The First Blaise Pascal Lecture
Ecole Polytechnique
10/22/09

Laser Acceleration and High Field Science: 1979-2009

Toshi Tajima
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and
LMU,MPQ, Garching

Acknowledgments for Advice and Collaboration: G. Mourou, late-J. Dawson, N. Rostoker, F. Krausz, D. Habs, S. Karsch, L. Veisz, F. Gruener, T. Esirkepov, M. Kando, K. Nakajima, A. Chao, A. Suzuki, F. Takasaki, S. Bulanov, A. Giullietti, F. Mako, X. Yan, J. Meyer-ter-Vehn, W. Leemans,T. Raubenheimer, A. Ogata, A. Caldwell, P. Chen, Y. Kato, late-A. Salam, M. Downer, S. Ichimaru, M. Tigner, V. Malka, A. Henig, H.C. Wu, K. Kondo, Y. Sano, M. Abe, S. Kawanishi, M. Hegelich, D. Jung, P. Shukla

Can the society continue to support ever escalating accelerators?

Accelerator = crown of 20th C science

supermagnets quench

beam dump

LHC at CERN

Terminated Texas tunnel. The SSC was abandoned after about 25% of the tunnel for the 87-kilometer-circumference large collider ring had been bored.

SSC tunnel

hadron therapy accelerator and gantry

Demise of SSC (Super collider)

Terminated Texas tunnel. The SSC was abandoned after about 25% of the tunnel for the 87-kilometer-circumference large collider ring had been bored.

By largest machine to probe smallest of structure of matter

size	10^2km
energy	20TeV
cost	\$10B

US :

Texas site decided (1989)

US Government decided to terminate its work: 1993

Tajima: 'Tamura Symposium' on the Future of Accelerator Physics @ UT Austin (1995)

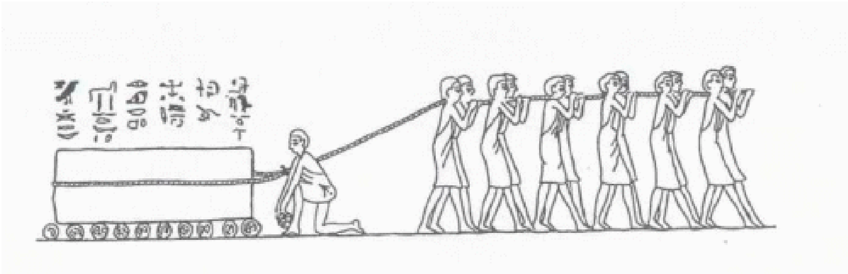
Dream Beams Symposium

MPQ Garching
Feb. 26 – 28, 2007

(given by F. Krausz and J. Meyer-ter-Vehn)

What is *collective force*？

How can a Pyramid have been built?



Individual particle dynamics → Coherent and collective movement

Collective acceleration (Veksler, 1956; Tajima & Dawson, 1979)

Collective radiation (N^2 radiation)

Collective ionization (N^2 ionization)

Collective deceleration (Tajima & Chao, 2008；Ogata, 2009)

Tutelage by giants of collective phenomena

Physics of individual particles;
Physics of collection of particles---collective phenomena

↑ Professor Ryogo Kubo ↑ Professor Iliya Prigogine (Austin, ~1984)

Advent of collective acceleration (1956)

CERN Symposium

ON HIGH ENERGY ACCELERATORS

AND PION PHYSICS

Geneva, 11th - 23rd June 1956

Proceedings

COHERENT PRINCIPLE OF ACCELERATION OF CHARGED PARTICLES

V. I. VEKSLER

Electrophysical Laboratory, Academy of Sciences, Moscow

This paper will include a very brief description of a new principle regarding the acceleration of charged particles.

In all existing accelerators of charged particles, the constant and varying electric field accelerating them is created by a powerful external source, and hence the strength of the field is independent, in the first approximation, of the number of particles which are being accelerated.

In resonance accelerators, the electromagnetic field has to be synchronized with the movement of the particles (this is of particular importance in linear accelerators). Finally, none of the existing methods permits the acceleration of neutral bunches of particles.

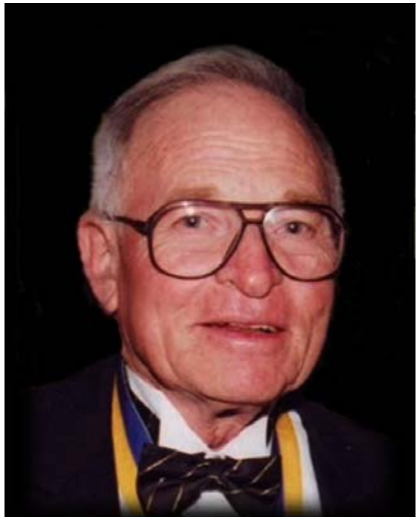
A new principle of particle acceleration is set forth below. Its distinctive feature lies in the fact that the particle-accelerating electric field is produced by the interaction of a geometrically small group of accelerated particles with another group of charges, plasma or an electromagnetic wave. This method has a number of important features. It appears, in the first place, that the magnitude of the accelerating field produced by this interaction and acting on each particle depends on the number

Theoretical studies of various aspects of the coherent acceleration method have been made by M. S. Rabinovich, A. A. Kolomenski, B. M. Bolotovski, L. V. Kovrizhnikh and I. V. Iankov, as well as by A. I. Akhiezer, Ia. Fainberg and their collaborators. The calculations made by these theoretical workers shed light on a number of complicated problems connected with the development of the different variants of this new acceleration principle, and it therefore seems appropriate to describe the new method despite the fact that a great many problems involved still await solution.

1. *Acceleration of charged bunches by means of the medium*

It was pointed out in a paper by Tamm that the loss of energy by particles due to Čerenkov radiation could be reversed, i.e. the medium travelling at a great velocity past charged particles should be able to convey energy to the latter. Up to now, however, no attention has been paid to the possibility of developing an acceleration process of this kind by using a high density electron beam (plasma) as the moving medium. Of course, if a single charge e is

Prehistoric activities (1973-75,…84)



Professor N. Rostoker

Collective ion acceleration by a reflexing electron beam: Model and scaling

F. Mako
Naval Research Laboratory, Washington, D. C. 20375
T. Tajima
Institute for Fusion Studies, University of Texas, Austin, Texas 78712

(Received 21 June 1983; accepted 2 April 1984)

Analytical and numerical calculations are presented for a reflexing electron beam type of collective ion accelerator. These results are then compared to those obtained through experiment. By constraining one free parameter to experimental conditions, the self-similar solution of the ion energy distribution agrees closely with the experimental distribution. Hence the reflexing beam model appears to be a valid model for explaining the experimental data. Simulation shows in addition to the agreement with the experimental ion distribution that synchronization between accelerated ions and electric field is phase unstable. This instability seems to further restrict the maximum ion energy to several times the electron energy.

I. INTRODUCTION

Experiments on collectively accelerating ions utilizing a reflexing intense relativistic electron beam in a plasma have been carried out.[1,2] These experiments began to reveal sever-chronous fashion. Thus, energetic ions would be expected. The ion energy would, of course, be bounded above by the ion to electron mass ratio times the initial electron energy; that is, the energy is bounded when the ions reach the initial

Collective acceleration suggested:
Veksler (1956)
(ion energy)~ (M/m)(electron energy)

Many experimental attempts (~'70s):
led to no such amplification
(ion energy)~ (several)x(electron)

Mako-Tajima analysis (1978;1984)
sudden acceleration, ions untrapped, electrons return
→ #1 **gradual acceleration necessary**

→ #2 **electron acceleration** possible with **trapping** **(with Tajima-Dawson field)**, more tolerant for sudden process

Path once trodden

Collective acceleration of ions by electron beam

F.Mako / T. Tajima

Ions <u>left out</u>, while electrons shoot backward

→ laser electron acceleration (1979)

→ laser ion acceleration of limited ion mass (2009)

The electric field is

$$\epsilon = \frac{\phi_0}{v_0 t}\frac{5}{36}\left(\frac{6}{\sqrt{3}} - \frac{z}{v_0 t}\right),$$

where the conservation of energy was used as a boundary condition, i.e.,

$$U^2/2 + \psi = 0 \quad \text{at} \quad \zeta = 0\,.$$

The maximum ion energy can now be obtained by setting $n_i = 0$, i.e,

$$E_{i\max} = 6q\phi_0 \quad \text{at} \quad \zeta = 6/\sqrt{3}\,.$$

In the experiment the diode voltage was 0.8 MV and the ions were doubly ionized helium,[6] thus the maximum ion energy predicted by theory is

$$E_{i\max} = 9.6 \ \text{MeV}\,.$$

The experimental result[6] for the maximum helium ion energy was 9.6 MeV and therefore is in good agreement with the theory.

The ion number as a function of energy is calculated to be

$$N_i(E_i) = \frac{n_0 A}{\beta}\left[\left(\frac{6}{5}\right)^{1/2} - \left(\frac{E_i}{5q\phi_0}\right)^{1/2}\right]^6, \qquad (15)$$

where

$$n_0 A = \frac{16}{5}\frac{J_0 A}{e}\left(\frac{2m}{e\phi_0}\right)^{1/2},$$

$$\beta = (\tfrac{3}{5})^{1/2}\,(1/v_0 t)\,,$$

$$A = \pi r_b^2\,, \quad r_b = \text{electron beam radius}\,,$$

and

$$v_0 = (q\phi_0/M)^{1/2}\,.$$

Equation (15) is our main result. The natural logarithm of Eq. (15) is plotted in Fig. 2 along with the experimental data. The following experimental values were used: $J_0 = 40$ kA, $\phi_0 = 0.8$ MV, $q = 2e$ (doubly ionized helium), $t = 100$ ns and $r_b = 2.5$ cm. The agreement between Eq. (15) and the experiment[6] is reasonable. The relation in Ref. 3 does not provide such a good fit: it has too weak a slope.

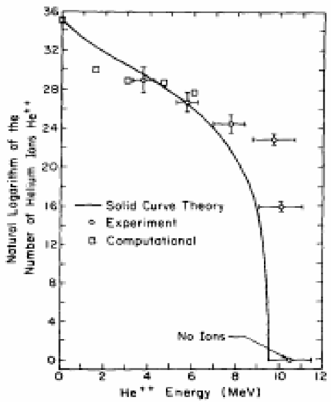


FIG. 2. Comparison between theory, experiment, and simulation, of the natural logarithm of the ion number versus energy.

