Plenary Talk
EuCARD, European Network for Novel Accelerators
CERN, Geneva
Tuesday, May 3, 2011

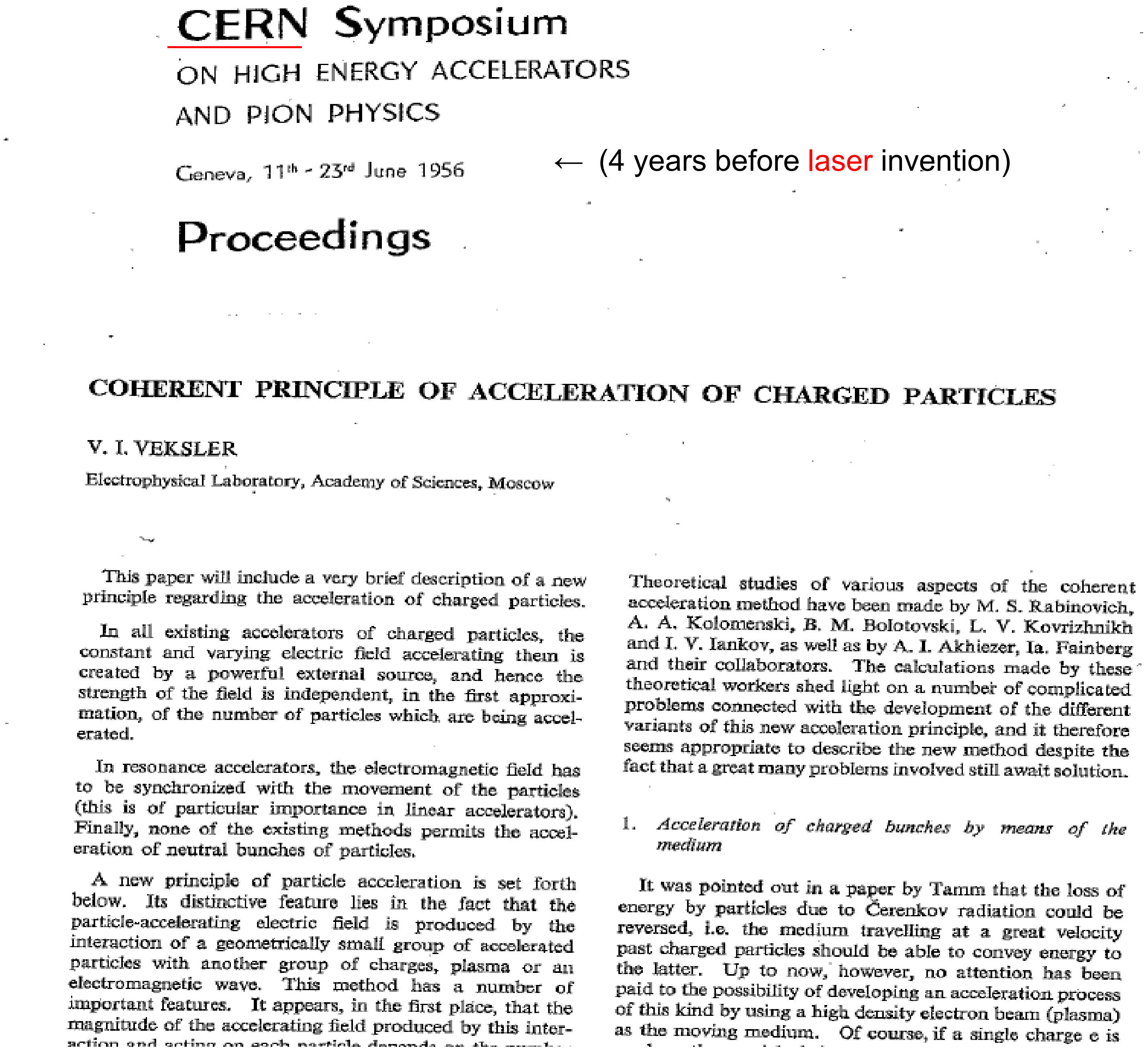
History and Outlook of Plasma Acceleration

Toshiki Tajima
LMU and MPQ, Garching

Acknowledgments for Collaboration and advice: G. Mourou, W. Leemans, K. Nakajima, K. Homma, C. Barty, P. Chomaz, D. Payne, H. Videau, V. Malka, F. Krausz, T. Esirkepov, S. Bulanov, M. Kando, W. Sandner, A. Suzuki, M. Teshima,, J. Chambaret, E. Esarey, R. Assmann, R. Heuer, A. Caldwell, S. Karsch, F. Gruener, M. Zepf, M. Somekh, E. Desurvire, D. Normand, J. Nilsson, W. Chou, F. Takasaki, M. Nozaki, K. Yokoya, D. Payne, S. Chattopadhyay, , A. Chao, P. Bolton, E. Esarey, S. Cheshkov, C. Chiu, M. Downer, C. Schroeder, J.P. Koutchouk, K. Ueda, Y. Kato, X. Q. Yan, J. E. Chen, R. Li, J. Rossbach, A. Ringwald, E. Elsen, C. Joshi, G. Xia,, S. Chattopadyay, D. Jaroszynski, J. Osterhoff

1. Brief history of collective acceleration:
Collectively driven wakefields: emerging tools for HEP
    (both by charged bunches and laser pulses)
2. Broad applications of LWFA (and lasers)
    HEP(colliders, XFEL, ion sources, ion acceleration,
        $\gamma\gamma$ collider)
    cancer therapy (IORT),
    ultrafast radiolysis, THz, X-ray sources,….
3. Bridge between laser and accelerator communities:
    ICUIL-ICFA collaboration, Bridgelab, EuCARD,….
4. Collider physics challenges
5. Laser technology development for colliders. e.g. ICAN
6. Energy frontier at PeV with attosecond metrology
7. Alternative route to fundamental physics:
    High Field (instead of high momentum)
        explores low energy new fields

Advent of collective acceleration (Veksler, 1956)



CERN Symposium

ON HIGH ENERGY ACCELERATORS

AND PION PHYSICS

Geneva, 11th - 23rd June 1956

← (4 years before laser invention)

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 inter-

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, 78,84)

Electron beam-driven acceleration of ions

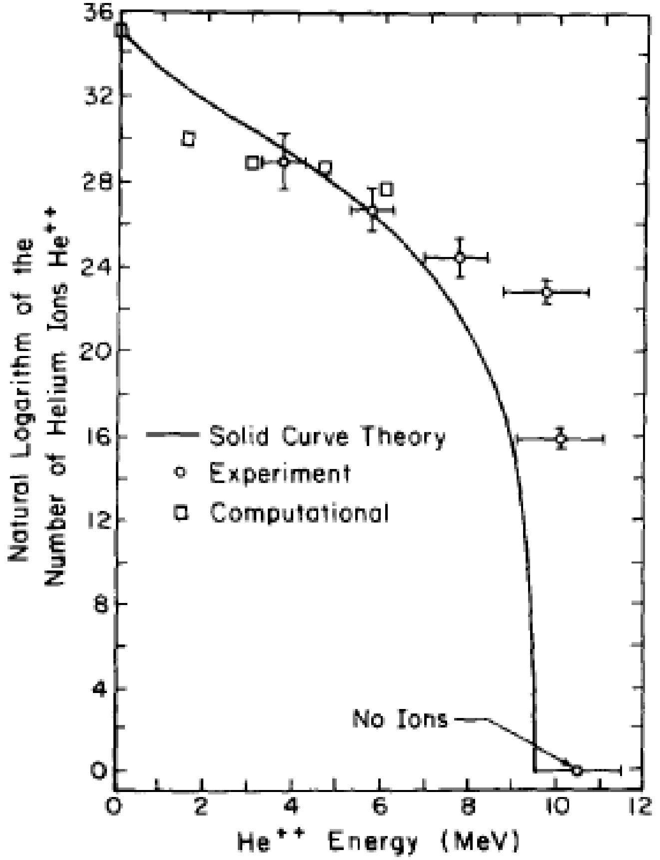
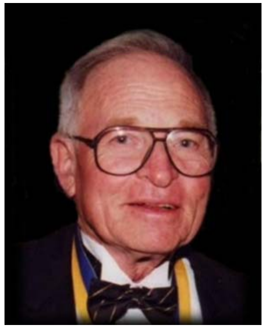


FIG. 2. Comparison between theory, experiment, and simula natural logarithm of the ion number versus energy.

Ion energy spectrum



Rostoker' lab

Cf: recent (> 2000) TNSA acceleration of ions by laser

Collective acceleration suggested:

Veksler (1956)

(ion energy)~ (M/m)(electron energy)

Many experimental attempts (~'70s):

← (example)

no such amplification observed

(ion energy)~ (several)x(electron)

Mako-Tajima analysis (1978;1984)

sudden acceleration, ions untrapped

[O'Neil's trapping width $\sim\sqrt{(E_L/M)}$]

→ #1 large amplitude accelerating field necessary to trap ('ride on surf')

→ #2 electron acceleration possible with trapping (with relativistic field)

→ #3 gradual acceleration(ion velocity close to the phase velocity)

Wakefield : a Collective Phenomenon

All particles in the medium participate = collective phenomenon

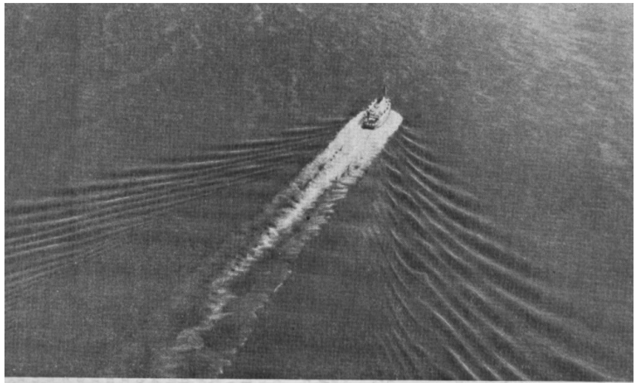
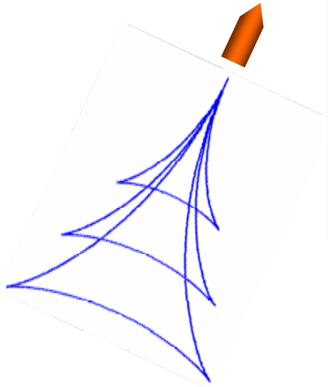
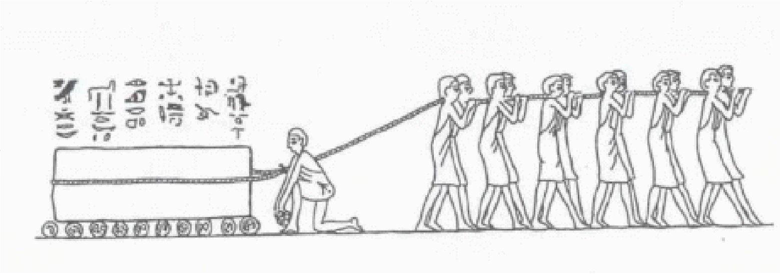


Рис. 71. Наблюдаемая картина корабельных волн. [Любезно предоставлено Aerofilms Ltd.]

Kelvin wake

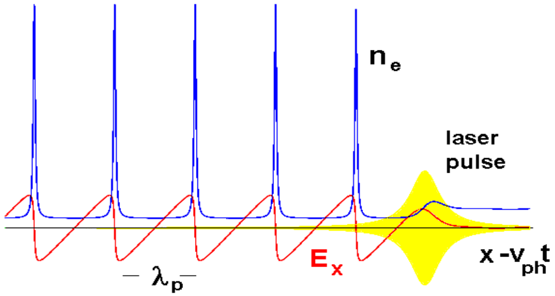


Colletive dynamics



(cf. individual
particle dynamics)

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



(The density cusps.
Cusp singularity)

$\longleftarrow$ **relativity regularizes**

Wave **breaks** at v<c

Hokusai

Dawson

First LWFA demonstration (SMLWFA regime)
fs TW CPA laser driven

CPA-based laser (with sufficient intensity and shortness of pulses) in 1990’s
following pioneering beat-wave experiments

First proof-of-principle LWFA
at KEK/Osaka 1994,95

The first demonstration of
30 GV/m Self-Modulated LWFA

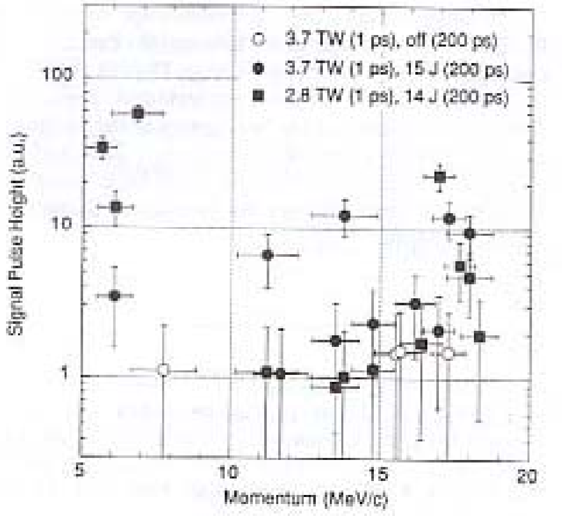
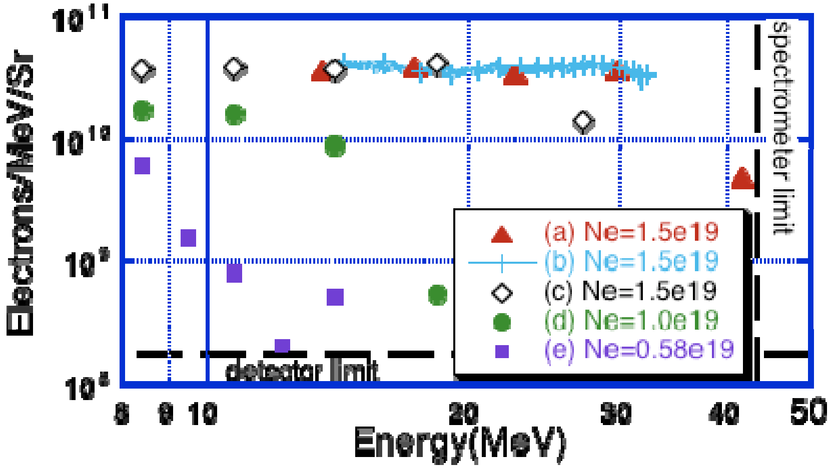


FIG. 2. Observed momentum spectra of accelerated electrons for a He gas jet at the back pressure 7.8 atm.

