The Second Blaise Pascal Lecture
Ecole Polytechnique
11/18/09

Laser Electron Acceleration and its Future

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Acknowledgments for Advice and Collaboration: G. Mourou, V. Malka, J. Fuchs, C. Labaune, H. Videaux, P. Mora, 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, W. Leemans, T. Raubenheimer, A. Ogata, A. Caldwell, P. Chen, Y. Kato, M. Downer, M. Tigner, H.C. Wu, K. Kondo, S. Kawanishi, M. Hegelich, P. Shukla, S. Chattopadyay, K. Yokoya、S. Cheshkov

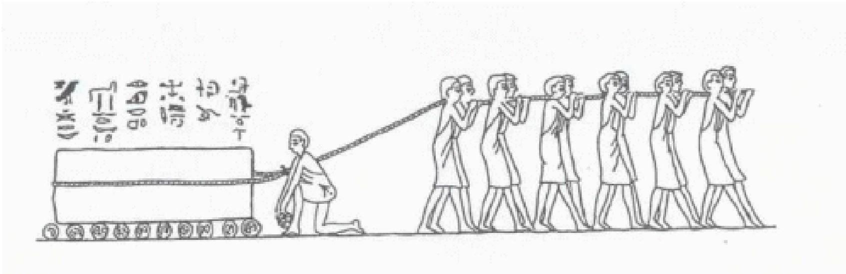
Pascal Lecture Plan

(tentative, need your feedback)

- Oct.22: First Lecture (General) “ Laser Acceleration and High Field Science: 1979-2009”
- Nov.18: Second Lecture “Laser Electron Acceleration and its Future”
- Dec.9: Third Lecture “Laser Ion Acceleration”
- January,2010: “Relativistic Engineering”
- February: “High Field Science”
- March: “Photonuclear Physics”
- April: “Medical Applications”
- ……

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; Ogata,2006)

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

Plasma lens (Chen, 1987; Toncian et al. 2006)

Wakefield : a Collective Phenomenon

All particles in the medium participate = collective phenomenon

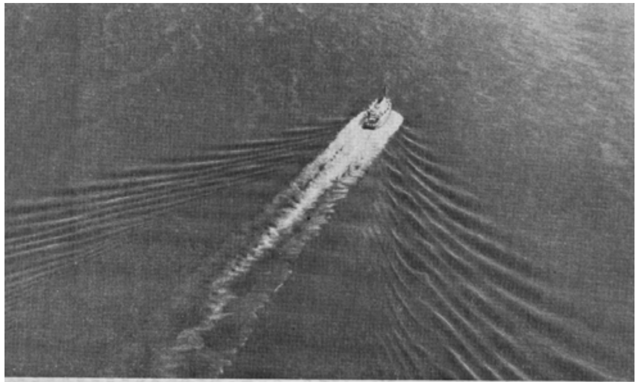
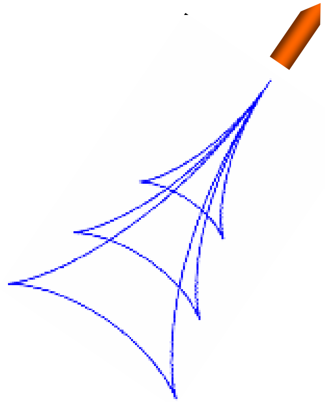


Рис. 71. Наблюдаемая картина корабельных волн. [Любезно предоставлено Aerofilms Ltd.]



Kelvin wake

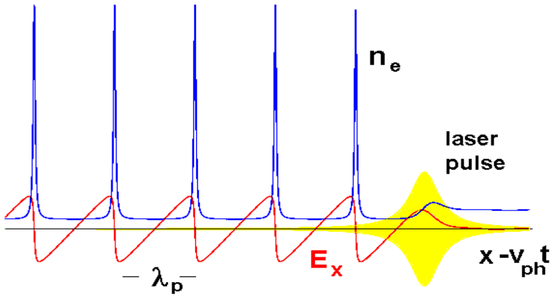
$$\omega = \sqrt{kg}$$

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

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

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

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



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

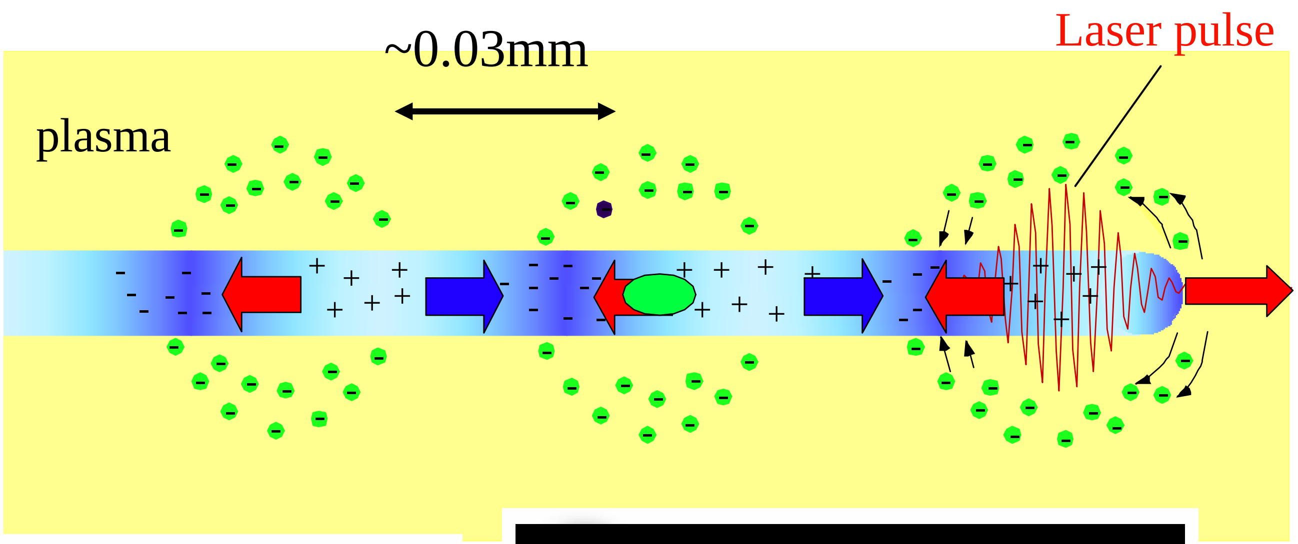
$$\omega_{pe} = \left(4\pi n e^2 / m_e\right)^{1/2}$$

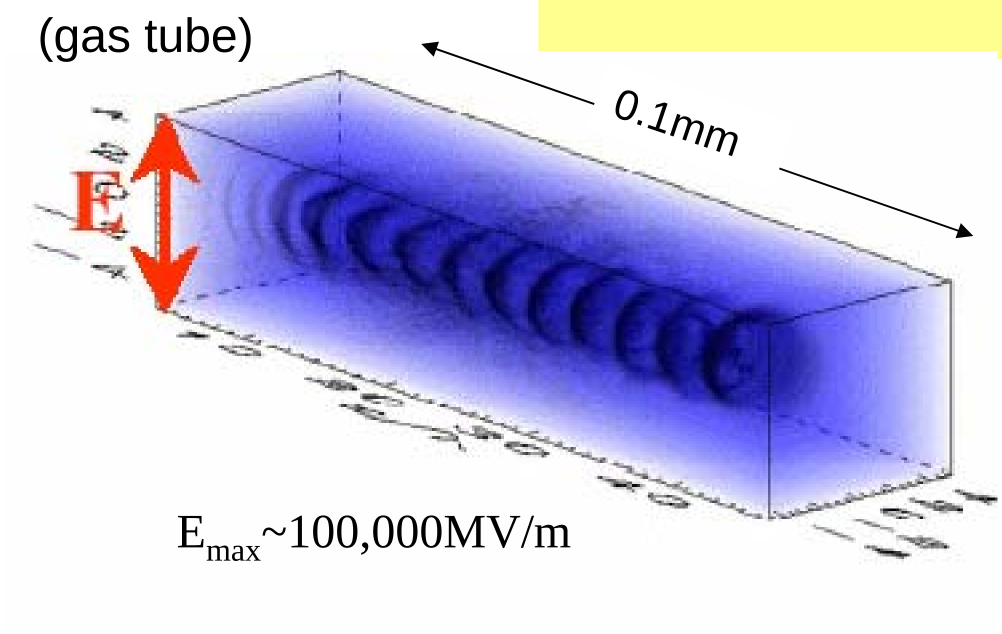
(The density cusps.
Cusp singularity)

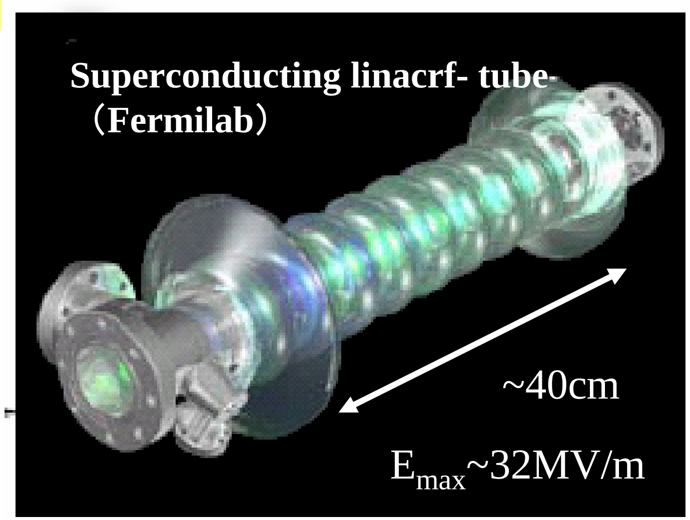
Wave **breaks** at v<c

Thousand-fold Compactification

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



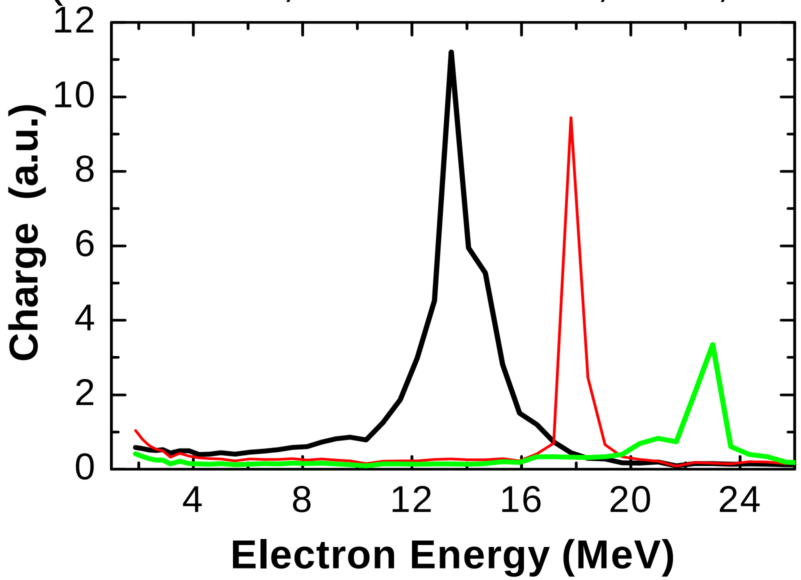




MPQ Laser Acceleration Effort (1)

