Particle acceleration in plasma

By

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Outline

- Plasma universe
- Plasma wave excitation
- Laser driven acceleration and production of the monoenergetic electrons beam
- Ion acceleration
- Concluding remark

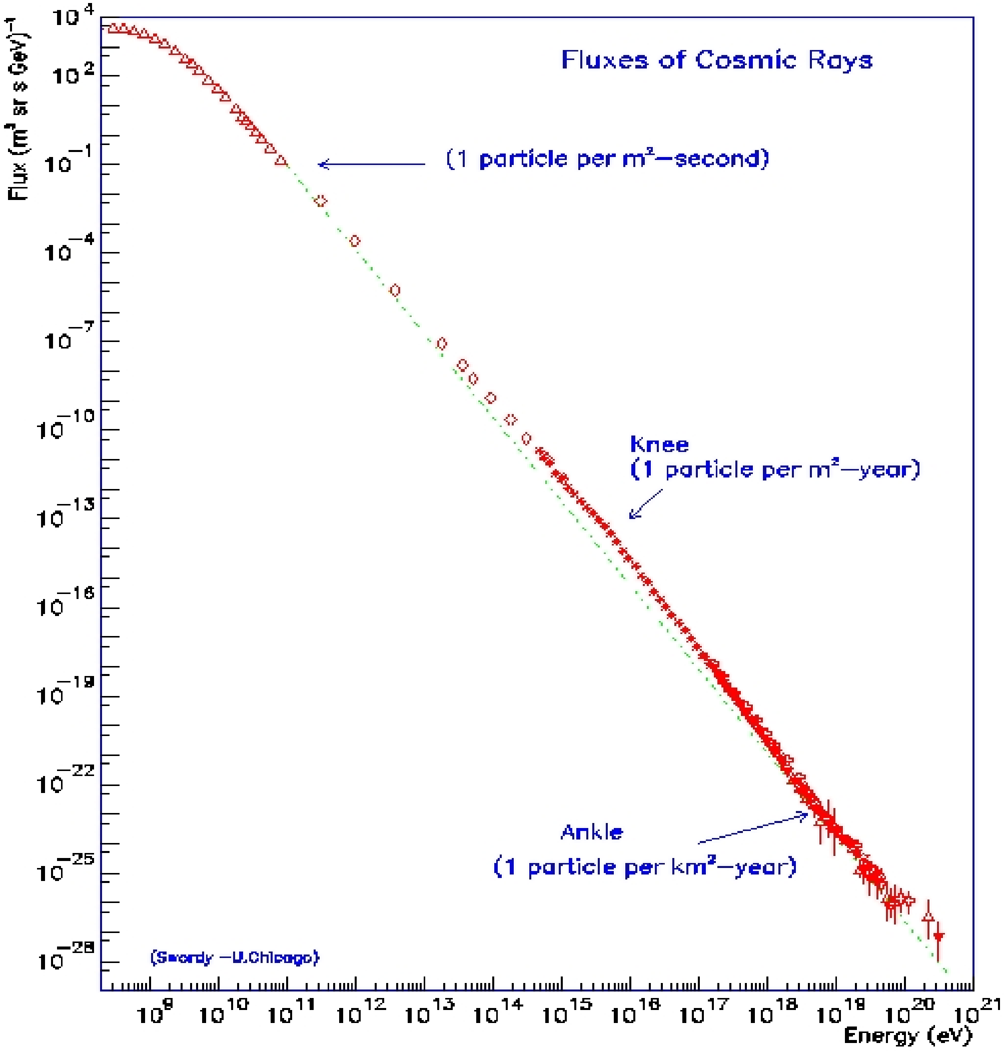
Plasma universe

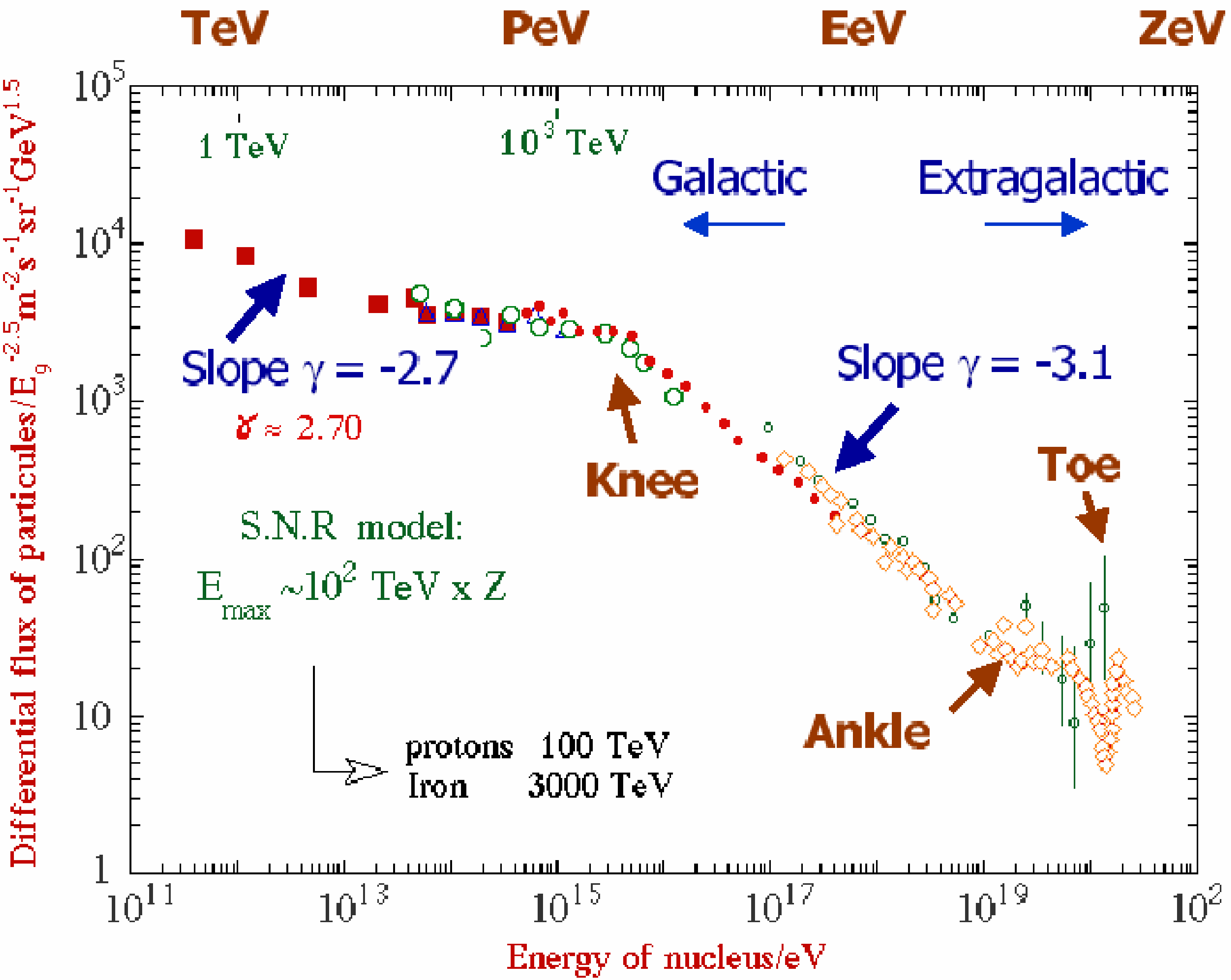
Three minutes after Big Bang ----- Plasma dominated universe

Radio jets, X-ray sources, γ -ray bursts, pulsar, accretion disk etc….

We observed this universe mostly by EM waves, its dispersion, e.g. distance of pulsars by dispersion relation, $\omega^2 = \omega_p^2 + k^2c^2$

