高強度レーザーと荷電粒子加速

High intensity laser and charged particle acceleration

近藤公伯

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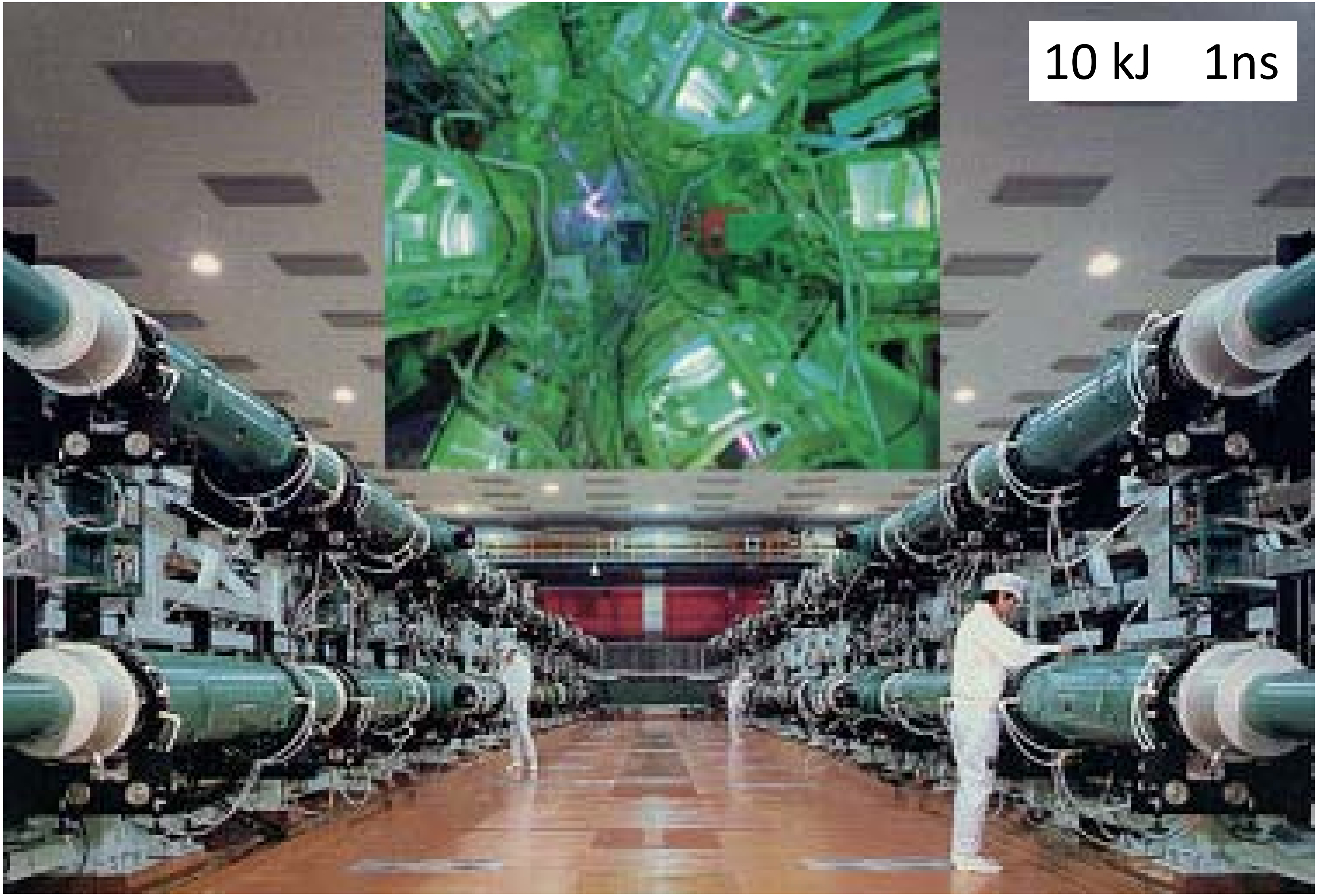
理研仁科センター月例コロキウム
2010年12月21日

Contents

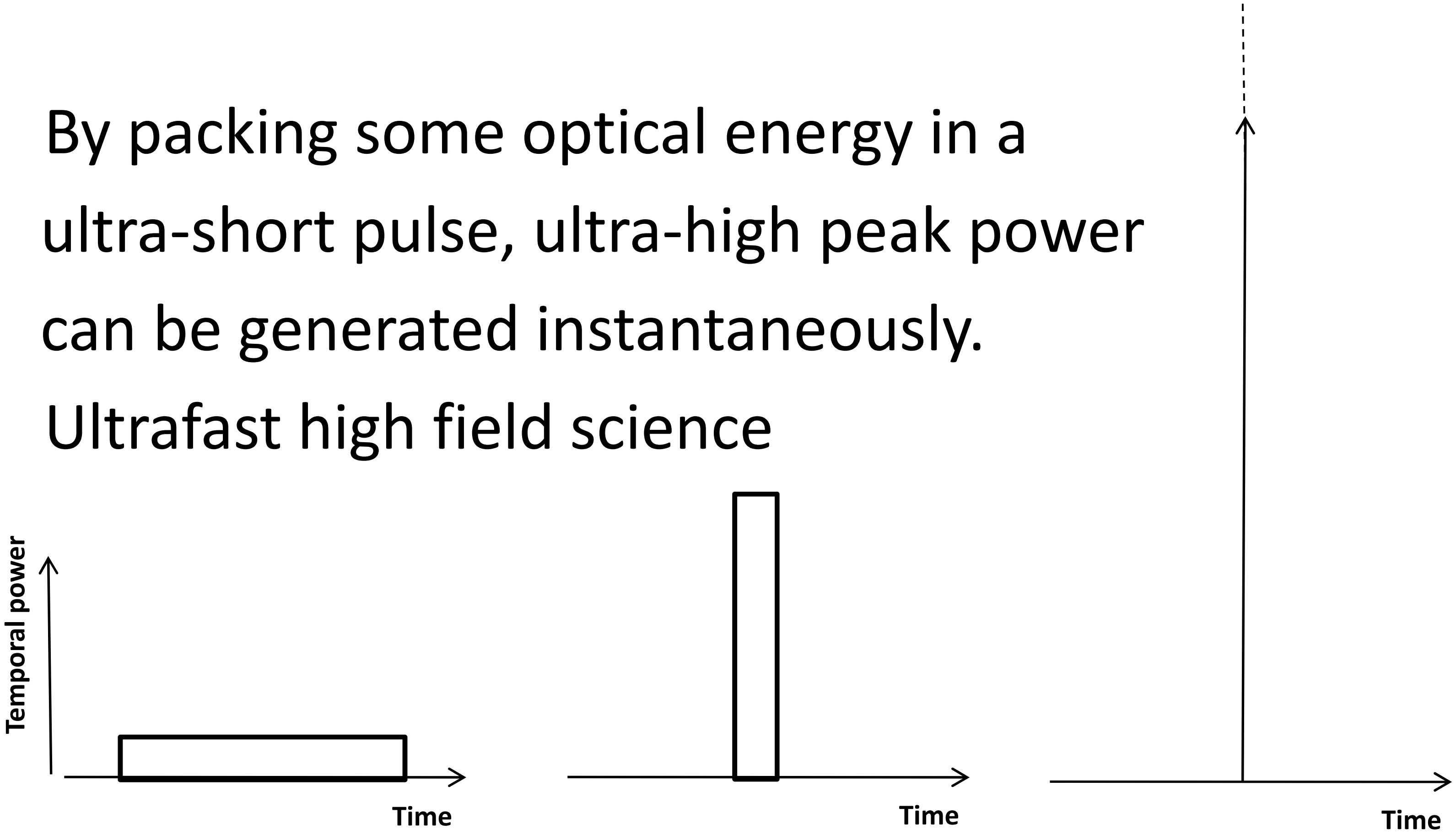
- Intense laser, especially high peak power laser
- Multi-photon process in atomic transition
- Laser wakefiled electron acceleration
- Laser driven ion acceleration and its medical application
- High field interaction with the energetic quantum beam by the accelerator

10 TW Laser system in 80's



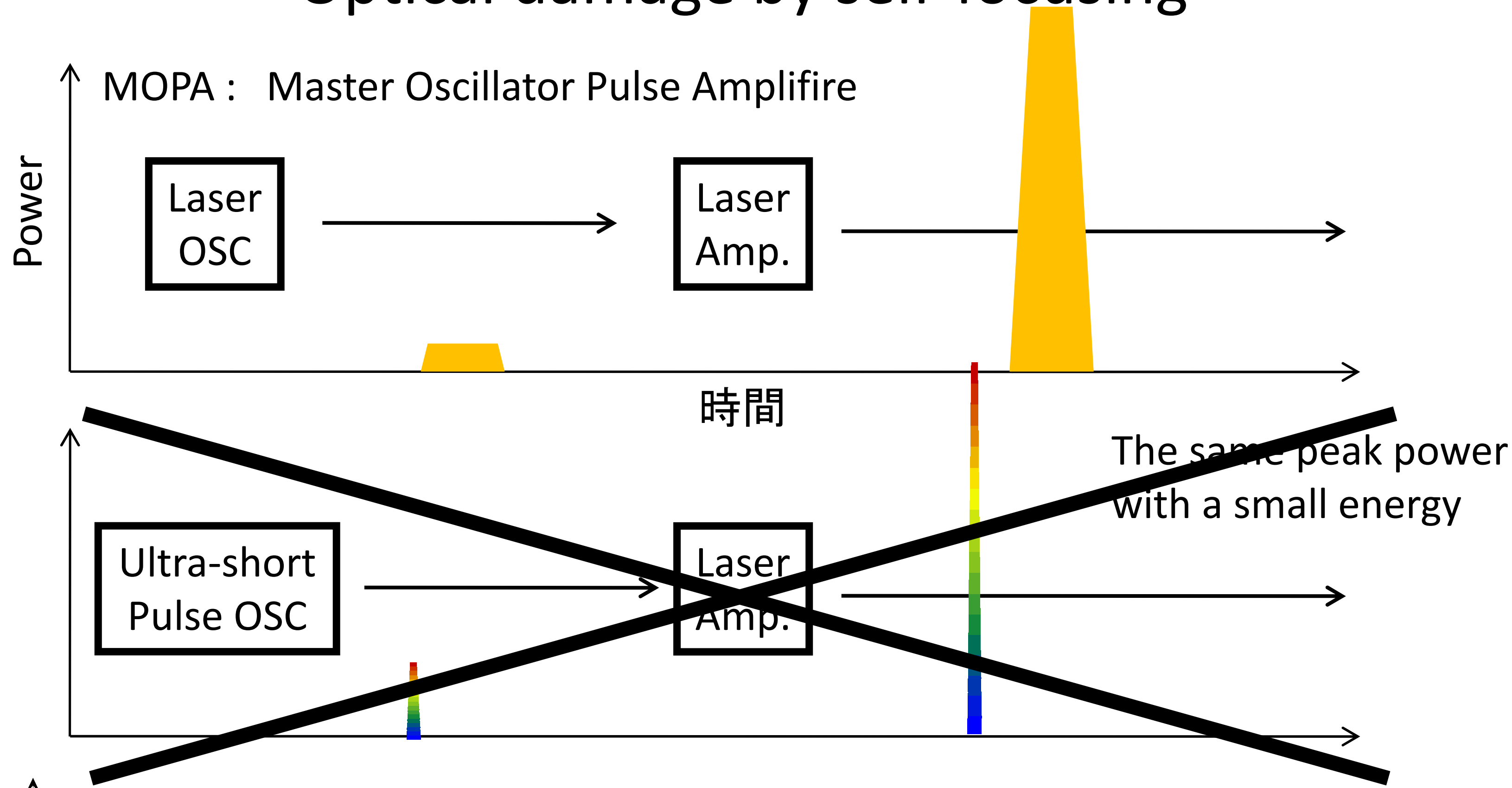
High Peak Power Laser

- By packing some optical energy in a ultra-short pulse, ultra-high peak power can be generated instantaneously.
- Ultrafast high field science



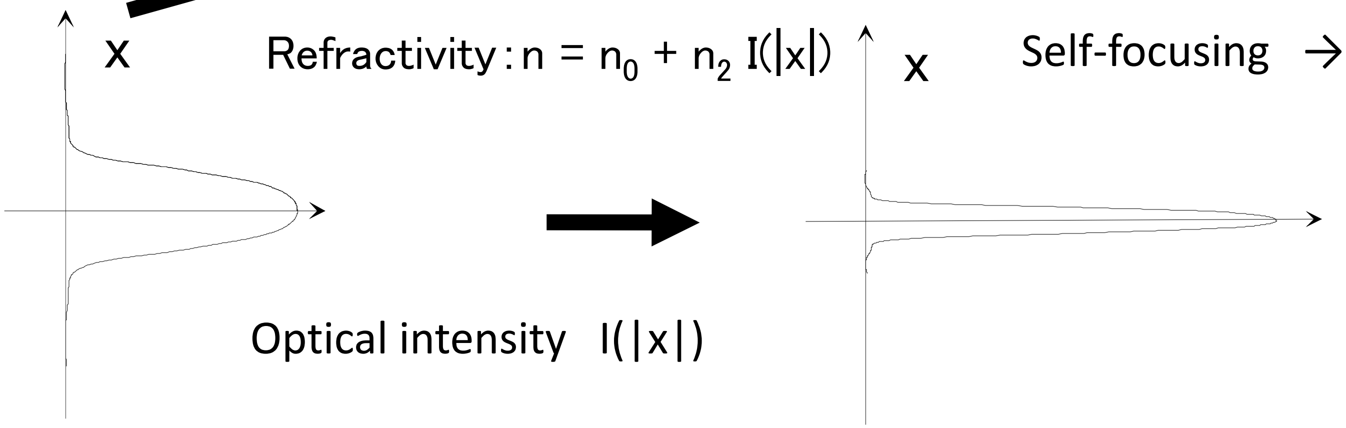
(Instantaneous power) = (optical energy)/(pulse duration)

Optical damage by self-focusing



Refractivity : $n = n_0 + n_2 I(|x|)$

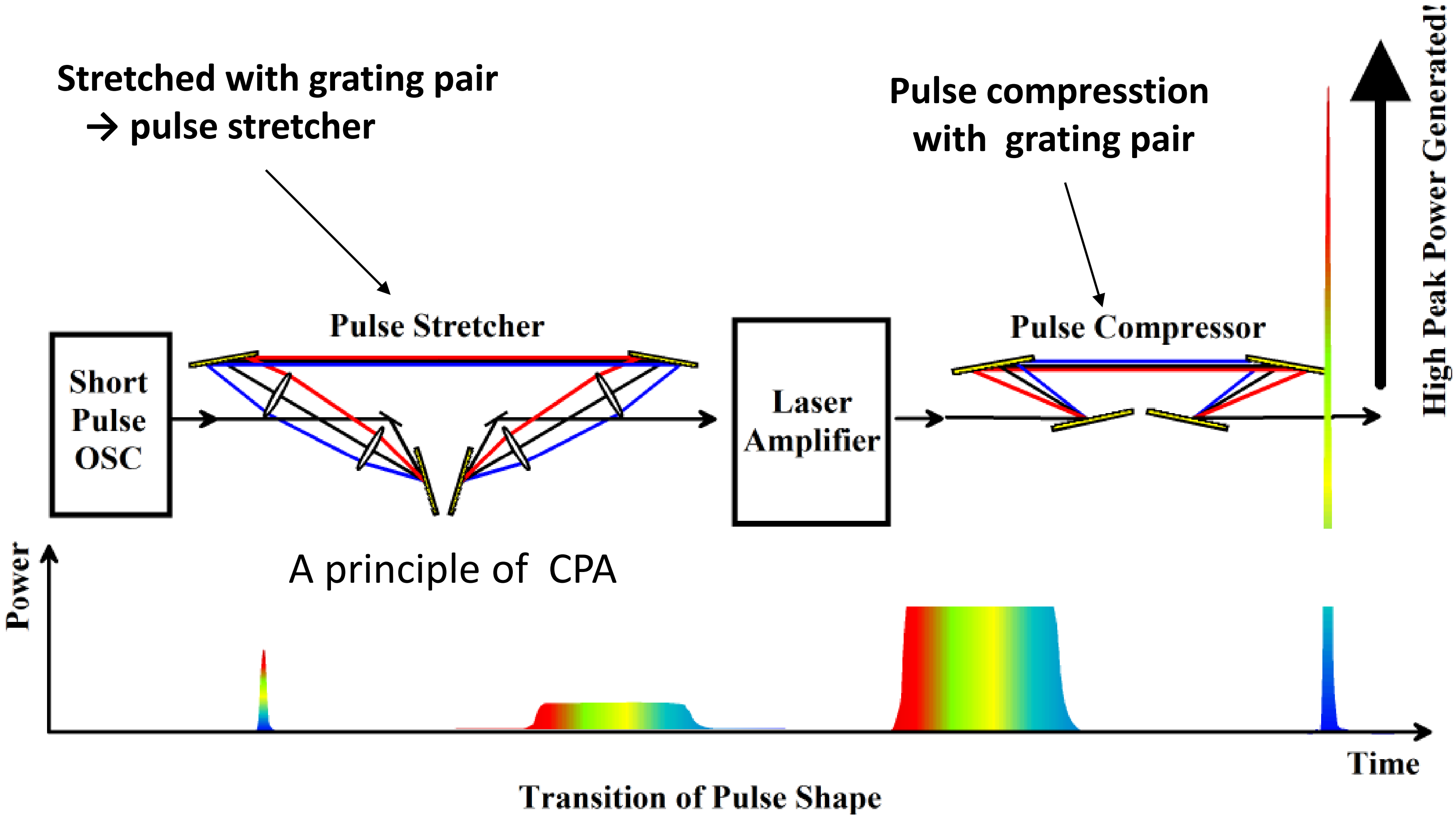
Self-focusing → Optical damage



Chirped pulse amplification

Stretched with grating pair
→ pulse stretcher

Pulse compresstion
with grating pair

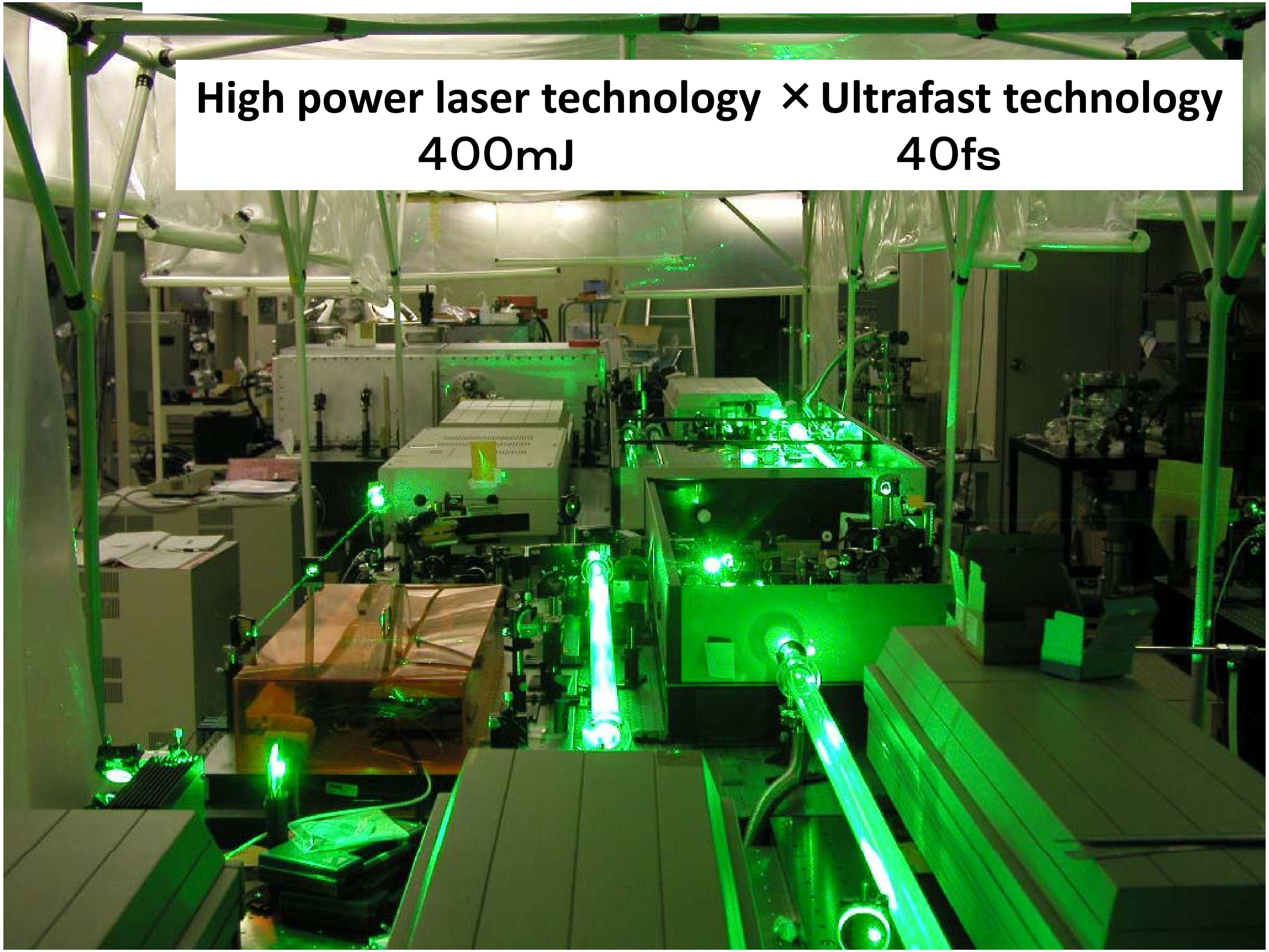


A principle of CPA

Strickland and Mourou, Opt. Comm. (1985)

10TW class CPA laser in Osaka Univ. 2004

High power laser technology ×Ultrafast technology
400mJ 40fs



SCIENCE • VOL. 264 • 13 MAY 1994
ARTICLES

Terawatt to Petawatt Subpicosecond Lasers

Michael D. Perry and Gerard Mourou

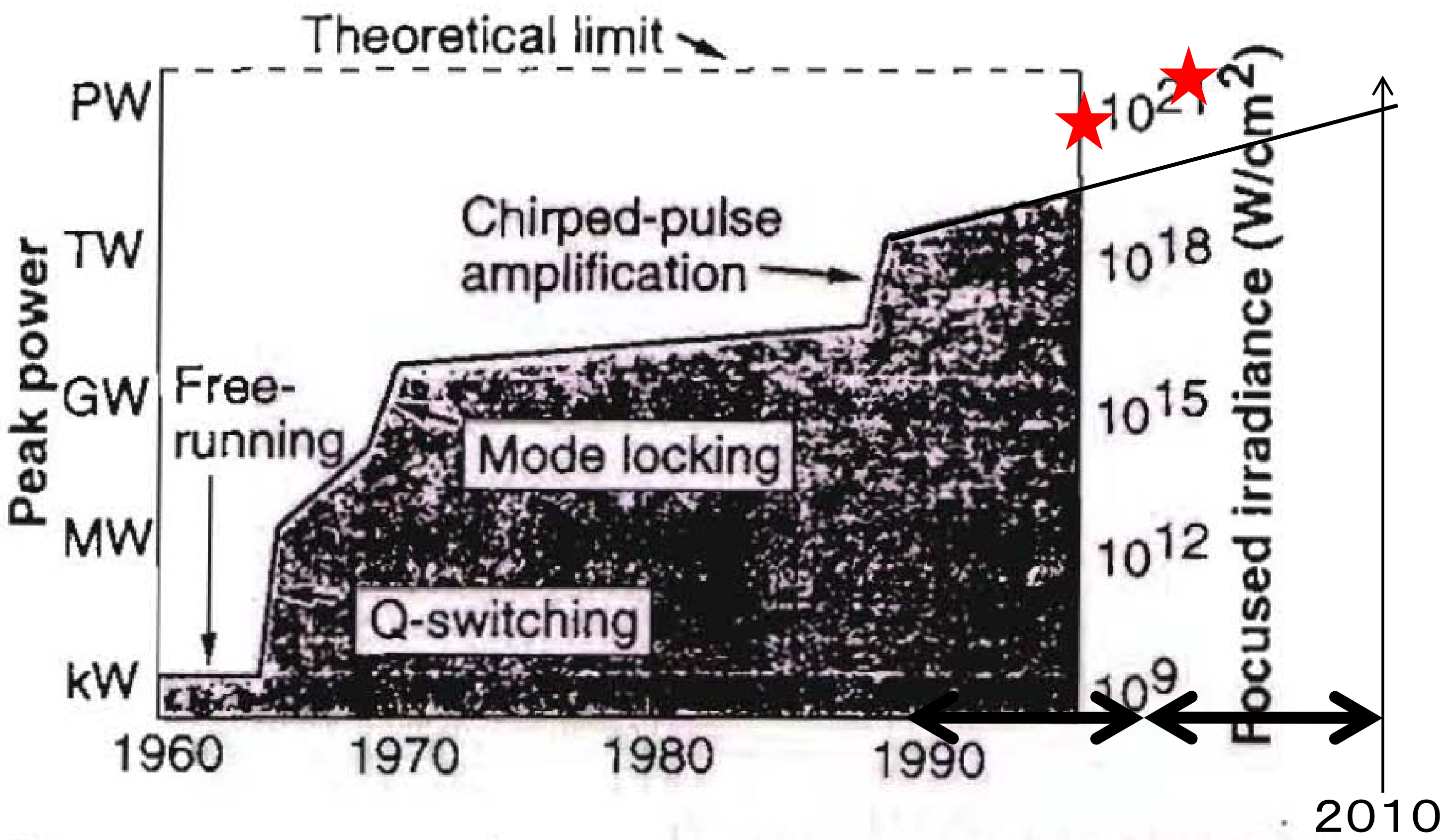


Fig. 1. Increase in peak power and focused irradiance of small-scale (area, 1 cm²) lasers.