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

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

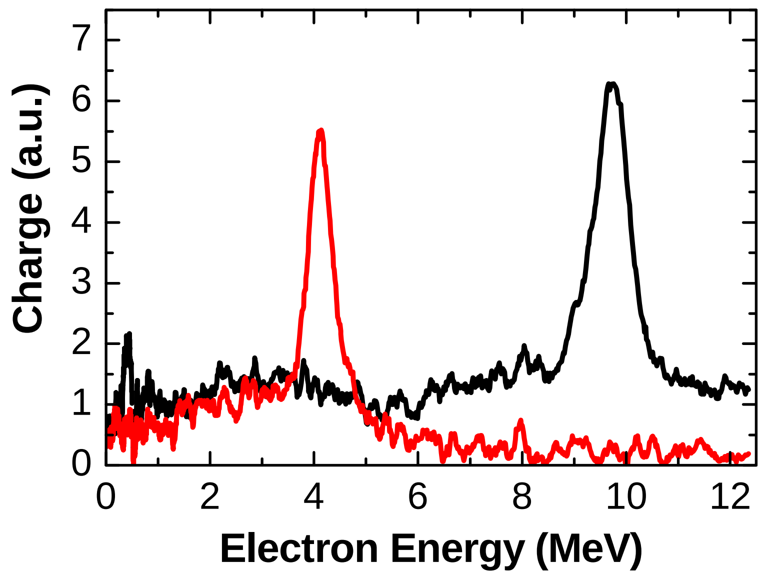


Large electron spectrometer 2 – 400 MeV

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

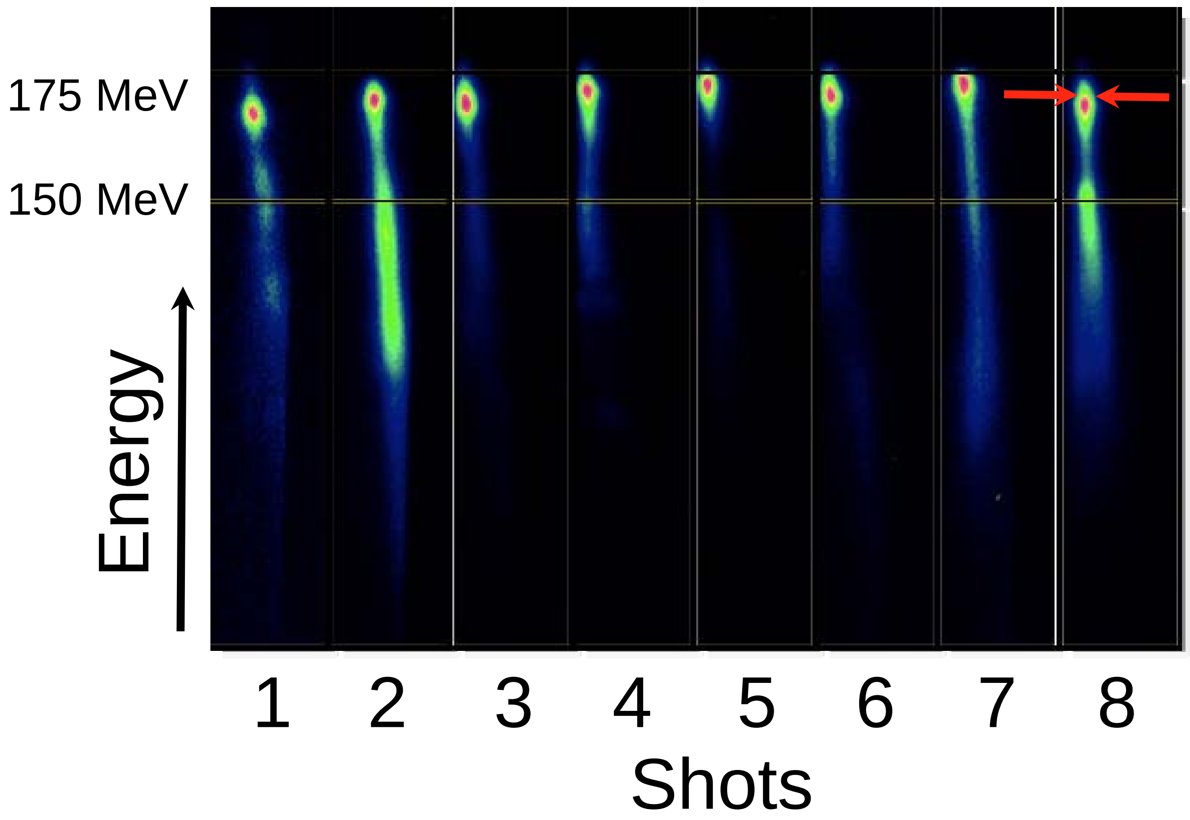
Small electron spectrometer:

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



MPQ Laser Acceleration Effort (2)

<u>Reproducible</u> acceleration conditions



$E \approx 169.7 \pm 2.0$ MeV

1.1% peak energy fluctuation !

$\Delta E/E \approx 1.76 \pm 0.26\%$ 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)

Toward Coherent Control of Wakefields:
Frequency-domain Holography

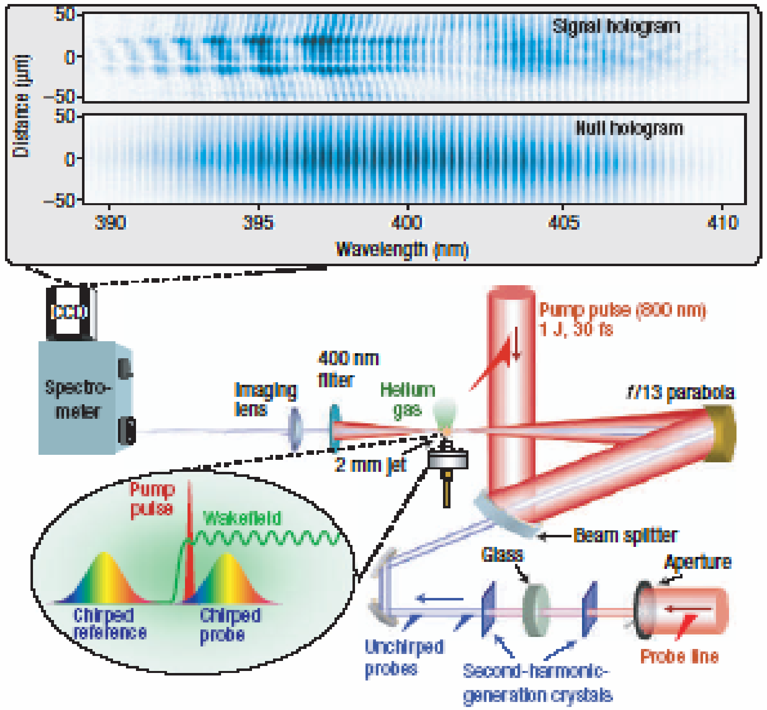


Figure 1 Experimental setup for FDH of laser wakefields. An $f/13$ parabola focuses an intense 30 fs pump pulse into a jet of helium gas, creating a plasma and laser wakefield. Two chirped, frequency-doubled 1 ps pulses, temporally synchronized and co-propagating with the pump, take holographic snapshots of the ionization front and wake. Phase alterations imposed on the trailing probe by these plasma disturbances are encoded in an FD interferogram, shown at the top with (upper) and without (lower) a pump, recorded by a charge-coupled-device camera at the detection plane of an imaging spectrometer. The wake structure is recovered by Fourier-transforming this data.

(Matlis et al.,2006)

M.Downer (UTexas)

Snapshot of wakefields:
phase sensitive instantaneous single-shot detection

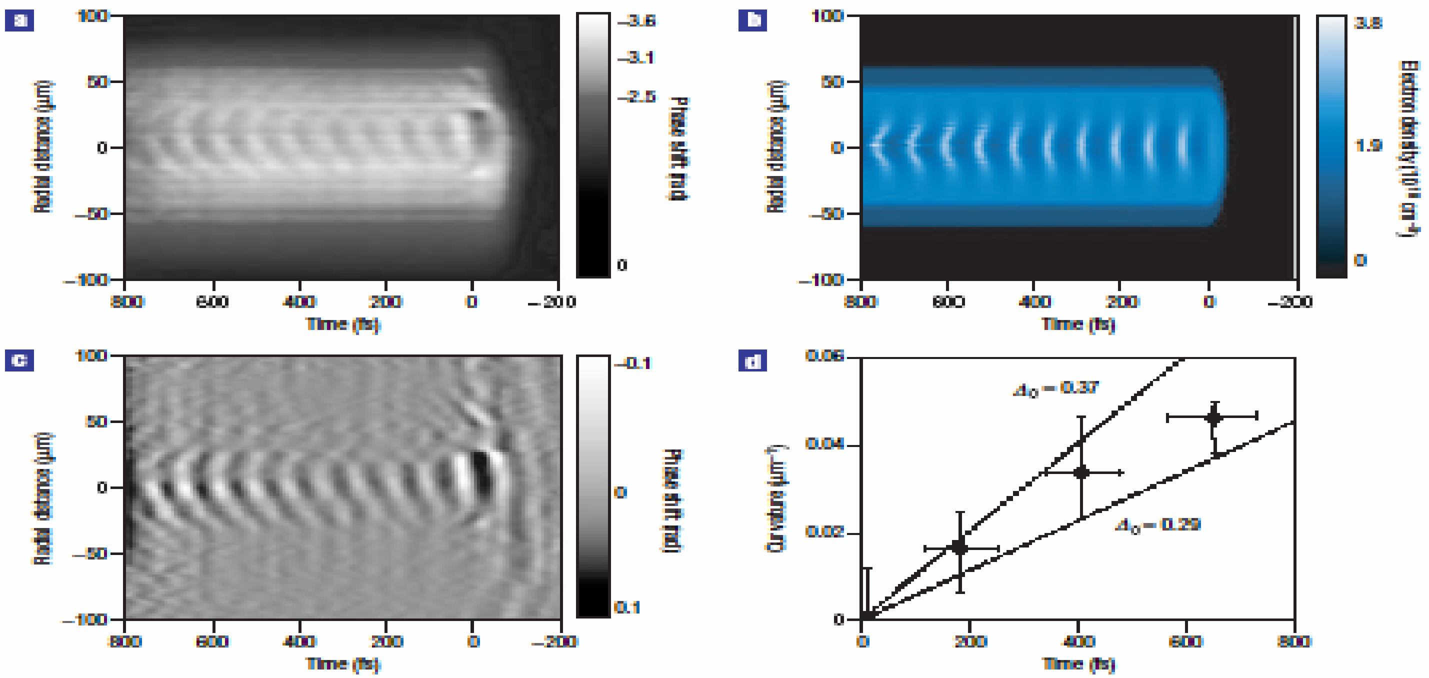


Figure 3 Strongly driven wake with curved wavefronts. **a**, Probe phase profile $\Delta\phi_{pr}(r,\xi)$ for an ~30 TW pump, $\bar{n}_e^{max} = 2.2 \times 10^{18}$ cm^{-3} in the He^{2+} region. **b**, Simulated density profile $n_e(r,\xi)$ near the jet centre. **c**, Same data as in **a**, with the background $\bar{n}_e$ subtracted to highlight the wake. **d**, Evolution of the reciprocal radius of wavefront curvature behind the pump (data points), compared with calculated evolution (dashed lines) for indicated wake potential amplitudes. Each data point (except at $\xi = 0$) averages over three adjacent periods. The horizontal error bars extend over the three periods averaged, and the vertical error bars extend over the range of fitted curvature values averaged.

(Matlis et al, 2006)

Phase and Phase Language is Critical

temporal phase expansion (stacking of fields):

$$\phi(t) = \phi_o + \frac{\partial \phi}{\partial t}(\Delta t) + \frac{1}{2}\frac{\partial^2 \phi}{\partial t^2}(\Delta t)^2 + \ldots = \phi_o - \omega_o \Delta t - \frac{1}{2} b (\Delta t)^2 - \ldots$$

$$\Rightarrow \omega_o \equiv -\frac{\partial \phi}{\partial t} \equiv ref.\ freq. \qquad b \equiv -\frac{\partial^2 \phi}{\partial t^2} = linear\_chirp\_parameter$$

$$\Rightarrow \omega(t) \equiv \omega_o + b(\Delta t) + \ldots$$

(chirp, b means temporal dependence of frequency))

spectral phase expansion (stacking of spectral components):

$$\vartheta(\omega) = \vartheta_o + \frac{\partial \vartheta}{\partial \omega}(\Delta\omega) + \frac{1}{2}\frac{\partial^2 \vartheta}{\partial \omega^2}(\Delta\omega)^2 + \ldots; \qquad \vartheta \equiv z\beta$$

$$\Rightarrow T_o \equiv \frac{\partial \vartheta}{\partial \omega} \equiv ref.group\_delay \quad \& \quad \frac{\partial^2 \vartheta}{\partial \omega^2}(\Delta\omega) \equiv group\_delay\_dispersion = GDD$$

$$\Rightarrow T = T_o + \frac{\partial^2 \vartheta}{\partial \omega^2}(\Delta\omega) + \ldots = T_o + GDD + \ldots$$

(GDD means spectral dependence of time delay)