Cosmic ray acceleration




TeV
PeV
EeV
ZeV
1 TeV
10³ TeV
Galactic
Extragalactic
Slope γ = -2.7
γ ≈ 2.70
Knee
Slope γ = -3.1
Toe
S.N.R model:
E max ~10² TeV x Z
protons 100 TeV
Iron 3000 TeV
Ankle
Differential flux of particules/E g^-2.5 m^-2 s^-1 sr^-1 GeV^1.5
Energy of nucleus/eV
10^5
10^4
10^3
10^2
10
1
10^11
10^13
10^15
10^17
10^19
10^21

"Why plasma is such a capitalistic society in which so much energy is given to so few electrons" ??

Eugene Parker

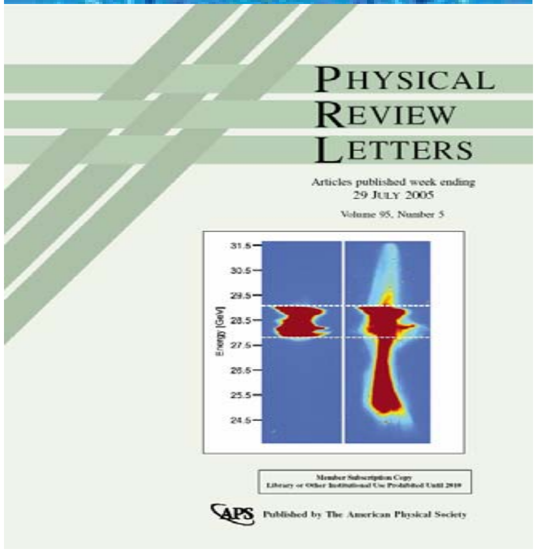
Monoenergetic electron beam observation and maximum acceleration of an electron beam

