LASER-PLASMA ACCELERATORS: PRODUCTION OF HIGH-CURRENT ULTRA-SHORT e$^-$-BEAMS, BEAM CONTROL AND RADIATION GENERATION

I.Yu. Kostyukov, E.N. Nerush (*IAP RAS, Russia*)

A. Pukhov, S. Kiselev (*Düsseldorf University, Germany*)

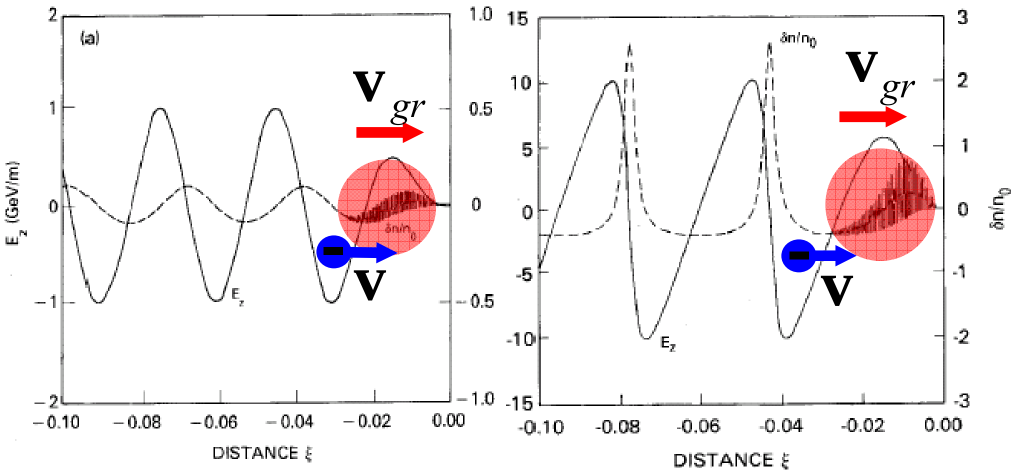
OUTLINE

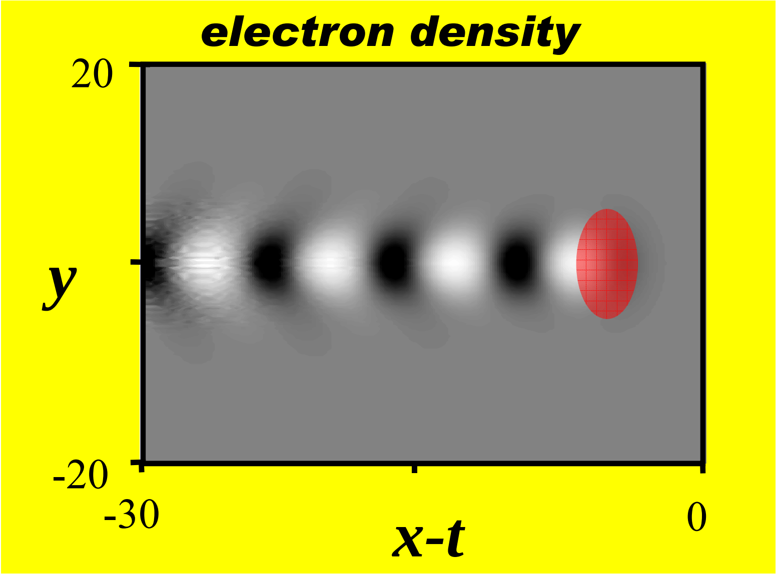
- INTRODUCTION
  - Electron Acceleration
  - Bubble Regime
  - Experiments
- BUBBLE REGIME: PHENOMENOLOGICAL THEORY
  - Electromagnetic field in plasma cavity
  - Plasma electron trapping and acceleration
  - Beam control
- ELECTROMAGNETIC RADIATION
  - Spectrum of betatron radiation
  - Laser-plasma x-ray source
  - Radiation effects
- SUMMARY

ELECTRON ACCELERATION

Ya.B. Fainberg, UFN **93**, 617, (1967)
acceleration by relativistic electron bunch in plasma

T. Tajima and J.M. Dawson, PRL **43**, 267, (1979)
acceleration by laser pulse in plasma



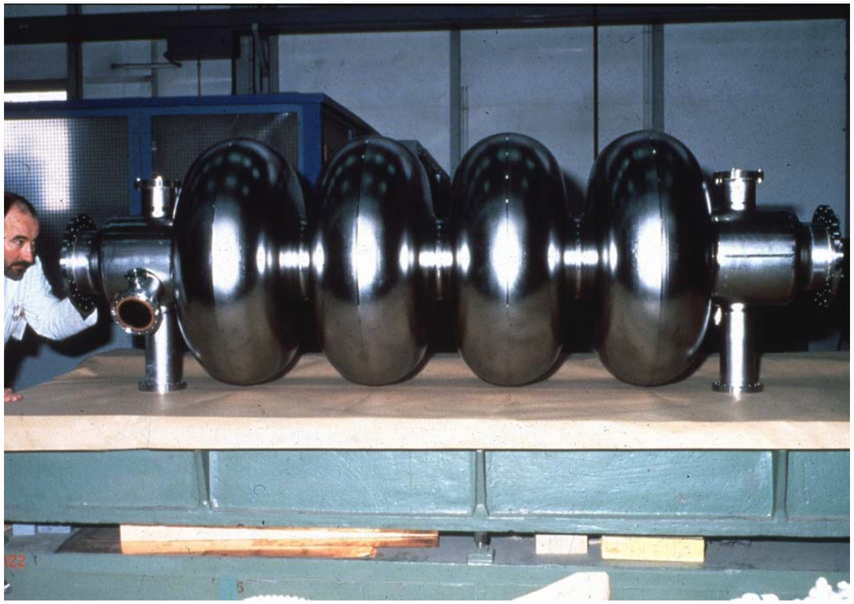


$$v_{ph} = v_{gr} \approx c(1-\omega_p^2/2\omega^2) \approx c$$

$$E_0[\hat{A}/\tilde{n}\grave{i}\ ] \approx 0.96\sqrt{n_0[\tilde{n}\grave{i}^{\ -3}]}$$

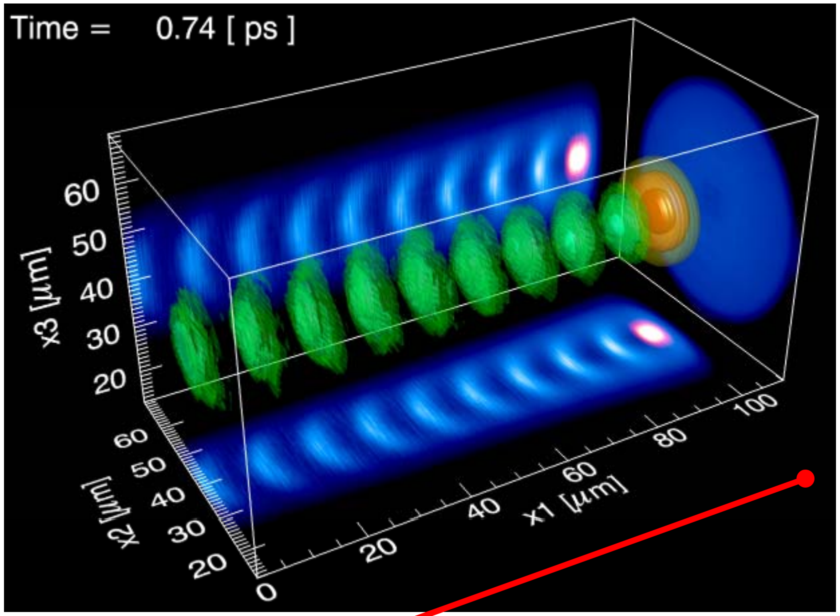
$$n_0 = 10^{19}\,см^{-3} \quad E_0 = 300\,ГВ/м$$

ELECTRON ACCELERATION



1 m

RF cavity

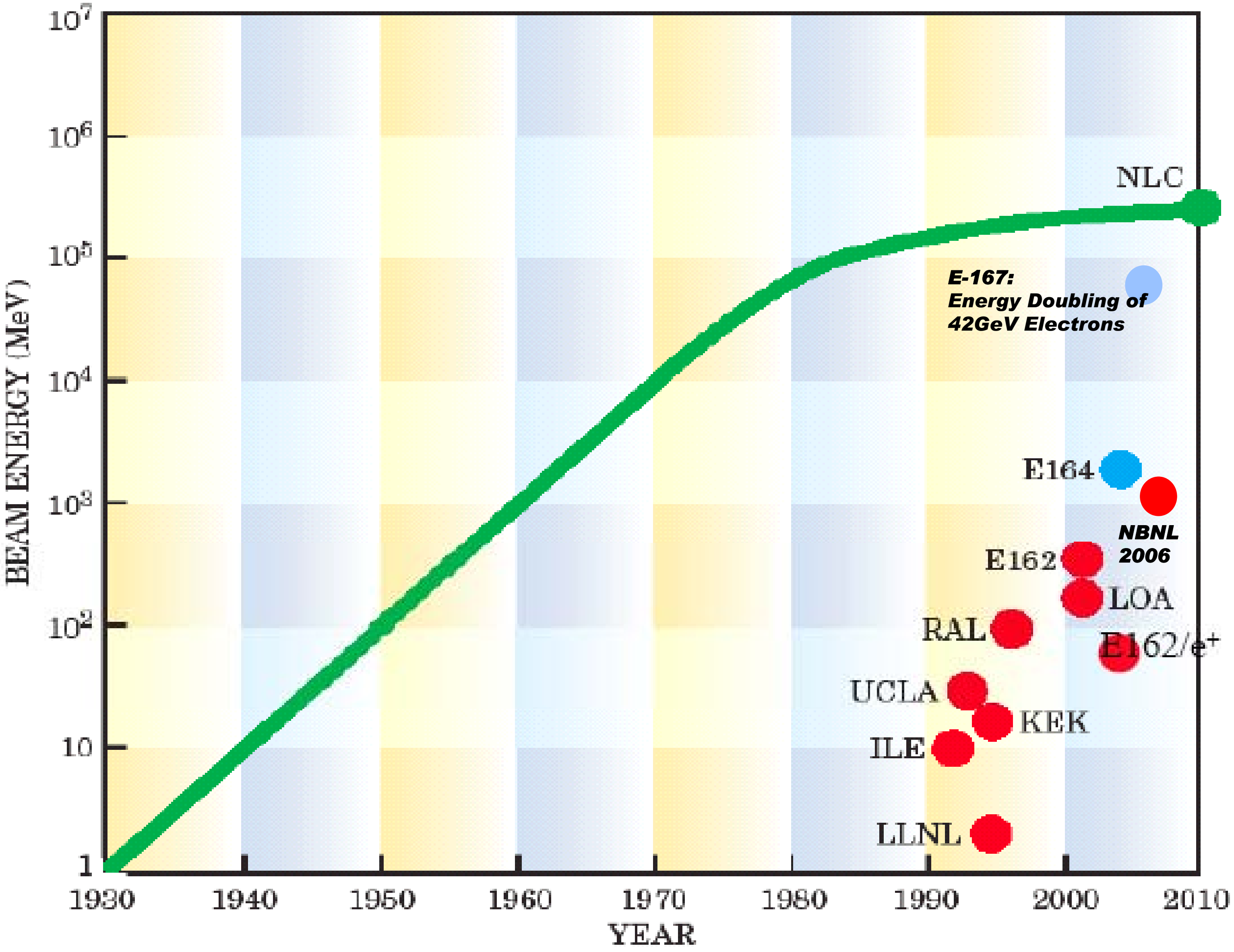


100 µm

Plasma cavity

V. Malka, Dream beam, 2007

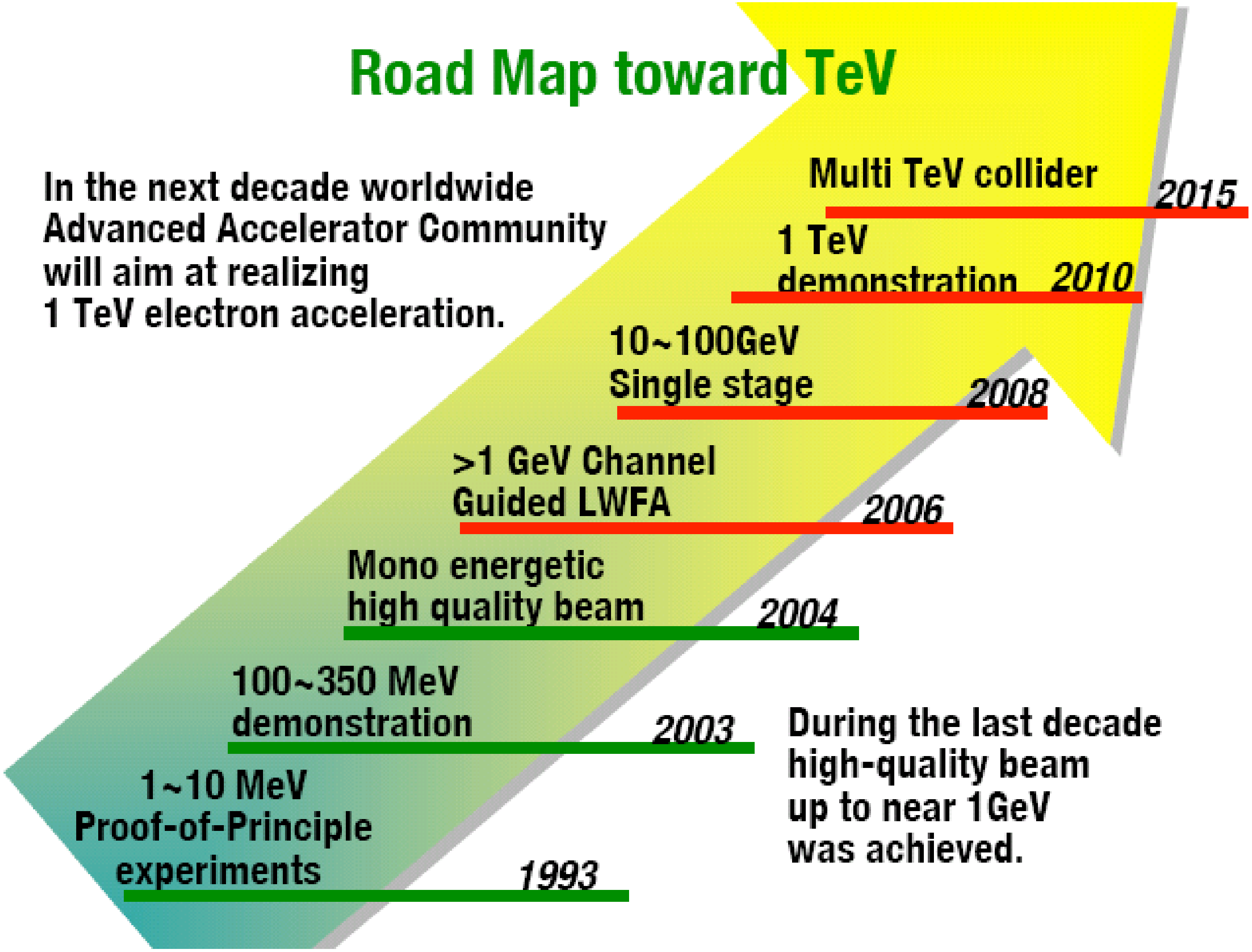
ELECTRON ACCELERATION



C. Joshi and T. Katsouleas, Physics Today, June 2003

ELECTRON ACCELERATION

Road Map toward TeV



In the next decade worldwide
Advanced Accelerator Community
will aim at realizing
1 TeV electron acceleration.

