Lasers and Accelerators: Particle Acceleration with High Intensity Lasers
Stellenbosch Institute of Advanced Study Stiαs
15 January 2009

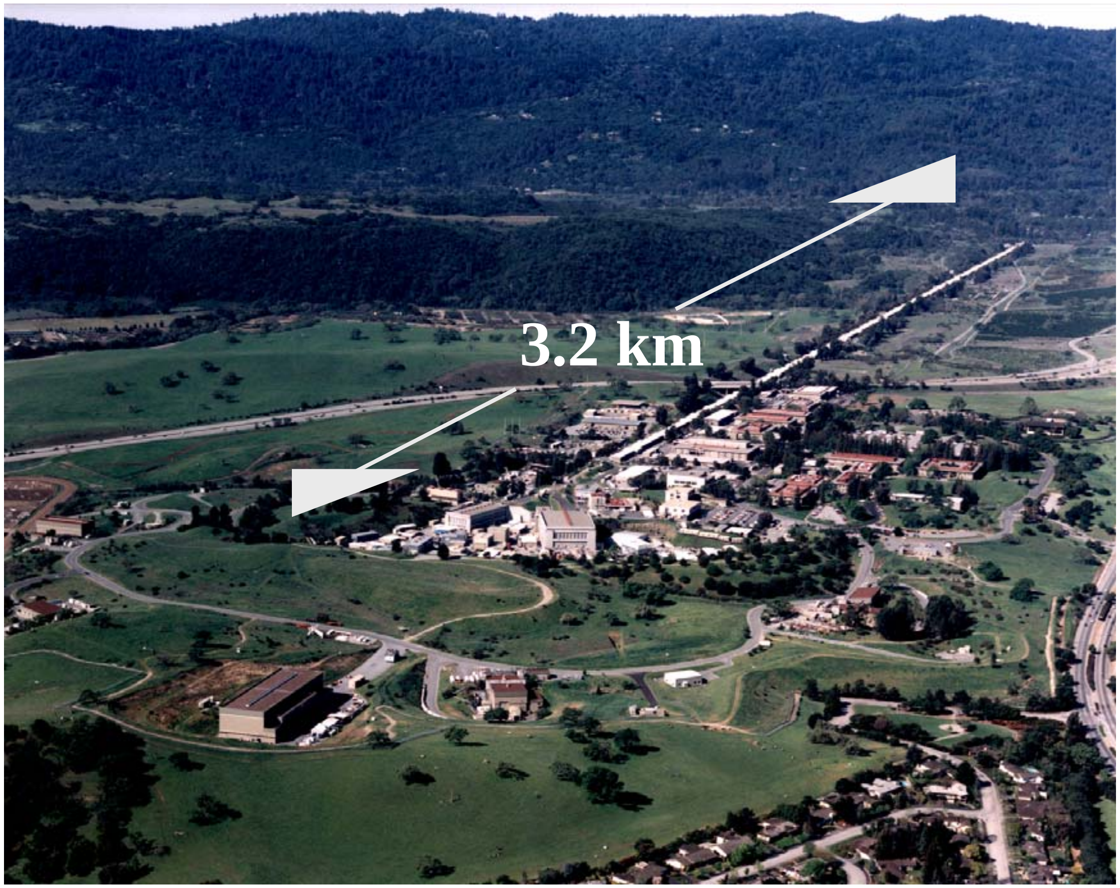
Laser-plasma experiments: lecture 3 of 4

Fruit of our labor:

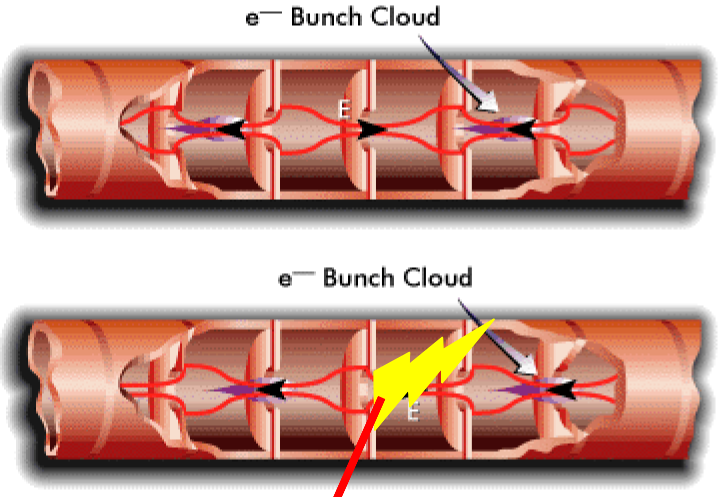
Observations of accelerated particles from laser-driven plasmas

Mike Downer
University of Texas-Austin

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)

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

$1 \text{ GeV} \Rightarrow 0.1 \text{ km}$

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

$1 \text{ TeV} \Rightarrow 100 \text{ km}$

LASER-PLASMA ACCELERATORS:
overcome 3 problems simultaneously

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

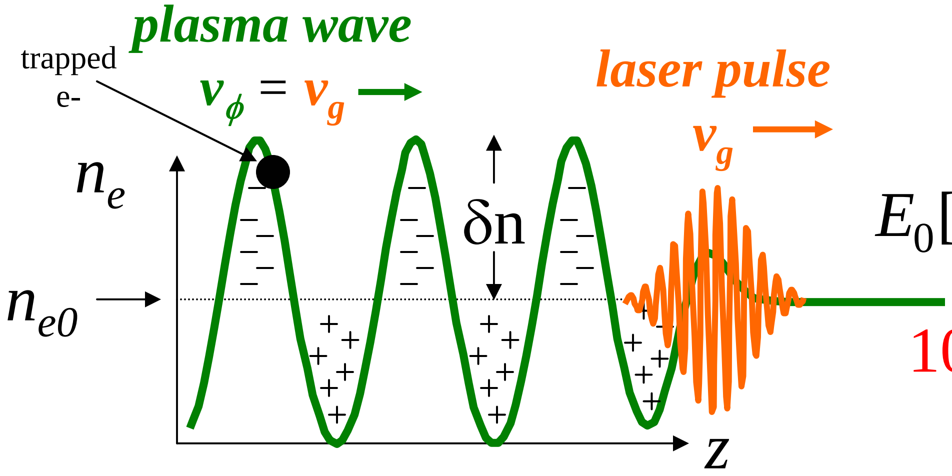
LASER → **PLASMA** → **CHARGED PARTICLE**

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

(1) $E_\perp \rightarrow E_z$

(2) *fully damaged*

(3) *supports large internal electrostatic fields*

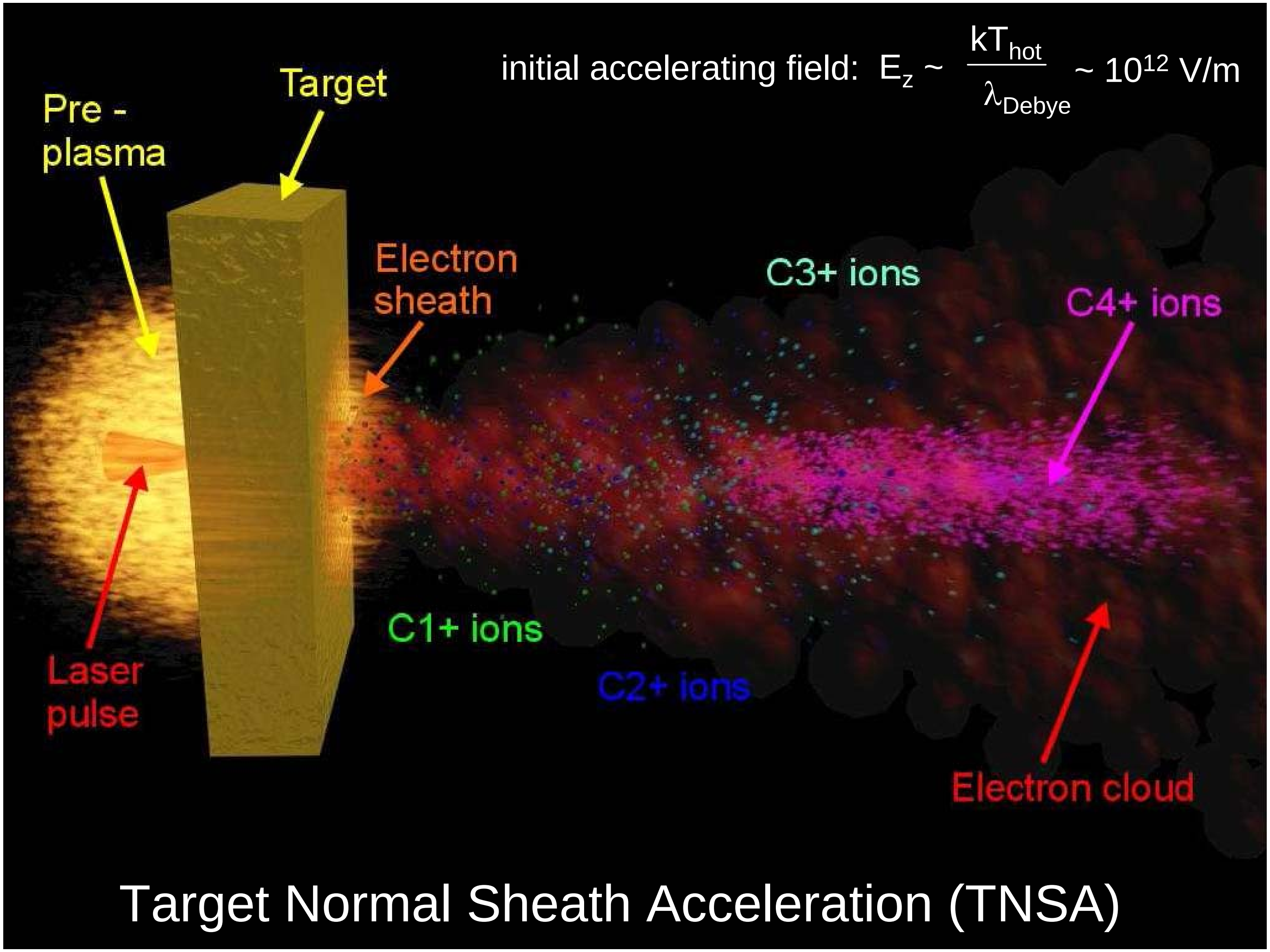


$$E_0[V/cm] = \frac{mc\omega_p}{e} = 0.96(n_e[cm^{-3}])^{1/2}$$

10^{11} V/m

10^{18} cm^{-3}

I) Proton, ion, positron acceleration in laser-driven overdense plasmas



initial accelerating field: $E_z \sim \frac{kT_{hot}}{\lambda_{Debye}} \sim 10^{12}$ V/m

Target Normal Sheath Acceleration (TNSA)

Early experiments yielded proton energies << 200 MeV & broad energy distributions

Clark, *Phys. Rev. Lett.* **84**, 670 (2000); *Phys. Rev. Lett.* **85**, 1654 (2000)
Maksimchuk, *Phys. Rev. Lett.* **84**, 4108 (2000)
Snavely, *Phys. Rev. Lett.* **85**, 2945 (2000)
MacKinnon *Phys. Rev. Lett.* **86**, 1769 (2001)

QuickTime™ and a
decompressor
are needed to see this picture.

QuickTime™ and a
decompressor
are needed to see this picture.

Robson, *Nature Phys.* (2006)

Angular divergence: 30° - 60°

QuickTime™ and a
decompressor
are needed to see this picture.

Scaling TNSA to 200 MeV protons requires ~ 4×10^{21} W/cm^2

$\Rightarrow$ PW pulse focused to $w_0 < 10\ \mu m$

Acceleration of quasi-mono-energetic protons from microstructured targets

Schwoerer, *Nature* **439**, 4492 (2006)

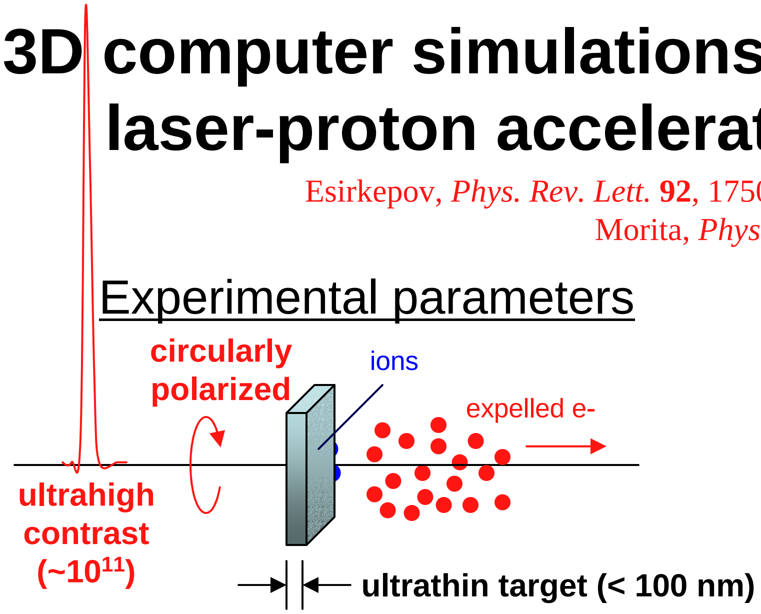
close-up of target micro-structure

Conclusion: **Much of the energy spread of the proton beam originates from non-uniformity of the virtual cathode field**

3D computer simulations suggest a modified approach to laser-proton acceleration will scale more favorably:

Esirkepov, *Phys. Rev. Lett.* **92**, 175003 (2004); Silva, *Phys. Rev. Lett.* **92**, 015002 (2004);
Morita, *Phys. Rev. Lett.* **100**, 145003 (2004)

Experimental parameters



Dominant acceleration mechanisms

- **Radiation Pressure Acceleration (RPA)**
- **Coulomb explosion**

Circ-polarized RPA

2x10^{21} W/cm^{2}

- **monoenergetic**
- **> 200 MeV**
- **achievable intensity**

QuickTi e™ and a
decor ɔressor
are needed to s e this picture.