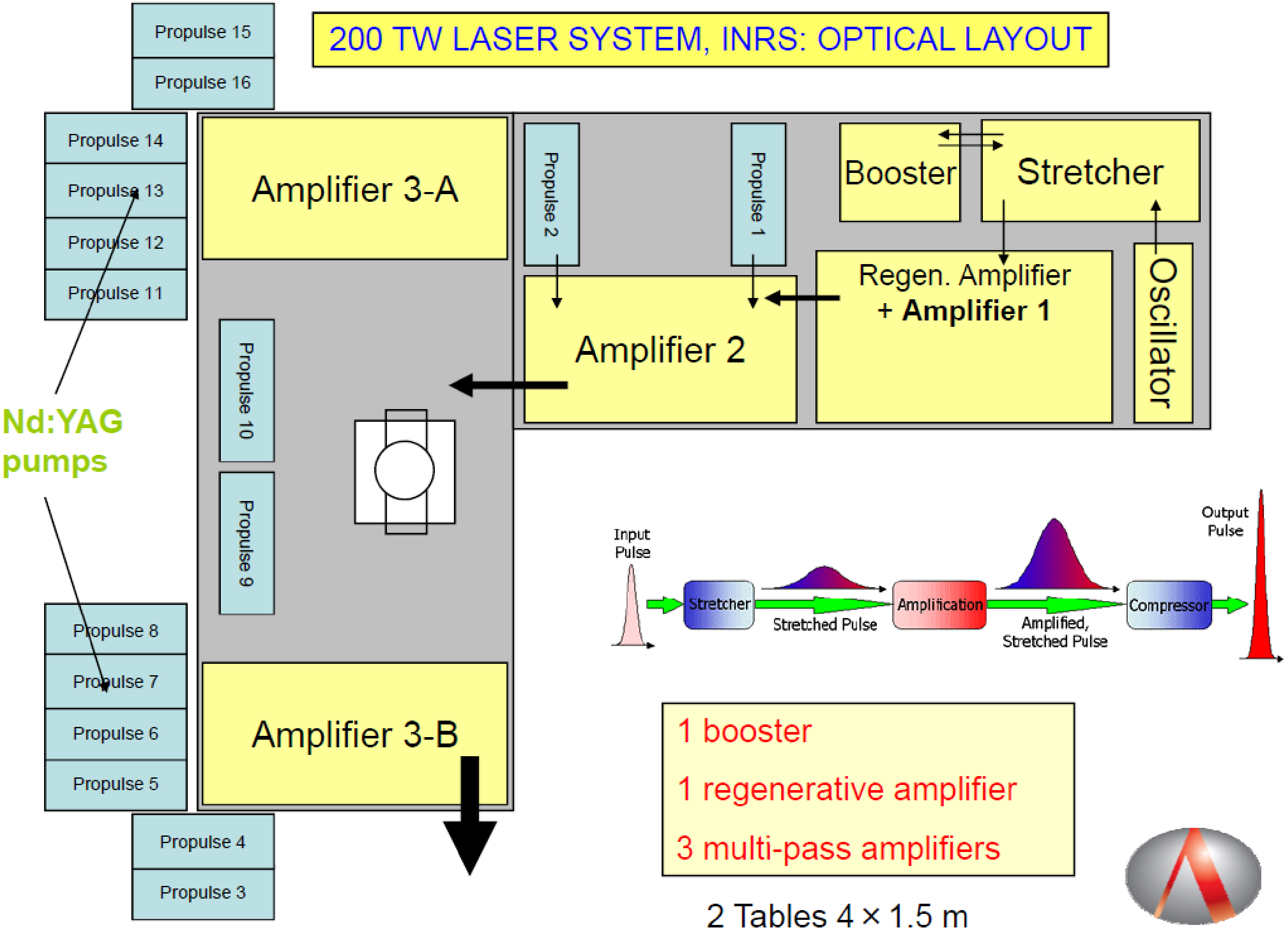
KPSI in JAEA leaded the ultrashort high peak power laser development

- １００TW，１０Hz Ti:sapphire laser
  K. Yamakawa, et al., Opt. Lett. (1998)

- Single shot type１PW、20fs Ti: sapphire laser
  M. Aoyama, et al., Opt. Lett. (2003)

PW-class laser in KPSI, JAEA
(J-KAREN) 2003

Amplitude 200 TW commercial machine



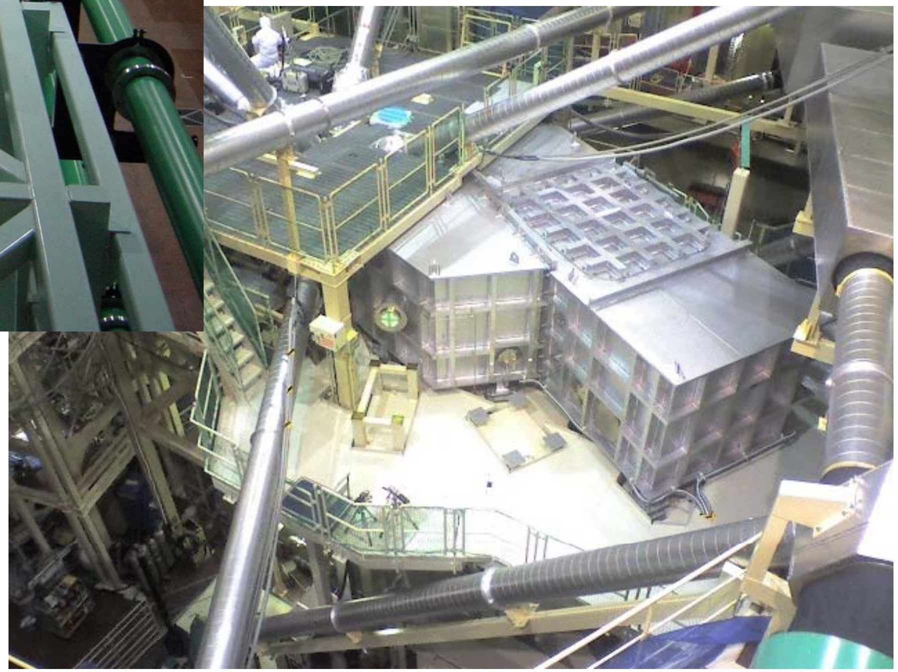
1 booster

1 regenerative amplifier

3 multi-pass amplifiers

2 Tables 4 × 1.5 m

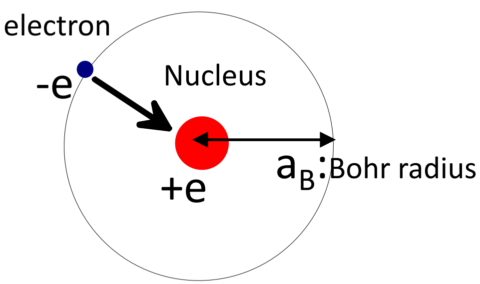
10 PW-class laser LFEX
in ILE Osaka Univ. LFEX for fast ignition in ICF



If 1TW laser pulse is focused, what happens ?

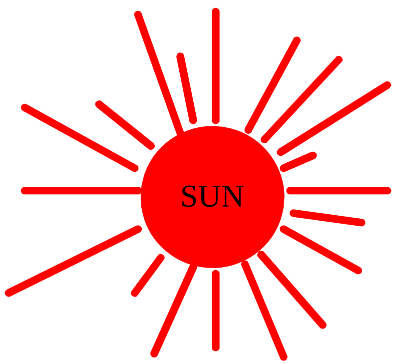
$$\frac{\text{1 trillion watt}}{\text{10 micrometer area}} = 10^{18}\text{W/cm}^2 \ (2.7\times10^{12}\text{V/m})$$

Coulomb field
in a hydrogen atom



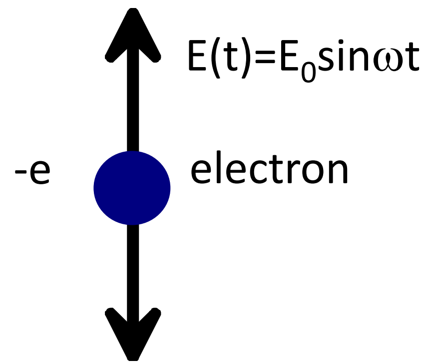
e/a_B^2: 5.1×10^{11}V/m
↓
3.5×10^{16}W/cm^2

Center of Sun



Central Temp. :15 million K
Black Body Temp:σT^4
2.9×10^{17}W/cm^2

Zigzag motion
（quiver motion)



Kinetic energy
Up: 100keV (λ: 1μm)
Velocity ～ c/2

・Normalized vector potential：

$$a_0 \sim 0.8 \times 10^{-9} (I[W/cm^2])^{0.5} \lambda[\mu m]$$

I: Optical intensity、 λ: Wavelength

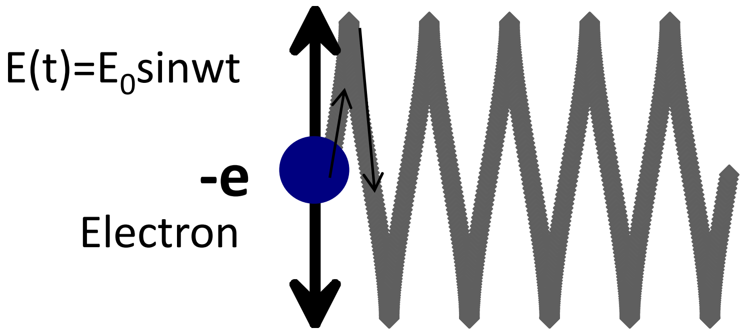
Ex. When we focus 1 TW to 10 μm size,

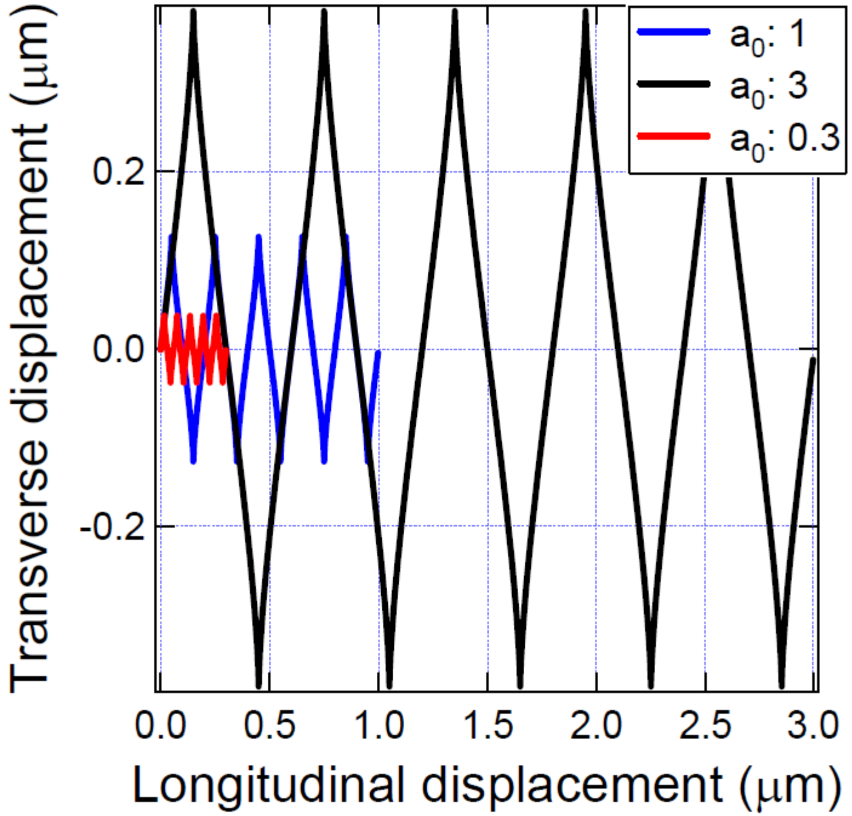
I becomes 10^{18} W/cm² → $a_0 \sim 1$

$a_0 > 1$

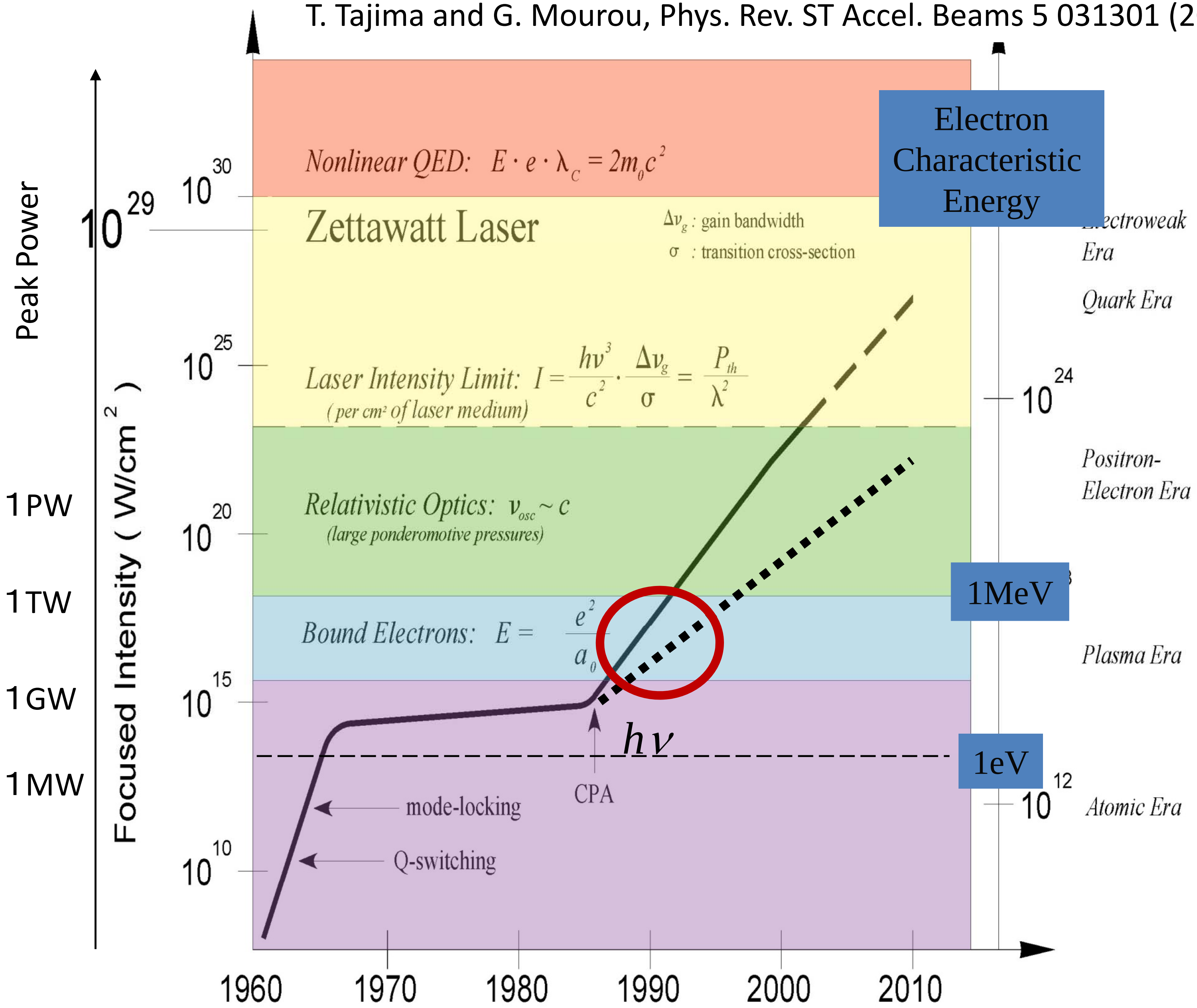
→ Electron motion becomes relativistic.

Zig-zag motion affected by the magnetic field.



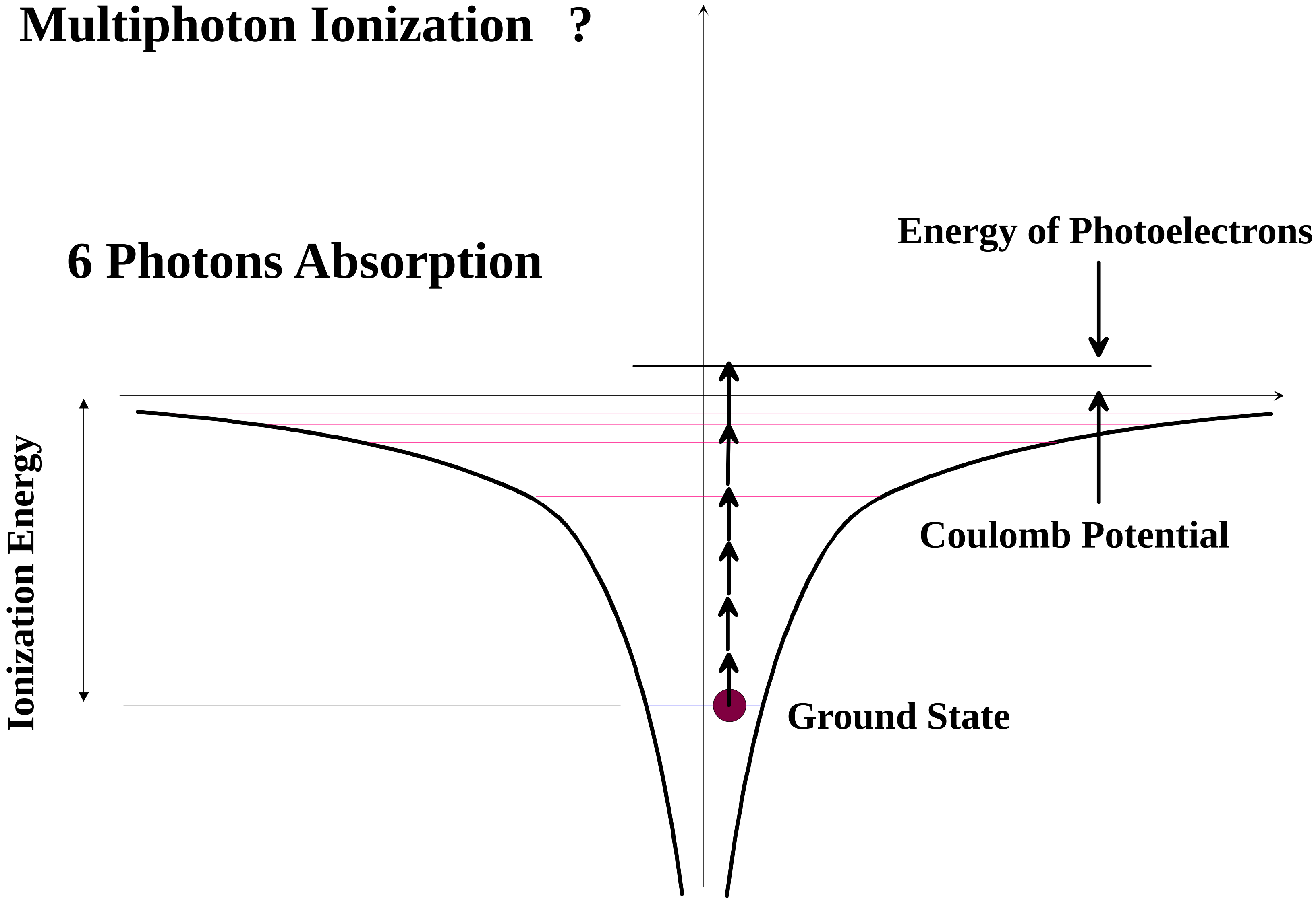


T. Tajima and G. Mourou, Phys. Rev. ST Accel. Beams 5 031301 (2002)

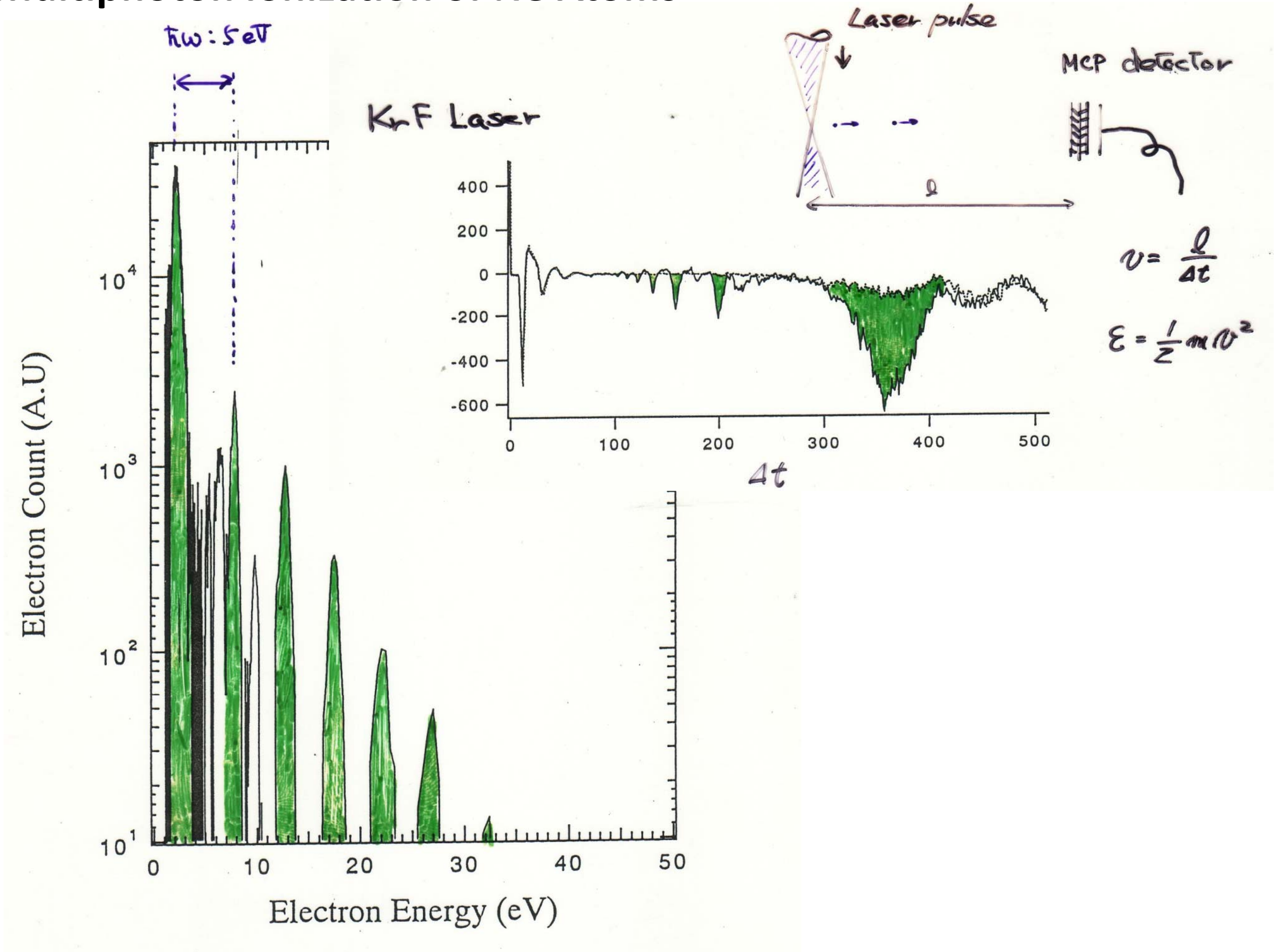


Multiphoton Ionization ?

