Colloquium
Fermilab
Batavia, IL
Wednesday, July 20, 2011

Laser Wakefield Acceleration and Fundamental Physics

Toshiki Tajima
LMU and MPQ, Garching, Germany

Acknowledgments for Collaboration and advice: G. Mourou, W. Leemans, K. Nakajima, K. Homma, D. Habs, K. Witte, C.. Barty, P. Chomaz, D. Payne, H. Videau, P. Martin, V. Malka, F. Krausz, T. Esirkepov, S. Bulanov, M. Kando, W. Sandner, A. Suzuki, M. Teshima,, B. Cros, 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, E. Goulielmakis, X. Q. Yan, J. E. Chen, R. Li, J. Rossbach, A. Ringwald, E. Elsen, H. Ruhl, T. Ostermayr, S. Petrovic, C. Klier, B. Altschul, Y. K. Kim

1. Relativistic coherence:
   Relativistic Optics, Laser Wakefield, FEL
2. Applications of Laser Wakefield Accelerator:
   cancer therapy (IORT), ultrafast radiolysis,
   THz, X-ray radiation sources, compact XFEL,
   ion acceleration, collider, collective decelerator,
   extreme high energy acceleration,…
3. Bridge between laser and accelerator communities:
   ICUIL-ICFA collaboration, ELI, 'Mega Project',….
4. A future collider option----low density operation
5. Collider physics challenges
6. Laser technology development for collider: ICAN
7. Energy frontier at PeV with attosceond metrology:
   Non-luminosity paradigm
8. High Field explores low energy new fields:
   high momentum ↔ high field

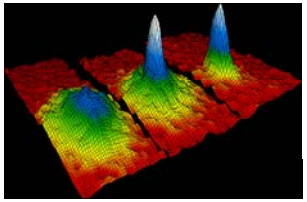
Energy frontier ← High field science, high intensity laser

relativistic optics: *relativistic coherence*

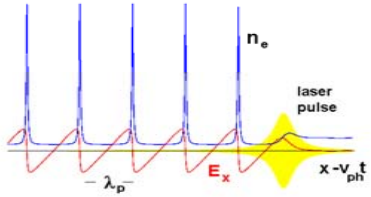
cf. quantum optics: *quantum coherence*

Quantum optics
Cold Atoms
feV-neV

2010



1eV



Relativistic
optics
GeV-TeV

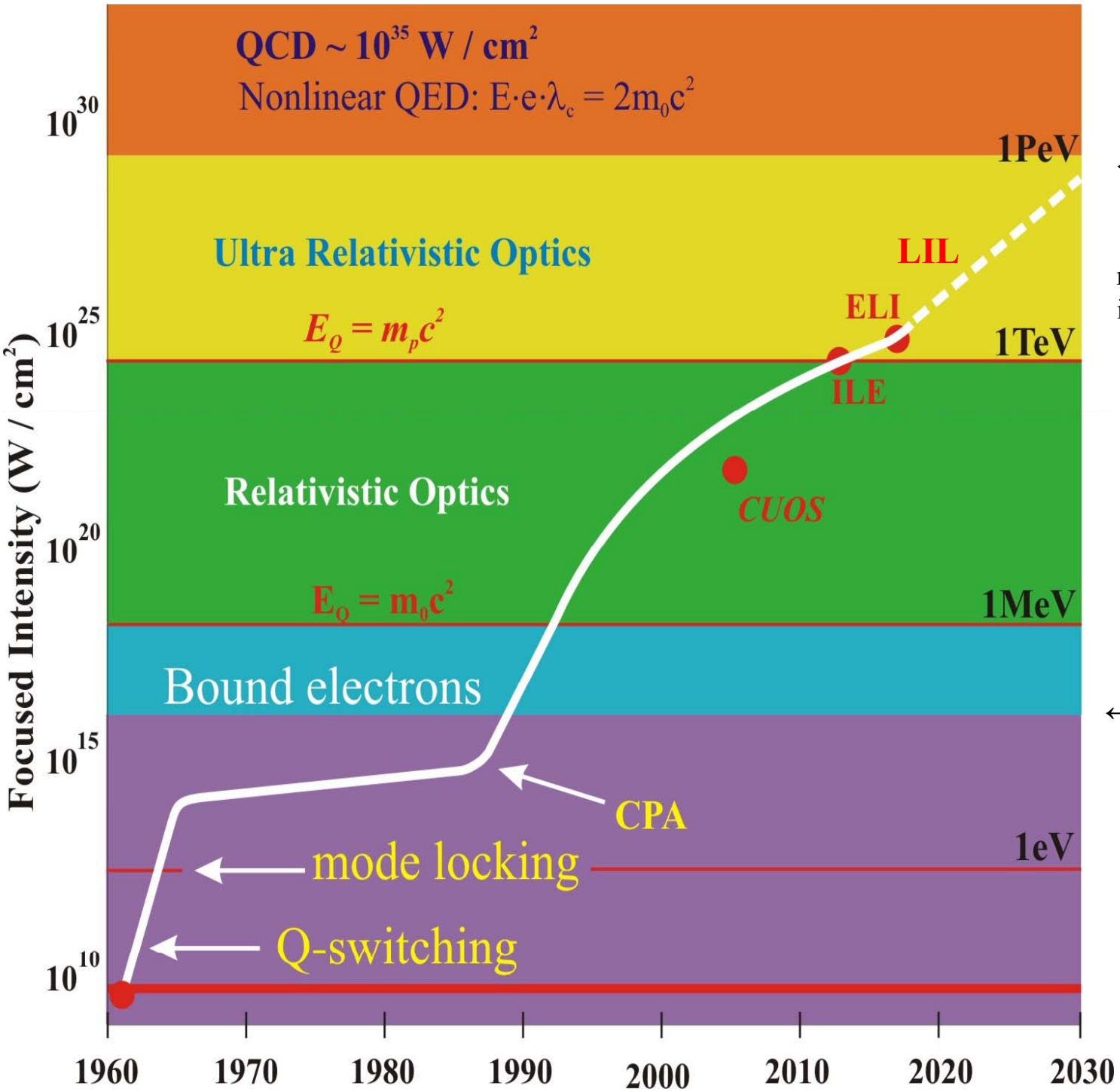
2010

1960

Cohen-Tannoudji,Chu,
Ketterle,…

Relativistic Optics, RMP, Mourou (2006)

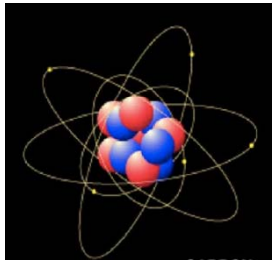
High field science ⟷ **High energy Physics (fundamental physics)**



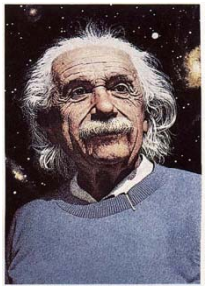
boiled vacuum

←**Schwinger field**

relativistic ions



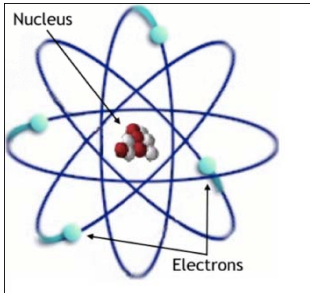
relativistic electrons



plasma

←**Keldysh field**

atoms



Relativistic nonlinearity under intense laser

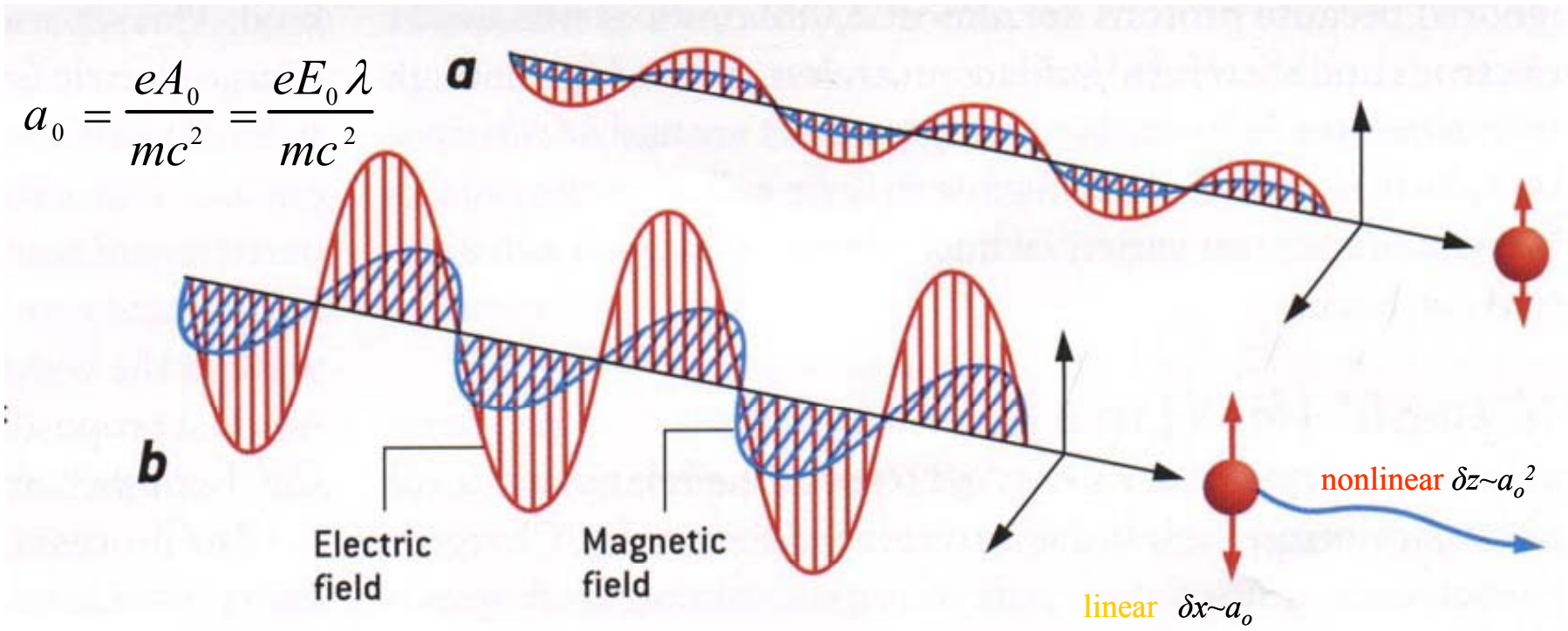
a) Classical optics : $v << c$,

$a_0 << 1$: δx only

b) Relativistic optics: $v \sim c$

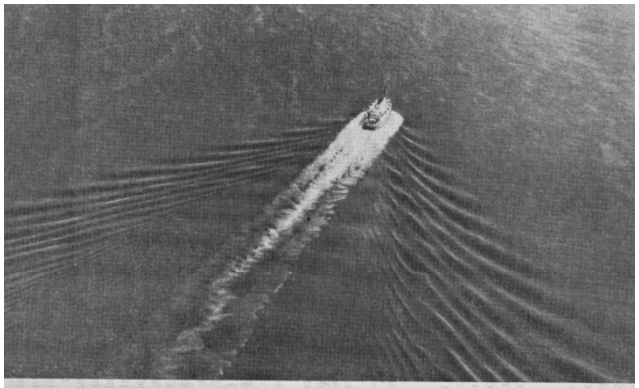
$a_0 >> 1$: $\delta z >> \delta x$

$$a_0 = \frac{eA_0}{mc^2} = \frac{eE_0\lambda}{mc^2}$$

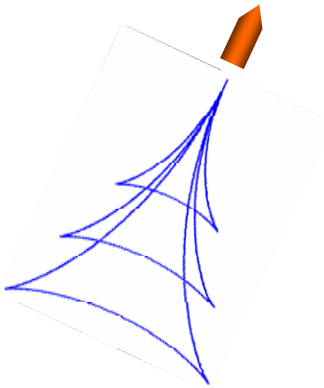


Wakefield : a Collective Phenomenon

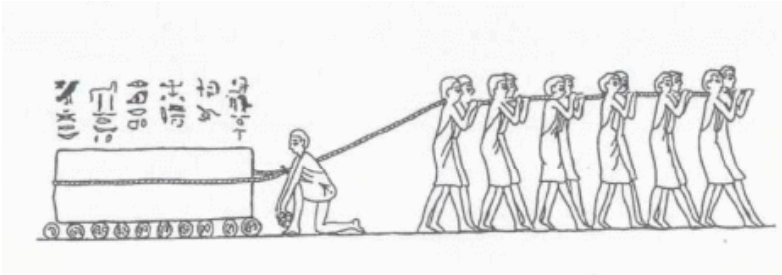
All particles in the medium participate = collective phenomenon



Kelvin wake

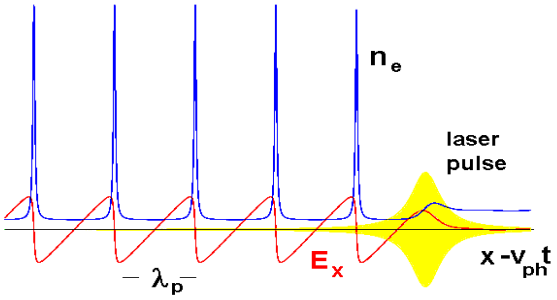


Colletive dynamics



(cf. individual particle dynamics)

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



(The density cusps. Cusp singularity)

← **relativity regularizes**

Wave **breaks** at v＜c

Hokusai

Intra-Operative Radiation Therapy (IORT)

LWFA* electron sources: *technology transferred to company

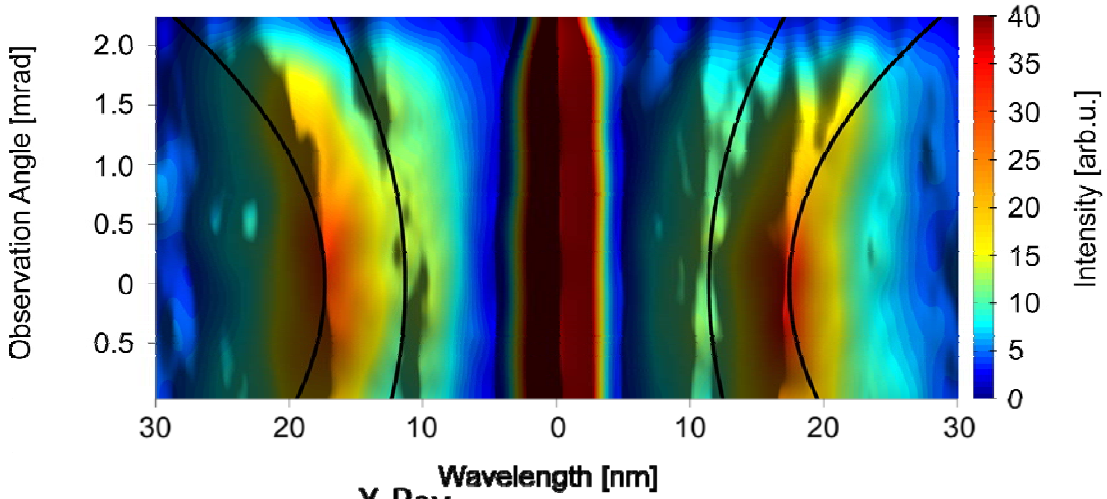
NOVAC7 *(HITESYS SpA) RF-based*	vs.	**CEA-Saclay experim. source** *Laser-based*
El. Energy < 10 MeV (3, 5, 7, 9 MeV)		*El. Energy > 10 MeV (10 - 45 MeV)*
Peak curr. 1.5 mA		*Peak curr. > 1.6 KA*
Bunch dur. 4 μs		*Bunch dur. < 1 ps*
Bunch char. 6 nC		*Bunch char. 1.6 nC*
Rep. rate 5 Hz		*Rep. rate 10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

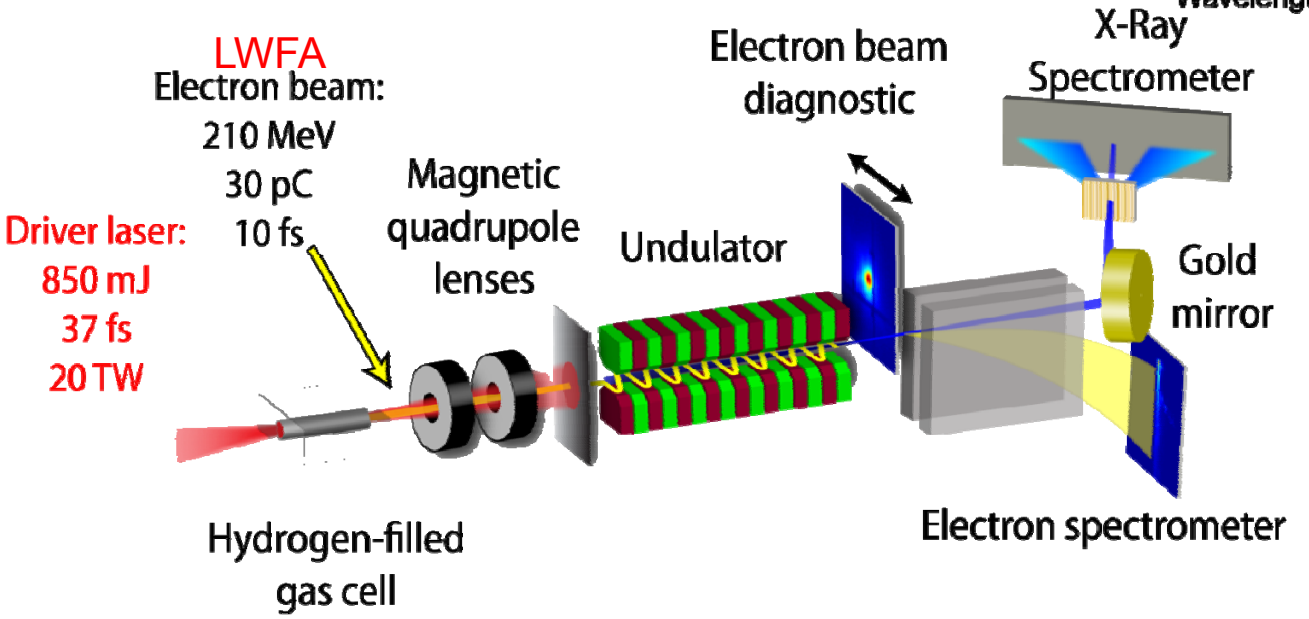
(A. Giulietti et al., Phys. Rev. Lett.,2008 : INFN)