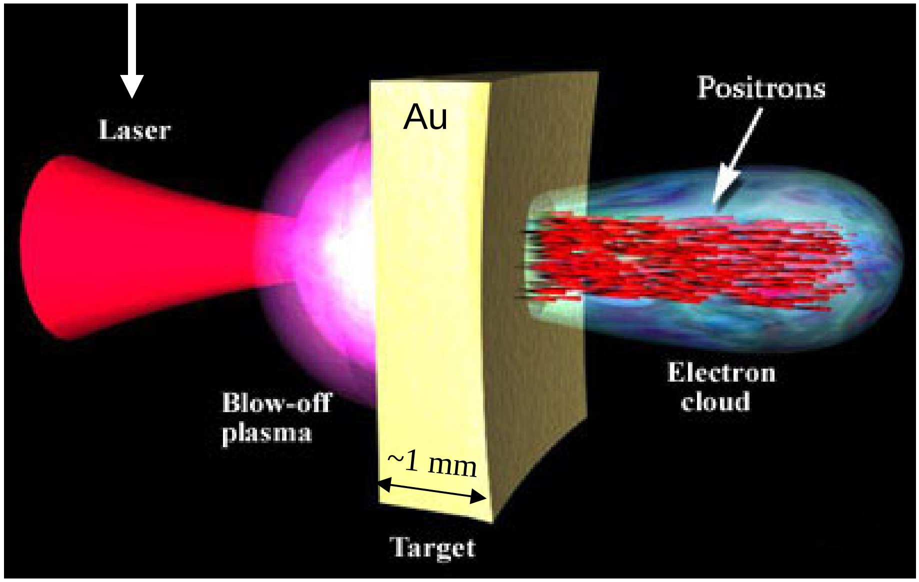
Conventional TNSA

2x10^{21} W/cm^{2}

Positron Creation & Acceleration in Overdense Plasmas

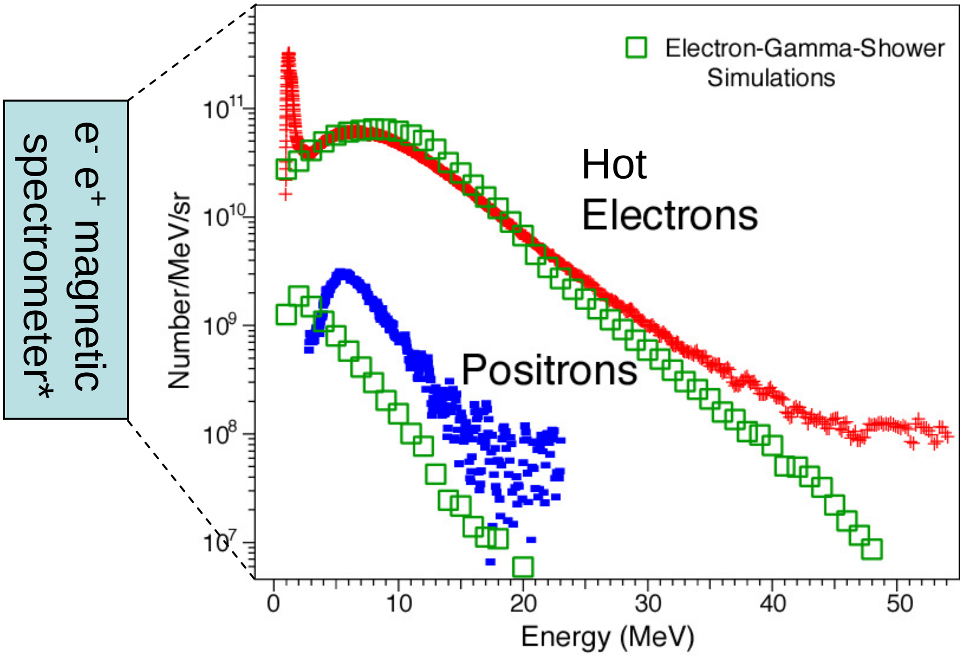
Theory: Liang, *Phys. Rev. Lett.* **81**, 4887 (1998)
Experiment: Chen, *Rev. Sci. Instrum.* **77**, 10E703 (2006)*
Chen, APS-DPP abstract TO4 4 (2008); submitted to *Phys. Rev. Lett. (2009)*

LLNL 2-pulse TITAN laser
Short pulse: 1 μm, ~150 J, ~ 1 ps, w_0 ~ 10 μm
Long pulse: 0.5 μm, ~150 J, ~ 1 ns, w_0 ~ 600 μm

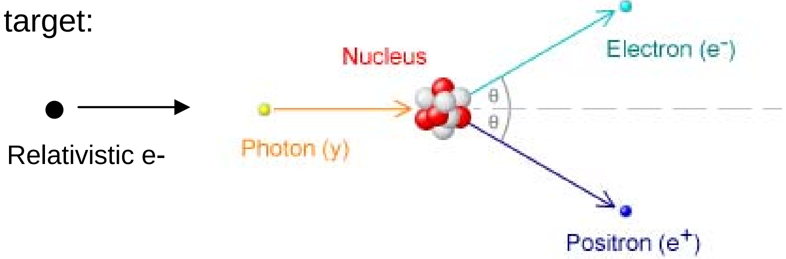


TNSA creates a directed positron beam with:

10^{10} e^+/shot



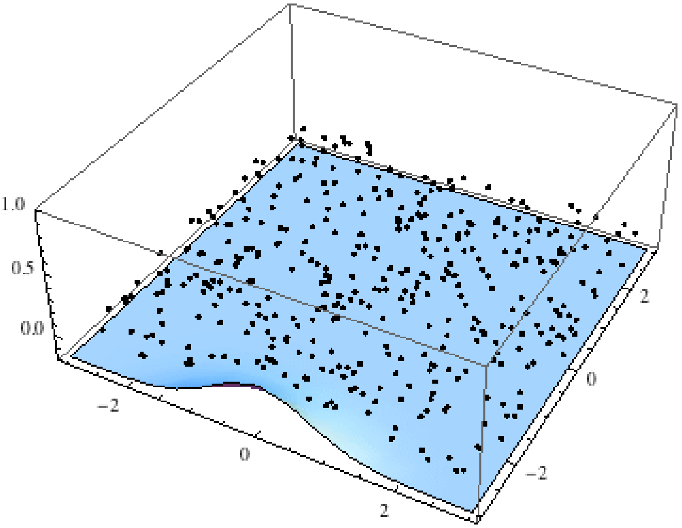
Pair production creates positrons inside Au target:



β-decay sources: $10^{6\text{-}12}$ e^+/s, E < 1 MeV
accelerator-based sources: 10^9 e^+/bunch, E > 100 MeV

courtesy Scott Wilks

II. Electron & Positron Acceleration by Underdense Plasma Waves



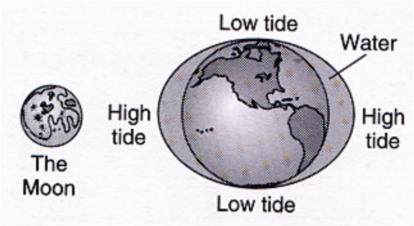
- **Resonantly-driven plasma waves**
  (linear regime)

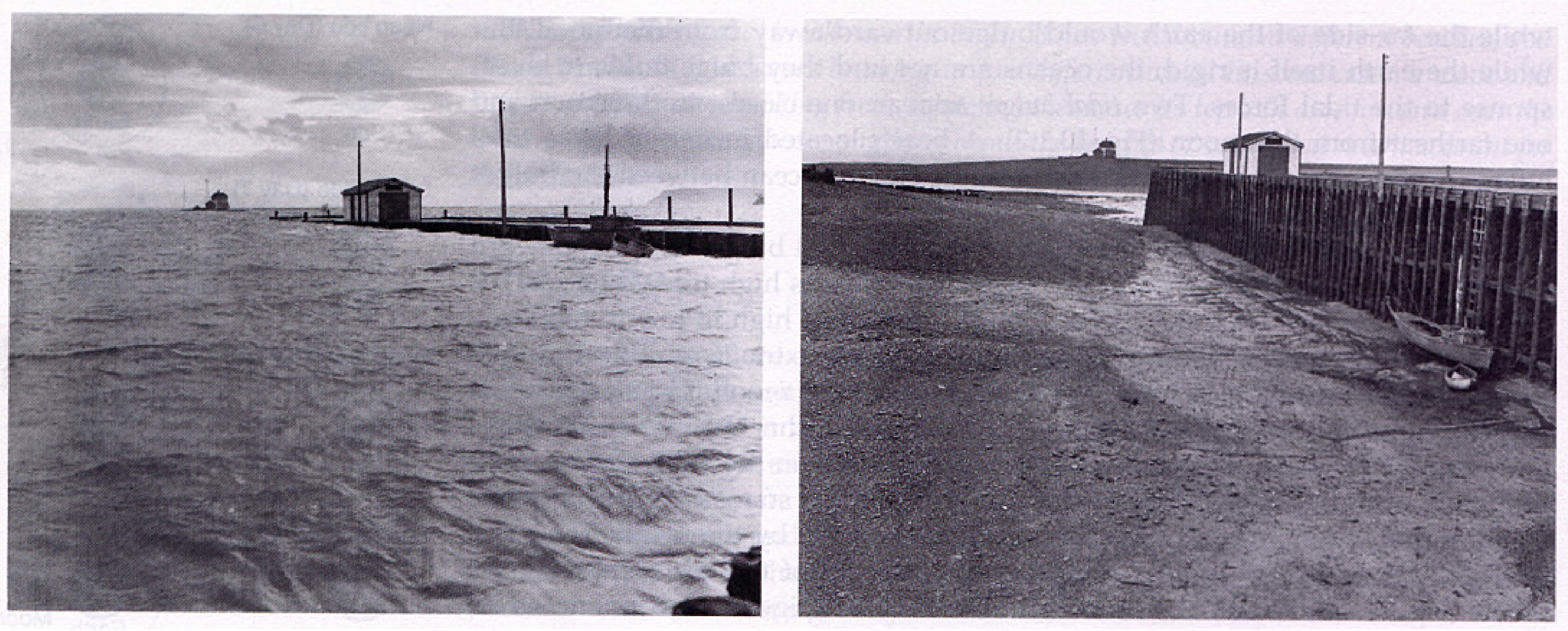
- **Far-off-resonantly-driven plasma waves**
  (nonlinear regime)

- **Resonantly-driven plasma waves**
  (nonlinear “bubble” or “blowout” regime)

  --- self-injected vs externally injected
  --- self-guided vs externally guided

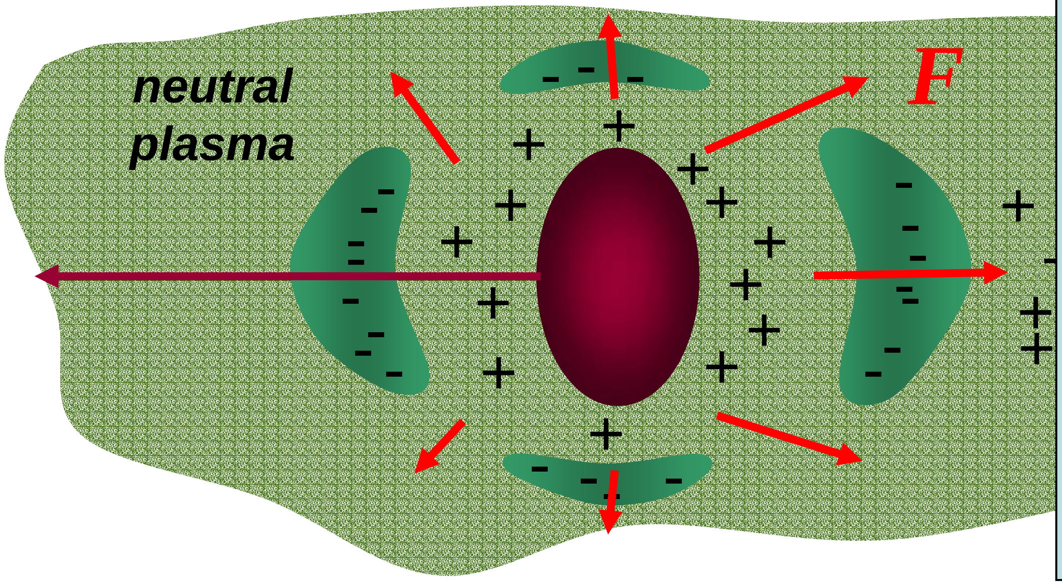
Resonant Excitation of a Water Waves creates High Tides

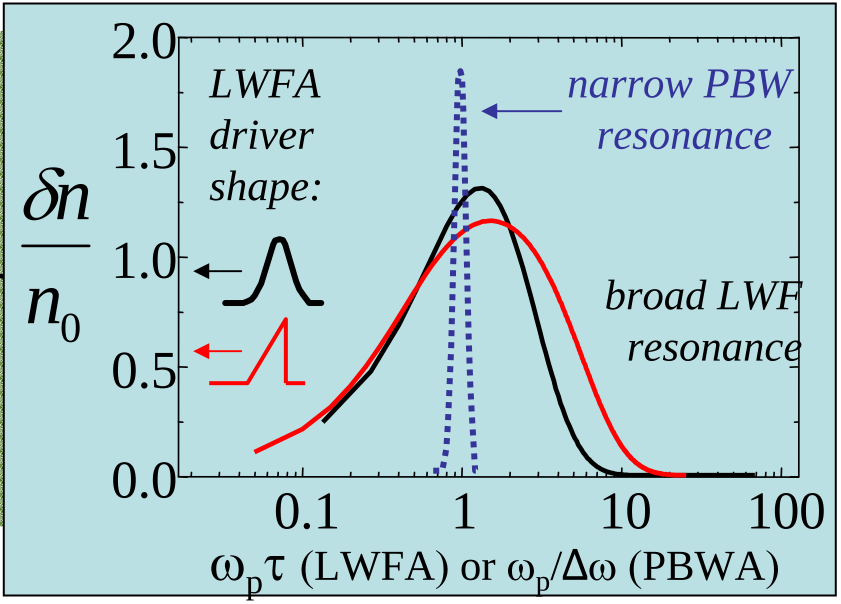




Bay of Fundy, Newfoundland

Laser-acceleration experiments have resonantly driven plasma waves in three ways





1) Single Laser Pulse Driver (LWFA)

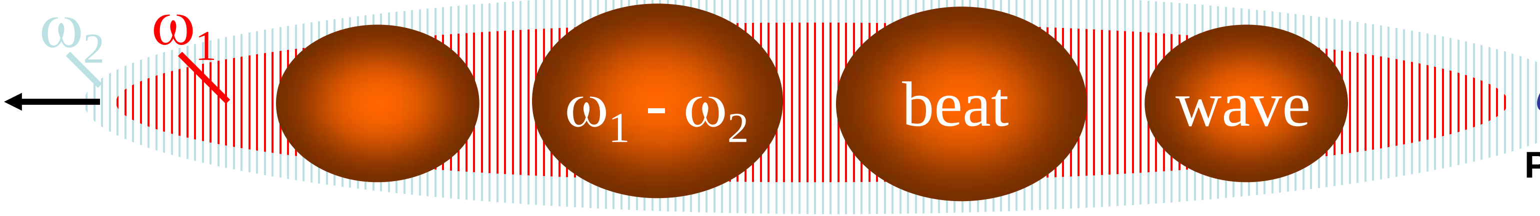
$$\vec{F}_{ponderomotive} = -\frac{e^2}{4m\omega^2}\vec{\nabla}(E^2)$$

2) Electron Bunch Driver (PWFA)

$$\vec{F}_{Coulomb} = -mc^2\,\vec{\nabla}\phi$$

$\tau_{pulse} \approx \omega_p^{-1}$ ← **Resonance condition (broad)** → $\tau_{bunch} \approx \omega_p^{-1}$

3) Two-pulse Beat-wave Driver (PBWA)



Resonance condition (sharp):

$$\omega_1 - \omega_2 = \omega_p$$

PBWA requires very UNIFORM plasma

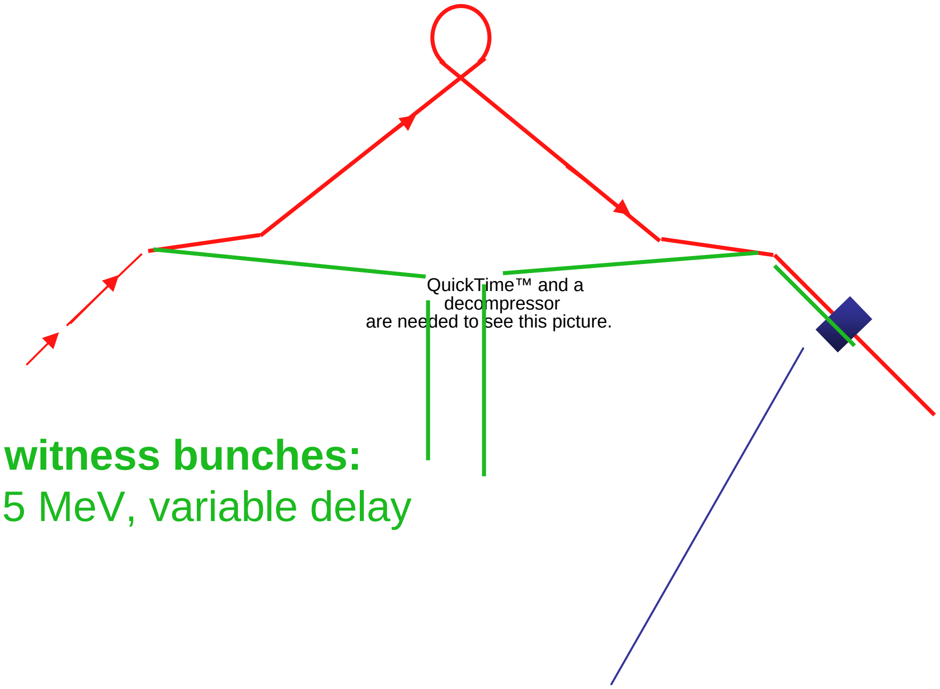
Resonant Plasma Wakefield Acceleration

Rosenzweig, *Phys. Rev. Lett.* **61**, 98 (1988); *Phys. Rev. A* **39**, 1586 (1989)

Linear regime: $n_{bunch} < n_e$

wakefield drive electron bunches:

21 MeV, ~ 8 ps, ~ 2 nC, $n_{bunch} \approx 10^{12}$ cm^{-3}



witness bunches:

15 MeV, variable delay

plasma: $n_e \approx 10^{13}$ cm^{-3}, L ≈ 30 cm

theory

QuickTime™ and a
decompressor
are needed to see this picture.

plasma density perturbation:

$\delta n_e / n_e \sim 0.1$

longitudinal accelerating field:

$E_z \sim 1$ MeV/m (less than SLAC)

Resonant Plasma Beat-Wave Acceleration

Clayton *et al.*, *Phys. Rev. Lett.* **70**, 37 (1993)
Everett *et al.*, *Nature* **368**, 527 (1994)

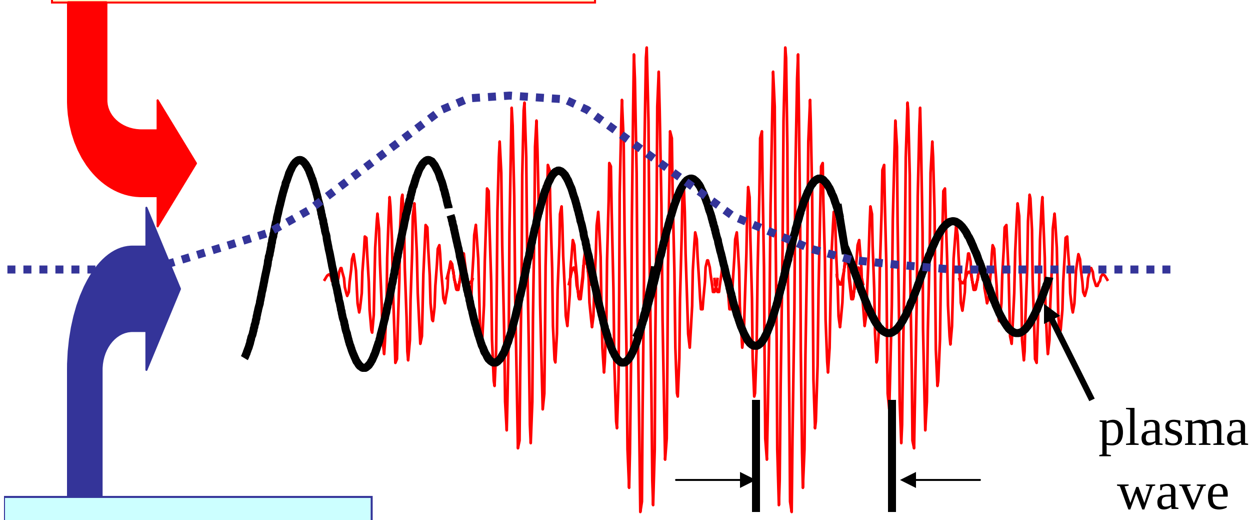
Electron Energy Spectrum

CO_2 laser:

- *λ = 10.6 μm, 10.3 μm*
- *n_{res} = 8.6 x 10^{15} cm^{-3}*

Other resonant PBWA results:
Kitagawa, *Phys. Rev. Lett.* **68**, 48 (1992)
Amiranoff, *Phys. Rev. Lett.* **68**, 3710 (1992)
Ebrahim, *J. Appl. Phys.* **76**, 7645 (1994)
Dyson, *Plasma Phys. Contr. Fusion* **38**, 509 (1996)

QuickTime™ and a
decompressor
are needed to see this picture.

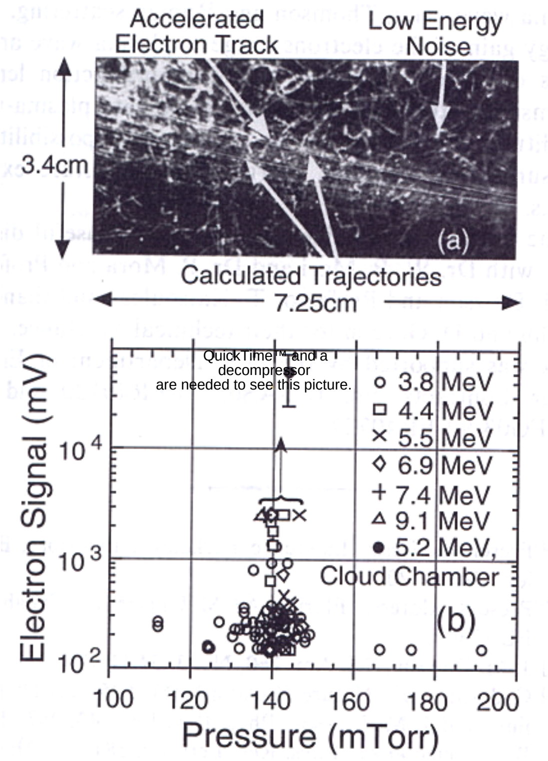


Injected e-
from rf linac:
- *2 MeV*
- *L = 6000 μm micropulses*
- *6π mm-mrad*

- λ_p = 360 μm

  ⇒ *L_{deph} ~ 50 cm*
- $\delta n/n_e$ ~ 0.3
- E_z ~ 2.8 GV/m
- L_{plasma} ~ 1 cm

Resonance



Resonant Laser Wakefield Acceleration

Amiranoff, *Phys. Rev. Lett.* **81**, 995 (1998)

resonance

laser: 400 fs, 1 μm, 4 to 9 J, $20 < w_0 < 30$ μm

externally injected e^-: **3 MeV**, 300 μA cw, $\sigma_r \sim 30$ μm

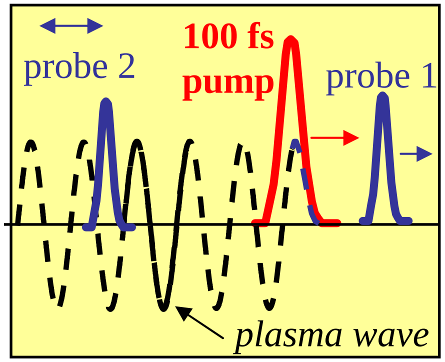
target: gas-filled chamber

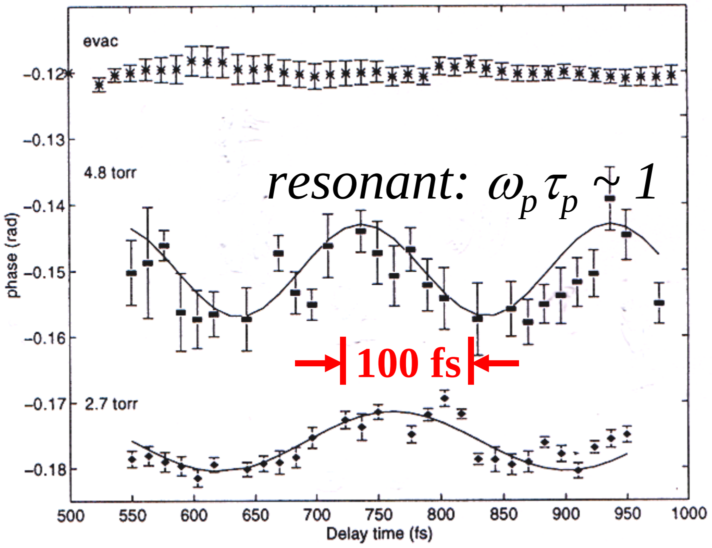
maximum energy gain observed: $\Delta E_{max} \sim 1.6$ MeV

acceleration gradient: $E_z \sim 1.5$ GV/m

Fs-time-resolved frequency-domain interferometry yielded sub-λ_p characterization of resonant LWF structures

Siders, *Phys. Rev. Lett.* **76**, 3570 (1996); Marquès., *Phys. Rev. Lett.* **78**, 3463 (1997).





resonant: $\omega_p \tau_p \sim 1$

100 fs

$n_e \sim 10^{17}$ cm^{-3},
$\delta n_e / n_e \sim 1$,
$E_z \sim 10$ GV/m,
$E_r \sim 5\,E_z$

Electron Acceleration by Plasma Waves Driven Resonantly & Linearly: Summary

- externally injected electrons needed
  - -- separate linac (PBWA, LWFA)
  - -- witness pulse split-off from drive pulse (PWFA)

- wide energy spread
  - -- reflects stringent requirements on injection

- low energy gains
  - -- ΔE ~ .05 MeV: PWFA
  - -- ΔE ~ 3-15 MeV: LWFA, PBWA

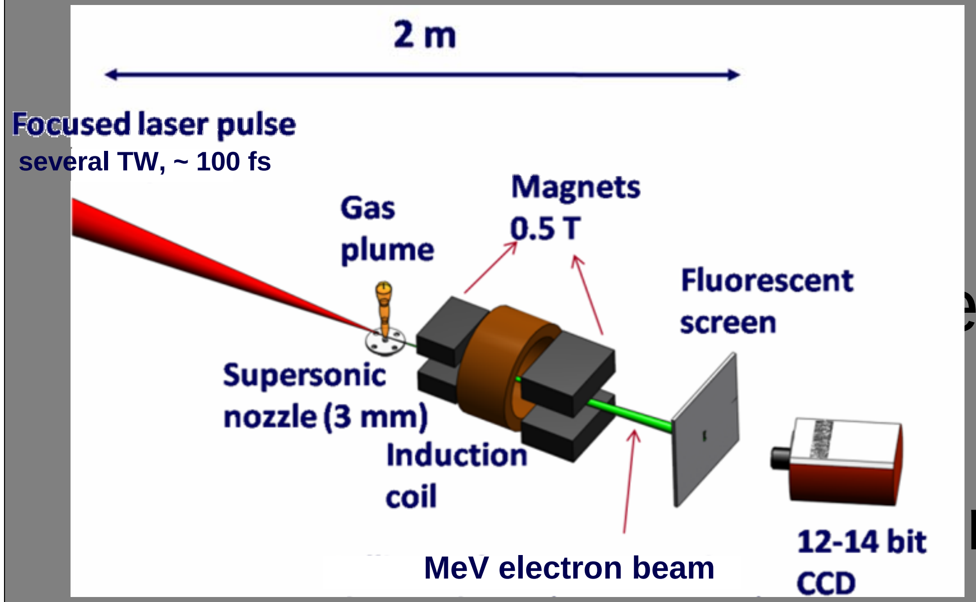
- high accelerating gradients demonstrated
  - -- $E_z \approx 10^6$ V/m (PWFA)
  - -- $E_z \approx 3 \times 10^9$ V/m (PBWA)
  - -- $E_z \approx 10^{10}$ V/m (LWFA)

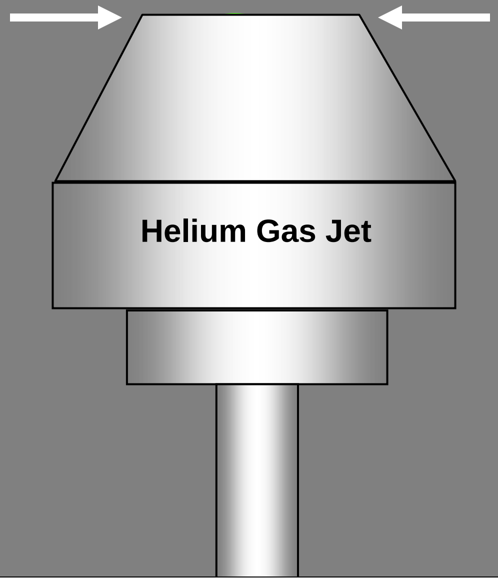
10^7 V/m (SLAC)

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!





about 3 mm

---

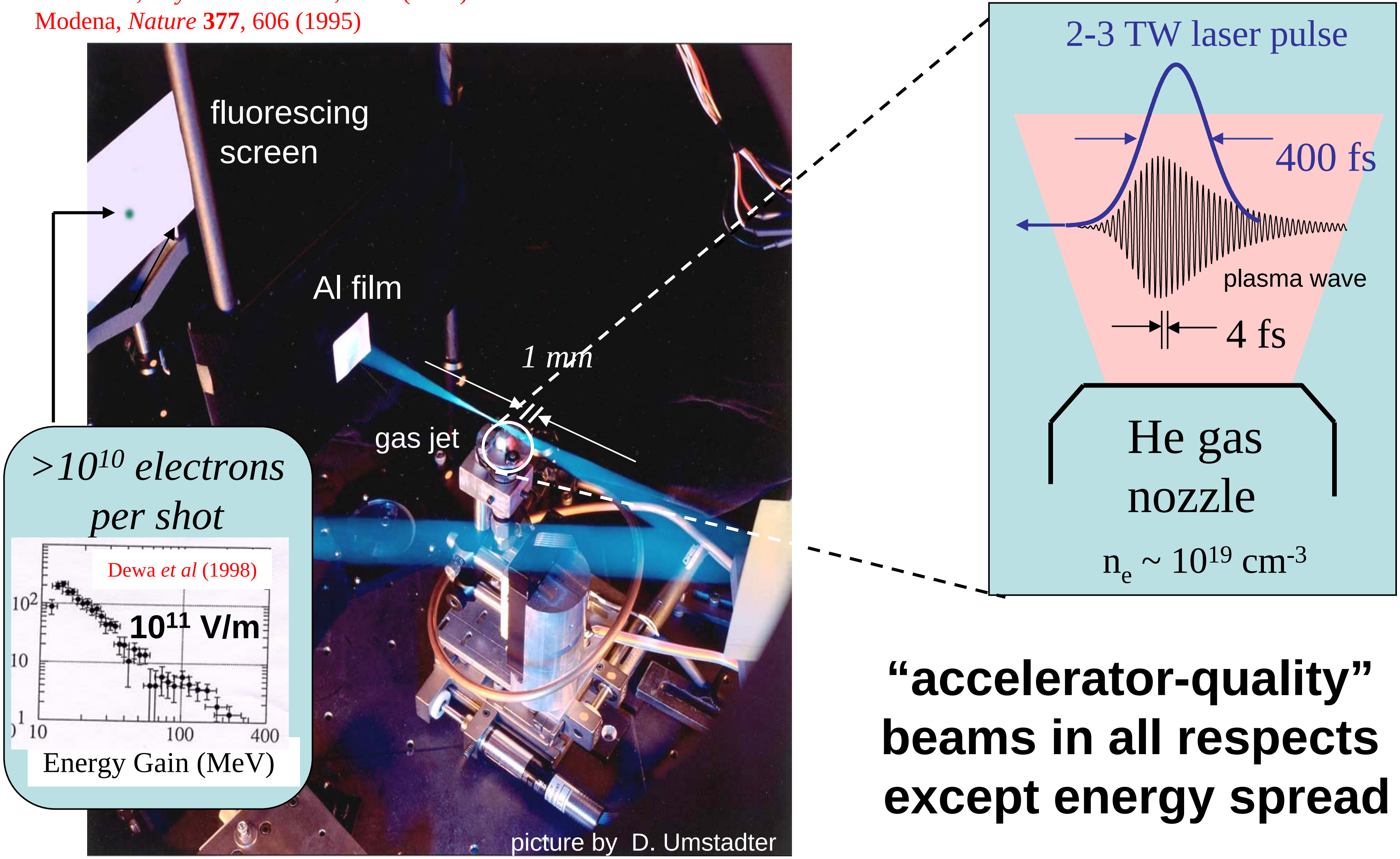
* *Katsouleas,, Phys. Plasmas* ***13****, 055503 (2006)*

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)

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



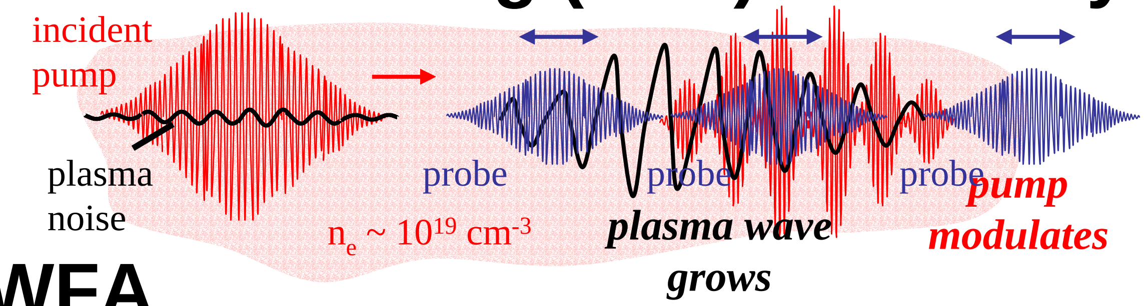
$>10^{10}$ electrons per shot

picture by D. Umstadter

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

Theory: “Self-modulated” LWFA (SM-LWFA) grows by Forward Raman Scattering (FRS) instability