Multi TeV collider 2015

1 TeV demonstration 2010

10~100GeV Single stage 2008

>1 GeV Channel Guided LWFA 2006

Mono energetic high quality beam 2004

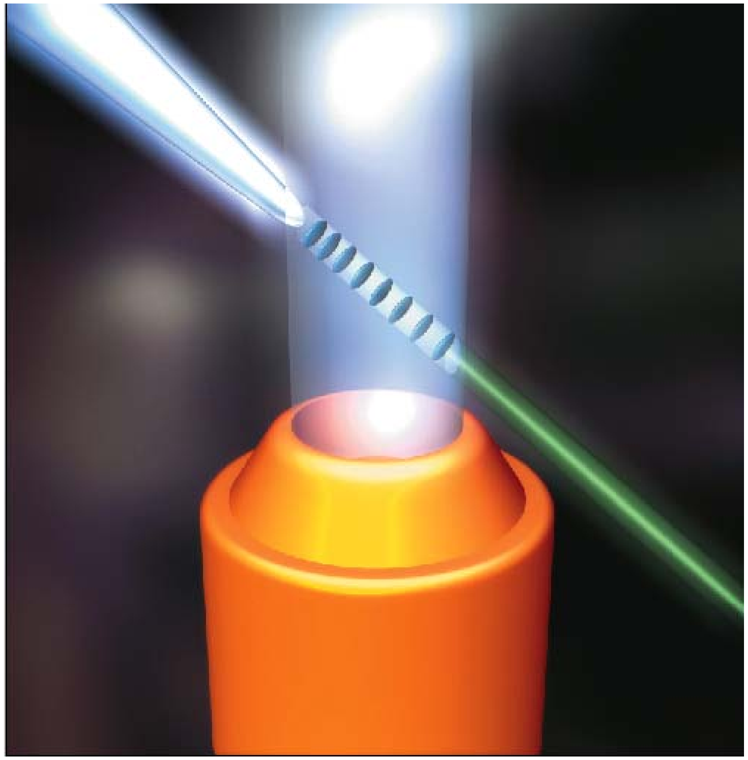
100~350 MeV demonstration 2003

1~10 MeV Proof-of-Principle experiments 1993

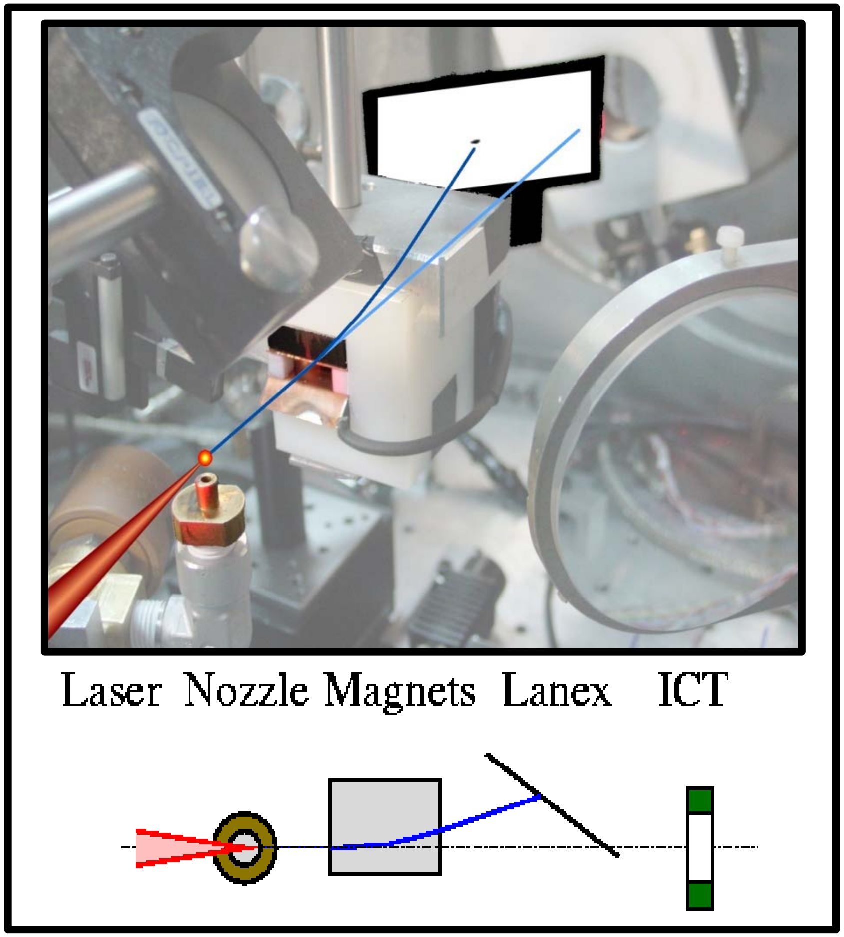
During the last decade
high-quality beam
up to near 1GeV
was achieved.

K. Nakajima, ***HEEAUP 2005***

ELECTRON ACCELERATION



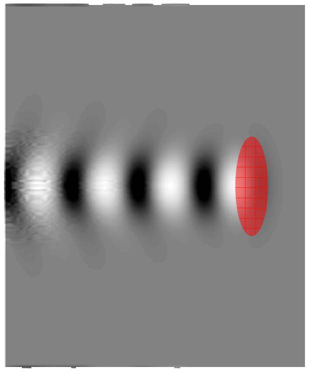
Scheme of principle



Experimental set up

V. Malka, Dream beam, 2007

LASER-PLASMA PARAMETERS



- ***plasma density*** $n < n_{cr}$

$$n_{cr}^2 = \frac{m\omega^2}{4\pi e^2}$$ **critical density**

- ***laser intensity***

$$a = \frac{eA}{mc^2} \propto \frac{W_\sim}{mc^2} = \gamma_\sim$$

ratio of electron quiver energy to the energy at rest

$a >> 1$ **relativistically strong laser field**

- ***laser pulse duration***

$$\lambda_l << cT \le \lambda_p = \frac{2\pi c}{\omega_p} = \lambda_l \sqrt{\frac{n_{cr}}{n}}$$ **short pulse**

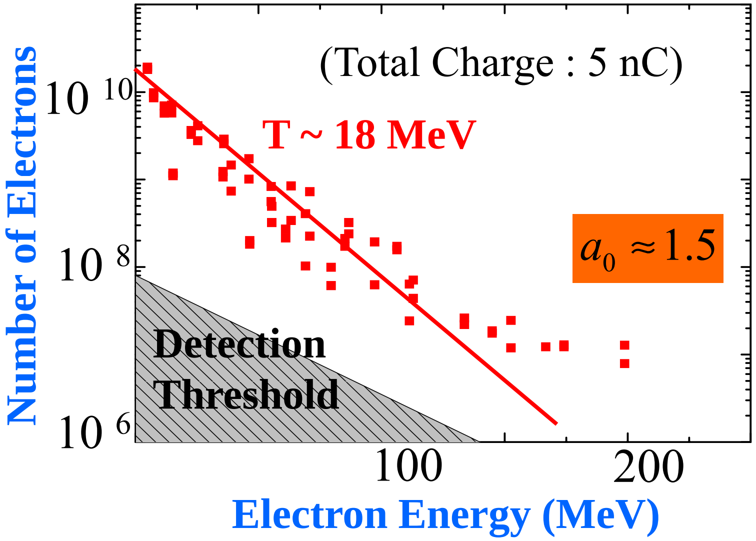
$$\omega_p^2 = \frac{4\pi e^2 n}{m}$$ plasma frequency

- ***hot spot size*** $r_\perp \Box \lambda_p$

ELECTRON ACCELERATION

100% ENERGY SPREAD IN EARLY EXPERIMENTS

$I \approx 3 \times 10^{18}$ W/cm^2 1 J, 30 fs, 10 Hz



V.Malka *et al.*, Science **298,** 1596 (2002)

160 J, 650 fs, 6 μm

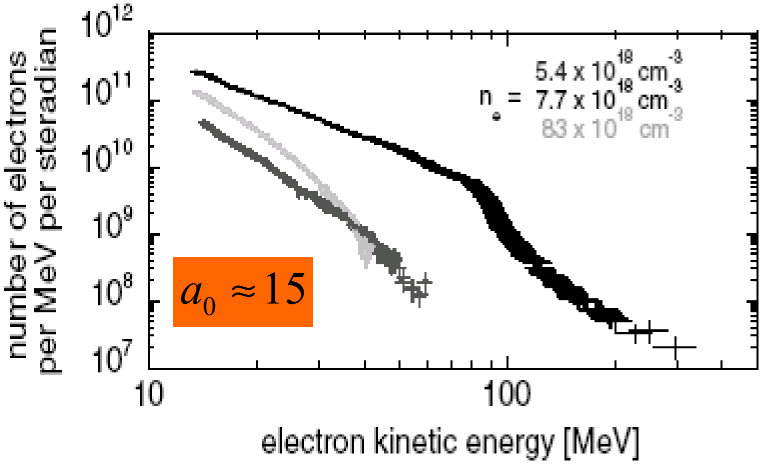


FIG. 1. Three example electron energy spectra observed at various background electron densities for laser intensity ~3×10^{20} W cm^{-2}.

S.P.D. Mangles *et al.*, PRL **94,** 245001 (2005)

QUASI-MONOENERGETIC e⁻ -BEAM

news and views

Electrons hang ten on laser wake

Thomas Katsouleas

Electrons can be accelerated by making them surf a laser-driven plasma wave. High acceleration rates, and now the production of well-populated, high-quality beams, signal the potential of this table-top technology.

Huge particle accelerators have been at the vanguard of research in particle physics for more than half a century; through high-energy collisions of accelerated particles, the fundamental building-blocks and forces of nature have been revealed. The latest project, the Large Hadron Collider (LHC) currently under construction at CERN in Geneva, will attempt to find the Higgs boson, a particle associated with the mechanism through which all other known particles are thought to acquire their masses. But the size and cost of such machines — for the LHC, a 27-km circumference and several billion euros — are fuelling a serious effort to develop new and more compact accelerator technologies. Three reports[1–3] in this issue (from page 535) announce fresh progress, using a principle known as plasma wakefield acceleration.

Plasmas — gaseous 'soups' of dissociated electrons and ions — offer a means of acceleration that could be realized on a table top[4]. Waves can be generated in a plasma using short laser pulses; electrons or their antimatter counterparts, positrons, can then 'surf' the electric field of a wave's wake. Particles have been accelerated in wakefields at rates that are more than a thousand times higher than those achieved in accelerators based on conventional large-scale technology. However, whether plasma wakefield accelerators could produce the high quality of beam needed for applications in high-energy physics, and in other areas of research and medicine, remained in question. The results now presented by Geddes *et al.*[1], Mangles *et al.*[2] and Faure *et al.*[3] are a milestone in this regard. They provide the first demonstration that a beam of electrons can be accelerated in a wakefield to a single energy. Moreover, their beams are of high quality (having a small angular divergence) and significant charge (about 10^9 electrons).

In a conventional accelerator, charged particles such as electrons, protons or their antiparticles are accelerated by an alternating, radio-frequency electric field through long metallic cavities (around a metre long for medical applications, but several kilometres long for high-energy physics). The rate of acceleration is limited by the peak power of the radio-frequency source and, ultimately, by electrical breakdown at the metal walls of the accelerator. Laser-driven plasma waves overcome both of these limitations: the high peak power of lasers is unmatched, and the plasma, as it is already an ionized gas, is impervious to electrical breakdown. In 1995, Modena *et al.*[5] made clear the remarkable potential of this scheme, and it has been confirmed by subsequent experiments. Using the radiation pressure of a laser to drive a compressive oscillation in the plasma (like a sound wave, but with electrostatic repulsion rather than pressure as the restoring force), electrons have been accelerated from rest to an energy of 100 megaelectronvolts (MeV) within a distance of 1 mm — more than 5,000 times shorter than the distance required to reach that energy in a conventional accelerator.

But acceleration rate is only one measure of a good accelerator. The number of particles in a beam, and their spread in angle and energy, also matter. In 2002, Malka *et al.*[6] showed that well-collimated beams of 10^8 electrons could be produced within an angular spread of 3° by a laser-driven wakefield; in these experiments, however, the energy spread of the beams was 100%. This wide range of energies occurred because the particles were trapped from the background plasma — in much the same way that white-water gets trapped and accelerated in an ocean wave — rather than injected into a single location near the peak of the wave (as is done in a conventional accelerator). But injection is difficult in a wakefield accelerator because the wavelength of the plasma wave is tiny — typically 10,000 times shorter than the usual 10-cm wavelengths of the radio-frequency fields in conventional accelerators. Successfully injecting tightly packed bunches of particles near the plasma-wave

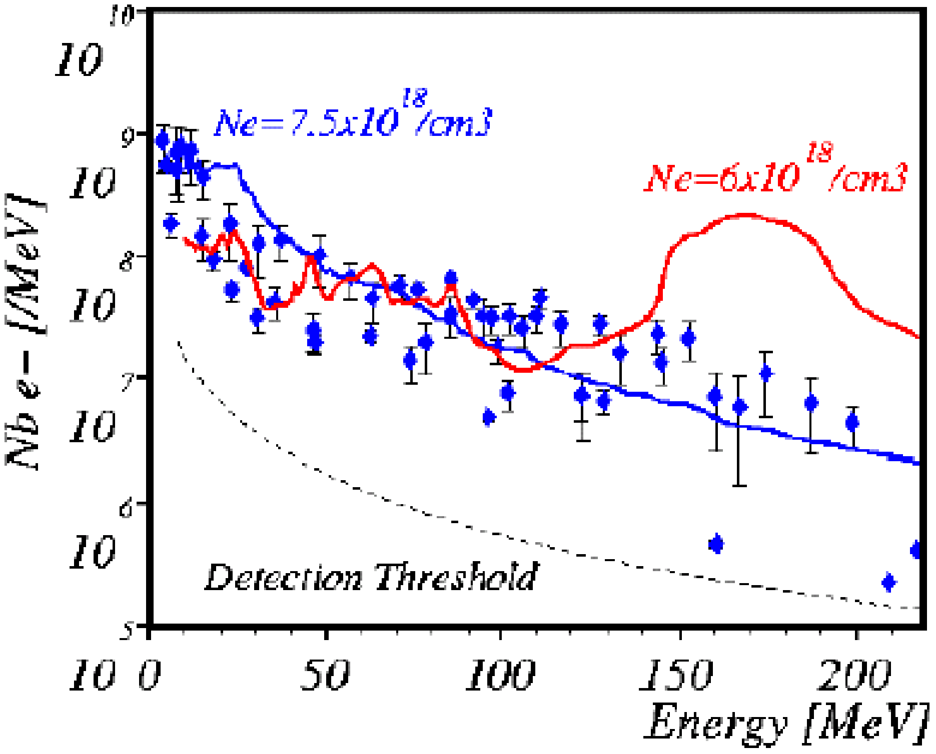
NATURE | VOL 431 | 30 SEPTEMBER 2004 | www.nature.com/nature

©2004 Nature Publishing Group

515

1) T. Katsouleas, Nature **431,** 515 (2004)

2) S.P.D. Mangles *et al*., Nature **431,** 535 (2004)
3) C.G.R. Geddes *et al*., Nature **431,** 538 (2004)
4) J.Faure *et al*., Nature **431,** 541 (2004)

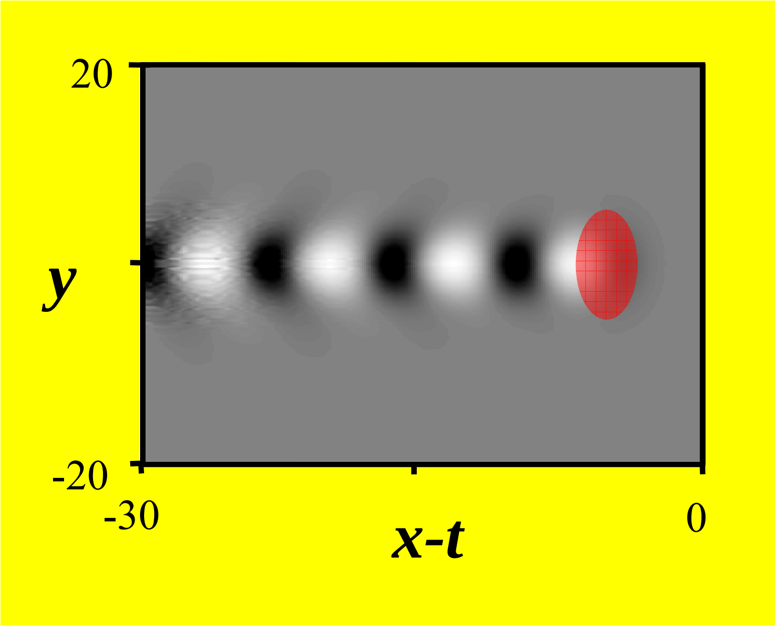


Extremely collimated beams with 10 mrad divergence and 0.5±0.2nC of charge at 170±20MeV have been produced.

