Magistral Lecture
Ultraintense Laser Interaction Science (ULIS) 2009
5/25/09

Laser Acceleration and its Scope and Impact: 1979-2009

Toshi Tajima
LMU,MPQ
Garching

Acknowledgments for Advice and Collaboration: late-J. Dawson, N. Rostoker, F. Krausz, D. Habs, S. Karsch, L. Veisz, F. Gruener, G. Mourou, 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

Dream Beams Symposium

MPQ Garching
Feb. 26 – 28, 2007

(from F. Krausz and J. Meyer-ter-Vehn)

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

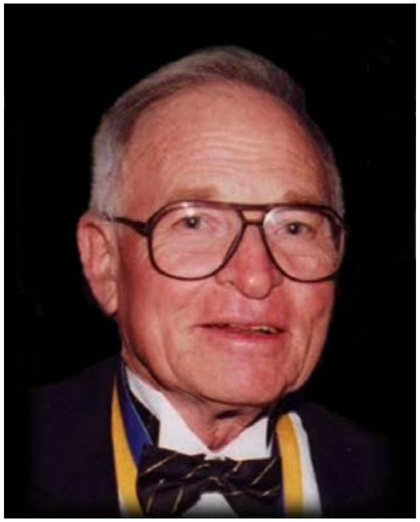
US:

Texas site decided (1989)

US Government decided to terminate its work: 1993

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

Prehistoric activities(1973-75,…84)



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

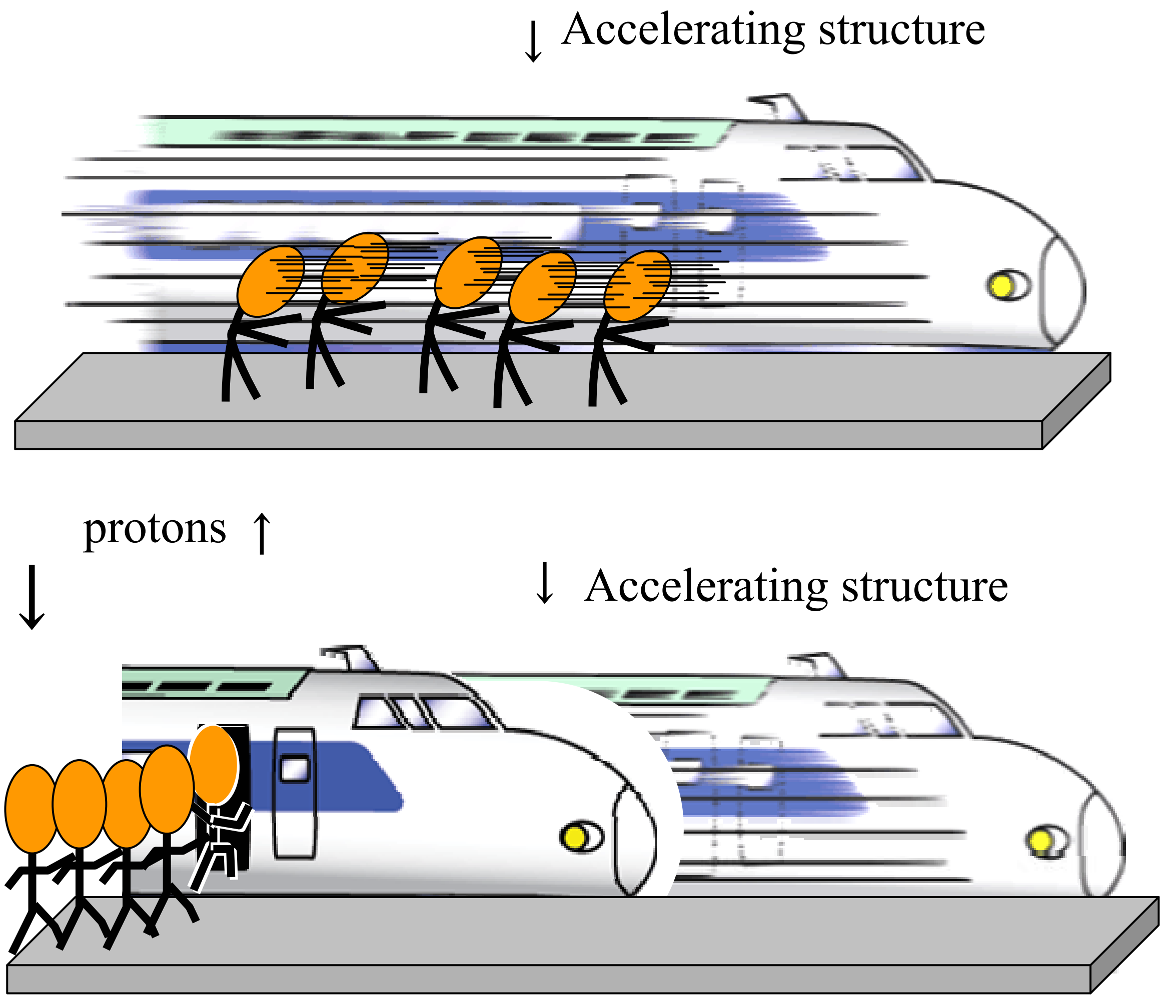
Collective acceleration suggested:
Veksler (1956)
(ion energy)~ (M/m)(electron energy)

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

Adiabatic (gradual) acceleration



Inefficient if <u>suddenly</u> accelerated

Efficient when <u>gradually</u> accelerated

#1 → Relevant to ion acceleration

Laser Acceleration of Electrons

← Lesson #2 of collective ion acceleration

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 threshould.

'collective ion acceleration' (Veksler, 1956): ion trapping difficult

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)

→ High Field Science

Ultrafast pulses

fs regime: ions immobile; enhanced with collective electron resonance

absence of 'notorious' hydrodynamical plasma instabilities; controllability;

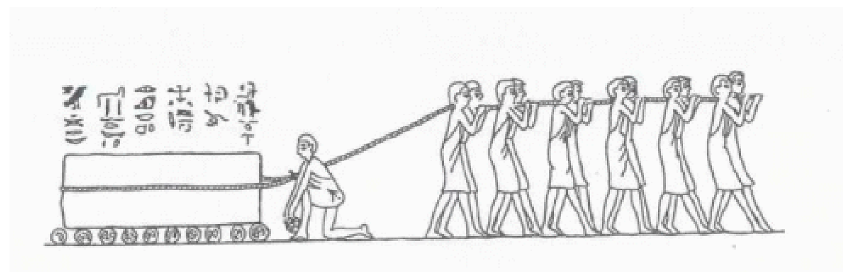
relatively small laser energy (e.g. ELI)

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

Low emittance (< mm mrad regime）

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)