Joshi, *Phys. Rev. Lett.* **47**, 1285 (1981)
Forslund, *Phys. Rev. Lett.* **54**, 558 (1985)
Mori, *Phys. Rev. Lett.* **72**, 1482 (1994)



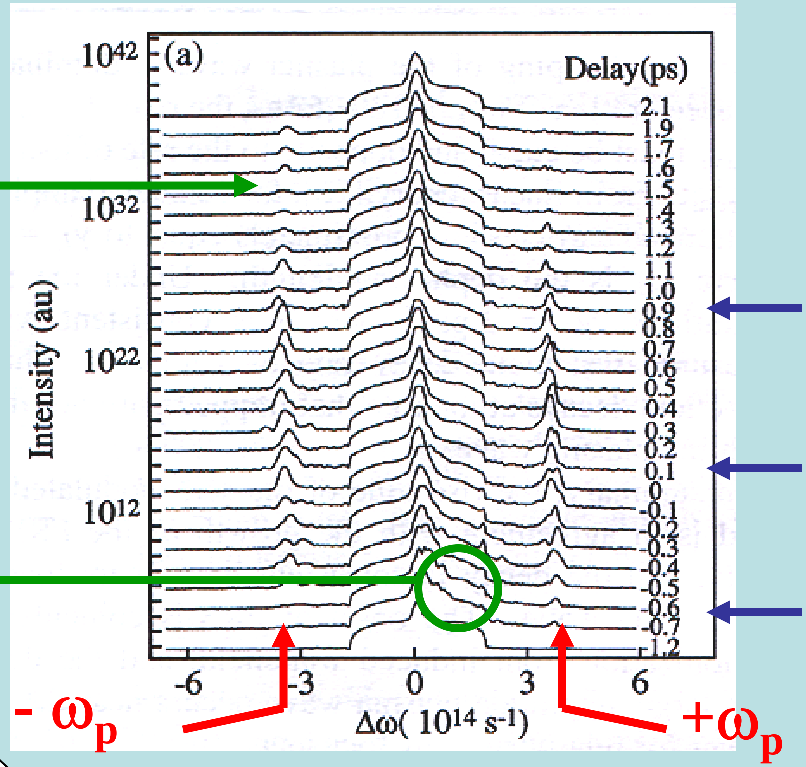
Experiment 2: SM-LWFA produces red/blue side-bands on a probe pulse*

Plasma Wave Decays in < 2 ps because of Beam Loading

LeBlanc, *Phys. Rev. Lett.* **77**, 5381 (1996)
Ting, *Phys. Rev. Lett.* **77**, 5377 (1996)
Gordon, *Phys. Rev. Lett.* **80**, 2133 (1998)

Ionization front triggers growth of Plasma Wave

time-resolved forward probe scatter



data from LeBlanc (1996)

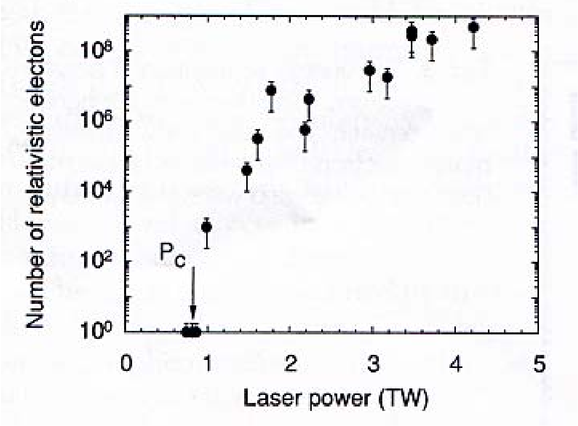
* a.k.a. “collective Thomson scatter”

RELATIVISTIC SELF-FOCUSING guides laser pulse, collimates e- beam during self-modulated LWFA

Litvak, Sov. Phys. JETP **30**, 344 (1969)
Max *et al.*, Phys. Rev. Lett. **33**, 209 (1974)

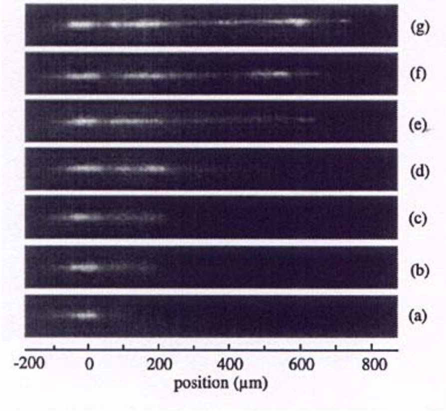
$$P_{crit} = 17(\omega_0/\omega_p)^2 \text{ GW}$$

Umstadter *et al.*, Science (1996)



Side scatter from jet

Wagner *et al.*, PRL **78**,3125 (1997)

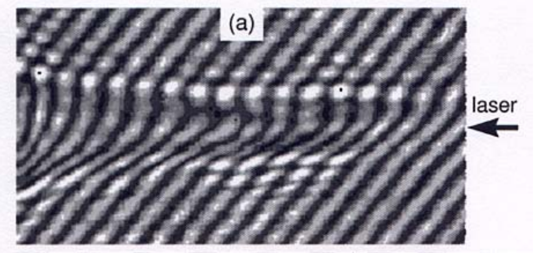


9.1
8.4
7.2
5.5
3.9
2.6
1.6

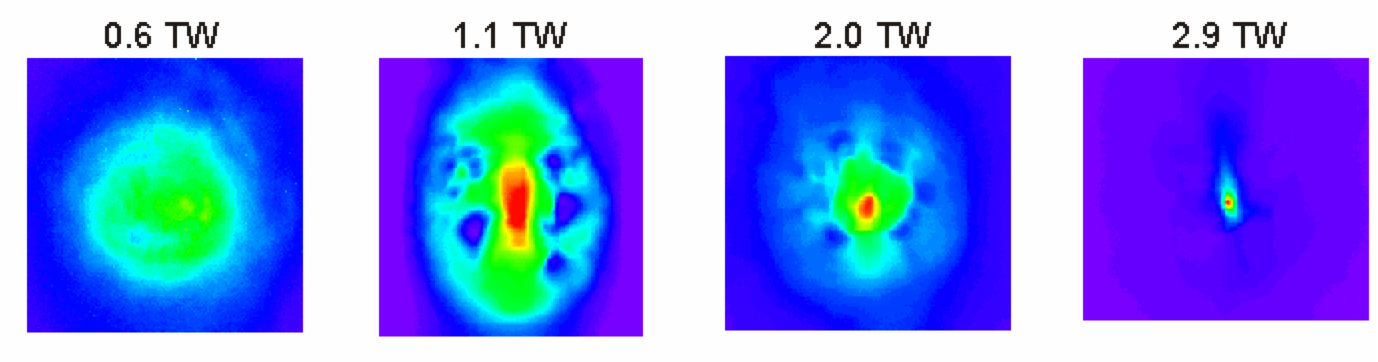
P/P_{crit}

Density depression on axis

Chen *et al.*, PRL **80**, 2615 (1998)



Electron beam profile:



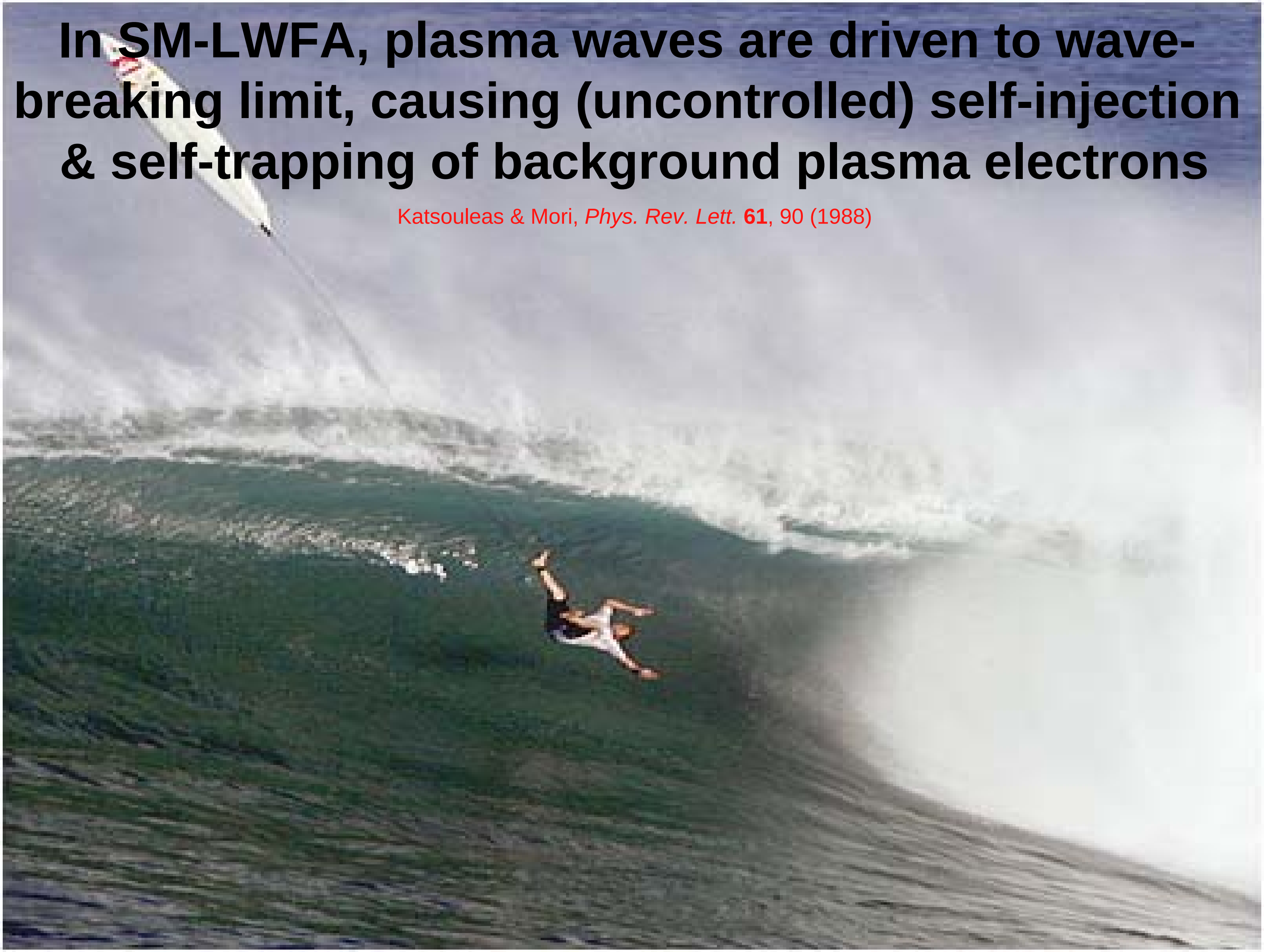
$\Delta\Theta = 1°$

$\varepsilon_t = 0.06\ \pi$ mm mrad

Chen *et al.*, *Phys. of Plasmas*, **7**, 403 (2000).

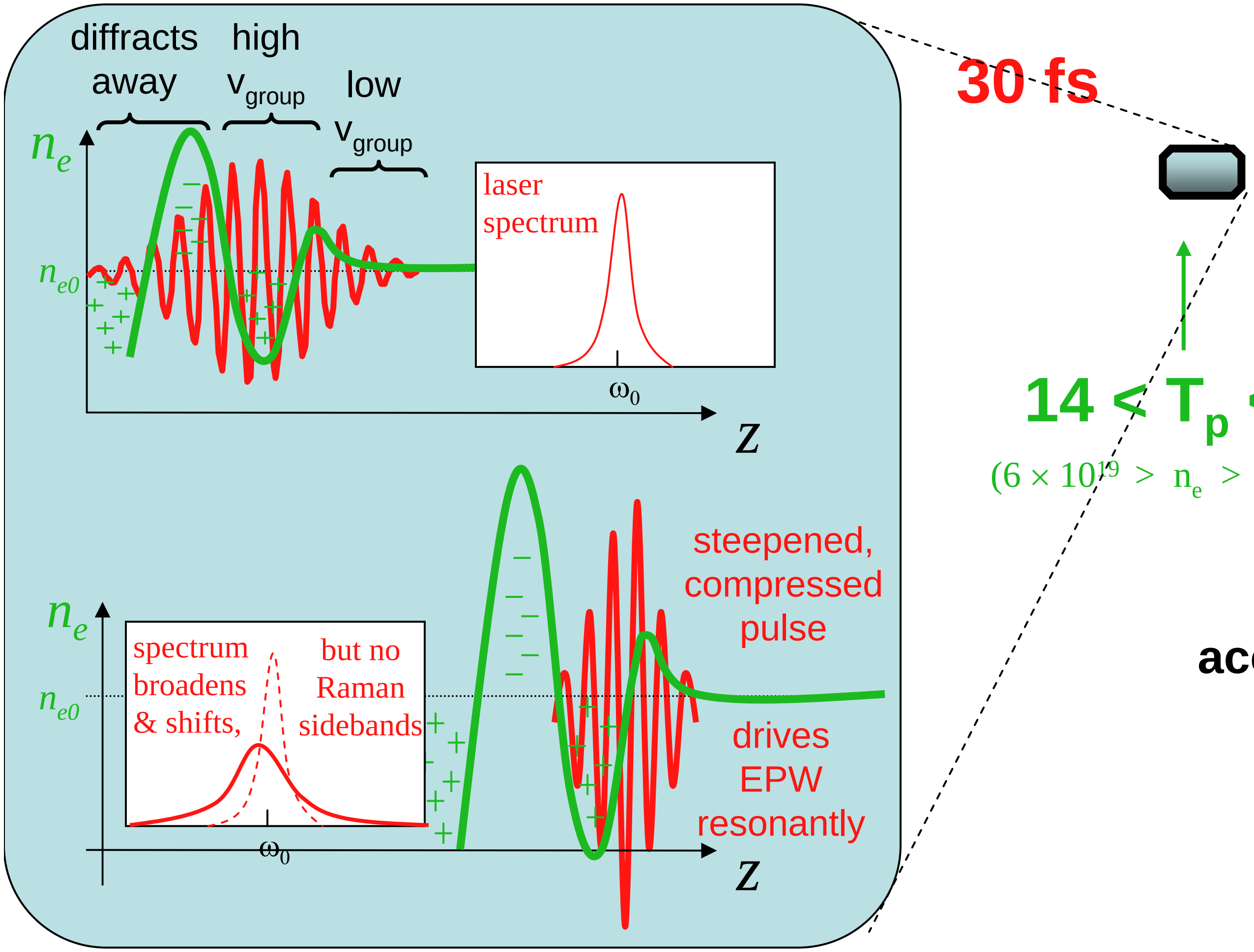
In SM-LWFA, plasma waves are driven to wave-breaking limit, causing (uncontrolled) self-injection & self-trapping of background plasma electrons

Katsouleas & Mori, *Phys. Rev. Lett.* **61**, 90 (1988)



TW laser pulses get shorter: $\tau_p \rightarrow \omega_p^{-1}$ and "Self-modulated" → "Forced" LWFA

Malka, *Science* **298**, 1596 (2002)



30 fs

$14 < T_p < 25$ fs

$(6 \times 10^{19} > n_e > 2 \times 10^{19}\ \mathrm{cm}^{-3})$

QuickTime™ and a
decompressor
are needed to see this picture.

**acceleration to 200 MeV,
but spectrum still
broad**

QuickTime™ and a
decompressor
are needed to see this picture.

Laser pulse can evolve in ways that enhance LWFA

Self-modulated & Forced Laser Wakefield Acceleration: the early "jet-age"

- Electrons self-inject uncontrollably as high-amplitude ($\delta n_e/n_e \sim 1$) plasma wave breaks
- Laser pulse self-guides by relativistic self-focusing, extending acceleration length & collimating beam
- Laser pulse can self-compress prior to generating wake
- high energy gains (ΔE up to 200 MeV)
- ultrahigh accelerating gradients ($E_z \sim 10^{11}$ V/m)
- wide energy spread (~ 100%)

Items in red are the important legacy of the early jet age for the modern jet age

2004: “Bubble” regime bursts on the scene

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

QuickTime™ and a
decompressor
are needed to see this picture.

QuickTime™ and a
decompressor
are needed to see this picture.

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}

QuickTime™ and a
decompressor
are needed to see this picture.

→ ←

3%
spread

QuickTime™ and a
decompressor
are needed to see this picture.

data from
Faure (2004)

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

QuickTime™ and a
decompressor
are needed to see this picture.