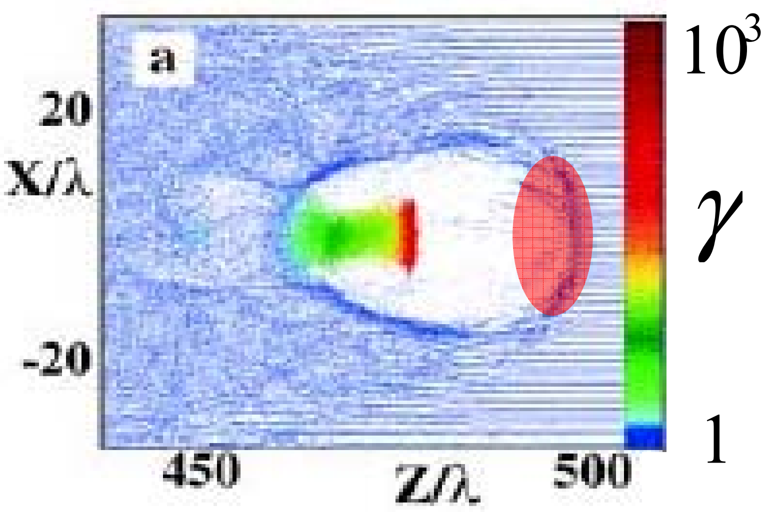
[J.Faure *et al*., Nature **431,** 541 (2004)]

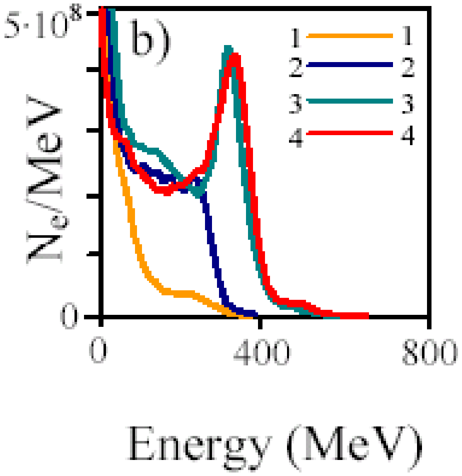
BUBBLE REGIME

plasma wave



bubble

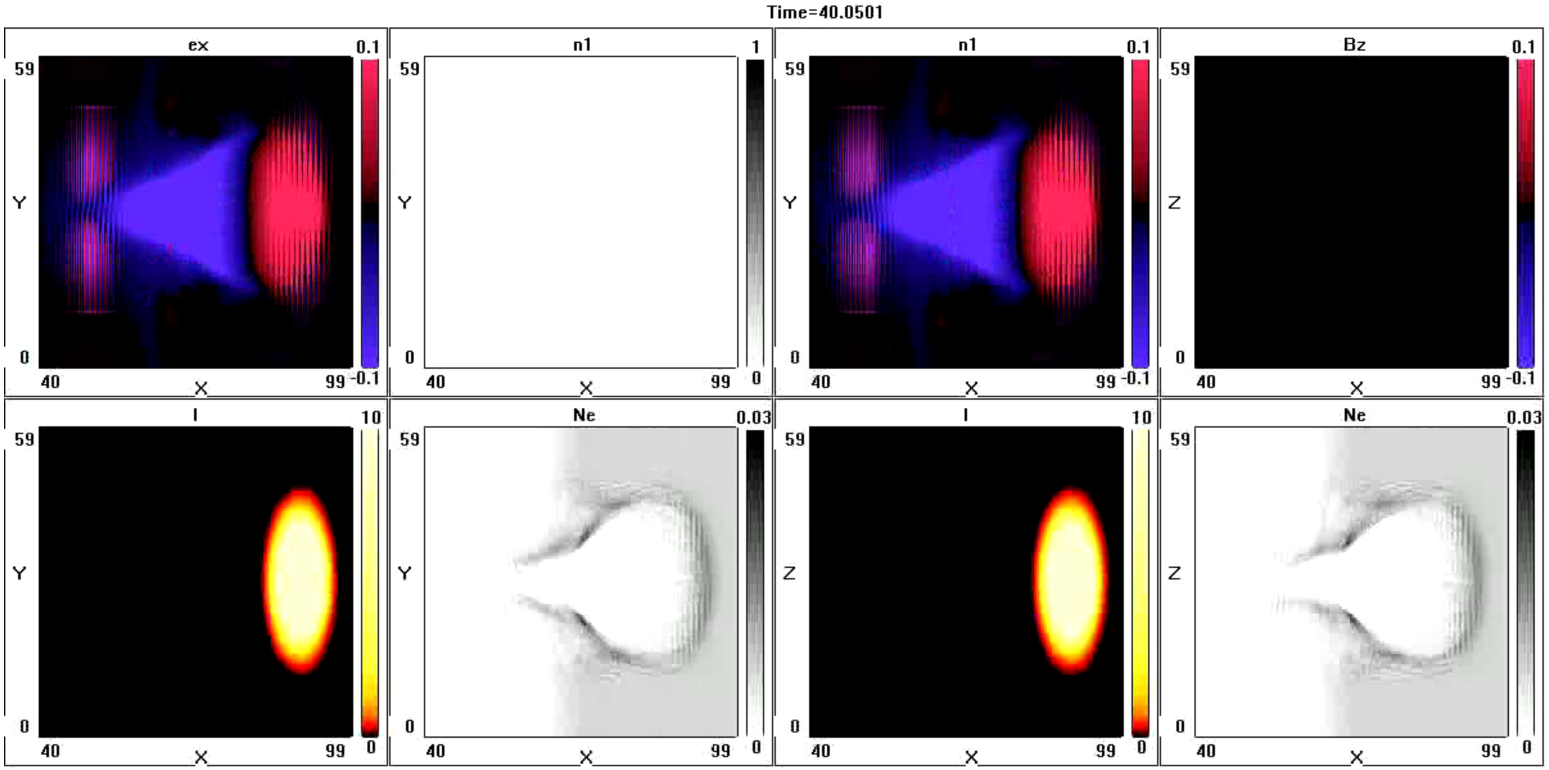




Ponderomotive force of laser pulse push out plasma electrons from region where laser intensity is high, while heavy ions can be considered as immobile.

A. Pukhov and J. Meyer-ter-Vehn, Applied Physics B**, 74,** 355 **(**2002)

BUBBLE REGIME



circular polarization

$$A(r_\perp, z) = A_0 \exp\left(-\frac{r_\perp^2}{r_L^2} - \frac{x^2}{T_L^2}\right)$$

$$\lambda_L = 0.82\,\mu m, \quad eA_0/mc^2 = 10, \quad r_L = 5c/\omega_p, \quad T_L = 2c/\omega_p, n_0/n_c = 0.01$$

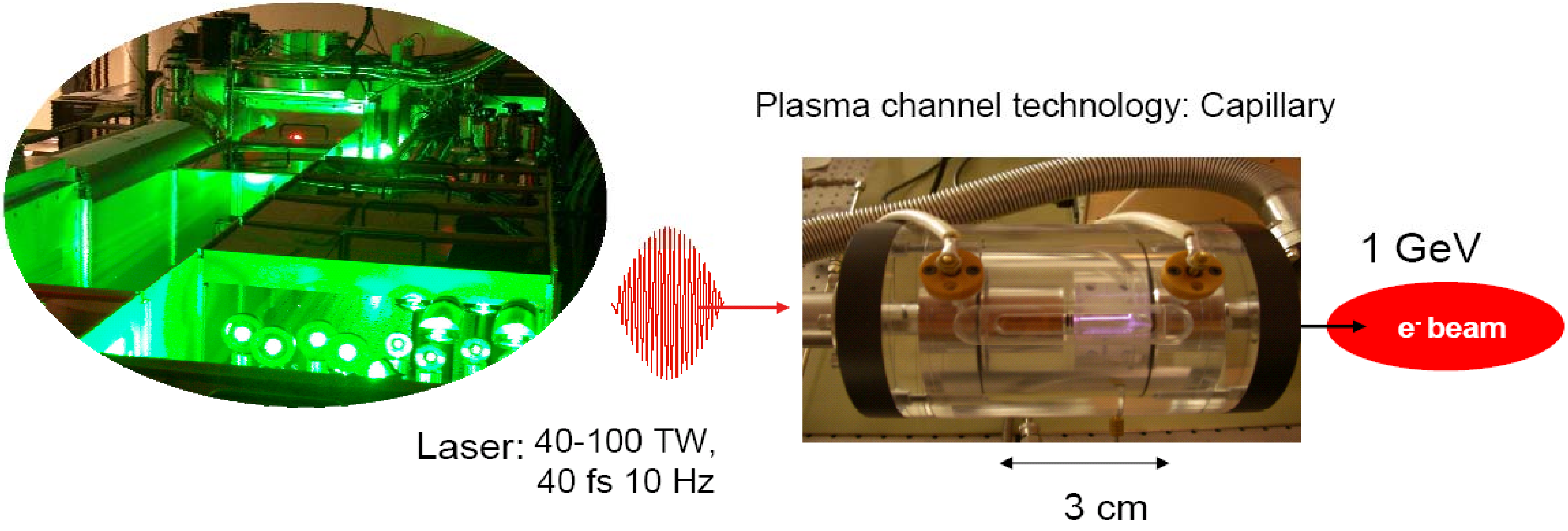
GEV: CHANNELING OVER CM-SCALE

LNBL EXPERIMENT

- Increasing beam energy requires increased dephasing length and power:

$$\Delta W[\mathrm{GeV}] \sim I[\mathrm{W/cm^2}]/n[\mathrm{cm^{-3}}]$$

- Scalings indicate cm-scale channel at ~ 10^{18} $\mathrm{cm^{-3}}$ and ~50 TW laser for GeV
- Laser heated plasma channel formation is inefficient at low density
- Use capillary plasma channels for cm-scale, low density plasma channels



W.P. Leemans et al., Nature Physics 2 (2006)

0.5 GEV BEAM GENERATION

225 μm diameter and 33 mm length capillary

Density: 3.2-3.8x10^{18}/cm^3

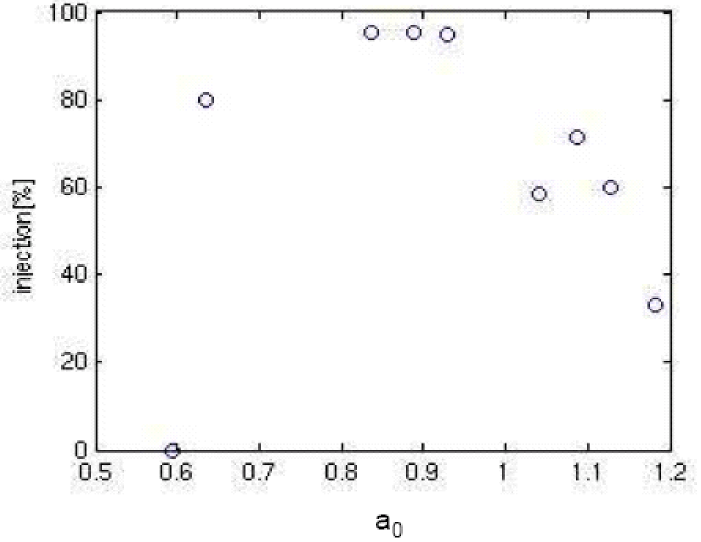
Laser: 950(±15%) mJ/pulse (compression scan)

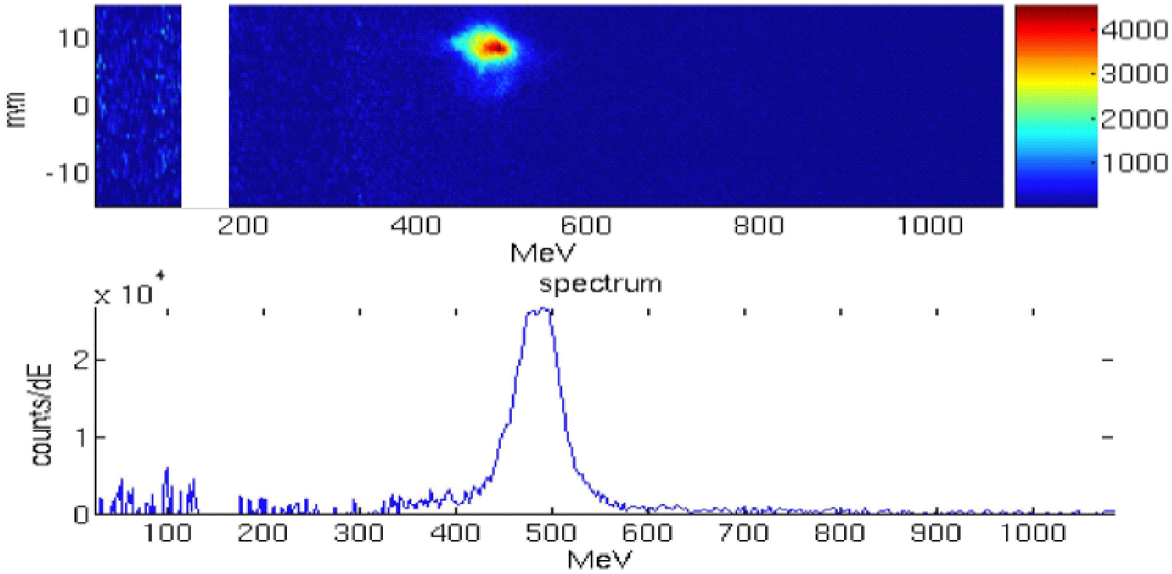
Injection threshold: a_0 ~ 0.65 (~9TW, 105fs)

Less injection at higher power

-Relativistic effects

-Self modulation





Stable operation

500 MeV Mono-energetic beams:

a_0 ~ 0.75 (11 TW, 75 fs)

Peak energy: 490 MeV
Divergence(rms): 1.6 mrad
Energy spread (rms): 5.6%
Resolution: 1.1%
Charge: ~50 pC