Table-top Brilliant Undulator X-ray Radiation from LWFA

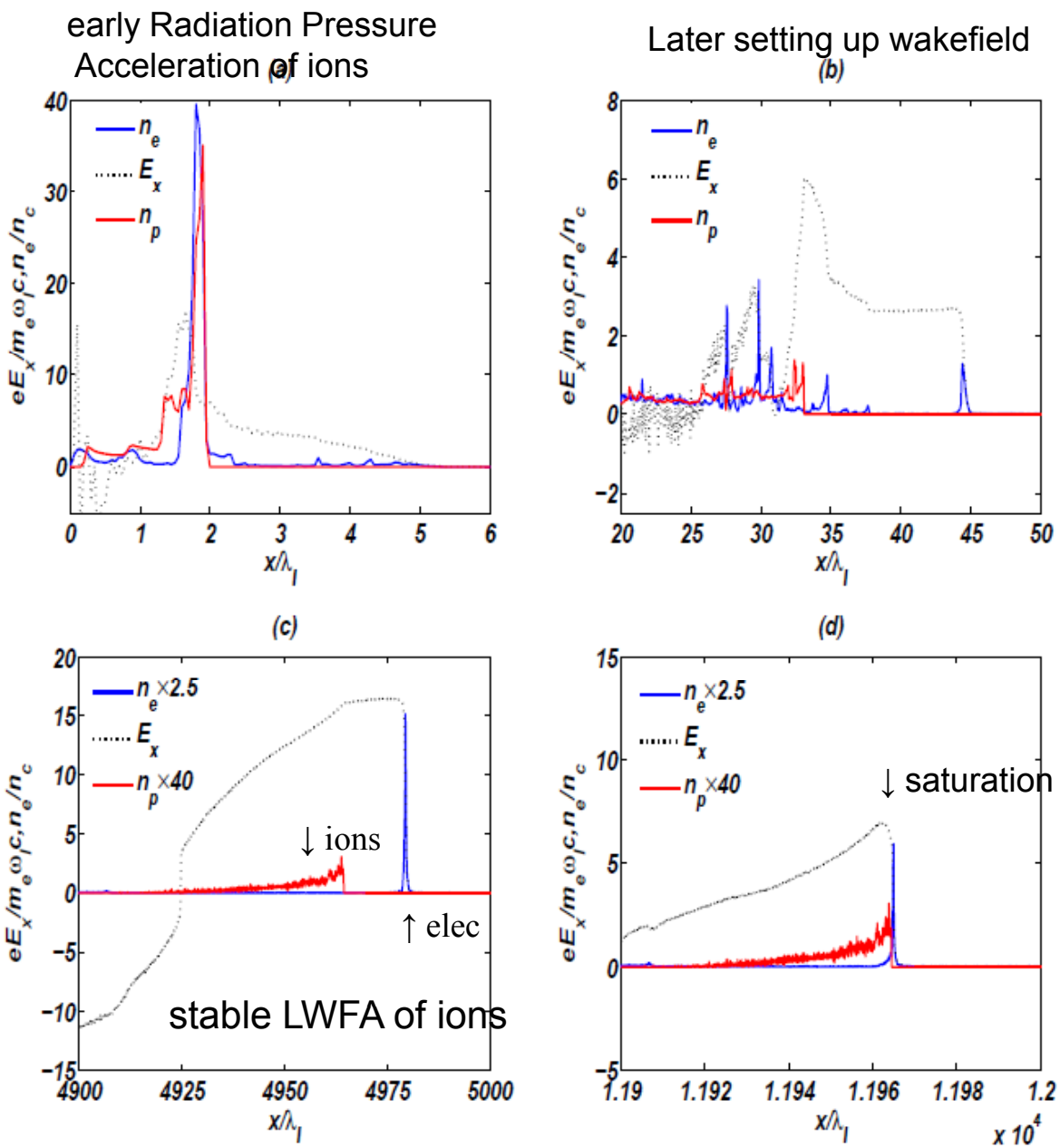
(M. Fuchs, et al., Nature Phys., 2009)

Observed undulator radiation spectrum





TeV proton acceleration by LWFA



High Intensity regime
$I = 10^{23}$ W/cm^2

$$E_i = (1/6)\, a_0^2\, (n_c/n_e)\, mc^2$$

Snowplow LWFA
of ions injected by RPA
as injector at multi-GeV

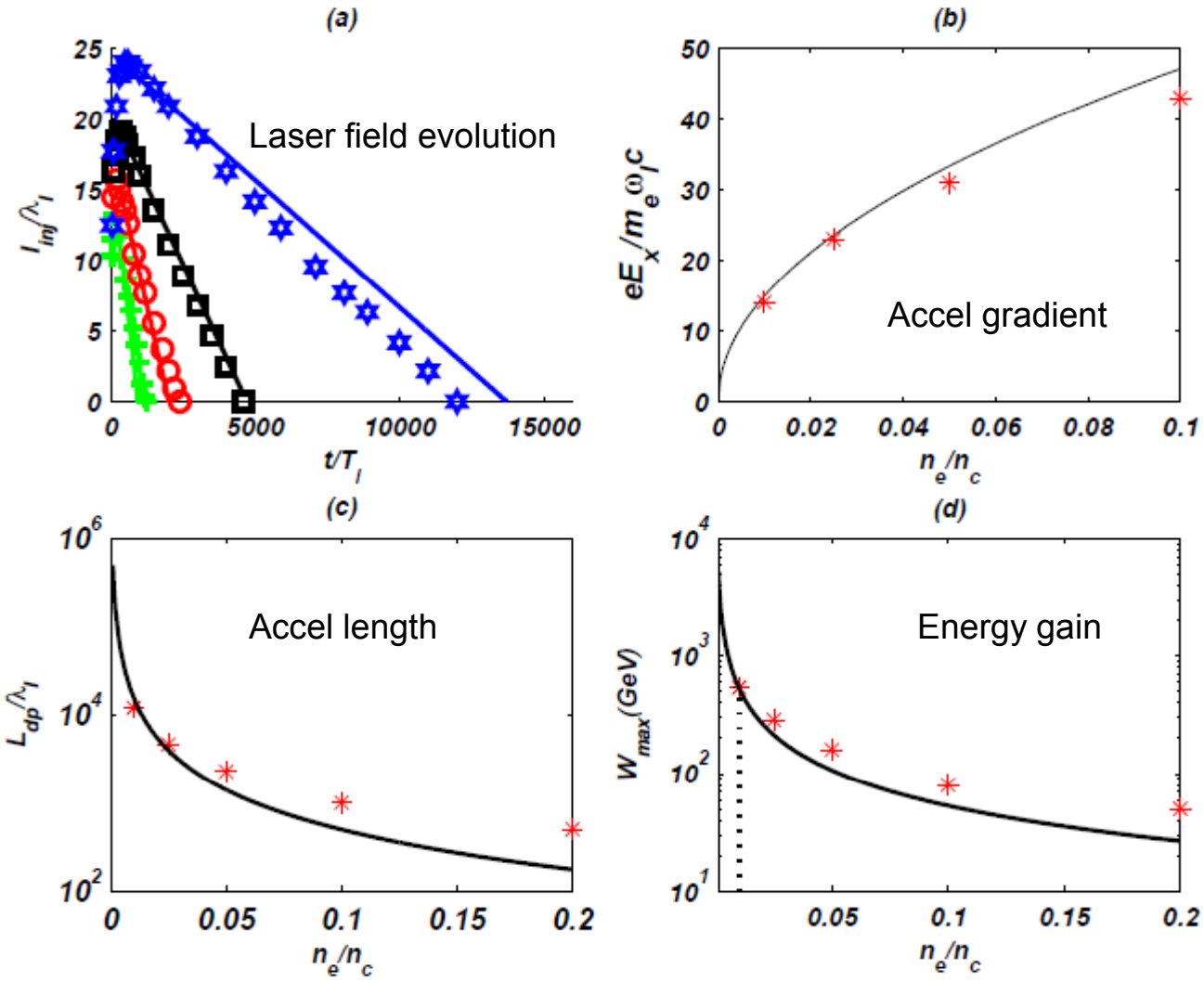
0.5TeV over

dephasing length of 1cm

Zheng et al., 2011

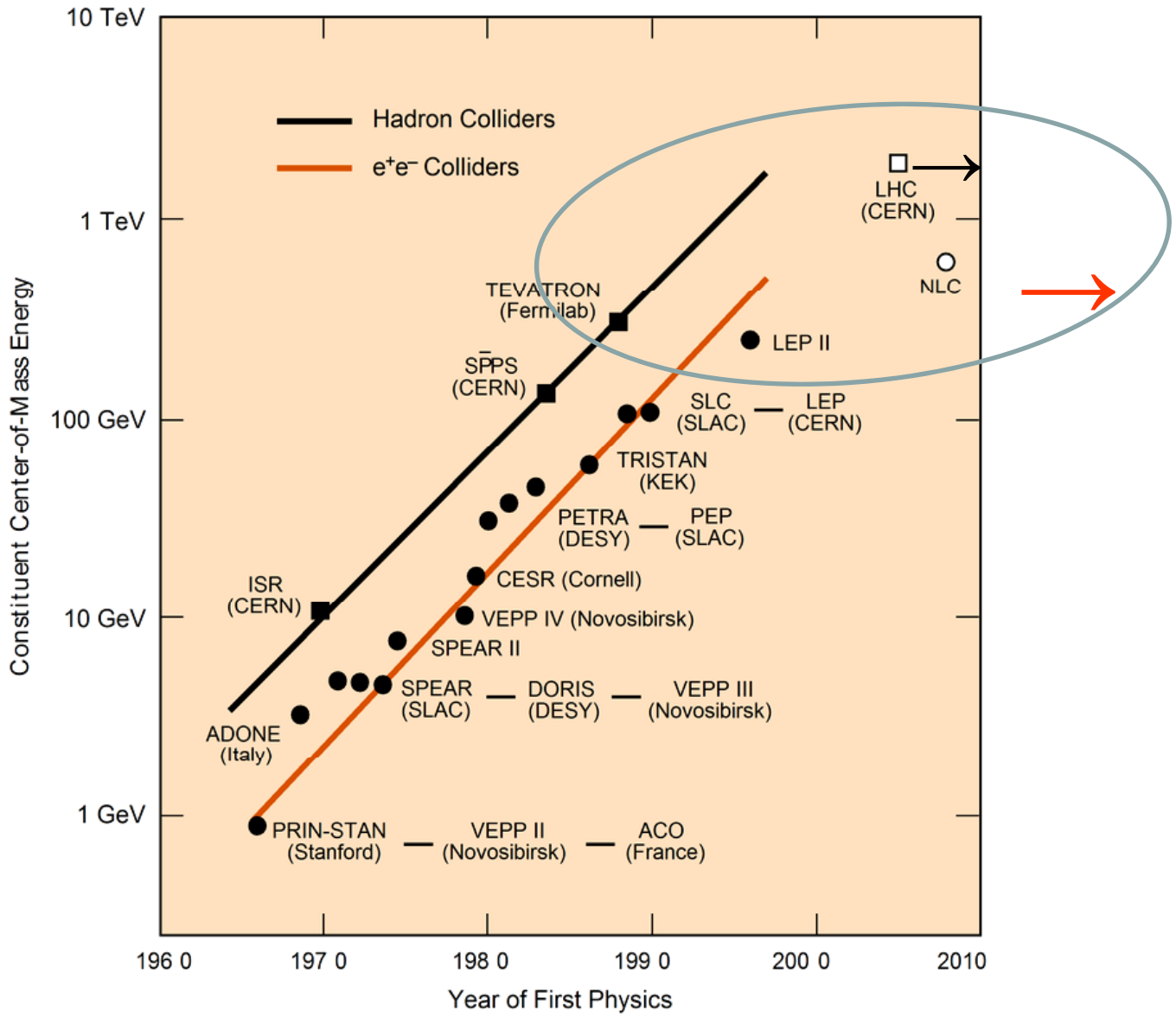
TeV proton Energy Scalings(RPA x LWFA)

TeV over cm @ 10^{23}W/cm^2



(Zheng et al. 2011)

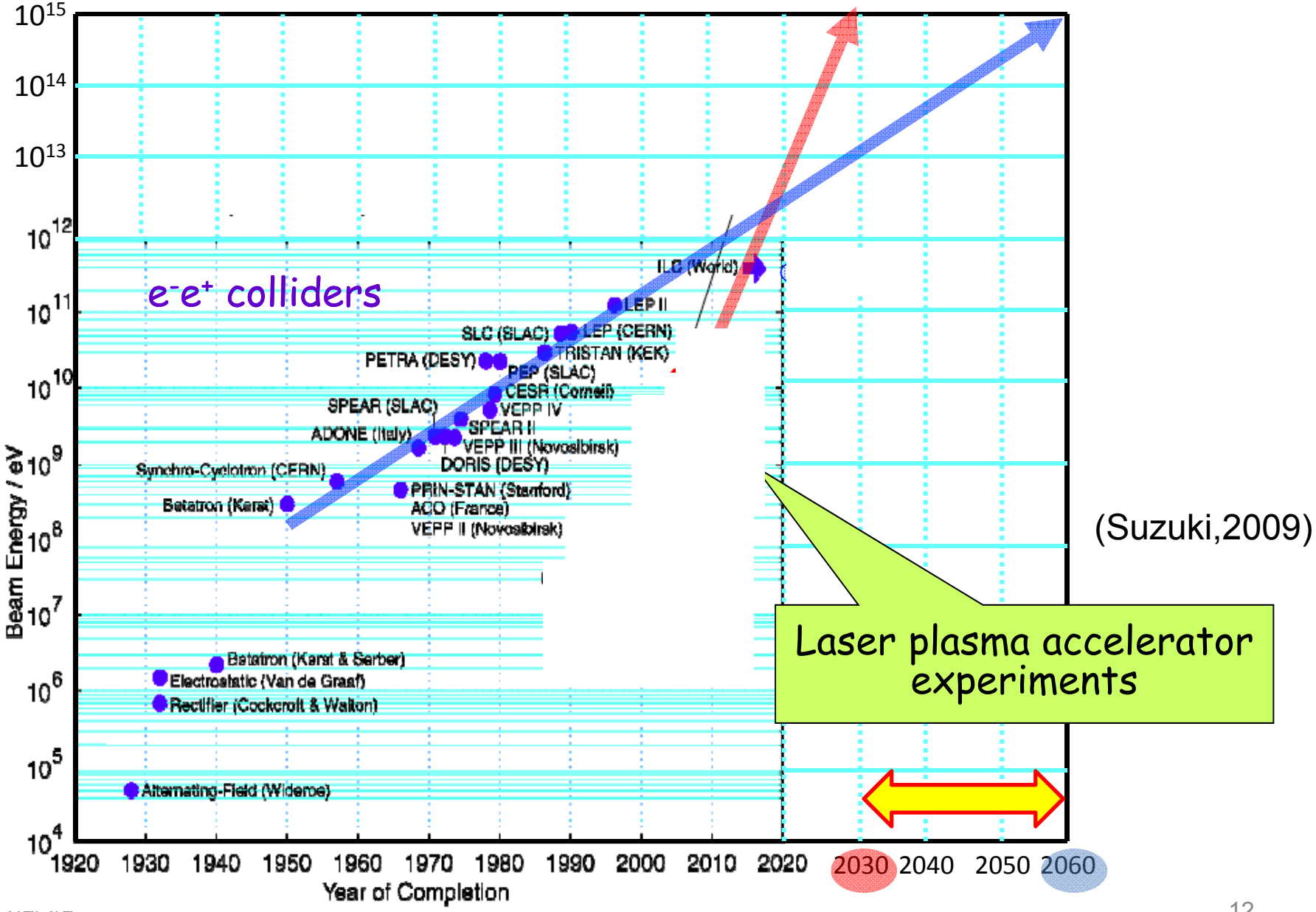
Livingston Chart and Recent Saturation



(Suzuki, 2009)

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

‘When can we reach 1 PeV ?’: Suzuki Challenges



(Suzuki,2009)

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

Latest Development: CERN getting into the game

EuroNNAc Workshop on novel accelerators (May 3-6, 2011)

Tuesday 03 May 2011

Introductory Presentations - Kjell Johnsen Auditorium (08:30-10:30)

- Conveners: Dr. Collier, Paul (CERN)

time	title	presenter
08:30	Goals of Network and Workshop (00h15')	ASSMANN, Ralph (CERN)
08:45	Accelerator R & D as Driver of Innovation (00h45')	HEUER, Rolf (CERN)
09:30	History and Outlook for Plasma Acceleration (00h30')	TOSHI, Tajima (LMU Munich)
10:00	Modern Lasers for Novel Acceleration Methods (00h30')	MOUROU, Gerard (ILE)

Coffee Break - 30-7-012 (10:30-11:00)

Introductory Presentations - Kjell Johnsen Auditorium (11:00-12:30)

- Conveners: Dr. Collier, Paul (CERN)

time	title	presenter
11:00	Accelerator R & D for Particle Physics (00h30')	MYERS, Steve (CERN)
11:30	Status Report Asia (00h30')	SHENG, Zhengming (Shanghai Jiao Tong University)
12:00	Status and Plans US (beam driven) (00h15')	HOGAN, Mark (SLAC)
12:15	Status and Plans US (Laser driven) (00h15')	ESAREY, Eric (LBNL)

ELI (2010), now Mega Project on Extreme Laser (2011)

Extreme Light Infrastructure: EU decided (2010) at Czech, Hungary, and Romania
Now, Russia announced July 5, 2011: 6 Mega Projects (3-4B Euro) include **Extreme Laser**

Beyond Exawatt
Beyond 10kJ

ELI: serving Chair, Scientific Advisory Committee
Extreme Laser Mega Project (in budget negotiation):
Chief Scientific Advisor/
Mega Grant Honorary Director (suggested)
International team being formed:
IZEST (International Center for Zetawatt / Exawatt Science and Technology)

S&TRF
НАУКА И ТЕХНОЛОГИИ РФ

Евразийский открытый институт, используя обучение через интернет, реализует 18 программ ба..