Mangles et.al, Nature, 431, 535 (2004),

Faure et.al., Nature, 431, 541 (2004),

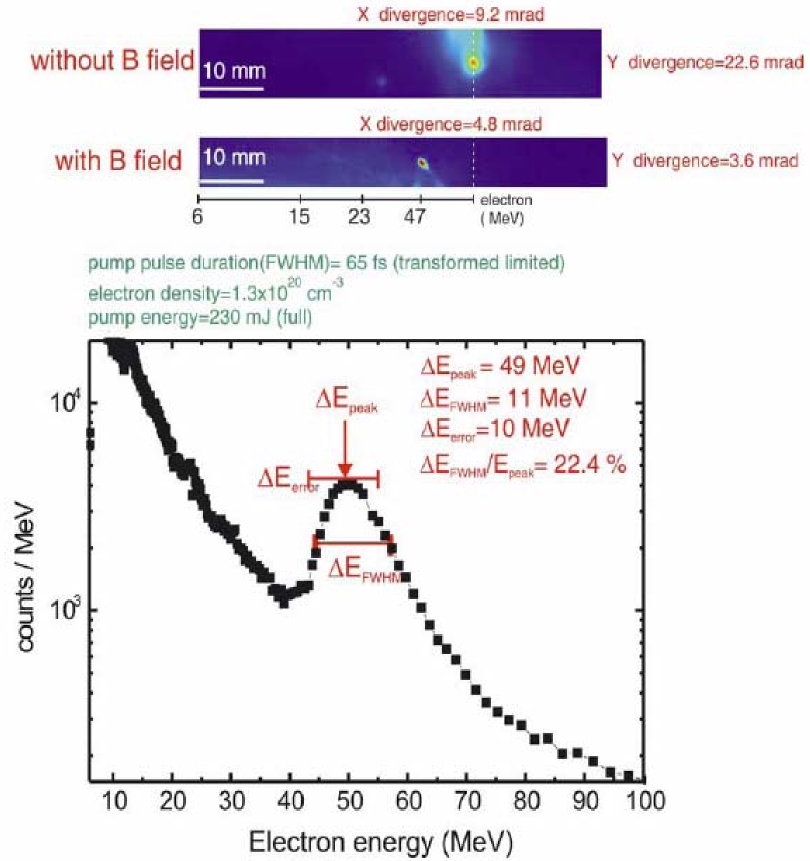
Geddes et.al., Nature, 431, 538 (2004)

Hogan *et.al.* Phys. Rev. Lett. 95, 054802 (2005)



Observation of monoenergetic beam of electrons with energy 50-170 MeV by three groups and demonstration of highest possible acceleration in beam driven wakefield acceleration

Electron energy spectrum for using 1-mm gas jet



- The beam divergence of the mono-energetic electron beam is only about 4 mrad. The energy spread is much less than 22%, with the measurement resolution limited by the electron beam size on the detector plane.

Chen, et.al.(Particle accelerator group, Academia Sinica, NTU)

Plasma as medium for waves

linear:

- Plasma wave $\omega^2 = \omega_p^2 + 3k^2\upsilon_e^2$
- Ion wave $\omega^2 = k^2 c_s^2$
- EM wave $\omega^2 = \omega_p^2 + k^2 c^2$

$\upsilon_{ph} = \omega/k$

Ponderomotive pressure, $-\nabla\left(\dfrac{nm|\upsilon_{os}|^2}{2}\right) = -n\nabla|a^2| = -mc^2\nabla\gamma$ $\quad a = \dfrac{eE}{m\omega_0 c}$

Oscillatory velocity, $\upsilon_{osc} = eE/m\omega_0 c$

Wave particle resonance and hence acceleration is possible if, $\upsilon_{osc} = \upsilon_{ph}$

No acceleration is possible by direct light wave but by plasma wave and ion wave

Nonlinear wave-wave interaction

Parametric instabilities:

- Raman scattering
- Brillouin scattering
- Two plasmon decay instability

These processes can produce both plasma wave and ion wave

Acceleration gradient

Maximum acceleration gradient limited by the wave breaking

$$\xi = \frac{eE}{m\omega_0 c} \sim \lambda$$ and $$E_0\left[V/cm\right] = mc^2 \frac{\omega_p}{c} = 0.96\sqrt{n_0}\left[cm^{-3}\right]$$

giving, $E_0 = 100\,GV/m$, for $n_0 = 10^{18}\left[cm^{-3}\right]$.

Non-relativistic wave-breaking amplitude

SLAC on a slab !!!

Relativistic wave-breaking amplitude

$$E_R\left[V/cm\right] = E_0\sqrt{\gamma_p - 1}$$

$$E_R >> E_0$$

γ_p is the Lorentz factor for plasma wave

How to generate plasma wave ??