6 Photons Absorption

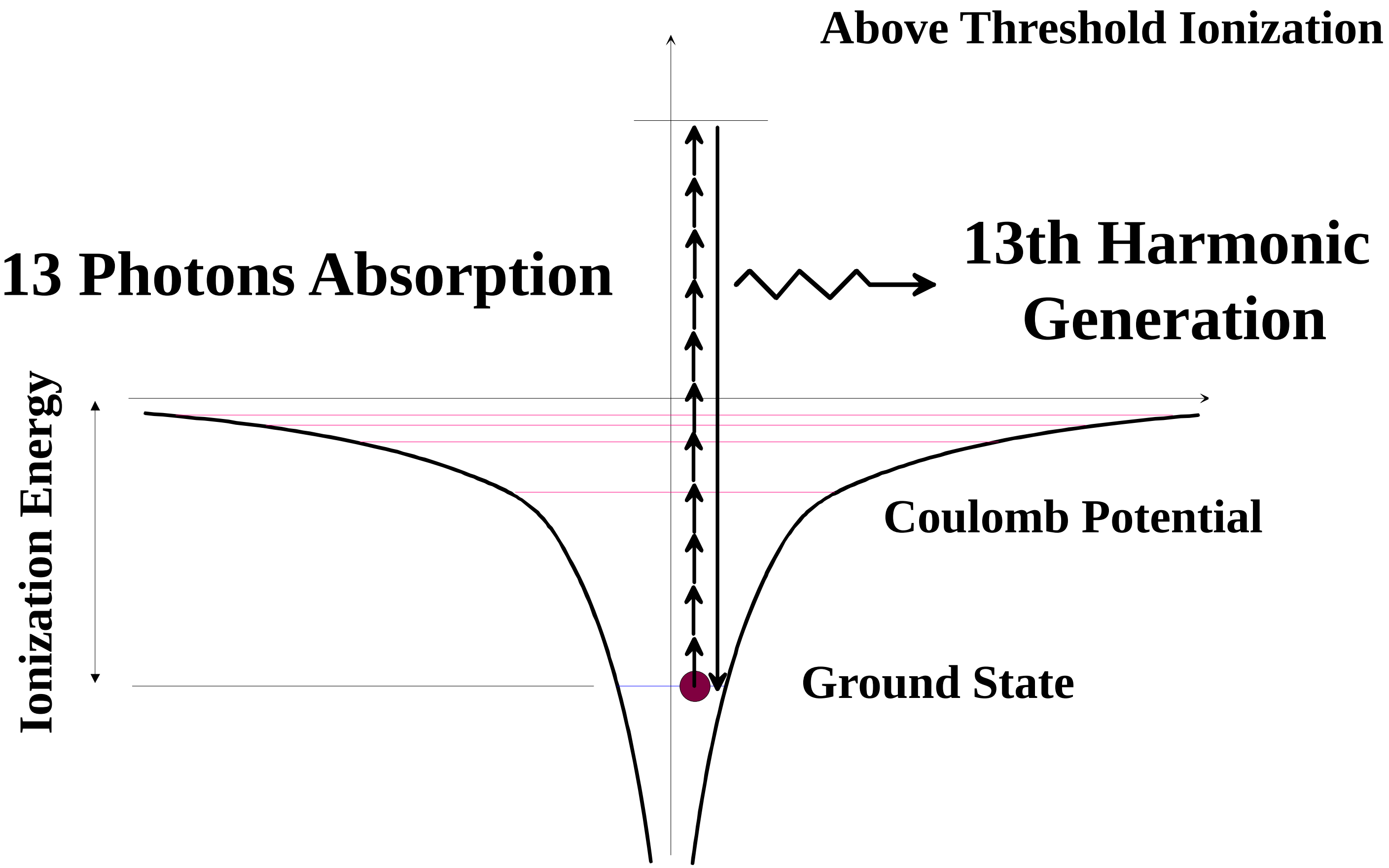


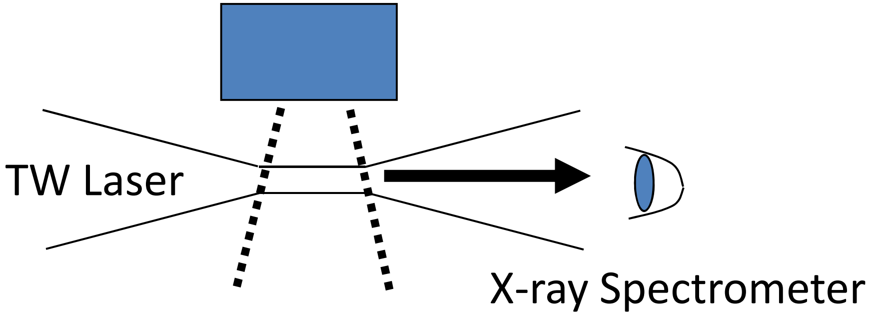
Multiphoton Ionization of Ne Atoms



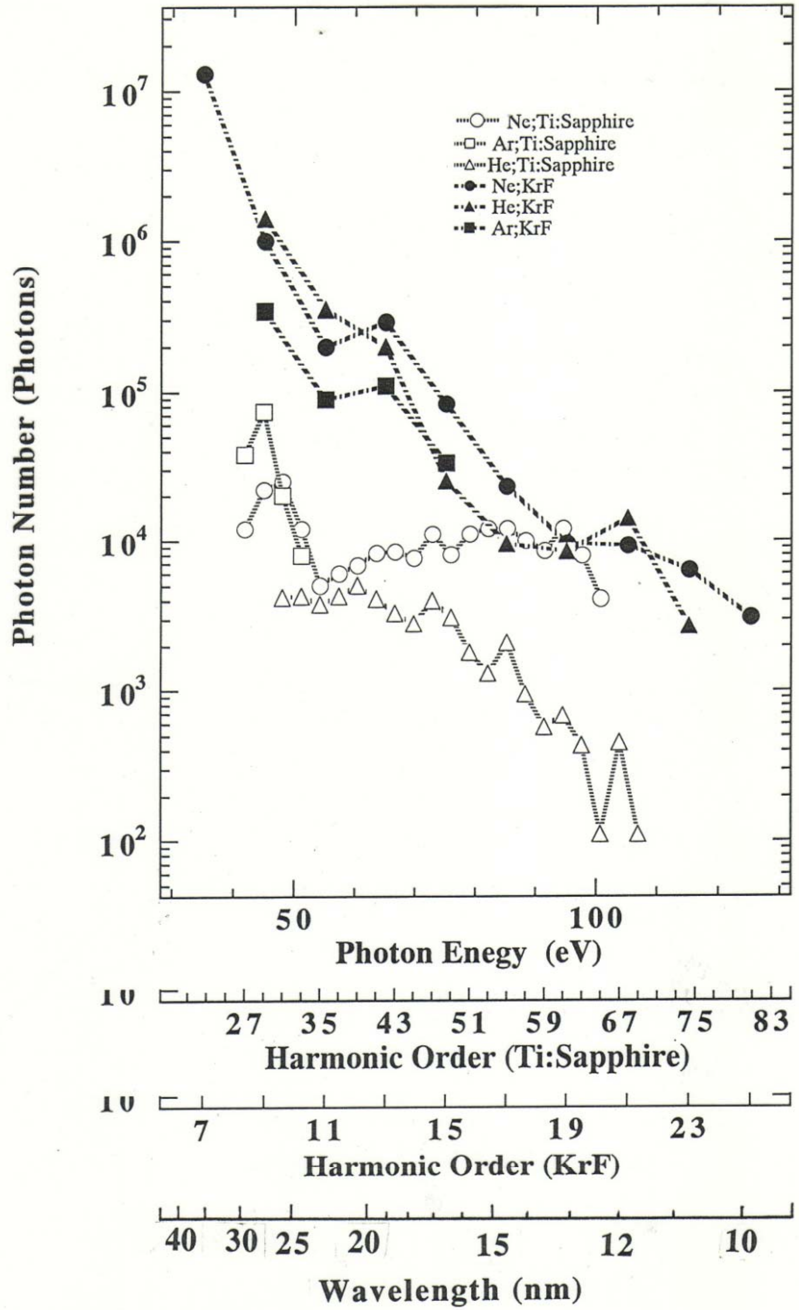
High Harmonic Generation with Multiphoton Ionization

Keldysh parameter: $\gamma > 1$

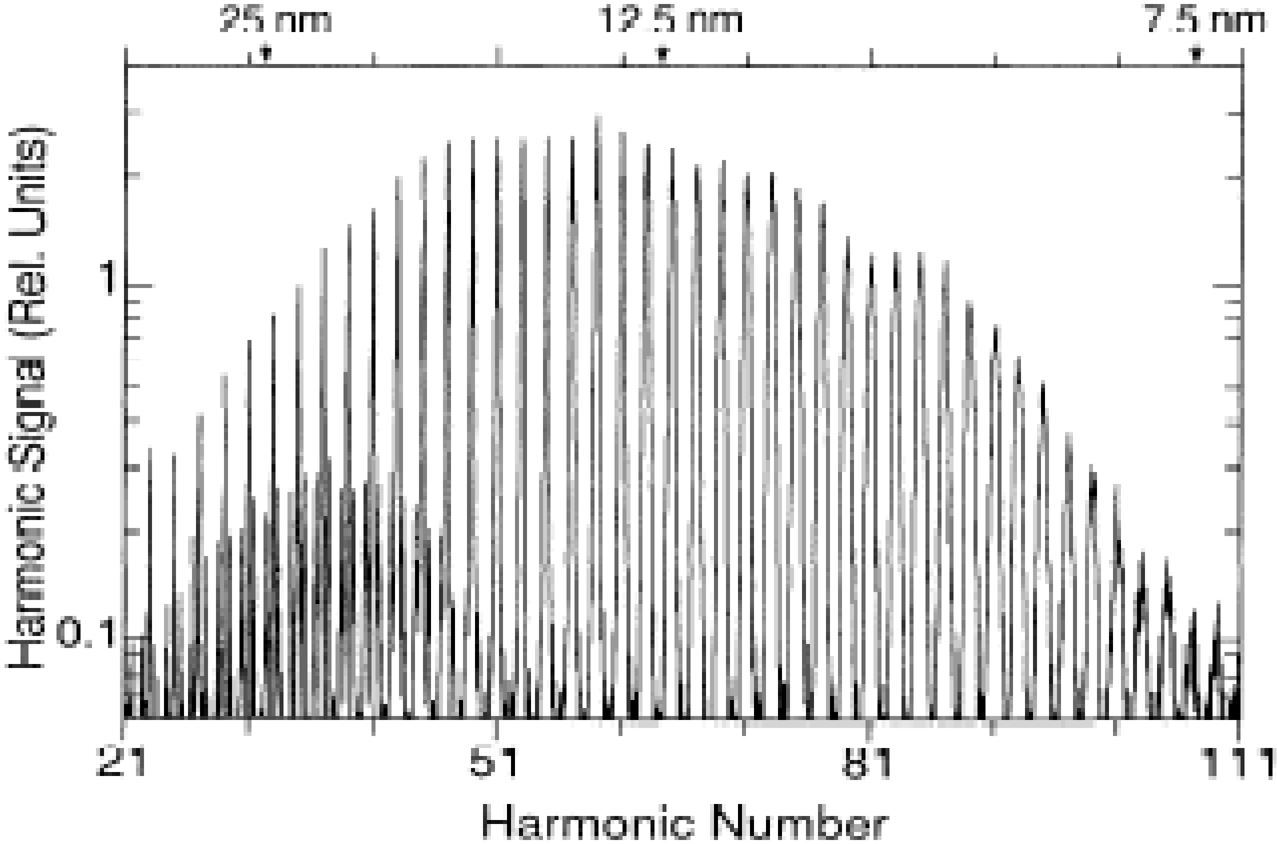




K. Kondo et al. Phys. Rev. A 49 3881 (1994)

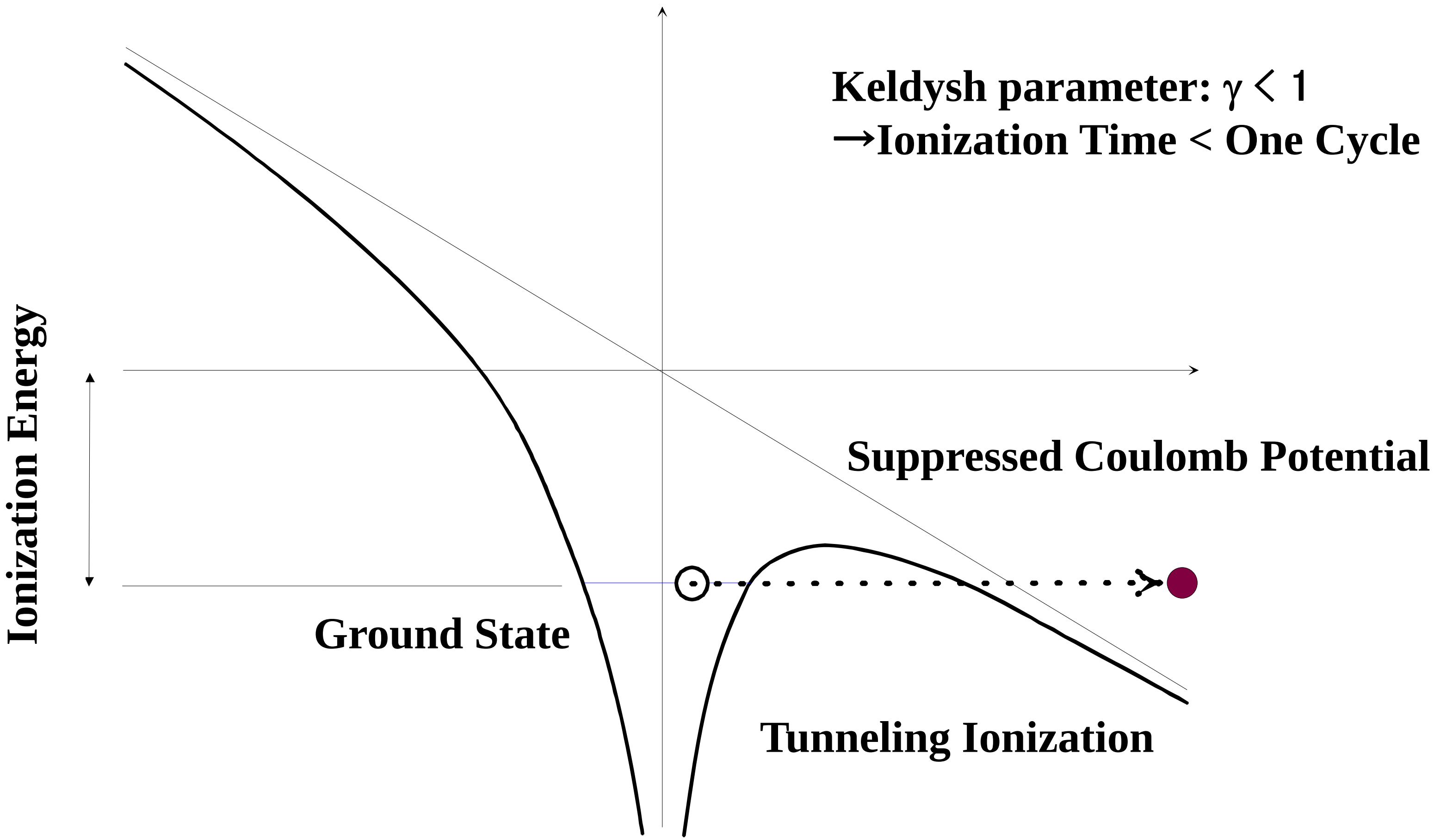


Higher harmonics generation with a plateau in the spectrum



In 1991,Stanford Univ. group has observed over 100^{th} order harmonics with TW Ti:S laser.

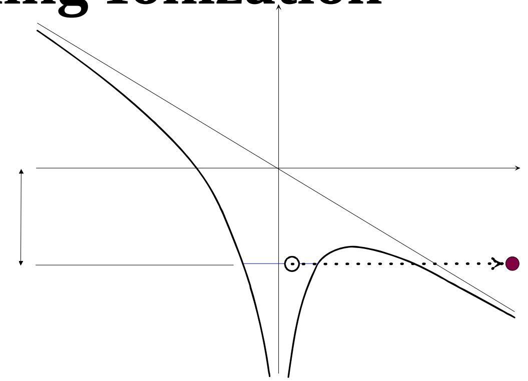
Tunneling Ionization



High Harmonic Generation with Tunneling Ionization
Two Step Quasi Static Model by Corkum

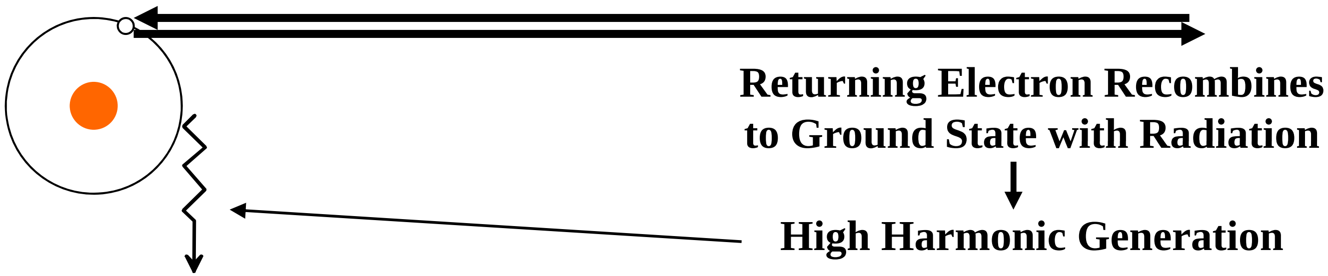
P. B. Corkum Phys. Rev. Lett. 71, 1994 (1993)

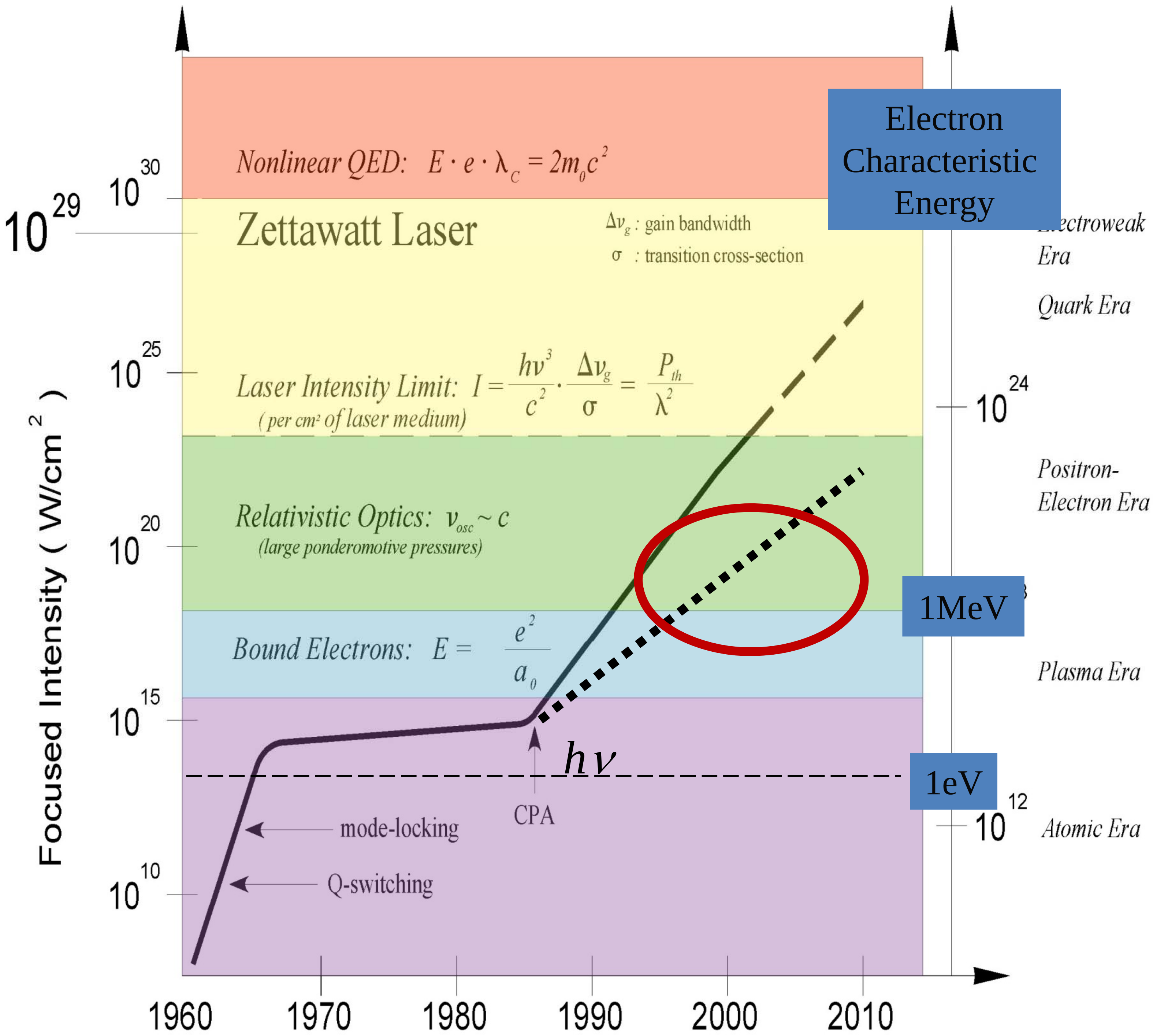
1st Step: Tunneling Ionization



2nd Step: Classical Motion in Optical Electric Field

Electron Excursion
x >> (Bohr Radius)

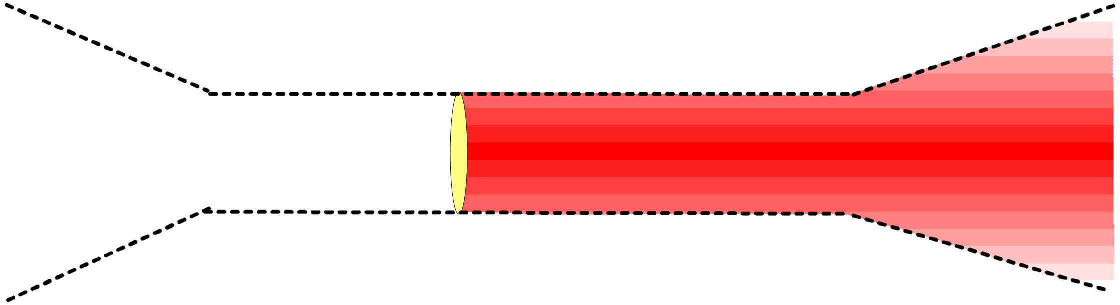




Focused Intensity (W/cm 2)
10 30
10 29
10 25
10 20
10 15
10 10
Nonlinear QED: E · e · λC = 2m0c2
Zettawatt Laser
Δνg : gain bandwidth
σ : transition cross-section
Laser Intensity Limit: I = hν3/c2 · Δνg/σ = Pth/λ2
(per cm2 of laser medium)
Relativistic Optics: vosc ~ c
(large ponderomotive pressures)
Bound Electrons: E = e2/a0
mode-locking
Q-switching
CPA
hν
1960
1970
1980
1990
2000
2010
Electron Characteristic Energy
1MeV
1eV
10 24
10 12
Electroweak Era
Quark Era
Positron-Electron Era
Plasma Era
Atomic Era

Comparatively low irradiation intensity

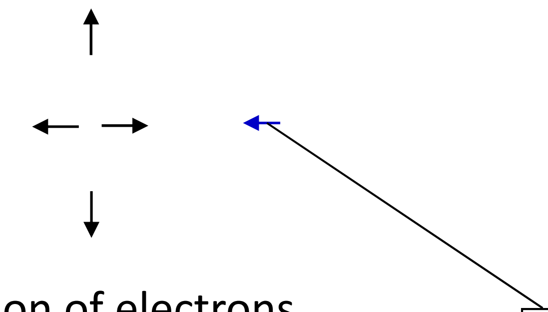
Propagation of Laser Pulse with Ionization



Electrons can be accelerated by laser wakefield .