По диаметру отверст можно определить и веществ у ..

05.07.11
Σ Стерлигов Иван
Правительственная комиссия по высоким технологиям и инновациям; Обсуждение

Обсуждение
Версия для печати
добавить ссылку

Сверхмощный лазер как интегратор науки

В числе меганаучных проектов, которые будут реализованы на территории России, – Международный центр исследований экстремальных световых полей на основе сверхмощного лазерного комплекса в Нижнем Новгороде. Руководит центром всемирно известный физик Жерар Муру при поддержке Минобрнауки России. STRF.ru подробно рассказывал об этой работе в статье «Российские учёные строят сверхмощный лазер». Насколько значим этот проект для мировой науки, мы выяснили у Тосики Тадзимы, заведующего кафедрой физического факультета Университета Людвига Максимилиана в Мюнхене, председателя Международного комитета по сверхмощным лазерам (International Committee on Ultra-High Intensity Lasers, ICUIL).

Тосики Тадзиме не терпится поучаствовать в российском мегапроекте по созданию сверхмощного лазера

Справка STRF.ru:
Международный комитет по сверхмощным лазерам – подразделение Международного союза фундаментальной и прикладной физики, основанное в 2003 году. Задача ICUIL – продвижение науки и технологии сверхмощных лазеров и координация исследований и разработок в этой области. Под сверхмощными лазерами в комитете понимают лазеры с интенсивностью 10^{19} ватт на см^2 и мощностью около 10 тераватт

На Ваш взгляд, что примечательного произошло в области сверхмощных лазеров в последнее время?

– Прошлый год стал эпохальным для нас благодаря решению Евросоюза о запуске проекта Extreme Light Infrastructure [ELI, включает целый ряд сверхмощных лазеров в нескольких регионах Европы], а также началу реальной работы National Ignition Facility в США – альтернативный токамакам проект термоядерной энергетики, основанный на лазерном нагреве и инерционном удержании плазмы. Мы предполагаем, что развитие сверхмощных лазеров и сопутствующих областей науки значительно ускорится, и стараемся способствовать

http://strf.ru/

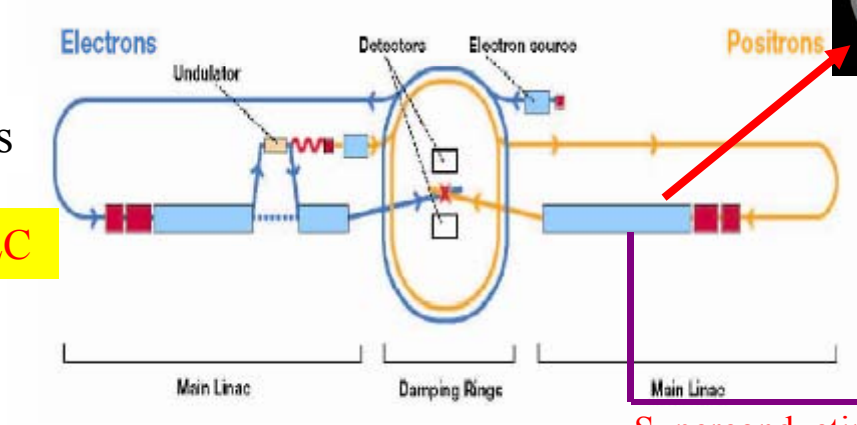
Accelerator

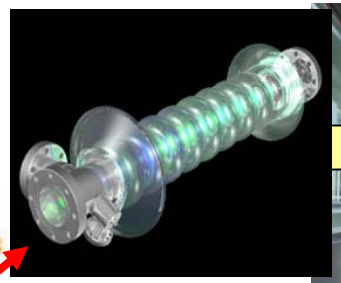
Evolution of Accelerators and their Possibilities （Suzuki,2008)

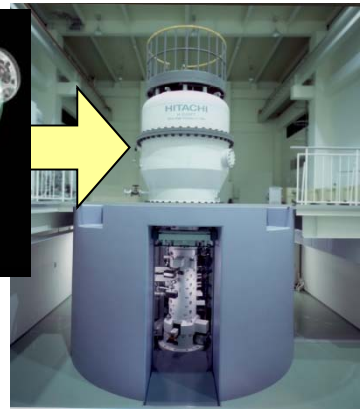
E=40 MV/m

2020s

ILC

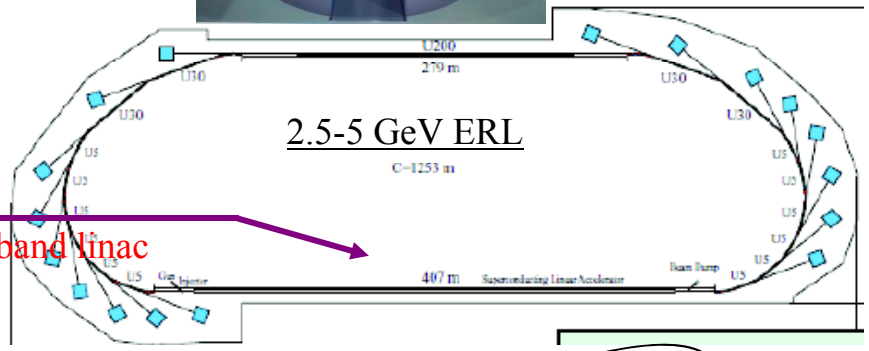






Ultra-High Voltage STEM with Superconducting RF cavity

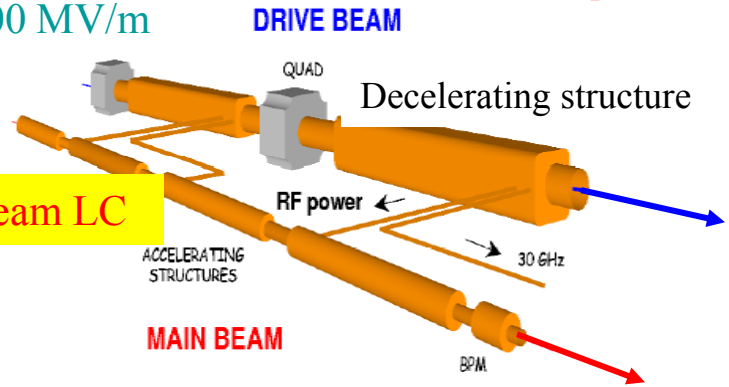
Superconducting L-band linac

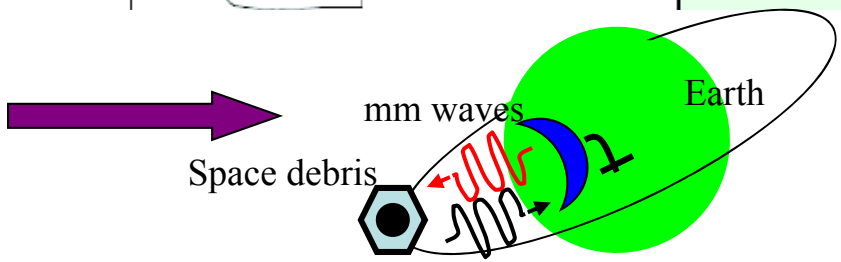


E=200 MV/m

2030s

Two-beam LC





Earth-based space debris radar

E=10 GV/m

10cm-10GeV Plasma Channel Accelerator

2040s

Laser-plasma LC

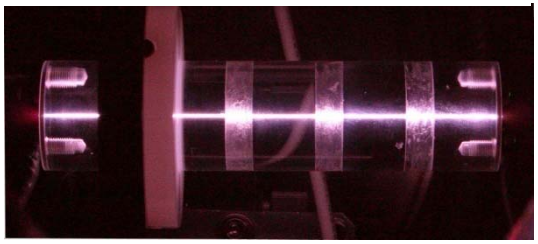


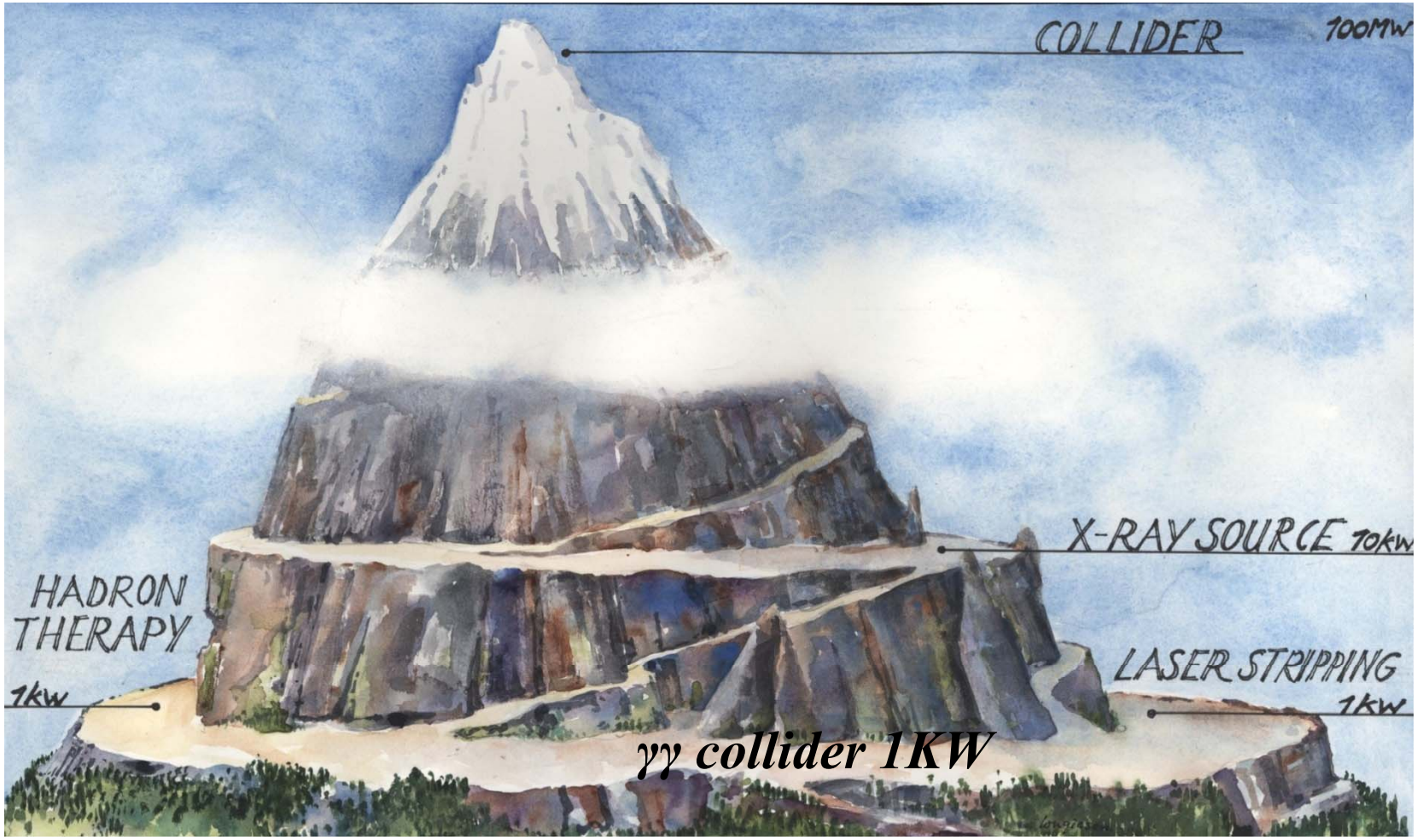
Table-top high energy accelerator

Brief History of *ICUIL – ICFA* Joint Effort

- *ICUIL* Chair 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)
- EuroNNAc Workshop at CERN (coordinator) (May, 2011)

Mountain of Lasers

(average power)



