CLEO 2013 QTh3A.1

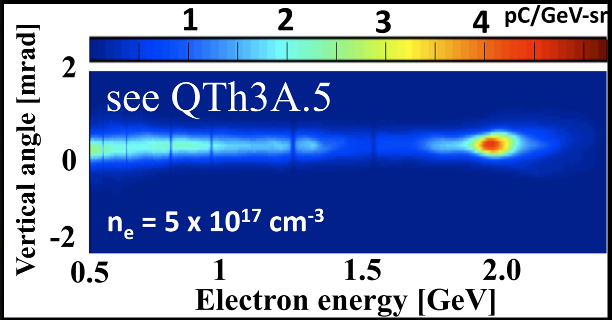
Laser-Plasma Acceleration of Electrons and Plasma Diagnostics at High Laser Fields

Mike Downer
University of Texas at Austin

August 2008 UT Tower Lighting dedicating Texas PW Laser

- TW → PW lasers
- MeV → GeV electrons

Wang *et al.*, *Nature Commun.* **4**, *1988* (2013)



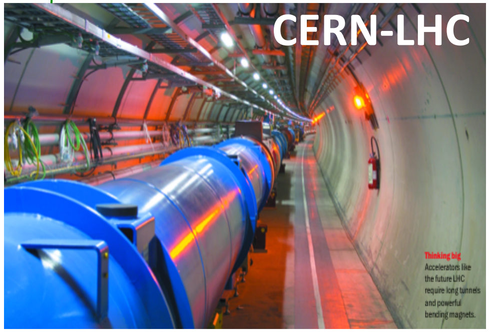
- VUV → hard x-ray coherent radiation

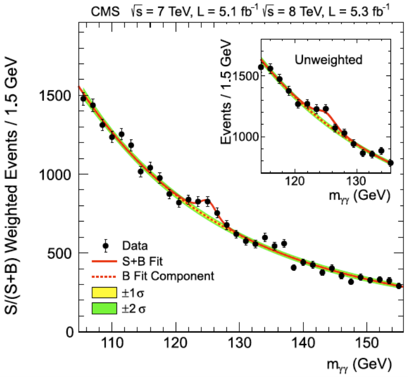
Particle accelerators have evolved into the 21st century's most powerful* scientific instruments

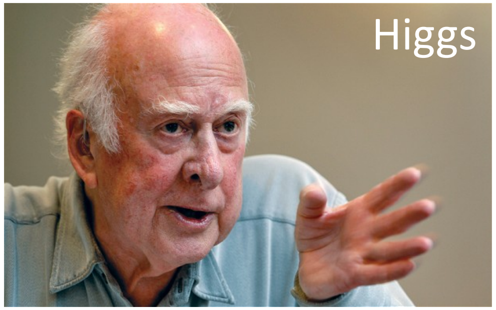
* and largest and most expensive

$6 B

TeV:

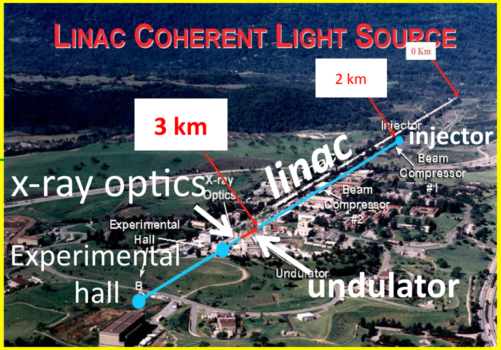


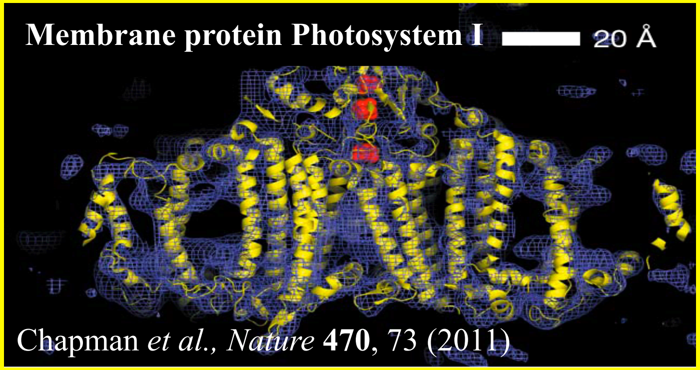




$0.5 B

GeV:



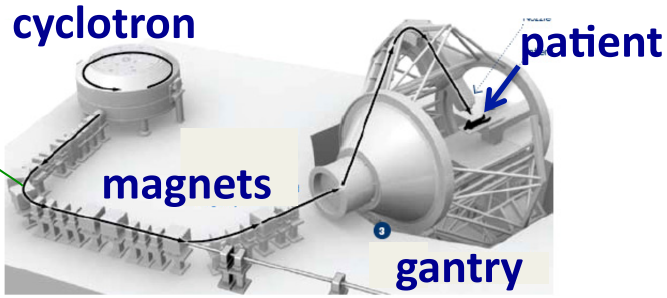


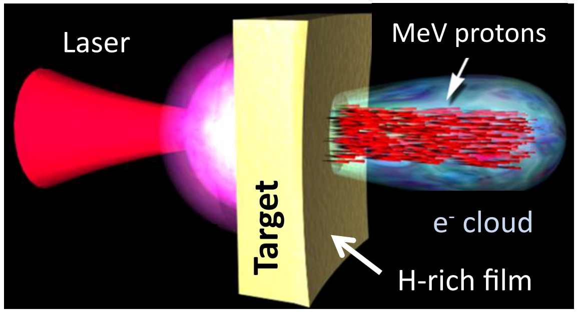
Chapman *et al.*, *Nature* **470**, 73 (2011)

GeV Laser-Plasma electron accelerators are poised to transform biology, chemistry and physics by putting table-top femtosecond X-ray free-electron lasers in every major research university

MeV:

$0.2 B





Laser-plasma <u>proton</u> accelerators are poised to miniaturize proton cancer therapy.

Electrons Accelerating on a Laser-Driven Plasma Wave

Tajima & Dawson, Phys. Rev. Lett. ***43***, *267 (1979)*

Accelerating Field:

$$E_z = \frac{mc\omega_p}{e} \approx (n_{e0}[cm^{-3}])^{1/2}\ \frac{V}{cm}$$

$2\text{x}10^9$ V/cm $4\text{x}10^{18}$ cm^{-3}

$0.7\text{x}10^9$ V/cm $5\text{x}10^{17}$ cm^{-3}

~10^5 V/cm (conventional accelerators)

Acceleration Length:

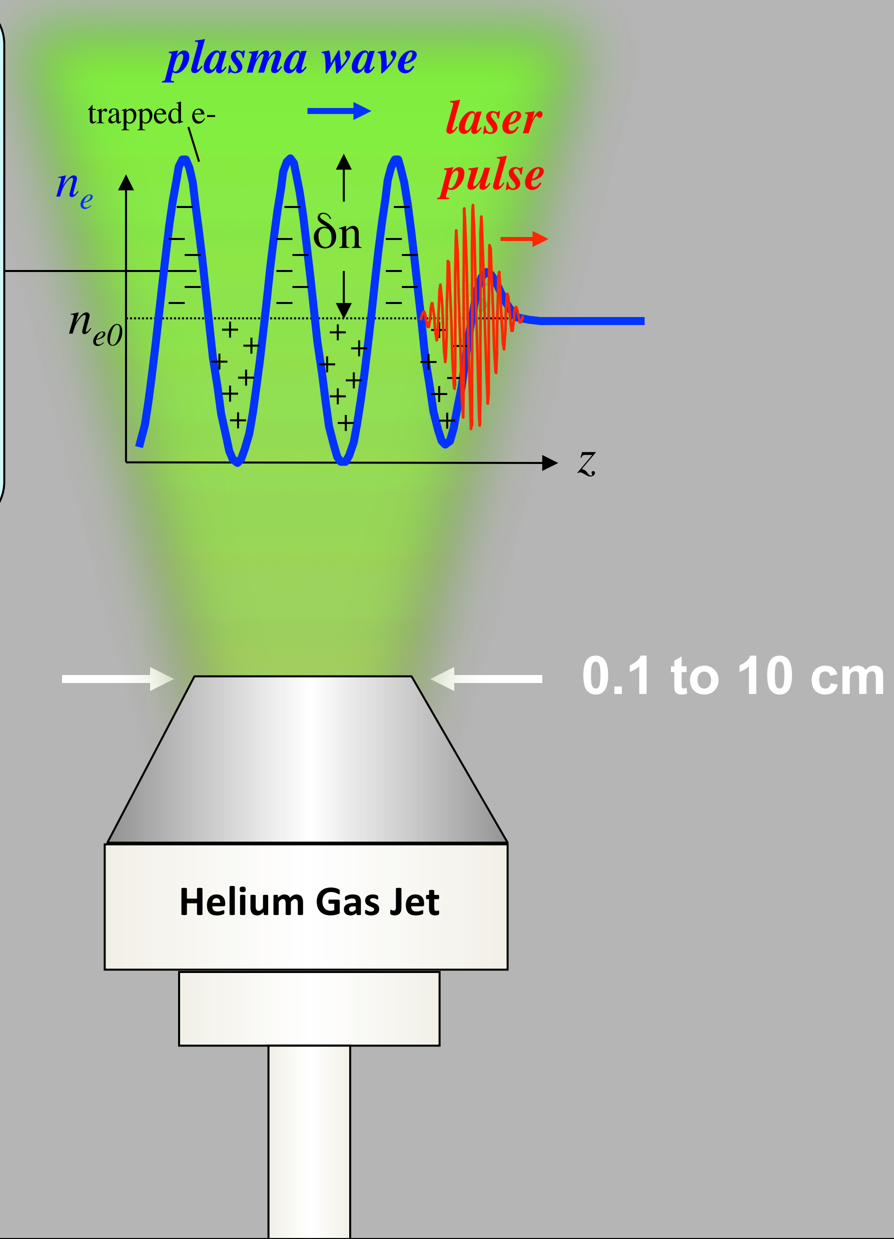
$$L_D = \frac{\lambda_p^3}{\lambda_0^2} \approx 3.3\times(n_{e0}[10^{18}\,cm^{-3}])^{-3/2}\ \text{cm}$$