> 10^{18} W/cm^2

Wakefield

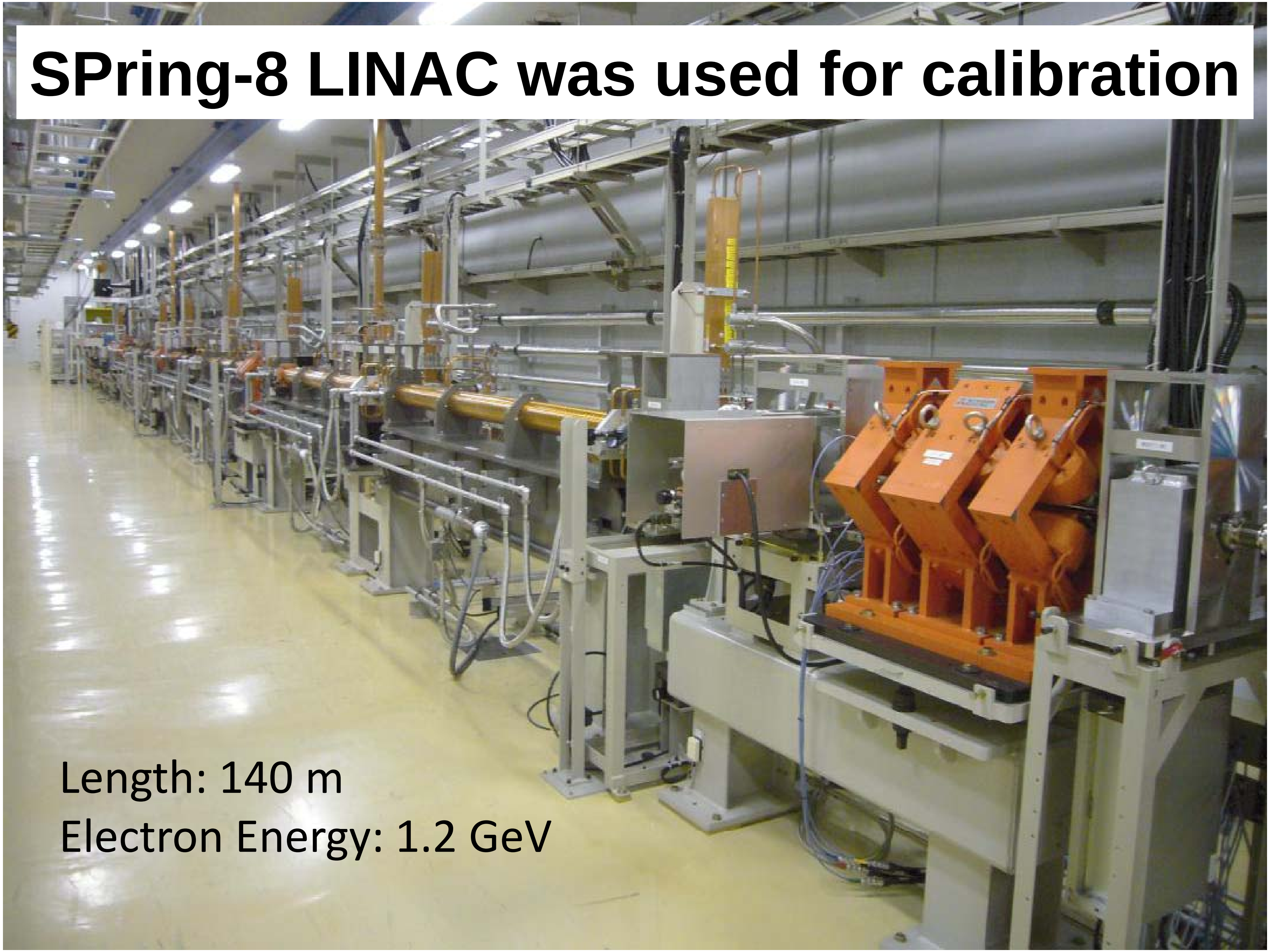


Ejection of electrons
by a ponderomotive force

> 10 GV/m

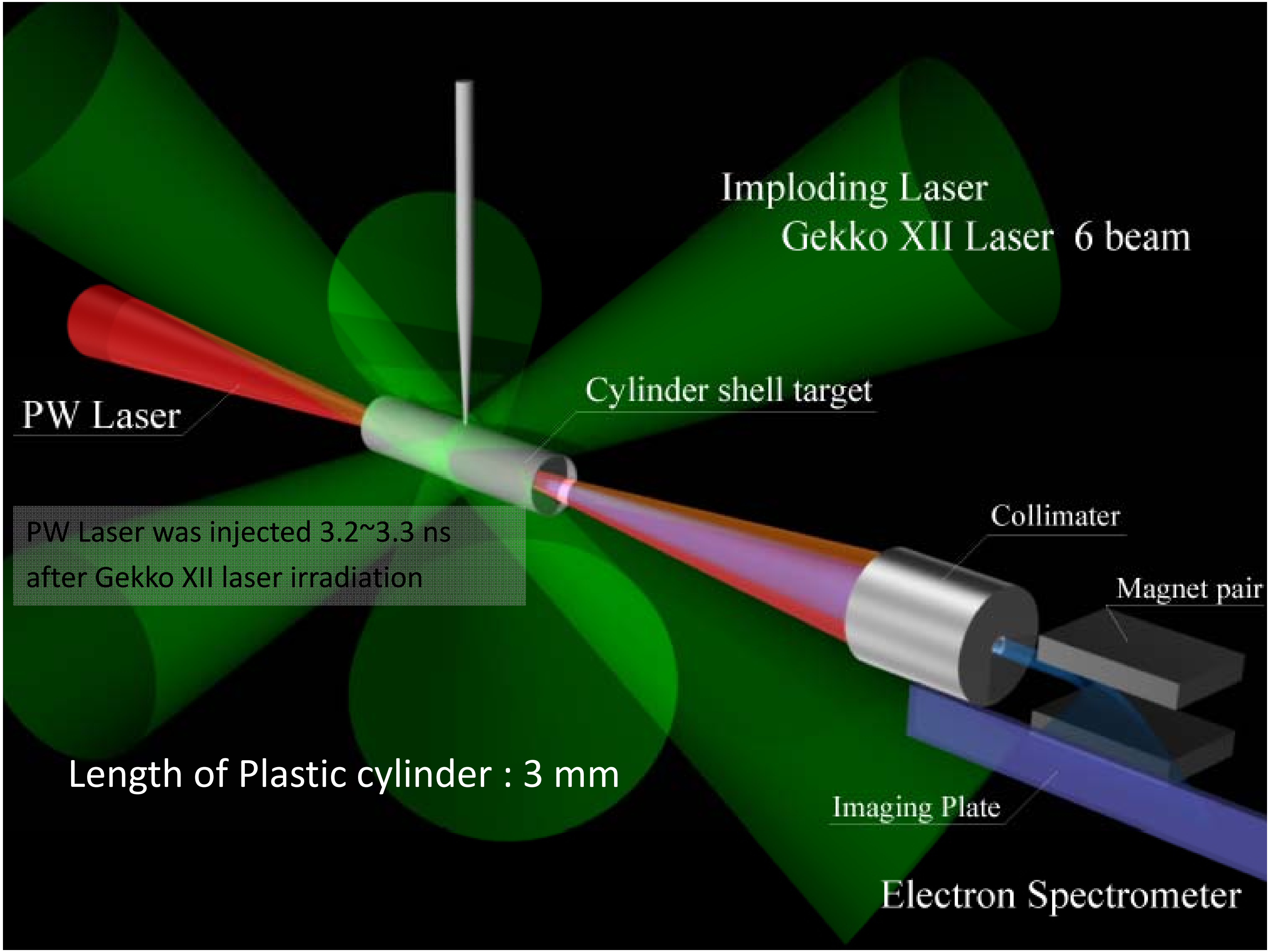
T. Tajima and J. M. Dawson, Phys. Rev. Lett. 43 267 (1979)

SPring-8 LINAC was used for calibration



Length: 140 m

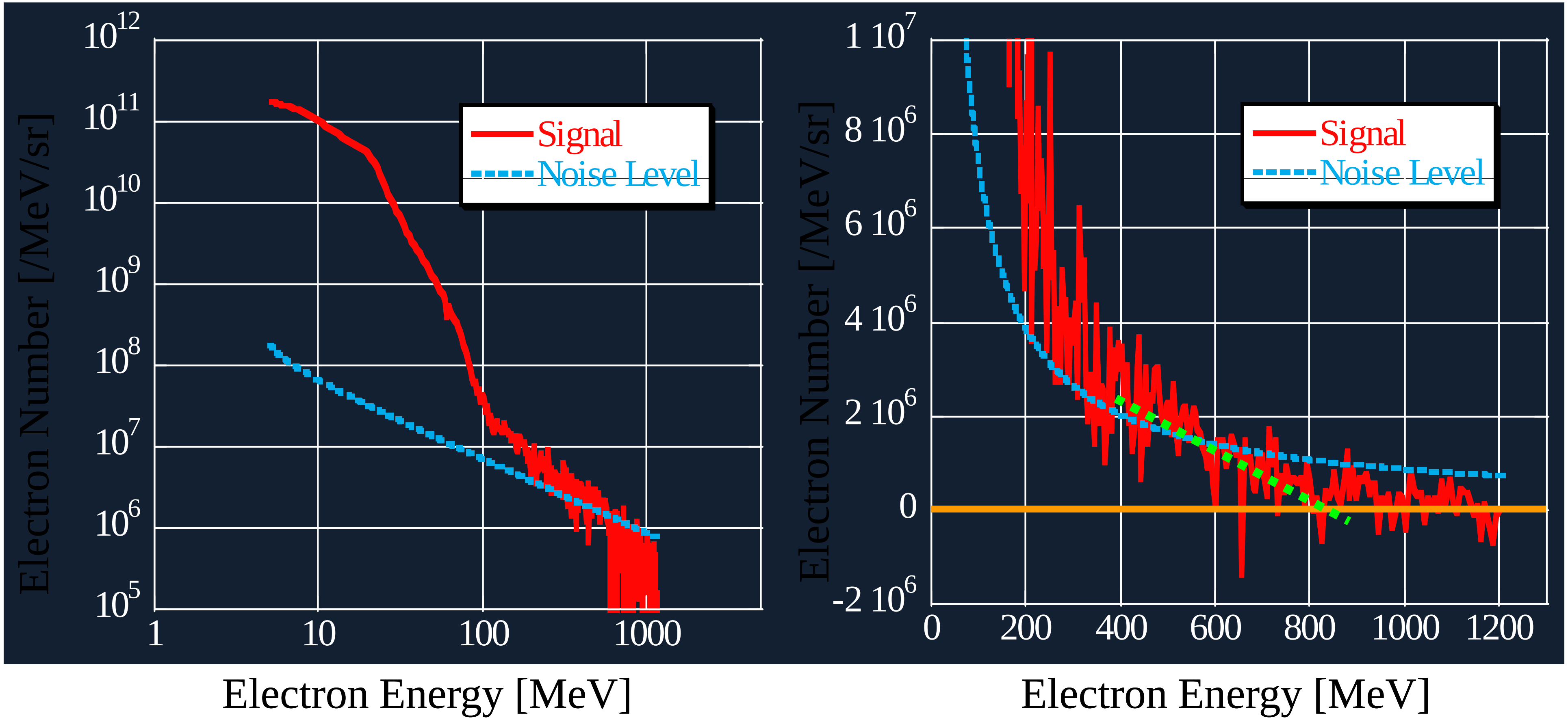
Electron Energy: 1.2 GeV


Imploding Laser
Gekko XII Laser 6 beam
PW Laser
Cylinder shell target
PW Laser was injected 3.2~3.3 ns
after Gekko XII laser irradiation
Collimater
Magnet pair
Imaging Plate
Length of Plastic cylinder : 3 mm
Electron Spectrometer

Electron energy spectrum

Electron density at the center: 2.7 × 10^{19} cm^{-3}

N. Nakanii et al., Appl. Phys. Lett. 93, 081501 (2008)
To be published in Phys. Plasmas



Above 600MeV

electrons generated

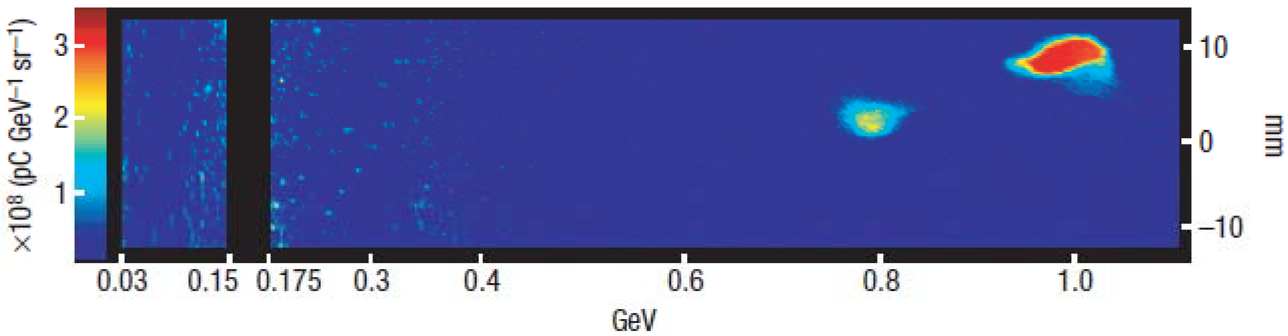
3.6 × 10^{20} cm^{-3}	*400MeV*
4.2 × 10^{20} cm^{-3}	*350MeV*

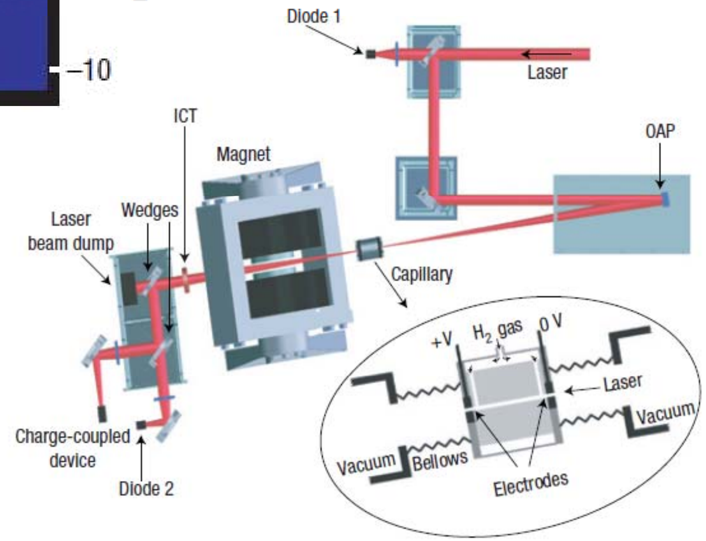
GeV electron beams from a centimetre-scale accelerator

W. P. LEEMANS[1*†], B. NAGLER[1], A. J. GONSALVES[2], Cs. TÓTH[1], K. NAKAMURA[1,3], C. G. R. GEDDES[1], E. ESAREY[1*], C. B. SCHROEDER[1] AND S. M. HOOKER[2]

[1]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA
[2]University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK
[3]Nuclear Professional School, University of Tokyo, 22-2 Shirane-shirakata, Tokai, Naka, Ibaraki 319-1188, Japan
*Also at: Physics Department, University of Nevada, Reno, Nevada 89557, USA
†e-mail: WPLeemans@lbl.gov

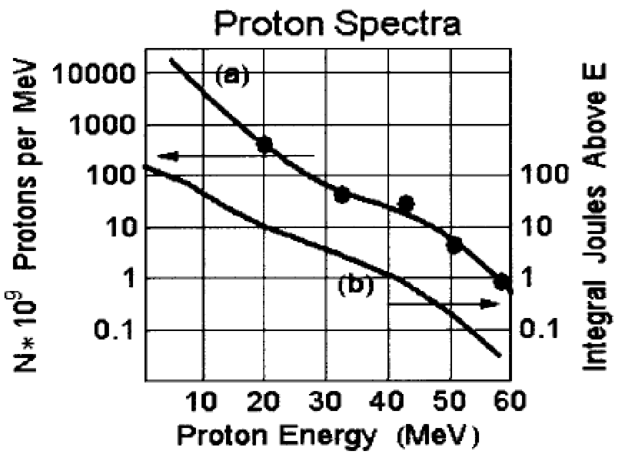
Nature Physics **2** 696 (2006)





Length of discharging capillary: 3 cm

High peak power laser can derive the energetic protons



R. Snavely et al. Phys Rev. Lett. 2000

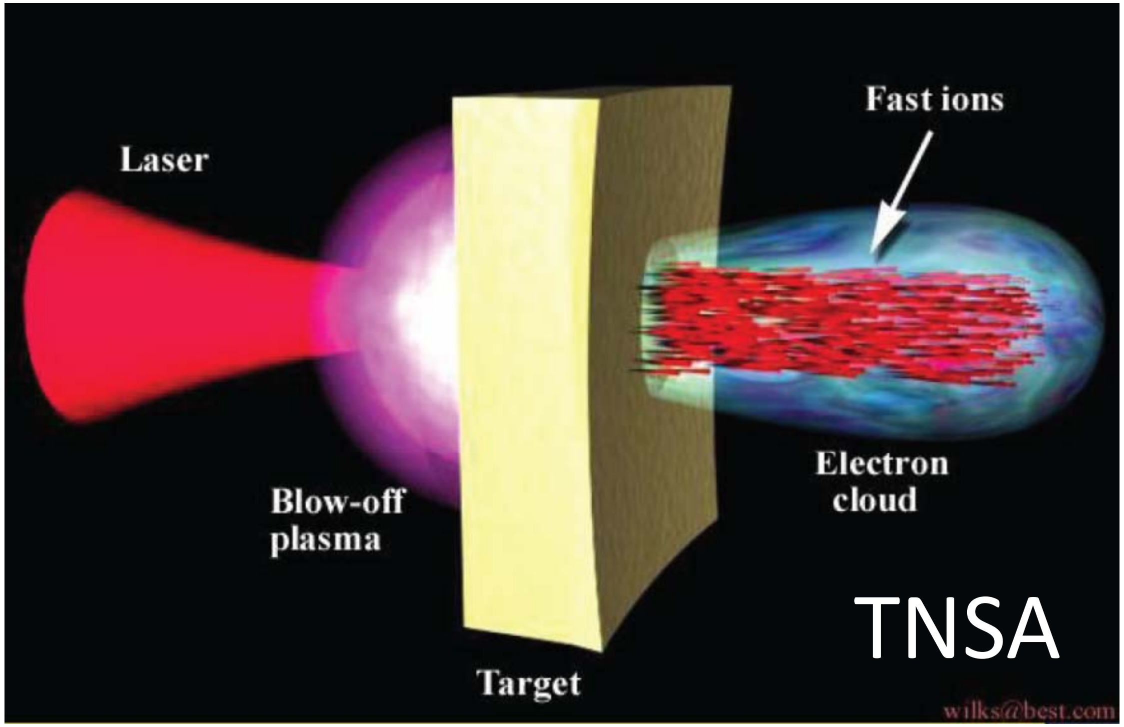
VOLUME 85, NUMBER 14 PHYSICAL REVIEW LETTERS 2 OCTOBER 2000

Intense High-Energy Proton Beams from Petawatt-Laser Irradiation of Solids

R. A. Snavely,[1,2] M. H. Key,[1] S. P. Hatchett,[1] T. E. Cowan,[1] M. Roth,[3,*] T. W. Phillips,[1] M. A. Stoyer,[1] E. A. Henry,[1] T. C. Sangster,[1] M. S. Singh,[1] S. C. Wilks,[1] A. MacKinnon,[1] A. Offenberger,[4,*] D. M. Pennington,[1] K. Yasuike,[5,*] A. B. Langdon,[1] B. F. Lasinski,[1] J. Johnson,[6] M. D. Perry,[1] and E. M. Campbell[1]

[1]*Lawrence Livermore National Laboratory, University of California, P.O. Box 808, Livermore, California 94550*

～60 MeV proton generation



PW laser with plasma mirror

M. Perry et al. Opt. Lett. 1999

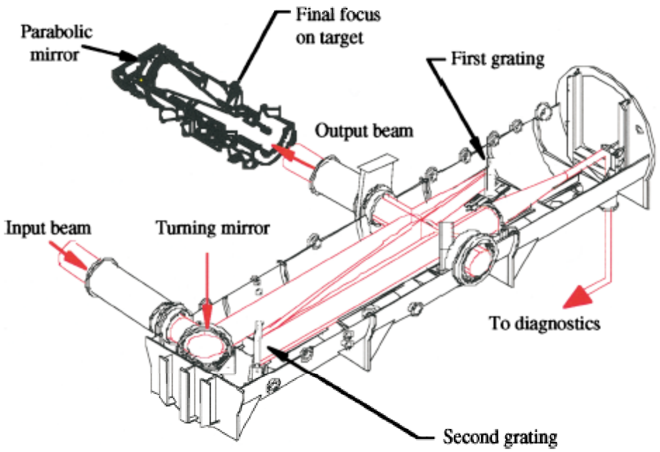
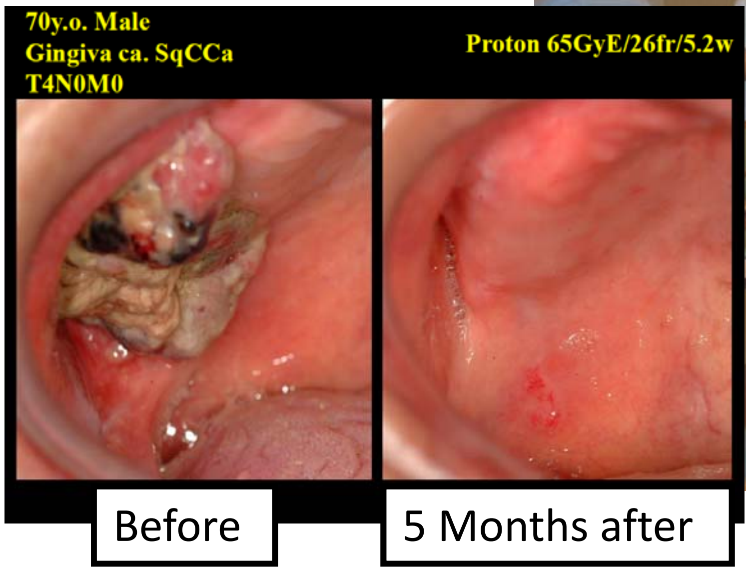


Fig. 2. Pulse compressor and single-beam target chamber.

Particle beam cancer therapy do not require surgery treatment

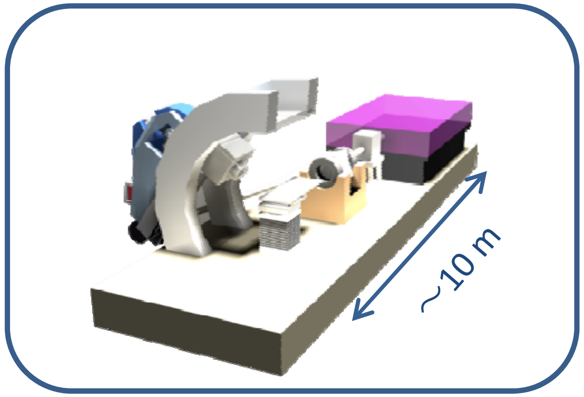
Medical innovation



Development of laser driven cancer therapy machine at Photo Medical Research Center (PMRC) in JAEA

○By using a ion beam generated with high peak power laser
We can make a **compact ion beam cancer therapy machine**.

100m Over 100 M US$ for construction



～10 M US$ for construction

It can be set at a comparatively large hospital.