(Nakajima)

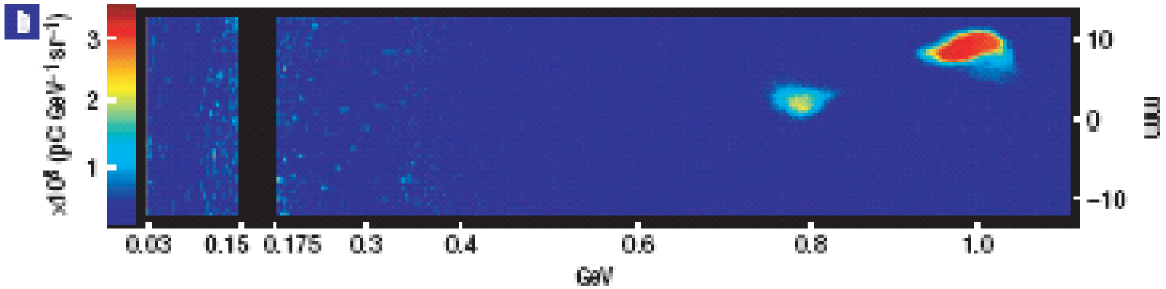
Electron acceleration from the breaking of relativistic plasma waves: Raman Forward Scattering

A. Modena et al. **Nature** 377, 606 (1995)



(Joshi)

GeV electrons from a centimeter accelerator driven by a relativistic laser

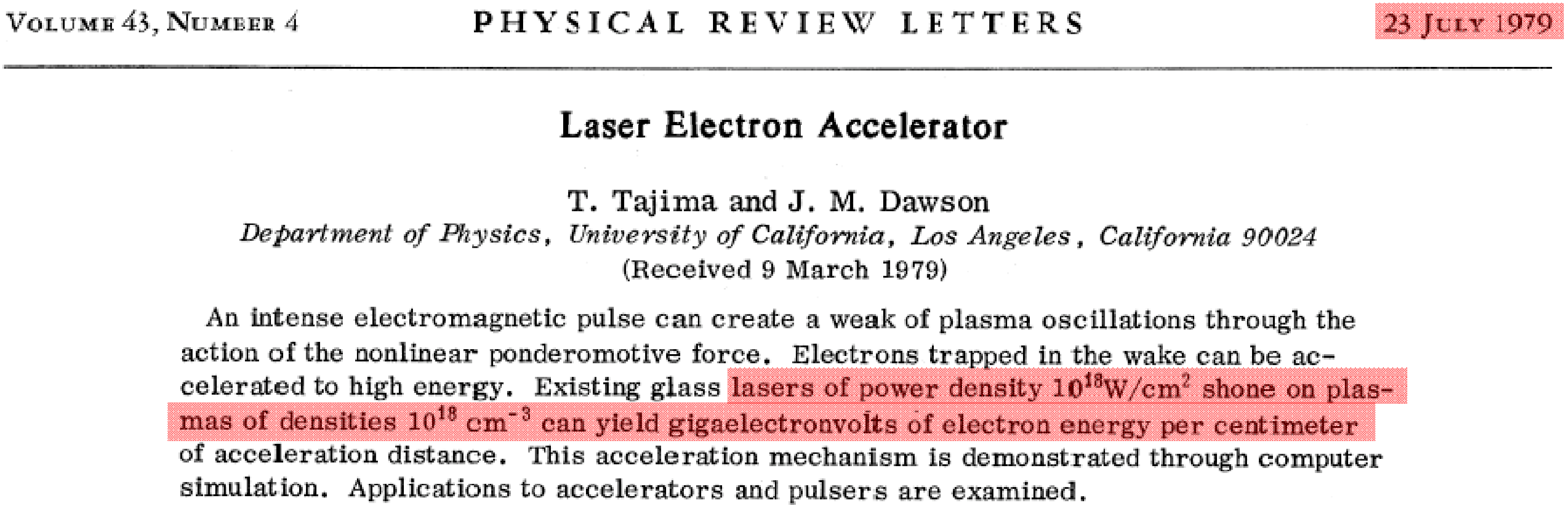


310-μm-diameter channel capillary

P = 40 TW

density 4.3×10^{18} cm^{-3}.

Leemans et al., Nature Physics, september 2006 (following monoenergetic LWFA acceleration demo by Faure; Geddes; Mangles' seminal papers (2004))



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.

(a slide given by S. Karsch; emphasis by him)

Experimental Observation of Plasma Wakefields

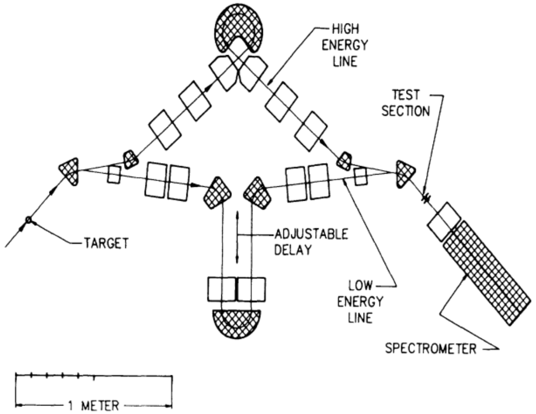


FIG. 1. Schematic of Argonne National Laboratory AATF layout.

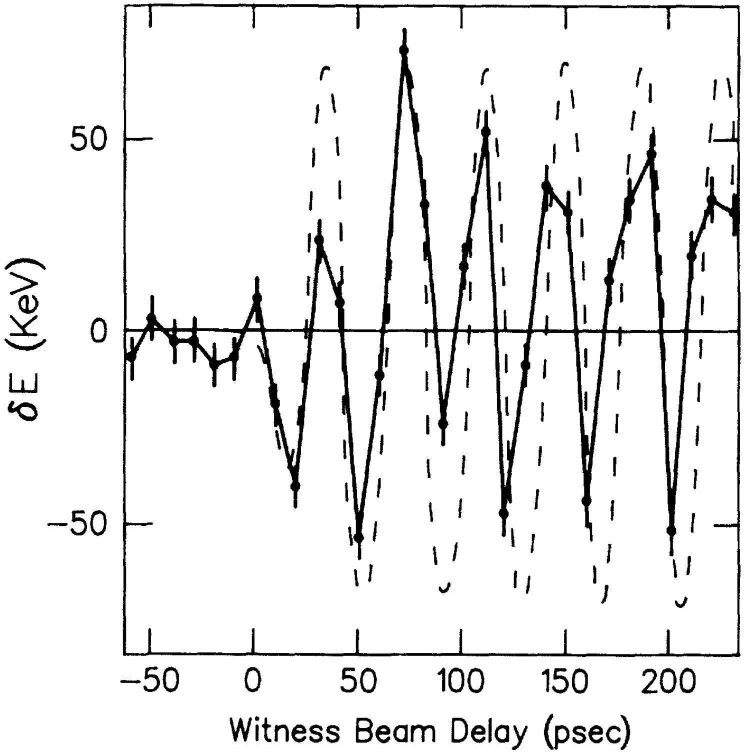
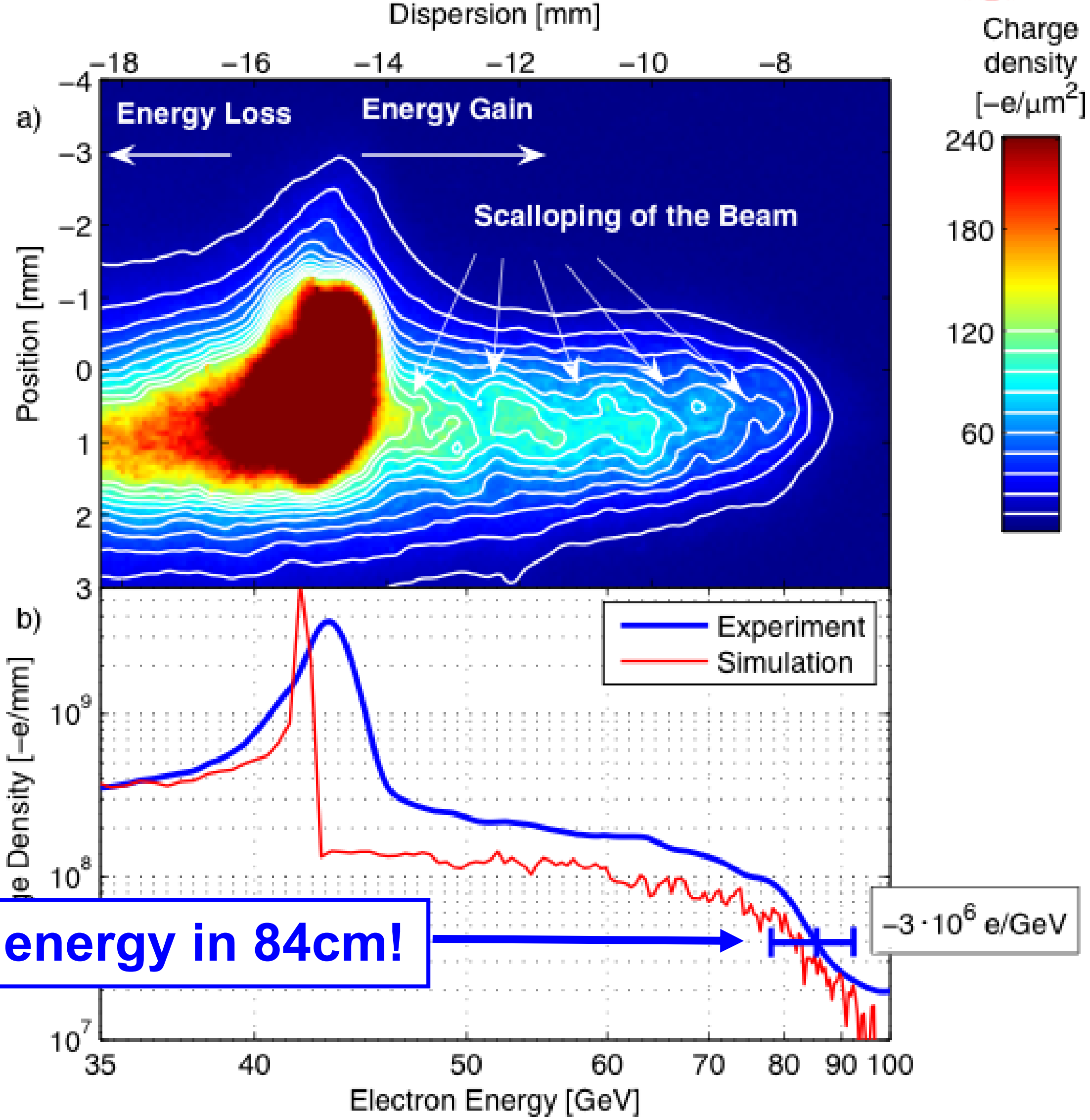


FIG. 2. Scan 1: Witness-beam energy-centroid change δE vs time delay behind driver. Total driver-beam charge $Q = 2.1$ nC; plasma parameters $L = 28$ cm and $n_e = 8.6\times10^{12}$ cm^{-3}. Theoretical predictions are given by the dashed line.

Rosenzweig et al. PRL(1988)

E-167: Energy Doubling with a Plasma Wakefield Accelerator in the FFTB



Linac running all out to deliver compressed 42GeV Electron Bunches to the plasma

Record Energy Gain

Highest Energy Electrons Ever Produced @ SLAC

Some electrons double their energy in 84cm!

Nature Feb.15 2007

(C. Joshi)

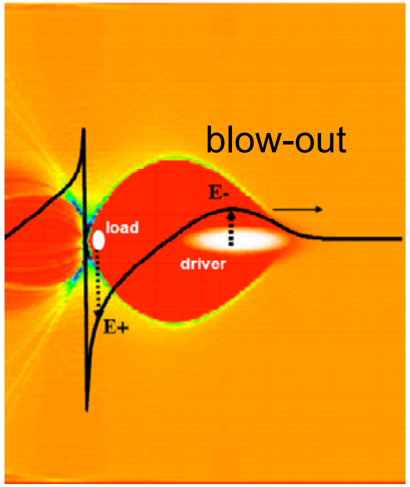
PWFA *vs*. PDPWA

Pros. of PWFA

Plasma electrons are expelled by space charge of beam, a nice bubble will be formed for beam acceleration and focusing.

The short electron beam is relatively easy to have (bunch compression).

Wakefield phase slippage is not a problem.



Cons. of PWFA

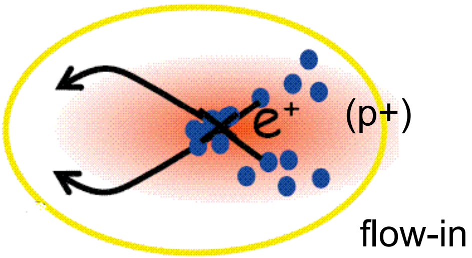
One stage energy gain is limited by transformer ratio, therefore maximum electron energy is about 100 GeV using SLC beam.

Easy to be subject to the head erosion due to small mass of electrons

Pros. of PDPWA

Very high energy proton beam are available today, the energy stored at SPS, LHC, Tevatron

SPS (450 GeV, 1.3e11 p/bunch) ~ 10 kJ
LHC (1 TeV, 1.15e11 p/bunch) ~ 20 kJ
LHC (7 TeV, 1.15e11 p/bunch) ~ 140 kJ
SLAC (50 GeV, 2e10 e-/bunch) ~ 0.1 kJ

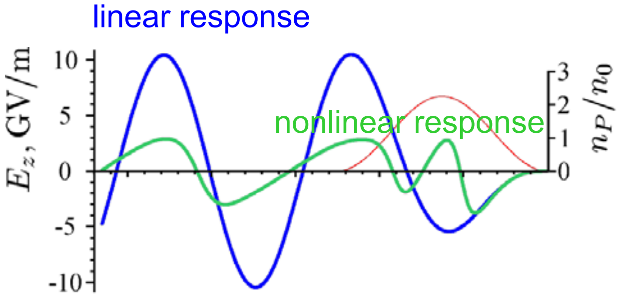


Cons. of PDPWA

Flow-in regime responds a relatively low field *vs*. blow-out regime.

Long proton bunches (tens centimeters), bunch compression is difficult.

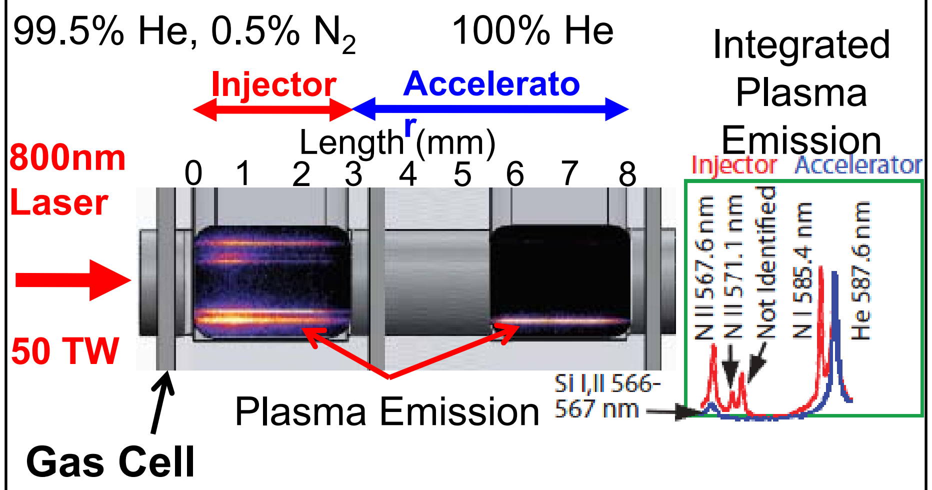
Wave phase slippage for heavy mass proton beam (small γ factor), especially for a very long plasma channel



(A. Caldwell et al)

Two-stage gas cell LWFA experiments

Electron injection can be controlled using a two-stage gas cell

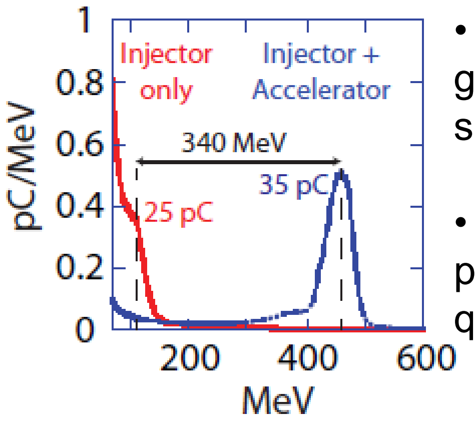


- The electron density throughout the cell is measured with interferometry to be 3×10^{18} cm^{-3}
- No self-trapping is observed in pure He for densities below 4×10^{18} cm^{-3}

Plasma emission imaging indicates that N_2 is only present in the injector stage

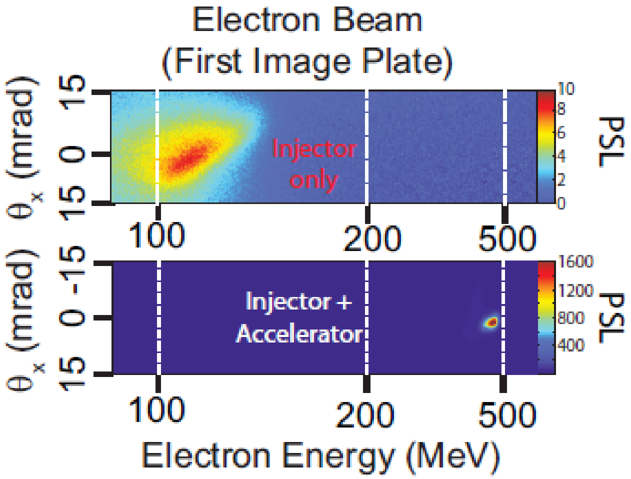
B.B. Pollock et.al., submitted 2011

Ionization-induced injection from the N_2 terminates after the injector stage



- Filling only the injector gives a low energy, broad spectrum feature
- Filling both stages produces high energy, high quality electron beams

