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U.S. DEPARTMENT OF ENERGY
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Prospects for a Laser-Plasma Accelerator based FEL

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Outline

- Present status 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
    - compact 10 GeV LPA

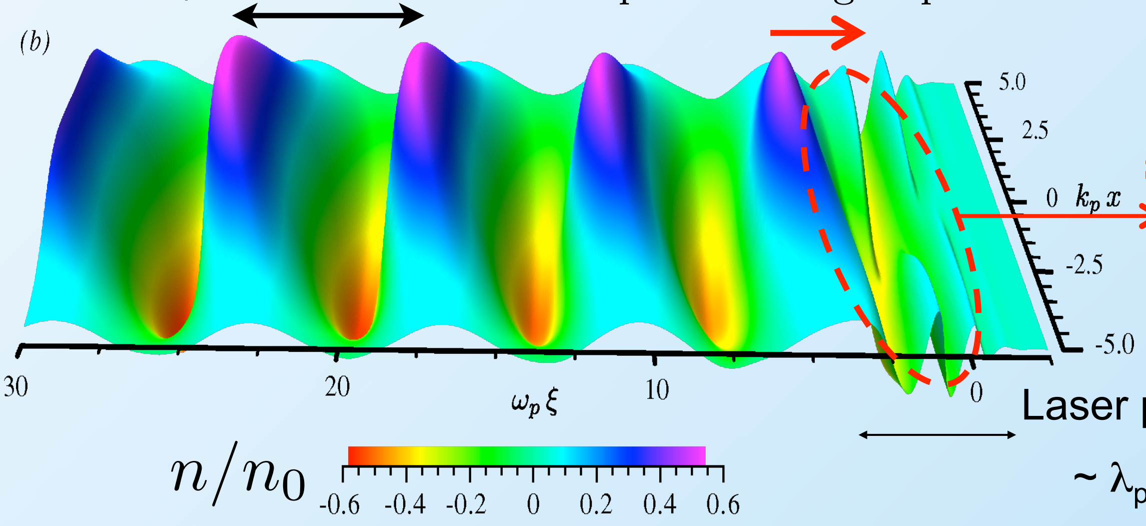
Laser-plasma accelerators (LPAs)

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

$$\underbrace{\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_0}}_{\text{Plasma wave: electron density perturbation}} = \underbrace{c^2\nabla^2\frac{1}{4}\left(\frac{eE_{\mathrm{laser}}}{mc^2\omega}\right)^2}_{\text{Laser ponderomotive force (radiation pressure)}}$$

$\lambda_p = 2\pi c/\omega_p = (\pi r_e^{-1/2})\, n_p^{-1/2} \sim 10\ \mu\mathrm{m}$

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



short pulse, ultra-intense laser: I~10^{18} W/cm^2

Laser pulse duration

~ λ_p/c ~ tens fs

electron plasma density perturbation

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

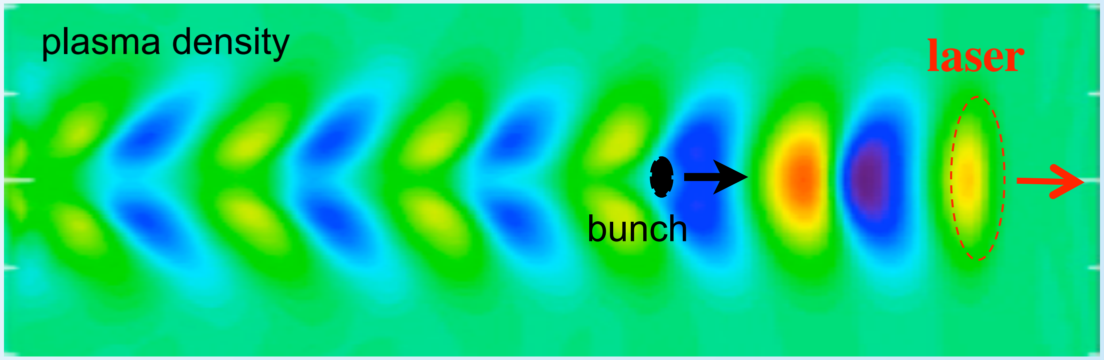
$$E \sim \left(\frac{mc\omega_p}{e}\right) \approx (96\ \mathrm{V/m})\sqrt{n_0[\mathrm{cm}^{-3}]}$$

plasma wave (wakefield) E ~100 GV/m (for n~10^{18} cm^{-3})

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

Accelerating bucket ~ plasma wavelength

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

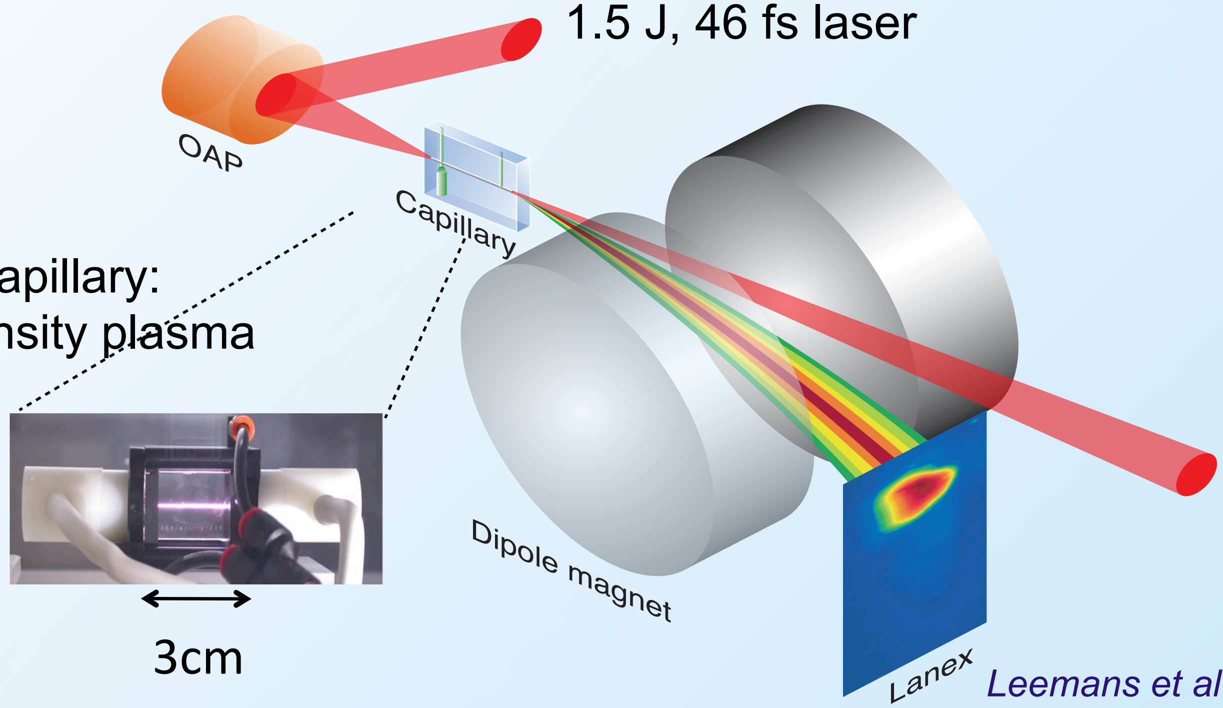


- beam charge (set by beam loading): ~10-100 pC
- beam duration (set by trapping physics and density): <10 fs

} ➔ **high peak current**

~10 kA

Experimental demonstration: GeV Beam in 3 cm using LPA



1.5 J, 46 fs laser

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

3cm

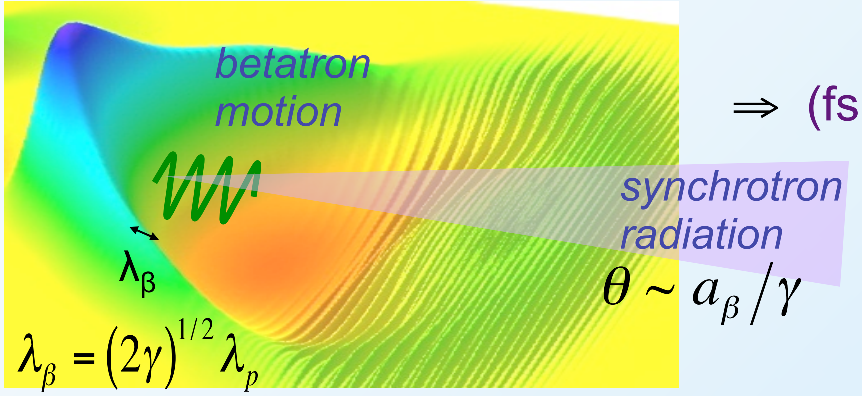
Leemans et al., Nature Phys. (2006)

Strong focusing forces in plasma wave produces synchrotron radiation

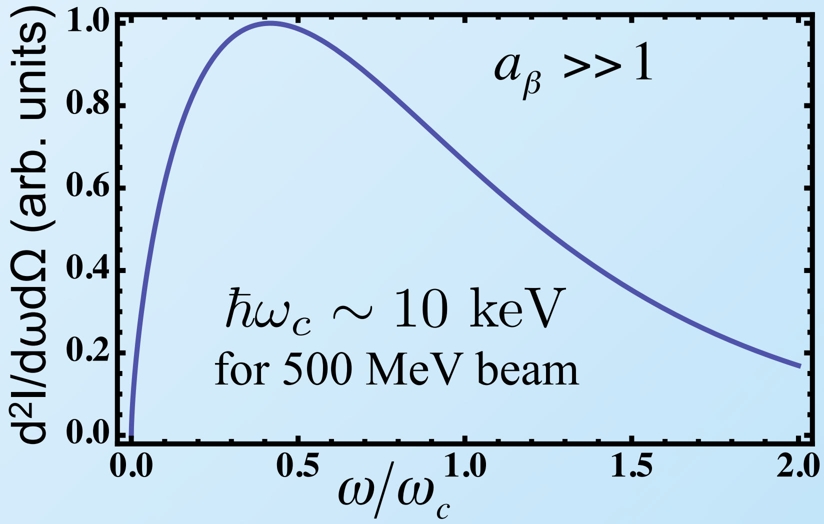
Strong transverse focusing forces of plasma wave:

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

⇒ (fs, broadband, hard x-ray) synchrotron radiation



Esarey et al., PRE (2002)



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

Faraday rotation used to measure bunch length: ~5 fs

A. Buck et al. “Real-time observation of laser-driven electron acceleration.” *Nature Physics*, 7:543, (2011).

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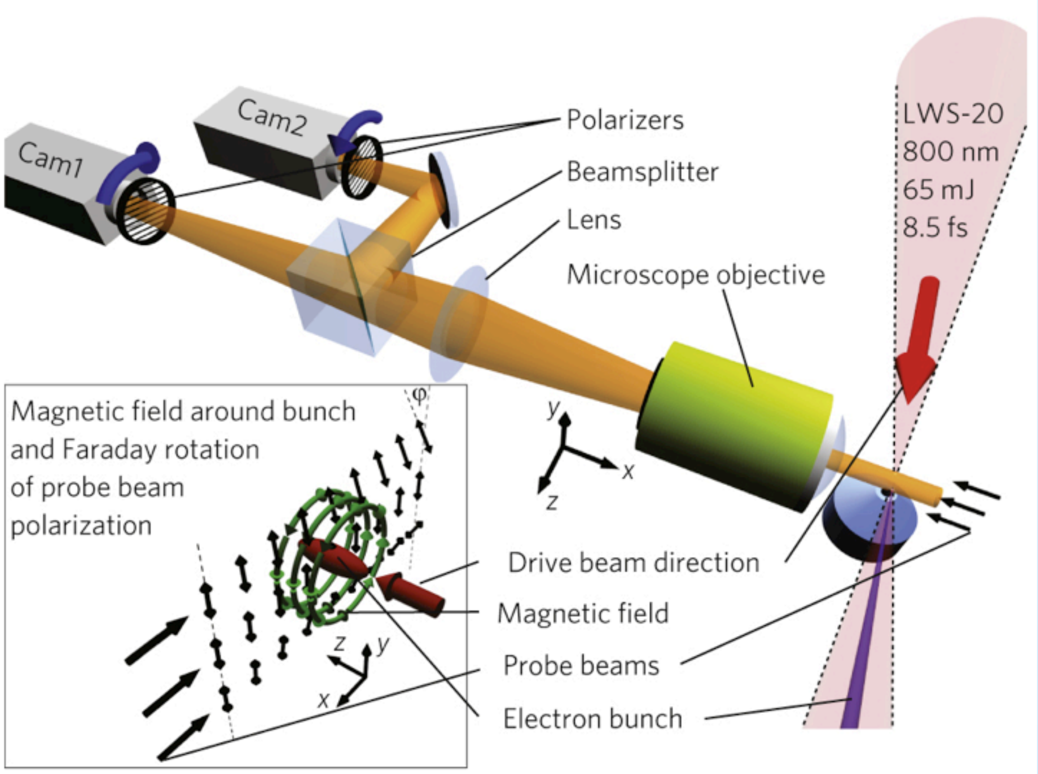
für Quantenoptik



e-beam: 20 MeV, few pC

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

Faraday rotation: R- and L-wave along direction of B in plasma have different phase velocities (polarization rotation)

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 electron bunch duration: **τ = 5.8 fs FWHM**

CTR spectrum used to determine bunch length: ~few fs

Lundh et al., “Few femtosecond, few kiloampere electron bunch produced by a laser–plasma accelerator” Nature Physics, 7:219 (2011).

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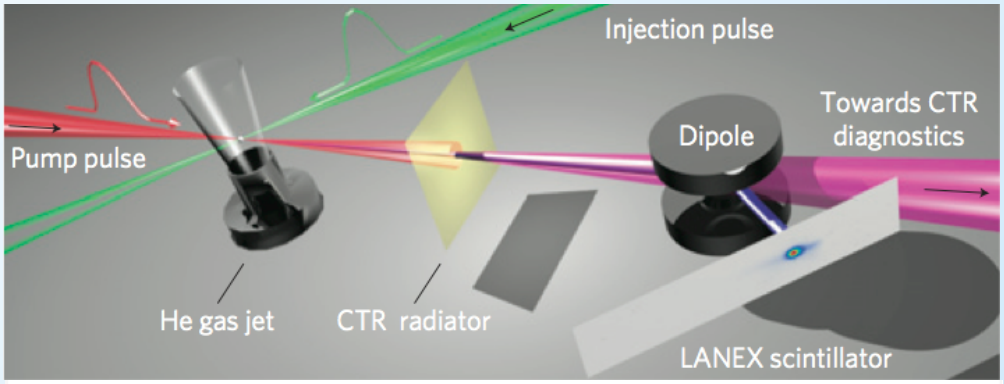
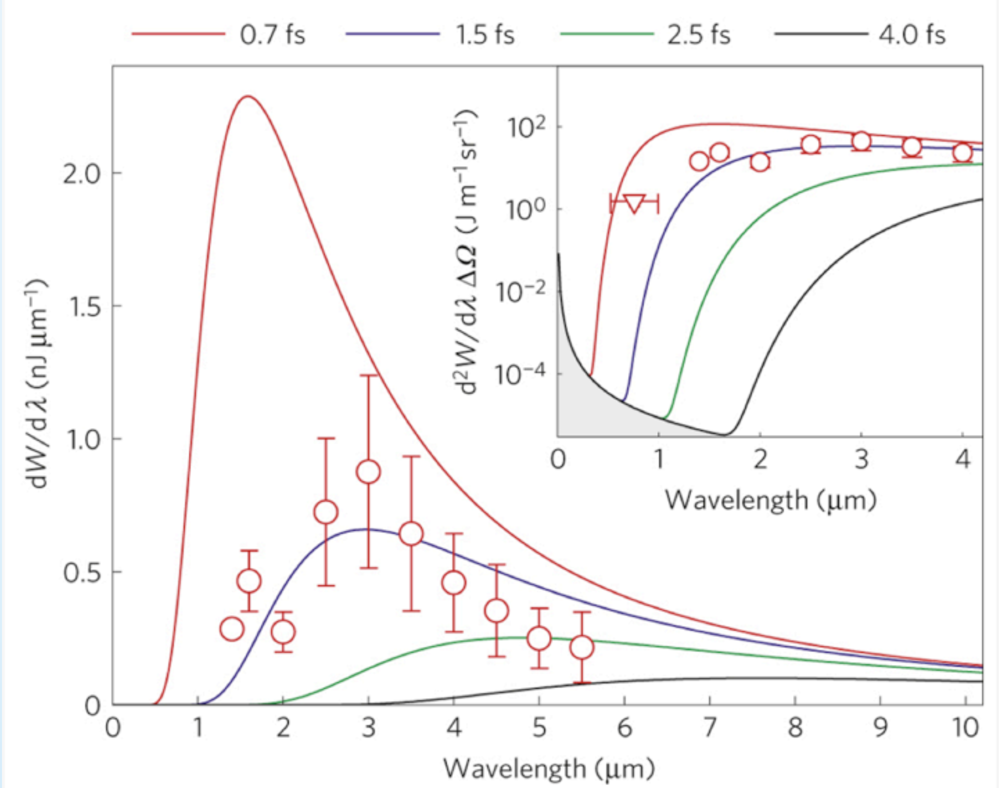
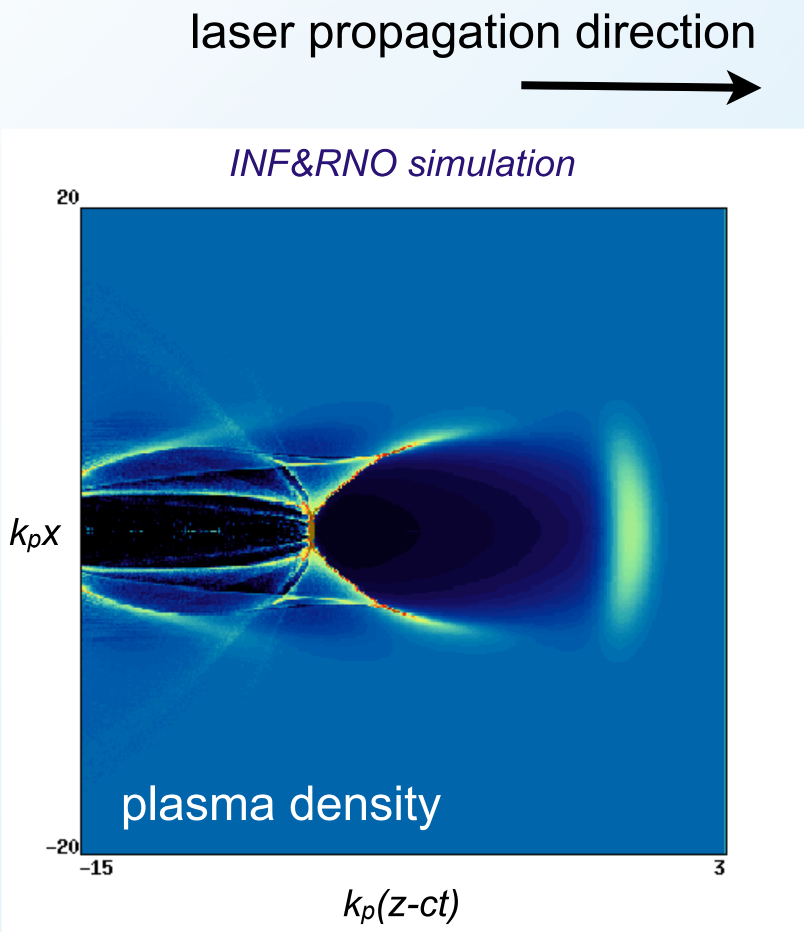


