The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

1856-37

2007 Summer College on Plasma Physics

30 July - 24 August, 2007

Plasma Accelerators

R. Bingham
Rutherford Appleton Laboratory,

Didcot, UK

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

Trieste Summer School, 2007

Plasma Accelerators

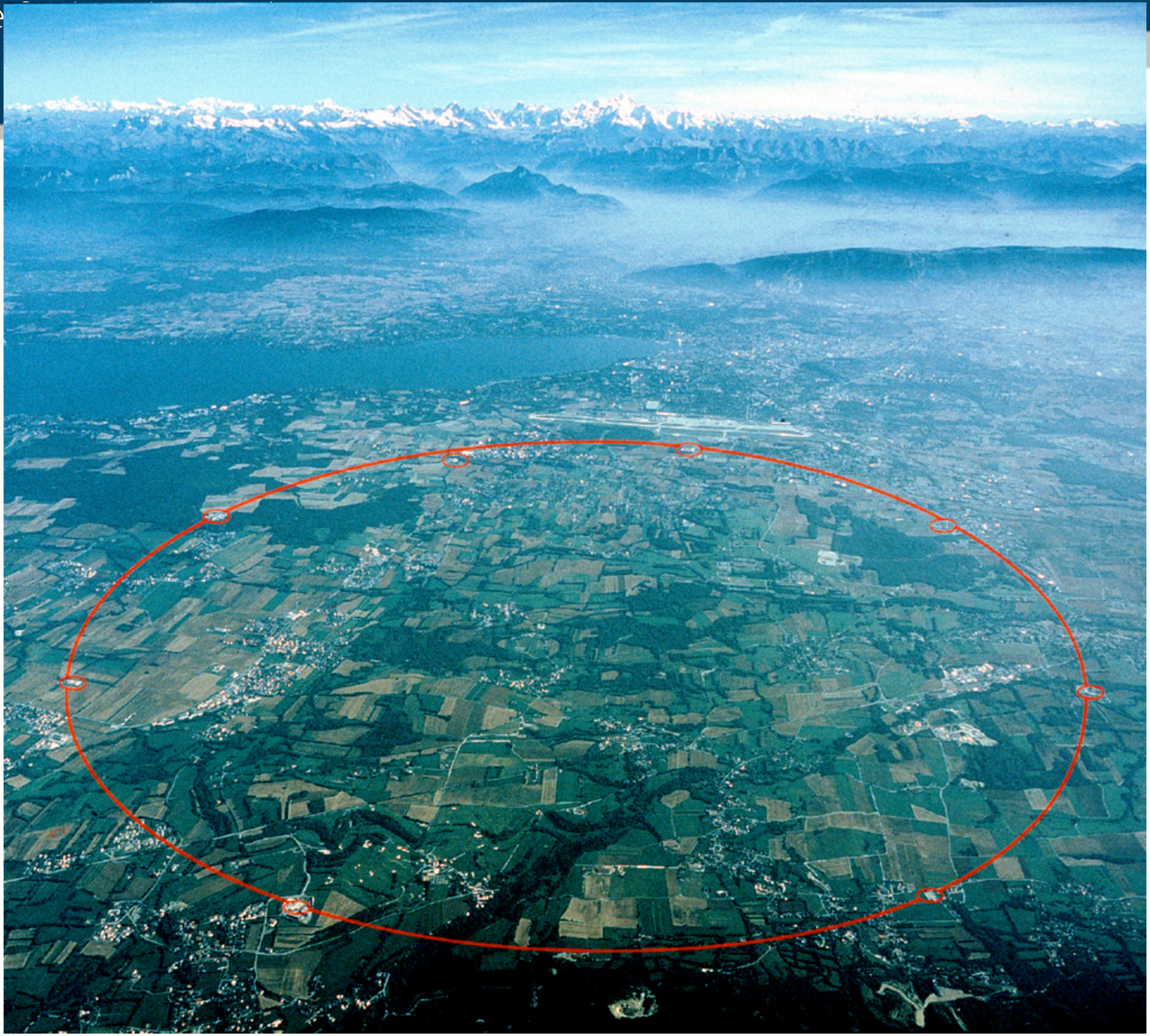
Robert Bingham

Rutherford Appleton Laboratory,
Space Science & Technology Department
Centre for Fundamental Physics

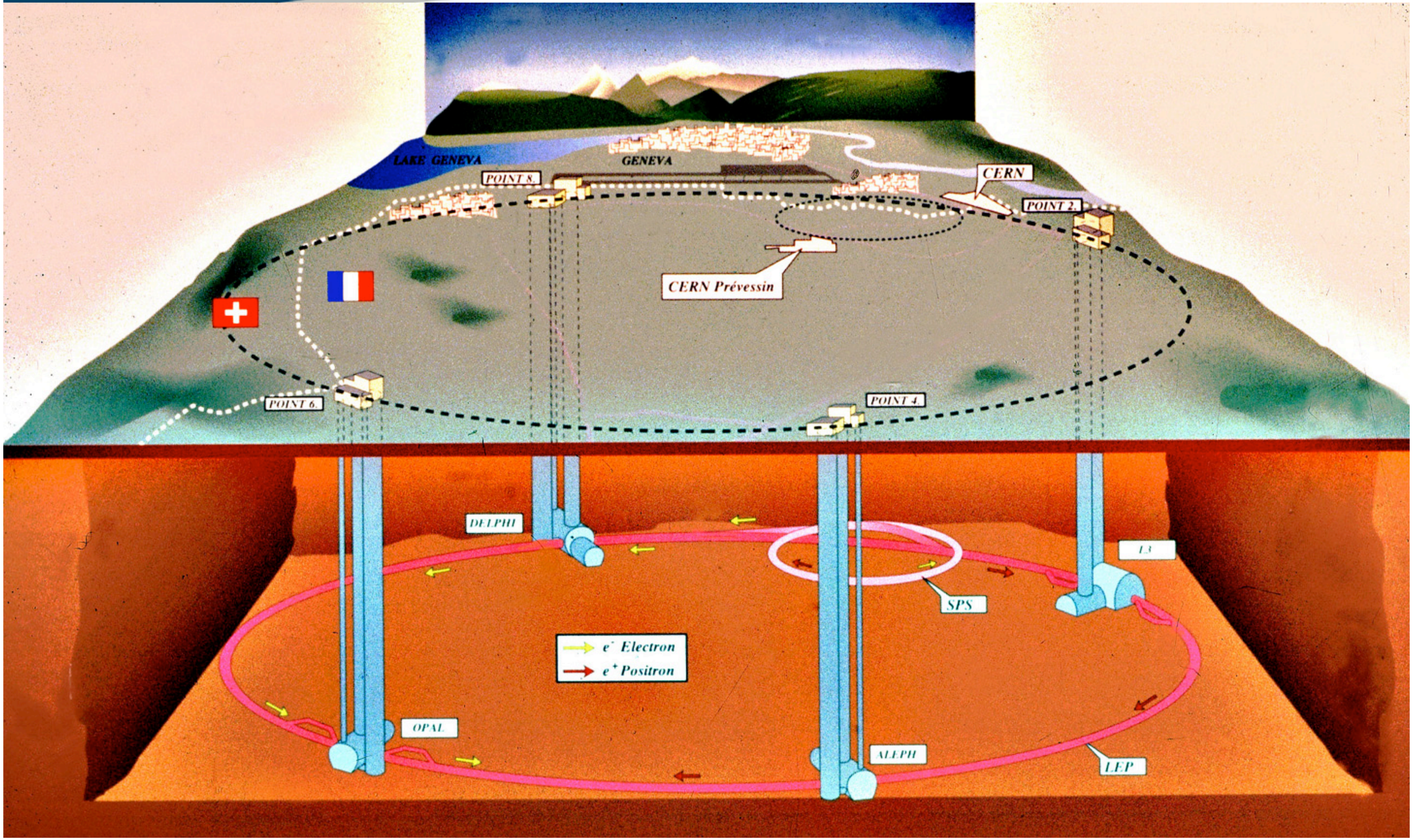
Introduction

- **General Principles**
  - Laser-plasma accelerators
  - Electron-beam-plasma accelerators
  - Theory – Simulations
  - Experiments
  - Future

CERN – LEP

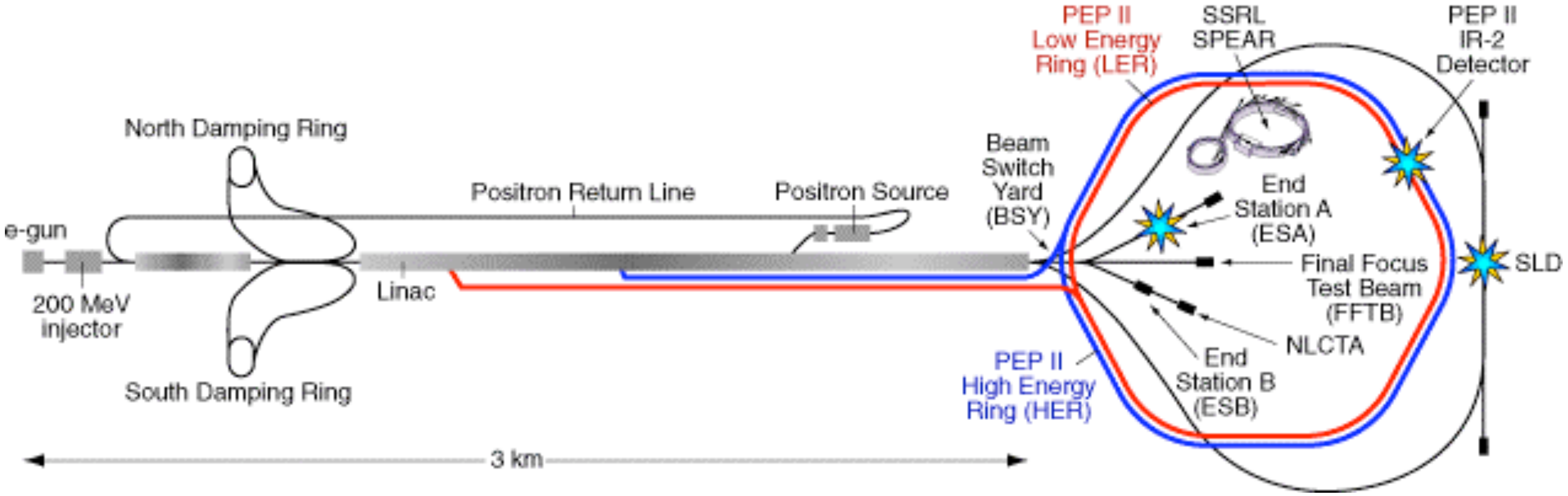


CERN – LEP schematic

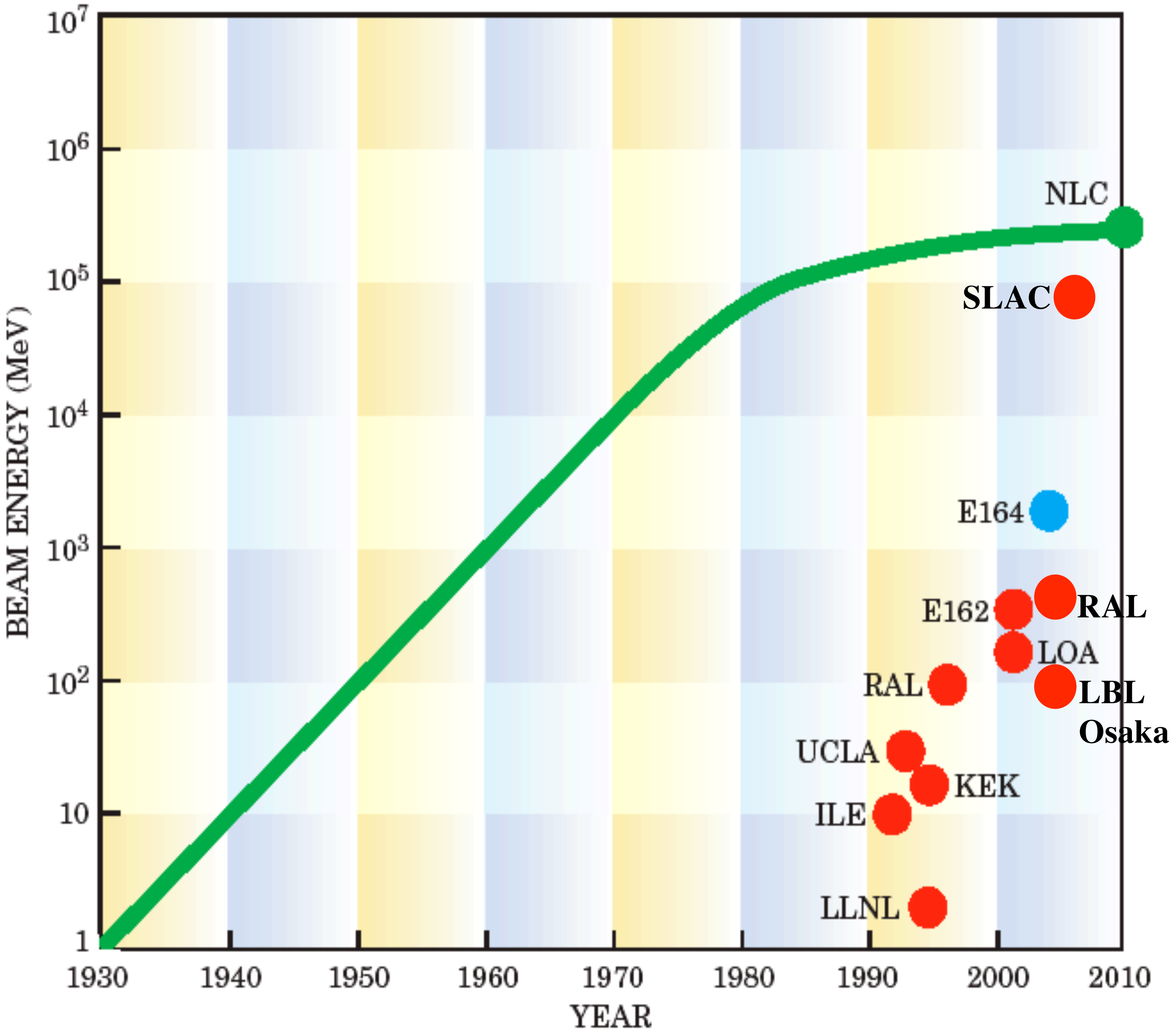


SLAC

SLAC Schematic



Plasma Accelerator Progress and the Livingston Curve



Particle Accelerators – compact to country size
Rich Physics and Applications

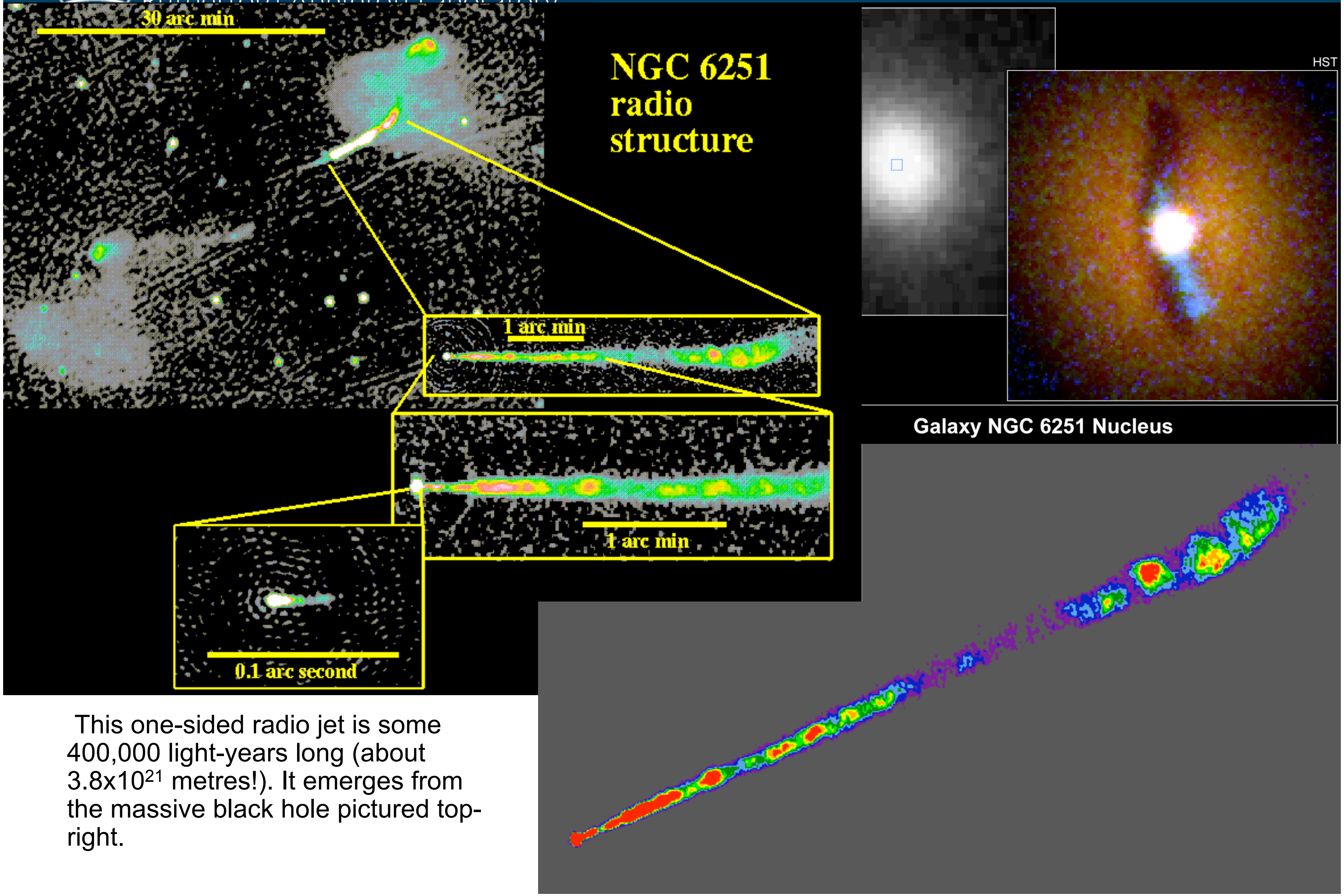
Large

- Verified Standard Model of Elem particles
- W, Z bosons
- Quarks, gluons and quark-gluon plasmas
- Asymmetry of matter and anti-matter
- In pursuit of the Higgs Boson (cause of mass)

Compact

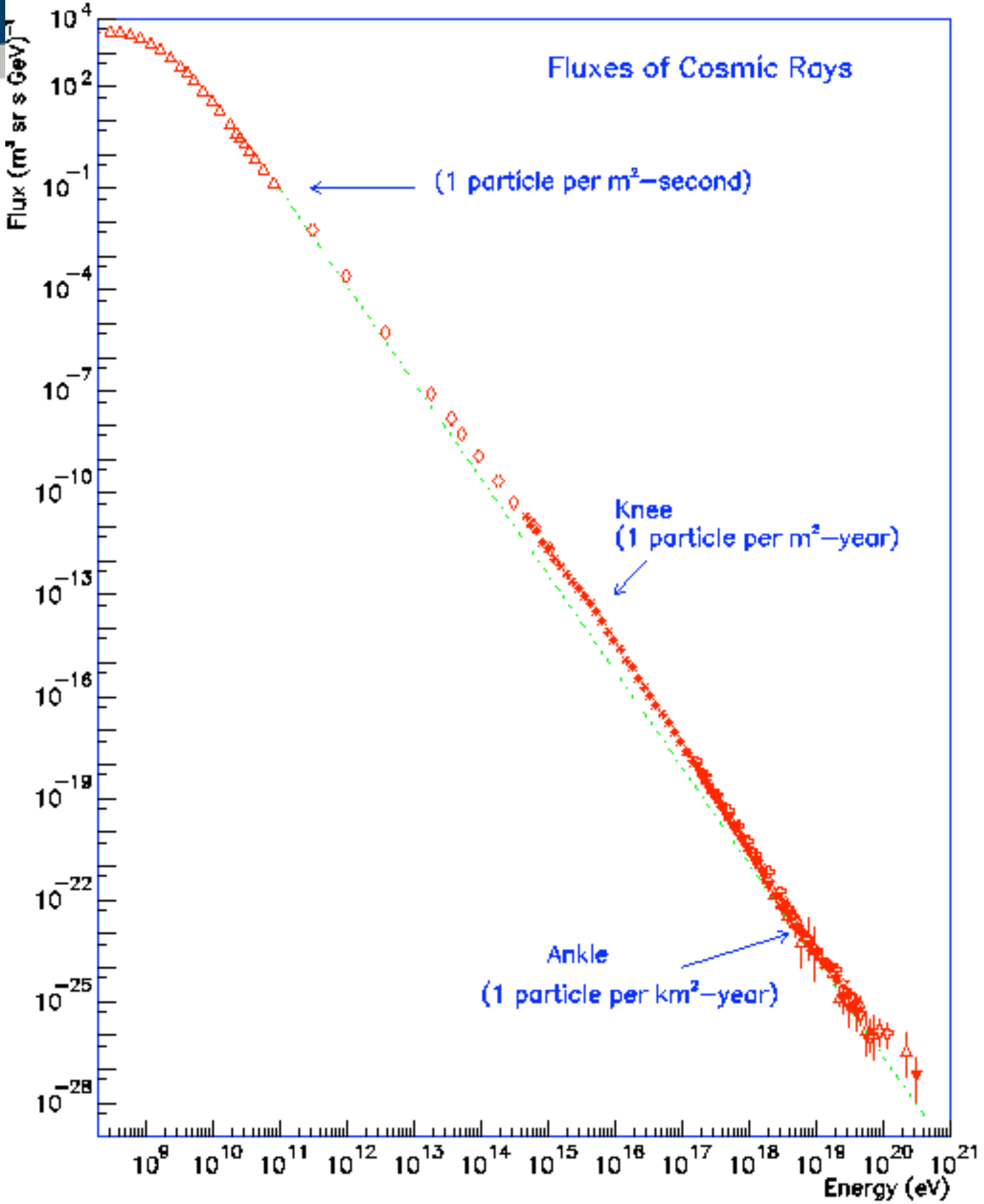
- Medicine
  - Cancer therapy, imaging
- Industry and Gov’t
  - Killing anthrax
  - lithography
- Light Sources (synchrotrons)
  - Bio imaging
  - Condensed matter science

NGC6251 – Astronomical Accelerator!



This one-sided radio jet is some 400,000 light-years long (about 3.8×10^{21} metres!). It emerges from the massive black hole pictured top-right.

Highest Energy Cosmic Rays



Examples of Energetic Particle Acceleration

- Cosmic Rays
  - e^-, p^+, He^+, heavy ions ⇒ $10^7 – 3x10^{20}$ eV
- Solar flares
  - e^-, p^+ ⇒ $10^5 – 10^9$ eV
- Aurora in planetary magnetospheres
  - e^-, p^+ ⇒ $10^4 – 10^6$ eV
- Runaways in tokamaks
  - e^- ⇒ $10^5 – 10^6$ eV
- Laser fusion
  - e^- ⇒ $10^5 – 10^7$ eV
- Plasma accelerators
  - e^- ⇒ 1 GeV – 100GeV, ions 10's MeV

Plasma Acceleration

- Electric fields generated in a plasma can accelerate electrons, protons, ions to high energies
- Definition

$$\Delta T = q\, v_0\, (t).E(r_0(t), t)\, dt$$

ΔT is change in particle kinetic energy
E is the electric field
q is the particle charge
v_0 is the particle velocity

- Deterministic System
  - *E(r,t)* does not change significantly during the acceleration phase.
- Stochastic
  - *E(r,t)* changes in a random fashion.

Proposed Acceleration Mechanisms

Coherent $t_{acc} > t_{change}$

E-Fields

- Generated by reconnection – inductively driven field
- Double layers – conservative field cannot energise particle, can only locally accelerate them (KE at expanse of PE)

- Coherent waves
  - Acceleration mechanisms, Beat-Wave, wake field need large amplitudes or large distances of uniform plasma
- Coulombic Explosions

Stochastic Acceleration

- In laboratory, space and astrophysical plasmas stochastic acceleration by turbulent wave fields is important.
- In astrophysics, the best known stochastic acceleration is Fermi acceleration.
- Fermi acceleration -- cosmic ray particles accelerated by colliding with moving magnetized structures i.e. galaxies.
- The collision is effective via the magnetic mirror and the particle either gains or losses energy proportional to the velocity of the structure.

Fermi Acceleration

- The acceleration takes place via many small steps with multiple collisions between particles and magnetic clouds.
- Acceleration is non-isotropic energy being put into the parallel direction.
- Energy distribution among a large number of particles is redistributed among a few very high energy particles.

Note: Fermi acceleration requires pre-acceleration.

Wave-Particle Resonance

- Simplest is Cerenkov resonance $\omega = kv$
- corresponds to law of momentum and energy conservation particle emits wave quantum $\hbar\omega,\ \hbar k$

$$\Delta E = \hbar\omega = \Delta\,\underline{p}.\underline{v} \qquad \text{where} \quad \Delta\,\underline{p} = \hbar\,\underline{k} \quad \& \quad \omega = \underline{k}.\underline{v}$$

In a Magnetic Field

- Resonant particle moves along a spiral on Larmor orbit $\omega_c = \frac{eB}{m}$
- Particle may be treated as an oscillator with energy $n\hbar\omega_c = (n = 0, 1, 2, \ldots)$ moving along *B*
- Both energy of translational motion and oscillator energy may change

$$\Delta E = \hbar\omega = \Delta p_z v_z + n\hbar\omega_c \qquad \Delta p_z = \hbar k_z$$

$$\omega = k_z v_z + n\omega_k \qquad n = 0, \pm 1, \pm 2, \ldots$$

Electron Accelerators

1) Electron beam-induced Plasma Wakefield Accelerator (PWA)
2) Laser-induced Plasma Wakefield Accelerators
    a) Plasma Beat-Wave Accelerator (PBWA)
    b) Laser Plasma Wakefield Accelerator (LPWA)
    c) Self-Modulated Laser Wakefield Accelerator (SMLWA)
3) Inverse Cherenkov Laser Accelerator
4) Surfatron Accelerators

Plasma Accelerators – Why Plasmas?

Conventional Accelerators

- Limited by peak power and breakdown
- 20-100 MeV/m
- Large Hadron Collider (LHC) -- 27km, 2010
- Plans for “Next” Linear Collider (NLC) -- 100km ?

Plasma

- No breakdown limit
- 10-100 GeV/m

Laser

- >1 GeV in several cm

e-beam

- ~100 GeV in 1m

Particle Accelerators – Requirements for High Energy Physics

- High Energy
- High Luminosity (event rate)
  - $L=fN^2/4\pi\sigma_x\sigma_y$
- High Beam Quality
  - Energy spread $\delta\gamma/\gamma$ ~ .1 - 10%
  - Low emittance: $\varepsilon_n \sim \gamma\sigma_y\theta_y < 1$ mm-mrad
- Low Cost (one-tenth of $6B/TeV)
  - Gradients > 100 MeV/m
  - Efficiency > few %

Compact Proton/Heavy Ion Accelerators

1) **Laser-induced Coulomb Explosions**
2) **Laser-induced Plasma Accelerator**
3) **Laser Shock Wave Accelerator**
4) **Laser $\underline{\mathbf{v}}_p \times \underline{B}$ Accelerator**
5) **Electron Ring Accelerator**

Synchrotron Sources

Laser Undulator - radiation generation system

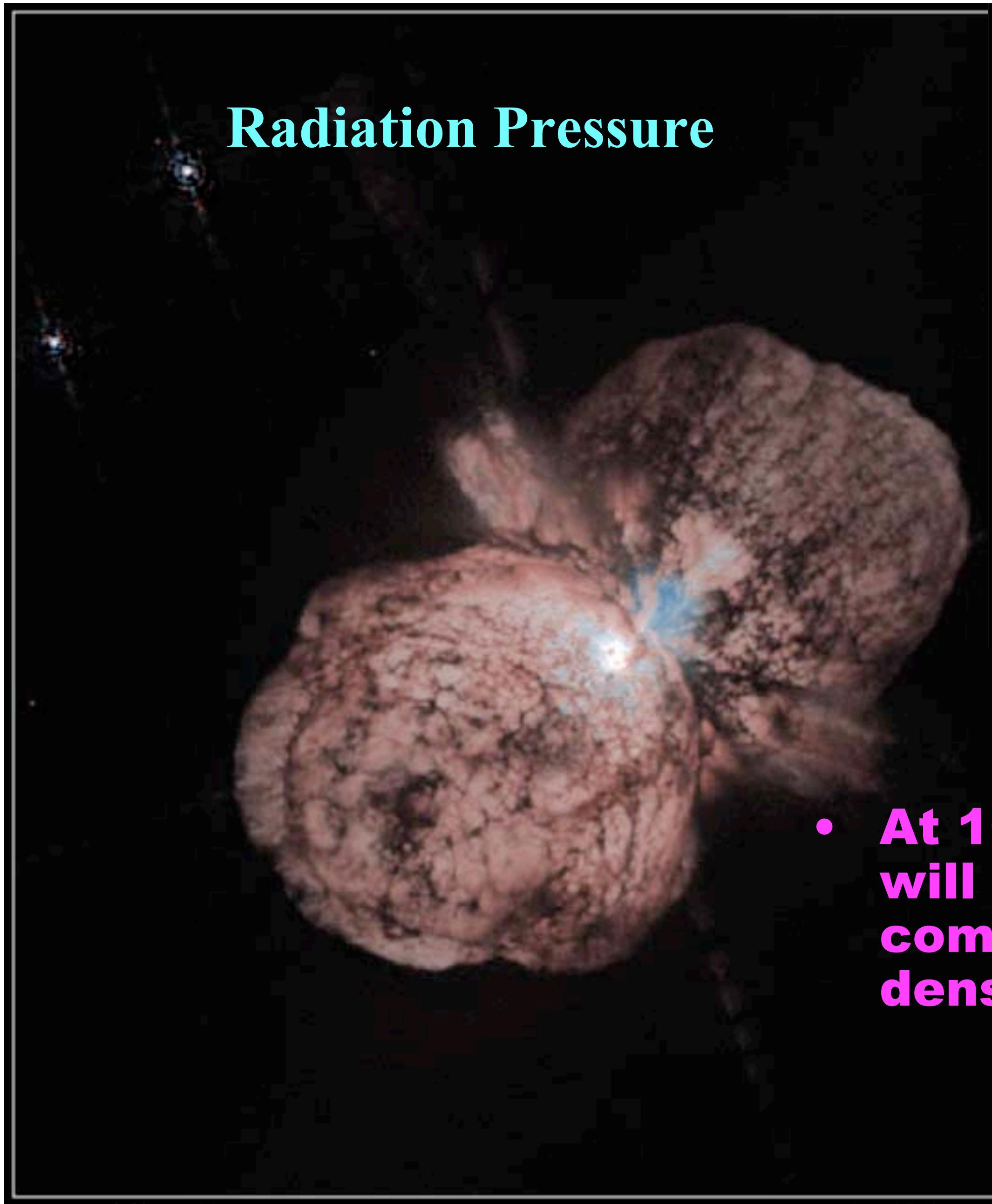
Drivers for Plasma Based Accelerators

- Lasers – Terawatt, Petawatt Compact Lasers 10^{12}–10^{15} Watts already exist.
  - Some with high rep. Rates *i.e.* **10 Hz**.
  - Capable of 10^{19}–10^{21} *Watts/cm*^{2} on target.
  - Future ~10^{23} *Watts/cm*^{2} using OPCPA.

- Electrons Beams – Shaped electron beams such as the Stanford/USC/UCLA experiment generate 100*GV/m* accelerating gradient using the 30 – 50*GeV* beam in a 1 meter long Lithium Plasma.

VULCAN

Radiation Pressure



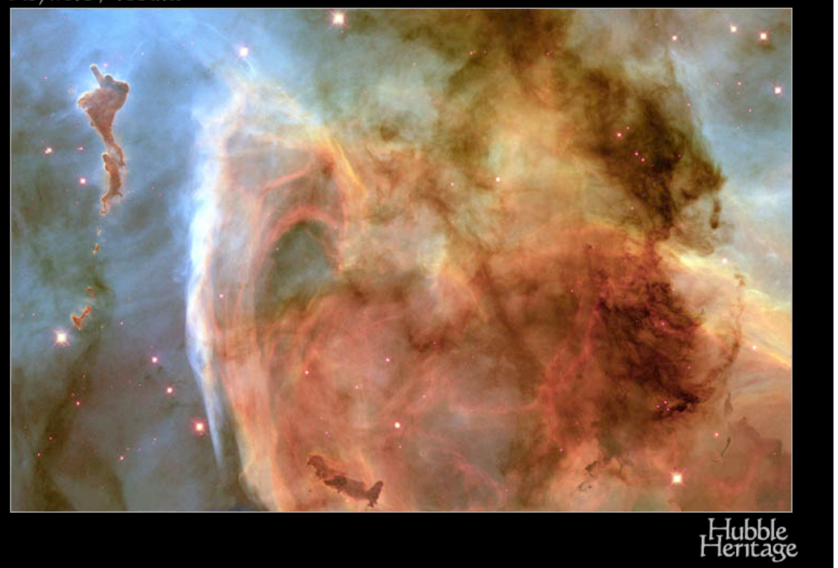
Eta Carinae

HST • WFPC2

PRC96-23a • ST ScI OPO • June 10, 1996

J. Morse (U. CO), K. Davidson, (U. MN), NASA

Keyhole Nebula



Hubble Heritage

NASA and The Hubble Heritage Team (STScI) • Hubble Space Telescope WFPC2 • STScI-PRC00-06

- At 10^{21} Wcm^{-2}, the light pressure will exceed 10^{9} atmospheres, compressing material to densities found inside stars.

Laser Plasma Accelerators

- The electric field of a laser in vacuum is given by

$$E_{\perp} = 30\sqrt{I} \ \ \text{V/cm}$$

- For short pulse intense lasers,

$$P = 10 \text{ TW}, \ \ \lambda_0 = 1 \ \mu\text{m}, \ \ I = 1.6\text{x}10^{18} \ \ \text{W/cm}^2$$

$$E_{\perp} = 40 \ \ \text{GV/cm}$$

- Unfortunately, this field is perpendicular to the direction of propagation and no significant acceleration takes place.
- The longitudinal electric field associated with electron plasma waves can be extremely large and can accelerate charged particles.

Plasmas

- Conventional accelerators limited by electrical breakdown of accelerating structures
- Plasmas are already broken down.
  - The accelerating fields limited only by plasma density.
- Plasmas can support longitudinal accelerating fields moving close to the speed of light; Relativistic electron plasma waves.
- Lasers easily couple to plasmas and can generate relativistic electron plasma waves.

Laser Plasma Accelerators

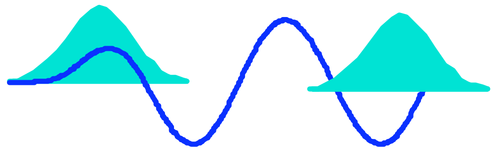
- Large accelerating fields ~1 *GeV/cm*
- No electrical breakdown limit
- But also, Low repetition rates
- … and can be expensive!

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Concepts For Plasma Based Accelerators*

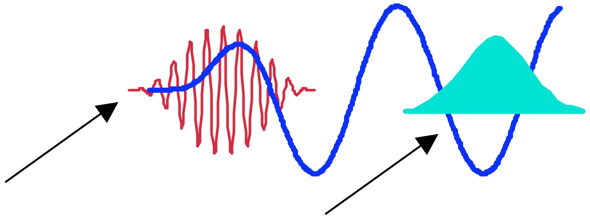
- Plasma Wake Field Accelerator(PWFA)

  A high energy electron bunch



- Laser Wake Field Accelerator(LWFA, SMLWFA, PBWA)

  A single short-pulse of photons

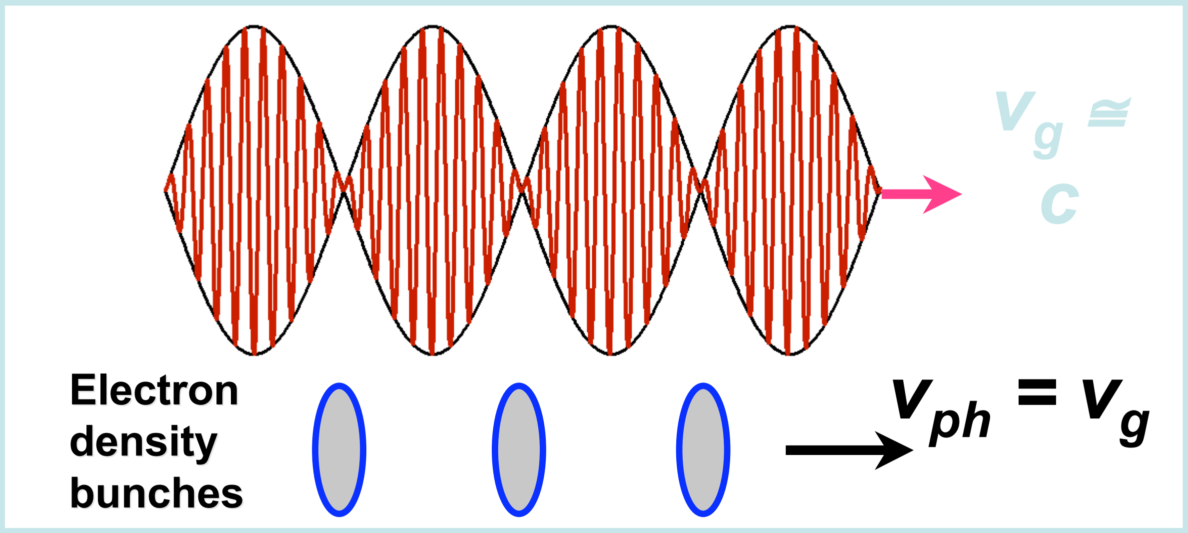


- Drive beam
- Trailing beam

***Godfather of the field: Prof. John Dawson**

Plasma Beat Wave Accelerator (PBWA)

- In the Plasma Beat Wave Accelerator (PBWA) a relativistic plasma wave is resonantly excited by the “ponderomotive” force of two lasers separated by the plasma frequency ω_p.
- The two laser beams beat together forming a modulated beat pattern in the plasma.



- For relativistic plasma wave the accelerating field $E_{||}$ is given by

$$E_{\parallel} = \varepsilon\sqrt{n_0} \quad \text{V/cm}$$

ε is the fractional electron density bunching, n_0 is the plasma density. For $n_0 = 10^{18}\ \text{cm}^{-3}$, $\varepsilon = 10\%$ $\Rightarrow$ $E_{\parallel} = 10^{8}\ \text{V/cm}$

Plasma Beat Wave

Relativistic plasma wave driven by beating 2 lasers in a plasma

$$\omega_1 - \omega_2 \cong \omega_p$$ energy

$$\underline{k}_1 - \underline{k}_2 \cong k_p$$ momentum

For $\omega_1, \omega_2 >> \omega_p$ i.e. $\omega_1 = 10\omega_p \quad \omega_2 = 9\omega_p$

Then
$$\left.\begin{array}{l} k_1 - k_2 \sim \Delta k \\ \omega_1 - \omega_2 \sim \Delta\omega \end{array}\right\} \quad \frac{\Delta\omega}{\Delta k} = \mathrm{v}_g$$

v_g is the group velocity of the laser beat pattern.

But **$k_1 - k_2 \sim k_p$; $\omega_1 - \omega_2 \sim \omega_p$**

$$\Rightarrow \frac{\omega_p}{k_p} = \mathrm{v}_{ph} \equiv \mathrm{v}_g \qquad \mathrm{v}_g = c\left(1 - \frac{\omega_p^2}{\omega_{1,2}}\right)^{1/2}$$

For $\omega_1, \omega_2 \rangle\rangle\, \omega_p$ ⇒ **$v_g \approx c$** ⇒ “Hence relativistic”

Poisson’s Equation

- From Poisson’s equation we can estimate how large these longitudinal electron plasma waves can be $\underline{\nabla} \cdot \underline{E} = 4\pi e \delta n_e$

δn_e is perturbed electron density of the plasma ions immobile on short time scale.

Largest field exists for $\delta n_e = n_0$ *i.e.* background density.

- Electron plasma waves oscillate with frequency $\omega_p = \left(4\pi n_0 e^2 / m_e\right)^{1/2}$ cgs, or $\left(n_0 e^2 / m_e \varepsilon_0\right)^{1/2}$ MKS.