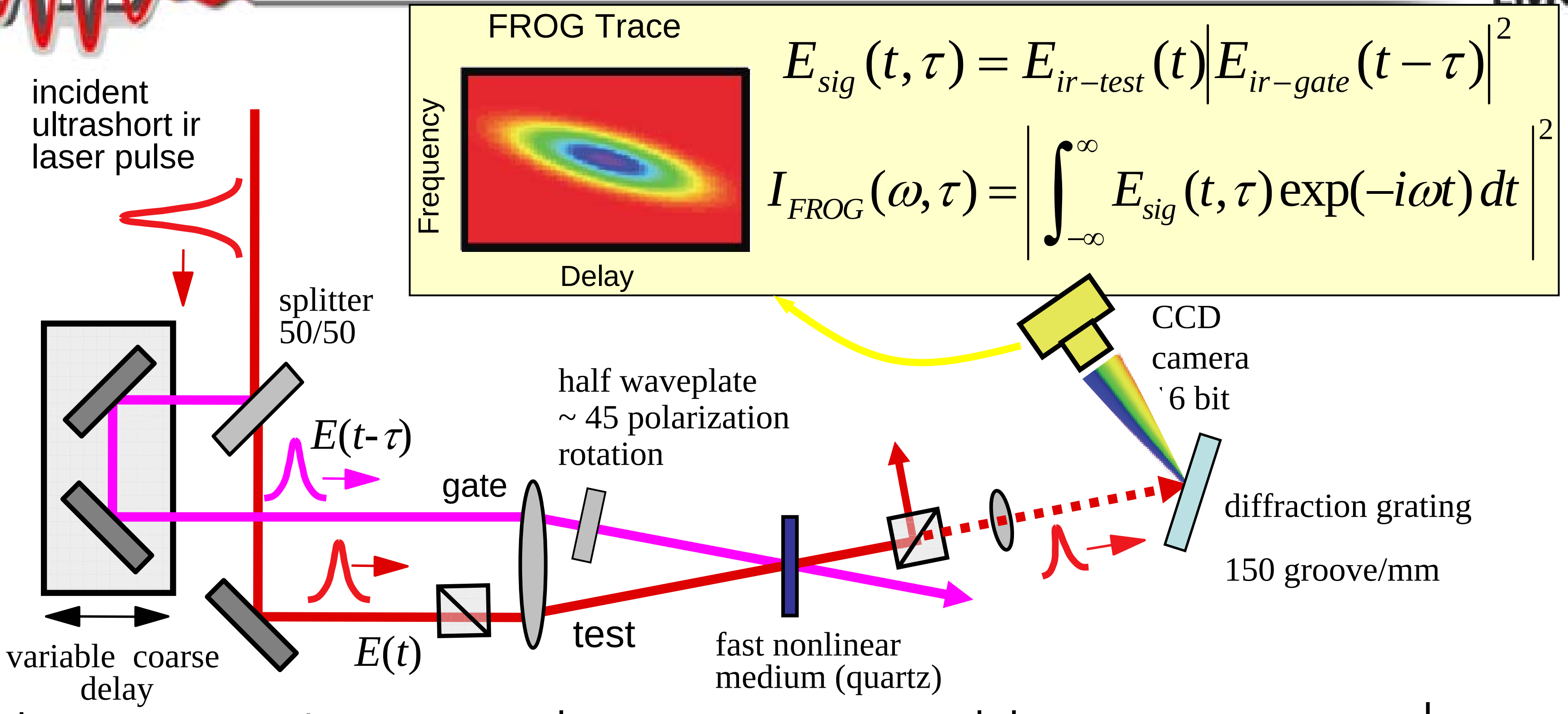
(P.Bolton)

in terms of group velocity →

$$T_o \equiv z\frac{\partial \beta}{\partial \omega} \quad where \quad \frac{\partial \beta}{\partial \omega} \equiv \frac{1}{v_{group}} \ \& \quad GDD \equiv z\frac{\partial^2 \beta}{\partial \omega^2}(\Delta\omega)$$

$$where \quad GVD \propto \frac{\partial^2 \beta}{\partial \omega^2} = -\frac{1}{v_{group}^2}\frac{\partial v_{group}}{\partial \omega}$$

Polarization-Gated (PG) FROG: Single Pulse Dynamics a Finesse Approach



gate beam generation

the pulse to be measured is split into a replica pair and one replica pulse (the 'gate') is delayed with a polarization rotation ~ 45˚

Kerr effect polarization gating

the two pulses are coincident
In an isotropic medium, Kerr-induced birefringence by the gate pulse yields an autocorrelation

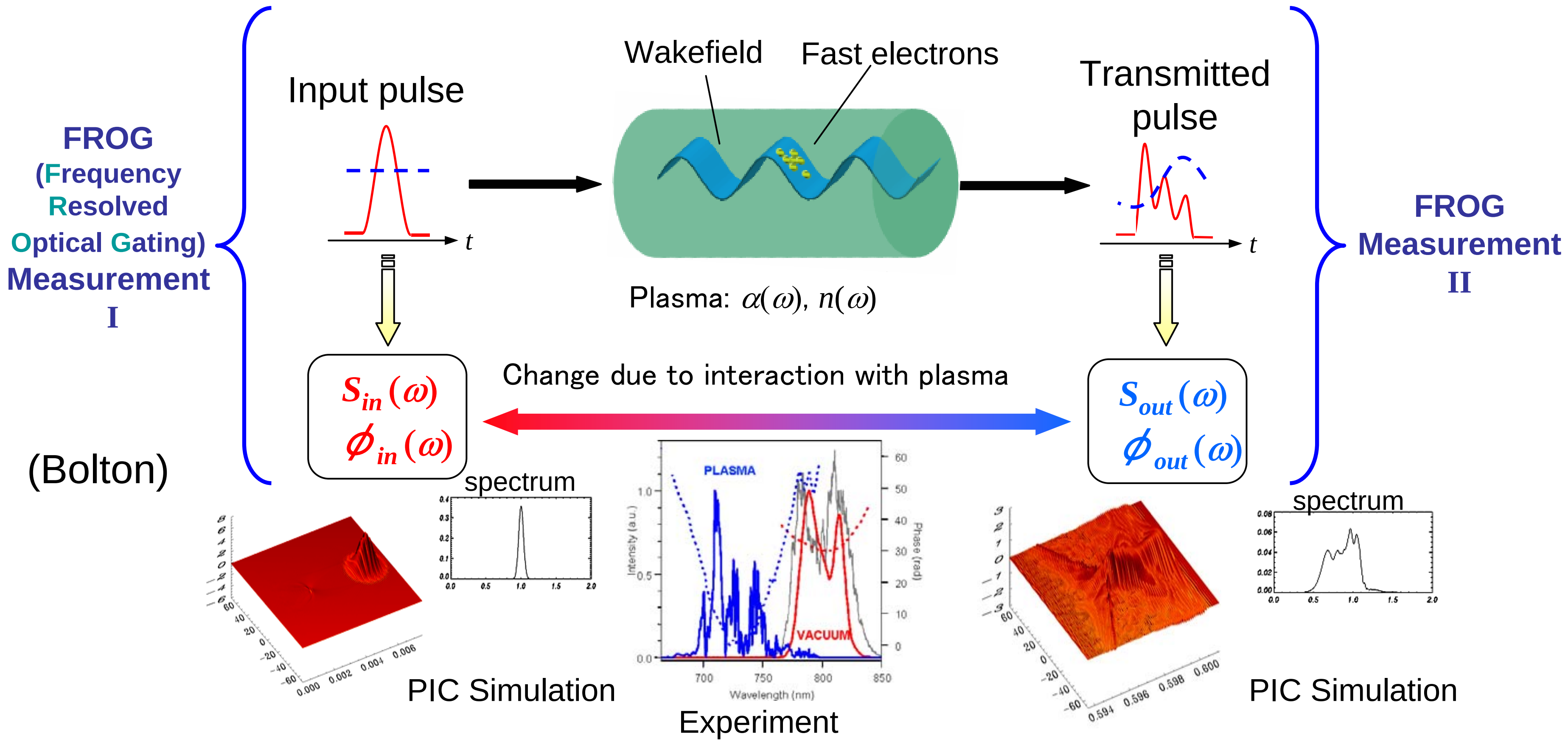
imaging and spectral dispersion

grating provides spectral resolution for a 2D FROG trace

P.Bolton + Y. Fukuda

Single Shot Phase-Preserved fs Metrology of the Laser system and Laser-Plasma Interaction

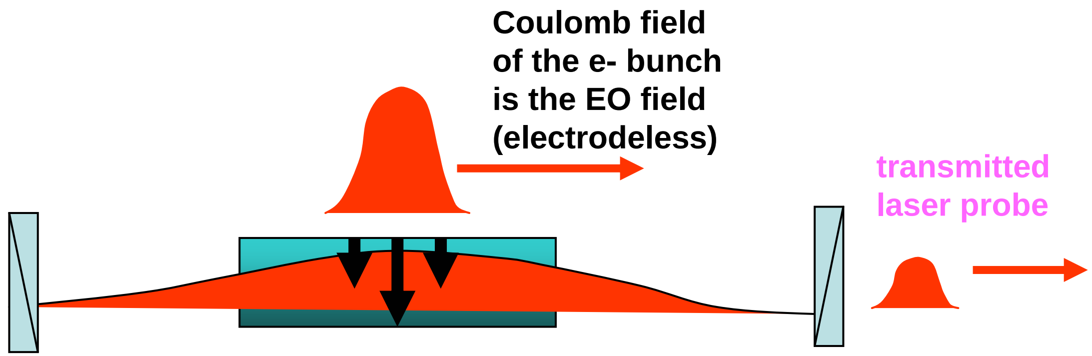
Laser pulse spectrum modified in plasma;
Dynamical information of ultrafast interaction 'encoded' onto the laser waveform
Extract spectrum and phase of the transmitted laser pulse.
Feed back info to laser by simple feedback, neural net, genetic algorithm,….



Another Finesse Single-shot Diagnosis: Electro-Optical Method

- can be noninvasive
- important for future accelerators
- all-optical:
  - optical controls in ideal laser setting
  - can apply optics sophistication
- jitterless (probe synchronized with laser driver)
- ultrafast – single bunch profile (~ 100 fsec)
- high repetition rate – multi-bunch timing jitter
- potential for feedback and beam (facility) control

<u>Electrodeless Case</u>

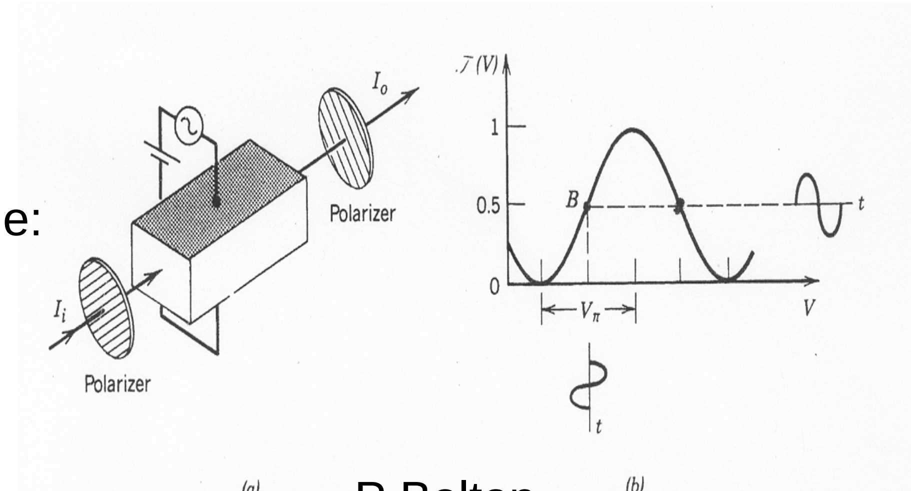


overlapping (coincident) portion of the laser probe pulse experiences the phase retardation in transit across the crystal

Use reference ‘pi’ field instead of ‘pi’ voltage:

$$transmission, T(E) \propto \sin^2\left(\frac{\varphi_o}{2} - \frac{\pi}{2}\frac{E}{E_\pi}\right)$$

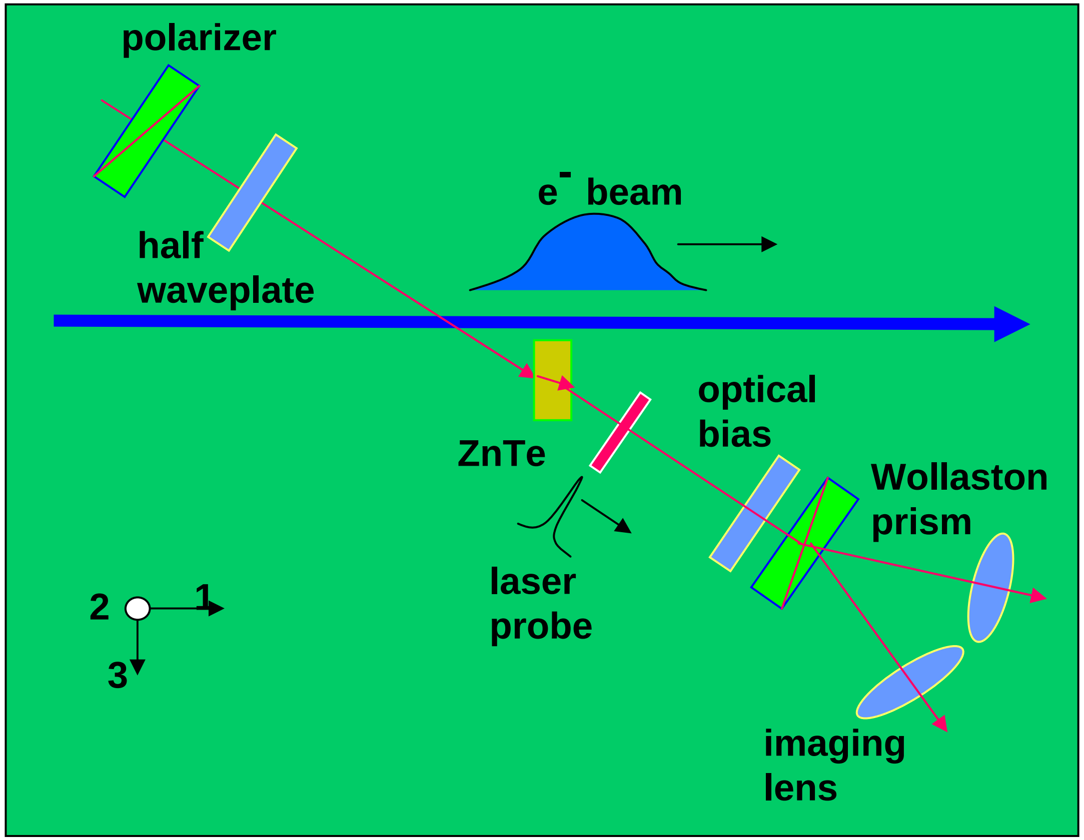
$$\Rightarrow want\_low\_E_\pi$$



P.Bolton

EO Example: Spatial-Temporal Transcription with Pockels Effect

- require ultrashort probe and thinnest possible EO crystal
- optional horizontal line focus of probe at crystal