0.5 cm $4\text{x}10^{18}$ cm^{-3} 1 GeV

9.5 cm $5\text{x}10^{17}$ cm^{-3} 7 GeV

>10^5 cm (conventional GeV accelerators)

PW peak power needed to self-guide and self-inject at < 10^{18} cm^{-3} plasma density

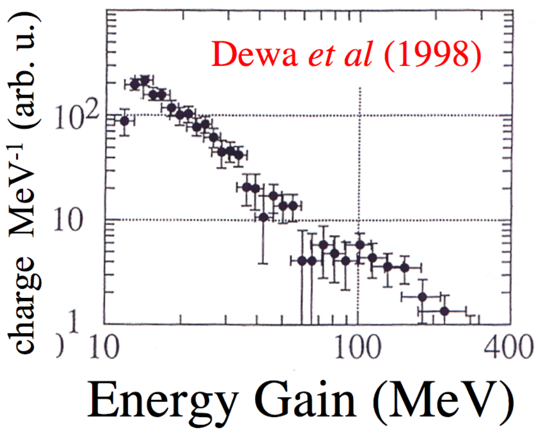


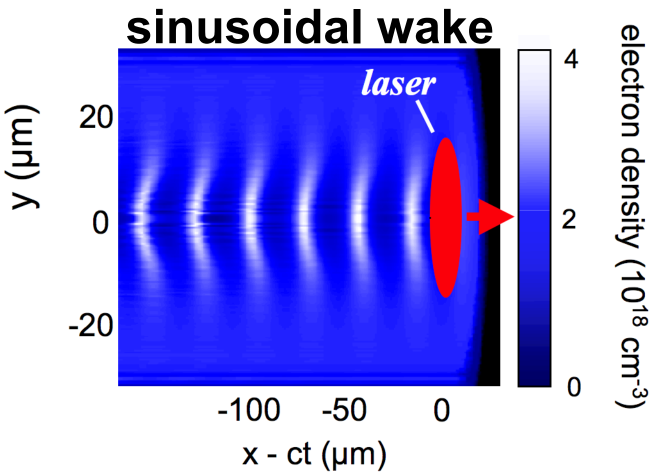
Accelerator performance depends critically on plasma structure…

Review: Esarey, *Rev. Mod. Phys.* **81**, 1229 (2009)

Before 2004:

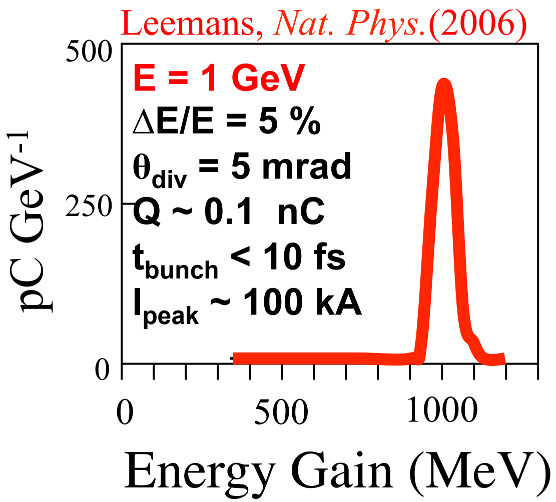
New precise electron injection techniques may revive the quasi-linear LPA regime


Dewa *et al* (1998)

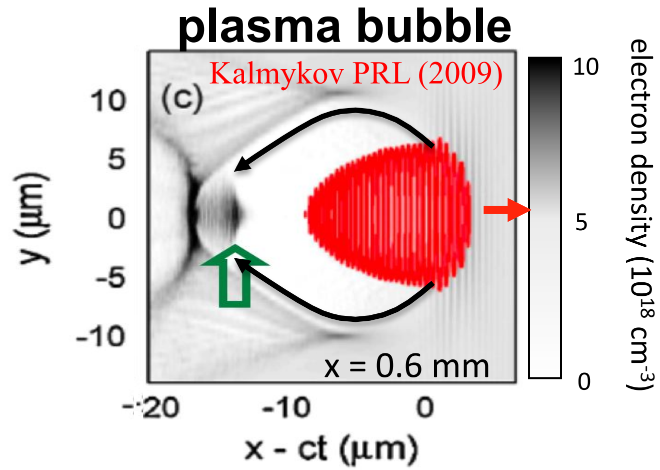

sinusoidal wake

After 2004:

Highly nonlinear, challenging to control


Leemans, *Nat. Phys.*(2006)

E = 1 GeV
$\Delta E/E$ = 5 %
θ_{div} = 5 mrad
Q ~ 0.1 nC
t_{bunch} < 10 fs
I_{peak} ~ 100 kA

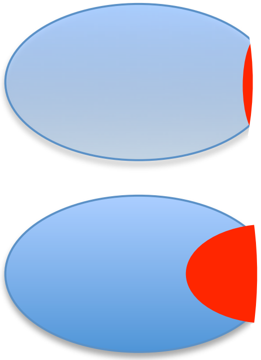

plasma bubble
Kalmykov PRL (2009)

... Today, most LPAs operate in the "bubble" regime

The bubble regime offers trade-offs in designing multi-GeV LPAs

Wei Lu *et al.*, *Phys. Rev. Special Topics - Accel. & Beams* **10**, 061301 (2007)
"Generating multi-GeV electron bunches using single stage laser wakefield acceleration in a 3D nonlinear regime"

Pulse duration ($\omega_p\tau < 1$)

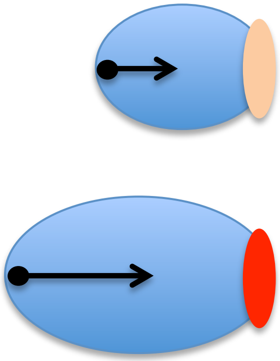


τ = 30 fs, 1 PW pulse

τ = 150 fs, 1 PW pulse

Greater pump depletion length L_{pd}

Self- or channel-guided intensity ($I \sim a_0^2$)

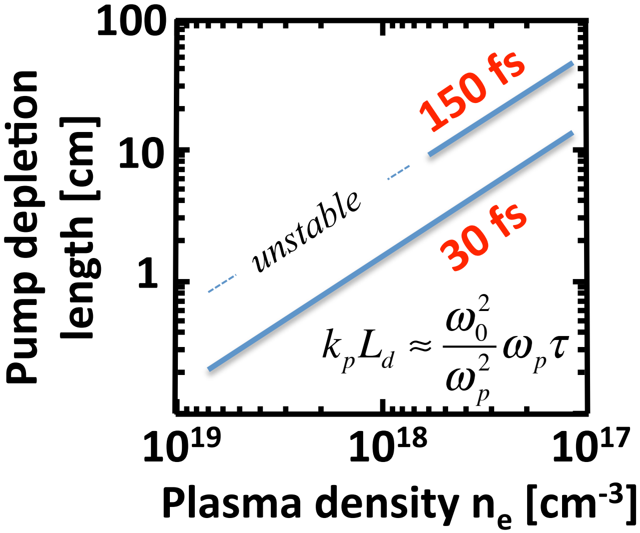


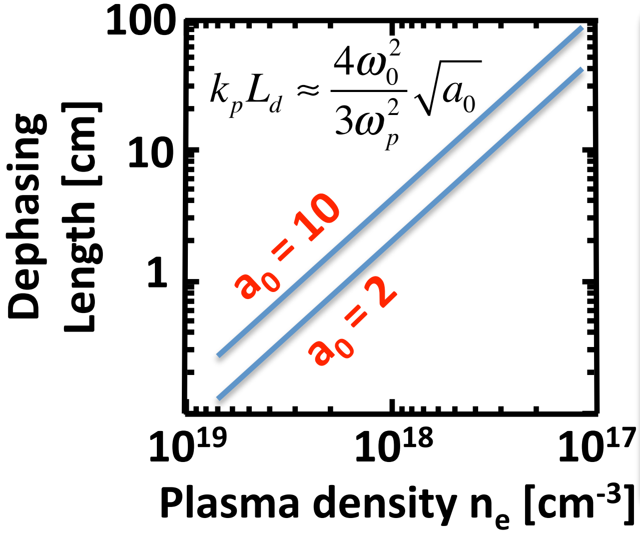
low a_0

$k_pR \sim 2\sqrt{a_0}$

high a_0

Greater dephasing length L_d





What is a_0?