III. SCALING AND ACCESSIBILITY OF THE MODEL

In the preceding section, the analysis assumed that a self-similar state could be reached. To address the question of whether a self-similar state can be attained, a detailed analysis of the initial value problem is required. This detailed analysis should include a self-consistent treatment of the dy-

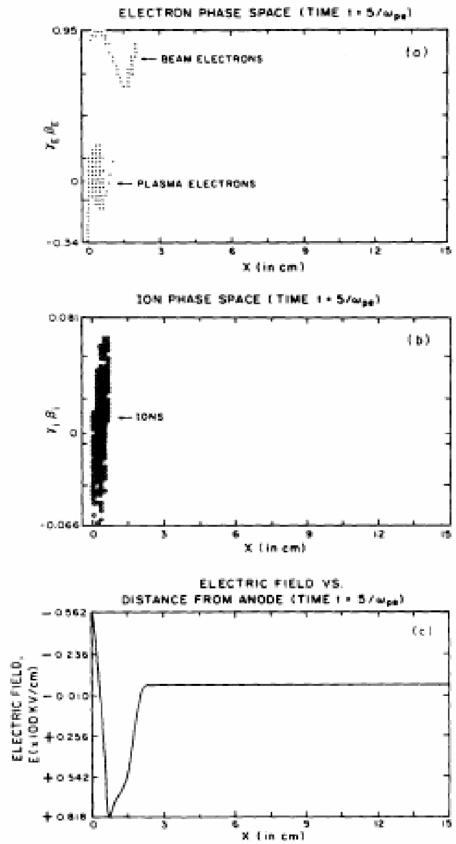


FIG. 3. Simulation phase space at early time $t = 5/\omega_{pe}$. (a) Electron phase space (beam and plasma), (b) ion phase space, (c) electron field versus position.

Laser Acceleration of Electrons

← Lesson #2 trapping of electrons easier

Gradient limit：breakdown threshold for microwave（< 100MeV/m)

E. Lawrence: cyclotron (c. 1932)

SSC:10^2 km circumference († 1993); Linear Collider: > 10km (~2020?）

Plasma：already 'broken' matter. No breakdown threshold.

'collective ion acceleration' (Veksler, 1956): ion trapping difficult ($v_{tr,ion} << c$)

Introduction of laser acceleration (Tajima and Dawson, 1979)

Linear EM field: cannot accelerate: *Woodward-Lawson Theorem*

Strong nonlinear fields

longitudinal acceleration (rectification of laser fields; v x B/c ~ O(E))

laser plays master, plasma slaves------ provides hard structure

electron trapping possible (revisit of ion acceleration now) ($v_{tr,e} \sim c$)

→ High Field Science

Ultrafast pulses

fs regime: ions immobile; enhanced with collective electron resonance

absence of 'notorious' hydrodynamical plasma instabilities; controllability;

relatively small laser energy (e.g. ELI)

Large gradient (> 10GeV/m, leap by > 3 orders of magnitude）

Low emittance (< mm mrad regime）

Wakefield : a Collective Phenomenon

All particles in the medium participate = collective phenomenon

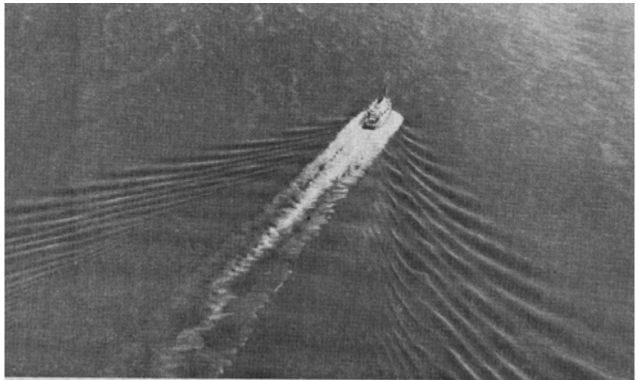
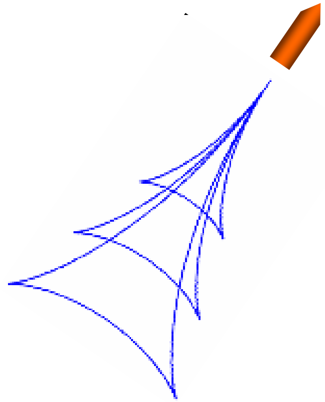


Рис. 71. Наблюдаемая картина корабельных волн. [Любезно предоставлено Aerofilms Ltd.]



Kelvin wake

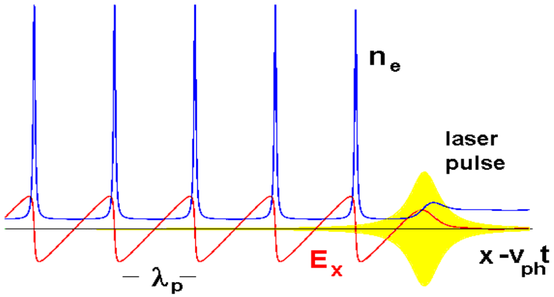
$$\omega = \sqrt{kg}$$

$$x = X_1 \cos\theta \left(1 - \frac{1}{2}\cos^2\theta\right)$$

$$y = X_1 \cos^2\theta \sin\theta$$

$$-\pi/2 < \theta < \pi/2$$

No wave breaks and wake **peaks** at v≈c



$$\lambda_p = 2\pi / k_p \qquad k_p v_{ph} = \omega_{pe}$$

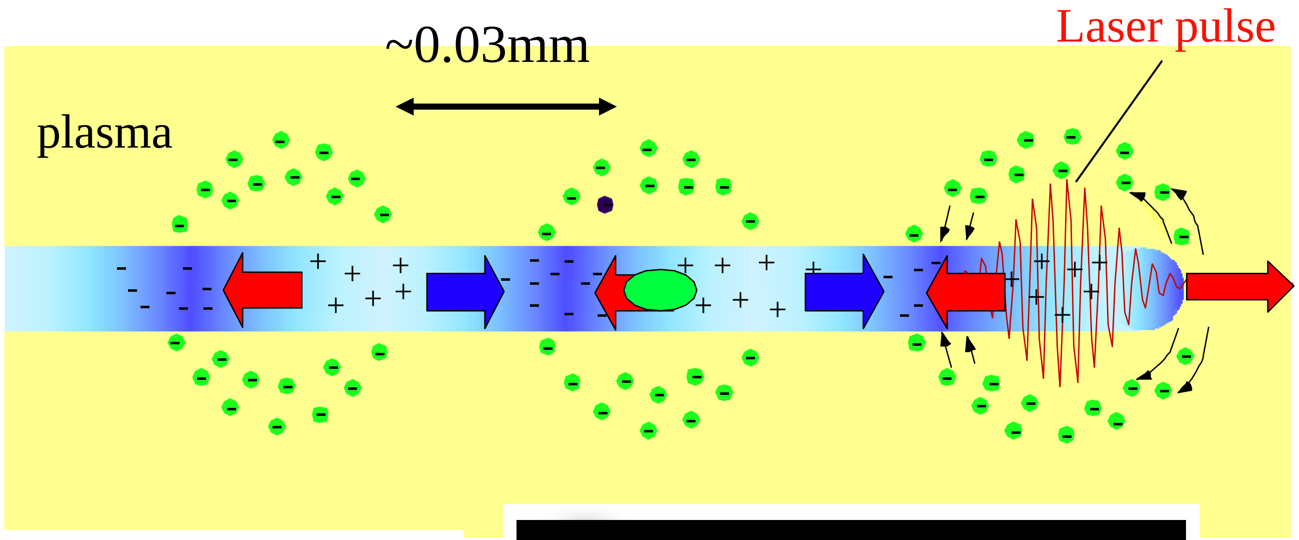
$$\omega_{pe} = \left(4\pi n e^2 / m_e\right)^{1/2}$$

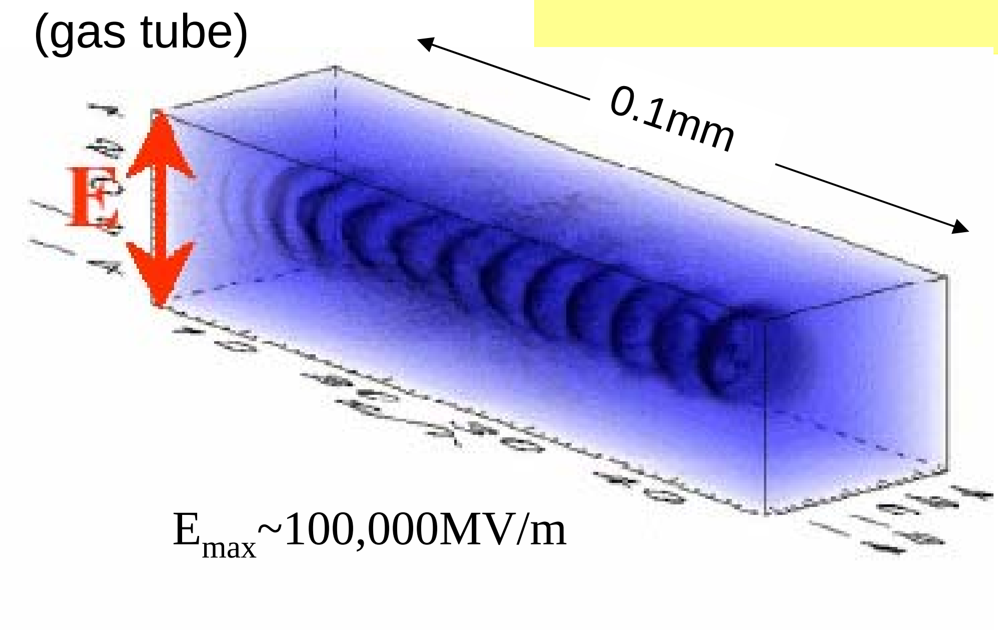
(The density cusps.
Cusp singularity)