The electron beams are dispersed by a ~0.5 T dipole magnet



Intra-Operative Radiation Therapy (IORT)

LWFA ***electron sources:*** ***technology transferred to company***

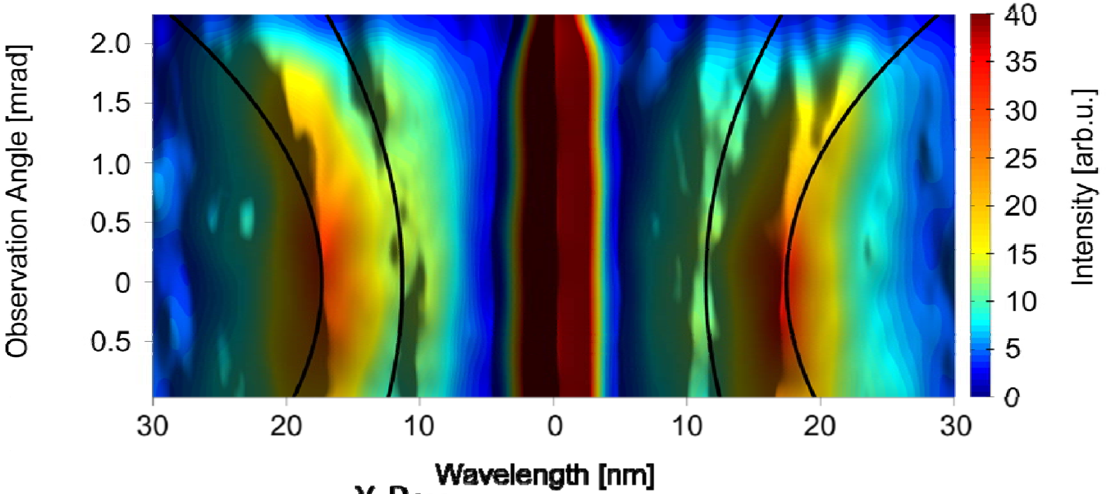
NOVAC7 *(HITESYS SpA)* *RF-based*	vs.	**CEA-Saclay experim. source** *Laser-based*
El. Energy < 10 MeV *(3, 5, 7, 9 MeV)*		*El. Energy > 10 MeV* *(10 - 45 MeV)*
Peak curr. 1.5 mA		*Peak curr. > 1.6 KA*
Bunch dur. 4 μs		*Bunch dur. < 1 ps* ←
Bunch char. 6 nC		*Bunch char. 1.6 nC* ←
Rep. rate 5 Hz		*Rep. 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*

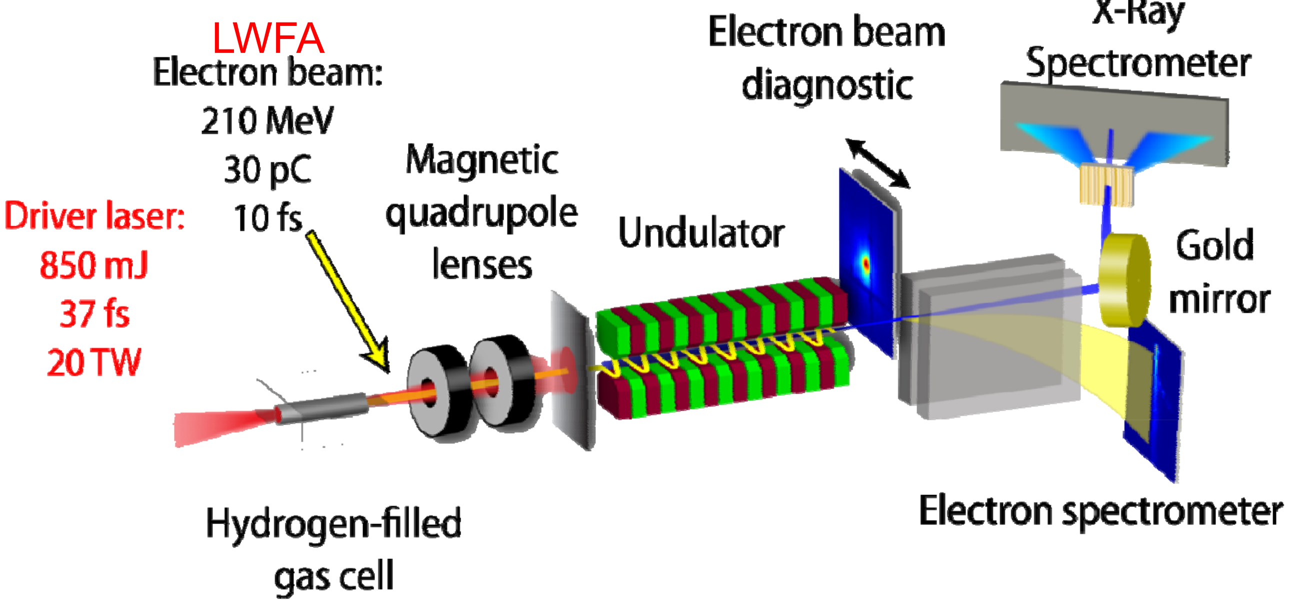
(A. Giulietti et al., Phys. Rev. Lett.,2008 : INFN)

Table-top Brilliant Undulator X-ray Radiation from **LWFA**

(M. Fuchs, et al., Nature Phys., 2009)

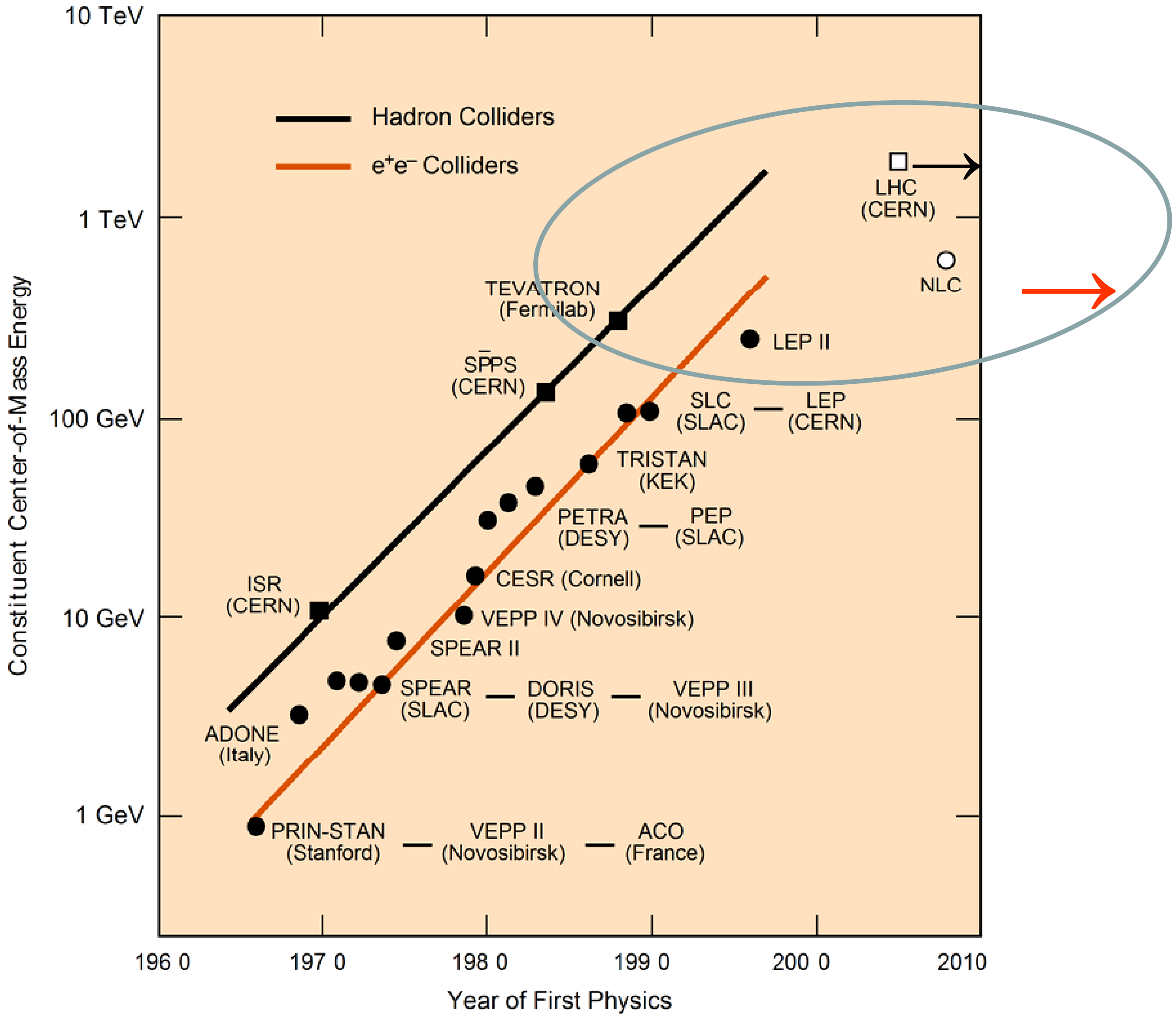
<u>Observed</u> undulator radiation spectrum





Toward compact XFEL

Livingston Chart and Recent Saturation



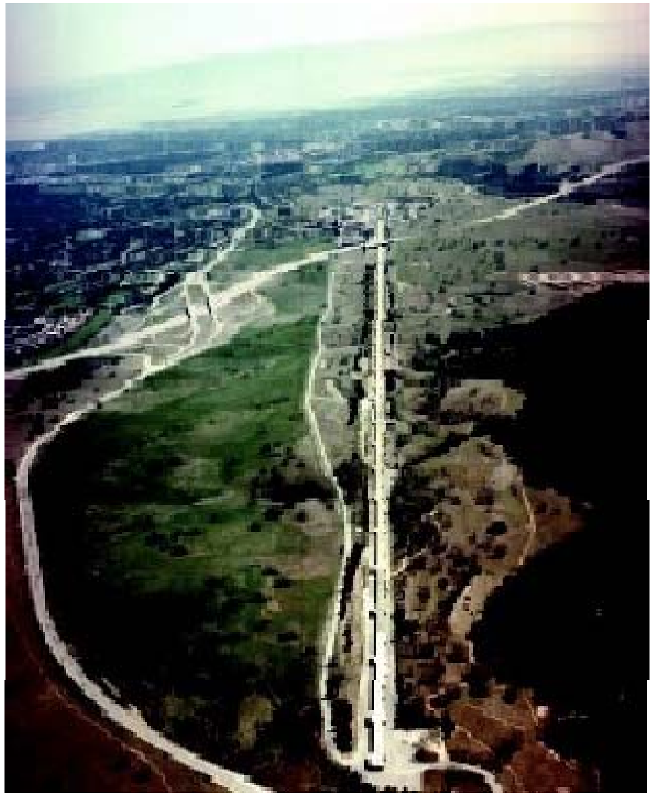
(Suzuki, 2009)

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

(Bridgelab Symposium, ILE,2011)

'Bridgelab' goal = to bridge laser and accelerator communities

Initiatives considered, emerging: *CERN, LBL, DESY, ILE, KEK, IOP, …*



***SLAC*'s 2 mile linac (50GeV)**

→

toward more compact accelerators

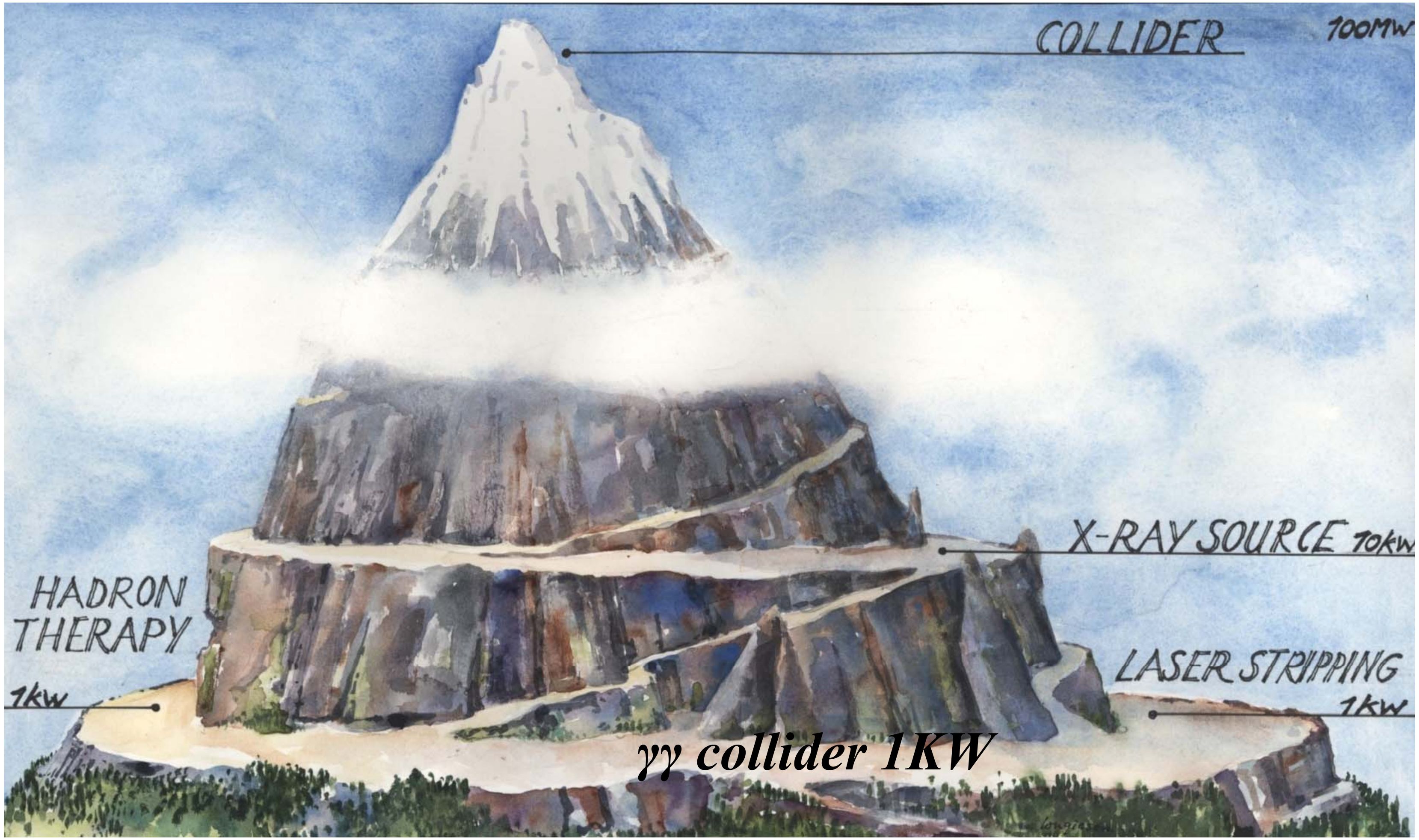
Laser acceleration =

- no material breakdown (→ 3/4 orders higher gradient); however:
- 3 orders finer accuracy, and 2 orders more efficient laser needed

