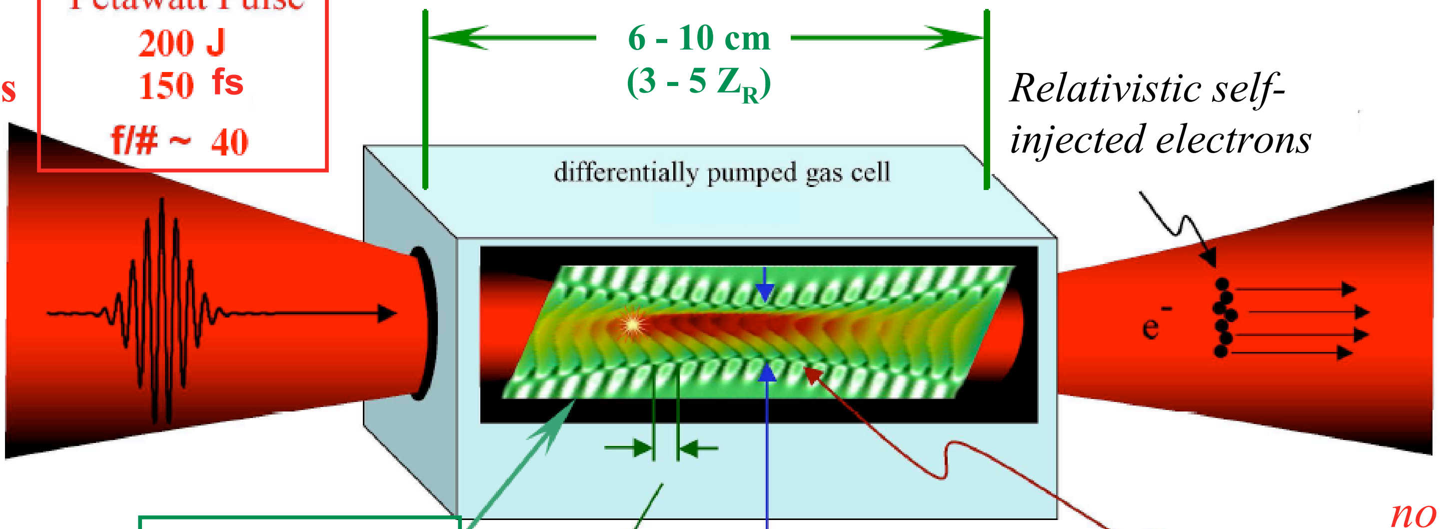
Science with High-Power Lasers and Pulsed Power Workshop, Santa Fe, July 28, 2009

Wakefield Acceleration with Texas Petawatt Laser

Mike Downer, U. Texas-Austin



fixed parameters

Petawatt Pulse
200 J
150 fs
f/# ~ 40

6 - 10 cm
(3 - 5 Z_R)

Relativistic self-injected electrons

ONE variable parameter

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

$\lambda_P \approx 65$ µm

2 w_0 ≈160 µm

a_0 ~ 3.3 – 10
Wakefield

not too short,
not too long;
it's just right!

TPW combines **unique** pulse parameters (1 PW, 150 fs)

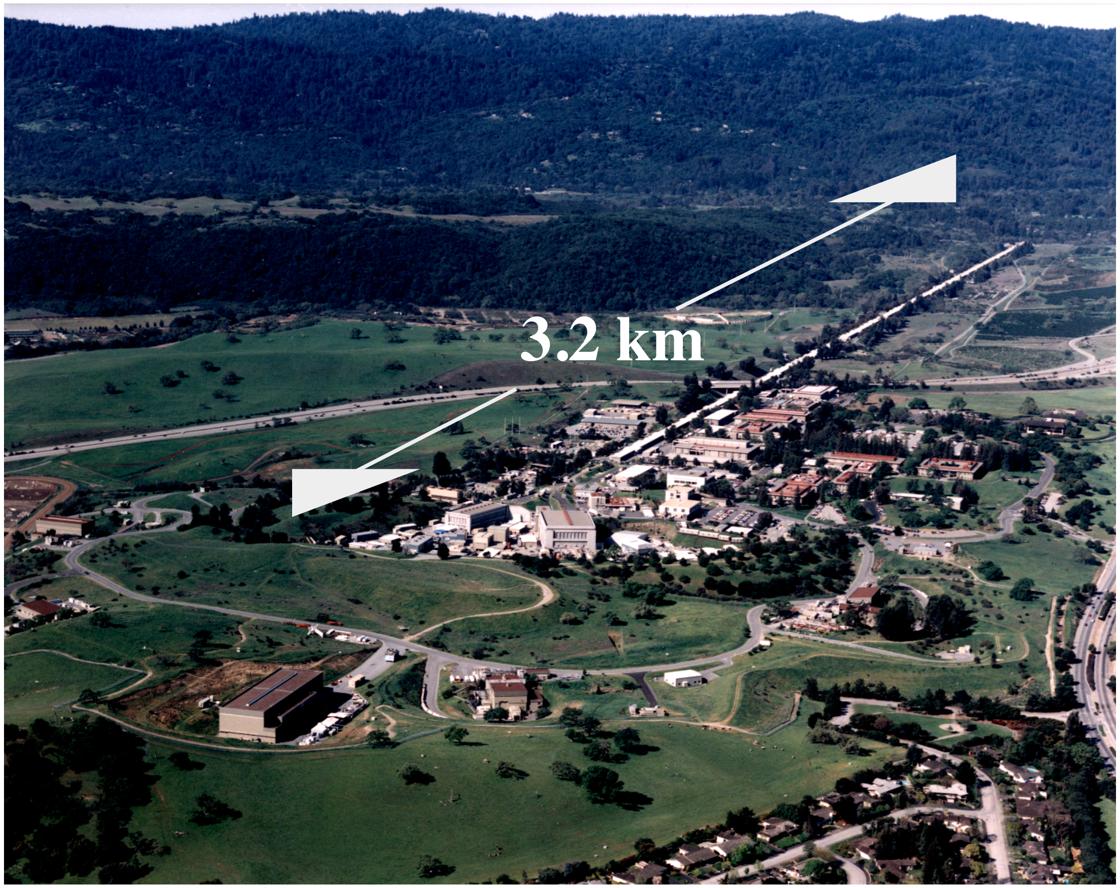
that enable the most energetic "simple" LWF accelerator to date

~ 5 GeV
quasi-mono-energetic

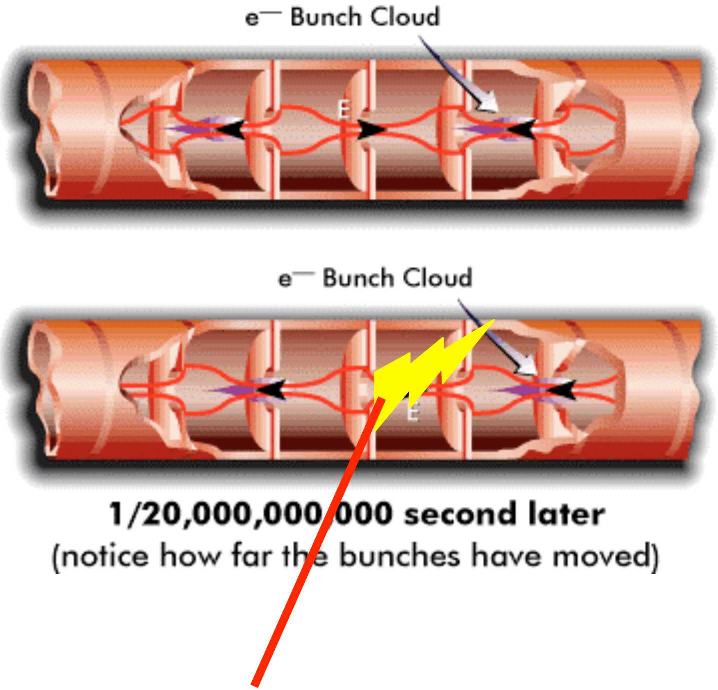
single stage
self-injected
self-guided

1.0 ± .05 GeV
(Leemans 2006)
$n_e \approx 4.3 \times 10^{18}$ cm^{-3}
channel-guided

Conventional RF acceleration is limited by material breakdown



Stanford Linear Accelerator Center



1/20,000,000,000 second later

(notice how far the bunches have moved)

$$E_{breakdown} \sim 10^7 \text{ to } 10^8 \text{ V/m}$$

$$10 \text{ GeV} \Rightarrow 1 \text{ km}$$

$$30 \text{ GeV} \Rightarrow \mathbf{3\ km} \text{ (SLAC)}$$

$$500 \text{ GeV} \Rightarrow 50 \text{ km (ILC)}$$

LASER-PLASMA ACCELERATORS:
overcome 3 problems simultaneously

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

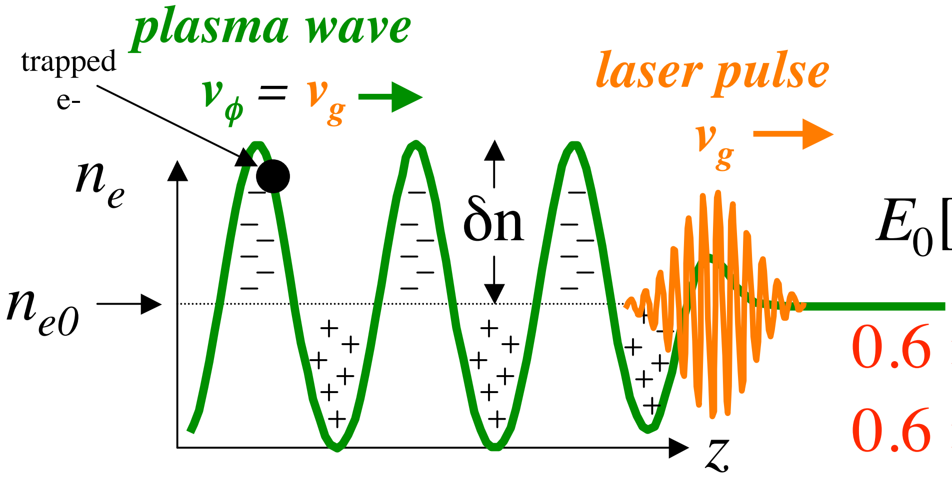
LASER → **PLASMA** → **CHARGED PARTICLE**

PLASMA
- *underdense (e^-, e^+)*
- *overdense (p^+, ions, e^+)*

(1) $E_\perp \rightarrow E_z$

(2) *fully damaged*

(3) *supports large internal electrostatic fields*



$$E_0[V/cm] = \frac{mc\omega_p}{e} = 0.96(n_e[cm^{-3}])^{1/2}$$

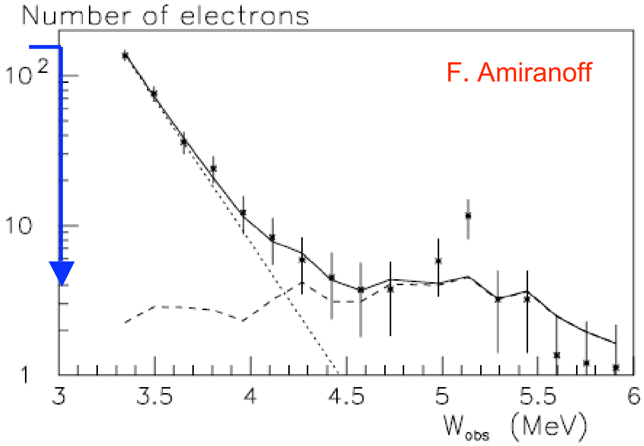
0.6×10^9 V/cm

0.6×10^{11} V/m

0.36×10^{18} cm^{-3}

Electron & Positron Acceleration by Underdense Plasma Waves

externally injected **3 MeV e- from linac**

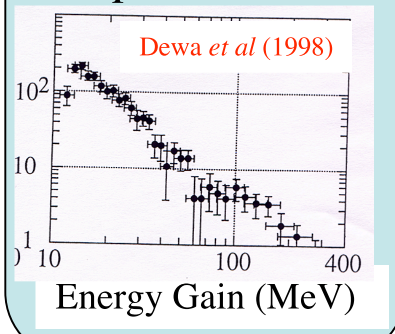


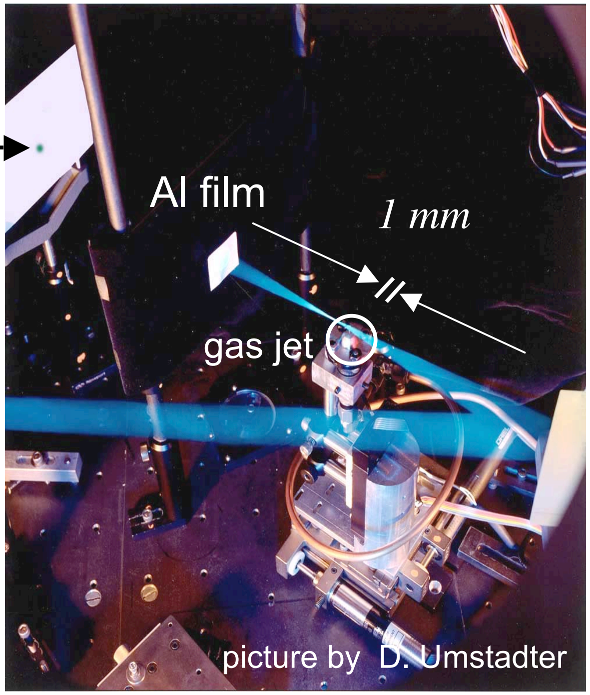
- **Iron Age (1988-95):**
  Resonantly-driven plasma waves (linear regime), external injection from linac, gas-filled chamber target, no guiding

