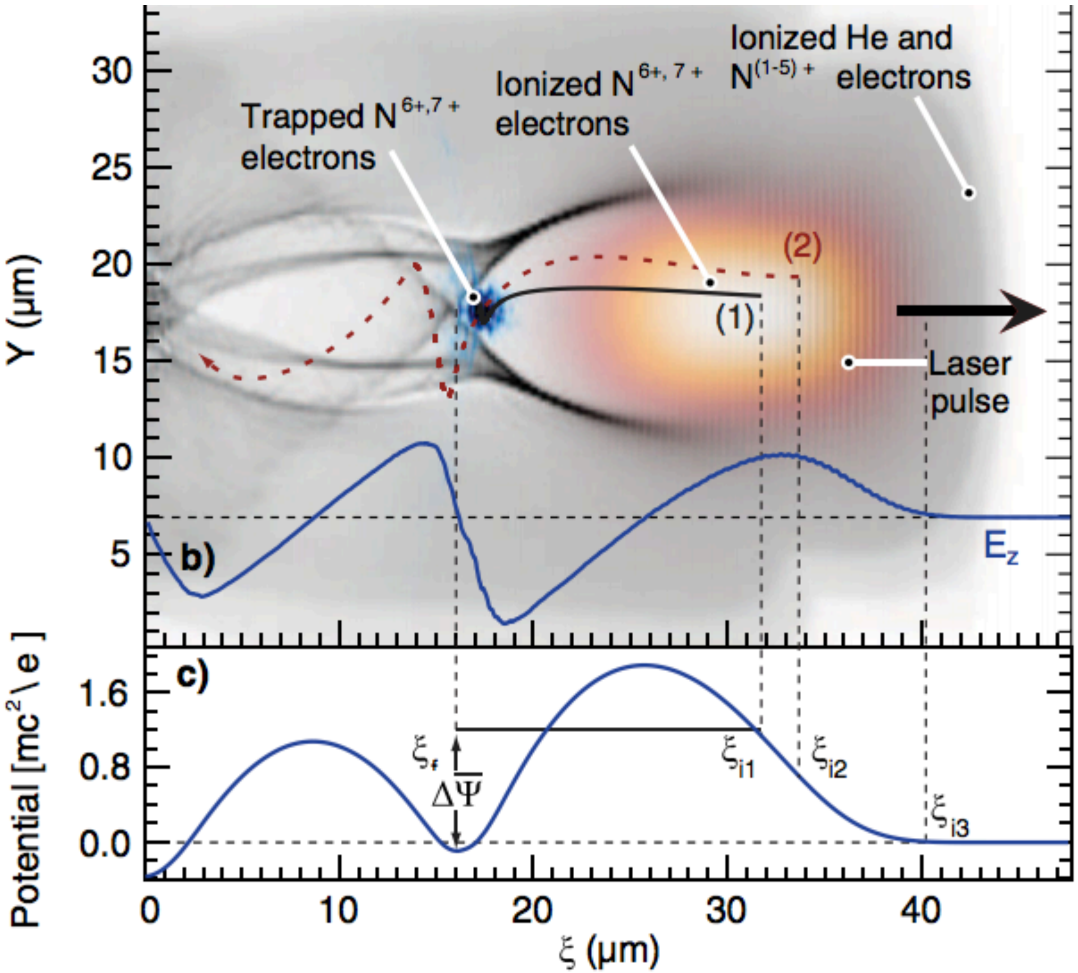


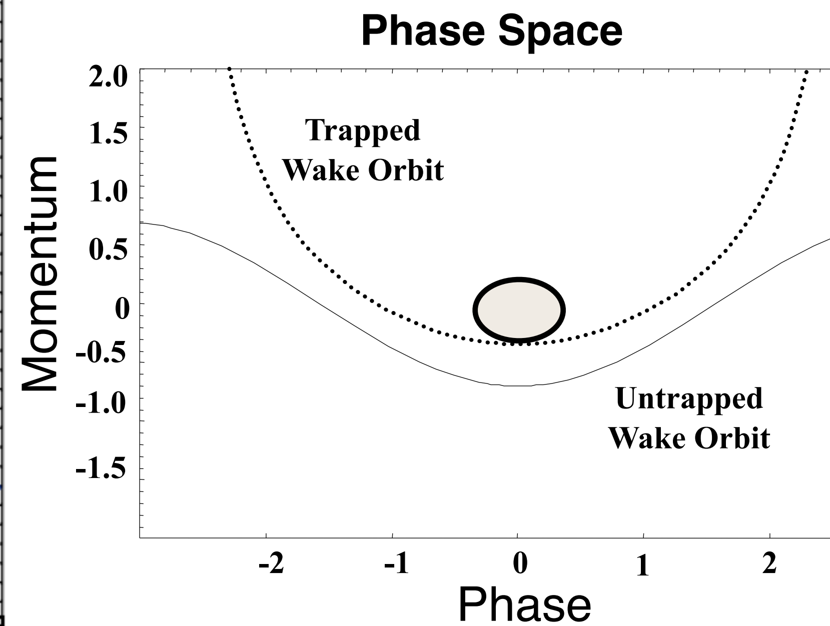
Energy spread 1% (10 pc)

LOA, France:

J. Faure *et al.*, Nature (2006);
C. Rechatin *et al.*, Phys. Rev. Lett. (2009)
O. Lundh et al., Nature Physics, (2011)

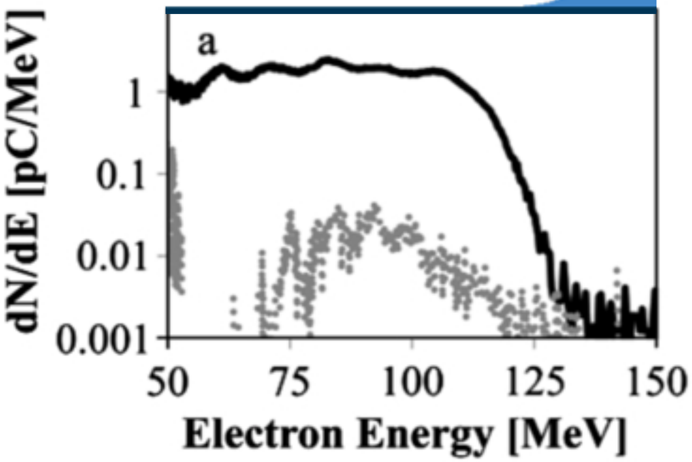
Ionization at peak of laser pulse: place electrons at correct phase for injection