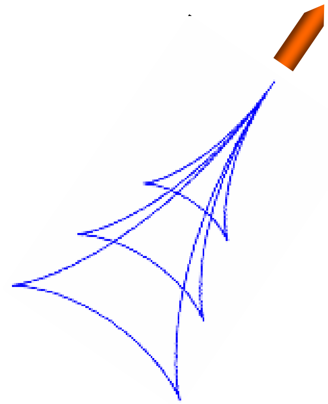
Collective ionization (N^2 ionization)

Collective deceleration (Tajima & Chao,2008)

Wakefield : a <u>Collective</u> Phenomenon

All particles in the medium participate = collective phenomenon

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



Kelvin wake

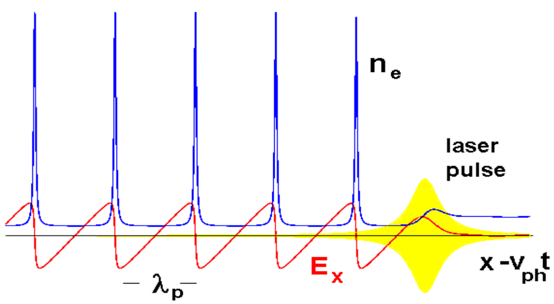
$$\omega = \sqrt{kg}$$

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

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

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

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



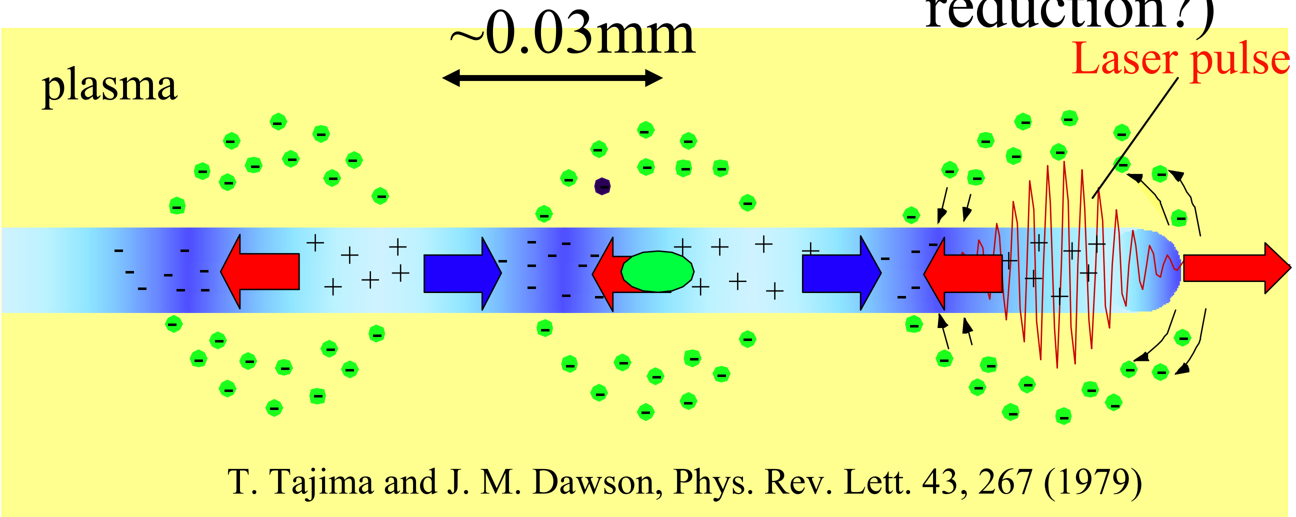
$$\lambda_p = 2\pi / k_p \qquad k_p v_{ph} = \omega_{pe}$$

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

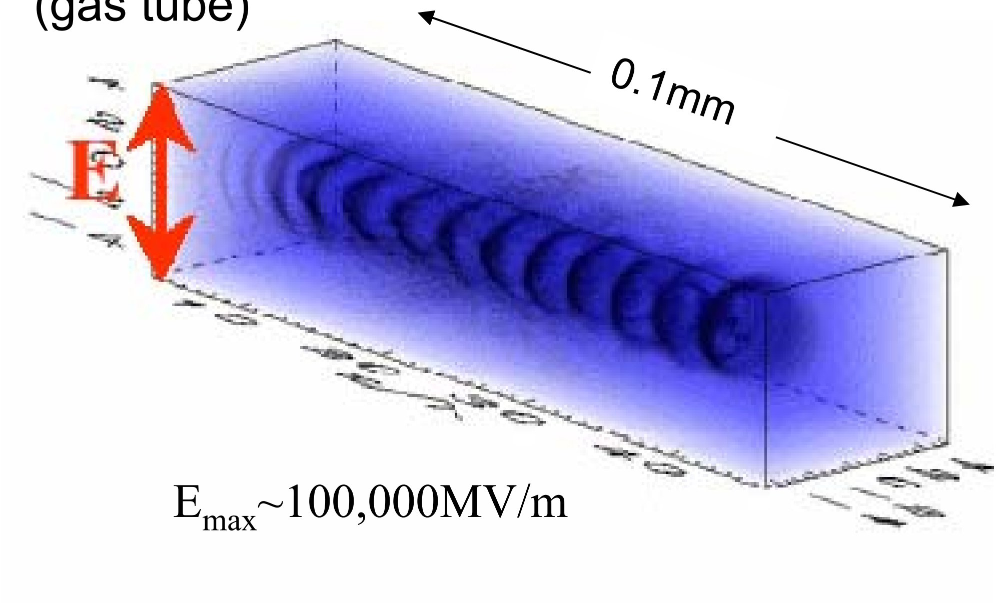
Wave **breaks** at v<c

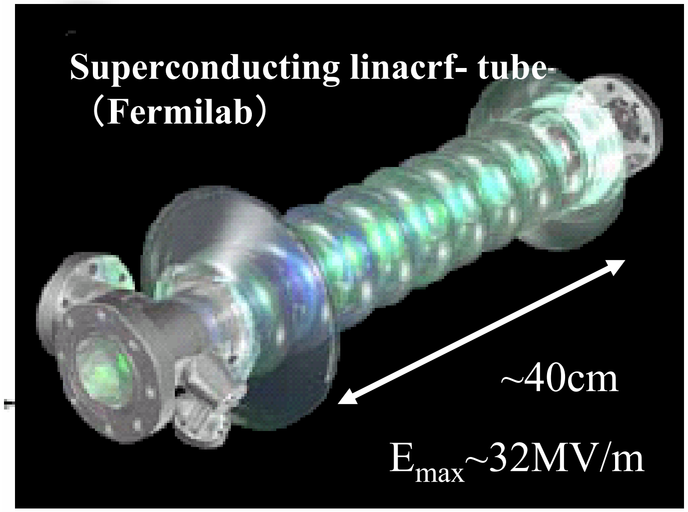
Thousand-fold Compactification

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



(gas tube)





Collective deceleration

High energy particle beams: harder to stop and more hazardous radioactivation ever
Gas (plasma) **collective force** to shortstop the HE beams
- shorter the bunch is, the easier (ideally suited for laser wakefield accelerated beams)
- possible energy recovery
- little radioactivation (good for environment)

an example of 'Toilet Science'