E. Esarey, Dream beam, 2007

1 GEV BEAM GENERATION

312 μm diameter and 33 mm length capillary

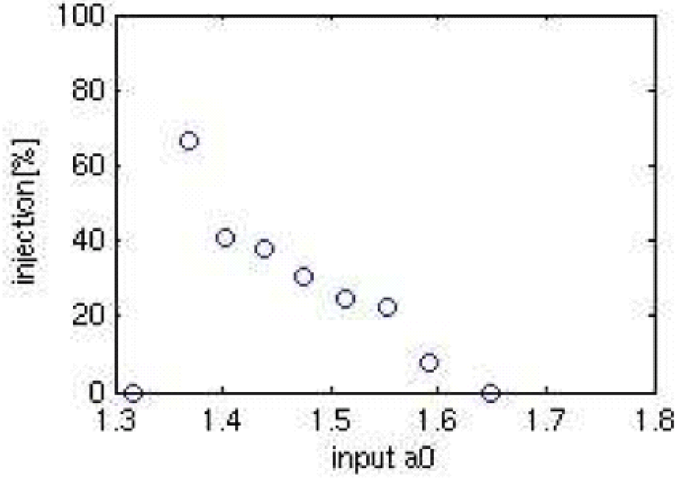
Laser: 1500(±15%) mJ/pulse

Density: 4x10^{18}/cm^3

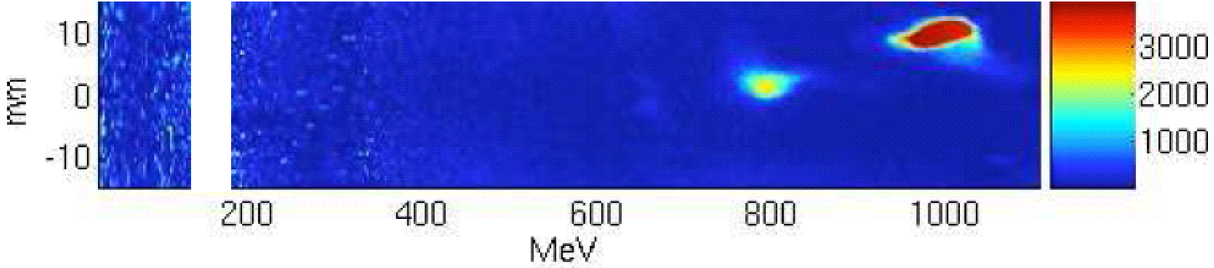
Injection threshold: a_0 ~ 1.35 (~35TW, 38fs)

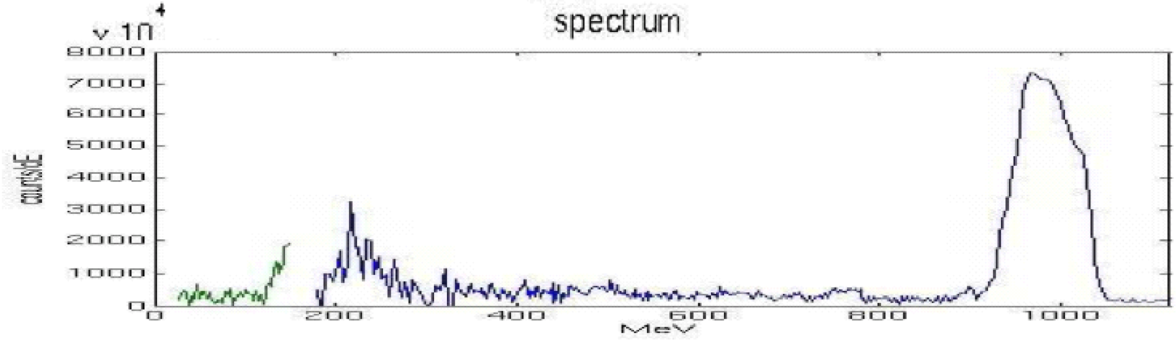
Less injection at higher power

Relativistic effect, self-modulation



1 GeV beam: a_0 ~ 1.46 (40 TW, 37 fs)





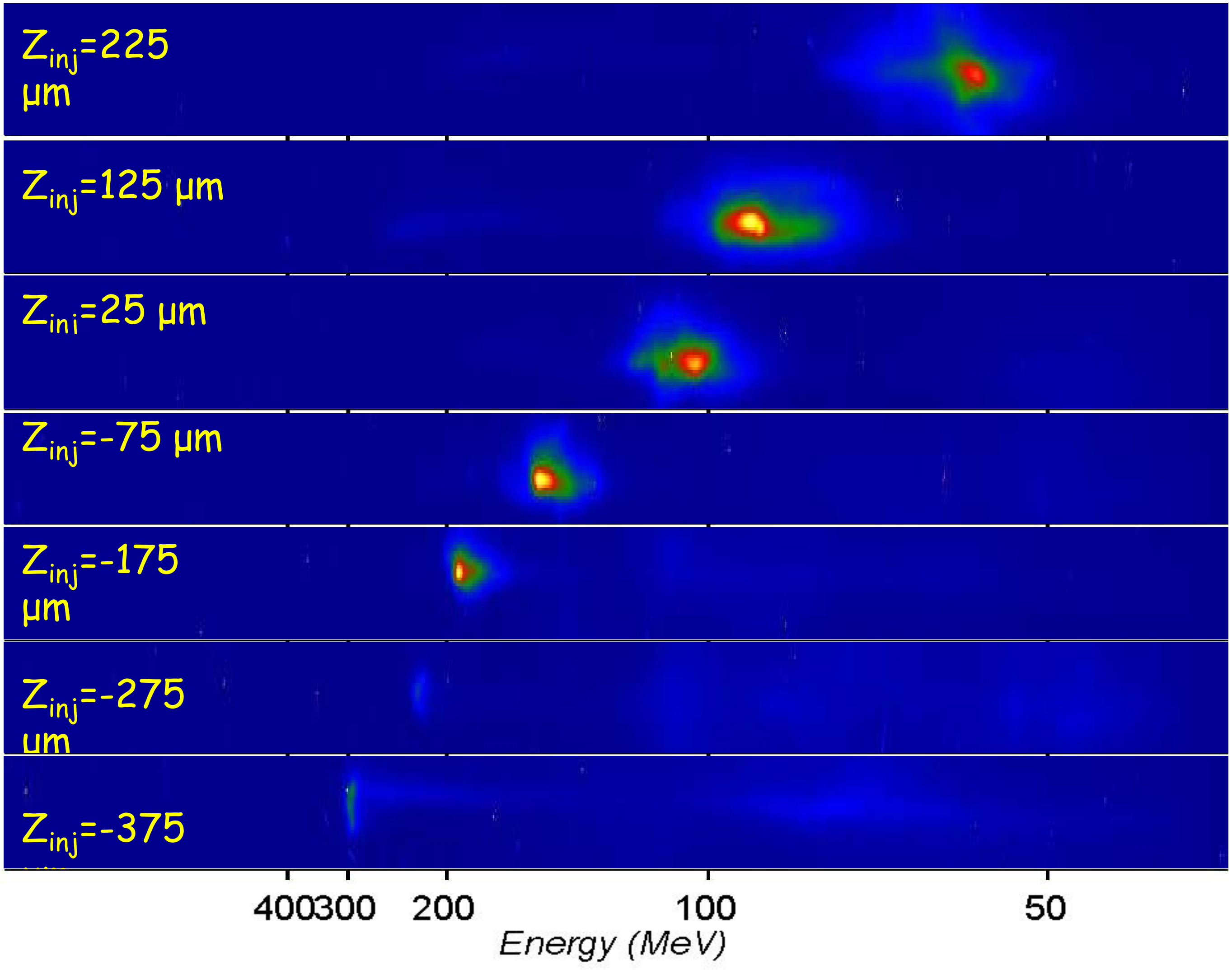
Peak energy: 1000 MeV
Divergence(rms): 2.0 mrad
Energy spread (rms): 2.5%
Resolution: 2.4%
Charge: > 30.0 pC

Less stable operation

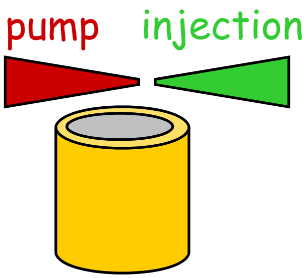
Laser power fluctuation, discharge timing, pointing stability

E. Esarey, Dream beam, 2007

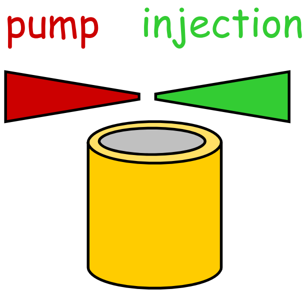
TUNABLE e^--ACCELERATOR: USING COLLIDING PULSE



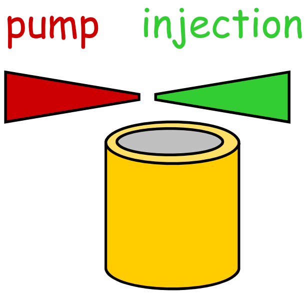
J. Faure et al., Nature december 2006



late injection



middle injection



early injection

PW LASER SYSTEM IN INSTITUTE OF APPLIED PHYSICS

E=30 TeV/m

$$W = 24J,\ \ \tau = 43\,fs,\ \ R = 12\mu m,\ \ P = 0.56PW,\ \ I = 1.1\cdot 10^{20} W/cm^2,\ \ \lambda = 0.911\mu m,\ \ a_0 = 11.4$$

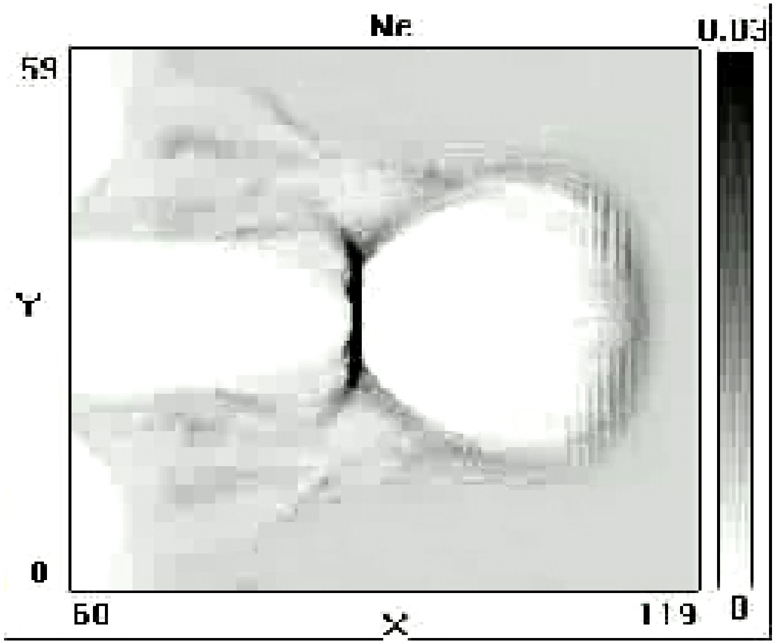
CONCLUSIONS

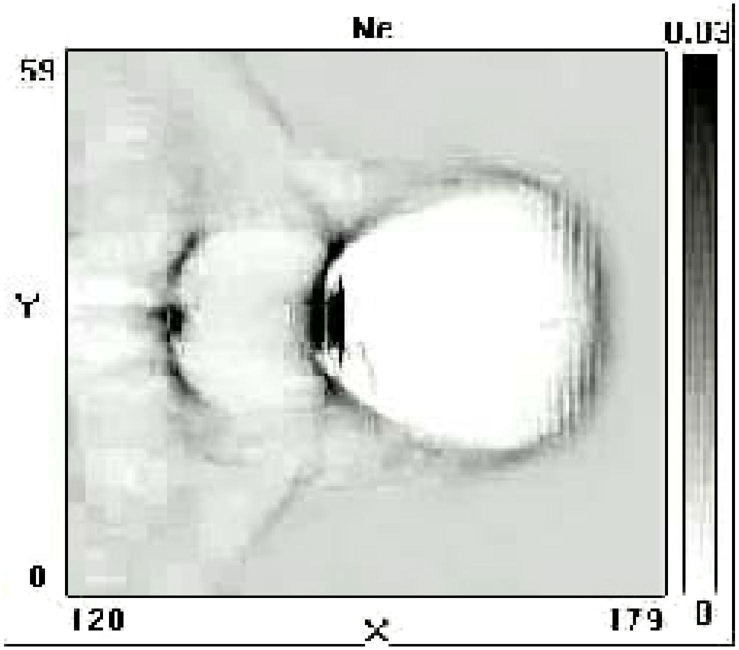
Rapid progress in laser-plasma acceleration:
GEV in 3 cm,
tunable quasi-monoenergetic e^--bunches

BUBBLE REGIME: PHENOMENOLOGICAL THEORY

QUASISTATIC APPROXIMATION

$$\xi = x - v_{gr} t$$





QUASISTATIC APPROXIMATION

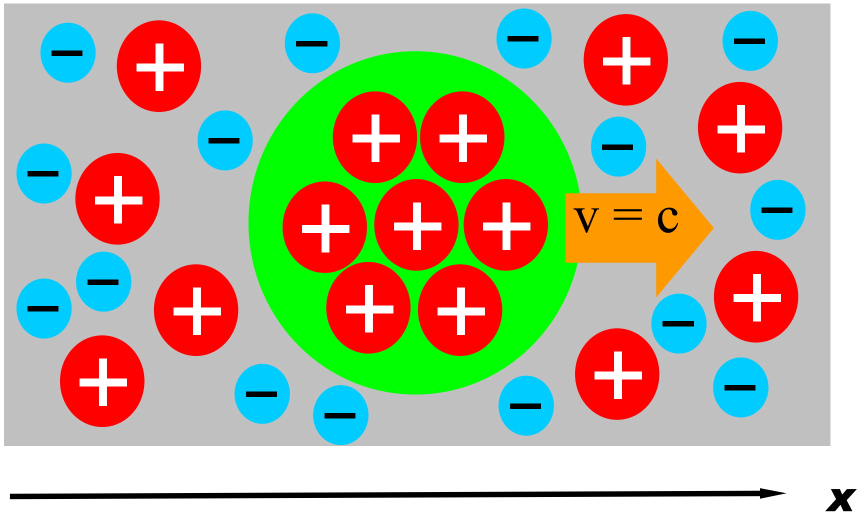
$A_x = -\varphi$ - gauge

$\Phi = \varphi - A_x$ - wakefield potential

$$\begin{cases} \Delta\Phi = -\dfrac{3}{2}(1-n) - n\dfrac{p_x}{\gamma} + \dfrac{1}{2}\dfrac{\partial}{\partial\xi}(\nabla_\perp \cdot \mathbf{A}_\perp), \\ \Delta_\perp \mathbf{A}_\perp - \nabla_\perp(\nabla_\perp \cdot \mathbf{A}_\perp) = n\dfrac{\mathbf{p}_\perp}{\gamma} - \dfrac{1}{2}\nabla_\perp \dfrac{\partial\Phi}{\partial\xi}, \end{cases}$$

$$|e| = m = c = n_0 = 1$$

$$\gamma_{gr}^{-2} = 1 - v_{gr}^2 / c^2 << 1$$



$\xi = x - v_{gr} t$

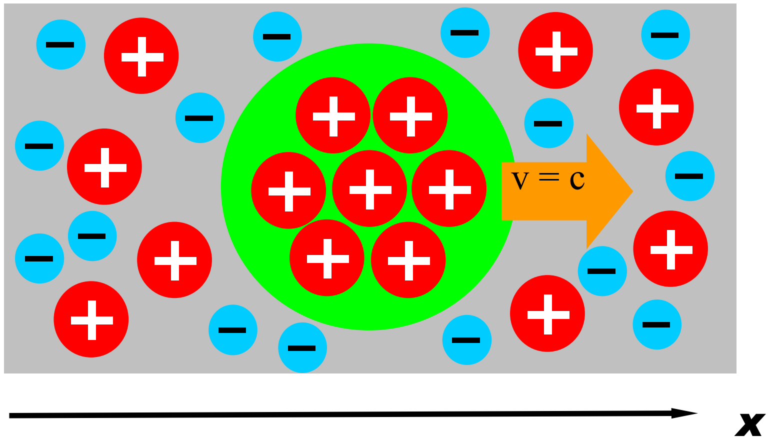
relativistic electron hole in plasma (not relativistic ion ball)