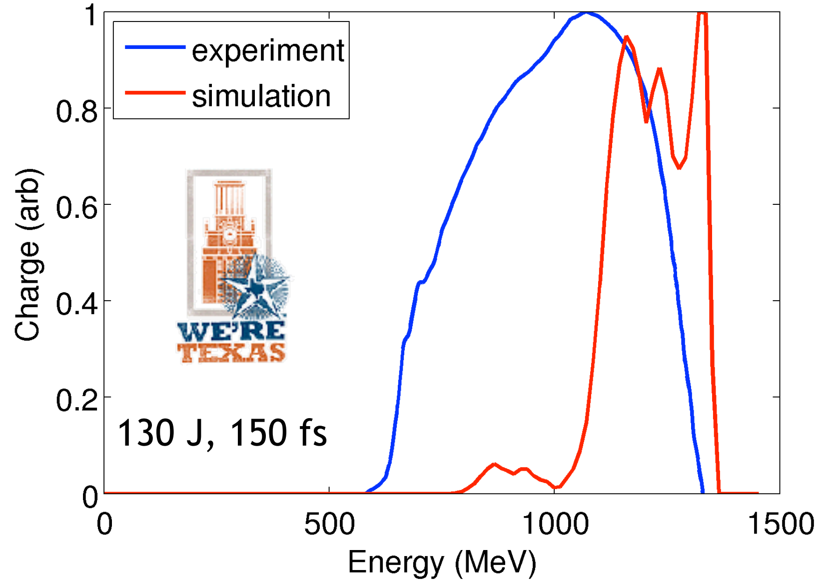


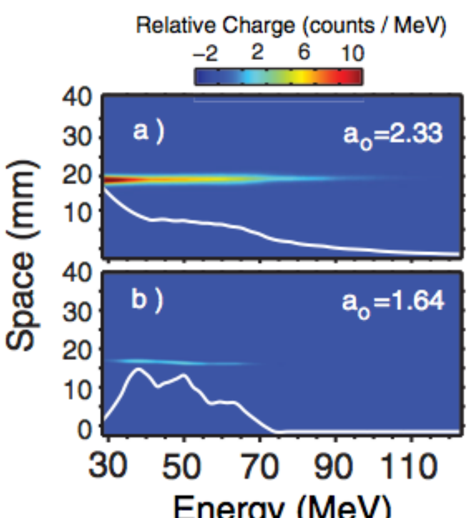


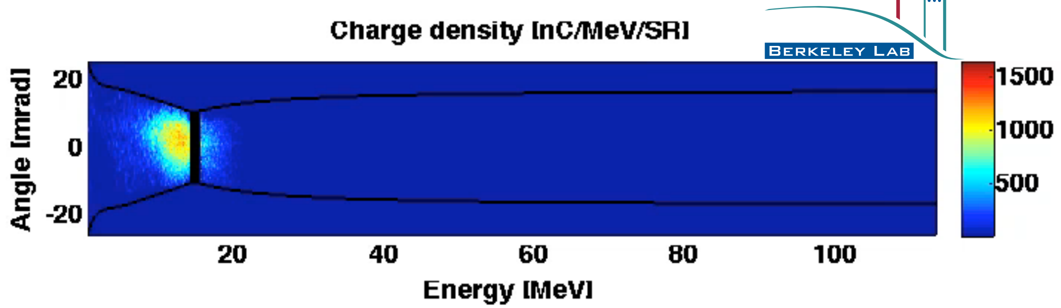
M. Chen et al., JAP (06); T. Rowlands-Rees et al., PRL (08); Pak et al., PRL (10); C. McGuffey et al., PRL (10)

Ionization Injection Demonstrated By Several Groups



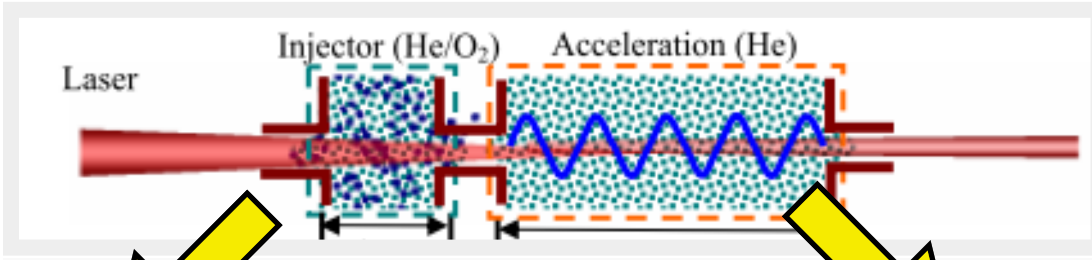




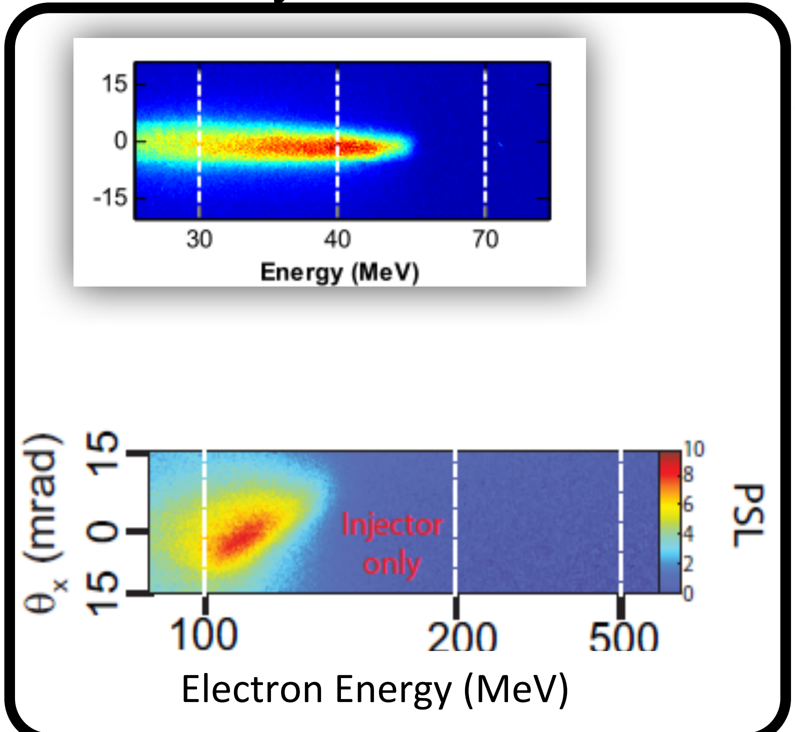


Pak et al.; PRL **104**, (10); C. McGuffey et al.; PRL. **104**, (10); talk by X. Wang