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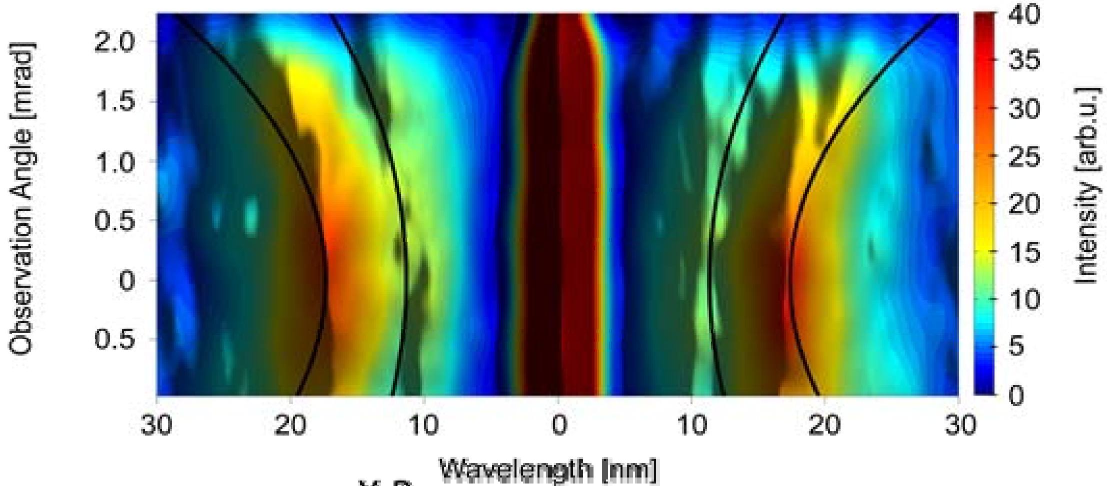
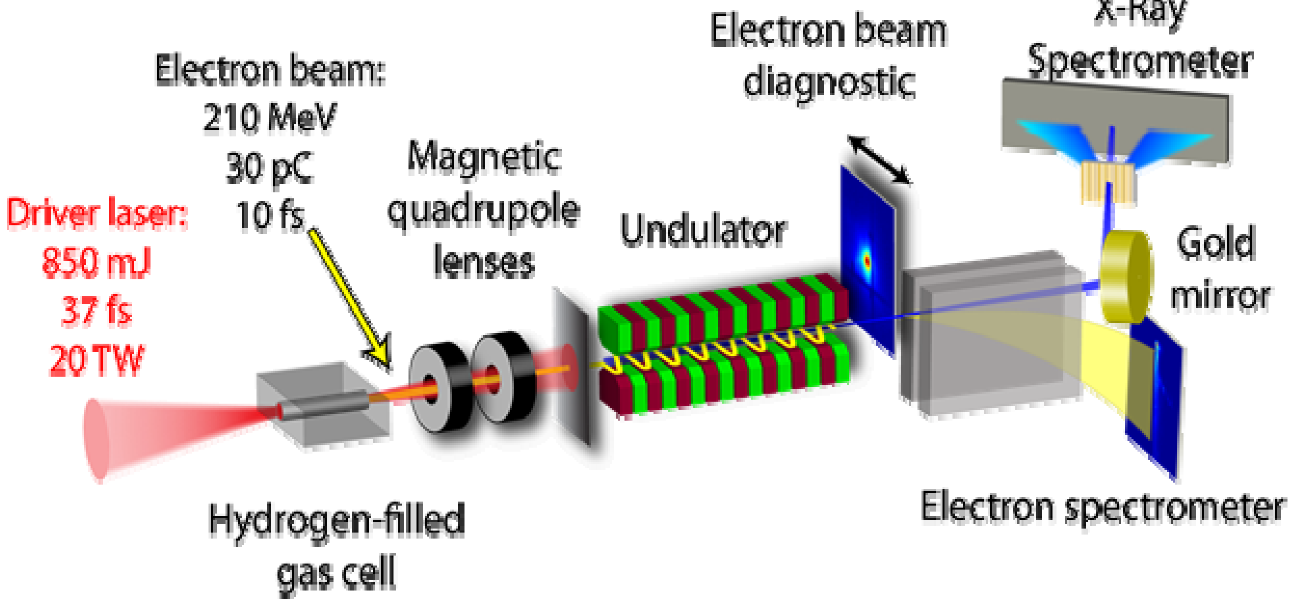
MPQ Laser Acceleration Effort (3)

Laser-driven Soft-X-Ray Undulator Radiation

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

Characteristic undulator radiation spectrum





Intra-Operative 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		*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 :INFN)

Collective deceleration

Beam dump: <u>harder to stop</u> and more <u>hazardous radioactivation</u>

↓

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 <u>downstream</u>

  (as opposed to 'Kitchen Science' of 20th C that tends <u>upstream</u>)

- possible energy recovery

Tajima and Chao, (2008 applied for patent)
H. C. Wu et al. (2009)

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.

High energy beam dump: a nasty business

Stopping range

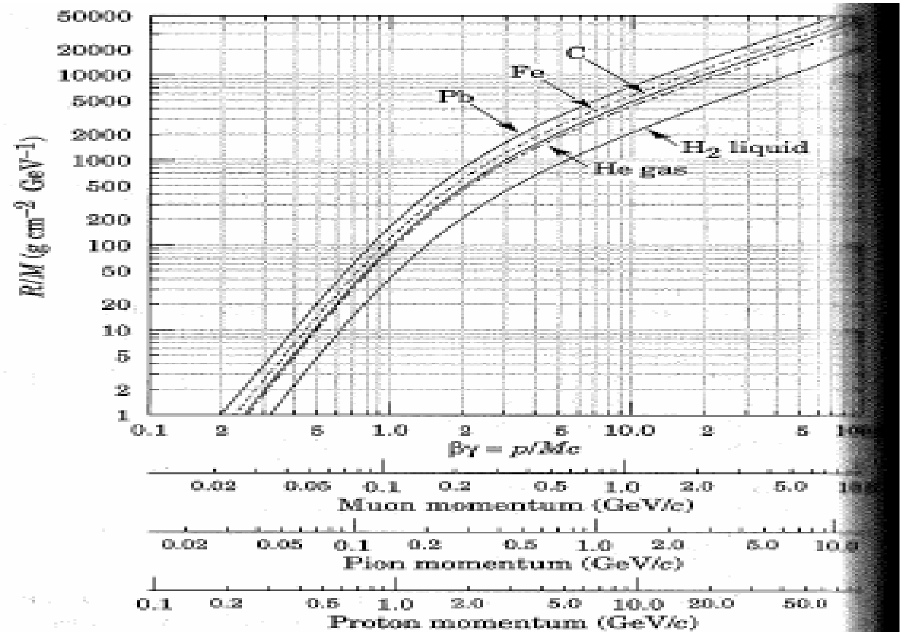


Figure 26.4: Range of heavy charged particles in liquid (bubble chamber) hydrogen, helium gas, carbon, iron, and lead. For example: For a K^+ whose momentum is 700 MeV/c, $\beta\gamma = 1.42$. For lead we read $R/M \approx 396$, and so the range is 195 g cm^{-2}.

$$T_{max} = \frac{2m_ec^2\beta^2\gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$$

In older references [3,4] the "low-energy" approximation $T_{max} = 2m_ec^2\beta^2\gamma^2$, valid for $2\gamma m_e/M \ll 1$, is often implicit. For a pion in copper, the error thus introduced into dE/dx is greater than 6% at 100 GeV. The correct expression should be used.

Radiation length of
high energy charged particles

(1) <u>Stopping length</u> increases rapidly as energy ↑

(2) <u>Amount of radiation</u> increases rapidly as energy ↑

(3) Fraction of <u>useful interaction</u> decreases rapidly as energy ↑

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)

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

Wakefield <u>De</u>celerator: attention to the downstream

Can we employ collective force to tackle this problem?

Given the TeV-beam, its decelerating field in the plasma is $E_{\rm decel}$, which is on the order of the Tajima-Dawson field,

$$E_{\rm decel} = \frac{m_e \omega_p c}{e} \tag{3}$$

or numerically,

$$E_{\rm decel} = \sqrt{\frac{n_p}{n_{14}}}\ \mathrm{GeV/m} \tag{4}$$

Here n_{14} is the density of 10^{14} cm^{-3}. If we choose $n_p = 10^{14}$ cm^{-3}, the beam particles lose 1 GeV per meter in the plasma. To stop a 1 TeV beam in 100 m would require a plasma with $n_p = 10^{16}$ cm^{-3}. The corresponding plasma frequency then becomes 900 GHz.

We now estimate the radial extent of the plasma oscillation driven by the intense electron beam with N electrons. Most of the plasma oscillation energy will be within this radial distance to the plasma column axis. We assume a blow-out regime in which all plasma electrons are driven out radially by the beam while the plasma ions stay stationary providing the Coulomb force drawing the plasma electrons back toward the column axis. Consider a plasma electron initially at rest at radial position r_0. After the driving electron bunch passes by, this plasma electron receives a radial kick yielding an initial radial velocity

$$\dot{r}_0 = \frac{2Ne^2}{m_e c r_0}\left(1 - e^{-r_0^2/2\sigma_r^2}\right) \tag{5}$$

where σ_r is the rms radial size of the driving electron beam. We have assumed that the driving beam has a circular transverse cross-section, and that the motion of the plasma electron is nonrelativistic. Maximum kick occurs when $r_0 \approx 1.6\sigma_r$, in which case, the initial velocity reads

$$\dot{r}_0 \approx \frac{0.9\,Ne^2}{m_e c \sigma_r} \tag{6}$$

(Tajima and Chao, 2008)

- **<u>stop short</u> in mm, rather than in m**
- **dump <u>without</u> much <u>radiation/activation</u>**
- **<u>convert</u> its energy into electricity**

... ionization is incurred by the entering intense electron beam each time. Given the TeV-beam, its decelerating gradient in the plasma is G_{dec}, which is on the order of the Tajima-Dawson field of

$$G_{dec} \sim m_e \omega_p c / e. \tag{9}$$

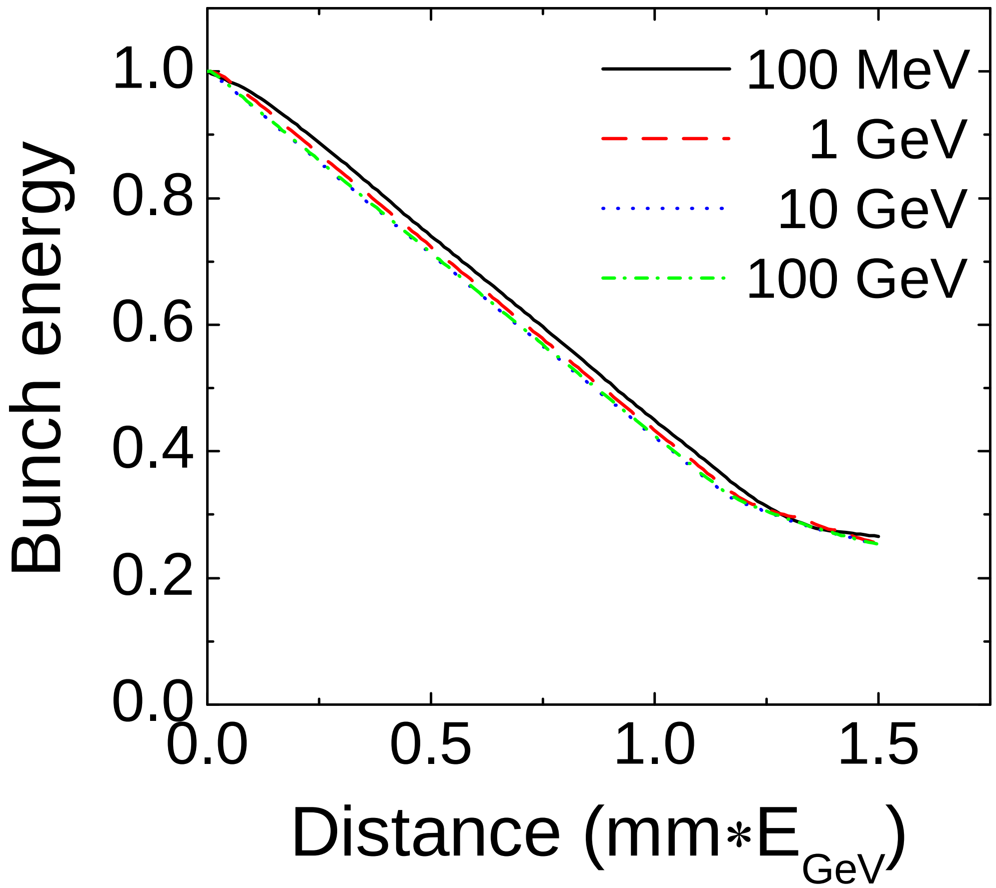
The plasma oscillation will last for time τ_p, which is the inverse of the Landau damping decrement γ_L before extraction of energy of the excited waveguide mode. A coupling window between the microwave (more accurately THz waves) structure and the plasma medium allows the plasma to fill the structure with microwave. (If we assume a plasma density of 10^{14} cm^{-3}, the exciting rf wave becomes 90 GHz, which is a familiar frequency as W-band and many industrial components are available.) A traveling wave rf structure is to be designed that couples into this plasma rf source. The input plasma rf power will be fed into the structure with critical coupling so that there is no reflected power. The higher the plasma temperature, the smaller the τ_p is due to the Landau damping. We dictate that the energy extraction time from the waveguide shorter that this damping time of τ_p. The details are provided by Chao and Tajima [27].