Brief History of *ICUIL* – *ICFA* Joint Effort

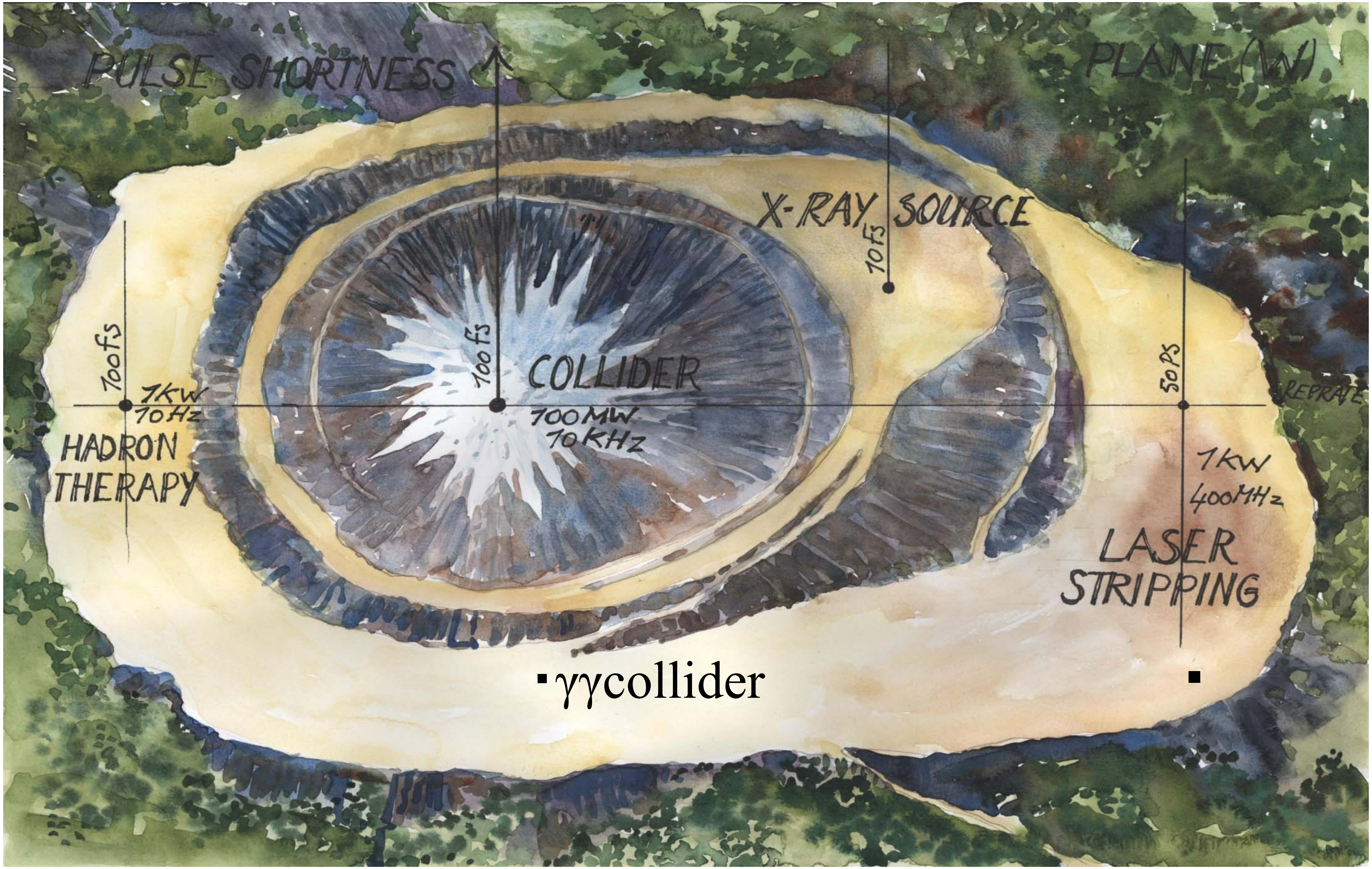
- *ICUIL* Chair Tajima sounded on A. Wagner (Chair *ICFA*) and Suzuki (incoming Chair) of a common interest in laser driven acceleration, Nov. 2008
- Leemans appointed in November 2008 to lay groundwork for joint standing committee of *ICUIL*
- *ICFA* GA invited Tajima for presentation by *ICUIL* and endorsed initiation of joint efforts on Feb. 13, 2009
- *ICFA* GA endorsed *Joint Task Force*, Aug. 2009
- *Joint Task Force* formed of *ICFA* and *ICUIL* members, W. Leemans, Chair, Sept, 2009
- First Workshop by *Joint Task Force* held @ GSI, Darmstadt, April, 2010
- Report to *ICFA* GA (July,2010) and *ICUIL* GA (Sept, 2010) on the findings
- ‘Bridgelab Symposium’ at L’Orme (Jan., 2011)

Mountain of Lasers
(average power)



(HEP Examples from *ICFA-ICUIL* JTF)
Friday 6pm Rochester: open JTF

Range of laser parameters



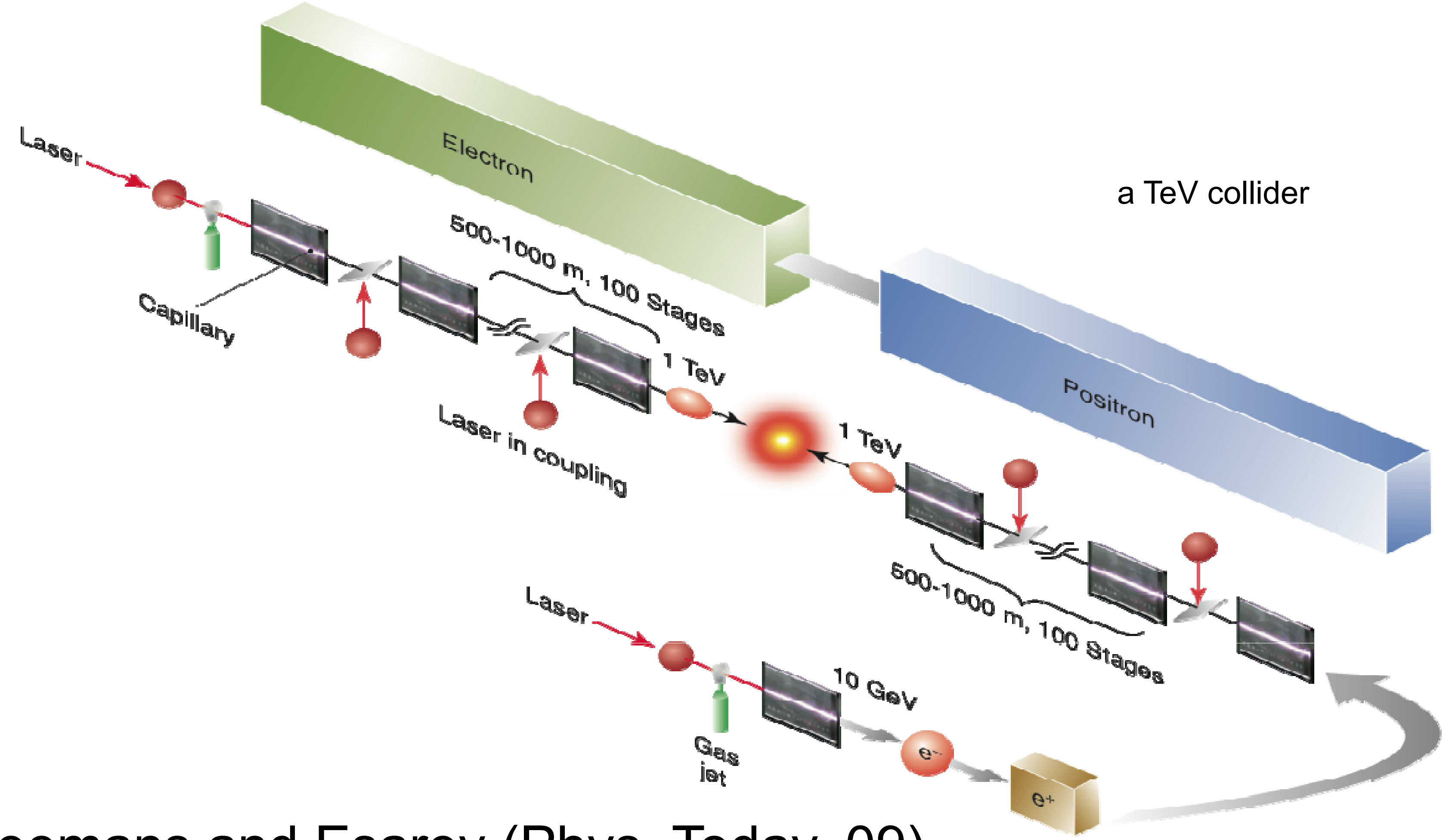
- γγcollider

Suggestions to ICFA-ICUIL JTF

- Science efforts by US, Europe, Asia mounting to extend the laser technology toward HEP accelerators
- Technology efforts still lacking in developing suited laser technology(ies) for HEP accelerators
- Technologies: emerging and credible for these
- ICFA-ICUIL collaboration: important guide of direction
- Lead lab(s) necessary to lead and do work on this initiative
- ‘Bridgelab’ / test facility?
- Other applications important (light sources, medical, nuclear waste management, fusion, defense, etc.)

(Tajima; April 10, 2010)

Laser driven collider concept



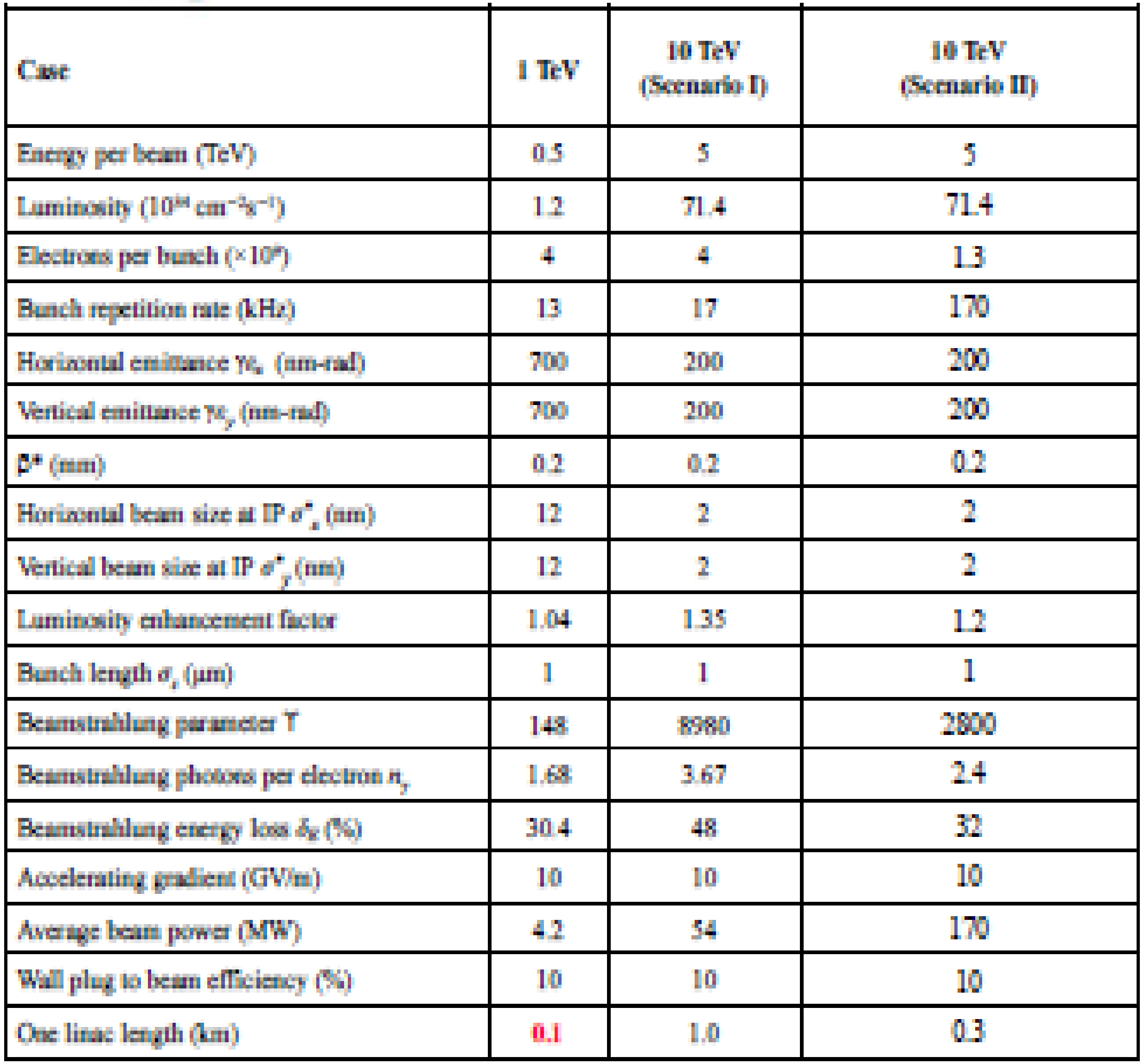
a TeV collider

Leemans and Esarey (Phys. Today, 09)

ICFA-ICUIL Joint Task Force on Laser Acceleration(Darmstadt,10)

ICFA-ICUIL Joint Task Force
on laser acceleration (Darmstadt, 2010)

W. Leemans,
Chair of JTF



Case	1 TeV	10 TeV (Scenario I)	10 TeV (Scenario II)
Energy per beam (TeV)	0.5	5	5
Luminosity (10^{34} cm^{-2}s^{-1})	1.2	71.4	71.4
Electrons per bunch ($\times 10^{9}$)	4	4	1.3
Bunch repetition rate (kHz)	13	17	170
Horizontal emittance $\gamma\varepsilon_x$ (nm-rad)	700	200	200
Vertical emittance $\gamma\varepsilon_y$ (nm-rad)	700	200	200
β^* (mm)	0.2	0.2	0.2
Horizontal beam size at IP σ^*_x (nm)	12	2	2
Vertical beam size at IP σ^*_y (nm)	12	2	2
Luminosity enhancement factor	1.04	1.35	1.2
Bunch length σ_z (μm)	1	1	1
Beamstrahlung parameter Υ	148	8980	2800
Beamstrahlung photons per electron n_γ	1.68	3.67	2.4
Beamstrahlung energy loss δ_E (%)	30.4	48	32
Accelerating gradient (GV/m)	10	10	10
Average beam power (MW)	4.2	54	170
Wall plug to beam efficiency (%)	10	10	10
One linac length (km)	0.1	1.0	0.3

Collider subgroup
List of parameters
(W. Chou)

Table 1
Collider parameters

Plasma density determined by beam quality and power requirement

(Nakajima, 2011)

Radiation damping effect

- Electrons accelerated by LPA undergo betatron oscillations due to strong focusing force
- Emission of synchrotron radiation results in a energy loss and radiation damping with its rate.

$$P_x \cong \frac{2e^2\gamma^2}{3m^2c^3}F_\perp^2 \qquad \nu_\gamma = \frac{P_s}{\gamma mc^2} = \frac{\tau_R\gamma}{m^2c^2}F_\perp^2$$

where $\tau_R = 2r_e/3c \cong 6.26\times10^{-24}$ s

$r_e = e^2/mc^2 = 2.818\times10^{-13}$ cm

$$F_\perp = -mc^2K^2x$$
$$K^2 = 2x_c^{-2}\left(e\phi_0/mc^2\right)$$

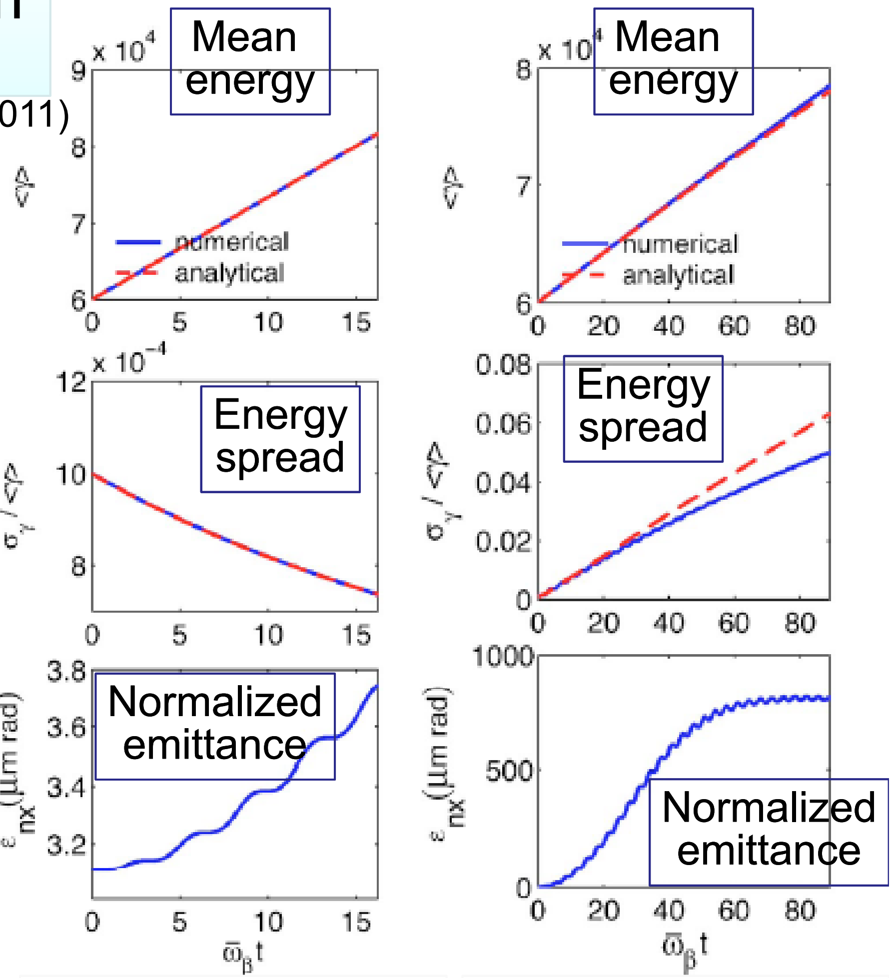
for the linear regime with potential ϕ_0, characteristic channel width x_c

$$K = k_p/\sqrt{2}$$

for the blowout (or bubble) regime

Power requirement for the linear collider

- Collision frequency: $f \propto N^{-2} \propto n_0$ for a constant required luminosity
- Beam power: $P_b = fNE_b \propto n_0^{1/2}$
- Average laser power per stage: $P_{avg} \cong fU_L \sim f\cdot P_L\tau_L \propto n_0\cdot n_0^{-1}\cdot n_0^{-1/2} \propto n_0^{-1/2}$
- Total wall plug power $P_{wall} \propto N_{stage}P_{avg} \propto n_0^{1/2}$