- **Jet Age (1995-2004)**
  Far-off-resonantly-driven plasma waves (nonlinear regime), self-injection, self-guided poly-energetic electrons, gas jet target

- **Bubble Era (2004-present)**
  Resonantly-driven plasma waves (nonlinear "blowout" regime), self-injection, self-guided, quasi-mono-energetic electrons

$>10^{10}$ electrons per shot





picture by D. Umstadter

2004: “Bubbles” burst on the scene

Mangles, *Nature* **431**,535 (2004) --- RAL (UK)
Geddes, *Nature* **431**, 538 (2004) --- LOA (France)
Faure, *Nature* **431**, 541 (2004) --- LBNL (USA)

30 September 2004
International weekly journal of science

nature

www.nature.com/nature

Dream beam

The dawn of compact particle accelerators

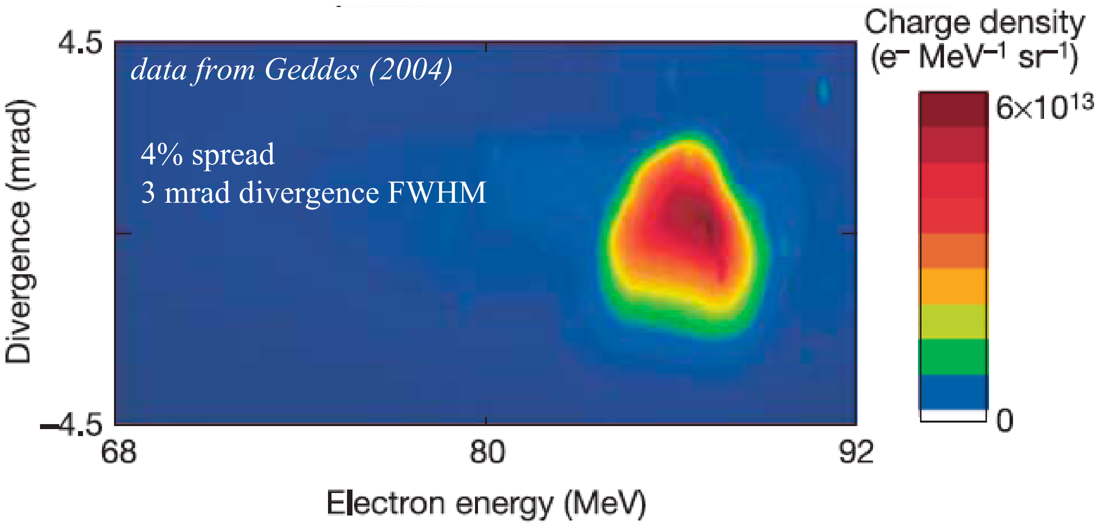
Disease control
Europe plays catch-up

The Earth's hum
Sounds of air and sea

Protein folding
Escape from the ribosome

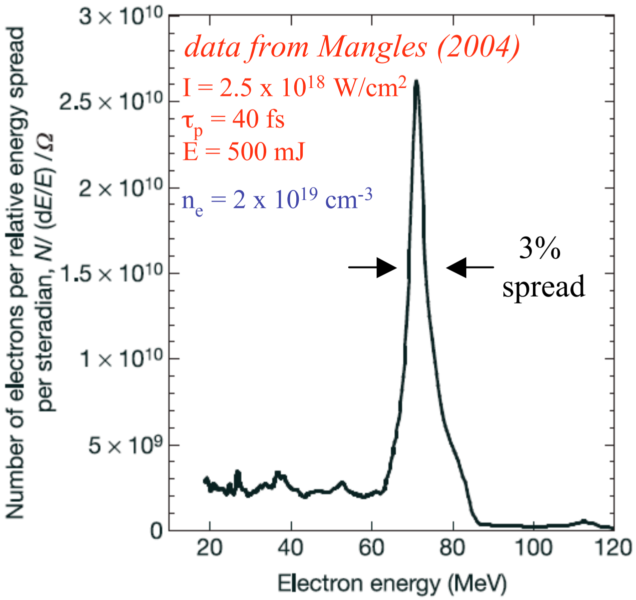
Human ancestry
One from all and all from one

technology feature RNA interference



data from Geddes (2004)

4% spread
3 mrad divergence FWHM



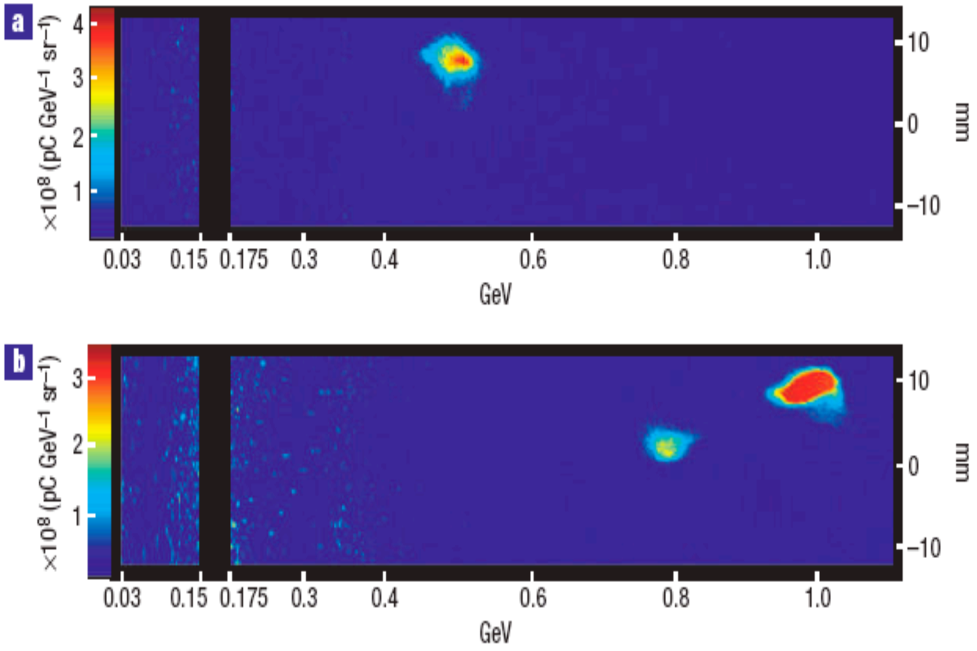
data from Mangles (2004)

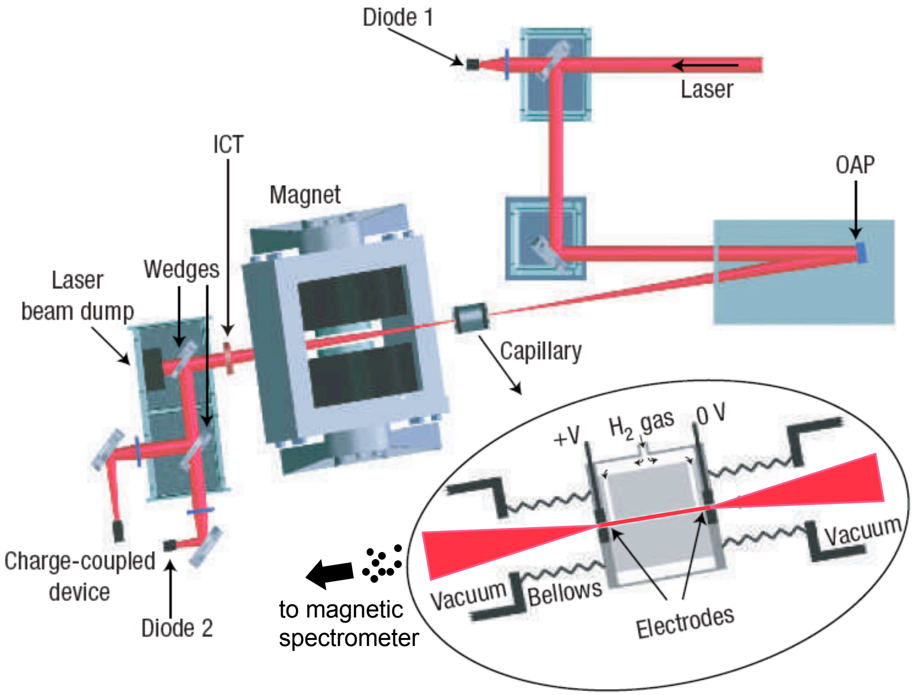
$I = 2.5 \times 10^{18}$ W/cm^2
$\tau_p = 40$ fs
$E = 500$ mJ
$n_e = 2 \times 10^{19}$ cm^{-3}

3% spread

1 GeV quasi-monoenergetic beams have been achieved only with the help of a PLASMA CHANNEL

Leemans *et al.*, *Nature Physics* **2**, 636 (2006)   (LBNL-Oxford collaboration)





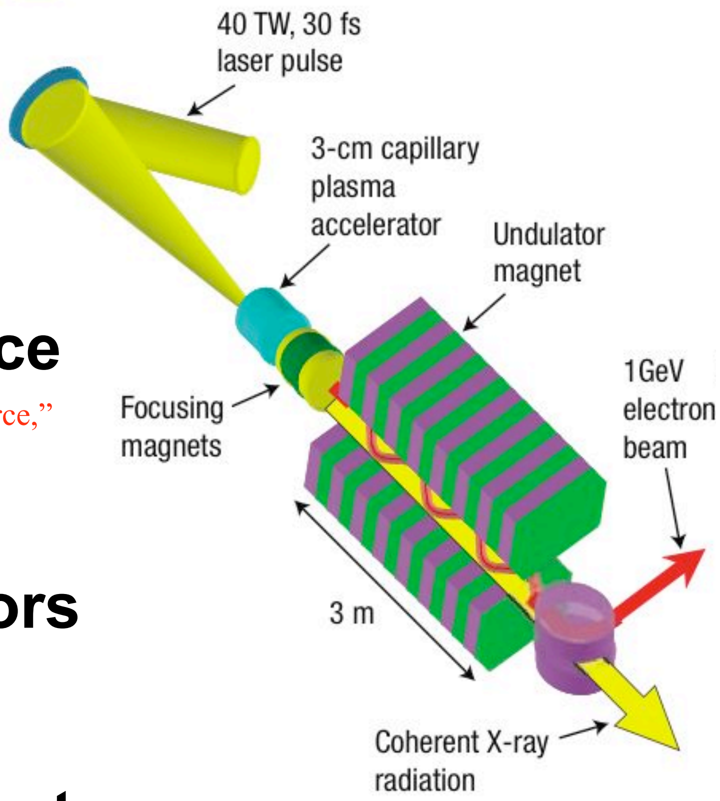
Spence & Hooker,
Phys. Rev. E **63**, 015401 (R) (2001)

BEYOND GeV:

- PW laser pulses
- staging

beam divergence: 1.6 mrad
energy spread: 5%
charge per bunch: ~ 0.1 nC
accelerator length: **3 cm**

The achievement of quasi-monoenergetic laser-plasma accelerated e$^-$ up to 1 GeV opens a multitude of applications



- **Table-top, fs X-ray FELs**

  Nakajima, “Toward a table-top free-electron laser,” *Nature Phys*. **4**, 846 (2008)

- **γ-ray radiography for materials science**

  Glinec, “High-resolution γ-ray radiography produced by a laser-plasma electron source,” *Phys. Rev. Lett.* **94**, 025003 (2005).

- **Compact injectors for HEP accelerators**

- **Efficient on-site production of radioisotopes**

  Reed, “Efficient initiation of photonuclear reactions using quasi-monoenergetic electron beams from laser wakefield acceleration,” *J. Appl. Phys.* **102**, 073103 (2007)

- **Radiotherapy with tunable, high-energy electrons**

  DeRosiers, “150-250 MeV electron beams in radiation therapy,” *Phys. Med. Biol.* **45**, 1781 (2000)
  Glinec, “Radiotherapy with quasi-monoenergetic laser-plasma accelerators,” *Med. Phys.* **33**, 155 (2006)

How far can laser-plasma acceleration go?

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

3D computer simulations increasingly guide development of future experiments

Laser Power [PW]	Pulse Duration [fs]	Plasma Density [cm^{-3}]	Spot Size [μm]	Int. Length [m]	e- charge [nC]	Energy Gain [GeV]	comments
0.04	30	1.5x10^{18}	14	0.011	0.25	**0.95**	channel-guided, self-injected Leemans (2006)
1.0	**80**	**5x10^{17}**	**34**	**0.08**	**1.3**	**5.7**	**self-guided, self-injected**
2.0	100	3x10^{17}	47	0.18	1.8	10.2	self-guided, self-injected
2.0	310	10^{16}	140	16.3	1.8	**100**	
20	1000	10^{15}	450	500	5.7	**1000**	

within reach of existing technology (rows 1–3)

requires a "miracle" in channel guiding technology (rows 4–5)

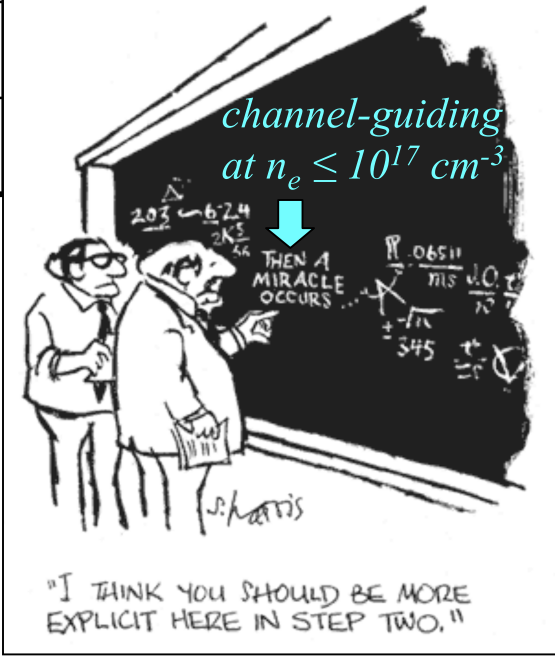
Texas Petawatt

Table entries feature:

1. stable plasma structure

2. $L_{dephasing} = L_{pump\ depletion}$

3. balance between energy extraction & beam quality



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

One school of thought maintains that the "bubble" regime is scalable all the way to the energy frontier

Simulation Tools and Strategy

S. Kalmykov, S. A. Yi, V. Khudik, G. Shvets

WAKE P. Mora and T. M. Antonsen, Jr., Phys. Plasmas **4**, 217 (1997)	**Virtual Laser Plasma Lab (VLPL)** A.Pukhov, J.Plasma Physics **61**,425(1999)
• Fully relativistic PIC code, “moving window” • Quasi-paraxial solver for radiation beam propagation • Quasi-static electron response to cycle-averaged ponderomotive force excludes electron self-injection; enormously speeds-up particle pushing • 2D planar or 3D axi-symmetric geometry • Fully 3D test particle tracking code (approximate model of self-injection)	• Fully electromagnetic explicit relativistic 3D PIC code; moving window • Maxwell solver with no numerical GVD in propagation direction preserves accuracy over cm-long propagation distance in rarefied plasmas • Parallelized (MPI, domain decomposition)

Quick parameter scans & optimization of laser and plasma wake dynamics

Brute force tool: self-consistent model of electron self-injection

Simulations of LWFA with the Texas PW laser

S. Kalmykov, S. A. Yi *et al*., "Laser wakefield electron acceleration on the Texas Petawatt facility: towards GeV electron energy in a single self-guided stage," to appear in *High Energy Density Physics* (2009).