- Mode conversion
- Two laser pulse: Beat wave excitation
- Short pulse laser wakefield generation (Raman scattering)
- Relativistic electron beam wakefield generation

Beat wave excitation

– Two long laser pulses (ps)

$$E_1 = E_1' \sin(k_1 x - \omega_1 t)$$

$$E_2 = E_2' \sin(k_2 x - \omega_2 t)$$

– Plasma wave excitation possible if, $\omega_p = \omega_1 - \omega_2$

– Maximum saturated amplitude of the plasma wave due to relativistic mass effect

$$\frac{E_{max}}{E_0} = (16\alpha_1\alpha_2/3)^{1/3} << 1 \qquad \alpha_j = \frac{eE_j'}{m\omega_j c},\ j = 1,2$$

(Rosenbluth and Liu, PRL, 1972)

Raman Scattering by Plasma Wave

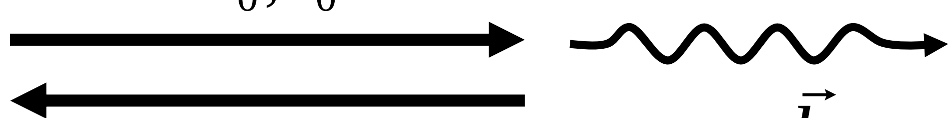
$$\omega^2 = \omega_p^2 + 3k^2 v_{th}^2 \qquad \omega_p^2 = \frac{4\pi n e^2}{m}, \;\; v_{th}^2 = \frac{kT}{m}$$