DISCUSSION AND CONCLUSIONS

(Kando et al, 2008)

Collective deceleration over mm

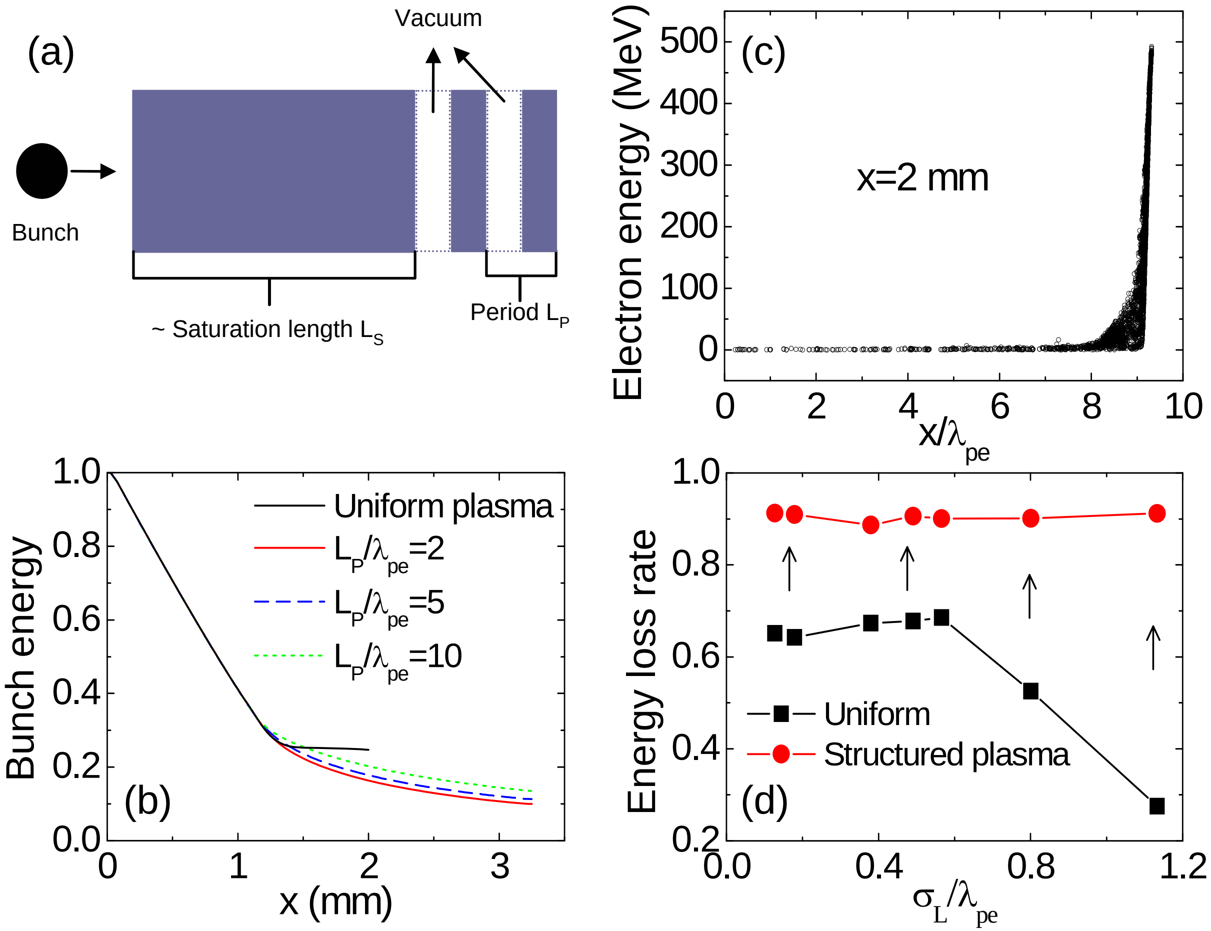
Results of computer simulation



isomorphic, regardless of energies

(Wu et al, 2009)

To enhance the conversion, avoid trapping



(Wu et al. 2009)

Technique of <u>phase velocity modulation</u> (PVM)

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

Option for future collider (Raubenheimer-SLAC)

Examples of TeV Collider Parameters

	Laser	Plasma	CLIC	ILC
CMS Energy (GeV)	1000	1000	1000	1000
Luminosity (10^{34} $cm^{-2}s^{-1}$)	2.4	3.5	2.3	2.8
Luminosity in 1% of Ecms	~2	1.3	1.1	1.9
Bunch charge (10^{10})	3.80E-06	1	0.37	2
Bunches / train	193	125	312	2820
Repetition rate (Hz)	1.50E+07	100	50	4
Beam Power (MW)	11.6	20	9.2	36.2
Emittances $\varepsilon_{n,x}$ / $\varepsilon_{n,y}$ (mm-mrad)	1e-4 / 1e-4	2 / 0.05	0.7 / 0.02	10 / 0.04
IP Spot sizes sx/sy (nm)	1.0 / 1.0	140 / 3.2	140 / 2	554 / 3.5
IP bunch length sz (μm)	0.1 –> 300	10	30	300
Drive beam / Laser / RF Power (MW)	58	58	36.8	80
Gradient (MV/m)	400	25000	100	31.5
Two linac length (km)	~4	~6	14	47
Drive beam / Laser / RF generation eff.	60%	45%	49%	53.95%
Drive beam / Laser / RF coupling eff.	20%	35%	25%	49.01%
Overall efficiency	12%	15.70%	12.10%	17.90%
Site Power (MW)	~137	~170	~150	300

Collider application: Early version(1997)

Studies of Laser-Driven 5 TeV e^+e^- Colliders in Strong Quantum Beamstrahlung Regime

M. Xie[1], T. Tajima[2], K. Yokoya[3] and S. Chattopadhyay[1]

[1] Lawrence Berkeley National Laboratory, USA
[2] University of Texas at Austin, USA
[3] KEK, Japan

(AIP Proc. **398**, 1997)

Abstract.

We explore the multidimensional space of beam parameters, looking for preferred regions of operation for a e^+e^- linear collider at 5 TeV center of mass energy. Due to several major constraints such a collider is pushed into certain regime of high beamstrahlung parameter, Υ, where beamstrahlung can be suppressed by quantum effect. The collider performance at high Υ regime is examined with IP simulations using the code CAIN. Given the required beam parameters we then discuss the feasibility of laser-driven accelerations. In particular, we will discuss the capabilities of laser wakefield acceleration and comment on the difficulties and uncertainties associated with the approach. It is hoped that such an exercise will offer valuable guidelines for and insights into the current development of advanced accelerator technologies oriented towards future collider applications.

INTRODUCTION

It is believed that a linear collider at around 1 TeV center of mass energy can be built more or less with existing technologies. But it is practically impossible to go much beyond that energy without employing a new, yet largely unknown method of acceleration. However, apart from knowing the details of the future technologies, certain collider constraints on electron and positron beam parameters are considered to be quite general and have to be satisfied, e.g. available wall plug power and the constraints imposed by collision processes: beamstrahlung, disruption, backgrounds, etc. Therefore it is appropriate to explore and chart out the preferred region in parameter space based on these constraints, and with that hopefully to offer valuable guide-

With a plasma density of $10^{17}\mathrm{cm}^{-3}$, such a gradient can be produced in the linear regime with more or less existing T^3 laser, giving a plasma dephasing length of about 1 m [13]. If we assume a plasma channel tens of μm in width can be formed at a length equals to the dephasing length, we would have a 10 GeV acceleration module with an active length of 1 m. Of course, creating and maintaining a plasma channel of the required quality is no simple matter. To date, propagation in a plasma channel over a distance of up to 70 Rayleigh lengths (about 2.2 cm) of moderately intense pulse ($\sim 10^{15}\mathrm{W/cm}^2$) has been demonstrated [14]. New experiment aiming at propagating pulses with intensities on the order of $10^{18}\mathrm{W/cm}^2$ (required for a gradient of 10 GeV/m) is underway [13].

Table 1. Beam Parameters at Three Values of Beam Power

CASE	P_b(MW)	$N(10^8)$	f_c(kHz)	ε_y(nm)	$\beta_y(\mu m)$	σ_y(nm)	$\sigma_z(\mu m)$
I	2	0.5	50	2.2	22	0.1	0.32
II	20	1.6	156	25	62	0.56	1
III	200	6	416	310	188	3.5	2.8

Table 2. Results Given By the Formulas

CASE	Υ	D_y	F_{oide}	n_γ	δ_E	n_p	$\mathcal{L}_g(10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1})$
I	3485	0.93	0.89	0.72	0.2	0.19	1
II	631	0.29	0.89	0.72	0.2	0.12	1
III	138	0.081	0.91	0.72	0.2	0.072	1

Table 3. Results Given By CAIN Simulations

CASE	n_γ	δ_E	σ_e/E_0	n_p	$\mathcal{L}/\mathcal{L}_g(\mathrm{W_{cm}} \in 1\%)$	$\mathcal{L}/\mathcal{L}_g(\mathrm{W_{cm}} \in 10\%)$
I	1.9	0.38	0.42	0.28	0.83	1.1
II	0.97	0.26	0.36	0.12	0.65	0.80
III	0.84	0.21	0.32	0.06	0.62	0.75

Although a state-of-the-art T^3 laser, capable of generating sub-ps pulses with 10s of TW peak power and a few Js of energy per pulse [11], could almost serve the need for the required acceleration, the average power or the rep rate of a single unit is still quite low, and wall-plug efficiency inadequate. In addition, injection scheme and synchronization of laser and electron pulse from

Incorporated collider physics at collision point (beamstrahlung, Oide limit, etc.)

Toward energy frontier : Multistaging (earliest version,1985)

(pre-CPA version)

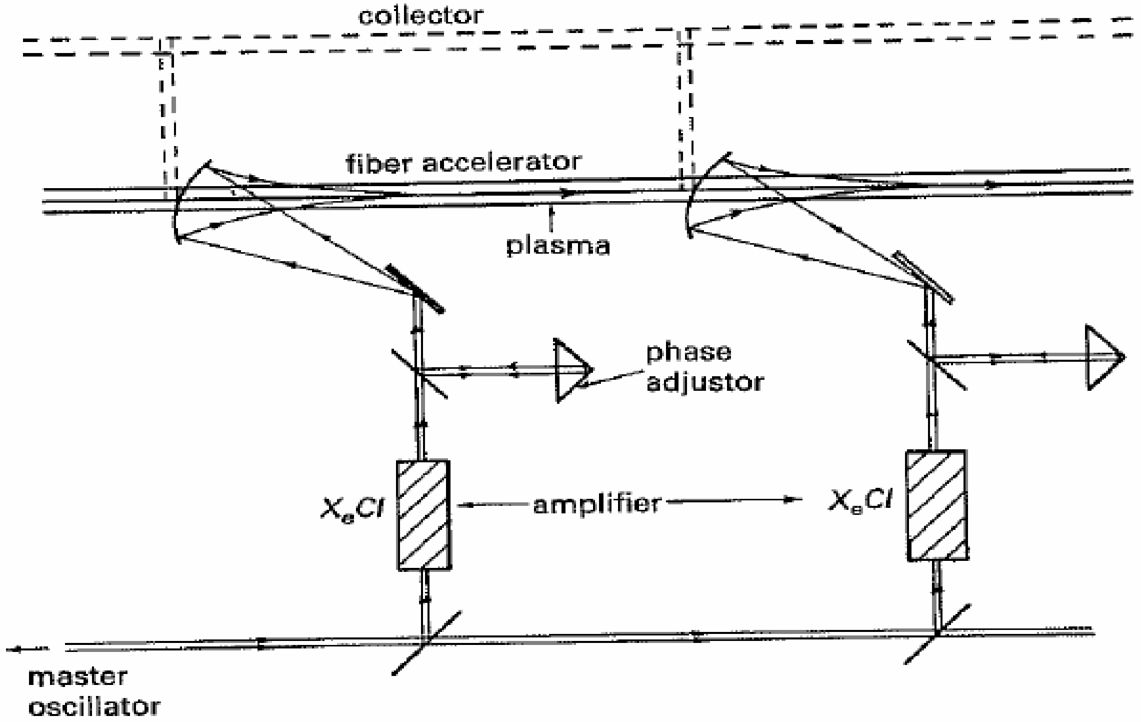


FIGURE 34. A conceptual plasma fiber accelerator with laser staging amplification *in situ*. The separation between the modules is characterized by the sum of the focal length and the pump depletion length. An example of X_eCl lasers is taken.