Questions we aim to answer:

- Can TPW pulse self-guide over multiple $Z_R \approx 2$ cm in a near-resonantly-driven plasma ($1 < \omega_{pe}\tau_{laser} < 2\pi$) w/o catastrophic filamentation or hyper-sensitivity to hot spots?

$$\tau_{laser} = 150\text{ fs} \quad \Rightarrow \quad 0.14 < n_e < 5.5 \times 10^{17}\text{ cm}^{-3}$$

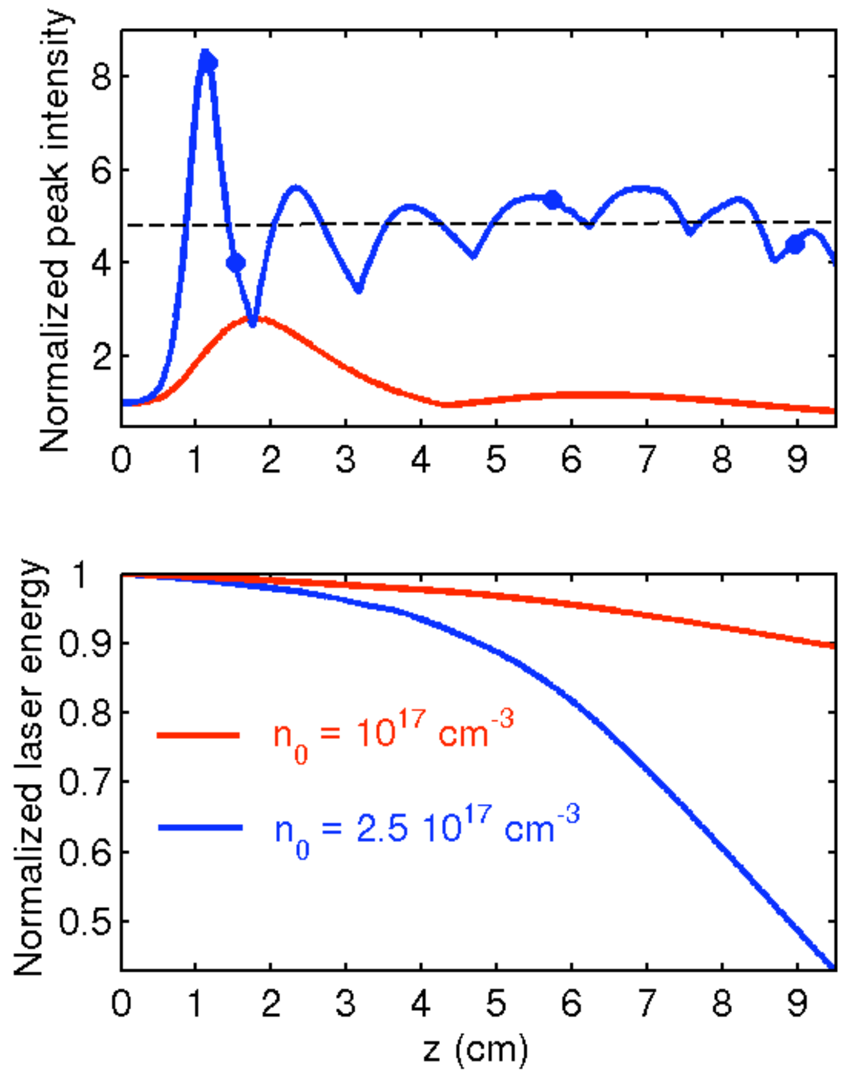
$$\Rightarrow \quad 1.2\text{ PW} > P_{crit} > .03\text{ PW} \quad \Rightarrow \quad P_{crit} << P_{laser}$$

n.b. All self-guided LWFAs to date have been limited to few mm propagation

- Will the self-guided TPW pulse form a plasma bubble that captures and accelerates surrounding plasma electrons quasi-mono-energetically to multiple GeV?

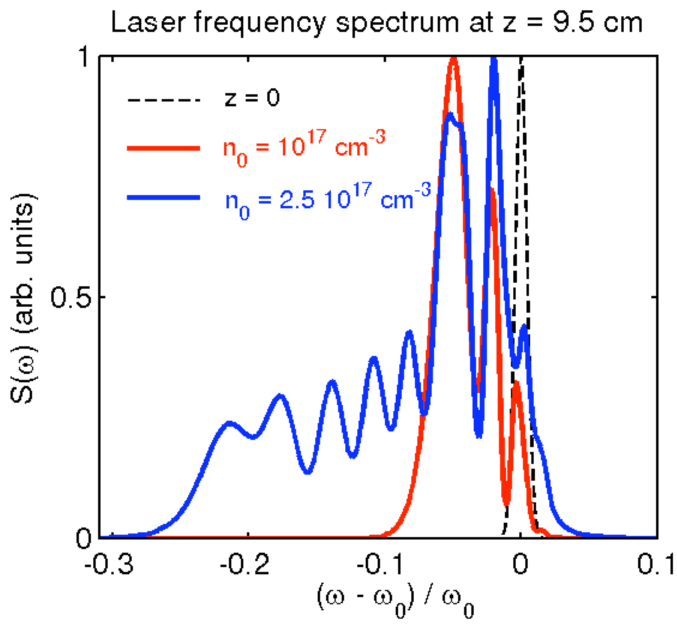
n.b. All self-injected LWFAs to date have operated in denser plasma ($n_e > 5\ 10^{18}\text{ cm}^{-3}$)

WAKE shows the laser pulse self-guides stably for low 10^{17} cm^{-3} uniform plasma density

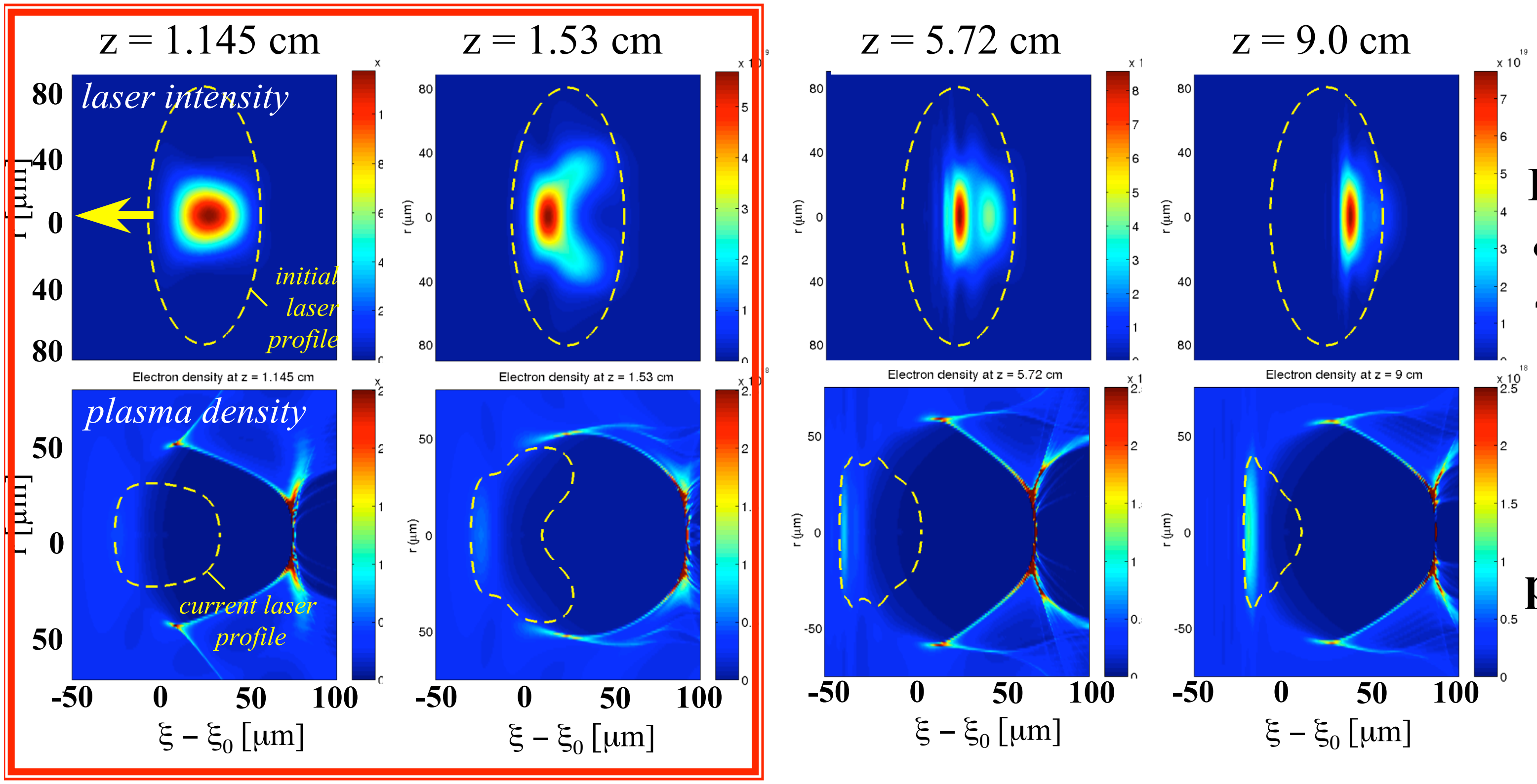


$I \approx 6 \cdot 10^{19}$ W/cm^2
$R_{\text{bubble}} \approx 55\ \mu$m

Laser pulse red-shift


Laser frequency spectrum at z = 9.5 cm

WAKE run for $n_e = 2.5 \cdot 10^{17}$ cm^{-3}



Laser self-guides & compresses to 45 fs over 10 cm.

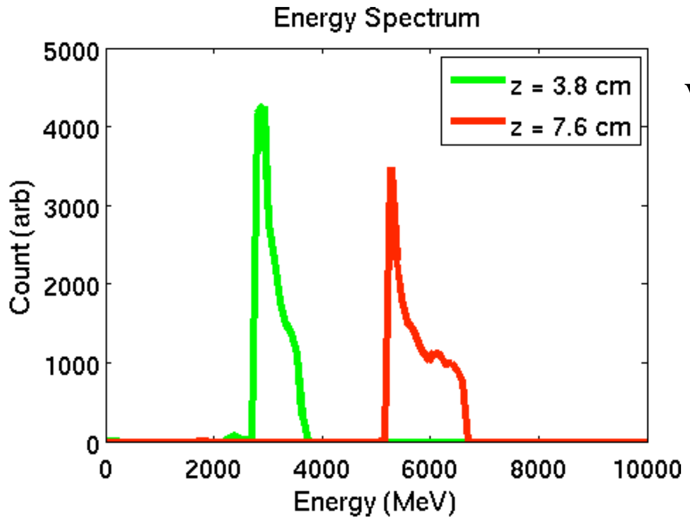
Bubble initially grows rapidly, persists for 10 cm

Bubble rapidly grows: signature of self-injection

⇓

inject test electrons here

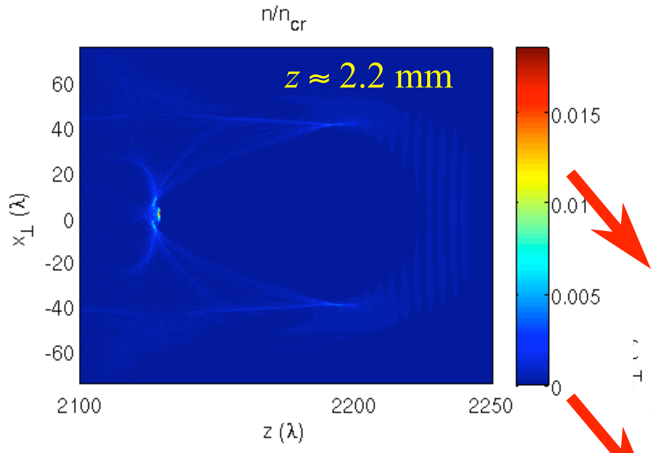
⇨



WAKE test-particle simulation shows quasi-monoenergetic acceleration to > 6 GeV

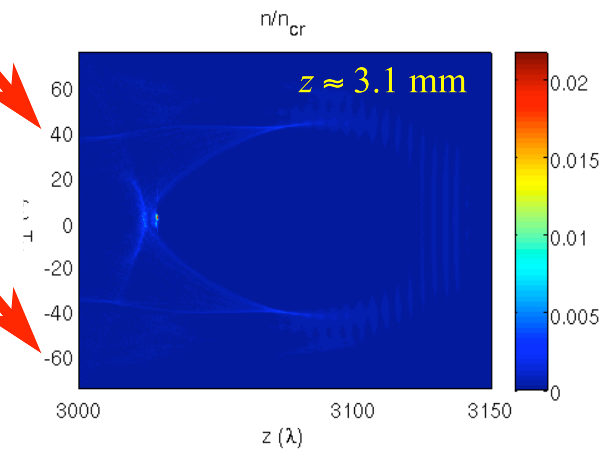
VLPL confirms self-injection for $n_e \approx 2.5 \cdot 10^{17}$ cm^{-3}