$$\overbrace{W}^{\text{work on } e^-} = \overbrace{(eE)}^{\text{force}} \times \overbrace{(c/\omega)}^{\text{distance}}$$

$$a_0 \equiv \frac{W}{mc^2} = \frac{eE}{m\omega c} = \frac{eA}{mc}$$

$$a_0^2 \approx .7(\lambda[\mu\text{m}])^2\, I\left[10^{18}\,\frac{\text{W}}{\text{cm}^2}\right]$$

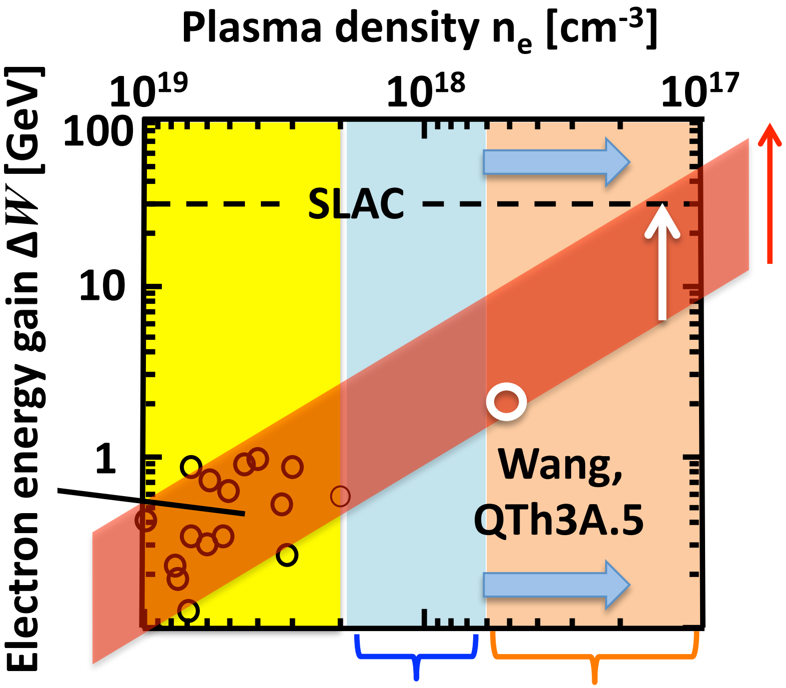
$a_0 = 1$: ***relativistic threshold***

THE UNIVERSITY OF TEXAS AT AUSTIN

Two complementary INITIAL approaches to PW, multi-GeV laser-plasma acceleration are emerging

$$\boxed{\Delta W\,[mc^2] \approx \frac{2\omega_0^{\,2}}{2\omega_p^{\,2}}\,a_0}$$

a_0: 2 → 10 $\omega_p^{\,2}$ α n_e



Previous TW LPA experiments (1992-2012)

Development of ~10^{17} cm^{-3} plasma channels will open additional opportunities for both approaches

e.g. LBNL "BELLA"

e.g. Texas PW

"Short Pulse PW": $\tau_L \sim 40$ fs, $E_L \sim 40$ J

- plasma channel guiding (best near 10^{18} cm^{-3})
- "stimulated" injection

☺
- highly controlled propagation & injection
- up to 1 Hz commercial Ti:S laser
- designed for 10 GeV at n_e ~ 1 x 10^{17} cm^{-3}

☹
- highly engineered channel & injector
- shorter depletion length

"Long Pulse PW": $\tau_L \sim 150$ fs, $E_L \sim 150$ J

- self-guiding
- "spontaneous" injection

☹
- nonlinear, hard to control
- 1 pulse/hr. home-built glass laser

☺
- simple accelerator design
- longer depletion length
- > 10 GeV may be accessible with channeling

OUTLINE

1) Initial 2 GeV PW-laser-driven e- acceleration results

- long pulse PW (Texas)
- short pulse PW (LBNL)

2) How do we reach 10 GeV or more?

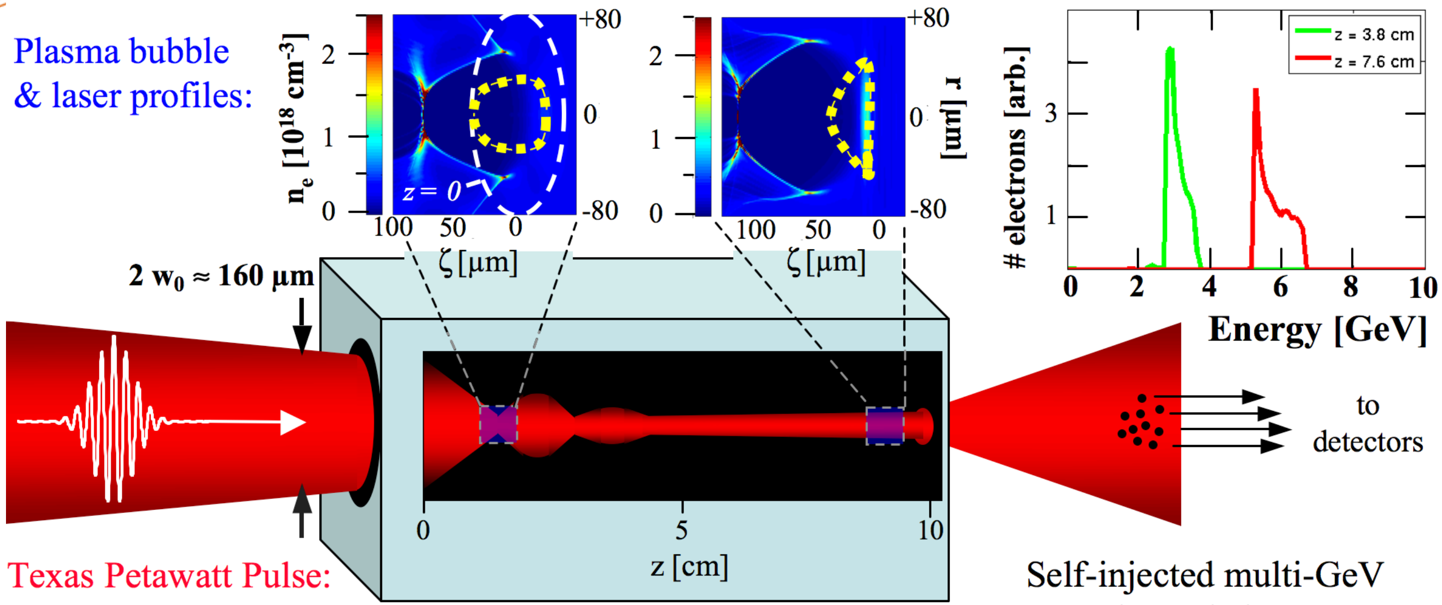
- high PW beam quality
- robust plasma channels at $n_e \sim 10^{17}$ cm^{-3}
- specialized injection techniques yielding $\Delta E/E < 1\%$
- 4D single-shot laboratory visualization of laser wakes

3) Vision of future LPA-driven x-ray FELs

Experiments at the Texas Petawatt Laser aim to produce quasi-mono-energetic multi-GeV e^- beams in one 10 cm stage

Kalmykov *et al.*, *New J. Physics* **12**, 045019 (2010)

"Numerical modeling of multi-GeV laser wakefield accelerator driven by self-guided petawatt pulse,"



Plasma bubble & laser profiles:

Texas Petawatt Pulse:
100 J, 150 fs, f/# ~ 40

differentially pumped He gas cell

Self-injected multi-GeV accelerated electrons

KEY DIFFERENCES FROM PREVIOUS EXPERIMENTS:

Lower n_e (10^{17} vs 10^{19} cm^{-3}): longer dephasing (L_d) & pump depletion (L_{pd}) lengths

Longer interaction (8 cm gas cell vs < 1 cm jet): to exploit longer L_d and L_{pd}