e-beam:
85 MeV, 15 pC



RMS beam duration 1.4 fs
peak current 4 kA

“Bubble regime”: uncontrolled trapping



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

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

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

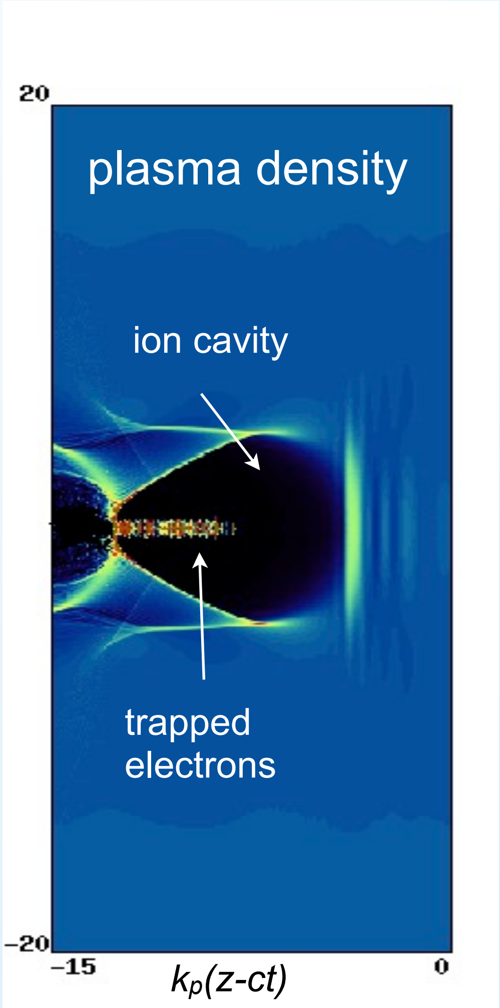
- Low plasma wave phase velocity (and large wave amplitude) allow self-trapping of plasma electrons

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

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

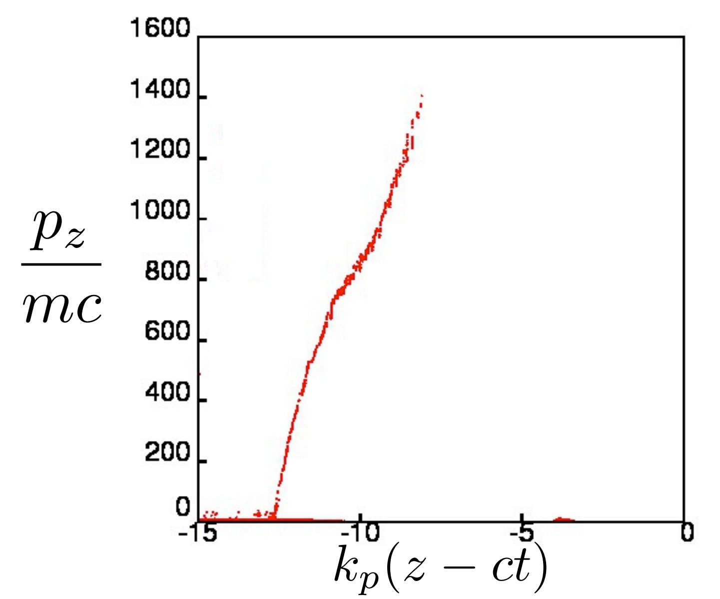
Trapping physics results in large energy spread, chirped energy distribution

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



INF&RNO simulation

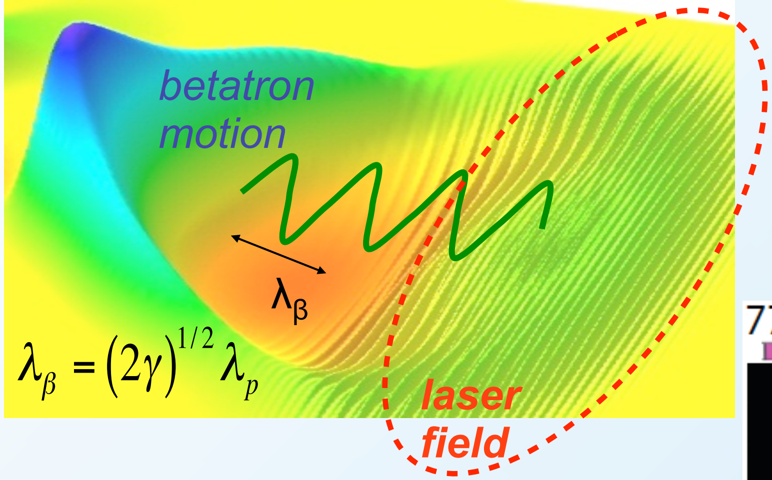
longitudinal phase space



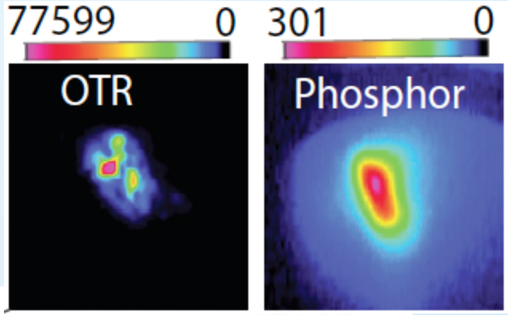
- controlled (triggered) trapping ➡ improve stability and energy spread

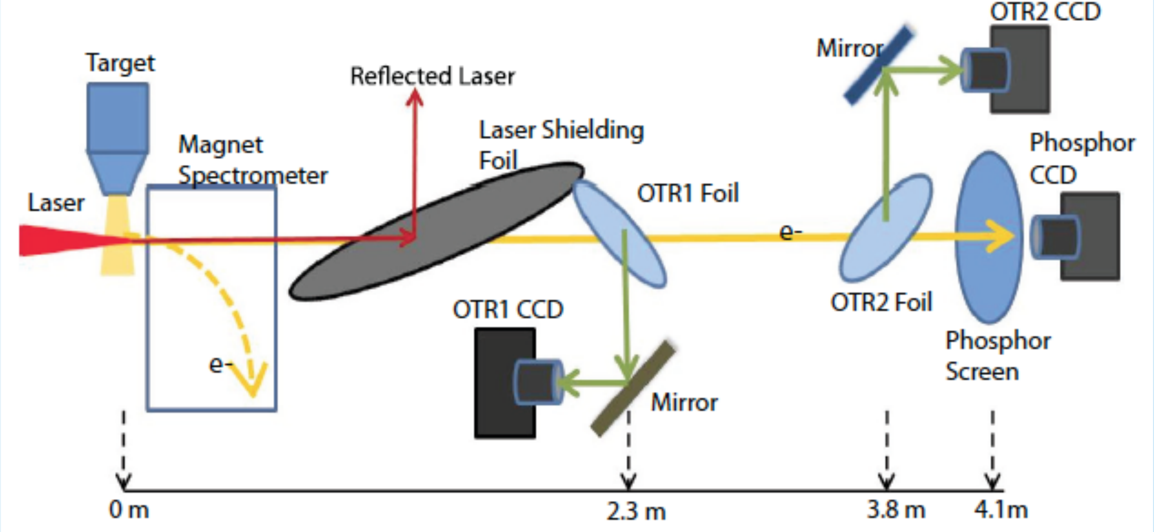
CTR of laser-plasma generated microbunching indicates small slice energy spread

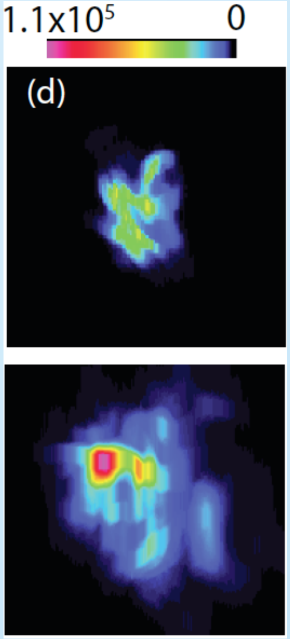
- operate plasma at high density (~10^{19} cm^{-3}) such that λ_p short, laser group velocity slow
- beam interacts with drive laser ➡ momentum modulations (~laser period)



C. Lin et al., PRL (2012)







OTR1

OTR2

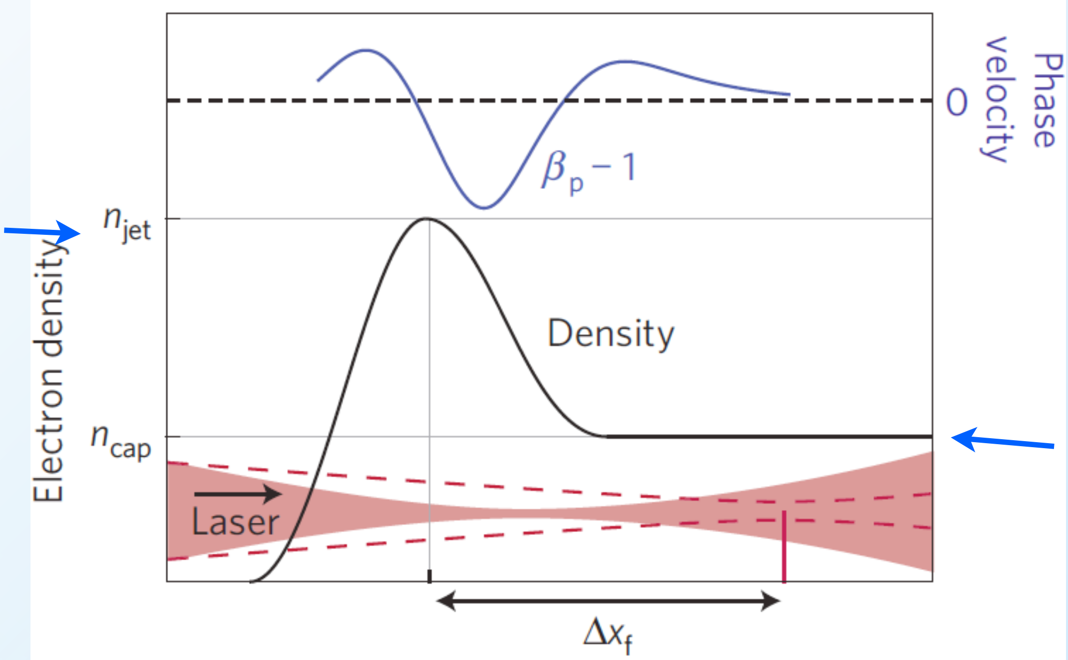
Coherent enhancement observed in spectral range 0.4 - 0.9 micron