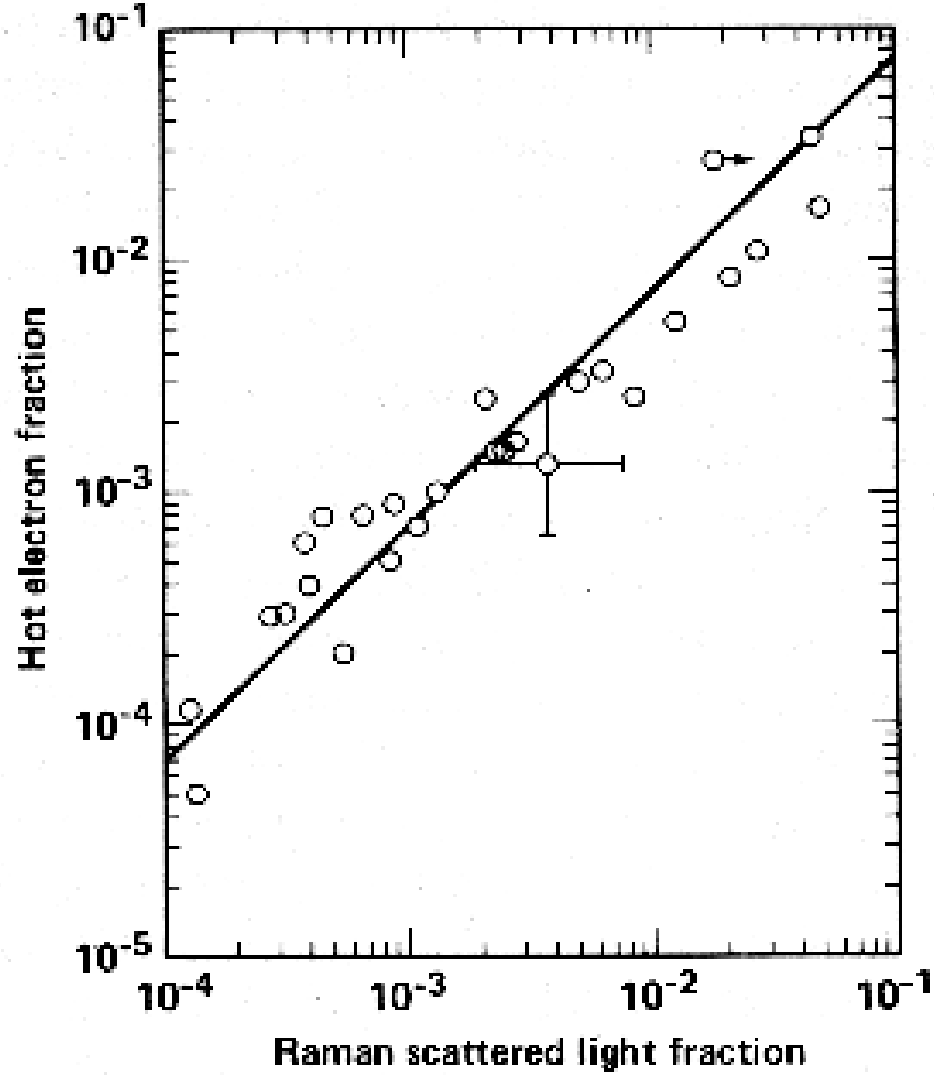
Laser light: $(\omega_0, \vec{k}_0)$

Scattered light: $(\omega_1, \vec{k}_1)$

$$\omega_0 = \omega_1 + \omega \qquad \vec{k}_0 = \vec{k}_1 + \vec{k}_p$$

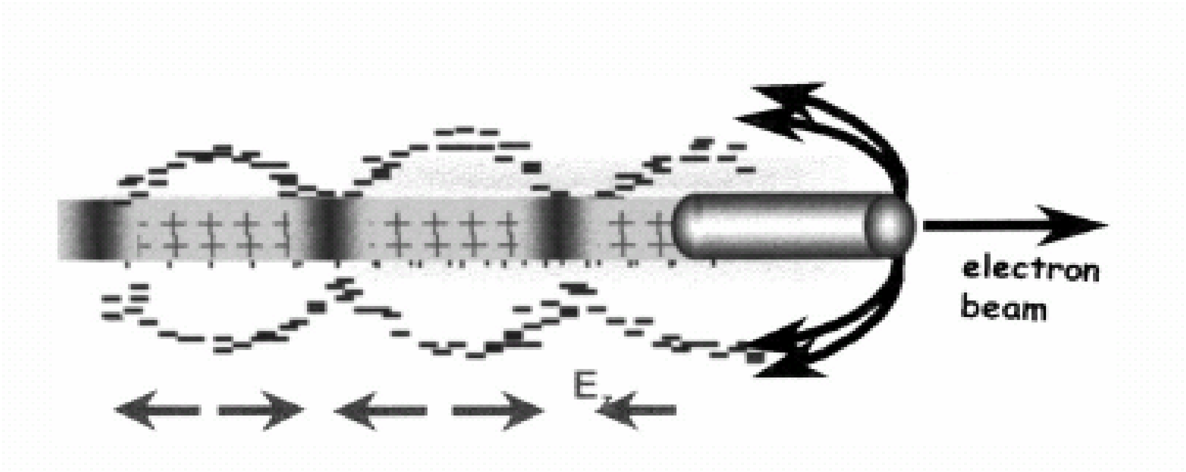
For $\omega_p << \omega_0$, $\vec{k}_1 \cong -\vec{k}_0$ (i.e., backscattering)





Hot electron fraction
Raman scattered light fraction
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}

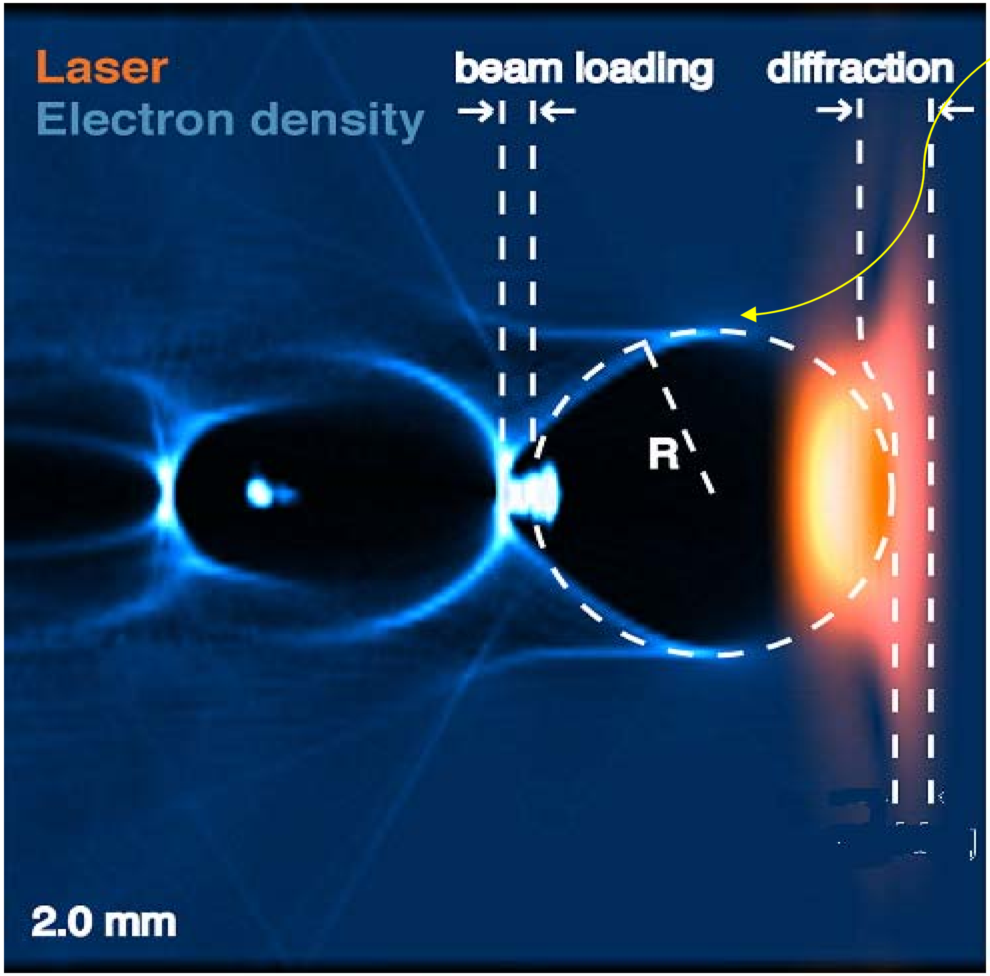
Relativistic electron beam plasma wave excitation



Maximum electric field of the plasma wave

$$\frac{E_{max}}{E_0} = \frac{n_b}{n_0}$$

Laser wakefield acceleration and ion channel formation



Micro magnetosphere

Relativistic self focusing

Laser power, $P \geq P_{cr}$ where

$$P_{cr} = 17\left(\frac{\omega^2}{\omega_p^2}\right) \text{GW}$$

Relativistic dielectric constant

$$\varepsilon = 1 - \frac{\omega_p^2}{\gamma\omega^2}$$

Relativistic effect $\rightarrow \gamma$ increases

Ponderomotive effect $\rightarrow \omega_p^2$ decreases

Resultant effect $\rightarrow$ ion channel formation

Wei Lu et.al.