Laser parameters for the plane of nonlinear focus are taken from WAKE run; ***self-injection is observed***

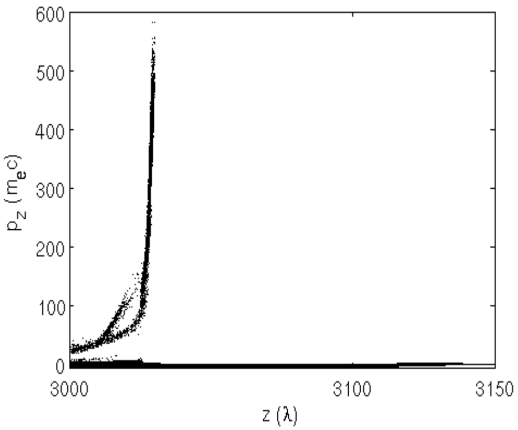


$r_{\text{bubble}} \approx 27$ µm

$a_0 = 9.9$



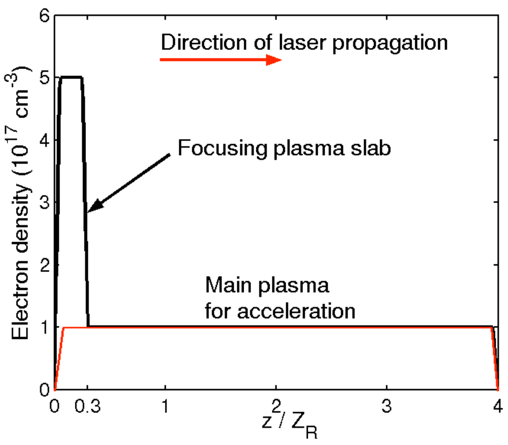
electron longitudinal momentum



No self-injection, however, for $n_e \approx 1 \cdot 10^{17}$ cm^{-3} ...

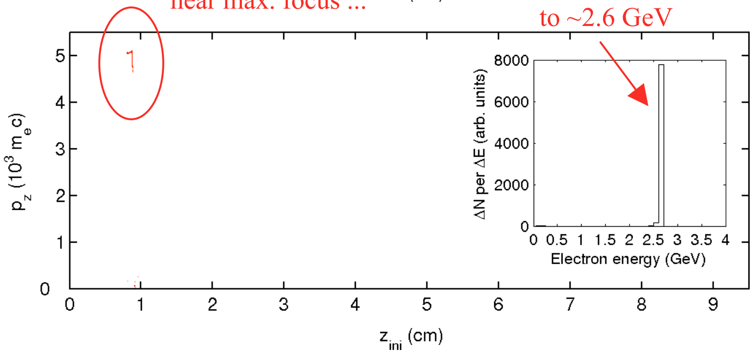
Laser focusing and resulting bubble evolution are too steady → no self-injection in homogeneous plasmas.

... unless we insert a dense slab at the plasma entrance



electrons self- injected near max. focus ...

... and accelerated mono-energetically to ~2.6 GeV

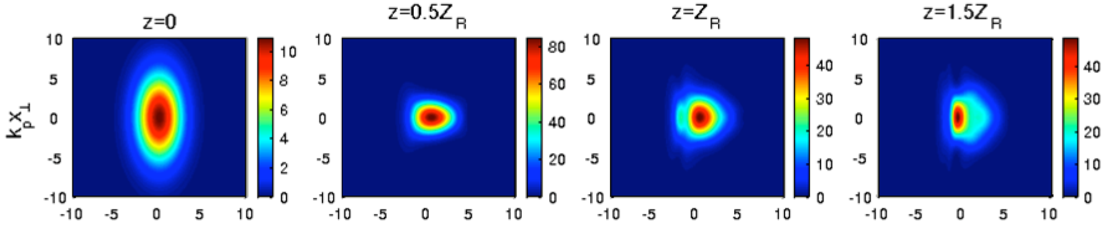


Hot spots: good news and bad news

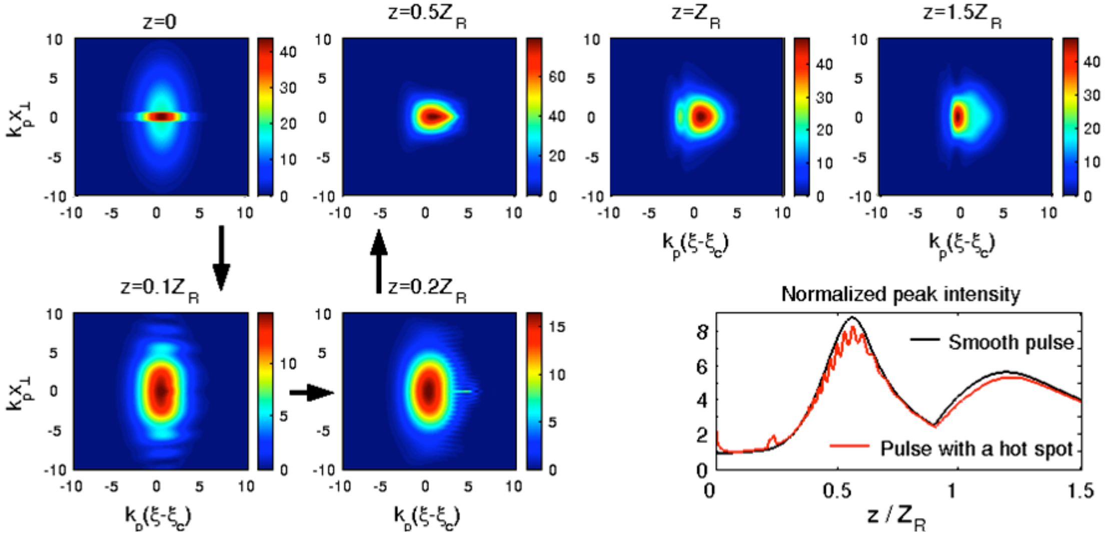
WAKE (3D axi-symmetric)

good news: crappy laser pulse propagates almost as stably as perfect Gaussian

Gaussian:

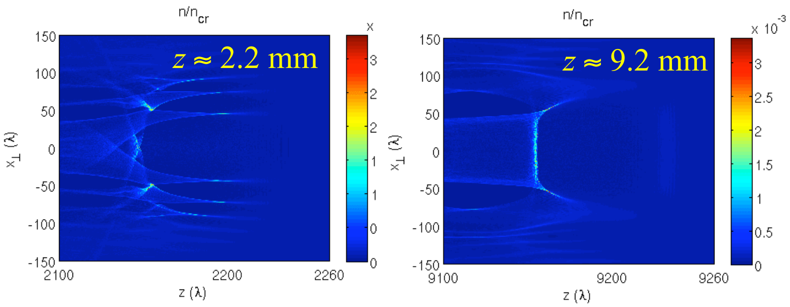


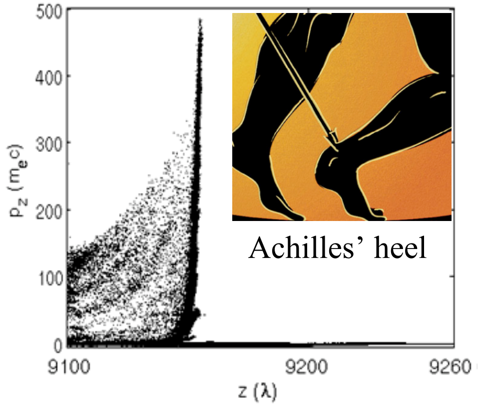
Gaussian + hot spot + local phase perturbation:



VLPL (2D planar)

bad news: as transient structures in laser pulse evolve rapidly, the bubble traps *too many* electrons and overloads.*