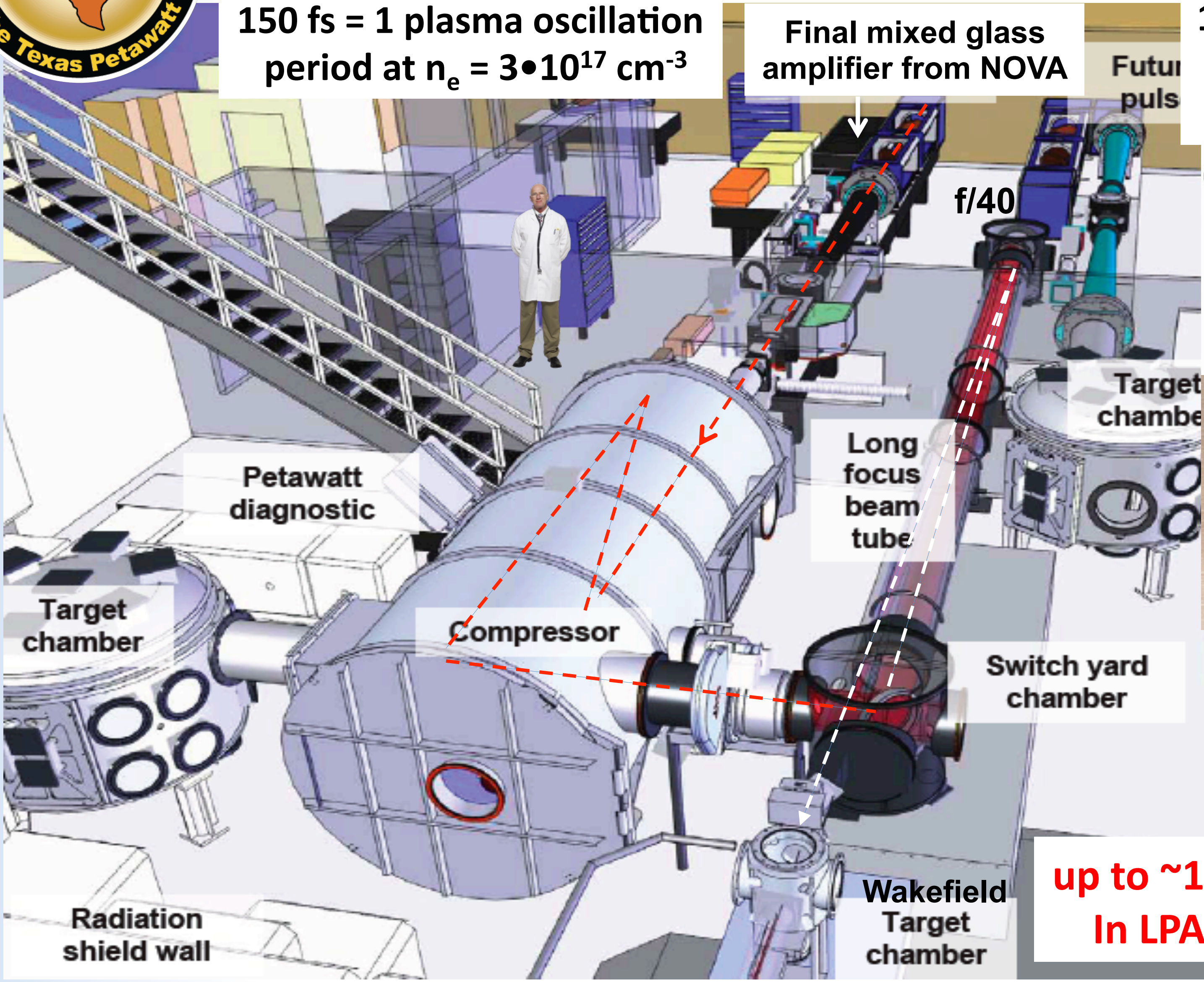
Longer τ_{pulse} (150 fs vs < 60 fs): to excite plasma waves resonantly

Higher peak power (~ 1 PW vs < 0.18 TW): to self-guide, create plasma bubble, trigger self-injection at low n_e

The Texas Petawatt Laser delivers 1.05 μm, 150 fs pulses up to 150 J on target

150 fs = 1 plasma oscillation period at $n_e = 3 \bullet 10^{17}$ cm^{-3}

Final mixed glass amplifier from NOVA



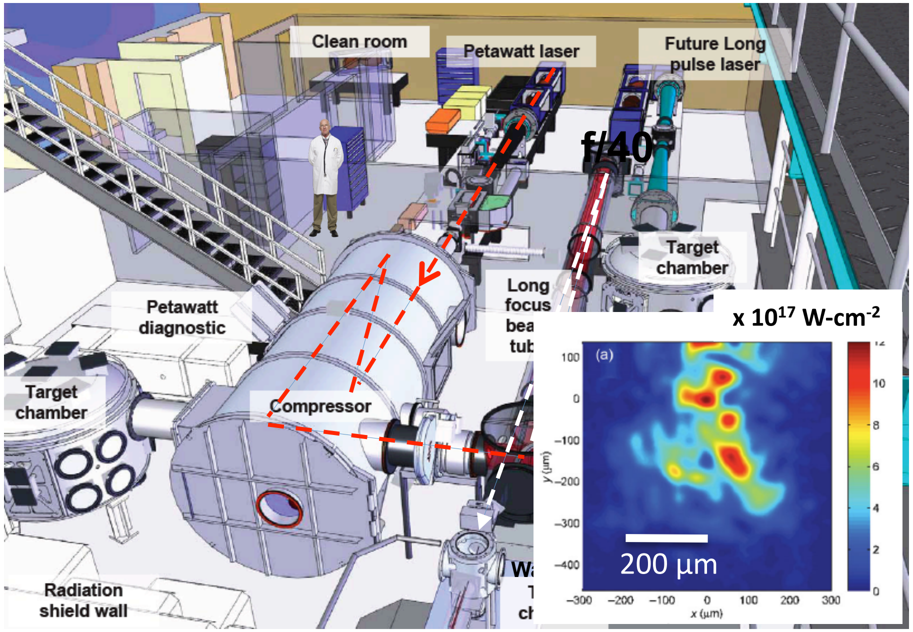
150 J = muzzle energy of .22LR caliber pistol bullet

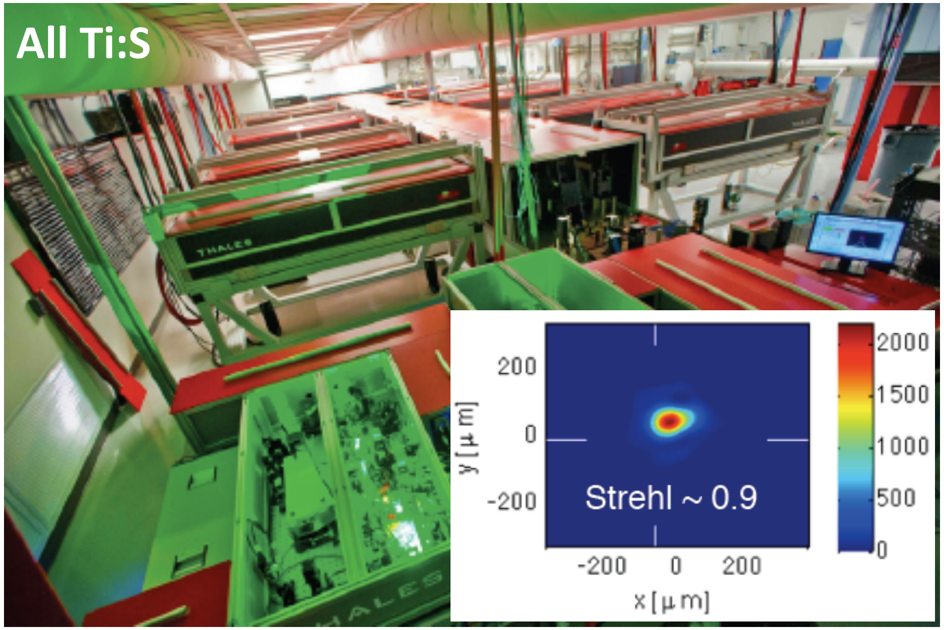
up to ~100 J used so far In LPA experiments

E. Gaul *et al.*, *Appl. Opt.* **49**, 1676 (2010)

The Texas Petawatt Laser delivers 1.05 μm, 150 fs pulses up to 150 J on target

BELLA delivers 0.8 μm, 40 fs pulses up to 40 J on target





Advertised locally as: “The world’s most powerful laser” “The world’s most powerful laser”

Facility Size: 150 m^2 + 100 m^2 = 250 m^2
(laser) (target bay) (total)

300 m^2 + 80 m^2 = 380 m^2
(laser) (target bay) (total)

Mission: multi-purpose (~15% LPA)

85%: WDM, atomic physics, lab astrophysics, proton acceleration …
e.g. Talk **QTh3A.4**: neutron source developed at Texas PW