Solitons and acceleration of electrons in 1-D

The Eqs. for 1-D solitons are

$$\frac{\partial^2 A}{\partial t^2} - \frac{\partial^2 A}{\partial z^2} + \frac{N_c}{\gamma_c} A = 0$$

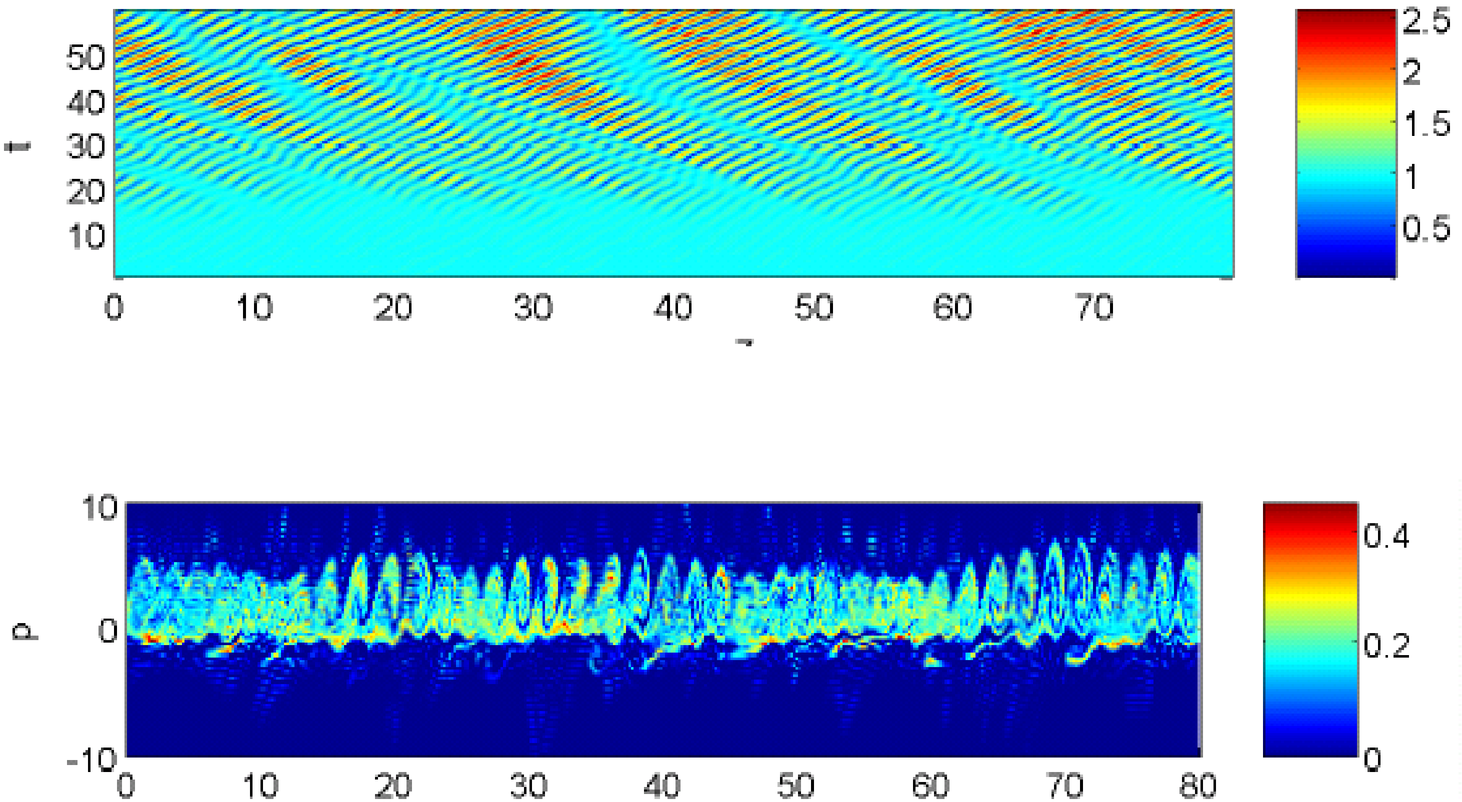
$$\gamma_c = \left(1 + P_{cz}^2 + |A|^2\right)^{1/2}$$

$$\frac{\partial f}{\partial t} + \frac{p_z}{\gamma_h}\frac{\partial f}{\partial z} + \frac{\partial(\phi - \gamma_h)}{\partial z}\frac{\partial f}{\partial p_z} = 0$$

$$\frac{\partial^2 \phi}{\partial z^2} = \int_{-\infty}^{\infty} f \, dp_z - N_0(z)$$

γ_c and γ_h are the relativistic Lorentz factor for cold and hot electrons

Eliasson et.al.submitted to PRE



Time development of EM wave envelope and phase space evolution of electrons for A=1.0 and k_0=3.0 at time t=60.

