The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

SMR 1673/49

AUTUMN COLLEGE ON PLASMA PHYSICS

5 - 30 September 2005

Plasma Accelerators

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Space Science & Technology Department
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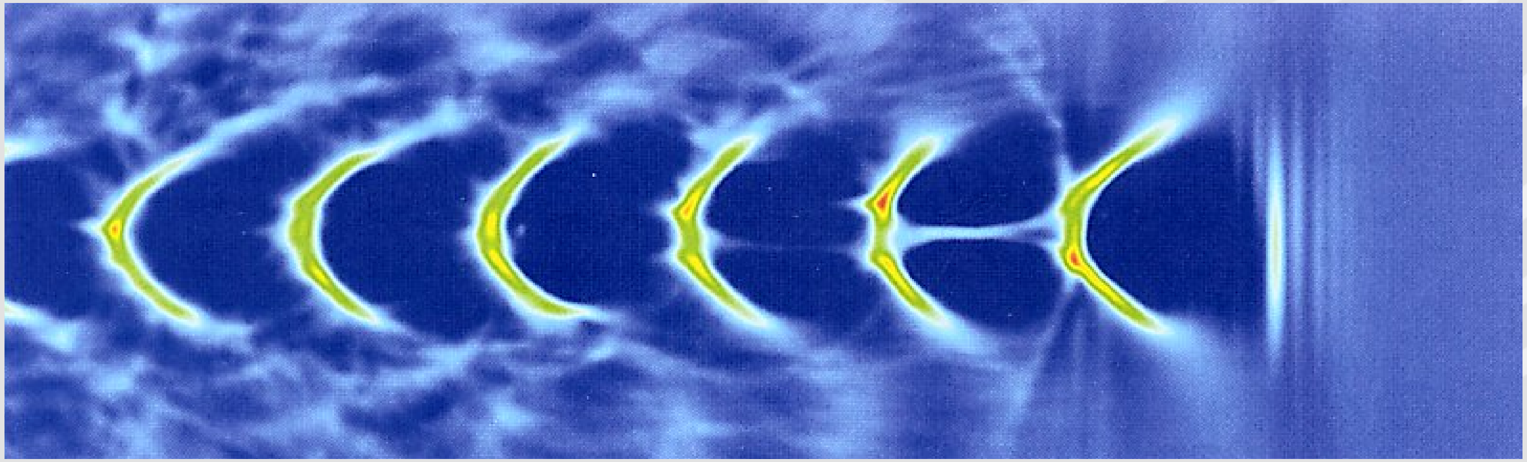
Abdus Salom ICTP Plasma Physics , 2005

Rosenbluth Symposium

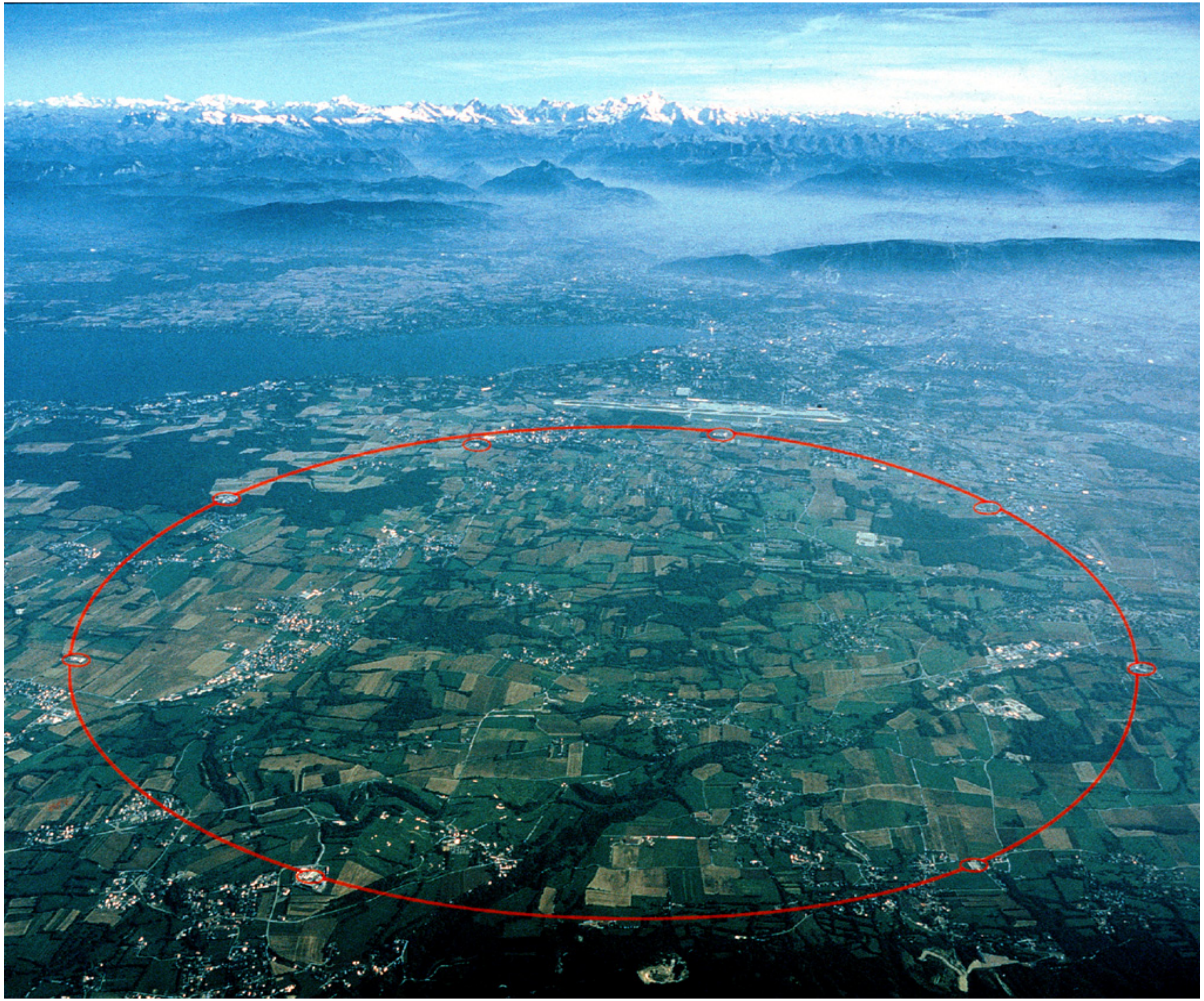
Plasma Accelerators

Robert Bingham

Rutherford Appleton Laboratory,
Centre for Fundamental Physics



CERN – LEP



SLAC

Laser Plasma Interactions

Marshall Rosenbluth contribution enormous!

Parametric Instabilities:

Raman, Brillouin, filamentation, self-modulational, scattering.

Seminal papers on role of inhomogeneity PRLs

(All important for laser fusion)

Plasma Accelerators:

Relativistic Plasma Wave

- Saturates by relativistic de-tuning
- Rosenbluth Lui saturation PRL (1972)

Nonlinear Vacuum:

Photon-photon scattering PRL (1970)

Laser Plasma Accelerators

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

Plasma Accelerators – Why Plasmas?

Conventional Accelerators

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

Plasma

- No breakdown limit
- 10-100 GV/m

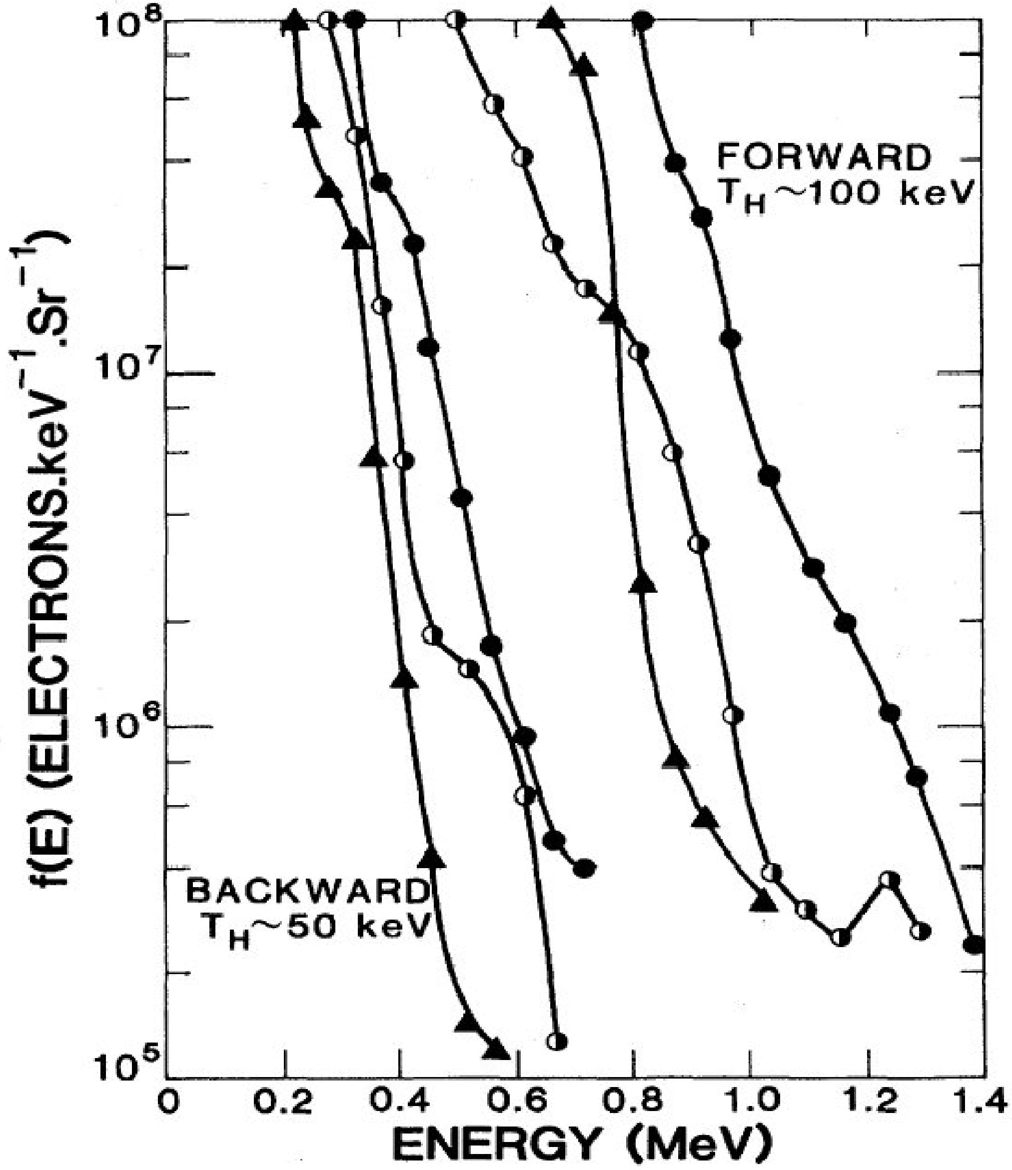
High Energy Particles

- 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

PRL, 43, 267 (1979), PRL, 54, 693 (1985)

Joshi, PRL 47, 1285, 1981

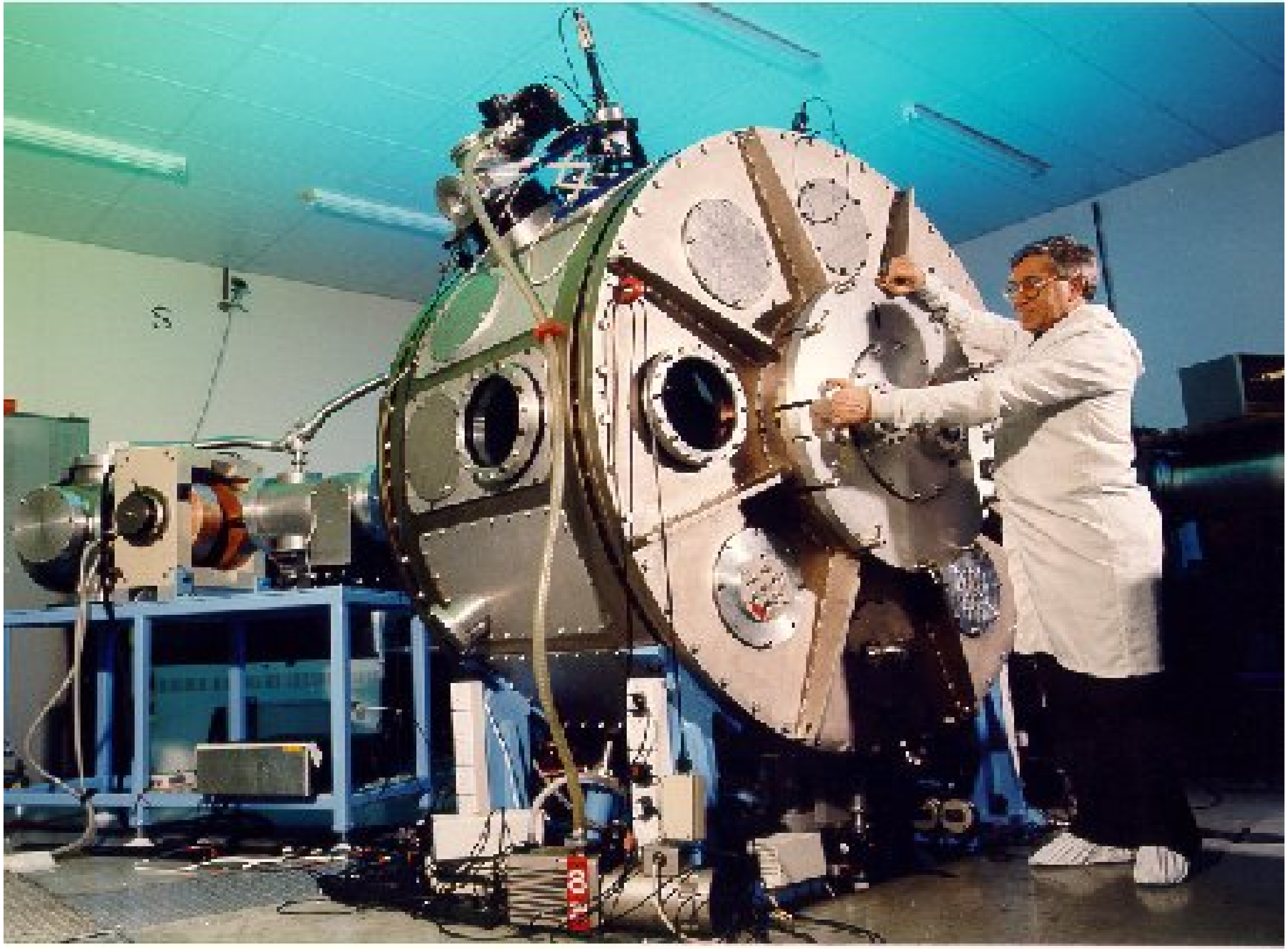
Experimental electron energy distributions in the forward and backward directions. Three different shots are represented.



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 proposed Stanford/USC/UCLA experiment to generate 1*GV/m* accelerating gradient using the 30 – 50*GeV* beam in a 1 meter long Lithium Plasma.

Vulcan Target Area



Laser Plasma Accelerators

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

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

- For short pulse intense lasers,

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

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

- 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.