Laser: 37 TW, 35 fs, 24 µm spot

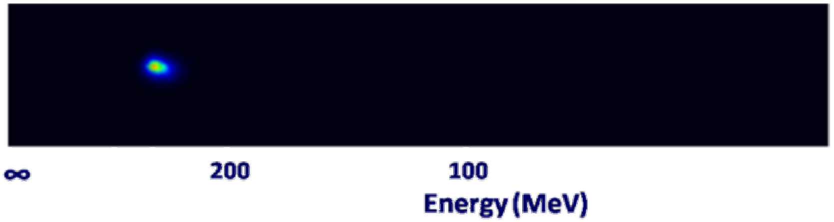
Jet: n_0 ~ 7 x 10^{18} cm-3, L ~ 3 mm

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)

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

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



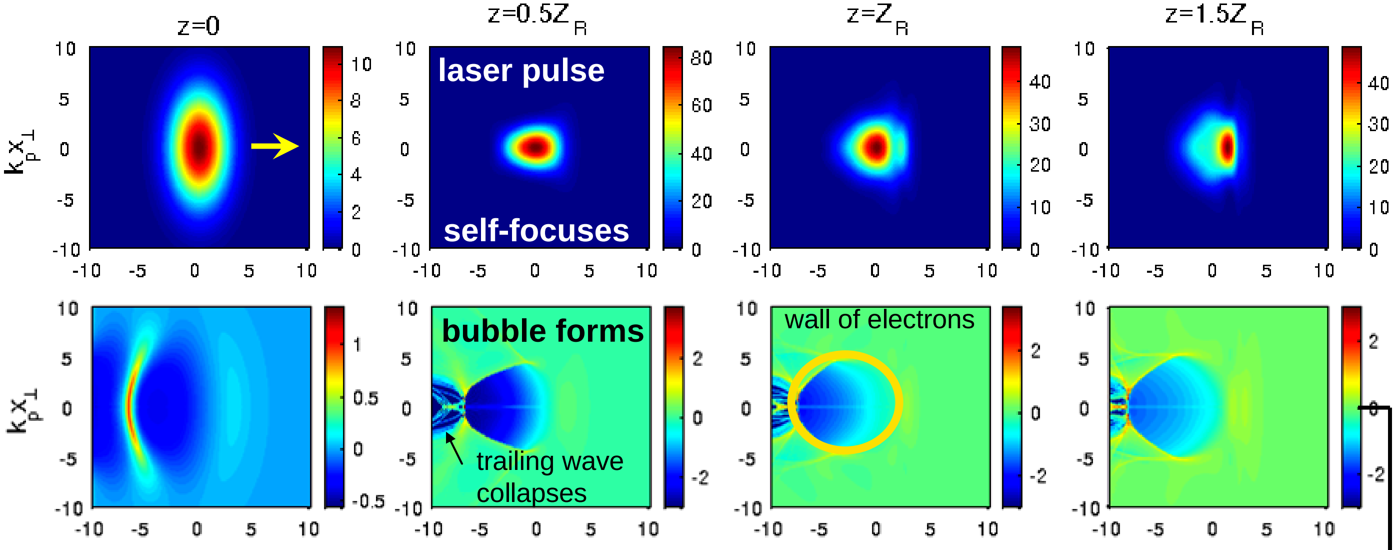
Parameter	Angular position (mrad)	Divergence (mrad)	Energy (MeV)	Energy spread (MeV)
Mean	0	5.3	344	38.4
Standard deviation	1.1	1.7	35	4.8

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

Production of quasi-monoenergetic electrons is a highly nonlinear process that includes formation of plasma “bubble”

Pukhov, *Appl. Phys B* **74,** 355 (2002)
Tsung, *Phys. Rev. Lett.* **93**, 185002 (2004)

simulations below courtesy S. Kalmykov



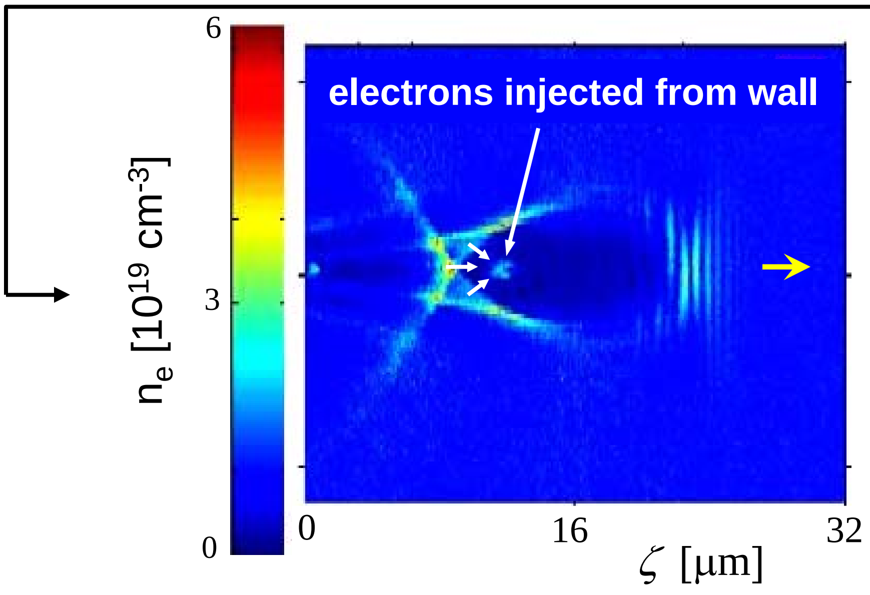
Laser pulse self-focuses & self-compresses, then blows out an electron-evacuated cavity (bubble) filled with ions and surrounded by dense wall of electrons (like a moon crater).

↓

When n_e at the walls reaches a threshold value self-injection occurs at the back of the bubble, then stops abruptly when the the trapped e^- density approaches the wall density

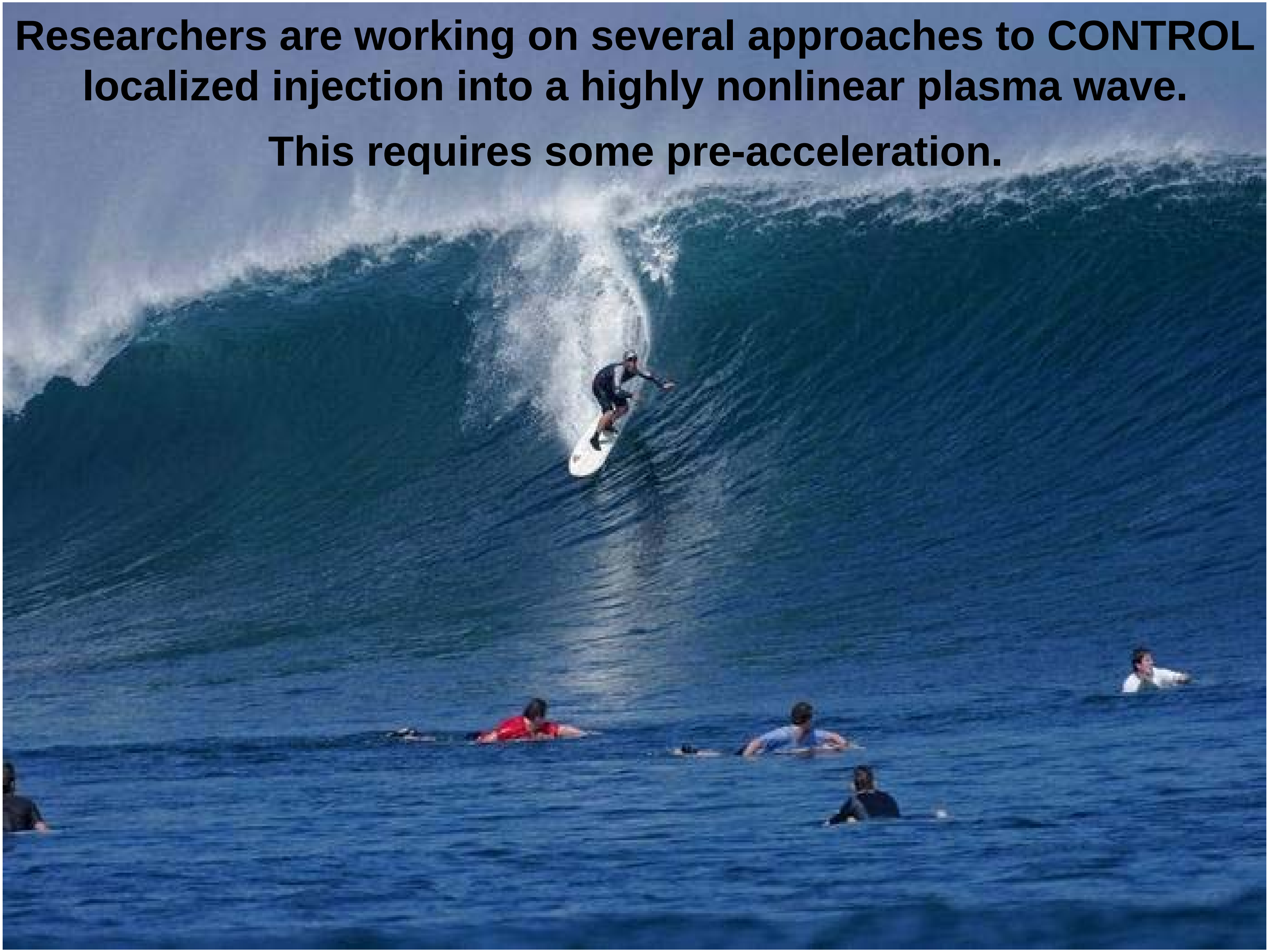
↓

Short, localized injection leads to formation of a quasi-monoenergetic electron bunch.



BUT, self-injection is nonlinear & uncontrolled.

Injection from conventional linacs is not an option -- the bunches are too short ...



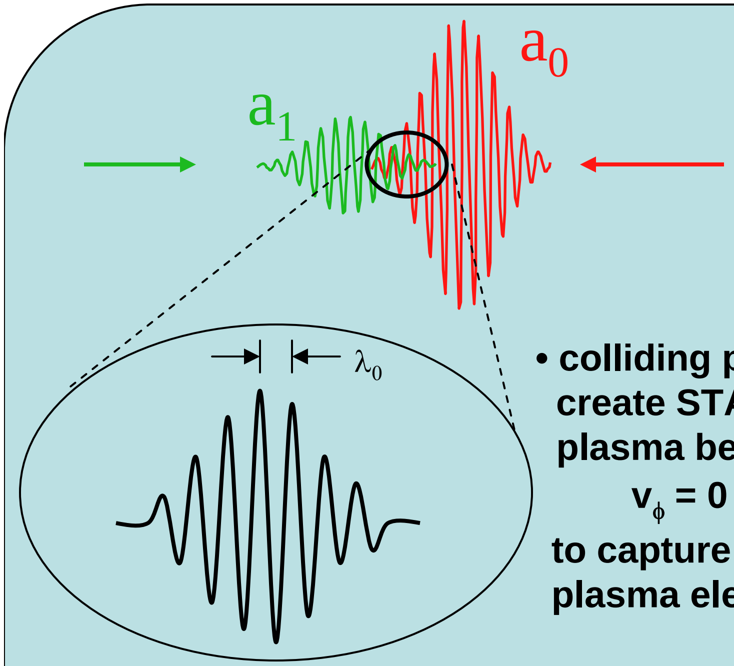
Researchers are working on several approaches to CONTROL localized injection into a highly nonlinear plasma wave.

This requires some pre-acceleration.

Injection controlled using a second “colliding” laser pulse

Theory: Esarey, *Phys. Rev. Lett.* **79**, 2682 (1997)
Fubiani, *Phys. Rev. E* **70**, 016402 (2004)

Experiment: Faure, *Nature* **444**, 736 (2006)



- colliding pulses create STANDING plasma beat wave
  $v_\phi = 0$
  to capture SLOW plasma electrons.

Short scale length $\lambda_0/2$

$\Rightarrow$ strong, highly localized pondero-motive injection force $F \propto 2a_0a_1/\lambda_0$

QuickTime™ and a
decompressor
are needed to see this picture.

ickTime™ and a
lecompressor
d to see this picture.

pump laser only

QuickTime™ and a
decompressor
are needed to see this picture.

Injection location & electron energy
are easily tuned by adjusting
pump-injection pulse time delay

Gas-filled capillary discharge waveguides extend acceleration length to several cm ...

Spence, *Phys. Rev. E* **63**, 015401 (2001): Butler, *Phys. Rev. Lett*. **89**, 185003 (2002)

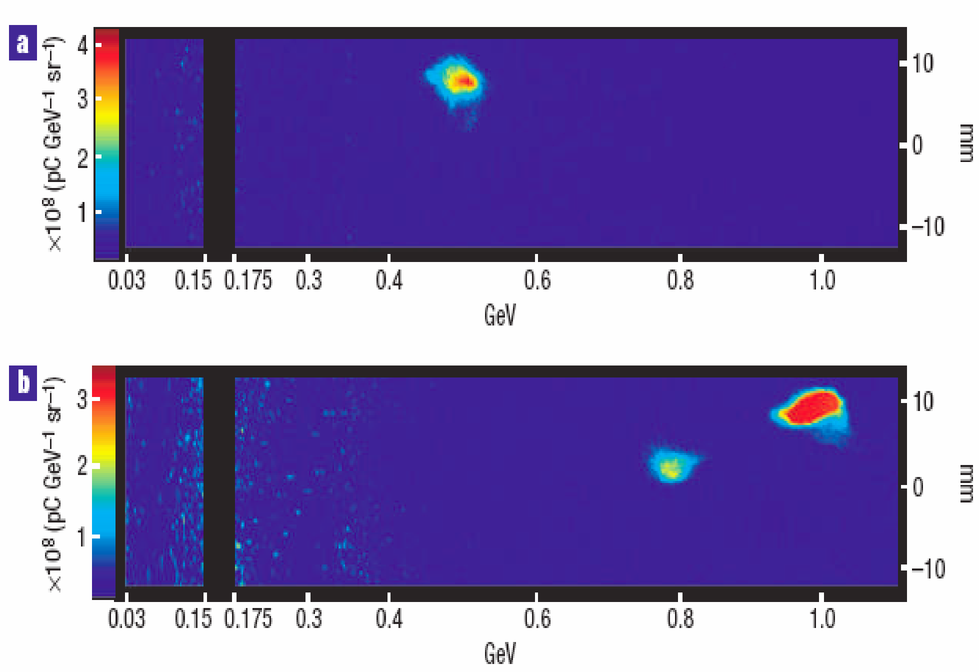
n_e is minimum, and refractive index maximum, on the waveguide axis.

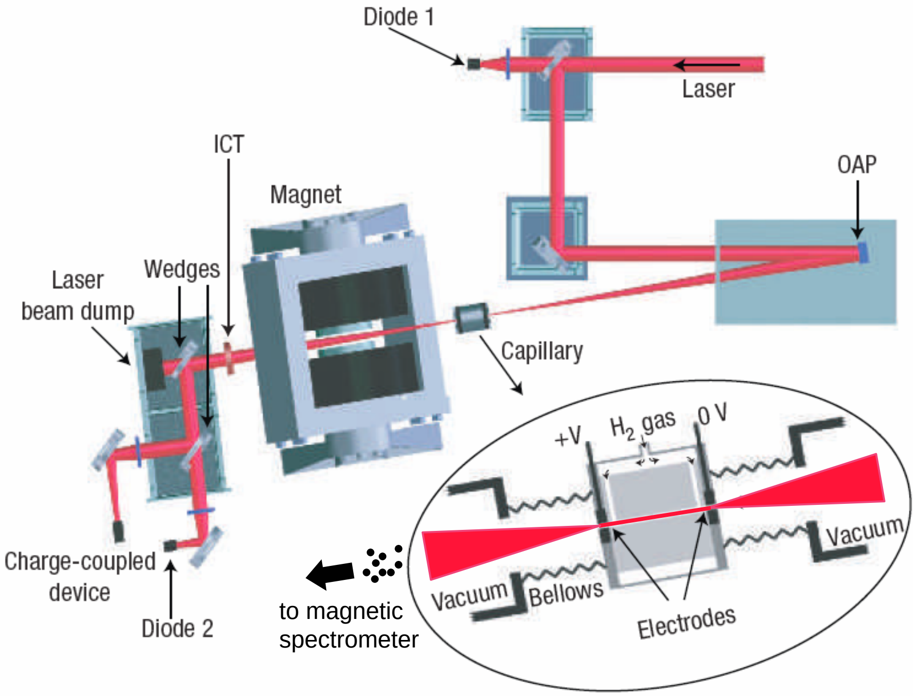
QuickTime™ and a
decompressor
are needed to see this picture.

