The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA

2155-29

International Workshop on Cutting-Edge Plasma Physics

5 - 16 July 2010

Outline of Lecture on Laser Plasmas Physics

Kunioki Mima

Institute of Laser Engineering
Osaka University
Japan

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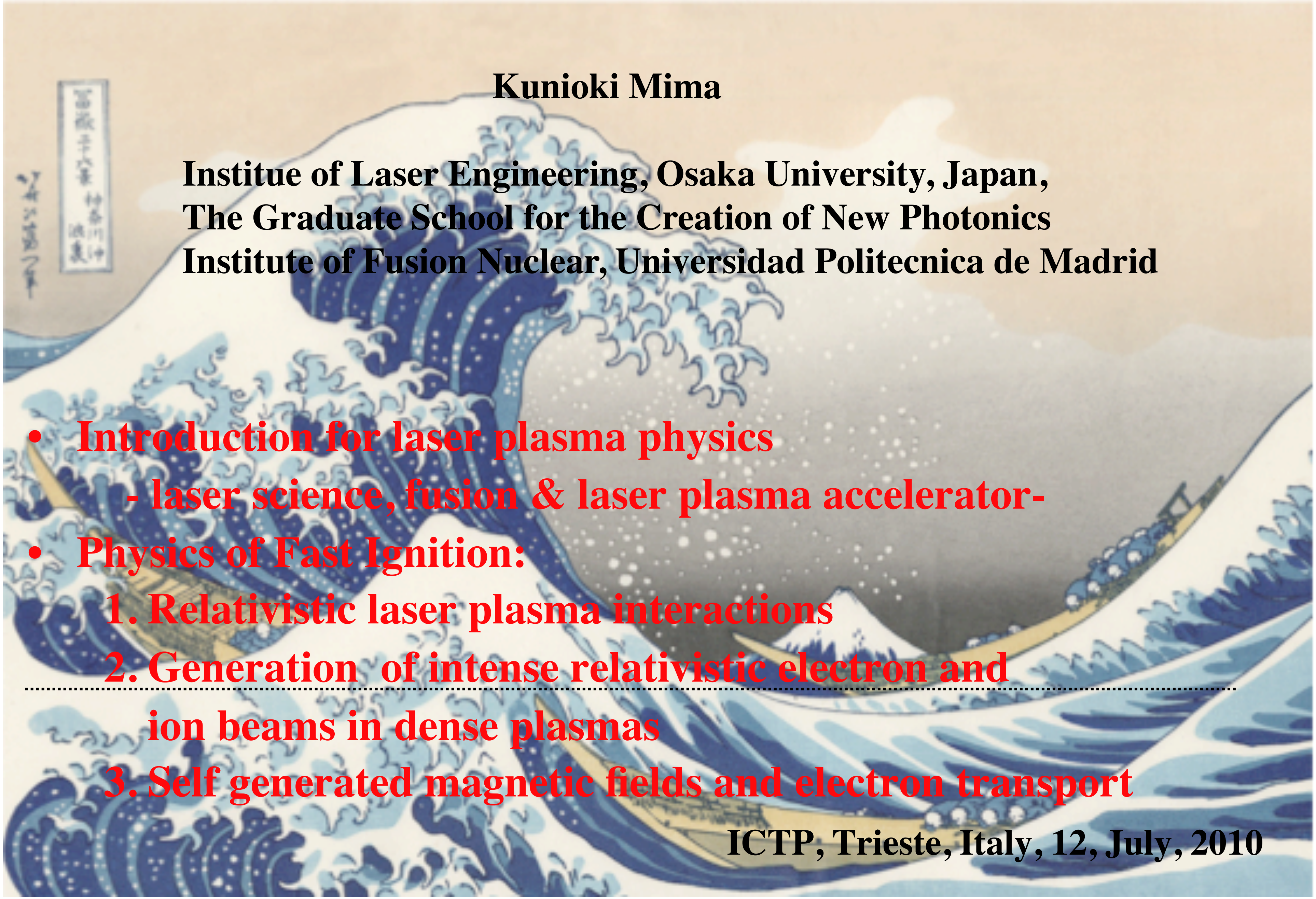


Kunioki Mima

Institue of Laser Engineering, Osaka University, Japan,
The Graduate School for the Creation of New Photonics
Institute of Fusion Nuclear, Universidad Politecnica de Madrid