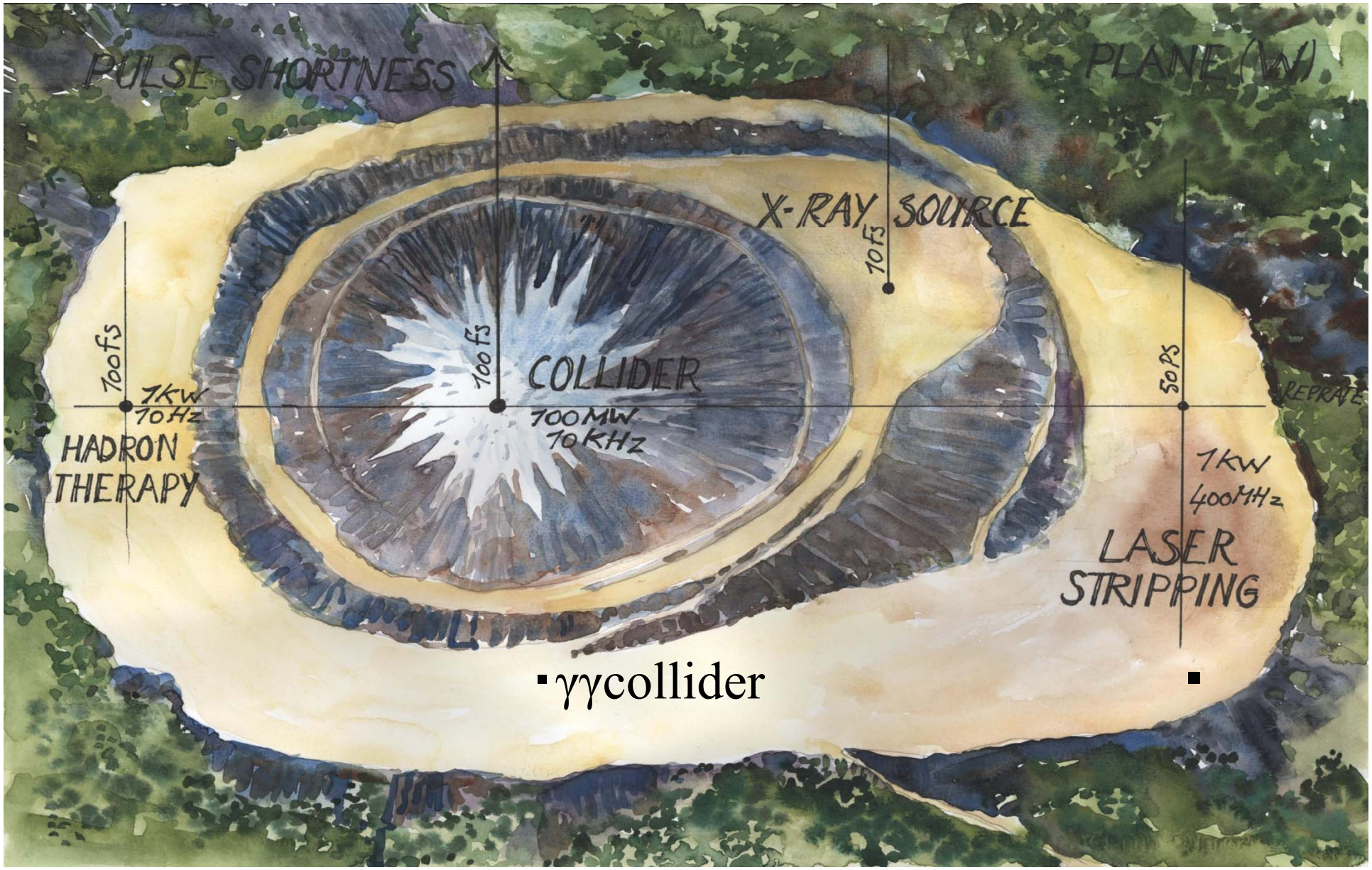
← average power

→ pulse shortness

→ rep rate

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

Range of laser parameters



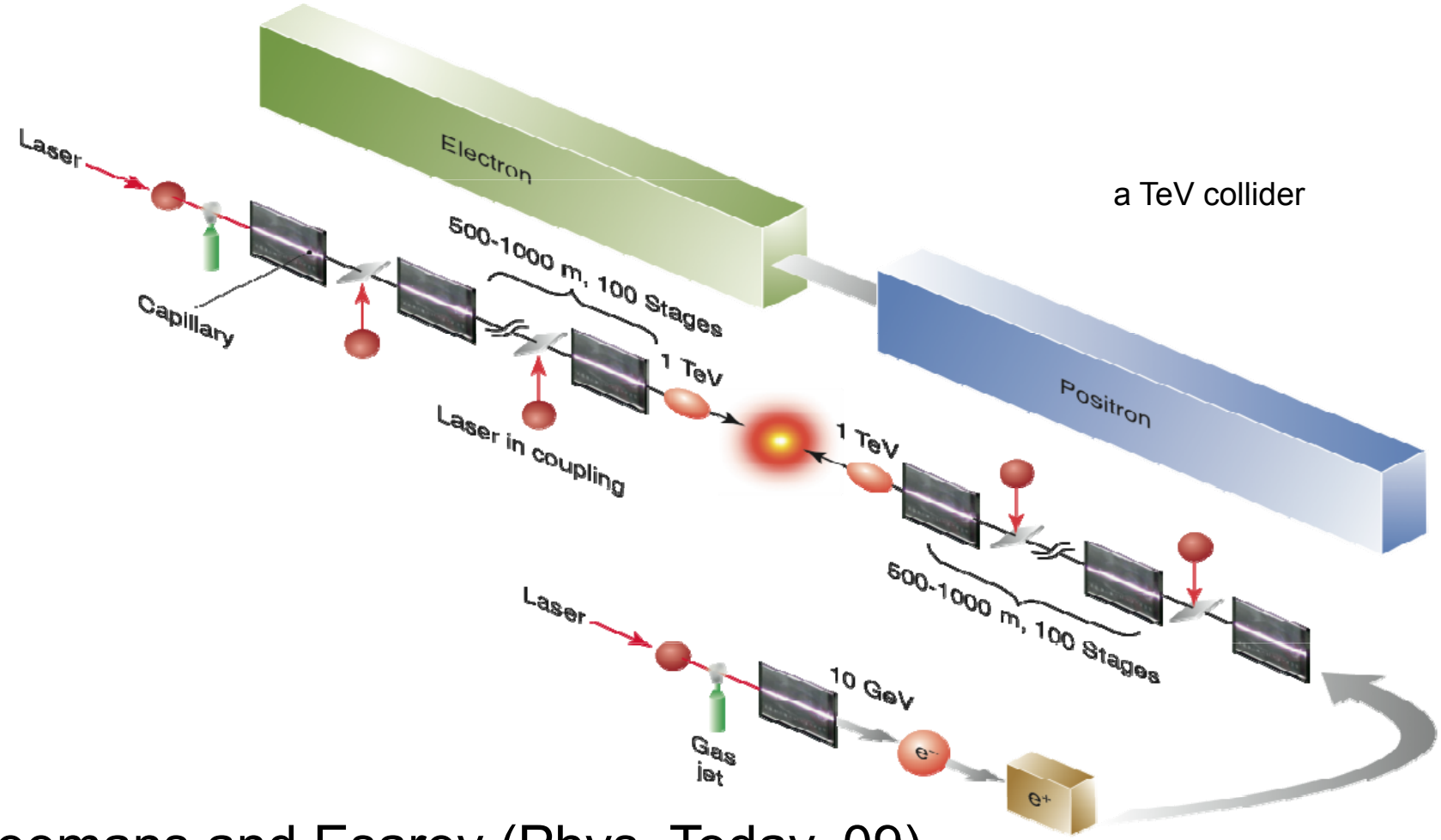
▪ γγcollider ▪

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



Leemans and Esarey (Phys. Today, 09)

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

Issues for LWFA Collider

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

First LWFA Collider Study (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*

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}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 ($\sim 10^{15}\text{W/cm}^2$) has been demonstrated [14]. New experiment aiming at propagating pulses with intensities on the order of 10^{18}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)	$\beta_y(\mu\text{m})$	σ_y(nm)	$\sigma_z(\mu\text{m})$
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	$\mathcal{L}_g(10^{35}\text{cm}^{-2}\text{s}^{-1})$
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	$\mathcal{L}/\mathcal{L}_g(\text{W}_{\text{cm}} \in 1\%)$	$\mathcal{L}/\mathcal{L}_g(\text{W}_{\text{cm}} \in 10\%)$
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

Xie et al. AAC Conference Proc. (1997)

Also, Chattopadhay et al., Snowmass (1996)

Collider Physics I

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

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

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

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

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

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

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

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

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

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

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

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 : optimal plasma density

(Nakajima, 2011)

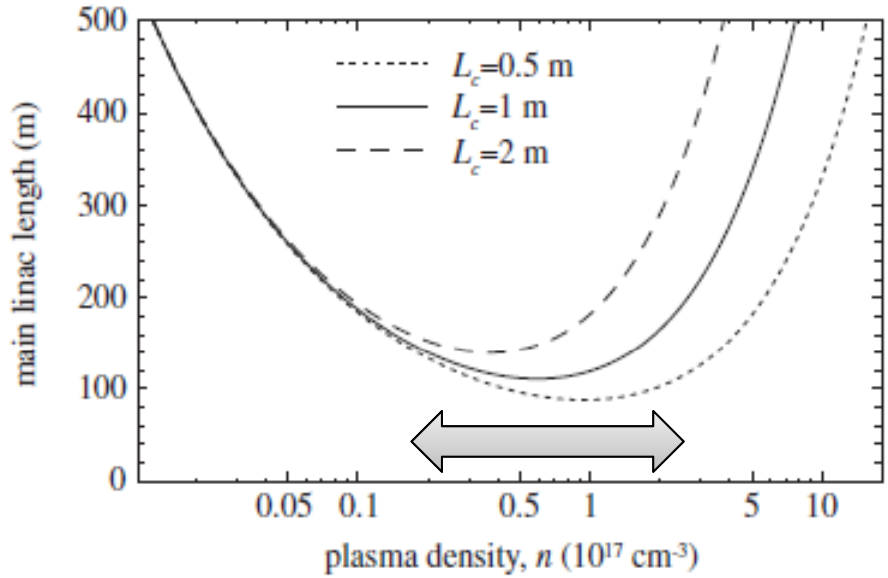
The electron plasma frequency:

- Plasma electron density n_0 corresponds to frequency of RF cavity, which characterizes accelerator performance .

- Minimizing the overall length of LPA linac

$$L_{total} = \left[L_{stage} + L_c\right]\frac{E_b}{W_{stage}}$$

E_b : the final beam energy
W_{stage} : the energy gain in a single stage
L_{stage} : the single stage plasma length
L_c : the required coupling distance



C. B. Schroeder et al., PRST-AB 13, 101301

$$W_{stage} \propto E_z L_d \propto n_0^{-1} \quad L_{stage} \approx L_{pd} \propto n_0^{-3/2}$$

For E_b =0.5 TeV, a_0 =1.5,
coupling distance $L_c \lesssim$ 1m

The required operation plasma density ≈ 10^{17} cm^{-3}

- With minimization condition $L_c \sim L_{stage} \approx L_{pd}$

$$L_{total} \propto L_{pd} N_{stage} \propto n_0^{-1/2}$$

Selection of plasma density
is not a big issue.

- Plasma density is continuously tunable over the broad range.
- Plasma accelerator structure is not so expensive.

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

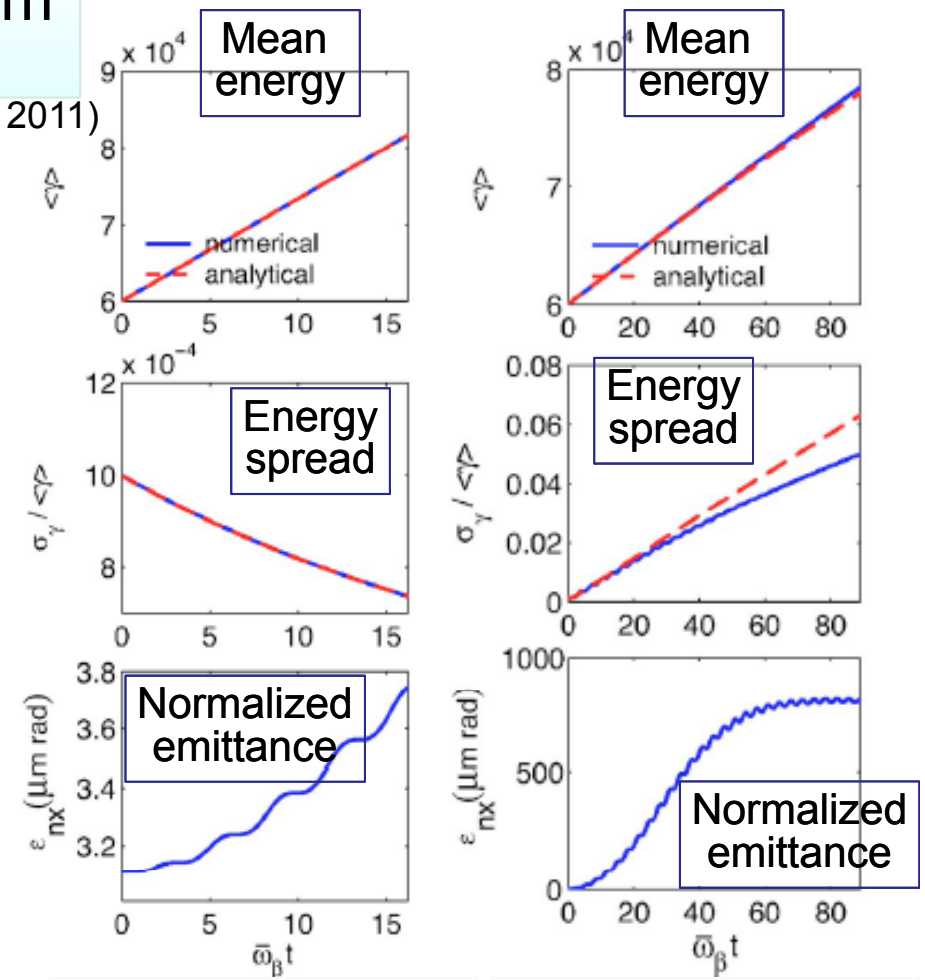
- Collision frequency: $f \propto N^{-2} \propto n_0$

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 = 3×10^{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}

Collider Phys III

Designs of collider
low density scenario
vs.
prevailing design

(Nakajima et al, 2011)

TABLE I. Parameters for a 2 TeV laser-plasma linear collider

Beam energy E_b[GeV]	1000	1000	1000	1000	1000
Injection beam energy E_i[GeV]	1	1	1	1	1
Plasma density n_e [cm^{-3}]	10^{15}	10^{16}	$2.3 \cdot 10^{16}$	10^{17}	10^{18}
Plasma wavelength λ_p [μm]	1056	334	220	106	33
Accelerating field E_z [GV/m]	1.5	4.7	7.2	15	47
Energy gain per stage W_{stage} [GeV]	500	45	19	4.5	0.47
Number of stages N_{stage}	2	22	50	222	2125
Stage length L_{stage} [m]	333	9.7	2.8	0.3	0.01
Total linac length L_{total} (L_{compt}) [m]	1000 (167)	321 (4.9)	210 (1.4)	100 (0.15)	32 (0.005)
Total linac length L_{total} (L_{compt}) [m]	686 (10)	433 (10)	640 (10)	2287 (10)	21271 (10)
Total linac length L_{total} (L_{compt}) [m]	668 (1)	235 (1)	190 (1)	289 (1)	2146 (1)
Number of particles per bunch N_b [10^9]	7.5	2.4	1.6	0.75	0.24
Beam radius σ_{x0}[μm]	168	53	35	17	5.3
Bunch length σ_{bz} [μm]	4.1	1.3	0.9	0.4	0.13
Normalized laser intensity a_0	1.4	1.4	1.4	1.4	1.4
Laser wavelength λ_0 [μm]	1	1	1	1	1
Laser pulse duration τ_L [fs]	950	300	200	100	30
Laser spot radius r_L [μm]	504	160	105	51	16
Channel depth at r_L $\Delta n_c/n_e$	0.44	0.44	0.44	0.44	0.44
Laser peak power P_L [TW]	10913	1091	474	109	11
Laser energy per stage U_L [J]	10367	327	95	11	0.33
Radiative energy spread σ_γ/γ_f [%]	0.7	2.1	3.2	6.7	21
Collision frequency f_c [kHz]	0.9	9	20	89	868
Luminosity L[10^{34}cm^{-2}s^{-1}]	4	4	4	4	4
Beam power P_b [MW]	1.1	3.3	5	11	33
Average laser power P_{avg} [MW]	9.2	2.9	1.9	0.98	0.29
Efficiency (wall-plug to beam) [%]	1.6	1.6	1.6	1.6	1.6
Wall plug power P_{wall} [MW]	123	425	633	1460	4108

Density scalings for collider

Accelerating field E_z	$\propto n_e^{1/2}$
Focusing constant K	$\propto n_e^{1/2}$
Stage length L_{stage}	$\propto n_e^{-3/2}$
Energy gain per stage W_{stage}	$\propto n_e^{-1}$
Number of stages N_{stage}	$\propto n_e$
Total linac length L_{total}	$\propto n_e^{-1/2}$
Number of particles per bunch N_b	$\propto n_e^{-1/2}$
Laser pulse duration τ_L	$\propto n_e^{-1/2}$
Laser peak power P_L	$\propto n_e^{-1}$
Laser energy per stage U_L	$\propto n_e^{-3/2}$
Radiation loss $\Delta\gamma$	$\propto n_e^{1/2}$
Radiative energy spread σ_γ/γ_f	$\propto n_e^{1/2}$
Initial normalized emittance ε_{n0}	$\propto n_e^{-1/2}$
Collision frequency f_c	$\propto n_e$
Beam power P_b	$\propto n_e^{1/2}$
Average laser power P_{avg}	$\propto n_e^{-1/2}$
Wall plug power P_{wall}	$\propto n_e^{1/2}$

(Nakajima, 2011)

Collider Physics IV

LWFA model for collider

Stage accelerator matrix

$$\frac{d\gamma}{dz} = k_p \Phi_0 \cos(\Psi), \tag{19}$$

$$\frac{d\Psi}{dz} = \frac{k_p}{2\gamma_p^2}. \tag{20}$$

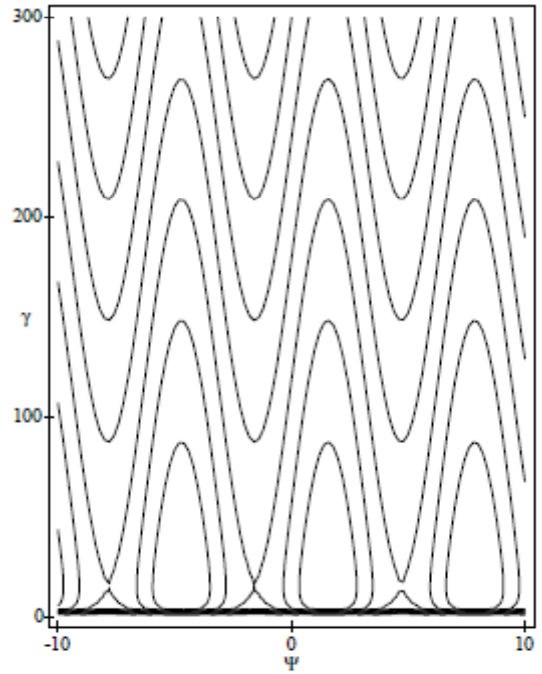


FIG. 1. The longitudinal phase space: electron Lorenz factor γ vs its phase with respect to the wakefield Ψ. The parameters used were $\gamma_p = 15$, $\Phi_0 = 0.2$.