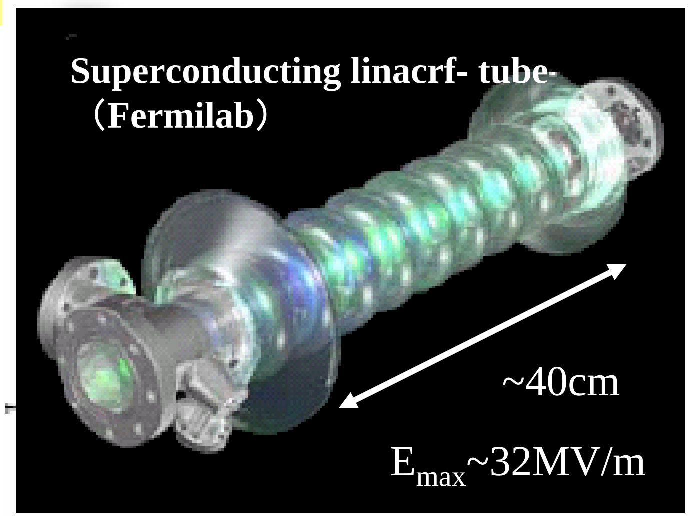
Wave **breaks** at v<c

Thousand-fold Compactification

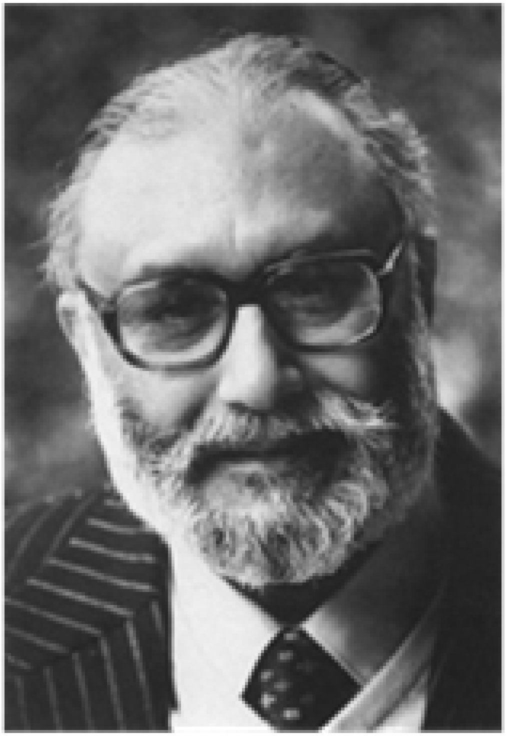
Laser wakefield: thousand folds gradient (and emittance reduction?)







The late Prof. Abdus Salam



At ICTP Summer School (1981),
Prof. Salam summoned me and discussed about laser wakefield acceleration.

Salam***: ‘Scientists like me began feeling that we had less means to test our theory. However, with your laser acceleration, I am encouraged’.*** (1981)

He organized the Oxford Workshop on laser wakefield accelerator in 1982.

Effort: many scientists over many years to realize his vision / dream
High field science: spawned

Laser technology invented (1985)

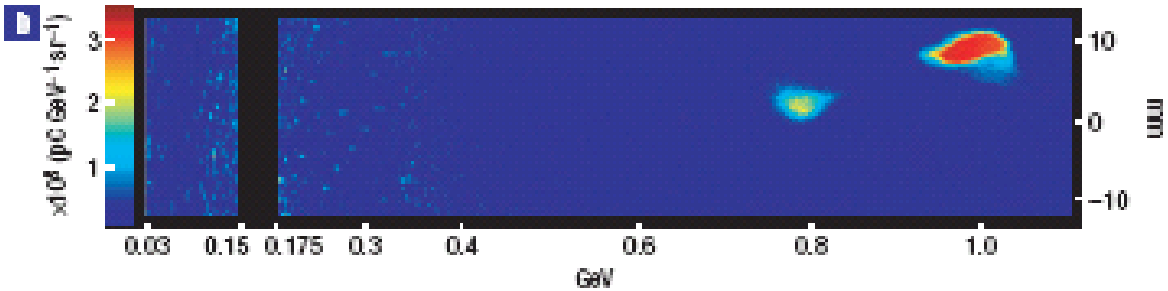
(Professor Gerard Mourou)

Chirped pulse amplification (CPA) invented:
to overcome the gain medium nonlinearities in spatially expanded amplification to temporal expansion:
smaller, shorter pulse, more intense, higher reprate,
all simultaneous.

→ many table-top TW and PW lasers world-wide
first Chair, ICUIL (International Committee for Ultra Intense Lasers)
toward EW laser (*Extreme Light Infrastructure)*

→First LWFA experiments
(Nakajima et al 1994; Modena et al1995)
→drives High Field Science

GeV electrons from a centimeter accelerator
(a slide given by S. Karsch)



310- μ m-diameter channel capillary

P = 40 TW

density 4.3×10^{18} cm^{-3}.

Leemans et al., Nature Physics, september 2006

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

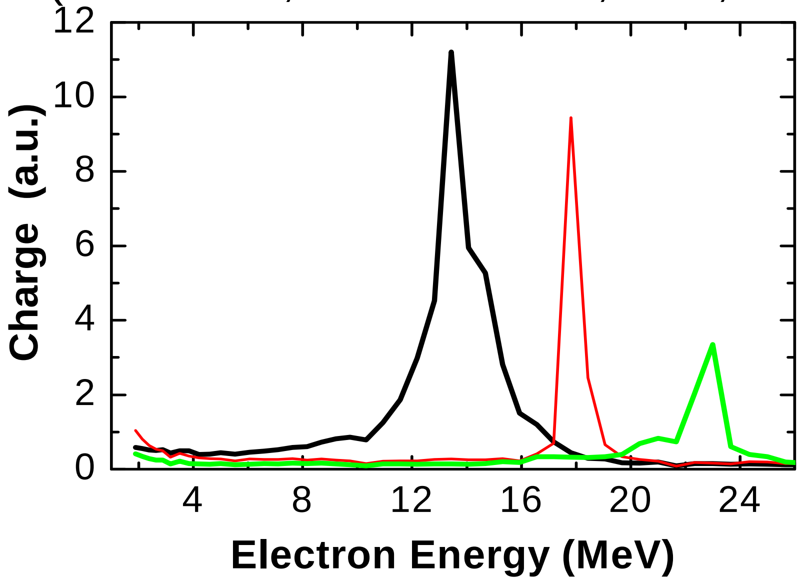
T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

MPQ Laser Acceleration Effort (1)

Monoenergy electron spectra: from few-cycle laser (LWS-10)

(K. Schmid, L. Veisz et al., PRL, 2009)

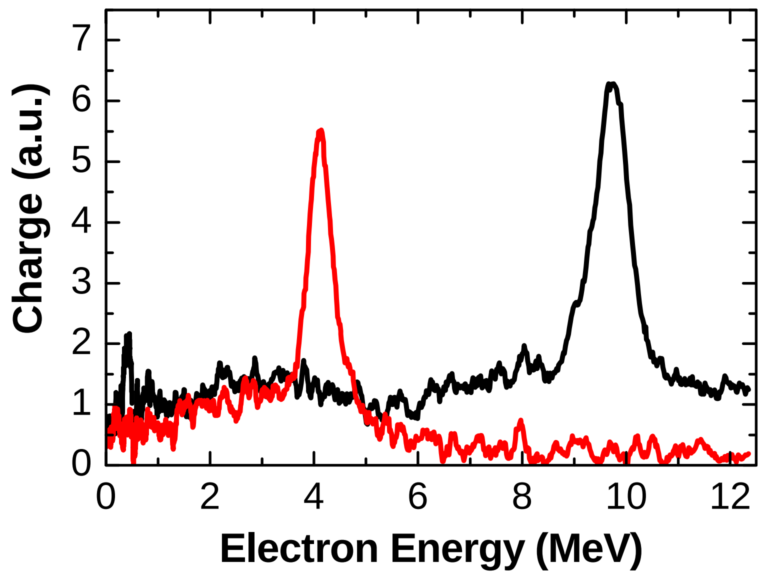


Large electron spectrometer 2 – 400 MeV

- **No thermal background !**
- **Energies: 13.4 MeV, 17.8 MeV, 23 MeV**
- **FWHM energy spread: 11%, 4.3%, 5.7 %**
- **~ 10 pC charge**

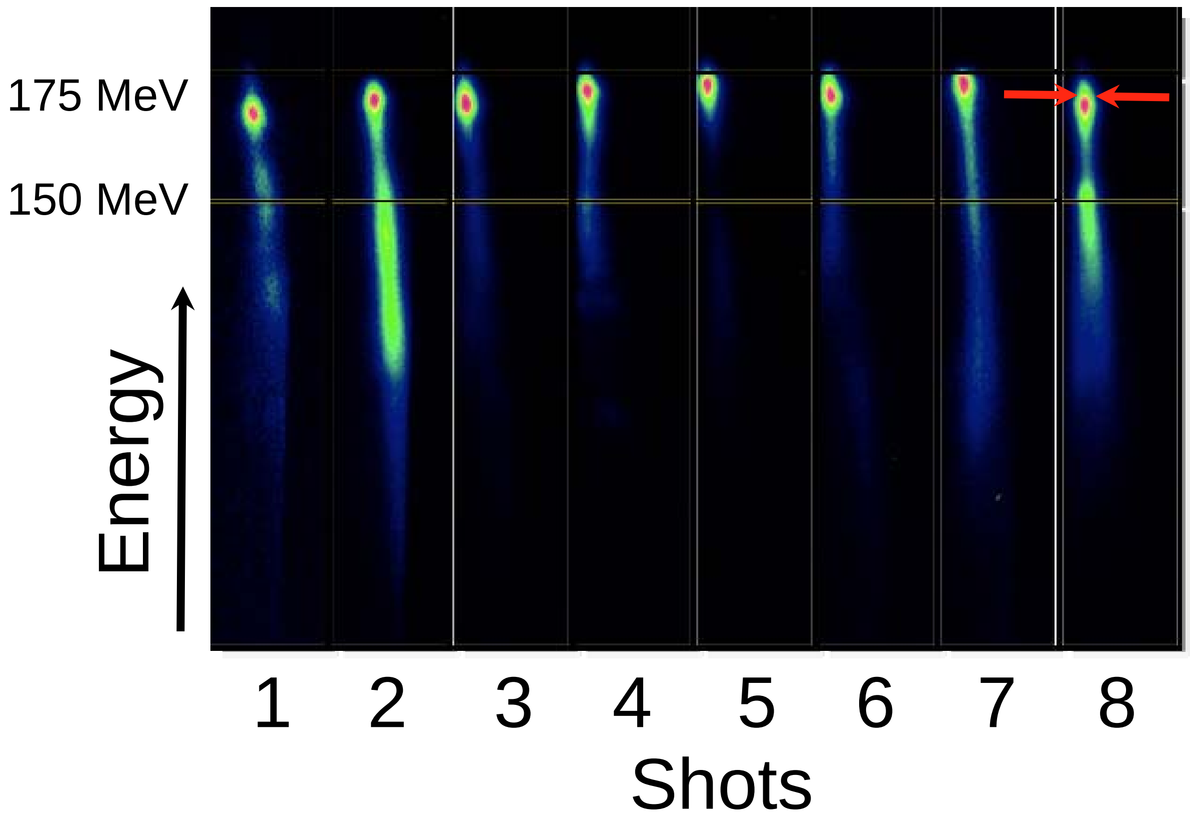
Small electron spectrometer:

- **Electron energies below 500keV**
- **No thermal background !**
- **4.1 MeV (14%); 9.7 MeV (9.5%)**



MPQ Laser Acceleration Effort (2)

Reproducible acceleration conditions



E ≈ 169.7 ± 2.0 MeV

1.1% peak energy fluctuation !