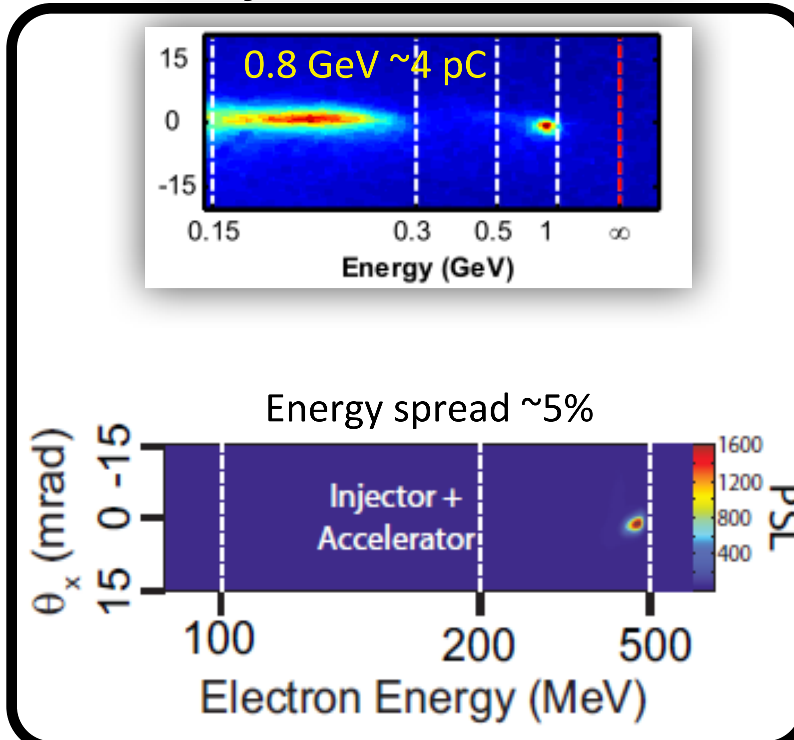
Energy spread reduced by mixed gas injector & pure He accelerator



Injector

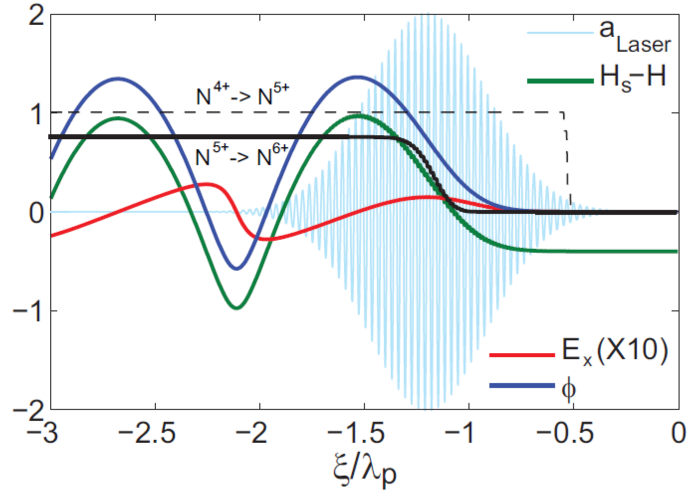


Injector+Accelerator

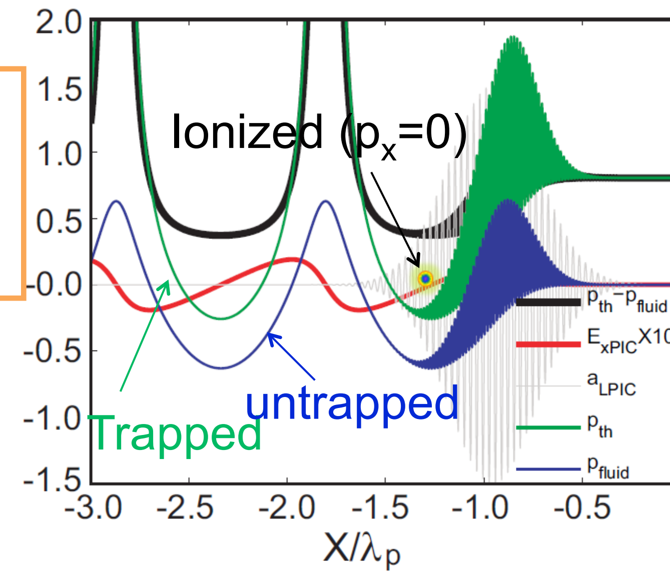


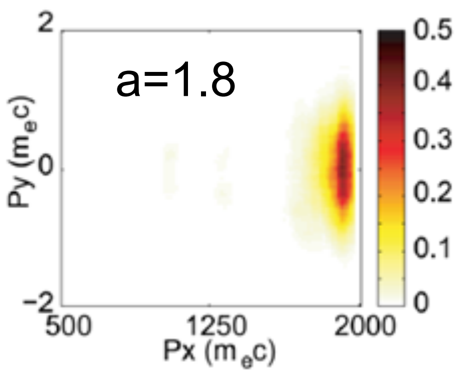
J.S. Liu et al., Phys. Rev. Lett. 107, 035001 (2011); B.B. Pollock et.al., PRL 107, 045001 (2011)

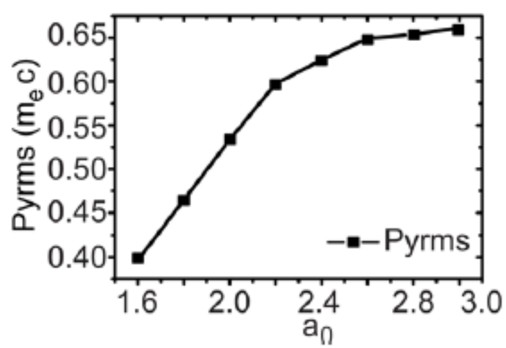
Ionization injection: transverse momentum spread

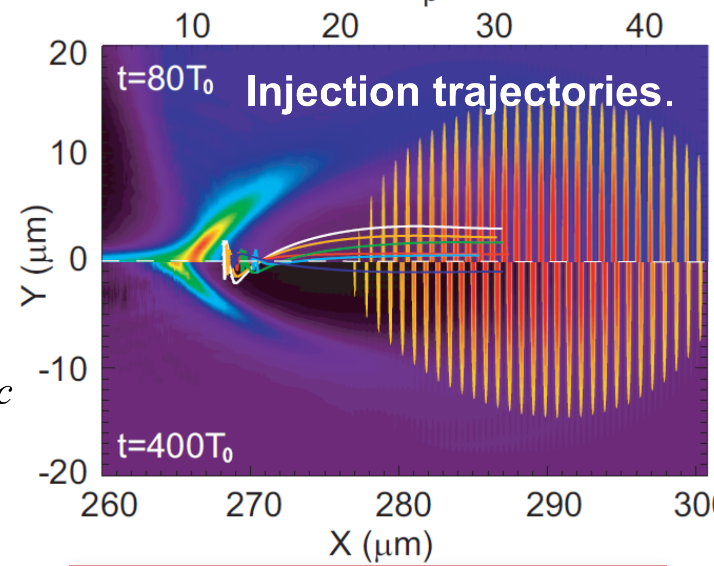


Injected electrons: Ionization of high atomic states near peak of laser pulse.