Cheshkov et al (2000)

Longitudinal dynamics

The linearized equations of motion for the longitudinal degrees of freedom are

$$\delta\Psi_{n+1} = \delta\Psi_n, \tag{23}$$

$$\delta\gamma_{n+1} = 2\gamma_p^2\Phi_0[\cos(\Psi_s + \Delta) - \cos(\Psi_s)]\delta\Psi_n + \delta\gamma_n, \tag{24}$$

Transeverse dynamics

$$\ddot{\tilde{u}} + \left[\omega_\beta^2 \sin(\omega_s z + \Psi_s + \delta\Psi_n) - \frac{1}{2}\frac{\ddot{\gamma}}{\gamma} + \frac{1}{4}\frac{\dot{\gamma}^2}{\gamma^2}\right]\tilde{u} = 0, \tag{25}$$

where

$$\omega_s = \frac{k_p}{2\gamma_p^2}, \tag{26}$$

$$\omega_\beta = \left(\frac{4\Phi_0}{\gamma r_s^2}\right)^{1/2} \tag{27}$$

$$M = \begin{pmatrix} \cos(\frac{\omega}{\omega_s}\Delta) & \frac{1}{\omega}\sin(\frac{\omega}{\omega_s}\Delta) \\ -\omega\sin(\frac{\omega}{\omega_s}\Delta) & \cos(\frac{\omega}{\omega_s}\Delta) \end{pmatrix} \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}, \tag{29}$$

where L is the drift distance between the wakefield stages and $1/\omega$ is the betatron length in the wakefield. The matrix (29) may be also written as

$$M = \begin{pmatrix} \cos(\frac{\omega}{\omega_s}\Delta) & \frac{1}{\omega}\sin(\frac{\omega}{\omega_s}\Delta) + L\cos(\frac{\omega}{\omega_s}\Delta) \\ -\omega\sin(\frac{\omega}{\omega_s}\Delta) & -L\omega\sin(\frac{\omega}{\omega_s}\Delta) + \cos(\frac{\omega}{\omega_s}\Delta) \end{pmatrix}. \tag{30}$$

The transverse map $\mathcal{M}$ for the whole accelerator system is

$$\mathcal{M} = M^N, \tag{31}$$

Collider Physics V

Cumulative effects over multistages

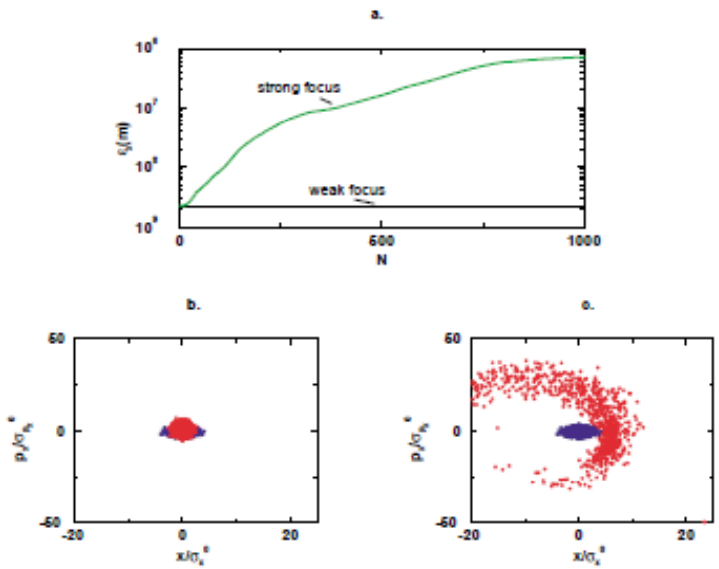
Strong LWFA betatron oscillations lead to emittance degradation

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
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

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

where $\mathcal{D}_n$ is the stochastic misalignment ($\tilde{\mathcal{D}}_n = \sqrt{\gamma_n}\,\mathcal{D}_n$). 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

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



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

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

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

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

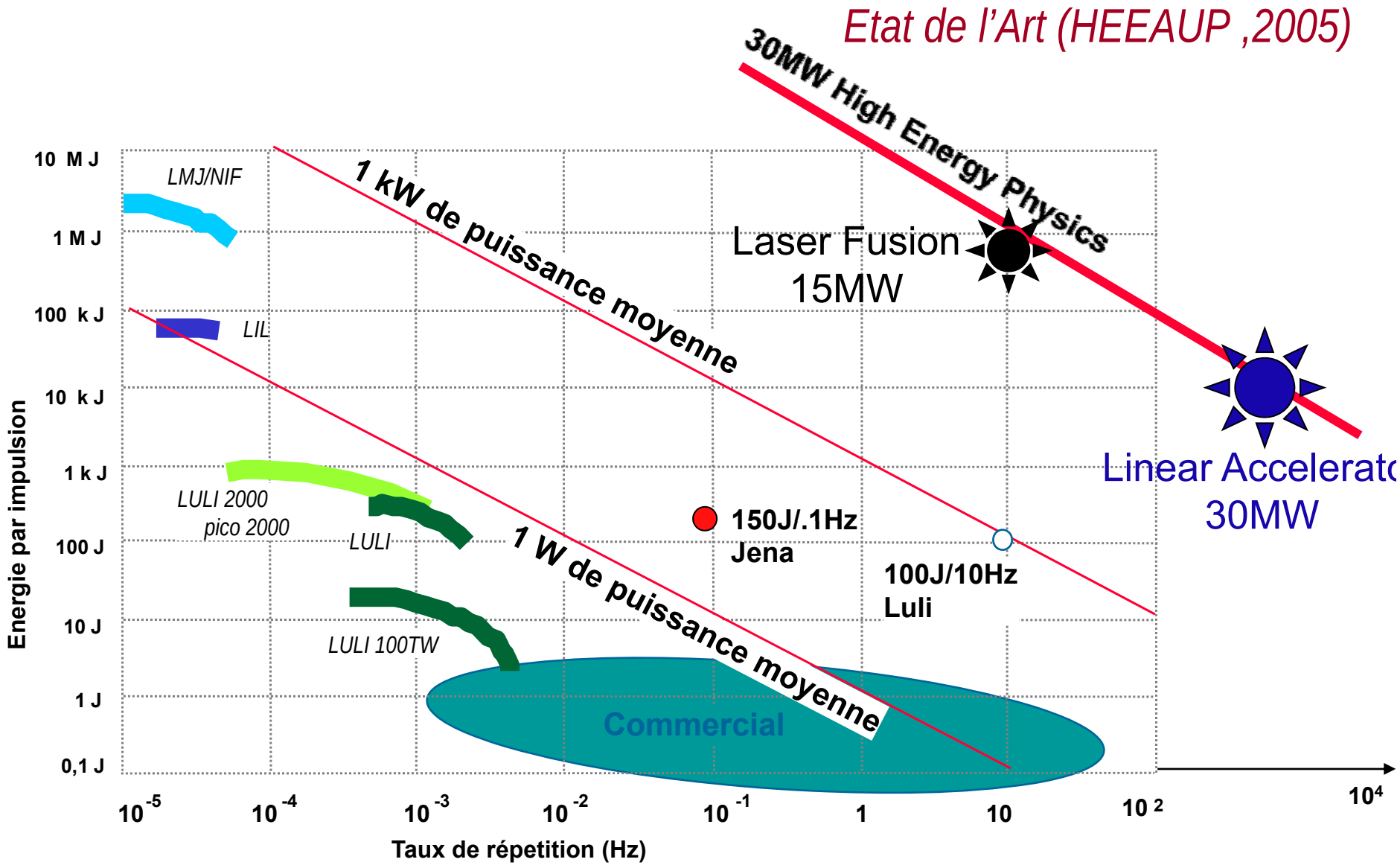
$$\Delta\epsilon \approx \omega D\, z = \frac{1}{2}\gamma\omega(\omega l)^2 \sigma_{\mathcal{D}}^2 N. \qquad (43)$$

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

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

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

High Average Power Lasers



G. Mourou (2005)

Toward high-average power efficient HEP driver laser

Formation of consortium of three communities
(laser community, HEP community, and plasma community)

Proposal to form 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"

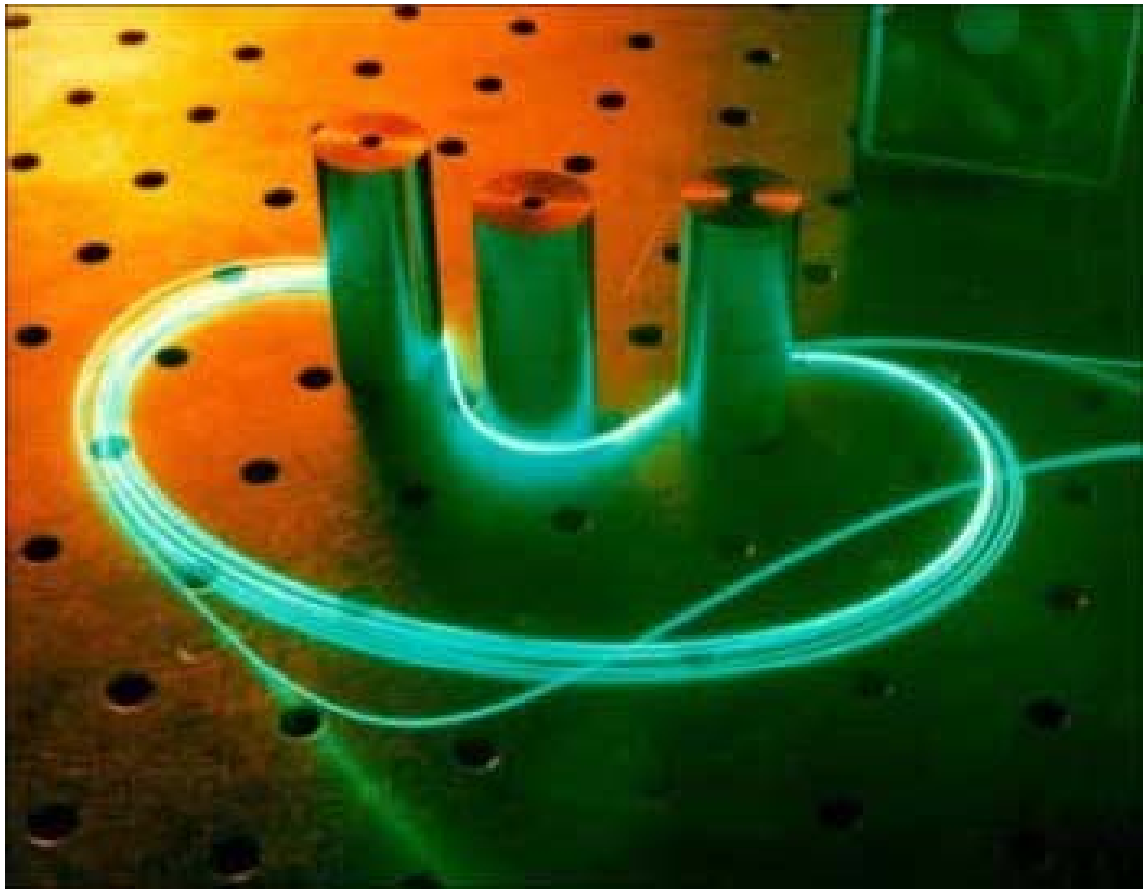
(Coordinator G. Mourou, submitted to the EU November 25, 2010:

Fermilab, a partner)

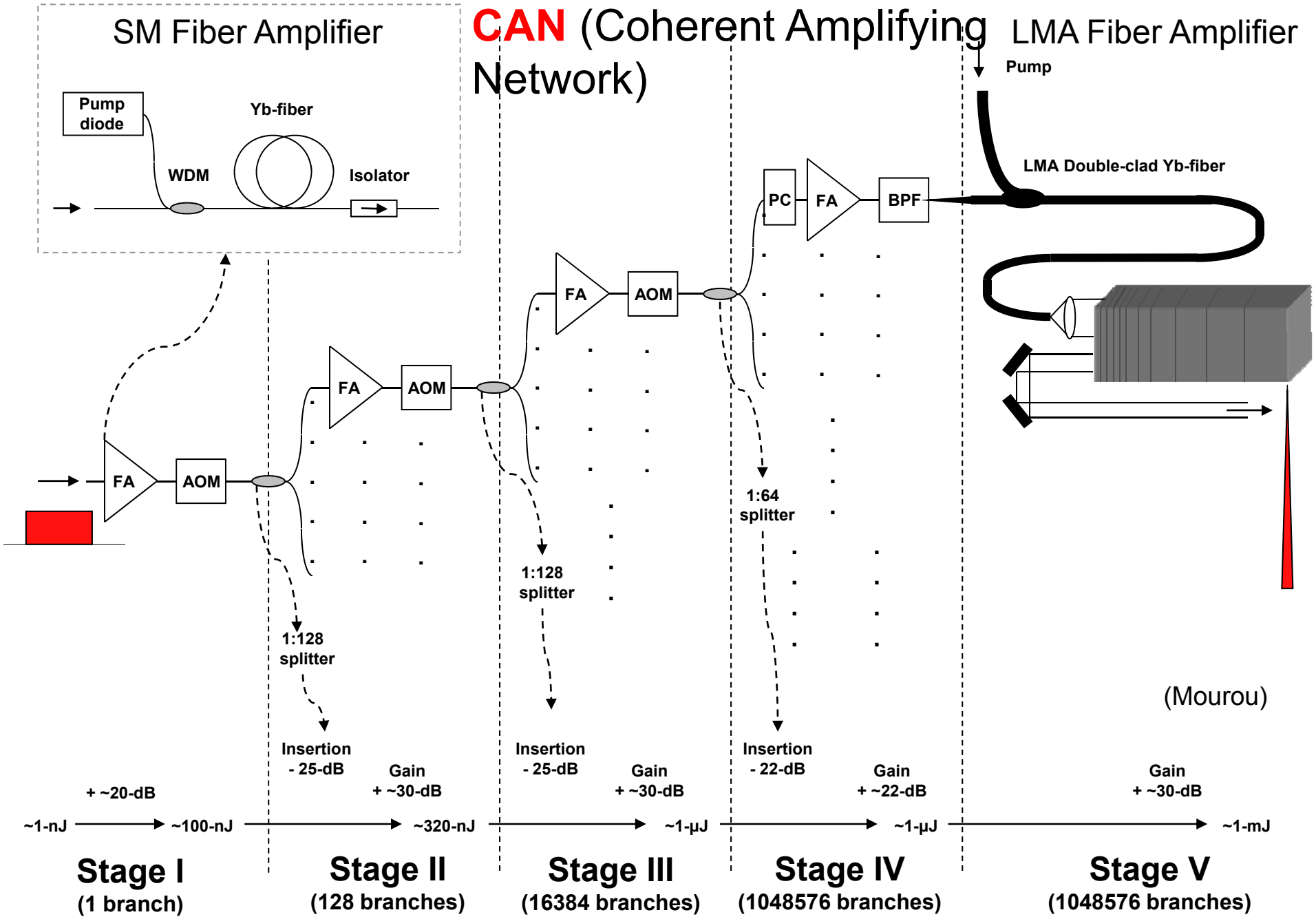
Now negotiating with EU on budget amendment (June, 2011)

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
- mass-produced at low cost.

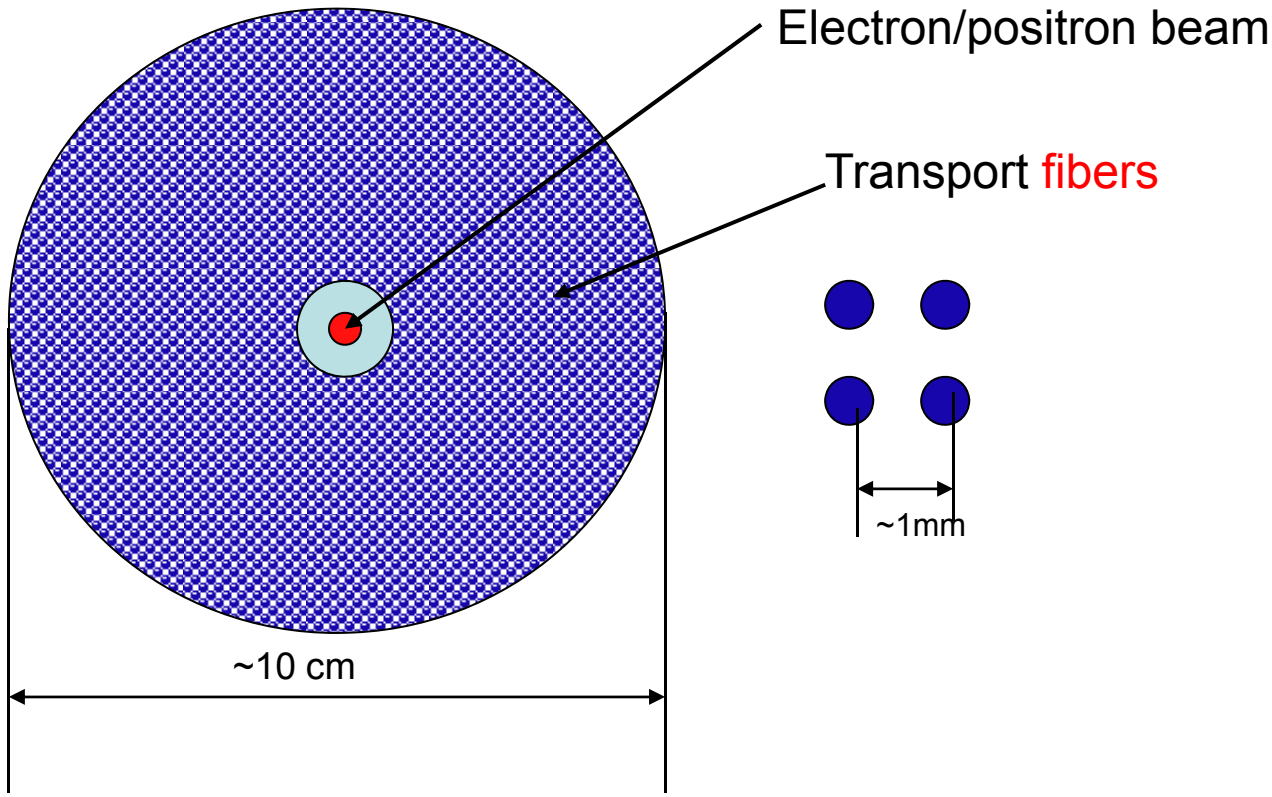


(G. Mourou)


SM Fiber Amplifier
Pump diode
Yb-fiber
WDM
Isolator
CAN (Coherent Amplifying Network)
LMA Fiber Amplifier
Pump
LMA Double-clad Yb-fiber
FA
AOM
PC
BPF
1:128 splitter
1:128 splitter
1:64 splitter
Insertion - 25-dB
Insertion - 25-dB
Insertion - 22-dB
Gain + ~30-dB
Gain + ~30-dB
Gain + ~22-dB
Gain + ~30-dB
+ ~20-dB
~1-nJ
~100-nJ
~320-nJ
~1-μJ
~1-μJ
~1-mJ
Stage I (1 branch)
Stage II (128 branches)
Stage III (16384 branches)
Stage IV (1048576 branches)
Stage V (1048576 branches)
(Mourou)

Concept: coherent fiber bundles

Because the transport fibers lossless, assembled
in a bundle just before the focusing optics.
all coherently phased.