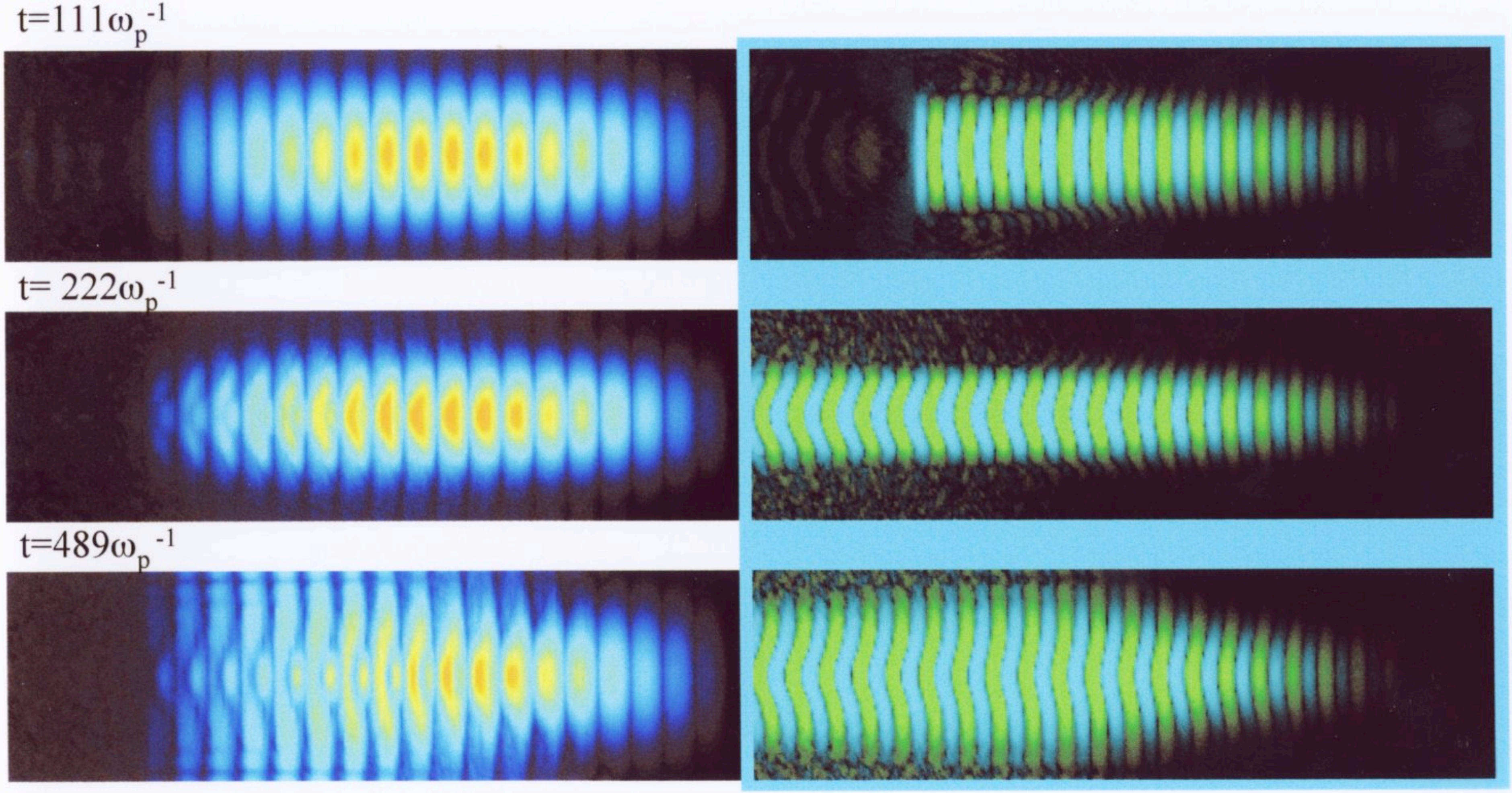
Relativistic plasma waves have phase velocities close to c

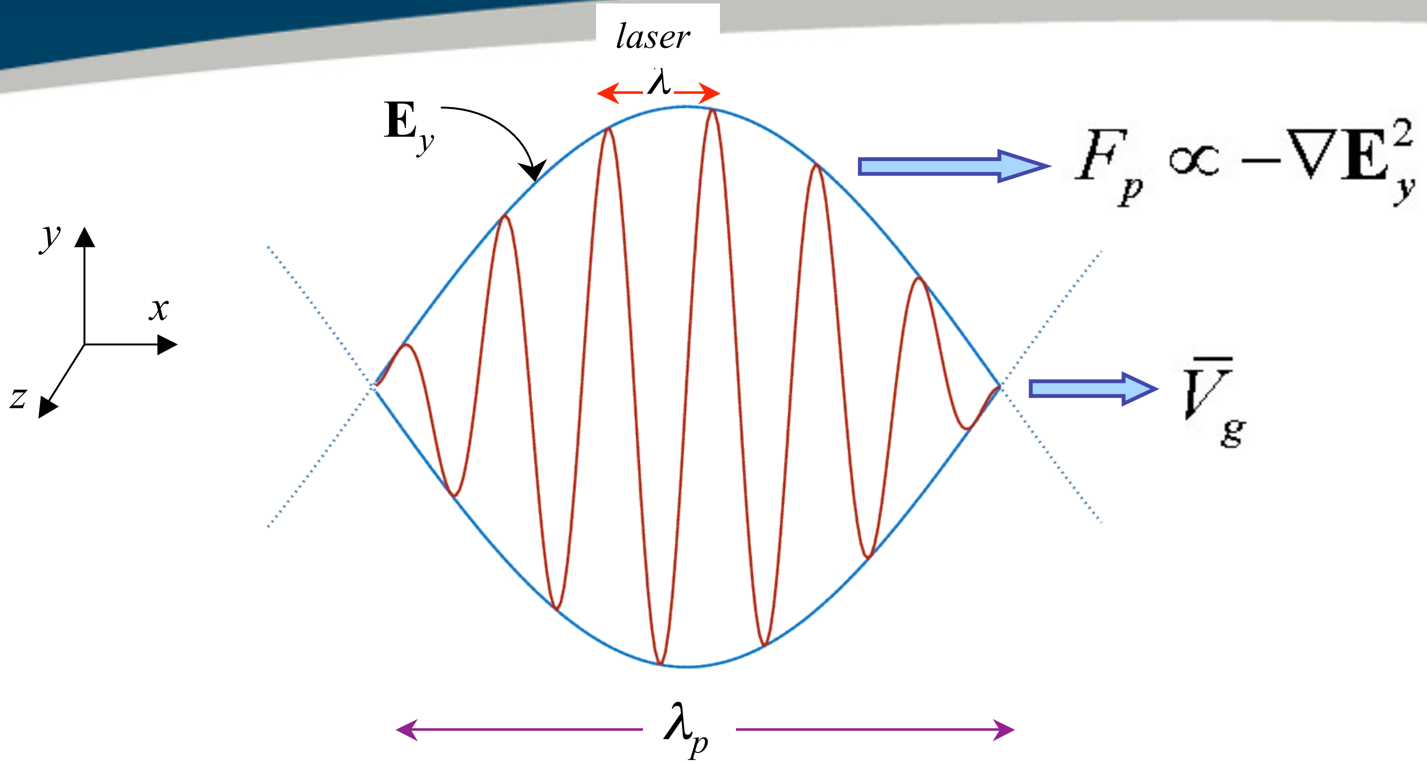
i.e. $\dfrac{\omega_p}{k_p} \cong c.$

- With Poisson’s equation we get $eE_{MAX} \approx \dfrac{4\pi n_0 e^2}{\left(\omega_p / c\right)} \cong 0.97\sqrt{\mathrm{n}}$ eV/cm

i.e. $eE_{MAX} \approx \sqrt{\mathrm{n}}$ eV/cm

PBWA: Evolution of Laser Intensity and Accelerating Field





- Envelope of high frequency field moving at group speed $\underline{v}_g$

$$\underline{v}_g = c\left(1-\frac{\omega_{pe}^2}{\omega^2}\right)^{1/2} \quad \Bigg\} \quad \begin{aligned} &\omega^2 = \omega_{pe}^2 + c^2k^2 \\ &v_g = \frac{d\omega}{dk} = \frac{c^2k^2}{\omega} = c\left(1-\frac{\omega_{pe}^2}{\omega^2}\right)^{1/2} \end{aligned}$$

- Ponderomotive force $F_p \propto -\nabla \mathbf{E}_y^2$ Laser field $\mathbf{E}_y$

Lorentz Force

- The Lorentz force due to the interaction of the lasers produces a longitudinal force or “ponderomotive” force of the beat pattern proportional to the gradient of
- Each beat (pulse) adds to the plasma waves amplitude.
  - The growth in time $$eE_{||} = \frac{m_e c\omega_p}{4}\int_0^{t_0} \alpha_1\alpha_2 dt$$
- $\alpha_{1,2} = eE_{\perp 1,2} / m_e c\omega_{1,2}$ is the quiver velocity of an electron in the laser field, normalized to the speed of light *c*
- From Gauss’s Law the accelerating field $E_{||}$ can be estimated

$$E_{||} = \varepsilon \frac{m_e c\omega_p}{e}$$

or

$$E_{||} = \varepsilon\sqrt{n_0} \quad \mathrm{V/cm}$$

- ε is plasma wave amplitude (fractional electron density bunching n_l / n_0 , n_0 is ambient density).

Energy Gain

- For $n_0 = 10^{18}$ cm^{-3}, $\varepsilon = n_1 / n_0 = 10\%$
- Gain in energy of electron ΔW

- $\gamma = \omega_1/\omega_p$ is the Lorentz factor
- For a neodymium laser, ω_1/ω_p ~30 , and $n_0 \sim 10^{18}$ cm^{-3}

$$E_p = \frac{e}{k_p}\delta n = \frac{ec}{\omega_p}\delta n$$

$$l = \frac{\lambda_p}{2}\chi \quad \Rightarrow \quad \chi = \frac{c}{c - v_{ph}} \quad \Rightarrow \quad v_{ph} \simeq c\left(1 - \frac{\omega_p^2}{\omega^2}\right)^{1/2}$$

$$l = \frac{\lambda_p}{2}\frac{\omega^2}{\omega_p^2} = \frac{\lambda_p}{2}\gamma^2$$

$$eEl = 2\varepsilon\gamma^2 m_e c^2$$

- Maximum energy gain $\Delta W \approx eE_p l$ $\Delta W = 2\ \varepsilon\ \gamma^2 m_e c^2$

$$\boxed{\Delta W \approx 100\ MeV}$$

The Relativistic Plasma Wave is described by

$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\delta n=\frac{3}{8}\omega_p^2\frac{\delta n^2}{n_0^2}\delta n-\frac{n_0}{2}\omega_p^2\alpha_1\alpha_2 e^{-i\delta t}$$

$$\alpha_j=\frac{eE}{m_e\omega_j c}\qquad ;\ \delta=\omega_1-\omega_2$$

For $\alpha_1 = \alpha_2 =$ constant

$$\frac{\delta n}{n_0}=\frac{\delta n_0(0)}{n_0}+\frac{1}{4}\alpha_1\alpha_2\omega_p t$$

Linear growth: However due to 1st term on RHS i.e. cubic non-linearity wave saturates before reaching wave breaking limit $\delta n/n \sim 1$; acts as nonlinear frequency shift.

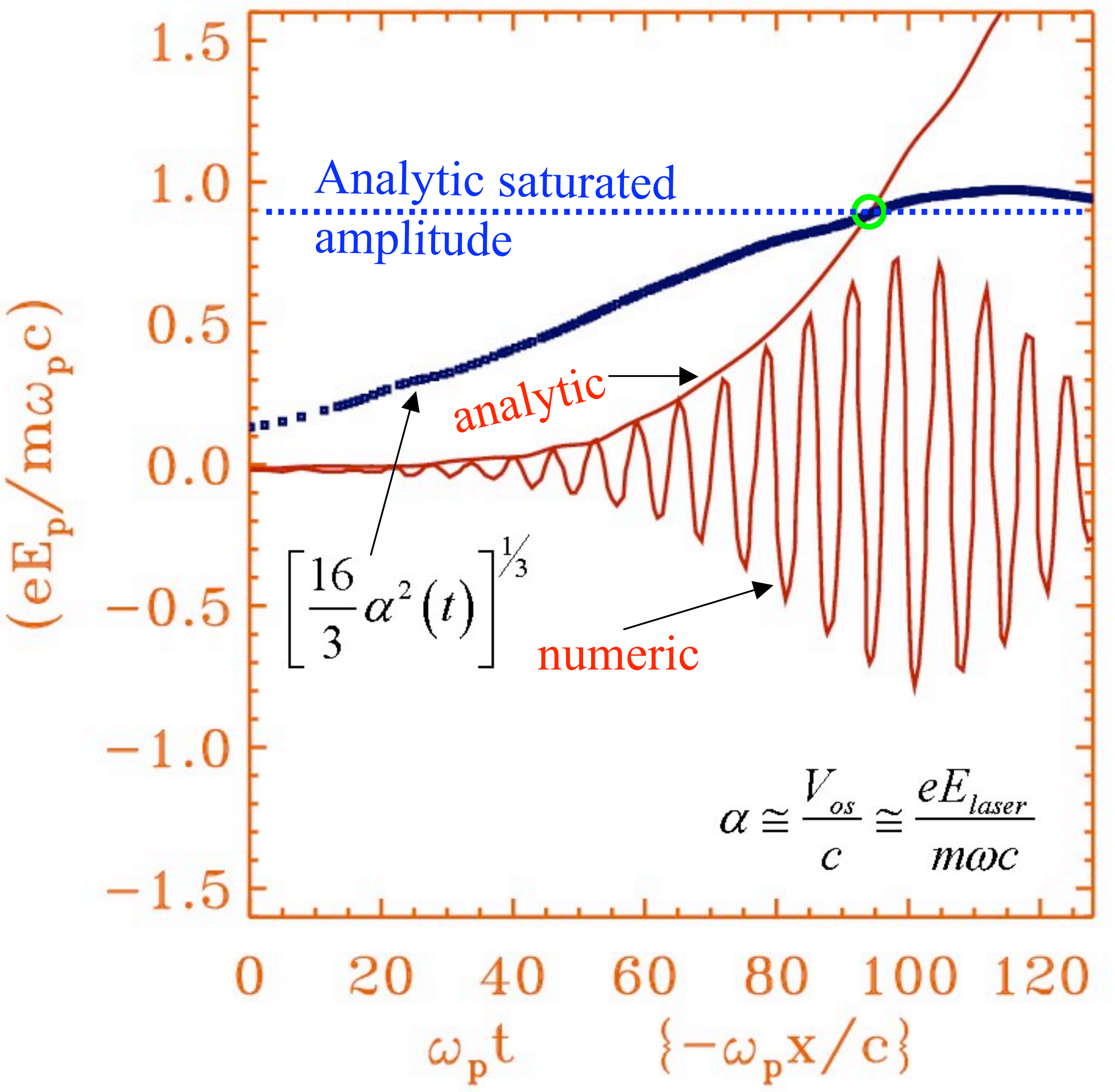
$$\frac{\delta n}{n}\max=\left(\frac{16}{3}\alpha_1\alpha_2\right)^{1/3}=\varepsilon$$

Relativistic mass increase of electrons reduces natural frequency

$$\omega_p^1=\omega_p\left(1-\frac{3}{8}\frac{\mathrm{v}_{osc}^2}{c^2}\right)^{1/2}=\omega_p\left(1-\frac{3}{8}\frac{\delta n^2}{n^2}\right)^{1/2}$$

This results in $\omega_1 - \omega_2 \neq \omega_p$ ⇒ non-resonant interaction ⇒ saturation.

Beat Wave Growth



Analytic saturated amplitude

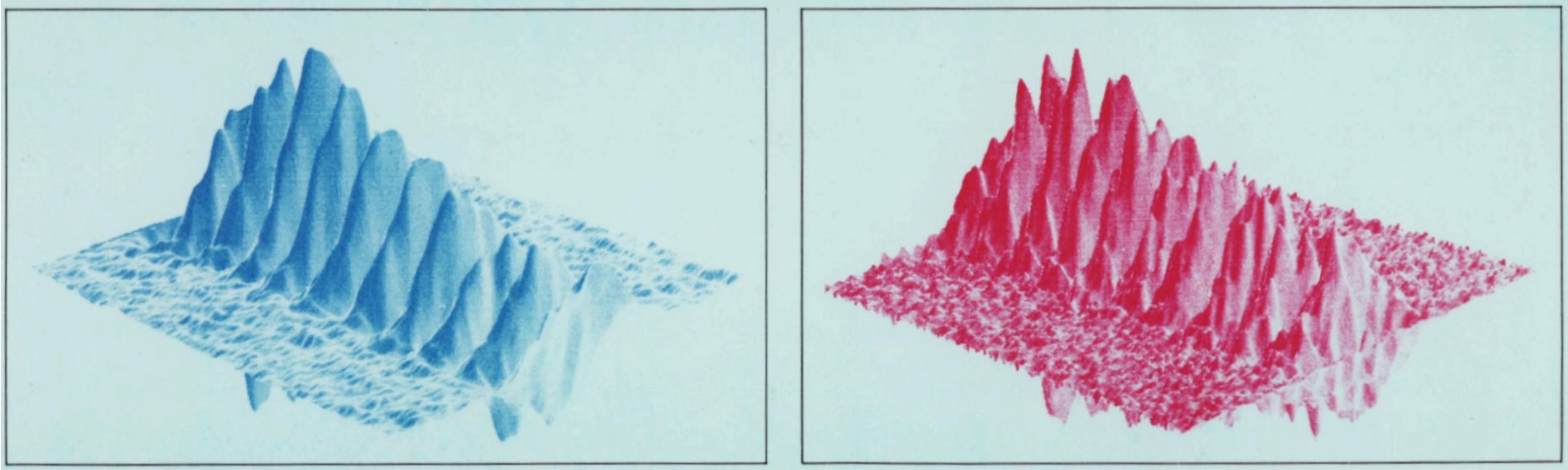
analytic

numeric

$$\left[\frac{16}{3}\alpha^2(t)\right]^{1/3}$$

$$\alpha \cong \frac{V_{os}}{c} \cong \frac{eE_{laser}}{m\omega c}$$

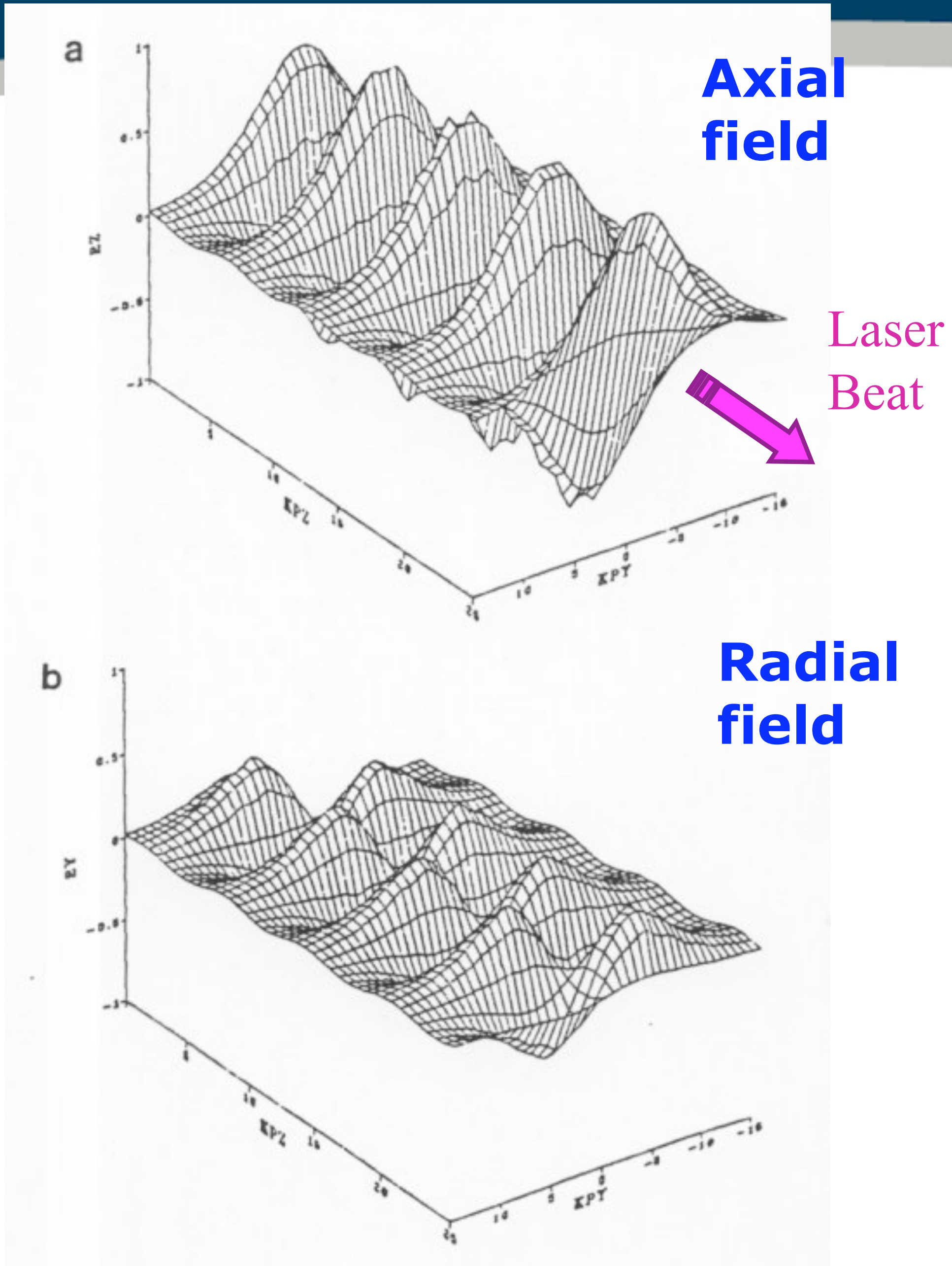
Computer Simulations



PLASMA WAVE (*left*) from a computer simulation of the beat-wave method generates an electric field (*right*). If a group of charged particles was injected into a plasma and moved in phase with the electric field, the group would accelerate.

Beat Wave Generated Plasma Wave

- PBWA –
  Plasma Beat Wave
  Accelerator

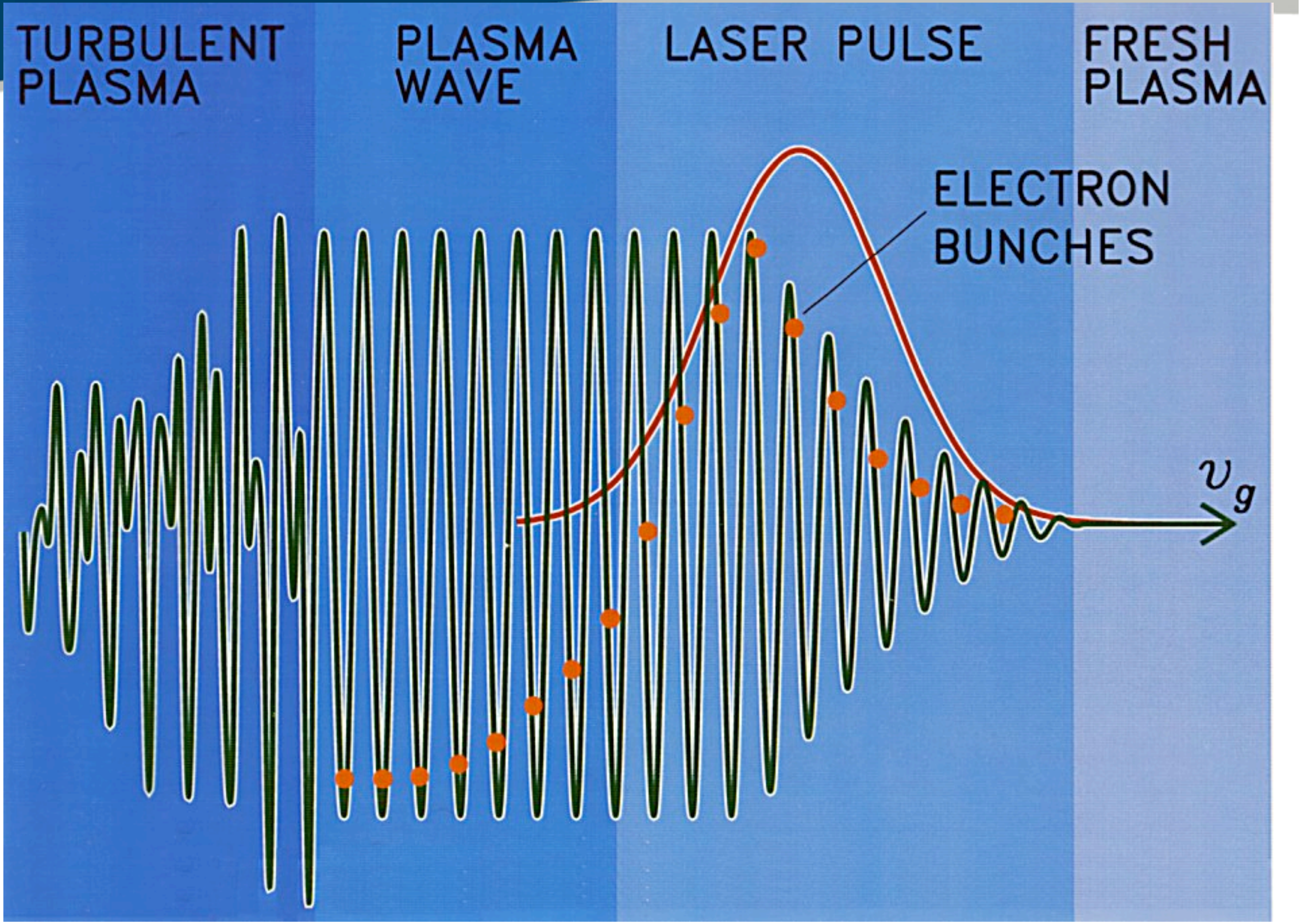


Axial field

Laser Beat

Radial field

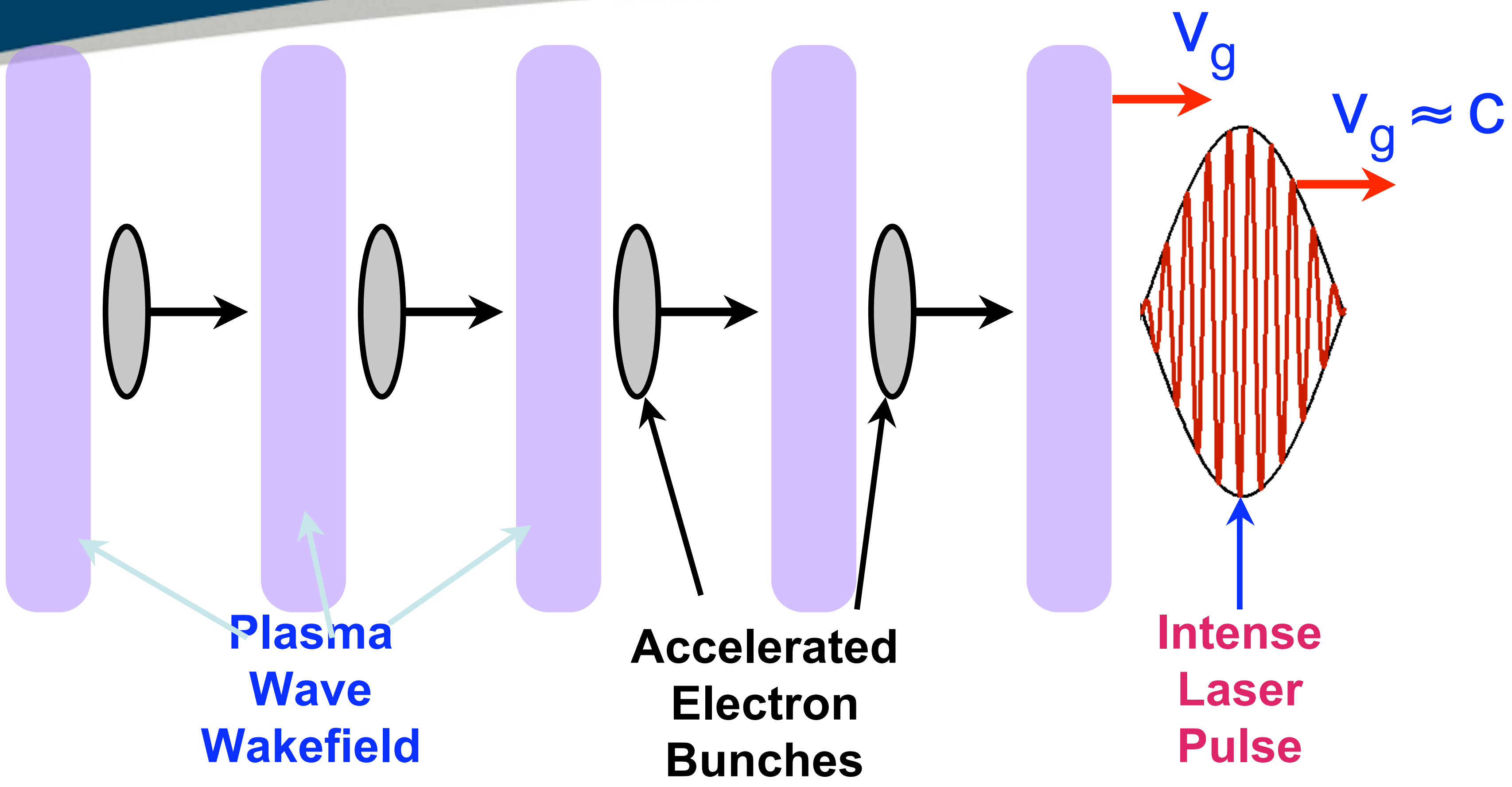
[S. Wilks *et al*. PPG. 1262]


TURBULENT PLASMA
PLASMA WAVE
LASER PULSE
FRESH PLASMA
ELECTRON BUNCHES
v_g

Surfing The Waves!

At 10^{21} W.cm^{-2}, electrons will be accelerated to beyond 100 MeV, generating gamma rays, proton beams and exotic isotopes.

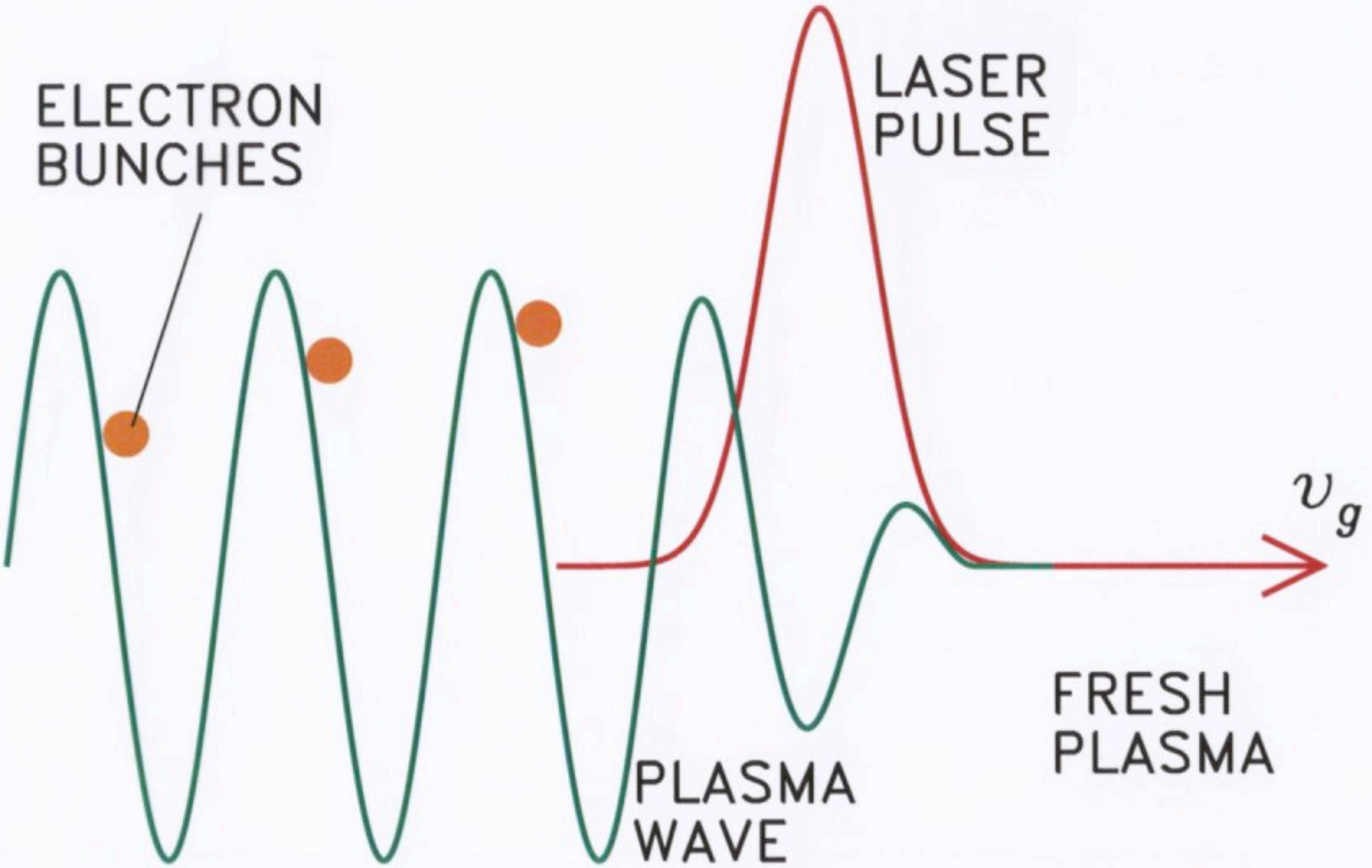
Laser Wakefield Experiments (LWFA)



Confirmation of wakefield generation - J.R. Marques *et al.* PRL **76** 3566 (1996)
C.W. Siders *et al.* PRL **76** 3570 (1996)

Acceleration - F. Amiranoff *et al.* PRL **81** 995 (1998)

Laser Wakefield



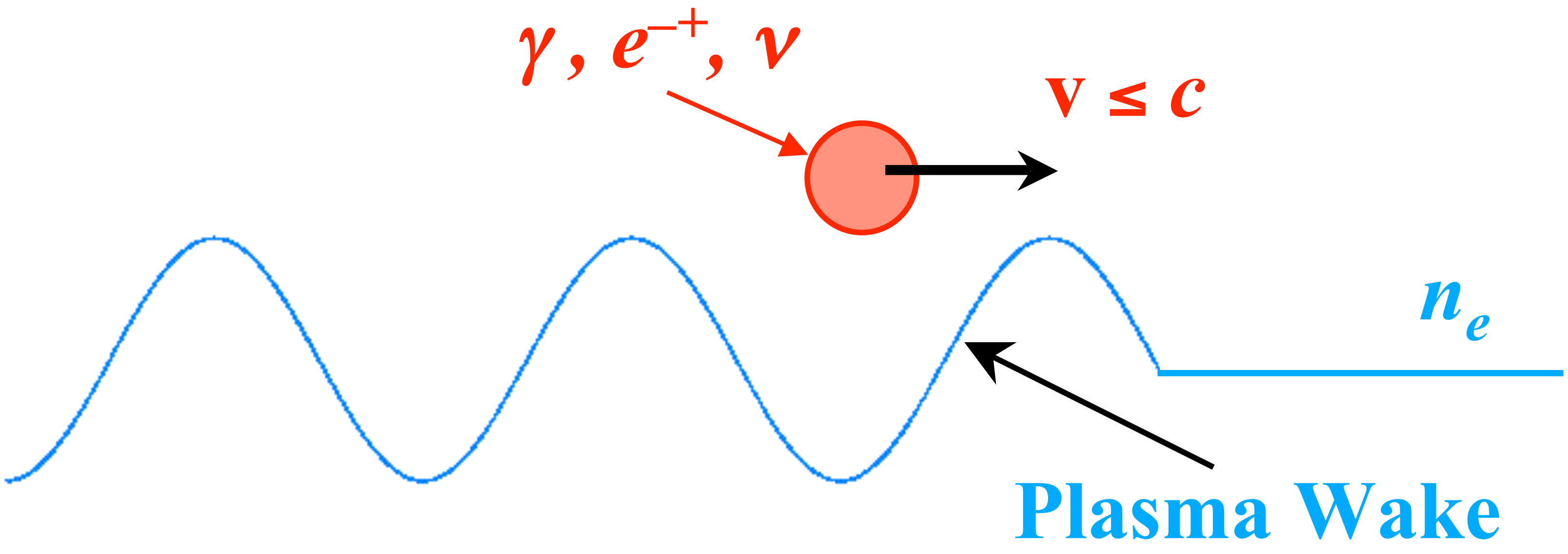
Plasma Wakes

photon beam
electron beam
neutrino beam

All very similar

⇓

* **Drive Plasma Wakes**



Science & Technology Facilities Council
Rutherford Appleton Laboratory

Plasma Wakes (2)

- Plasma wake is a relativistic electron plasma wave

$$v_{ph} \leq c$$

- Capable of growing to large values

$$E_W = \varepsilon\sqrt{n_e} \qquad \varepsilon < 1$$

- For $n_e \sim 10^{14}\ \mathrm{cm}^{-3}$ and $\varepsilon \sim 10\%$

$E_W \approx 10^8\ V/m$ or 1 GeV in <u>10m</u>

- For $n_e \sim 10^{20}\ \mathrm{cm}^{-3}$

$E_W \approx 10^{11}\ V/m$ or 1 TeV in <u>10m</u>

Linear Plasma Wakefield Theory

$$(\partial_t^2 + \omega_p^2)\frac{n_1}{n_o} = -\omega_p^2\left(\frac{n_b}{n_o} + k_p^2\nabla^2\sqrt{1+a_o^2}\right)$$

Large wake for a beam density **$n_b \sim n_o$** or laser amplitude **$a_o = eE_o/m\omega_o c \sim 1$** for τ_{pulse} of order $\omega_p^{-1} \sim 100\text{fs}\,(10^{16}/n_o)^{1/2}$ and speed $\sim c = \omega_p/k_p$

$$\nabla \bullet E = -4\pi e n_1 \;\Rightarrow\; eE = \frac{n_1}{n_o}\sqrt{\frac{n_o}{10^{16}cm^{-3}}}10\,GeV/m\,\cos\omega_p(t - z/c)$$

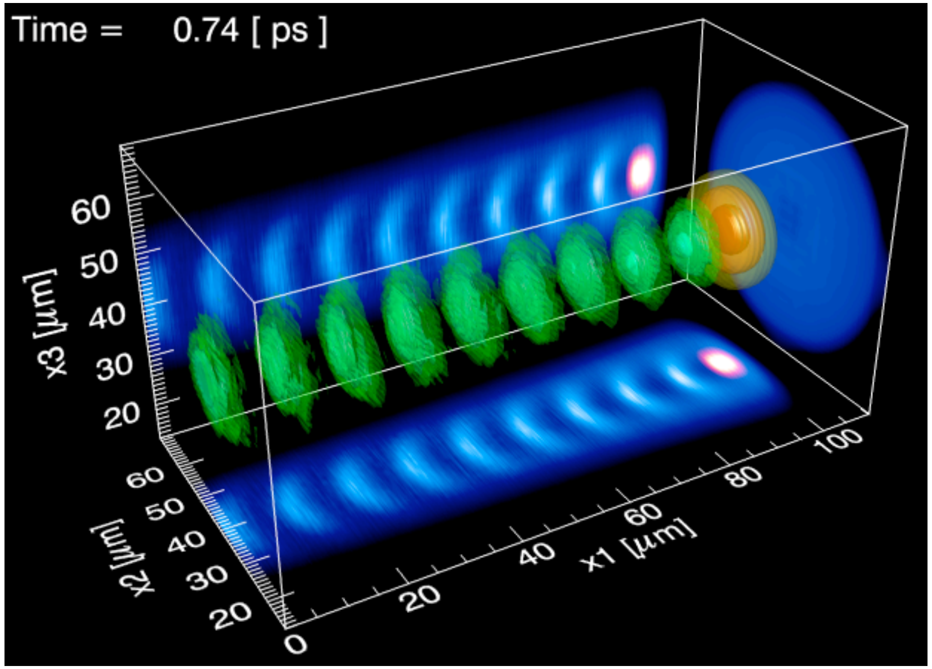
But interesting wakes are very nonlinear => PIC simulations

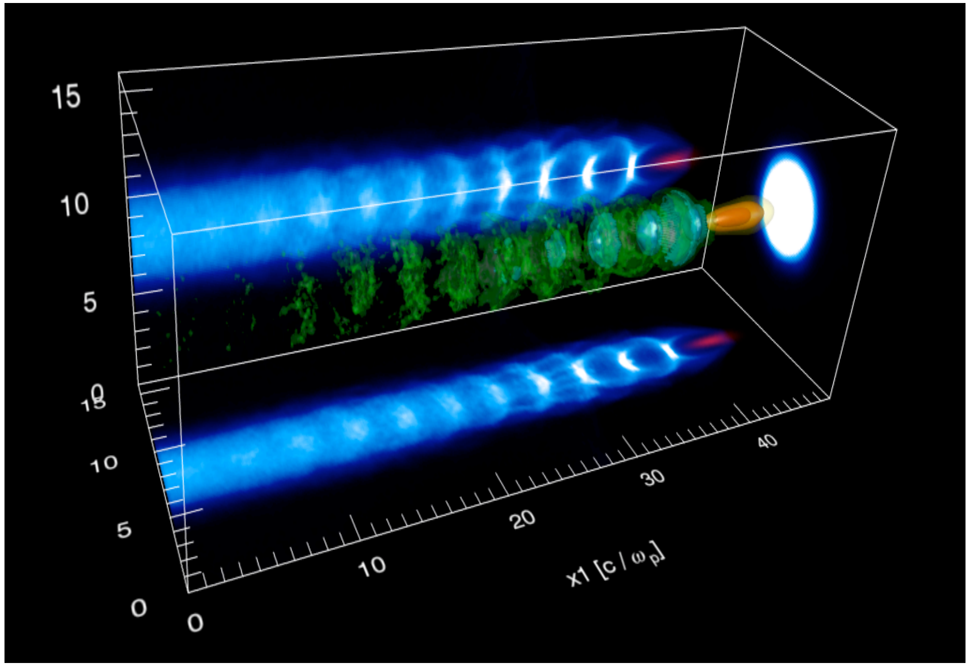
Laser & Electron Wakes

Nonlinear wakes are *similar* with laser or particle beam drivers:

3-D PIC OSIRIS Simulation

(self-ionized gas)





Laser Wake **Electron beam Wake**

Plasma waves driven by electrons, photons, and neutrinos

Electron beam

$$\left(\partial_t^2 + \omega_{pe0}^2\right)\delta n_e = -\omega_{pe0}^2 n_{e-beam}$$

δn_e .. Perturbed electron plasma density

Photons

$$\left(\partial_t^2 + \omega_{pe0}^2\right)\delta n_e = \boxed{\frac{\omega_{pe0}^2}{2m_e}\nabla^2\int\frac{d\mathbf{k}}{(2\pi)^3}\hbar\frac{N_\gamma}{\omega_{\mathbf{k}}}}$$

Neutrinos

$$(\partial_t^2 + \omega_{pe0}^2)\delta n_e = \boxed{\frac{\sqrt{2}n_{e0}G_F}{m_e}\nabla^2 n_\nu}$$

Ponderomotive force

physics/9807049
physics/9807050

+

Kinetic/fluid equations for electron beam, photons, neutrinos coupled with electron density perturbations due to PW

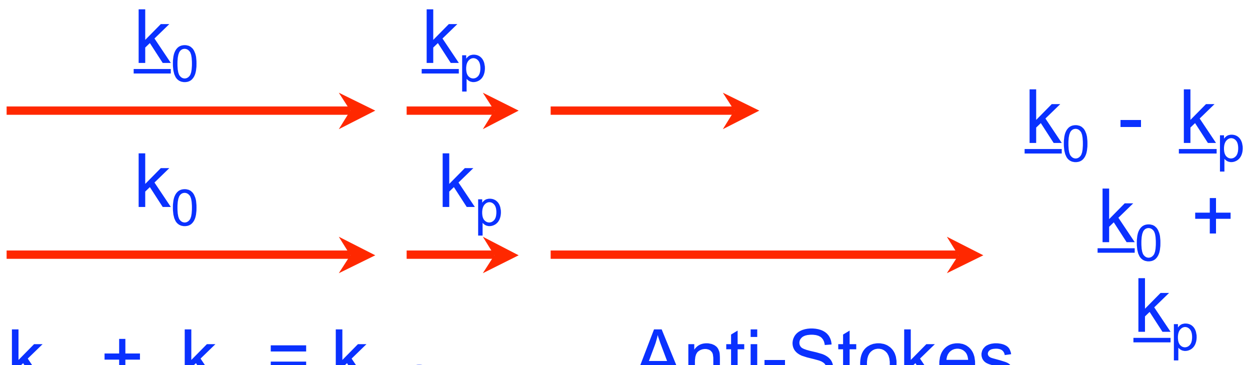
Self-consistent picture of collective e,γ,ν-plasma interactions

Self-Modulated Wakefield

Break-up of a long pulse $L >> k_p$

via Forward Raman Scattering in 1-D limit or

via an Envelope-Self-Modulation instability in 2-D limit.