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

Plasma density tailoring for triggered injection via phase velocity control

- Couple (short, high plasma density) injector to (long, low density) plasma channel:

Injector, ~mm, n_{jet}~10^{19} cm^{-3}



accelerator: L~cm, n_{cap}~10^{18} cm^{-3}

1. Triggered electron trapping in high plasma density region (low wave phase velocity)

2. Post-acceleration in low plasma density region (high wave phase velocity)

Gonsalves et al., Nature Phys. (2011)

Injection via control of plasma wave phase velocity:

$$\underbrace{\beta_p \approx \beta_g}_{\text{laser group velocity}} \left(1 + |\zeta| \underbrace{\lambda_p^{-1} d\lambda_p/dz}_{\text{plasma wavelength evolution}}\right)^{-1}$$

laser group velocity

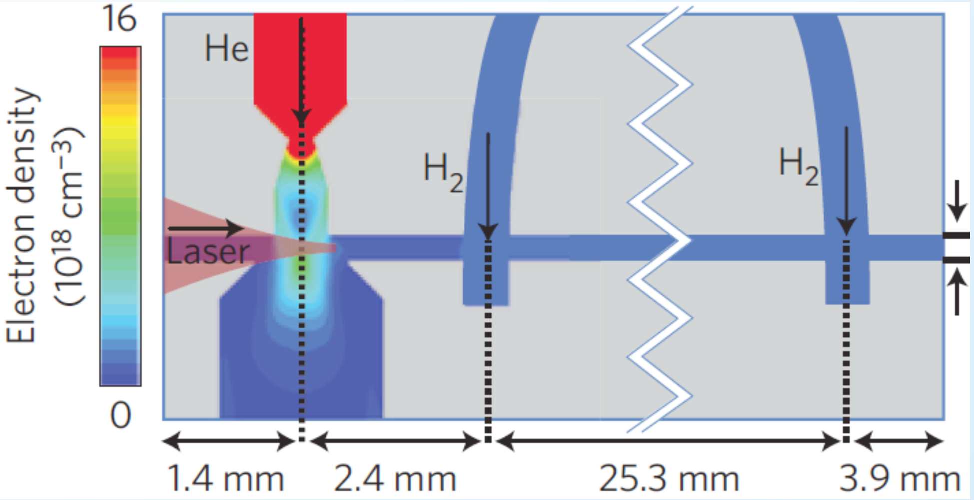
plasma wavelength evolution

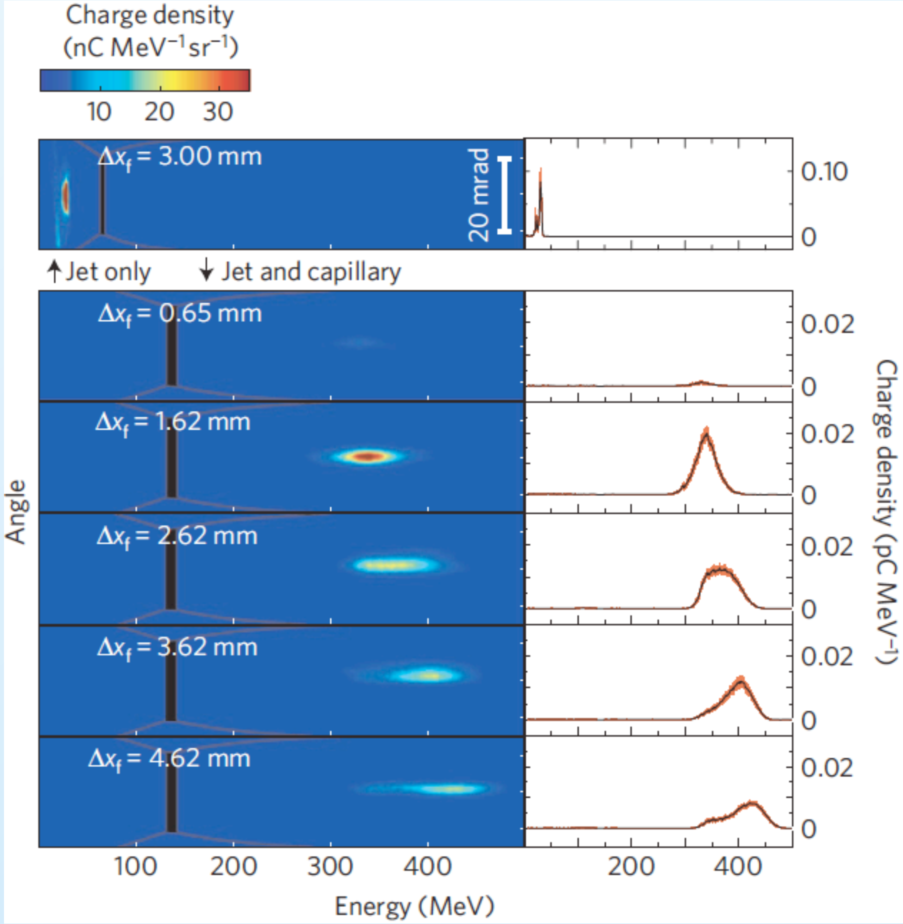
$$\left.\right\} \quad \frac{1}{\lambda_p}\frac{d\lambda_p}{dz} = \underbrace{\frac{1}{2n}\frac{dn}{dz}}_{\text{plasma density evolution}} + \underbrace{\frac{1}{\hat{\lambda}}\frac{d\hat{\lambda}}{d\hat{E}_m}\frac{d\hat{E}_m}{da}\frac{da}{dz}}_{\text{laser evolution: relativistic self-focusing}}$$

Bulanov et al., PRE (1998)
Schroeder et al., PRL (2011)

Integrated injector and accelerator demonstrates improved stability

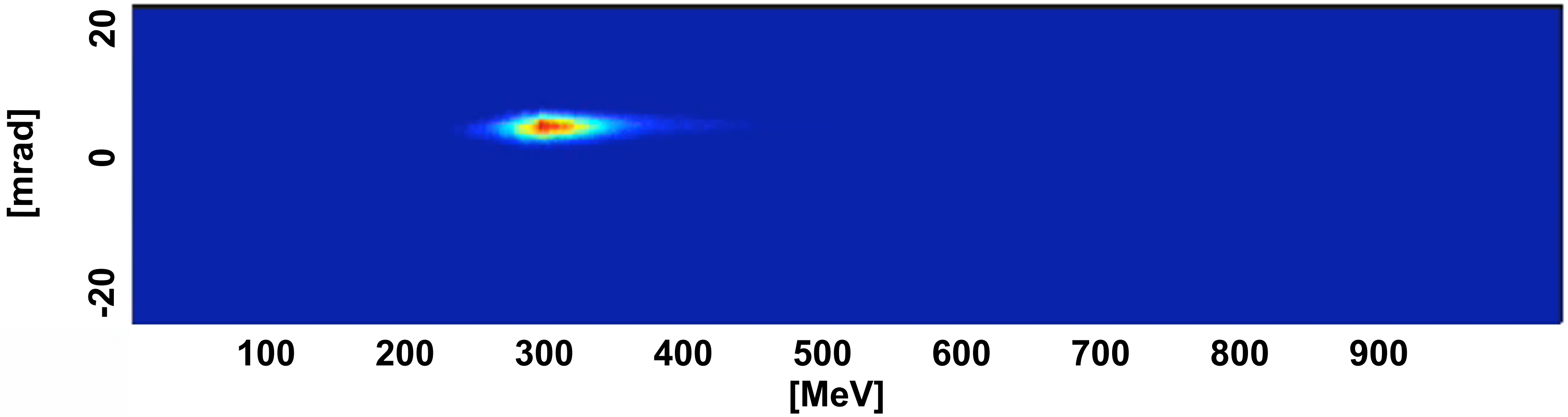
Gonsalves et al., Nature Physics (2011)





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

Gas jet triggered injections provides for enhanced stability & tuning

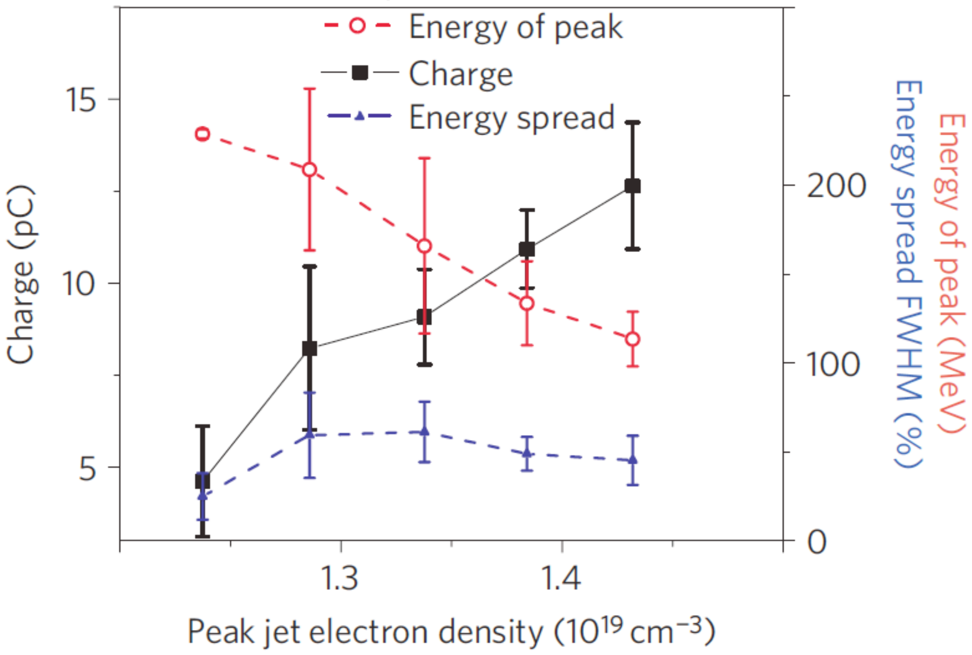


Shot-to-shot e-beam stability:

RMS variation (at 300 MeV):
- 1.9% energy centroid
- 0.57 mrad divergence
- 6% charge

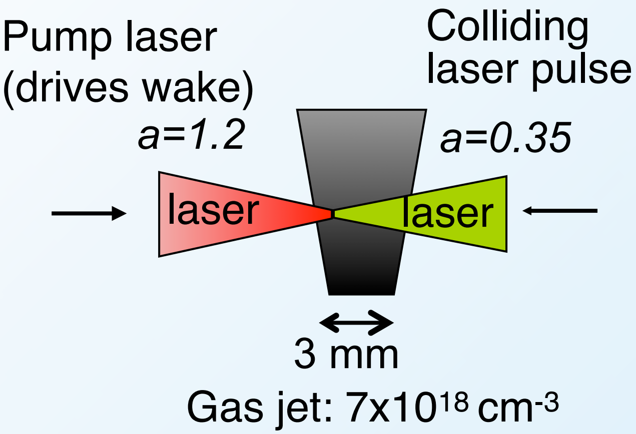
Laser energy fluctuation: 3%

x_f=0.62 mm



Controlled injection using colliding laser pulses improves beam quality

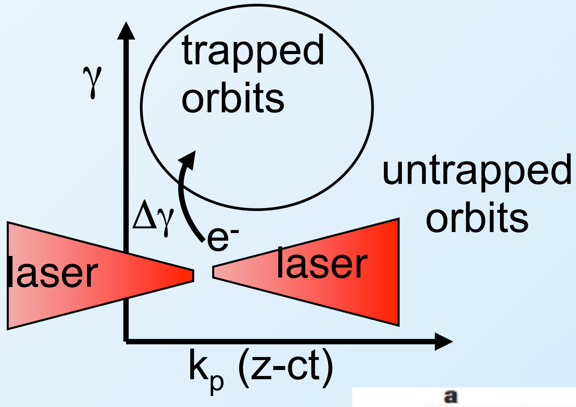
Theoretical development:


Pump laser
(drives wake)
a=1.2
laser

Colliding
laser pulse
a=0.35
laser

3 mm
Gas jet: 7x10^{18} cm^{-3}

Colliding pulse injection: Esarey et al. PRL (1997); Schroeder et al. PRE (1999); Fubiani et al. PRE (2004)

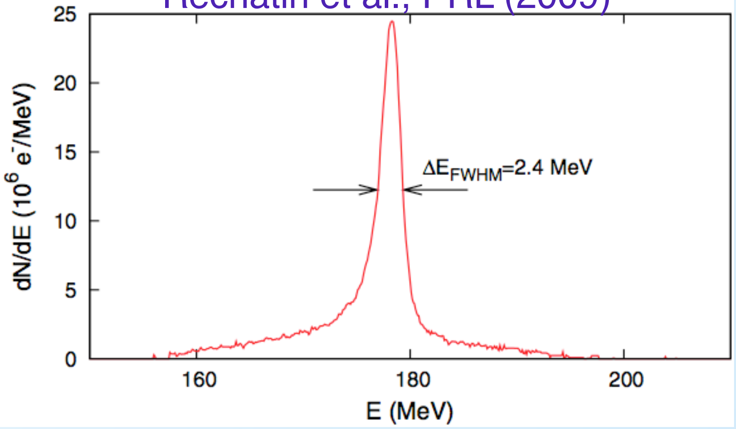

γ
trapped
orbits
untrapped
orbits
Δγ
e-
laser
laser
k$_p$ (z-ct)

$$F_{\text{beat}} \sim mc^2(2k_L)a_1a_2$$

Experimental demonstration:

Faure et al. Nature (2006)

Rechatin et al., PRL (2009)



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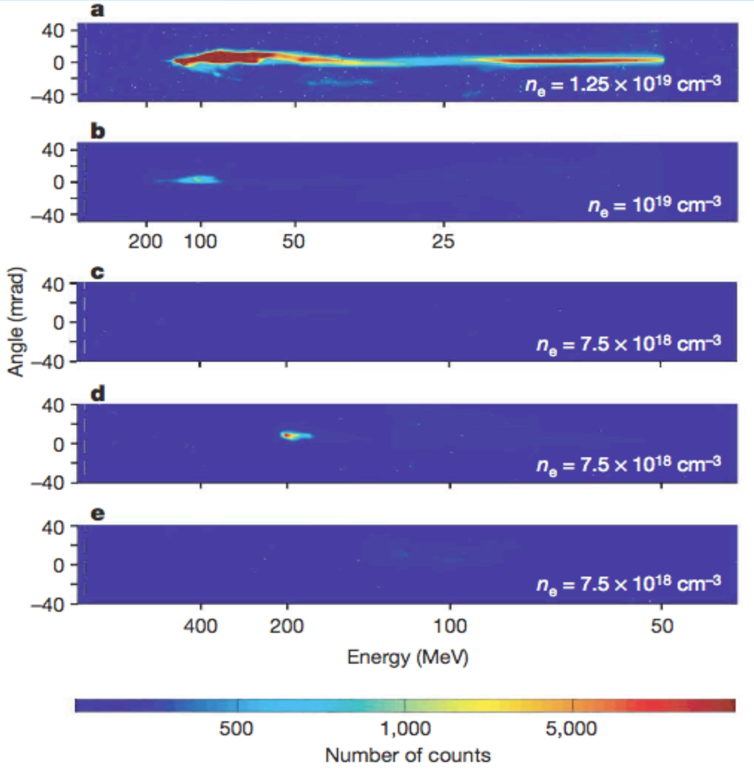
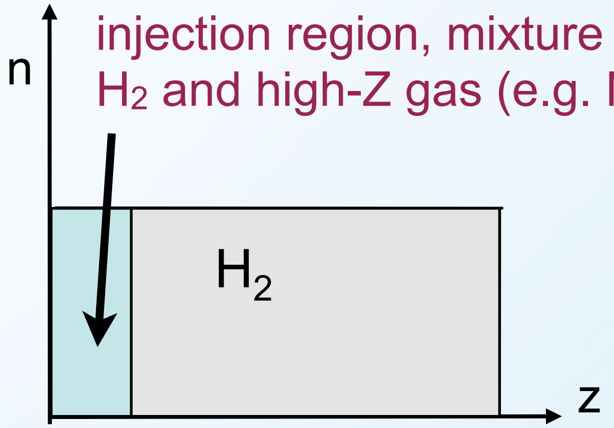


Triggered injection by laser ionization

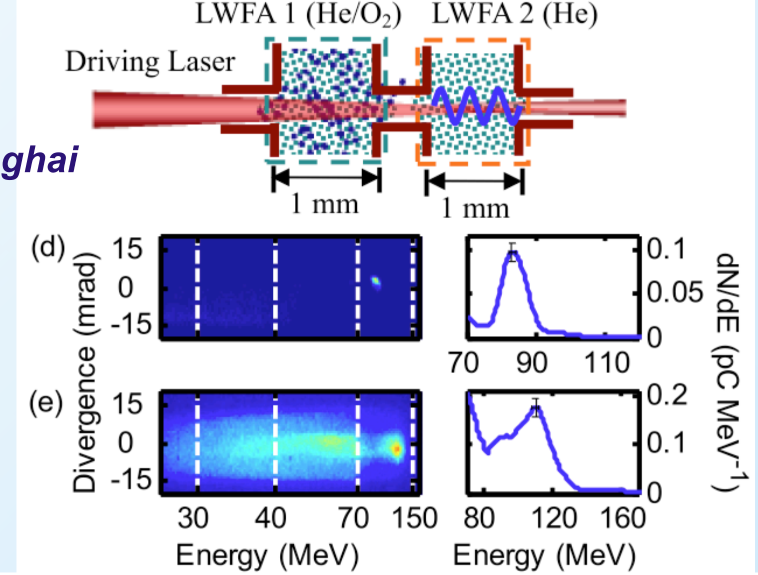


injection region, mixture of H_2 and high-Z gas (e.g. N_2)

- trapped charge determined by length of injection region (<< dephasing length)