Beam Stopping and its Energy Recovery Using Plasma

February 25, 2008

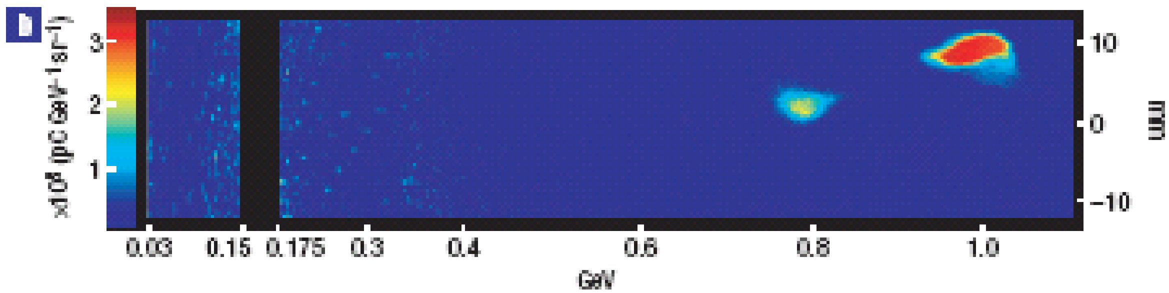
Toshiki Tajima and Alexander W. Chao

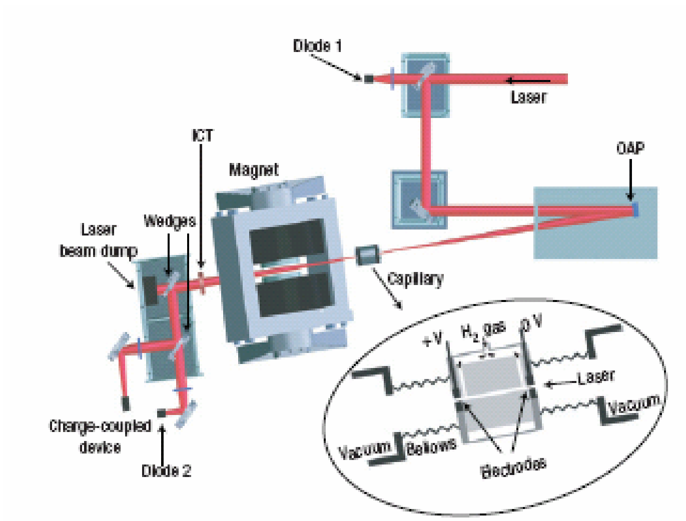
1 Motivations

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.

GeV electron beams from a « centimetre-scale » accelerator





310-μm-diameter channel capillary

P = 40 TW

density 4.3×10^{18} cm^{-3}.

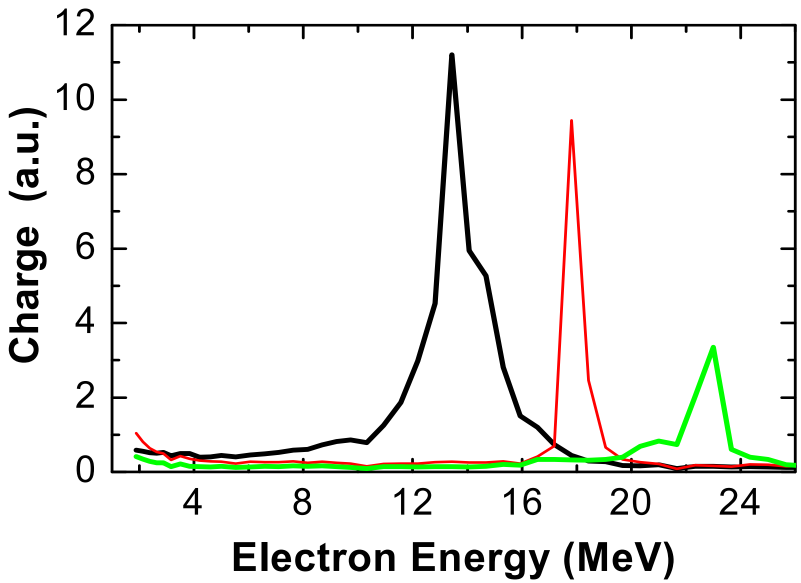
Leemans et al., Nature Physics, september 2006

LOA

MPQ Efforts in Laser Accelerator (1)