30 GeV injection 30 cm plasma channel E_z = 37 GV/m $n_0 = 10^{16}$ cm^{-3}	30 GeV injection 30 cm plasma channel E_z = 37 GV/m $n_0 = 3\times10^{17}$ cm^{-3}

P. Michel et al., PRE 74, 026501

From points of high quality and power cost, choose plasma density of the order of 10^{16} cm^{-3}

Issues for LWFA Collider

- Collider Physics issues (what is unique and challenging to LWFA)
  - strong acceleration (compactness)
  - small emittance (strong beam)
  - strong transverse force/large betatron oscillations
  - large quantum beamstrahlung effects
  - miniature finesse issues
- Driver issues (high rep rate, high average power lasers)

Collider Physics I

Basic parameters and scalings of LWFA Collider in Maximizing luminosity with constraintsof beamstrahlung , disruption, and γ emission

$$f_c = \left(\frac{P_b}{E_{cm}}\right)\left(\frac{1}{N}\right) \tag{1}$$

$$\sigma_y = \left(\frac{1}{\sqrt{4\pi}}\right)\left(\frac{1}{\sqrt{R}}\right)\left(\sqrt{\frac{P_b}{E_{cm}\mathcal{L}_g}}\right)\left(\sqrt{N}\right)$$

$$\Upsilon = \left(\frac{5\sqrt{\pi}r_e^2}{6\alpha mc^2}\right)\left(\frac{\sqrt{R}}{1+R}\right)\left(\sqrt{\frac{E_{cm}^3\mathcal{L}_g}{P_b}}\right)\left(\frac{\sqrt{N}}{\sigma_z}\right)$$

$$D_y = \left(16\pi mc^2 r_e\right)\left(\frac{R}{1+R}\right)\left(\frac{\mathcal{L}_g}{P_b}\right)(\sigma_z)$$

$$n_\gamma = 2.54U_0(\Upsilon)F\,, \quad \delta_E = 1.24\Upsilon U_1(\Upsilon)F \tag{5}$$

$$F = \left(\frac{5\sqrt{\pi}r_e^2}{3\lambda_c}\right)\left(\frac{\sqrt{R}}{1+R}\right)\left(\sqrt{\frac{E_{cm}\mathcal{L}_g}{P_b}}\right)\left(\sqrt{N}\right). \tag{6}$$

$$f_c \sim 1/N\,, \quad \sigma_y \sim \sqrt{N}\,, \quad D_y \sim \sigma_z\,, \quad \Upsilon \sim \sqrt{N}/\sigma_z \tag{7}$$

$$n_\gamma \sim U_0(\Upsilon)\sqrt{N}\,, \quad \delta_E \sim \Upsilon U_1(\Upsilon)\sqrt{N}. \tag{8}$$

In the limit $\Upsilon \gg 1$, $U_0(\Upsilon) \to 1/\Upsilon^{1/3}$, $\Upsilon U_1(\Upsilon) \to 1/\Upsilon^{1/3}$. Eq.(8) becomes

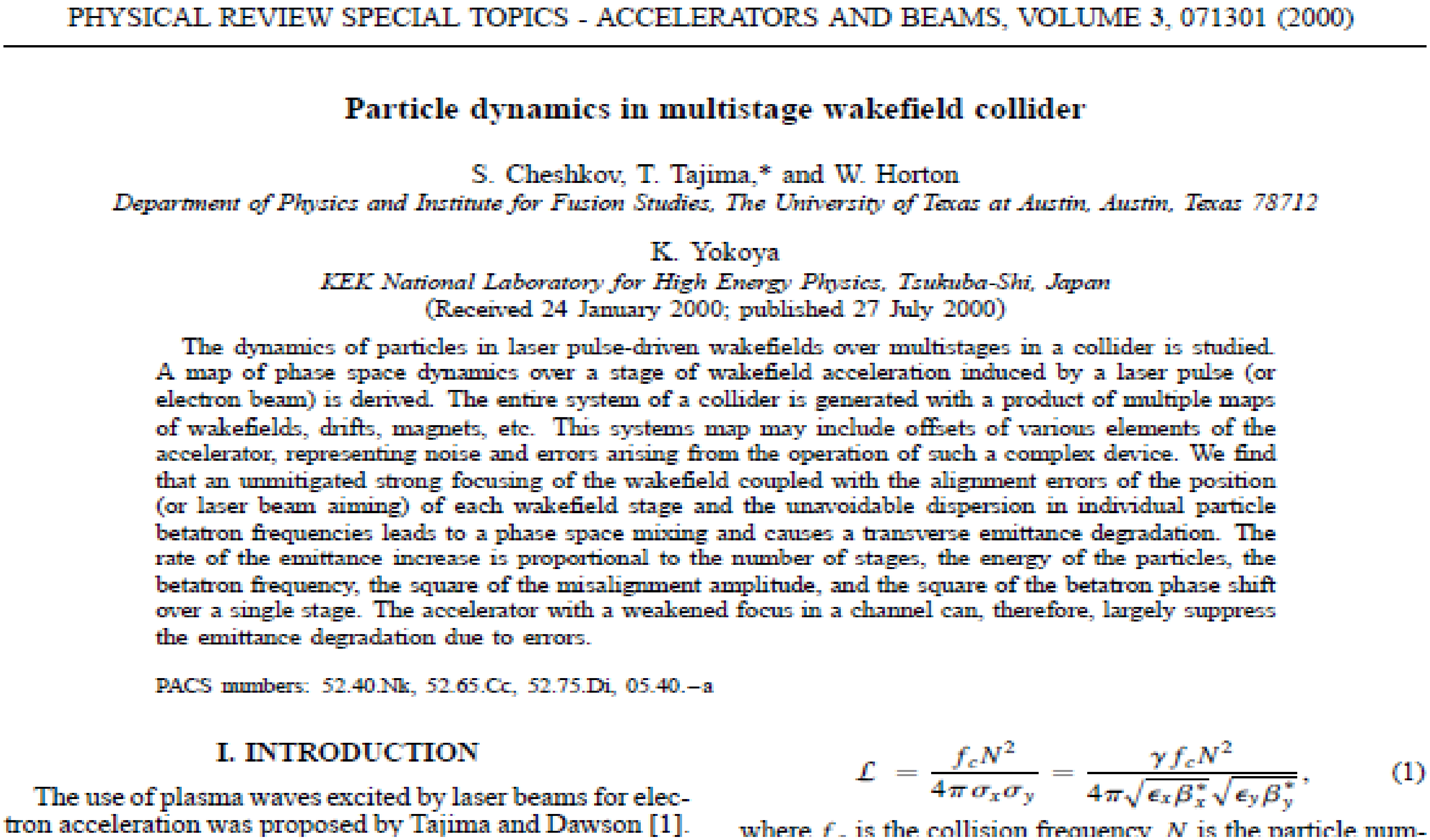
$$n_\gamma \sim (N\sigma_z)^{1/3}\,, \quad \delta_E \sim (N\sigma_z)^{1/3}. \tag{9}$$

First paper on LWFA collider
Xie, M., Tajima, T., Yokoya, K. and Chattopadyay, S., *Studies of Laser-Driven 5TeV e+e- Colliders in Strong Quantum Beamstrahlung Regime*, (AIP Conference Proceedings, New York, 1997), **398**, p. 233-242.

Collider Physics II

LWFA properties under multistage collider design

First multistage model for LWFA collider



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 3, 071301 (2000)

Particle dynamics in multistage wakefield collider

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K. Yokoya
KEK National Laboratory for High Energy Physics, Tsukuba-Shi, Japan

(Received 24 January 2000; published 27 July 2000)

The dynamics of particles in laser pulse-driven wakefields over multistages in a collider is studied. A map of phase space dynamics over a stage of wakefield acceleration induced by a laser pulse (or electron beam) is derived. The entire system of a collider is generated with a product of multiple maps of wakefields, drifts, magnets, etc. This systems map may include offsets of various elements of the accelerator, representing noise and errors arising from the operation of such a complex device. We find that an unmitigated strong focusing of the wakefield coupled with the alignment errors of the position (or laser beam aiming) of each wakefield stage and the unavoidable dispersion in individual particle betatron frequencies leads to a phase space mixing and causes a transverse emittance degradation. The rate of the emittance increase is proportional to the number of stages, the energy of the particles, the betatron frequency, the square of the misalignment amplitude, and the square of the betatron phase shift over a single stage. The accelerator with a weakened focus in a channel can, therefore, largely suppress the emittance degradation due to errors.

PACS numbers: 52.40.Nk, 52.65.Cc, 52.75.Di, 05.40.−a

I. INTRODUCTION

The use of plasma waves excited by laser beams for electron acceleration was proposed by Tajima and Dawson [1].

$$\mathcal{L} = \frac{f_c N^2}{4\pi\sigma_x\sigma_y} = \frac{\gamma f_c N^2}{4\pi\sqrt{\epsilon_x\beta_x^*}\sqrt{\epsilon_y\beta_y^*}}, \qquad (1)$$

where f_c is the collision frequency, N is the particle num-

Collider Physics III

Cumulative effects over multistages

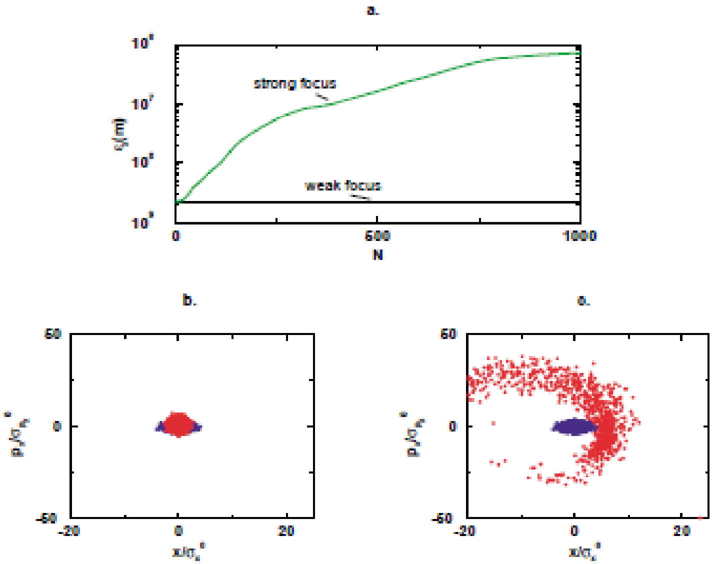
Strong LWFA betatron oscillations lead to emittance degradation

severe transverse emittance growth. Basically, what
ens is that the particles rotate at different angular ve-
ies in the transverse phase space and, if there is a
e position shift present, we get a characteristic banana-
ed distribution (see Fig. 3c) (it is banana shaped only
e dislocation size is larger than the beam size, but in
case the particle distribution gets diluted because of
nisalignments). This process critically depends on the
nitude of the betatron frequency spread. This means
the typical strength of the focusing force is of great
ortance. Of course, additional information can be ex-
ed from the other total phase space cross sections; see
4. However, here we concentrate on the transverse
tance as a figure of merit due to its importance to the
luminosity of the collider. The effect of plasma noise
ther noise, such as laser or the boundary) on the par-
dynamics over a stage may also be incorporated in a

$$\begin{pmatrix} \bar{x}_{n+1} \\ \dot{\bar{x}}_{n+1} \end{pmatrix} = M_n \begin{pmatrix} \bar{x}_n - \bar{\mathcal{D}}_n \\ \dot{\bar{x}}_n \end{pmatrix} + \begin{pmatrix} \bar{\mathcal{D}}_n \\ 0 \end{pmatrix}, \qquad (34)$$

where $\mathcal{D}_n$ is the stochastic misalignment ($\bar{\mathcal{D}}_n = \sqrt{\gamma_n}\,\mathcal{D}_n$). The longitudinal degrees of freedom are not affected. For this map to describe realistically the electron motion, we assume that $\sigma_{\mathcal{D}} \ll r_s$. The total transverse map (in the presence of errors) can be written in the form

$$\begin{aligned} \begin{pmatrix} \bar{x}_{n+1} \\ \dot{\bar{x}}_{n+1} \end{pmatrix} &= M_n M_{n-1} \cdots M_2 (1 - M_1) \begin{pmatrix} \bar{\mathcal{D}}_1 \\ 0 \end{pmatrix} \\ &+ \cdots (1 - M_n) \begin{pmatrix} \bar{\mathcal{D}}_n \\ 0 \end{pmatrix} \\ &+ M_n M_{n-1} \cdots M_1 \begin{pmatrix} \bar{x}_1 \\ \dot{\bar{x}}_1 \end{pmatrix}. \qquad (35) \end{aligned}$$



Cheshkov et al (2000)

$$\langle \mathcal{D} \rangle = 0, \qquad (38)$$

$$\langle \mathcal{D}(z_1)\mathcal{D}(z_2) \rangle = \sigma_{\mathcal{D}}^2 l \,\delta(z_1 - z_2). \qquad (39)$$

Applying the theory of random walk of a harmonic oscillator driven by a random force, we obtain

$$\langle \bar{x} \rangle = 0, \qquad \langle \dot{\bar{x}} \rangle = 0, \qquad \langle \bar{x}\dot{\bar{x}} \rangle = 0, \qquad (40)$$

$$\langle \bar{x}^2 \rangle = Dz = DNl, \qquad \langle \dot{\bar{x}}^2 \rangle = D\omega^2 z, \qquad (41)$$

where the diffusion coefficient D is given by

$$D = \frac{1}{2}\gamma\omega^2 l \sigma_{\mathcal{D}}^2. \qquad (42)$$

We are also assuming that the emittance growth is large (compared to the initial emittance). So, using (40) and (41), we obtain

$$\Delta\epsilon \approx \omega D z = \frac{1}{2}\gamma\omega(\omega l)^2 \sigma_{\mathcal{D}}^2 N. \qquad (43)$$