30 K US$ (advanced medical technology)
→ 10 K US$（1／3）
If Health insurance support → Patient's Fee 3 K US$

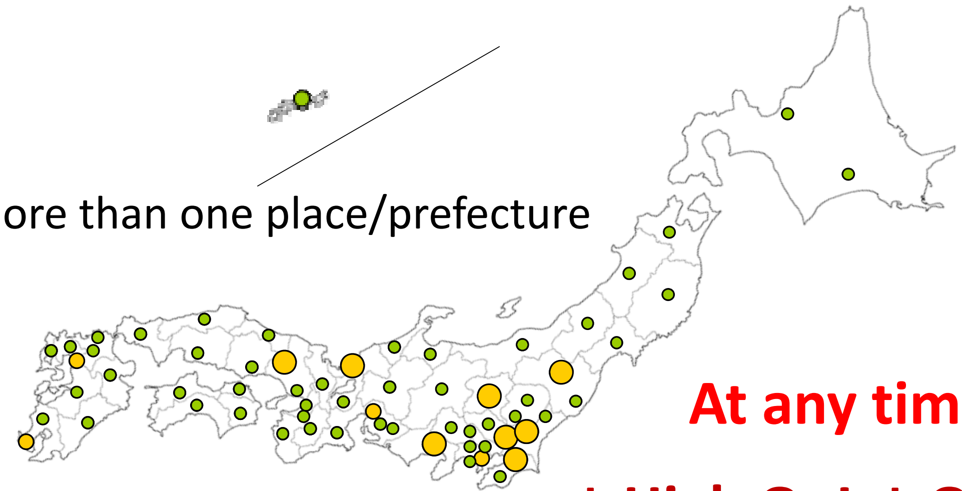
Laser driven cancer therapy machine : Setting up in Japan with a usual type

8 places

ion beam cancer therapy machine

Innovation
10 years after now

More than one place/prefecture

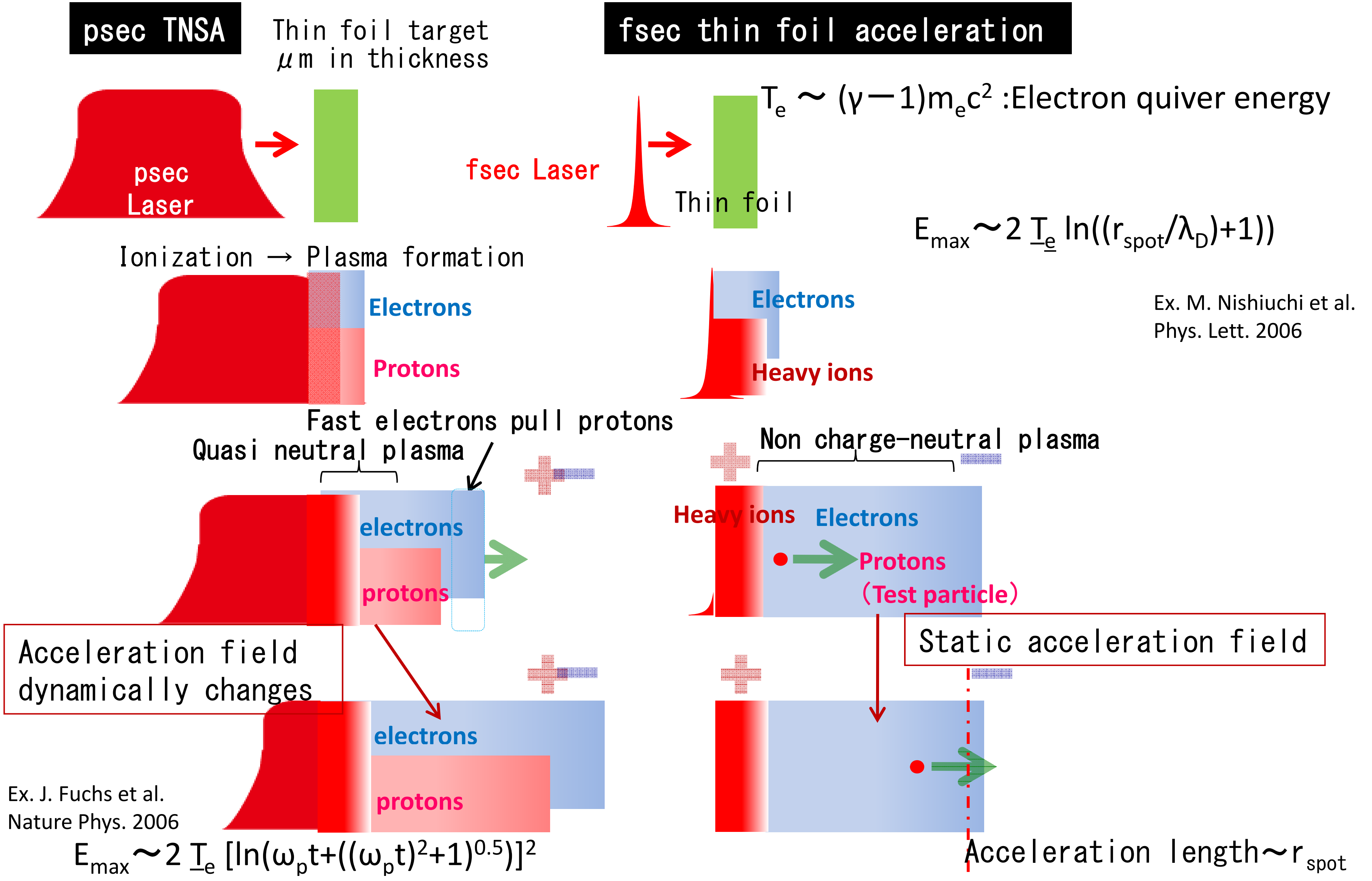


Additional
Laser driven ion
Beam cancer therapy machine

At any time, for any body, at anywhere

＊High QoL ＊Quick social rehabilitation
＊Medical treatment as an outpatient

Interaction between the optical high field and the thin solid target for psec and fsec pulses

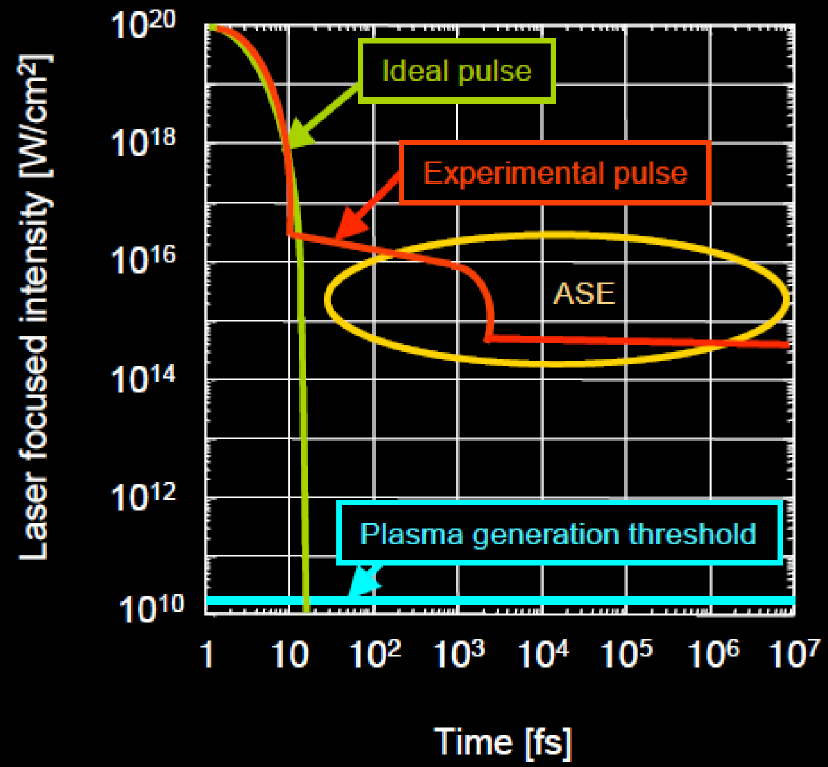


Problem remains to be solved for the application of ultra-high intensity lasers in high-field physics

APR Advanced Photon Research Center

✓ Principal issue with multi-terawatt laser experiments

Modern Ti:sapphire chirped-pulse amplification (CPA) lasers reach intensities greater than 10^{20} W/cm^2. However, in the laser systems, a background of the amplified spontaneous emission (ASE) can generate unwanted plasmas before the main pulse arrives on the target.



✓ Objective

To develop $>10^{10}$ temporal contrast laser supporting multi-terawatt power level with an OPCPA preamplifier in Ti:sapphire laser system

- Making higher contrastby Double CPA and high power OPCPA frontend
H. Kiriyama, et al., Opt. Lett. (2008)

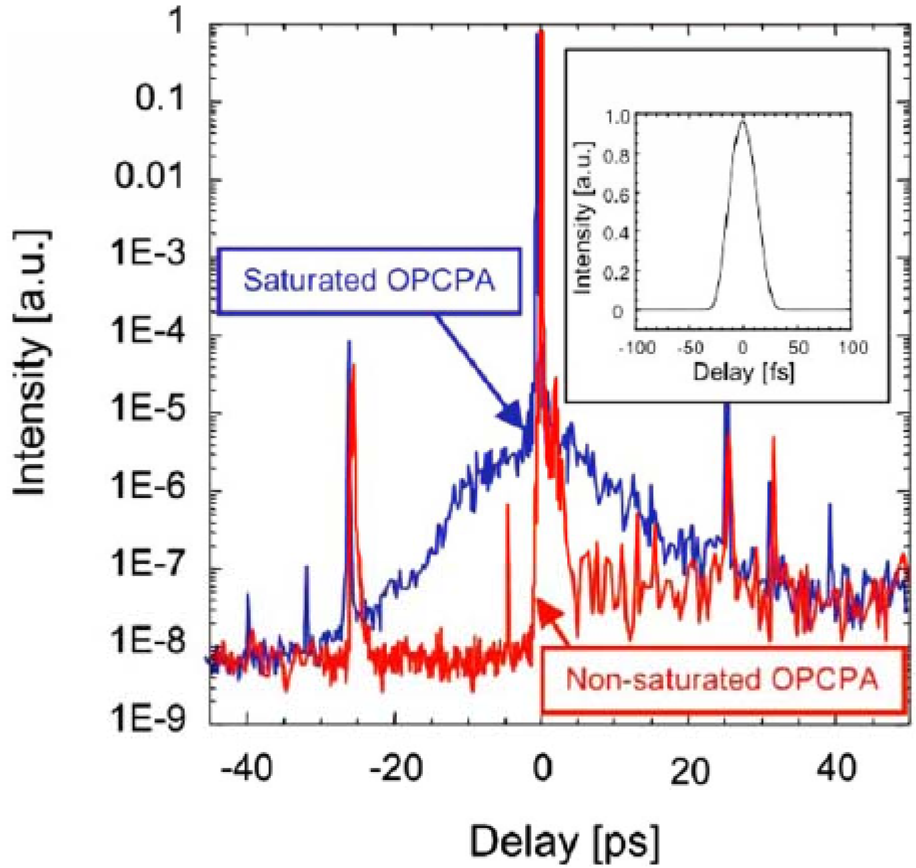
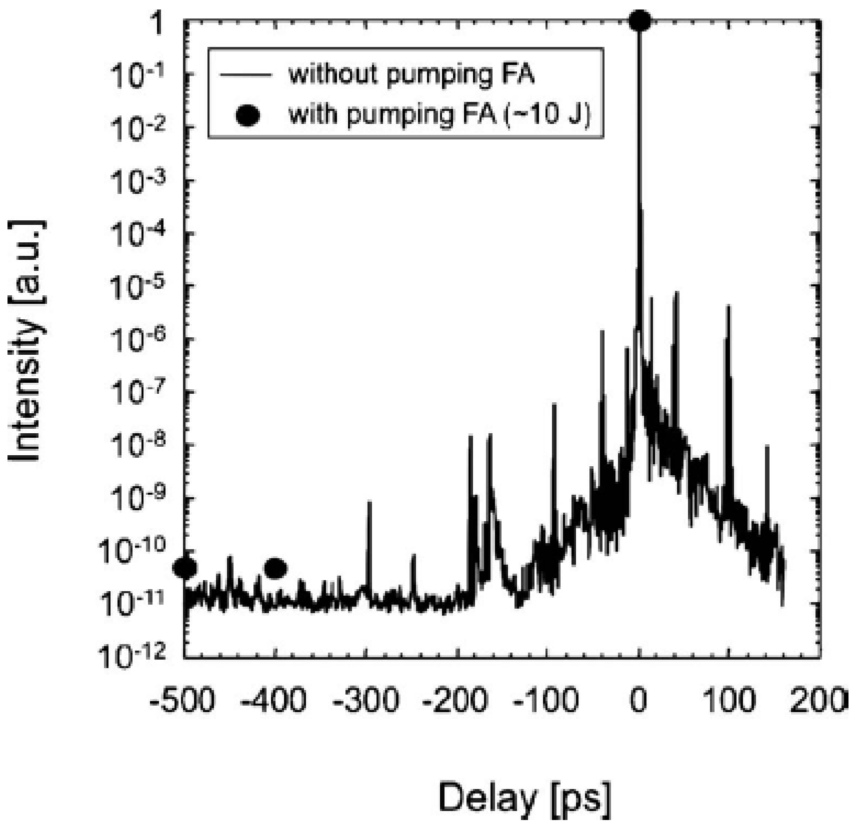


Fig. 3. (Color online) Temporal contrast of the amplified pulse. Inset, recompressed amplified pulse intensity autocorrelation.

With booster amplifier, the contrast ratio is larger that 10^{10}



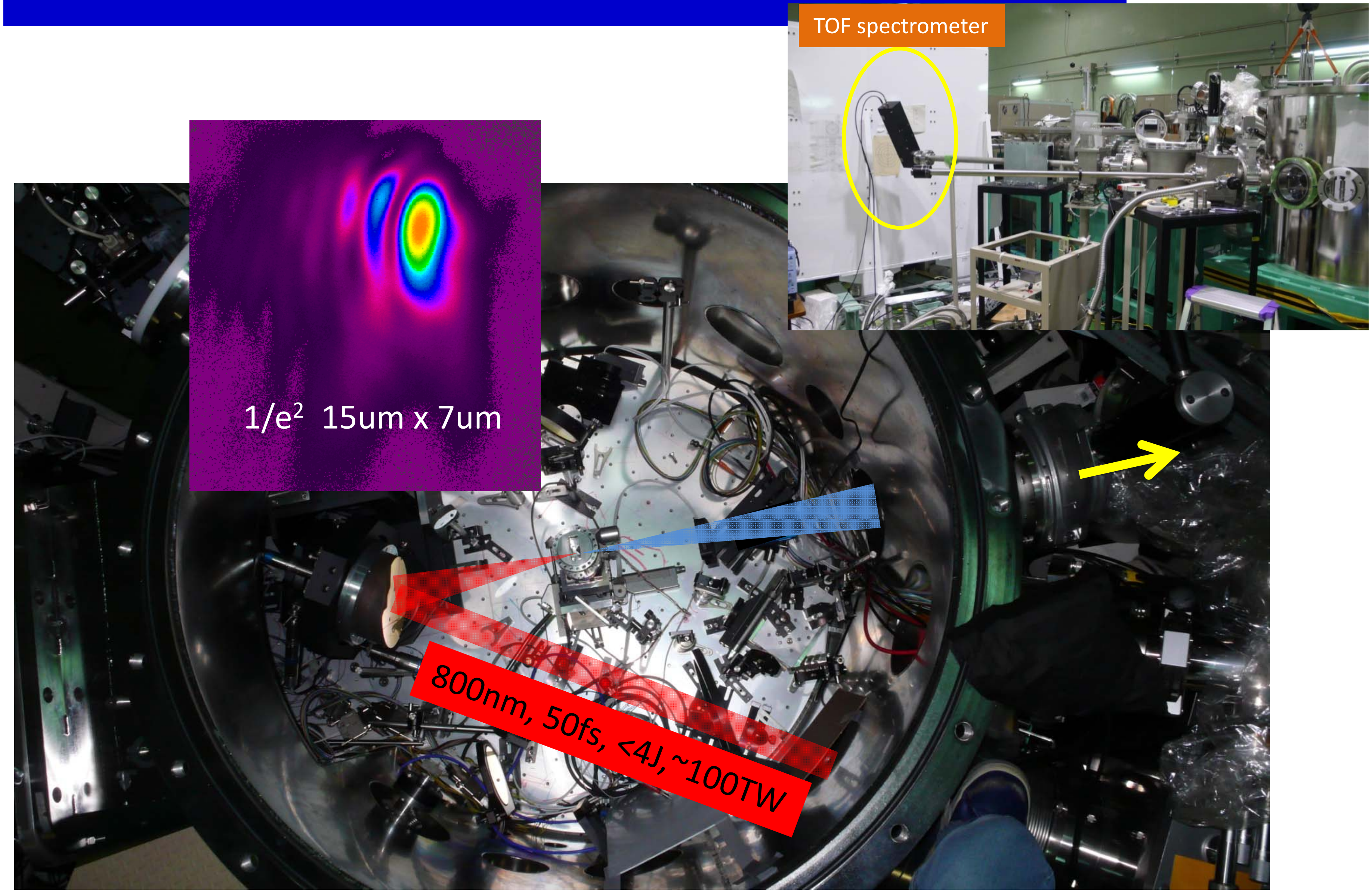
May 15, 2010 / Vol. 35, No. 10 / OPTICS LETTERS 1497

High temporal and spatial quality petawatt-class Ti:sapphire chirped-pulse amplification laser system

Hiromitsu Kiriyama,[1,*] Michiaki Mori,[1] Y. Nakai,[1] T. Shimomura,[1] H. Sasao,[1] M. Tanoue,[1] S. Kanazawa,[1] D. Wakai,[1] F. Sasao,[1] H. Okada,[1] I. Daito,[1] M. Suzuki,[1] S. Kondo,[1] K. Kondo,[1] A. Sugiyama,[1] P. R. Bolton,[1] A. Yokoyama,[1] H. Daido,[1] S. Kawanishi,[1] T. Kimura,[2] and T. Tajima[3]