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

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

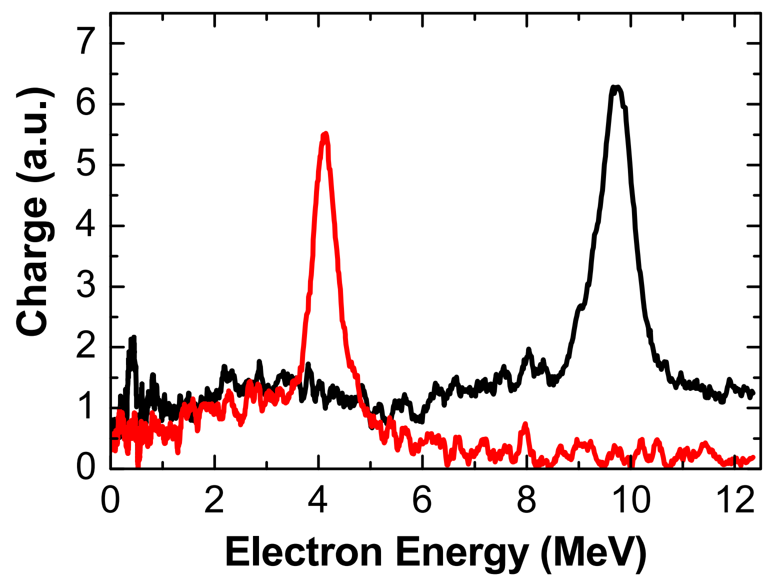


Large electron spectrometer 2 – 400 MeV

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

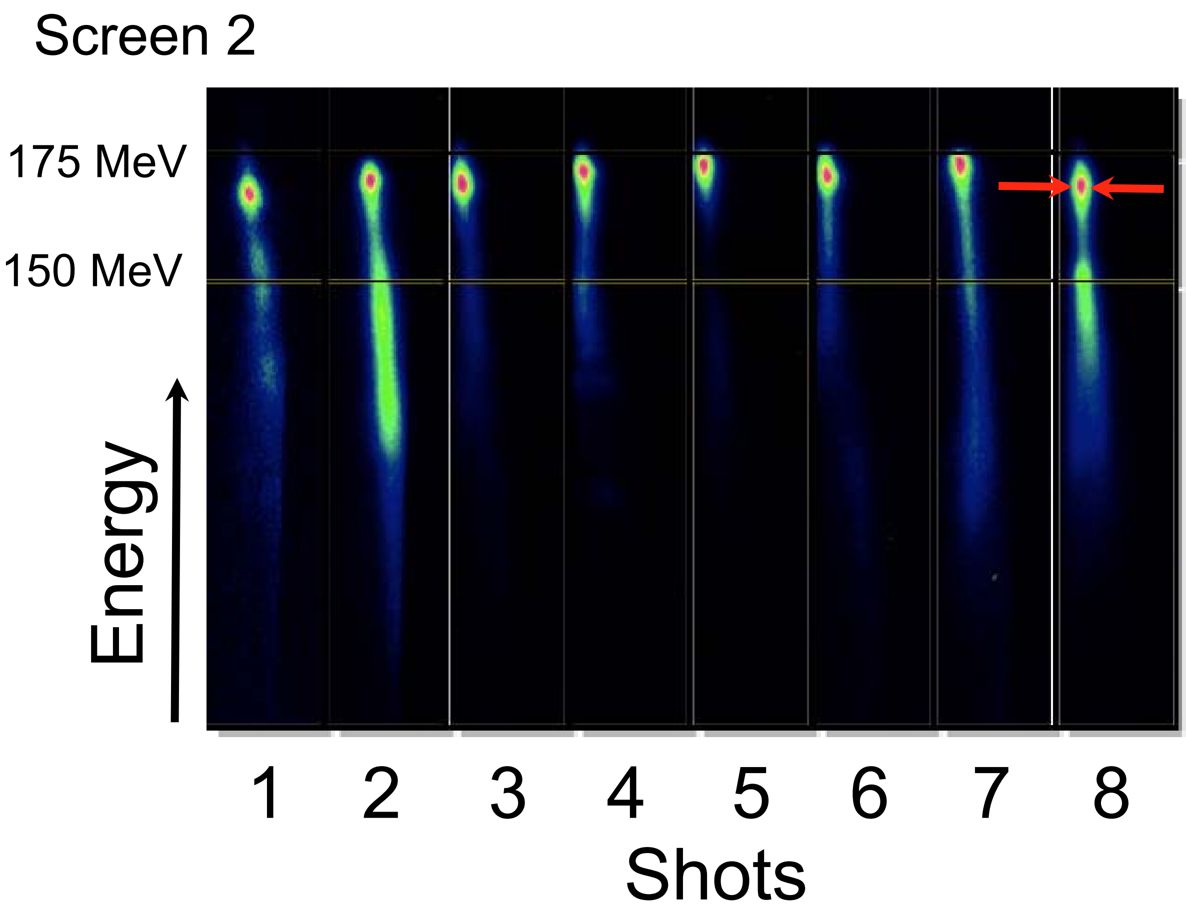
Small electron spectrometer:

- **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 !

Δ E/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

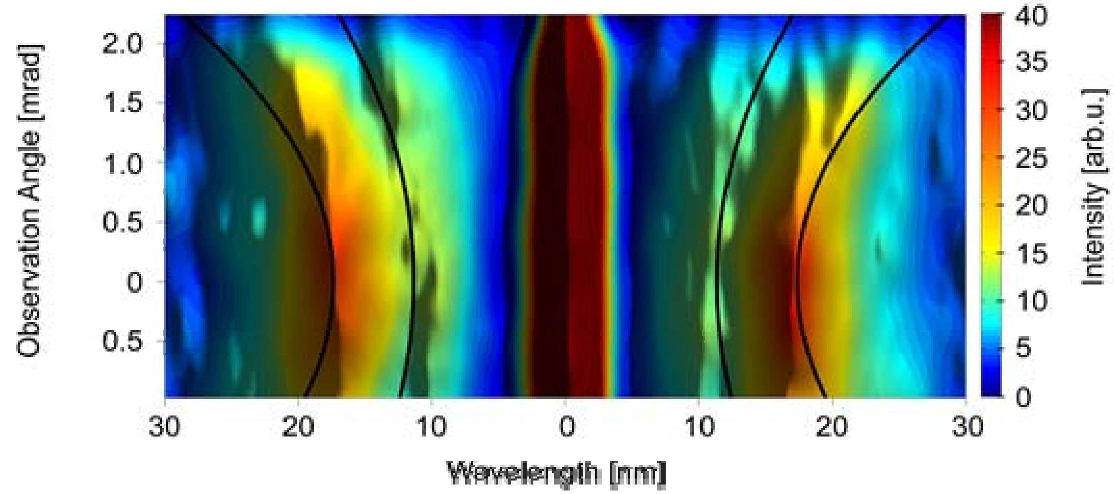
(J. Osterhoff,…S. Karsch, PRL 2008 et al.)

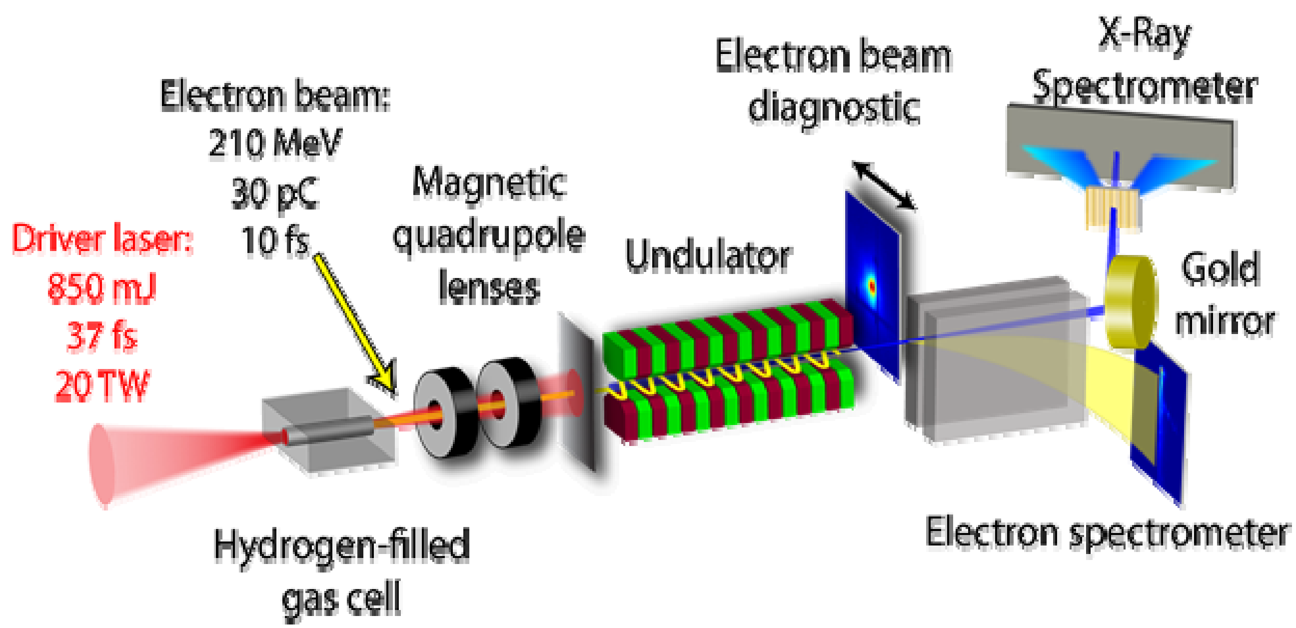
MPQ Laser Acceleration Effort (3)

Laser-driven Soft-X-Ray Undulator Radiation

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

Characteristic undulator radiation spectrum





Intra-Operatory Radiation Therapy (IORT)

LWFA electron sources: technology transferred to co.