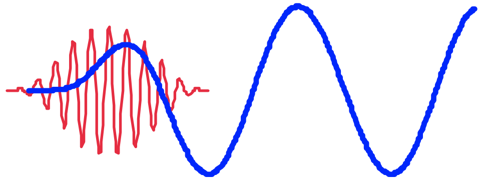
Laser Plasma Accelerators

- Large accelerating fields ~1 *GeV/cm*
- No electrical breakdown limit

Laser Wakefield Acceleration

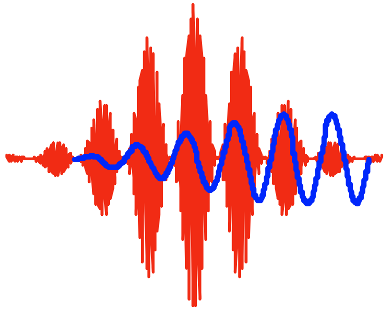
- Laser Wake Field Accelerator(LWFA)

  A single short-pulse of photons



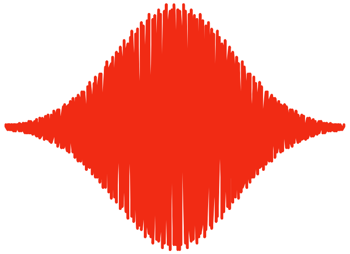
- Plasma Beat Wave Accelerator(PBWA)

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

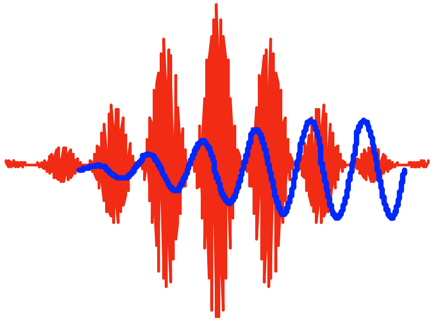


- Self Modulated Laser Wake Field Accelerator(SMLWFA)

  Raman forward scattering instability



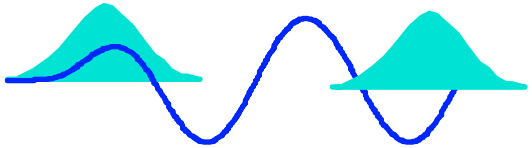
evolves to



Concepts for Plasma based Accelerators

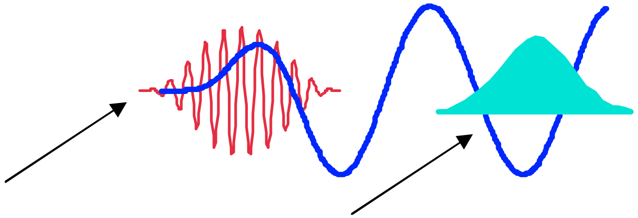
- Plasma Wake Field Accelerator(PWFA)

  A high energy electron bunch



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

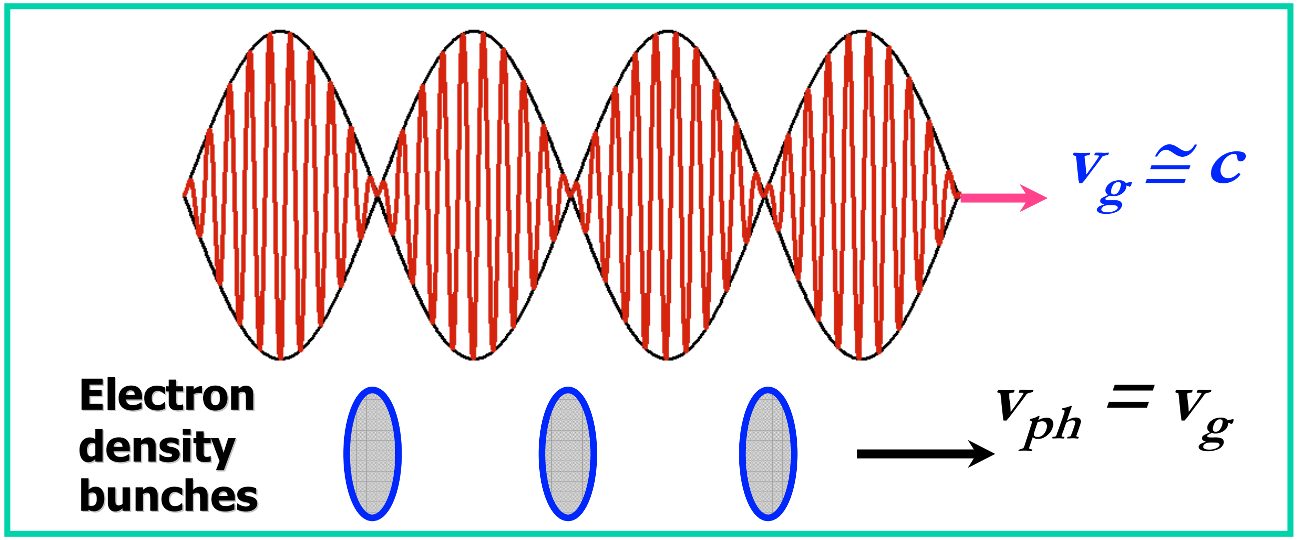
  A single short-pulse of photons



- Drive beam
- Trailing beam

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

$$E_{||} = \varepsilon\sqrt{n_0} \qquad \text{V/cm}$$

ε is the fractional electron density bunching, n_0 is the plasma density. For $n_0 = 10^{18}$ cm^{-3}, $\varepsilon = 10\%$ $\Rightarrow$ $E_{||} = 10^8$ 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. $\omega_1 = 10\omega_p$ $\omega_2 = 9\omega_p$

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

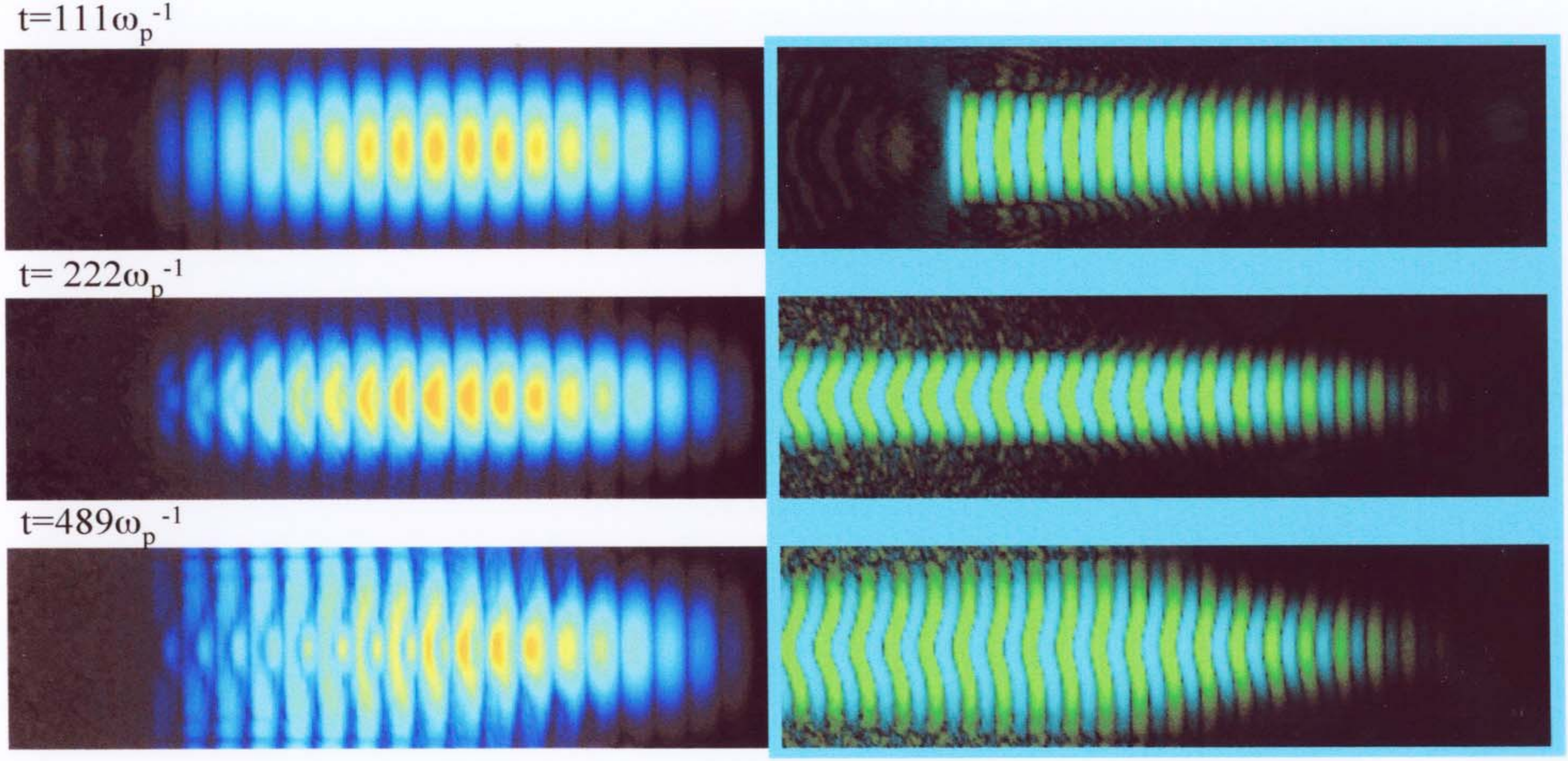
$\mathbf{v_g}$ is the group velocity of the laser beat pattern.

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 $\omega_1, \omega_2 \rangle\rangle\, \omega_p \Rightarrow \mathrm{v_g} \approx c \Rightarrow$ “Hence relativistic”

PBWA: Evolution of Laser Intensity and Accelerating Field



$t=111\omega_p^{-1}$

$t=222\omega_p^{-1}$

$t=489\omega_p^{-1}$

Energy Gain

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

$$\Delta W = 2\,\varepsilon\,\gamma^2 m_e c^2$$

- $\gamma = \omega_1/\omega_p$ is the Lorentz factor
- For a neodymium laser, $\omega_1/\omega_p \sim 30$, and $n_0 \sim 10^{18}$ cm^{-3}
- Maximum energy gain $\Delta W \approx eE_p\, l$

l dephasing length

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

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

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

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.

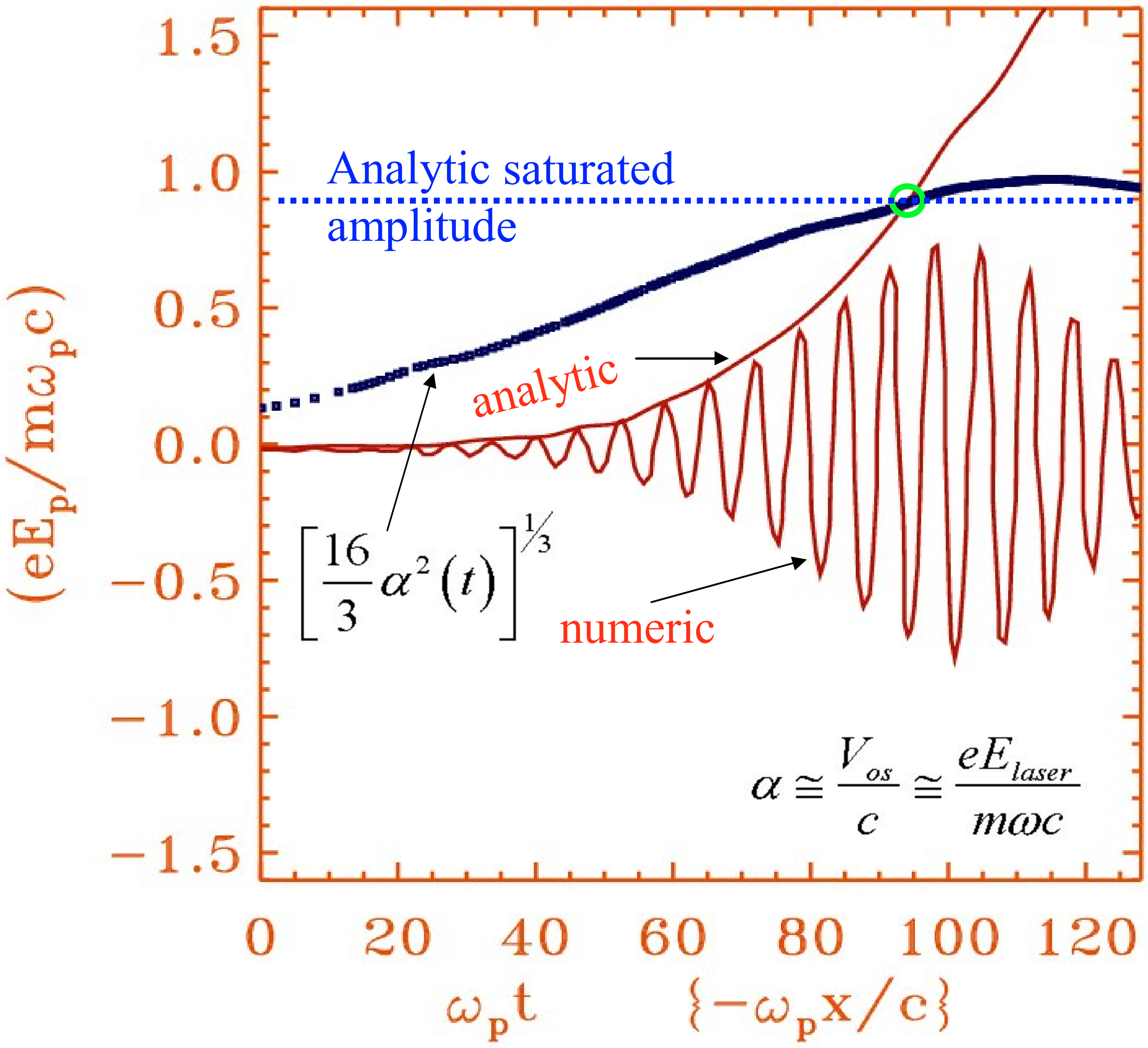
$$\frac{\delta n}{n}\max = \left(\frac{16}{3}\alpha_1\alpha_2\right)^{1/3} = \varepsilon$$

Relativistic mass increase of electrons reduces natural frequency

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

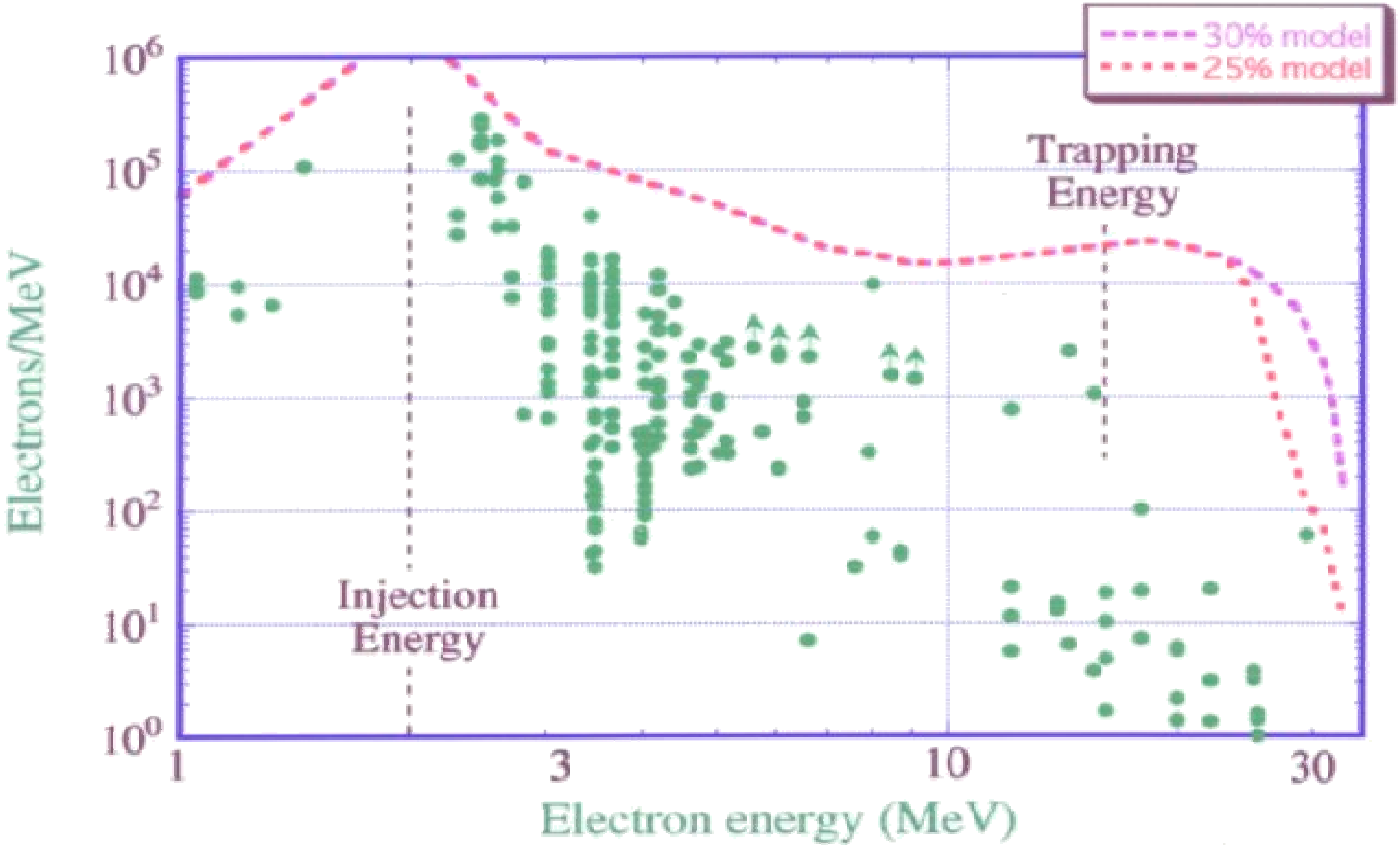
This results in $\omega_1 - \omega_2 \neq \omega_p$ ⇒ non-resonant interaction ⇒ saturation.