- **Introduction for laser plasma physics**
  - laser science, fusion & laser plasma accelerator-
- **Physics of Fast Ignition:**
  1. Relativistic laser plasma interactions
  2. Generation of intense relativistic electron and ion beams in dense plasmas
  3. Self generated magnetic fields and electron transport

ICTP, Trieste, Italy, 12, July, 2010

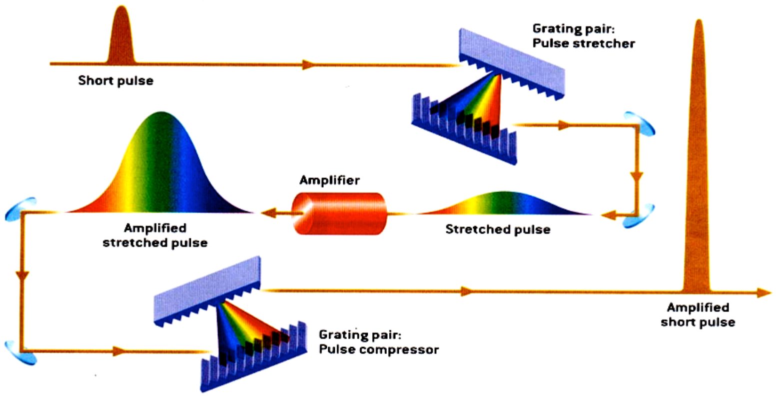
Development of Laser Technology

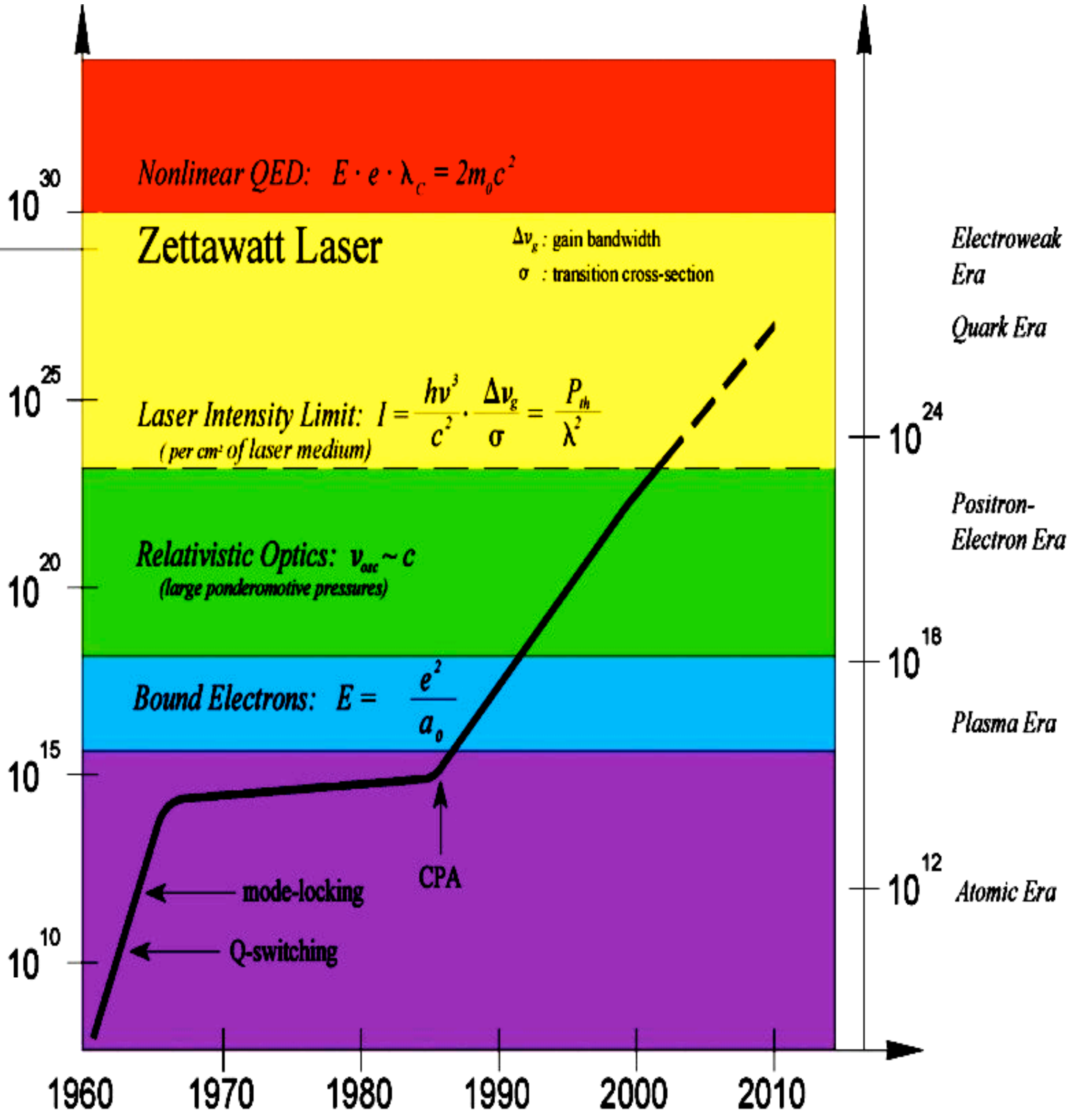
Ultra high intensity opens new plasma world