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		*Peak curr. > 1.6 KA*
Bunch dur. 4 μs		*Bunch dur. < 1 ps*
Bunch char. 6 nC		*Bunch char. 1.6 nC*
Rep. rate 5 Hz		*Rep. rate 10 Hz*
Mean curr. 30 nA		*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)

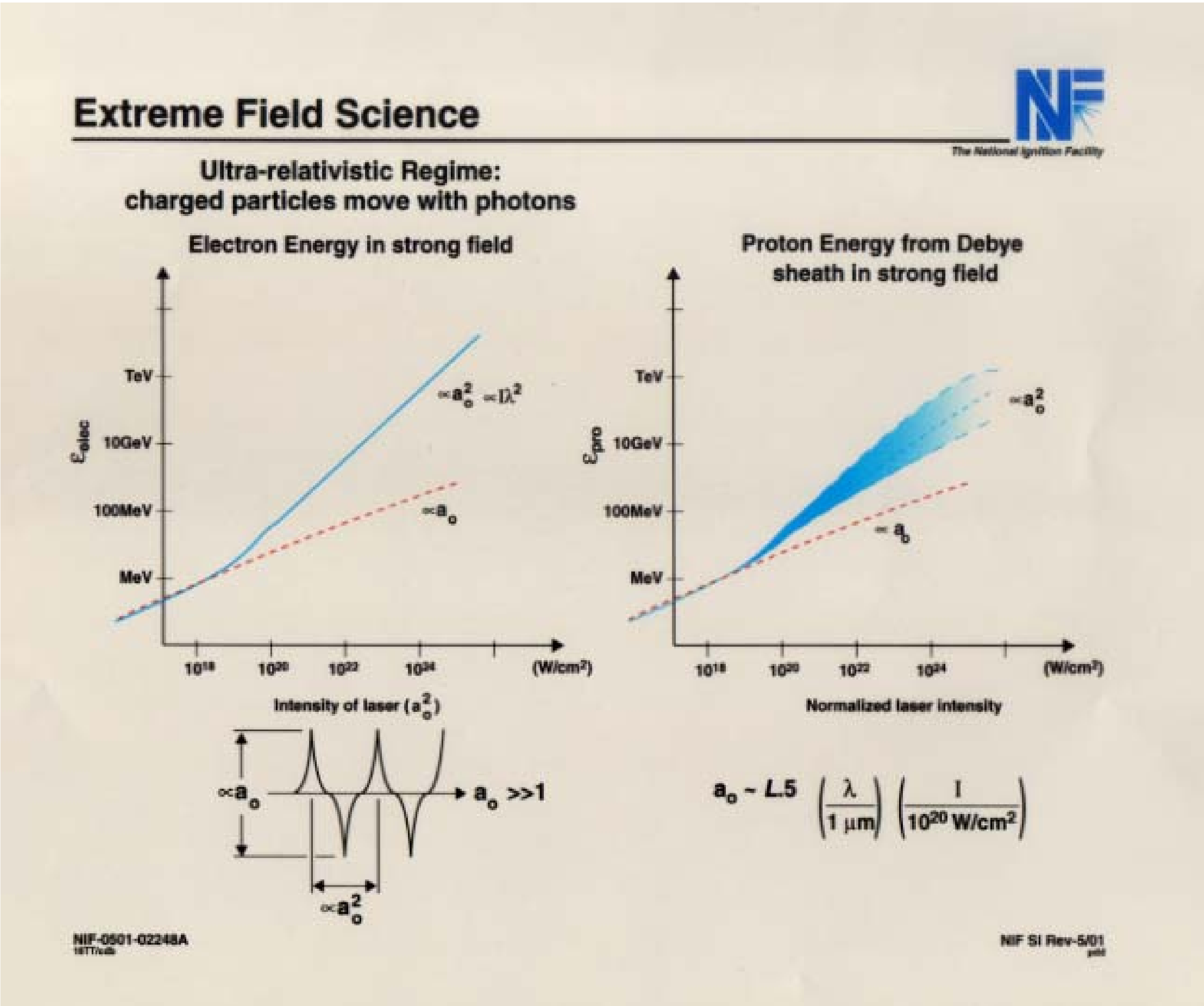
Keys issues of future colliders

(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

Relativity helps acceleration



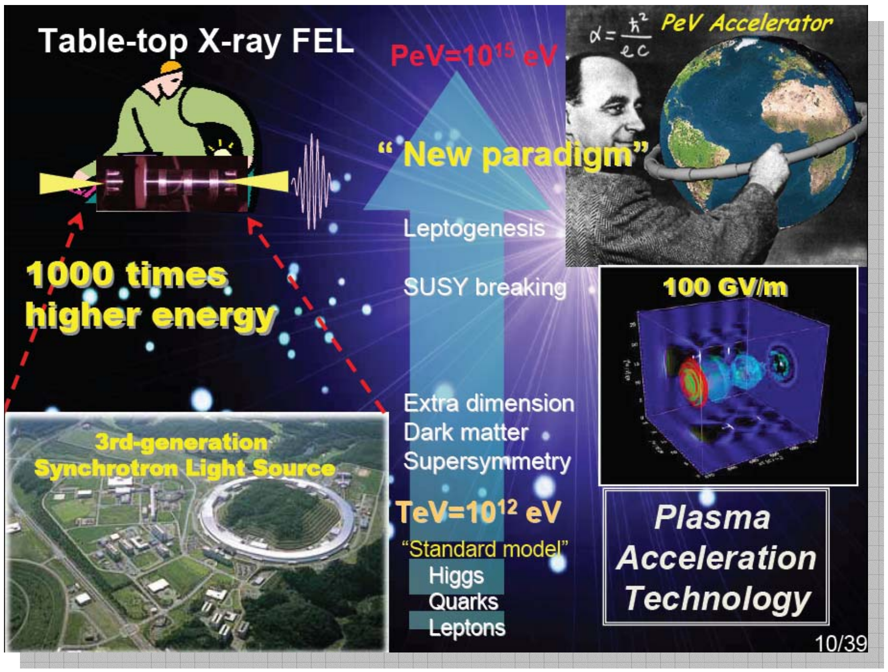
Strong fields:
rectifies laser
to longitudinal
fields