ELECTROMAGNETIC FIELD IN BUBBLE

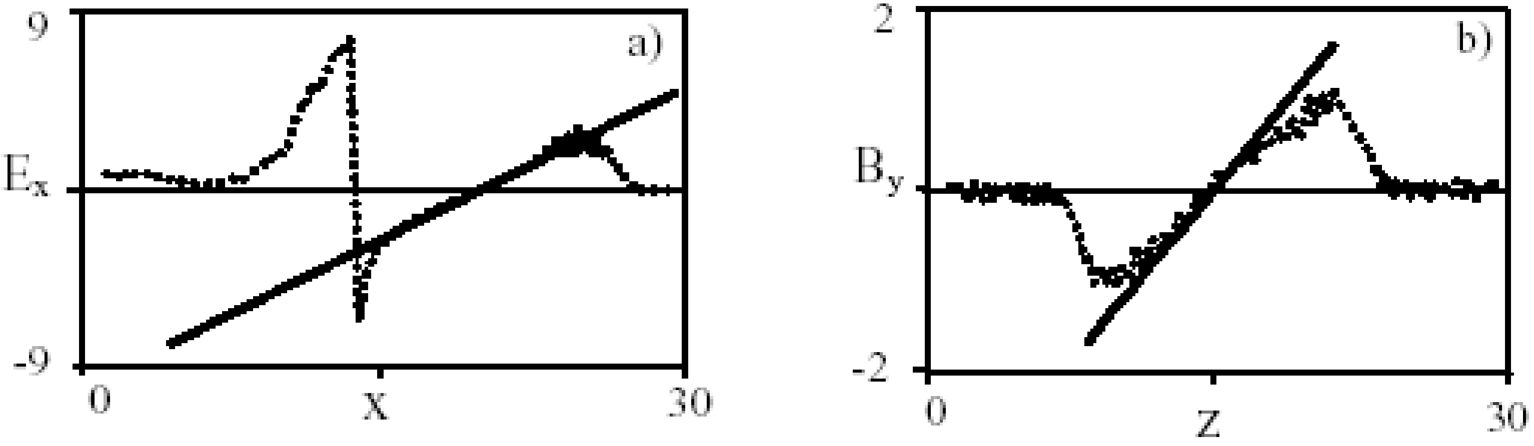
$$n_e = j_e = j_i = 0, \quad n_i = n_0 = const$$

$$\Delta\Phi = -\frac{3}{2}$$

$$\Phi = 1 + \frac{R^2}{4} - \frac{\xi^2 + y^2 + z^2}{4}$$



$$E_x = \xi/2, \quad E_y = -B_z = y/4, \quad E_z = B_y = z/4$$



I. Kostyukov, A. Pukhov, S. Kiselev, Phys. Plasmas, 2004, **11**, 5256 (LASER-PLASMA INTERACTION)

K.V. Lotov, Phys. Rev. E, 2004 **69**, 046405 (e^--BEAM-PLASMA INTERACTION)

ELECTRON TRAPPING

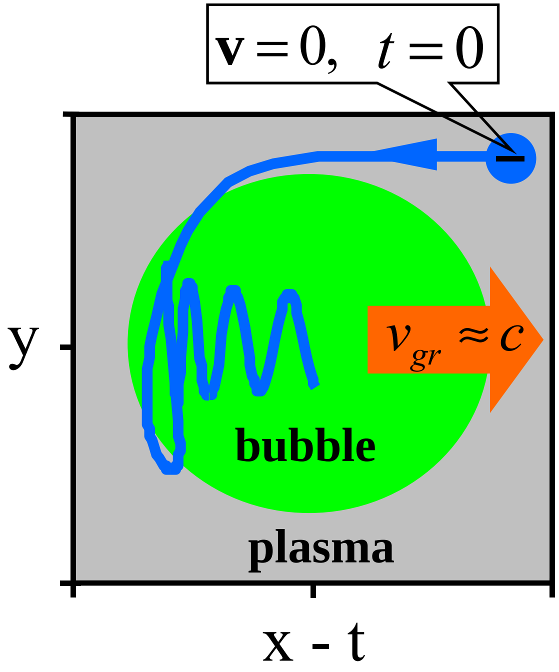
Hamiltonian of electron

$$H=\sqrt{1+\left[\mathbf{P}+\mathbf{A}(\mathbf{r}-\mathbf{v}_{gr}t)\right]^2+a_L^2(\mathbf{r}-\mathbf{v}_{gr}t)}-\varphi(\mathbf{r}-\mathbf{v}_{gr}t)\neq const$$

canonical transformation

$$S(\mathbf{r},\mathbf{P},t)=(\mathbf{r}-\mathbf{v}_{gr}t)\cdot\mathbf{P},\quad x\Rightarrow\xi=x-v_{gr}t$$

$$H=\gamma-\Phi(\xi)-v_{gr}p_x=const,\qquad v_{gr}\to c$$

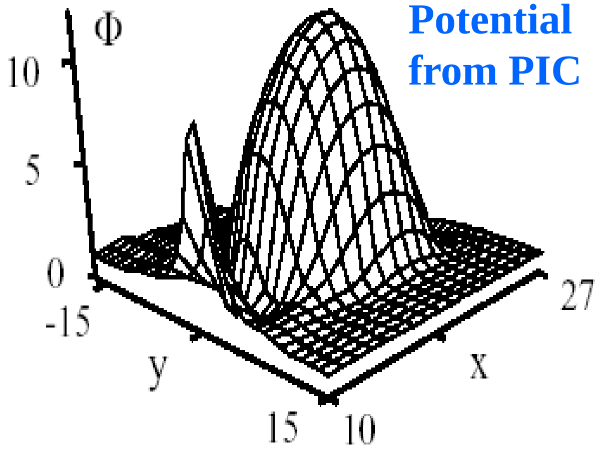


trapping condition

$$v_{gr}\leq v\qquad p_{\|}>v_{gr}p_{\perp}\gamma_{gr}=v_{gr}\gamma_{gr}^2\Phi$$

$$\begin{cases}\Phi=1+\dfrac{R^2}{4}-\dfrac{\xi^2+y^2+z^2}{4}, & r\leq R,\\ \Phi=1, & r>R\end{cases}$$

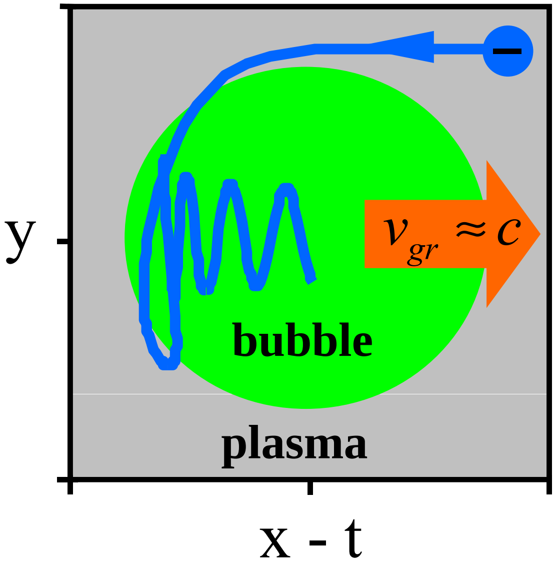
$$R>\gamma_0$$



Potential from PIC

ELECTRON ACCELERATION

$$p_x >> p_\perp, m\gamma_{gr}v_{gr} \qquad \frac{p_\perp}{p_x} << 1$$



$$H_\parallel = \frac{p_x}{2\gamma_{gr}^2} - \Phi(\xi, \mathbf{r}_\perp), \qquad \gamma_{gr} = 1/\sqrt{1-v_{gr}^2}$$

$$\xi \approx -R + \frac{t}{2\gamma_{gr}^2}, \qquad \gamma \approx \gamma_0 + \frac{t}{4}\left(2R - \frac{t}{2\gamma_{gr}^2}\right)$$

$$\Delta\gamma \approx 2\gamma_{gr}^2 \Delta\Phi \approx \gamma_{gr}^2 R^2 / 2$$

$$\Delta\gamma \approx eE_x L_{acc} \approx eE_x L_{bub} / v_r \approx 2\gamma_{gr}^2 \Delta\Phi \qquad v_r \approx 1 - v_{gr} \approx 1/2\gamma_{gr}^2$$

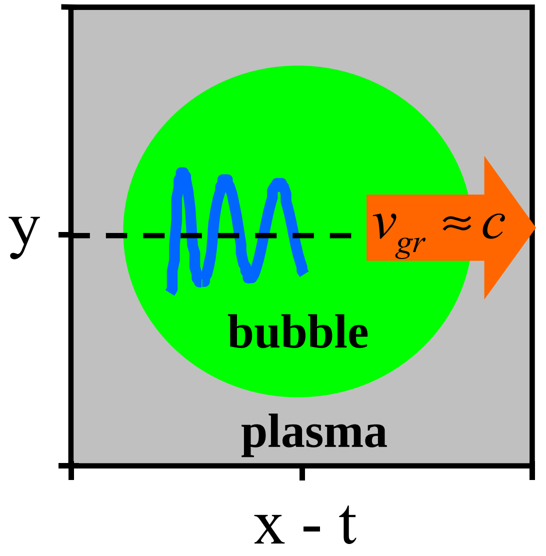
BETATRON OSCILLATIONS

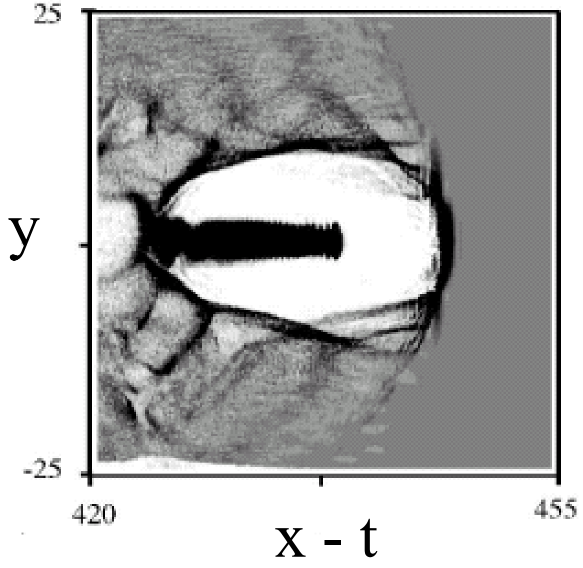
$$H_{\perp} = \frac{p_y^2}{2p_x(t)} + \frac{y^2}{4}$$

$$\frac{d^2 p_y}{dt^2} + \Omega_B^2(t) p_y = 0, \quad \Omega_B = \omega_p / \sqrt{2\gamma}$$

$$F_y = -E_y + B_z = -y/2$$

$$y \approx r_0 \left(\frac{\gamma_0}{\gamma(t)} \right)^{1/4} \cos\left[\int_0^t \Omega_B(t) dt \right]$$

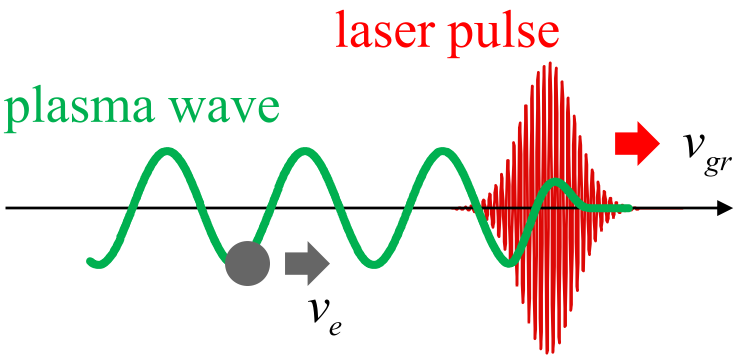




BEAM CONTROL BY PLASMA PROFILING

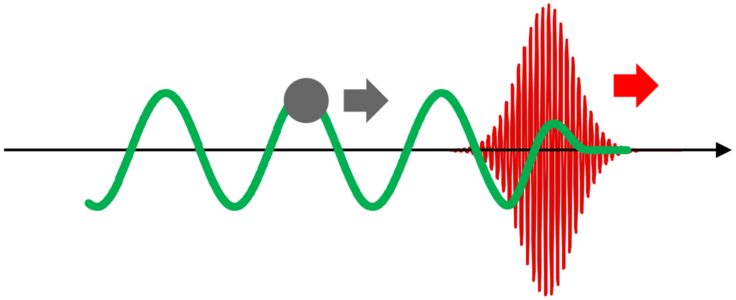
Dephasing: The accelerated electrons slowly outrun the plasma wave and leave the accelerating phase.

$$\frac{d}{dx}\left(\frac{\Phi}{\omega_p(x)}\right) \approx \frac{1}{c} - \frac{1}{v_{gr}}$$



$$n(x) = \frac{n_0}{\left(1 - x / L_{inh}\right)^{2/3}} \qquad L_{inh} = \frac{c}{\omega_p}\left(\frac{n_0}{n_c}\right)^{-3/2}\frac{2\Phi}{3}$$

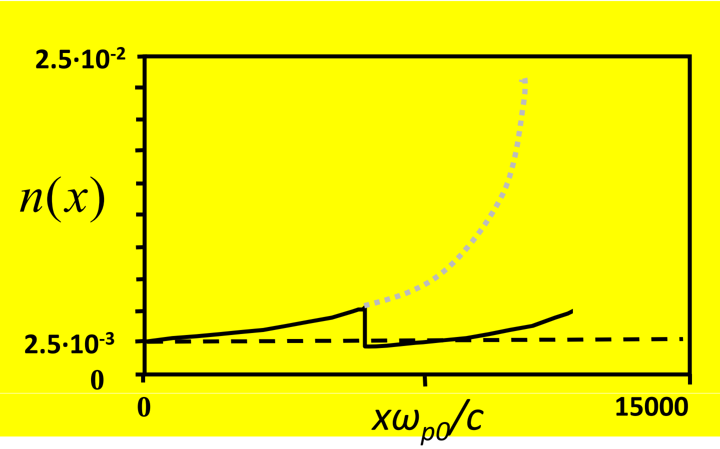
Choosing a proper density gradient one can uplift the dephasing limitation and keep the phase synchronism between the bunch of relativistic particles and the plasma wave over extended distances.