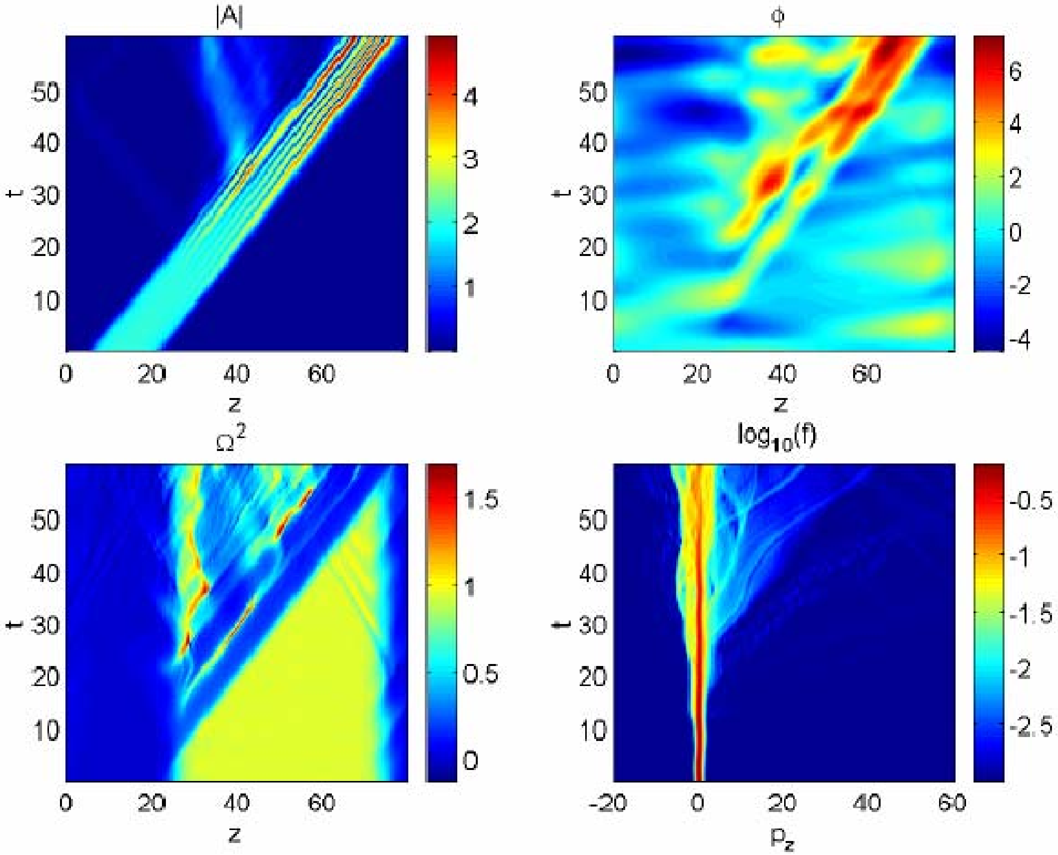


FIG. 7: The time development of the vector potential $|A|$ (the upper left panel), the potential ϕ (the upper right panel), the squared local plasma frequency (the lower left panel) and the averaged electron distribution function (the lower right panel, ten-logarithmic scale). for A=2.0 and k_0=3.0.