ΔE/E ≈ 1.76±0.26% RMS

→ Essential property for future table-top FEL operation

Source size image: provides emittance measurement, given the resolution can be improved

Electron trapping width

$v_{tr,e} \sim c\sqrt{a_0}$

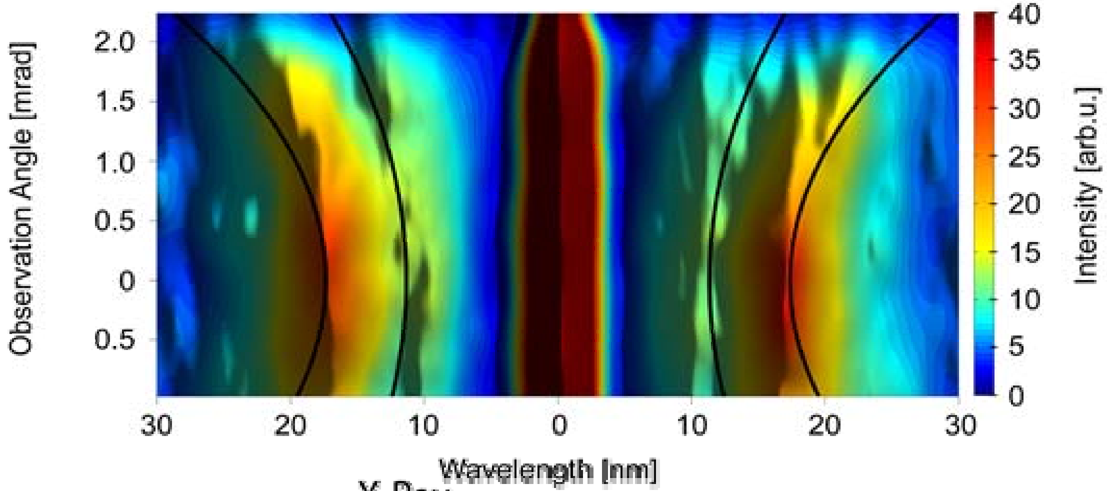
(J. Osterhoff,…S. Karsch, et al., PRL 2008)

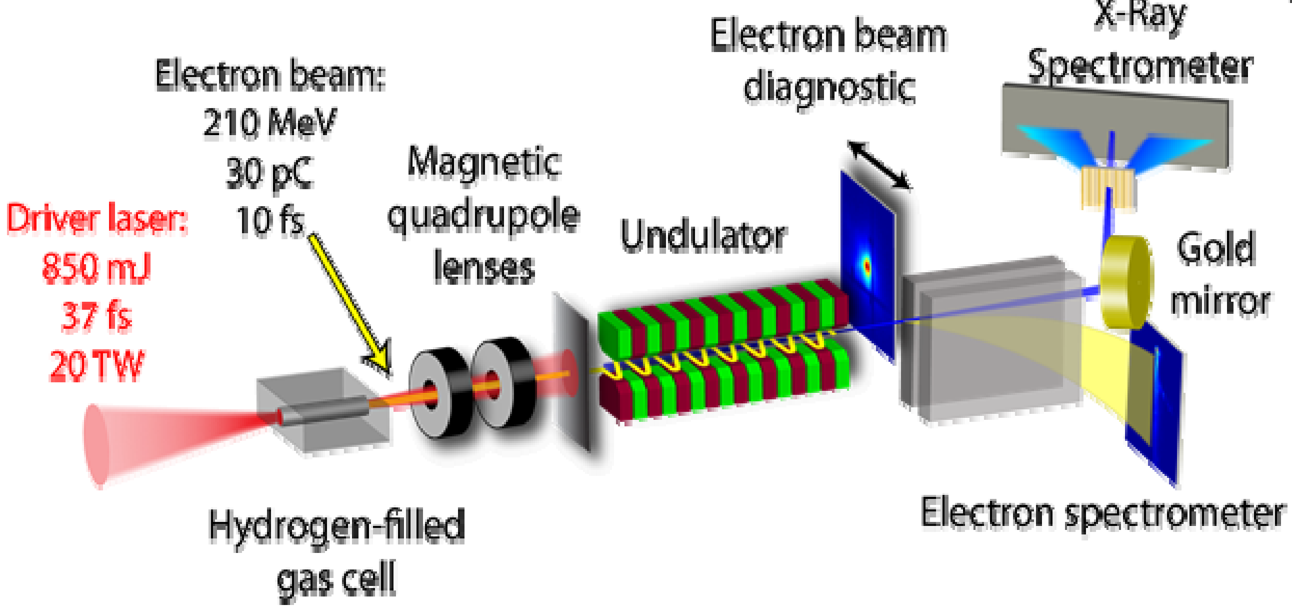
MPQ Laser Acceleration Effort (3)

Laser-driven Soft-X-Ray Undulator Radiation

(F. Gruener、S. Karsch, et al., Nature Phys., 2009)

Characteristic undulator radiation spectrum





Intra-Operatory Radiation Therapy (IORT)

LWFA electron sources: technology transferred to company

NOVAC7 *(HITESYS SpA)* *RF-based*	vs.	**CEA-Saclay experim. source** *Laser-based*
El. Energy < 10 MeV *(3, 5, 7, 9 MeV)*		*El. Energy > 10 MeV* *(10 - 45 MeV)*
Peak curr. 1.5 mA *Bunch dur. 4 μs* *Bunch char. 6 nC*		*Peak curr. > 1.6 KA* *Bunch dur. < 1 ps* *Bunch char. 1.6 nC*
Rep. rate 5 Hz *Mean curr. 30 nA*		*Rep. rate 10 Hz* *Mean curr. 16 nA*
Releas. energy (1 min) *@9 MeV (≈dose)* *18 J*		*Releas. energy (1 min)* *@20 MeV (≈dose)* *21 J*

(A. Giulietti et al., Phys. Rev. Lett.,2008)

Collective deceleration

Beam dump: harder to stop and more hazardous radioactivation

↓

Gas (plasma) **collective force** to shortstop the HE beams

- the shorter the bunch is, the easier to stop

  (ideally suited for laser wakefield accelerated beams)

- little radioactivation (good for environment)

  example of **'Toilet Science'** that tends impact of own produce

  (as opposed to 'Kitchen Science' of 20th C)

- possible energy recovery

Beam Stopping and its Energy Recovery Using Plasma

February 25, 2008

Toshiki Tajima and Alexander W. Chao

1 Motivations

1.1 Beam Stopping

In the effort to make a high energy accelerator system as compact as possible, it is necessary not only to make the accelerator compact, but also to make the beam stopping system compact. With this motivation, we introduce the concept of passive plasma decelerator at the end of the use of the high energy beam by immersing the beams to be decelerated into an appropriately designed plasma.

Tajima and Chao, (2008 applied for patent)

H. C. Wu et al. (2009)

Stopping power due to collective force

Bethe-Bloch stopping power in matter
Plasma stopping power due to individual force

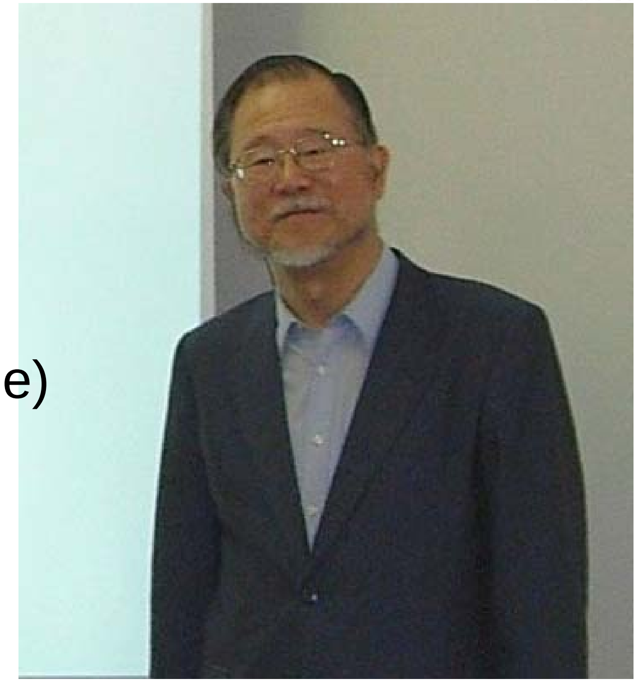
$$-(dE/dx)_{ind} = (F/\beta^2)\ln(m_e v^2/e^2 k_D)$$

That due to collective force (perturbative regime)

$$-(dE/dx)_{coll} = (F/\beta^2)\ln(k_D v/\omega_{pe})$$

$$F = 4\pi e^4 n_{e,m}/m_e c^2 = e^2 k_{pe,m}^2$$

(Ichimaru, 1973)



Professor Setsuo Ichimaru

Plasma stopping power due to short-bunch wakefield (wavebreak regime)

$$-(dE/dx)_C = m_e c\omega_{pe}(n_b/n_e)$$

(Wu et al, 2009)