Transverse momentum spread due to residual momentum and large transverse injection area
(δP_{yFWHM}>**1.0m_ec**)

$$p_\perp + qA_\perp / c = \text{constant}$$
$$p_{\perp f} = A_\perp\left(t = t_{ionization}\right)/c$$

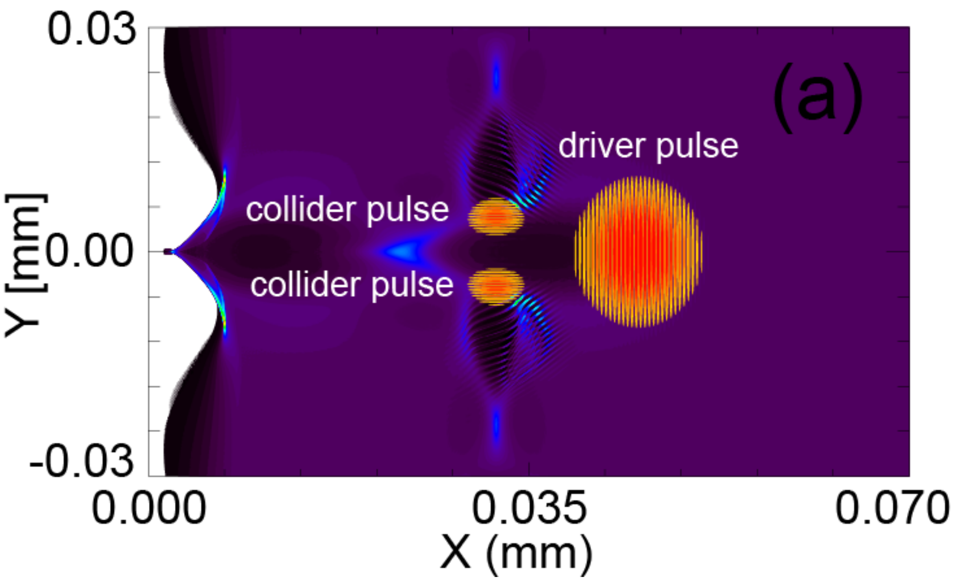
Larger transverse injection area.

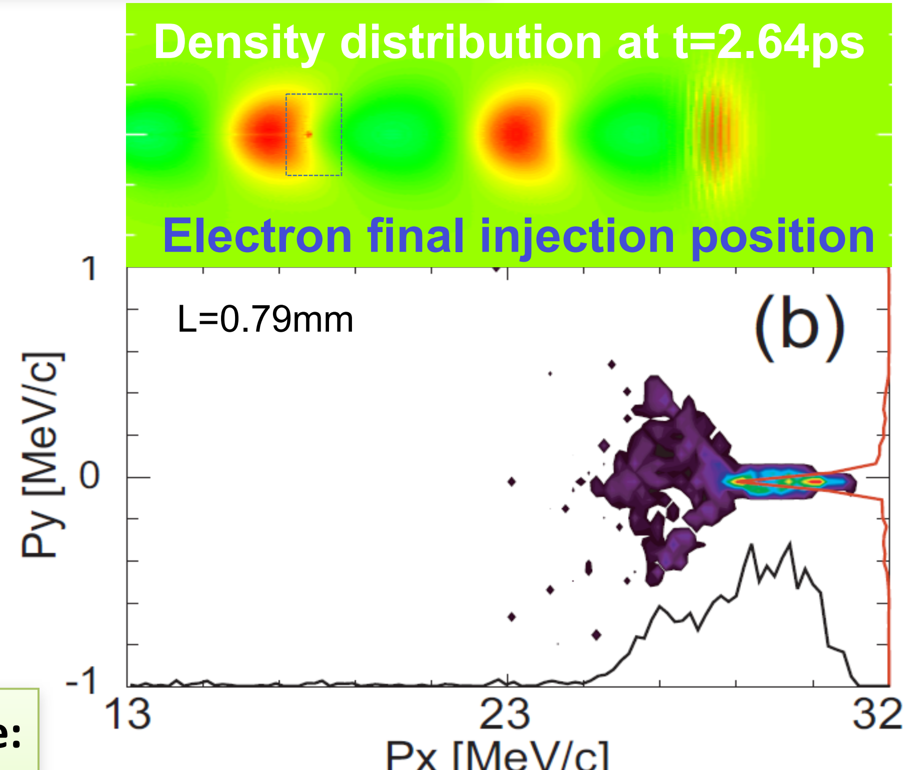
M. Chen et al., Phys Plasmas (2012)

Transverse colliding pulse + ionization injection: small emittance bunch

To get low transverse emittance injection:

1. Electrons have low initial transverse momentum at injection position
2. Injection position should be as close to the bubble axis as possible





Simulations show low transverse emittance:

$<0.08 m_e c$, $\sigma_b < 1 \mu m$, $\varepsilon_N \sim 0.05 \mu m$

Ionization can increase charge ~ 10 pC

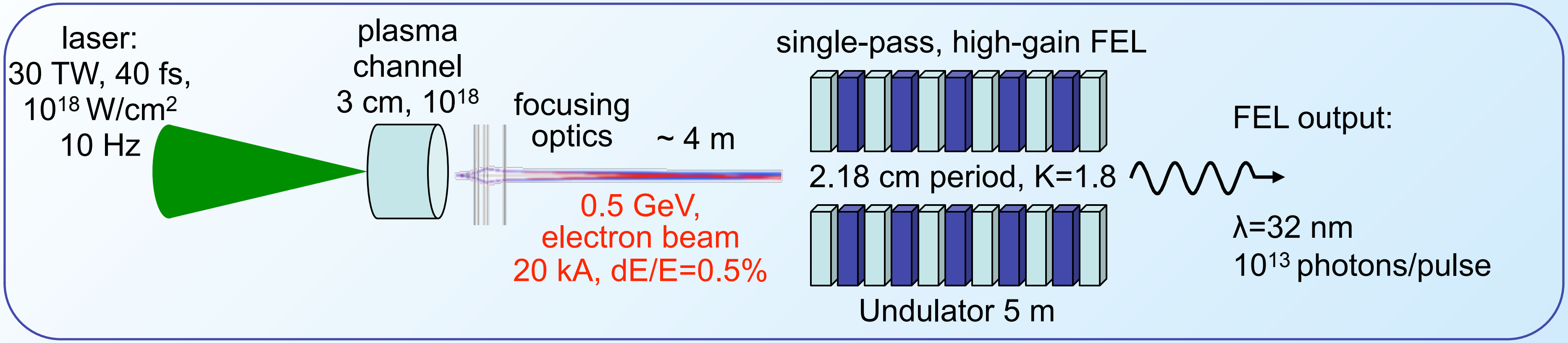
M. Chen et al., submitted (2012)

LPA beam parameters achievable today

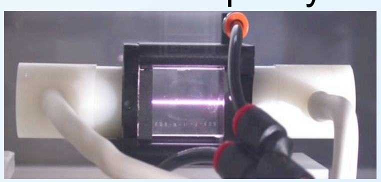
- Energy: ~ 100 MeV - 1 GeV
  - Using 10-100 TW lasers and mm - cm long plasmas
- Charge: ~ 1 - 100 pC
  - Depends on tuning, energy spread due to beam loading
- Energy spread: ~ 1 - 10% level
  - Depends on amount of charge, trapping physics
- Normalized Emittance: ~ 0.1 micron
  - Based on divergence (~ 1 mrad) and e-beam spot (~ 0.1 micron)
- Bunch duration: ~ 1 - 10 fs
  - Based on optical probe, CTR, and THz measurements
- Rep. rate (laser system): 1 - 10 Hz
  - Limited by availability of high average power lasers
- Foot-print (laser system): ~ (few meter) x (few meter)