Fast ignition laser fusion
Quick plasma heating

CPA

D. Strickland and G. Mourou,
1986, Opt. Commun. 56, 212





G. A. Mourou, C. P. J. Barty, and M. D. Perry,
1998, Phys. Today 51, 22

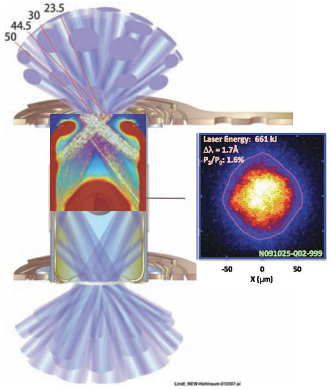
Relativistic Lasers Plasmas

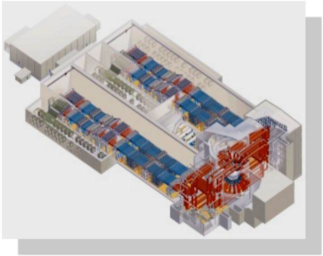
Morphology of Laser Plasmas

Laser Wake Acc. /Astro-Plasmas

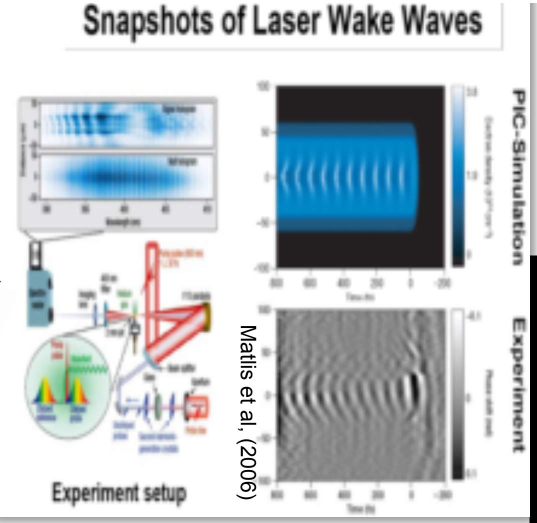
Fusion

NIF

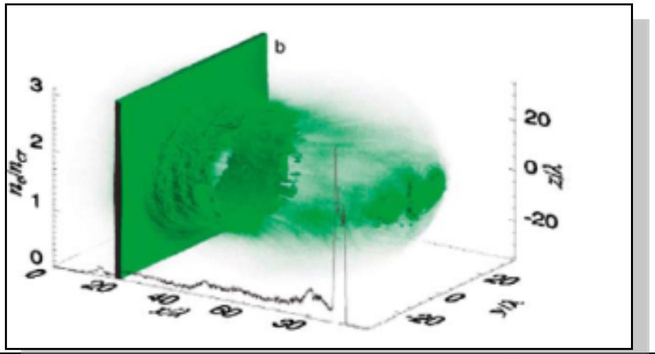




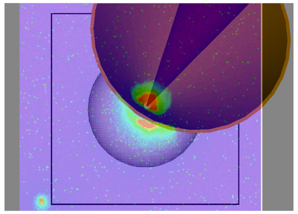
Laser electron acceleration

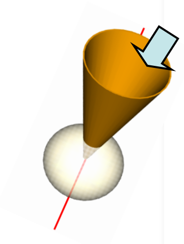


Matlis et al, (2006)