$\underline{k}_0 + \underline{k}_p = \underline{k}_{AS}$ Anti-Stokes

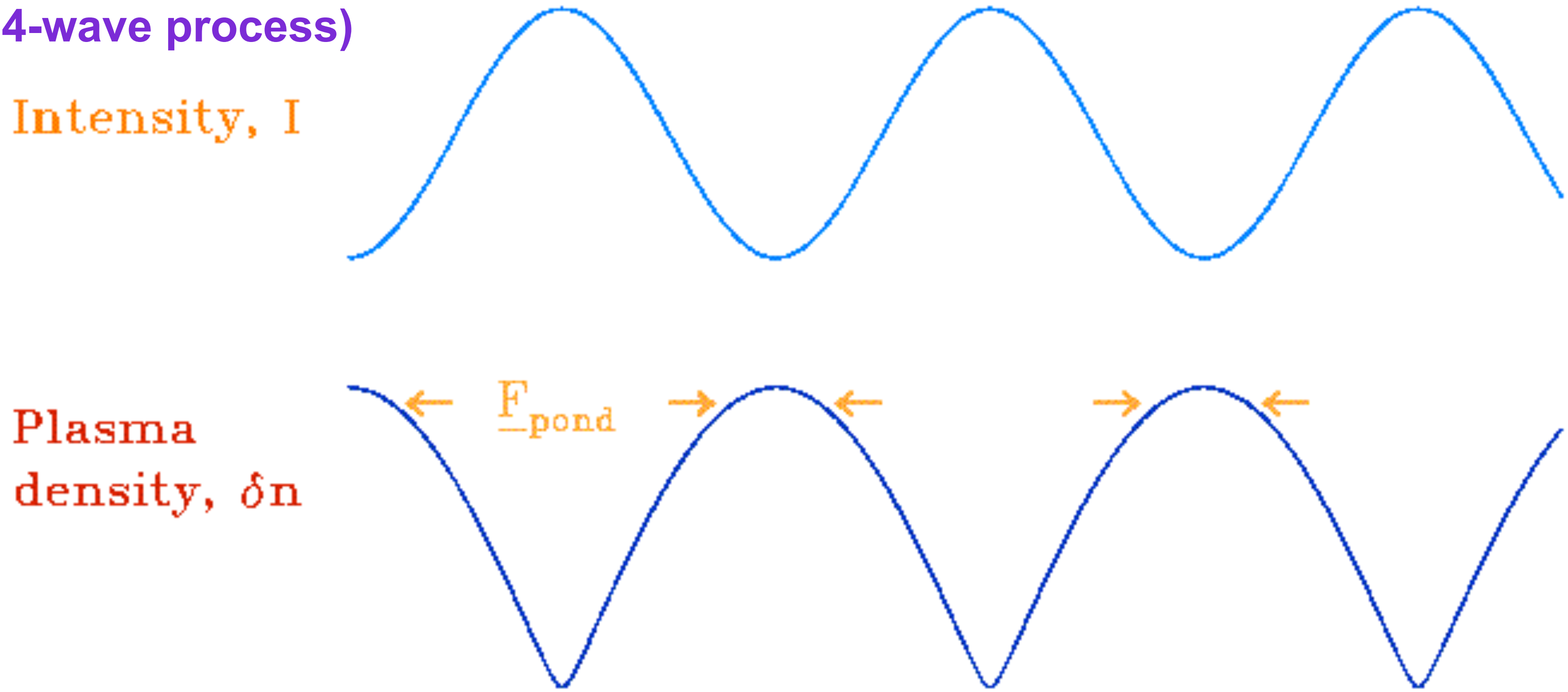
$\underline{k}_0 - \underline{k}_p = \underline{k}_S$ Stokes

Pulse Power > relativistic self-focusing

$$P > P_c = 17\frac{\omega^2}{\omega_p^2} \quad \text{GW}$$

Stimulated Raman & Modulational Instability

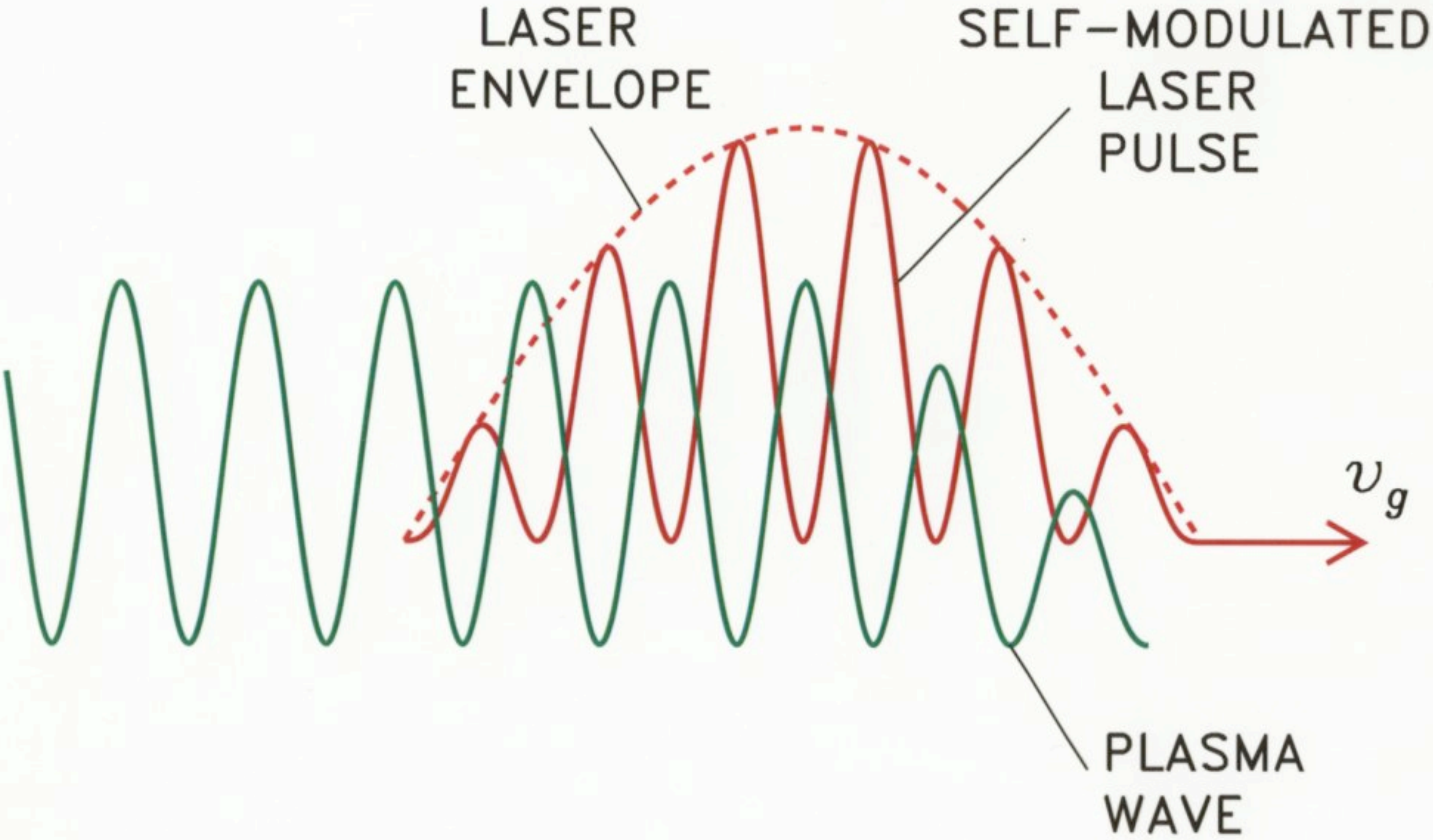
(4-wave process)



$$\underline{F}_{pond} \propto -\underline{\nabla} I$$

Physical mechanism for stimulated Raman scattering driven by Ponderomotive force.

Self-Modulated Laser Pulse



Surfatron Acceleration

- As a laser plasma accelerator with unlimited acceleration, main limitation is finite transverse dimension
  - T. Katsouleas, J.M. Dawson PRL (1983)
- Can overcome the main weakness of diffusive shock acceleration - the injection problem.
  - Shock surfing - M. Lee, V. Shapiro, R. Sagdeev JGR (1996)
- Simulations of Raman backscatter in magnetized plasma ⇒ Upper hybrid mode → accelerates electrons
  - J.M. Dawson *et al.* PRL (1983)
- Solar proton acceleration to 10 GeV within seconds
- Supernovæ remnant acceleration of both electrons and ions
- Acceleration in radio jets
- Produces ring velocities distributions - possible source of Cyclotron Maser Instability

Surfatron Concept

- **Similar to process of acceleration in ⊥ shocks**

Refs (1+4) deal with plasma waves moving ⊥ to $\underline{\mathbf{B}}_0$ field

- assumed to be generated in ⊥ shocks -

Refs (2+3) deal with ⊥ shocks [shock drift acceleration]

- **Surfatron** a) **phase locking particles in plasma wave**

  b) indefinite energy gain

  Assumptions **particle trapped in wave moving ⊥ to $\underline{\mathbf{B}}_0$**

- **The** $\frac{-e\mathbf{v}_{ph}\times\mathbf{B}}{c}$ **force deflects particle across wave front (c.f. surfer)**
- **Particle acquires v_y velocity,** $\frac{e\mathbf{v}_y\times\mathbf{B}}{c}$ **force; presses particle against wave - counteracts ($eE_p \sin kx$) accelerating wave ⇒ stable fixed point.**

Ideal to have wave moving at $v_x \le c$ to be significant.

Bibliography

1) **Katsouleas and Dawson, PRL, 51, 392 (1983)** *relativistic*
2) **Cairns, PRL, JPP (1973)** *non-relativistic*
3) **Sagdeev and Shapiro, JETP LETT, 17, 279 (1973)** *non-relativistic*
4) **Gribov, Sagdeev, Shapiro, Shev., JETP LETT, 42, 63 (1985)** *relativistic*

Surfatron Acceleration

- Waves such as Bernstein, upper-hybrid, lower-hybrid, magnetosonic *etc*., have a common damping mechanism resulting in energization perpendicular to the magnetic field
  - Energization
    - **STOCHASTIC** **(random heating)**
    - **NON-STOCHASTIC** **(regular acceleration, linear or non-linear)**

Non-stochastic acceleration occurs above and below the stochastic threshold

$$\frac{E}{B_0} = \frac{1}{4}\left(\frac{\omega_c}{\omega}\right)^{1/3} v_{ph}$$

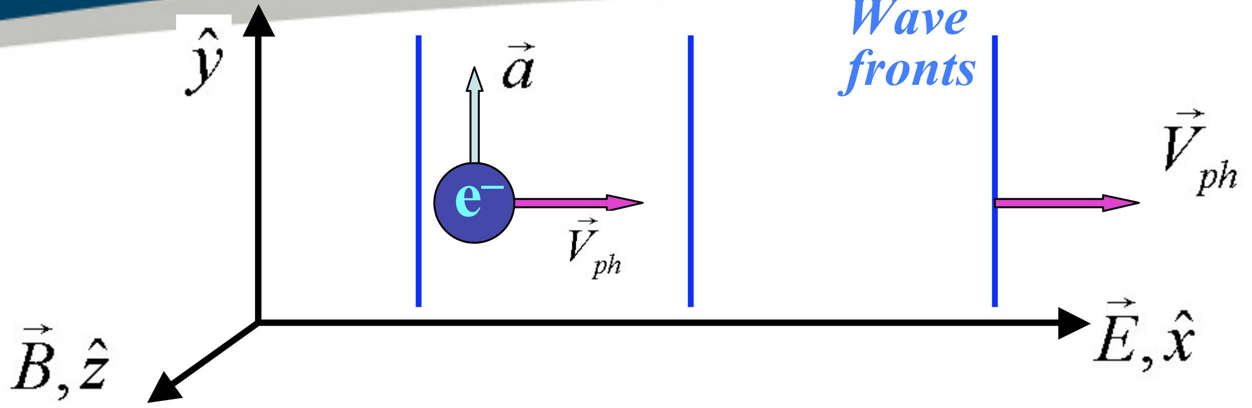
(Karney, C.F.F. 1978)

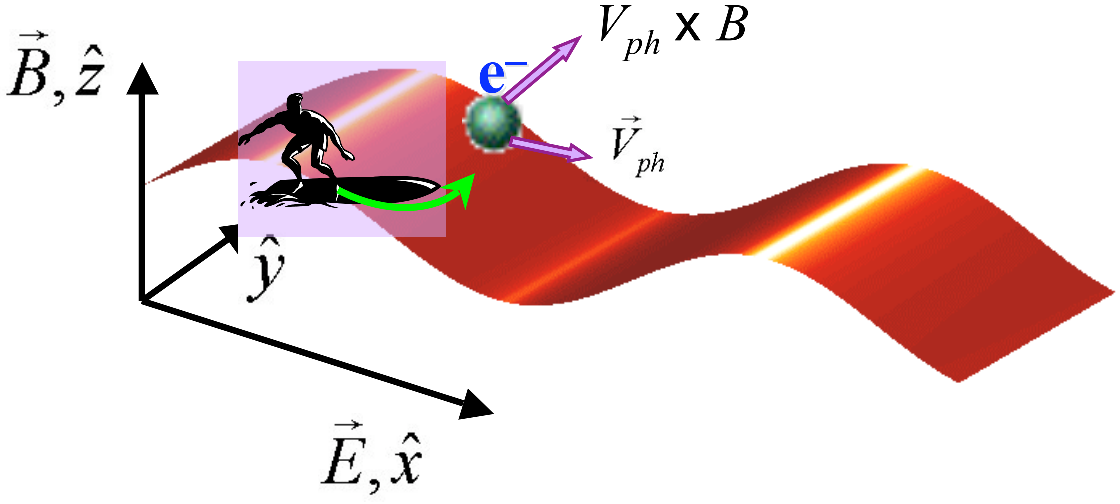
E - electric field amplitude
ω_c - cyclotron frequency
v_{ph} - wave phase velocity

B_0 - ambient magnetic field
ω - wave frequency

Surfatron Model

(Katsouleas, 1983)

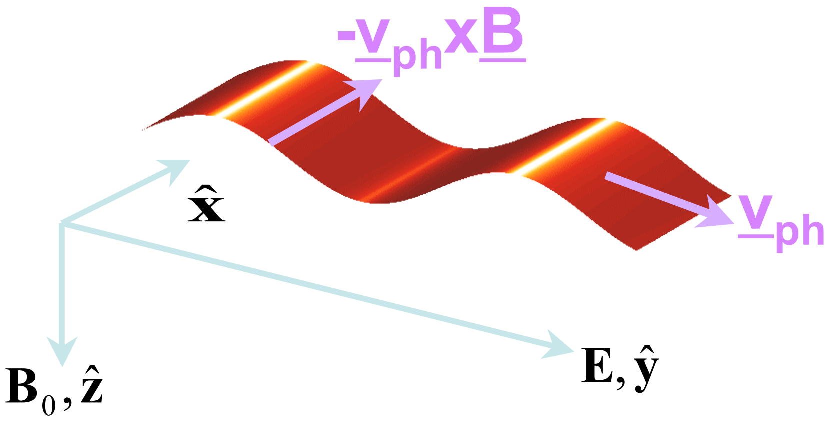




The electron is just like a surfer on a wave!

Surfatron Acceleration

- In the non-linear regime, trapped particles are accelerated across the wavefronts in a direction perpendicular to the wave propagation by the $\mathbf{v}_{ph} \times \mathbf{B}$ electric field.



Test particle model

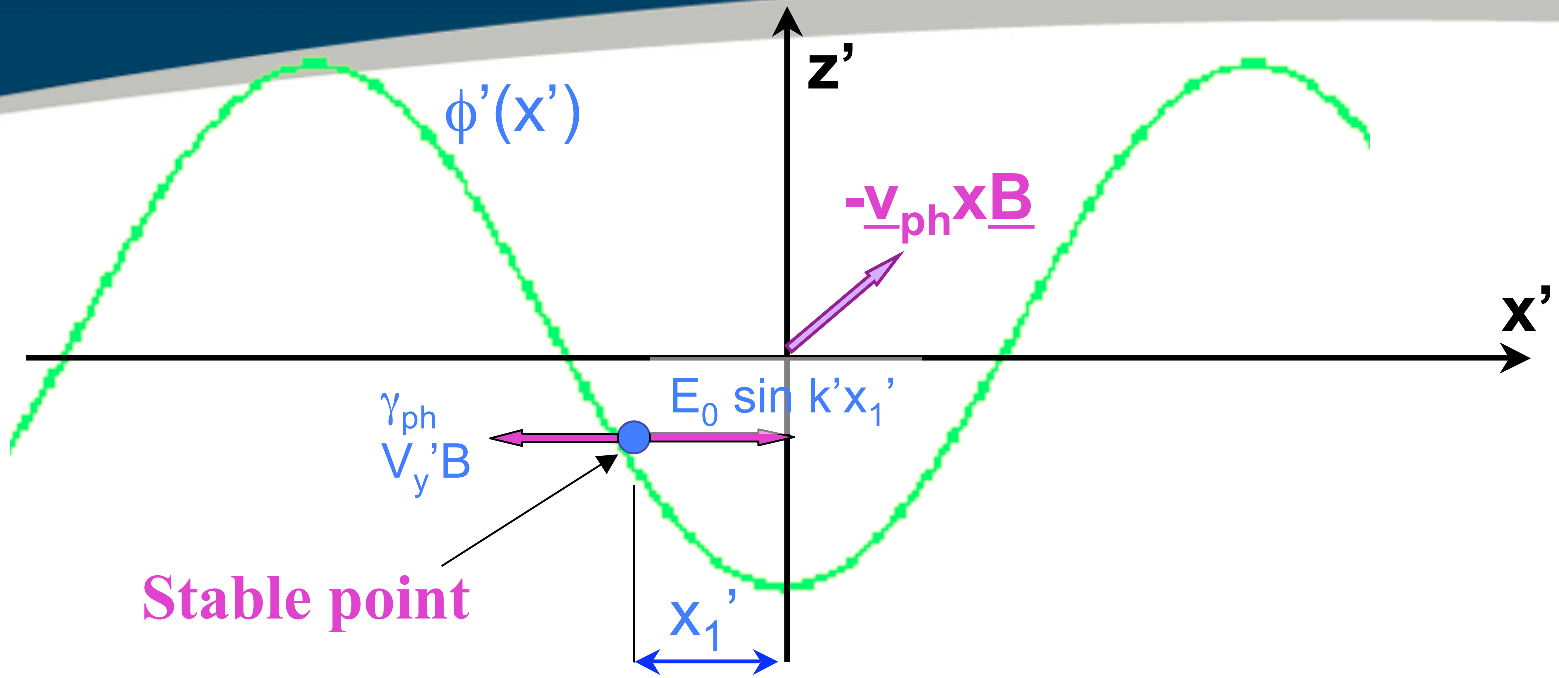
Model $\mathbf{B}_0, \hat{\mathbf{z}}$,$\mathbf{E}, \hat{\mathbf{y}}$,

Relativistic equations of motion for an electron are

$$\left.\begin{aligned} \dot{p}_x &= -eB_0 \frac{p_y}{m\gamma} \\ \dot{p}_y &= \mathrm{eB}_0 \frac{p_x}{m\gamma} - eE \sin(ky - \omega t) \\ \dot{y} &= \frac{p_y}{m\gamma} \end{aligned}\right\} \Rightarrow \begin{aligned} \dot{p}_x &= -\frac{p_y}{\gamma} \\ \dot{p}_y &= \frac{p_x}{\gamma} - \beta \sin(kY) \\ \dot{Y} &= \frac{p_y}{\gamma} - \alpha \end{aligned}$$

$$t \rightarrow t'\omega_c, \quad \beta = \frac{\mathrm{eE}}{\mathrm{mc}\omega_\mathrm{c}} = \frac{E}{cB}, \quad \alpha = \frac{\omega}{k}$$

Katsouleas, 1984



Stable point

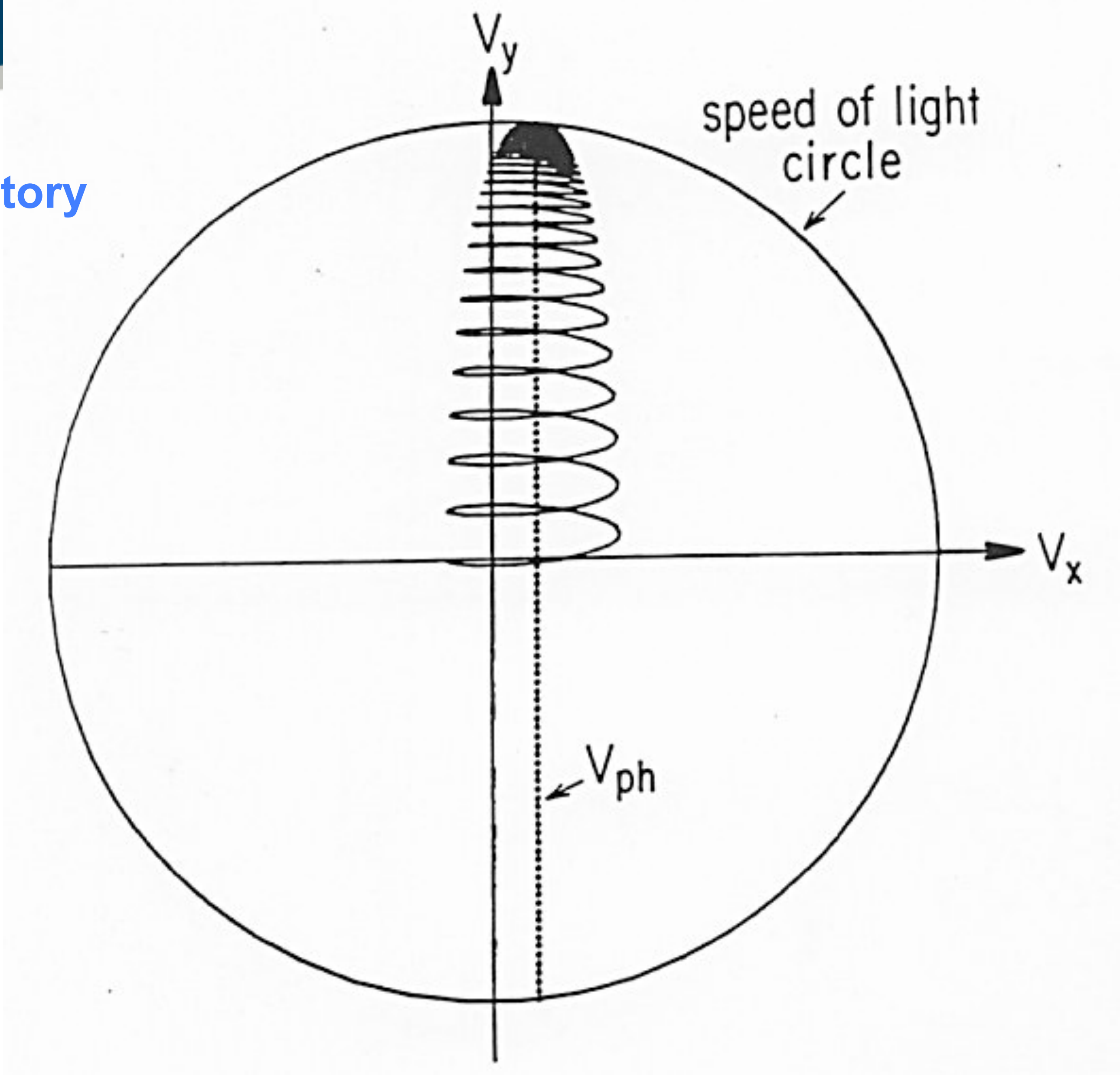
In the wave frame, a trapped particle comes to an equilibrium position (x') against the side of the potential well where the x forces balance:

$$E_0 \sin k' x_1' \approx \gamma_{ph} V_y' B / c \rightarrow \gamma_{ph} B / c$$

Katsouleas, 1984

Velocity-space trajectory of a particle in a low-phase-velocity wave

($V_{ph} = 0.1c$,
$E_0/B = 1.5$,
$\omega/\omega_c = 2$).



Laser Plasma Experiments

- Experiments are being conducted world-wide using the Plasma Beat Wave Scheme in the UK (RAL), USA (UCLA), France (CNRS) and Japan (KEK).

RAL EXPERIMENTS

- 2 variations a) Plasma Beat Wave Accelerator
  and b) Self-Modulated Laser Wakefield Accelerator

b) The Self-Modulated Laser Wakefield Accelerator uses a short pulse intense laser (Vulcan)

- $P = 25$ TW (25×10^{12} Watts)
- $\tau = 500$-800 fsec (500-800×10^{-15} seconds)
- Maximum Intensity $I = 6\times10^{18}$ Watts/cm^2
- Plasma Density $n_{PLASMA} = 1.5\times10^{19}$ cm^{-3}

- Particles accelerated from background to 44 MeV in a distance of 0.035 cm. This corresponds to an accelerating field of

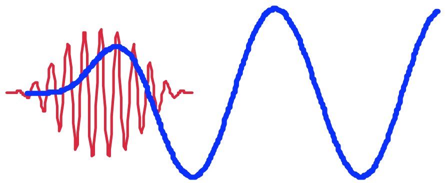
$$E_{||} \approx 1 \text{ GV/cm}$$

$\Rightarrow$ Particle energy ~ 100 MeV L ~ 1-2 mm; $N \sim 10^8$.

Laser Wakefield Acceleration

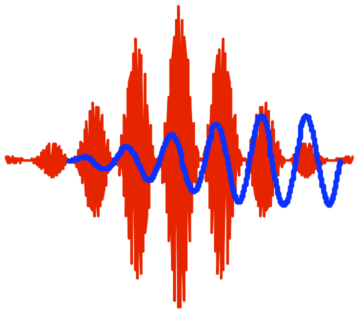
λ Laser Wake Field Accelerator(LWFA)

A single short-pulse of photons



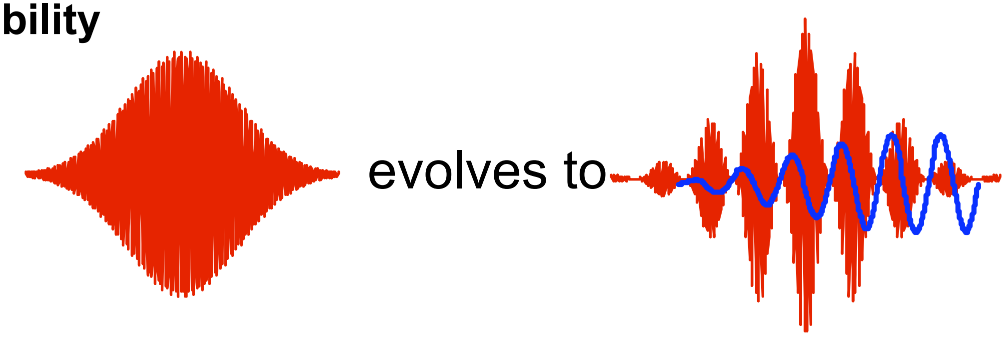
λ Plasma Beat Wave Accelerator(PBWA)

Two-frequencies, i.e., a train of pulses



λ Self Modulated Laser Wake Field Accelerator(SMLWFA)

Raman forward scattering instability



UCLA Experiments

- **UCLA Plasma Beat Wave Accelerator**

CO_2 Laser, 2 wavelengths $\lambda_1 = 10.29\ \mu m$, $\lambda_2 = 10.59\ \mu m$, $\lambda_p = 360\ \mu m$, $n_{PLASMA} = 10^{16}\ cm^{-3}$, $\alpha_1 = 0.17$, $\alpha_2 = 0.07$, $\tau = 150$ psec.

Electrons injected at 2.1 MeV are accelerated to 30 MeV in a plasma length of 1 cm. This corresponds to an accelerating field

$E_{||} = 30$ MeV/cm

Amplitude of relativistic plasma wave $\varepsilon = 30\%$ $n_0 = \delta n/n_0$

1st successful demonstration.

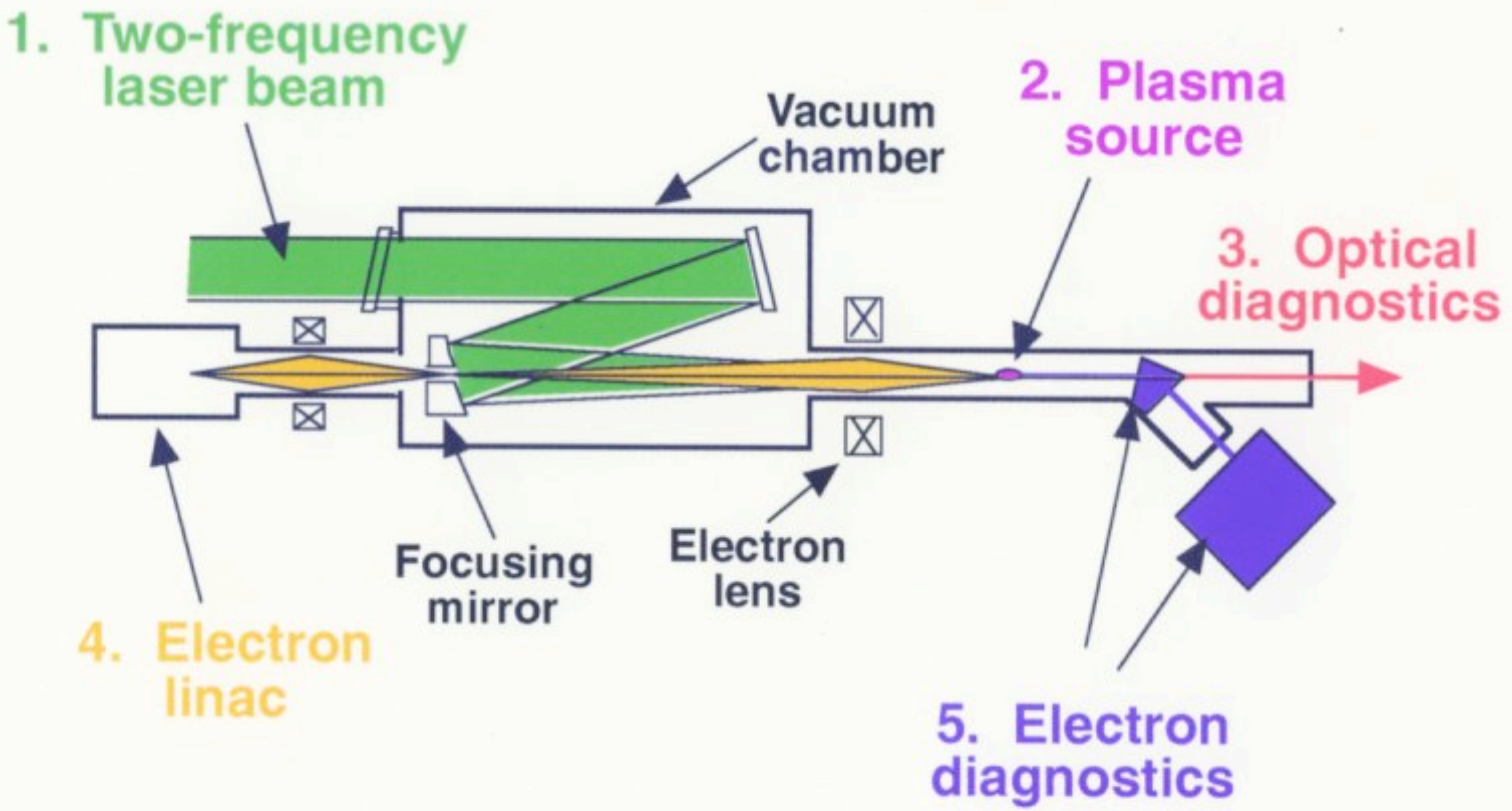
C. Clayton *et al.* *Phys. Rev. Lett.*, 70, 37 (1994)

M. Everett *et al.* *Nature*, 368, 527 (1994)

Science & Technology Facilities Council
Rutherford Appleton Laboratory

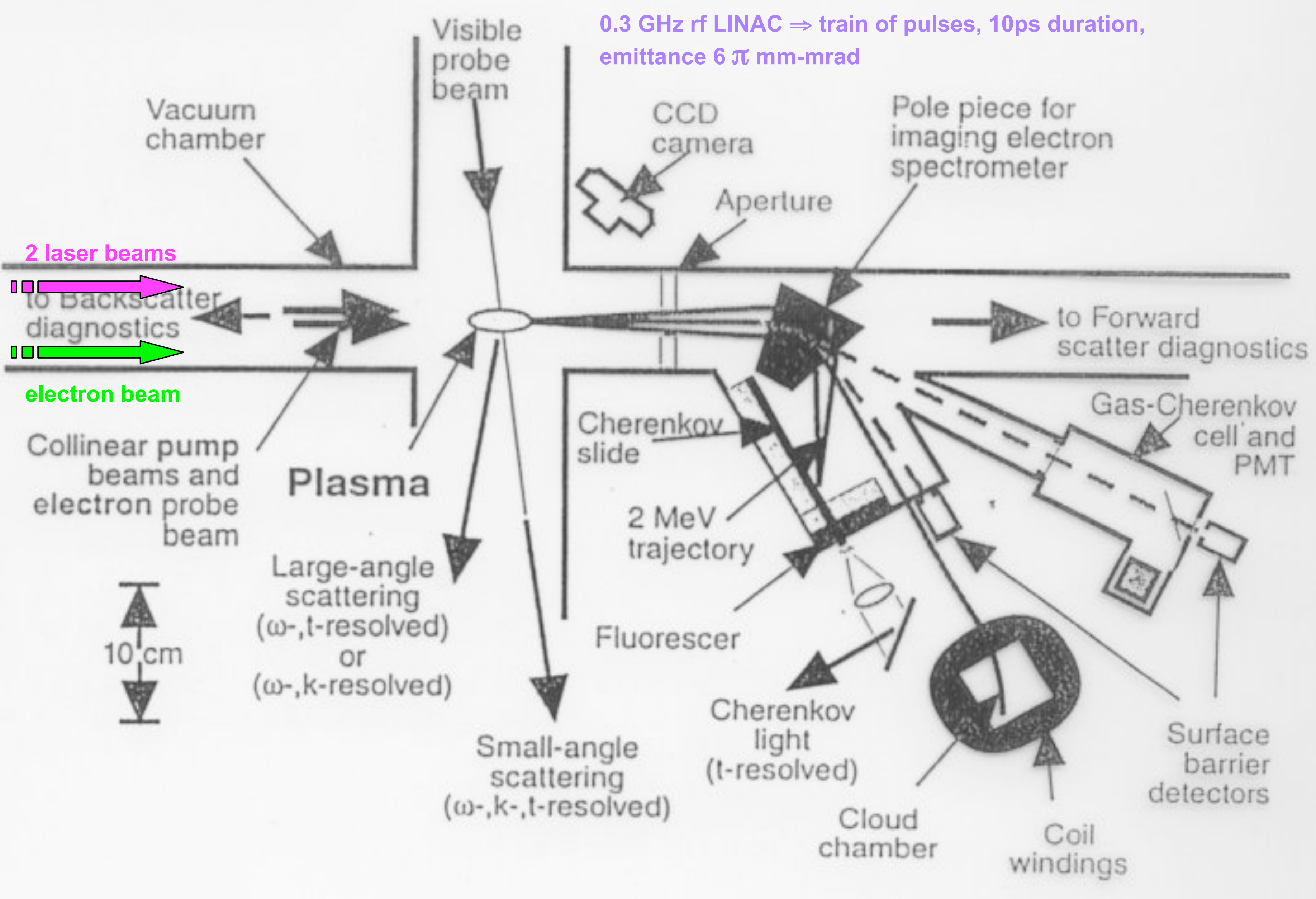
Overview of Beatwave Expt.

- Experiment consists of five major components …



Experiment – Schematic

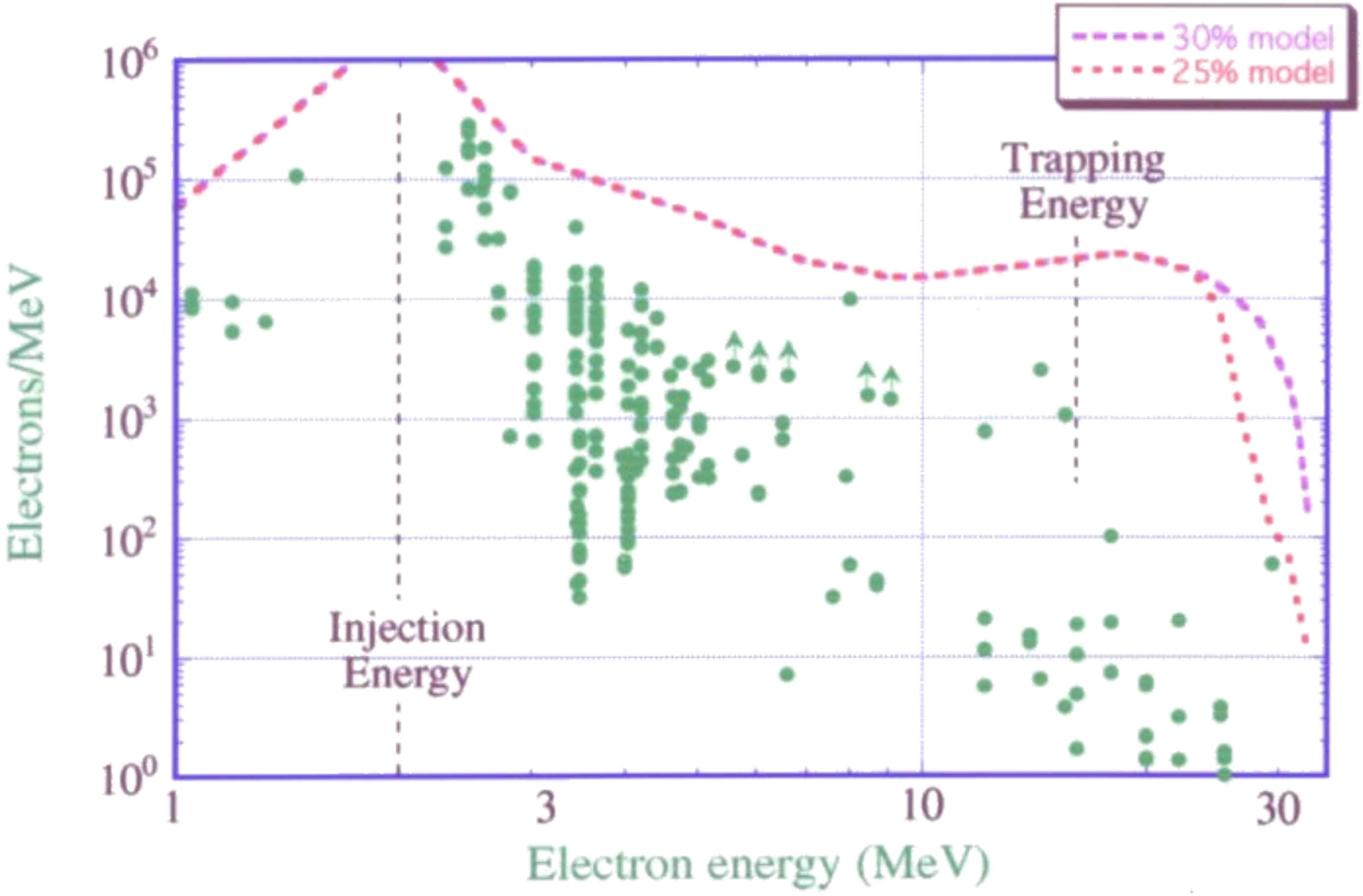
0.3 GHz rf LINAC ⇒ train of pulses, 10ps duration, emittance 6 π mm-mrad



Science & Technology Facilities Council
Rutherford Appleton Laboratory

UCLA Experimental Results

- Electrons injected from 0.3 GHz rf LINAC ⇒ train of pulses, <10ps duration

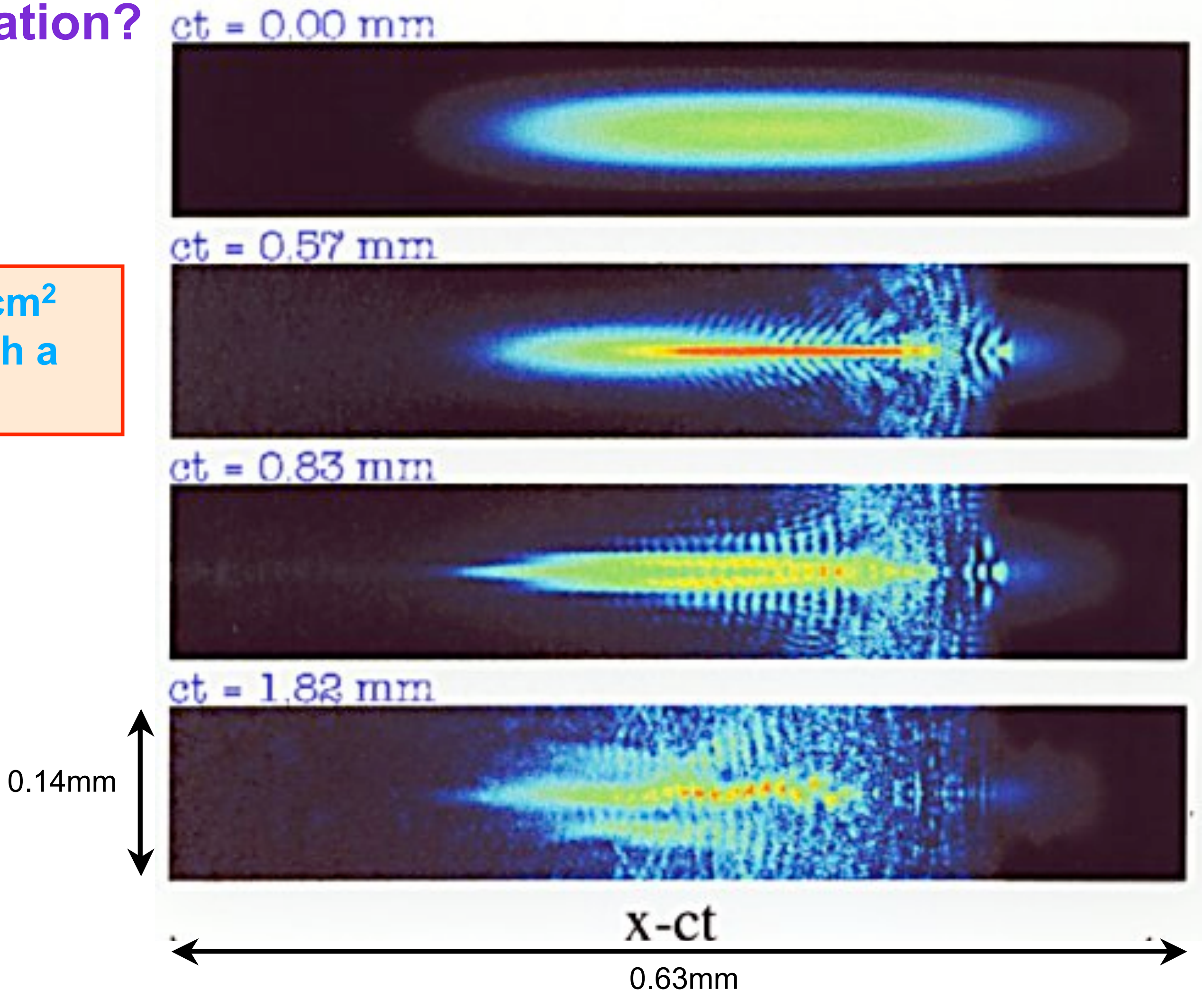


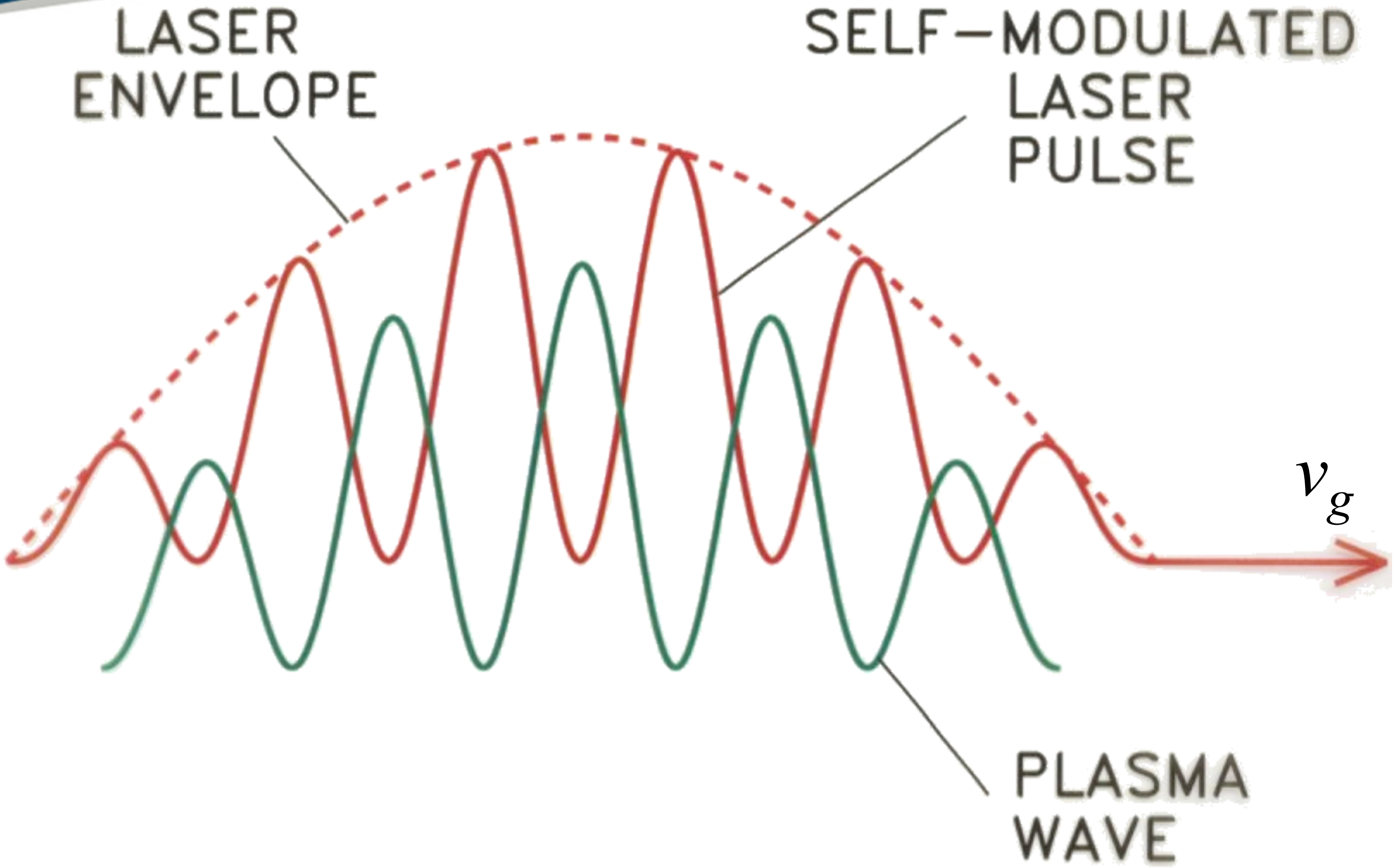
- 1% or 10^5 electrons are accelerated in the diffraction length of ~1cm.
- 2→30 MeV Gradient of 3 GeV/m