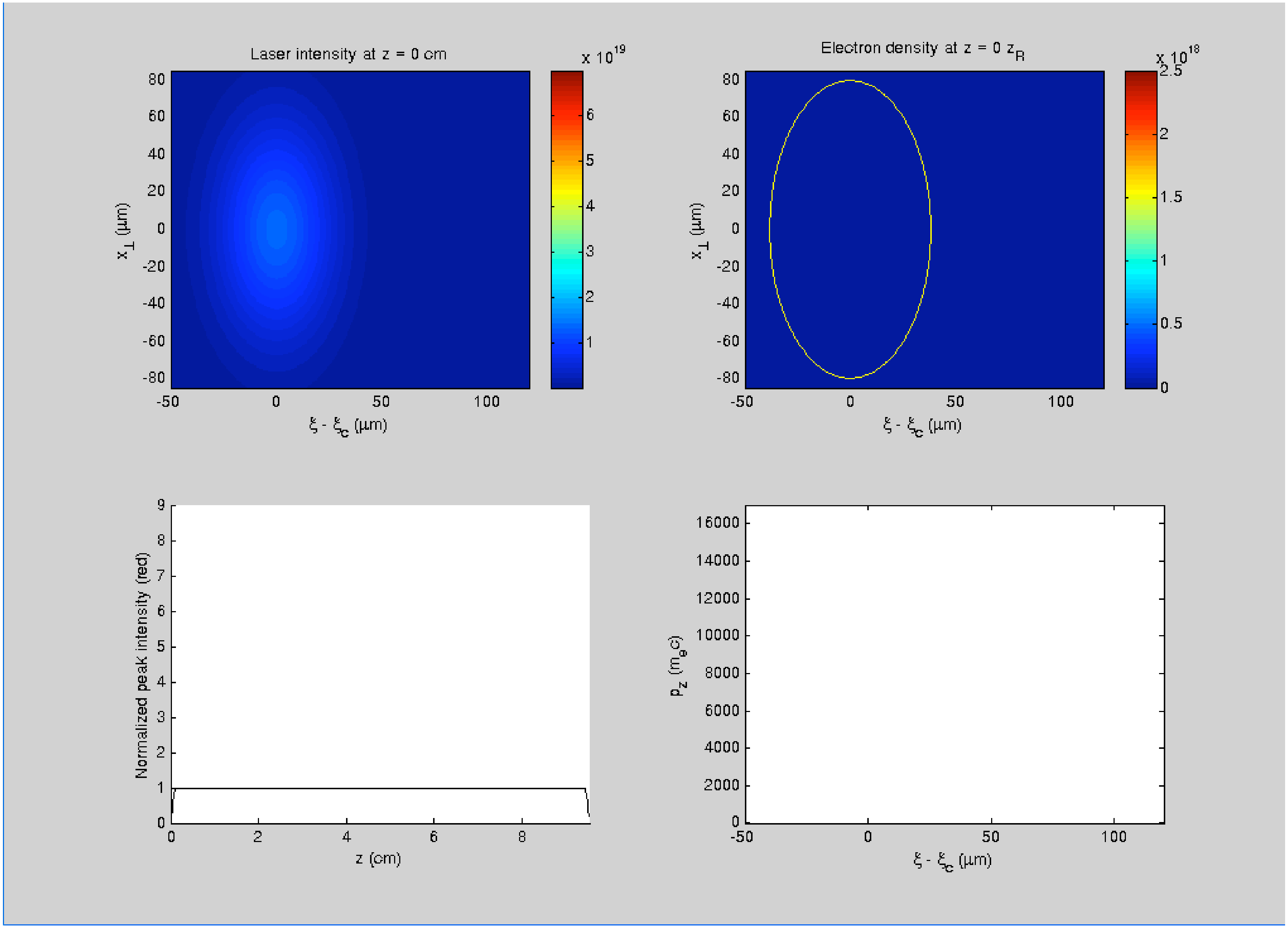




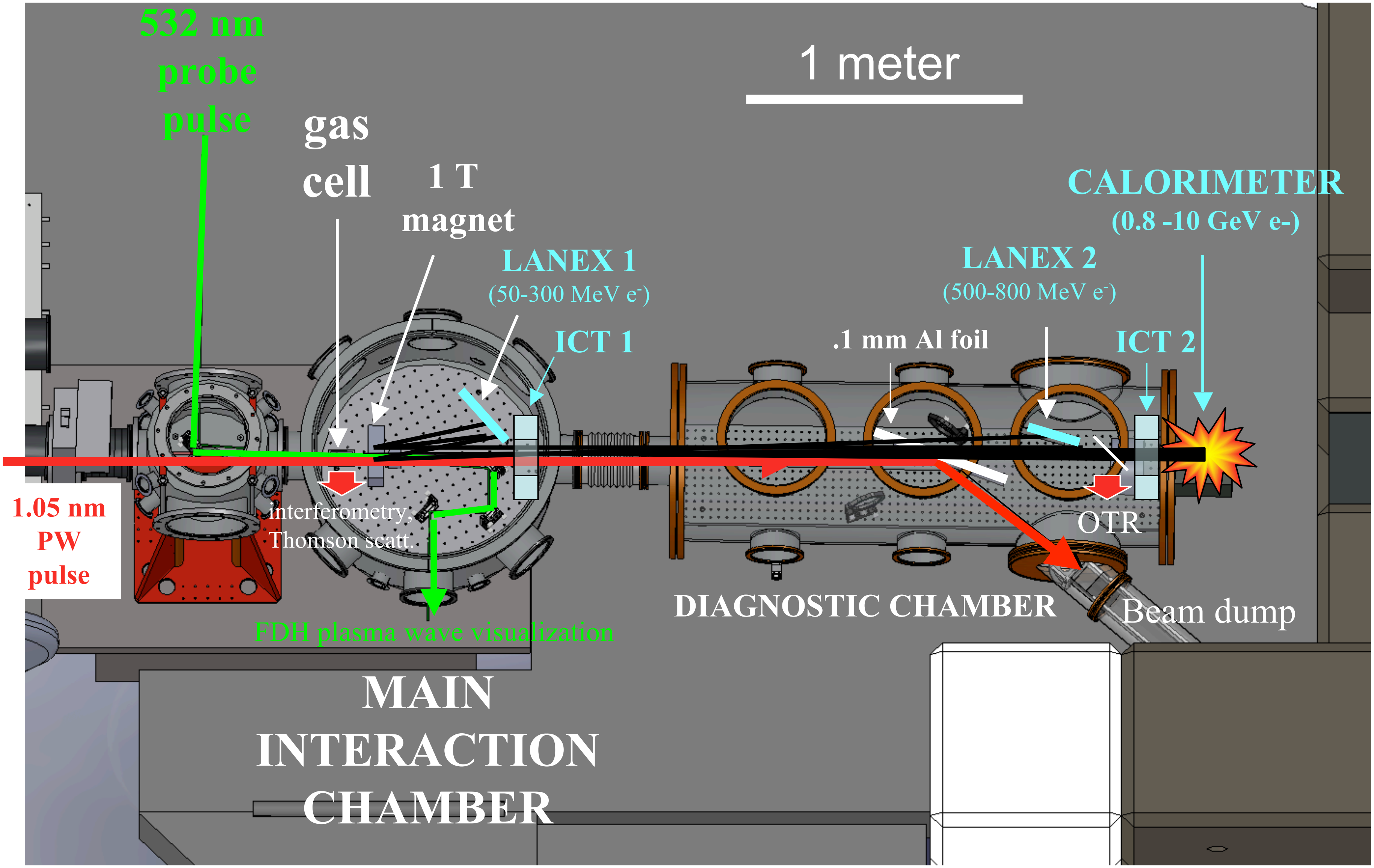
- wake won't survive past z ~ 1cm, sub-GeV acceleration, wide energy spread

Moral: hot spots facilitate self-injection, but maybe too much!

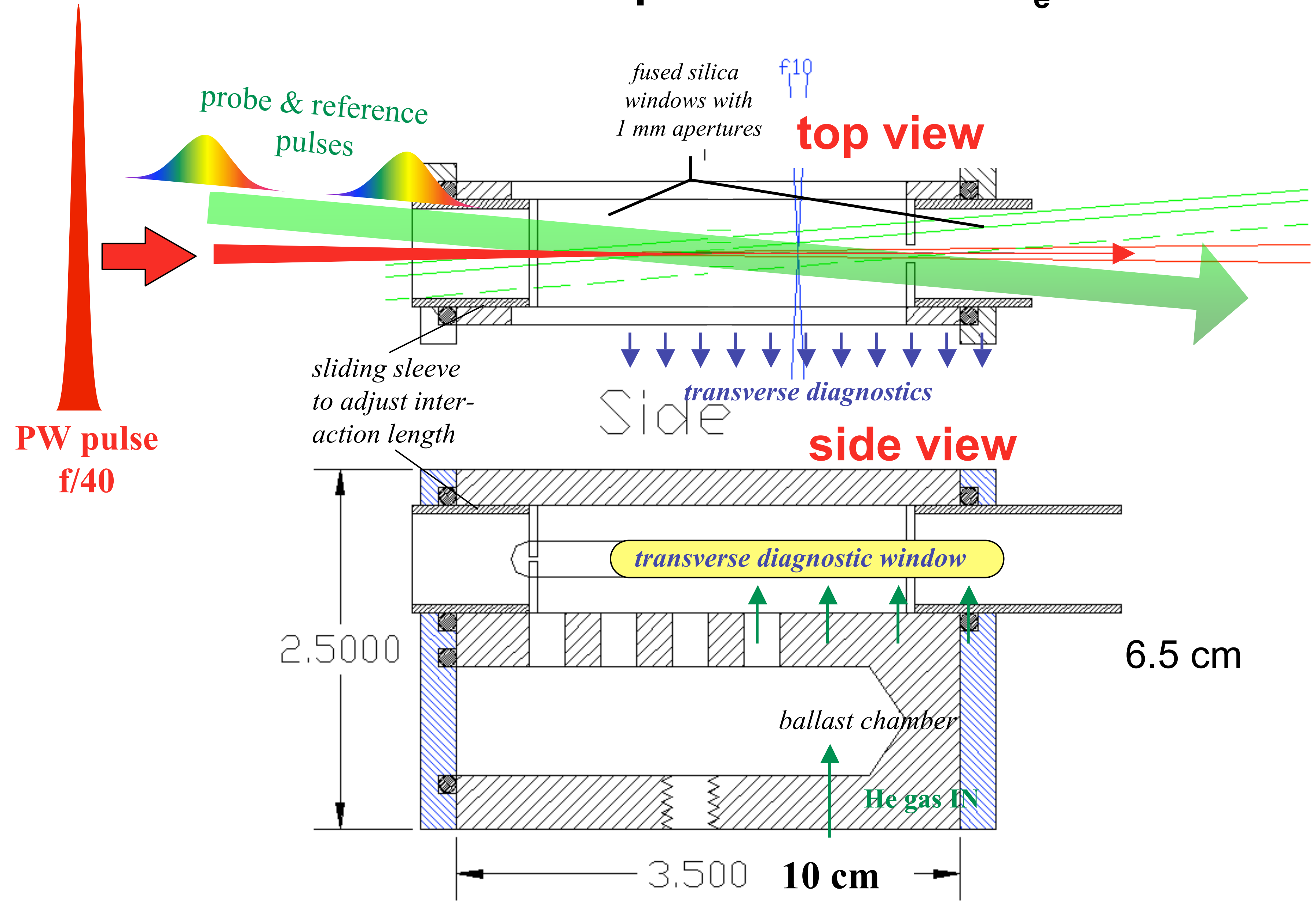
TEXAS PW LWFA: THE MOVIE



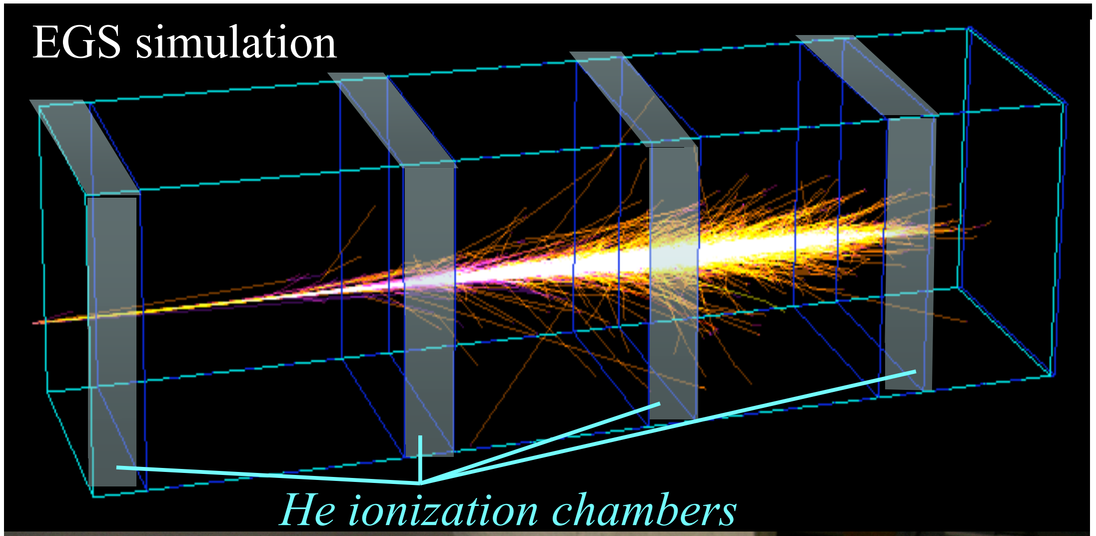
Petawatt LWFA hardware

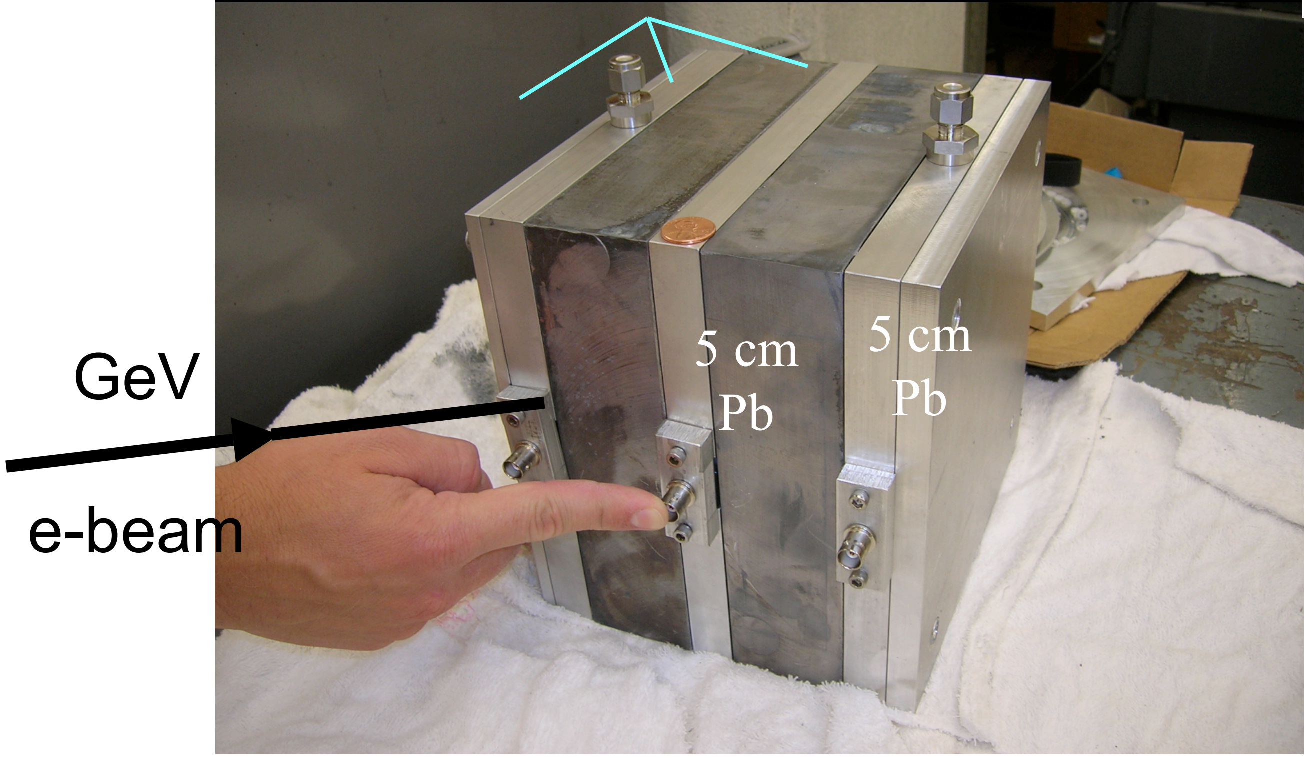


Differentially-pumped gas cell: uniform, optically accessible He plasma at $10^{17} < n_e < 5 \times 10^{17}$ cm^{-3}

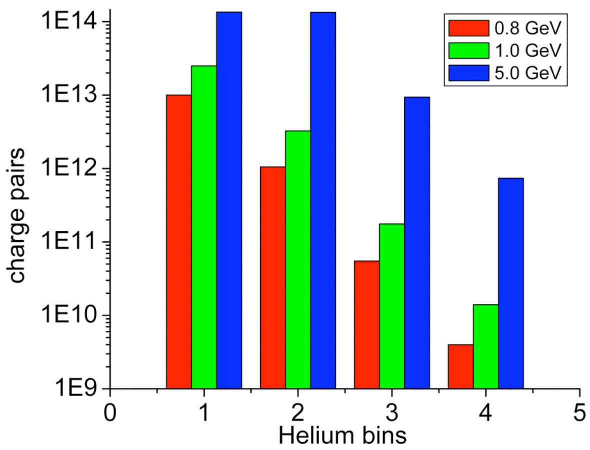


CALORIMETER: coarse, inexpensive GeV e^- energy measurement





Model results



He ionization rates

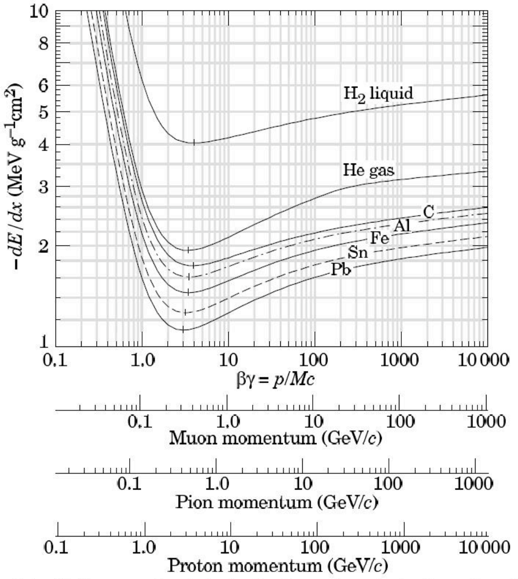


Figure 7.3: dE/dx curves due to ionization for various singly charged particles, taken from [101] (p. 4). This curve also applies for electrons as far as ionization losses are concerned, but this data is not an accurate measure of dE/dx i