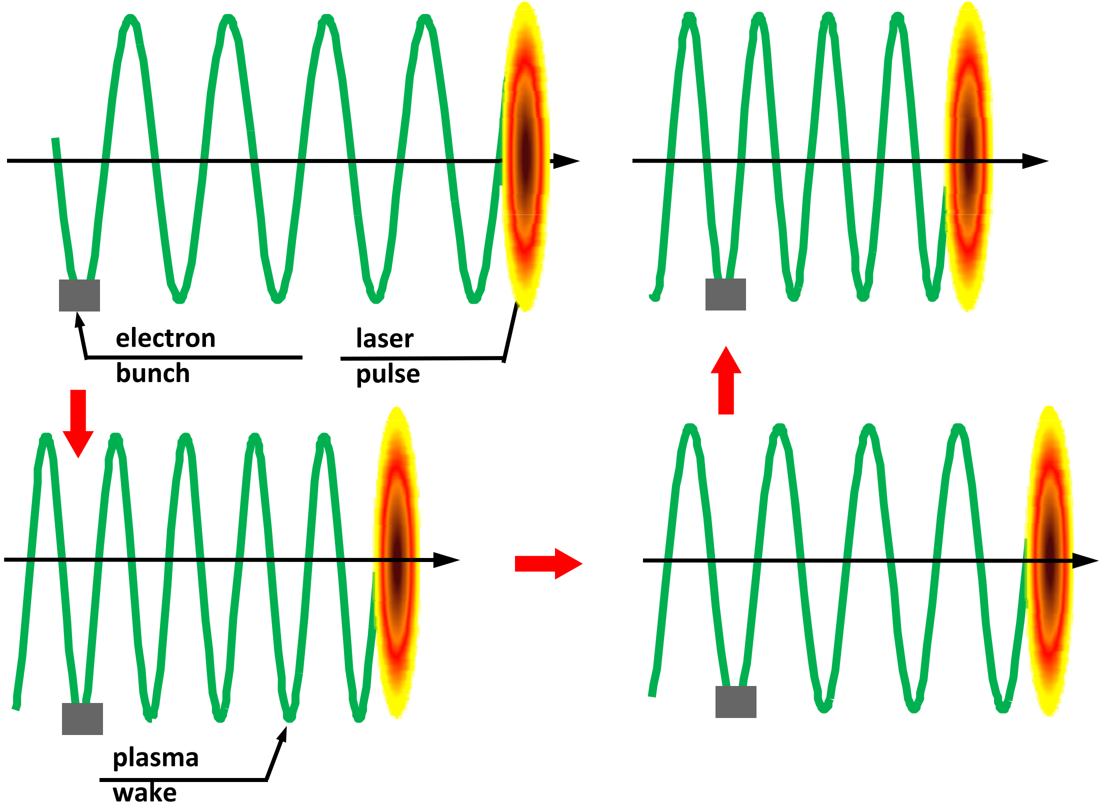


T. Katsouleas, Phys. Rev. A **33**, 2056 (1986).

LAYERED PLASMA

$$n(x) = \frac{n_0}{\left(1 - x/L_{inh}\right)^{2/3}}, \qquad n(x) \to \infty \quad \text{at} \quad x = L_{inh}$$



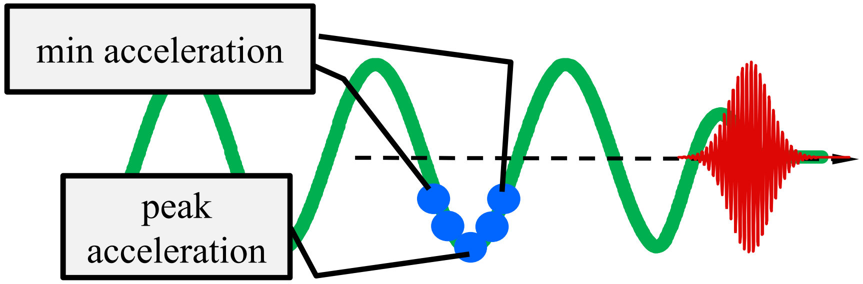


Putting electrons into the n-th wake period behind the driving laser pulse, the maximum energy gain is increased by the factor 2πn over that in the case of uniform plasma.

A. Pukhov, I. Kostyukov, Phys. Rev. E, **77**, 025401 (2008)

ENERGY SPREAD REDUCTION

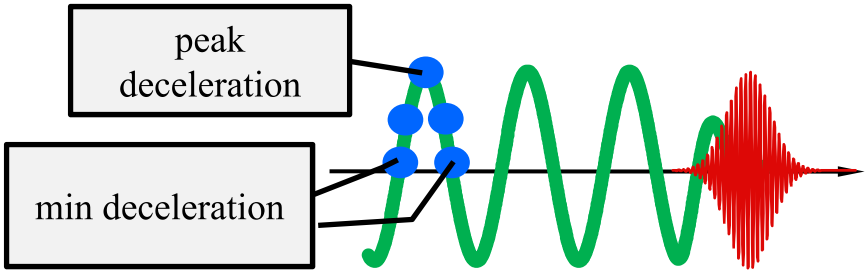
energy spread mechanism



min acceleration

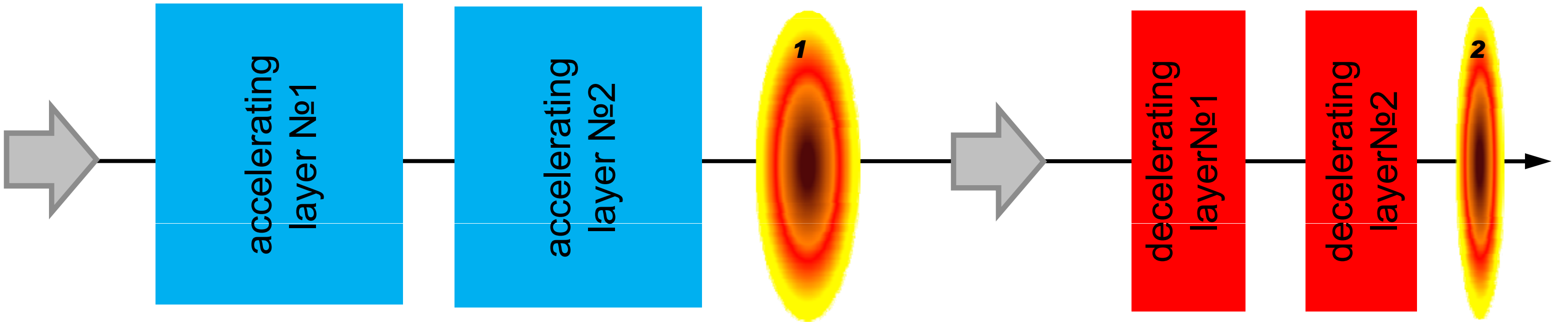
peak acceleration

energy spread reduction



peak deceleration

min deceleration

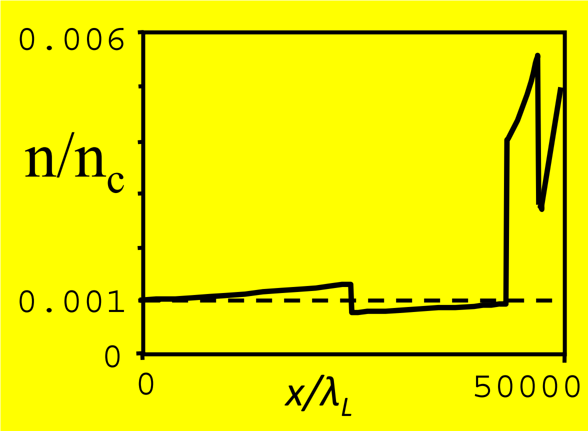


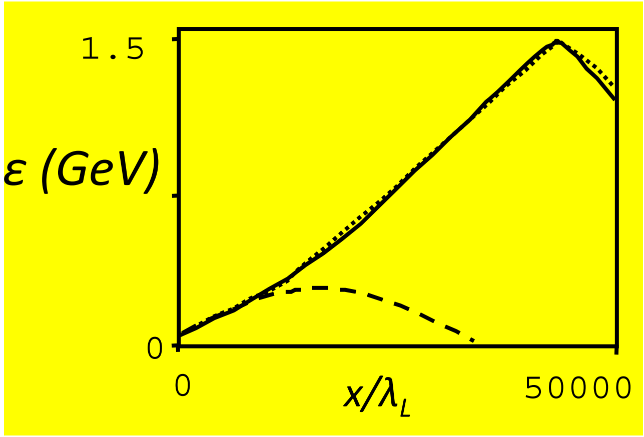
accelerating layer №1

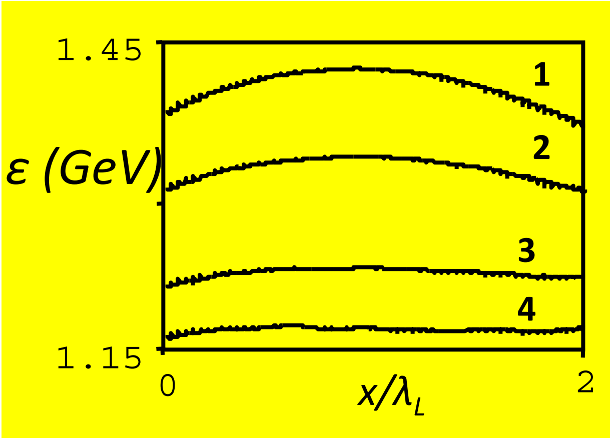
accelerating layer №2

decelerating layer№1

decelerating layer№2







CONCLUSIONS

1. The Bubble produces a quasi-monoenergetic e^-−beams.

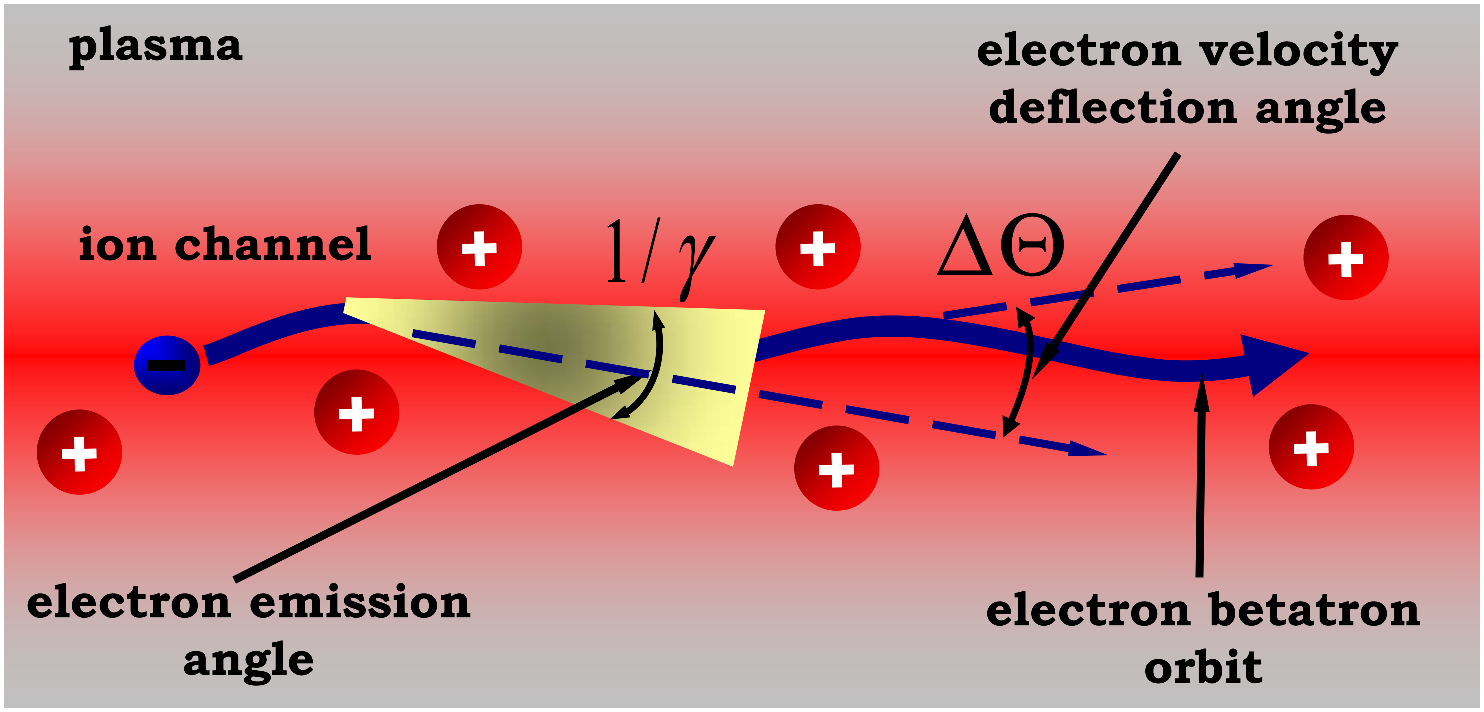
2. The Bubble is an efficient energy converter: 10..20% laser energy is transformed to the e^- −beam.

3. Self-guiding over many Rayleigh lengths.

4. Plasma density profiling for beam control

BETATRON RADIATION

DIPOLE RADIATION



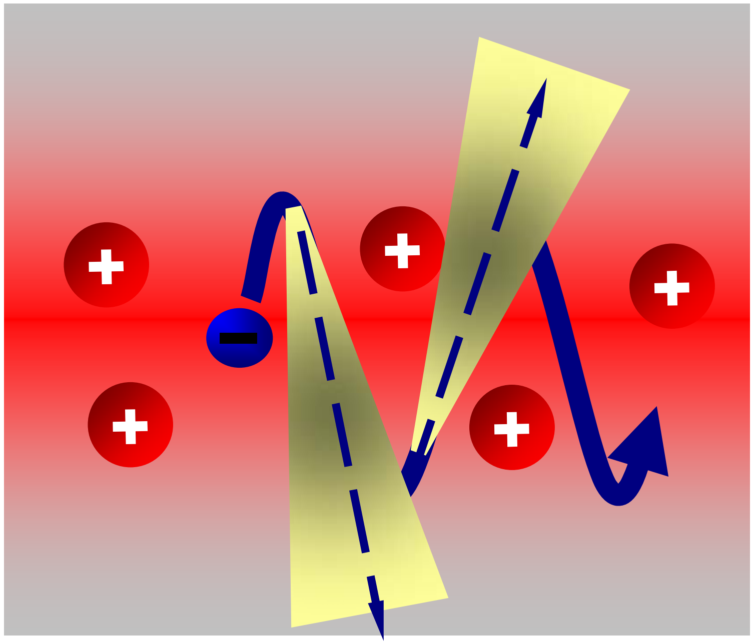
$\Omega_B = \omega_p / \sqrt{2\gamma}$ - betatron frequency

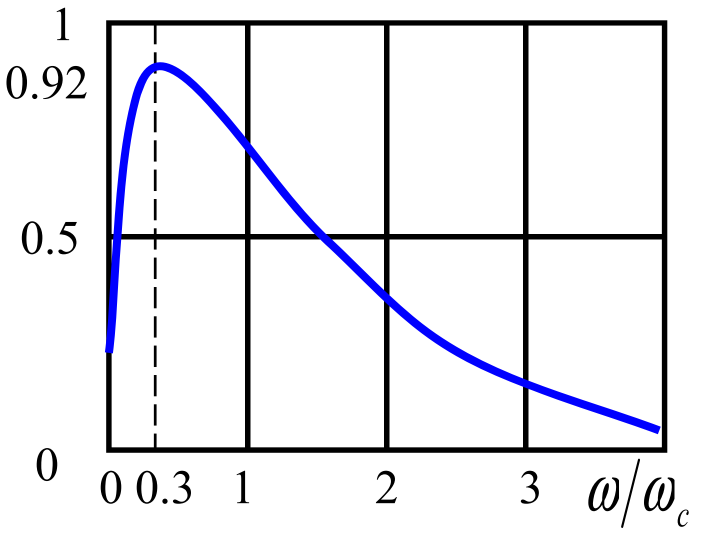
$\Delta\Theta \approx p_\perp / \gamma$

$\Delta\Theta << 1/\gamma \Rightarrow p_\perp / mc << 1$ **dipole regime of emission**

$\boxed{\omega = 2\Omega_B \gamma^2}$ - radiation frequency

SYNHROTRON RADIATION





quasi-continuous spectrum

$\Delta\Theta >> 1/\gamma$ → $p_\perp/mc >> 1$ **synchrotron regime of emission**

$$\boxed{\omega_c = 3\Omega_B^2\gamma^3 r_0/c \propto n\gamma^2 r_0}$$

- critical frequency

BETATRON RADIATION SPECTRUM

$K >> 1$

$$P_{spon} = 2N_\beta \left(\frac{\omega\rho}{c}\right)^2 \frac{e^2\chi^2}{3\pi^2 c}\left[\frac{\sin^2\theta\sin^2\phi}{\chi}K_{1/3}^2(q) + K_{2/3}^2(q)\right]$$