Beat Wave Growth



UCLA Beatwave Results

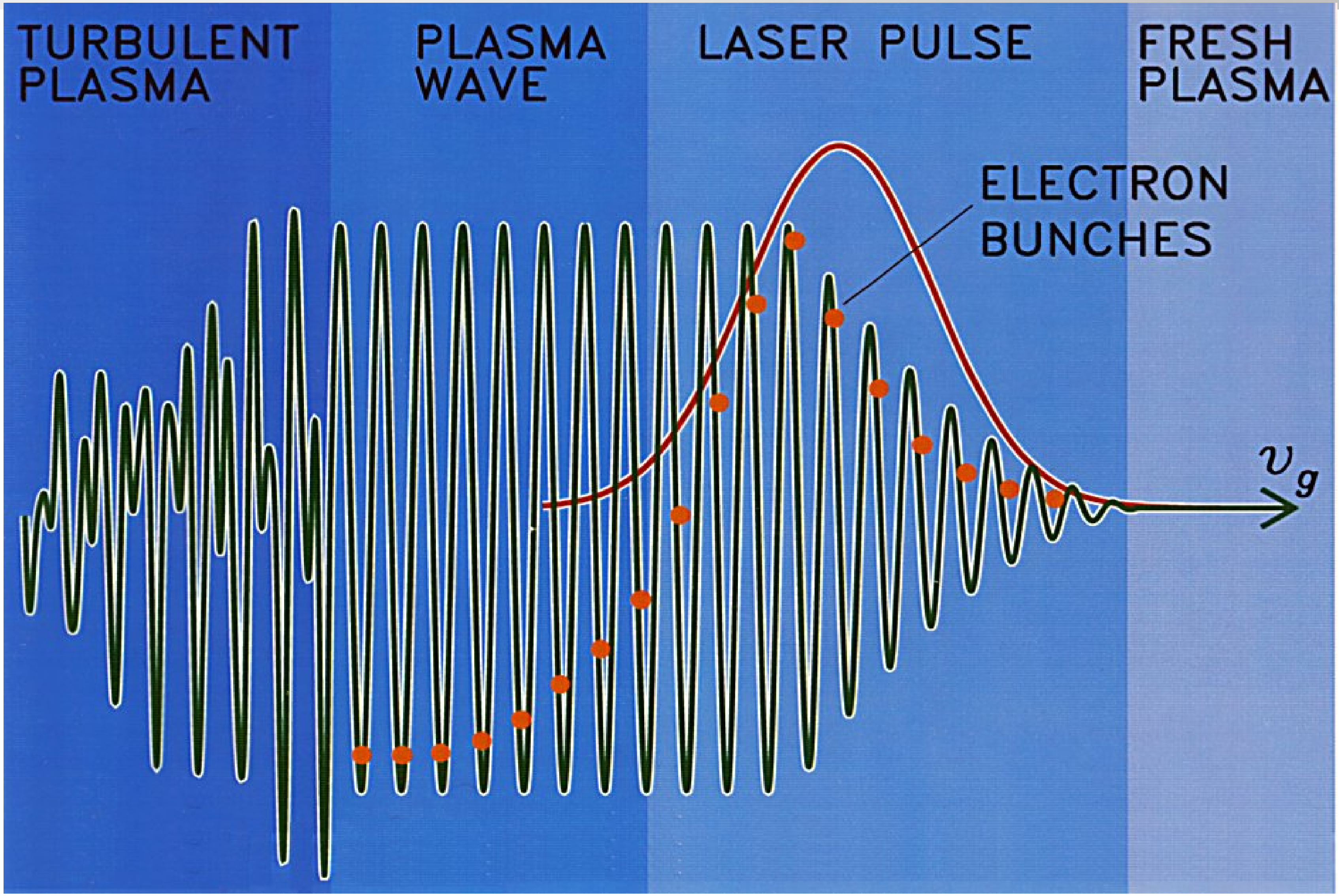
- Electrons injected from 0.3 GHz rf LINAC ⇒ train of pulses, <10ps duration



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

CCLRC
Rutherford Appleton Laboratory

Limitations of beatwave scheme



Ion dynamics becomes important: strong plasma turbulence driven by electron plasma waves destroys the accelerating wave structure.

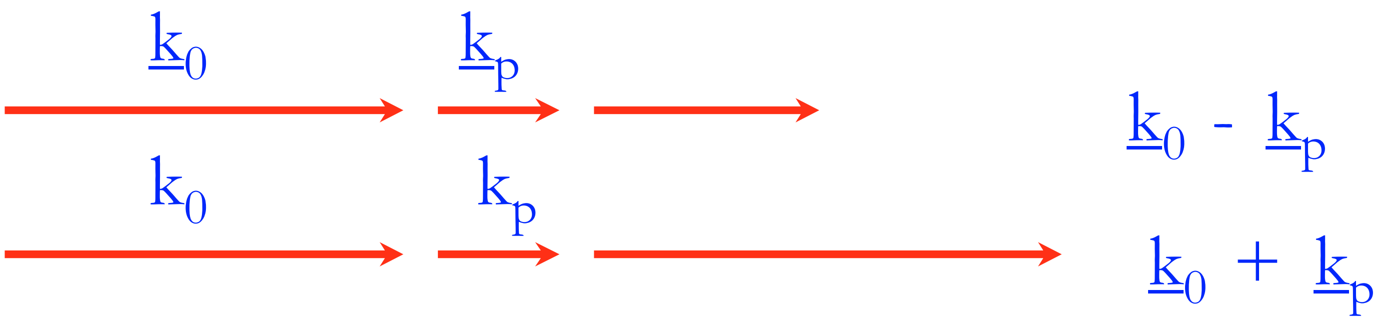
Surfing The Waves!

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

Self-Modulated Wakefield

High intensity long pulse lasers (pulse length greater than plasma wave period) $\tau_p \gg 1/\omega_p$

Break-up of a long pulse **L >> $\mathbf{k_p}$** **via** **Forward Raman Scattering** **or an** **Envelope-Self-Modulation** **instability.**



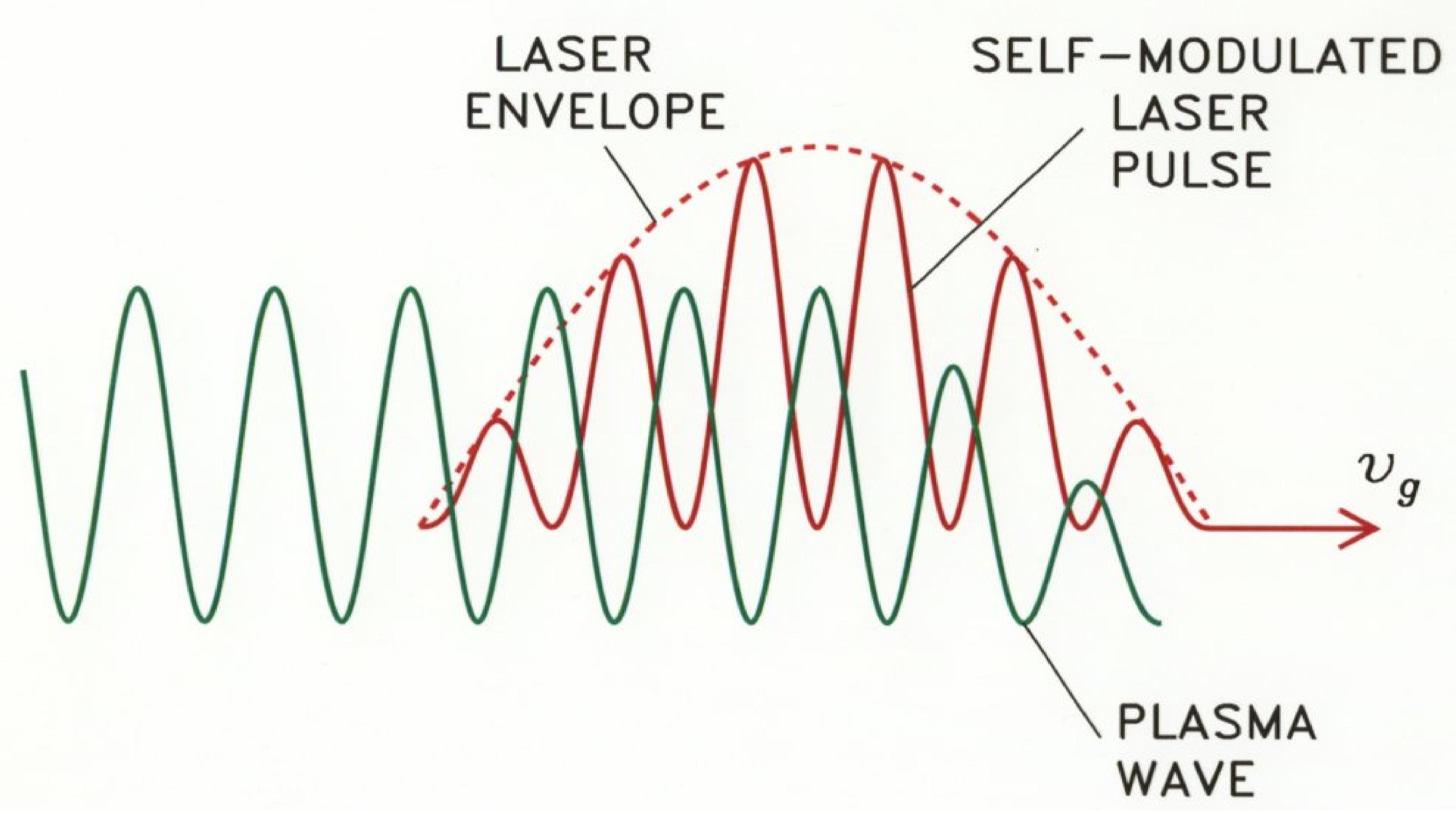
$\underline{k}_0 + \underline{k}_p = \underline{k}_{AS}$ Anti-Stokes

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

Pulse Power **> relativistic self-focusing**

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

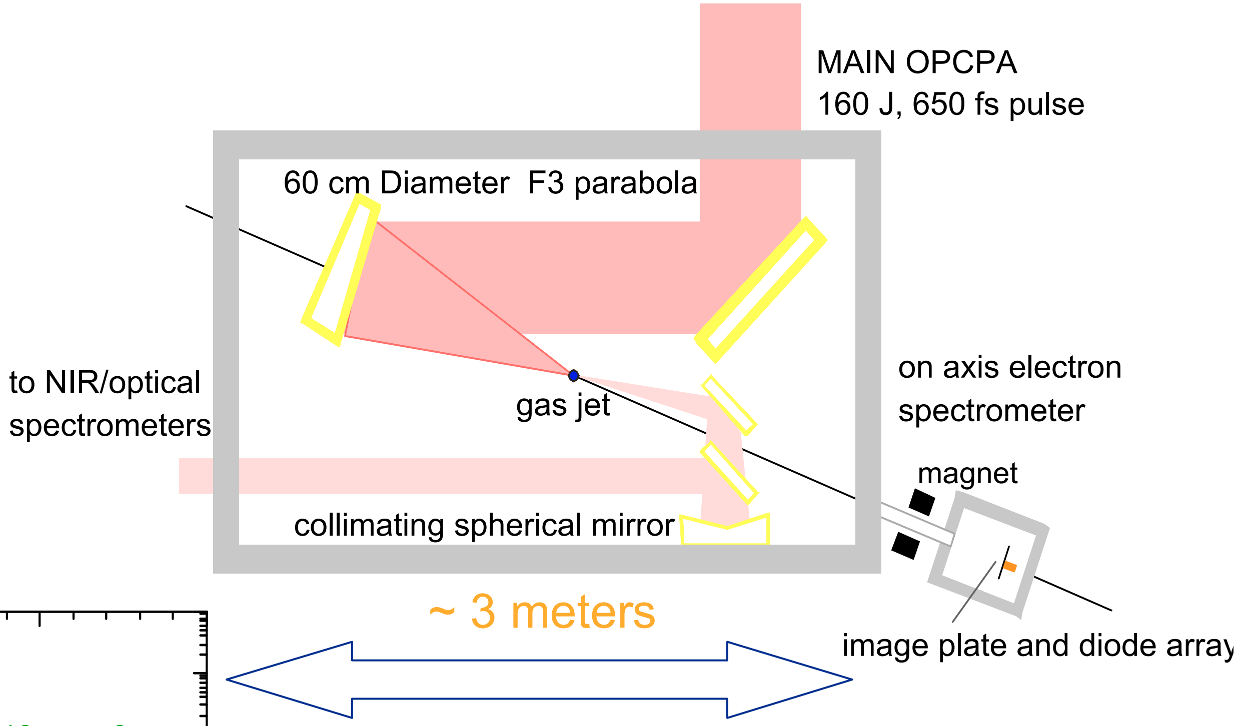
Self-Modulated Laser Pulse



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



MAIN OPCPA
160 J, 650 fs pulse

60 cm Diameter F3 parabola

gas jet

to NIR/optical
spectrometers

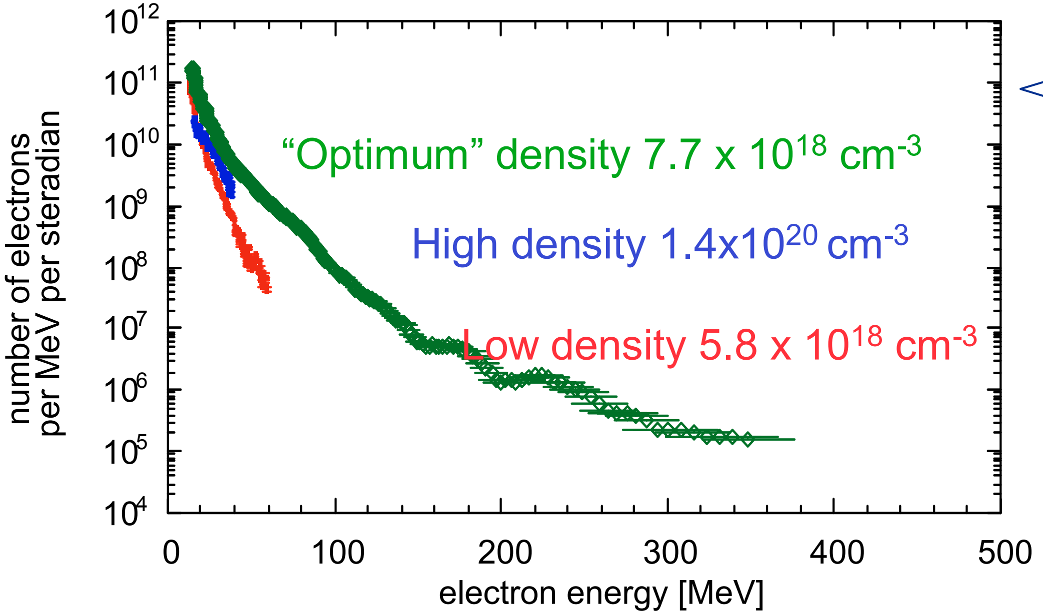
on axis electron
spectrometer

magnet

collimating spherical mirror

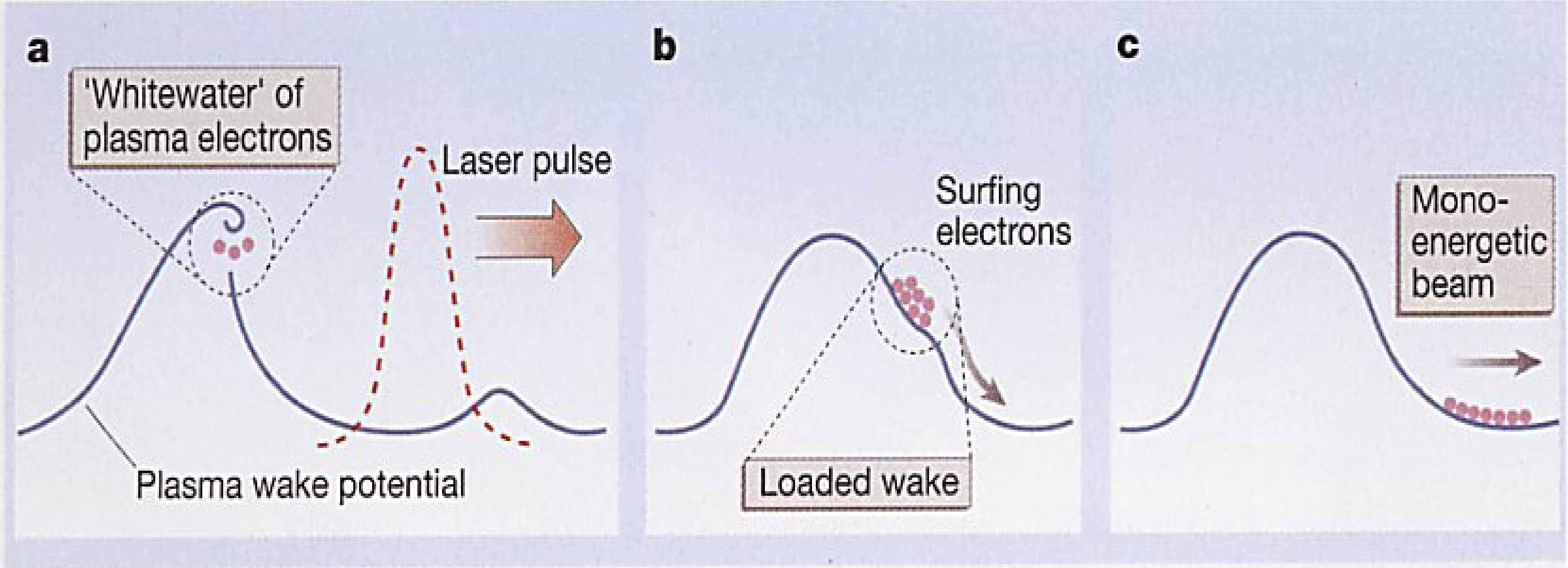
image plate and diode array

~ 3 meters



- 350 MeV electrons observed
- Energy spread large

Laser Wakefield



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.