Wakefield Snapshots using Frequency Domain Holography enrich experiment-theory dialog

N. Matlis *et al.*, *Nature Physics* **2**, 749 (2006)

30 TW Pump (ω)

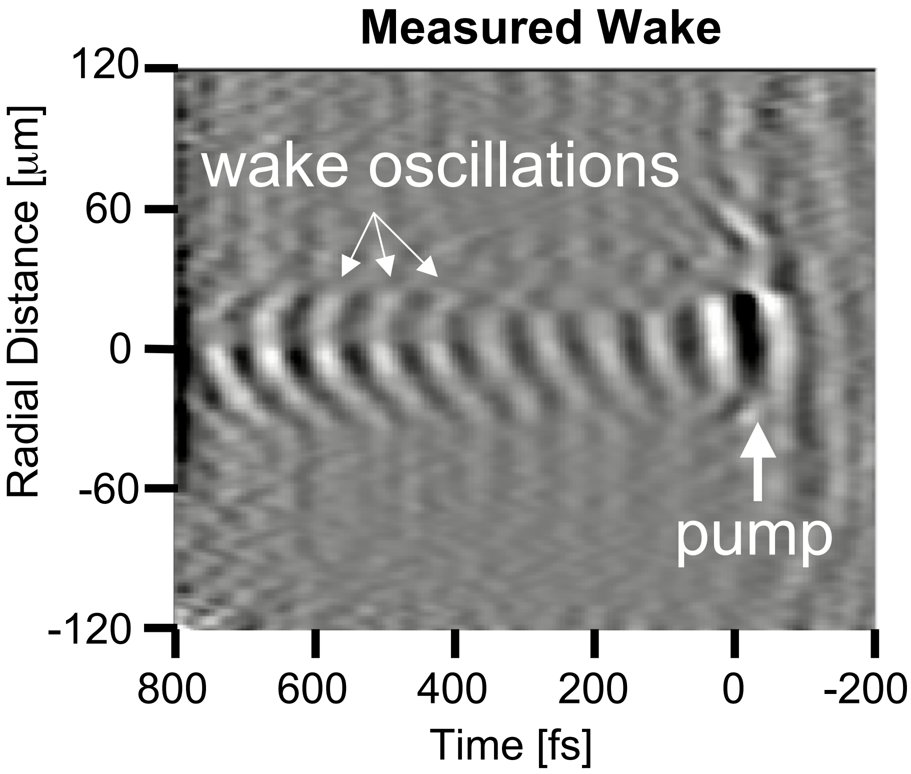
Wakefield $n_e = n_0 + \delta n_e(t)$

Chirped Probe (2ω)

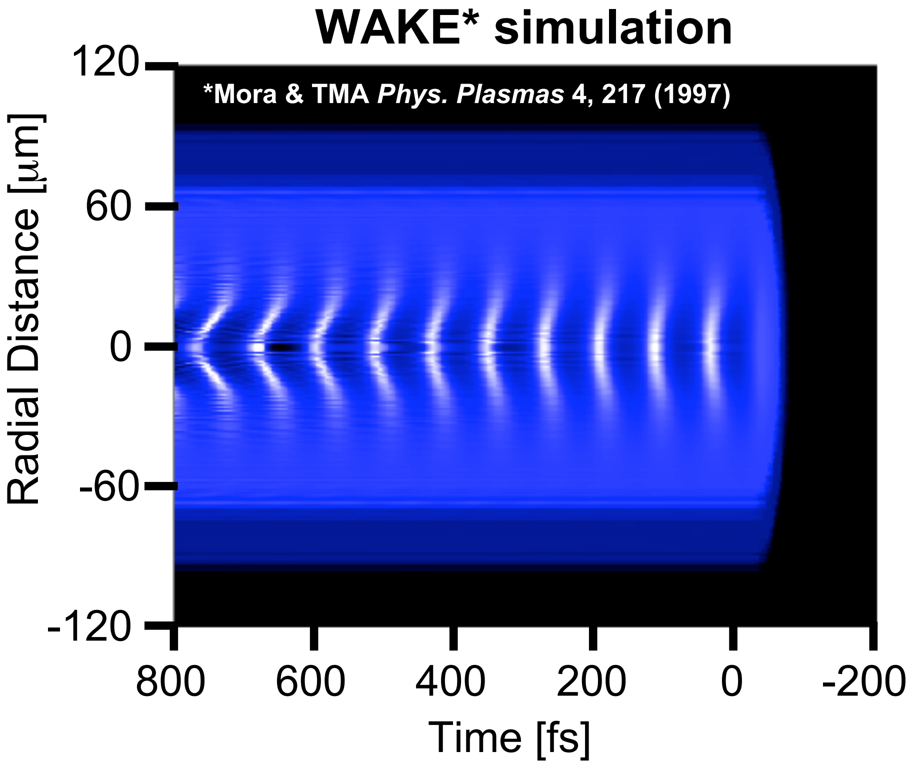
Ionization Front

Chirped Reference (2ω)

to spectrometer



Measured Wake



WAKE* simulation

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

simulation by S. Kalmykov, G. Shvets

GRAND CHALLENGES

- Perform comparative multi-GeV LWFA experiments at UT (TPW) and SNL (Z-PW).

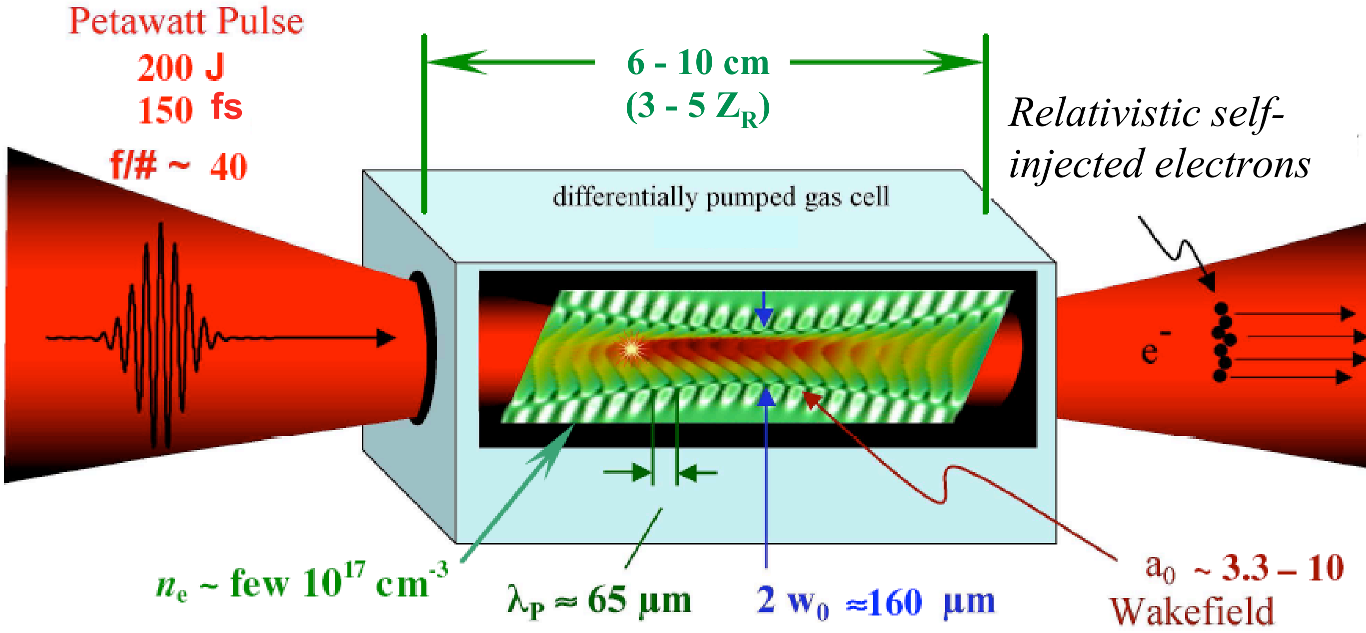
- Figure out how to guide PW pulses over > 10 m at $n_e < 10^{17}$ cm^{-3}

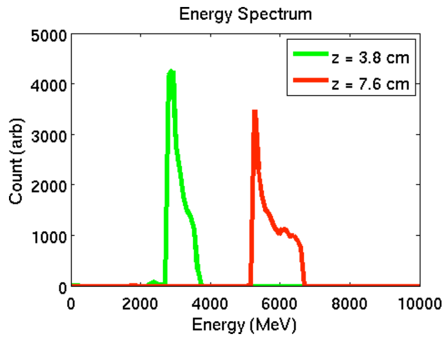
  ⇒ key to > 10 GeV LWFA

- Convert existing GeV-class LWFAs into table-top fs FELs that complement LCLS

- Figure out how use 10 GeV+ LWFA electrons to access astrophysics of GRBs, Pulsar W

SUMMARY





- The Texas PW laser can realize the full potential of “simple” bubble-regime LWFA:
  - up to 7.0 GeV electrons with ~10% energy spread achievable
  - robust self-guided propagation thru ~ 10 cm plasma ($1 < n_e < 5 \cdot 10^{17}$ cm^{-3})
  - self-injection for $\begin{cases} n_e \geq 2.5 \cdot 10^{17} \text{ cm}^{-3} \text{ (uniform plasma, Gaussian pulse)} \\ \text{lower } n_e \text{ (nonuniform plasma, non-Gaussian pulse)*} \end{cases}$

* hot spots pose danger of over-loading wake

- 1st generation experiments, scheduled during Fall 2009, can spur future science & funding
  - coarse, low-cost calorimetry of GeV electrons
  - FD holographic snapshots of bubble
  - multiple supporting diagnostics of e-beam, laser propagation, etc.

ACKNOWLEDGMENTS

Simulations

- Serguei Kalmykov
- Austin Yi
- V. Khudik
- G. Shvets
- E. Lefebvre
- A. Pukhov

LWFA Experiments

- Steve Reed
- Xiaoming Wang
- Watson Henderson
- Dong Peng
- Dongsu Du
- Stefan Bedacht

Texas PW Laser

- Erhard Gaul
- Mike Martinez
- Gilliss Dyer
- Aaron Bernstein
- Todd Ditmire

... and many others

US DOE grants DE-FG02-04ER41321
DE-FG02-07ER54945
DE-FG03-96ER40954

END

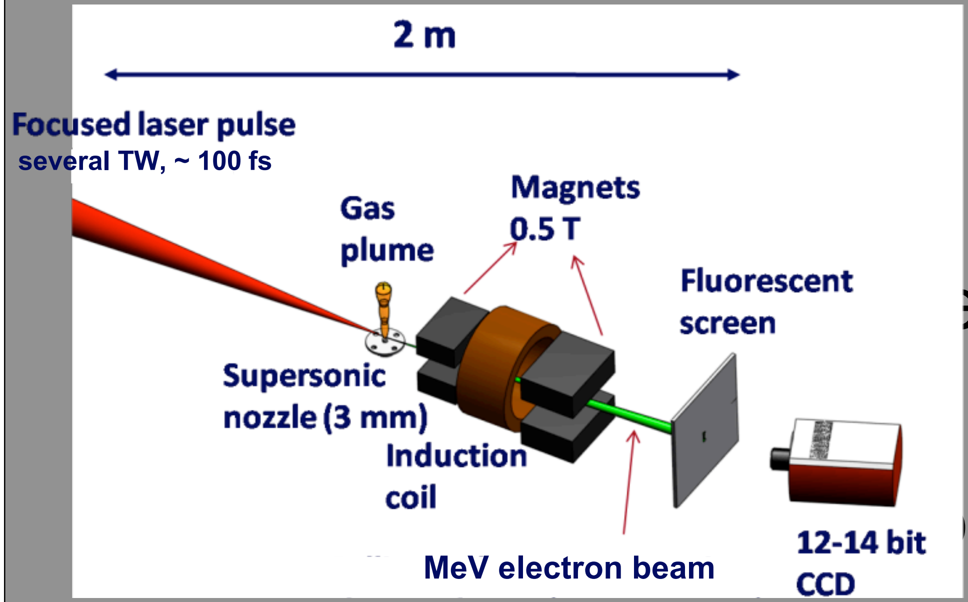
DESIGN CRITERIA:

- maximize $E_{electron}/E_{laser}$
- minimize $\Delta E_{electron}$, angular spread
- exploit unique TPW features -- 150 fs, 200 J
- simplify -- no pre-formed guiding structure, minimize # laser pulses

1995ff.: The “jet-age”* of laser-plasma accelerators

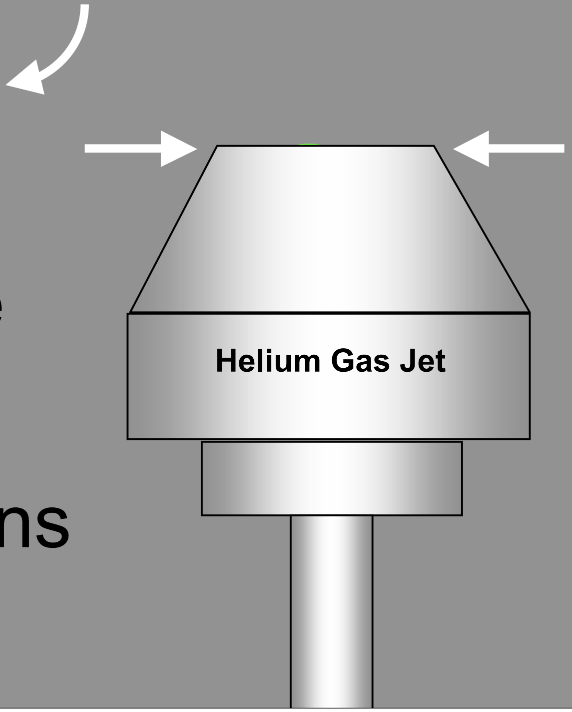
Characteristics of the jet-age:

- Driven by wide availability of TW-scale laser systems
- Simply focus TW laser pulse into a gas jet
- Self-injection of electrons
- Copious yield: up to 10^{10} e^-/shot, up to 100 MeV
- Highly collimated e^- beams
- Suddenly, laser-plasma acceleration had become easy!



e

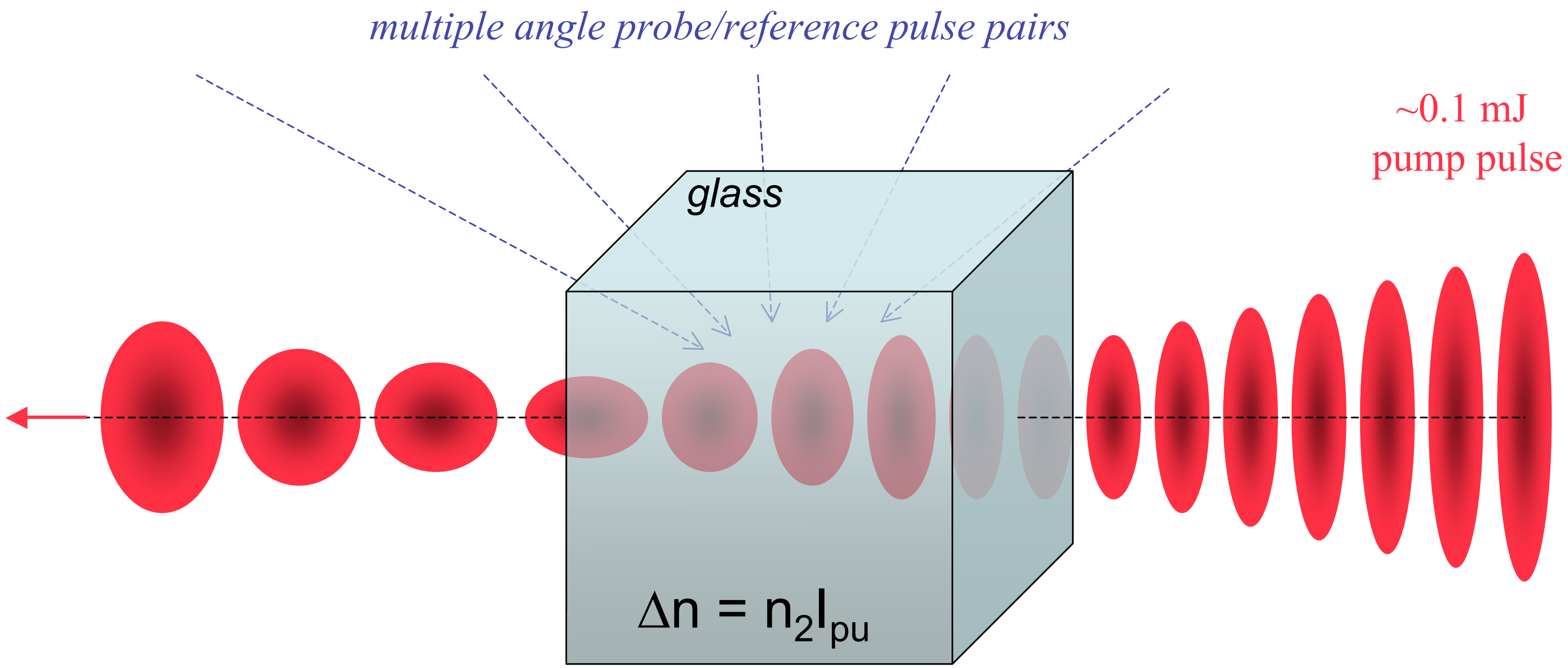
ns



about
3 mm

* *Katsouleas,, Phys. Plasmas* ***13****, 055503 (2006)*

We are setting up a prototype Frequency Domain Tomography experiment based on nonlinear index modulation in glass

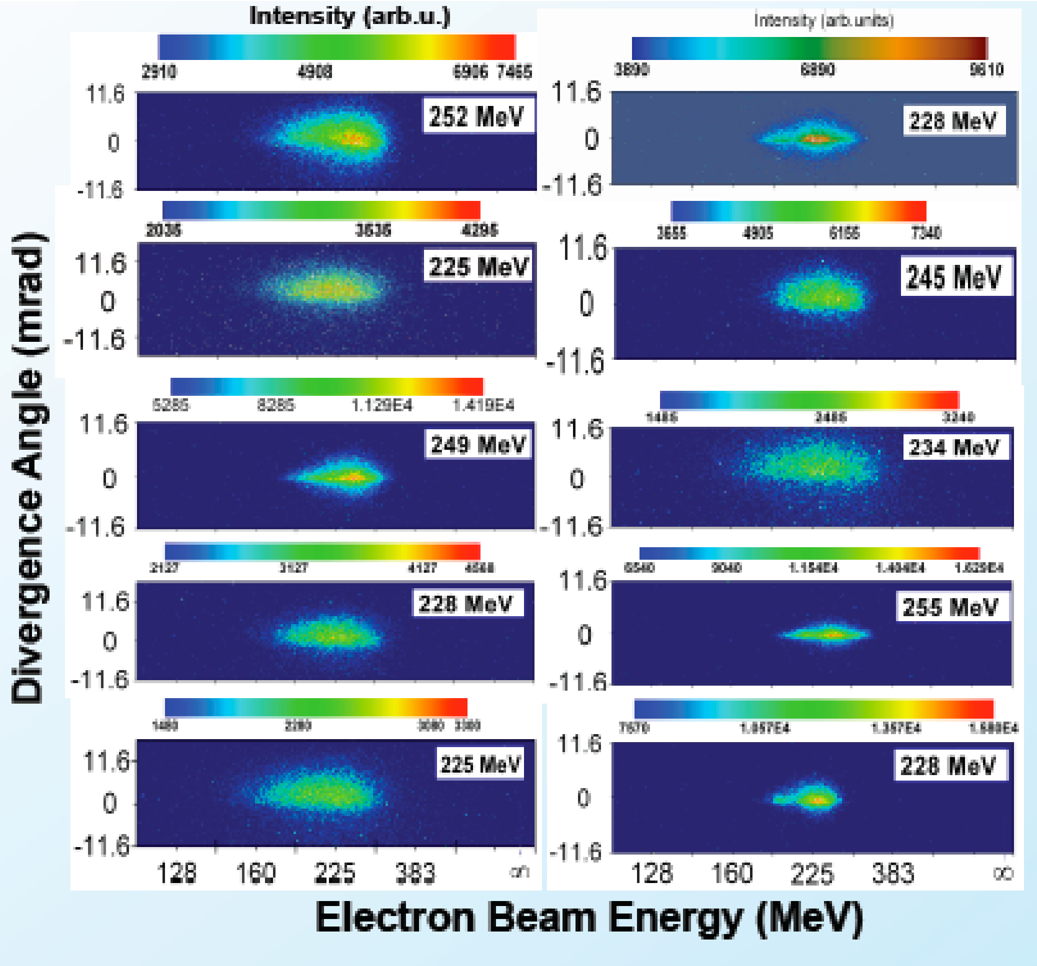


As pump self-focuses and broadens temporally by GVD, the $n_2 I_{pu}$ "bubble" changes shape.

Since 2004, quasi-monoenergetic electrons have been observed in laboratories around the world

Stable quasi-mono-energetic beams demonstrated

Hafz, *Nature Photonics* (2008) --- APRI, Korea



Laser: 37 TW, 35 fs, 24 μm spot

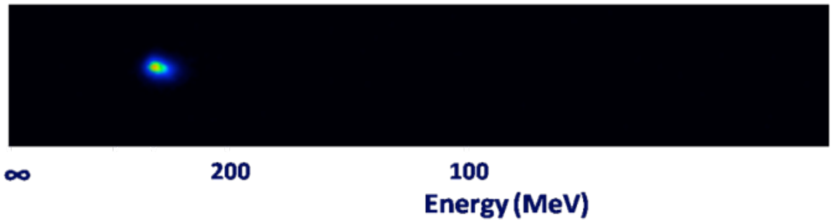
Jet: $n_0 \sim 7 \times 10^{18}$ cm-3, L ~ 3 mm

Electron energy: 237 MeV ± 5%

Hsieh, Phys. Rev. Lett. **96**, 095001 (2006)
Hidding, Phys. Rev. Lett. **96**, 105004 (2006)
Miura, Appl. Phys. Lett. **86**, 251501 (2005)
Hosokai, Phys. Rev. E **73**, 036407 (2006)
Kneip, Phys. Rev. Lett.**103**, 035002 (2009)

.... and many more .....

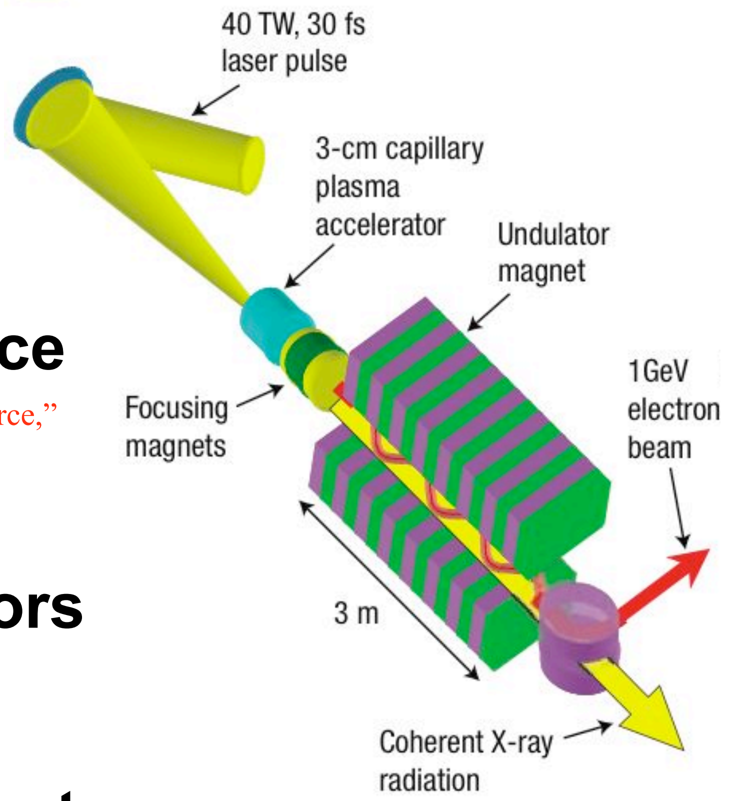
Unpublished data from Umstadter (U. Nebraska-Lincoln):



Parameter	Angular position (mrad)	Divergence (mrad)	Energy (MeV)	Energy spread (MeV)
Mean	0	5.3	344	38.4
Standard deviation	1.1	1.7	35	4.8

In follow-up data, impressive shot-to-shot stability has been achieved (empirically)

The achievement of quasi-monoenergetic laser-plasma accelerated e$^-$ up to 1 GeV opens a multitude of applications



- **Table-top, fs X-ray FELs**

Nakajima, "Toward a table-top free-electron laser," *Nature Phys*. **4**, 846 (2008)

- **γ-ray radiography for materials science**

Glinec, "High-resolution γ-ray radiography produced by a laser-plasma electron source," *Phys. Rev. Lett.* **94**, 025003 (2005).