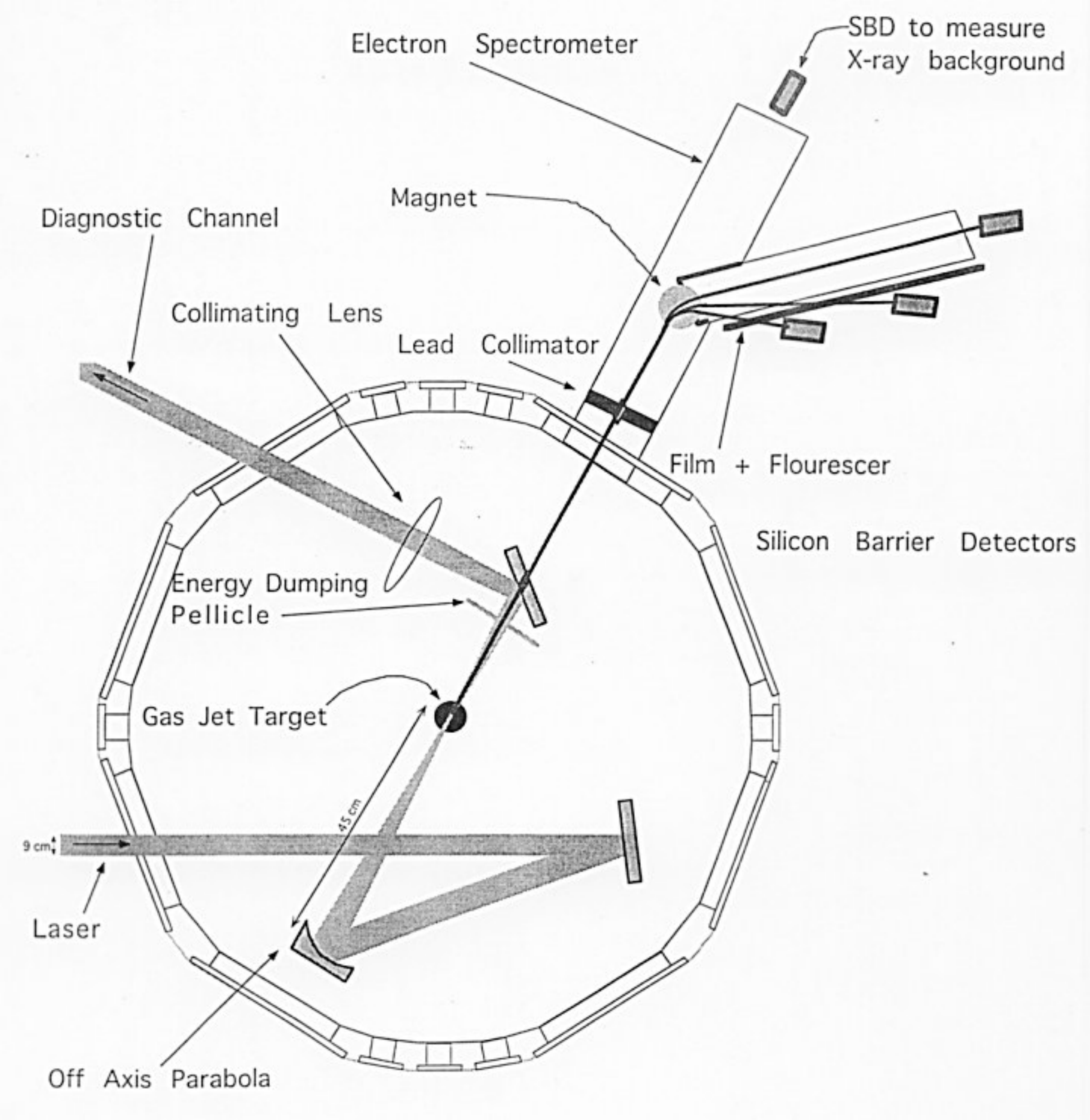
The interplay leads to highly nonlinear self-modulation

- **How can we understand this interplay and how does it effect self-trapped acceleration?**

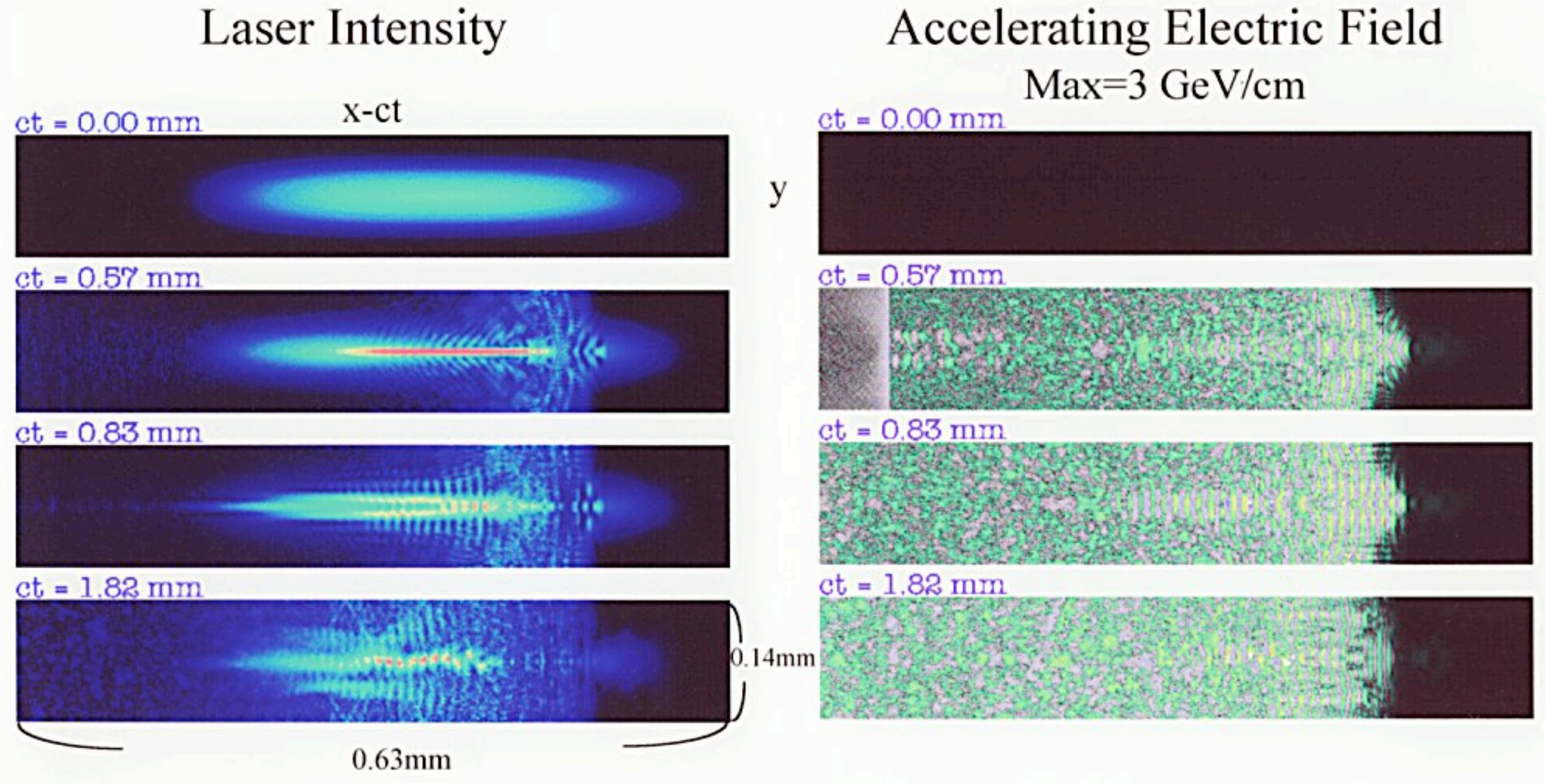
Evolution of a $5x10^{18}$ W/cm^2 laser propagating through a $1.4x10^{18}$ cm^{-3} plasma




LASER ENVELOPE
SELF–MODULATED LASER PULSE
v_g
PLASMA WAVE


Electron Spectrometer
SBD to measure X-ray background
Magnet
Diagnostic Channel
Collimating Lens
Lead Collimator
Film + Flourescer
Silicon Barrier Detectors
Energy Dumping Pellicle
Gas Jet Target
45 cm
9 cm
Laser
Off Axis Parabola

Evolution of Laser Intensity and Accelerating Electric Field



Santala *et al.*, PRL, 2001.

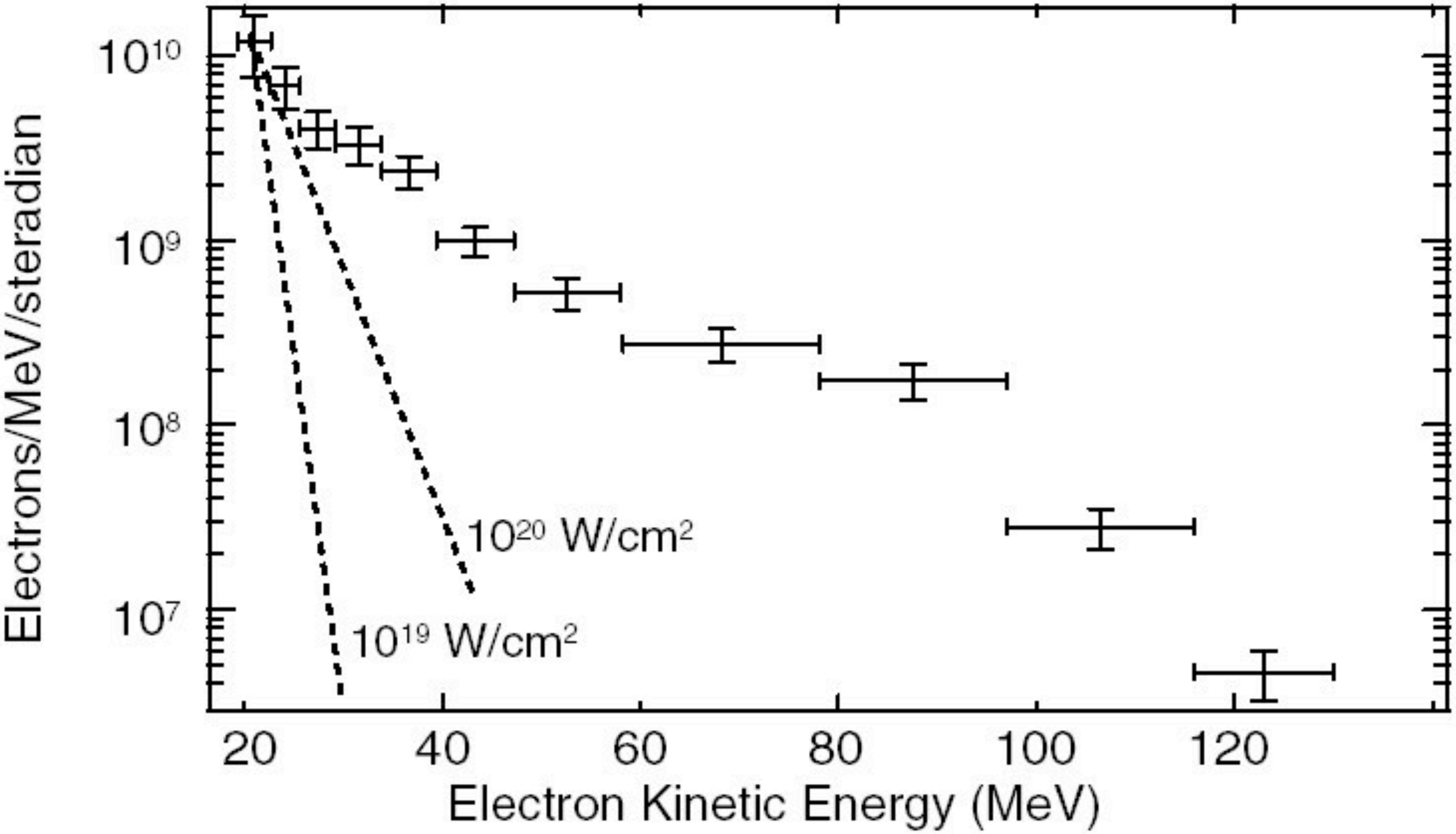


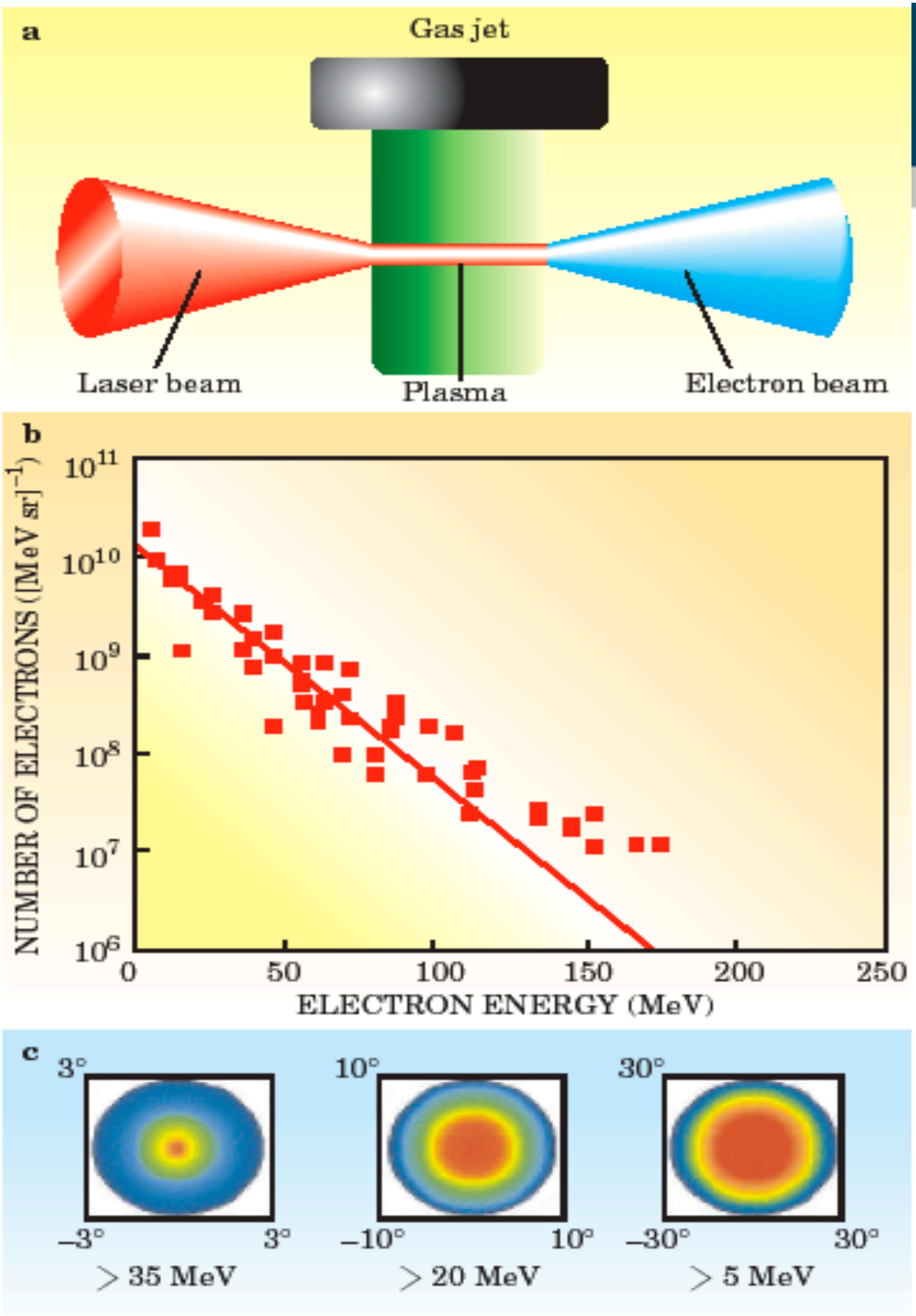
FIG. 3. A typical electron spectrum (unfolded) measured by an on-axis electron spectrometer. Ponderomotive scalings (Ref. [12]) at 10^{19} and 10^{20} W/cm^2 are also shown.

Laser Acceleration Results:

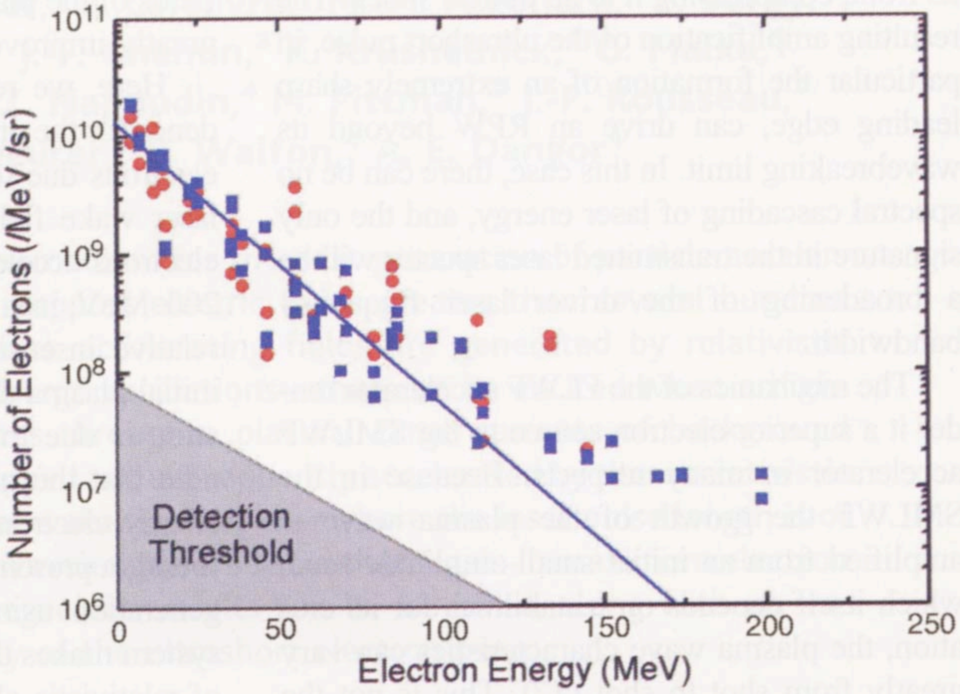
V. Malka *et al.*, LOA France, *Science*, 2002.

- •30TW, 35 fs laser
- •200 MeV energy gain in a 1mm gas jet (> 200 GeV/m)
- •Highly collimated beam: $\varepsilon_n \sim 1$ mm-mrad

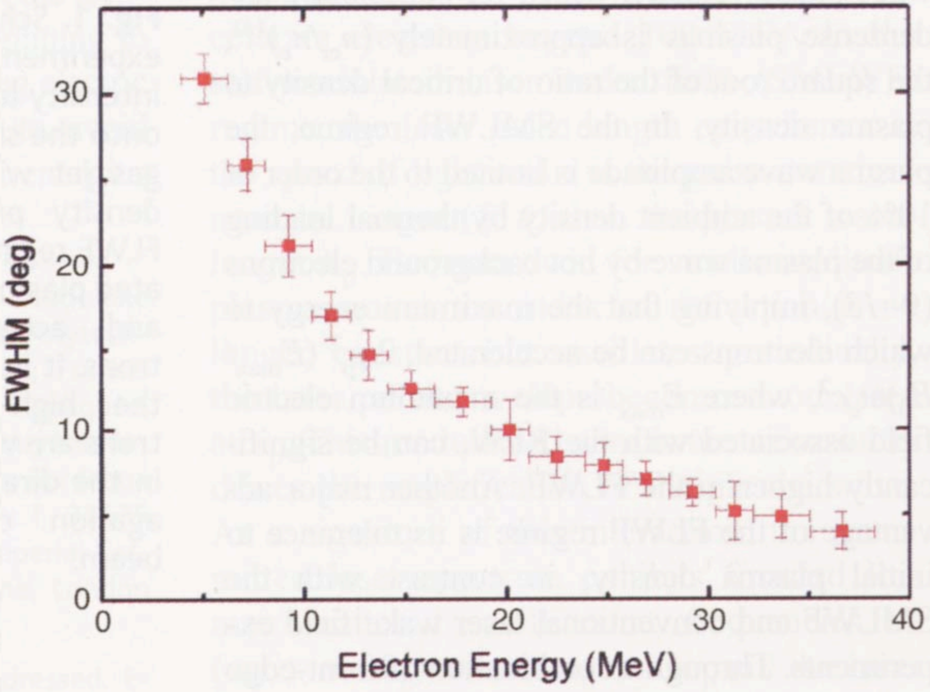
Fritzler et al., PRL92(2004)



Laser Wakefield Acceleration



Electron spectra for $n_e = 2.5\text{x}10^{19}$ cm^{-3} (blue) and for $n_e = 6\text{x}10^{19}$ cm^{-3} (red).



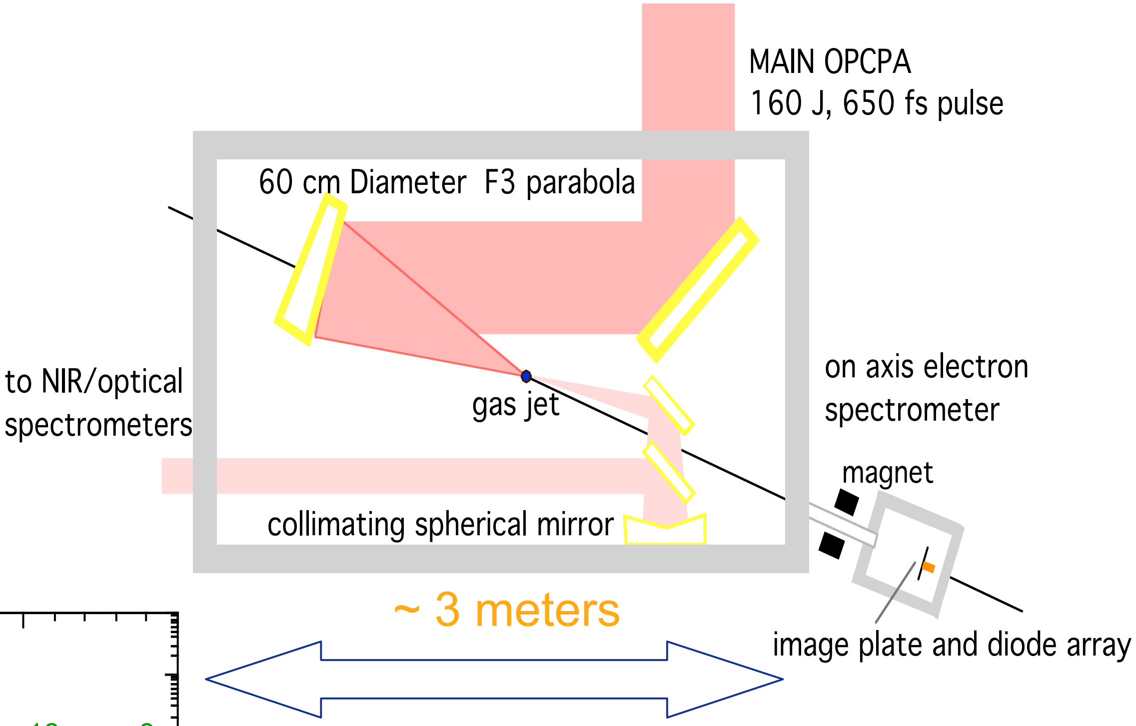
FWHM of the angular distribution of the electron beam.

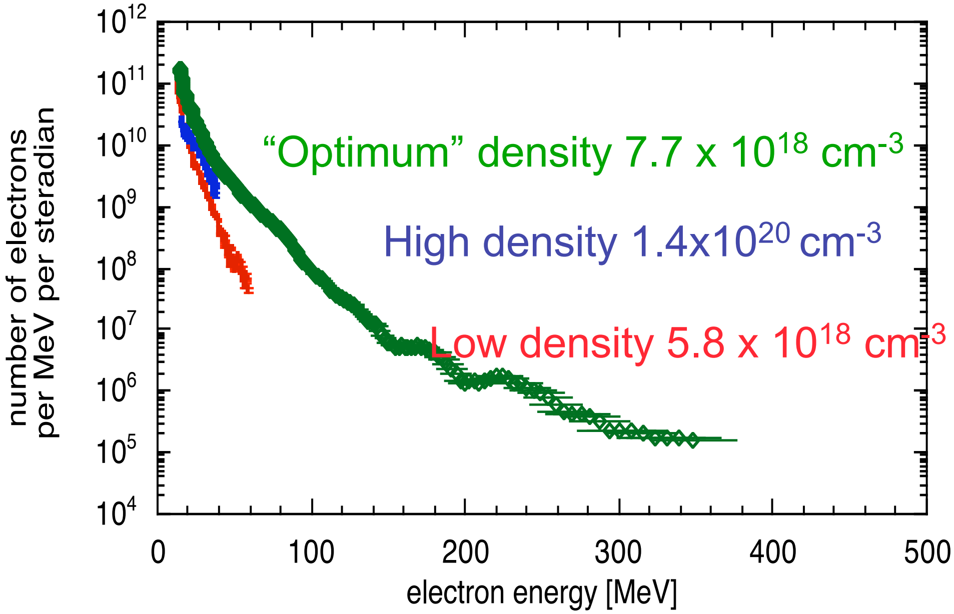
Malka *et al.*, 2002.

Laser acceleration experiments using the Rutherford VULCAN PetaWatt Laser

Courtesy of K. Krushelnick et al.

- Vulcan@RAL: 160 J in 650 fs
- Single shot laser





- 350 MeV electrons observed
- Energy spread large

The Bubble Regime

30 September 2004

International weekly journal of science

nature

$10.00

www.nature.com/nature

Dream beam

The dawn of compact particle accelerators

Offshore tuna ranches
A threat to US waters?

The Earth's hum
Sounds of air and sea

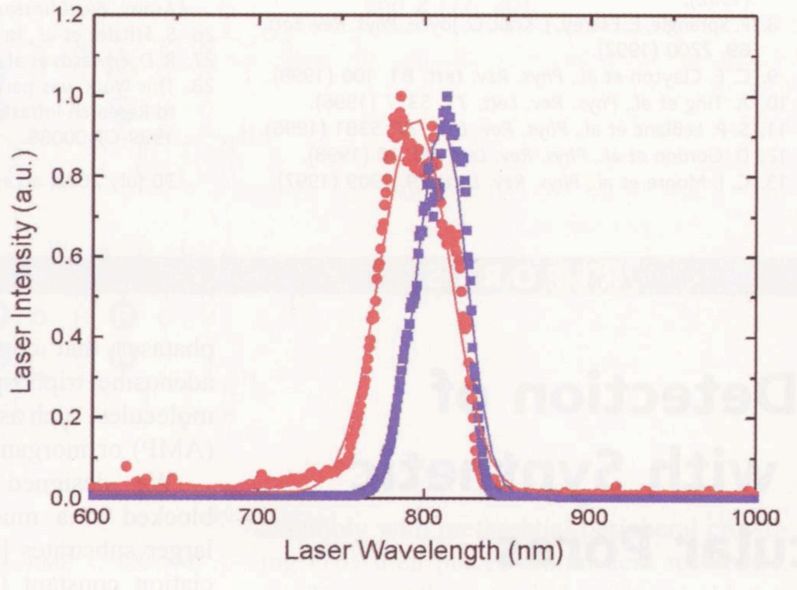
Protein folding
Escape from the ribosome

Human ancestry
One from all and all from one

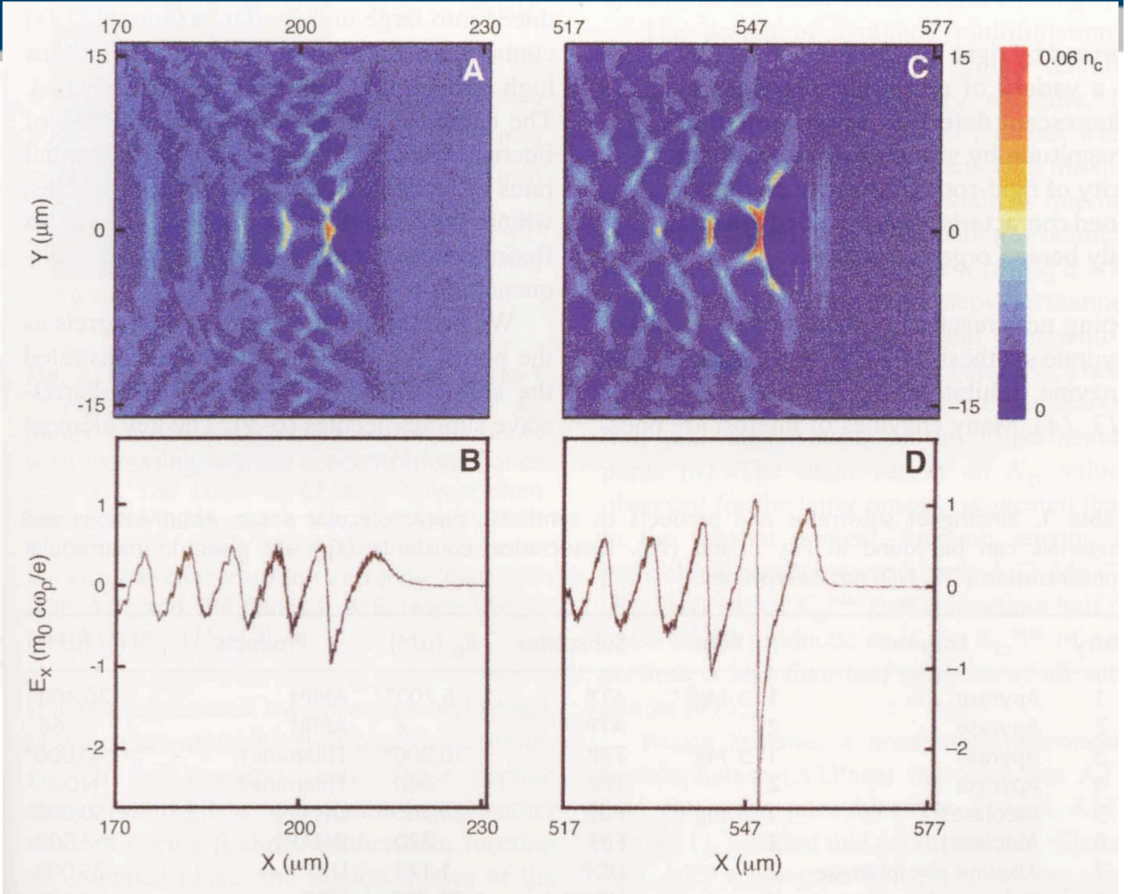
technology feature RNA interference

$10.00US $12.99CAN

Electron Acceleration by Intense Ultrashort Laser Pulse



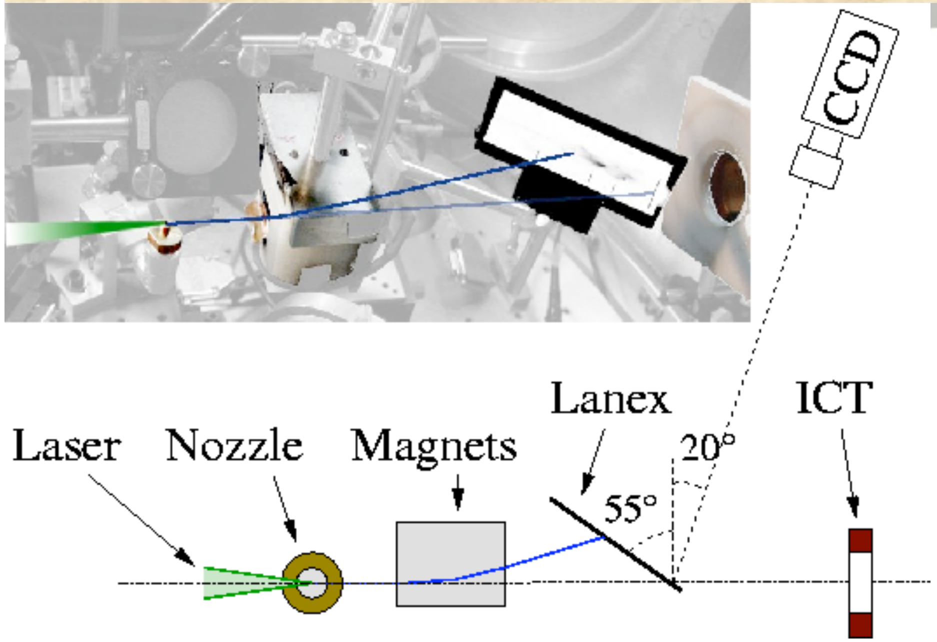
Transmitted laser intensity as a function of wavelength in vacuum (blue) and in the plasma (red).



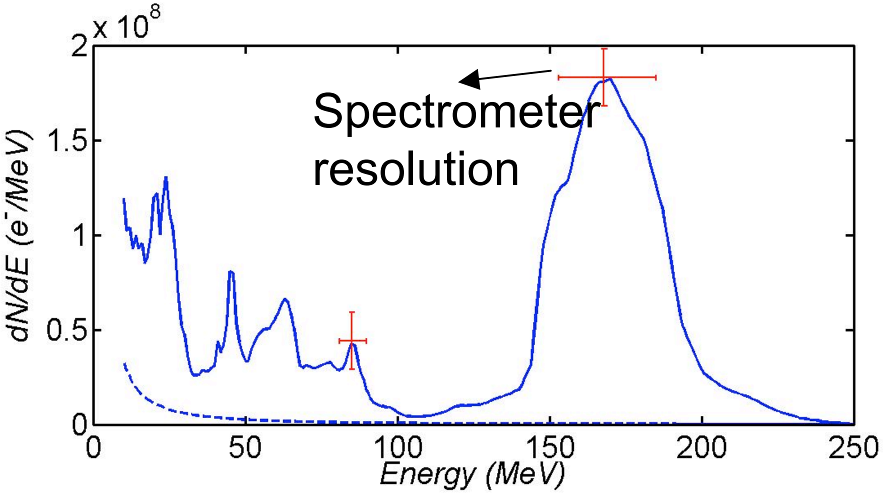
Electron density cuts along the z=0 plane and RPW electric field along the laser axis after propagation of 210 μm (A, B) and 560 μm (C, D).

Malka *et al*., 2002.

Recent Breakthrough -- Mono-energetic Beams! 3 Labs!



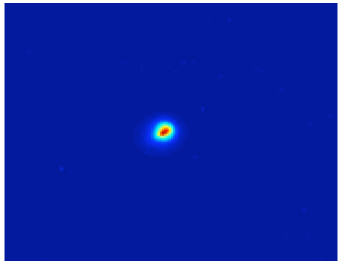
Quasi-monoenergetic spectrum
Hundreds of pC at 170 MeV +/- 20 MeV



Parameters: $n_e = 6\times10^{18}$ **cm**$^{-3}$**,**
$a_0 = 1.3$, $\tau = 30$ **fs** P=30 TW

Results obtained with 1 m off-axis parabola:
$w_0 = 18$ **µm,** $z_R = 1.25$ **mm**

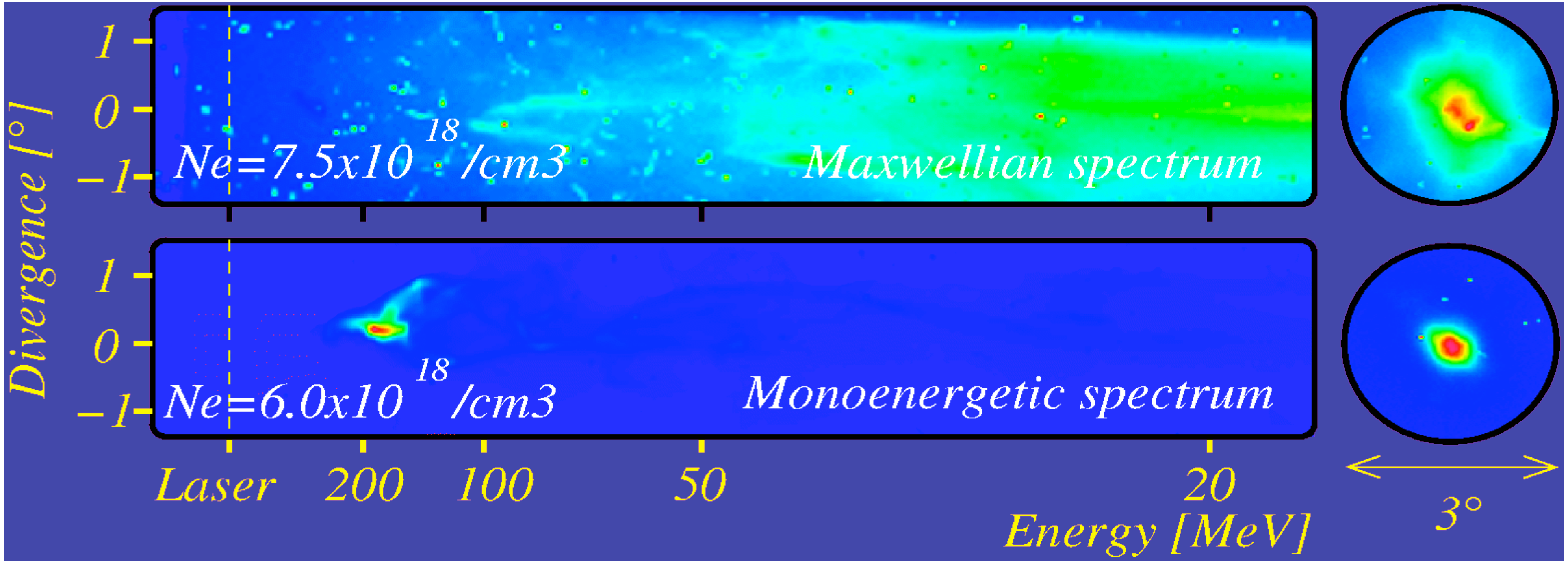
Electron beam profile on LANEX



Divergence FWHM = 6 mrad

Courtesy J. Faure, LOA

Results on e-beam :
Energy distribution improvements

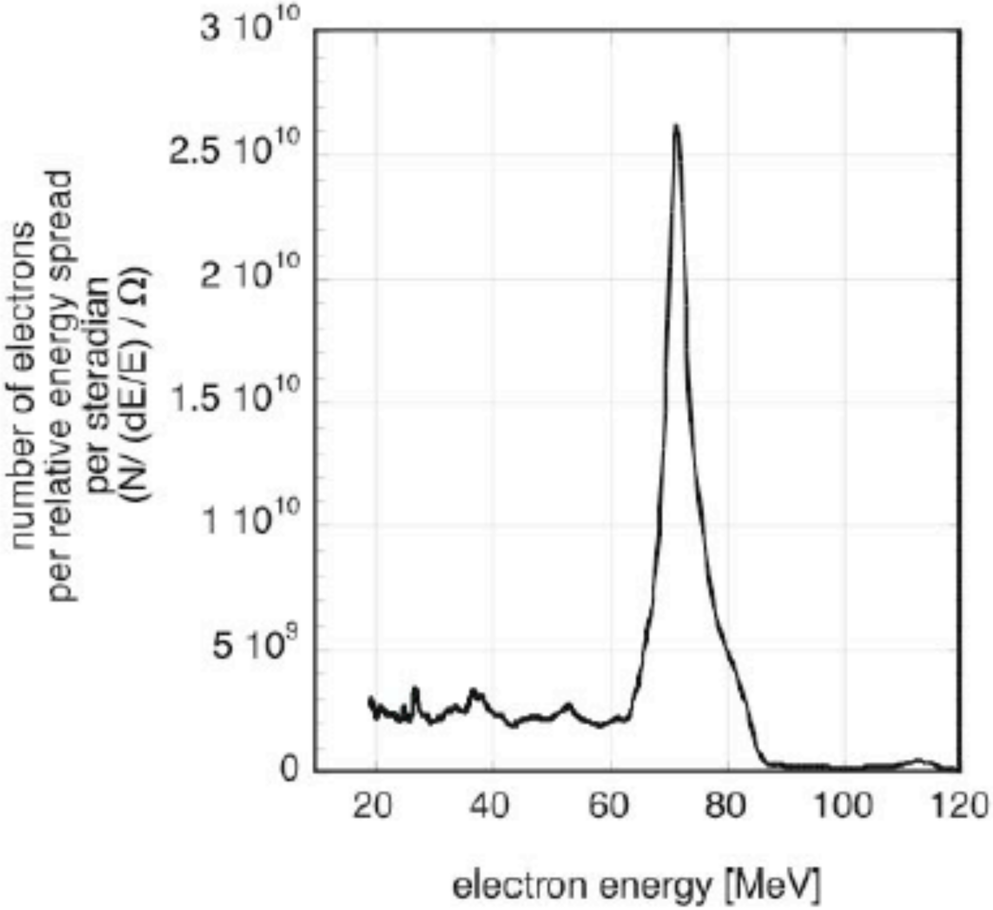


N.B. : color tables are different

J. Faure, LOA

Imperial College London

Mono-energetic spectra can be observed at higher power ($\Delta E/E = 6$ %)



E ~ 500 mJ,

pulse duration ~ 40 fsec

Focal spot ~ 25 µm

Density ~ 2 x 10^{19} cm^{-3}

Significant shot-to-shot fluctuations in

a) energy spread

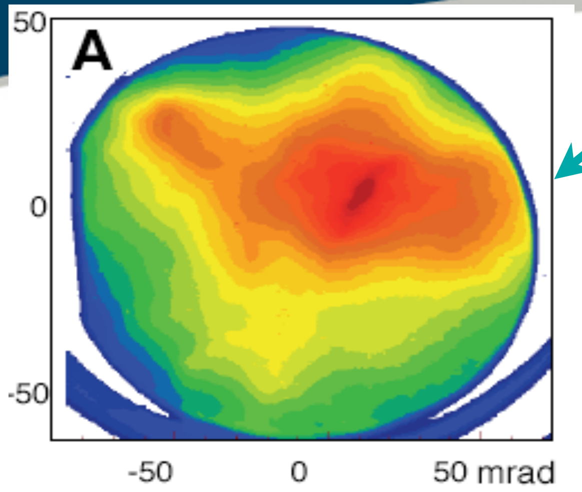
b) peak energy

Careful control of laser and plasma conditions is necessary

Courtesy: K. Krushelnick, IC

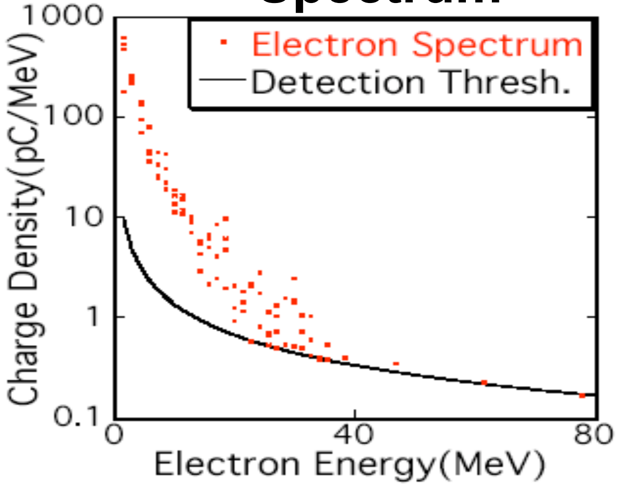
85 MeV e-beam with %-level energy spread observed from laser accelerator