Plasma Wakes – Scaling

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

$E_W \approx 10^8$ *V/m* or 1 *GeV* in 10*m*

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

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

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 $\sim c = \omega_p/k_p$

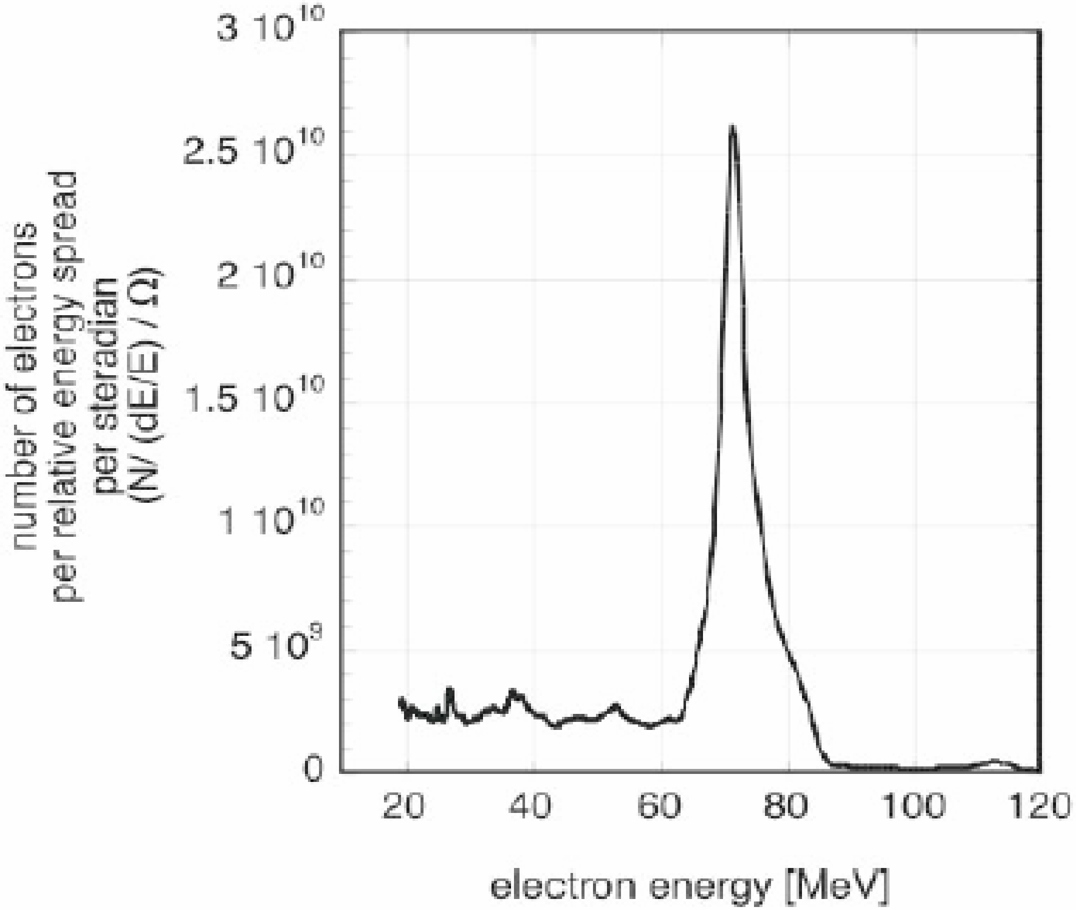
$$\nabla \bullet E = -4\pi e n_1 \Rightarrow \quad eE = \frac{n_1}{n_o}\sqrt{\frac{n_o}{10^{16}\,cm^{-3}}}\,10\,GeV/m \cos\omega_p(t - z/c)$$

But interesting wakes are very nonlinear – e.g. blowout regime
=> PIC simulations

Imperial College London

Recent breakthrough from three laboratories.

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

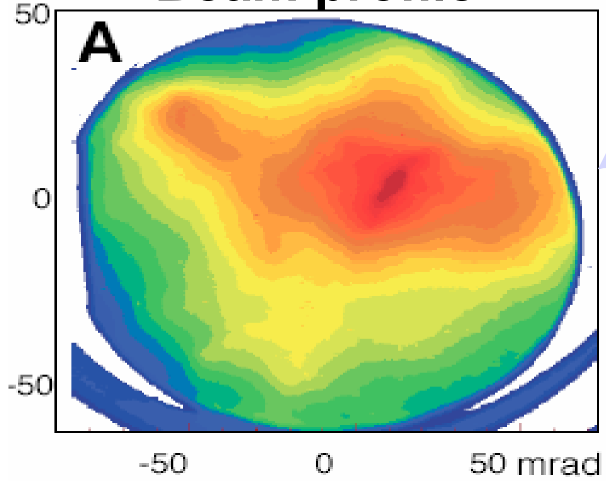
Careful control of laser and plasma conditions is necessary

Courtesy: K. Krushelnick, IC

Nature, 2004.

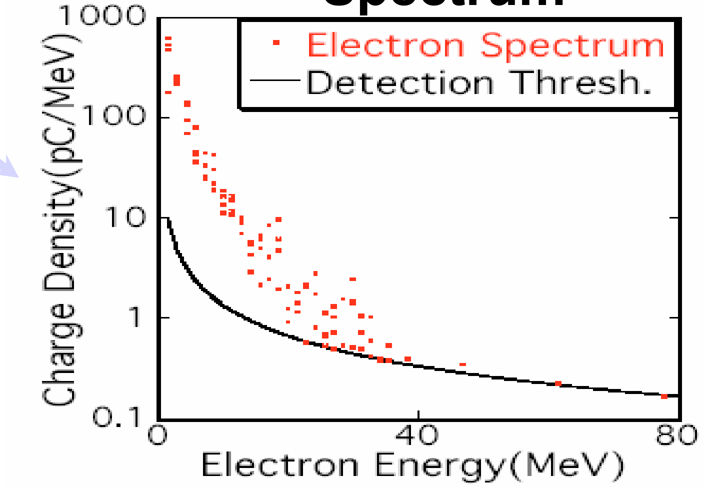
85 MeV e-beam with %-level energy spread observed from laser accelerator

Beam profile

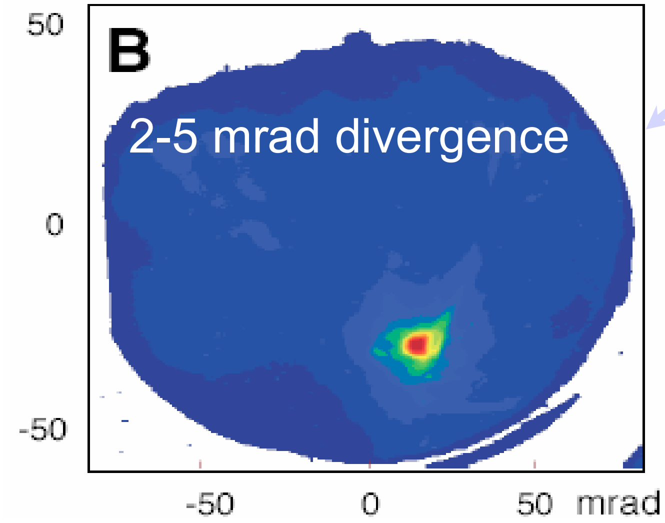


Unguided

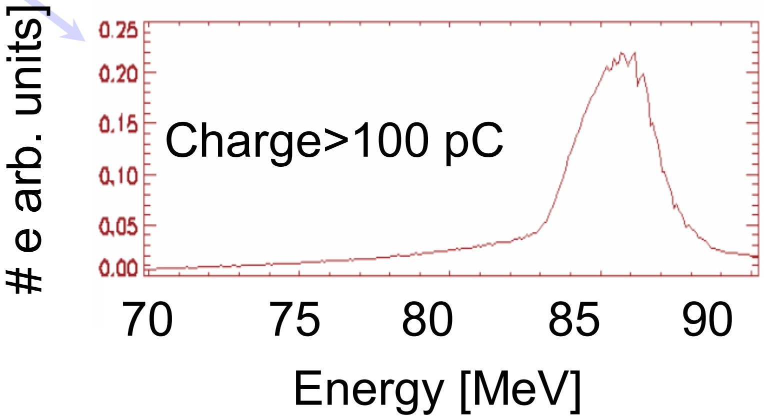
Spectrum



Guided



2-5 mrad divergence

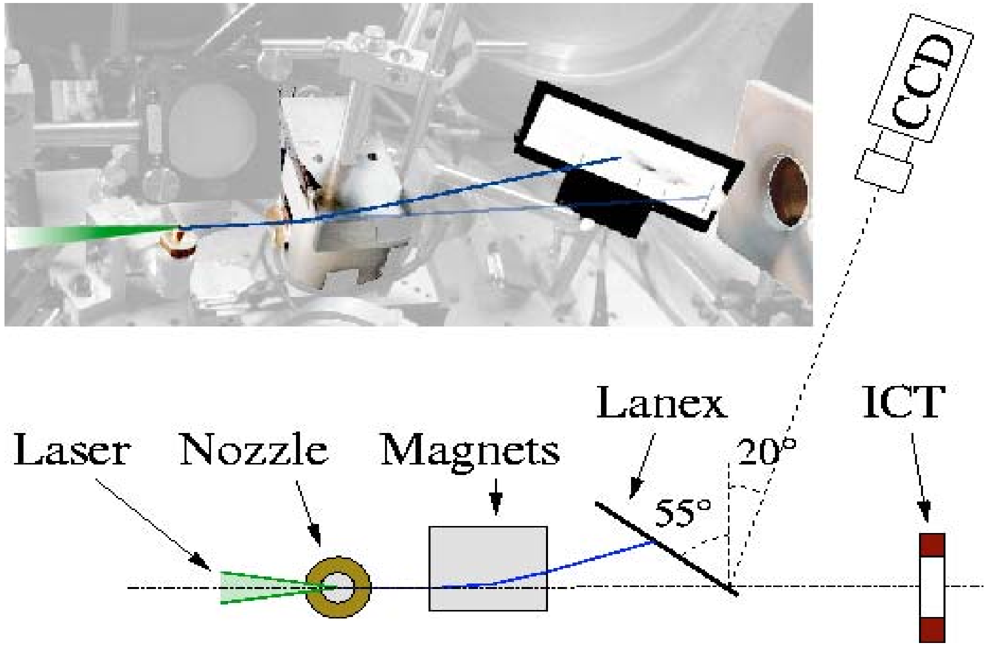


Charge>100 pC

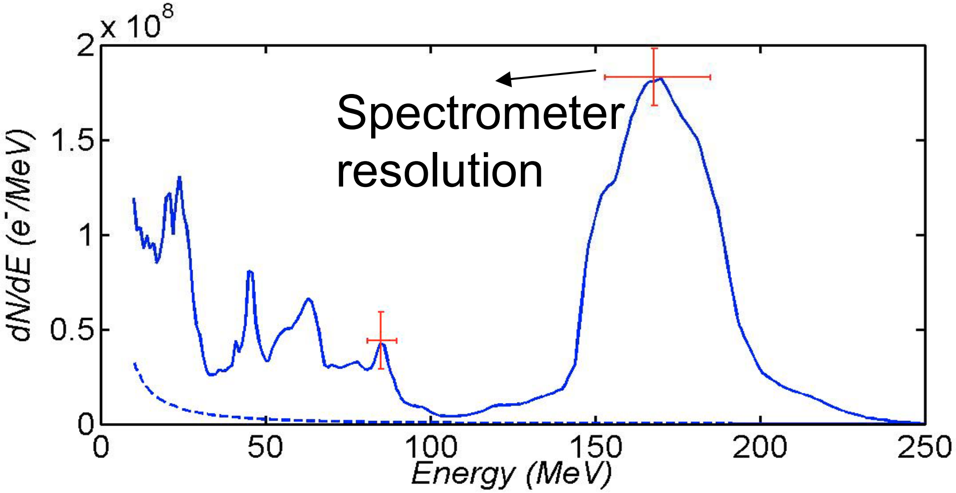
C.Geddes *et al.*, 2004. LBNL

Electrons > 150 MeV observed

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



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

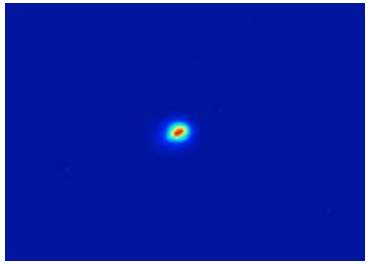


Parameters: $n_e=6\text{x}10^{18}$ cm^{-3},
$a_0=1.3$, $\tau=30$ fs

P=30 TW

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

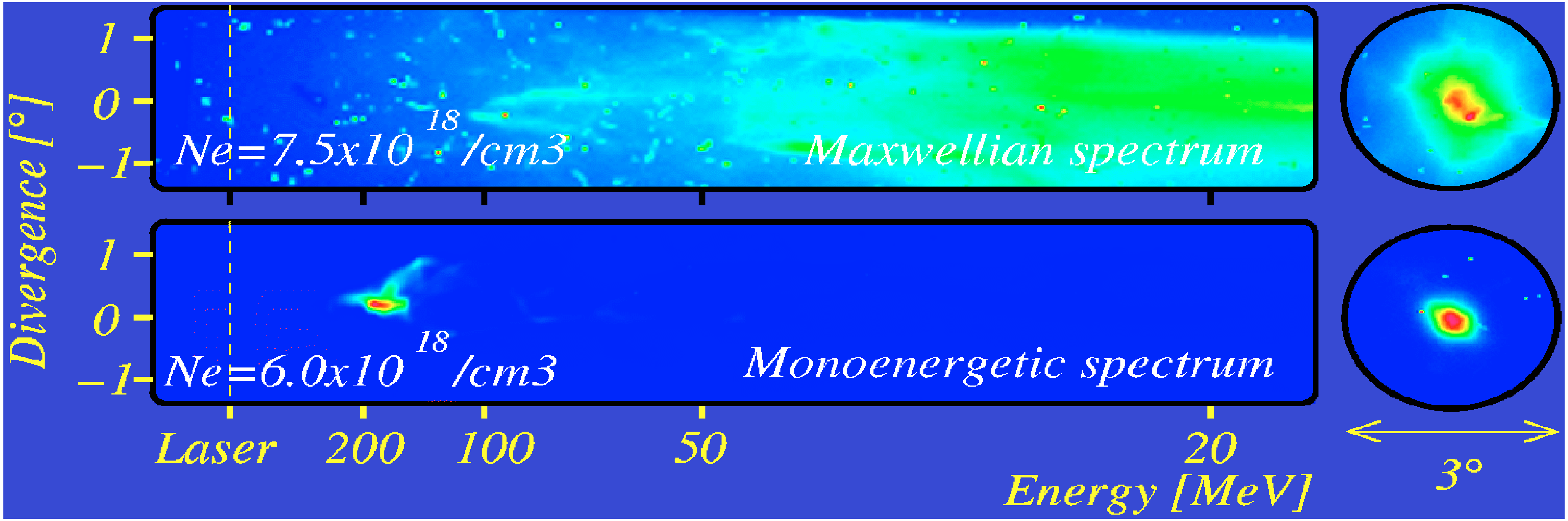
Electron beam profile on LANEX



Divergence FWHM = 6 mrad

Courtesy J. Faure, LOA

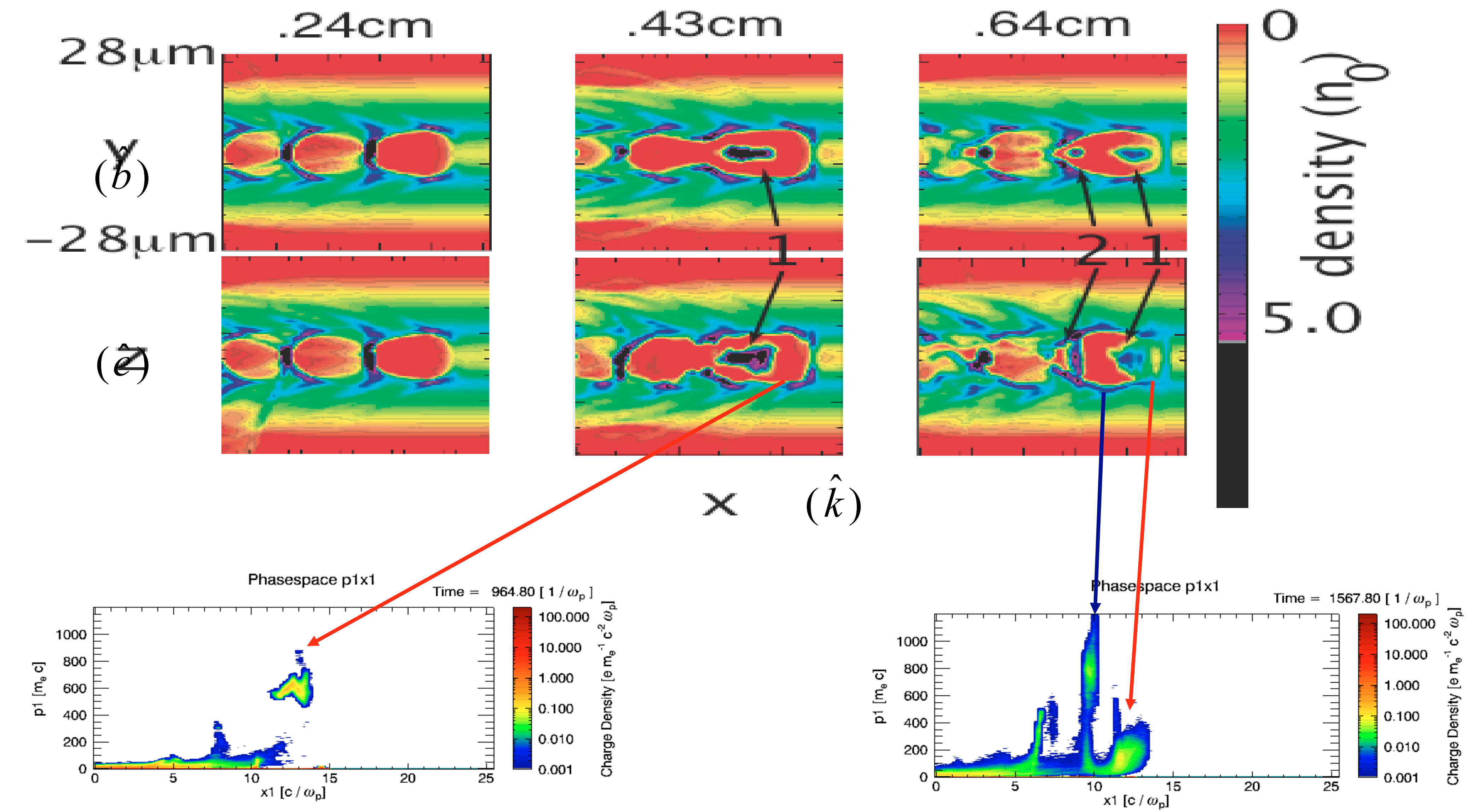
Recent results on e-beam : Energy distribution improvements