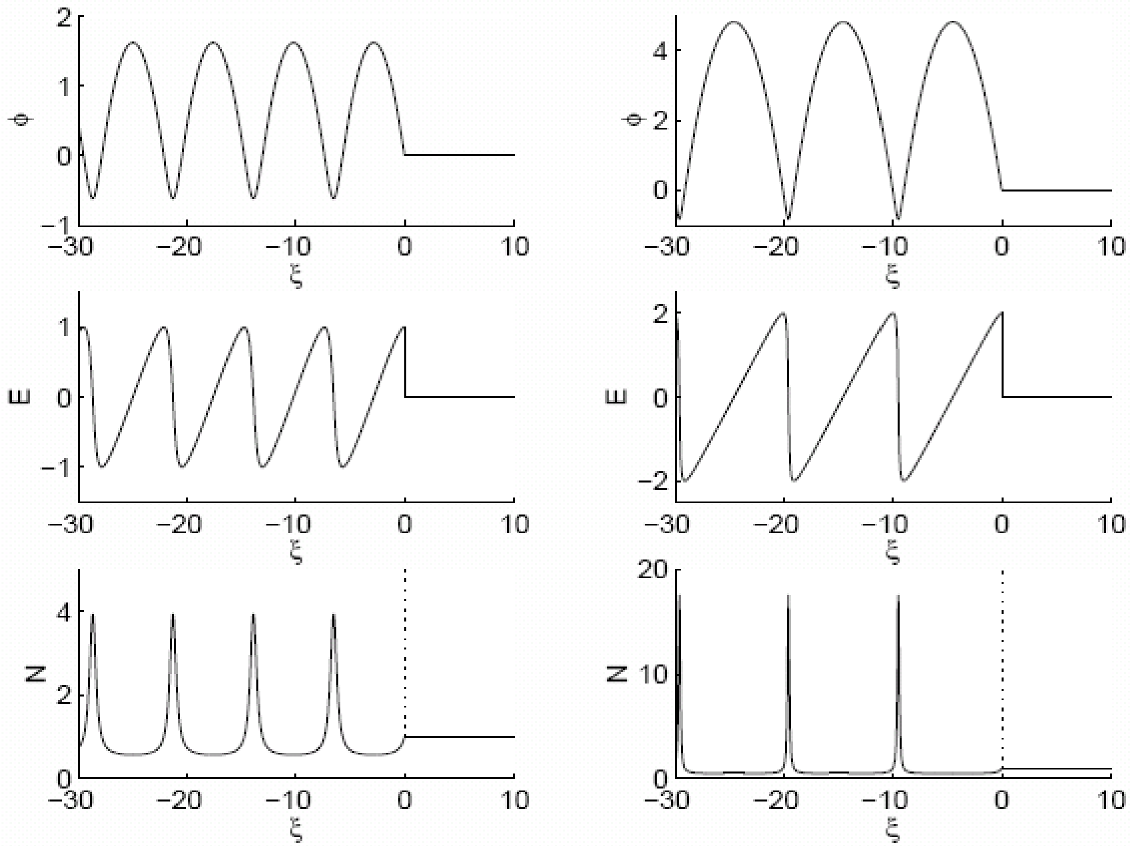


FIG. 9: The profile of the wake-field behind an ultra-short electromagnetic pulse of amplitude $Z_e = 1$ (left panels) and $Z_e = 2$ (right panels), moving with the speed of light. The pulse is located at $\xi = 0$ where $\xi = z - t$. Associated with the wake is the potential (upper panels), electrostatic field $E = -d\phi/d\xi$ (middle panels) and the electron charge $N_c = d^2\phi/d\xi^2 + 1$ (lower panels). The dotted line in the electron density represent the accumulated electron density $N = Z_e\delta(\xi)$.

Ion acceleration

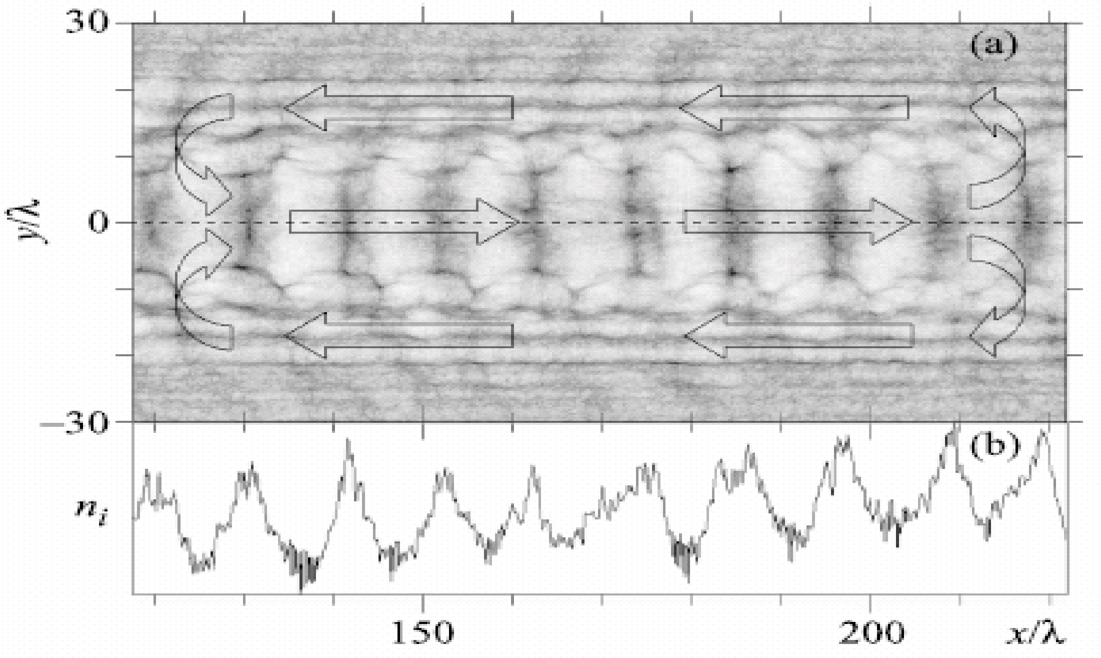


FIG. 2. (a) Ion density distribution in the (x, y) plane as obtained from the numerical simulations at $t = 2000$. A sketch of the large scale electron motion needed for the development of the Buneman instability is superimposed; (b) Ion density modulations at $y = 0$ along the pulse axis.

Borghesi et.al, PRL, 94, 195003 (2005)

Concluding remark

- With the recent breakthroughs in the plasma accelerator research, we can envisage that 21st century will be a century of plasma science and technology.

Thank you