Beam profile

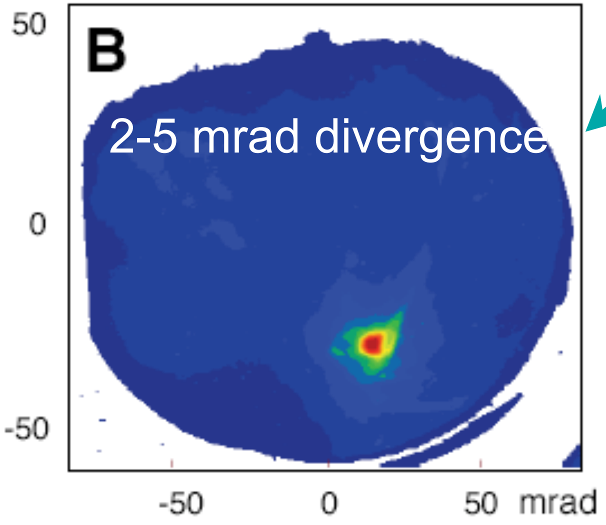


Unguided

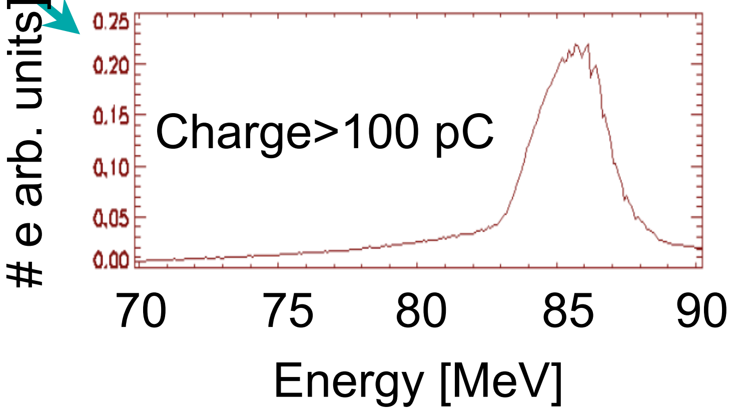
Spectrum



Guided



2-5 mrad divergence



Charge>100 pC

C.Geddes et al., submitted

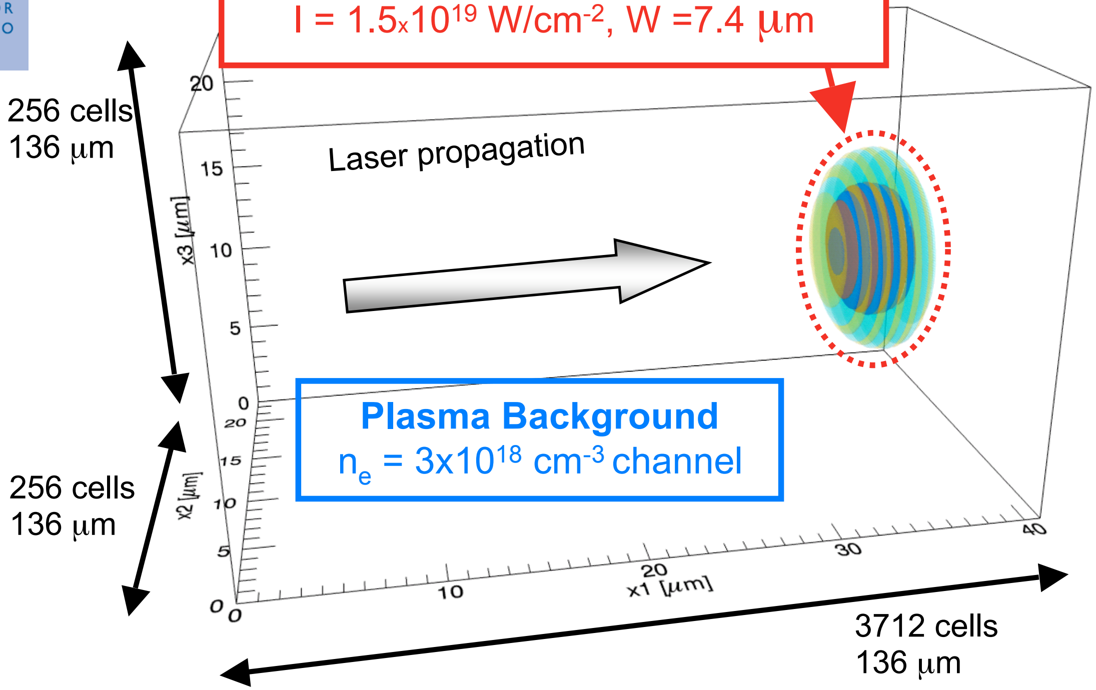
Electrons > 150 MeV observed

Full 3D LWFA Simulation

State-of- the- art ultrashort laser pulse

λ_0 = 800 nm, Δt = 50 fs

I = 1.5×10^{19} W/cm^{-2}, W =7.4 μm



Plasma Background

n_e = 3×10^{18} cm^{-3} channel

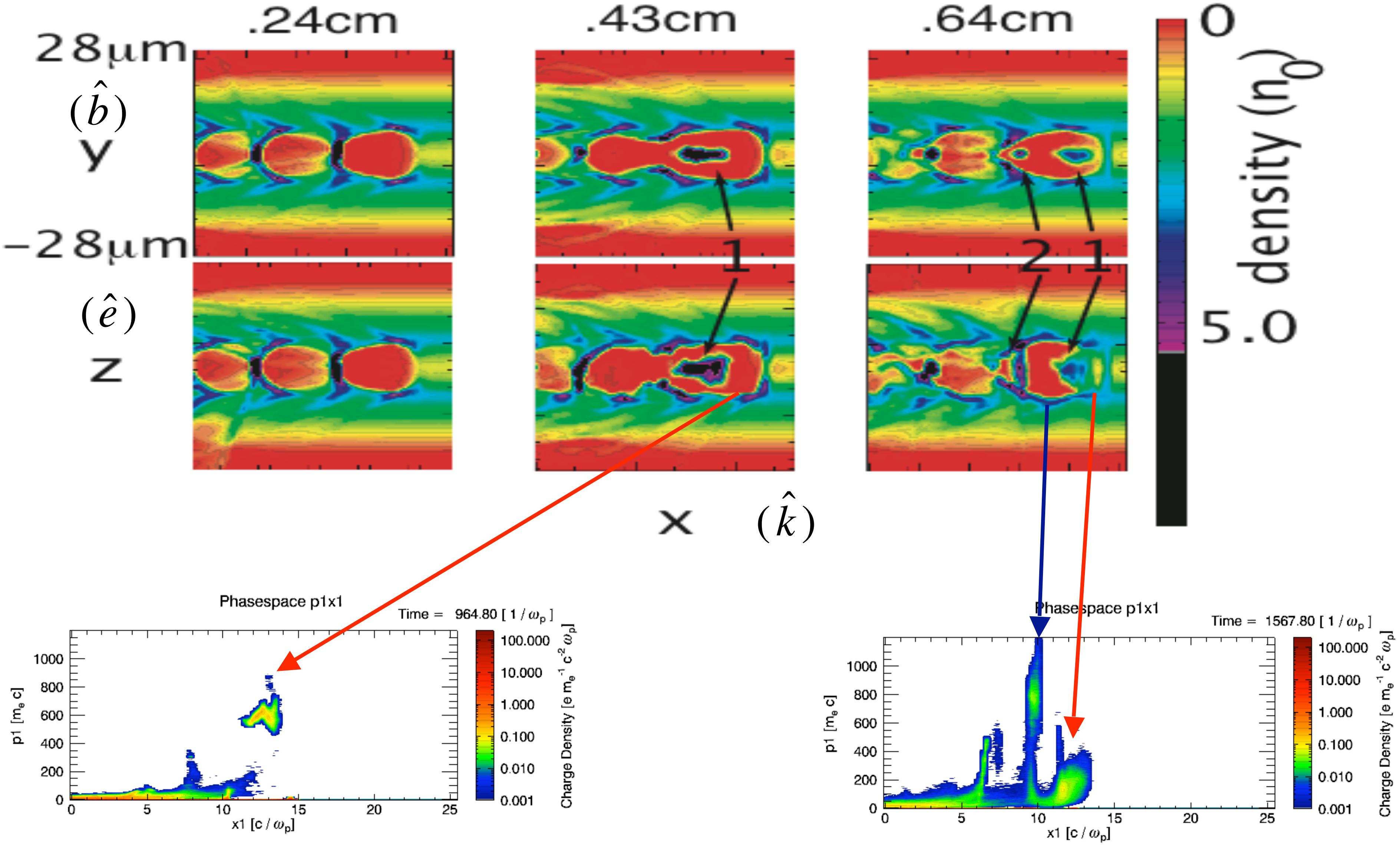
- Simulation Parameters
  - –Laser:
    - a_0 = 3
    - W_0=9.25 λ=7.4 μm
    - ω_l/ω_p = 22.5
  - –Particles
    - 1x2x2 particles/cell
    - 240 million total
  - –Channel length
    - L=.828cm
    - 300,000 timesteps
- The parameters are similar to those at LOA and LBNL

Simulation ran for 200,000 hours

(~40 Rayleigh lengths)

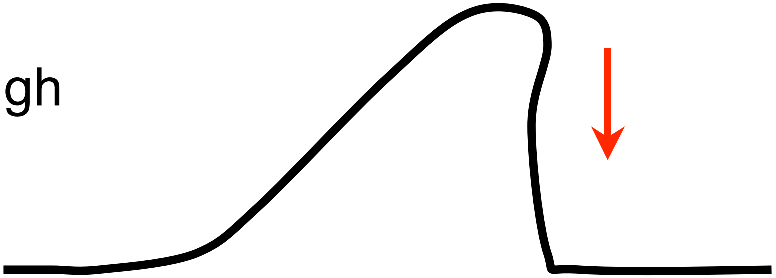
F. Tsung, W. Mori, *et al.*

Beam loading of first bunch contributes to the generation of a second bunch



Wavebreaking Amplitude

- Wavebreaking ⇒ crest “falls” into trough



cold plasma $$\frac{eE}{m\omega_p \mathrm{v}_{ph}} = 1$$ (Dawson 1958)

$$\frac{\partial E}{\partial x} \rightarrow \infty$$ and from Gauss’ law $n \rightarrow \infty$

cold relativistic oscillation

$$\frac{eE}{m\omega_p c} = \sqrt{2}\left(\gamma_{ph} - 1\right)^{1/2}$$ (Akhiezer & Polovin 1956)

$$\gamma_{ph} = \left(1 - \mathrm{v}_{ph}/c^2\right)^{-1/2}$$

warm relativistic oscillation

$$\frac{eE_{\max}}{mc\omega_p} = \frac{1}{\beta^{1/4}}\left(\ln 2\gamma_{ph}^{1/2}\beta^{1/4}\right)^{1/2}$$

(Katsouleas & Mori 1988)

Laser Wakefield

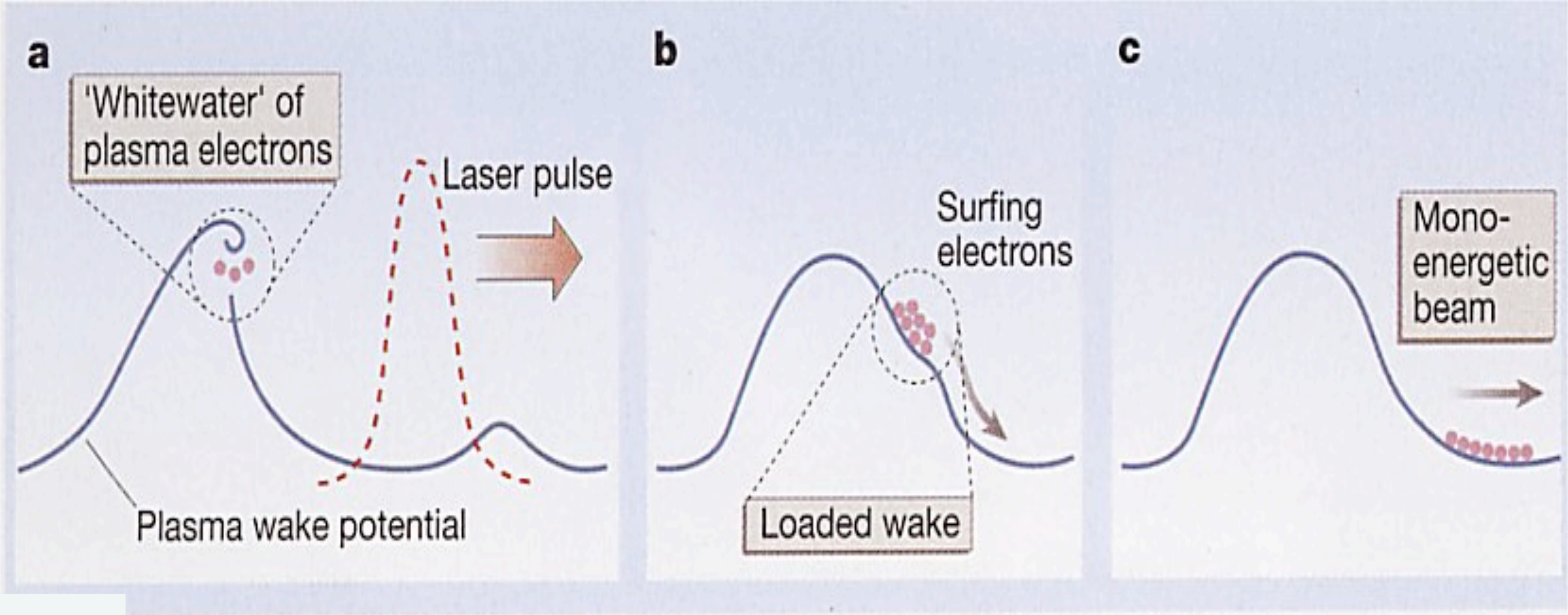


Figure 1 Wakefield acceleration. a, In a plasma excited by a laser pulse, the wake potential rises until it steepens and breaks. Electrons from the plasma are caught in the 'whitewater' and surf the wave. b, The load of the electrons deforms the wake, stopping further trapping of electrons from the plasma. c, As the electrons surf to the bottom of the wake potential, they each arrive bearing a similar amount of energy.

Production of a Monoenergetic Beam

1. Excitation of wake (e.g., self-modulation of laser)
2. Onset of self-trapping (e.g., wavebreaking)
3. Termination of trapping (e.g., beam loading)
4. Acceleration

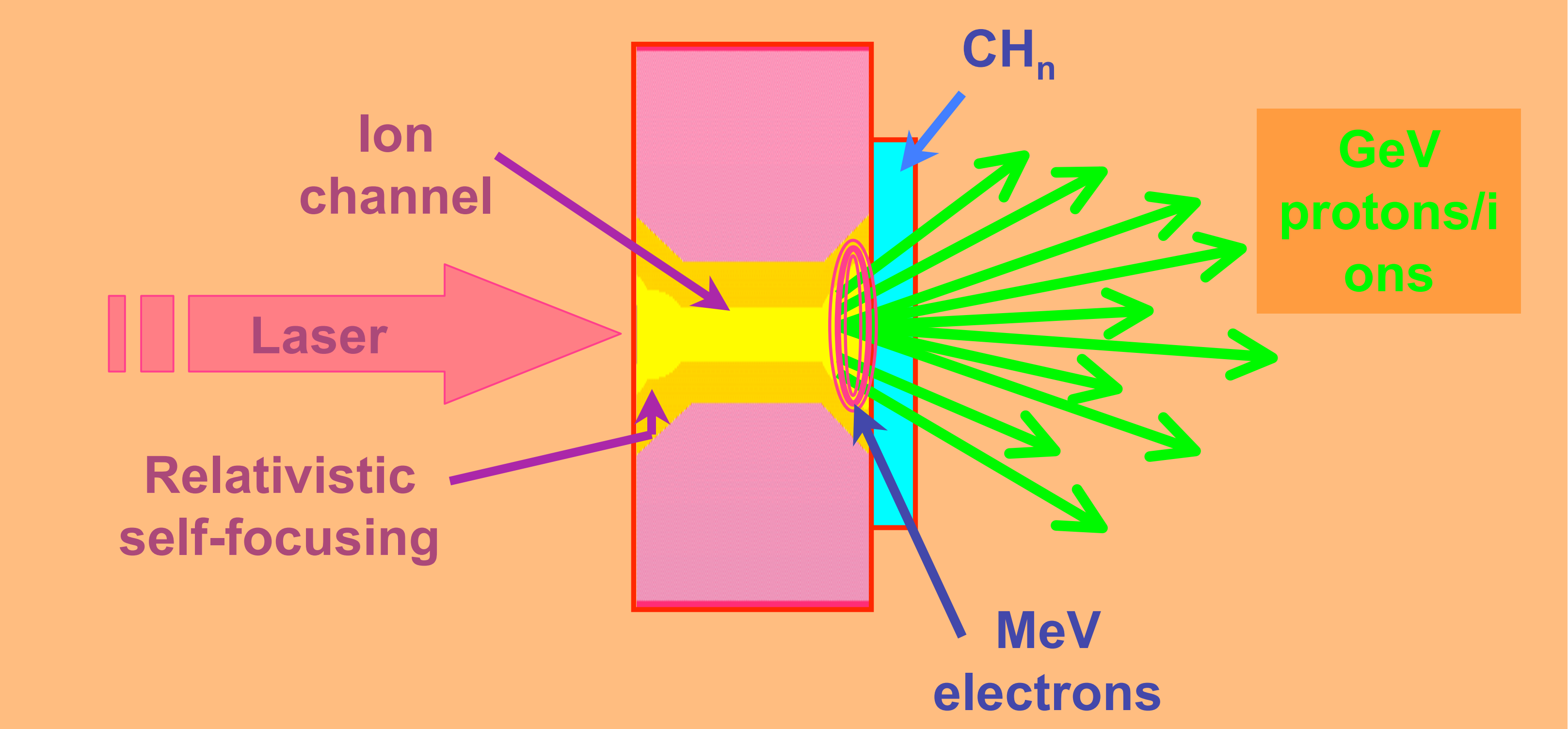
If > or < dephasing length: large energy spread

If ~ dephasing length: monoenergetic

$L_{accel} \sim L_{dephas} \sim 1/n_e^{3/2}$

Optimal choice of the plasma density: the smallest possible density For conditions 1 -4 to be fulfilled.

Proton Acceleration



At present, experiments achieve 10s of MeV per nucleon. Future experiments aim to reach 100s of MeV to GeV.

Heavy Ion/Proton Generation by Ultraintense Lasers

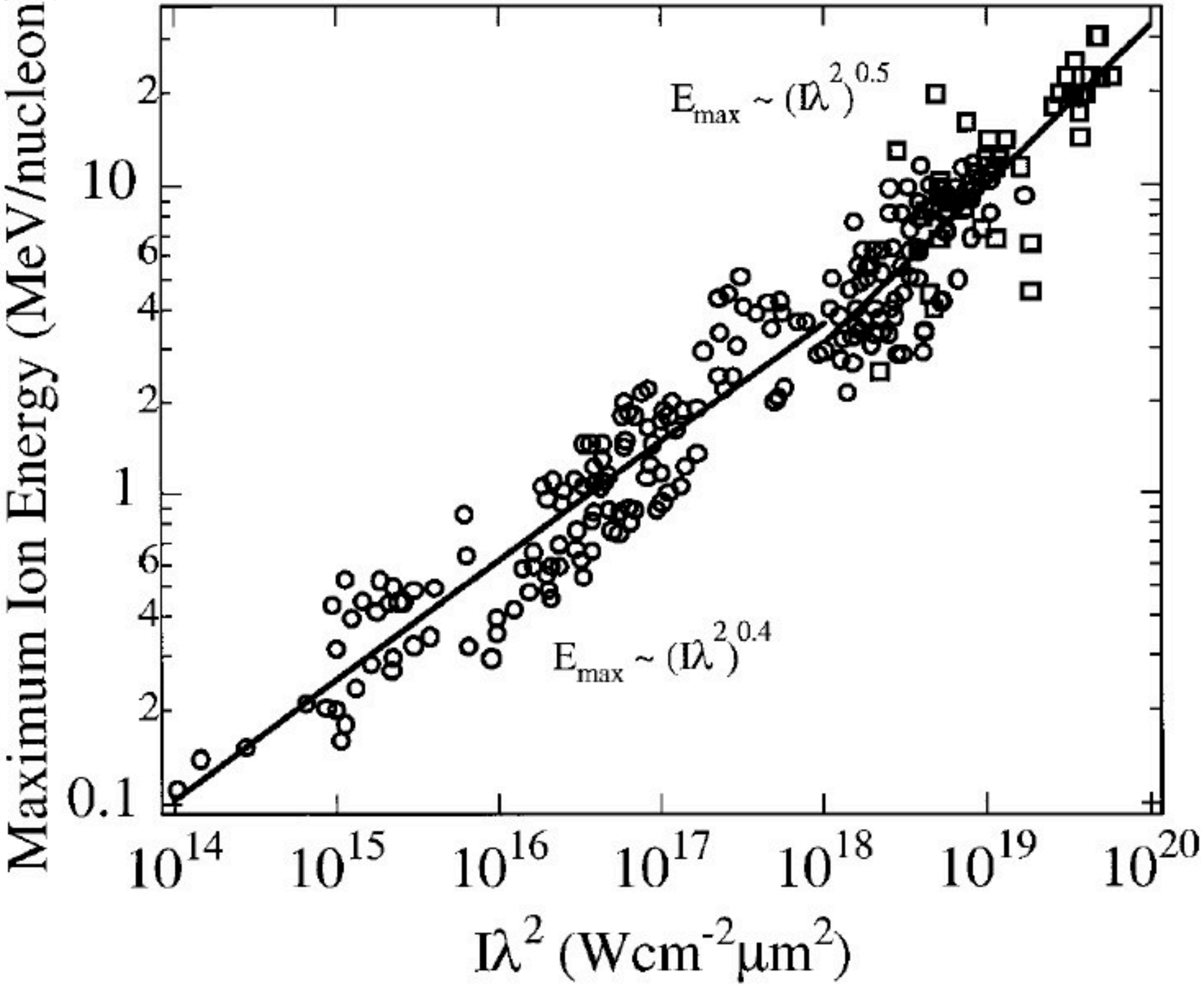
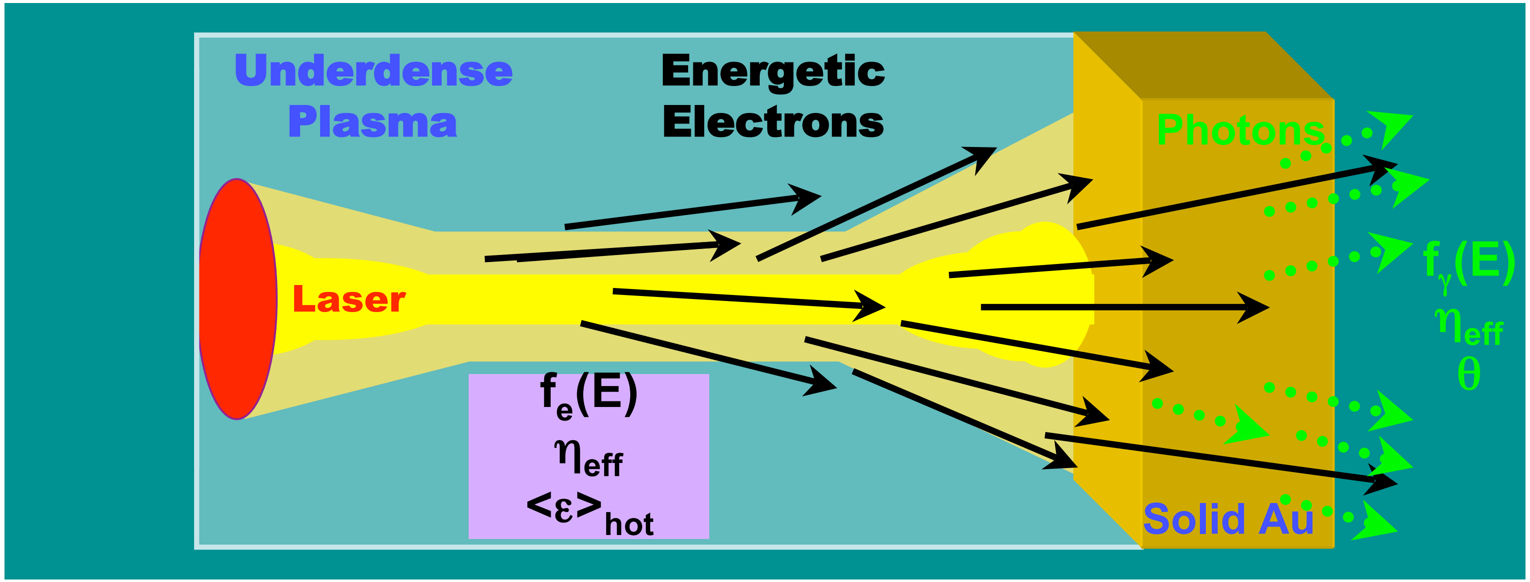


FIG. 4. Maximum ion energy as a function of $I\lambda^2$. Data from Refs. [7] and [10] are indicated by circles. Squares denote data from experiments discussed here.

Clark *et al*., 2000, PRL, 85, 1654.

2-D PIC Simulations of the Underdense Laser-plasma Interaction Show That Energies Higher Than U_{pond} Can Be Produced.

Physical Model of the Experiment



Typical ponderomotive scaling predicts $T_{hot} \sim 2$ MeV.

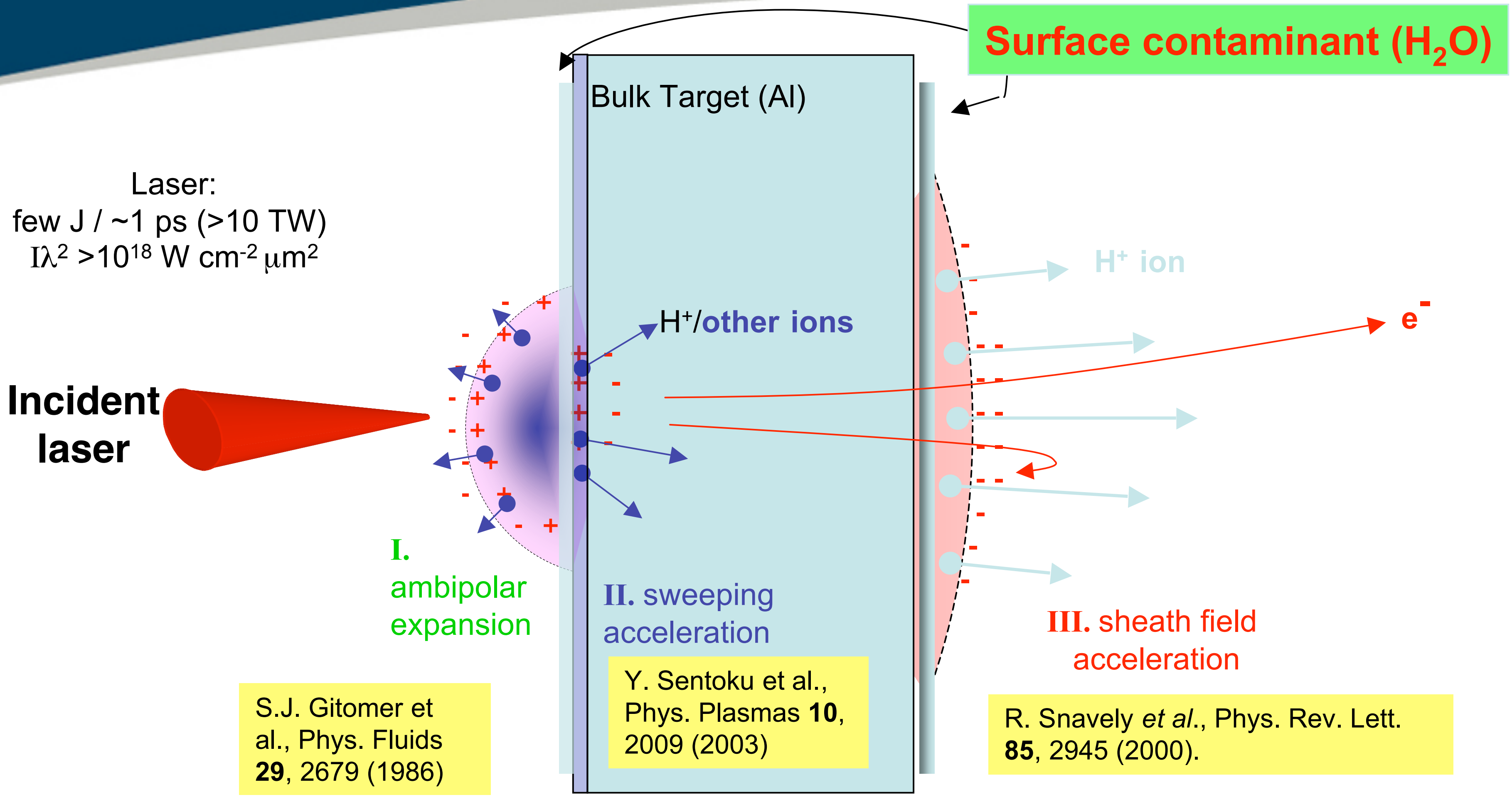
However, slope temperature measured from simulations

gives $T_{hot} \sim 7$ MeV for an intensity of 10^{20} W/cm^2,

agreeing with experimental electron spectrometer

Laser-acceleration of *ions* from solid targets

Laser:
few J / ~1 ps (>10 TW)
$I\lambda^2 > 10^{18}$ W cm^{-2} μm^2



Surface contaminant (H_2O)

Bulk Target (Al)

Incident laser

H^+/**other ions**

H^+ ion

e^-

I. ambipolar expansion

II. sweeping acceleration

III. sheath field acceleration

S.J. Gitomer et al., Phys. Fluids **29**, 2679 (1986)

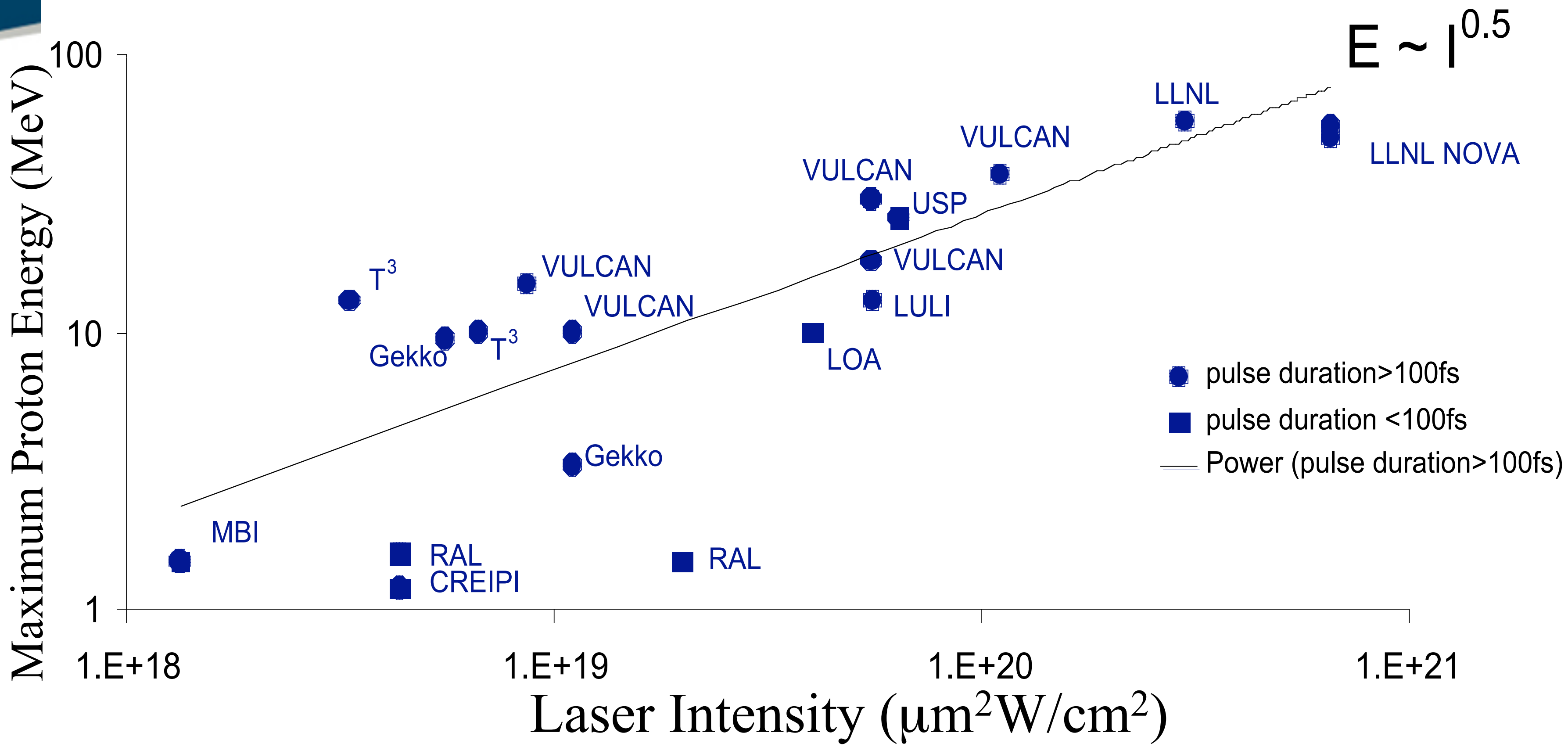
Y. Sentoku et al., Phys. Plasmas **10**, 2009 (2003)

R. Snavely *et al.*, Phys. Rev. Lett. **85**, 2945 (2000).

if target is heated \ efficient acceleration of heavy ions

[M. Hegelich et al., Phys. Rev. Lett. **89**, 085002 (2002).]

Proton Energy Scaling

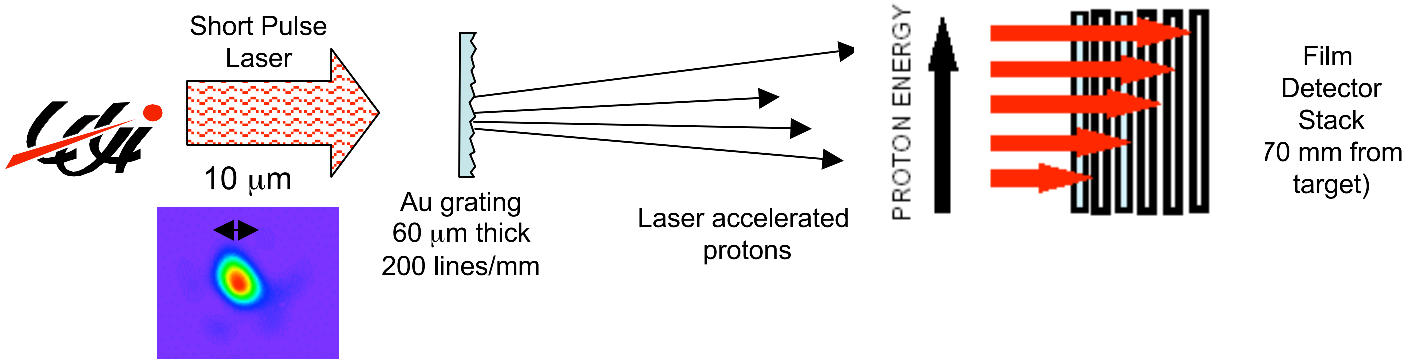


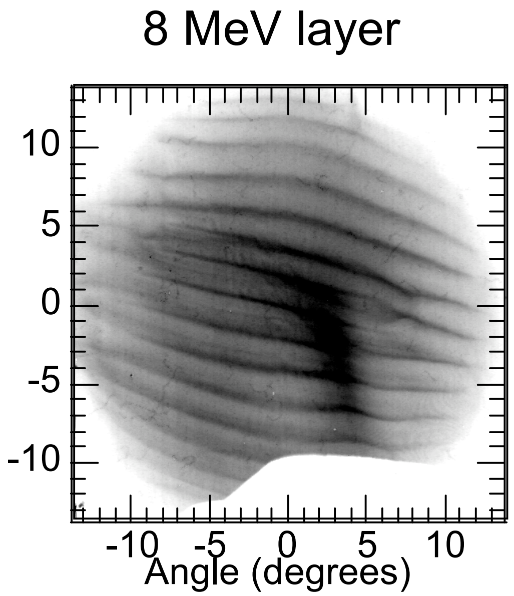
- •**Hi charge: 10^{10}-10^{13} ions**
- •**Short pulses**
- •**100's MA/cm²**

(Courtesy T. Lin)

Recent Highlight: Record beam quality en < .004 mm-mrad!

10x lower ε than conventional ion injectors





T. Cowan, J. Fuchs. H. Ruhl *et al.*,
Phys. Rev. Lett. **92**, 204801 (2004).

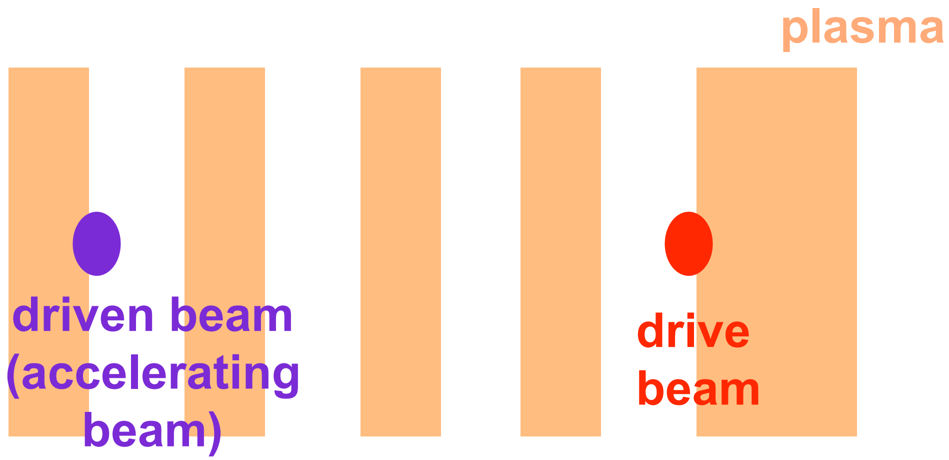
Intense Relativistic Beams in Plasmas: PW/m^2
New Plasma Physics

- Wake generation/ particle acceleration
- Focusing
- Hosing
- “Collective Refraction”
- Radiation generation
- Ionization effects

- Compact accelerators
- Plasma lens/astro jets
- E-cloud instability/LHC
- Fast kickers
- Tunable light sources
- Beam prop. physics/X-ray lasers

Beam-Induced Plasma Wakefield Accelerator (PWA)

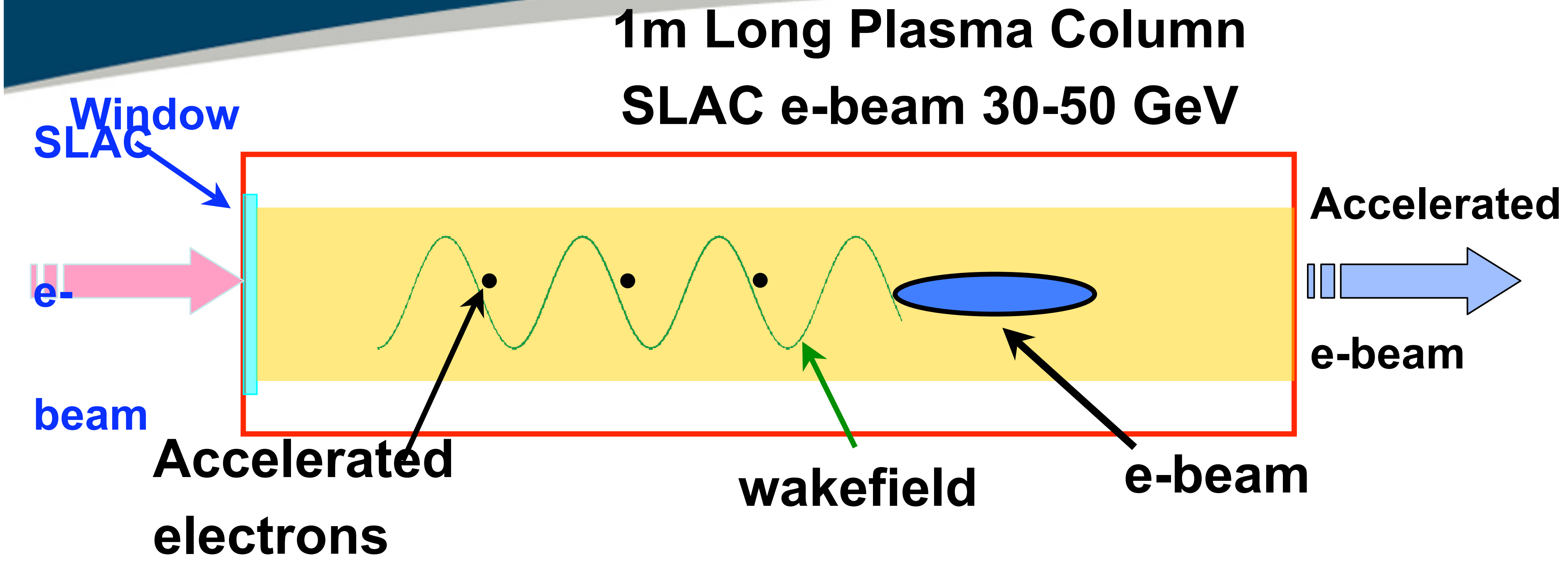
- **P. Chen, J.M. Dawson *et al.***



density fluctuations of a plasma (plasma wave)

Experiments: ***E157*** Stanford Linear Accelerator SLAC/UCLA
⇒ 30 GeV driver, 10^{14} cm^{-3} plasma
Argonne National Lab (ANL/UCLA)
⇒ aiming for 1 GeV/m, 10^{12} particles per pulse, 100 Hz repetition rate, emittance of 1mm.mrad

SLAC Electron Beam Plasma Experiment

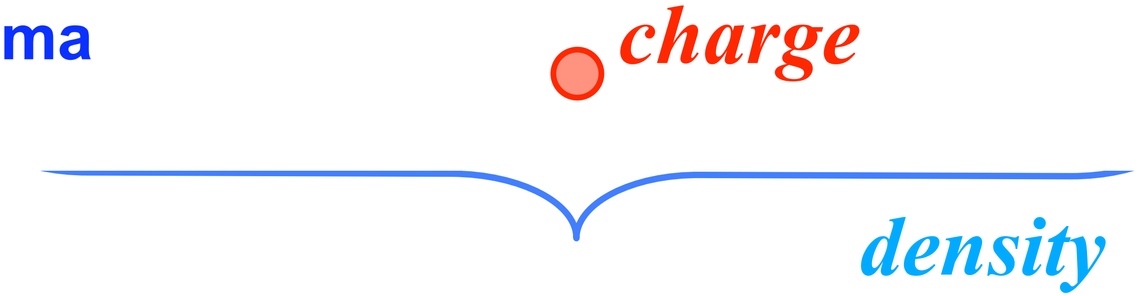


- Front of beam generates plasma wakefield
- Tail of beam particles interacts with wakefield

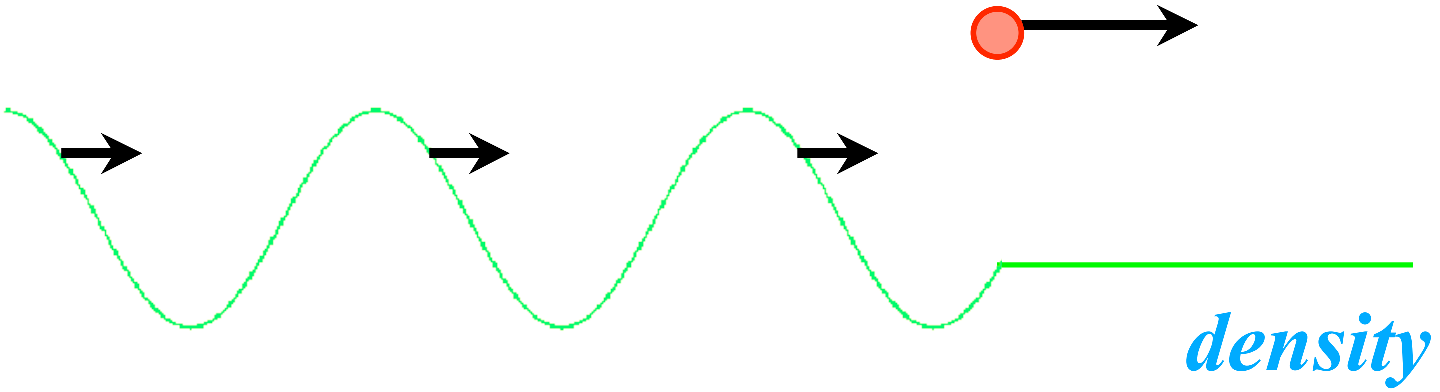
⇨ Accelerated and decelerated beam.