QuickTime™ and a
decompressor
are needed to see this picture.

... yielding quasi-monoenergetic beams up to 1 GeV, the current world record for laser-plasma acceleration

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





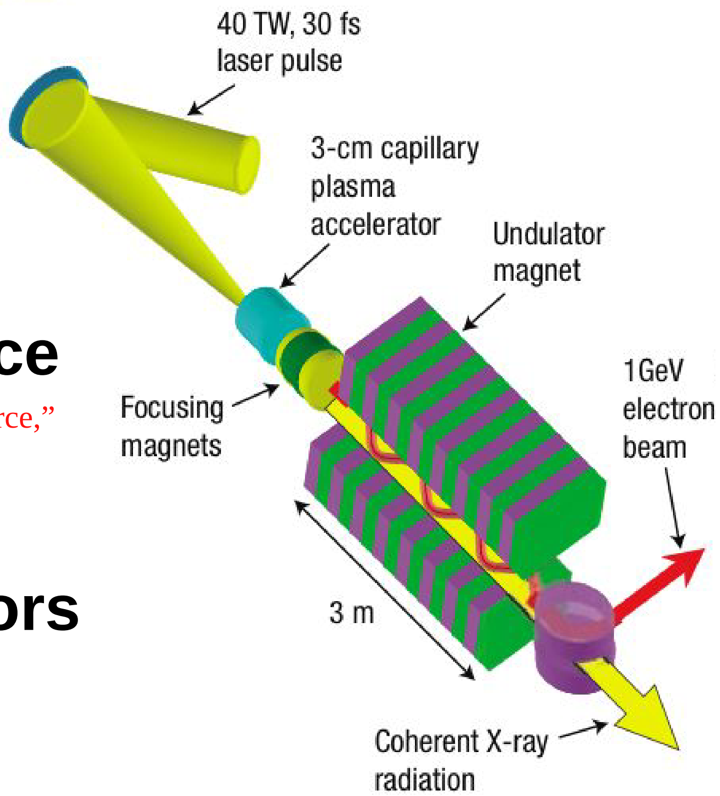
Spence & Hooker,
Phys. Rev. E **63**, 015401 (R) (2001)

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)

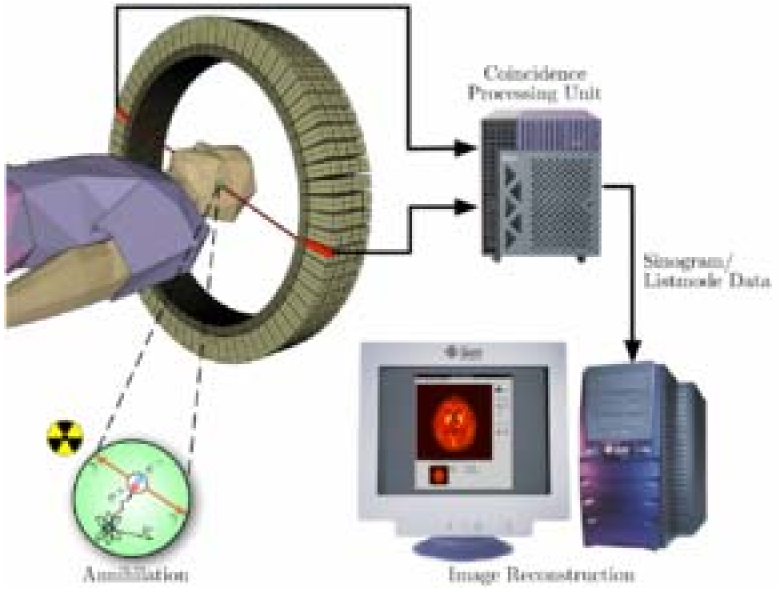
- **Radiotherapy with tunable, high-energy electrons**

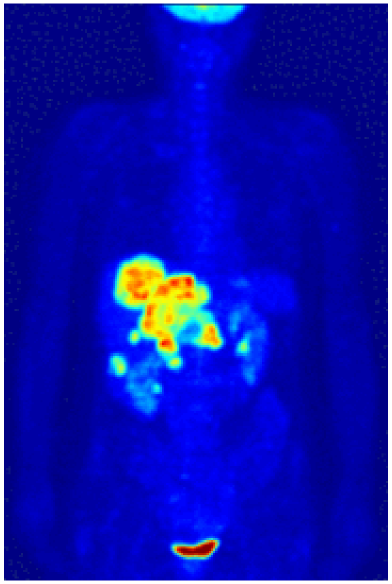
  DeRosiers, "150-250 MeV electron beams in radiation therapy," *Phys. Med. Biol*. **45**, 1781 (2000)
  Glinec, "Radiotherapy with quasi-monoenergetic laser-plasma accelerators," *Med. Phys*. **33**, 155 (2006)

On-site production of short-lived isotopes for medical imaging

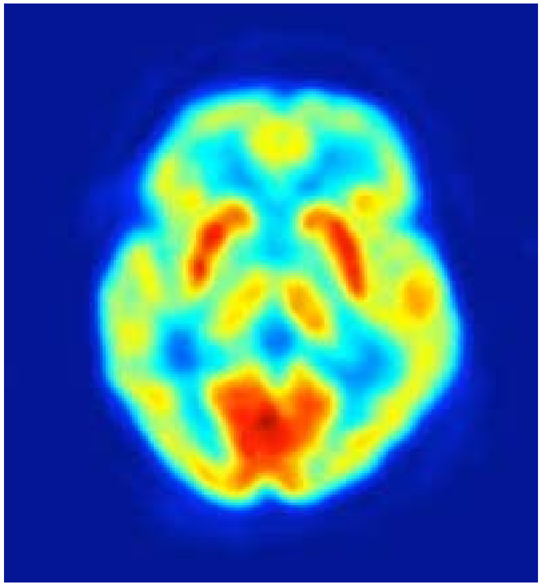
Limitations to the widespread use of PET arise from the high costs of cyclotrons needed to produce the short-lived radionucleotides for PET scanning .... Few hospitals and universities are capable of maintaining such systems ... *- Wikipedia -*

Positron Emission Tomography





^{18}F PET scan of tumor



^{15}O PET scan of human brain

radiotracer	activation reaction	half-life	medical use
^{15}O	^{16}O $(\gamma,n)^{15}$O	2 minutes	neuro-imaging
^{11}C	^{12}C$(\gamma,n)^{11}$C	20 minutes	neuro-receptor-specific brain imaging
^{18}F	^{19}F$(\gamma,n)^{18}$F	110 minutes	clinical oncology

on-site production essential

Laser-generated quasi-mono-energetic electrons efficiently photo-activate materials of interest.

- **High Rep rate**
- **Low cost**
- **Compact**

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

The “blowout” regime was first explored in connection with PWFA, and is a close analog of the LWFA “bubble” regime

Theory: Rosenzweig, *Phys. Rev. A* **44**, R6189 (1991)
Experiments: Barov, *Phys. Rev. Lett*. **80**, 81 (1998); Yakimenko, *Phys. Rev. Lett.* **91**, 014802 (2003)

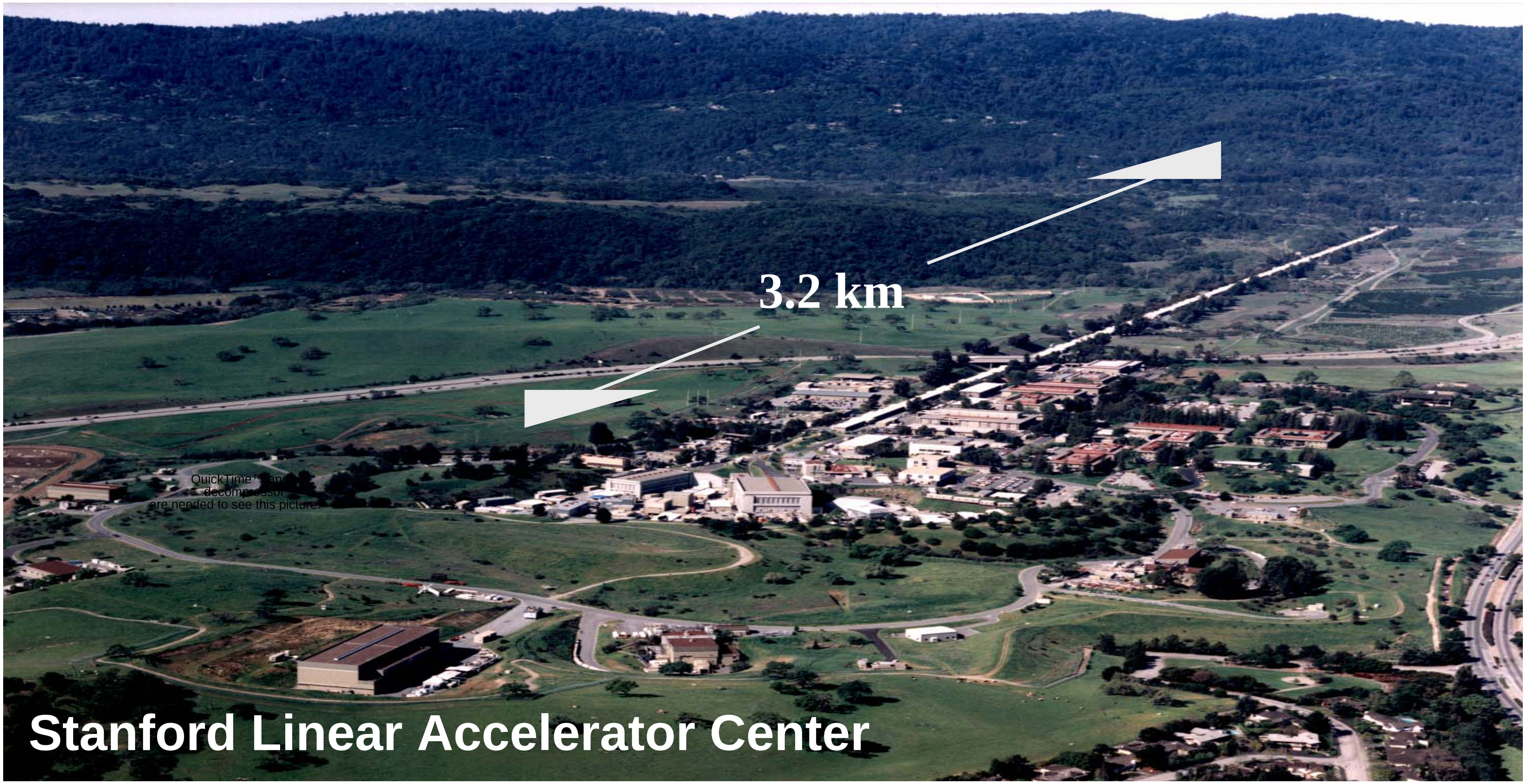
QuickTime™ and a
decompressor
are needed to see this picture.

nature

Vol 445|15 February 2007|

Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator

Ian Blumenfeld[1], Christopher E. Clayton[2], Franz-Josef Decker[1], Mark J. Hogan[1], Chengkun Huang[2], Rasmus Ischebeck[1], Richard Iverson[1], Chandrashekhar Joshi[2], Thomas Katsouleas[3], Neil Kirby[1], Wei Lu[2], Kenneth A. Marsh[2], Warren B. Mori[2], Patric Muggli[3], Erdem Oz[3], Robert H. Siemann[1], Dieter Walz[1] & Miaomiao Zhou[2]



Stanford Linear Accelerator Center

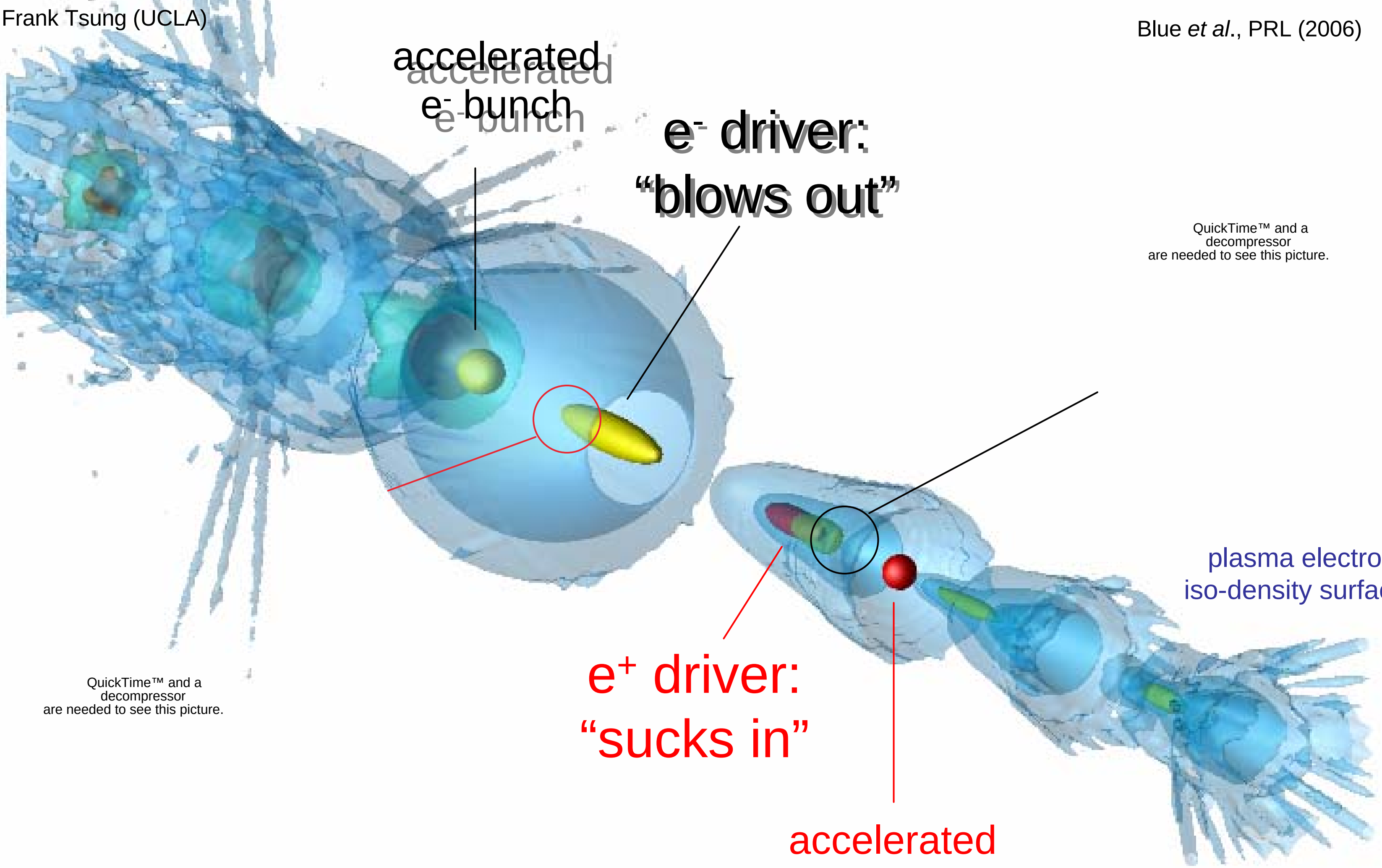
Plasma Afterburner:

e^- and e^+ driven wakes differ greatly in structure

S. Lee *et al.*, “Energy Doubler for Linear Collider,” Phys. Rev. STAB **5**, 011001 (2002)

courtesy Frank Tsung (UCLA)

Blue *et al.*, PRL (2006)



accelerated e^- bunch

accelerated e^- bunch

e^- driver: “blows out”

e^- driver: “blows out”

QuickTime™ and a decompressor are needed to see this picture.

plasma electron iso-density surfaces

QuickTime™ and a decompressor are needed to see this picture.

e^+ driver: “sucks in”

accelerated e^+ bunch

Plasma energy doublers can potentially impact high-energy colliders at the energy frontier