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

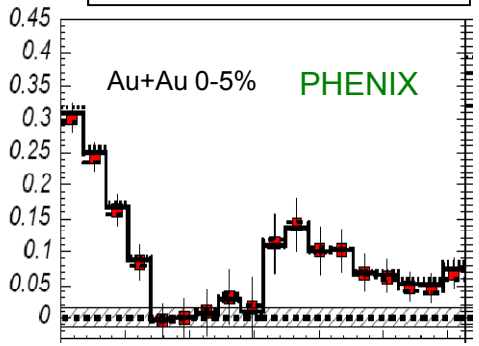
(Mourou et al)

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: collective deceleration by wakefield?
  - LWFA method, or Maldacena method?

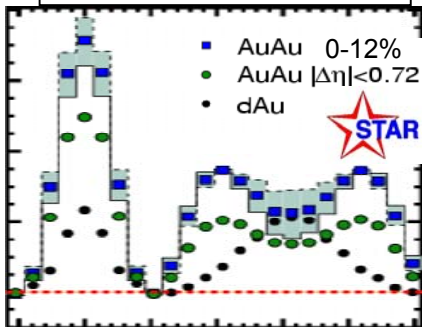
PHENIX PRL 97, 052301 (2006)

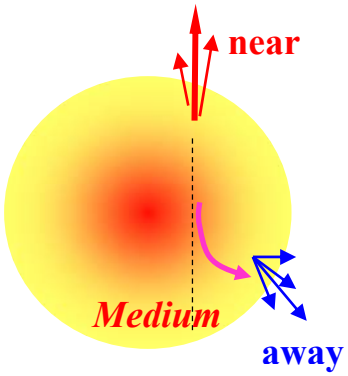
$2.5<p_T^{Trigger}<4$ GeV/c
$1<p_T^{Assoc}<2.5$ GeV/c



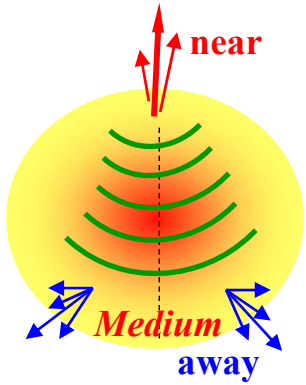
Horner (STAR) QM2006

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





Deflected Jets



Conical Emission

Wakefield even inside of a nucleus

All particles in the medium participate = collective phenomenon

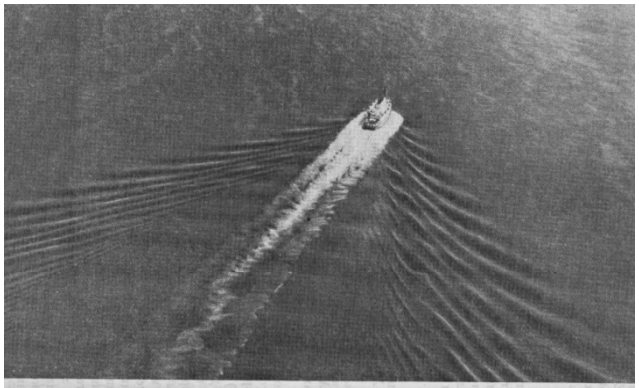
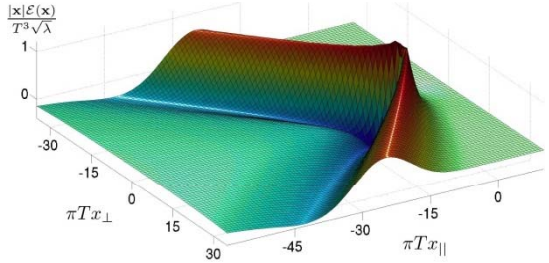


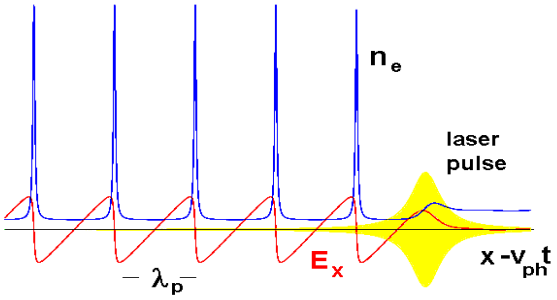
Рис. 71. Наблюдаемая картина корабельных волн. [Любезно предоставлено Aerofilms Ltd.]

Kelvin wake



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

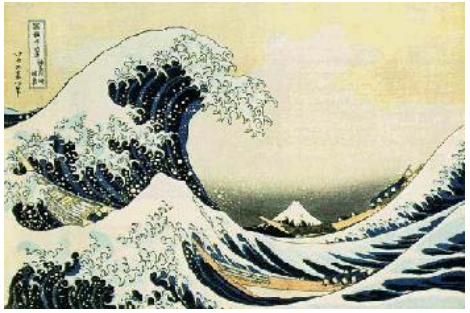
No wave breaks and wake **peaks** at v≈c



(The density cusps.
Cusp singularity)

← relativity regularizes

Wave **breaks** at v<c



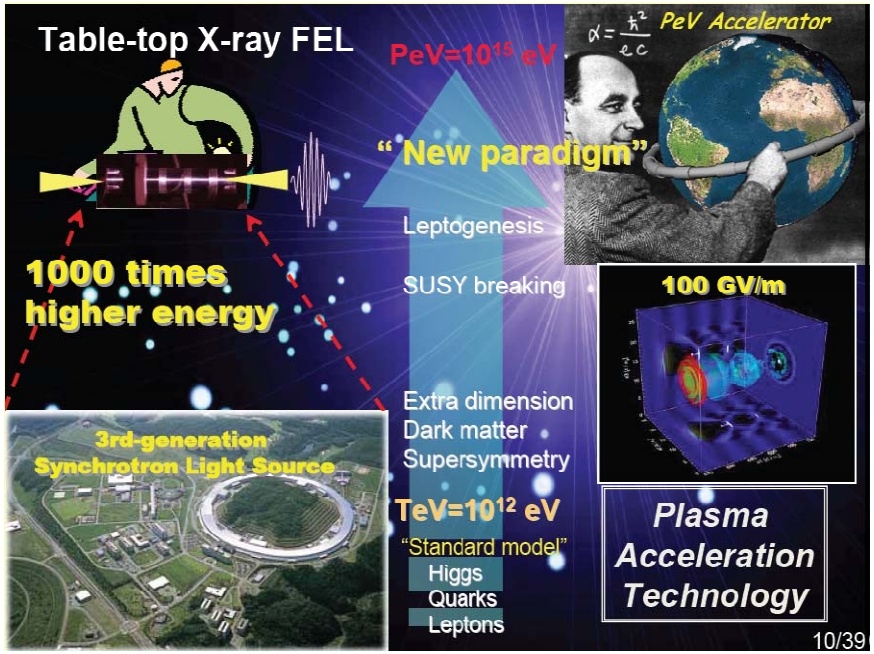
Hokusai

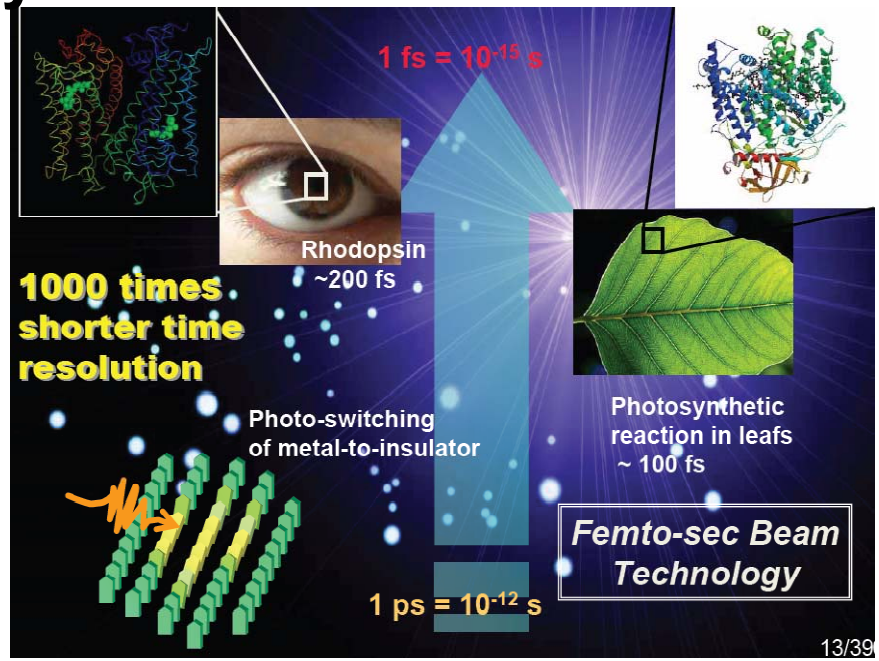
Maldacena

(Plasma physics vs.
String theory)

Challenge Posed by DG Suzuki

Frontier science driven by advanced accelerator





compact, ultrastrong *a*

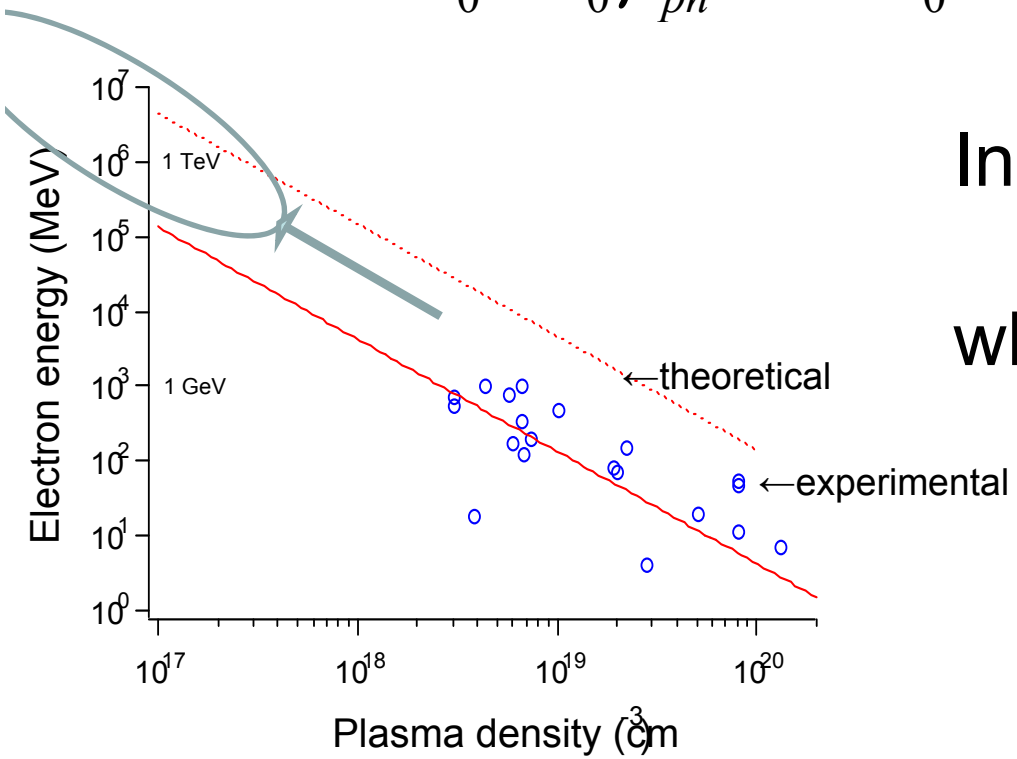
atto-, zeptosecond

Can we meet the challenge?

A. Suzuki @KEK(2008)

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

(Abdo, et al, 2009)

←lower energy

higher→

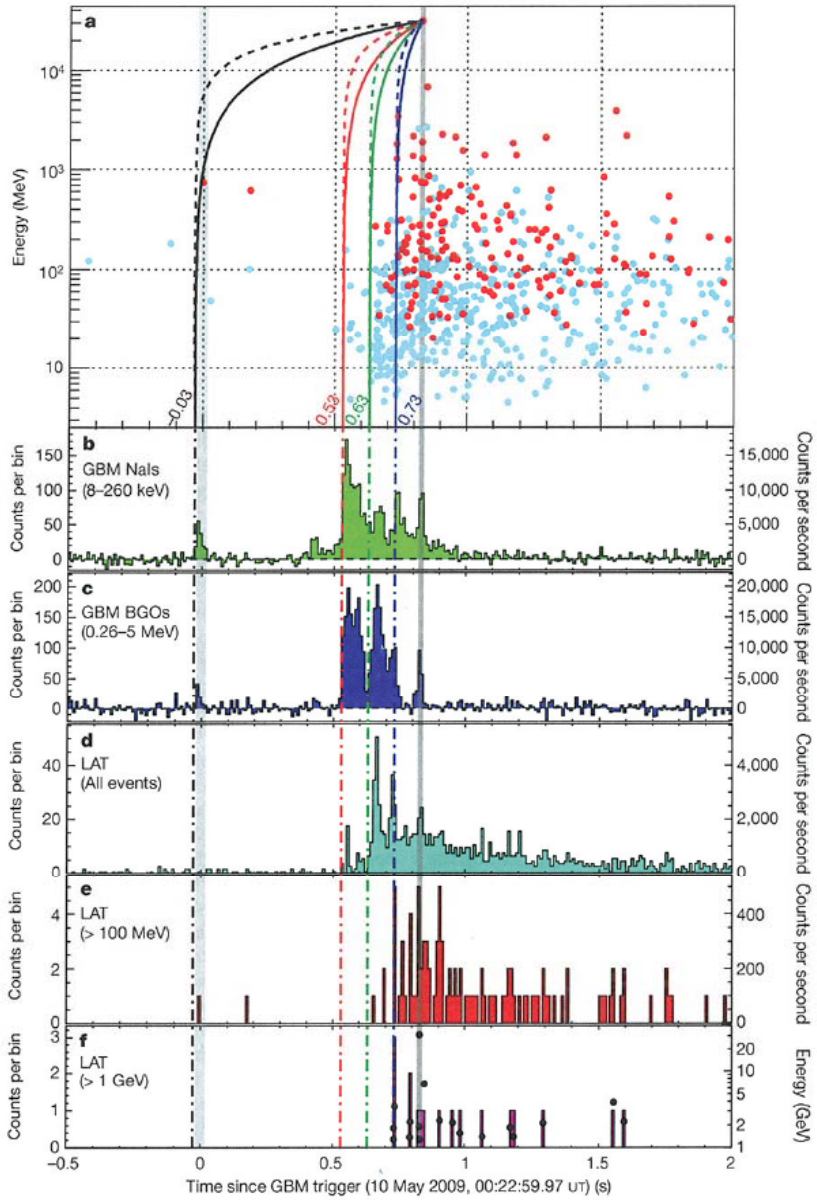


Figure 1 | Light curves of GRB 090510 at different energies. a, Energy ... lowest to highest energies. **f** also overlays energy versus arrival time for each

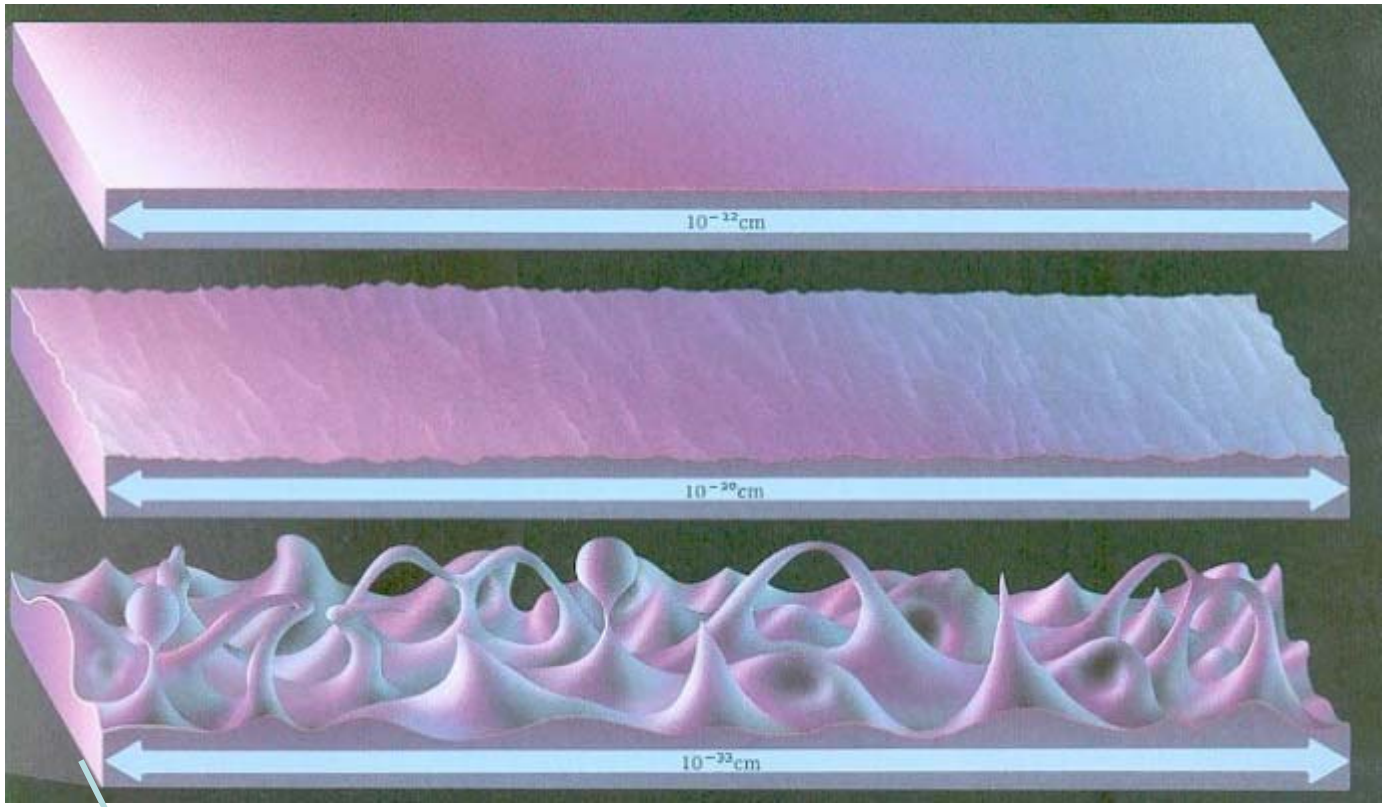
Energy-dependent **photon speed ?**
Observation of primordial Gamma Ray Bursts (GRB)
(limit is pushed up close to Planck mass)