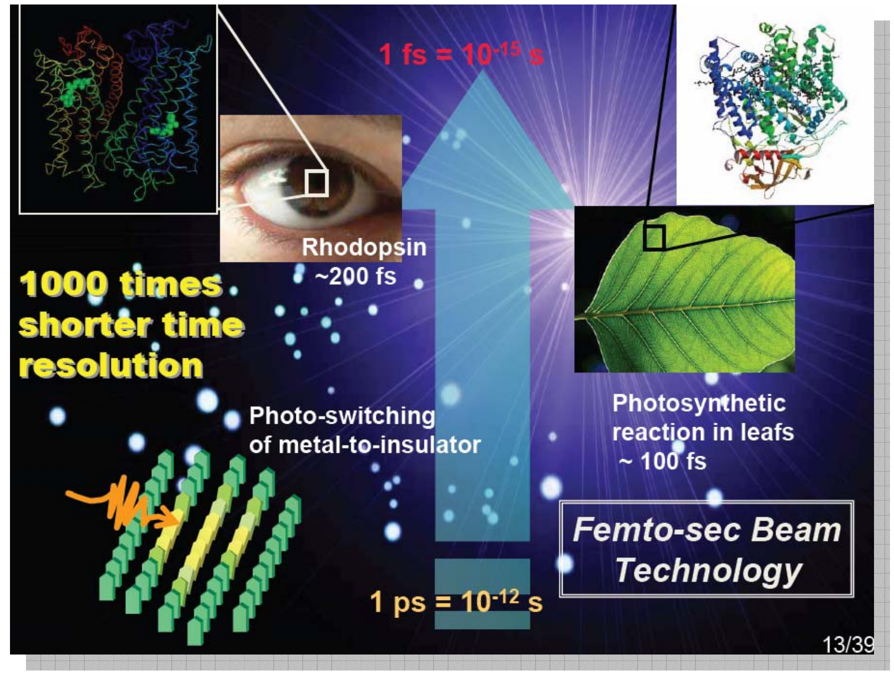
In relativistic regime,
photon x electrons
and even protons
couple stronger.

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

Challenge posed by DG Suzuki

Frontier science driven by advanced accelerator





compact, ultrastrong *a*

atto-, zeptosecond

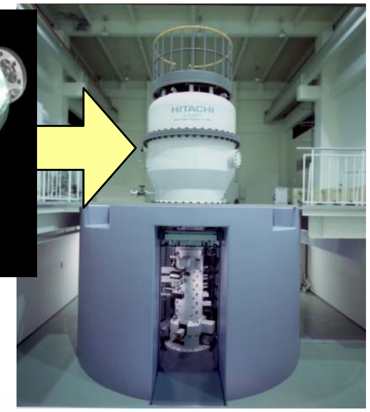
A. Suzuki @KEK(2008)

Can we meet the challenge?

in the memory of E. Fermi and his vision. On Via E. Fermi (5/24/09)

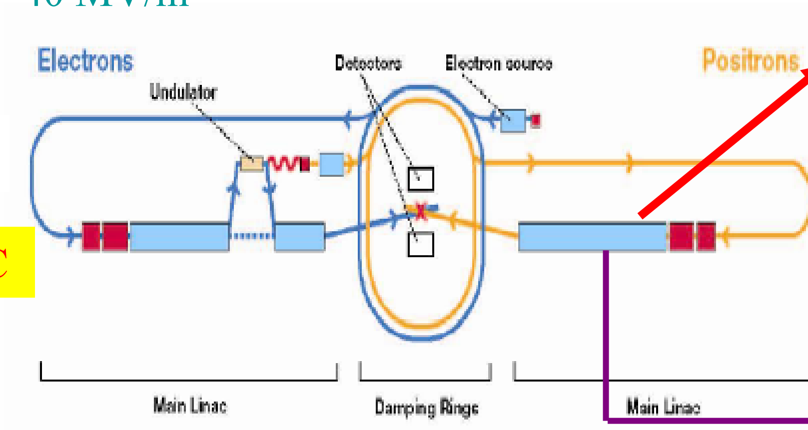
Accelerator

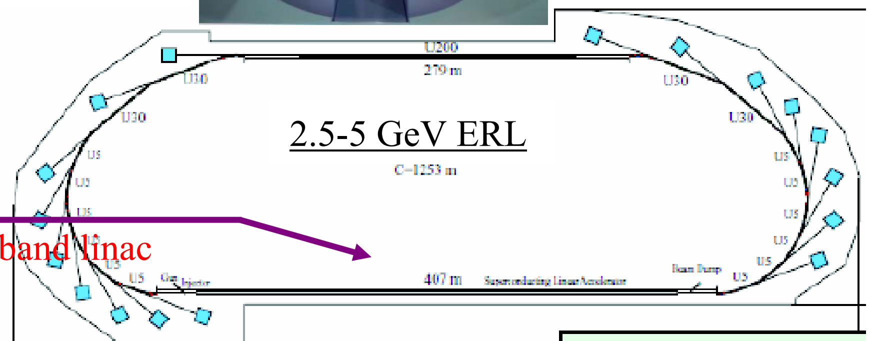
Evolution of Accelerators and their Possibilities （Suzuki,2008)