Driver for GeV Laser Plasma Accelerator:
Commercial 30 W-average (10 Hz), 100 TW-peak laser system

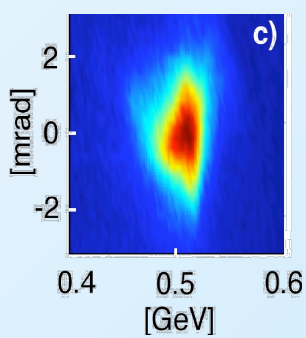
Laser-plasma accelerator driven XUV FEL at LBNL



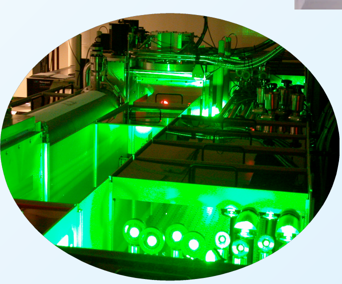
Plasma capillary



LPA e-beam

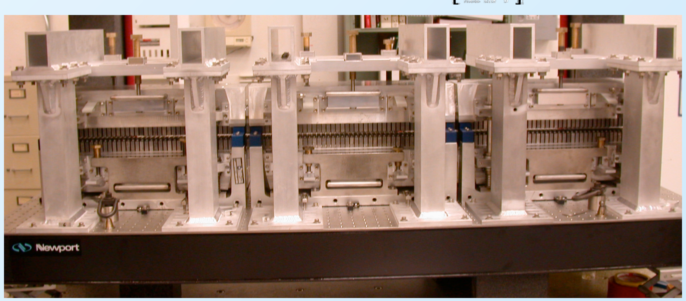


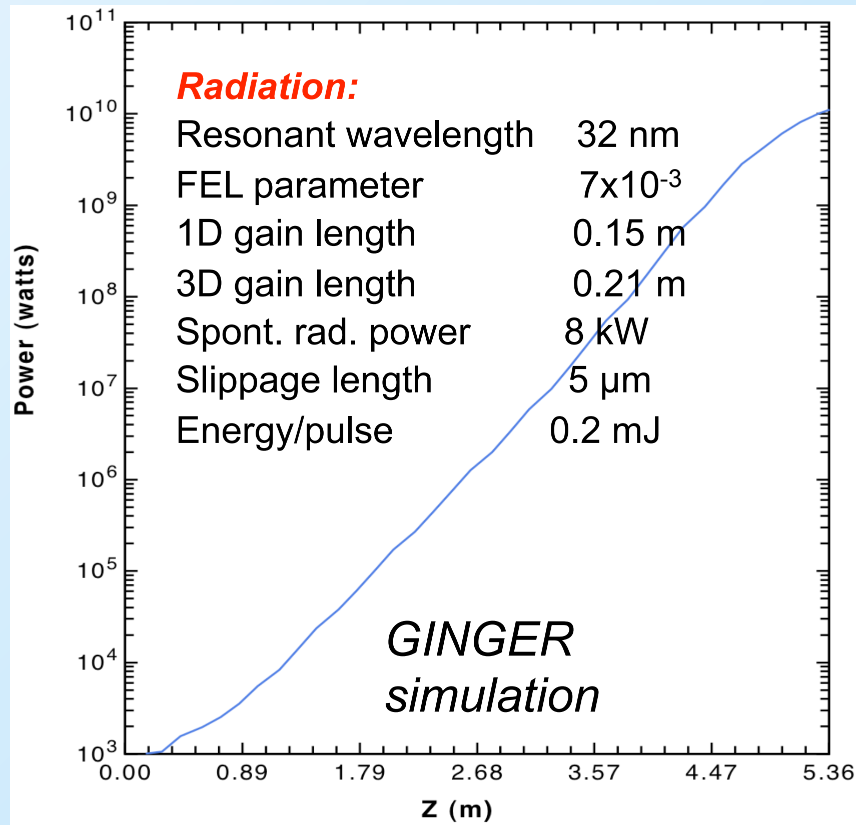
Ti:Al_2O_3 laser



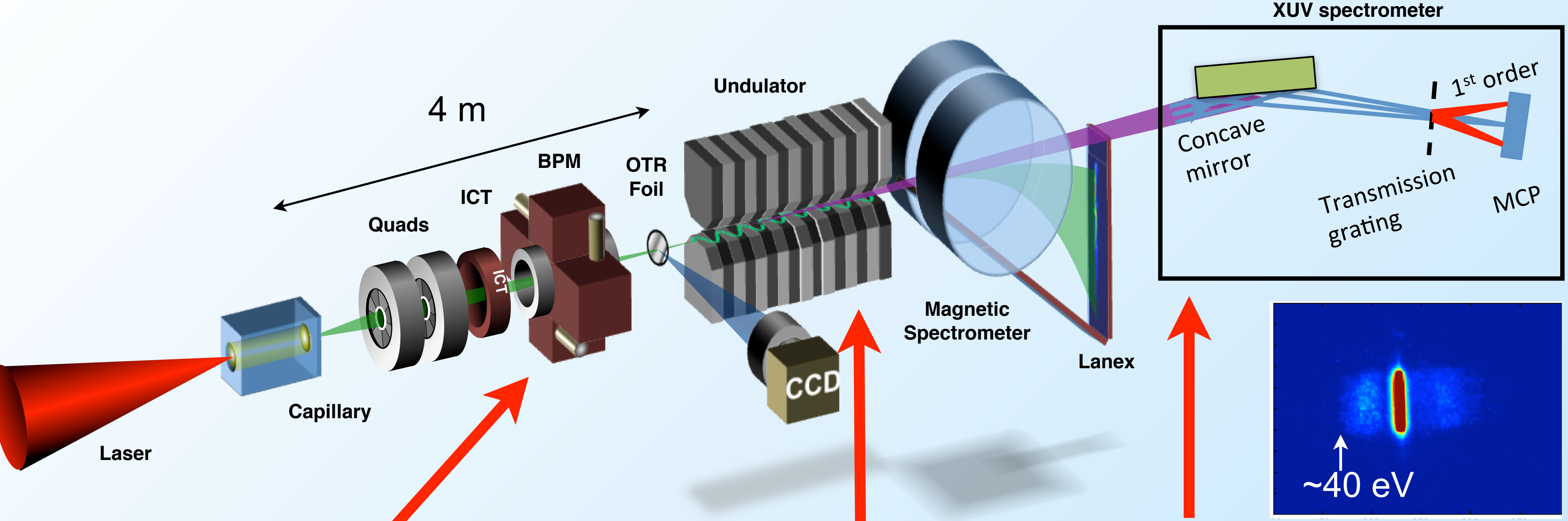
conventional undulator (THUNDER)