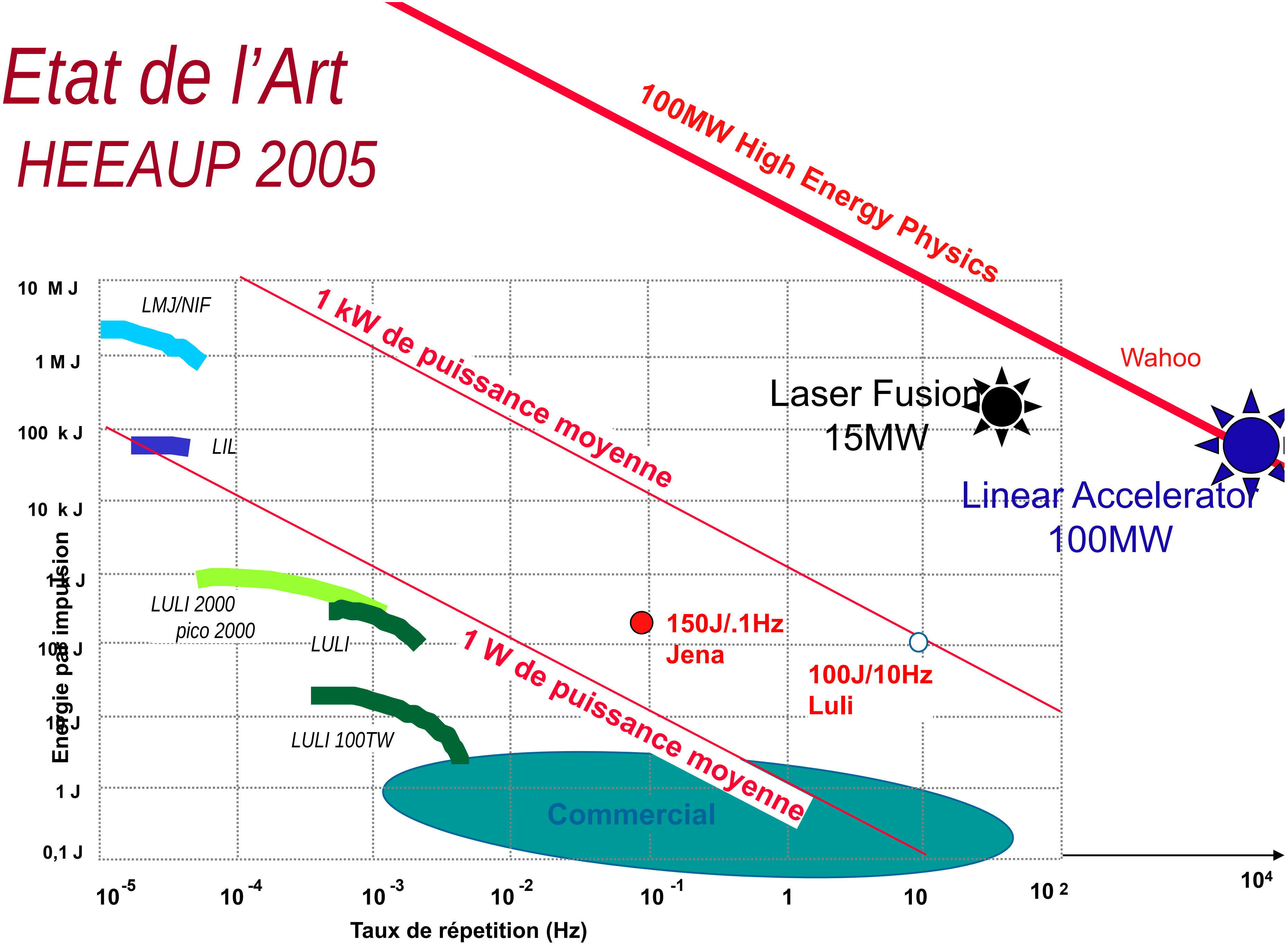
$$\Delta\epsilon \approx \frac{1}{2}\gamma\omega(\omega l)^2 \sigma_{\mathcal{D}}^2 \left(\frac{\gamma}{\Delta\gamma}\right)^{1/2} \sqrt{N \ln\left(1 + \frac{\Delta\gamma N}{\gamma}\right)}, \qquad (44)$$

where γ is the initial particle energy. Typically, $\Delta\gamma \approx a_0^2 E_0 l$ and $\omega \propto \frac{a_0}{r_s}$, so we obtain

$$\Delta\epsilon \propto \frac{l^{3/2} a_0^2 \sigma_{\mathcal{D}}^2}{r_s^3 E_0^{1/2}} \sqrt{N \ln\left(1 + \frac{\Delta\gamma N}{\gamma}\right)}. \qquad (45)$$

Etat de l'Art

HEEAUP 2005



G. Mourou (2005)

Toward a solution of laser driver fit for HEP

Formation of a consortium to study high efficiency,
high rep rate fiber laser system:

ICAN, International Coherent Amplification Network

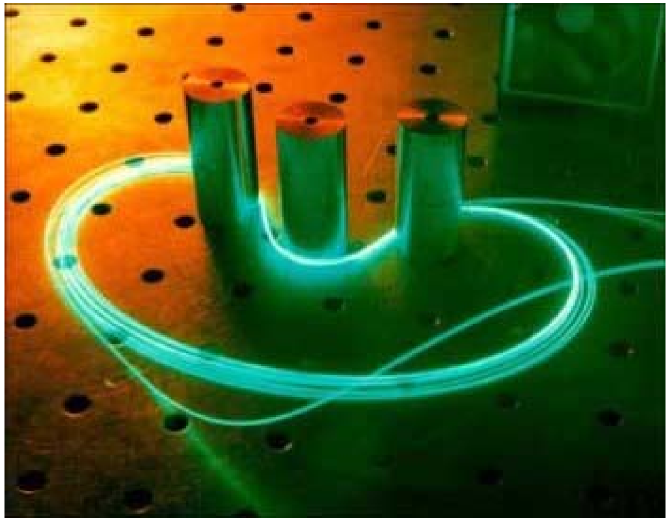
“Solving the efficiency problem in high peak and high average power laser: an international effort”

(Coordinator G. Mourou, submitted to the EU November 25, 2010)

Now in a shortlist in EU (March, 2011)

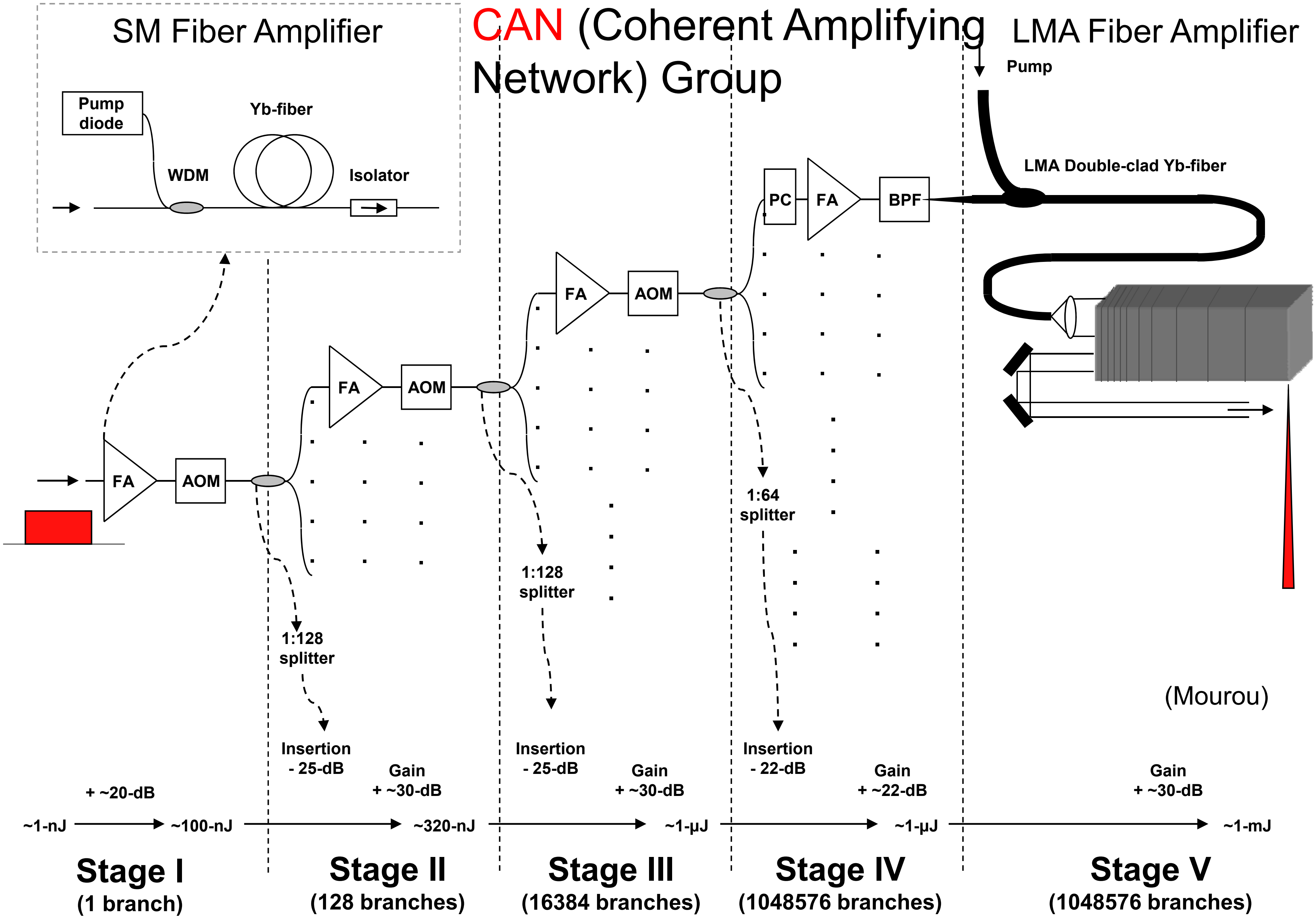
Fiber vs. Bulk lasers

- High Gain fiber amplifiers allow ~ 40% total plug-to-optical output efficiency
- Single mode fiber amplifier have reached multi-kW optical power.
- large bandwidth (100fs)
- immune against thermo-optical problems
- excellent beam quality
- efficient, diode-pumped operation
- high single pass gain
- They can be mass-produced at low cost.



(G. Mourou)

CAN (Coherent Amplifying Network) Group



Stage I
(1 branch)

Stage II
(128 branches)

Stage III
(16384 branches)

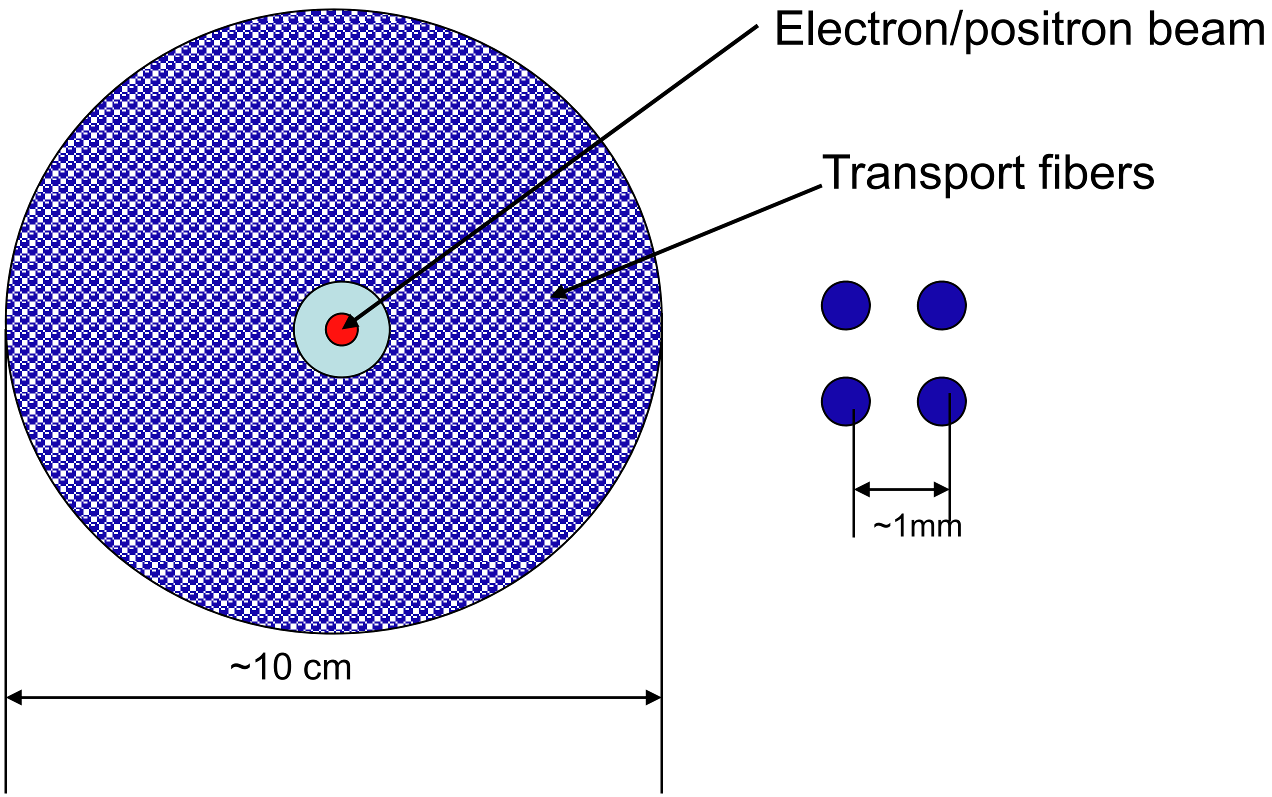
Stage IV
(1048576 branches)

Stage V
(1048576 branches)

(Mourou)

1.5 MW Fiber bundles (x100)

Because the transport fibers are lossless they will be assembled in a bundle just before the focusing optics. They will be all coherently phased.



Electron/positron beam

Transport fibers

~1mm

~10 cm

Length of a fiber ~5m   Total fiber length~ 5 10^4km

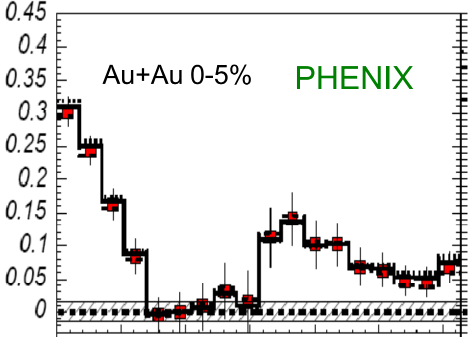
(Mourou et al)

Nuclear Wake?

- BNL (and CERN) heavy ion collider: **“monojet”**
- Could be caused by:
  - Large angle gluon radiation (Vitev and Polsa and Salgado).
  - Deflected jets, due to flow (Armesto, Salgado and Wiedemann) and/or path length dependent energy loss (Chiu and Hwa).
  - Hydrodynamic conical flow from mach cone shock-waves (Stoecker, Casalderrey-Solanda, Shuryak and Teaney, Renk, Ruppert and Muller).
  - Cerenkov gluon radiation (Dremin, Koch).
- Jet quenching: <u>collective deceleration</u> by wakefield?
  - LWFA method, or Maldacena method?