Ultra-High Voltage STEM with Superconducting RF cavity

E=40 MV/m



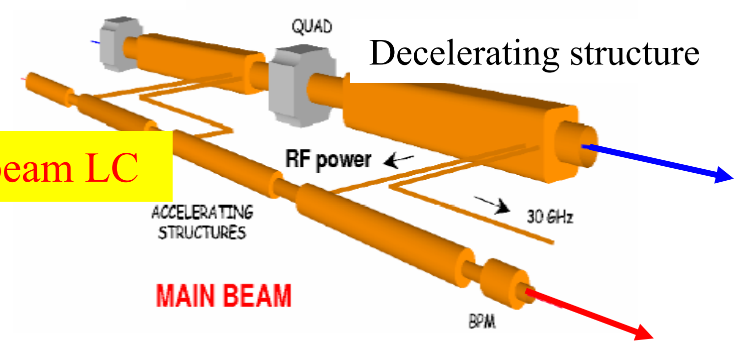


2020s

ILC

Superconducting L-band linac

E=200 MV/m



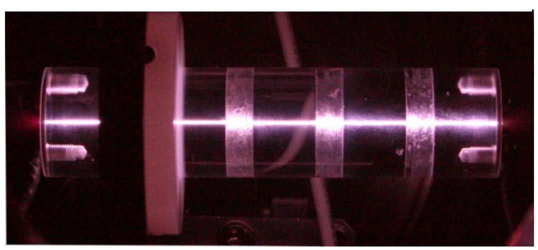
2030s

Two-beam LC

Earth-based space debris radar

E=10 GV/m

10cm-10GeV Plasma Channel Accelerator



2040s

Laser-plasma LC

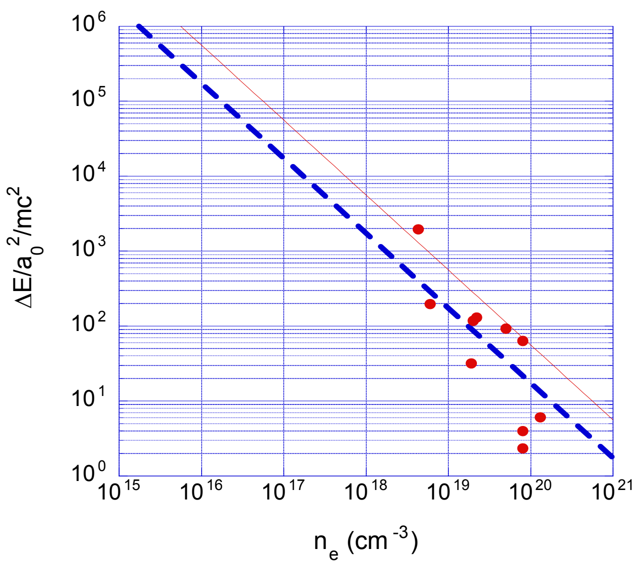
Table-top high energy accelerator

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)

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

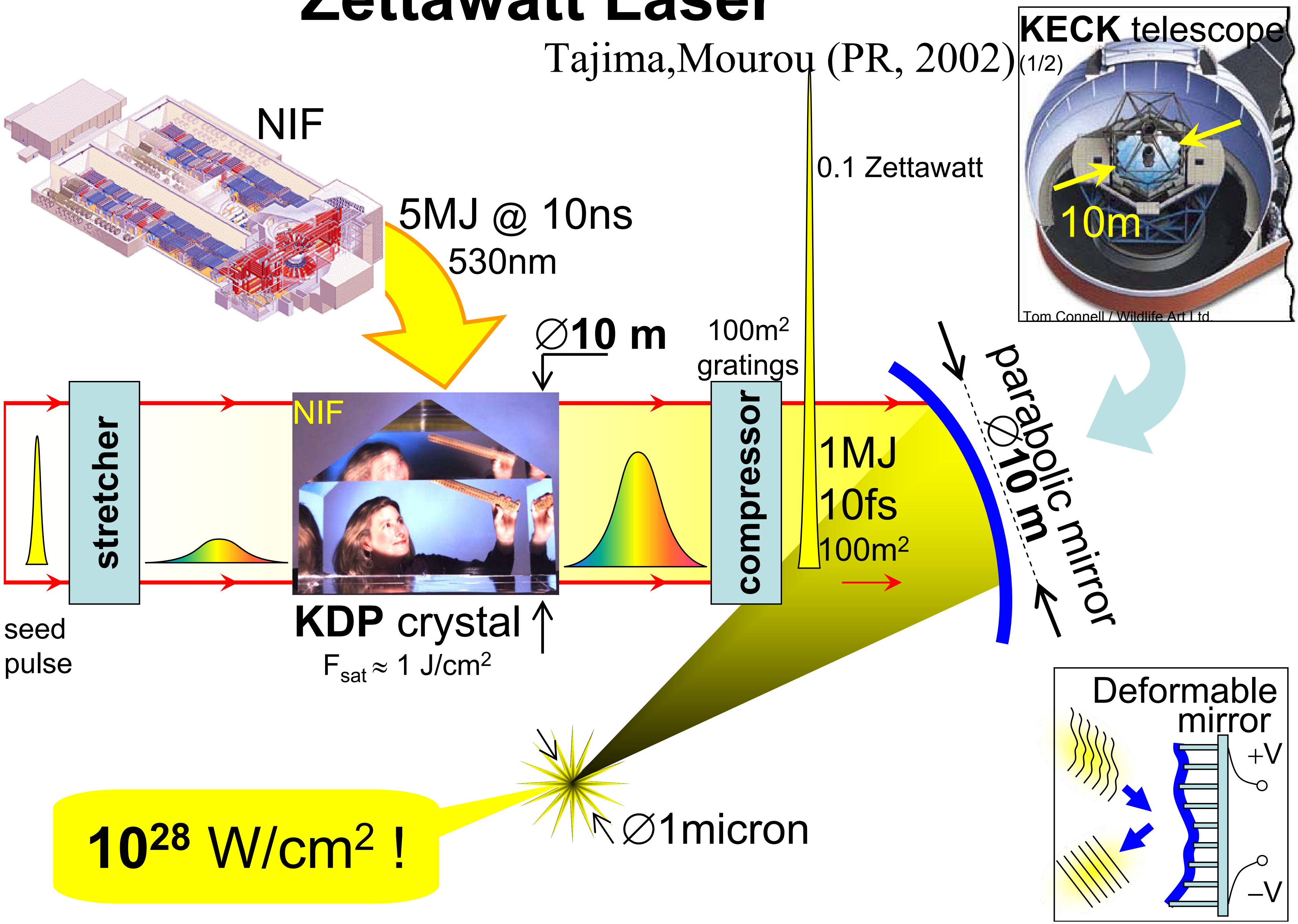


		case I	case II	case III
a_0		10	3.2	1
energy gain	GeV	1000	1000	1000
plasma density	cm^{-3}	$5.7\text{x}10^{16}$	$5.7\text{x}10^{15}$	$5.7\text{x}10^{14}$
acceleration length	m	2.9	29	290
spot radius	μm	32	100	320
peak power	PW	2.2	2.2	2.2
pulse duration	ps	0.23	0.74	2.3
laser pulse energy	kJ	0.5	1.6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

Even 1PeV electrons (and gammas) are possible, albeit with lesser amount
→ exploration of new physics such as the reach of relativity and beyond?
(laser energy of 10MJ, plasma density of 10^{16}/cc)

Zettawatt Laser

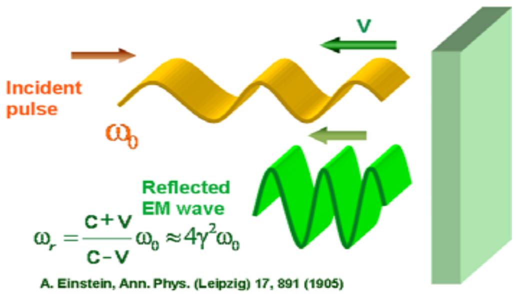
Tajima,Mourou (PR, 2002)