100% laser-plasma electron acceleration

Beam Quality: needs work

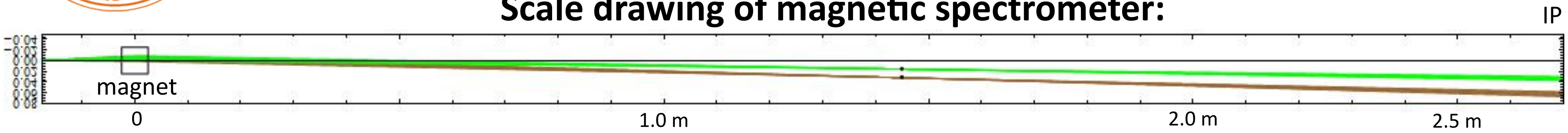
excellent

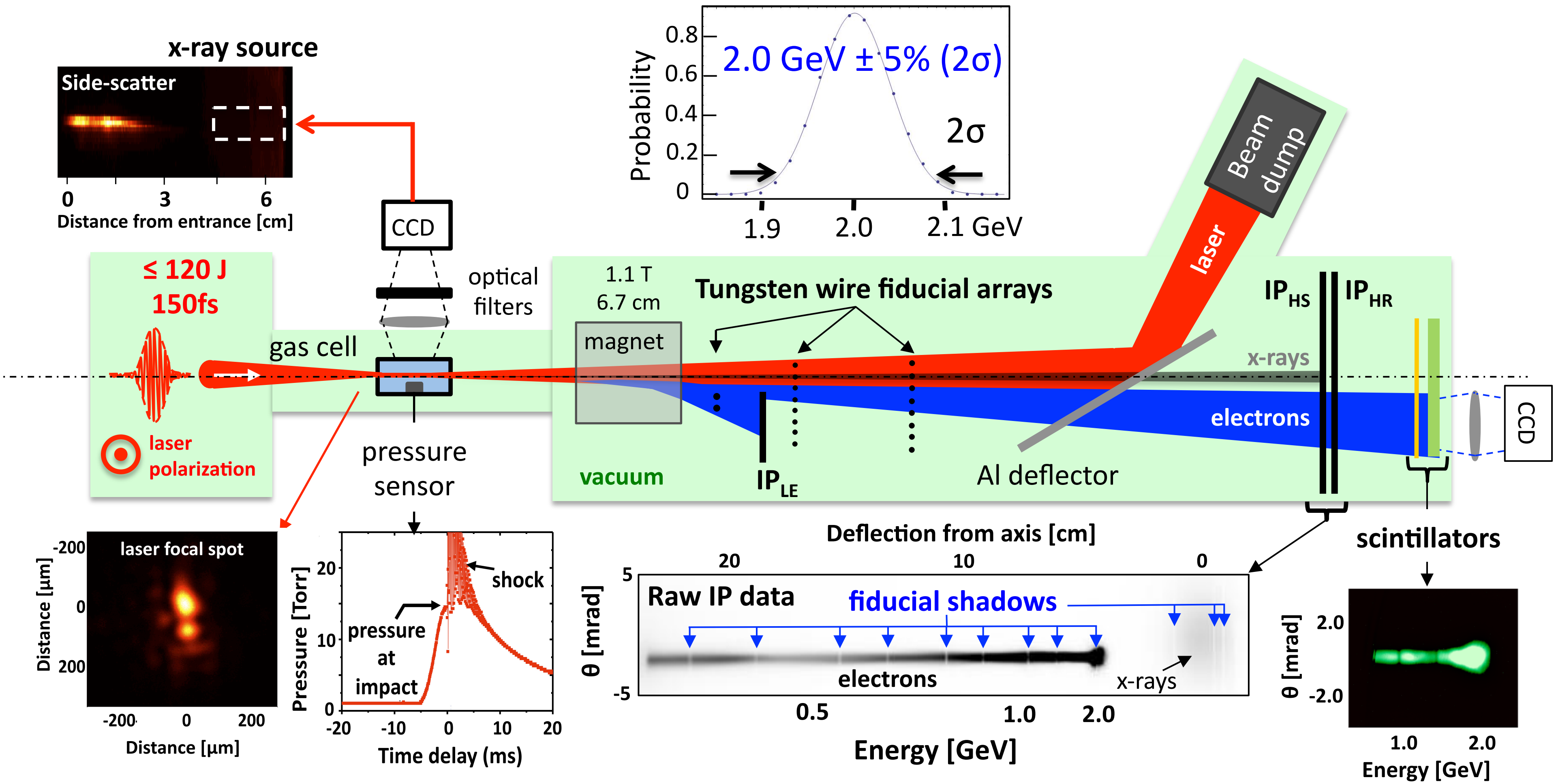
Rep rate: ~ 1 pulse/hour

capable of up to 1 Hz

Experimental setup emphasizes high precision & redundancy in e- energy measurement up to 2 GeV

Scale drawing of magnetic spectrometer:

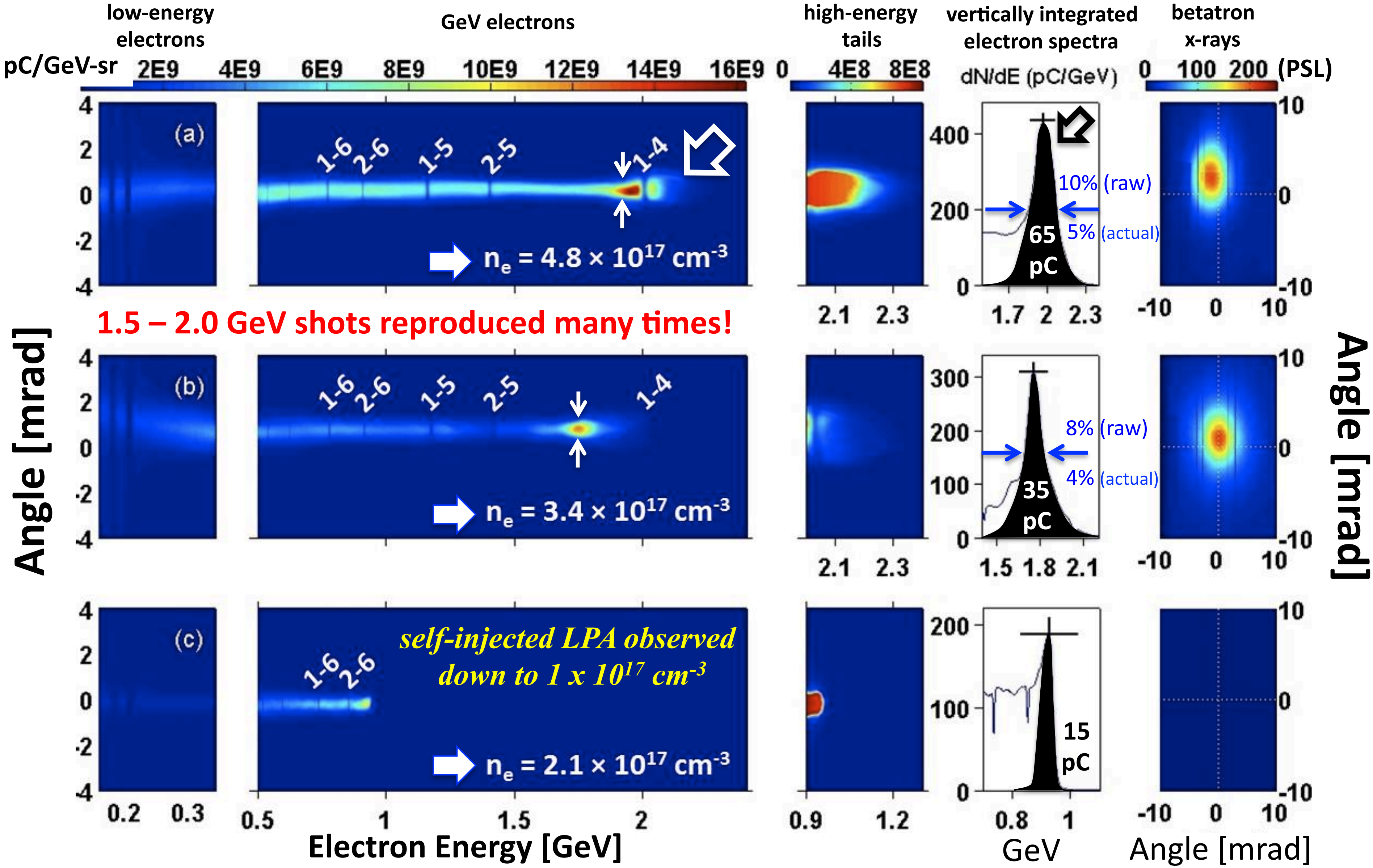




We observe quasi-mono-energetic peaks up to 2 GeV

Wang *et al.*, *Nature Commun.* **4**, *1988* (2013)