N.B. : color tables are different

J. Faure, LOA

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

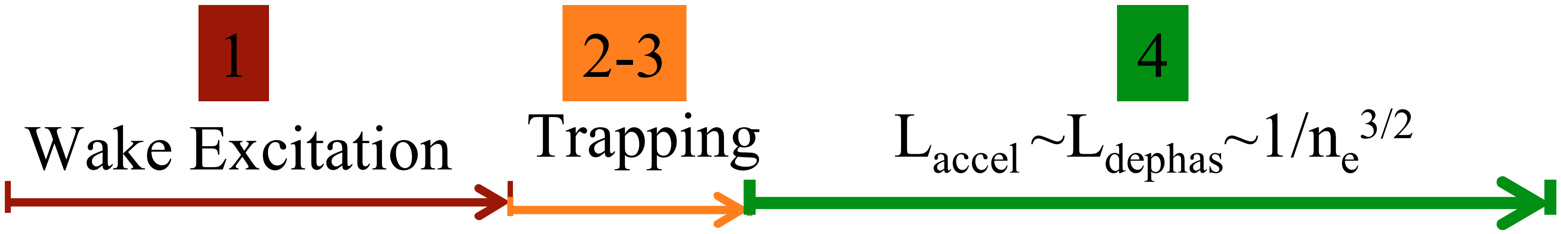


Production of a Monoenergetic Beam

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



1

Wake Excitation

2-3

Trapping

4

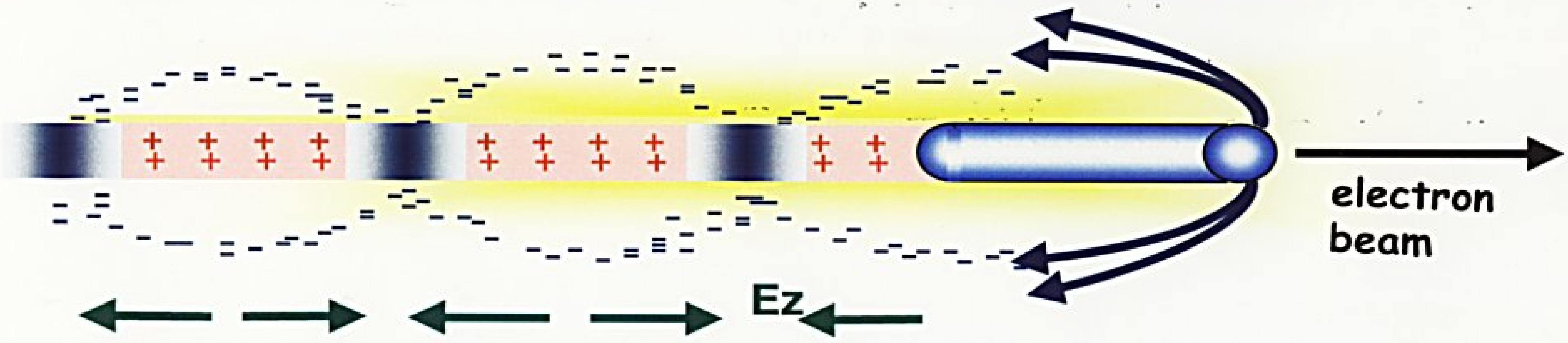
$L_{accel} \sim L_{dephas} \sim 1/n_e^{3/2}$

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

Physical Principles of the Plasma Wakefield Accelerator

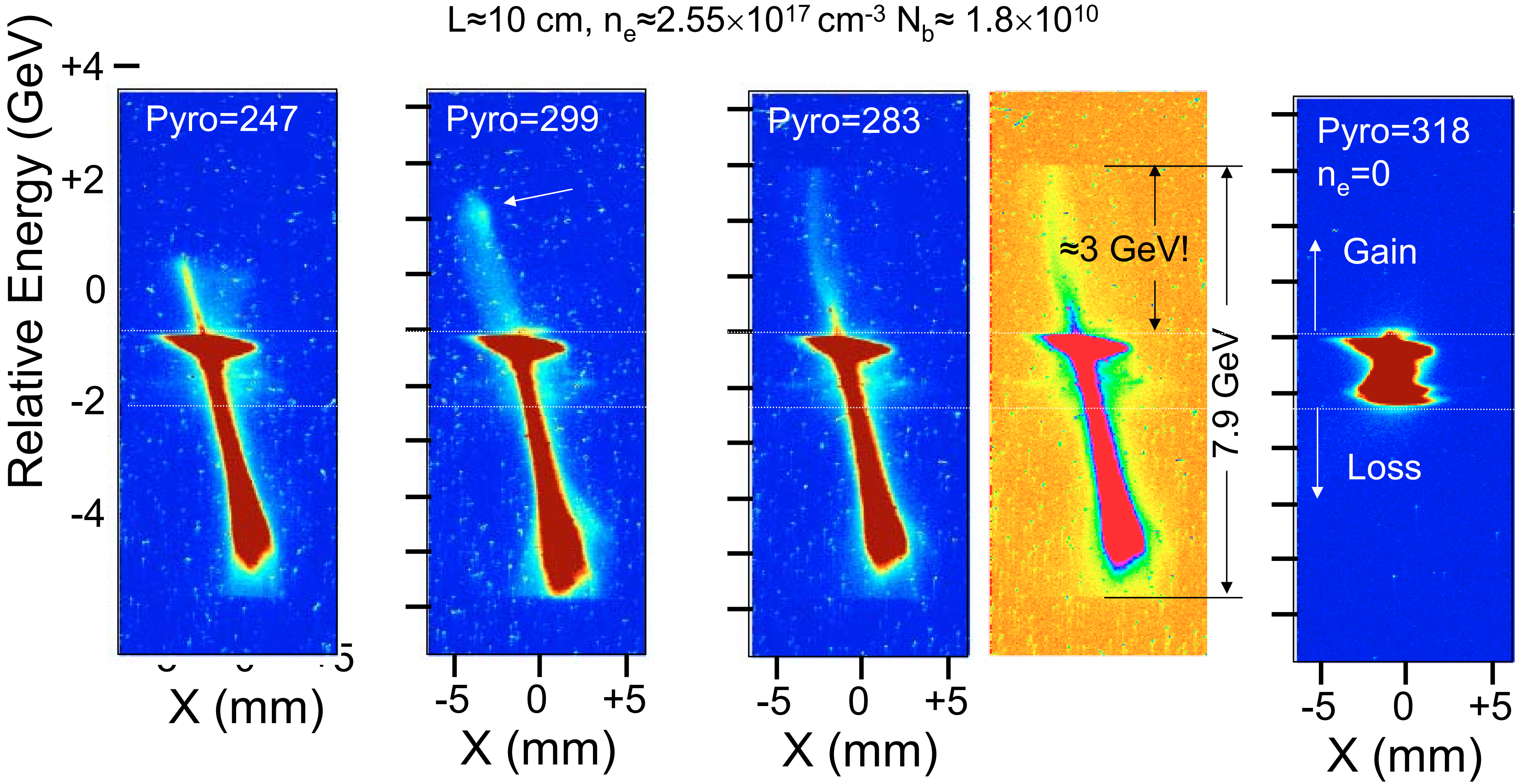
- Plasma is used to create a longitudinal accelerating gradient

- 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 $\propto N_b / \sigma_z^2$ $\quad (for\ 2\sigma_z \approx \lambda_p \propto \frac{1}{\sqrt{n_o}})$

E-164X Breaks GeV Barrier



Energy gain exceeds ≈ 4 GeV in 10 cm

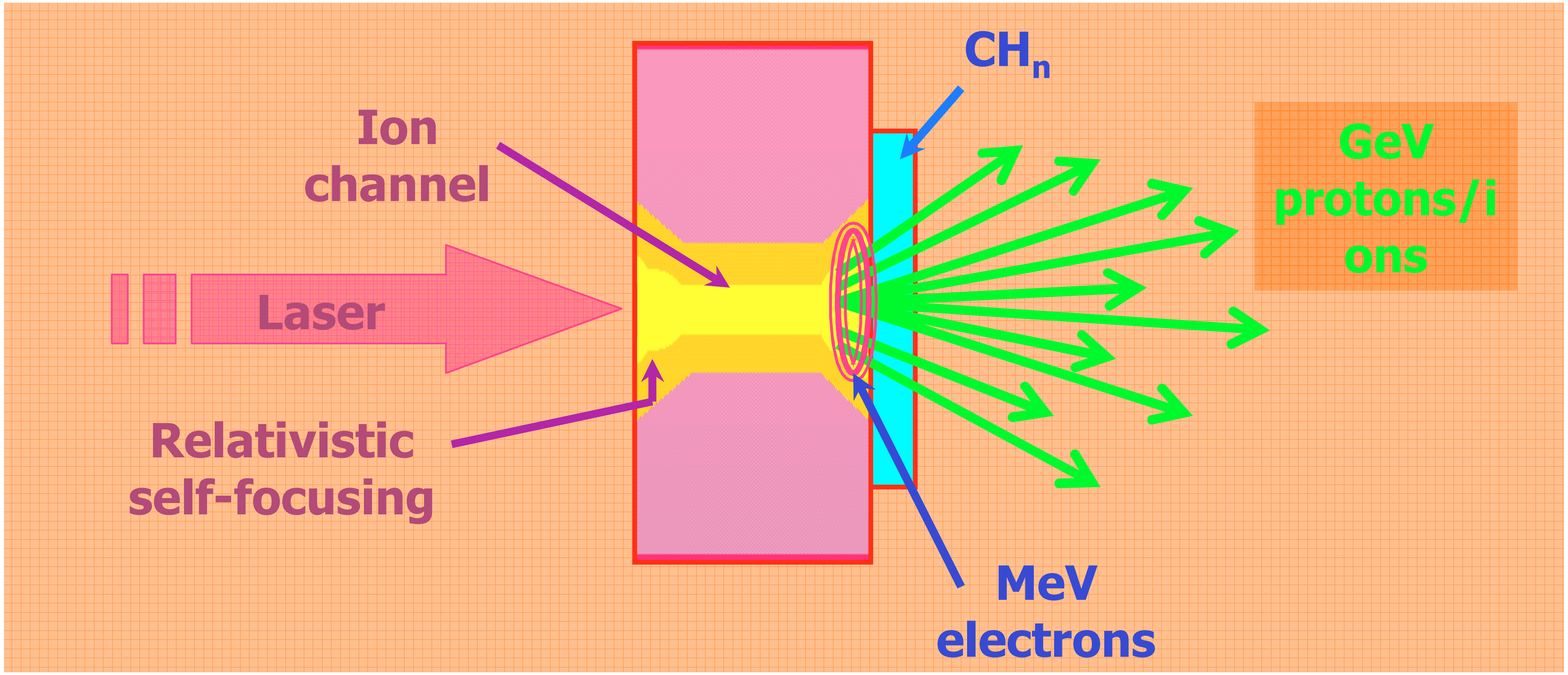
Plasma Wakefield

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

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

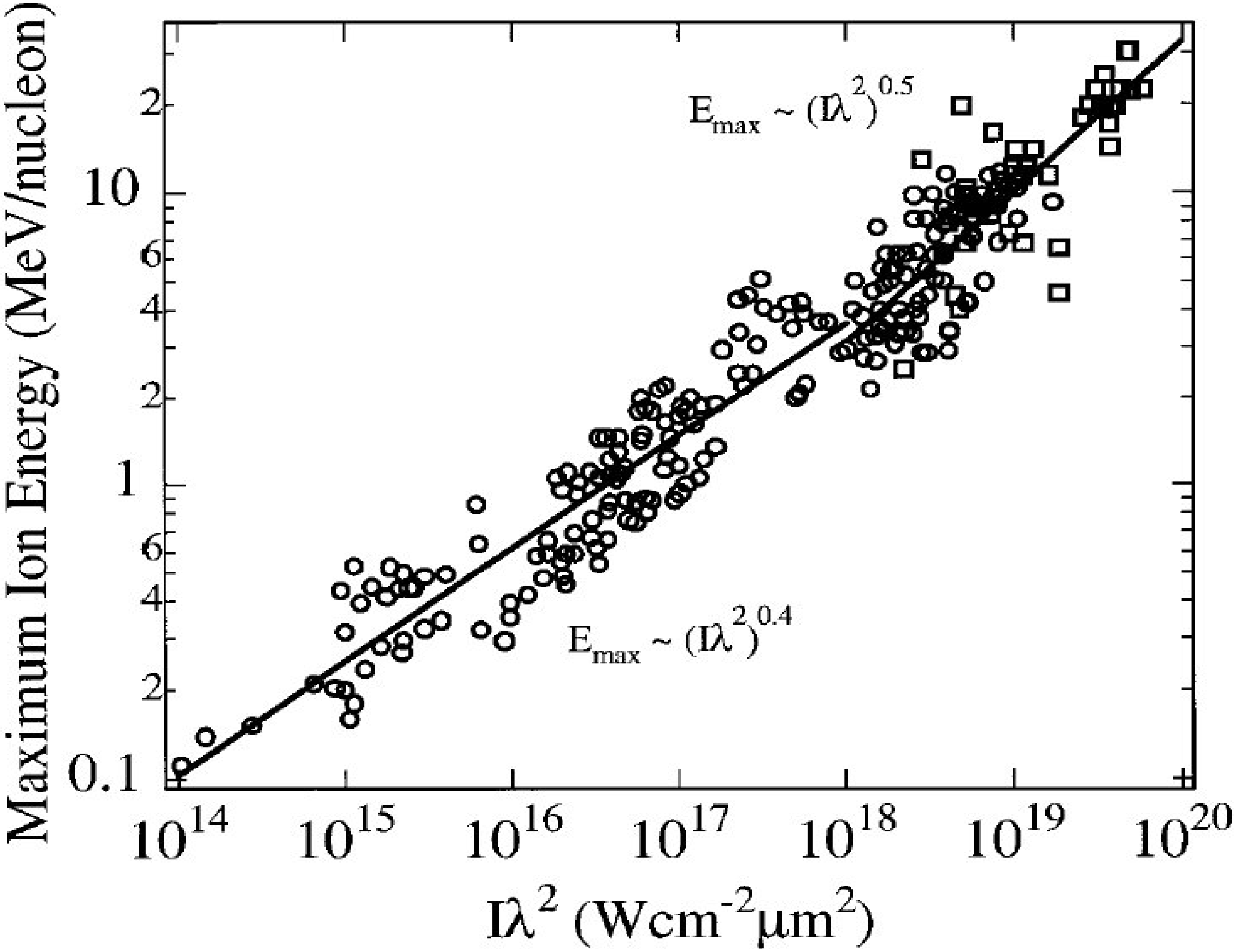
- So, a 1 kAmp pulse, of duration 4 picoseconds is needed to generate a 1 GeV/m wake.

Proton Acceleration



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

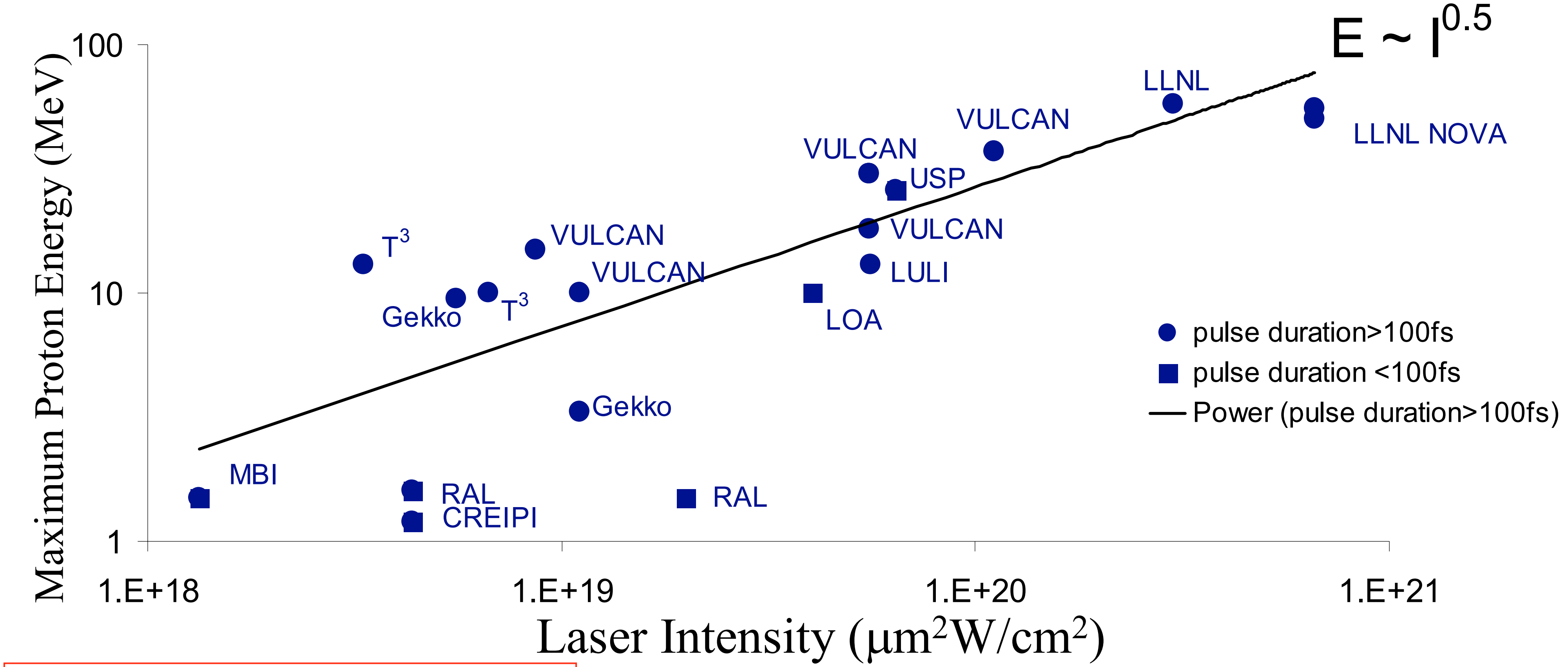
Heavy Ion/Proton Generation by Ultraintense Lasers



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

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.