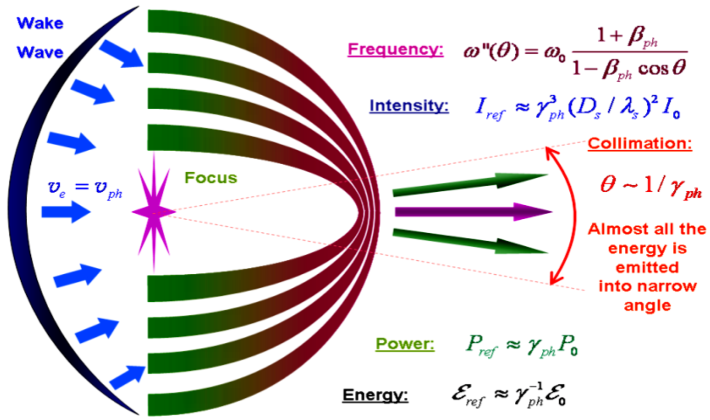


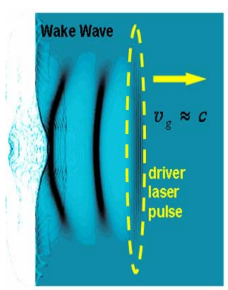
Relativistic Engineering: an example

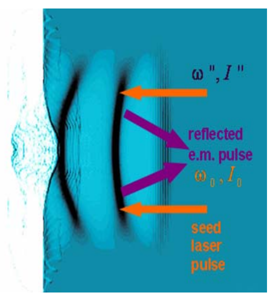
EM Pulse Intensification and Shortening by the Flying Mirror

(Bulanov, Esirkepov, Tajima, 2003)

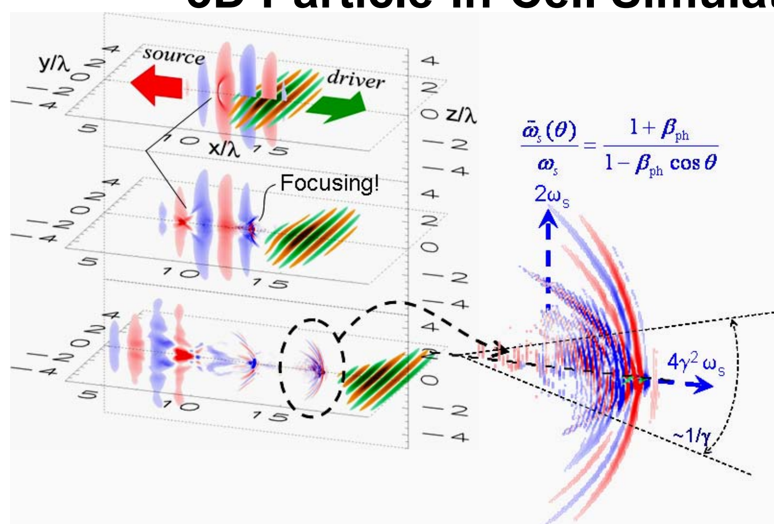




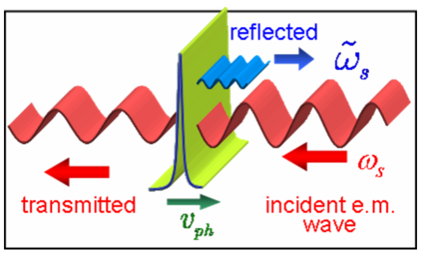




3D Particle-In-Cell Simulation



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



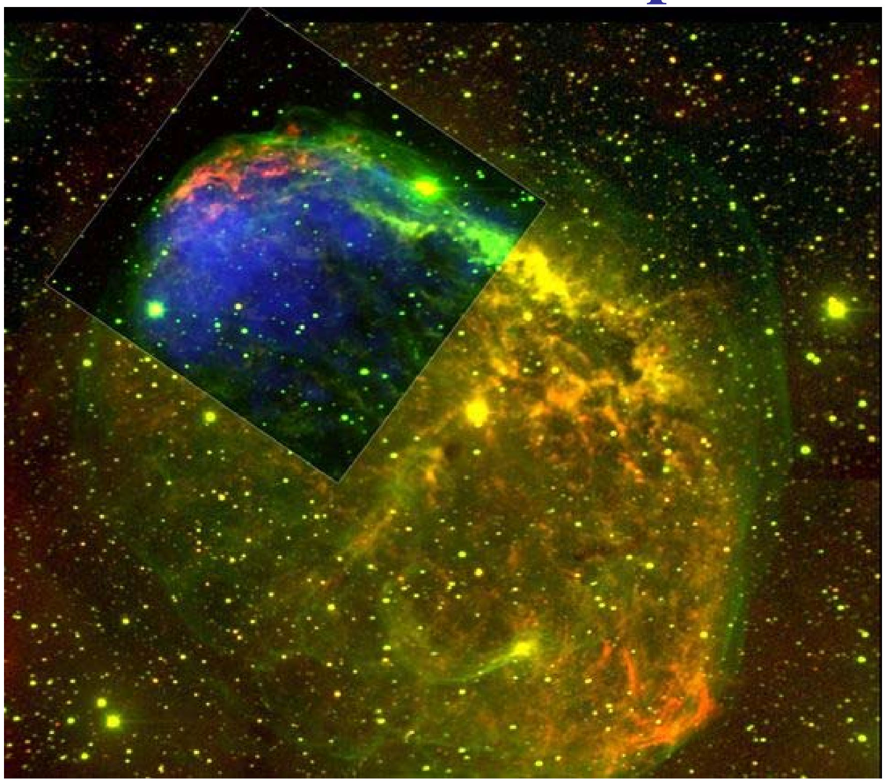
$$\kappa \sim \gamma_{ph}^{-3}$$

A lot ideas for new attosecond pulses

Conclusions

- Collective acceleration: hard birth and long way (electron→ion; laser→electron; laser→ion; laser→photon; electron→electron; ion→electron)
- Leap by many orders ($\geq$ 3) in many respects; equally more demanding by many orders : N^2 vs. N.
- Laser has come around to match the condition set 30 years ago; Still some ways to go to realize the dream
- GeV electrons; 10 GeV soon; 100GeV contemplated; laser collider contemplated; PeV ?
- Societal and other applications: already beginning, soon to flourish (e.g., cancer therapy, radiolysis, beam decelerator, nuclear detection, compact FEL source, compact radiation sources, ultrafast diagnosis,…)

Cosmic acceleration in the wake of intense radiation and particle flows



UHECR:
beyond **Fermi** acceleration,
wakefiled acceleration?

NGC 6888, also known as the Crescent Nebula, is a cosmic bubble of interstellar gas about 25 light-years across. Created by winds from the bright, massive star seen near the center of this composite image, the shocked filaments of gas glowing at optical wavelengths are represented in green and yellowish hues. X-ray image data from a portion of the nebula viewed by the Chandra Observatory is overlaid in blue. Such isolated stellar wind bubbles are not usually seen to produce energetic x-rays, which require heating gas to a million degrees celsius. Still, NGC 6888 seems to have accomplished this as slow moving winds from the central star's initial transition to a red supergiant were overtaken and rammed by faster winds driven by the intense radiation from the star's exposed inner layers.

(based on the slide given
by F.Krausz and J. Meyer-te-Vehn
from Dream Beams Symposium, 2007)

Grazie!

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Laser Electron Accelerator

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

Late-Professor John Dawson

Sergei Bulanov (Kyoto)

Warren Mori
Lu Wei (UCLA)

Luis Silva
Tito Mendonca
(Lisbon)