- highest energy (2 GeV)
- narrowest divergence (< 0.5 mrad)
- lowest density

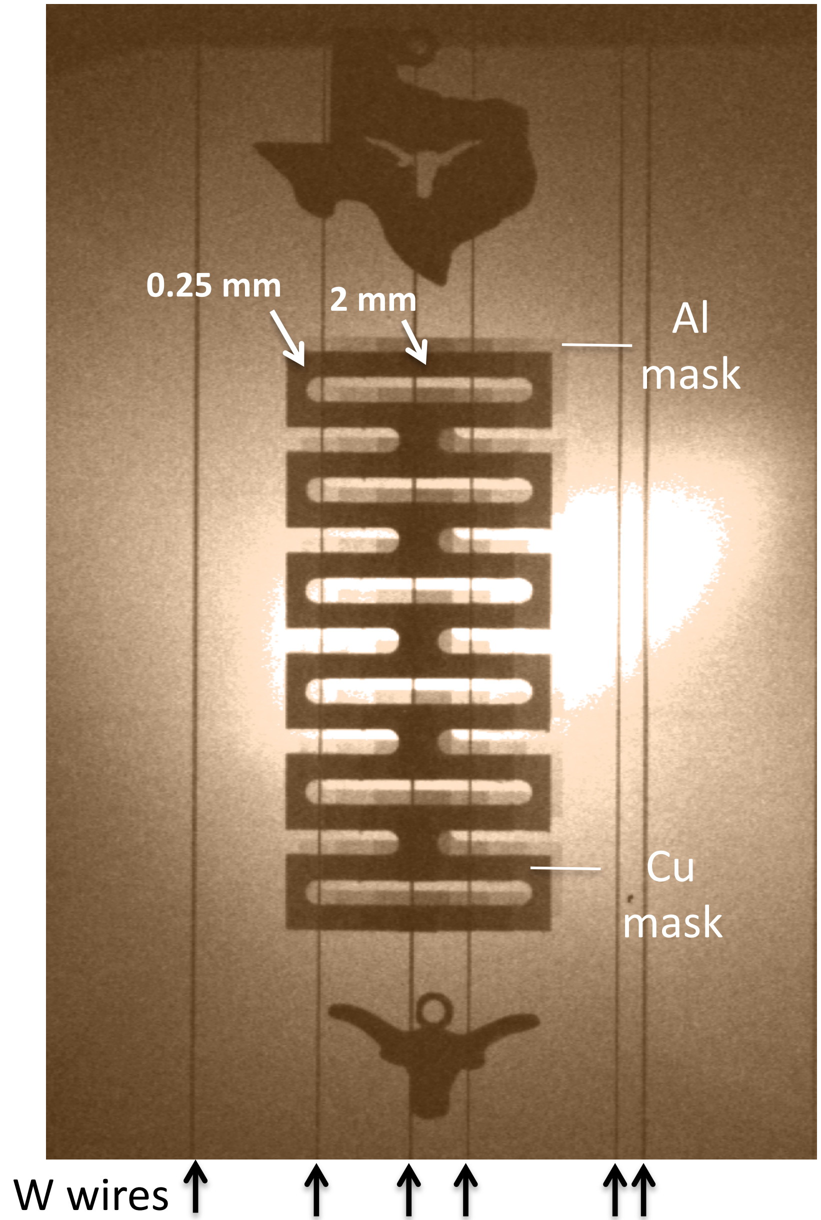


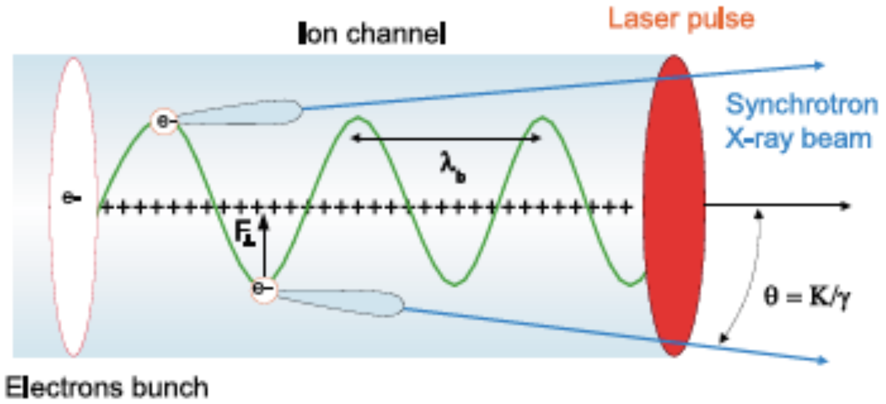
1.5 – 2.0 GeV shots reproduced many times!

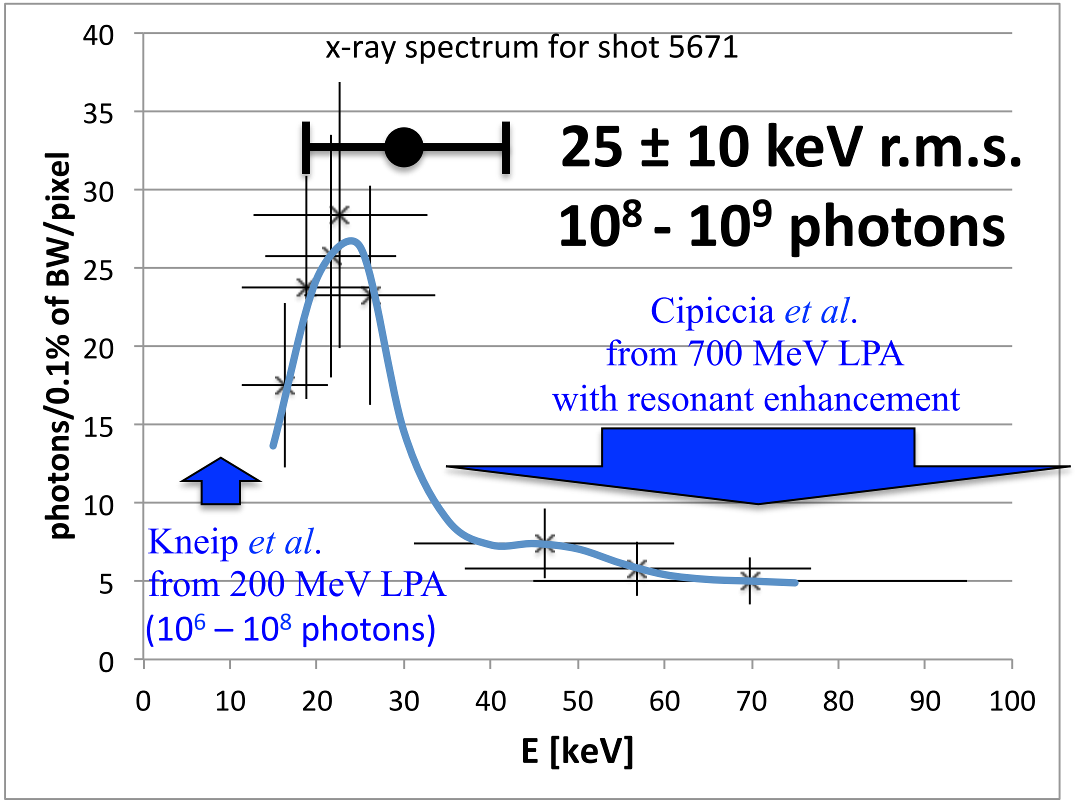
self-injected LPA observed down to 1 x 10^{17} cm^{-3}

Betatron x-rays: electrons wiggle while accelerating

Rousse, *PRL* **93**, 135005 (2004); Kneip *et al.*, *Nature Phys*. **6**, 980 (2010); Cipiccia *et al.*, *Nature Phys*. **7**, 867 (2011)







25 ± 10 keV r.m.s.

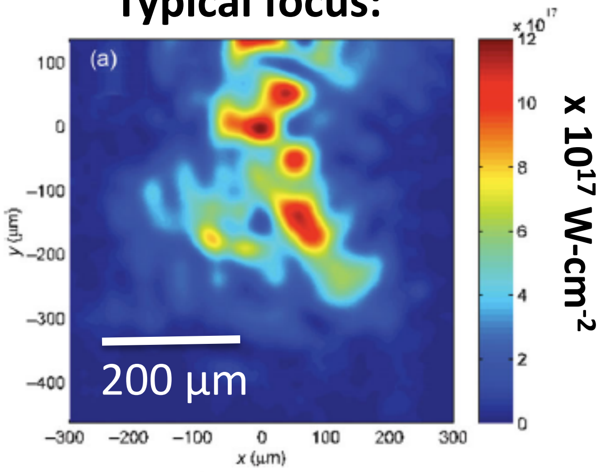
10^8 - 10^9 photons

Cipiccia *et al.*
from 700 MeV LPA
with resonant enhancement

Kneip *et al.*
from 200 MeV LPA
(10^6 – 10^8 photons)

Texas PW pulses do not focus to Gaussian spots. This has advantages[1] & disadvantages[2]

Typical focus:



[1] better self-injection

[2] slow self-focusing, ineffective self-guiding

Nonlinear Schrödinger Equation:

(describes initial propagation before density perturbations become important)

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial}{\partial t^2}\right)\mathbf{a}(\mathbf{x},t) = k_p^2\left(1-\frac{1}{2}\left\langle|\mathbf{a}|^2\right\rangle\right)\mathbf{a}(\mathbf{x},t)$$

Conserved quantity:
(Vlasov 1971)