(Tajima, Laser Part Beams,1985)

Multi-stage acceleration

Particle Dynamics and its Consequences in Wakefield Acceleration in a High Energy Collider

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AIP Proc. **472** (1999)

Abstract. The performance of a wakefield accelerator in a high energy collider application is analyzed by use of a nonlinear dynamics map built on a simple theoretical model of the wakefield generated by the laser pulse (or whatever other method) and a code based on this map [1]. The crucial figures of merit for such a system other than the final energy include the emittance (that determines the luminosity). The more complex the system is, the more "opportunities" the system has to degrade the emittance (or entropy of the beam). Thus our map guides us to identify where the crucial elements lie that affect the emittance. If the focusing force of the wakefield is strong when there

<u>Transverse</u> focusing/defocusing need to be mitigated. <u>Plasma channel</u> ideal

Toward energy frontier (earliest version,1985) (3)

High energy laser plasma accelerators 405

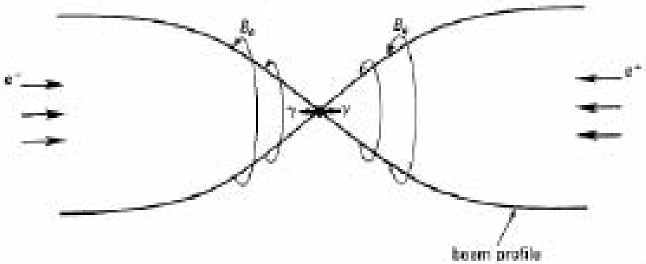


FIGURE 37. (Collective) beamstrahlung and collisions of γ–γ at the focus of a lepton collider.

(e^-e^+ beams) to efficiently convert the particle energy into high photon energies in turn, see figure 37. At the collision point the current-unneutralized and charge-neutralized colliding beams produce an intense magnetic field $B_\theta = 2eN/(a_\perp l_b)$ (easily exceeding MG), which leads to explosive pinching of beams. If this process, including collective emission of synchrotron radiation as a result of a pinch can occur in a self-similar fashion so that the entire energy of the beams is converted into γ-rays, hopefully in high frequency domains, a possibility of a γ–γ collider arises. A theoretical exploration of such a self-similar explosive solution for the collective beamstrahlung would be interesting. If this does not occur in a collective fashion, we should use the Bethe-Heitler formula for the γ-ray spectrum:

$$\frac{d\sigma}{d\omega} \sim \frac{16}{3}\frac{e^2}{c}\left(\frac{e^2}{mc^2}\right)^2\left(1-\frac{\hbar\omega}{E}+\frac{3\hbar^2\omega^2}{4E^2}\right)\left(\ln\frac{2EE'}{mc^2\hbar\omega}-\frac{1}{2}\right),$$

where the photon cutoff frequency is $\omega = E/\hbar$ instead of the classical value of $\omega_c = 3\gamma^3 c/\rho$ with ρ being the curvature radius of leptons in B_θ and $E = \gamma mc^2$ and E' their energies. Recently this point has been well appreciated (Erber 1966; Noble & Himel, 1985). According to Schwinger 1954 and Klepikov 1954, the radiated power loss by a constant magnetic field in the strong quantum effect limit is,

$$P_{QM} \simeq 0{\cdot}5 \times \frac{2}{3}c\alpha \cdot \frac{mc^2}{\lambda_c}\Upsilon^{\frac{2}{3}}, \quad (\Upsilon \gg 1),$$

Self-similar collision (beamstrahlung) toward 'a point' (enhanced luminosity) possible?

→flat beam profile control

(Tajima, 1985)

Renewed interest in γ - γ Collider

Large amount of cost down possible by $\gamma\,\gamma$ collider
perhaps half (or even a third)
clearer Higgs physics than e+e- collider
likely Higgs mass ~120GeV (← input from LHC)

2.1. HIGGS

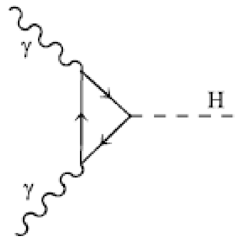


Figure 2.1: Couplings of the Higgs boson to two photons.

1.1. $\gamma\gamma$ COLLIDER

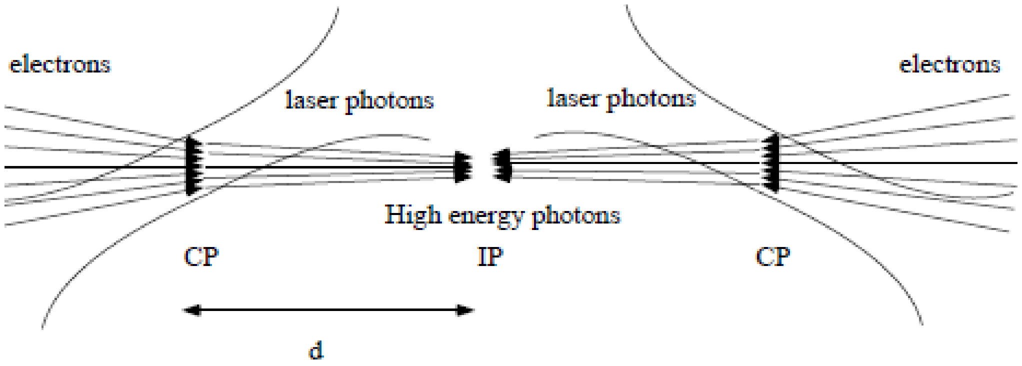


Figure 1.2: Conceptual view of the interaction region of a $\gamma\gamma$ collider

1.1 $\gamma\gamma$ Collider

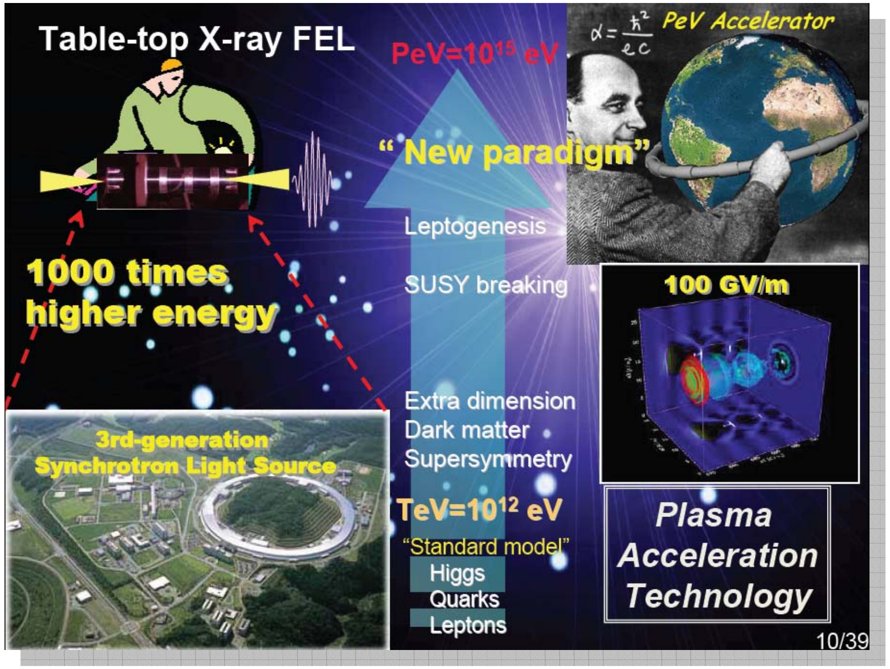
The idea of generating high-energy photons by backward-scattered Compton photons is discussed in [29, 30, 31, 72, 73] and recent status is summarized in [80, 27]. In $\gamma\gamma$ colliders, photon beams are generated by the inverse Compton scattering of electron- and laser-beams just before the interaction point. By this method, a photon beam of the highest energy close to the original electron beam can be

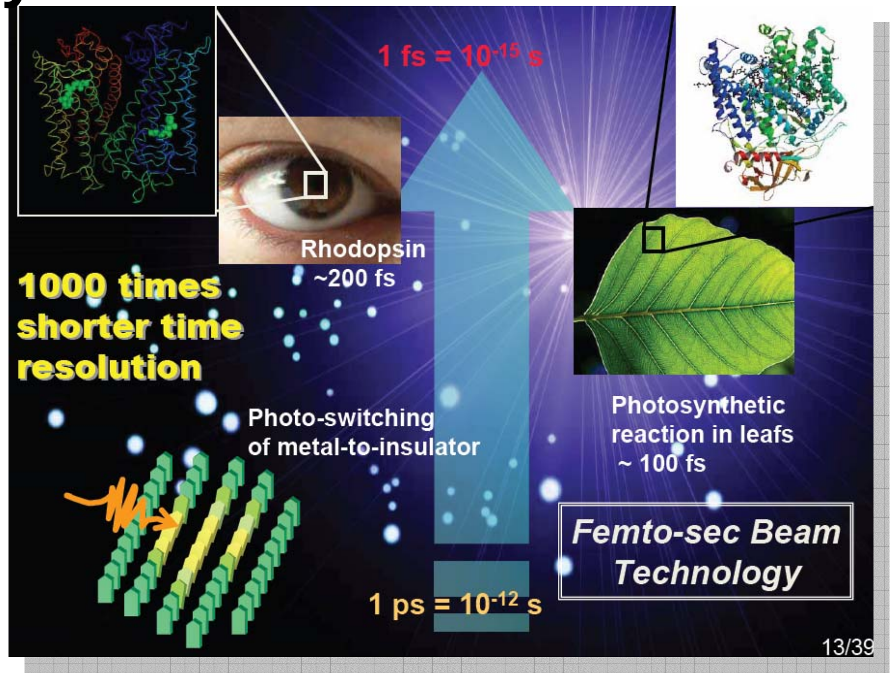
New:
Study Group started
at KEK-JAEA,
ELI discussion
(Sept, 2008)

→ a new strategy
for HEP?
more affordable

Challenge Posed by DG Suzuki

Frontier science driven by advanced accelerator





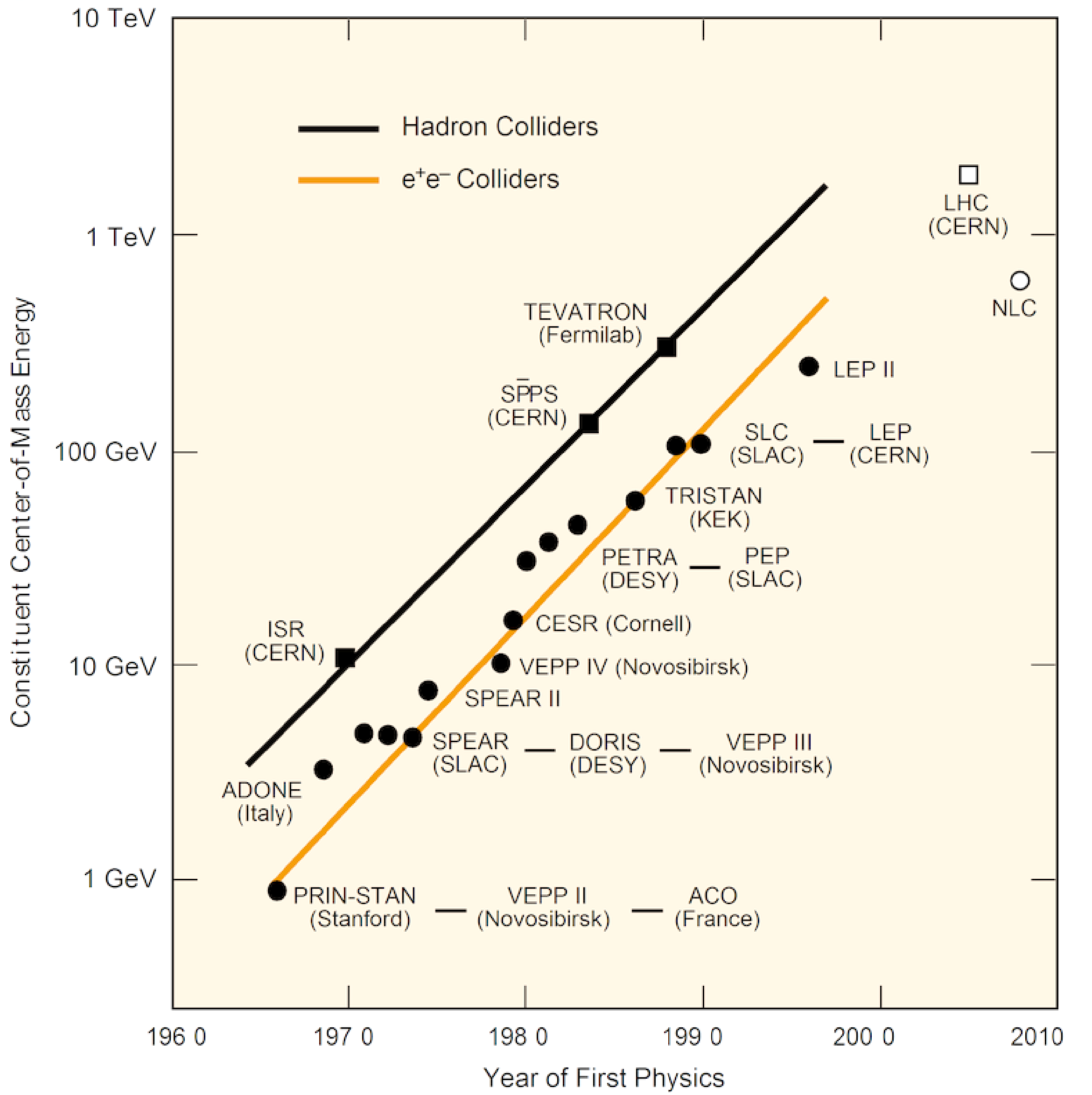
compact, ultrastrong *a*

atto-, zeptosecond

Can we meet the challenge?