Wakefield Generation

Charge in plasma



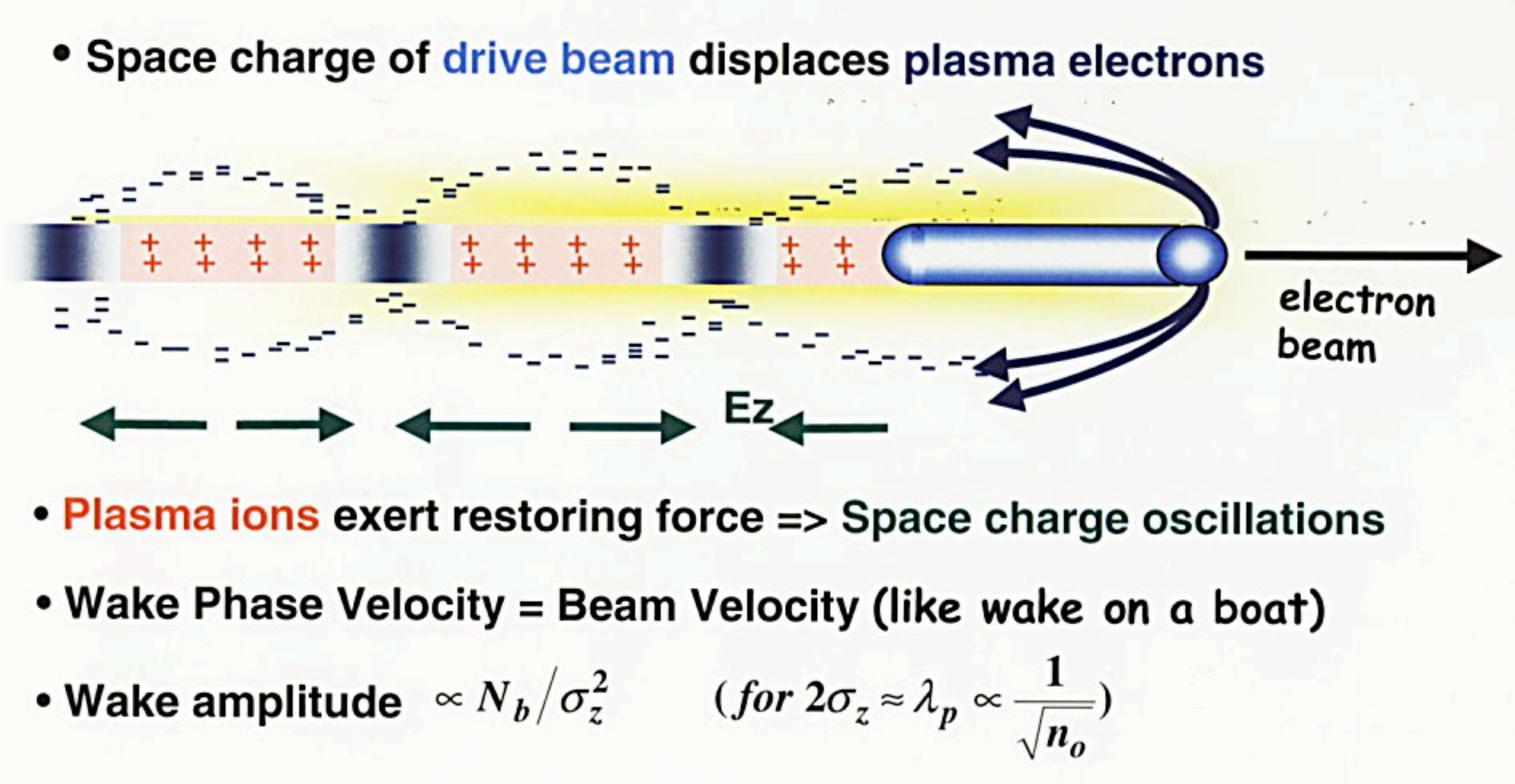
Moving charge



Cerenkov radiation

Physical Principles of the Plasma Wakefield Accelerator

- Plasma is used to create a longitudinal accelerating gradient



- Space charge of **drive beam** displaces **plasma electrons**
- **Plasma ions** exert restoring force => Space charge oscillations
- Wake Phase Velocity = Beam Velocity (like wake on a boat)
- Wake amplitude $\propto N_b/\sigma_z^2$ $\quad (for\ 2\sigma_z \approx \lambda_p \propto \frac{1}{\sqrt{n_o}})$

Plasma Wakefield

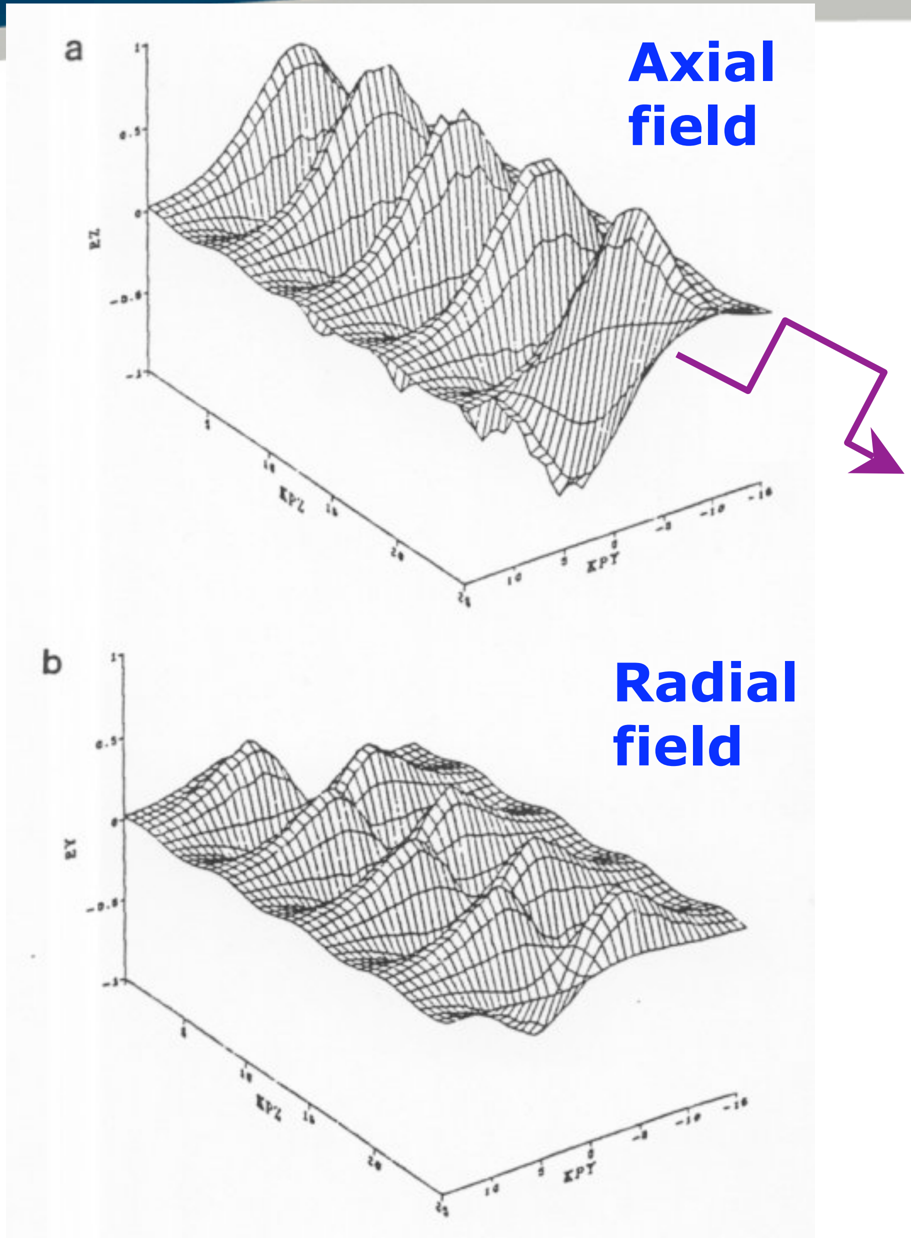
- The maximum plasma wake amplitude of an electron bunch scales as current over pulse length ($\tau=2\sigma_z/c$)

$$eE_z \cong 1GeV/m \frac{I}{kAmp} \bullet \frac{4\,ps}{\tau}$$

- So, a 1 kAmp pulse, of duration 4 picoseconds is needed to generate a 1 GeV/m wake.

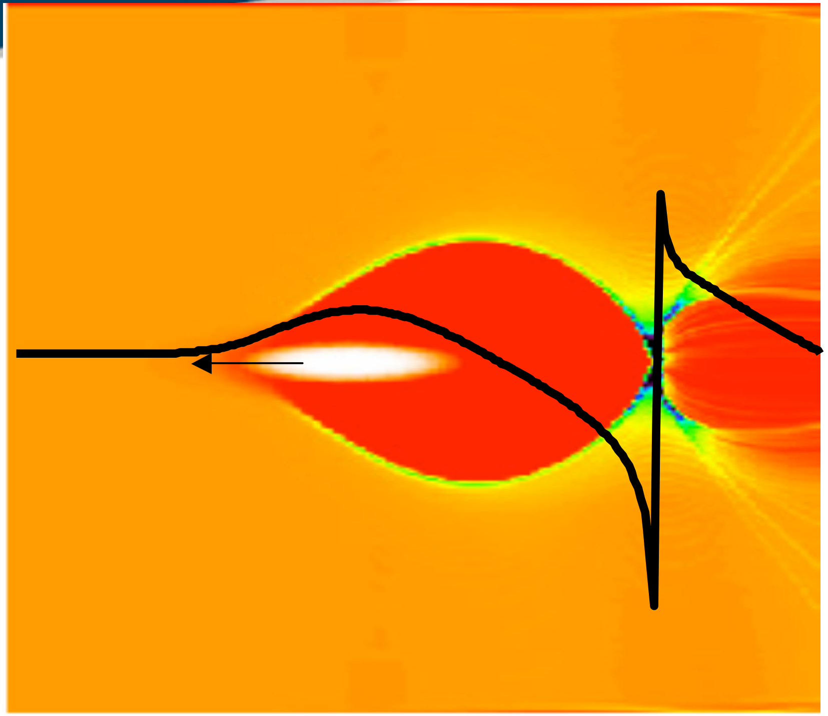
Electron Beam Generated Plasma Wave

- Similar to laser wakefield generation.

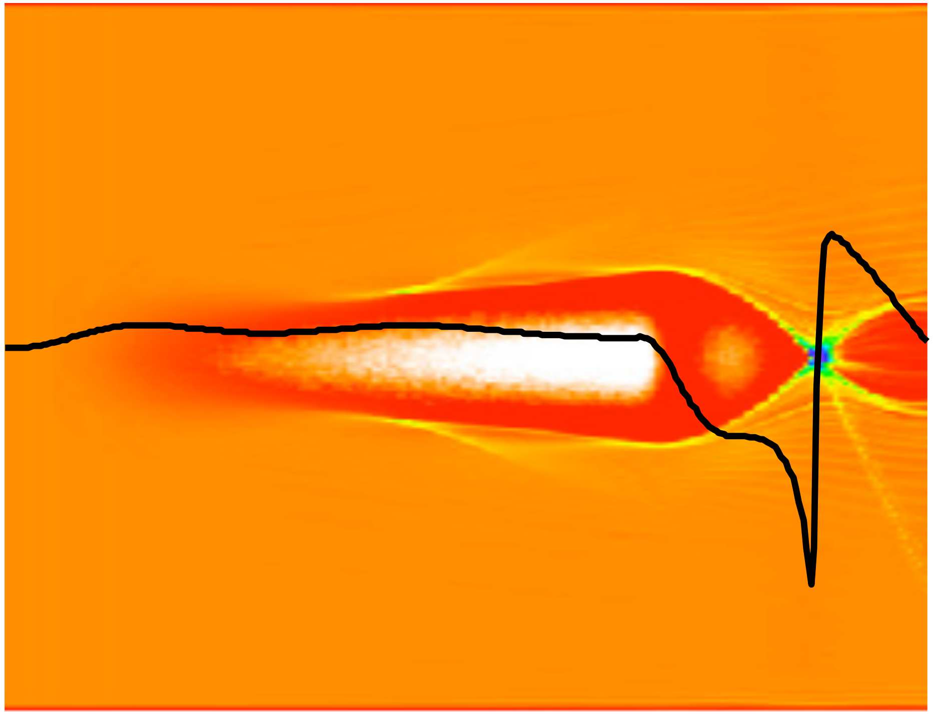


[S. Wilks *et al*. PPG. 1262]

PIC Simulation of Beam and Plasma Wakes



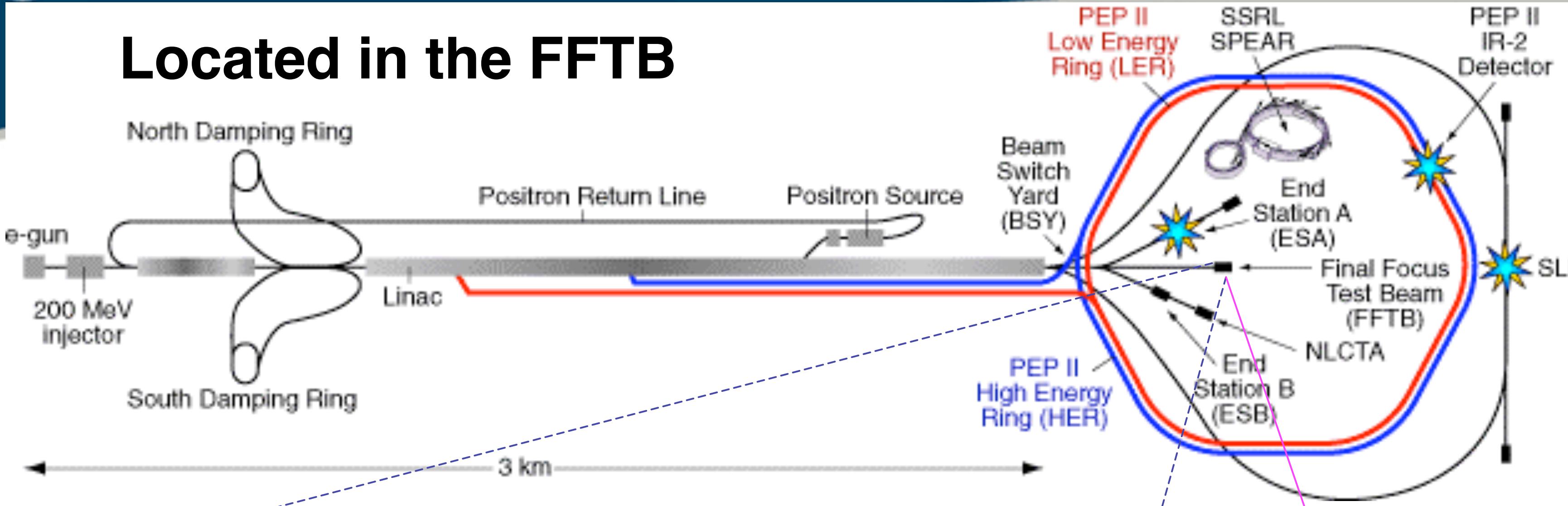
Bi-Gaussian shape
$\sigma_z = 1.2\ c/\omega_p,\ \ n_b/n_p = 26$

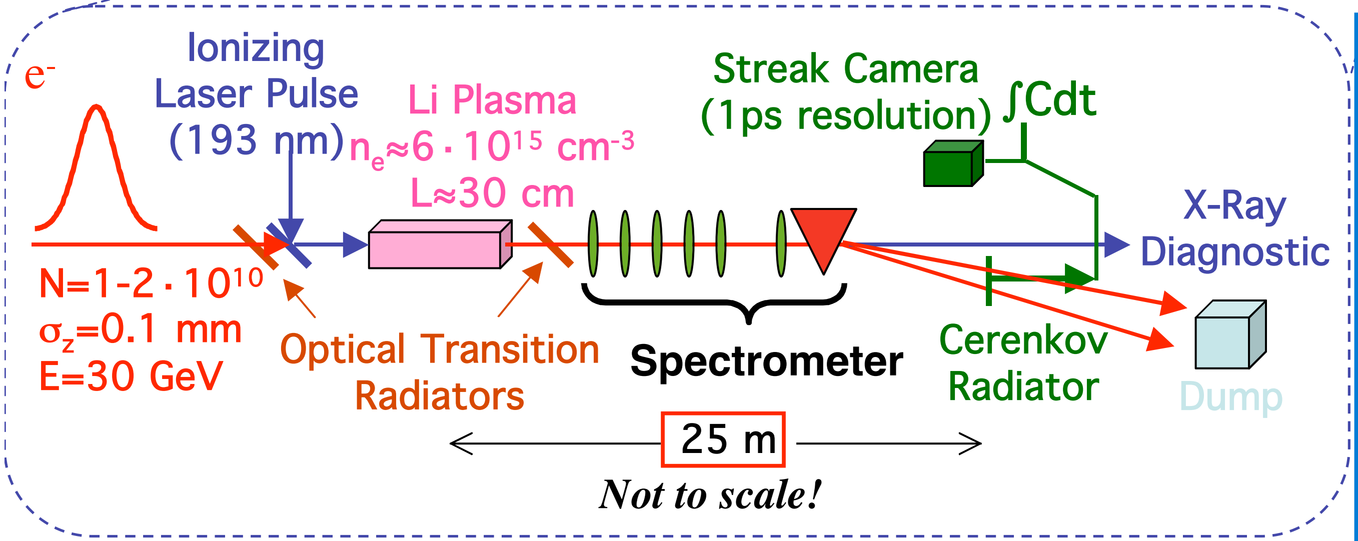


Wedge shape w/ beam load
beam length = $6\ c/\omega_{p,}\ \ n_b/n_p = 8.4,$
$N_{drive} = 3\mathrm{x}10^{10},\ N_{trailing} = 0.5\mathrm{x}10^{10}$

PWFA Experiments @SLAC Share Common Apparatus

Located in the FFTB





e^-

Ionizing Laser Pulse (193 nm)

Li Plasma
$n_e \approx 6 \cdot 10^{15}$ cm^{-3}
L≈30 cm

Streak Camera (1ps resolution)

$\int Cdt$

X-Ray Diagnostic

$N = 1\text{-}2 \cdot 10^{10}$
$\sigma_z = 0.1$ mm
E=30 GeV

Optical Transition Radiators

Spectrometer

Cerenkov Radiator

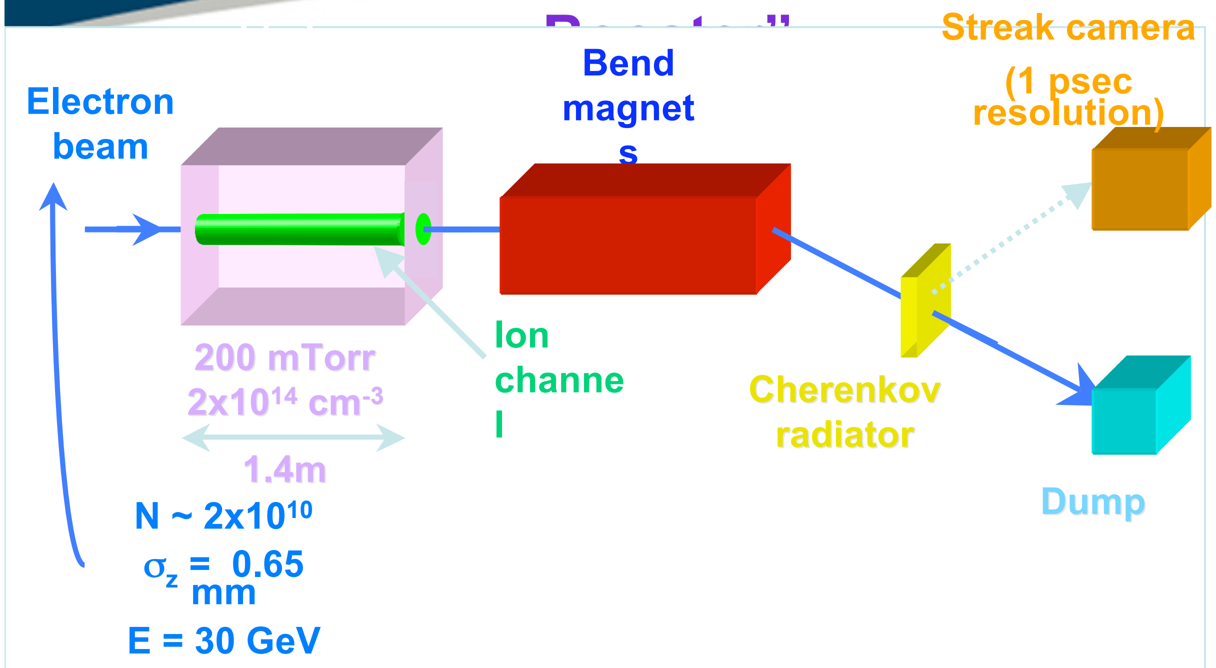
Dump

25 m

Not to scale!

Layout of SLAC-FFTB Plasma Wakefield Experiment

- **E157 Experimental Layout – Plasma "Turbo-**



Parameter	PWFA	Standard SLAC
Bunch Intensity	3.5-4.0x10^{10} e^-	3.5-4.0x10^{10} e^-
Bunch Length	0.6 mm	0.6-1.1 mm
Repetition Rate	10 Hz	1-120 Hz
$\gamma\varepsilon_y$ at plasma IR	15 mm-mrad	8 mm-mrad
σ_y at plasma IR	< 100 μm	37 μm at 1x10^{10} e^-

GOALS

1 GeV/m accelerating gradient

10^{12} particles/pulse

100 Hz Repetition rate

Emittance < 1mm.mrad

To date

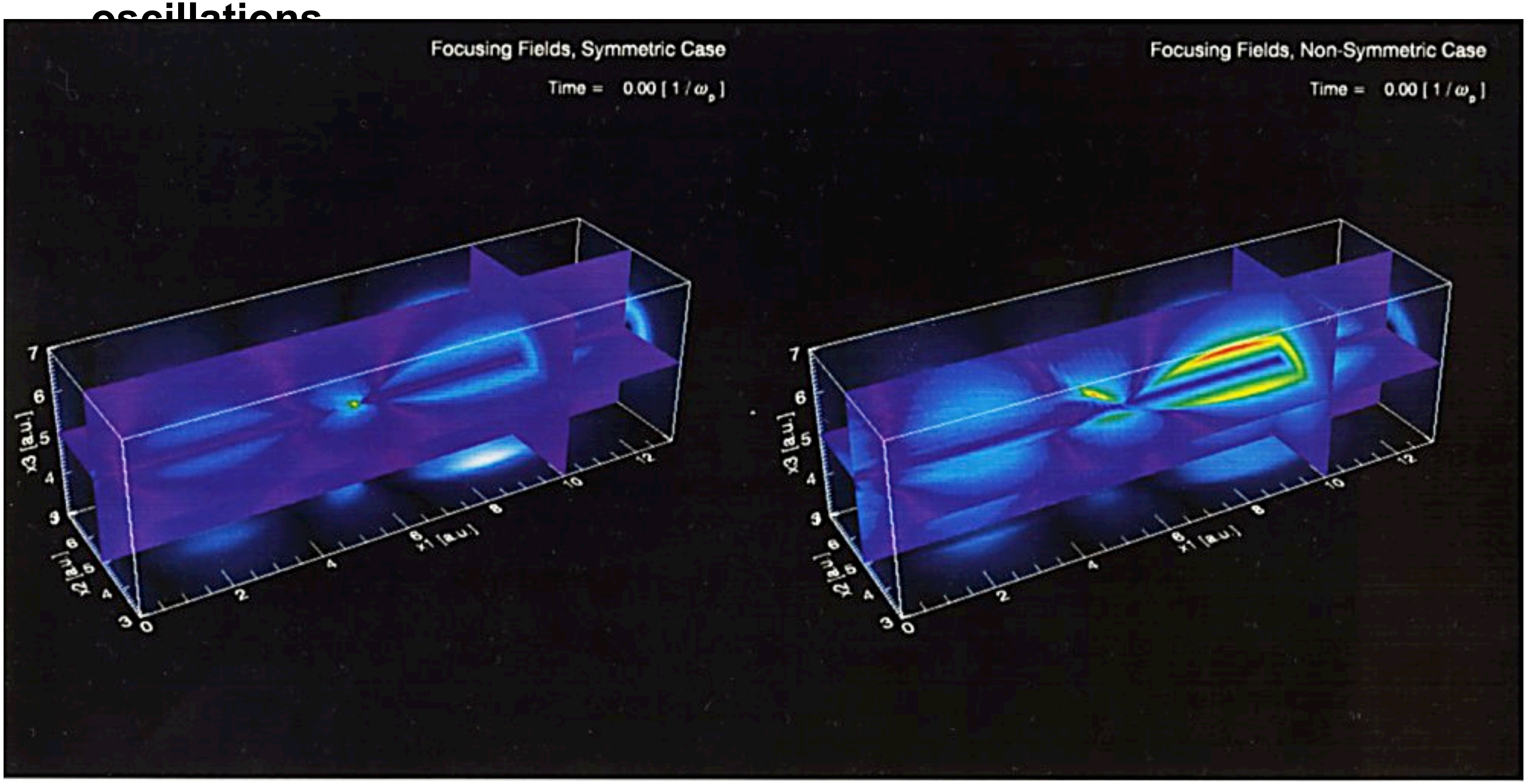
positron beam accel.

E ~ 50MV/m

e-beam gains 350 MeV

Reference: **R. Assmann *et al.*, Phys.Plasma (2000)**

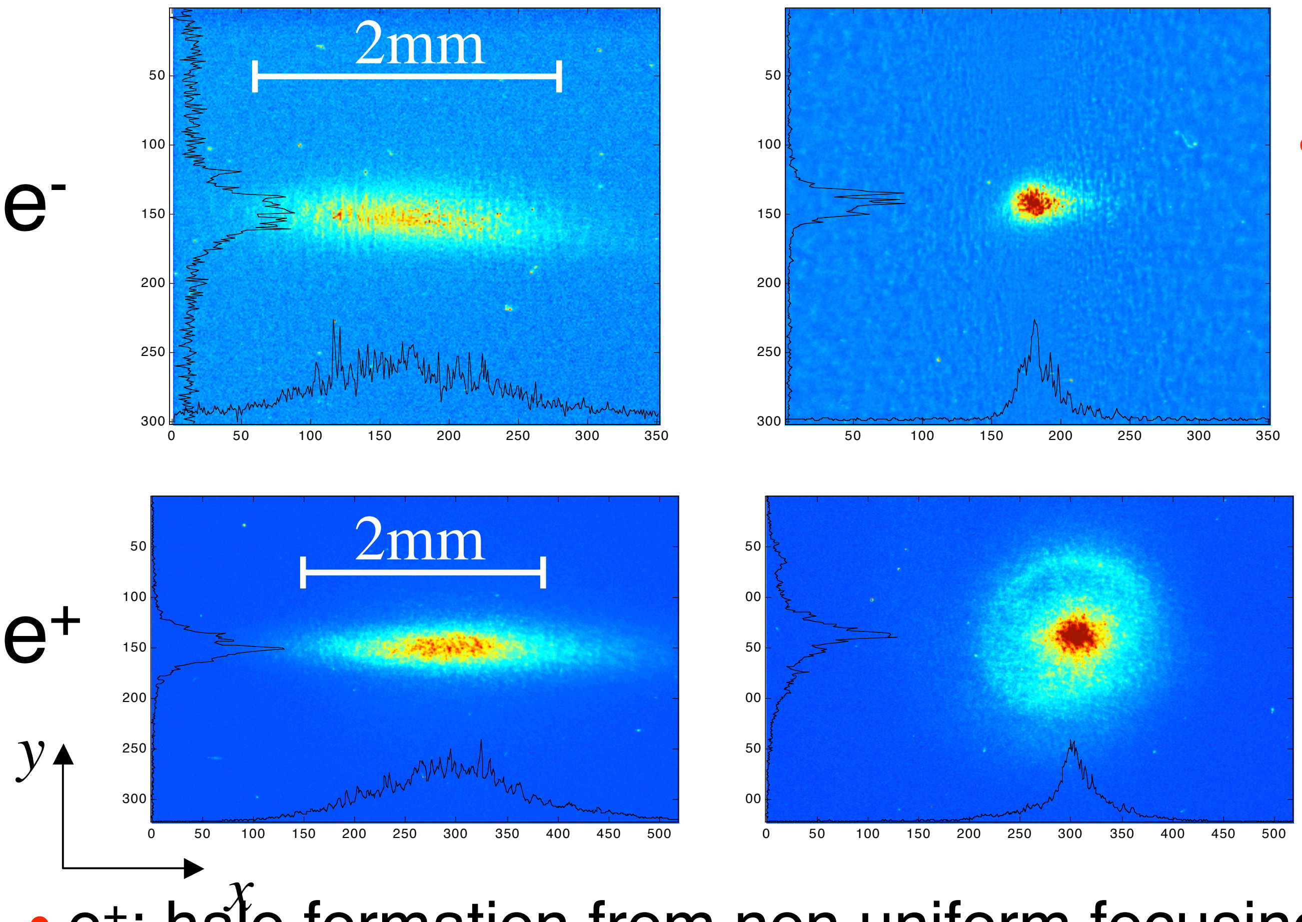
- **Different spot sizes lead to different focusing forces and betatron oscillations**



Focusing of e^-/e^+ Beam

- OTR images ≈1m from plasma exit ($\varepsilon_x \neq \varepsilon_y$)

n_e=0 $n_e \approx 10^{13}$ cm^{-3}

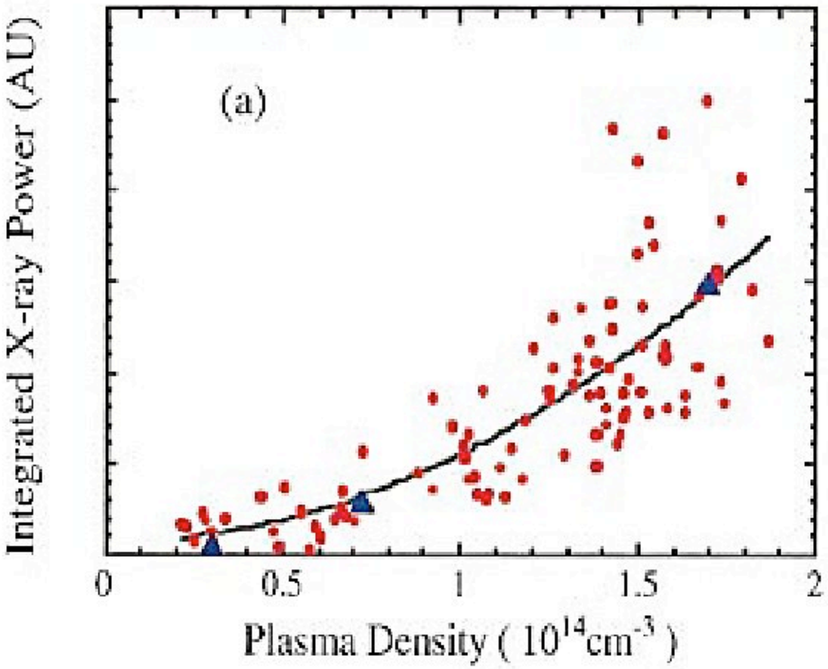


- Ideal Plasma Lens in Blow-Out Regime
- Plasma Lens with Aberrations
- e^+: halo formation from non uniform focusing

M.J. Hogan *et al.*, PRL, 2002; Also J. Ng et al., 2001 (**F/r~GG/cm**)

Betatron X-rays

- Joshi *et al*., Physics of Plasmas, 9, 1845, 2002.



I ~ 10^{19} photons/s-.1%bw-mm^2-mr^2 @6 keV

S. Wang et al. Phys. Rev. Lett. Vol. 88 Num. 13

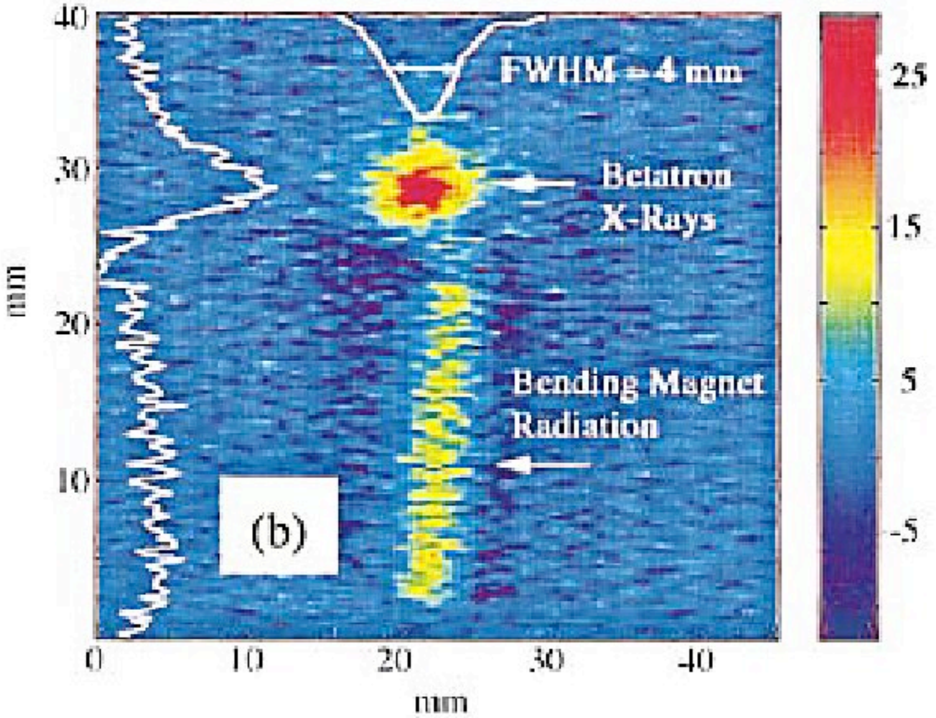
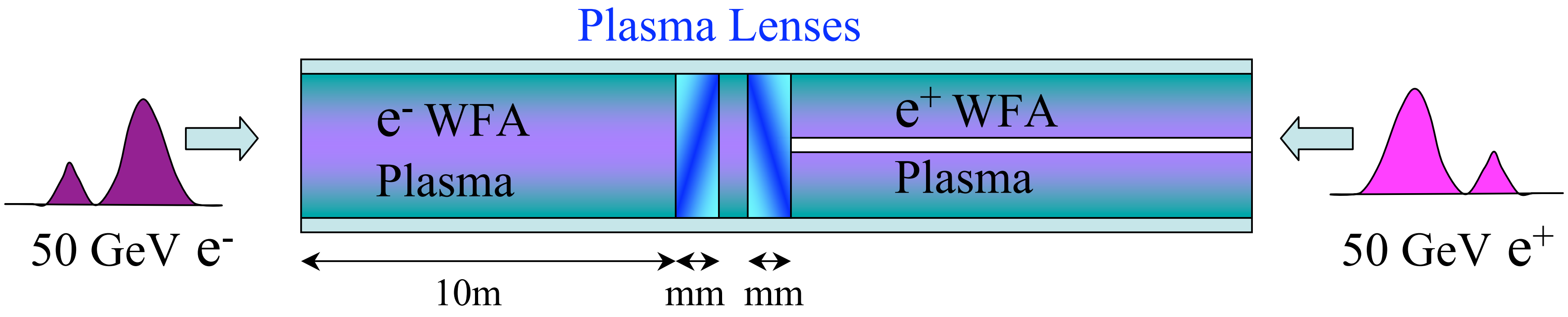


FIG. 8. (Color) (a) The estimated (triangles) and the measured (dots) x-ray energy in the 5–30 keV range as a function of plasma density. The solid line is a quadratic fit to the data. (b) Processed image produced on a fluorescent screen as recorded by a CCD camera showing the betatron x-rays produced by the plasma $n_p = 2\times10^{13}$ cm^{-3} (circle at the top) and a vertical stripe of remnant synchrotron radiation produced by a dipole bend magnet.

Wakefield Afterburner

High Energy Plasma Accelerator

Energy Doubler for a Linear Collider



- **Accelerating Gradients ~ 8 GeV/m**
- **SLAC 50 GeV beams boosted in a Plasma Wakefield Accelerator (PWFA) to ~ 100 GeV**
- **Possible to reach energies suitable for Higgs Boson detection**

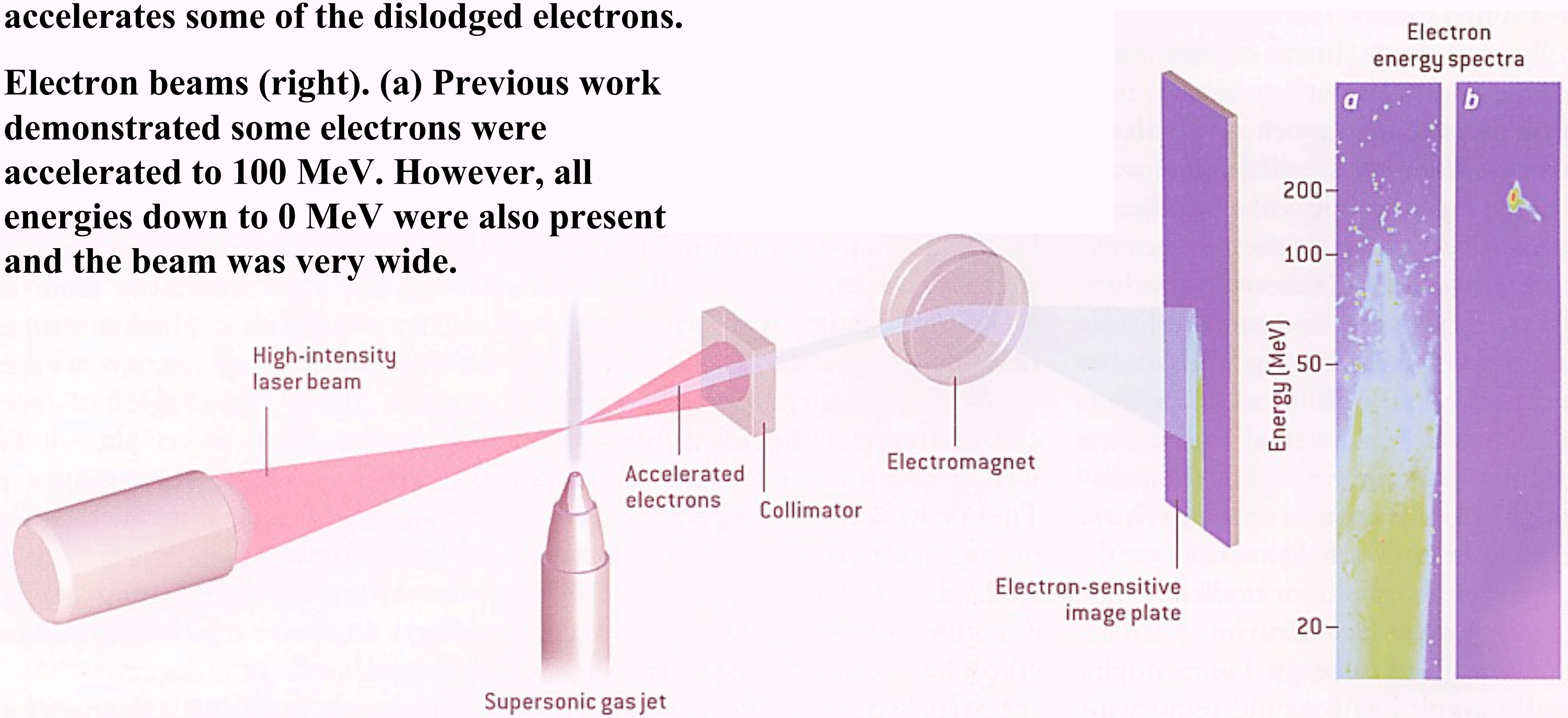
Laser Wakefield Acceleration

LASER WAKEFIELD ACCELERATOR

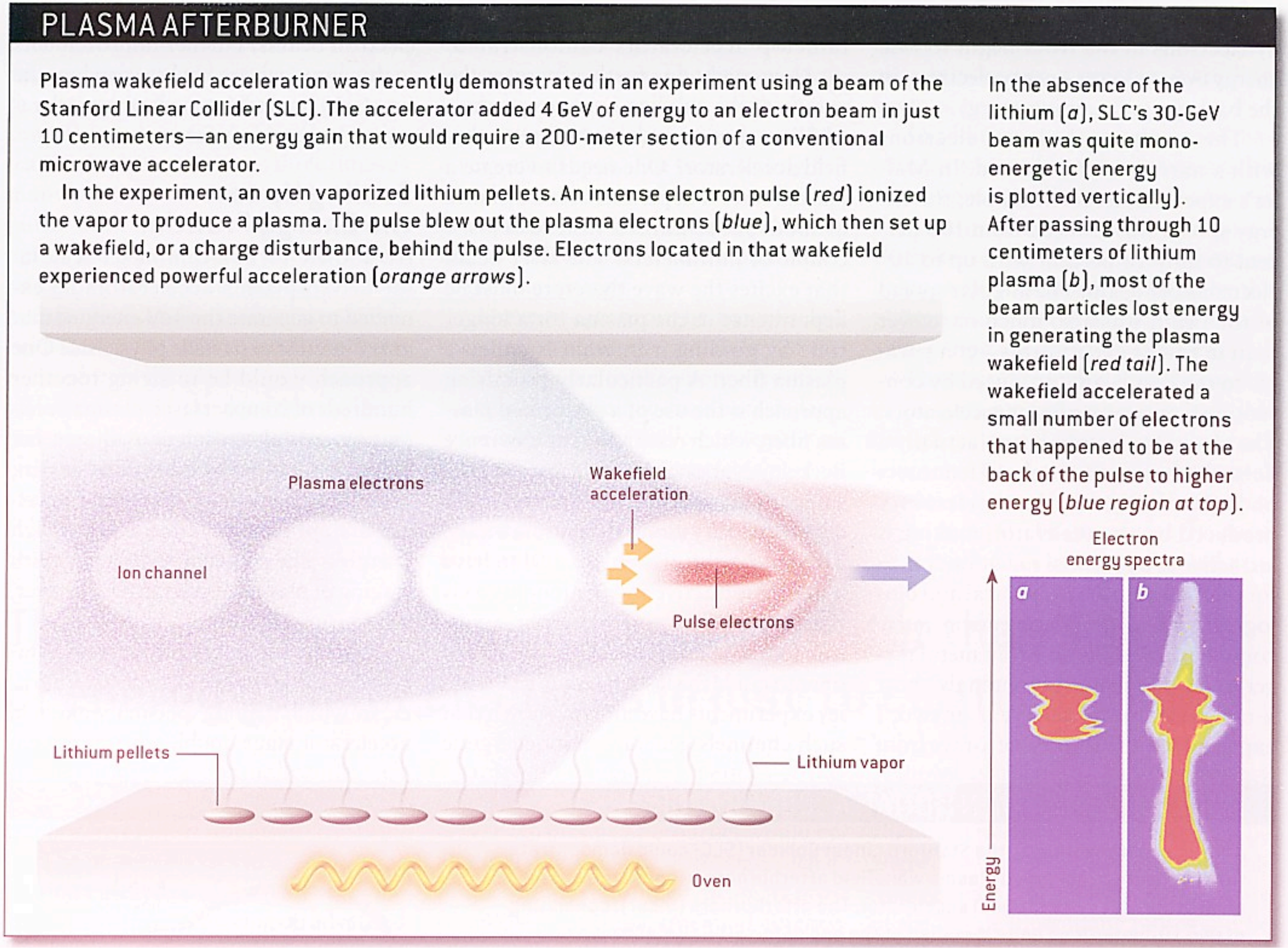
A tabletop plasma accelerator consists of: High intensity laser beam; supersonic jet of helium gas (below). The beam produces a plasma in the gas jet, and the wakefield accelerates some of the dislodged electrons.