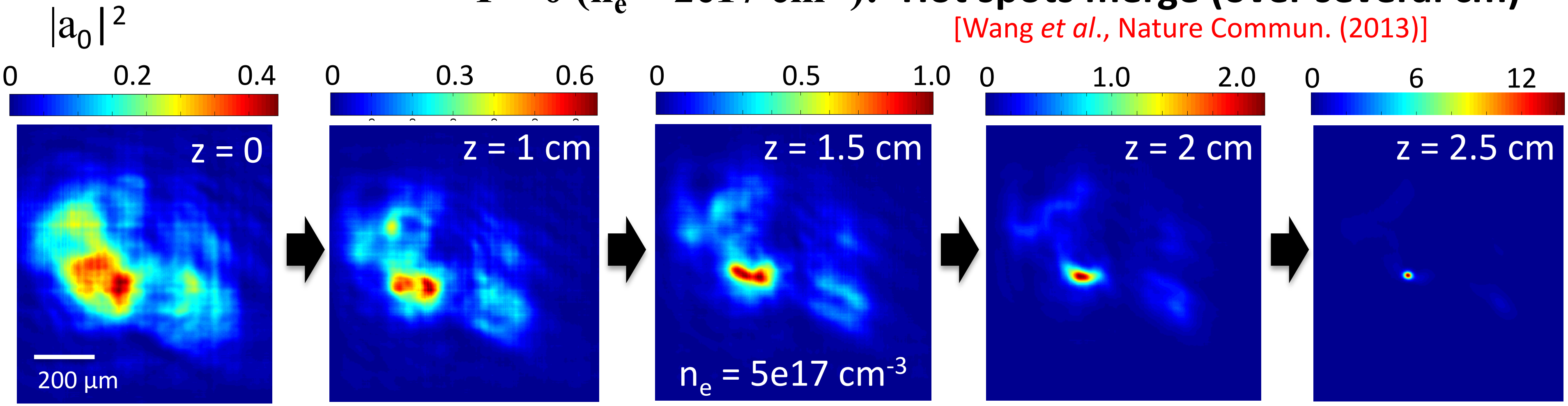
$$I \equiv \int\left(|\nabla_\perp a|^2 - \frac{k_p^2}{8}|a|^4\right)d\mathbf{x}_\perp$$

$I > 0$ ($n_e < 2e17\ cm^{-3}$): **Hot spots propagate independently**

[Wang *et al.*, J. Plasma Phys. **78**, 413 (2012)]

$I < 0$ ($n_e > 2e17\ cm^{-3}$): **Hot spots merge (over several cm)**

[Wang *et al.*, Nature Commun. (2013)]

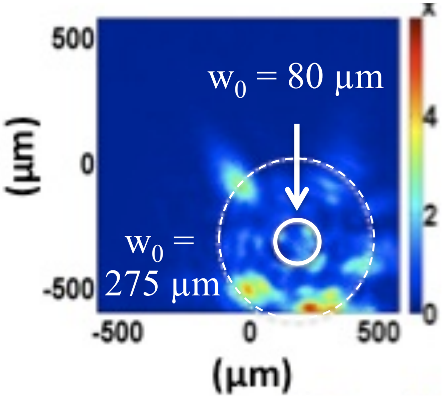


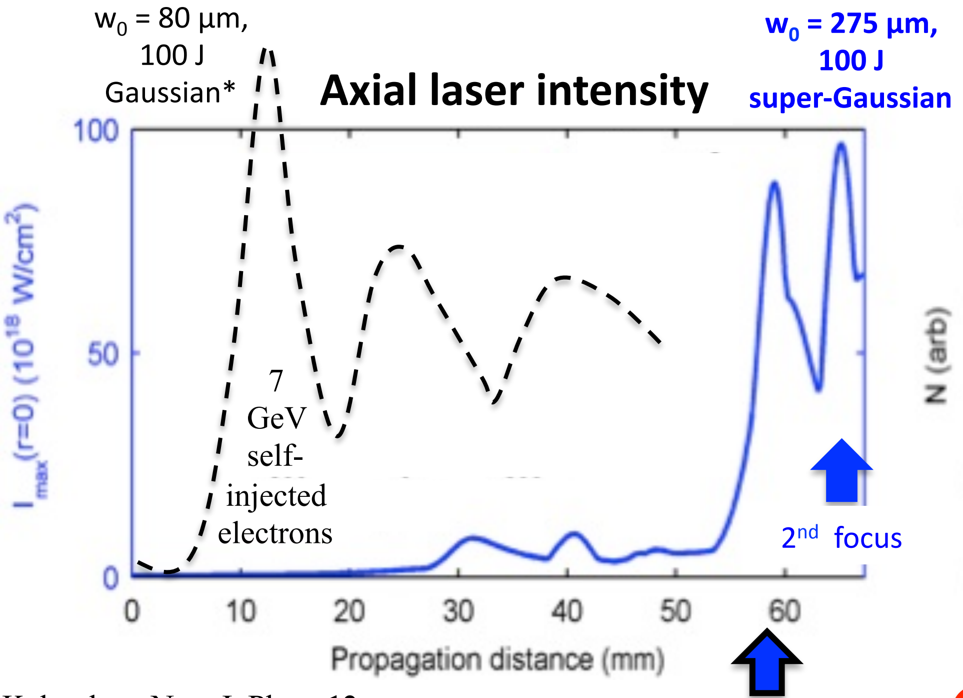
PIC Simulations using approximations of the real pulse profile reproduce the experimental results

Simulations by S. A. Yi, X. Zhang, G. Shvets using fully relativistic PIC code WAKE*

*Mora & Antonsen, *Phys. Plasmas* **4**, 217 (1997)

- **Pulse energy: 100 J**
- **Focus spread over w_0 ~ 275 µm w. hot spots**

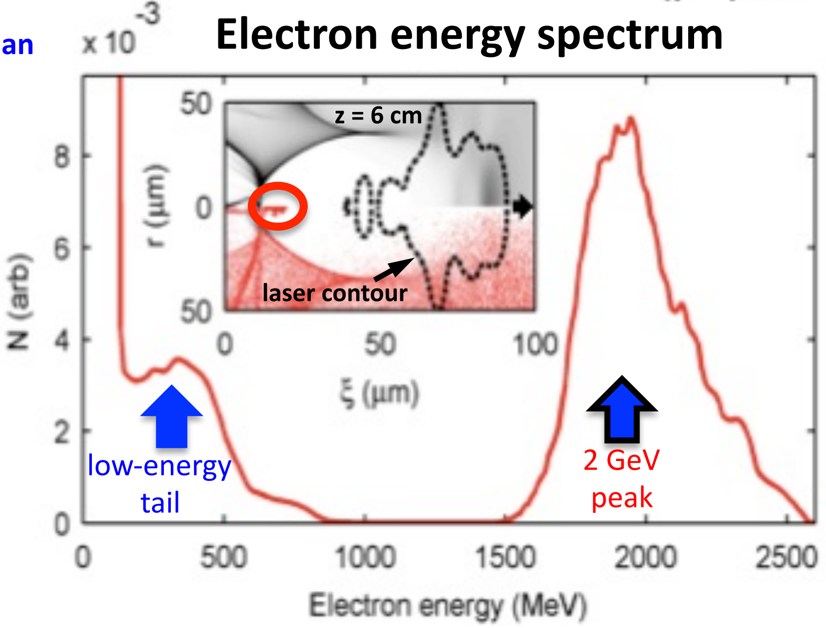




Axial laser intensity

1st self-focus

*Kalmykov, New J. Phys. **12**, 045019 (2010)