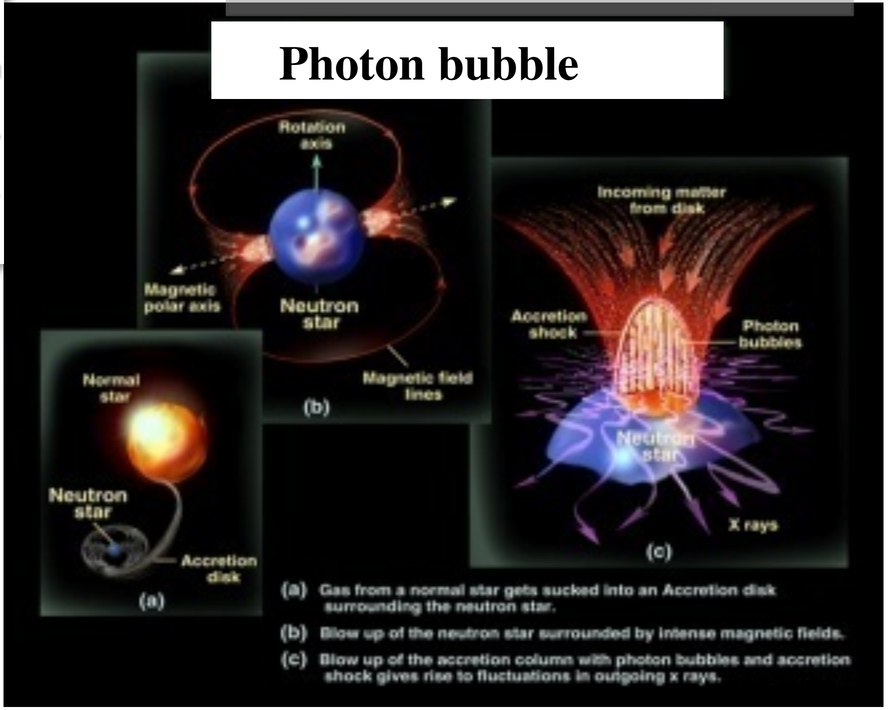


Fast ignition/FIREX





Photon bubble

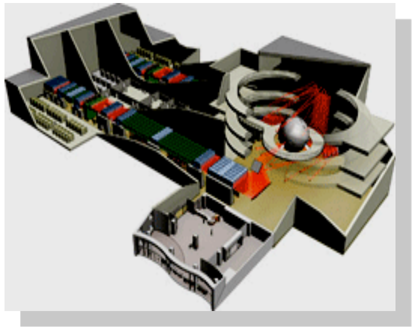


(a) Gas from a normal star gets sucked into an Accretion disk surrounding the neutron star.

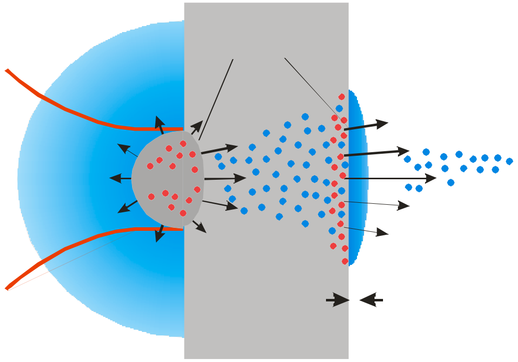
(b) Blow up of the neutron star surrounded by intense magnetic fields.

(c) Blow up of the accretion column with photon bubbles and accretion shock gives rise to fluctuations in outgoing x rays.