Electron beams (right). (a) Previous work demonstrated some electrons were accelerated to 100 MeV. However, all energies down to 0 MeV were also present and the beam was very wide.

(b) By contrast, a newly discovered "bubble" regime produces a narrow beam of monoenergetic 180 MeV electrons which are of much greater practical use.



Plasma Afterburner



PLASMA AFTERBURNER

Plasma wakefield acceleration was recently demonstrated in an experiment using a beam of the Stanford Linear Collider (SLC). The accelerator added 4 GeV of energy to an electron beam in just 10 centimeters—an energy gain that would require a 200-meter section of a conventional microwave accelerator.

In the experiment, an oven vaporized lithium pellets. An intense electron pulse (*red*) ionized the vapor to produce a plasma. The pulse blew out the plasma electrons (*blue*), which then set up a wakefield, or a charge disturbance, behind the pulse. Electrons located in that wakefield experienced powerful acceleration (*orange arrows*).

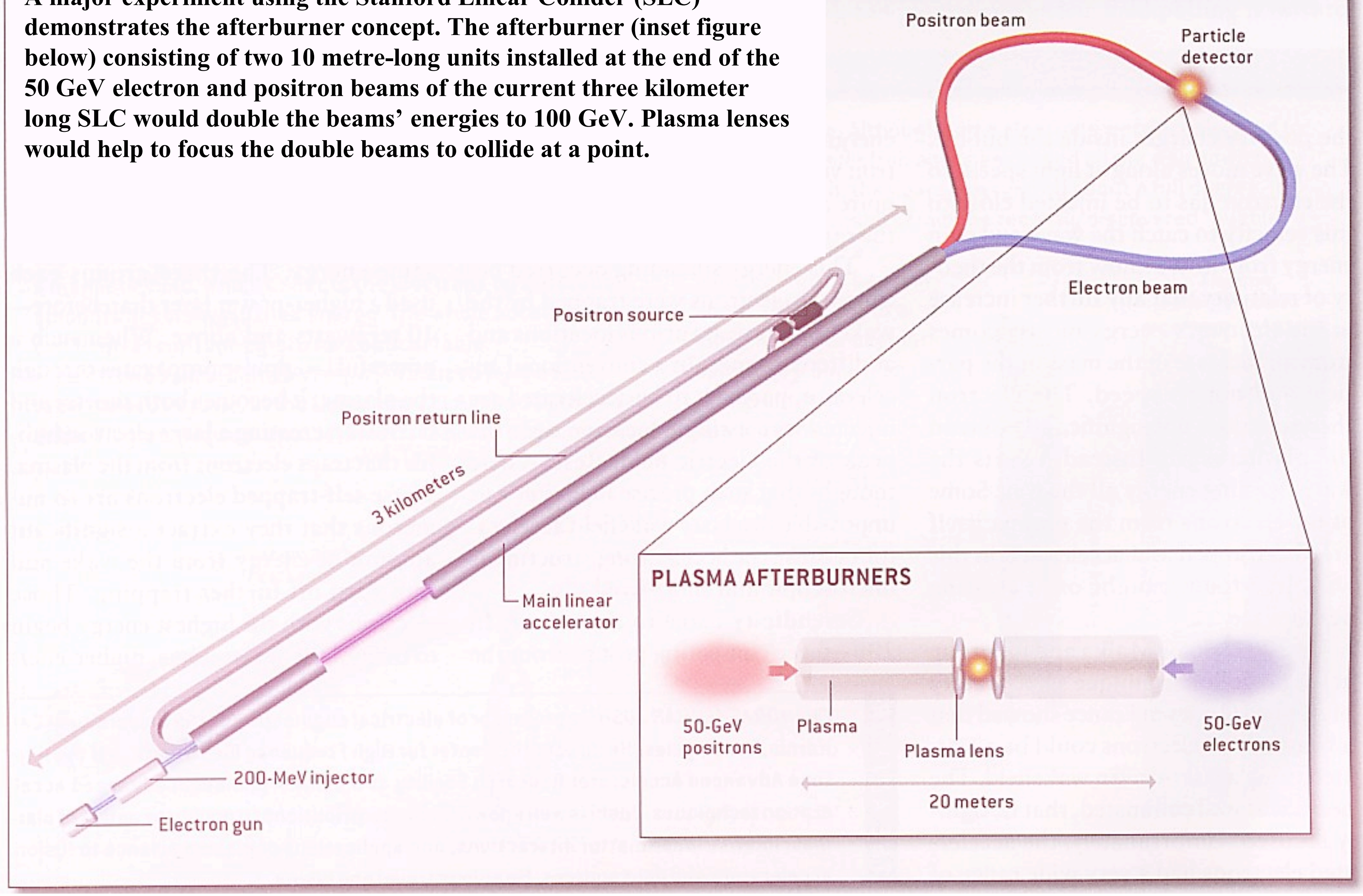
In the absence of the lithium (*a*), SLC's 30-GeV beam was quite monoenergetic (energy is plotted vertically). After passing through 10 centimeters of lithium plasma (*b*), most of the beam particles lost energy in generating the plasma wakefield (*red tail*). The wakefield accelerated a small number of electrons that happened to be at the back of the pulse to higher energy (*blue region at top*).

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Boosting a Conventional Accelerator

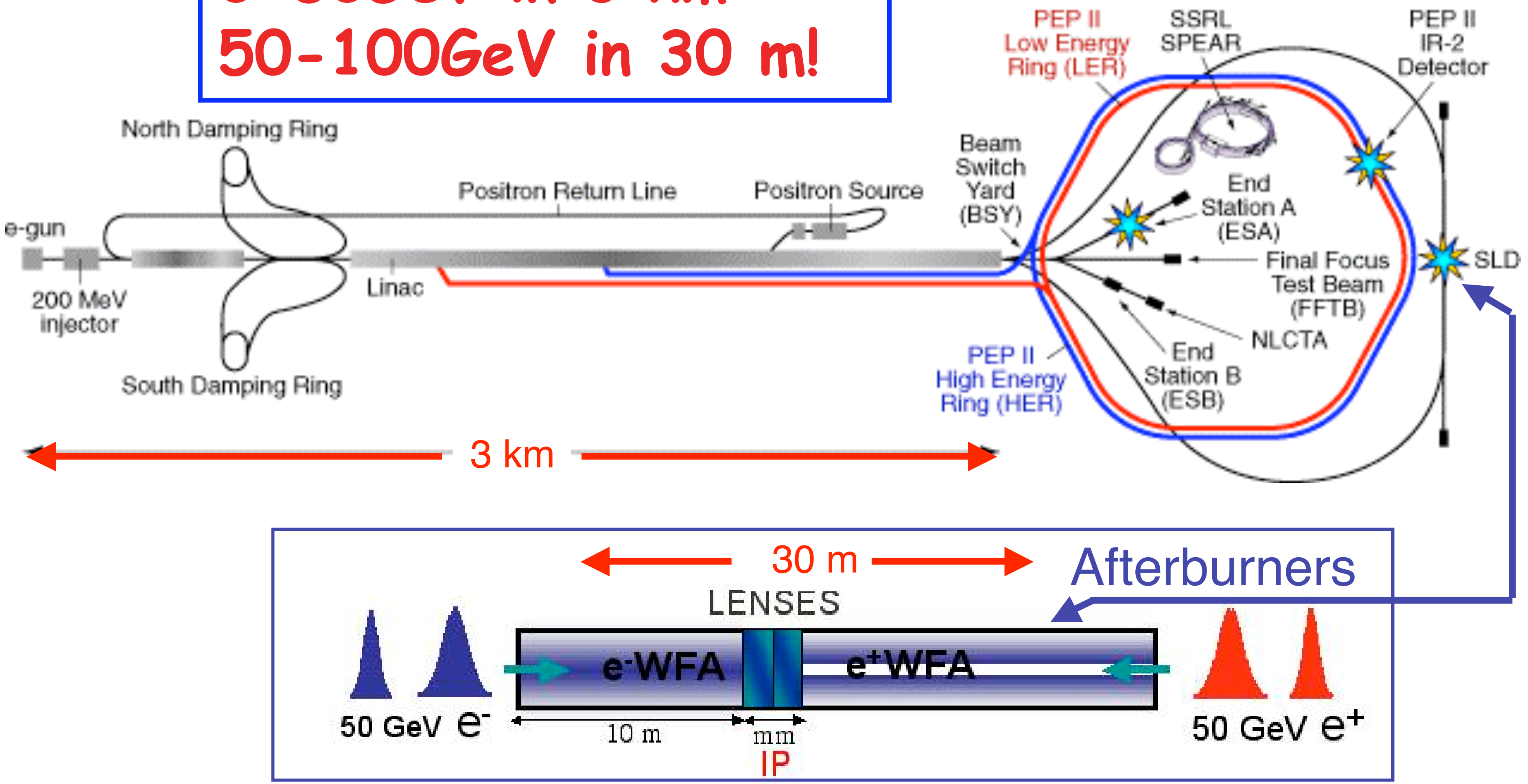
BOOSTING A CONVENTIONAL ACCELERATOR

A major experiment using the Stanford Linear Collider (SLC) demonstrates the afterburner concept. The afterburner (inset figure below) consisting of two 10 metre-long units installed at the end of the 50 GeV electron and positron beams of the current three kilometer long SLC would double the beams' energies to 100 GeV. Plasma lenses would help to focus the double beams to collide at a point.



A Plasma Afterburner (Energy Doubler) of Relevance to Future Colliders Could be Demonstrated at SLAC

0-50GeV in 3 km
50-100GeV in 30 m!



S. Lee *et al.*, Phys. Rev. STAB, 2001

High energy Plasma Science with an Ultrarelativistic electron beam

- Joshi *et al*., Physics of Plasmas, 9, 1845, 2002.

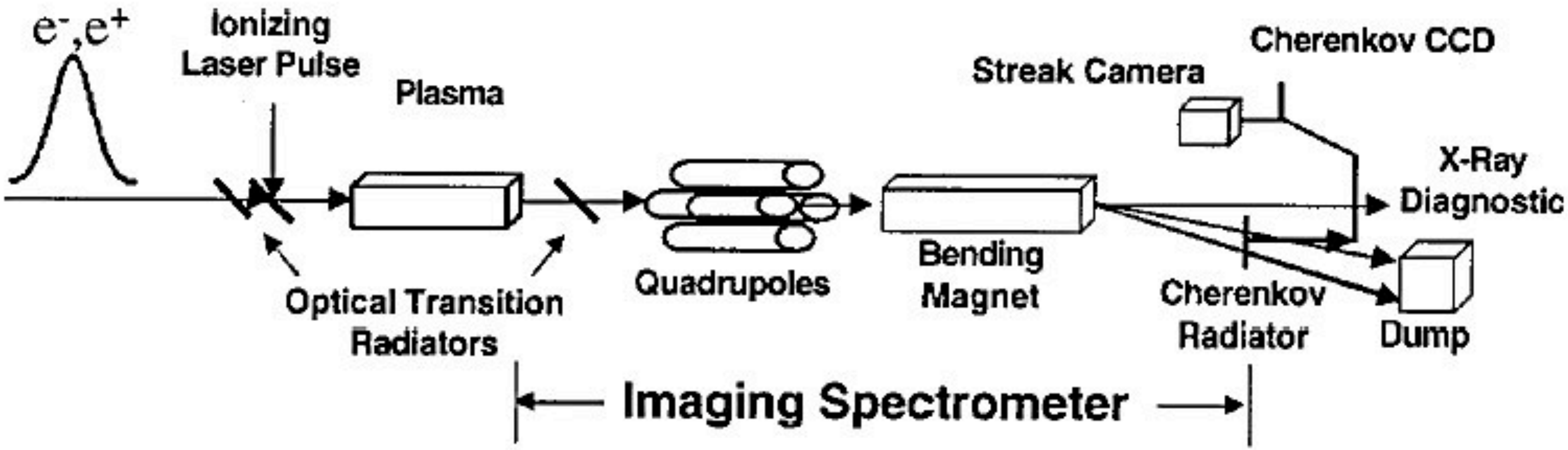
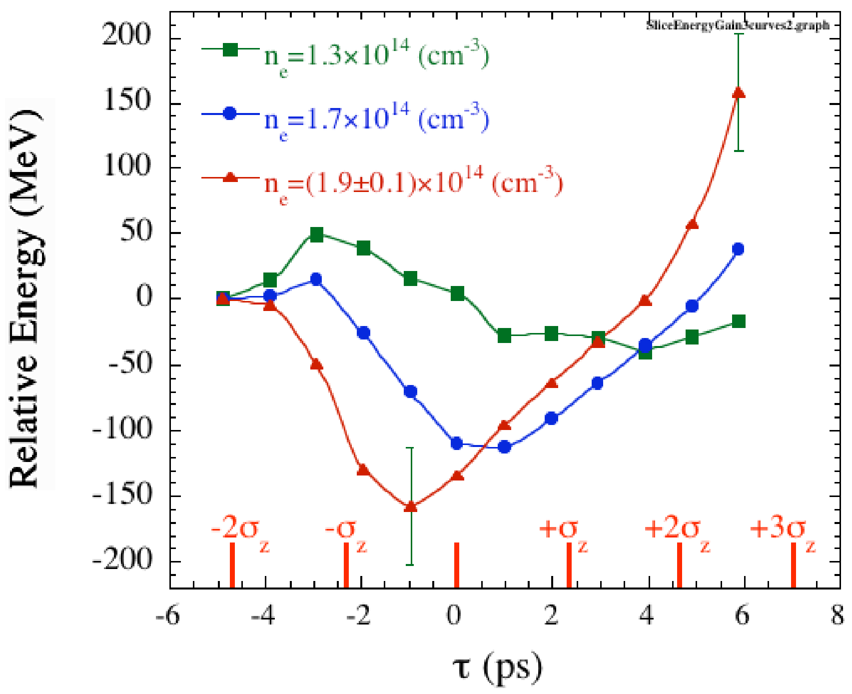


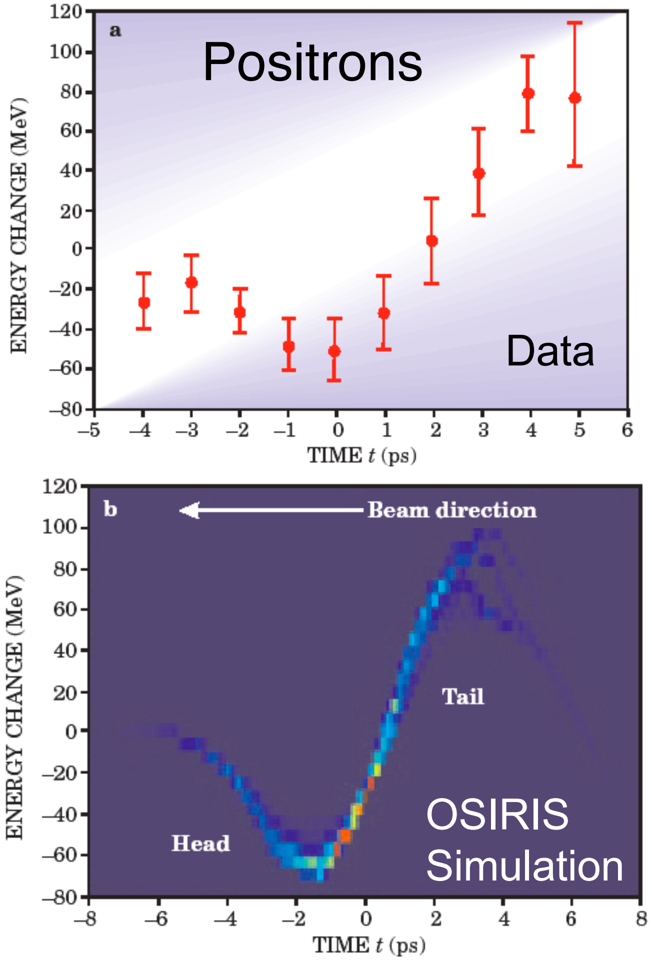
FIG. 1. The experimental set-up for studying beam-plasma interaction effects with a 28.5 GeV electron or positron beam that was used in most of the experiments described in the text. The detection set-up for x-rays in the forward direction is not shown.

Acceleration Of Electrons & Positrons: E-162

Electrons



- *Some electrons gained* *280 MeV (200 MeV/m)*
- *Now going for 2 GeV at a rate of 10,000 MeV/m this month at SLAC*

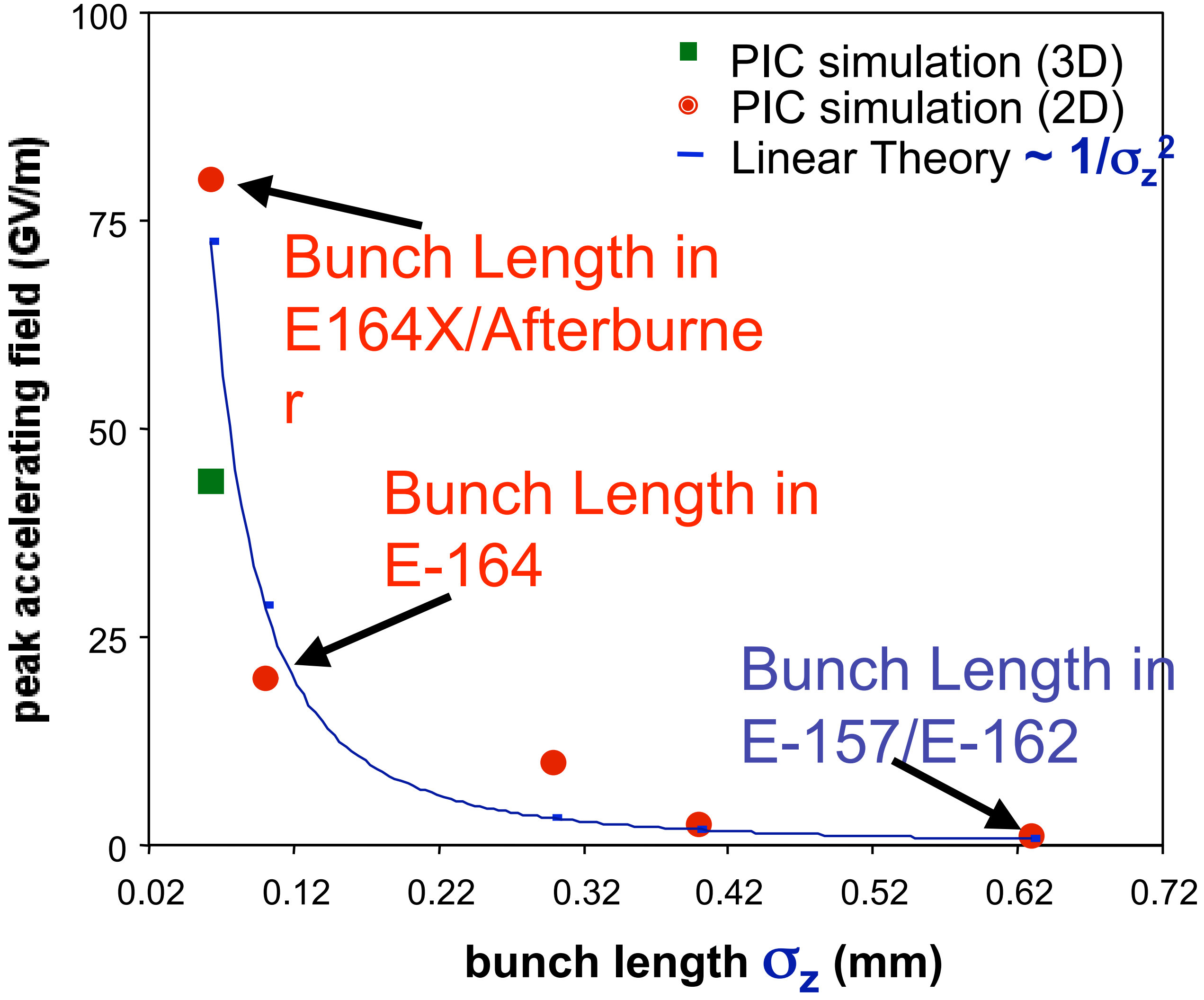


- Loss ≈ 50 MeV
- Gain ≈ 75 MeV

B. Blue *et al.*, *Phys. Rev. Lett*. 2003

R. Bingham, *Nature*, News and Views, 2003

PWA Experiments at SLAC



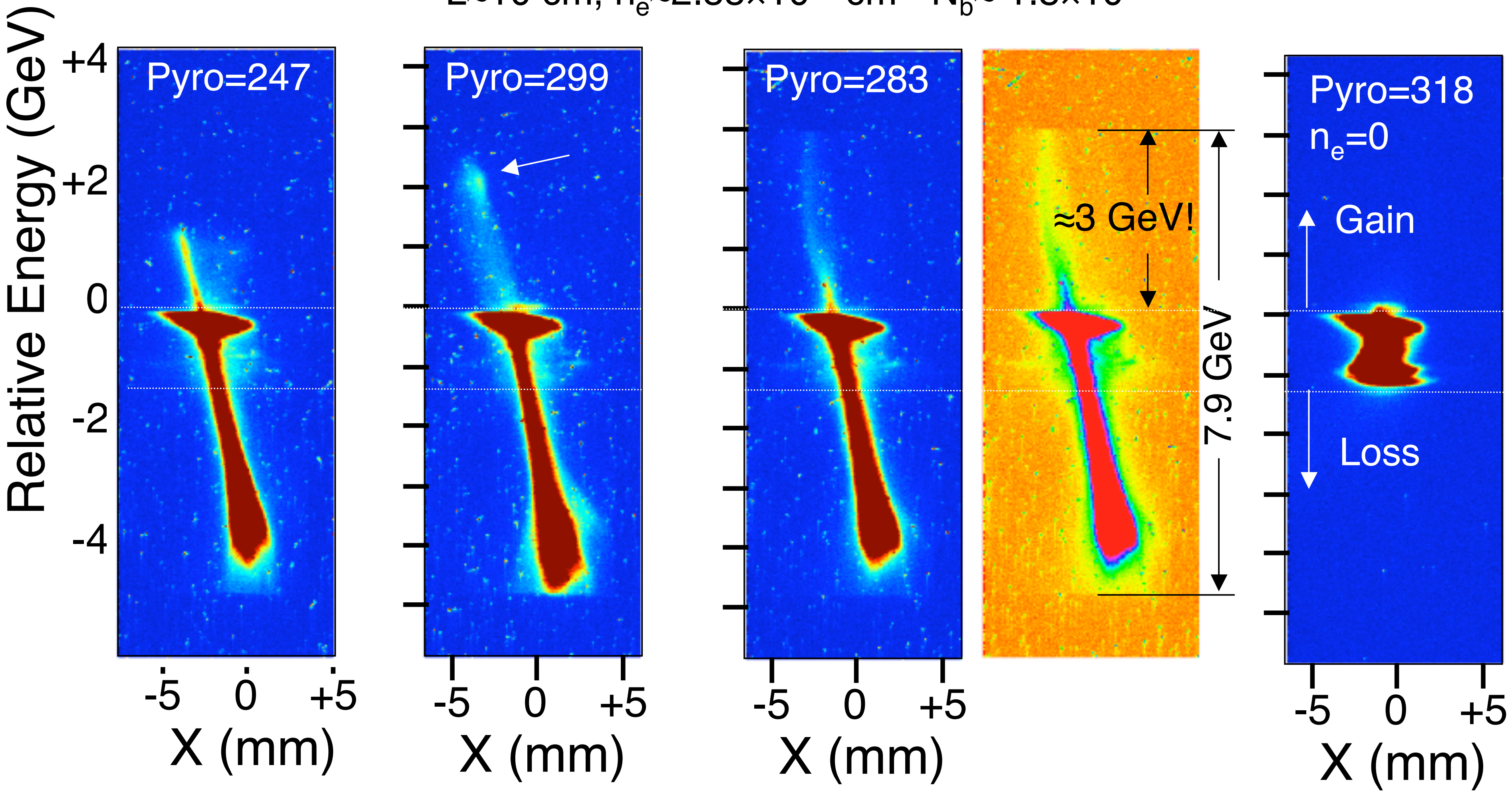
Bunch Length in E164X/Afterburner

Bunch Length in E-164

Bunch Length in E-157/E-162

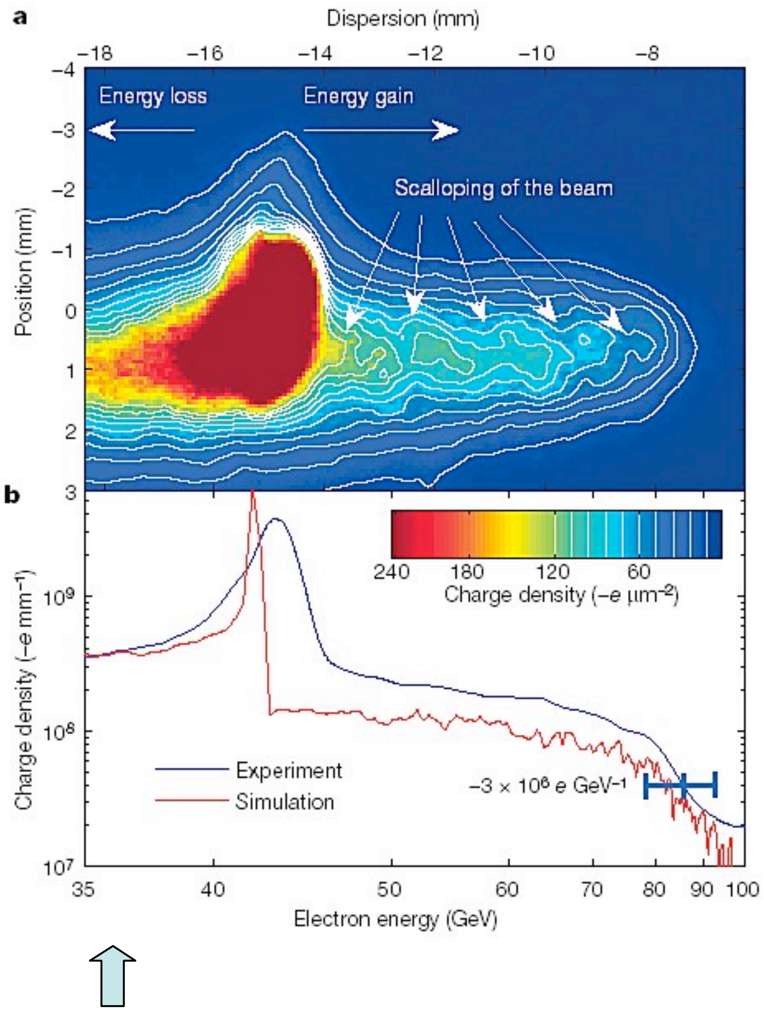
E-164X Breaks GeV Barrier

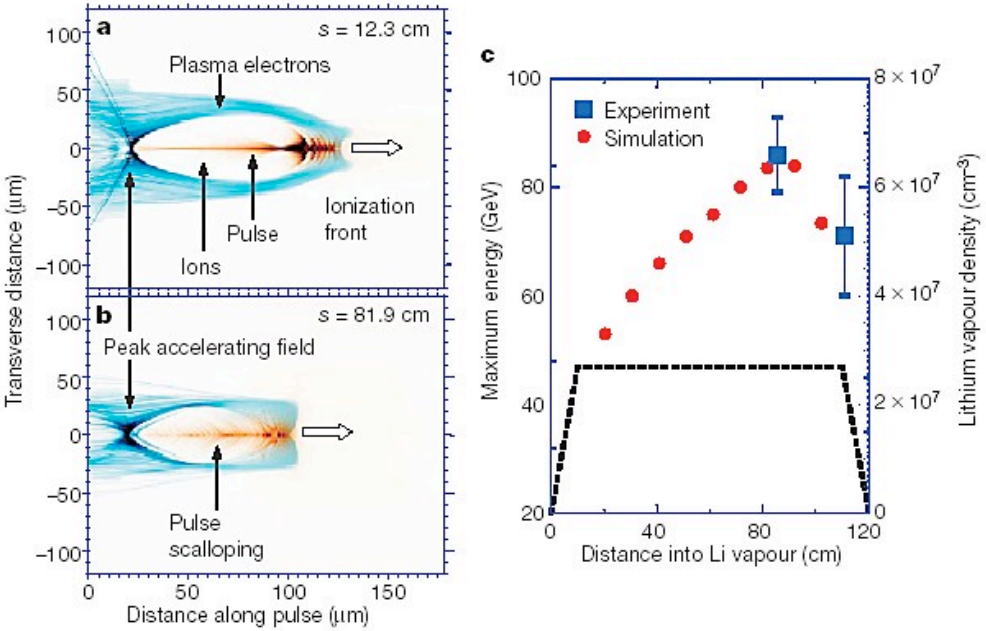
L≈10 cm, $n_e \approx 2.55\times10^{17}$ cm^{-3} $N_b \approx 1.8\times10^{10}$



➡ Energy gain exceeds ≈ 4 GeV in 10 cm

SLAC Plasma Wakefield Expt.





a,b) Density of electron pulse (brown) and plasma electrons (blue) at two different points in the plasma (12.3 and 81.9 cm). Scalloping features are the result of increasing focusing force.

c) Maximum energy reached after 85 cm. Saturation occurs due to the beam head spreading to the point that it can no longer ionize the lithium vapour.

⇧

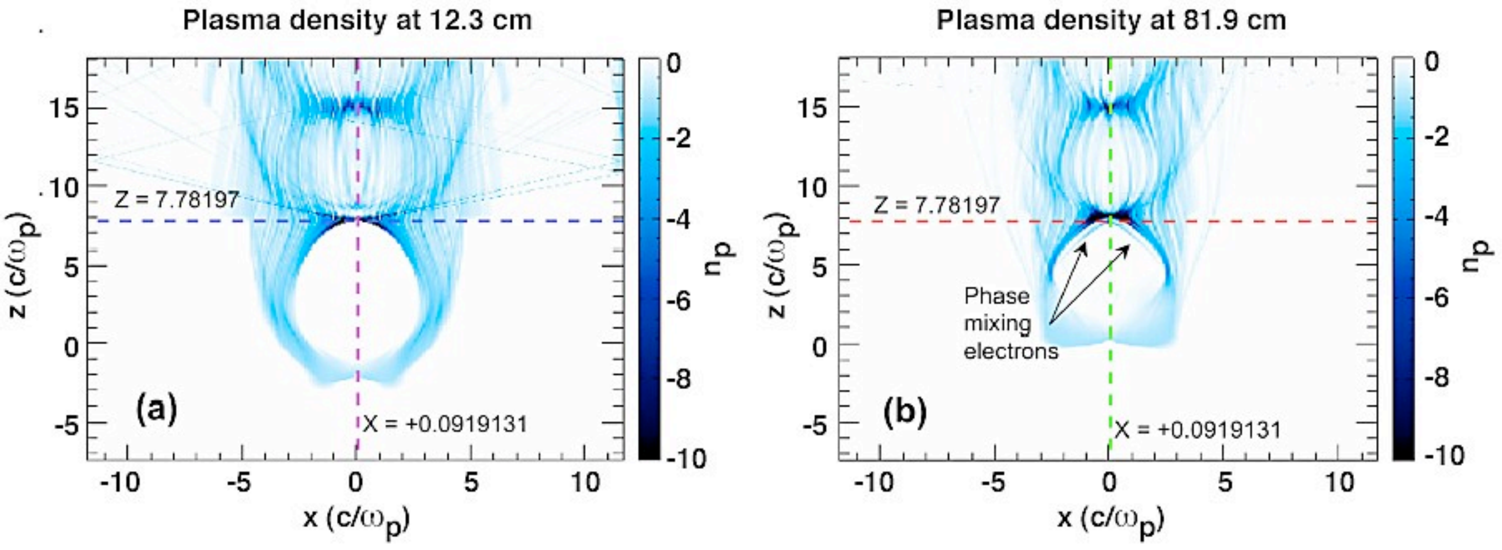
a) Energy spectrum of electrons in the 30-100 GeV range. Electrons reach 85 GeV (3x10^6 e/GeV).

b) Experimental (blue) and simulation (red)

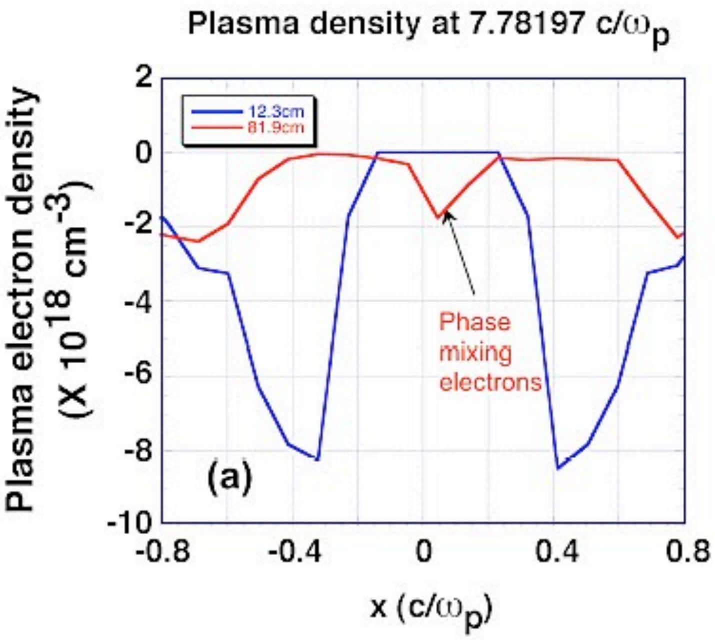
Reference: Blumenfeld *et al. Nature* (2007)

Plasma Density in Wakefield

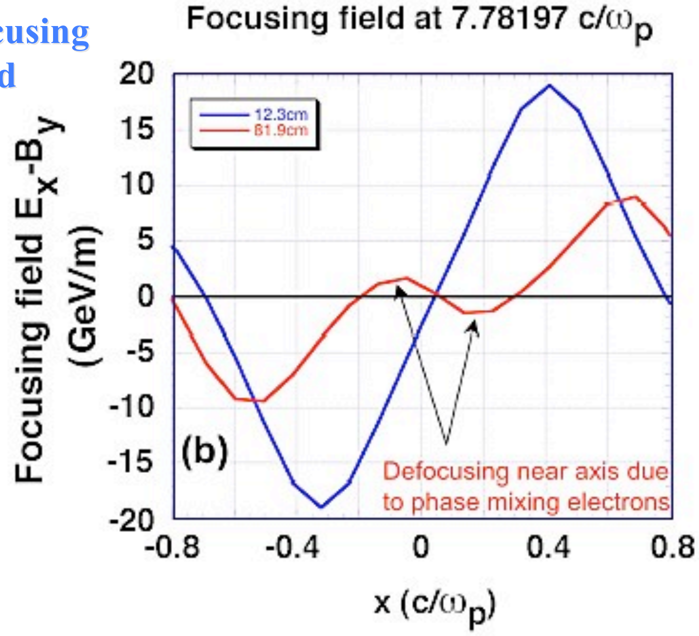
Plasma density (n_p) in units of 10^{18} cm^{-3} at two different locations.



Plasma density n_p at z = 7.78 c/ω_p

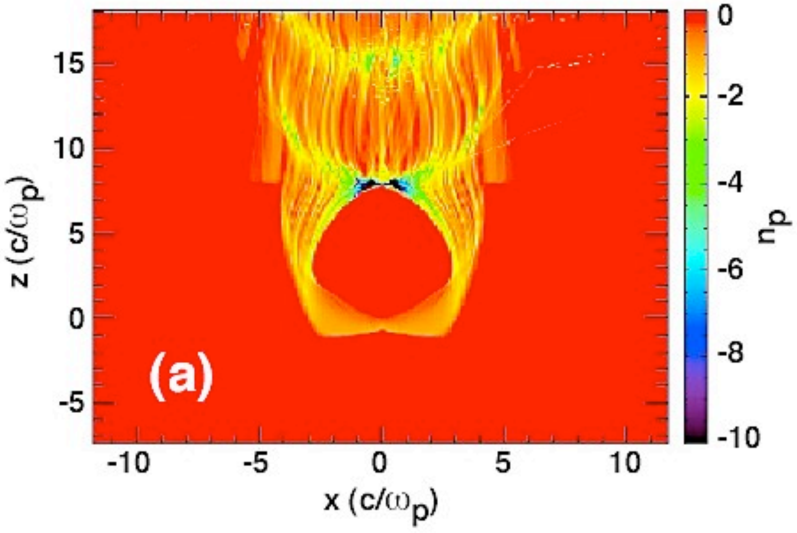


Focusing field

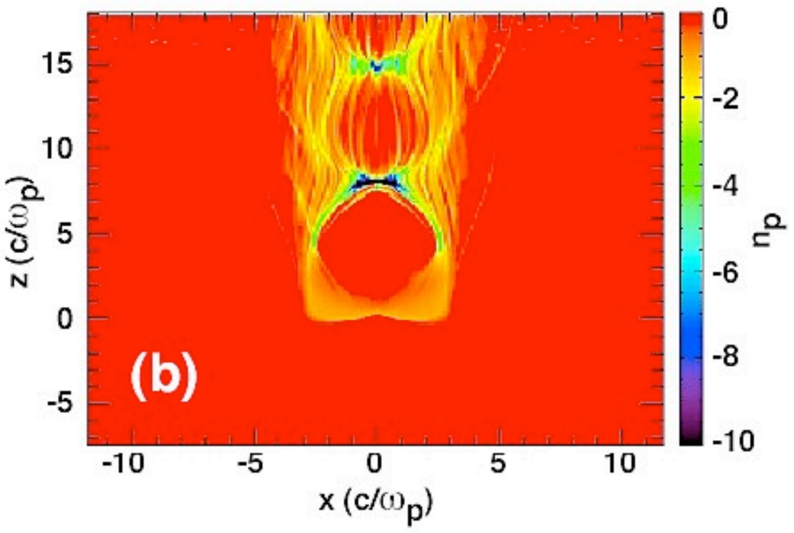


Plasma Density in Wakefield

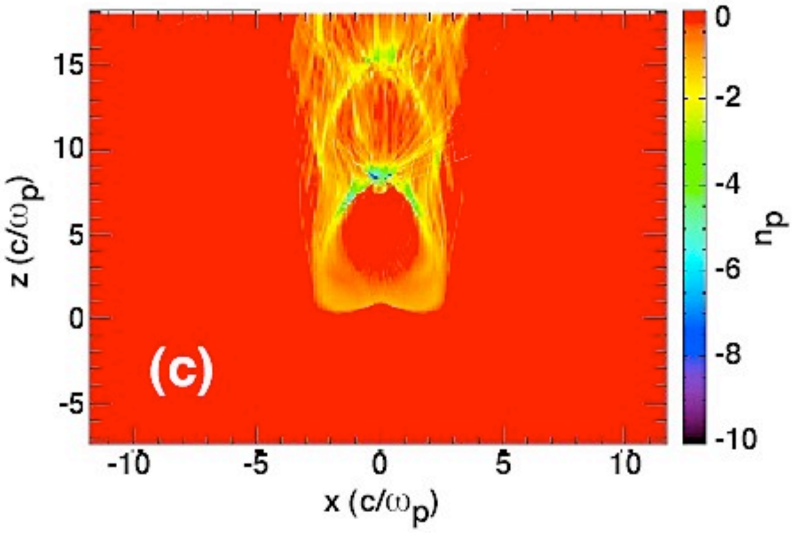
Plasma density at 61.4 cm



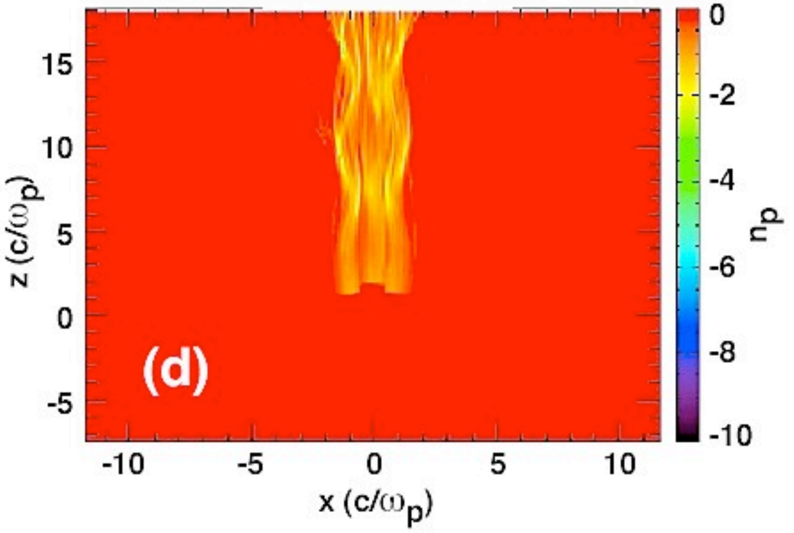
Plasma density at 81.9 cm



Plasma density at 90.1 cm

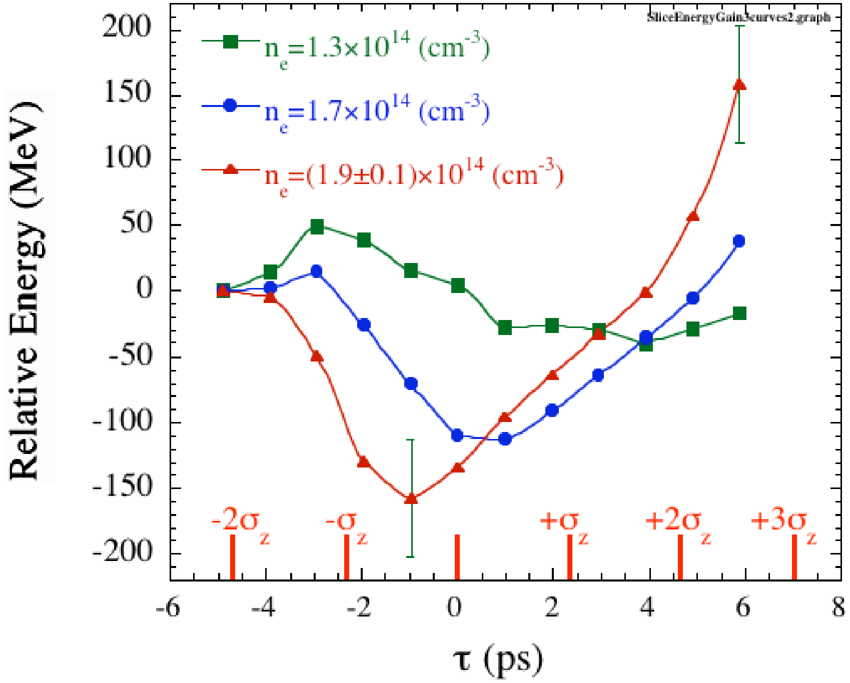


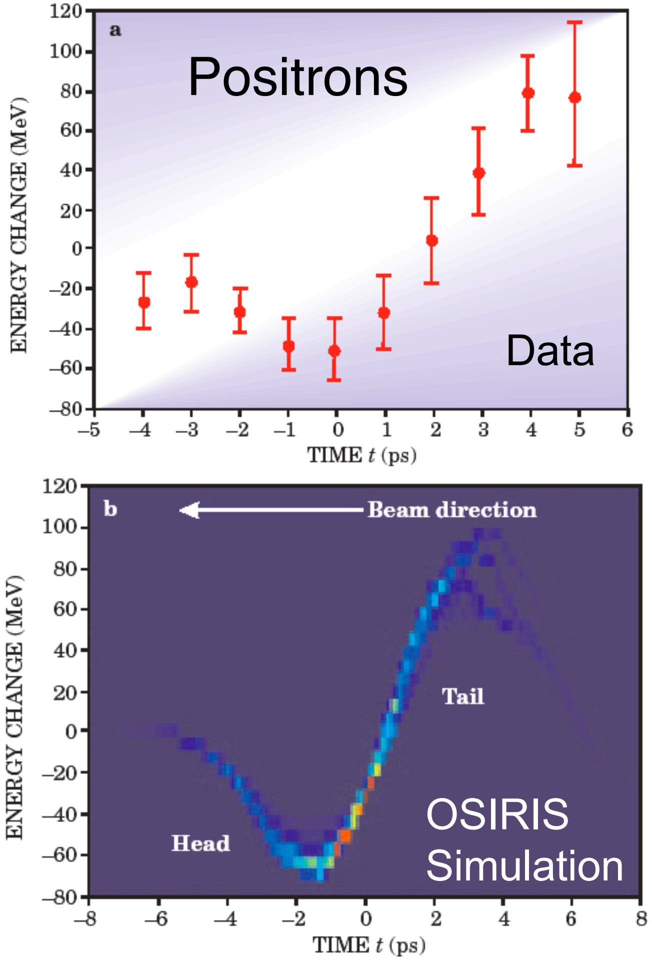
Plasma density at 94.2 cm



Acceleration Of Electrons & Positrons: E-162

Electrons





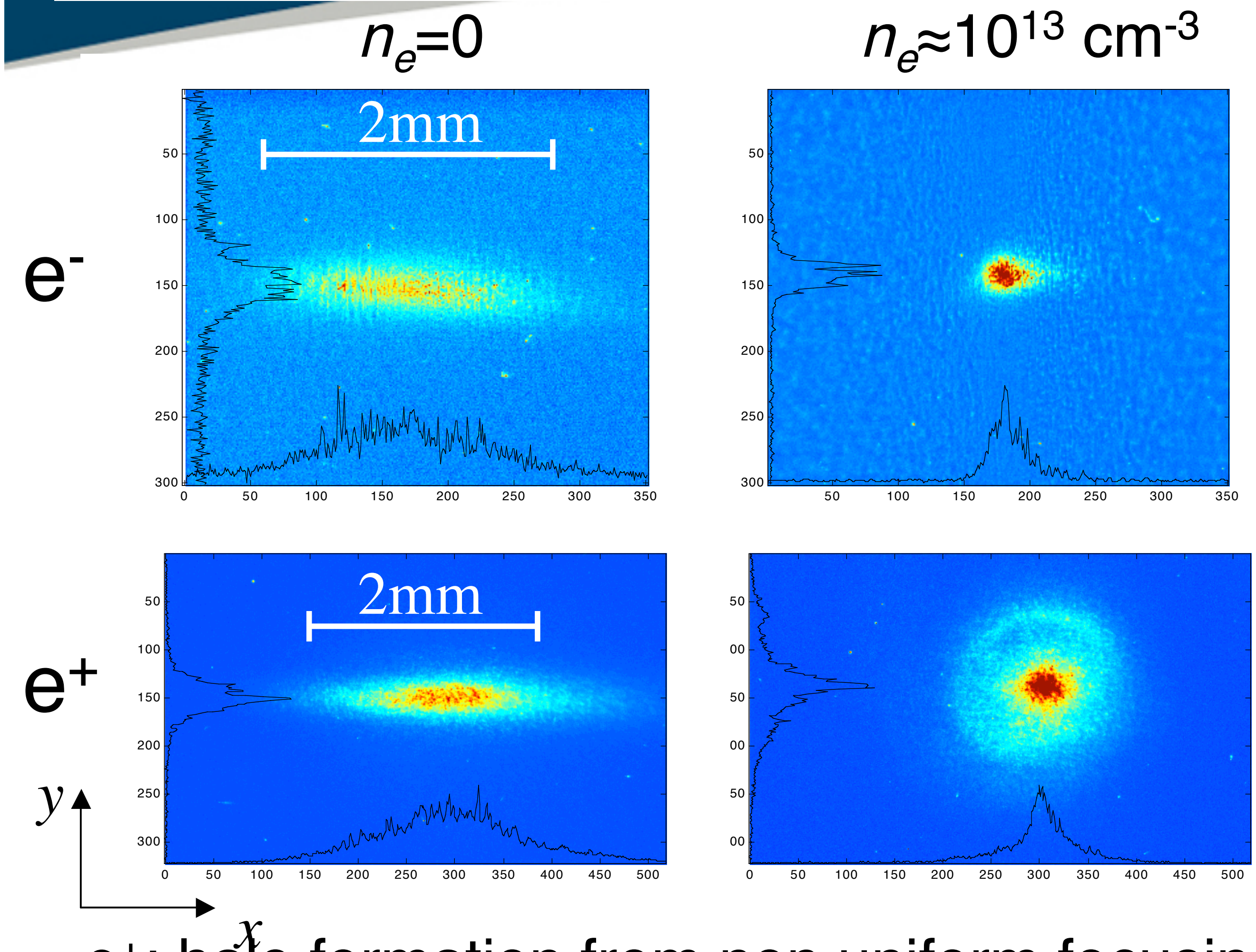
- Loss ≈ 50 MeV
- Gain ≈ 75 MeV

B. Blue *et al.*, *Phys. Rev. Lett*. 2003

R. Bingham, *Nature*, News and Views, 2003

Focusing of e^-/e^+ Beam

- OTR images ≈1m from plasma exit ($\varepsilon_x \neq \varepsilon_y$)