Proton Energy Scaling



- Hi charge: 10^{10}-10^{13} ions
- Short pulses
- 100's MA/cm^2

(Courtesy T. Lin)

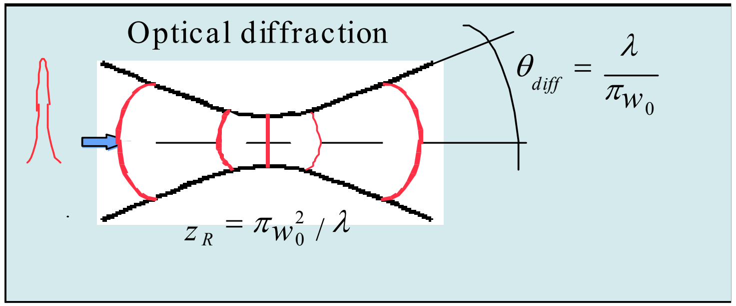
Key Issues

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)		Shaped driver and load
		Transformer Ratio
		Energy Spread

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

- Diffraction:

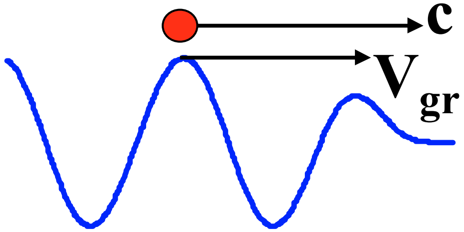
$$L_{dif} \cong \pi L_R = \pi^2 w_0^2 / \lambda$$



order mm!

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

- Dephasing:



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

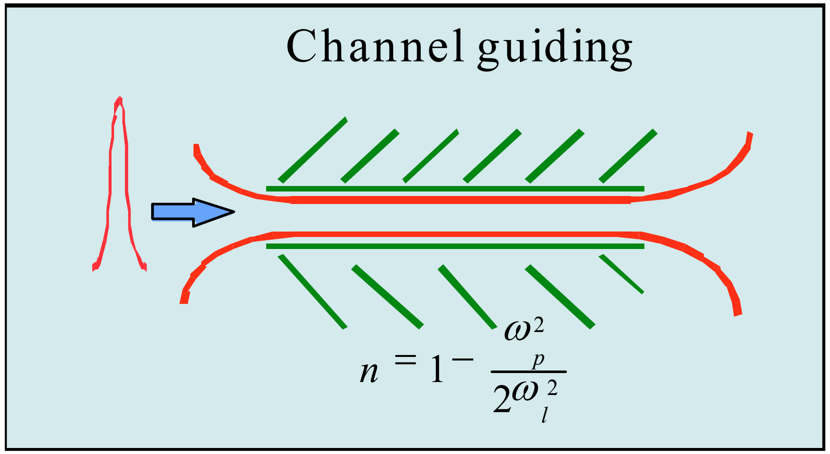
order 10 cm
x $10^{16}/n_o$

- Depletion:

For small a_0 >> L_{dph}
For a_0 >~ 1 L_{dph}~ L_{depl}

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

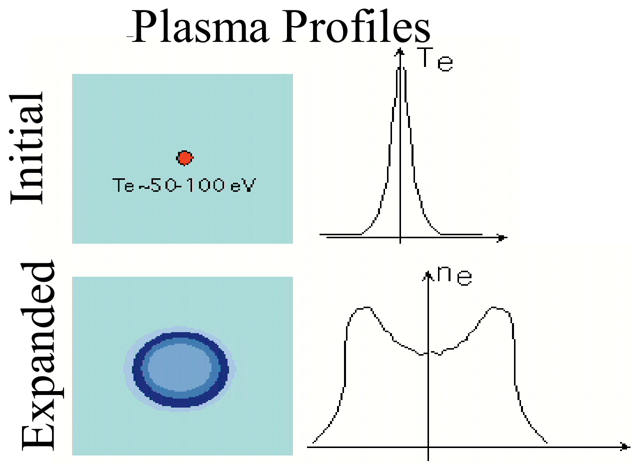
Plasma channel: structure for guiding and acceleration


Channel guiding

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

Step 1: Heat

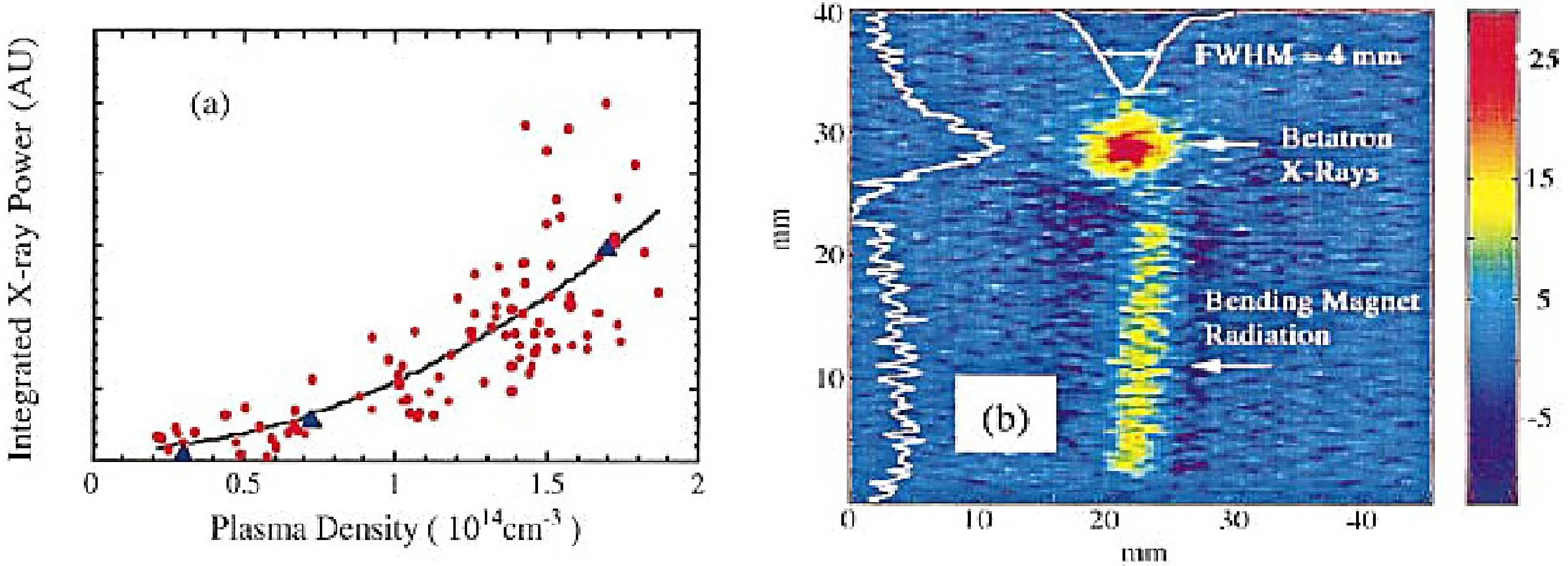
Step 2: expand


Plasma Profiles

- 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))

Radiation from Plasma Channels

Betatron X-rays   Radiation from energetic electrons in plasma channels.



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

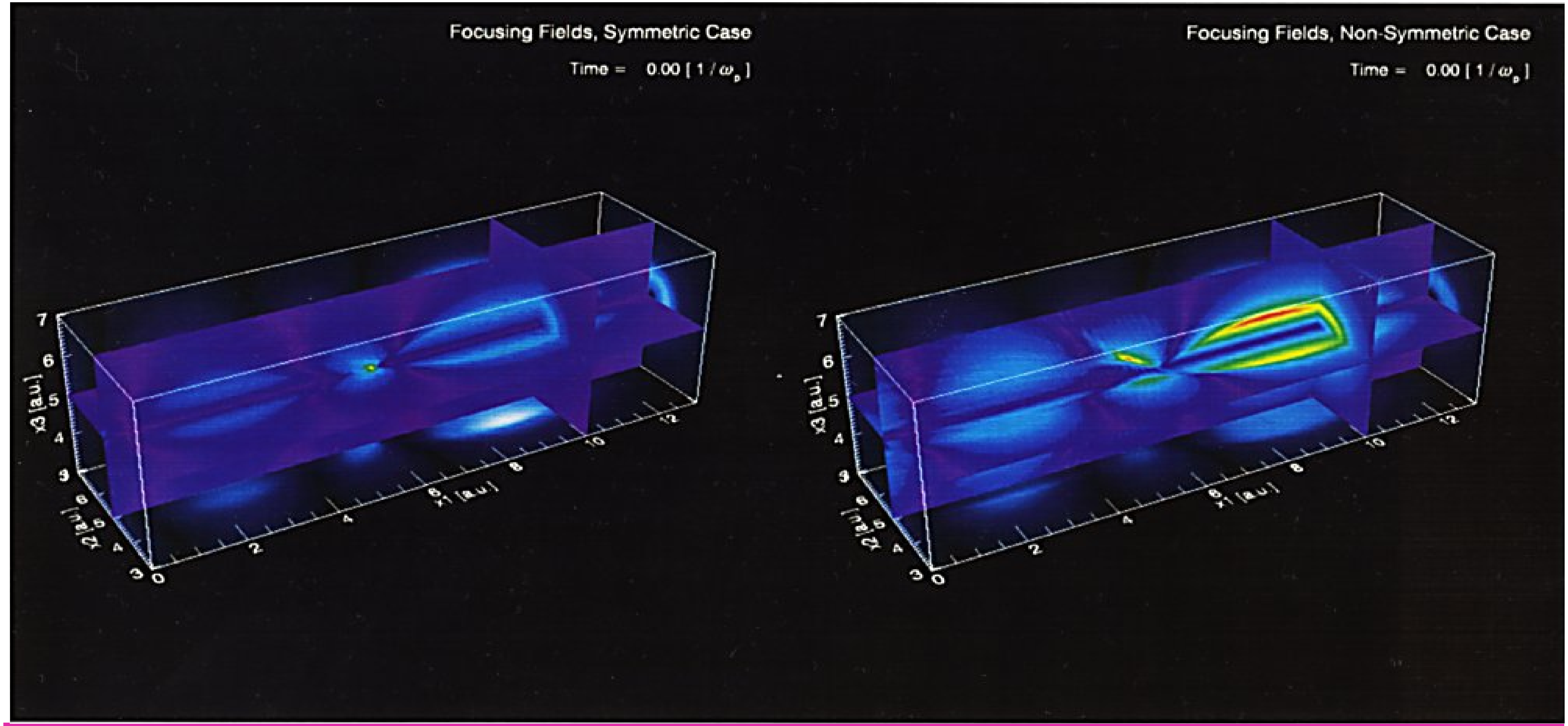
FIG. 8. (Color) (a) The estimated (triangles) and the measured (dots) x-ray energy in the 5–30 keV range as a function of plasma density. The solid line is a quadratic fit to the data. (b) Processed image produced on a fluorescent screen as recorded by a CCD camera showing the betatron x-rays produced by the plasma $n_p = 2 \times 10^{13}$ cm^{-3} (circle at the top) and a vertical stripe of remnant synchrotron radiation produced by a dipole bend magnet.

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

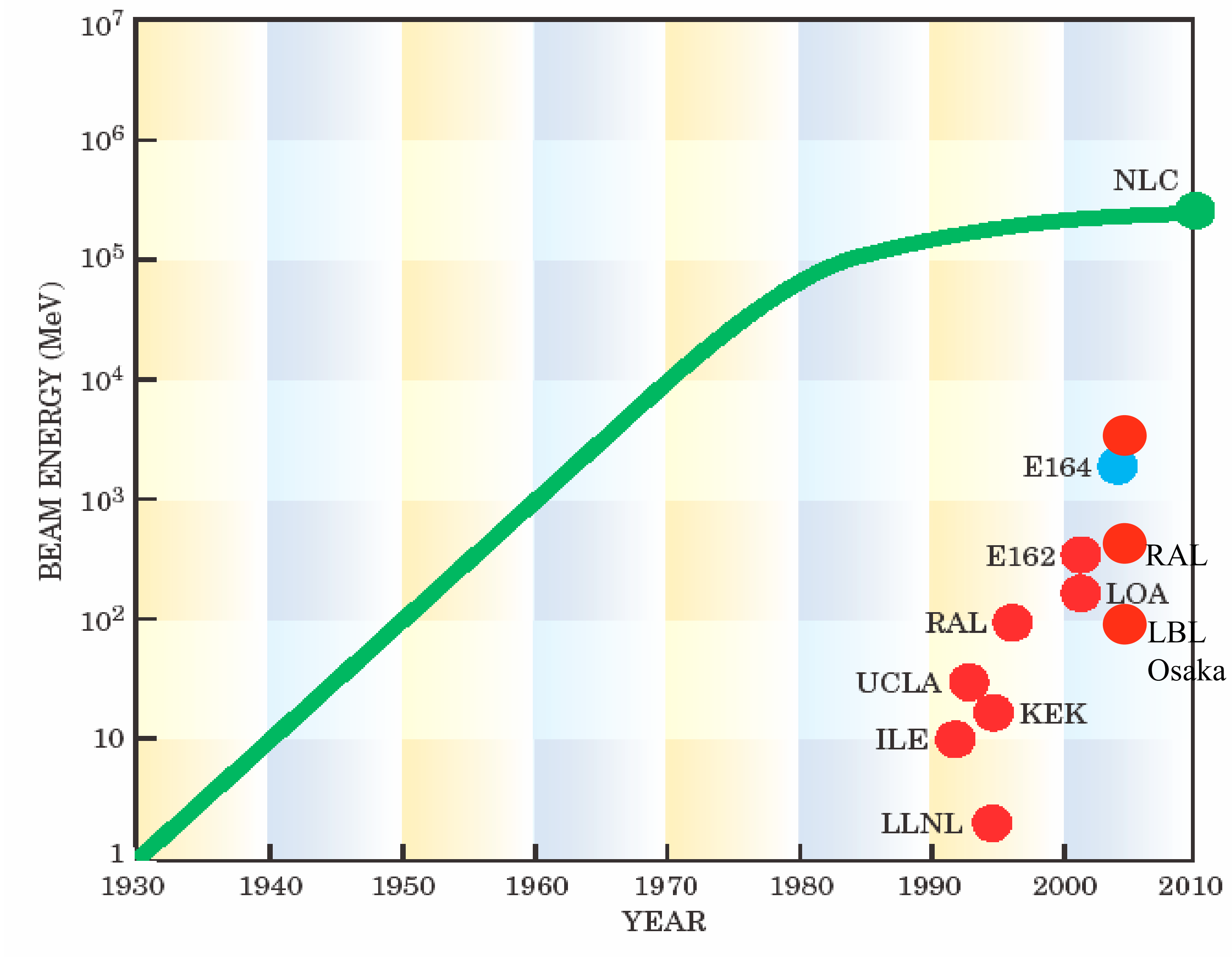
S. Wang et al. Phys. Rev. Lett. Vol. 88 Num. 13