- **Compact injectors for HEP accelerators**

- **Efficient on-site production of radioisotopes**

Reed, "Efficient initiation of photonuclear reactions using quasi-monoenergetic electron beams from laser wakefield acceleration," *J. Appl. Phys.* **102**, 073103 (2007)

- **Radiotherapy with tunable, high-energy electrons**

DeRosiers, "150-250 MeV electron beams in radiation therapy," *Phys. Med. Biol.* **45**, 1781 (2000)
Glinec, "Radiotherapy with quasi-monoenergetic laser-plasma accelerators," *Med. Phys.* **33**, 155 (2006)

Electron acceleration from underdense plasma with the Vulcan Petawatt laser

S. R. Nagel, S. P. D. Mangles, S. Kneip, C. Bellei, L. Willingale, A. E. Dangor and Z. Najmudin
The Blackett Laboratory, Imperial College London, Prince Consort Road, London, SW7 2BW, UK

R. J. Clarke, R. Heathcote and K. L. Lancaster
Central Laser Facility, STFC, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, UK

A. Gopal and M. Tatarakis
Technological Educational Institute of Crete, Chania, Crete, Greece

A. Maksimchuk, S. A. Reed and K. Krushelnick
University of Michigan, 1006 Gerstacker, Ann Arbor, MI 48109, USA

Laser Parameters:

$E = 85$ J

$\tau_p = 760 \pm 100$ fs

$Z_R \approx 90$ µm, $I \approx 10^{20}$ W/cm^2 @ f/5

Plasma Parameters:

supersonic He gas jet

$0.4 < n_e < 4 \times 10^{19}$ cm^{-3}

$\Rightarrow 30 \text{ fs} > \pi/\omega_p > 10 \text{ fs}$

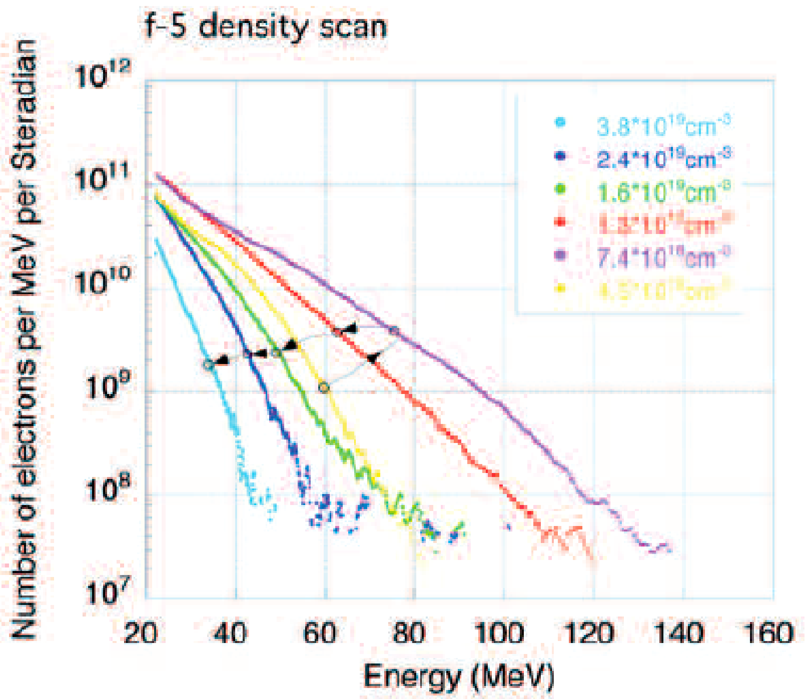


Figure 2. Electron spectra for density scan with f/5.

interesting x-ray results: Kneip *et al.*, PRL **100**, 105006 (2008)

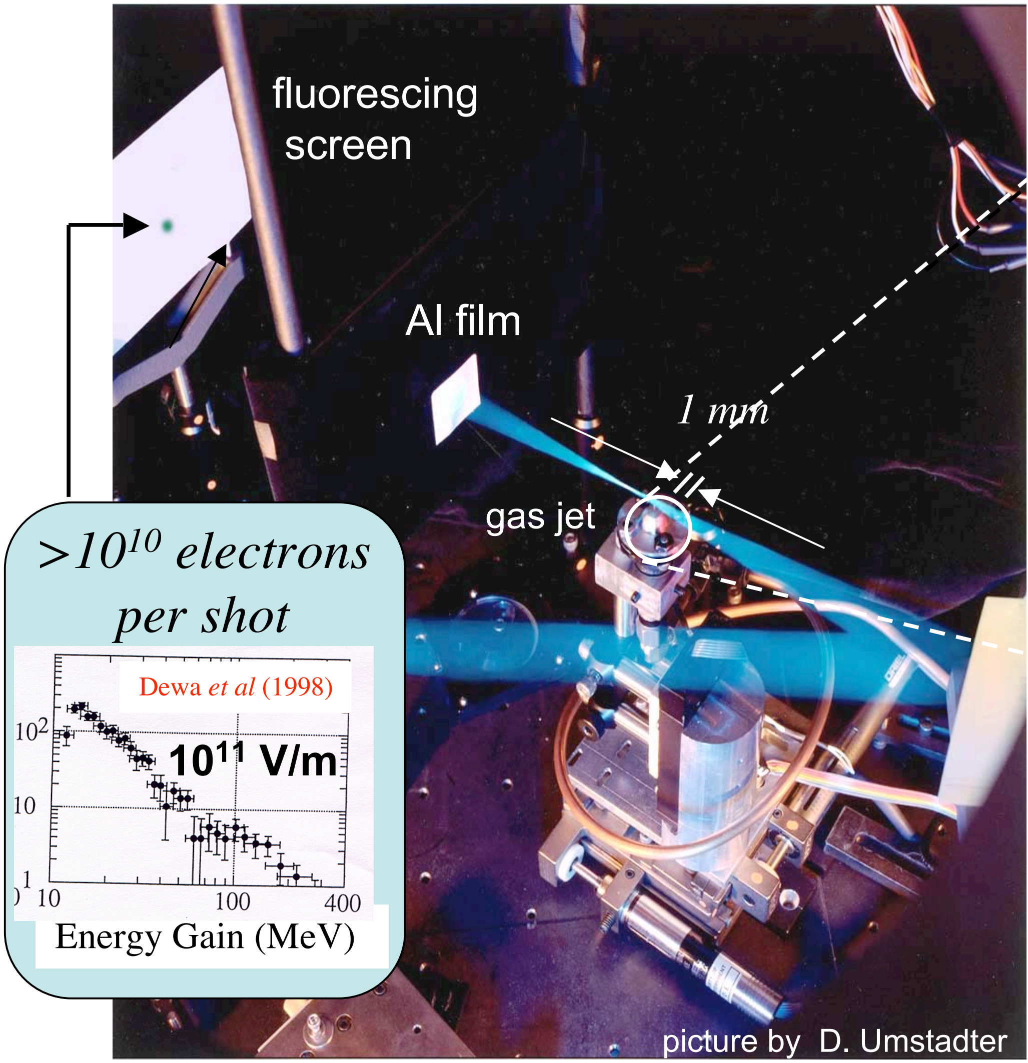
results of Kneip et al. (2009)

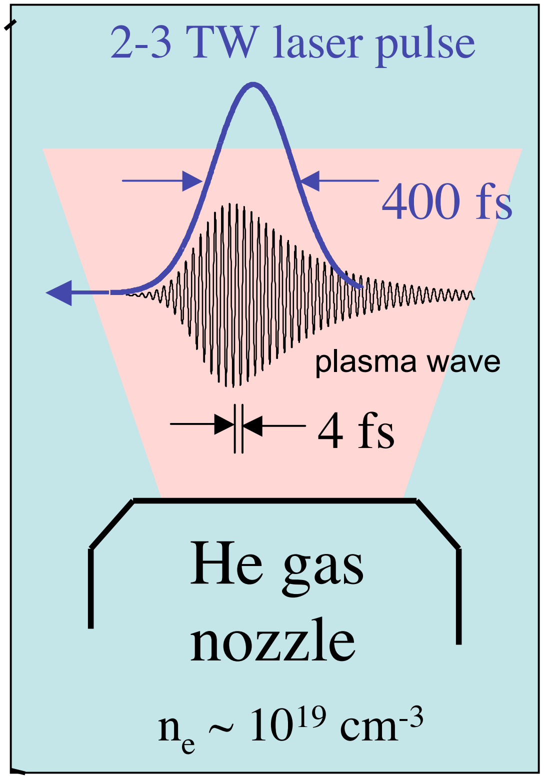
Jet Age: FAR-OFF-RESONANT LWFA in dense plasma yielded copious MeV electrons

Nakajima, *Phys. Rev. Lett.* **74,** 4428 (1995)
Coverdale, *Phys. Rev. Lett.* **74**, 4659 (1995)
Modena, *Nature* **377**, 606 (1995)

Umstadter, *Science* **273**, 472 (1996).
Ting, *Phys. Rev. Lett.* **77**, 5377 (1996)
LeBlanc, *Phys. Rev. Lett.* 77, 5381 (1996)

Clayton, *Phys. Rev. Lett.* **81**, 100 (1998)
Dewa, *NIMPRA* **410**, 357 (1998)

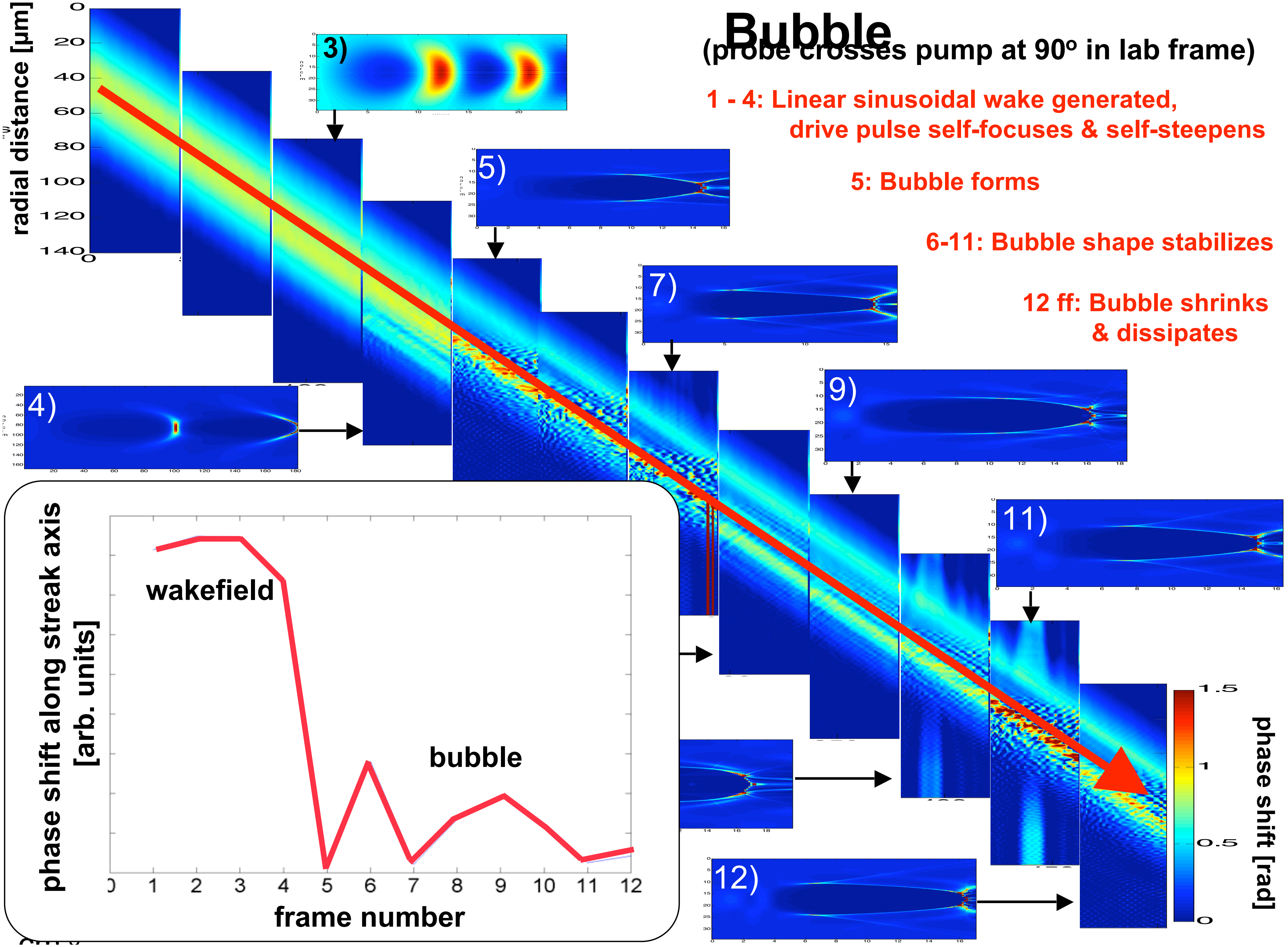




"accelerator-quality" beams in all respects except energy spread

Simulated Phase Streak of a Plasma Bubble

(probe crosses pump at 90º in lab frame)



1 - 4: Linear sinusoidal wake generated,
drive pulse self-focuses & self-steepens

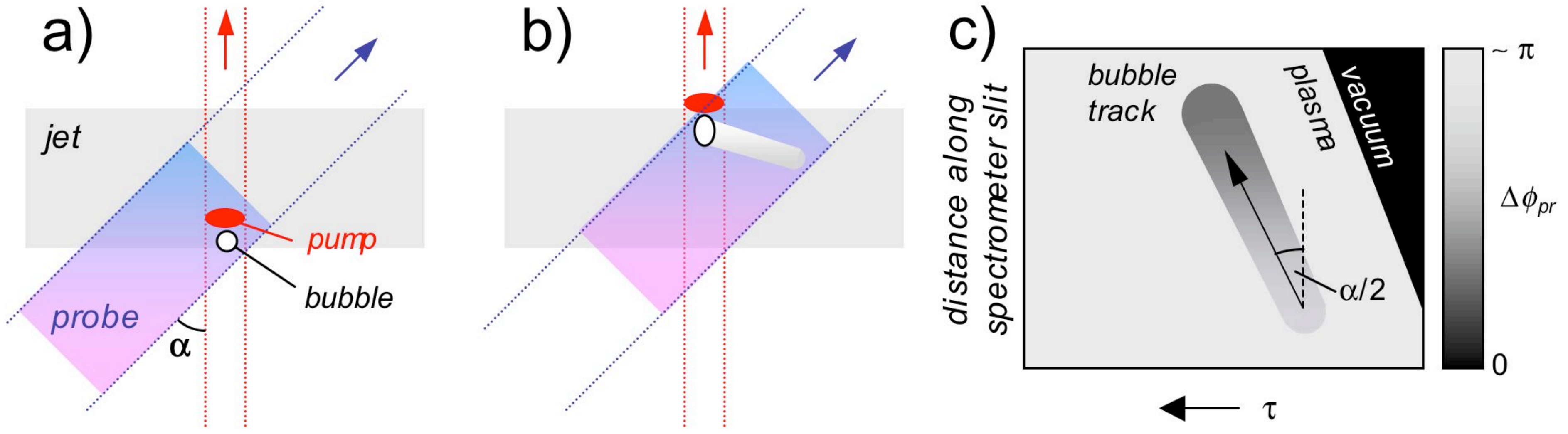
5: Bubble forms

6-11: Bubble shape stabilizes

12 ff: Bubble shrinks
& dissipates

Frequency-Domain “Streak Camera” Records Evolution of Plasma Bubble

n.b. refraction negligible for oblique probe because effective interaction length is small



- Oblique probe measures bubble evolution
- Collinear probe records longitudinally-averaged bubble structure