K. Robinson et al., IEEE QE (1987)

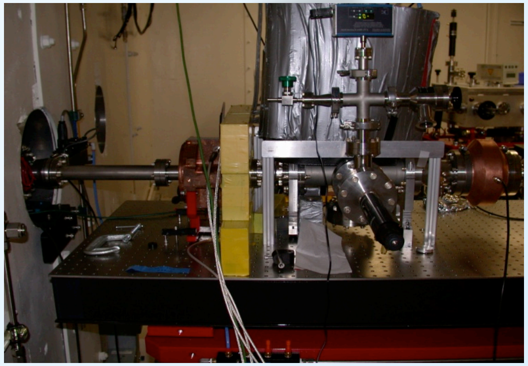




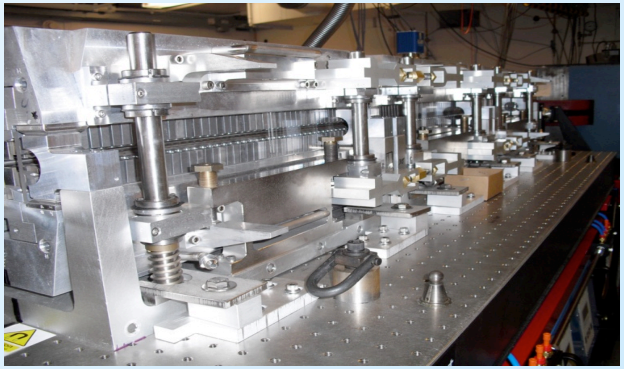
Coupling LPA electron beam to undulator at LBNL



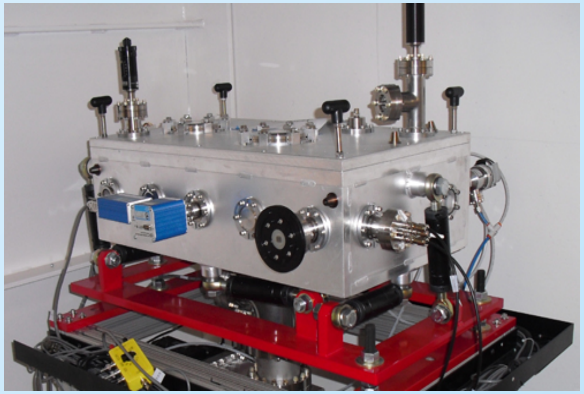
BPM & OTR



THUNDER Undulator



XUV Spectrometer



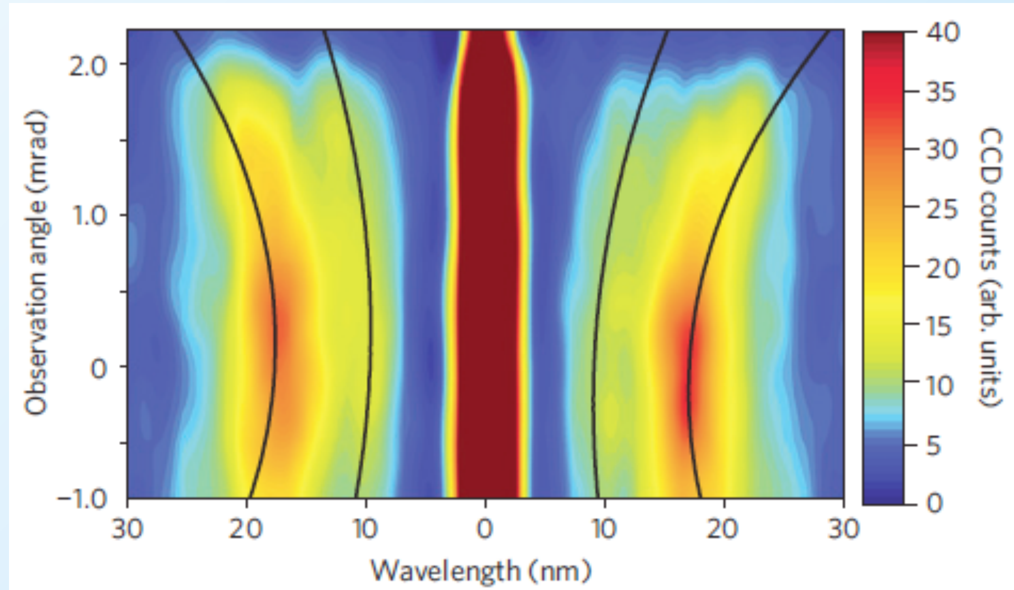
- Diagnostic of electron beam (emittance and energy spread)

Experimental measurement of undulator radiation at MPQ

M. Fuchs et al., Nature Physics (2009)

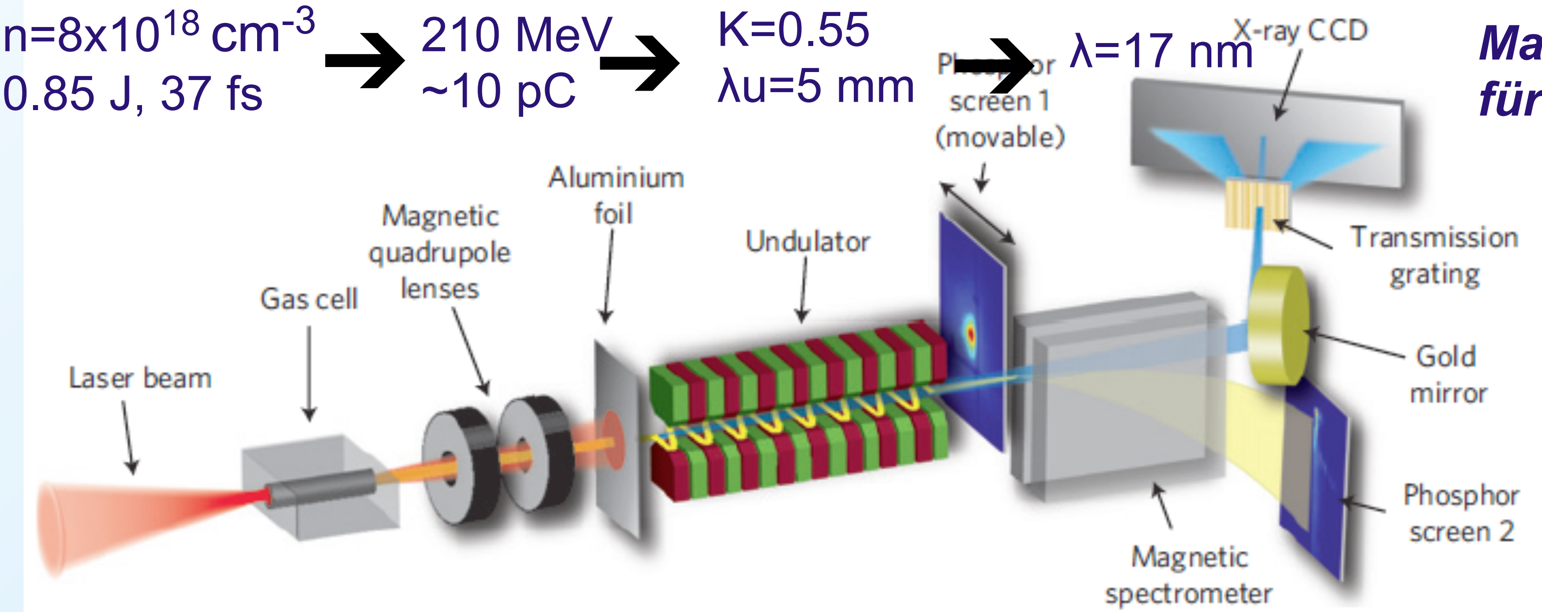
- Measured 1st and 2nd harmonic:

$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$



n=8x10[18] cm[-3] 0.85 J, 37 fs → 210 MeV ~10 pC → K=0.55 λu=5 mm → λ=17 nm

Max-Plank-Institut für Quantenoptik



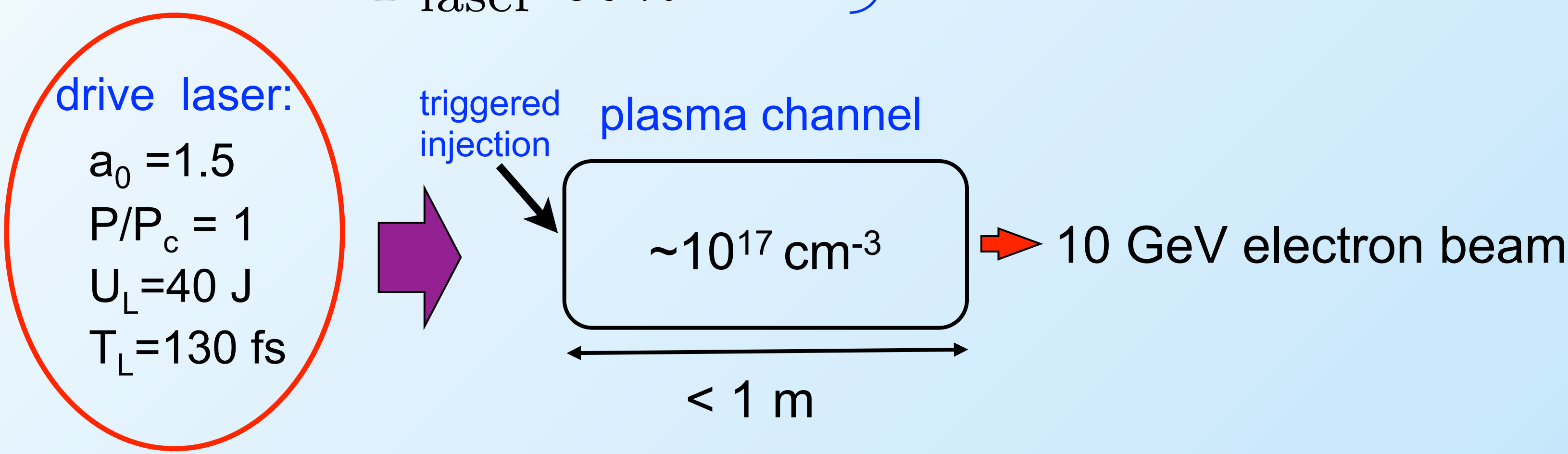
10 GeV laser-plasma accelerator requires ~ 10 J laser

Plasma density scalings:

Energy gain: $W \sim (mc\omega_p/e)\,L_{\rm acc} \propto 1/n$ ➡ low density plasmas (~10^{17} cm^{-3})

Accelerator length: $L_{\rm acc} \sim \lambda_p^3/\lambda_L^2 \propto n^{-3/2}$ ➡ long plasma channels (~m)

Laser energy/power:
$$U_{\rm laser} \propto n^{-3/2}$$
$$P_{\rm laser} \propto n^{-1}$$
➡ more laser energy (~10 J)



BELLA: BErkeley Lab Laser Accelerator

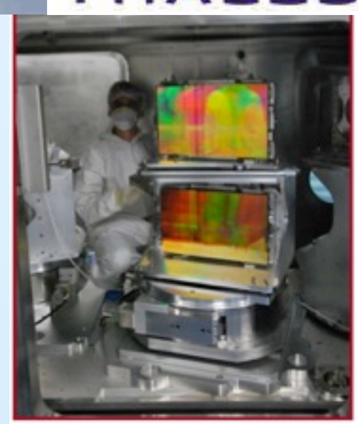
BELLA Project at LBNL:
>40 J in <40 fs at 1 Hz laser and supporting infrastructure

1 PW laser facility

10 GeV e-beam from a meter long plasma

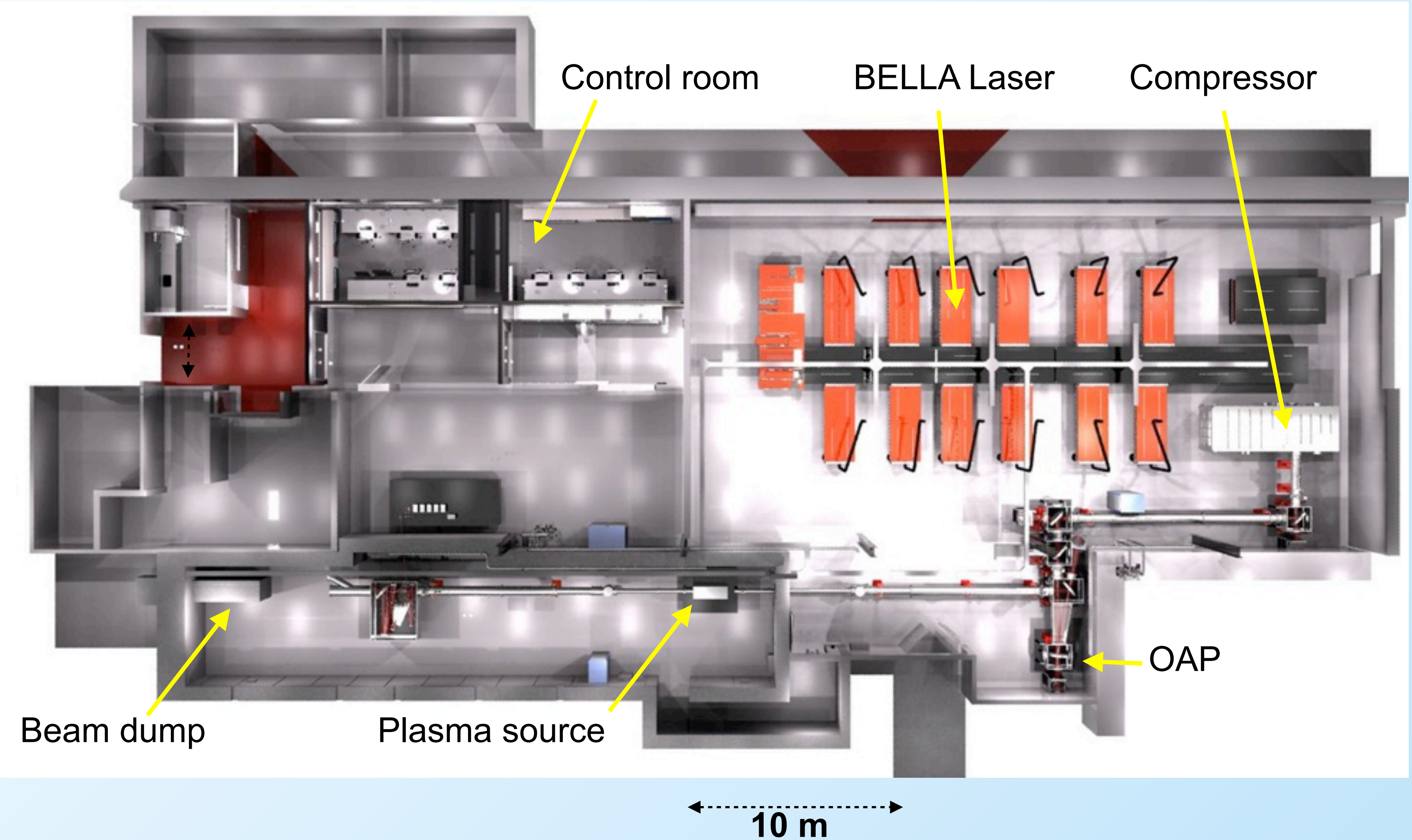
BELLA Project funded by:
Office of Science High Energy Physics