Experimental Setup

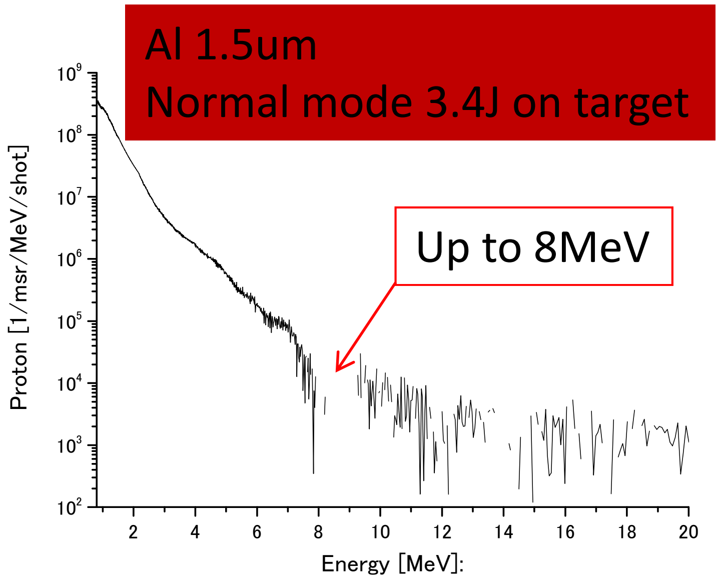
M. Nishiuchi et al., JAEA

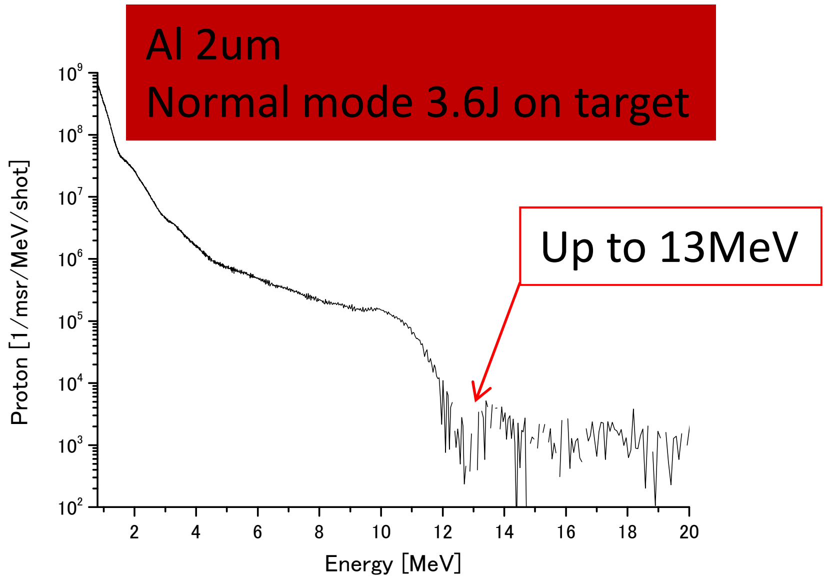


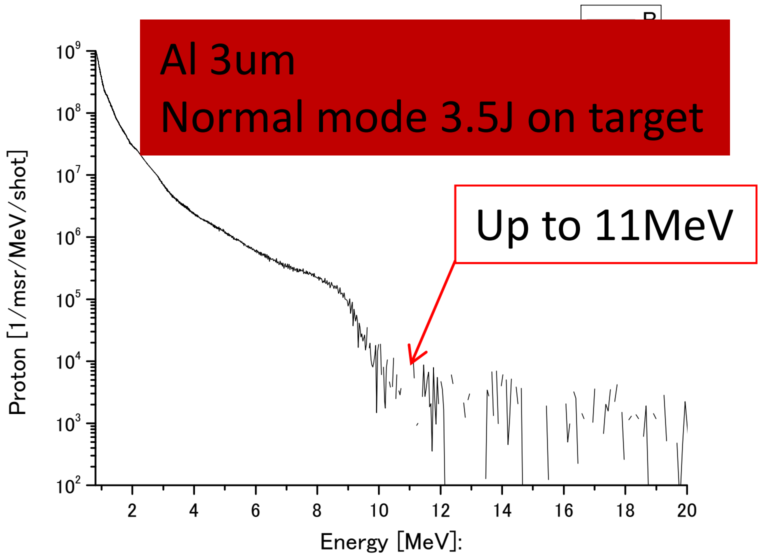
Al-Thin foil target shot

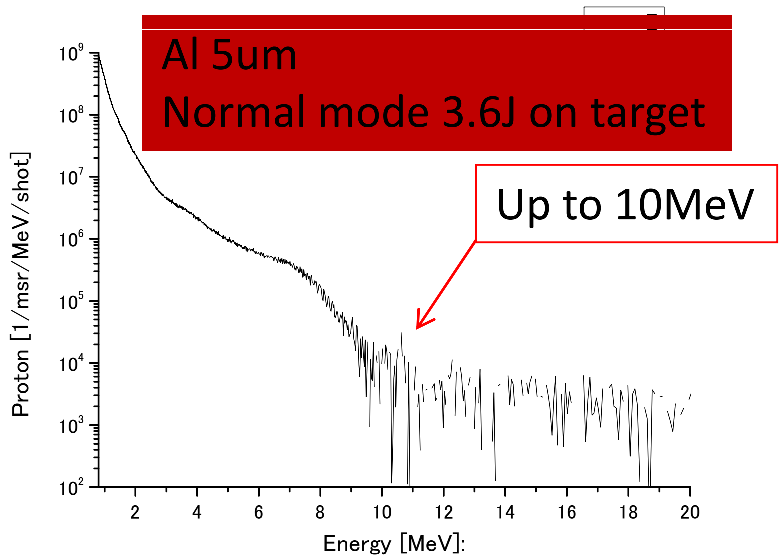
Foil thickness dependence

M. Nishiuchi et al., JAEA

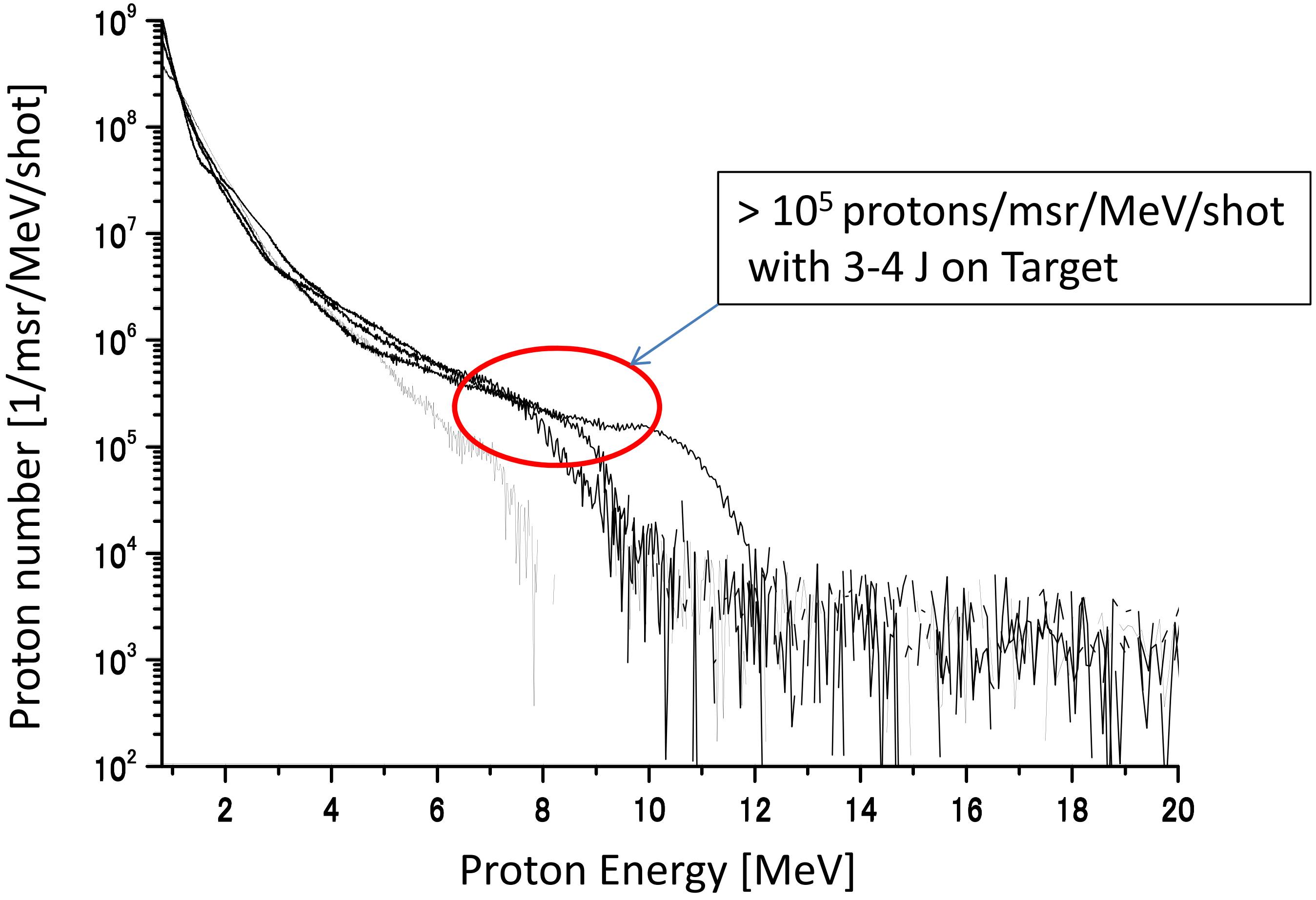






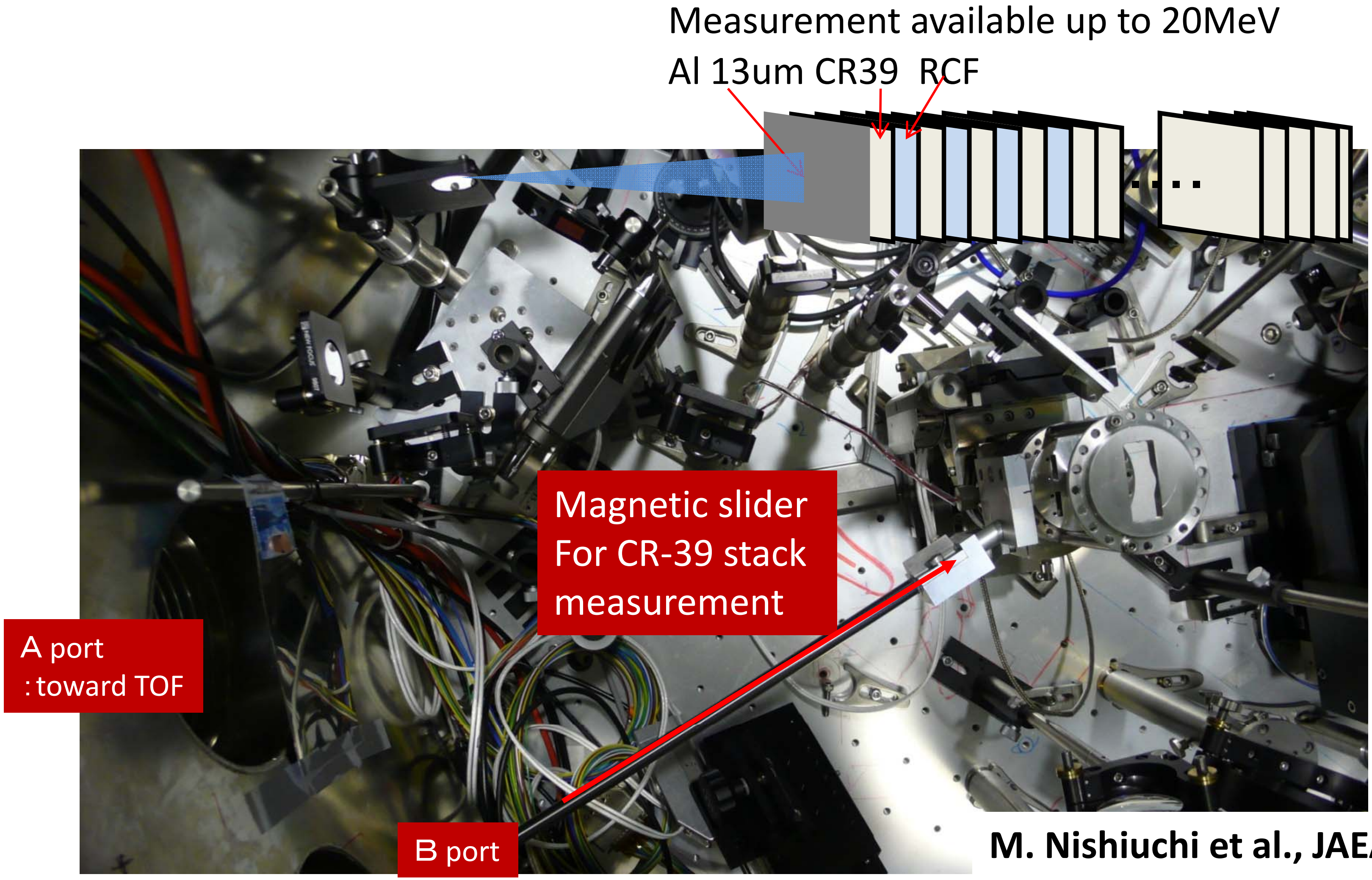


Proton number keeps almost same level at lower energy region



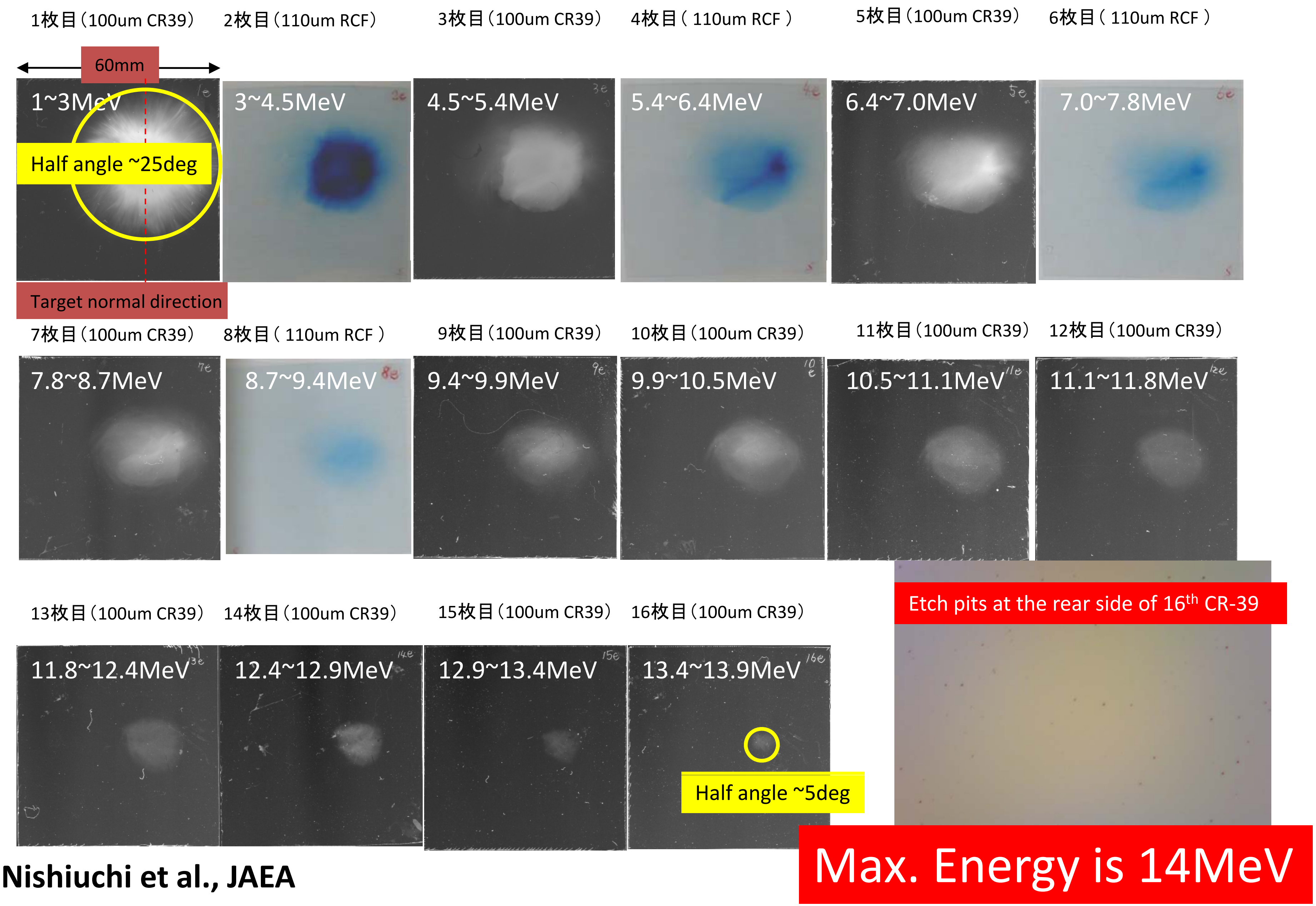
M. Nishiuchi et al., JAEA

Spatial distribution measurement (CR-39 stack (Al 2um)) &Determination of Max. energy



M. Nishiuchi et al., JAEA

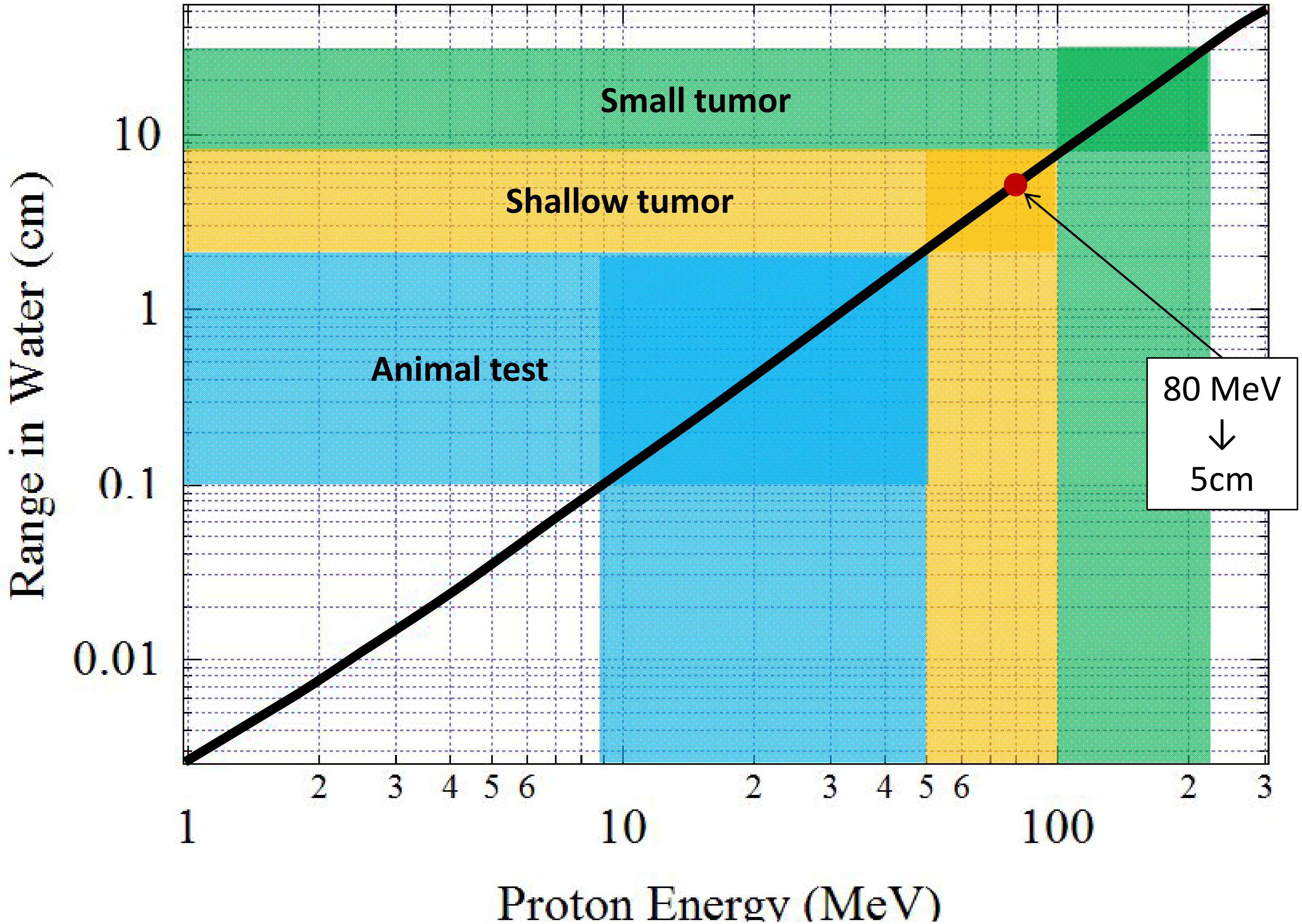
Beam pattern measurement for 2um Al target



M. Nishiuchi et al., JAEA

How much accelerated energy is required?

Stopping rage of proton for water



How many protons are required for killing tumor cells?

Let us assume 10Gy for killing tumor cells

10 Gy = 10 J/kg → 10^{-2}J/g → 10^{-2}J/cm^3

1 cm size tumor/10MeV

(When proton stops, the energy is decreased to ～10 MeV.)

→ 10^{-2}J /10^7 eV→ 6 × 10^9 protons

Patients stay only during ～10 min. =600 sec

Then, 1cm tumor: ～10^7 protons/sec

Even for 1cm tumor, at 10 Hz → ～10^6 protons/shot

at 100 Hz → ～10^5 protons/shot

Proton number is enough at sub 10 MeV!

$\sim 10^5$ protons/msr/MeV/shot at sub 10 MeV

ΔE is assumed to be ∼1MeV
Half angle: 5 deg → 24 msr

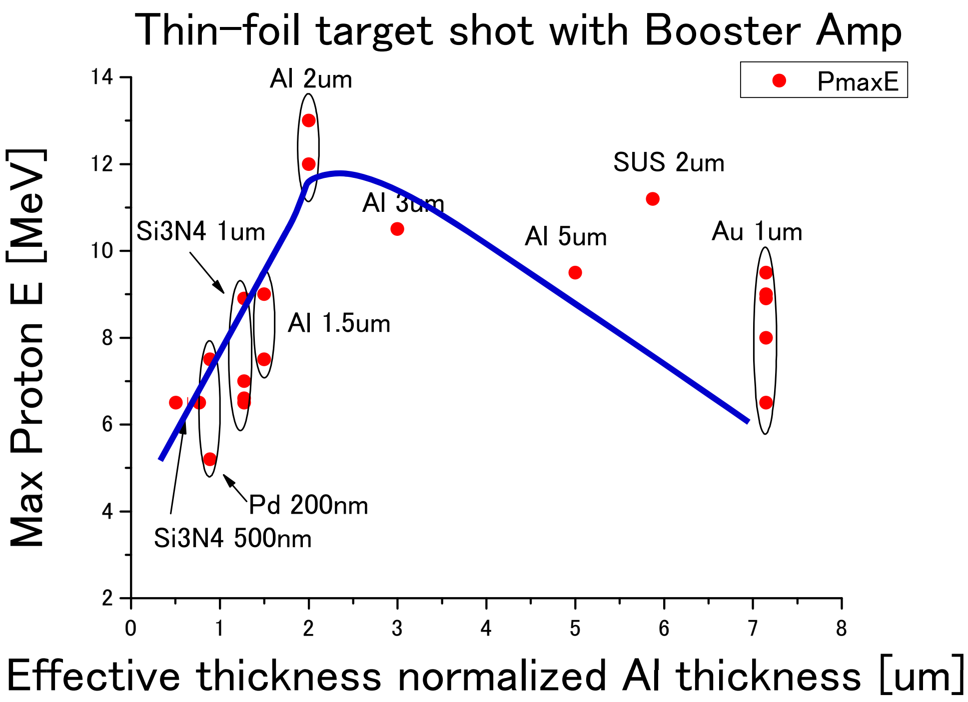
↓

2.4×10^6 protons/shot with 10^{20} W/cm^2
It is comparable with $\sim 10^6$ protons/shot for 100MeV

If this condition is repeated with 10 Hz,
10 min exposure gives 10 Gy on 1cm tumor
just under the skin !

Max. Proton E vs Target thickness

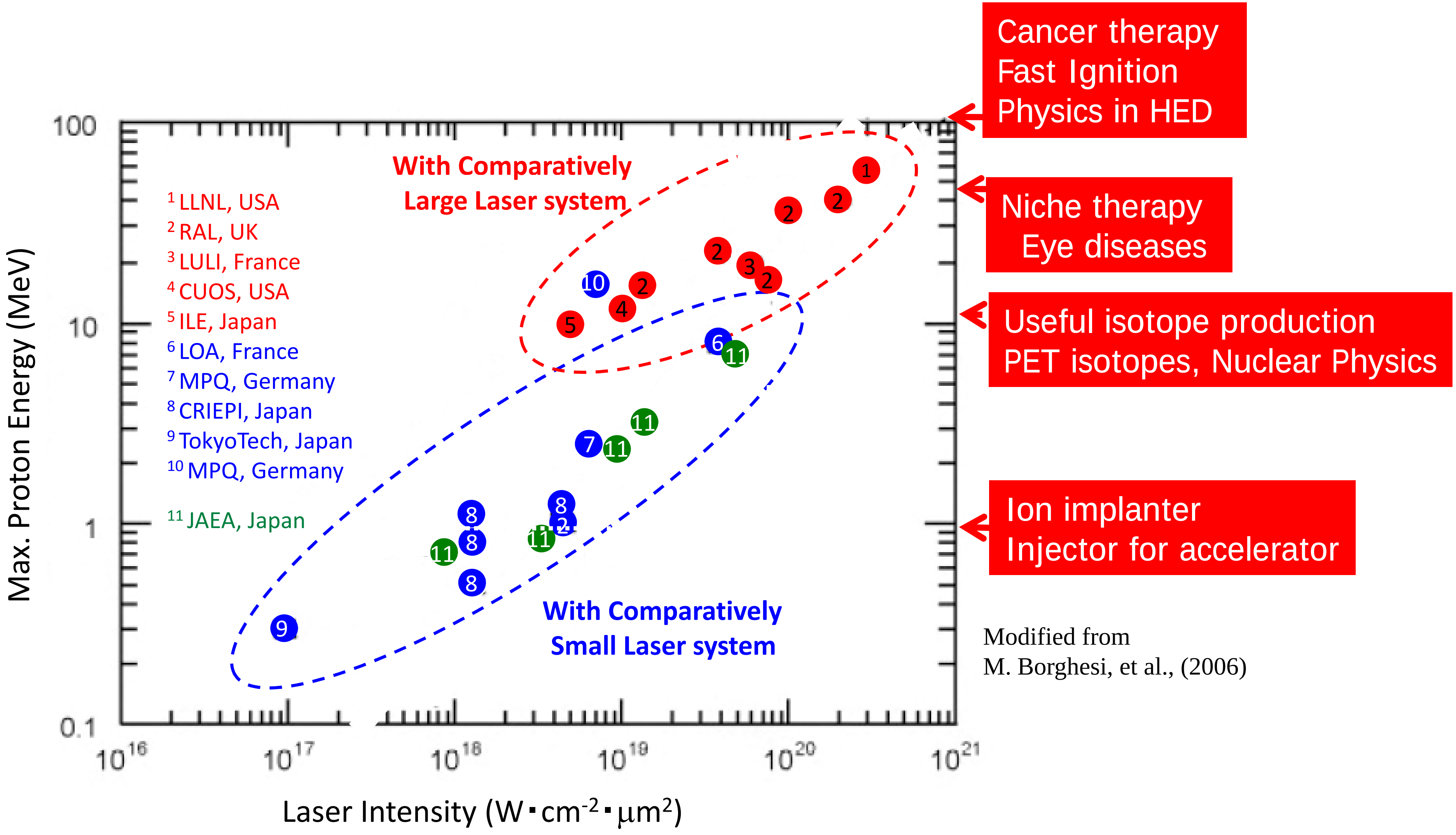
M. Nishiuchi et al., JAEA



Optimum thickness for the J-KAREN at this moment is Al ～2um

Plasma mirror system has to be installed !

Max. Proton energy increases as a function of laser intensity



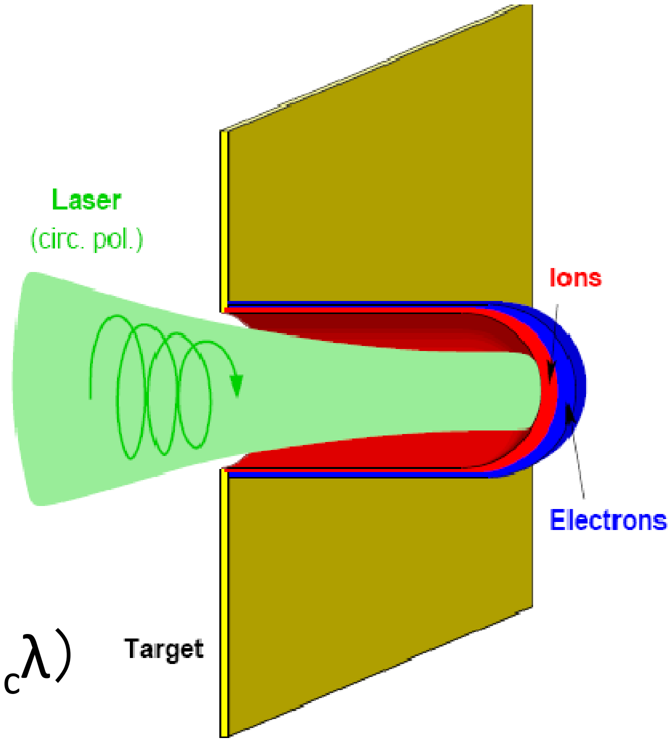
Modified from
M. Borghesi, et al., (2006)

Coherent Acceleration was demonstrated by Munchen group

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

CAIL (Coherent Acceleration of Ions by Laser)

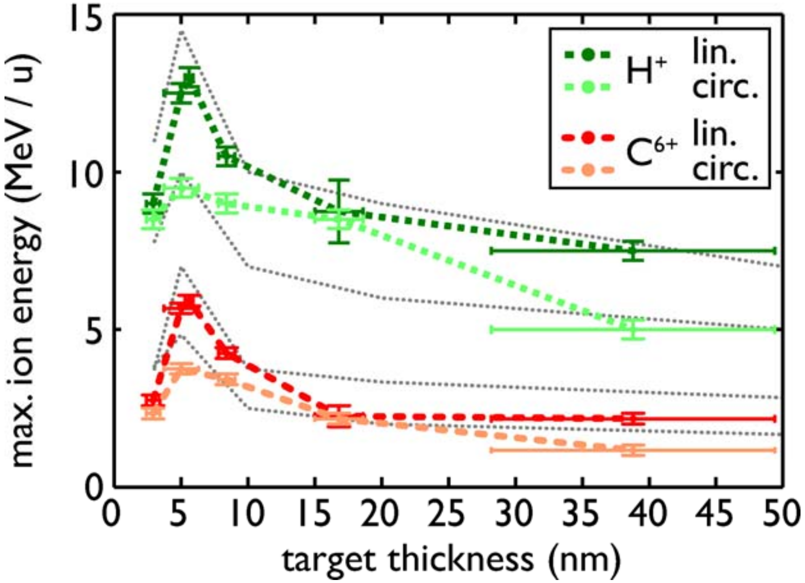
→ Radiation Pressure Regime (Laser Piston) by proposed Bulanov and Esirkepov et al.