A. Suzuki @KEK(2008)

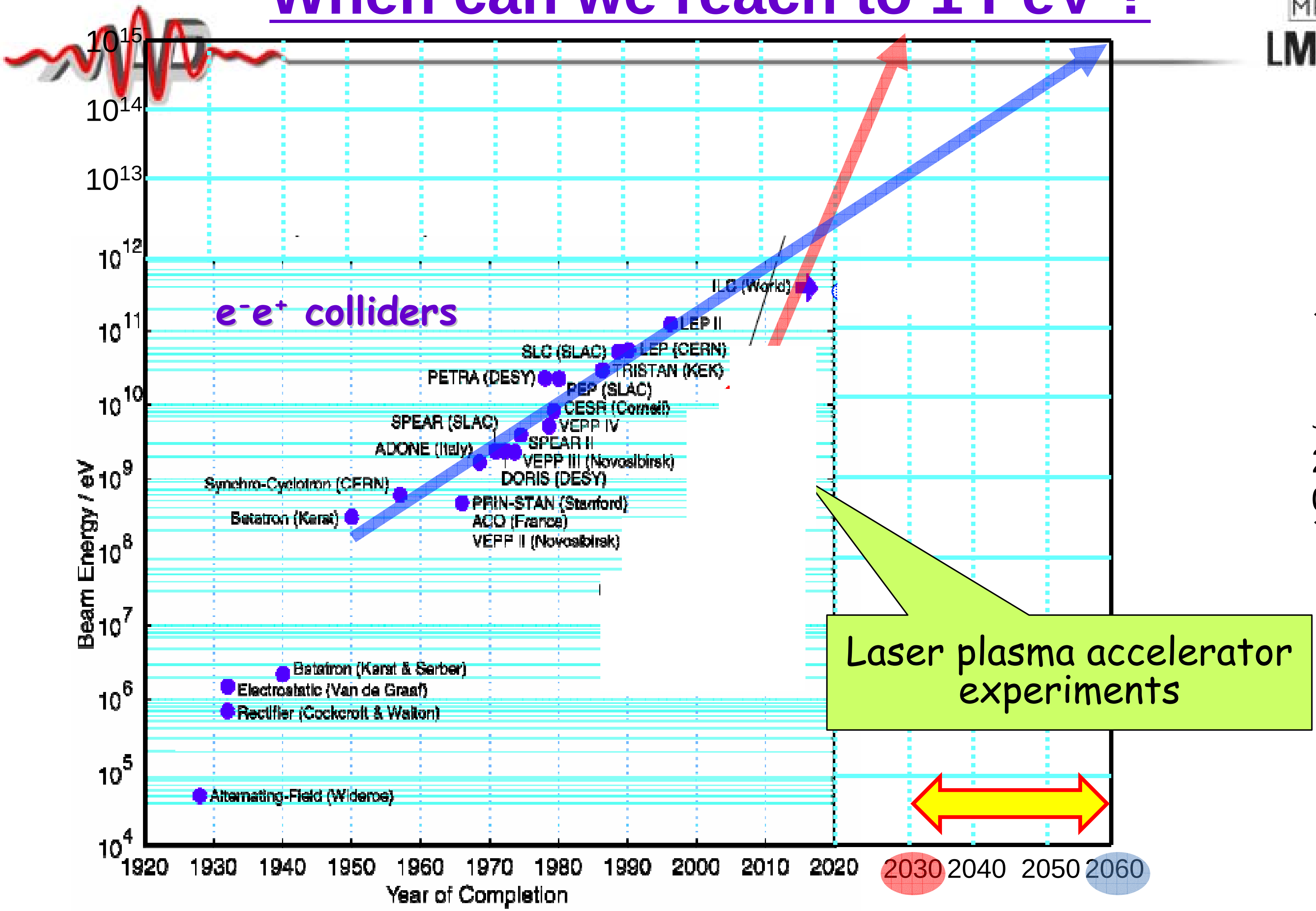
When can we reach to 1 PeV ?



(http://tesla.desy.de/~rasmus/media/Accelerator%20physics/slides/Livingston%20Plot%202.html)

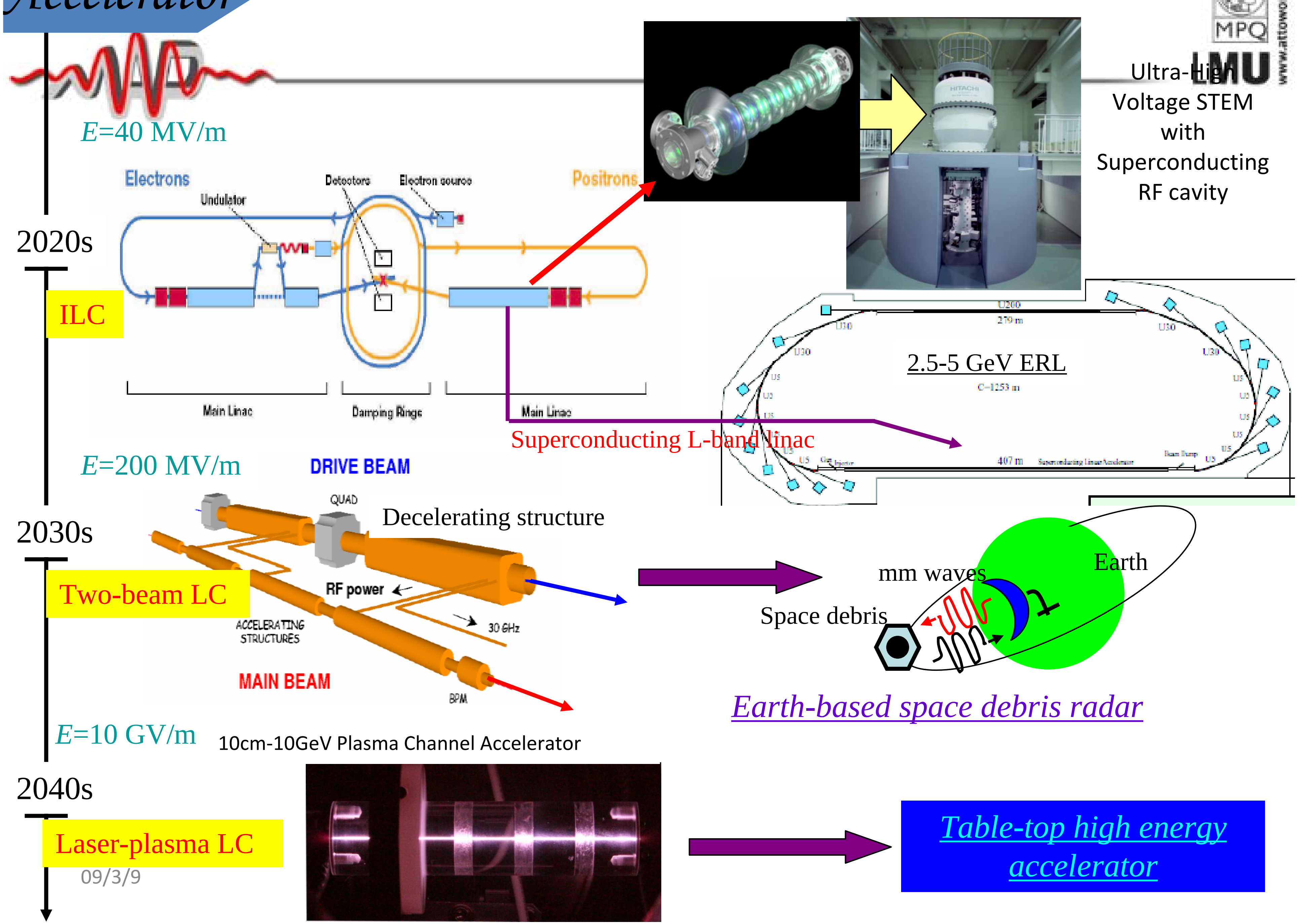
(Suzuki, 2009)

When can we reach to 1 PeV ?



V. Yakimenko (BNL) and R. Ischebeck (SLAC), AAC2006 Summary report of WG4

Evolution of Accelerators and their Possibilities (Suzuki,2008)

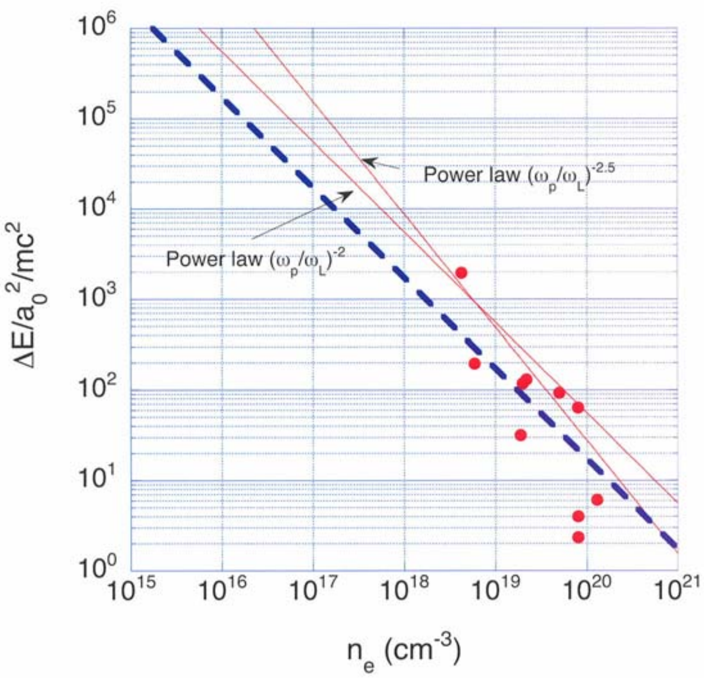


Meeting Suzuki's Challenge:

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

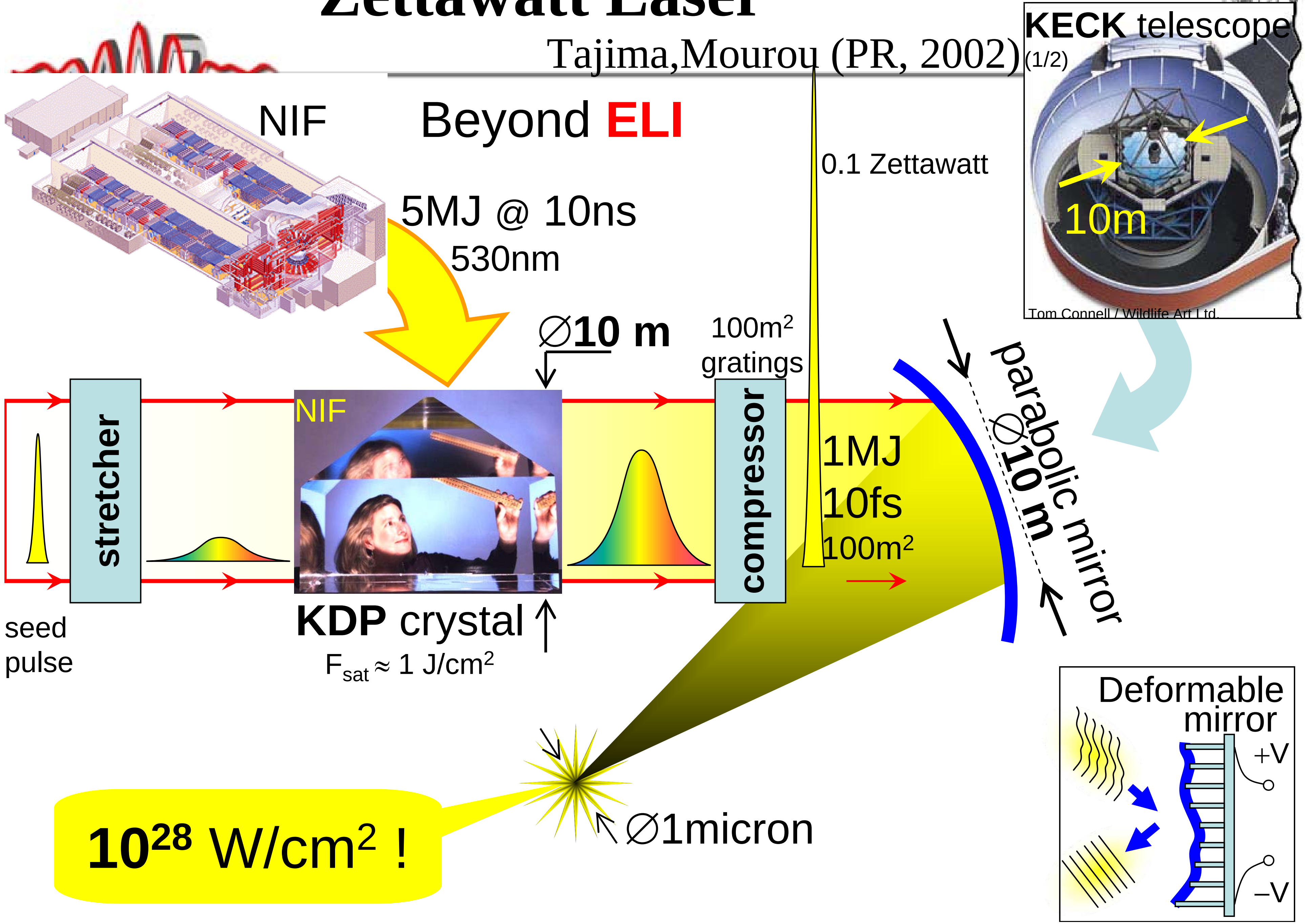
Even 1PeV electrons (and γ s) are possible, albeit with lesser amount