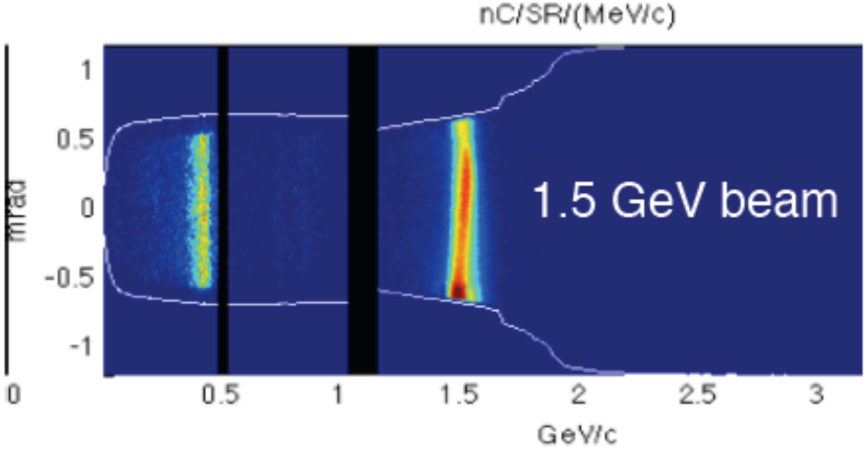


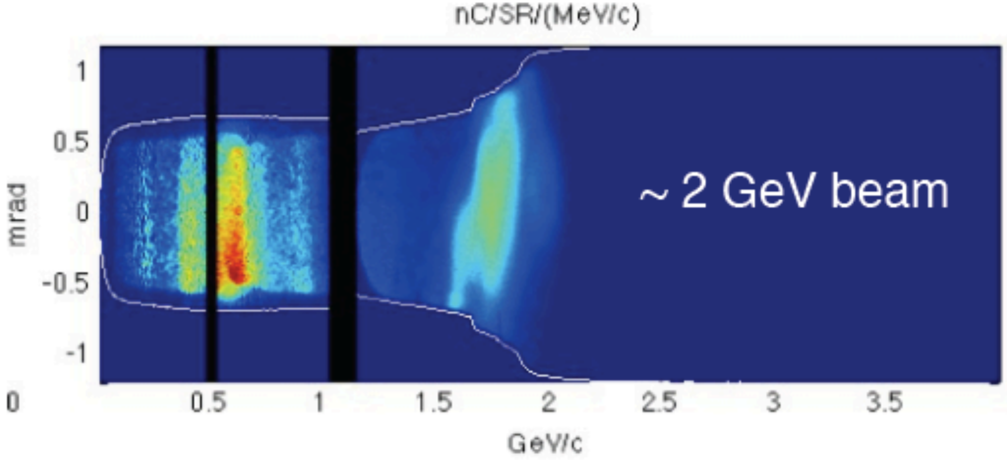
Electron energy spectrum

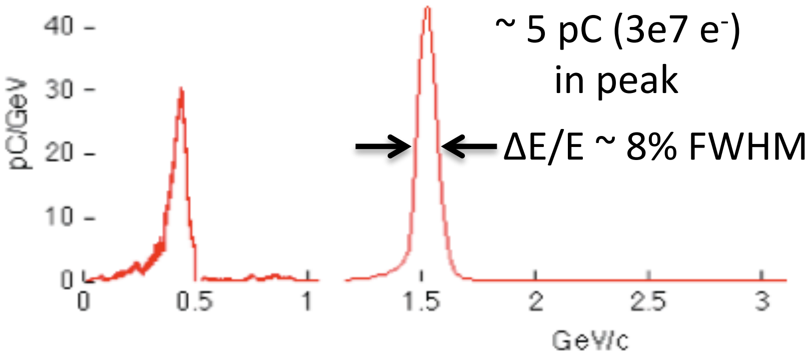
○ Self-injected e- confined within 2 µm of bubble axis, consistent with sub-mrad beam divergence

First BELLA experiments use 2 cm long gas jet, 16 J energy on target and produced near 2 GeV beams

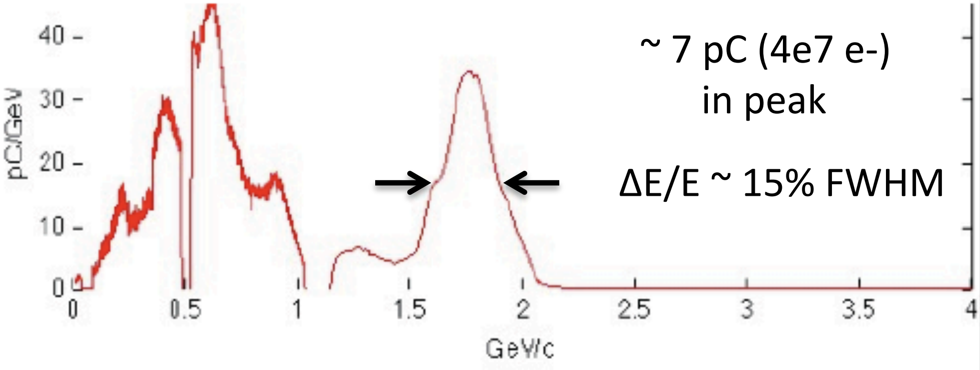
- He gas jet (from AASC) with front shock for injection
- Operated in density range 5-7x10^{17} cm^{-3}






~ 5 pC (3e7 e^-)
in peak

ΔE/E ~ 8% FWHM


~ 7 pC (4e7 e-)
in peak

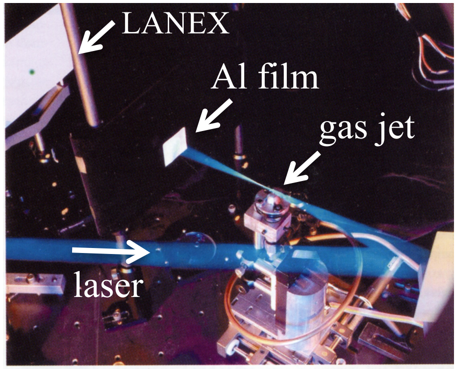
ΔE/E ~ 15% FWHM

Slide courtesy Wim Leemans

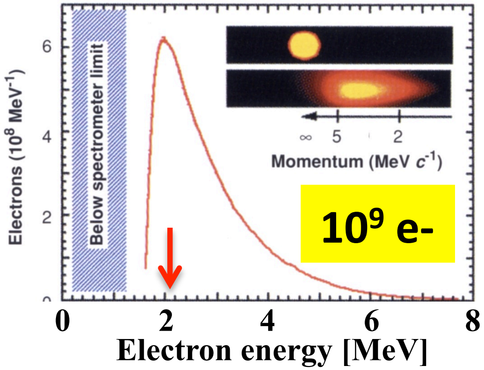
How efficient are PW-laser-driven accelerators?

Laser → Electrons
Energy Conversion Efficiency

1) Early days of TW-laser-driven plasma acceleration

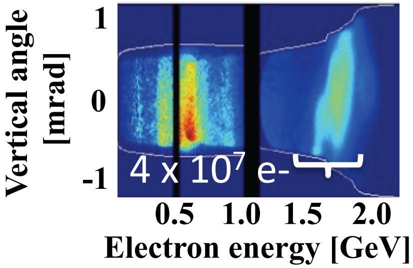


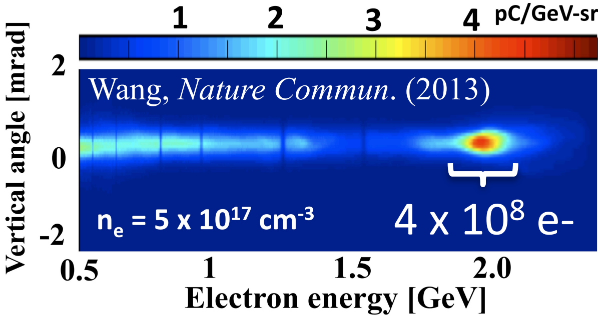
Umstadter, *Science* **273**, 472 (1996)



$$\frac{3\times10^{-4}\,J\,(e^{-})}{3\,J\,(laser)}=10^{-4}$$

2) Early days of PW-laser-driven plasma acceleration





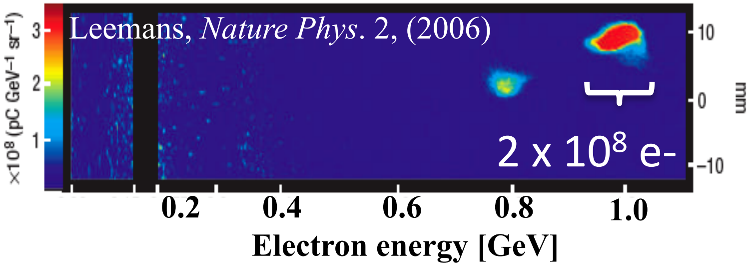
Wang, *Nature Commun.* (2013)

BELLA: $$\frac{0.012\,J\,(e^{-})}{16\,J\,(laser)}=0.78\times10^{-3}$$

Texas: $$\frac{0.13\,J\,(e^{-})}{10^{2}\,J\,(laser)}=1.3\times10^{-3}$$

3) TW-laser-driven plasma acceleration at maturity

utilizing channel guiding



Leemans, *Nature Phys.* 2, (2006)

$$\frac{3.2\times10^{-2}\,J\,(e^{-})}{1.6\,J\,(laser)}=2\times10^{-2}$$

Summary of ~2 GeV LPA results so far

	Laser-Plasma Conditions			Electron Beam Properties			
	Laser Pulse Energy [J]	**Laser Pulse Duration [fs]**	**Plasma Density $[10^{17}\ \mathrm{cm}^{-3}]$**	**E_{peak} [GeV]**	**% Energy Spread of Peak (FWHM)**	**Angular Divergence (FWHM) at peak [mrad]**	**Charge in peak [pC]**
Texas	**100**[a]	**160**	**4.8**[c]	**2.0**	**5**	**0.6**	**65**
BELLA	**16**[b]	**40**	**5 to 7**	**1.8**	**15**	**~1**	**7**

[a] up to 150 J available

[b] up to 40 J available

[c] self-injected LPA observed down to $1 \times 10^{17}\ \mathrm{cm}^{-3}$

We have made promising forays into the PW-laser-driven, sub-$10^{18}\ \mathrm{cm}^{-3}$, multi-GeV LPA regime via 2 complementary approaches