$a_0 \sim \sigma$

$\sigma = (n_e l)/(n_c \lambda)$

MAP + MBI (Henig et al, PRL 2009)



Current is power-law, characterized by α:coherence parameter

$$J(E) = -J_0(1 - E/E_{max})^{\alpha}$$

$$\varepsilon_{max,i} = (2\alpha + 1)\, Q\, \underline{T_e}$$

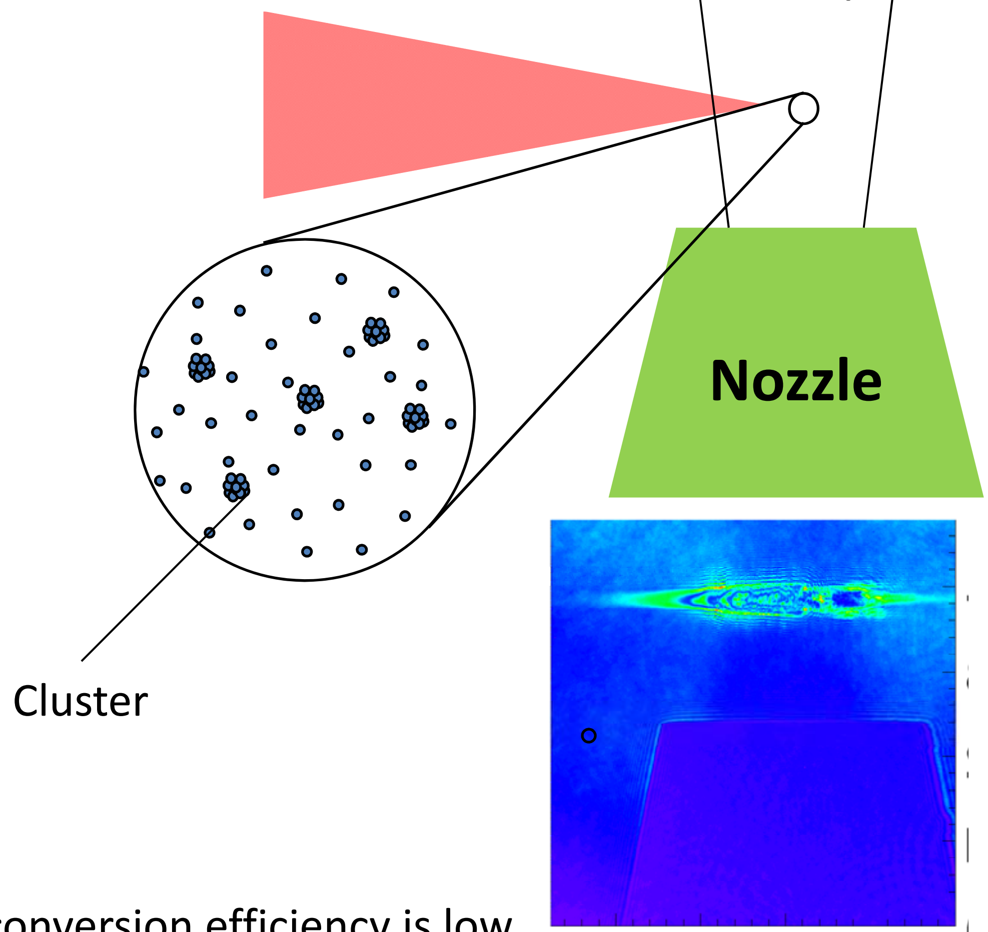
0.7 J Ti:S with Plasma M
Target 2.9-40 nm DLC

By Tajima-sensei's Power Point

Other approach for getting enough ion energy

Cluster target

Y. Fukuda et al. Phys. Rev. Lett. 103 165002 (2009)

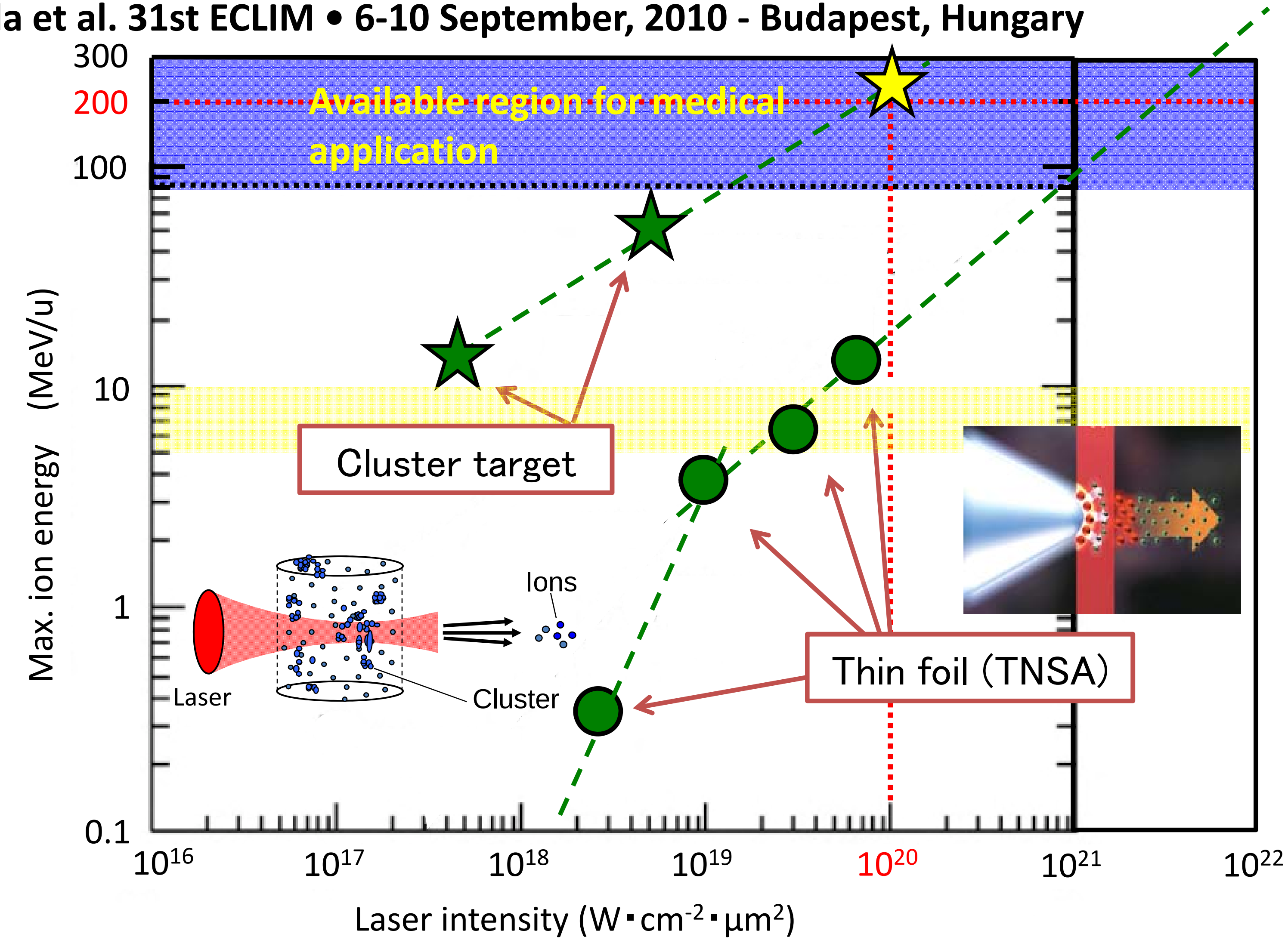


At present, conversion efficiency is low.
We need more studies for using this method.

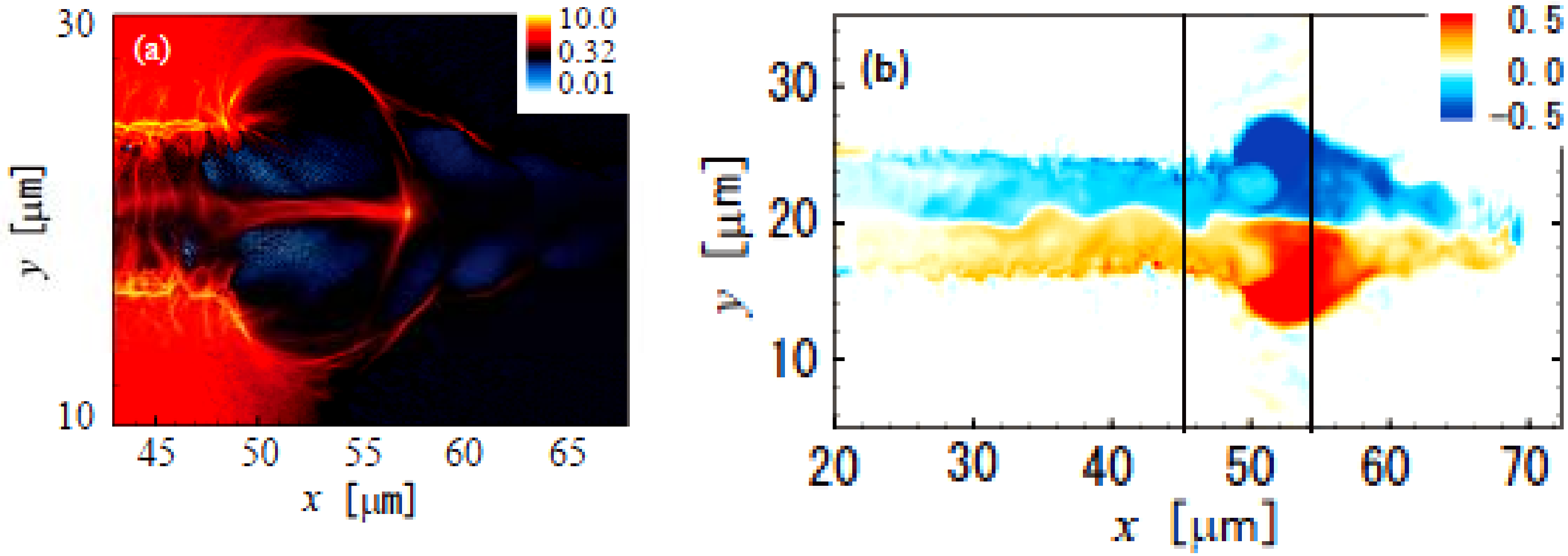
Max.18 MeV/u was achieved with only 150 mJ Ti:S laser!

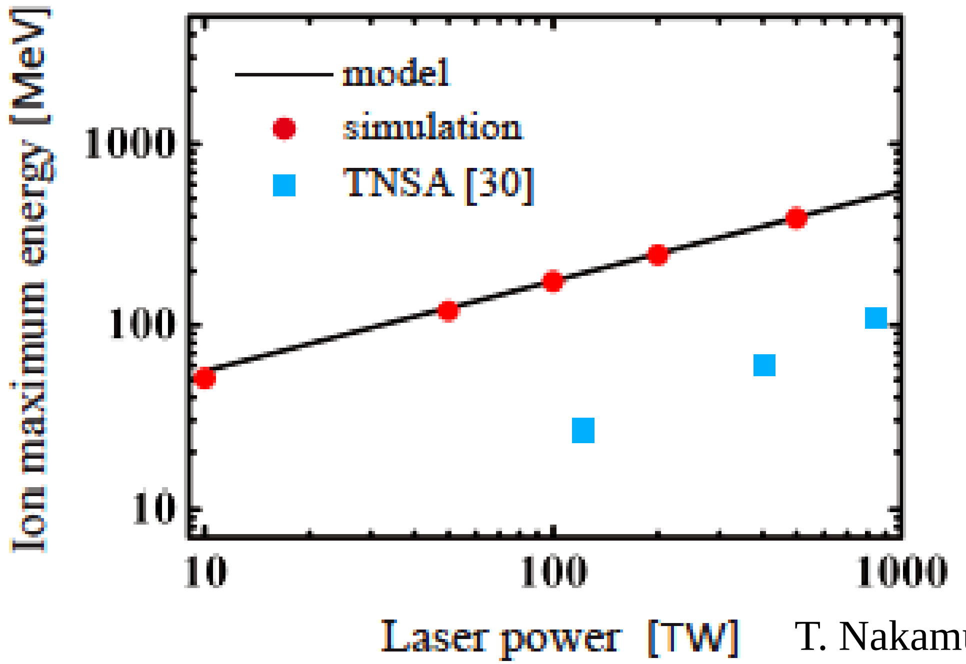
200MeV-class ion can be generated with 100 TW-class laser

Y. Fukuda et al. 31st ECLIM • 6-10 September, 2010 - Budapest, Hungary



100TW to 10μm size → 10^{20}W/cm^{2} → 200MeV/u can be reached！





T. Nakamura *et al*., Phys. Rev. Lett. **105**, 135002(2010).

10^{22} W/cm^2 was achieved in 2004 at Univ. Michigan

December 15, 2004 / Vol. 29, No. 24 / OPTICS LETTERS 2837

Generation and characterization of the highest laser intensities (10^{22} W/cm^2)

S.-W. Bahk, P. Rousseau, T. A. Planchon, V. Chvykov, G. Kalintchenko, A. Maksimchuk, G. A. Mourou, and V. Yanovsky

FOCUS Center and Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, Michigan 48109-2099

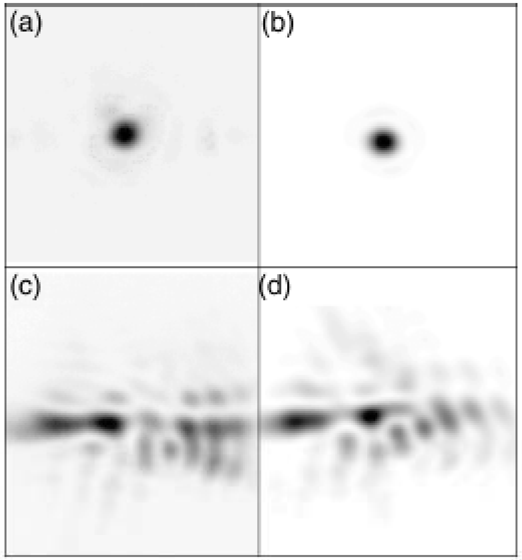
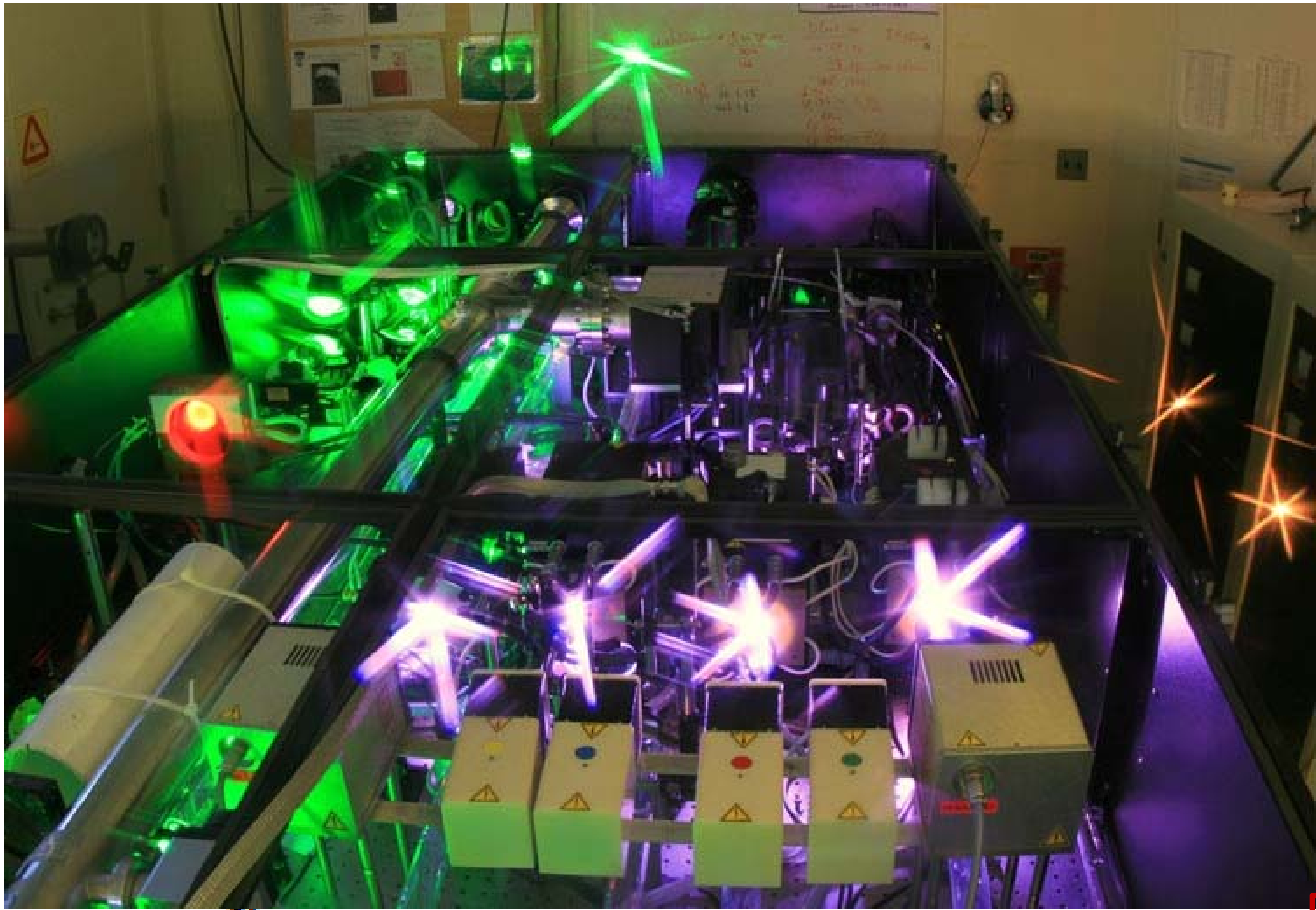


Fig. 3. (b), (d) Comparison of focal spot calculation and (a), (c) measurement with a 12-bit CCD camera at the regen level. (c), (d) Before correction; (a), (b) after correction. (b), (d) Calculated by use of measured phase and amplitude profile after focusing.

We have demonstrated that by focusing a 45-TW laser beam to a spot size of 0.8 μm a record peak intensity of 1×10^{22} W/cm^2 can be reached. To obtain such a tight focus with an excellent Strehl ratio of 0.9 we use an $f/0.6$ paraboloid and correct it by a 96-actuator deformable mirror. Applications for such high intensity

V. Yanovsky, et al., Opt. Express 16 2109 (2008)



Here we report the upgrade of the HERCULES laser to 300 TW output power at 0.1 Hz repetition rate. To our knowledge, this is the first multi-100TW-scale laser at high repetition rate. By using adaptive optics and f/1 parabola we focused the output beam into a 1.3 μ focal spot corresponding to unprecedented intensity of ~ 2 10^{22} W/cm^2 .

Vacuum beak down by the electric field Ⅰ

Rest mass of electron

$\Delta E = mc^2$: 0.511 MeV

Characteristic time determined by the uncertainty principle

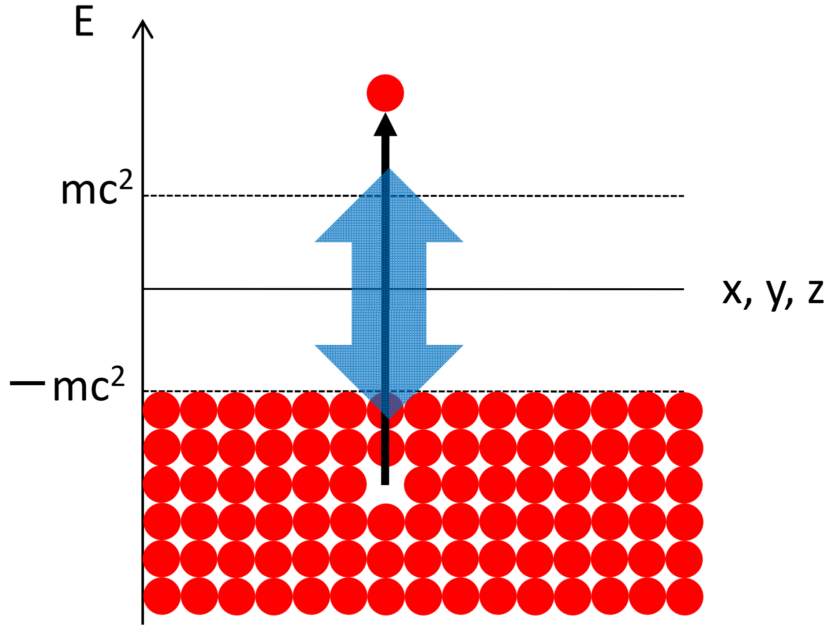
$\Delta t = \hbar/\Delta E$: 1.3×10^{-21} sec

Moving length during Δt

$\Delta x = c\,\Delta t = 390$ fm

→ Compton length

During Δ**t**: 1.3×10^{-21} sec
The energy state cannot be determined!



Vacuum beak down by the electric field Ⅱ

When we assume E_{QED} is the electric field, in which the energy of electron becomes mc^2 during Δx acceleration.

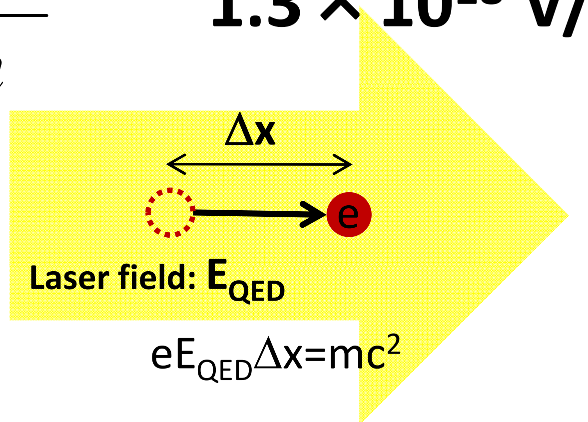
$$eE_{QED}\Delta x = mc^2$$

A pair creation might happens under ultra-strong electric field!

Schwinger field： $E_{QED} = \dfrac{m^2c^3}{e\hbar}$ **1.3×10^{18} V/m**

Ex.