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	1.5×10^{18}	14	0.011	0.25	**0.95**	channel-guided, self-injected Leemans (2006)
1.0	**80**	**5×10^{17}**	**34**	**0.08**	**1.3**	**5.7**	**self-guided, self-injected**
2.0	100	3×10^{17}	47	0.18	1.8	10.2	self-guided, self-injected
2.0	310	10^{16}	140	16.3	1.8	**99**	**channel-guided, externally injected**
40	330	4×10^{16}	146	4.2	8	106	self-guided, self-injected
20	1000	10^{15}	450	500	5.7	999	**channel-guided, externally-injected**

Texas Petawatt

Table entries feature:

1. *stable plasma structure*
2. $L_{dephasing} = L_{pump\ depletion}$
3. *balance between energy extraction & beam quality*

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

SUMMARY: Plasma acceleration experiments

Some review articles focusing on experiments:
Joshi, *Phys. Plasmas* **14**, 055501 (2007)
____ , *Scientific American* (Feb. 2006), pp. 41-47

I. OVERDENSE PLASMAS:

- **TNSA (2000-present)**
  - *low MeV protons, mostly wide energy spread*
- **RPA regime** (simulations, experiments at early stage)
  - *promise of >200 MeV quasi-monoenergetic protons at feasible intensity if stringent technological requirements (ultrahigh contrast laser pulses, ultrathin targets) can be met*

II. UNDERDENSE PLASMAS:

- **Early experiments (1988-94):** resonant, linear PWFA, PBWA, LWFA
  - *difficult, equipment-intensive experiments (injection accelerators, gas cells)*
  - *low MeV electron energy gain, wide energy spread, proof-of-principle only*
- **"Jet-age" of laser-plasma accelerators (1995-present):**
  - **-- off-resonant, nonlinear SM-LWFA & "forced" LWFA (1995-2003)**
    - *accelerator-quality electron beams in most respects except energy spread*
    - *relatively easy experiments yielding > 100 MeV, collimated electron beams*
  - **-- near-resonant, nonlinear "bubble" accelerators (2004-present)**
    - *quasi-monoenergetic e- bunches up to GeV, controlled injection, stable & tunable energy*
    - *multiple applications, appears scalable to multi-GeV (maybe further)*
    - *most experiments now operate in this regime*
- **Bunch-driven plasma-afterburner doubles energy of conventional accelerator (2007):** *Potential to impact high-energy colliders at the energy frontier*

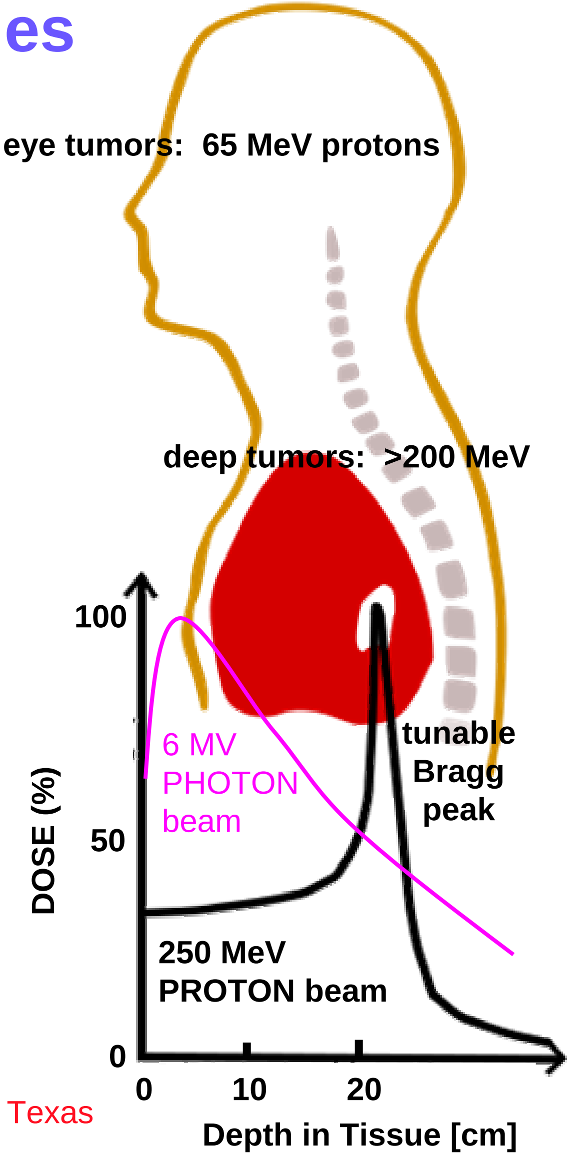
END

Proton Therapy enables precise exposure of small tumors with minimal damage to surrounding healthy tissue ...

... but requires large, expensive facilities

10,000 m^2, $125 M facility opened in 2006

12 m diameter, 250 MeV synchrotron



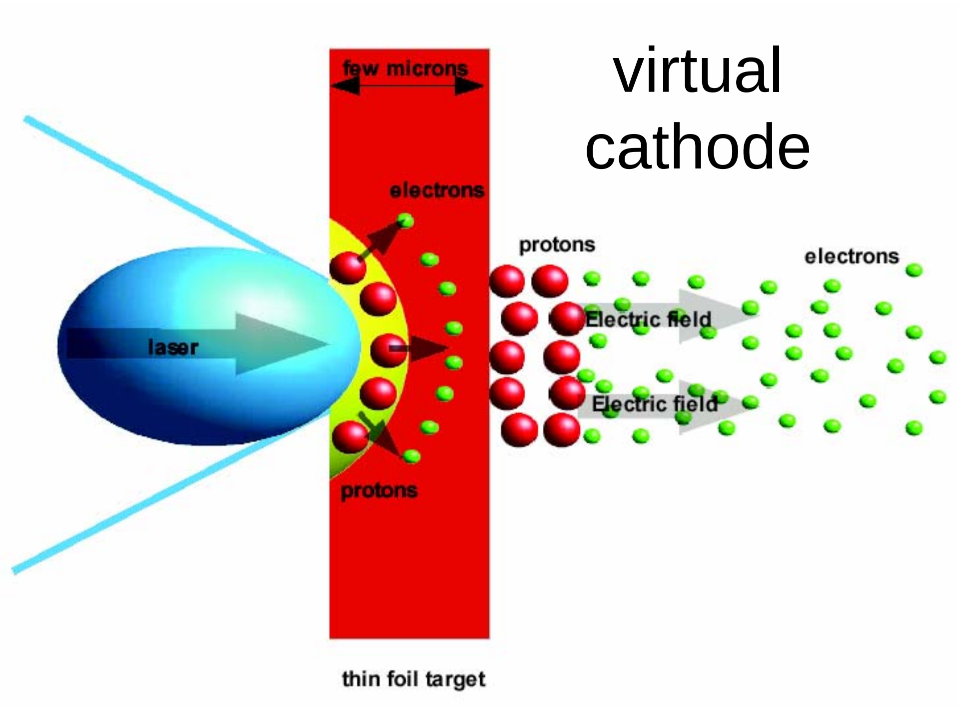
“There are too few physicists in the world, and they are an incredibly important part of doing this... We have one of the largest physics departments in the world, with more than 50 medical physicists.”

--- Dr. James D. Cox, head of Radiation Oncology at MD Anderson Cancer Center, Houston, Texas

Laser proton therapy could be much smaller & cheaper:

Fourkal, *Med. Phys.* **29**, 2788 (2002)
Malka, *Med. Phys.* **31**, 1587 (2004)

V. MeV Protons & Ion Beams

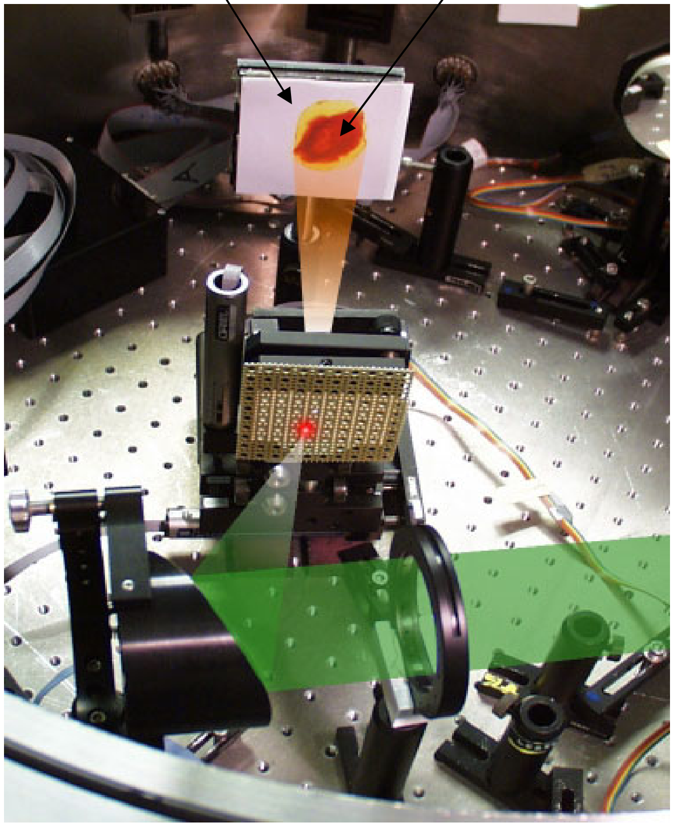


virtual
cathode

courtesy Prof. Dr. Oswald Willi, U. Düselldorf

CR39 or RCF

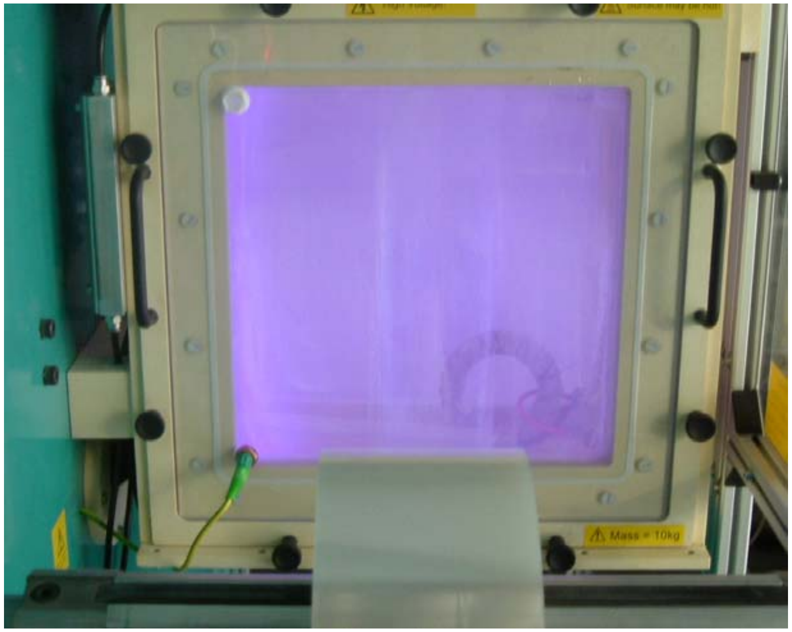
10^{10} to 10^{13} H^+

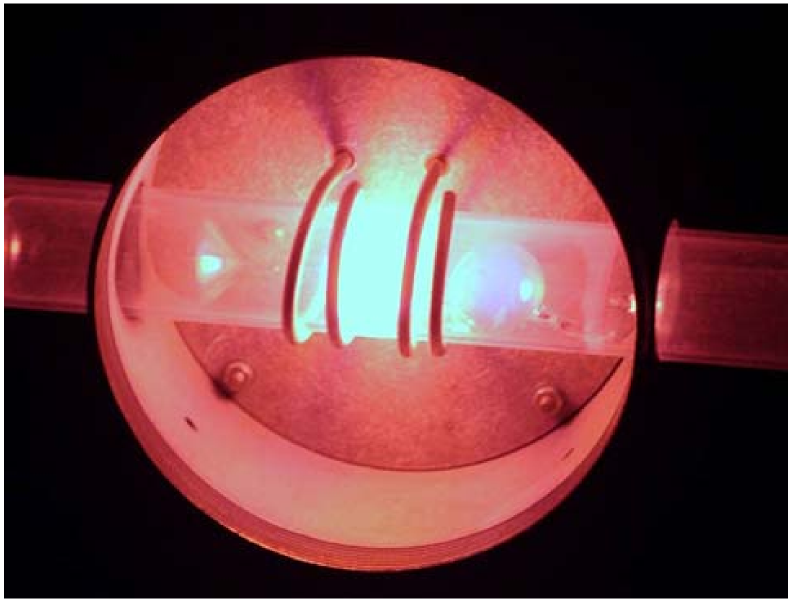


courtesy Prof. Don Umstadter, U. Nebraska-Lincoln

Target Normal Sheath Acceleration: hot electrons traversing target electrostatically accelerate impurity hydrogen ions on the rear surface

UNDERDENSE PLASMAS





OVERDENSE PLASMA

Radiation losses are negligible for linear accelerators

r_e = 2.82 x 10^{-13} cm

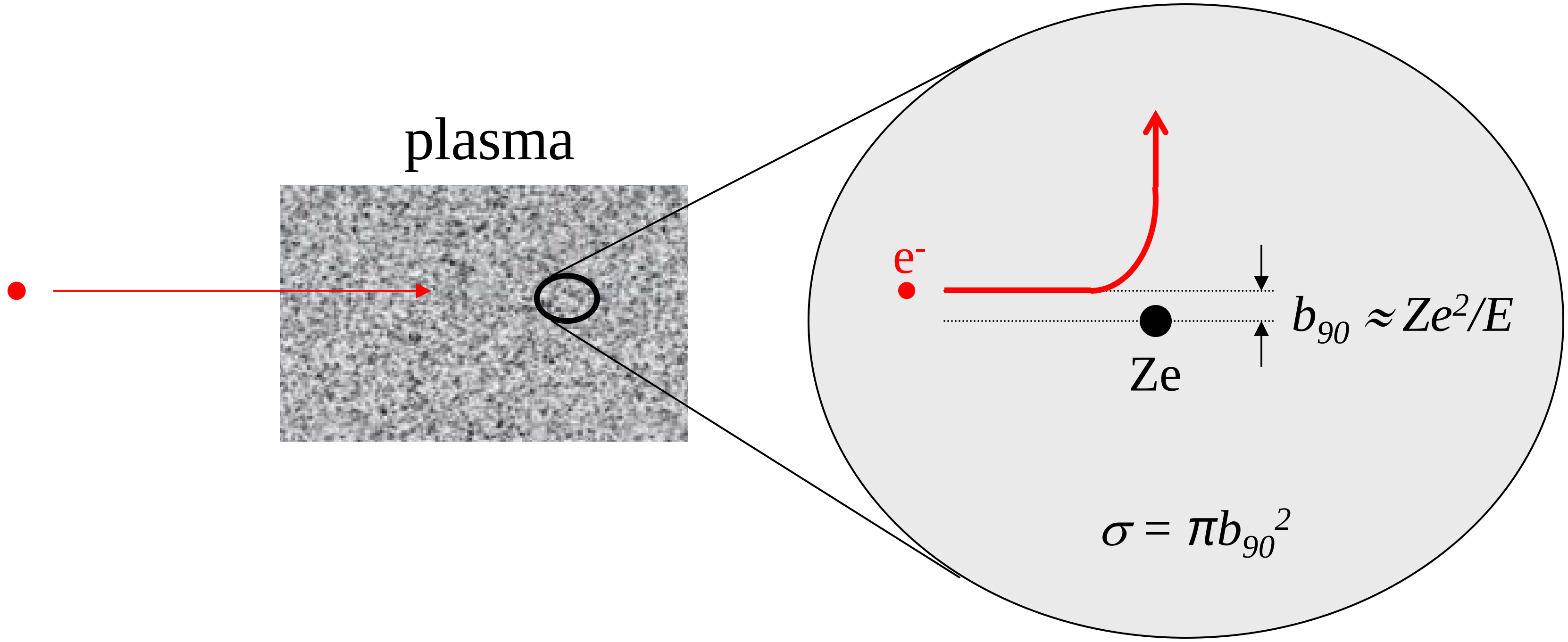
$$\boxed{\frac{P_{loss}}{P_{IN}} = \frac{2}{3}\frac{(e^2/mc^2)}{mc^2}\frac{dE}{dx}}$$

(Jackson 14.29)

0.5 MeV

→ 1 only for $dE/dx \sim 10^{20}$ V/m !!