- Ideal Plasma Lens in Blow-Out Regime

- Plasma Lens with Aberrations

- e^+: halo formation from non uniform focusing

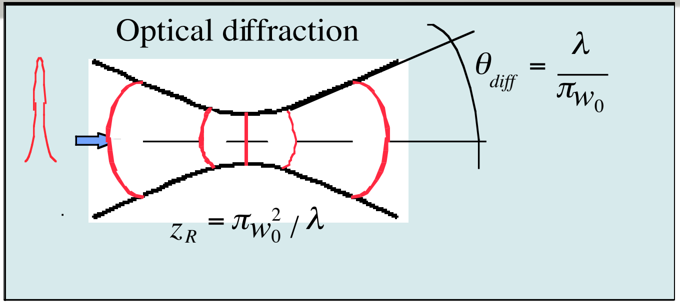
M.J. Hogan *et al.*, PRL, 2002; Also J. Ng et al., 2001

Key Issues

Key Issue	**Experiment**	**Theory/Simulation**
Acceler. Length	Channel Formation	1-to-1 models
mm → cm+		parallel
	Plasma Sources	3-D hybrid
Beam Quality	Injectors	Beam Dynamics
$\Delta\gamma$	50 fs bunch	matching β
ε	50 μm spot	injection phase
N	Blowout regime	
Efficiency		Drive beam evolution
(new) load		Shaped driver and
		Transformer Ratio

3 Limits to Energy gain DW=eE$_z$L$_{acc}$ (laser driver)

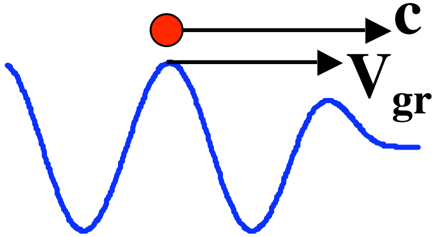
- **Diffraction:** $L_{dif} \cong \pi L_R = \pi^2 w_0^2 / \lambda$



order mm!

(but overcome w/ channels or relativistic self-focusing)

- **Dephasing:**



$$L_{dph} = \frac{\lambda_p/2}{1 - V_{gr}/c}$$

order 10 cm x 10^{16}/n$_o$

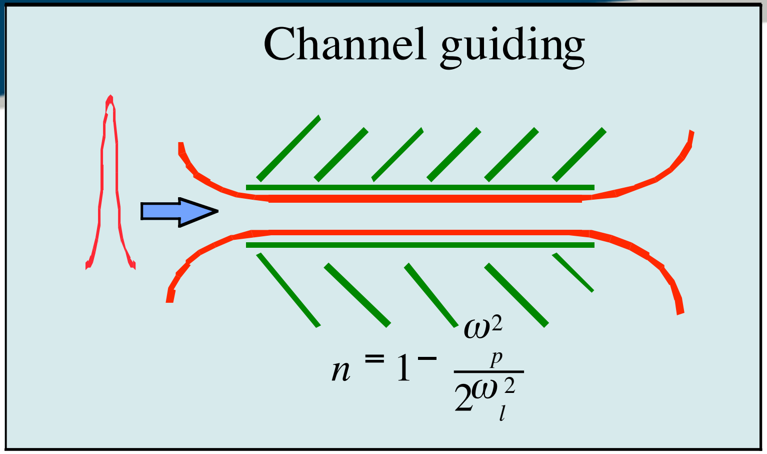
- **Depletion:**

For small a$_0$ >> L$_{dph}$
For a$_0$ >~ 1 L$_{dph}$~ L$_{depl}$

$$\Delta W_{ch}[MeV] \sim 60\left(\lambda_p / w_0\right)^2 P[TW]$$

Plasma channel: structure for guiding and acceleration

Channel guiding

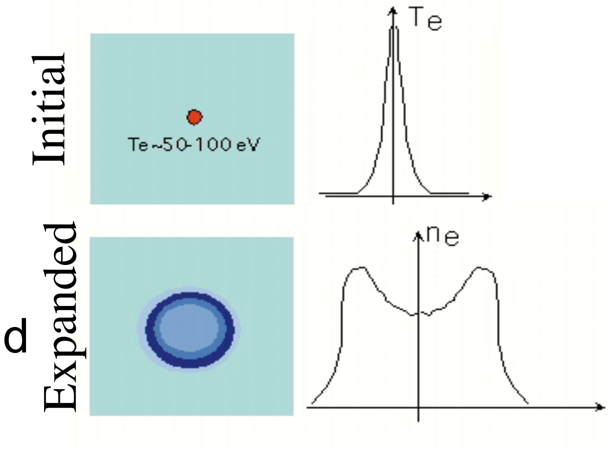


$$n = 1 - \frac{\omega_p^2}{2\omega_l^2}$$

Plasma Profiles

Step 1: Heat

Step 2: expand

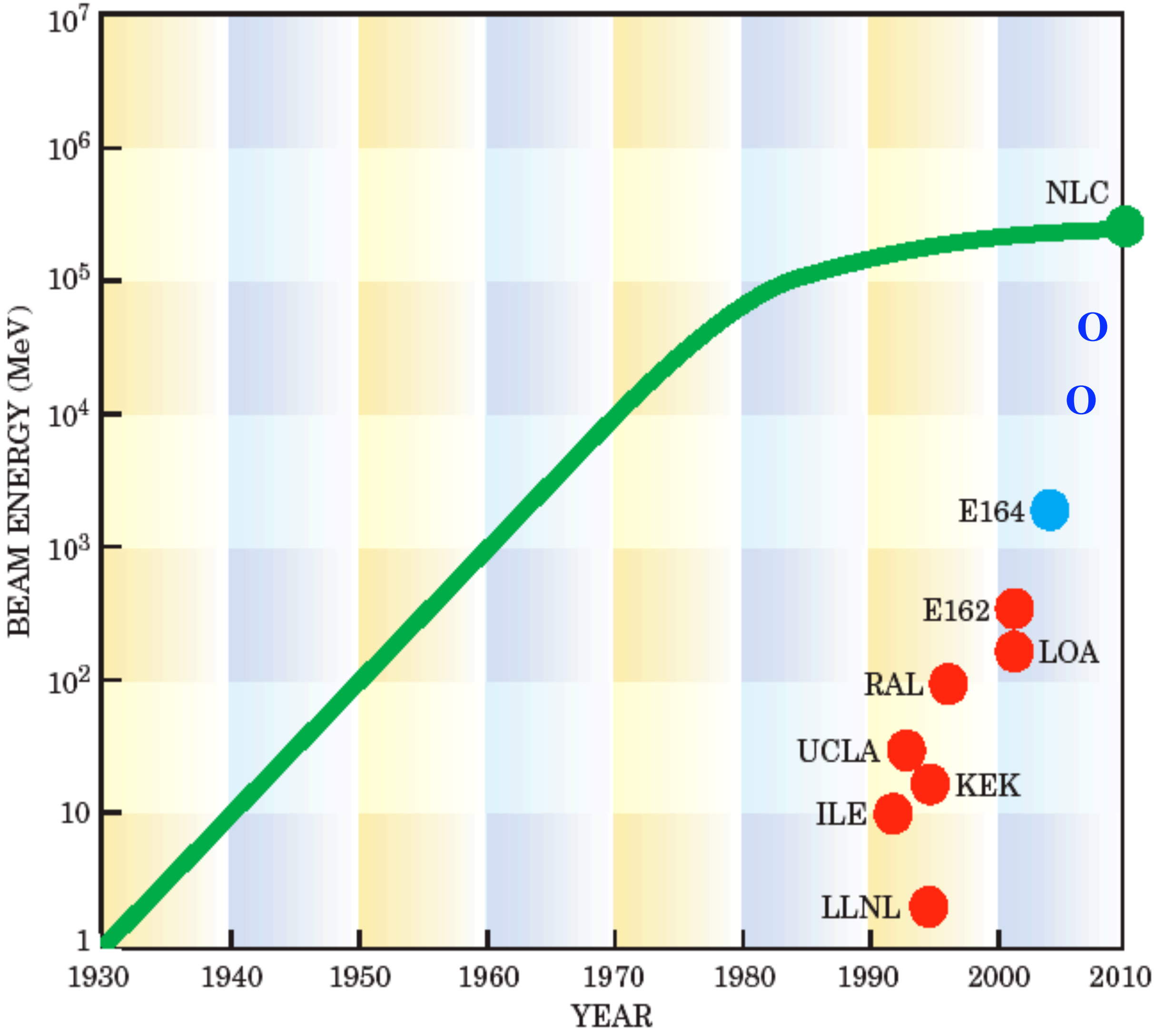


- Hydro-dynamically formed plasma channel
  - On-axis axicon (C.G. Durfee and H. Milchberg, PRL 71 (1993))
  - Ignitor-Heater (P. Volfbeyn et al., Phys. Plasmas 6 (1999))
  - Discharge assisted (E. Gaul et al., Appl. Phys. Lett. 77 (2000))
  - Cluster jets (Kim et al., PRL 90 (2003))
- Discharge ablated capillary discharges (Y. Ehrlich et al., PRL 77 (1996))
- Z-pinch discharge (T. Hosokai et al., Opt. Lett. 25 (2000))
- Hydrogen filled capillary discharge (D. Spence and S. M. Hooker, JOSA B (2000))
- Glass capillaries (B. Cross et al., IEEE Trans. PS 28(2000), Y. Kitagawa PRL (2004))

High Energy Particles

- Relativistic Plasma Wave Acceleration
- The problem is to generate large amplitude plasma wave travelling with a velocity close to the speed of light *c*
- 4 Approaches
  1. Plasma Beat Wave
  2. Laser Plasma Wakefield
  3. Self-Modulated Laser Wakefield (RFS)
  4. Electron Beam Plasma Wakefield

We are on the path to the energy frontier …



Requirements for High Energy Experiments

- Use Collider Parameters
- Luminosity = 10^{31} cm^{-2} sec^{-1}
- Beam Energy ~ 1 TeV
- No. of particles per pulse ~ 10^{11}
- Total Laser Energy (assuming 5% transfer efficiency) = 320 kJ/pulse
- Multiple staging required
- For a 100 stage accelerator requires 100 x 3 kJ lasers
- Power requirements :

$$P_{\mathrm{TOTAL}} = 320\ \mathrm{kJ} \times f \quad (\text{pulse rate second}^{-1})$$

$$P_{\mathrm{TOTAL}} = 1\ \mathrm{GW\ Power}$$

Ultra-Intense Laser Pulses

- Laser plasma accelerators and fast ignition both rely on ultra-intense laser pulses (CPA)

$I \geq 10^{18}$ W/cm^2

- Lorentz factor for oscillating electron

$\gamma \sim 2 - 10$

- For fast ignition a channel is formed guiding an intense laser pulse through the long scale length plasma to the compression core.
- Can the laser pulse propagate through the plasma and hit the core?
- Can instabilities like RFS absorb the energy?

⇒ relativistic electrons

⇒ pions

Conclusions

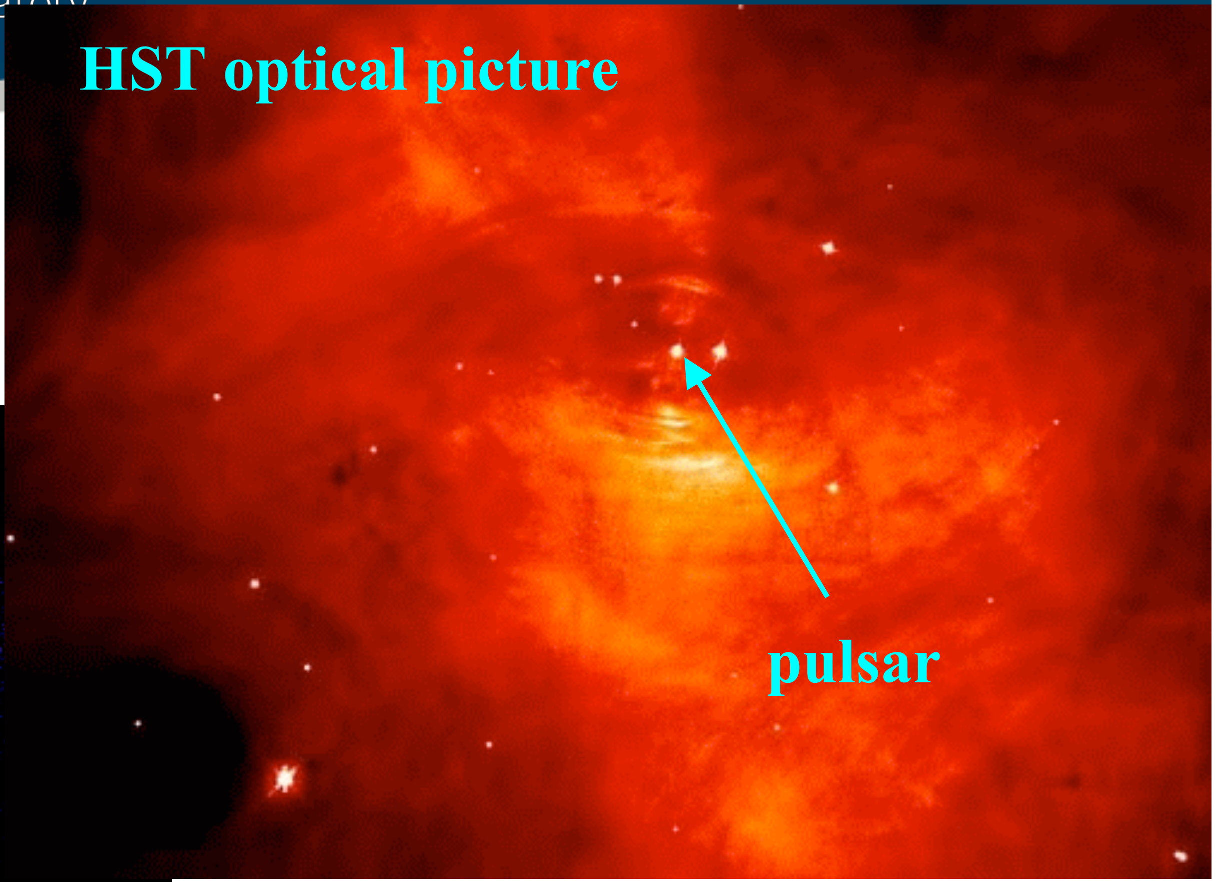
- Laser Plasma Accelerators > 1 GeV

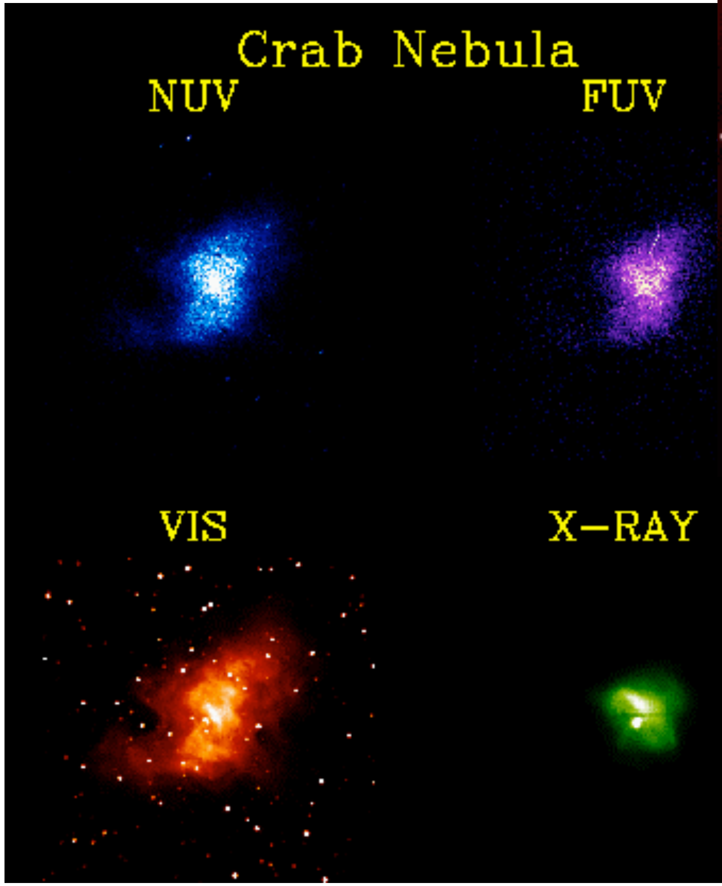
- 85 GeV achieved by SLAC e-beam Wakefield Experiment in 85cm.

- Numerous applications for 100 MeV-10 GeV beams – Medicine, Light Sources, Industry

- Ultra-High energies can be achieved by using a plasma afterburner on existing facilities – energies can be boosted up to 100 GeV

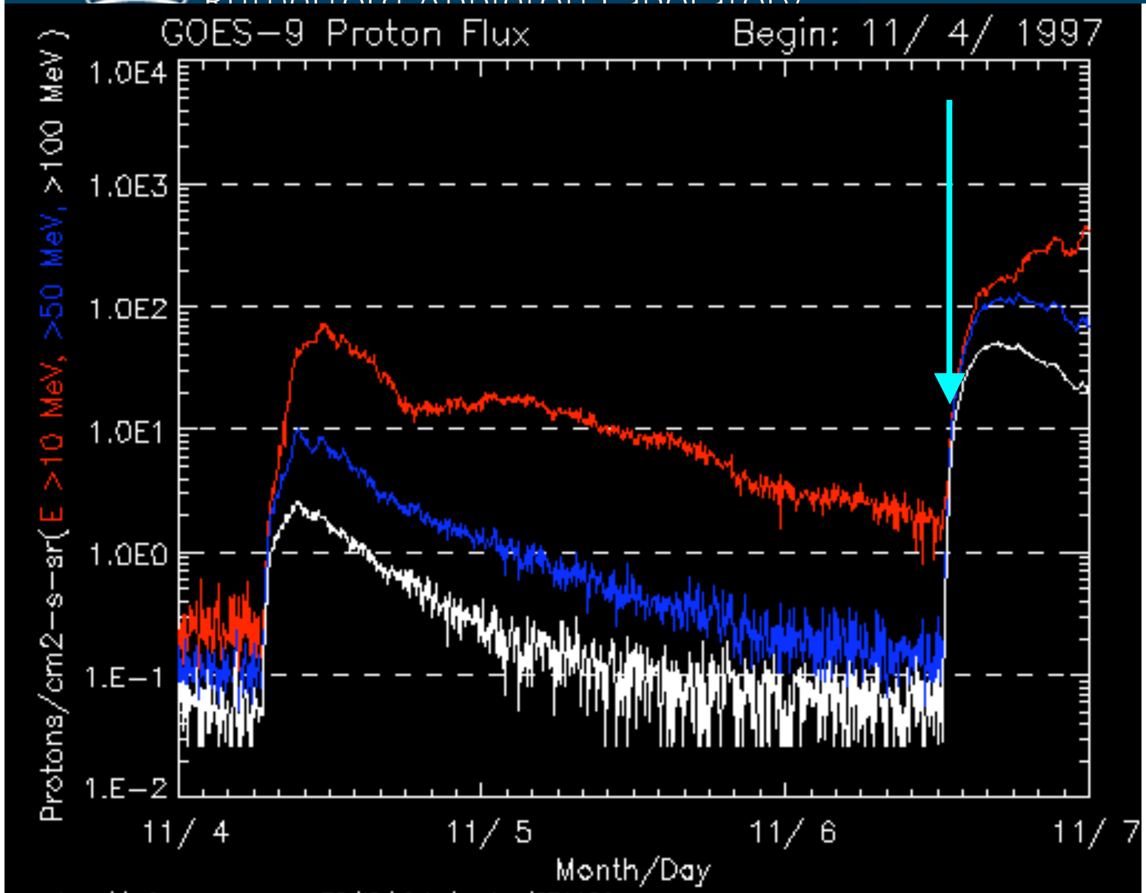
Pulsars – The Crab Nebula



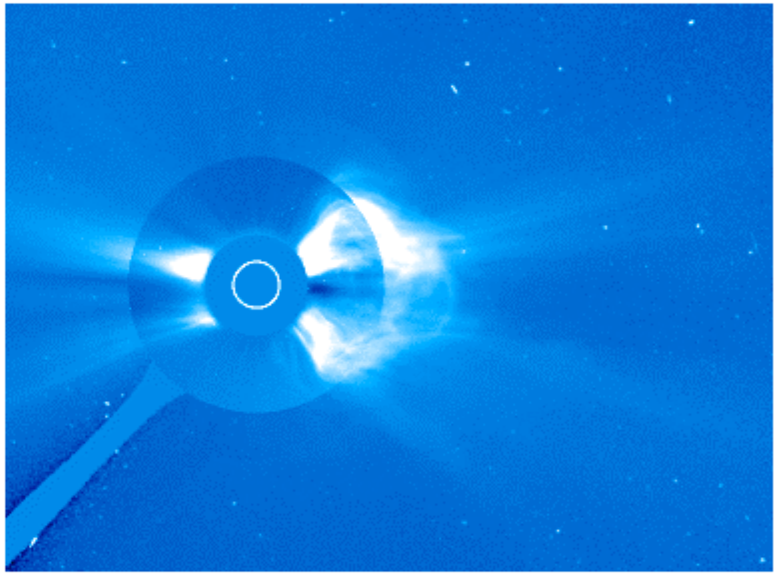


The Crab Nebula is the remnant of a supernova explosion seen by the ancient Chinese in AD 1054. The Crab pulsar is almost unique in being detectable from radio right down to gamma-ray wavelengths.

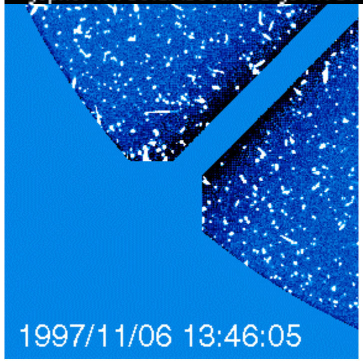
Solar Cosmic Rays



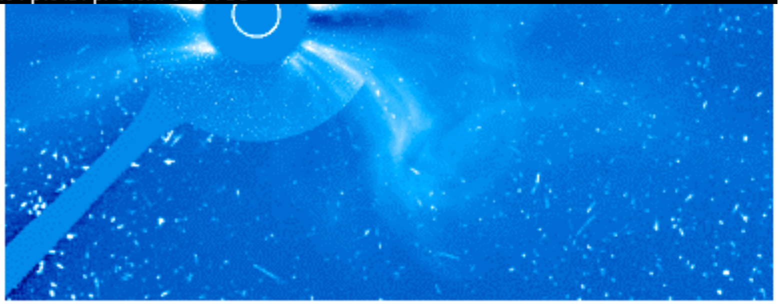
gopher://solar.sec.noaa.gov:70/I9/plots/proton/971106



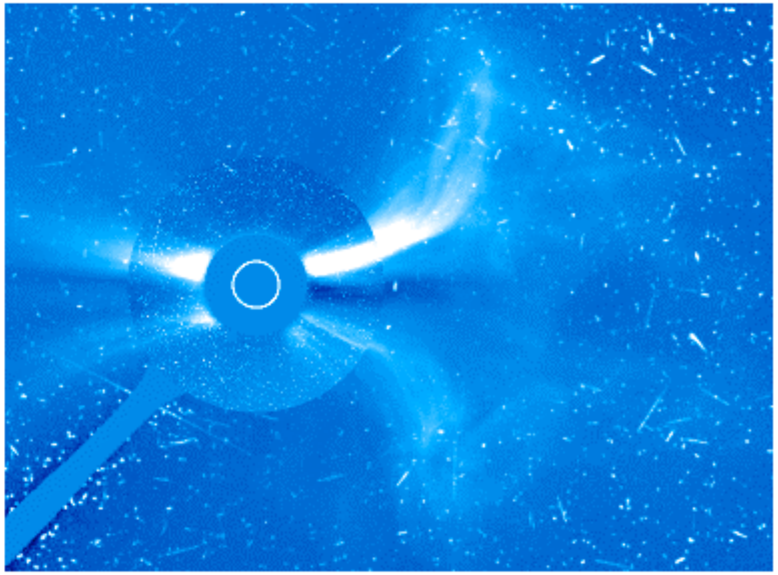
12:36(C2) 12:41(C3)



1997/11/06 13:46:05



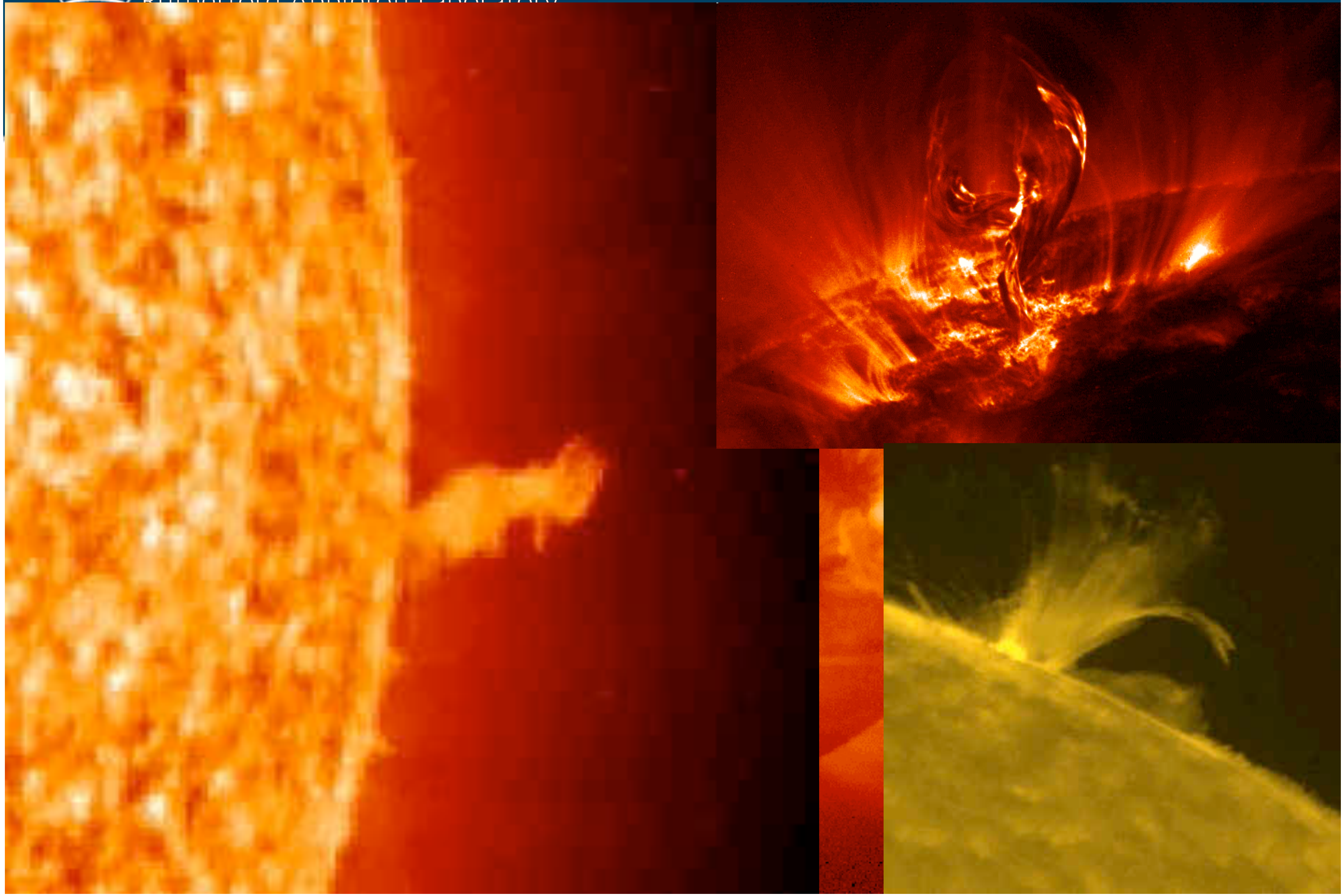
13:30(C2) 13:46(C3)



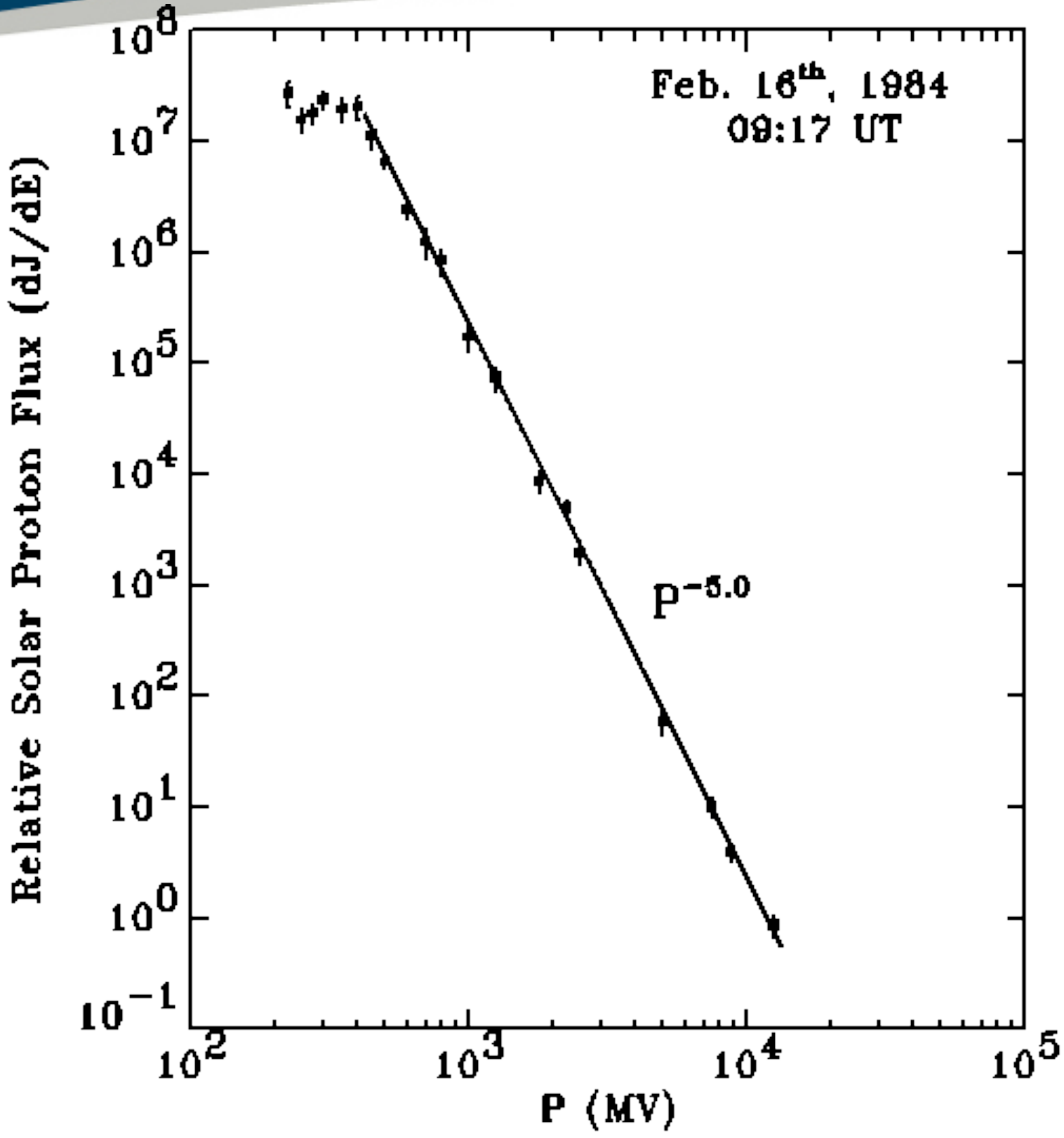
14:26(C2) 14:12(C3)

SOHO/LASCO

X-ray Sun



Solar Energetic Proton Spectrum



Plasma Acceleration

In space plasmas most of the energy is stored in the magnetic fields.

e.g. magnetic loops in the Sun, pile-up of magnetic flux at the bow shock, the front of comets and the tail of magnetospheres.

Through a violent disruption effect like reconnection of magnetic fields energy is transferred to the ions

⇒ **Ion streams**

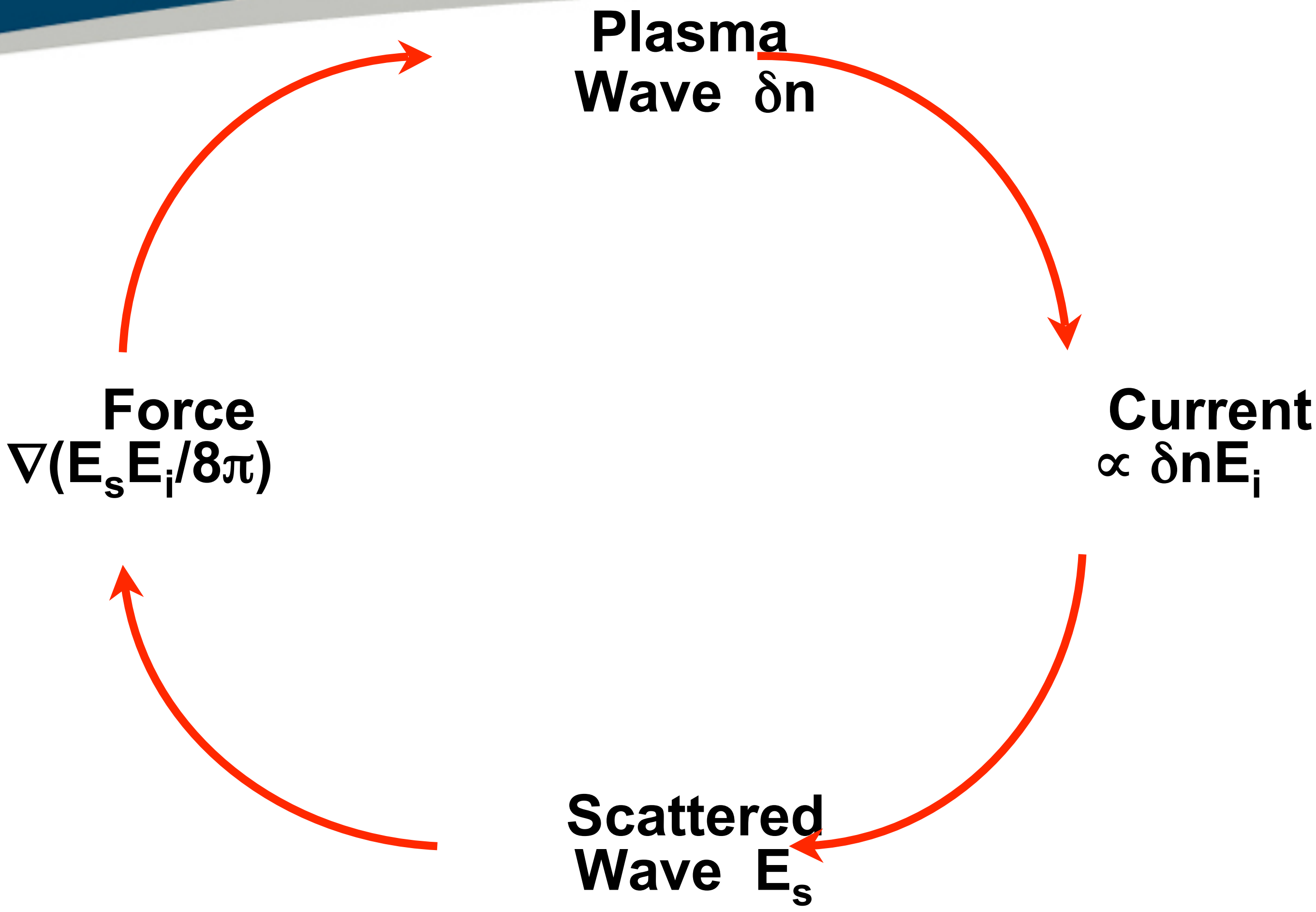
Observed in the magnetotail and the Sun?

The solar wind is also a source of free energy which can be used *i.e.* Interaction of the solar wind with the bow shock and with comets.

Supernovæ remnants - the shock catches up with the circumstellar material to create very hot plasma.

Relativistic jets - particles accelerated to relativistic energies. Also highly collimated.

Stimulated Raman Scattering



Plasma Wave δn

Current $\propto \delta n E_i$

Scattered Wave E_s

Force $\nabla(E_s E_i/8\pi)$

Feedback mechanism for stimulated Raman scattering.

Raman Forward Scattering

An EM wave (ω_0, $\underline{k}_0$) scatters into two co-propagating sidebands ($\omega_p \pm \omega_0$, $\underline{k}_p \pm \underline{k}_0$) and a plasma wave ($\omega_p$, $\underline{k}_p$)

Plasma wave

$$v_{ph} = \frac{\omega_p}{k_p} \approx c$$

The spatiotemporal growth rate is described as a gain

$$G = \left(\frac{1}{2\pi g}\right)^{1/2} e^{g}$$

$$g = \frac{a_0}{\sqrt{2}}\left(1 + \frac{a_0^2}{2}\right)\left(\frac{\omega_p}{\omega_0}\right)^2 \frac{\omega_0}{c}\sqrt{x\varphi} \qquad \text{(Mori et al. 1994)}$$

Fermi and MHD turbulence – Stochastic

- Fermi or stochastic acceleration of particles in turbulent fields is possible.
  - e.g. Pitch angle scattering from Alfvén waves
  - Mechanism needs pre-accelerator
  - Ω^* relativistic gyro frequency

$$\lambda_A \cong \rho_i$$

$$P_{initial} \cong m_i V_A$$

$$\omega = k_{||} V_A = k_{||} v_{||} + \mathrm{n}\Omega^*$$

Magneto acoustic turbulence + LH Turbulence

Ideal for protons etc., surfatron mechanism (similar to shock acceleration)

Possible to produce relativistic electrons (Lembege+Dawson *Phys.Fluids*, **B**1, 1001 [1989])

Protons

$$E_x \cong \frac{m_i}{e} V_A^2 \left(\frac{c}{\omega_{pe}} \right)^{-1} (M-1)^{3/2}$$

$$v_{\max} \cong \left(\frac{m_i}{m_e} \right)^{\frac{1}{2}} V_A (M-1)^{3/2}$$

$$E_{proton} \cong 1\, GeV$$

Steady State Solution

- The average gain is $\Delta T = \pm vT/c$, where T is the kinetic energy and v is the speed of the magnetic cloud.
- Positive gain for particle and cloud moving towards each other, negative gain for moving away.
- Statistically more head on collisions – particles gain energy on average.

$$\frac{dT}{dt} = n\left(\frac{v}{c}\right)^2 T$$

n is number of collisions per unit time

- If particles are lost at a rate l/τ, then obtain power law distribution

f number of particles in range dT then

$$\frac{\partial f}{\partial t} = -\frac{\partial}{\partial t}(\alpha T f) - \frac{f}{\tau}$$

$$\alpha = \left(\frac{v}{c}\right)^2 n$$

- Steady state solution ⇒ $f = const.\ \mathrm{x}\ T^{-(1+1/\alpha\tau)}$