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

Feel vacuum texture: PeV energy γ

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

$c < c_0$



Coarser, lower energy texture

Finer, higher energy texture

← (0.1PeV)

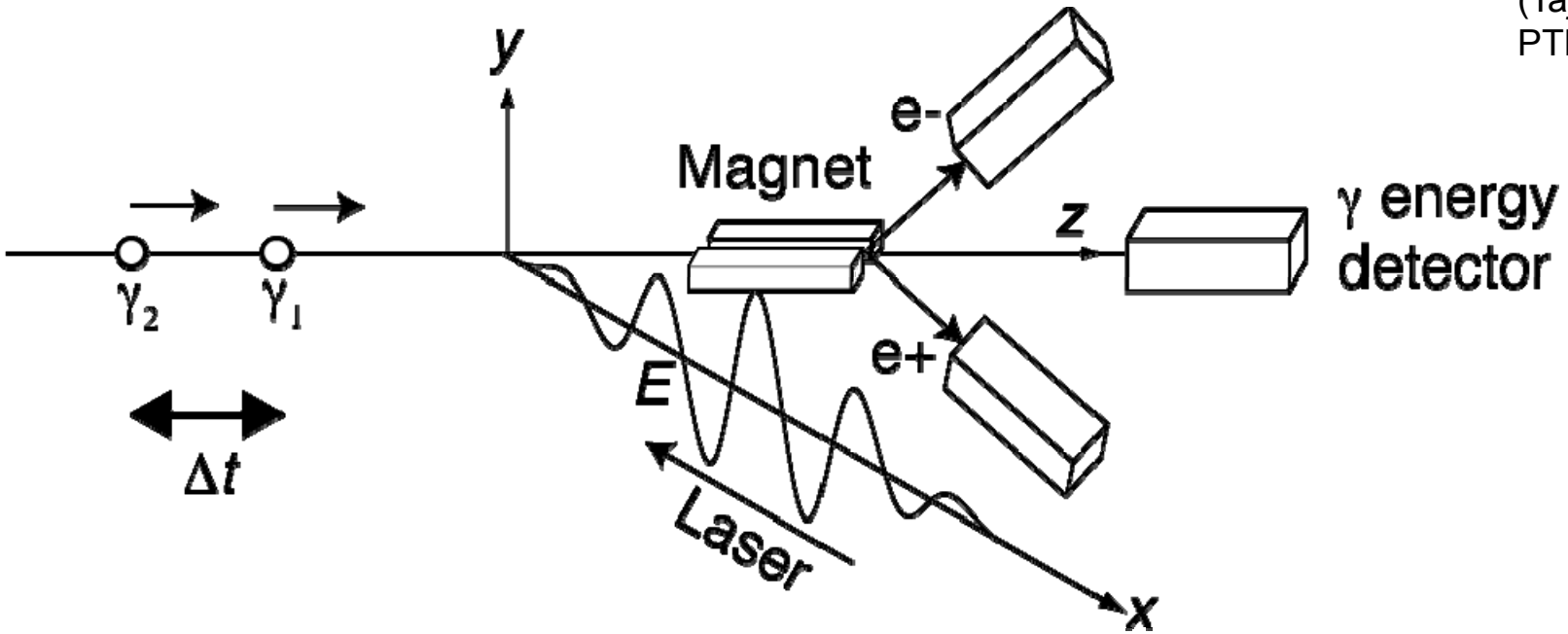
1km

←(1PeV : fs behind)

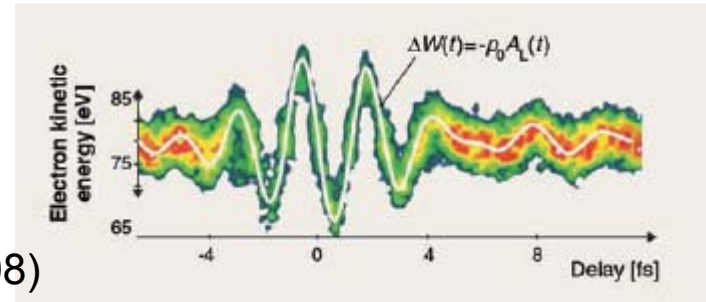
PeV γ (converted from e^-)

Attosecond Metrology of PeV γ Arrivals

(Tajima, Kando, PTP, 2011)



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



Goulielmakis(2008)

Extreme High Energy and Synchrotron Radiation

E > 30TeV: untested territory for Lorentz invariance

(B. Altschul, 2008)

with a modified Lorentz factor

$$\tilde{\gamma} = \frac{1}{\sqrt{1 + 2\delta_\gamma(\hat{v}) - v^2}}. \qquad (13)$$

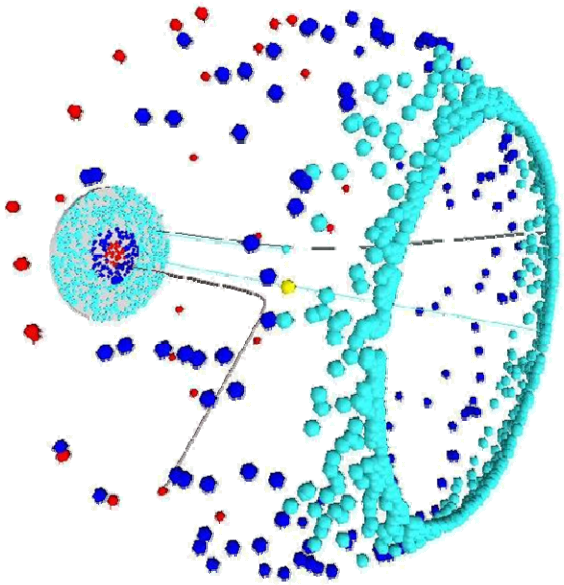
The power radiated would then be $P = \frac{e^2 a^2}{6\pi m^2}\tilde{\gamma}^4$.] For ultrarelativistic particles, $\gamma \approx [2(1-v)]^{-1/2}$ increases very rapidly as a function of v, since $\frac{d\gamma}{dv} = v\gamma^3 \approx \gamma^3$. The modified expression for $\vec{v}(\vec{p})$ changes the radiated power $P(\vec{p})$ to

$$P(\vec{p}) = P_0(\vec{p})\{1 + 4\gamma^2[\delta(\hat{p}) - \delta_\gamma(\hat{p})]\}, \qquad (14)$$

Synchrotron radiation
radiation

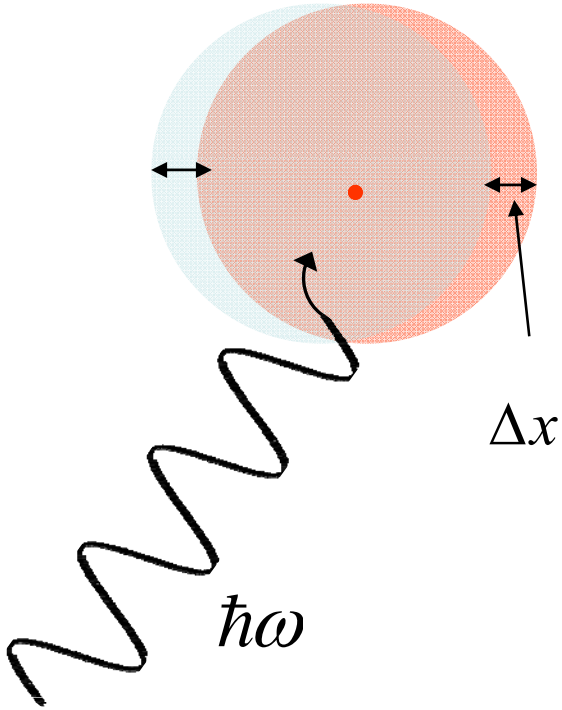
↑ Lorentz violating term

Laser probing nonlinearities in matter



$$\Delta x \sim \frac{\hbar}{p}$$

vs



$$\Delta x = \frac{eE}{\omega^2 m}$$

Rutherford's (accelerator) approach vs **Laser approach**

discover particles (colliders)

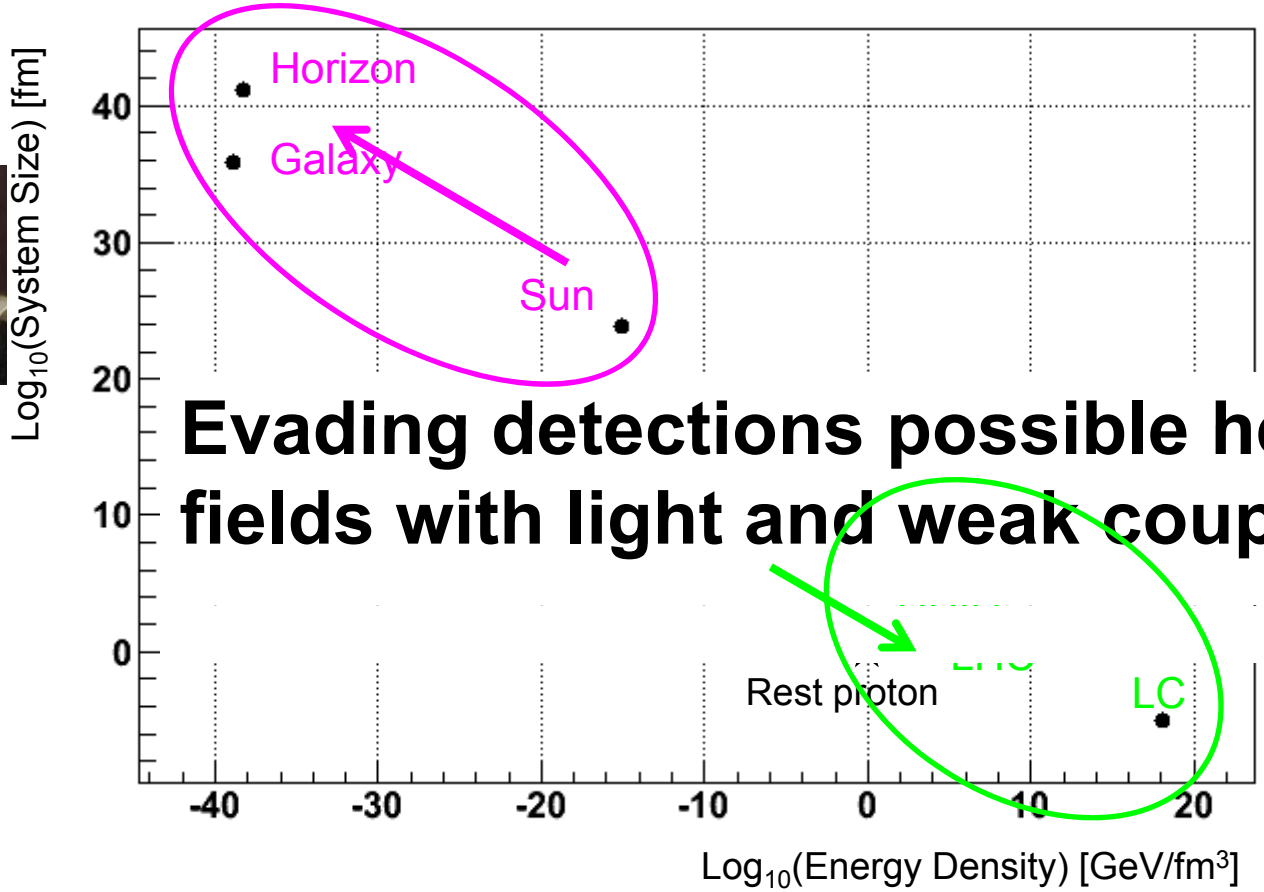
nonlinear optics, spectroscopy

Domains of physical laws

Astronomy and HEP explore extreme large and small domains

Cosmological observation

Weak coupling
m=0



Evading detections possible here: fields with light and weak coupling

Strong coupling
Heavy m

High energy collider

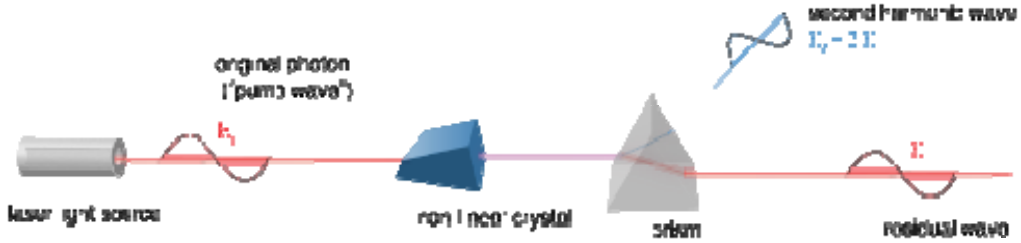
Homma, Habs, Tajima (2011)

Accessible by high-intensity lasers

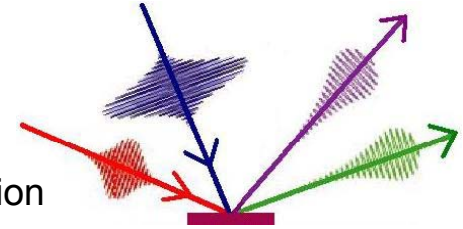
① Laser-laser interactions: new particle search in vacuum

Laser-induced nonlinear optics in vacuum ← cf. Nonlinear optics in crystal

Birefringence

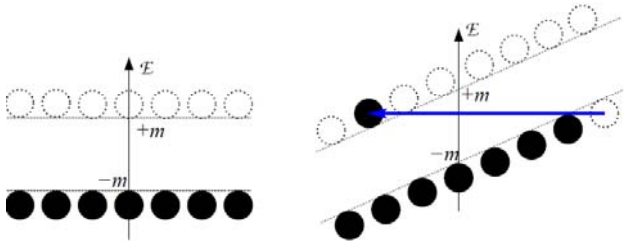


Second harmonic generation (P. Franken)

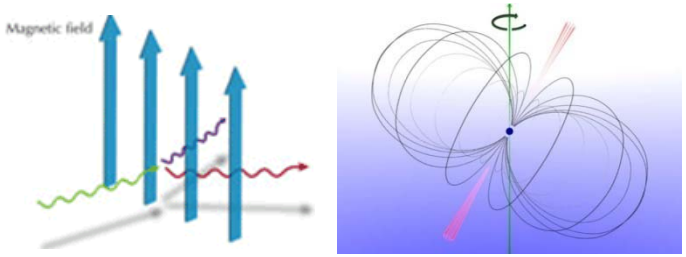


Higher harmonic generation

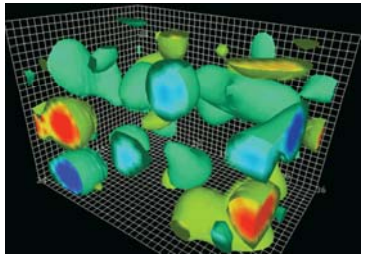
② Laser-γ interactions: non-perturbative aspect of vacuum



QED tunneling



Photon splitting (magnetor)



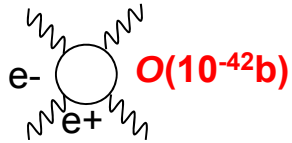
QCD vacuum

(Homma)