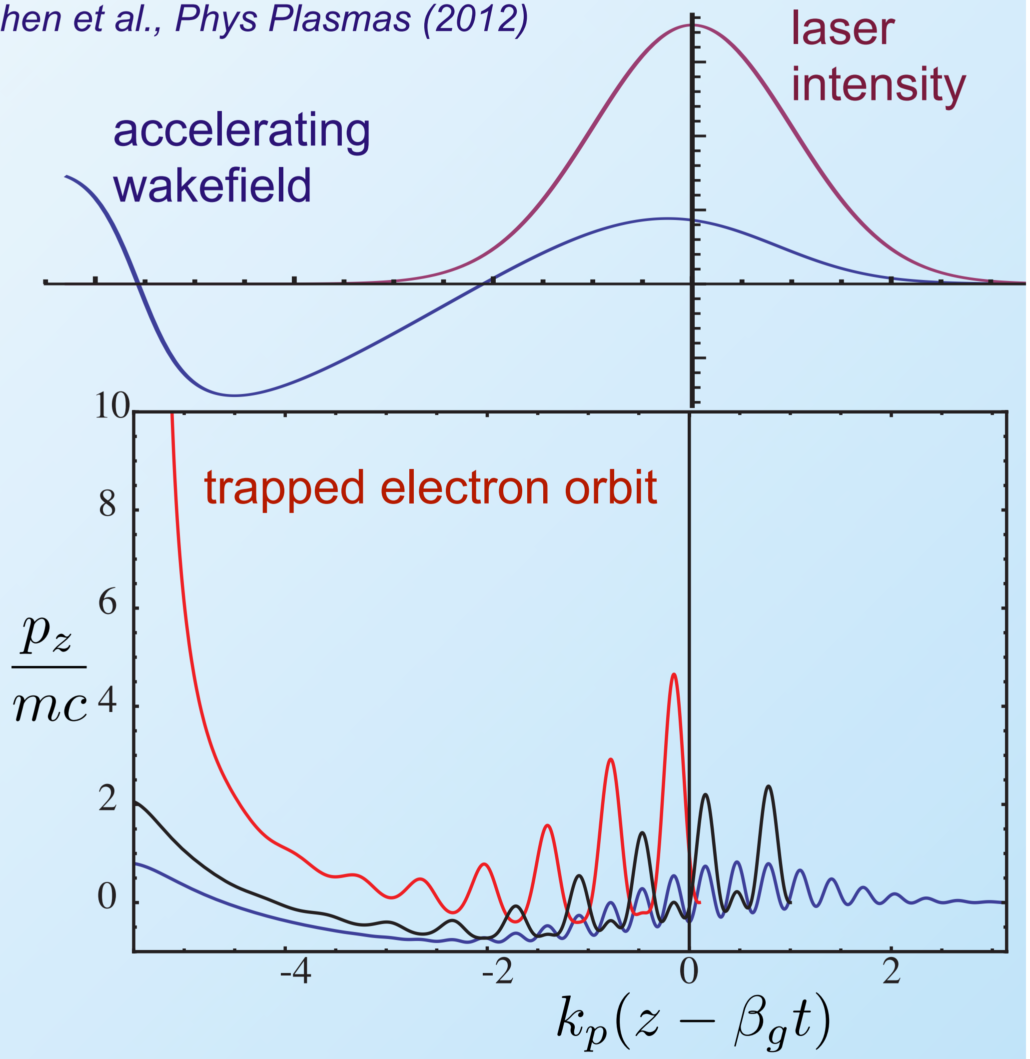
- **Experimental results:**

CAS, Shanghai



J. S. Liu et al., PRL (2011)

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



LPA beam parameters achievable today

- Energy: ~ 100 MeV - 1 GeV
  - Obtained with 10-100 TW laser pulses in 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 measurements (~ 1 mrad) and e-beam spot (~0.1 micron)
  - Improved measurements needed
- 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

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

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

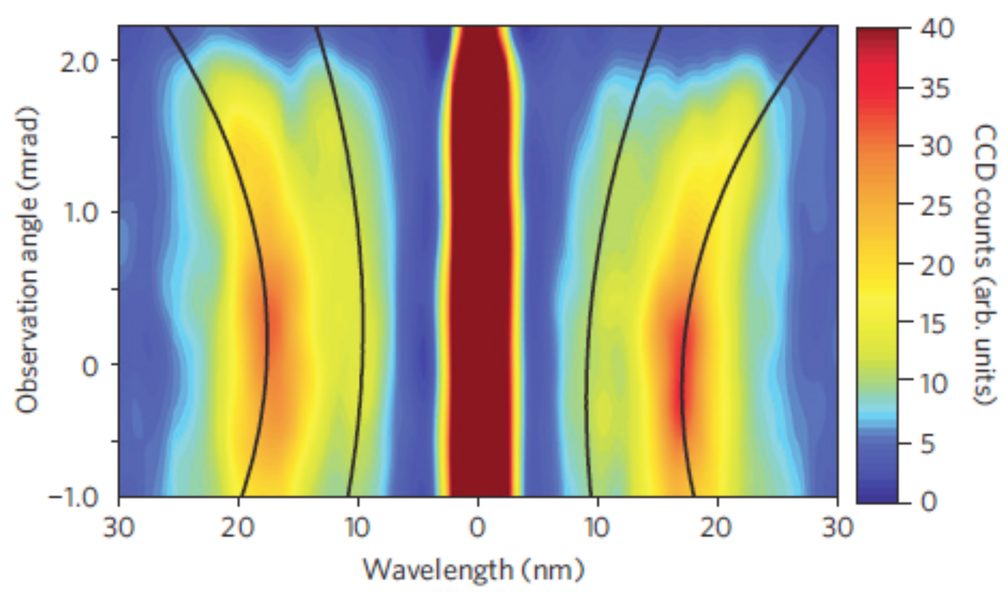
- Energy spread order of magnitude too large (for soft-x-ray FEL; $\rho \sim$ few $\times 10^{-3}$)
- Bunch duration < slippage length (for soft x-ray FEL)
- Emittance exchange?

Experimental measurement of undulator radiation at MPQ

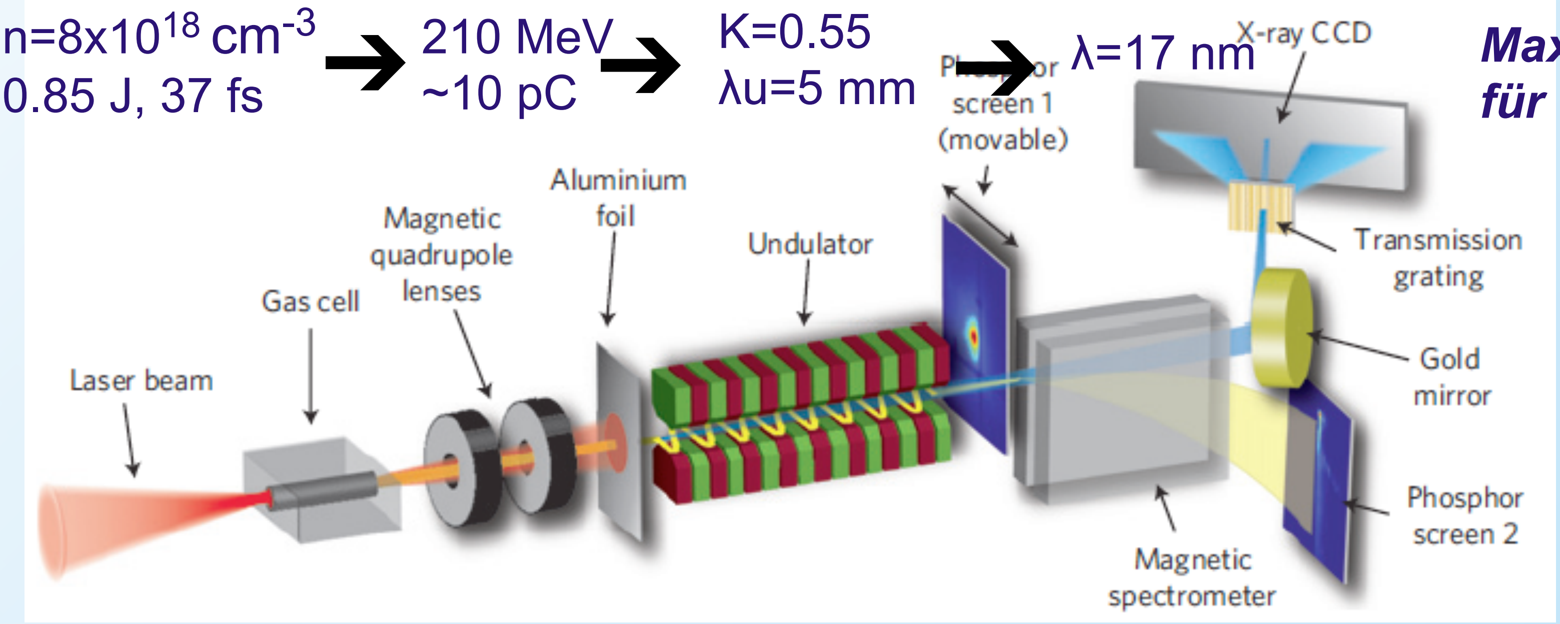
M. Fuchs et al., Nature Physics (2009)

- Measured 1st and 2nd harmonic:

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



$n=8\text{x}10^{18}$ cm^{-3} → 210 MeV → K=0.55 → λ=17 nm
0.85 J, 37 fs ~10 pC λu=5 mm