Greater by **several orders** in gas over Bethe-Bloch in solid

Key issues of future colliders

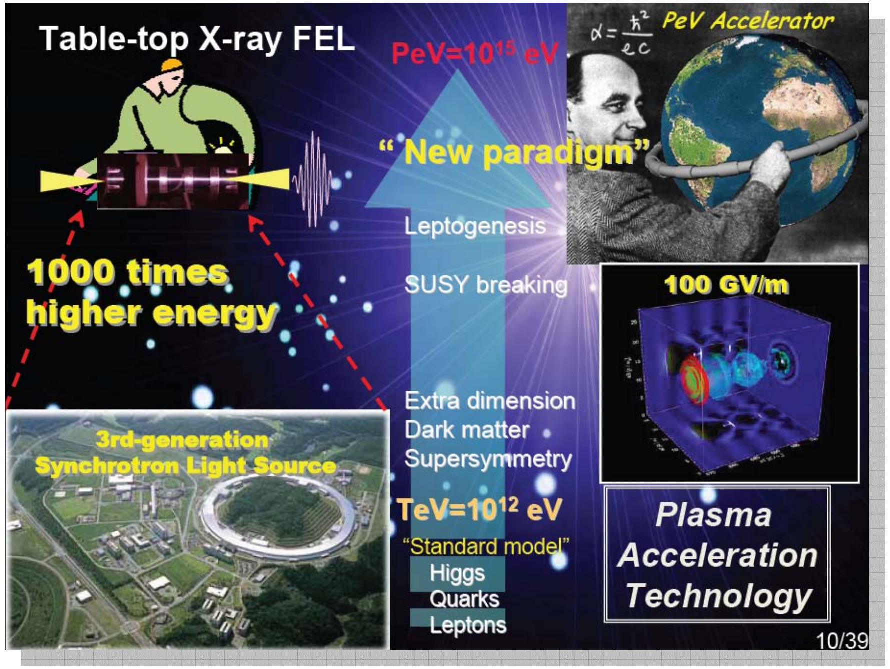
(T. Raubenheimer, SLAC, 2008)

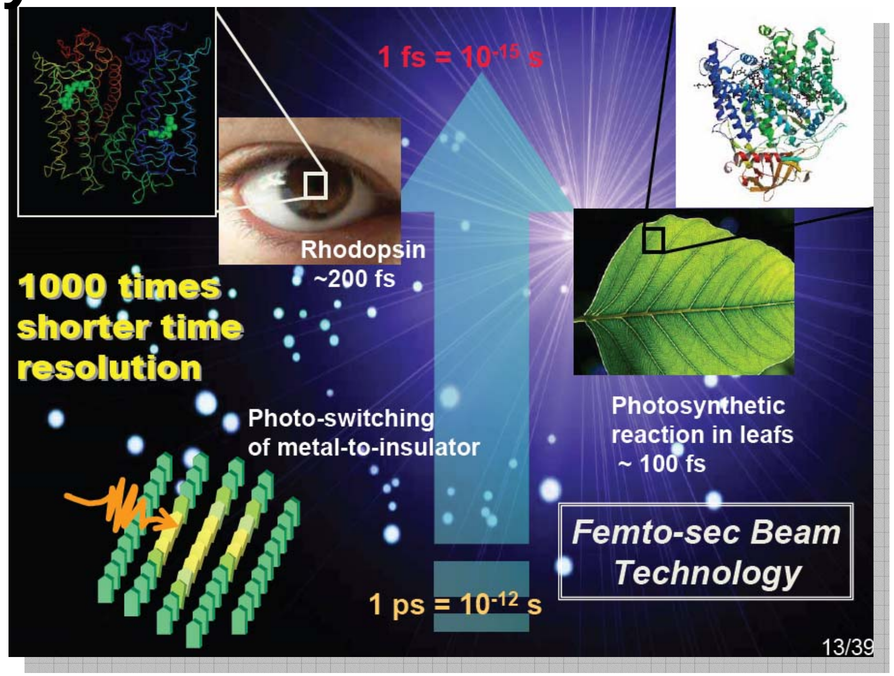
Beam Acceleration

* Largest cost driver for a linear collider is the acceleration
  - ILC geometric gradient is ~20 MV/m → 50km for 1 TeV
* Size of facility is costly → higher acceleration gradients
  - High gradient acceleration requires high peak power and structures that can sustain high fields
    - Beams and lasers can be generated with high peak power
    - Dielectrics and plasmas can withstand high fields
* Many paths towards high gradient acceleration
  - High gradient microwave acceleration } ~100 MV/m
  - Acceleration with laser driven structures
  - Acceleration with beam driven structures } ~1 GV/m
  - Acceleration with laser driven plasmas
  - Acceleration with beam driven plasmas } ~10 GV/m

Challenge Posed by DG Suzuki

Frontier science driven by advanced accelerator





compact, ultrastrong *a*

atto-, zeptosecond

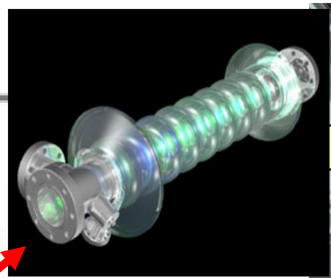
Can we meet the challenge?

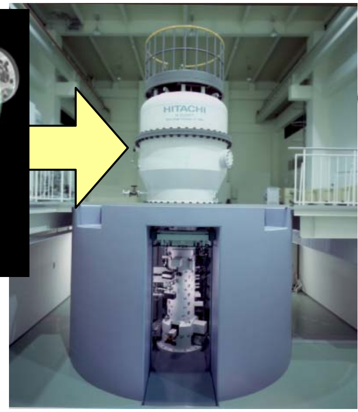
A. Suzuki @KEK(2008)

Accelerator

Evolution of Accelerators and their Possibilities (Suzuki,2008)

E=40 MV/m

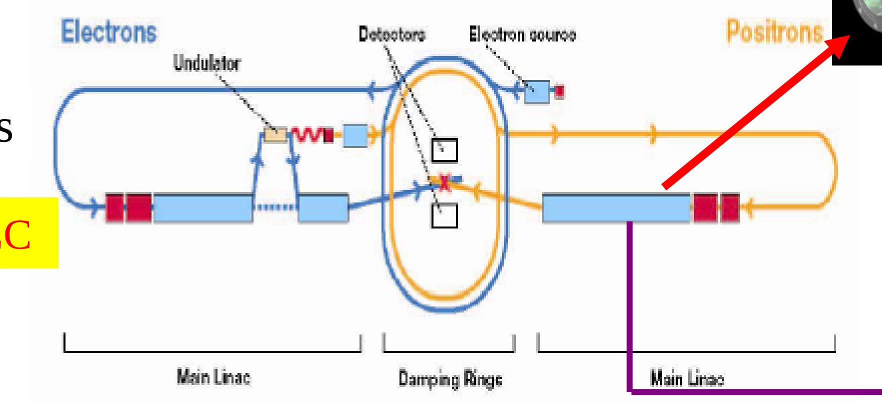




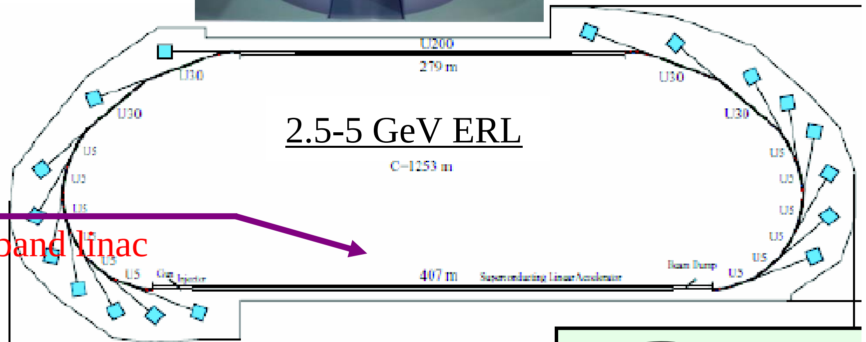
Ultra-High Voltage STEM with Superconducting RF cavity

2020s

ILC



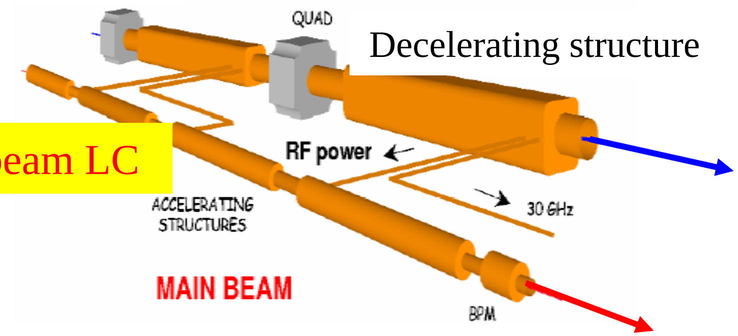
Superconducting L-band linac

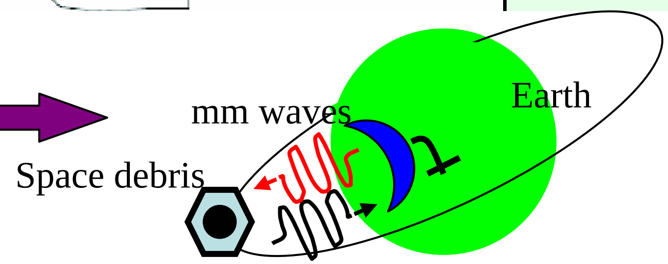


E=200 MV/m

2030s

Two-beam LC





Earth-based space debris radar

E=10 GV/m

10cm-10GeV Plasma Channel Accelerator

2040s

Laser-plasma LC

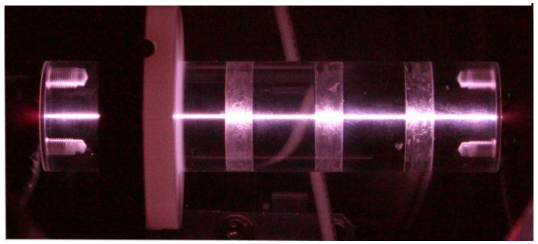


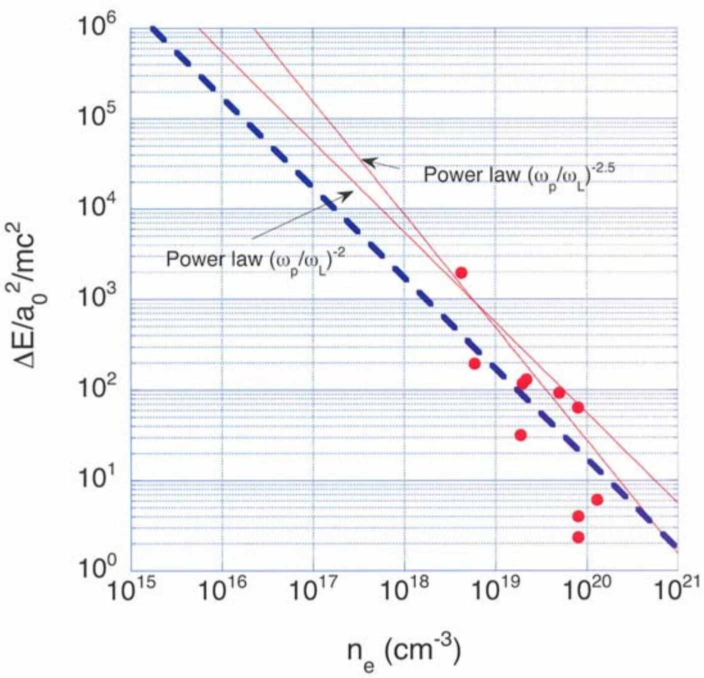
Table-top high energy accelerator

Meeting Suzuki's Challenge:

Laser acceleration toward ultrahigh energies

$$\Delta E \approx 2m_0c^2a_0^2\gamma_{ph}{}^2 = 2m_0c^2a_0^2\left(\frac{n_{cr}}{n_e}\right),$$ (when 1D theory applies)

$$L_d = \frac{2}{\pi}\lambda_p a_0^2\left(\frac{n_{cr}}{n_e}\right), \qquad L_p = \frac{1}{3\pi}\lambda_p a_0\left(\frac{n_{cr}}{n_e}\right),$$



		case I	case II	case III
a_0		10	3.2	1
energy gain	GeV	1000	1000	1000
plasma density	cm^{-3}	5.7x10^{16}	5.7x10^{15}	5.7x10^{14}
acceleration length	m	2.9	29	290
spot radius	μm	32	100	320
peak power	PW	2.2	2.2	2.2
pulse duration	ps	0.23	0.74	2.3
laser pulse energy	kJ	0.5	1.6	5

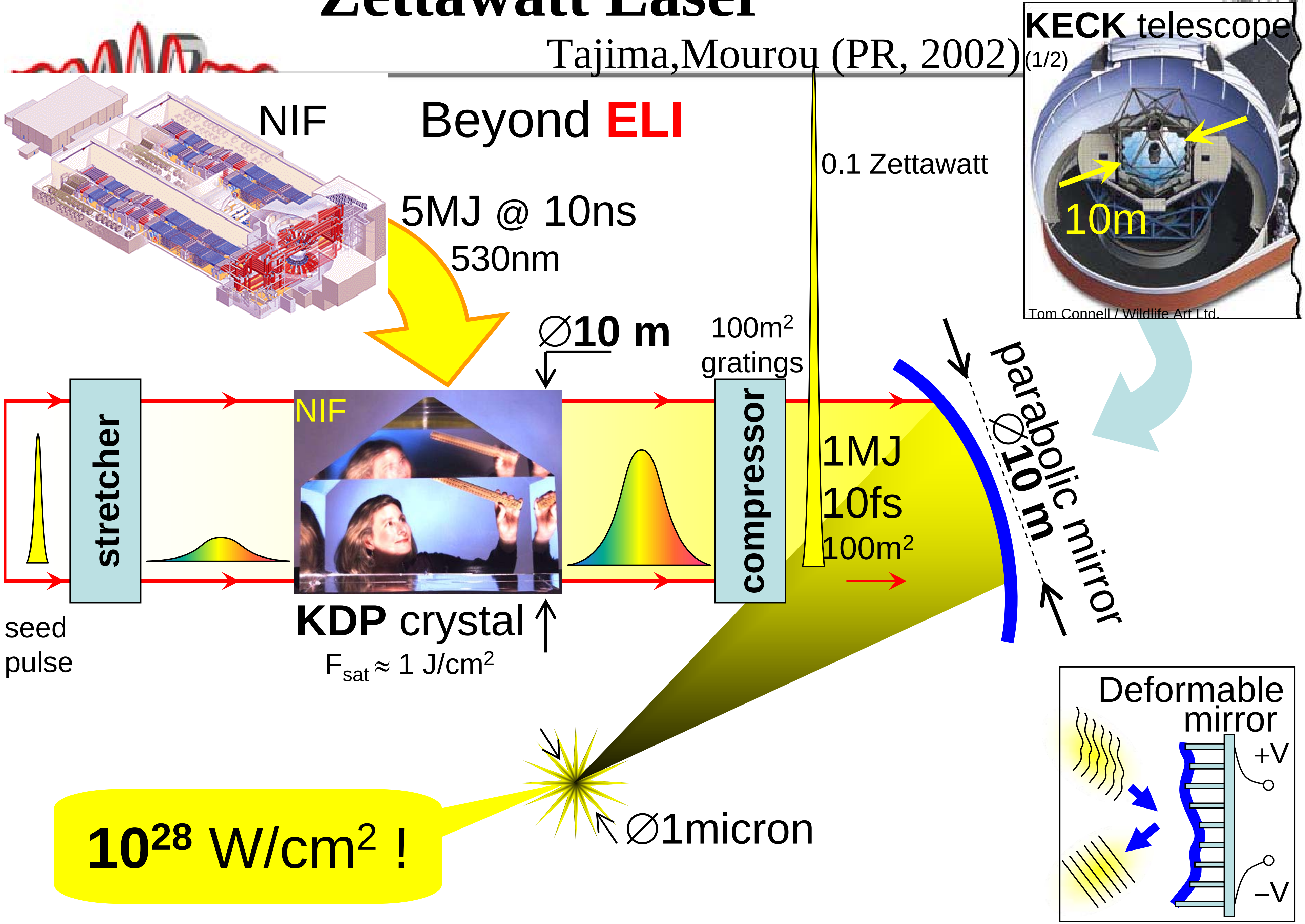
Even 1PeV electrons (and γ s) are possible, albeit with lesser amount

→ exploration of new physics such as the **reach of relativity** and quantum gravity (correlating with primordial gamma-ray burst [GRB] observation)?

(laser energy of 10MJ@plasma density of 10^{16}/cc; maybe reduced with index 5/4)

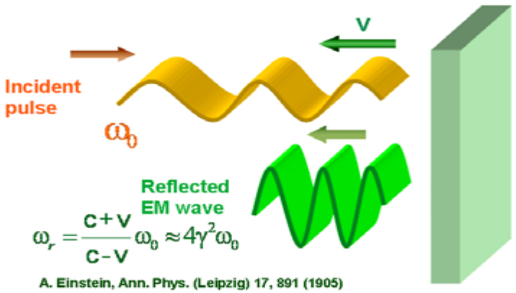
Zettawatt Laser

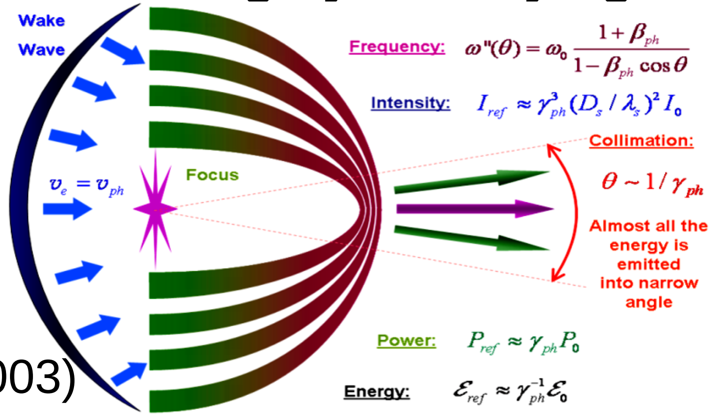
Tajima, Mourou (PR, 2002)



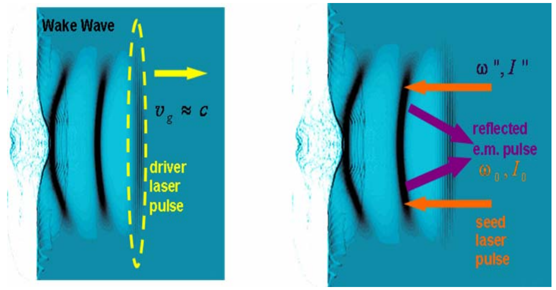
Relativistic Engineering: relativity as the guiding principle (cf. quantum engineering)

EM Pulse Intensification and Shortening by the Flying Mirror

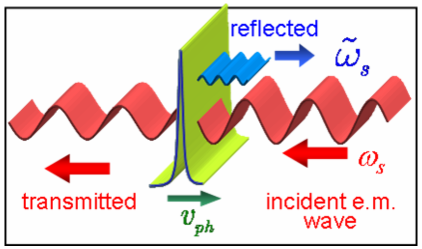




(Bulanov, Esirkepov, Tajima, 2003)

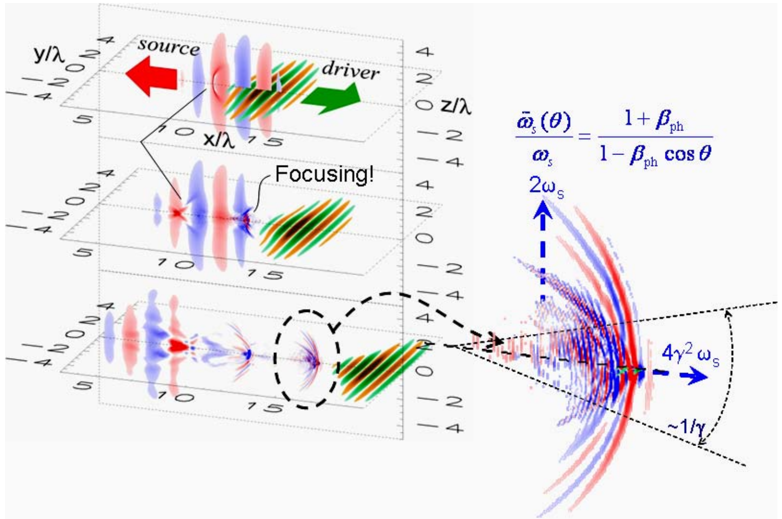


$$\omega'' = \frac{c+v_{ph}}{c-v_{ph}}\omega \approx 4\gamma_{ph}^2\omega_0 \qquad \frac{I''_{max}}{I_0} \approx \kappa\, \gamma_{ph}^6 \left(\frac{D}{\lambda}\right)^2$$