Betatron Oscillations

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



Plasma Accelerator Progress and the Livingston Curve

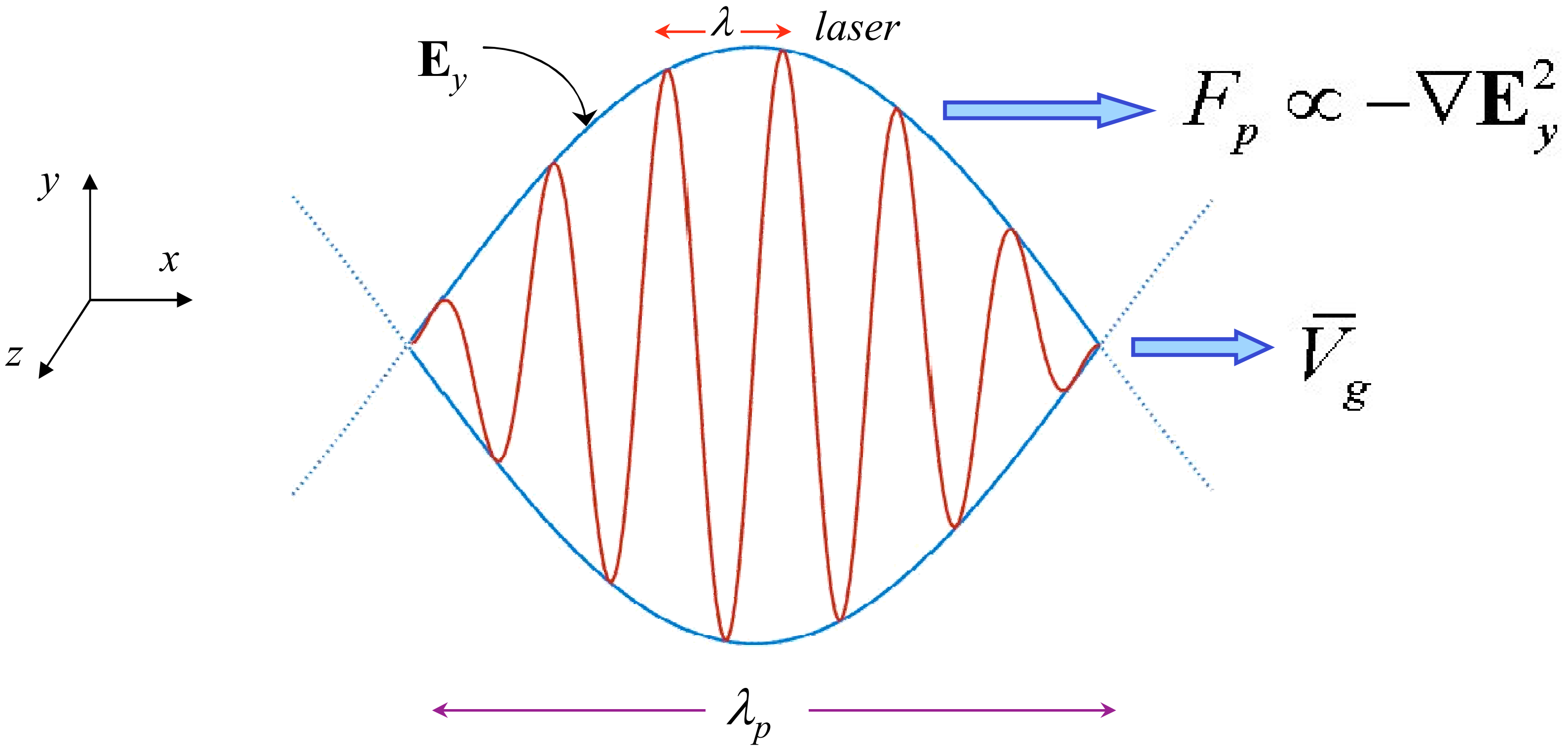


Conclusions

- The dawn of compact particle accelerators is here.
- Laser Plasma Accelerators > 100 MeV
- Numerous applications for 100 MeV-1 GeV beams – Medicine, Light Sources, Industry
- Future goals for laser plasma accelerators are mono-energetic, multi GeV beams.
- With advances in laser technology the TeV energy scale is a long term target.

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 $\delta\gamma/\gamma \sim .1 - 10\%$
  - 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 %



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

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

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

Plasma waves driven by electrons, photons, and neutrinos

Electron beam

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

$\delta n_e \equiv$ Perturbed electron plasma density

Photons

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

Neutrinos

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

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

Santala *et al.*, PRL, 2001.

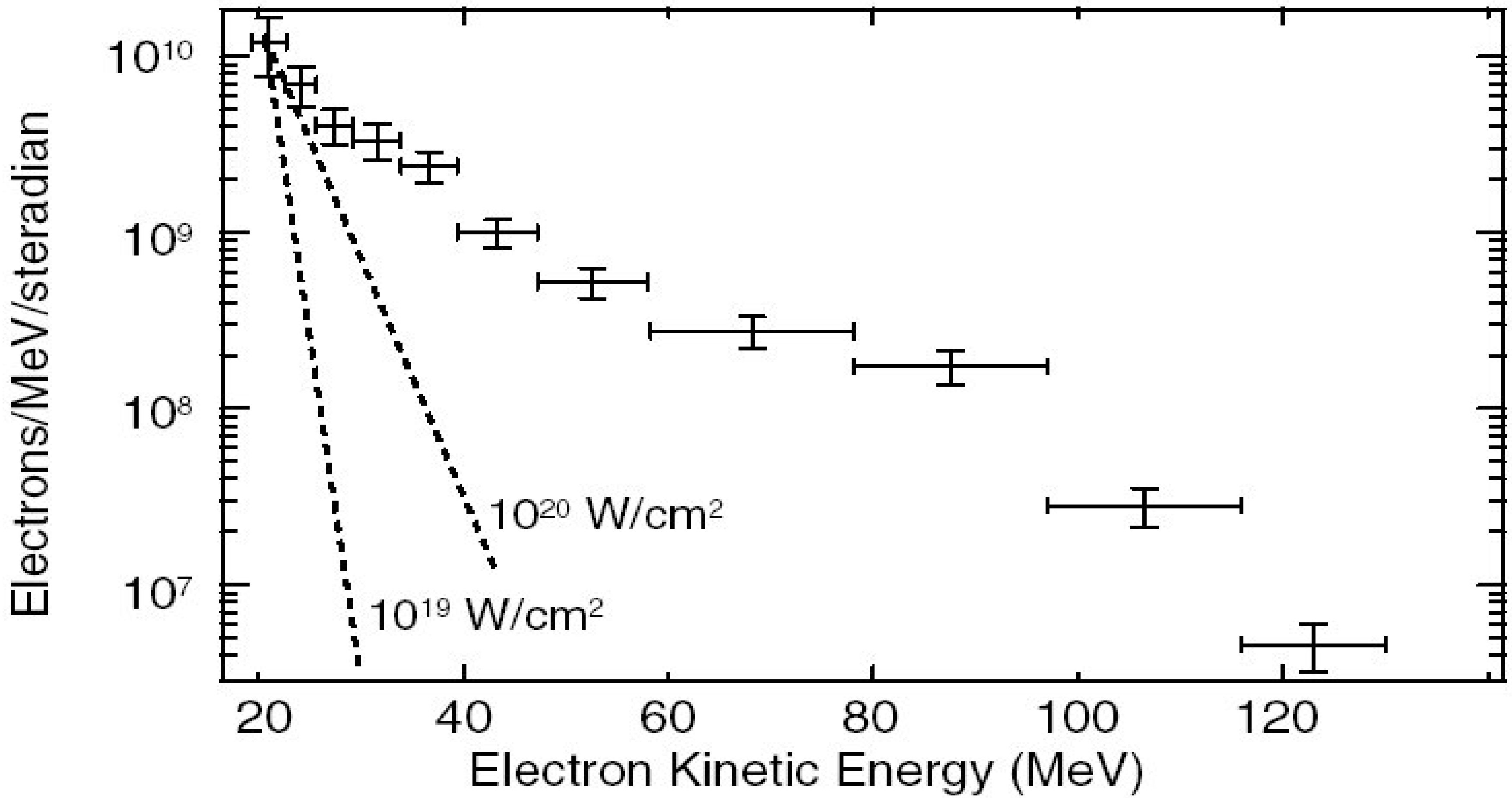
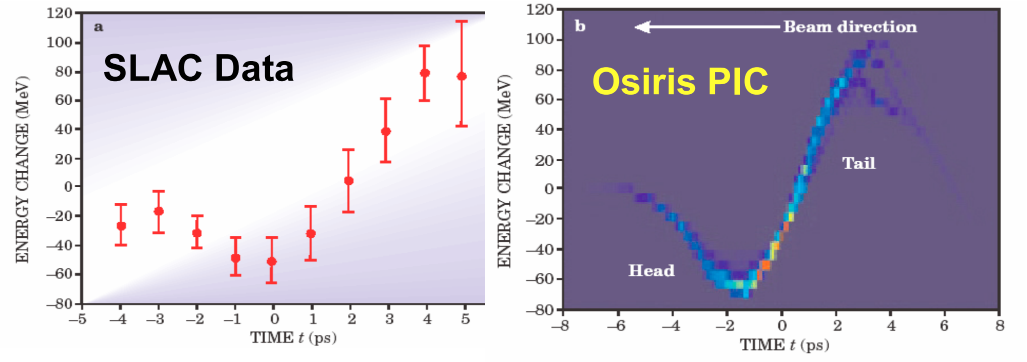


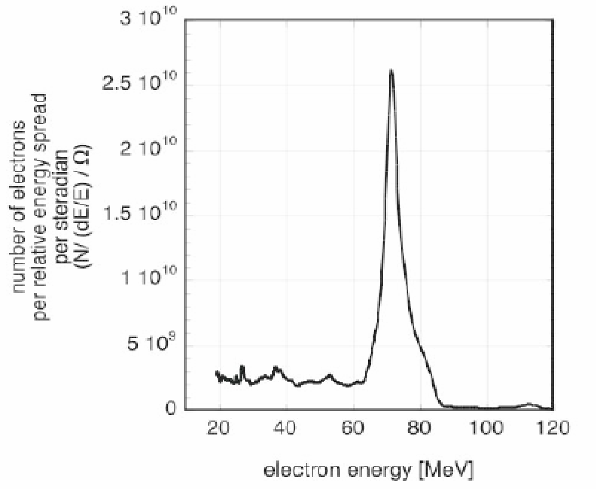
FIG. 3. A typical electron spectrum (unfolded) measured by an on-axis electron spectrometer. Ponderomotive scalings (Ref. [12]) at 10^{19} and 10^{20} W/cm^2 are also shown.

Plasma Accelerators

1. Positron acceleration/ 3-D Modeling

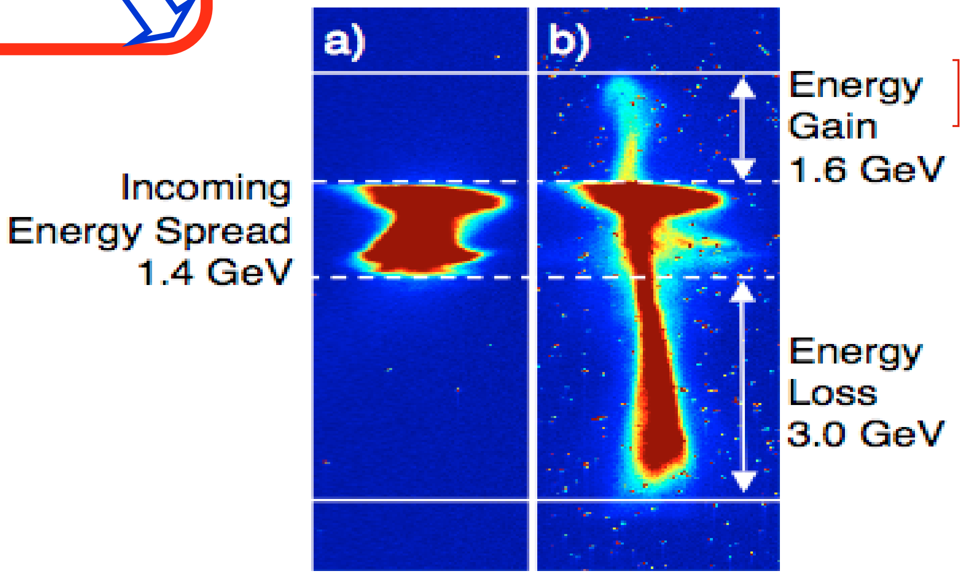


2. Monoenergetic electron beams

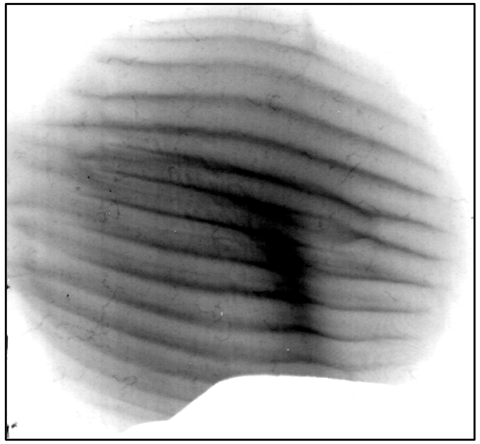


Four Highlights!

4. GeV Milestone

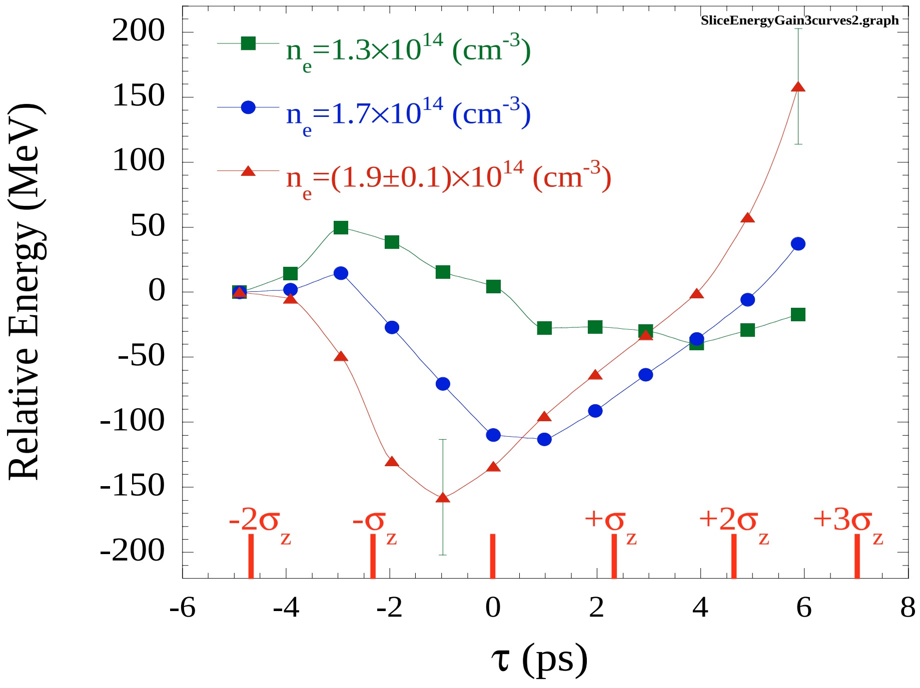


3. Multi-MeV proton beams

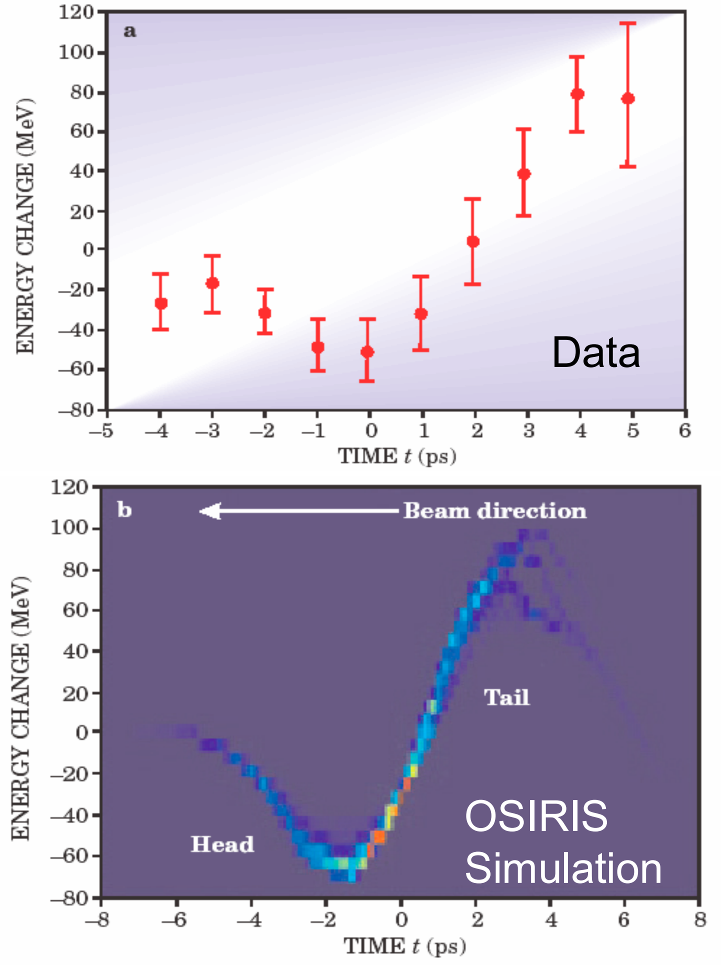


Acceleration Of Electrons & Positrons: E-162

Electrons



Positrons



- *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

Summary of Experimental Results

Mechanism	Labs	Energy gain	Acc field	Acc length
BW	UCLA, LULI, Canada, ILE	1 to 30 MeV	1 GV/m	1 to 10 mm
Laser Wakefield	LULI	1.5 MeV	1 GV/m	2 mm
Plasma Wakefield	SLAC-UCLA-USC-Berkeley	80 - 150 MeV	70 MV/m	1.4 m
SM Wakefield	RAL, LULI, LOA	60 to 200 MeV	100 to 400 GV/m	1 mm