Schedule:
Laser commissioned mid-2012
First LPA expts.: October 2012



BELLA

BELLA Facility: state-of-the-art PW-laser for laser accelerator science



BELLA

LPA 6D beam brightness comparable to conventional sources

$$B_{6\mathrm{D}} = \frac{N}{\epsilon_{nx}\epsilon_{ny}\epsilon_{nz}} \approx \frac{(I/I_A)}{r_e \epsilon_n^2 \sigma_\gamma} = b_6 \lambda_c^{-3}$$

LPA

ε_N = 0.1 micron
0.5 GeV
4% energy spread
I = 3 kA (~5 fs)

$b_6 \sim 9 \times 10^{-12}$

LCLS

ε_N = 0.4 micron
13.6 GeV
0.01% energy spread
I = 3 kA

$b_6 \sim 9 \times 10^{-12}$

- Energy spread order of magnitude too large (for soft-x-ray FEL; $\rho \sim$ few $\times 10^{-3}$)
- Bunch duration < slippage length (for soft x-ray FEL)
- Emittance exchange?

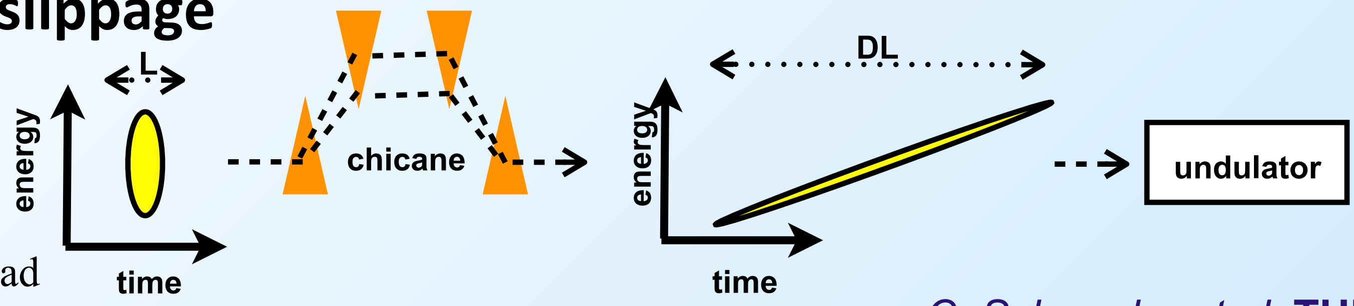
Application of (experimentally demonstrated) LPA beams to FELs

Beam stretching:

Mitigates slippage

LPA e-beam

$\varepsilon_N = 0.1$ micron
500 MeV
2% (rms) energy spread
I = 5 kA

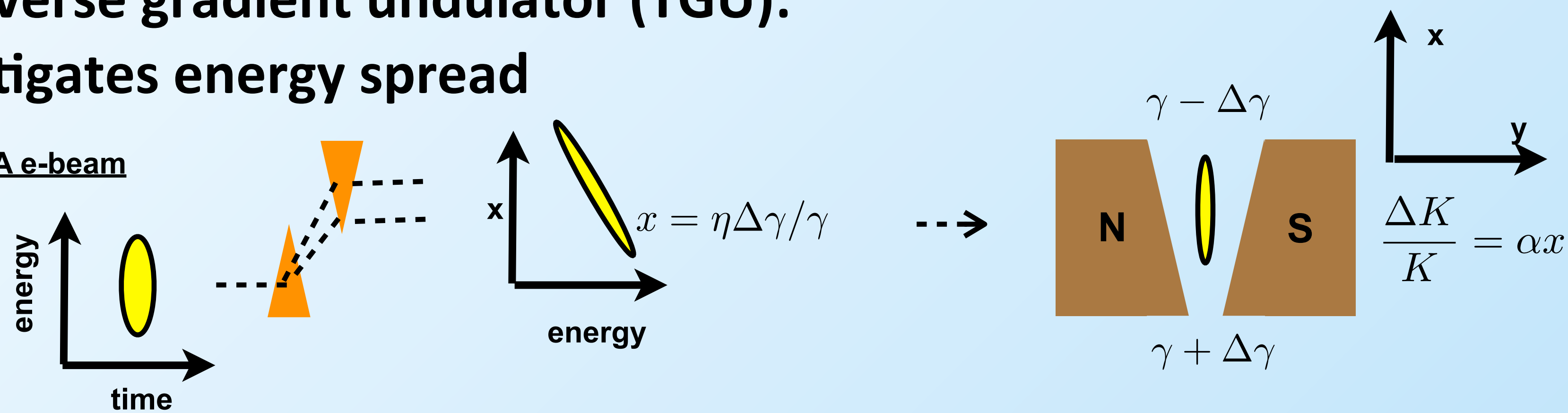


C. Schroeder et al, **THPD57**

Transverse gradient undulator (TGU):

Mitigates energy spread

LPA e-beam



Z. Huang et al, **THOB02**

Potential impact of LPA for future compact light source development

- *Compact accelerator*: multi-GeV beam from LPA: ~10-100 GV/m
  - Plasma accelerator: 1-10 GeV in < 1 m
  - Entire accelerator (laser) facility < 100 m^2, "university scale"
- *Ultra-short (moderate charge) bunch generation*:
  - 1-10 fs, 1-100 pC, high peak current (1-10 kA)
- *Intrinsically synchronized* particles and light
  - seeding (from laser harmonics)
  - pump-probe experiments
- *Hyper-spectral* (ultrashort x-rays, gamma rays, THz, protons, etc.)
- *Flexible*: single laser system drive multiple LPAs, multiple beamlines
- *High peak brightness source*:
  - average brightness presently limited by average laser power
  - advances (over next decade) in lasers (high average power, efficiency) will enable high average power applications