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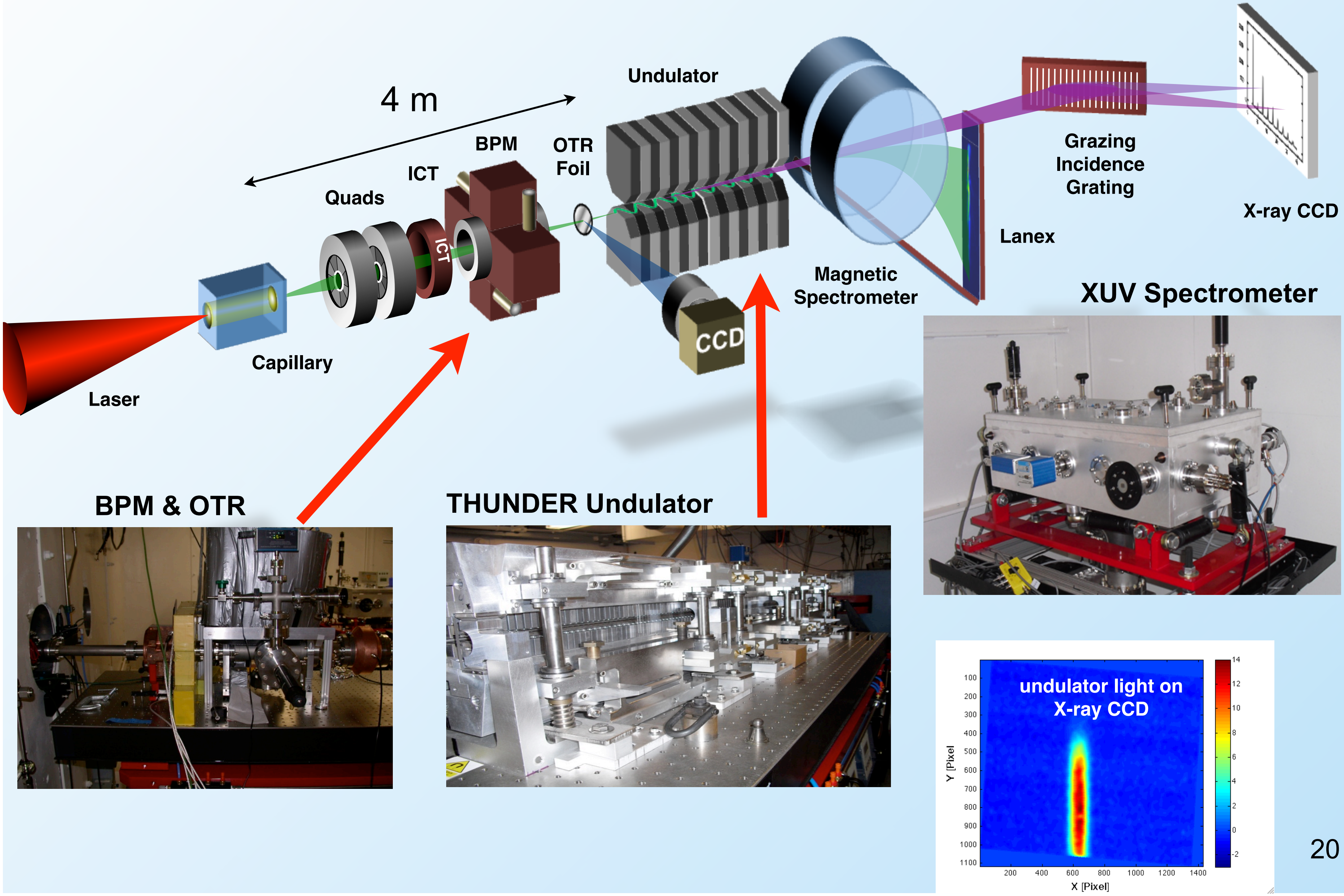
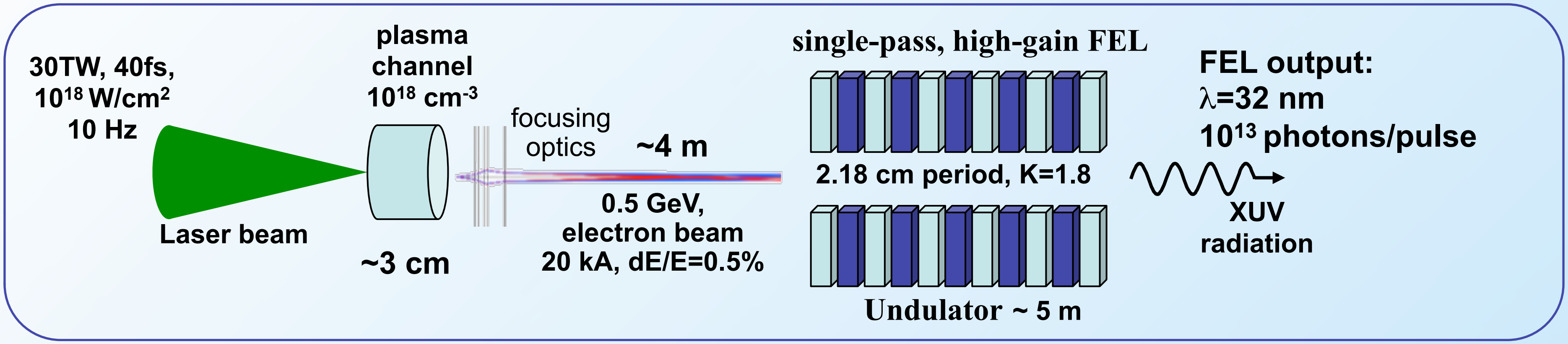
Coupling LPA electron beam to undulator (diagnostic)



Laser-plasma accelerator driven XUV FEL at LBNL



30TW, 40fs,
10^{18} W/cm^2
10 Hz

Laser beam

plasma
channel
10^{18} cm^{-3}

~3 cm

focusing
optics

~4 m

0.5 GeV,
electron beam
20 kA, dE/E=0.5%

single-pass, high-gain FEL

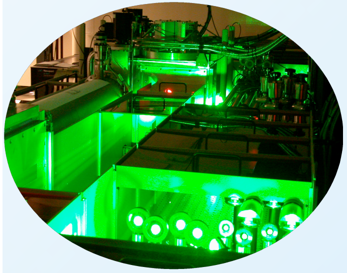
2.18 cm period, K=1.8

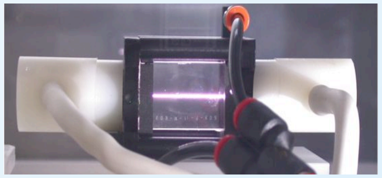
Undulator ~ 5 m

FEL output:
λ=32 nm
10^{13} photons/pulse

XUV
radiation

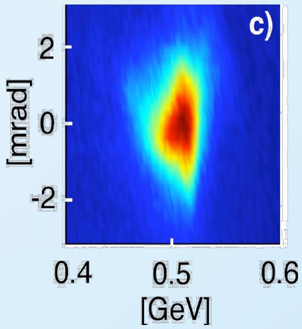
Ti:Al$_2$O$_3$ laser system





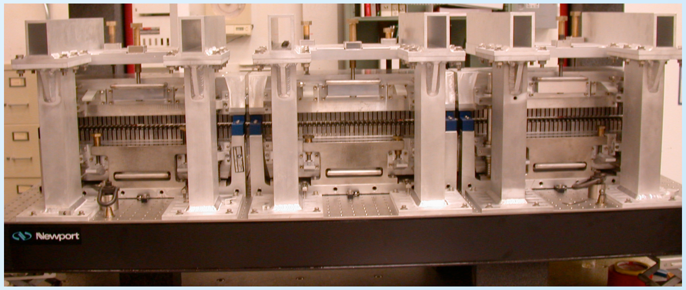
Plasma capillary technology

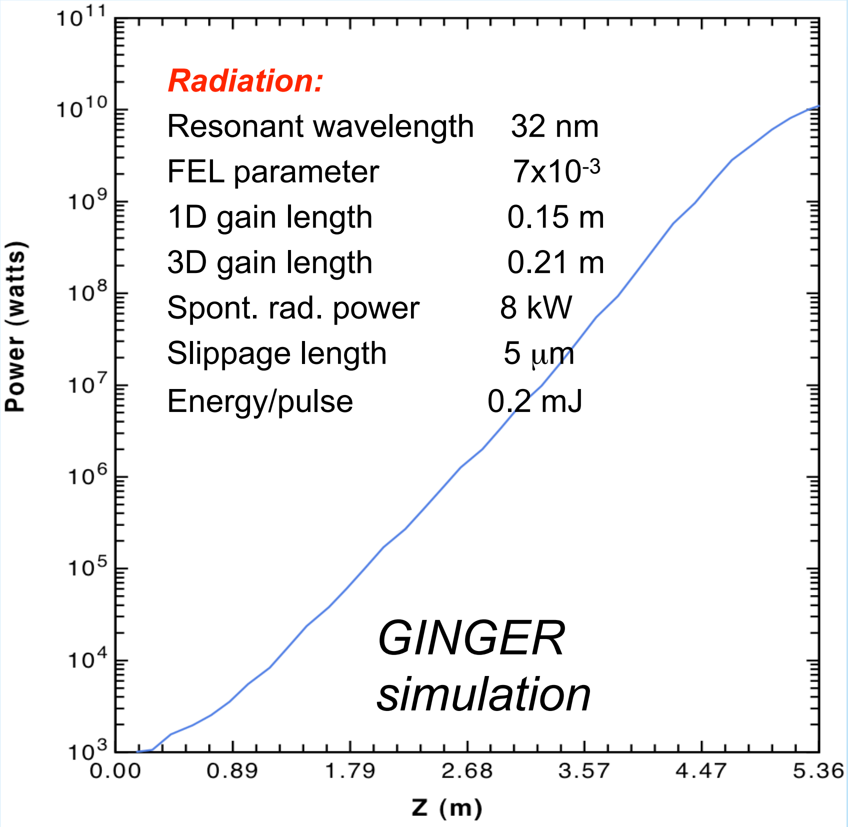
LPA electron beam



conventional undulator (THUNDER)