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

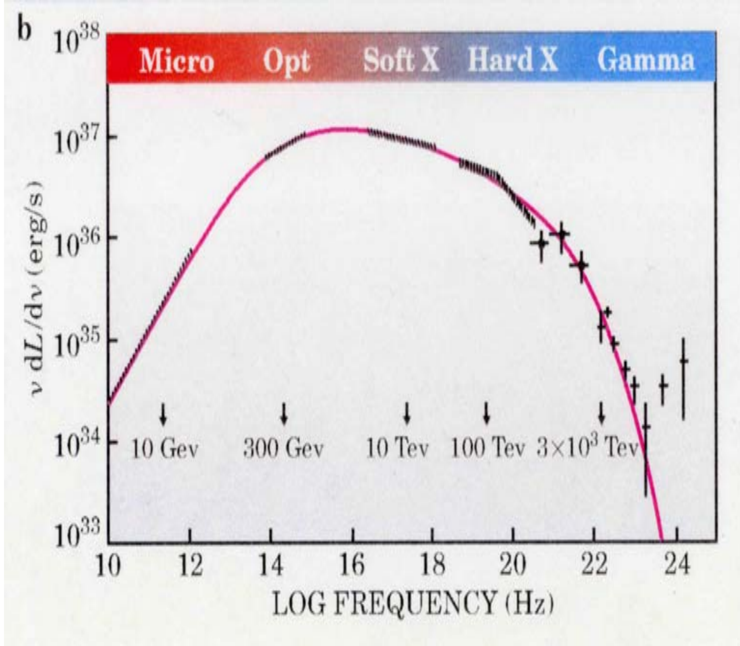
(laser energy of 10MJ@plasma density of 10^{16}/cc; maybe reduced with index 5/4)

Zettawatt Laser

Tajima, Mourou (PR, 2002)



PeV γ from Crab Nebula



Can we see manifestation of quantum gravity, Lorentz variance in high energy γ?
How PeV electrons accelerated?

The Crab Pulsar, a city-sized, magnetized neutron star spinning 30 times a second, lies at the center of this composite image of the inner region of the well-known Crab Nebula. The spectacular picture combines optical data (red) from the Hubble Space Telescope and x-ray images (blue) from the Chandra Observatory, also used in the popular Crab Pulsar movies. Like a cosmic dynamo the pulsar powers the x-ray and optical emission from the nebula, accelerating charged particles and producing the eerie, glowing x-ray jets. Ring-like structures are x-ray emitting regions where the high energy particles slam into the nebular material.

Special theory of relativity OK?

doi:10.1038/nature08574

nature

LETTERS

A limit on the variation of the speed of light arising from quantum gravity effects

A list of authors and their affiliations appears at the end of the paper

A cornerstone of Einstein's special relativity is Lorentz invariance—the postulate that all observers measure exactly the same speed of light in vacuum, independent of photon-energy. While special relativity assumes that there is no fundamental length-scale associated with such invariance, there is a fundamental scale (the Planck scale, $l_{\mathrm{Planck}} \approx 1.62 \times 10^{-33}$ cm or $E_{\mathrm{Planck}} = M_{\mathrm{Planck}}c^2 \approx 1.22 \times 10^{19}$ GeV), at which quantum effects are expected to strongly affect the nature of space–time. There is great interest in the (not yet validated) idea that Lorentz invariance might break near the Planck scale. A key test of such violation of Lorentz invariance is a possible variation of photon speed with energy[1–7]. Even a tiny variation in photon speed, when accumulated over cosmological light-travel times, may be revealed by observing sharp features in γ-ray burst (GRB) light-curves[2]. Here we report the detection of emission up to ~31 GeV from the distant and short GRB 090510. We find no evidence for

scale (when E_{ph} becomes comparable to $E_{\mathrm{Planck}} = M_{\mathrm{Planck}}c^2$). For $E_{\mathrm{ph}} \ll E_{\mathrm{Planck}}$, the leading term in a Taylor series expansion of the classical dispersion relation is $|v_{\mathrm{ph}}/c - 1| \approx (E_{\mathrm{ph}}/M_{\mathrm{QG},n}c^2)^n$, where $M_{\mathrm{QG},n}$ is the quantum gravity mass for order n and $n = 1$ or 2 is usually assumed. The linear case ($n = 1$) gives a difference $\Delta t = \pm(\Delta E/M_{\mathrm{QG},1}c^2)D/c$ in the arrival time of photons emitted together at a distance D from us, and differing by $\Delta E = E_{\mathrm{high}} - E_{\mathrm{low}}$. At cosmological distances this simple expression is somewhat modified (see Supplementary Information section 4).

Because of their short duration (typically with short substructure consisting of pulses or narrow spikes) and cosmological distances, GRBs are well-suited for constraining LIV[2,11,12]. Individual spikes in long[13] (of duration >2 s) GRB light-curves (10–1,000 keV) usually show[14] intrinsic lags: the peak of a spike occurs earlier at higher photon-energies. However, there are either no lags or very short lags

(Abdo et al, 2009)

γ -ray signal (GRB) from primordial GRB

LETTERS NATURE

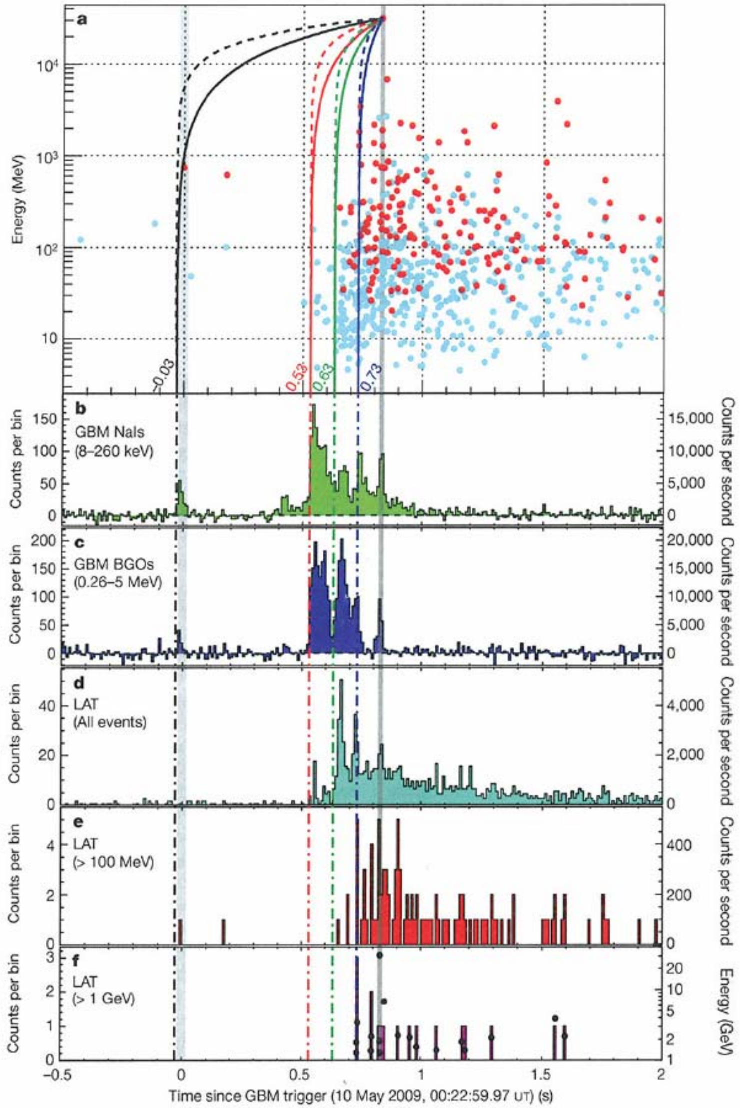


Figure 1 | Light curves of GRB 090510 at different energies. a, Energy … lowest to highest energies. f also overlays energy versus arrival time for each

(Abdo, eta l, 2009)

Energy-dependent Photon mass?

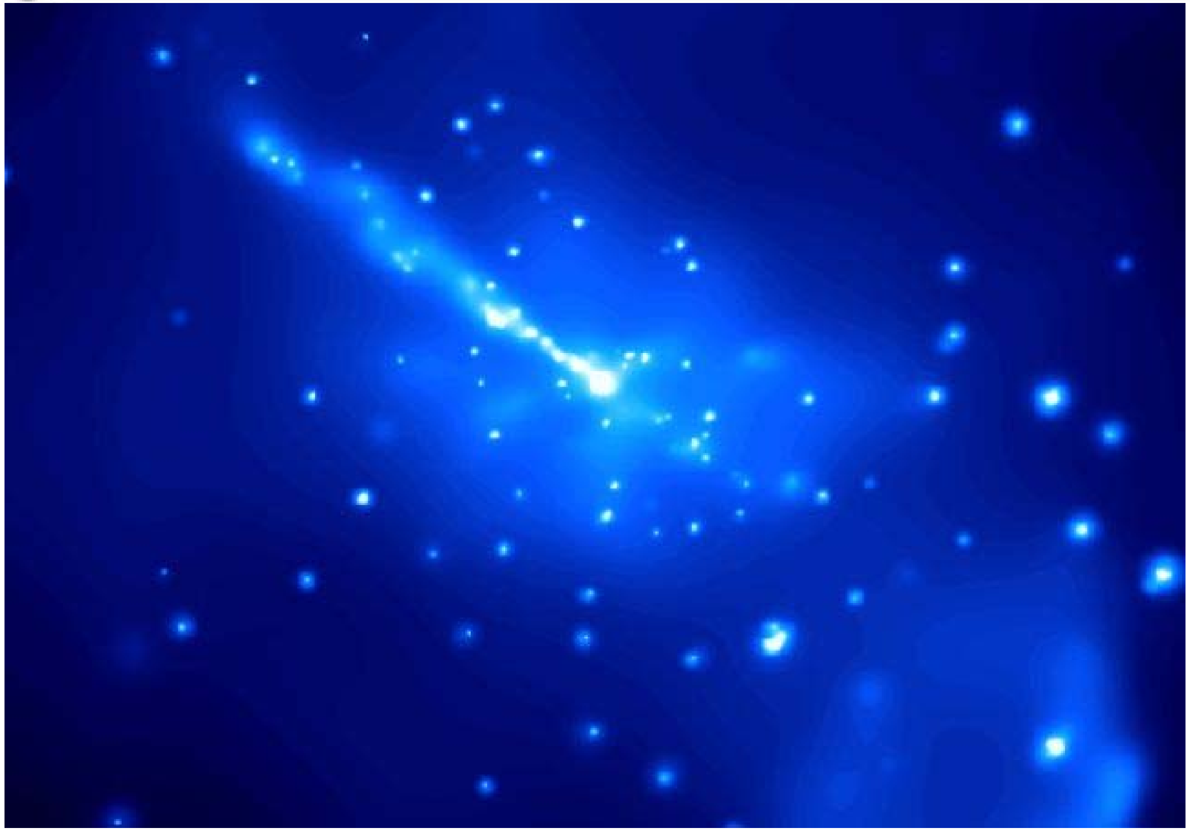
limit is pushed up to near Planck mass

PeV γ (from e-) Can explore this

Conclusions

- Laser electron acceleration: experimentally well established; its unique properties getting known
- 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 ?
- Beam control: greater attention necessary
- **Other applications**: already beginning, soon to flourish : radiolysis, intraoperative therapy, bunch decelerator, nuclear detection, compact FEL source, compact radiation sources, ultrafast diagnosis,…)
- Combination of laser accelerated electrons and other beams: new dimensions for science and applications



Centaurus A:

cosmic
wakefield
linac?

Merci Beaucoup
et a la Prochaine Fois!