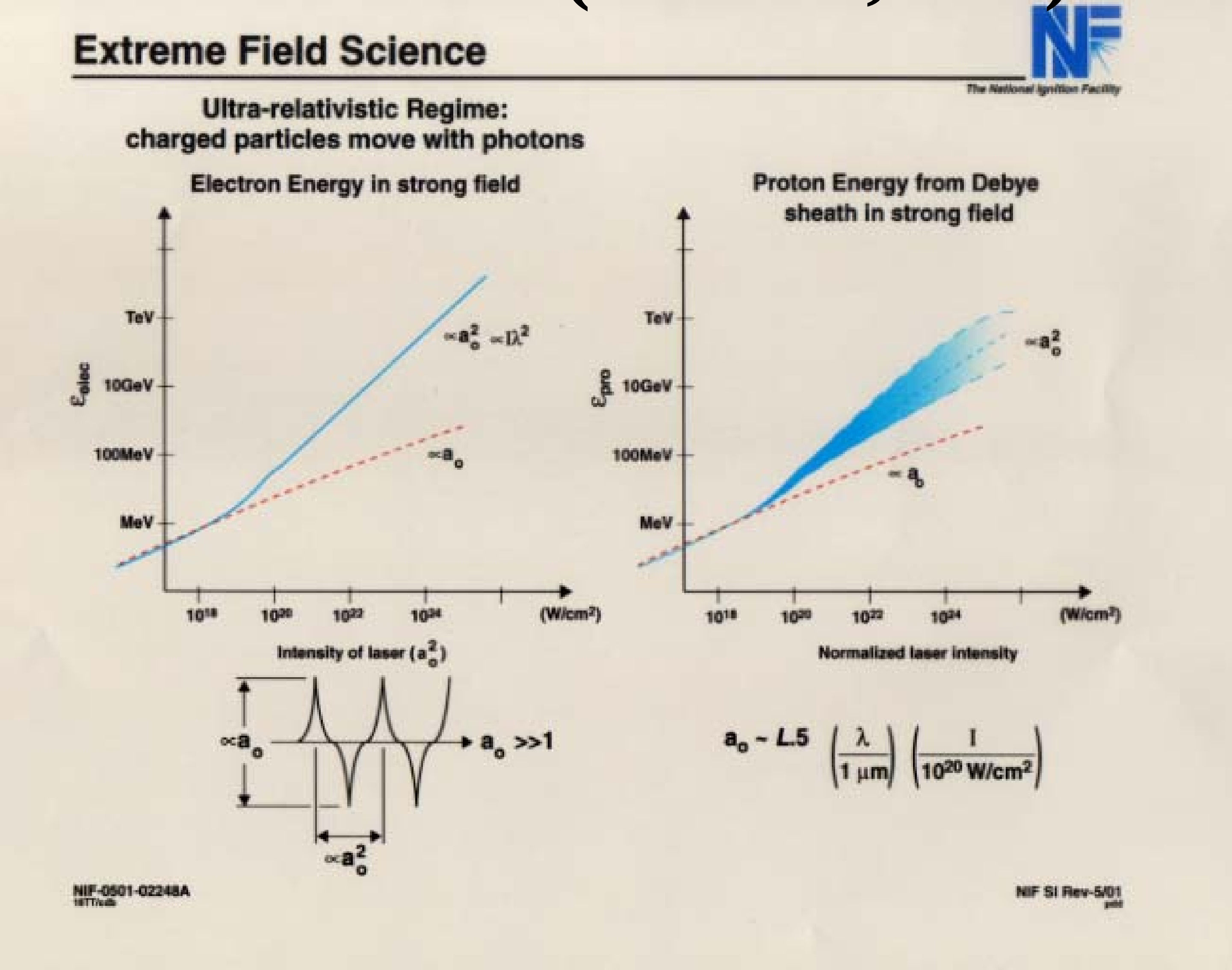
$$\kappa \sim \gamma_{ph}^{-3}$$

3D Particle-In-Cell Simulation



A lot of ideas for new attosecond pulses

Relativity Helps Acceleration (for Ions, too!)



Strong fields:
rectifies laser
to longitudinal
fields

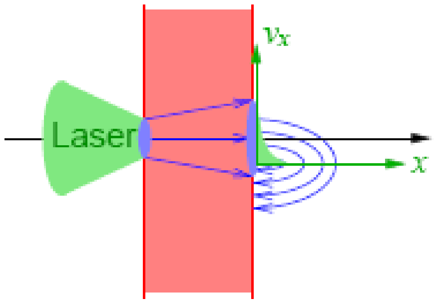
In relativistic regime,
photon x electrons
and even protons
couple stronger.

(Tajima, 1999
@LLNL;
Esirkepov et al.,
PRL,2004)

Comparison of the phase space dynamics: toward more Adiabatic Acceleration

TNSA

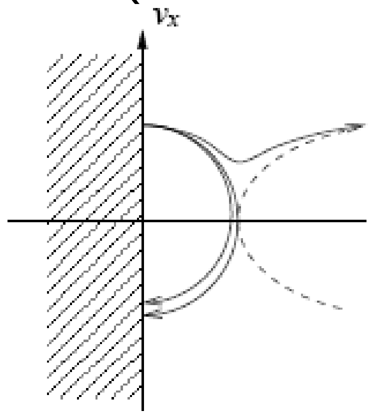
a)



thick target
(not moving)

(metallic boundary)

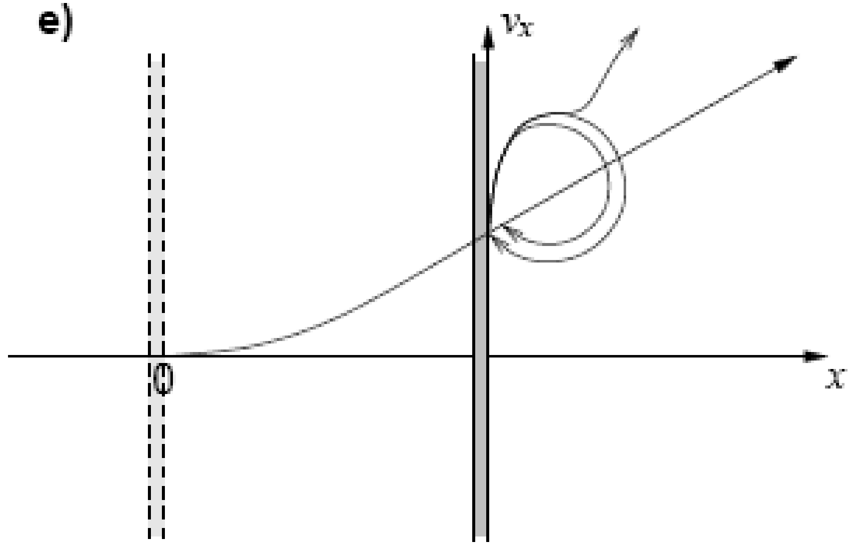
b)



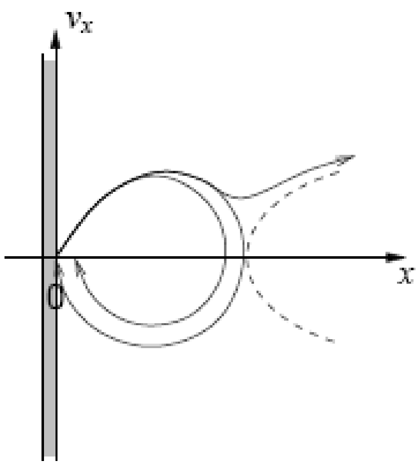
Ion trapping width:

$v_{tr,ion} \sim c\sqrt{a_0(m/M)}$

e)

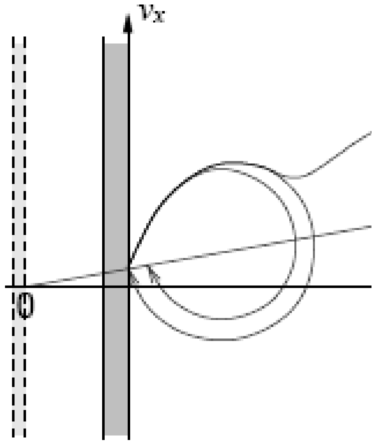


c)



thin target

d)



target moves

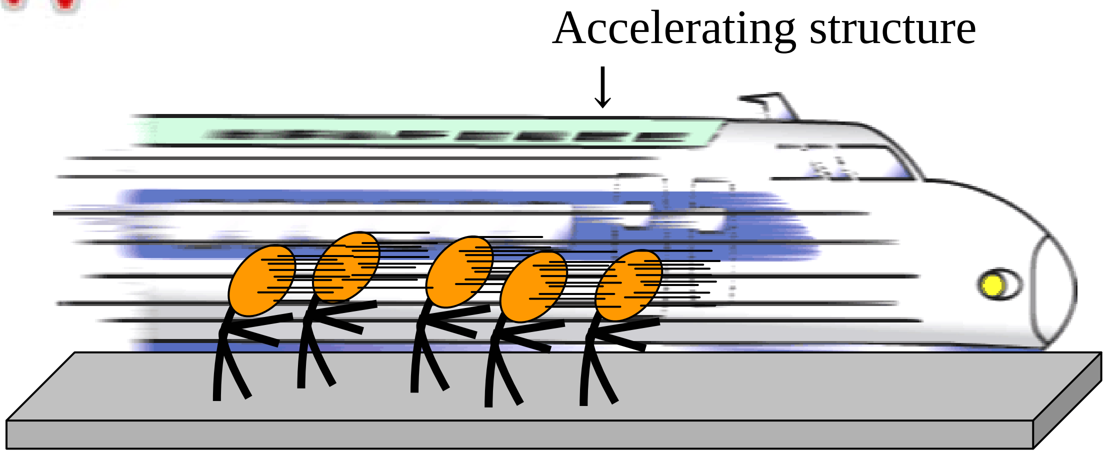
CAIL (with **CP**)

CAIL

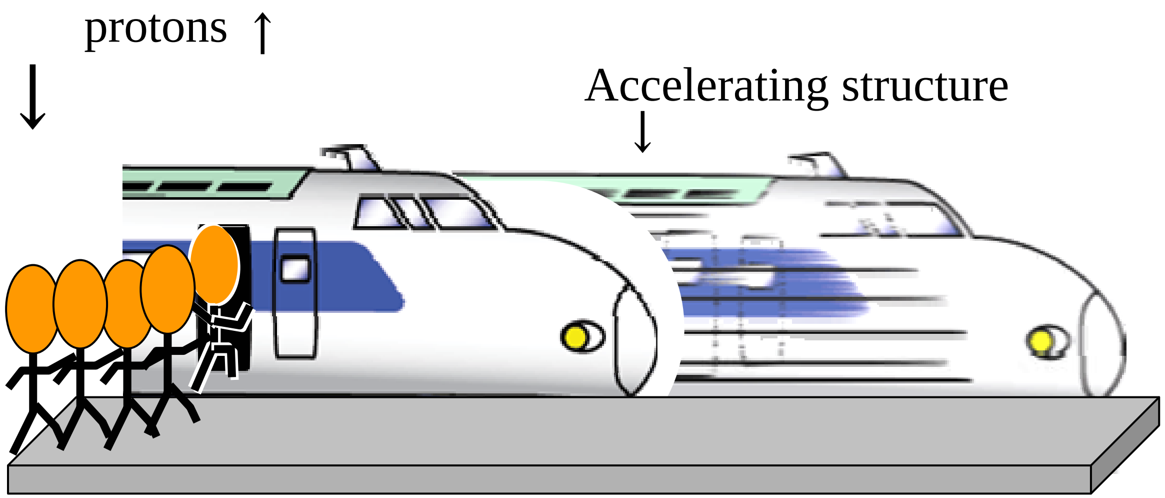
Rev. Accel. Sci. Tech.
(Tajima, Habs, Yan, 2009)