10^{18}W/cm^2 → 2.7×10^{12}V/m



Property of laser light：Good coherence of time and space

Concentration of optical energy in time and space

Ultra-intense optical high field can be generated ！

SOVIET PHYSICS JETP VOLUME 19, NUMBER 2 AUGUST, 1964

QUANTUM PROCESSES IN THE FIELD OF A PLANE ELECTROMAGNETIC WAVE AND IN A CONSTANT FIELD. I

A. I. NIKISHOV and V. I. RITUS

Lebedev Physical Institute of the Academy of Sciences of the USSR

Submitted to JETP editor July 30, 1963

J. Exptl. Theoret. Phys. (U.S.S.R.) 46, 776-796

1. INTRODUCTION

THE availability of powerful light beams from lasers offers in principle new possibilities for investigation of various quantum process. The study of quantum effects in a very large electromagnetic wave field should make it possible to obtain new information on the nature of the interactions of the particles participating in these processes. The dependences of these processes

A. I. Nikishov and V. I. Ritus, Sov. Phys. JETP 19 529 (1964)

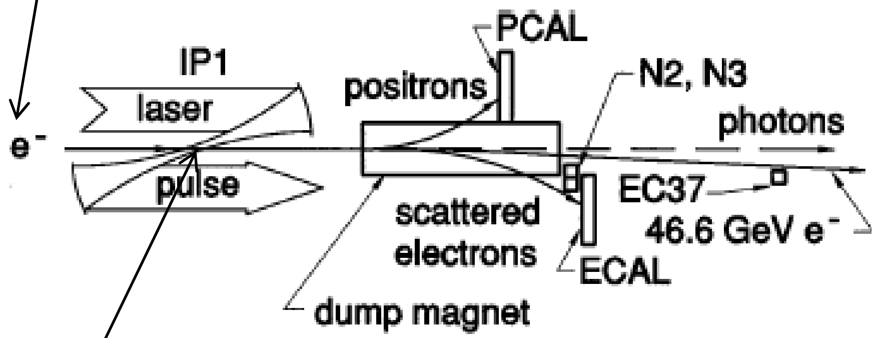
In 1997, 2 step multi-photon Breit-Wheeler process has been observed at SLAC

D. L. Burke, et al., Phys. Rev. Lett. **79** 1626 (1997).

46.6 GeV Electron beam

→ 29.2 GeV γ-ray

(Inverse Compton scattering)



Laser intensity:1.3 × 10^{18} W/cm^2

→ a_0～0.36 Wavelength 527 nm

→ Υ_γ ～0.1

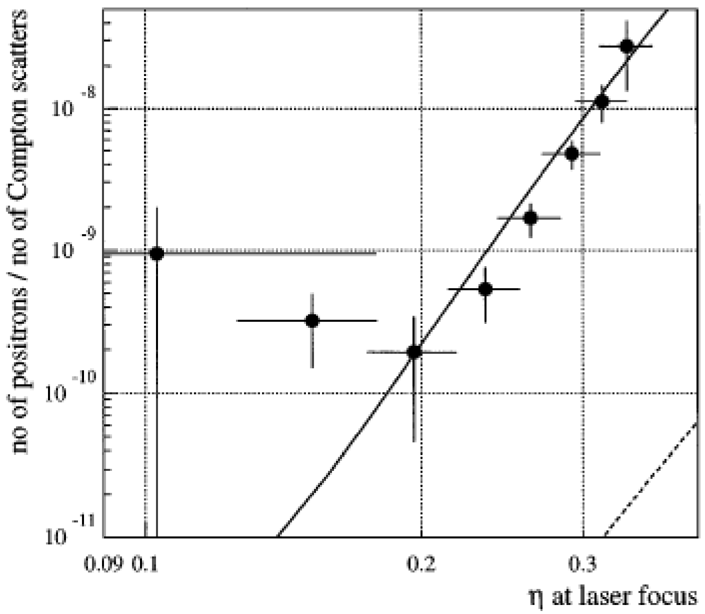
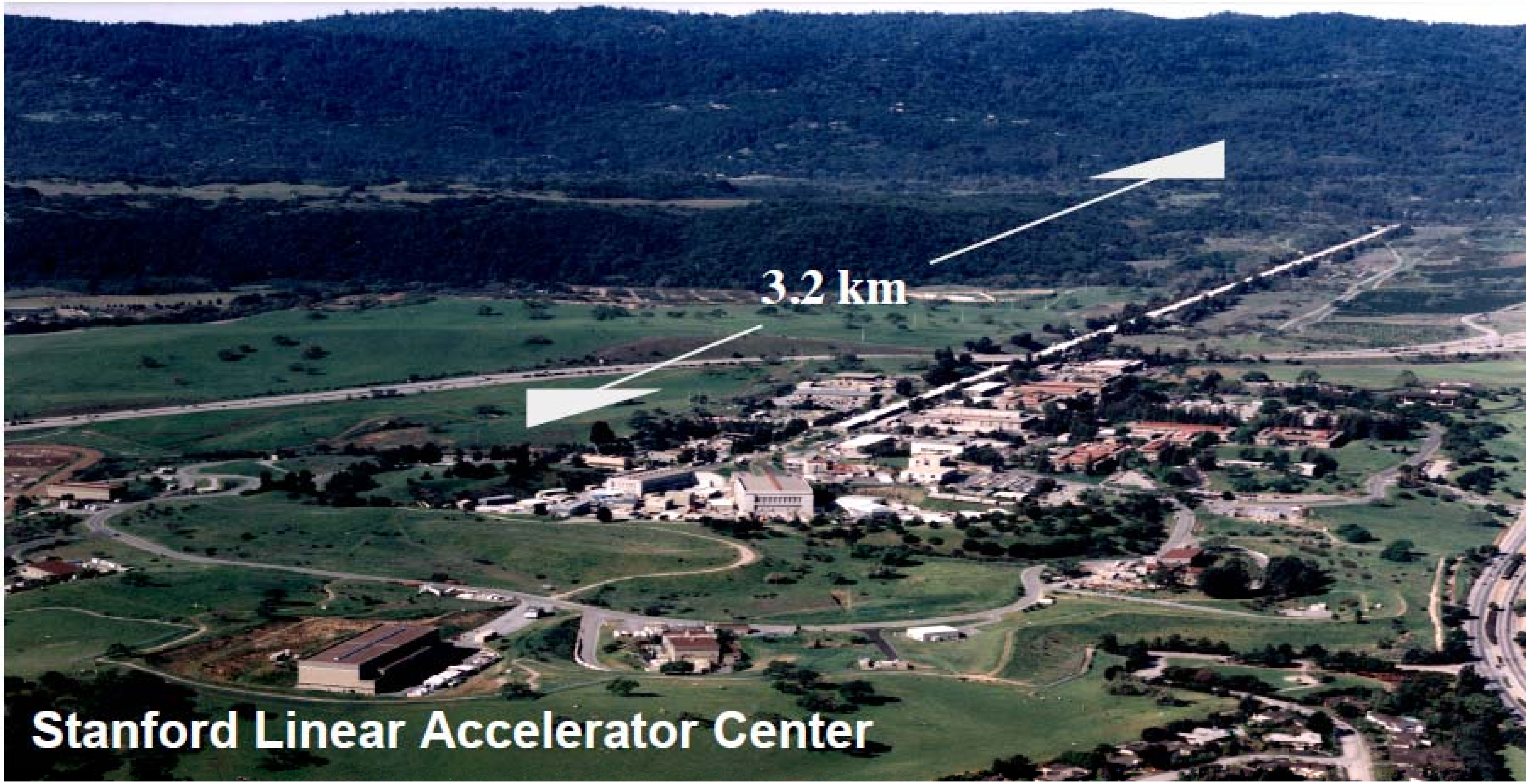


FIG. 5. Dependence of the positron rate on the laser field-strength parameter η when the rate is normalized to the number of Compton scatters inferred from the EC37 monitor. The solid line is the prediction based on the numerical integration of the two-step Breit-Wheeler process, (4) followed by (2). The dashed line represents the simulation for the one-step trident process (3).

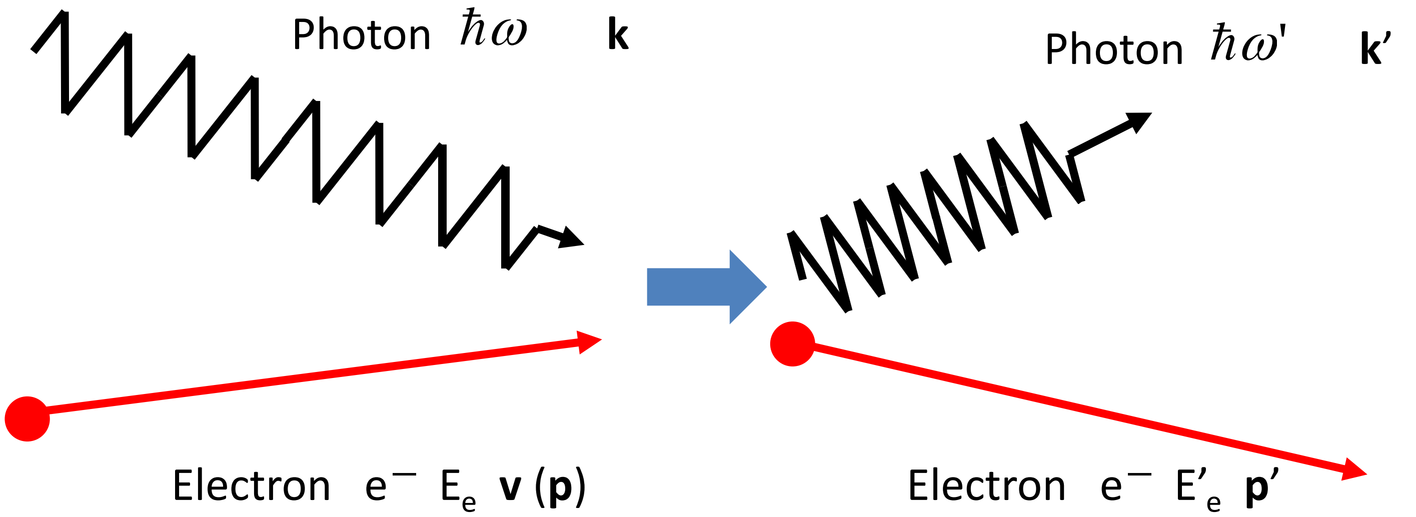
Trident process: $e + n\hbar\omega \rightarrow e' + e^- + e^+$ **No!**

2 step Beit-Wheeler process: $e + n\hbar\omega_0 \rightarrow e' + \hbar\omega$ $\hbar\omega + n\hbar\omega_0 \rightarrow e^+ + e^-$ **Yes!**

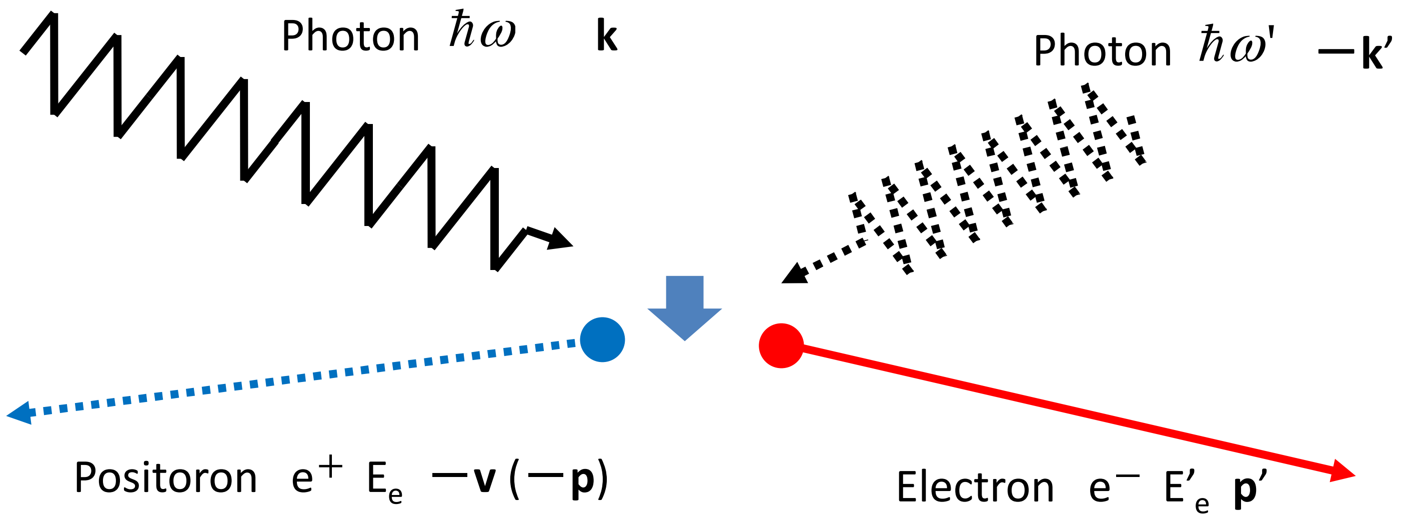
50 GeV Linac in SLAC



Inverse Compton scattering



Pair creation by photon-photon interaction



Invariant parameter Υ

Electron — Photon $\Upsilon_e = \frac{e\hbar}{m^3c^5}\sqrt{\left\langle \left(F_{\mu\nu}p^{\nu}\right)^2 \right\rangle}$ $\quad E_{QED} = \frac{m^2c^3}{e\hbar}$

γ-ray — Photon $\Upsilon_\gamma = 2a_0\left(\frac{\hbar\omega}{mc^2}\right)\left(\frac{\hbar\omega_\gamma}{mc^2}\right) = 2\left(\frac{E}{E_{QED}}\right)\left(\frac{\hbar\omega_\gamma}{mc^2}\right)$

$\Upsilon \gtrsim 1$, the interaction becomes effective.

ex. 10^{20}W/cm^2 at 0.8 μm and 1GeV γ-ray

→ $\Upsilon_\gamma \sim 0.08$

At SLAC experiment, 10^{18}W/cm^2 at 0.53μm and 30GeV γ-ray

→ $\Upsilon_\gamma \sim 0.2$

Pair creation cross section by pertubative non-linear QED for the interaction between the optical high field and γ-ray

$$\sigma_n = \frac{2\pi r_0^2 a_0}{\mathrm{Y}} \int_{u_{n0}}^{u_n} \frac{du}{u\sqrt{u(u-u_{n_0})}} \left(\frac{2}{a_0^2} J^2{}_n(z) + (2u-1)\left(J^2{}_{n-1}(z) + J^2{}_{n+1}(z) - 2J^2{}_n(z)\right) \right)$$

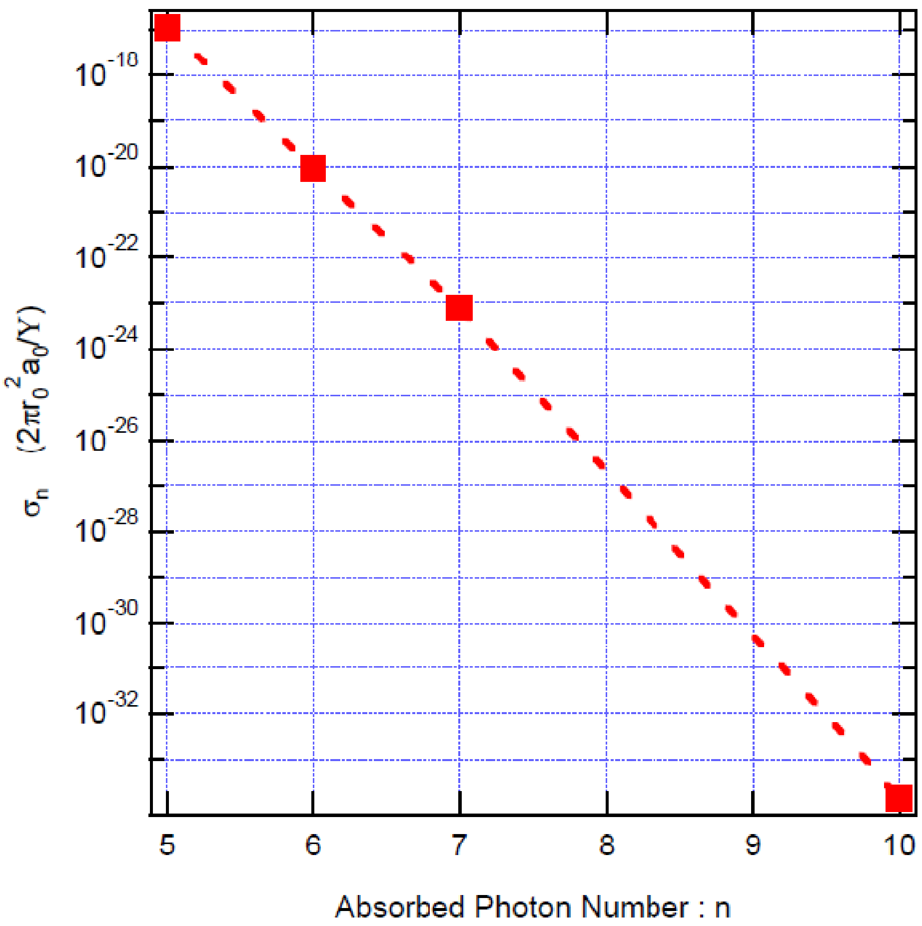
$$u = \frac{(kk')^2}{4(kq)(kq')} \approx \frac{\omega'^2}{u(\omega'-u)} \qquad u_n = \frac{n}{n_0} \qquad n_0 = \frac{2m^2(1+a_0^2)}{(kk')} = \frac{m^2(1+a_0^2)}{\omega\omega'} = \frac{2a_0(1+a_0^2)}{\mathrm{Y}}$$

$$z = \frac{4a_0^2\sqrt{1+a_0^2}}{\mathrm{Y}}\sqrt{u(u_n-u)}$$

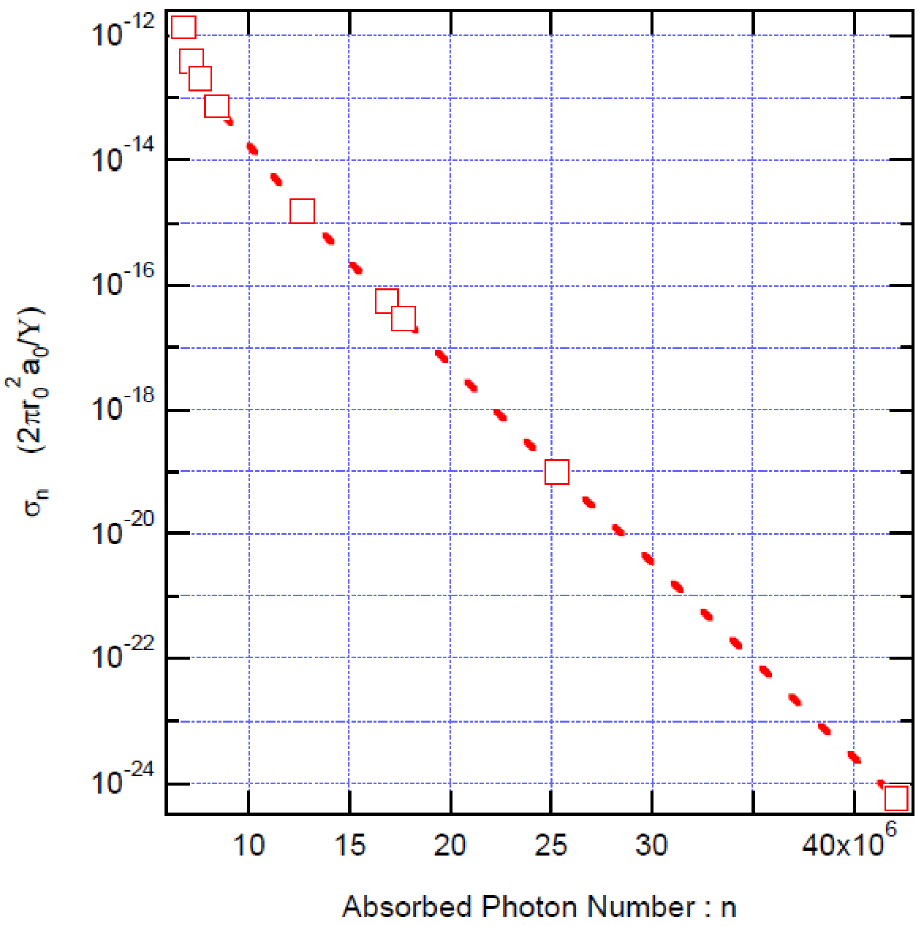
Here we assumed head on collision.

	SLAC experiment	Extremely high field
ħω of optical field	3.52 eV	1.55 eV
ħω' of γ-ray	29 GeV	2 GeV (Still SPRing8 Inv. Comp.)
optical field Int.	5×10^{17}W/cm^2	2.5×10^{22}W/cm^2
a_0	0.32	100
$\mathrm{Y} = 2a_0\frac{(\hbar\omega)(\hbar\omega')}{(mc^2)^2}$ Head on collision case	0.17	2.35

SLAC experiment



Extremely high field



	SLAC experiment	Extremely high field
Minimun photon number : n_0	n_0=4.15 → n: 5, 6, 7, …	n_0=6809191.489 → n: 6809192, 6809193, …
σ_{tot} (πr_0^2)	~σ_5: **3.08×10^{-18}**	$\sum(\sigma_{6.8e6}$~$\sigma_{1.3e7})$: **3.00×10^{-9}**

Simple questions by a laser researcher

- **ΔE ～1 MeV corresponds to Δt ～10^{-21} sec, which is the time scale of vacuum beak down.**

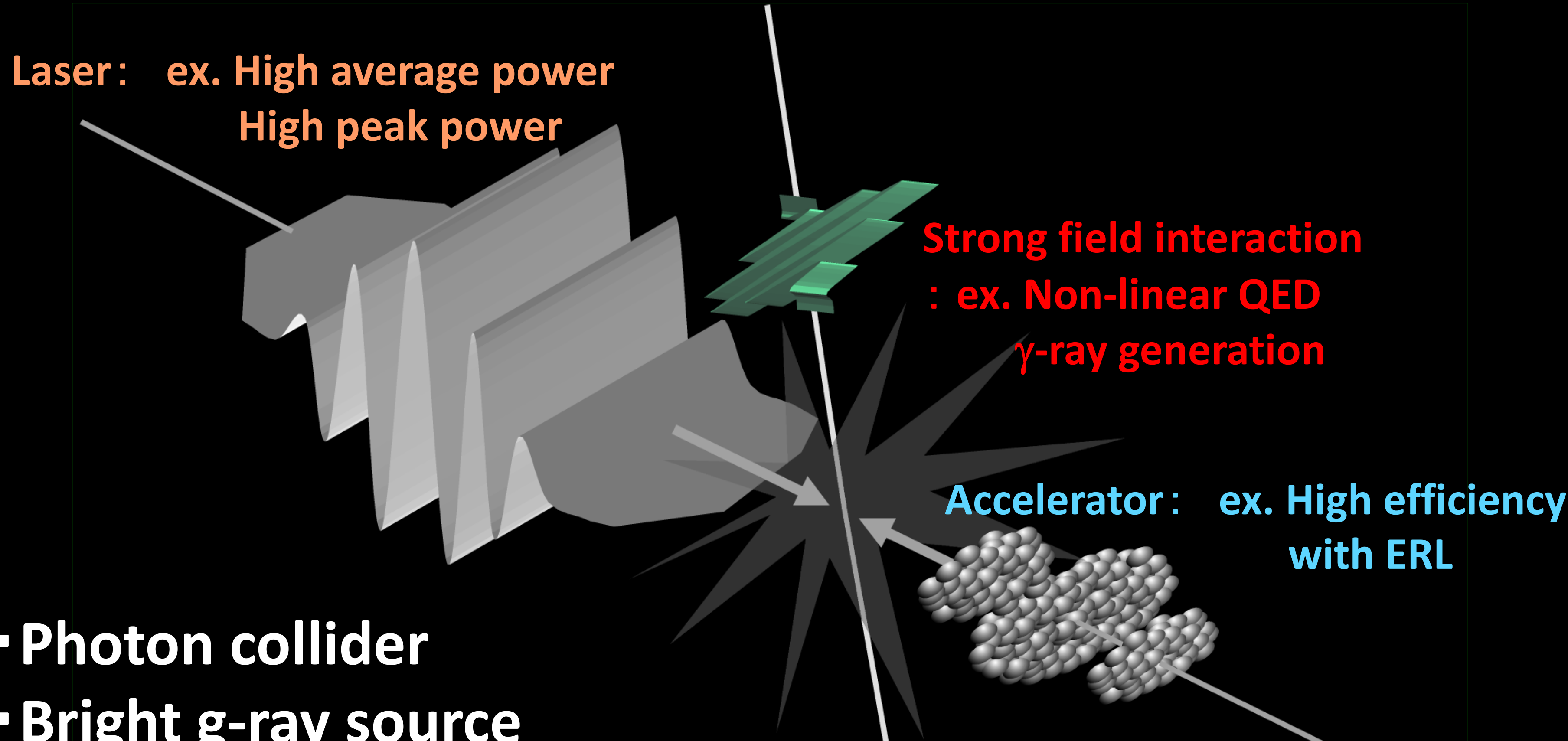
  The frequency of 1GeV γ –ray is ～10^{24}Hz

  The frequency of 0.8μm laser light is ～10^{15}Hz

→ When the optical field interacts with the vacuum, dose the optical field interact with the vacuum as a photon quantum?

- **Rather interact with the vacuum as the DC electric field?**
- **If so, we need not treat this interaction as the multi-photon process.**

Frontier study by fusion of laser and accelerator



- Photon collider
- Bright g-ray source
- Interaction between ultra relativistic high field and quantum beam from high energy accelerator

PIF 2010 has been held this Nov. at KEK

http://atfweb.kek.jp/pif2010/

Sooner or later, the experimental study with the GeV-class accelerator and the PW-class high peak power laser could be exciting!