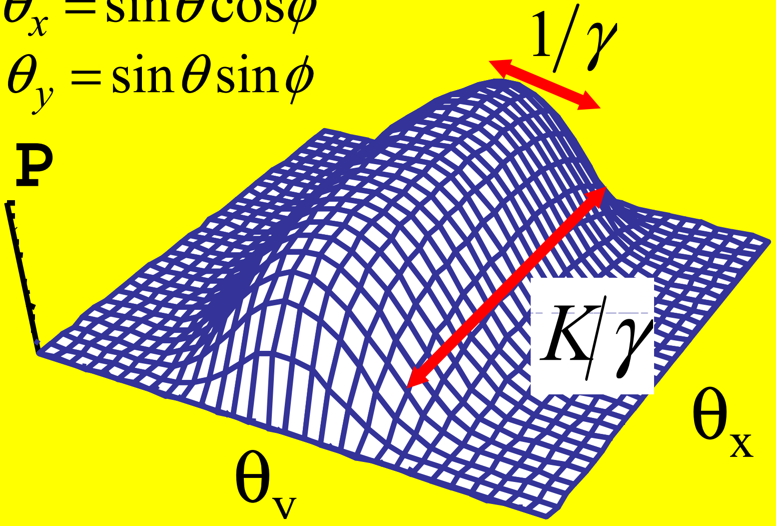
$$\mathbf{k} = \frac{\omega}{c}\left(\mathbf{e}_x\sin\theta\cos\phi + \mathbf{e}_y\sin\theta\sin\phi + \mathbf{e}_z\cos\theta\right)$$

$$\chi = \frac{1}{\gamma^2} + \sin^2\theta\sin^2\phi, \qquad q = \frac{\omega\rho\chi^{3/2}}{3c}$$

$$\rho = \frac{c}{\omega_\beta}\frac{\gamma}{\sqrt{K^2 - \gamma^2\sin^2\theta\cos^2\phi}}$$

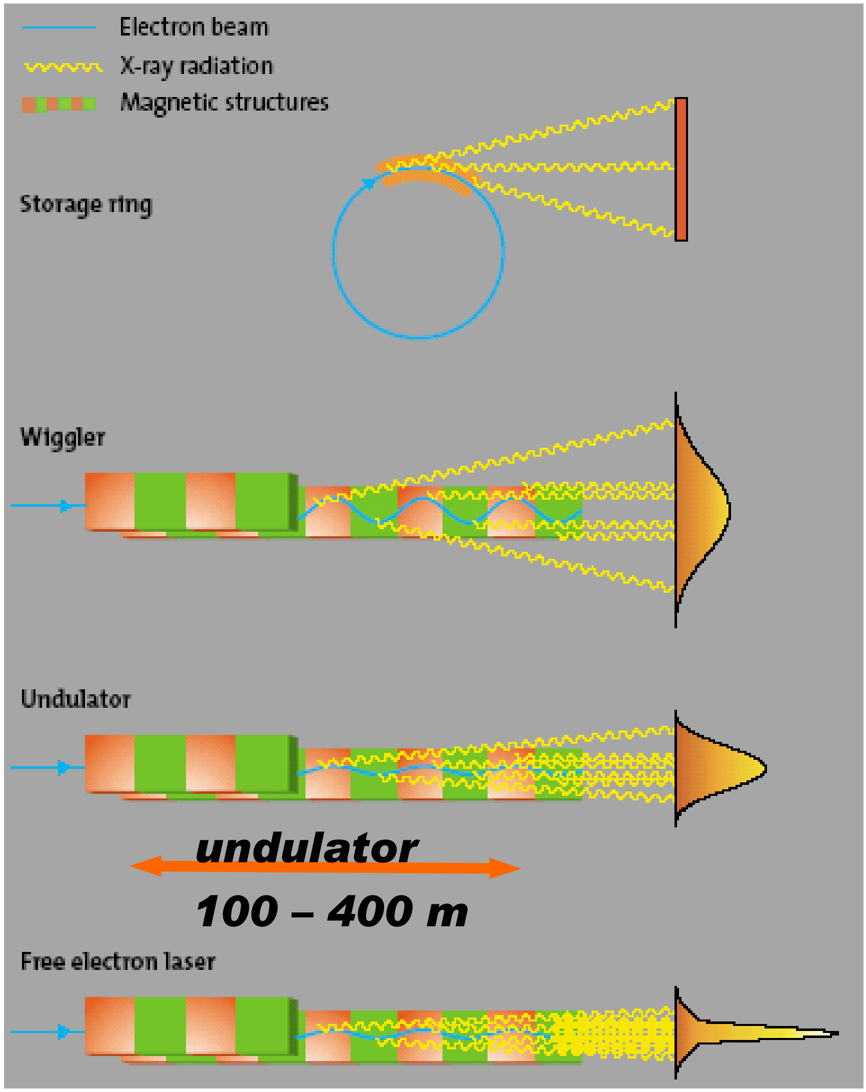
$$\theta_x = \sin\theta\cos\phi$$

$$\theta_y = \sin\theta\sin\phi$$



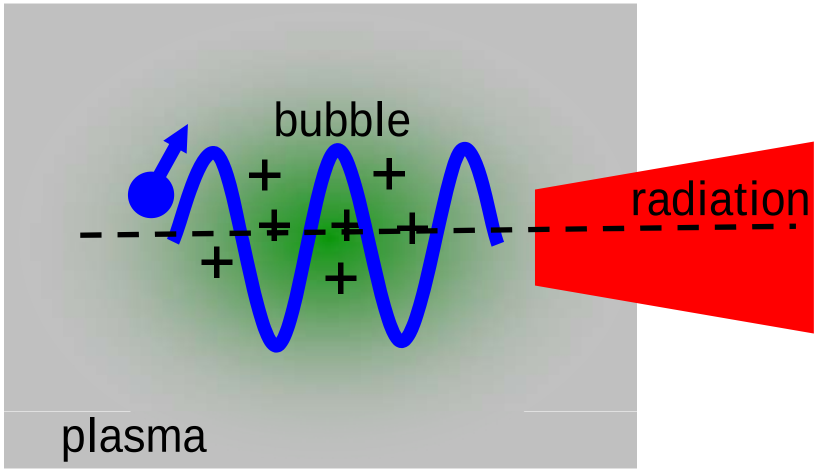
I. Kostyukov, S. Kiselev, A. Pukhov, Phys. Plasmas, 2003, **10**, 4818

SYNCHROTRON RADIATION



Advanced Photon Source, Argonne National Laboratory, http://www.aps.anl.gov/

LASER-PLASMA X-RAY SOURCE

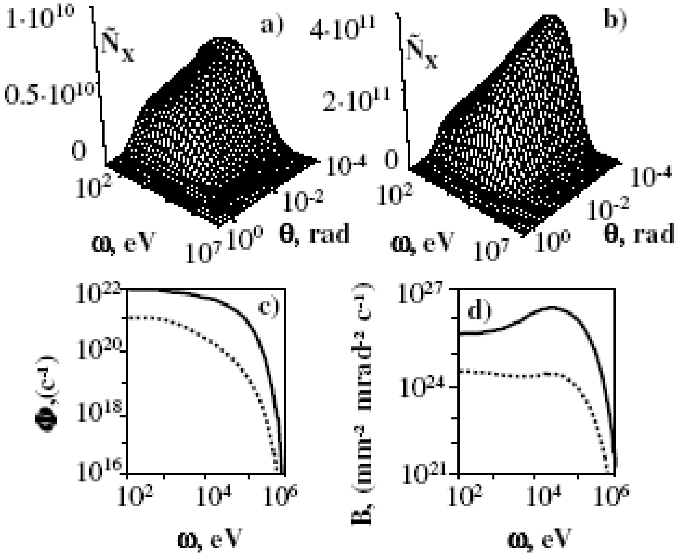


- **COMPACTNESS**
- ***simultaneous acceleration and x-ray generation***
- ***laser pulse propagates in plasma a few centimeters***
- ***laser systems sizes – several meters***
- **HIGH POWER**

$$P_e \propto \frac{2}{3}\gamma^2 F_\perp^2 \qquad \frac{F_{\perp,LPS}}{F_{\perp,FEL}} \approx \frac{\omega_{pe}^2 r_0}{\omega_{He} c} \approx \frac{\omega_{pe}}{\omega_{He}} \qquad \frac{P_{LPS}}{P_{FEL}} \approx 10^6$$

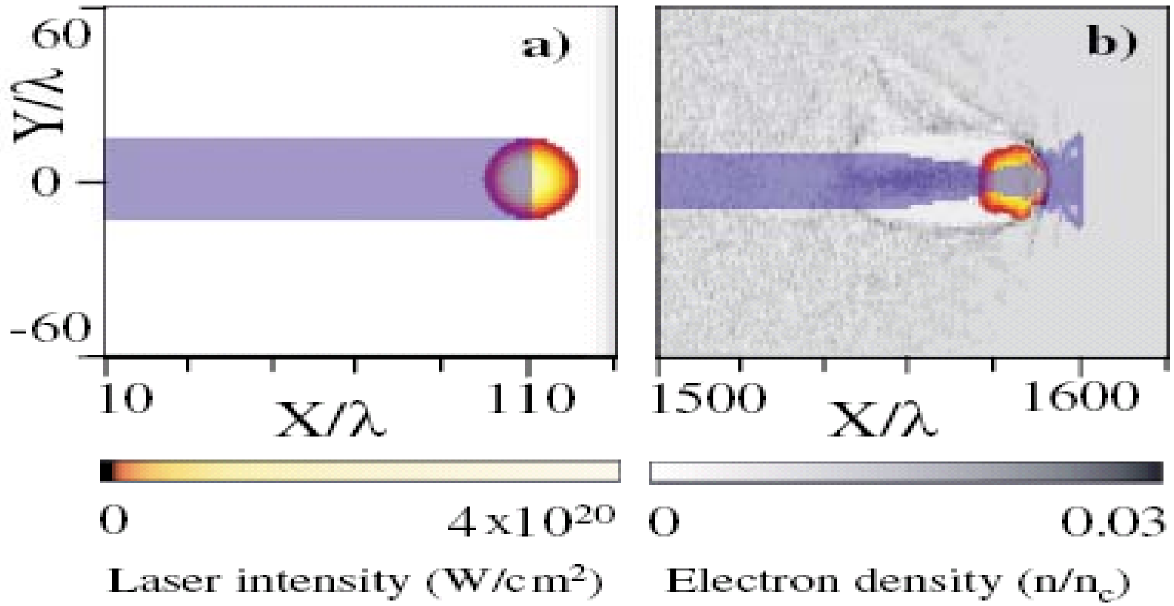
$$r_0 \approx c/\omega_{pe} \quad n_0 \approx 10^{19}\,\text{ñì}^{-3}, \quad B_{FEL} \approx 1\ \text{Òë,}$$

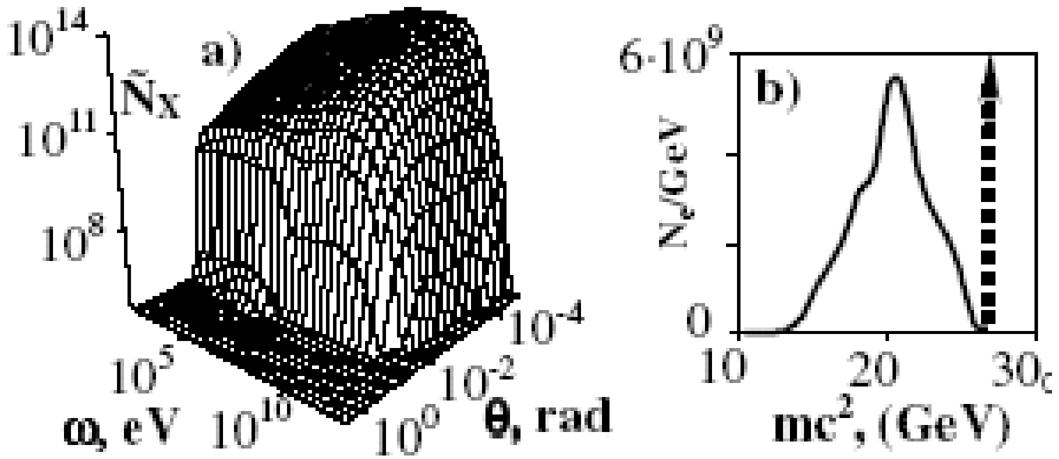
- **PHOTON ENERGY** $\hbar\omega \propto \gamma^2 F_\perp$
- **X-RAY PULSE DURATION** $5-50fs$



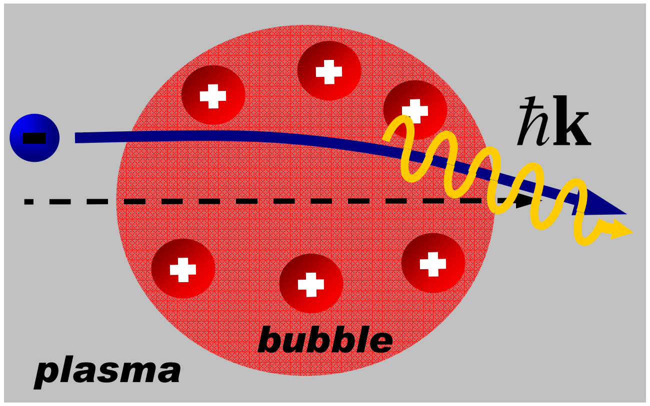
S. Kiselev, A. Pukhov, I. Kostyukov, Phys. Rev.Lett., 2004, **93**, 135004

RADIATION OF EXTERNAL e$^-$-BEAM



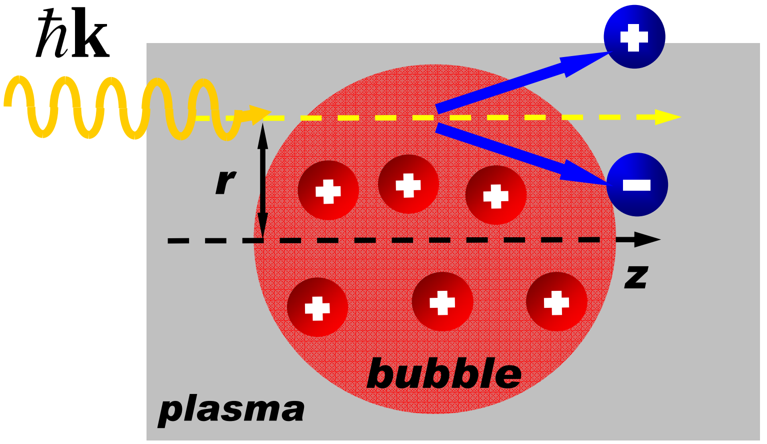


QUANTUM EFFECTS IN STRONG PLASMA FIELD



$$e + V_{pl} \rightarrow e' + \gamma$$

quantum photon emission



$$\gamma + V_{pl} \rightarrow e^{+}e^{-}$$

$e^{-}e^{+}$ pair production

1) electron motion is semiclassical $\gamma mc^2 >> \hbar\Omega_B$

2) photon emission is quantum $\hbar\omega \approx \gamma mc^2$

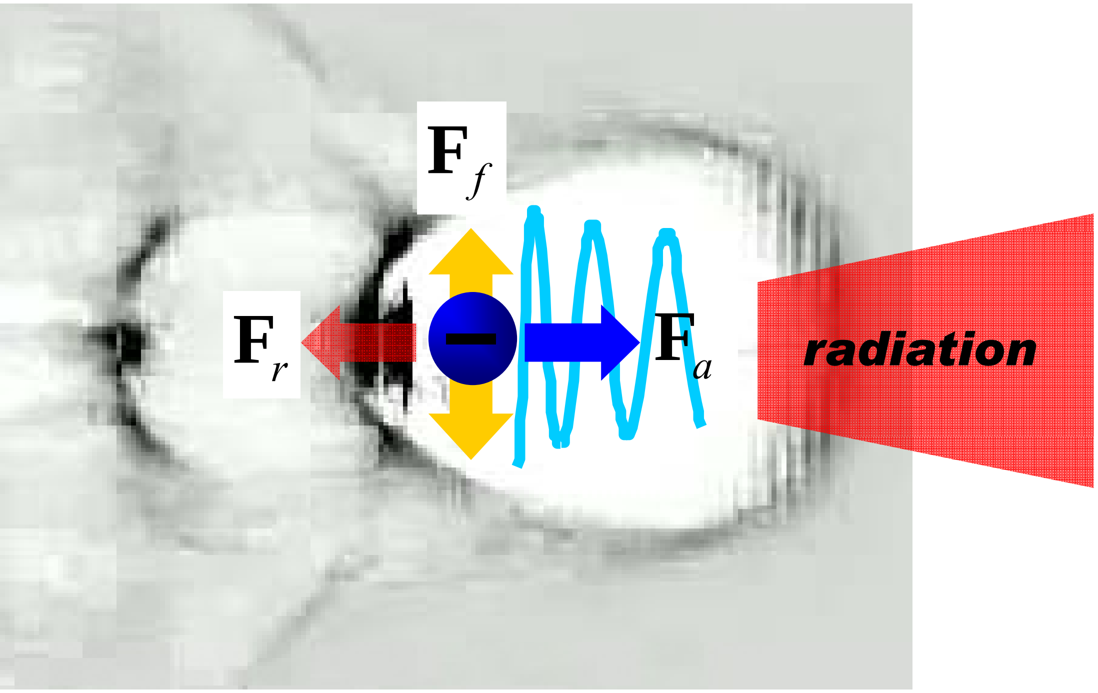
Semiclassical operator method

V.N.Baier, V.M.Katkov, V.M.Strakhovenko, *Electromagnetic Processes at High Energies in Oriented Single Crystals* (Singapore, World Scientific 1998).