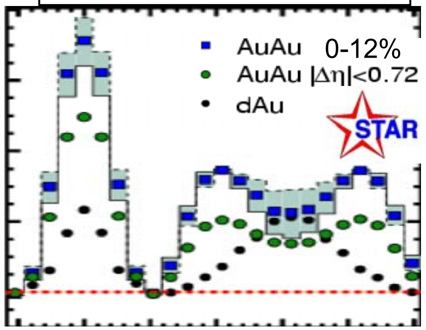
PHENIX PRL 97, 052301 (2006)

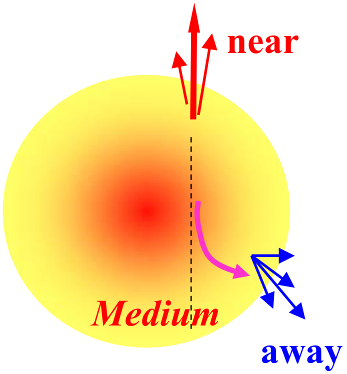
$2.5<p_T^{Trigger}<4$ GeV/c
$1<p_T^{Assoc}<2.5$ GeV/c



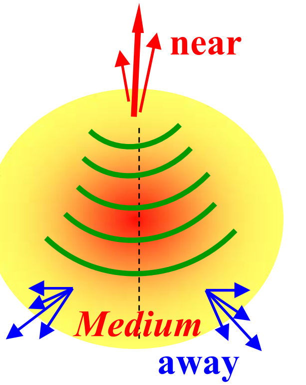
Horner (STAR) QM2006

$3<p_T^{Trigger}<4$ GeV/c
$1<p_T^{Assoc}<2.5$ GeV/c

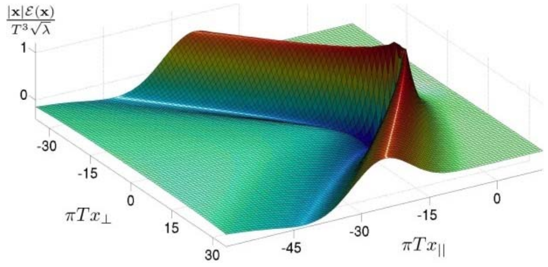




Deflected Jets



Conical Emission



Maldacena

Maldacena (string theory) method:
QCD **wake** (Chesler/Yaffe 2008)

Challenge Posed by DG Suzuki

Frontier science driven by advanced accelerator

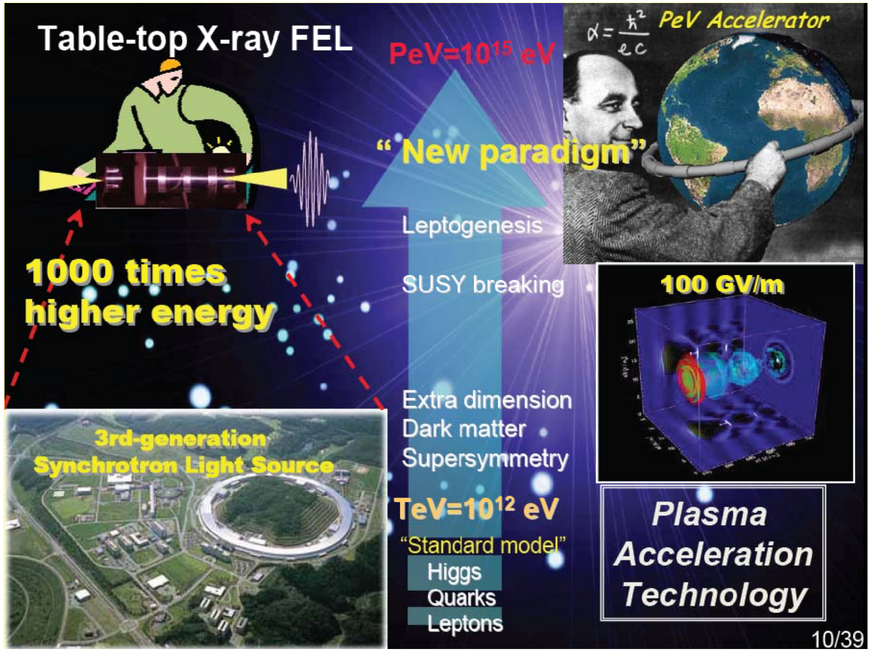


Table-top X-ray FEL

$PeV = 10^{15}$ eV

PeV Accelerator

"New paradigm"

Leptogenesis

SUSY breaking

1000 times higher energy

100 GV/m

Extra dimension
Dark matter
Supersymmetry

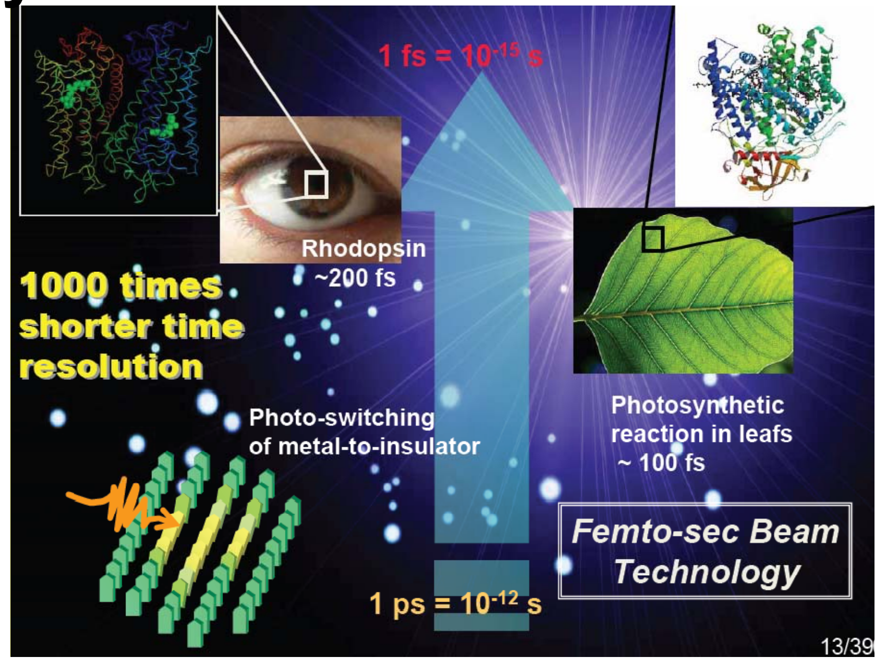
3rd-generation Synchrotron Light Source

$TeV = 10^{12}$ eV

"Standard model"
Higgs
Quarks
Leptons

Plasma Acceleration Technology

10/39



$1 \text{ fs} = 10^{-15}$ s

Rhodopsin
~200 fs

1000 times shorter time resolution

Photo-switching
of metal-to-insulator

Photosynthetic
reaction in leafs
~ 100 fs

Femto-sec Beam Technology

$1 \text{ ps} = 10^{-12}$ s

13/39

compact, ultrastrong *a*,
toward PeV

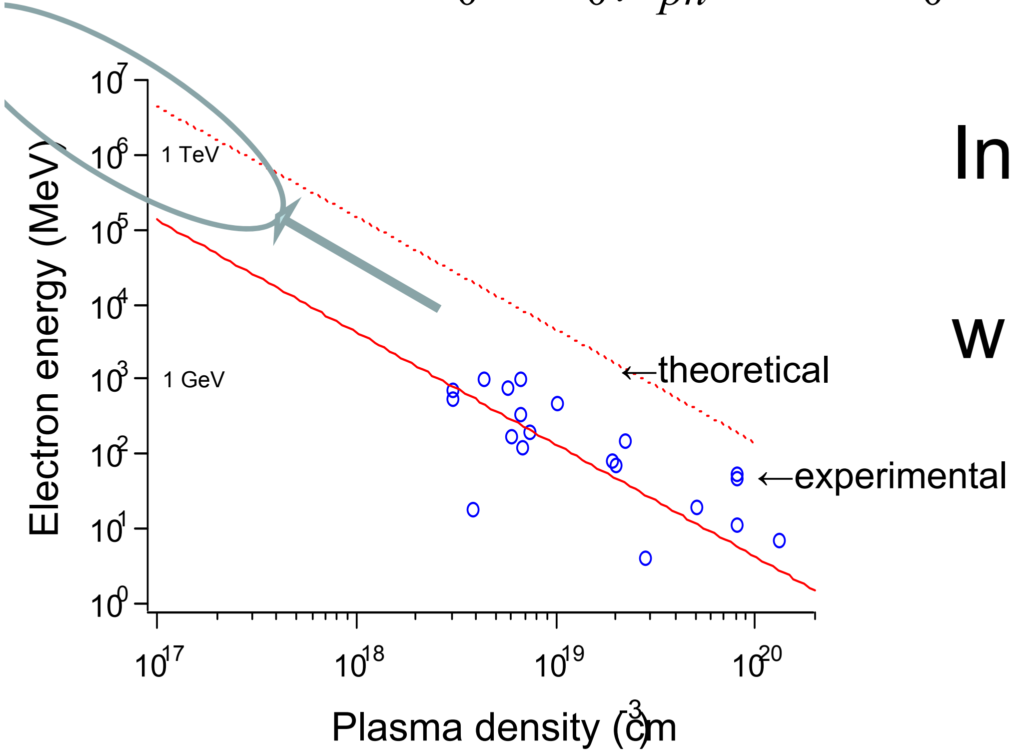
atto-, zeptosecond

Can we meet his challenge?

A. Suzuki @KEK(2008)

Theory of **wakefield** toward extreme energy

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



In order to avoid wavebreak,

$$a_0 < \gamma_{ph}{}^{1/2},$$

where

$$\gamma_{ph} = (n_{cr}/n_e)^{1/2}$$

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

dephasing length

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

pump depletion length

Adopt:
NIF laser (3MJ)
→ 0.7PeV
(with Kando, Teshima)

γ-ray signal from primordial GRB

LETTERS NATURE

(Abdo, et al, 2009)

←lower energy

higher→

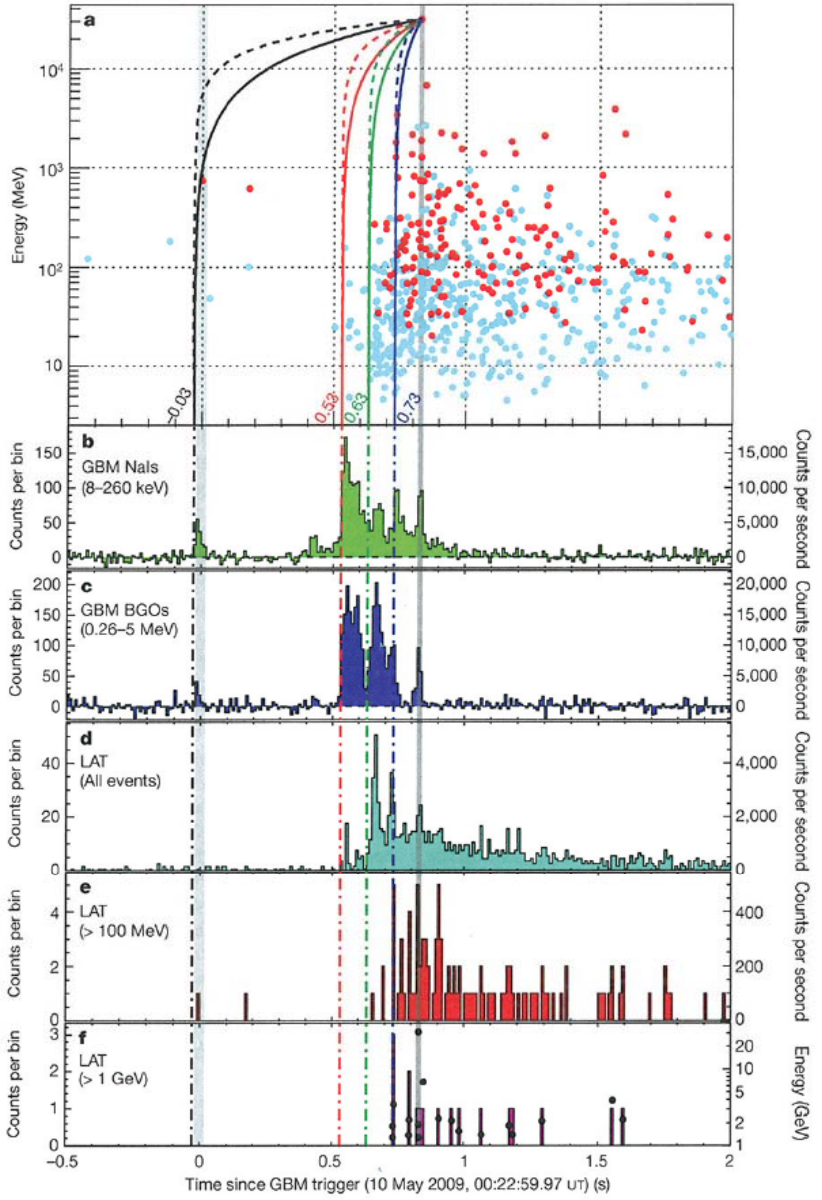


Figure 1 | Light curves of GRB 090510 at different energies. a, Energy lowest to highest energies. **f** also overlays energy versus arrival time for each

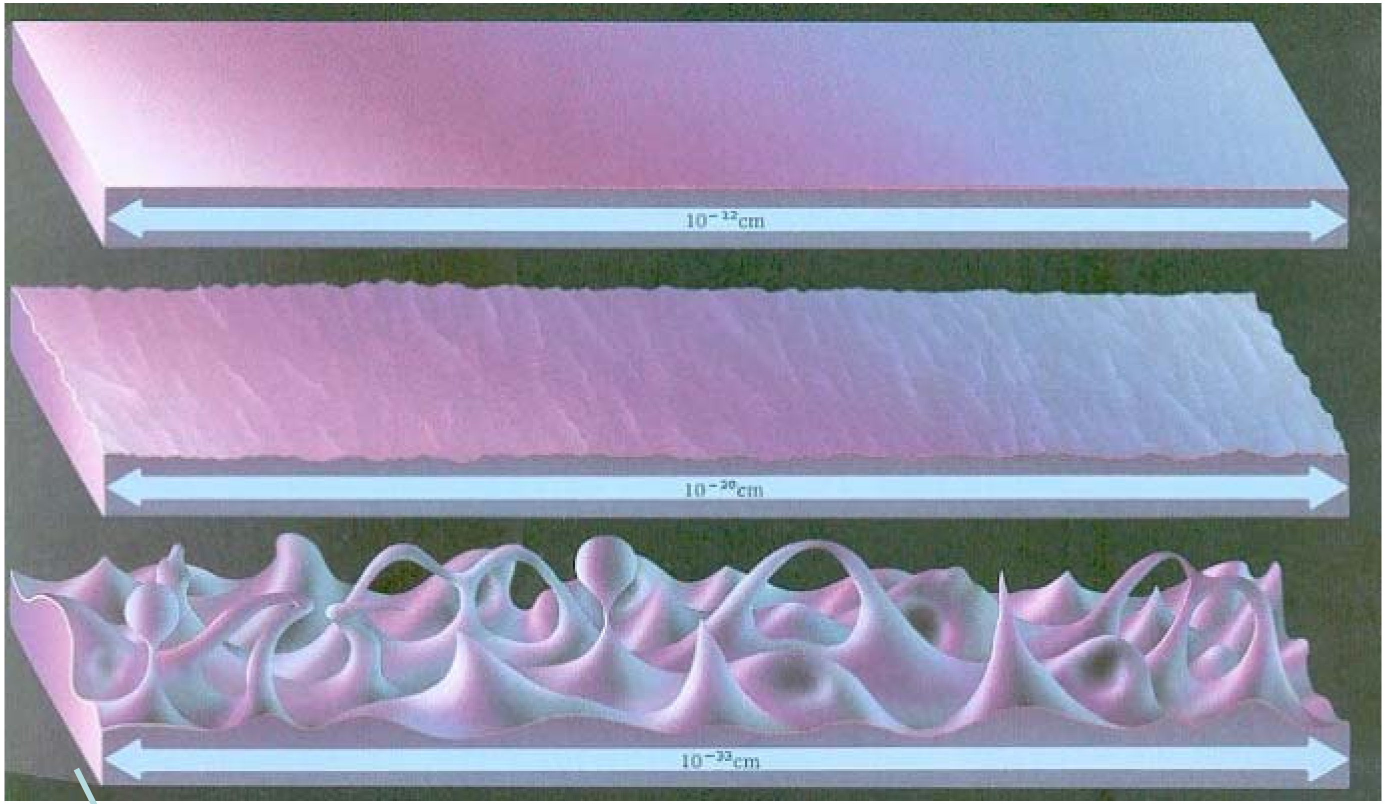
Energy-dependent
photon speed ? (Ellis, …)

Observation of primordial
Gamma Ray Bursts (GRB)
(limit is pushed up
close to Planck mass)

Lab PeV γ (from e-)
can explore this
with control

Feel vacuum texture: PeV γ

Laser acceleration → controlled laboratory test to see quantum gravity texture
on photon propagation (Special Theory of Relativity: c_0)