Adiabatic (Gradual) Acceleration

from #1 lesson of Mako-Tajima problem



Inefficient if <u>suddenly</u> accelerated

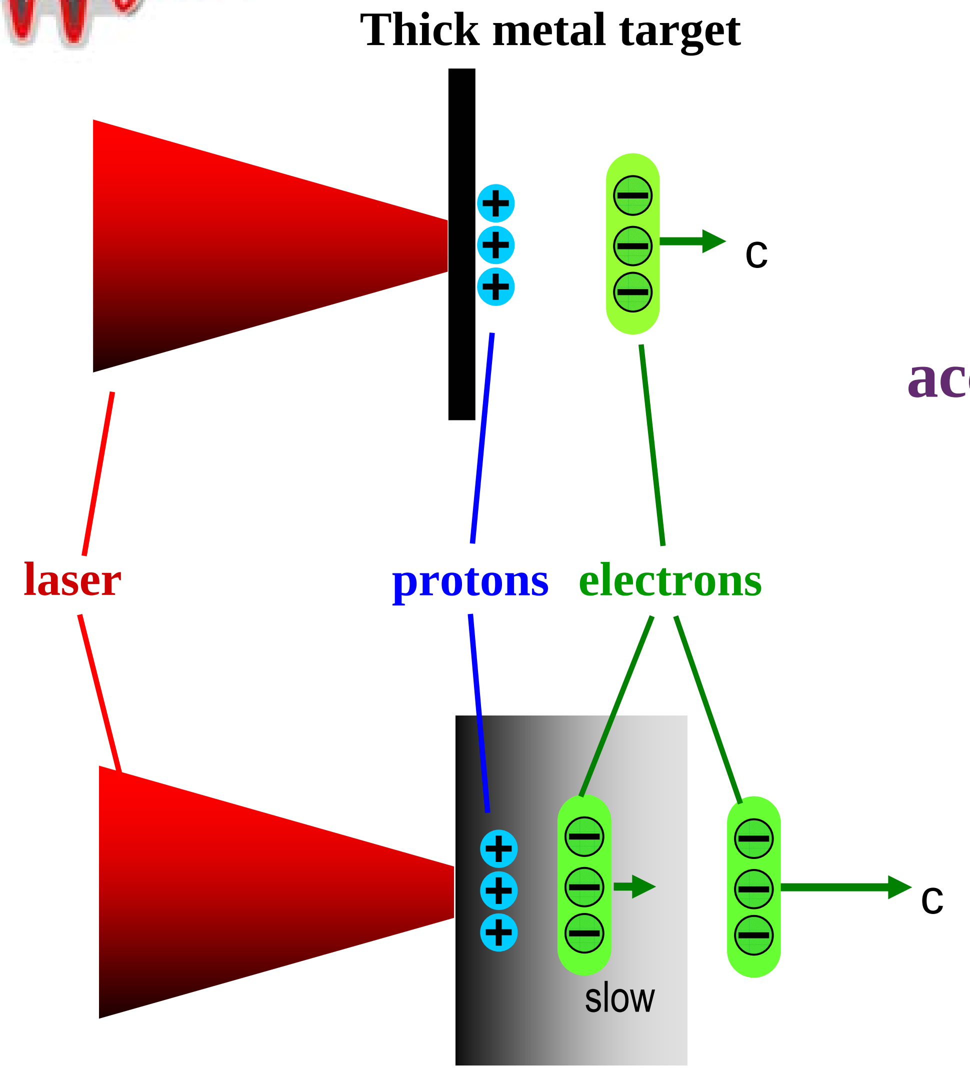


(cf.human trapping width: $v_{tr,human}$ ~ 1m/s << c_s)

Efficient when <u>gradually</u> accelerated

Lesson #1: gradual acceleration → Relevant for ions

Adiabatic acceleration (2)



Graded, thin (nm), or clustered target and/or circular polarization

Most experimental configurations of proton acceleration(2000-2009)

Innovation ("Adiabatic Acceleration")

(2009-)

= Method to make the electrons within ion trapping width

However, in **ELI** automatic

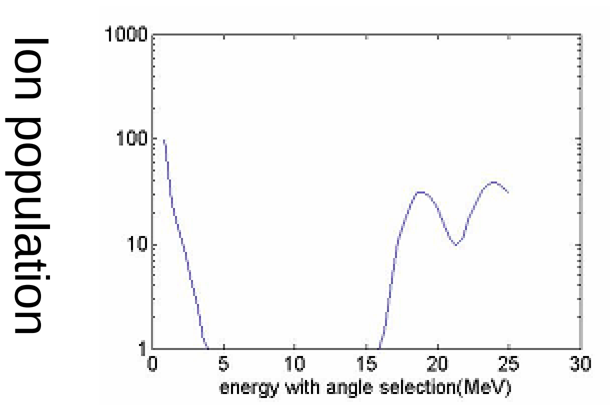
$v_{tr,\,ion} \sim c\,\sqrt{a_0(m/M)} \sim c$

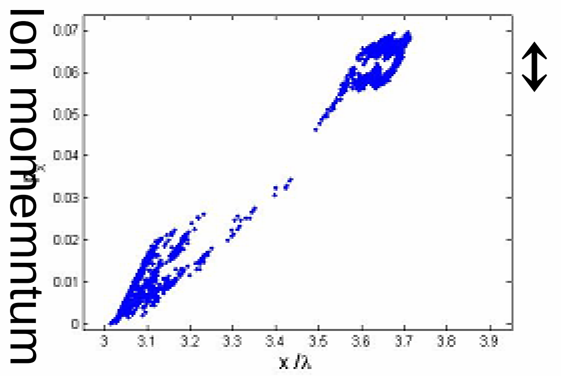
(ultrarelativistic $a_0 \sim M/m$)

Good quality ion beams

Circularly Polarized Laser drives ions out of ultrathin (nm) foil **adiabatically**
Monoenergy peak emerges; energy **more rapidly** increases as $\sim a_0^2$

Bucket trapping ions





Bucket width
$v_{tr,ion} \sim c\sqrt{a_0}(m/M)$

laser →

→

(X. Yan et al: 2009)

Ponderomotive force drives electrons,
Electrostatic force nearly cancels
Slowly accelerating bucket formed

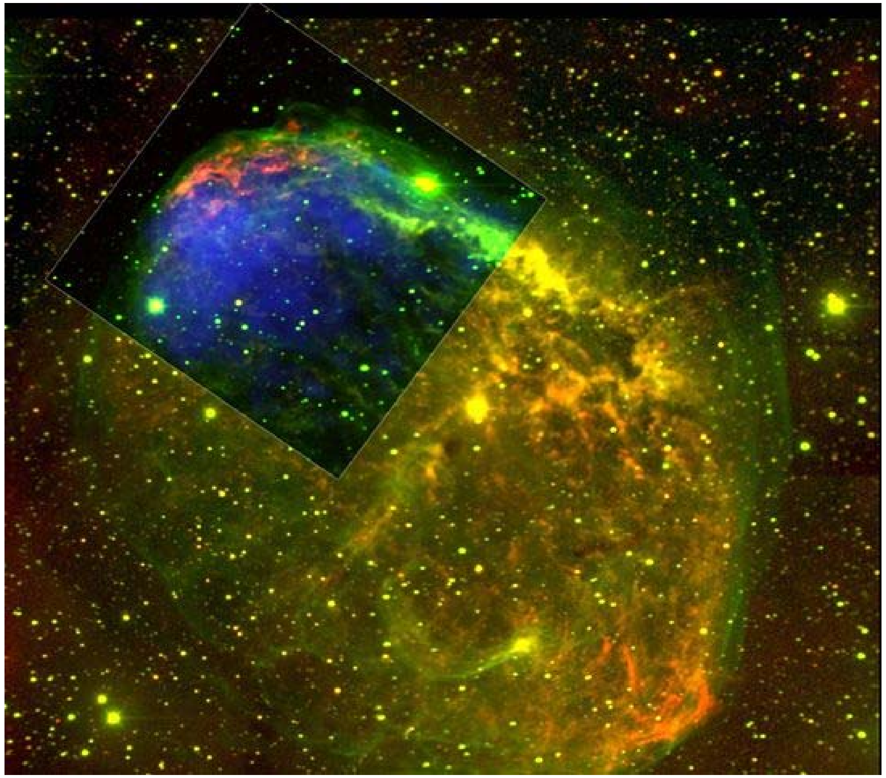
good-quality and efficient acceleration of ions

Conclusions

- **Collective acceleration**: **hard** birth / **long** way and near maturation(electron→ion; laser→electron; laser→photon; electron→electron; ion→electron); unexpected 'homecoming' (laser →ion), too
- Leap by **many orders** (≥ 3) in many respects; equally more demanding by many orders : **N²** vs. N.
- Laser has come around to match the condition set 30 years ago; Still some ways to go to realize the dream (such as ELI)
- GeV electrons; 10 GeV soon; 100GeV considered;

  TeV laser collider contemplated; PeV ?
- **Societal obligations and applications**: already beginning, soon to flourish (e.g., **cancer therapy**, radiolysis, **bunch decelerator**, nuclear detection, compact FEL source, compact radiation sources, ultrafast diagnosis,…)

Cosmic Acceleration in the Wake of Intense Radiation and Particle Flows



UHECR (ultra high energy cosmic rays):
- beyond **Fermi** acceleration necessary,
- wakefiled acceleration?

Merci Beaucoup et a la Prochaine Fois!

In dedication to the late-Professor John Dawson

I plan to give Pascal Lectures approximately once a month from now on.
Look forward to hearing your opinions and feedbacks.

Toshi Tajima