PLASMA FIELD INSTEAD OF CRYSTALLINE FIELD

E. Nerush, I. Kostyukov, Phys. Rev. E **75**, 057401 (2007)

RADIATION REACTION

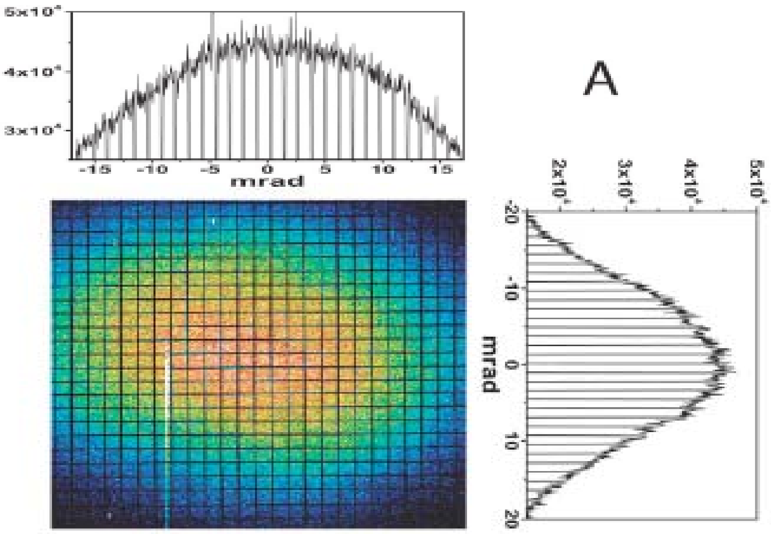


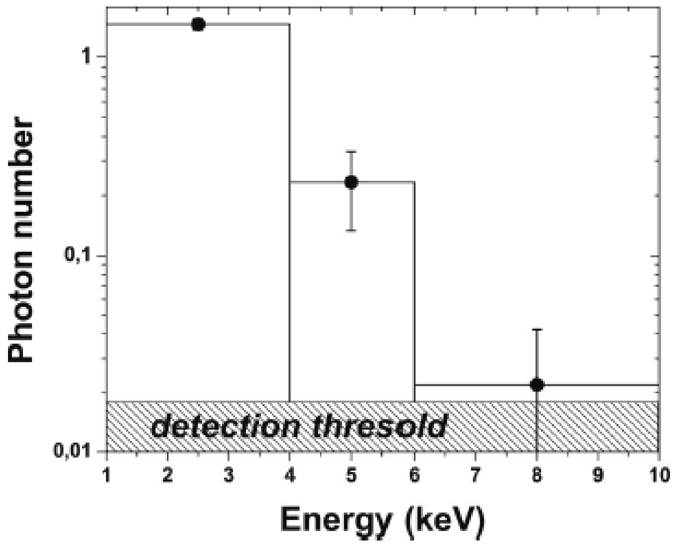
$$mc\frac{du^i}{ds} = \frac{e}{c}F^{ik}u_k + g^i$$

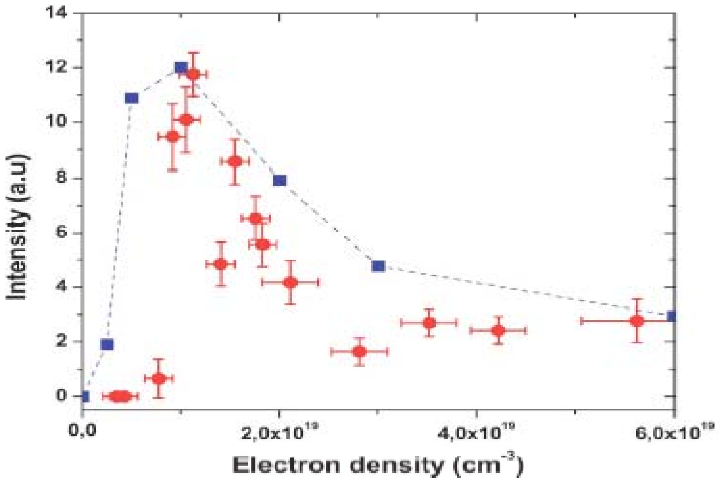
$$g^i = \frac{2e^3}{3mc^3}\frac{\partial F^{ik}}{\partial x^l}u_k u^l - \frac{2e^4}{3m^2c^5}F^{il}F_{kl}u^k + \frac{2e^4}{3m^2c^5}\left(F_{kl}u^l\right)\left(F^{km}u_m\right)u^i$$

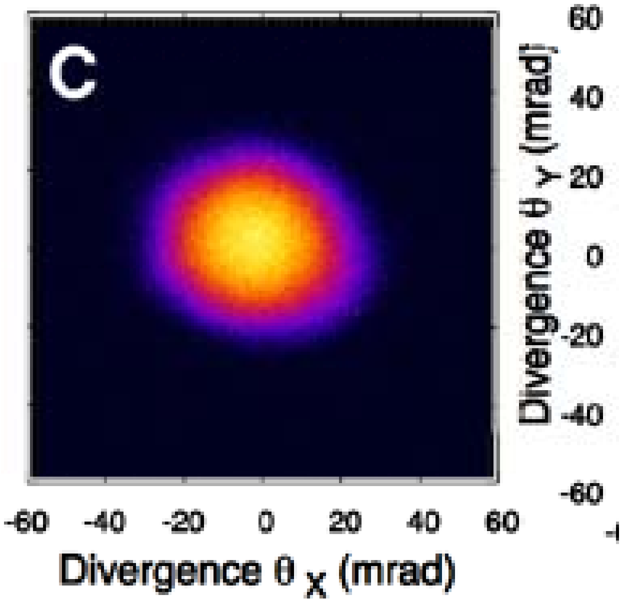
P. Michel, *et al.,* Phys. Rev.E **74**, 026501 (2006).
I. Kostyukov, E. Nerush, and A.Pukhov, JETP **103**, 800 (2006)

BETATRON RADIATION





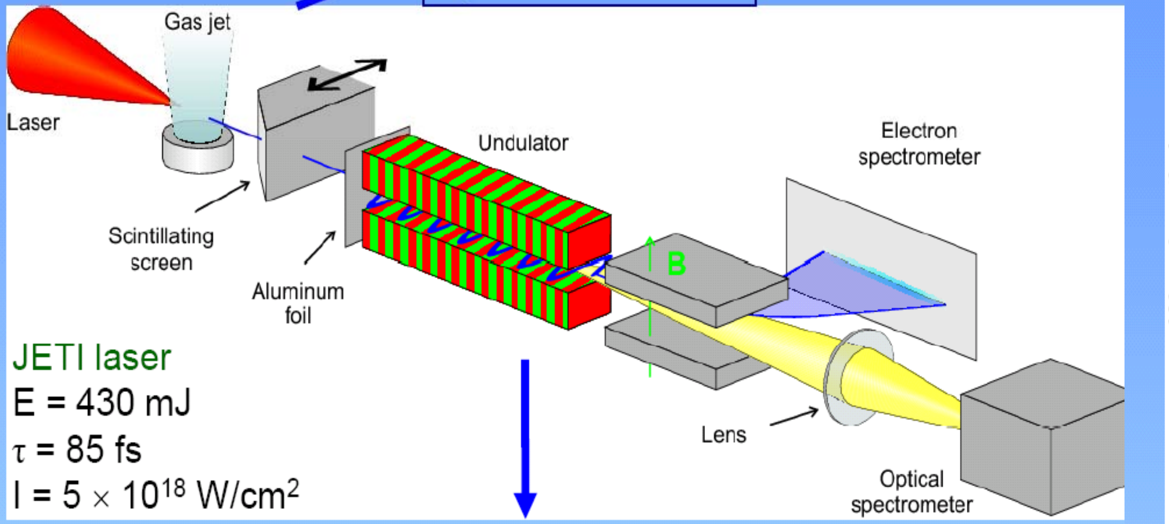




A. Rousse *et al.,* Phys. Rev.Lett. 2004, **93**, 135005

LASER-PLASMA SYNCHROTRON

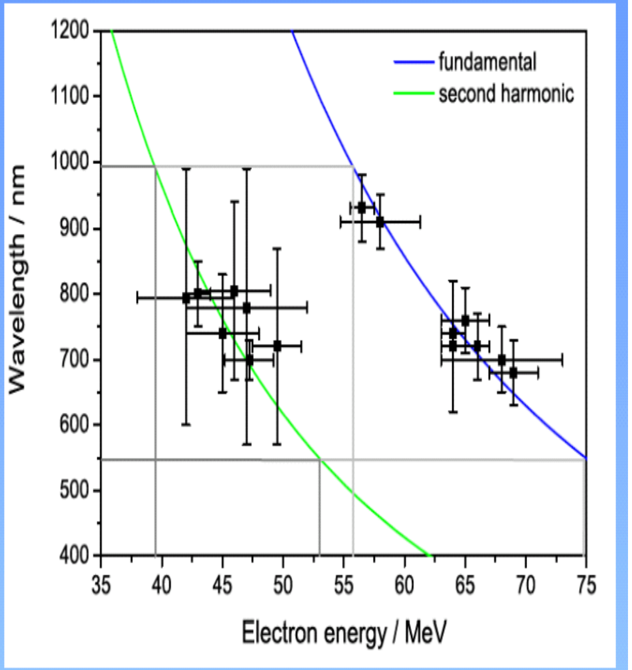
L = 2 mm
$n_e = 2 \times 10^{19}$ cm^{-3}



JETI laser
E = 430 mJ
τ = 85 fs
I = 5 × 10^{18} W/cm^2

N = 50
λ_u = 20 mm
K = 0.6

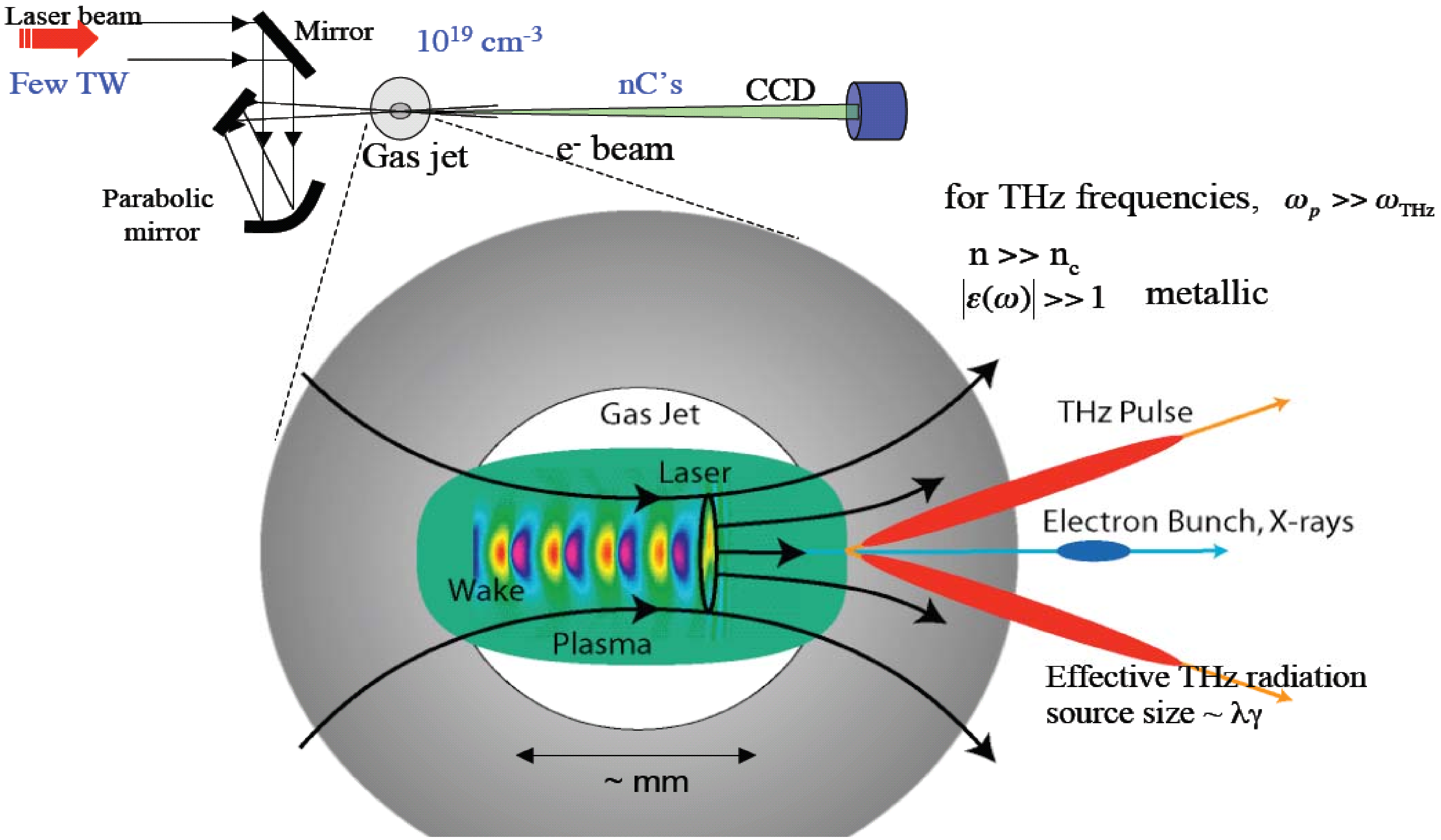
Simultaneous electron and radiation spectra



- Agreement with Undulator Equation: $\lambda\,[\mathrm{nm}] \cong \dfrac{3\times10^{6}}{E\,[\mathrm{MeV}]^{2}}$ [fundamental]
- The bars represent the spectral widths
- Electron beam energy spread - $\sigma_\gamma/\gamma \sim 1\%$
- Peak brilliance ~ 10^{16} photons /s /mrad²/mm²/0.1%BW (assuming $\tau \sim 10$ fs)

H.-P. Schlenvoigt *et al*, Nature Physics **4**, 130 - 133 (2008)

INTENSE COHERENT THZ RADIATION GENERATION



for THz frequencies, $\omega_p >> \omega_{THz}$

$n >> n_c$

$|\varepsilon(\omega)| >> 1$ metallic

extremely dense bunches (multi-nC, <50 fs) → Coherent transition raditaion (THz)

J. van Tilborg et al., Opt. Lett. (2006)

CONCLUSIONS

Compact and powerful laser-plasma radiation sources:
X-ray, optical and THz radiation

SUMMARY

- *Laser-plasma accelerators: GEV in 3 cm, tunable quasi-monoenergetic e$^-$-bunches*
- *The Bubble produces a quasi-monoenergetic e$^-$-beams with efficiency conversion 10..20%*
- *Laser plasma can be a compact and powerful source of X-rays, optical radiation and THz pulses.*