Coarser,
lower energy
texture

Finer,
higher energy
texture

$c < c_0$

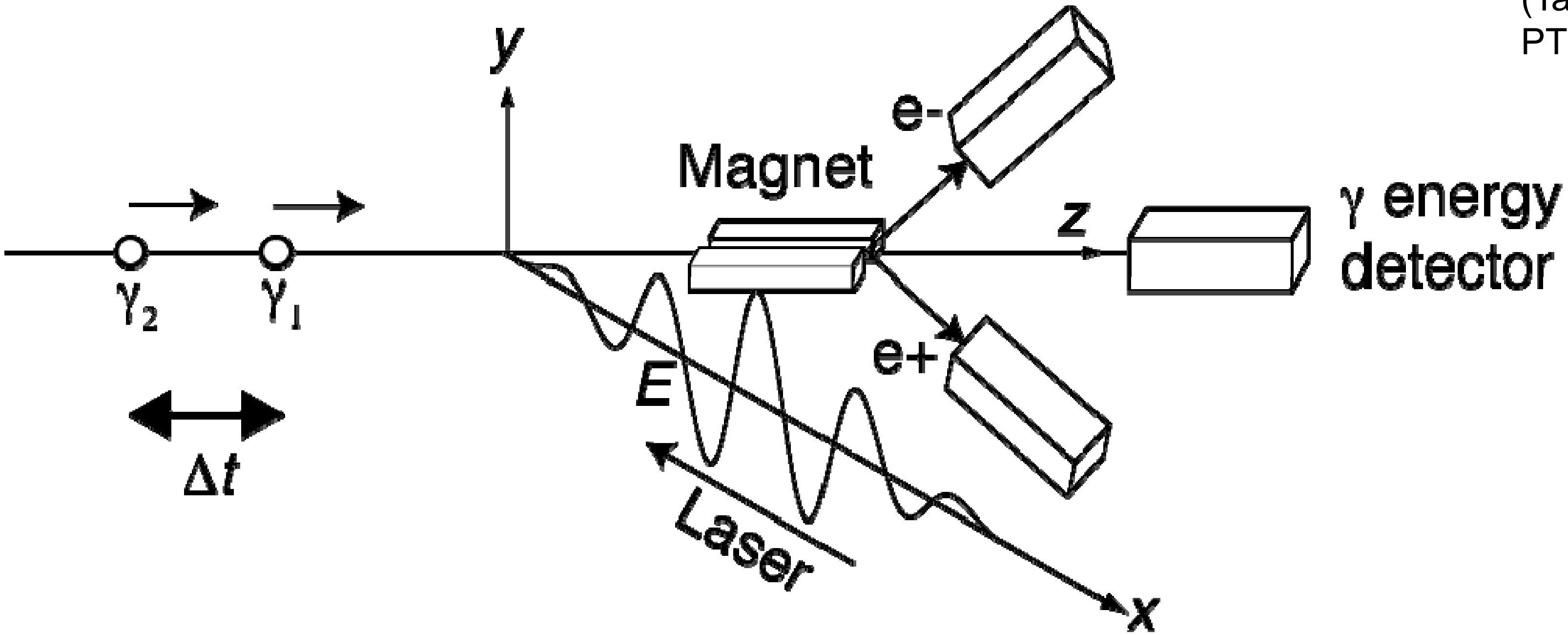
← (0.1PeV)

1km

←(1PeV : fs behind)

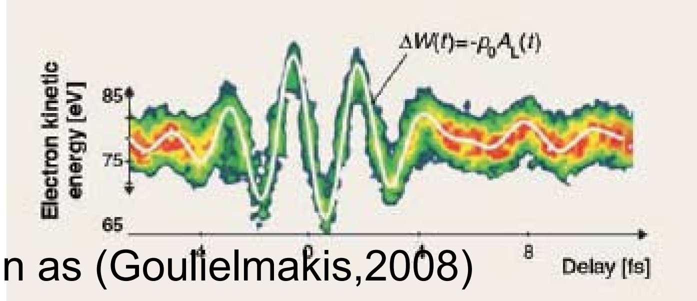
PeV γ (converted from e^-)

Attosecond Metrology of PeV γ Arrivals



(Tajima, Kando, PTP, 2011)

High energy γ- induced Schwinger breakdown (Narozhny, 1968)
CEP laser : phase sensitive electron-positron acceleration
Attosecond electron streaking of vacuum
γ- energy tagging possible

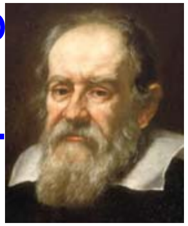


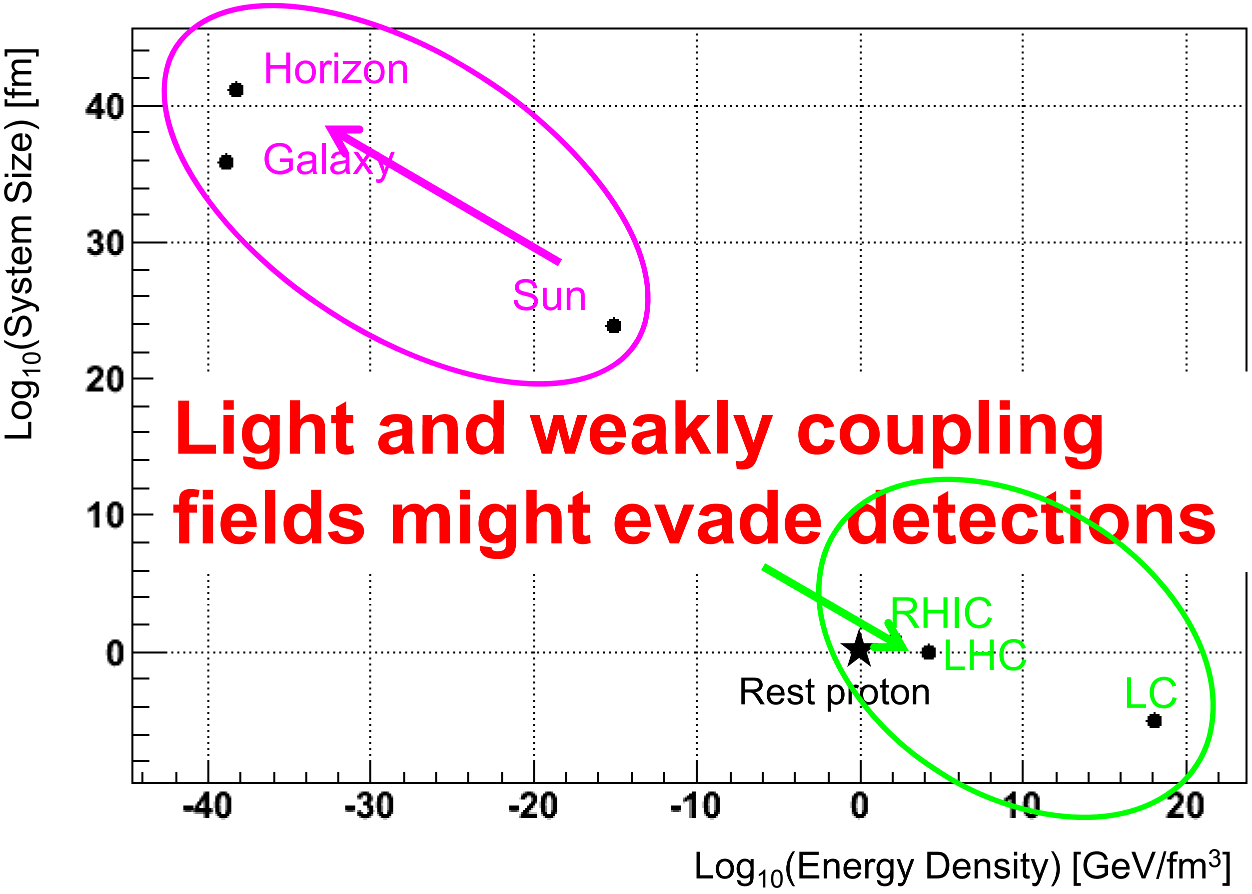
Atomic streaking in as (Goulielmakis,2008)

Domains of physical laws materialized: beyond colliders

Cosmological observation

Weak coupling
m=0





Light and weakly coupling fields might evade detections

Strong coupling
Heavy m

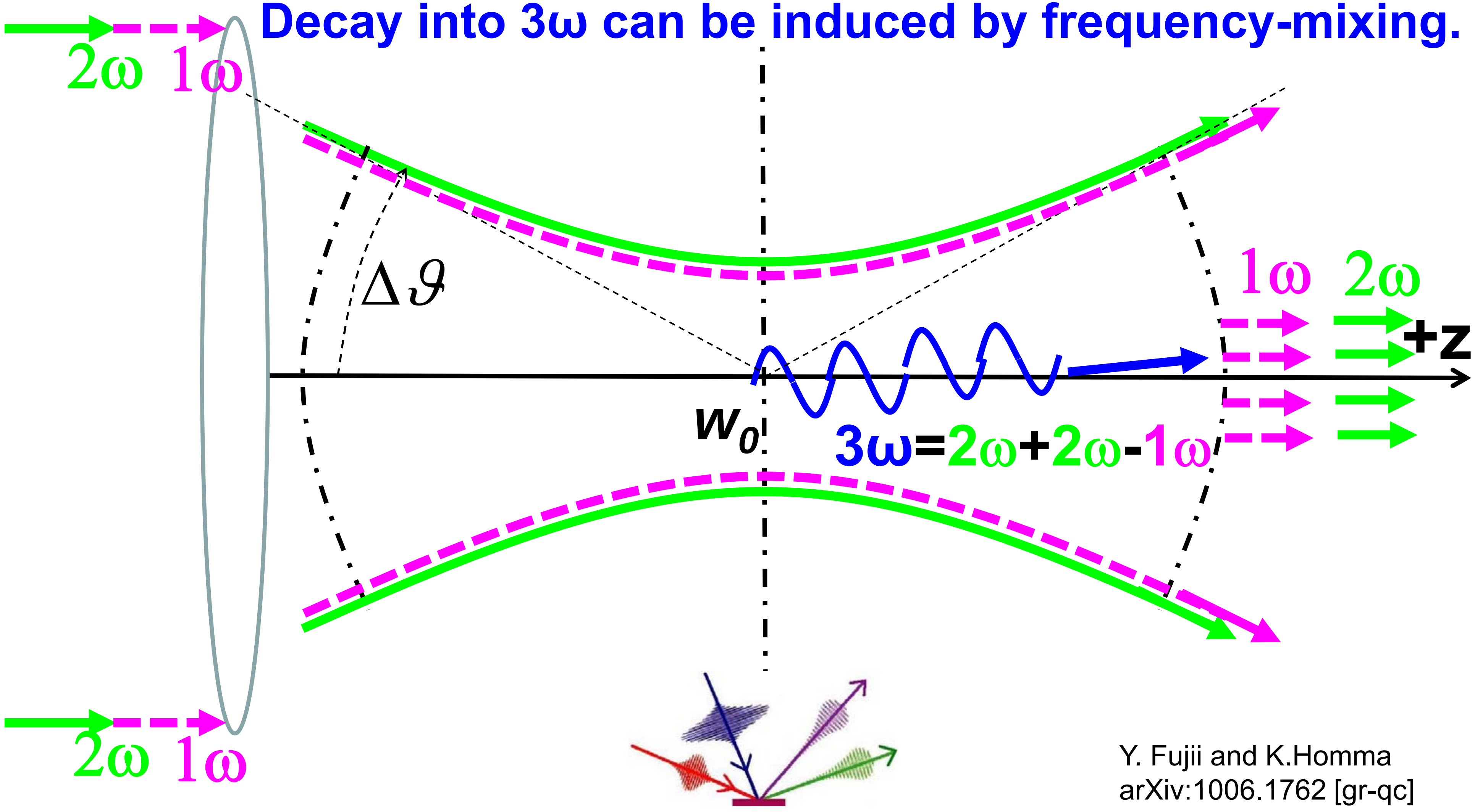
High energy collider

Homma, Habs, Tajima: to be published

Degenerated Four-Wave Mixing (DFWM)

Laser-induced field induction of vacuum ← Nonlinear optics idea

Decay into 3ω can be induced by frequency-mixing.

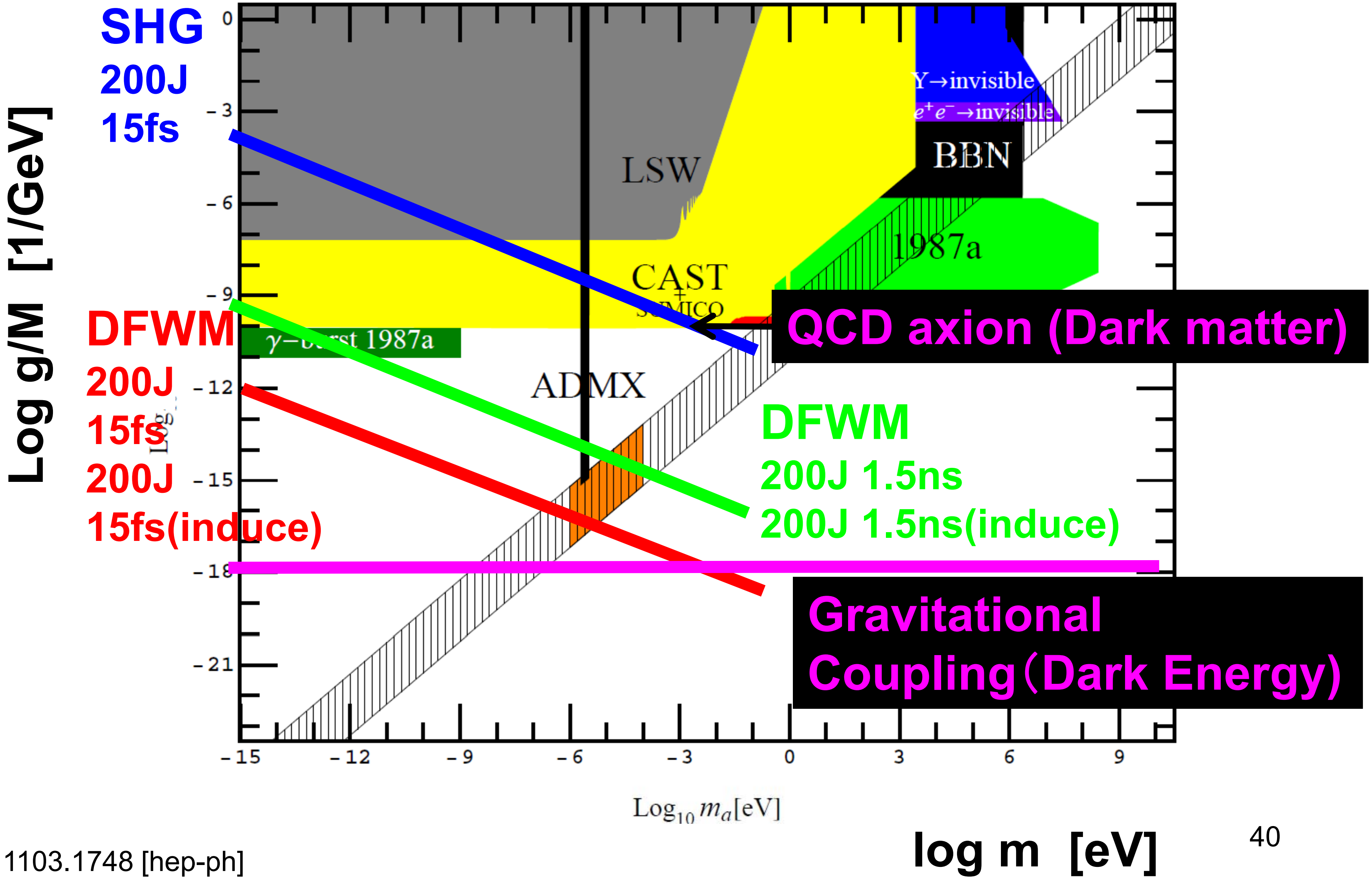


Possible detection of weak and light fields, such as dark matter (axions) and dark energy fields

Y. Fujii and K.Homma
arXiv:1006.1762 [gr-qc]

K.Homma, D.Habs, T.Tajima

HFS road to unknown fields: dark matter and dark energy



arXiv:1103.1748 [hep-ph]
K.Homma, D.Habs, T.Tajima

conclusions

- Collectively driven wakefield provides unique and new tool for HEP (and other applications)
- Bridge between accelerator and laser communities necessary-----a Bridgelab, ICUIL-ICFA collaboration, this EuCRAD, EuroNNAc, …
- Collider physics requirements: luminosity maximization, small beam, large betatron, emittance preservation: challenges
- Drive laser for collider: a huge challenge, but possible technologies emerging
- Energy frontier with precision w/ a few shots possible
- High field science approach: new capability to explore undiscovered new fields

Centaurus A:

cosmic
wakefield
Linac
for Ultra High
Energy Cosmic
Rays (UHECR)?

Thank you!