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





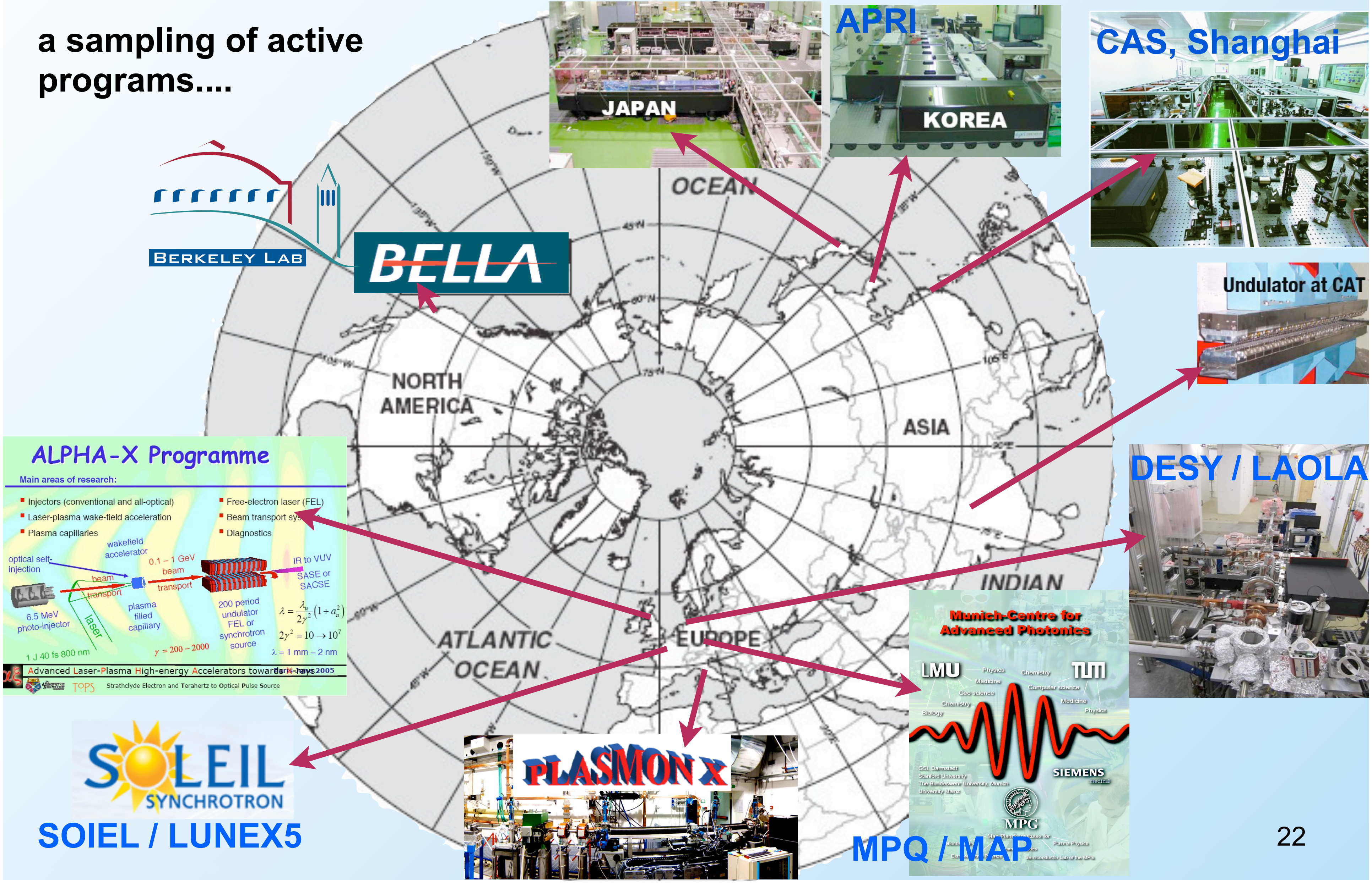
Radiation:

Resonant wavelength	32 nm
FEL parameter	7×10^{-3}
1D gain length	0.15 m
3D gain length	0.21 m
Spont. rad. power	8 kW
Slippage length	5 μm
Energy/pulse	0.2 mJ

GINGER simulation

World-wide interest in light sources driven by laser-plasma accelerator

a sampling of active programs....



ALPHA-X Programme

Main areas of research:

- Injectors (conventional and all-optical)
- Laser-plasma wake-field acceleration
- Plasma capillaries
- Free-electron laser (FEL)
- Beam transport sys
- Diagnostics

Advanced Laser-Plasma High-energy Accelerators towards X-rays Paris-June 2005

TOPS Strathclyde Electron and Terahertz to Optical Pulse Source

SOIEL / LUNEX5

10 GeV laser-plasma accelerator requires ~10 J laser

Plasma density scalings:

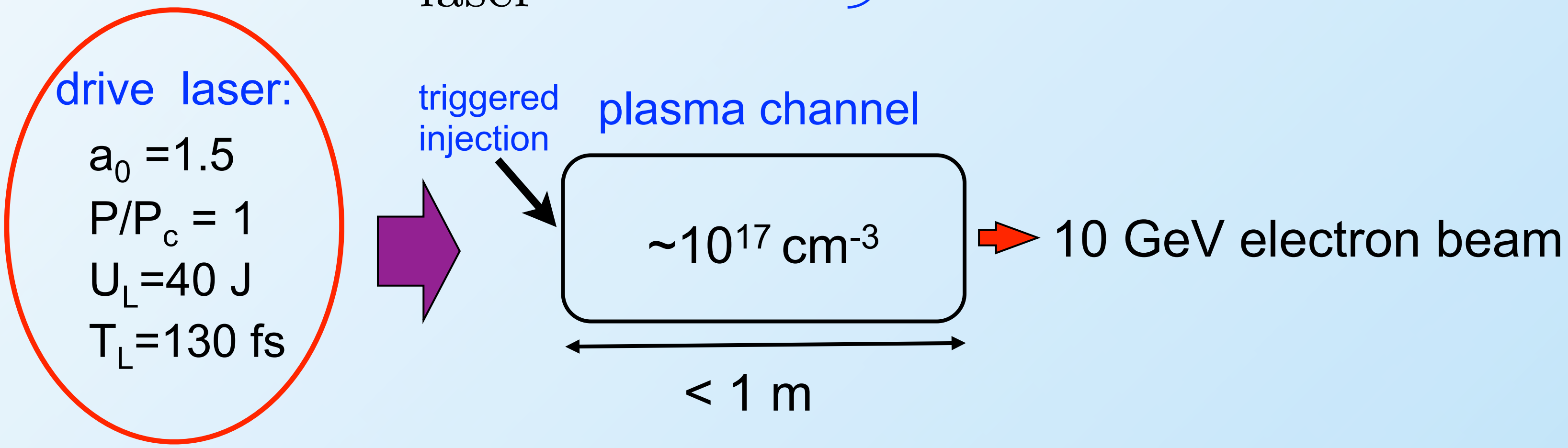
Energy gain: $W \sim (mc\omega_p/e)\, L_{\mathrm{acc}} \propto 1/n$ ⇨ low density plasmas (~10^{17} cm^{-3})

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

Laser energy/power:

$$\left.\begin{aligned} U_{\mathrm{laser}} &\propto n^{-3/2} \\ P_{\mathrm{laser}} &\propto n^{-1} \end{aligned}\right\}$$

⇨ more laser energy (~10 J)



drive laser:

a_0 =1.5

P/P_c = 1

U_L=40 J

T_L=130 fs

triggered injection

plasma channel

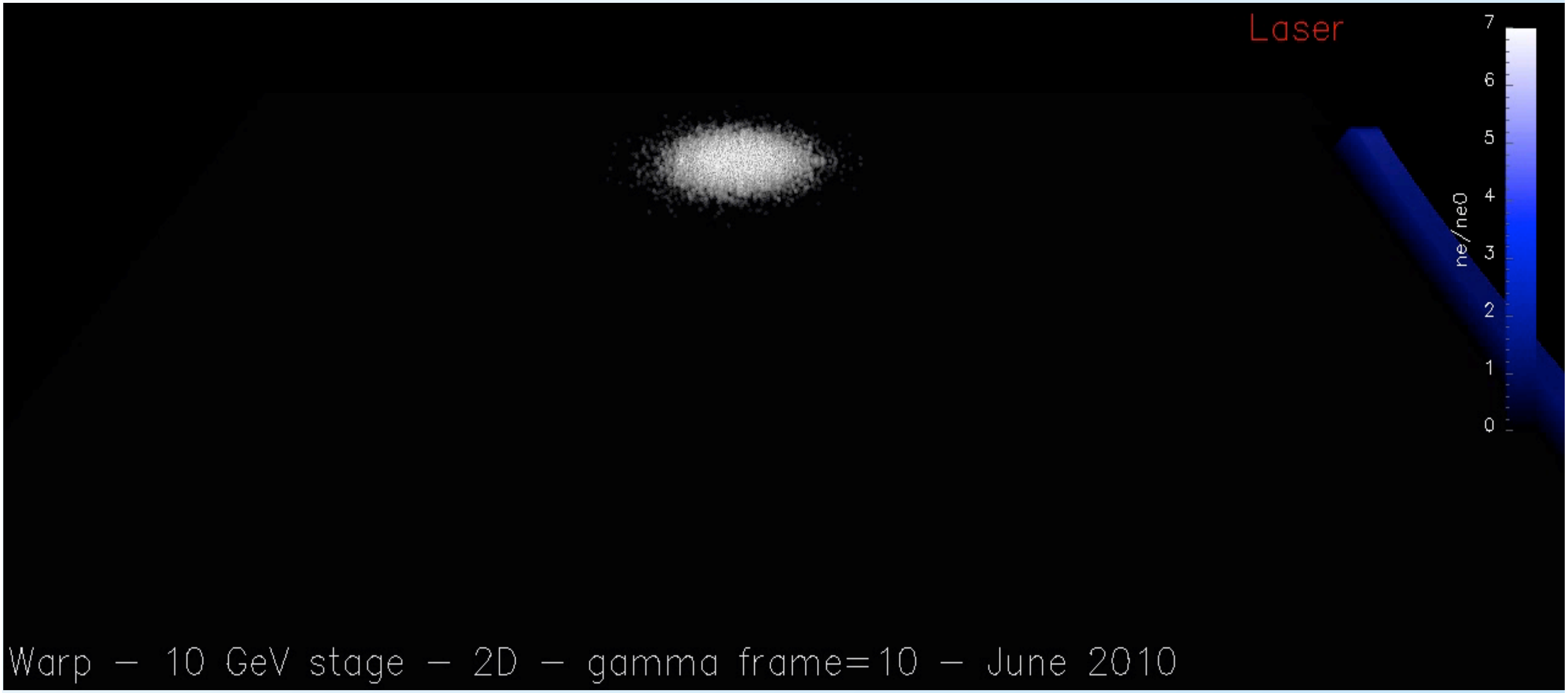
~10^{17} cm^{-3}

< 1 m

10 GeV electron beam

10 GeV LPA using BELLA Laser

WARP simulation (J.-L. Vay, LBNL)



➡ **BELLA (BErkeley Lab Laser Accelerator) laser parameters: 40 J, 1 PW peak power (at max. compression)**

➡ **Laser commissioning scheduled completion summer 2012**

Potential Impact of LPA for future compact light source development

- *Compact accelerator*: multi-GeV beam from compact LPA: ~10-100 GV/m acceleration gradients
  - 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
  - long-term prospects (over next decade): advances in laser tech. (high average power, efficiency) will enable high average power applications