Relativistic electrons propagate collisionlessly through plasmas

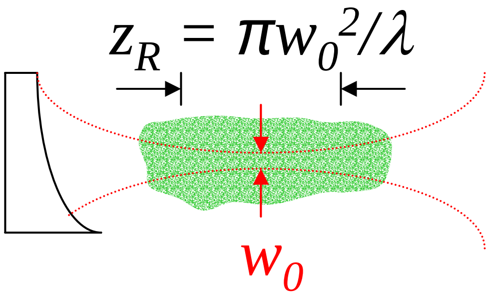


mean free path:

$$\lambda = (n\sigma)^{-1} \approx 10^{-7} \frac{E^2[eV]}{n[10^{19}\,cm^{-3}]}\,cm = \begin{cases} 10^{-3}\,cm & 1\,keV \\ 1\,km & 1\,MeV \\ 10^{6}\,km & 1\,GeV \end{cases}$$

Limits to Single-Stage Plasma Acceleration Length

Diffraction

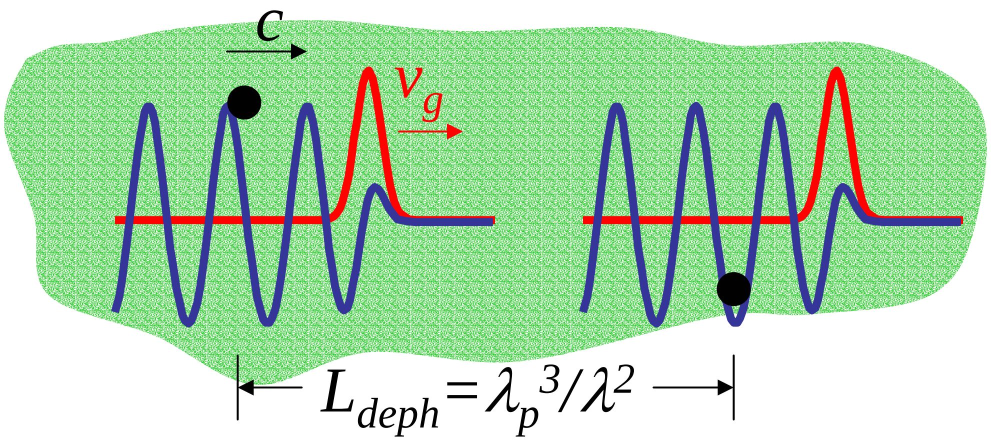


$z_R = \pi w_0^2/\lambda$

$10^{-2} < z_R < 10^{-1}$ cm

[1 TW] [10 TW]

Dephasing

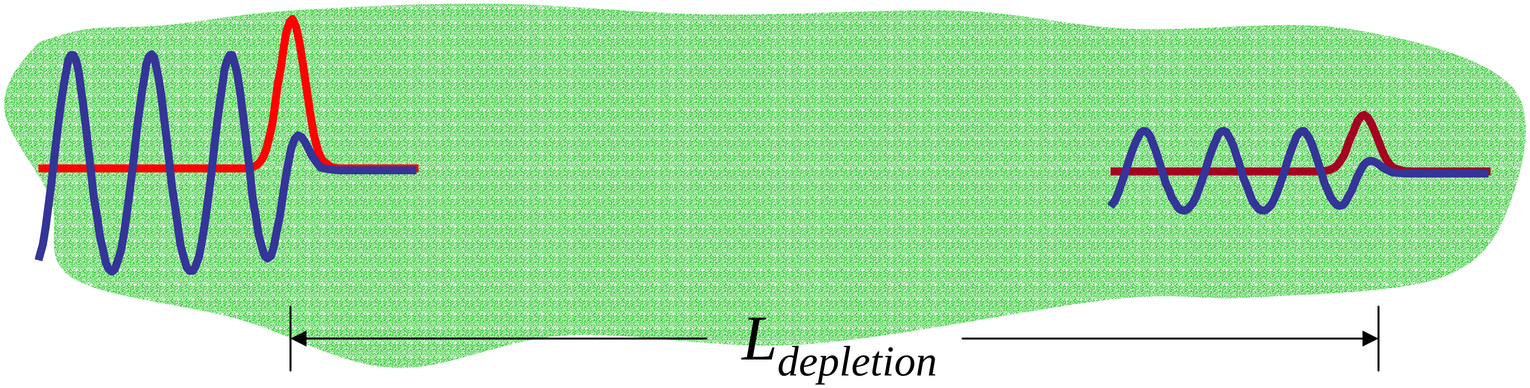


$L_{deph} = \lambda_p^3/\lambda^2$

10^{-1} cm $< L_{deph} < 10^3$ cm

[10^{19} cm^{-3}] [$3 \cdot 10^{16}$ cm^{-3}]

Depletion

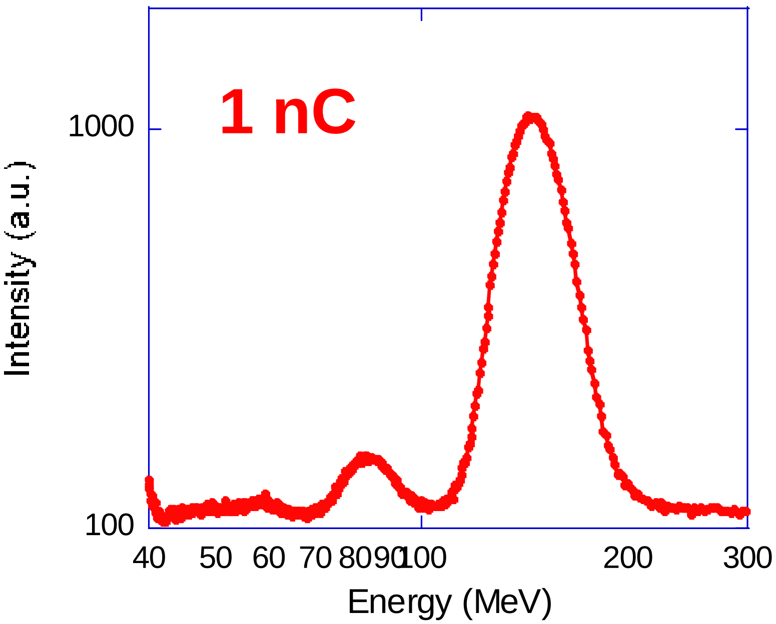


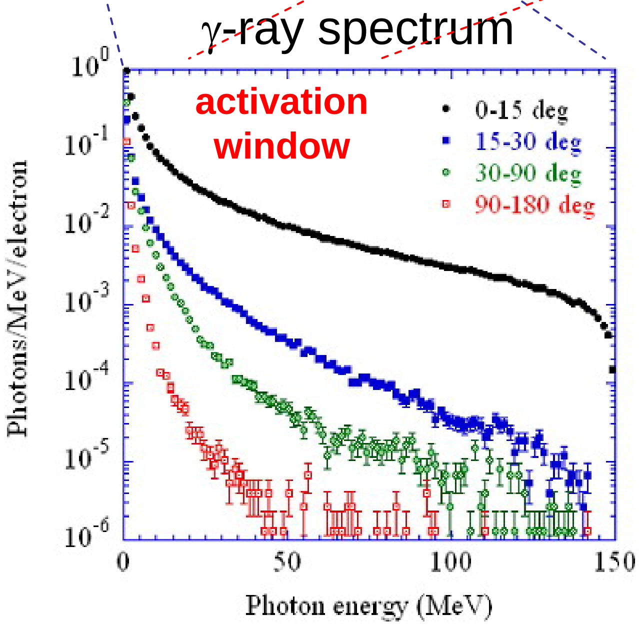
$L_{depletion}$

JOURNAL OF APPLIED PHYSICS 102, 073103 (2007)

Efficient initiation of photonuclear reactions using quasimonoenergetic electron beams from laser wakefield acceleration

1 J laser pulse → (10% efficiency) → ~150 MeV mono-energy electrons → (Ta converter) → brems-strahlung γ-rays → ($>10^5$ reactions) → activated tracer, *e.g.* $^{12}C(\gamma,n)^{11}C$



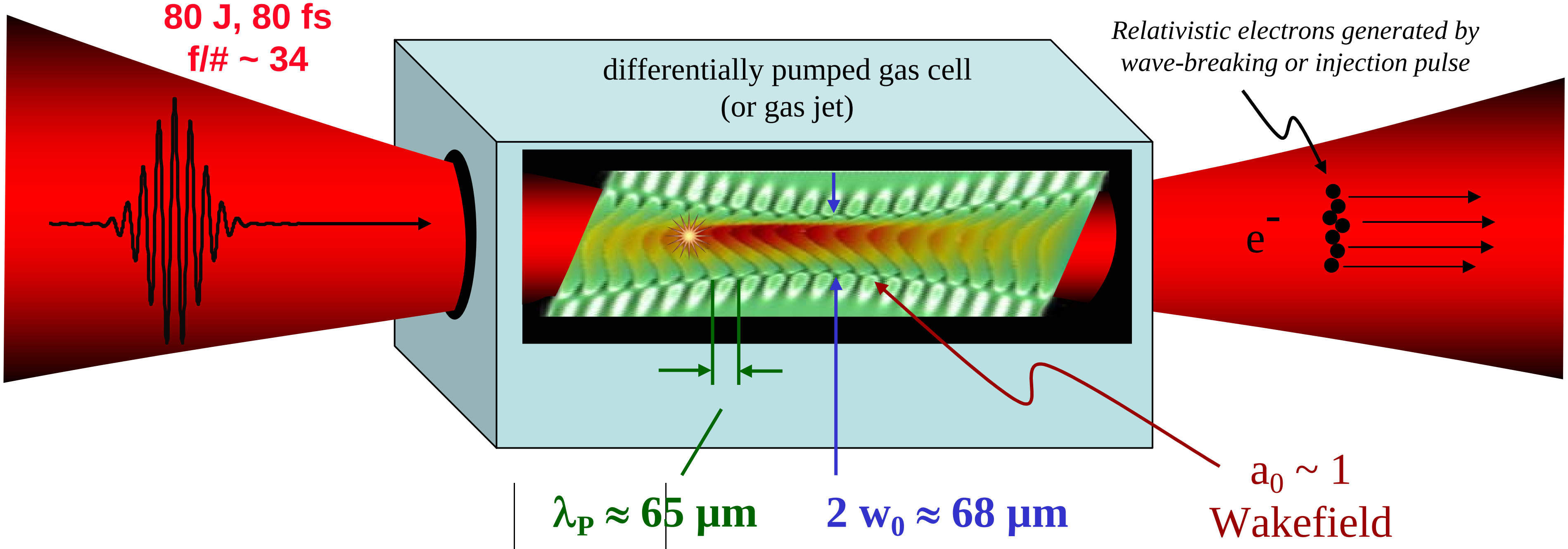


field
n in
ique
ssary
, Cu.
The
netic
laser

QuickTime™ and a
decompressor
are needed to see this picture.

~10 µm

Petawatt laser wakefield accelerators



Petawatt Pulse

80 J, 80 fs

f/# ~ 34

differentially pumped gas cell
(or gas jet)

Relativistic electrons generated by
wave-breaking or injection pulse

e^-

$\lambda_P \approx 65\ \mu m$

$2\ w_0 \approx 68\ \mu m$

$a_0 \sim 1$
Wakefield

Laser Power [PW]	Pulse Duration [fs]	Plasma Density [cm^{-3}]	Spot Size [µm]	Int. Length [m]	e-charge [nC]	Energy Gain [GeV]	comments	
0.02	30	10^{18}	14	0.016	0.18	**0.99**	Leemans (2006)	
1.0	**80**	**5×10^{17}**	**34**	**0.08**	**1.3**	**5.7**	**self-guided**	1st generation
2.0	310	10^{16}	140	16.3	1.8	**99**	**channel-guided**	2nd generation
20	1000	10^{15}	450	500	5.7	999	**channel-guided**	

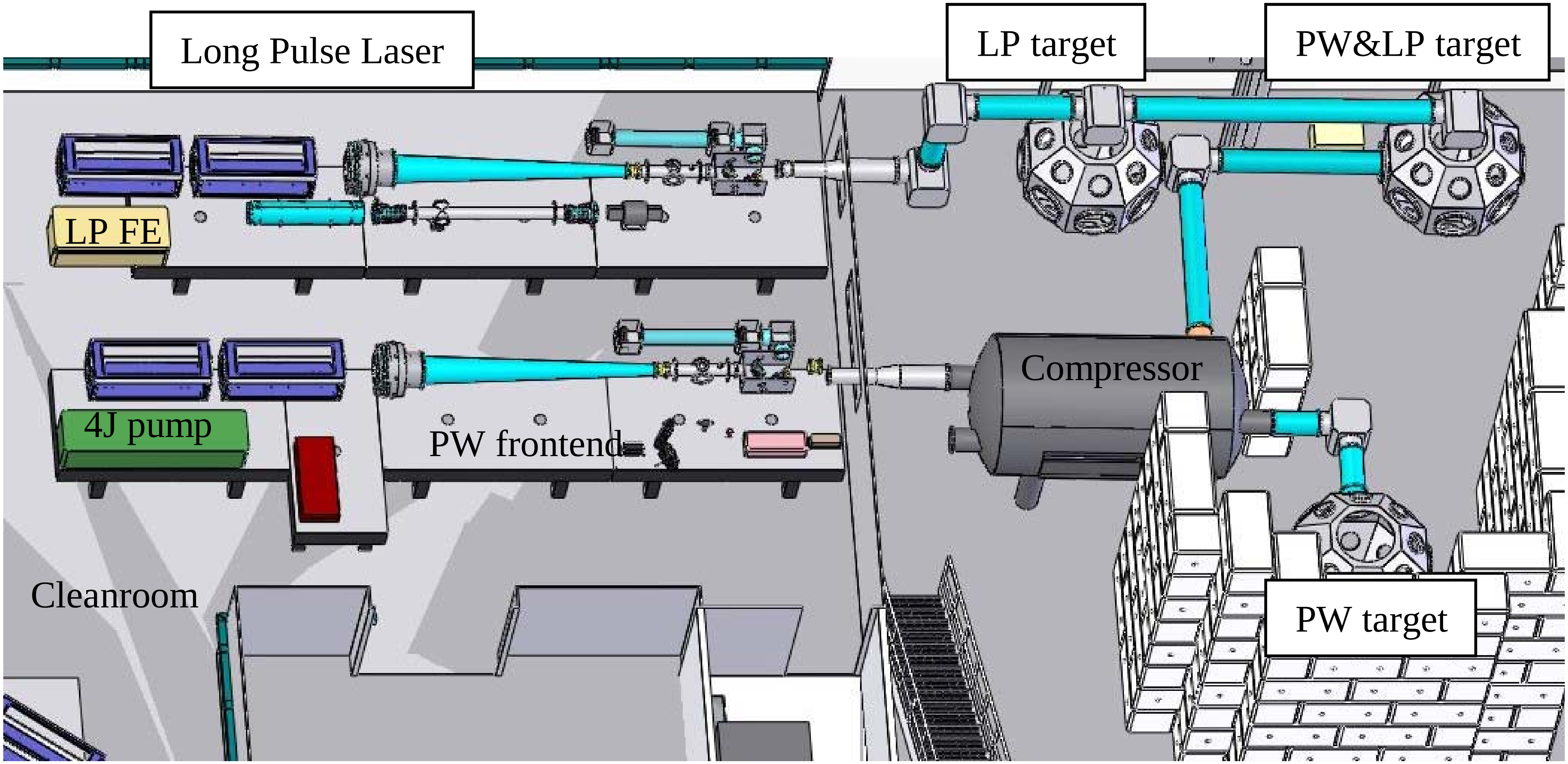
* from 3D PIC simulations by W. Lu, F. Tsung, M. Tsourfraz & W. B. Mori (UCLA)

Table entries feature: 1. stable plasma structure; 2. $L_{dephasing} = L_{pump\ depletion}$ 3. balance between energy extraction & beam quality

Texas Petawatt Laser

first light in 2007

Todd Ditmire, director



Pulse Energy: >100 J

Pulse Duration: 100 fs

Nonlinear “Blowout” or “Bubble” regime summary

-- 42 GeV: recent PWFA experiments at SLAC,
potential to impact high-energy
colliders at energy frontier

Most laser- and particle-beam driven plasma accelerators now operate in the “blowout” or “bubble” regime