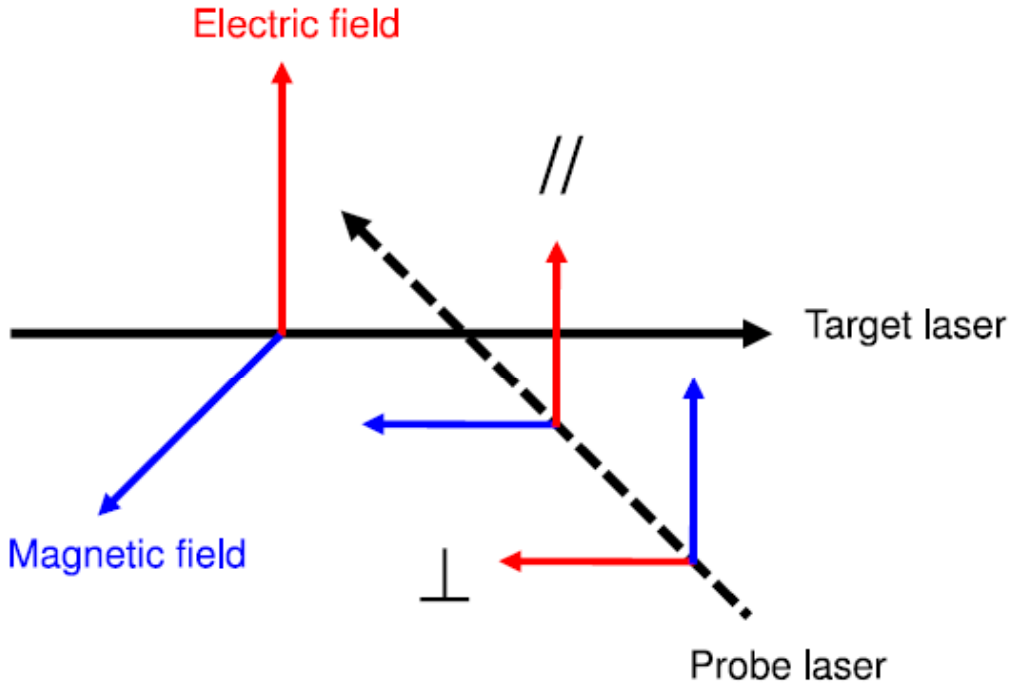
Birefringence by QED in eV range

Euler-Heisenberg one-loop Lagrangian

$$L_{QED} = \frac{1}{360}\frac{\alpha^2}{m^4}[4(F_{\mu\nu}F^{\mu\nu})^2 + 7(F_{\mu\nu}\tilde{F}^{\mu\nu})^2]$$



Refractive index depends on polarizations



$$n_{\parallel} = 1 + \frac{16}{45}\frac{\alpha^2 U}{U_e}, \quad n_{\perp} = 1 + \frac{28}{45}\frac{\alpha^2 U}{U_e}$$

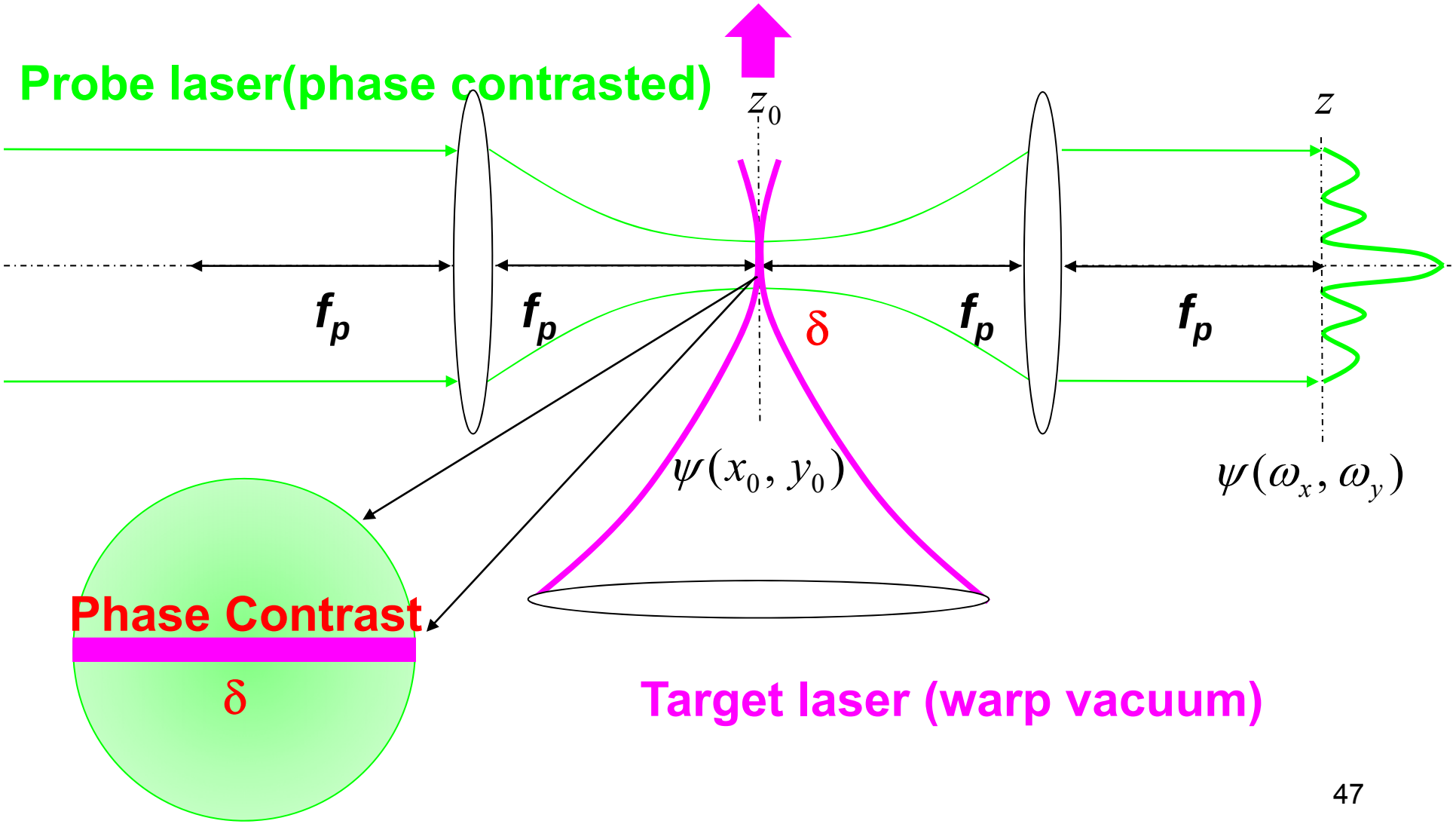
$U_e = m_e^4 c^5/\hbar^3 \approx$ 1.42x10^6 J/μm^3

ELI(~200J per ~20fs)

can reach $\Delta n \sim 10^{-9} \sim 10^{-10}$

(Homma, Habs, Tajima)

Phase contrast imaging of vacuum



K.Homma, D.Habs, T.Tajima (2011)

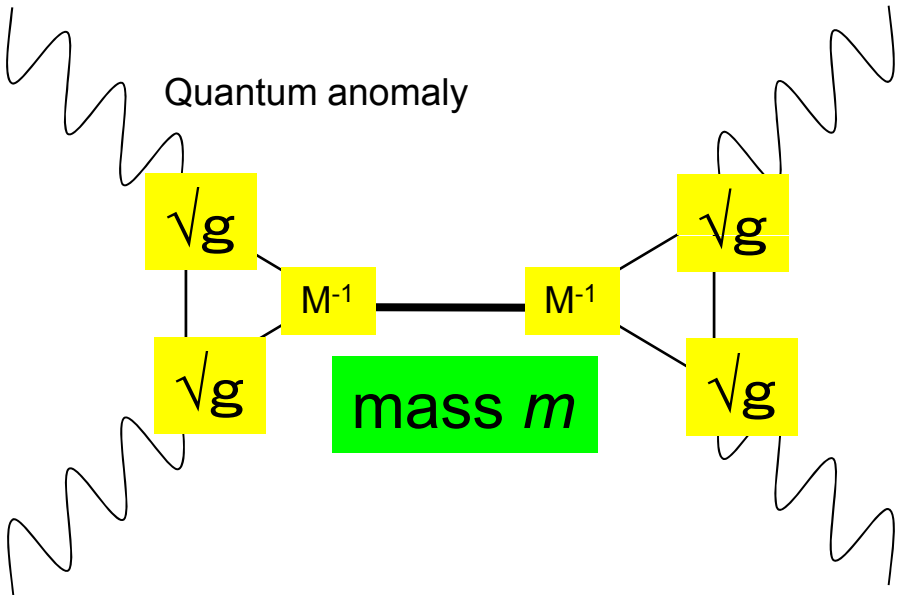
Beyond QED photon-photon interaction

$$L_{QED} = \frac{1}{360}\frac{\alpha^2}{m^4}[4(F_{\mu\nu}F^{\mu\nu})^2 + 7(F_{\mu\nu}\tilde{F}^{\mu\nu})^2]$$

$$\phi F_{\mu\nu}F^{\mu\nu} \qquad \sigma F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Away from 4 : 7 = QCD , low-mass scalar ϕ, or pseudoscalar σ

Resonance in quasi-parallel collisions in low cms energy



If M~M$_{Planck}$, Dark Energy

$$gM^{-1}F^{\mu\nu}F_{\mu\nu}\phi$$

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

QCD-instanton, Dark Matter

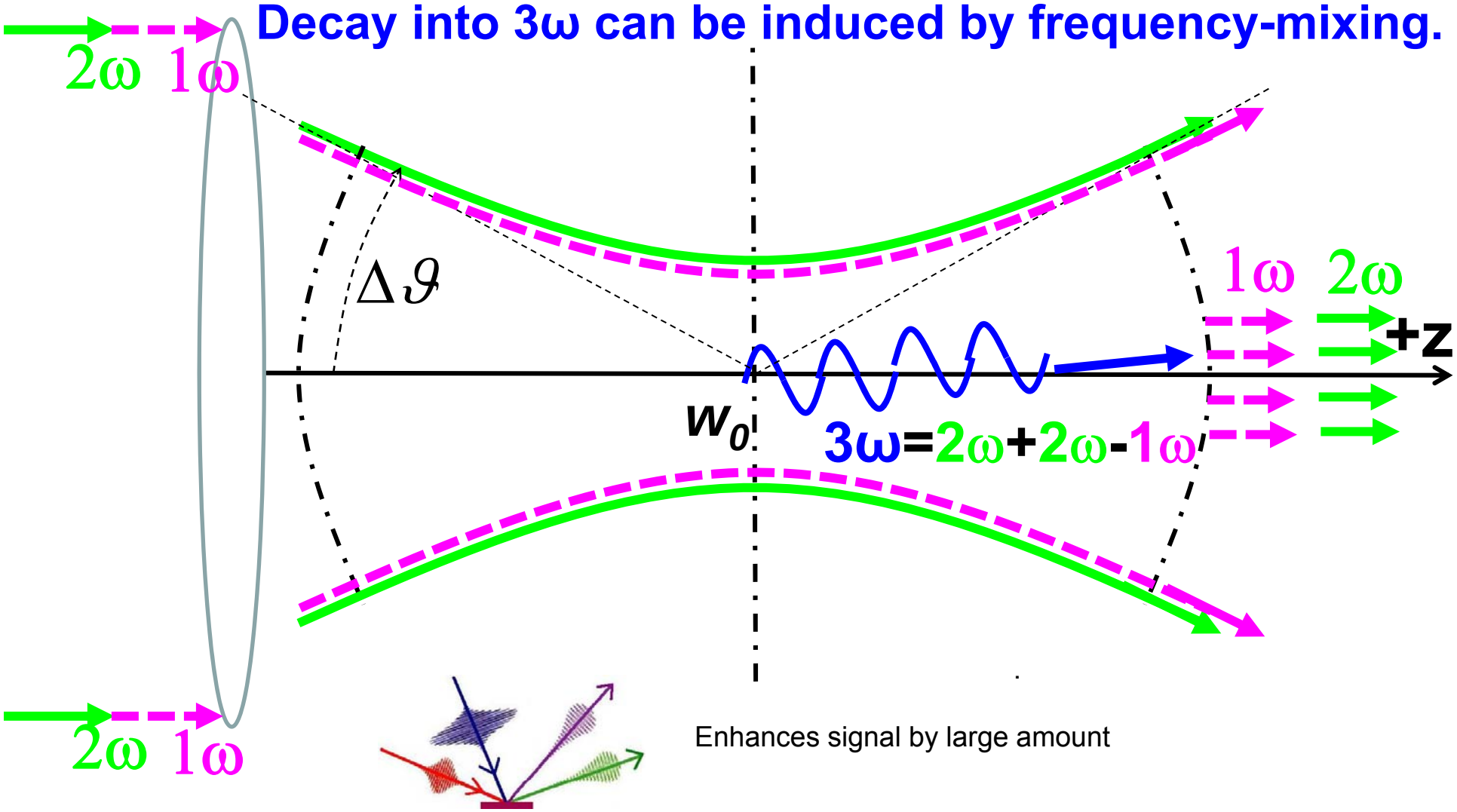
$$gM^{-1}F^{\mu\nu}\tilde{F}_{\mu\nu}\sigma$$

K.Homma, D.Habs, T.Tajima (2011)

Degenerate Four-Wave Mixing (DFWM)

Laser-induced nonlinear optics in vacuum (cf. Nonlinear optics in crystal)

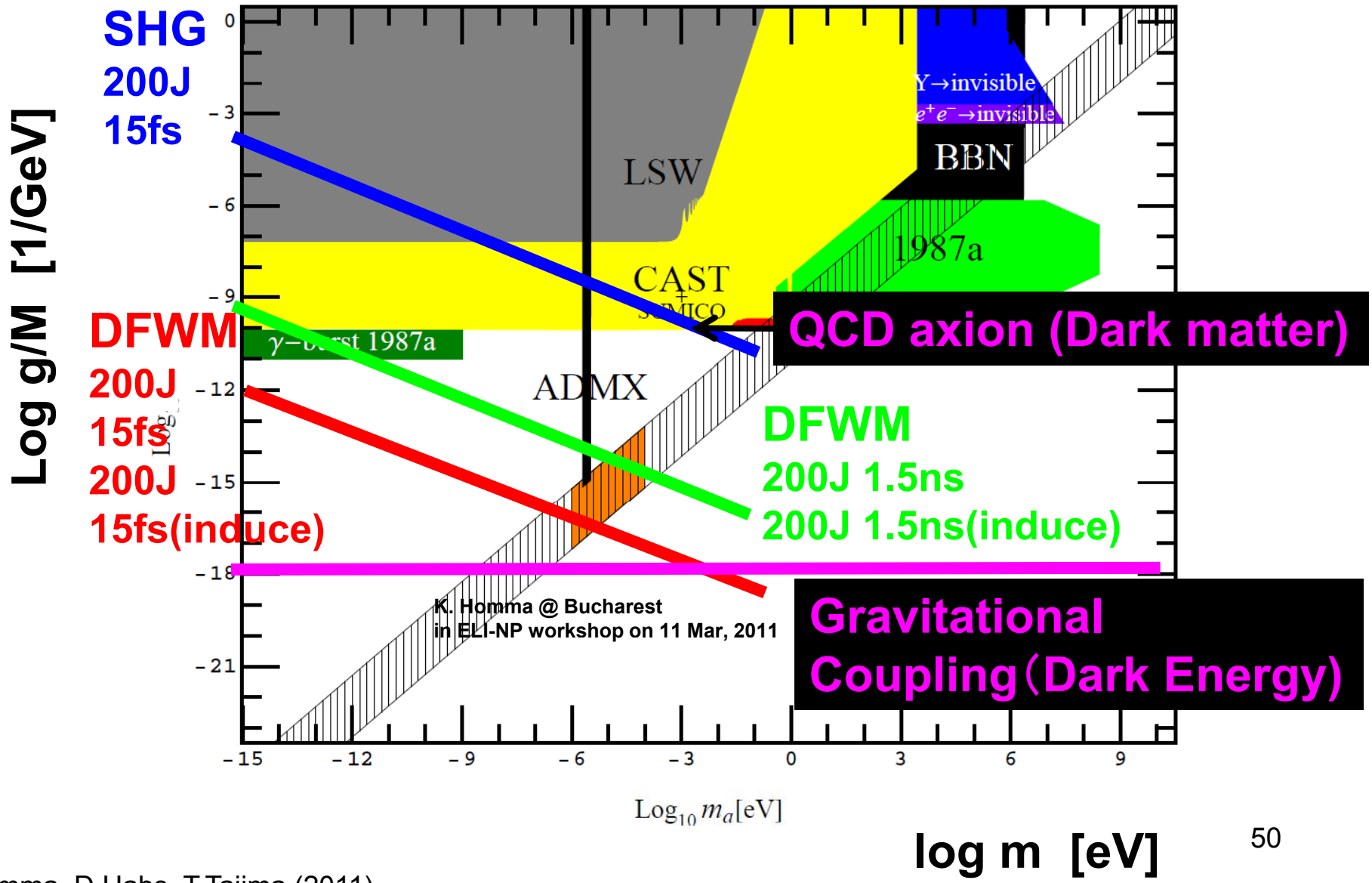
Decay into 3ω can be induced by frequency-mixing.



Enhances signal by large amount

K.Homma, D.Habs, T.Tajima
Appl. Phys. B (2011)

HFS road to unknown fields: dark matter and dark energy



K.Homma, D.Habs, T.Tajima (2011)

Conclusions

- Bridge between accelerator and laser communities necessary and ongoing
- Collider physics requirements: luminosity maximization, minimization of wall-plug power, beam dynamics: ==➔ low density operation
- Driver laser for collider: a challenge, but possible technologies emerging:
  e.g. ICAN Project (accelerator labs collaborating)
- Energy frontier with precision w/ a few shots possible
  e.g. Lorentz invariance test
- High field science approach: capability to explore new fields (dark matter; dark energy)

Centaurus A:

cosmic
wakefield
linac?

Thank you!