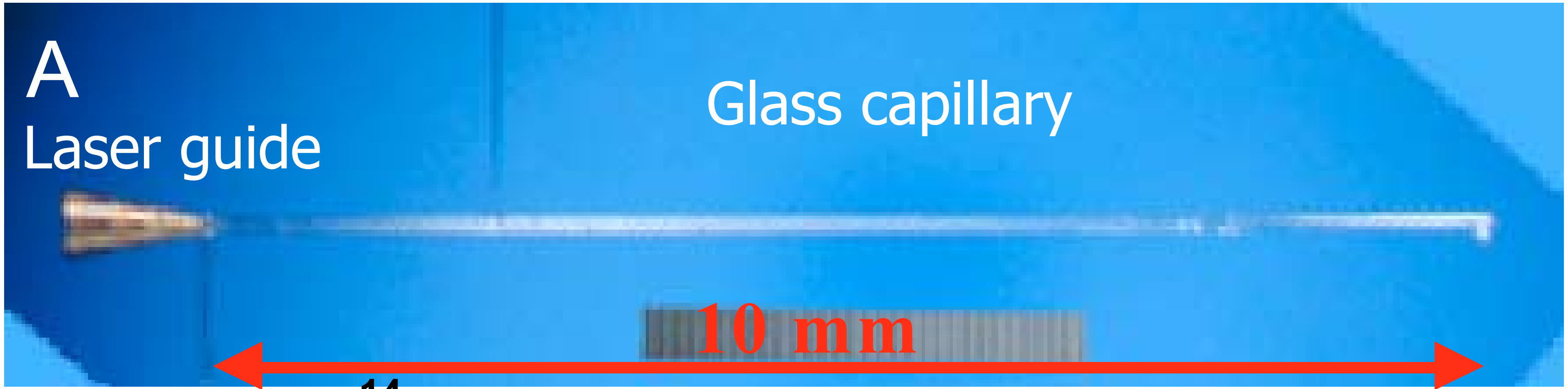
- Large accelerating gradients
- Agreement with theoretical predictions
- Broad spectrum due to inadequate injectors
- **Improvements are necessary**

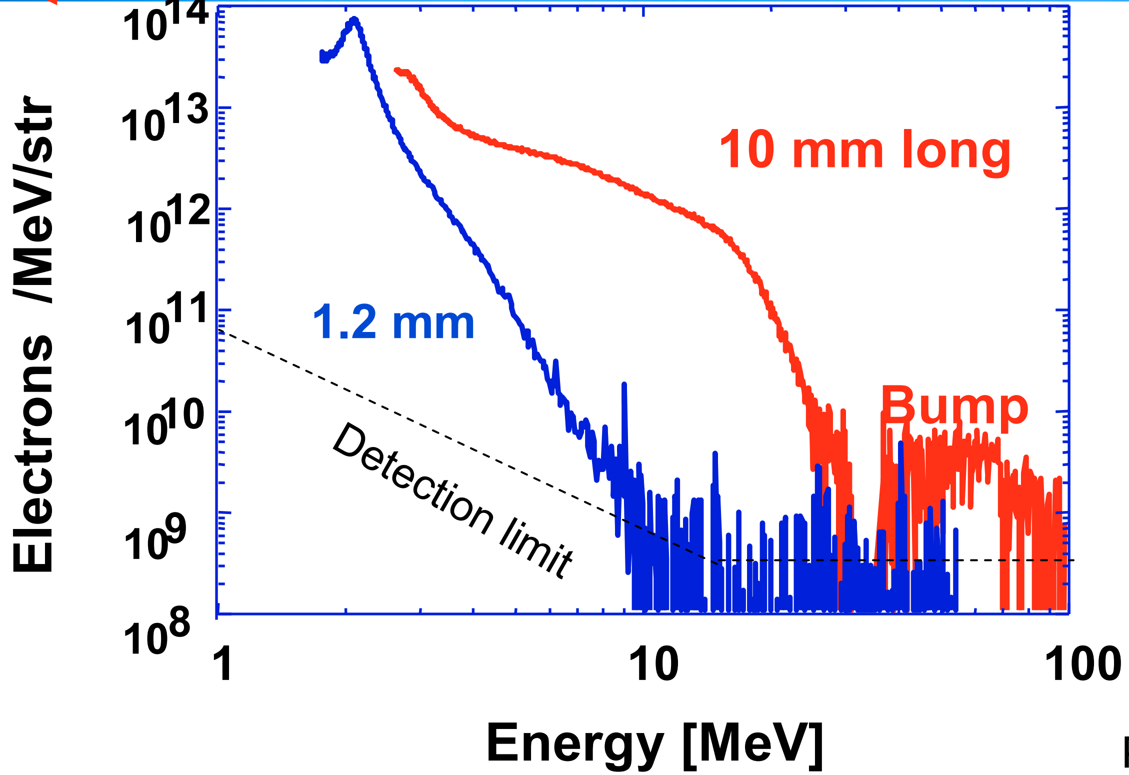
Intense Relativistic Beams in Plasmas: New Plasma Physics

- 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

Ultra-Intense Laser is illuminated into a glass capillary, which accelerates plasma electrons to 100 MeV-- Y.Kitagawa-Osaka





PRL Vol.92, No.20 (2004)

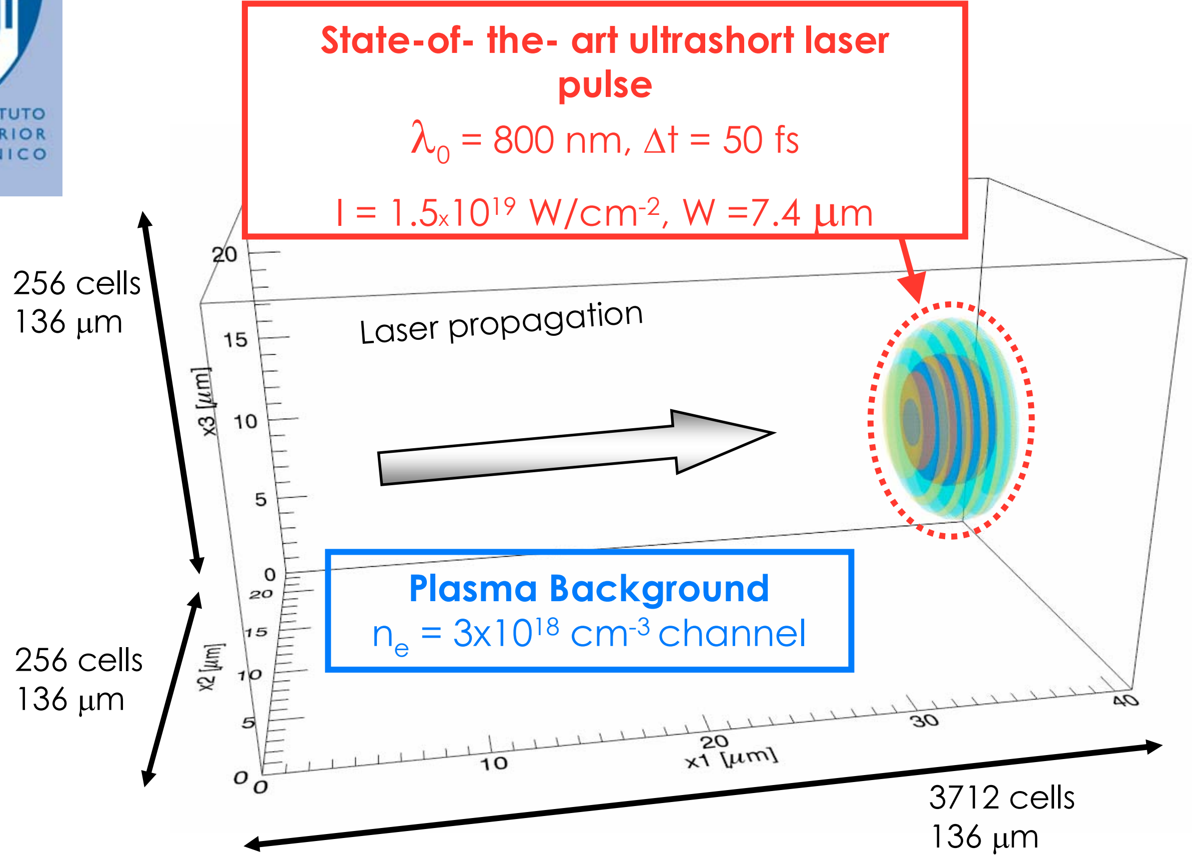
Electron Accelerators

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

Conclusions

- Laser Plasma Accelerators > 100 MeV
- Numerous applications for 100 MeV-1 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
- 1 GeV barrier was broken by SLAC e-beam Wakefield Experiment.

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

$n_e = 3\times10^{18}$ cm^{-3} channel

Simulation ran for 200,000 hours

(~40 Rayleigh lengths)

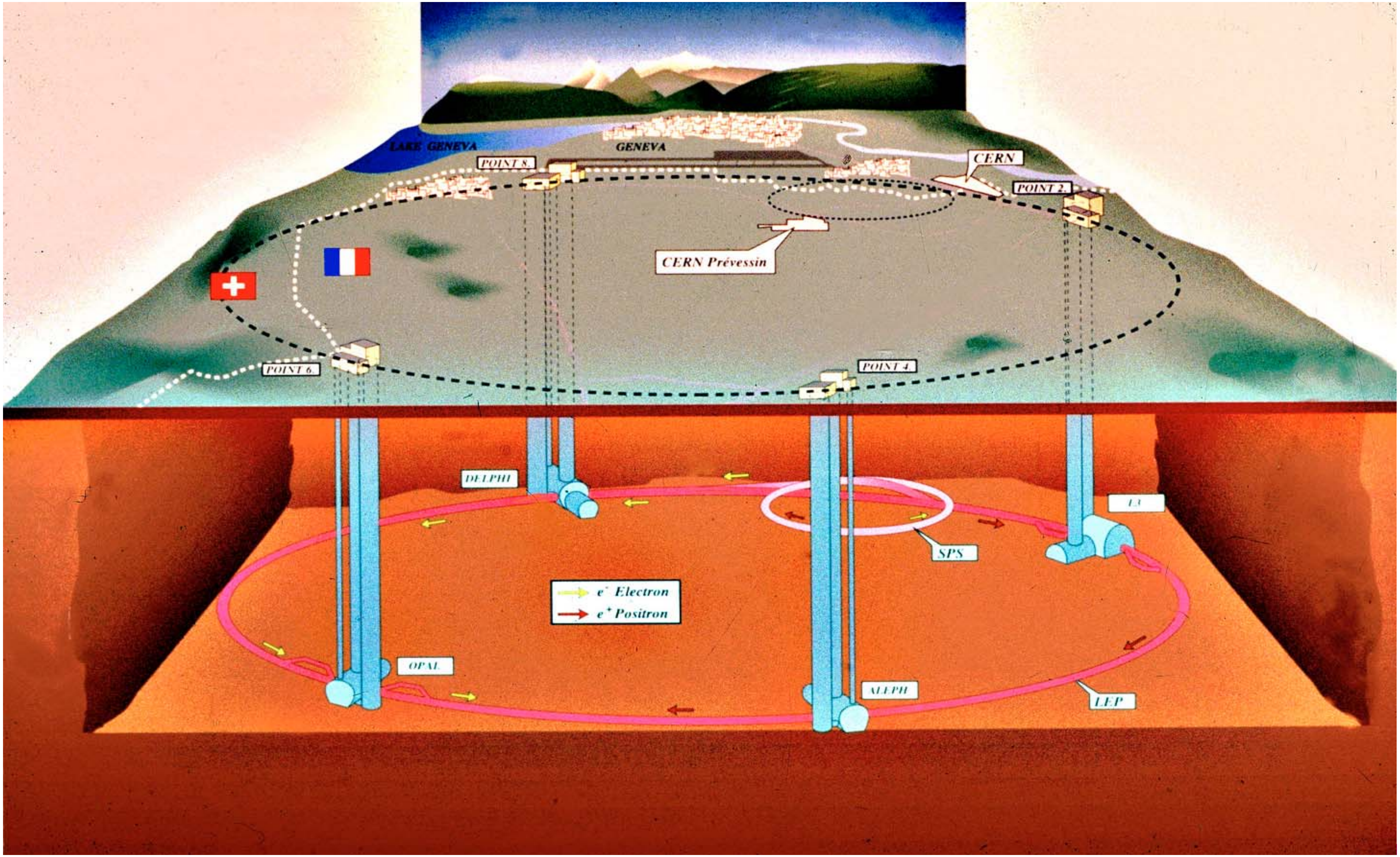
imulation Parameters

- –Laser:
  - $a_0 = 3$
  - W_0=9.25 λ=7.4 µm
  - $\omega_l/\omega_p = 22.5$
- –Particles
  - 1x2x2 particles/cell
  - 240 million total
- –Channel length
  - L=.828cm
  - 300,000 timesteps

•The parameters are similar to those at LOA and LBNL

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

CERN – LEP schematic

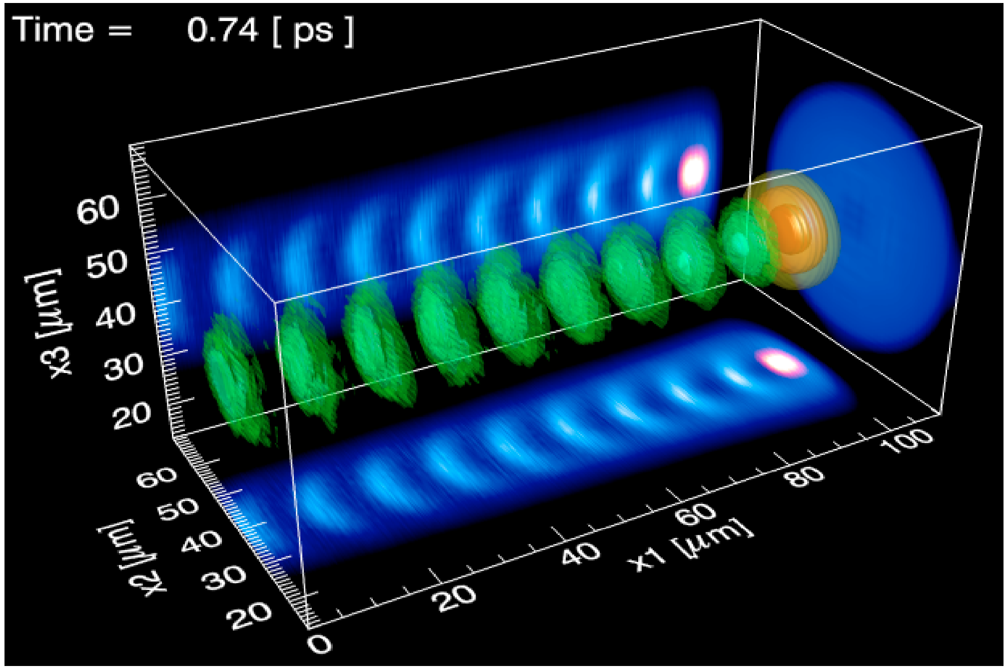


Laser & Electron Wakes

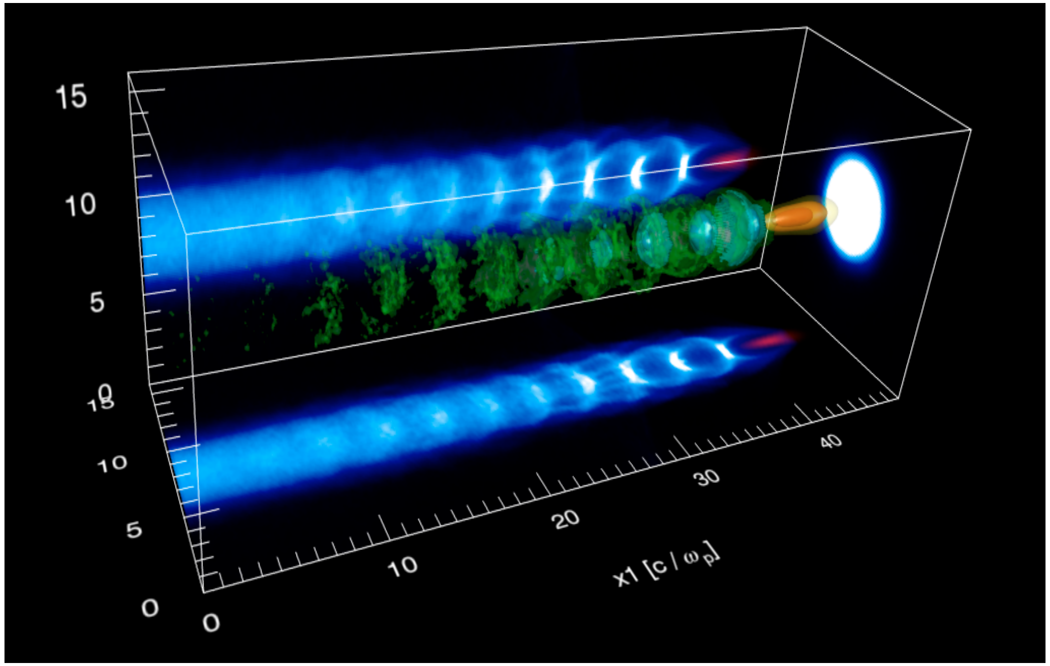
Nonlinear wakes are *similar* with laser or particle beam drivers:

3-D PIC OSIRIS Simulation

(self-ionized gas)



Laser Wake



Electron beam Wake