HiPER



Ion sheath acceleration

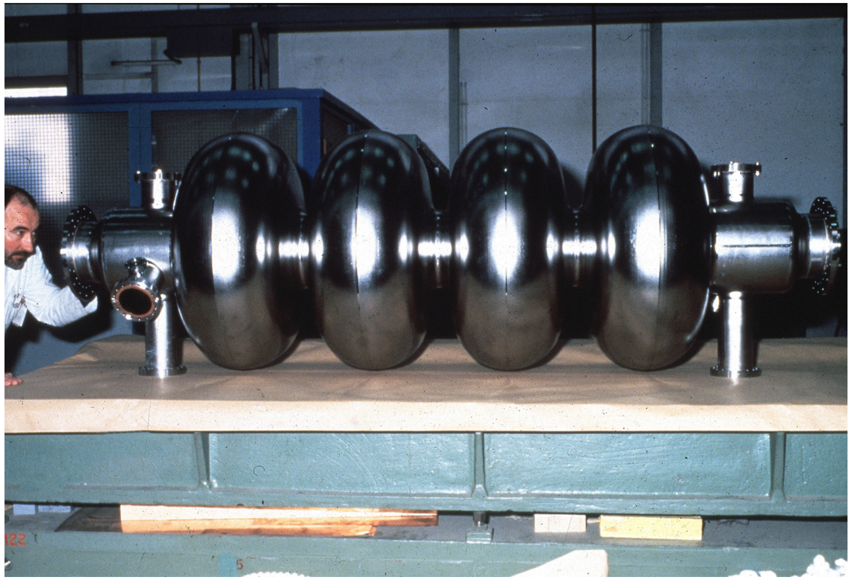


Advanced accelerator with laser plasma acceleraion

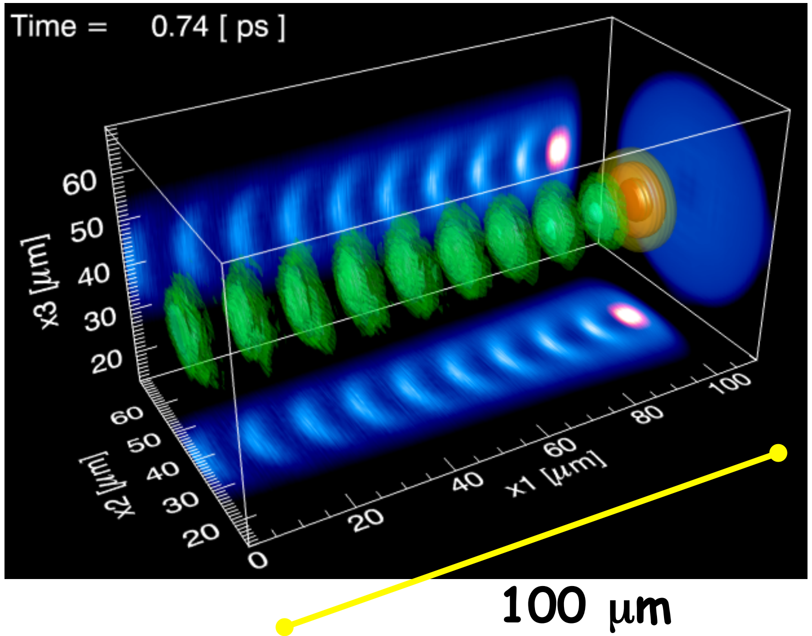
Conventional RF accelerator matured
Stable and high repetition rate
Max. E-field$_{max}$ $\approx$ a few MeV/m
limied by Breakdown
Large scale radiaion shielding

Laser Accelertor
Compact, local shielding
Poin source, ultra short pulse
Low repetition rate, unstable,
pre-mature

Courtesy of W. Mori & L. da Silva



1 m

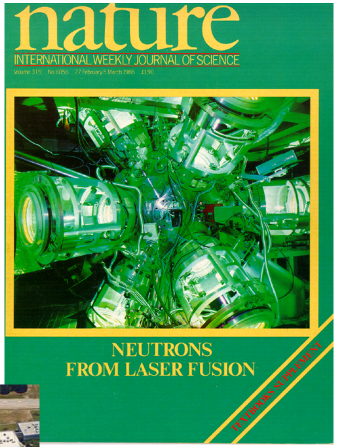


Experimens by M.Downer (PRL, 2006)

RF cavity

Laser plasma acceleration

History of Laser Fusion



1960: Laser innovation (Maiman)

1972: Implosion concept (J. Nuckolls)

1980~ : Understanding of Implosion physics.

GXII, Nova, OMEGA, and so on

Japan and US: T> 10keV and $10^{13} \sim 10^{14}$ neutrons

High-density demo

US	100-200 times liquid density
Japan	600 times liquid density

1990~ : NIF, LMJ construction

Fast ignition was proposed.

2000~: Ignition demonsraion

Central ignition

Fast ignition

NIF project, LMJ project. SNL-Z project

FIREX, OMEGA-EP, HiPER

Thermonuclear ignition in laboratory will happen in 2011.

Laser Fusion Plasma Conditions

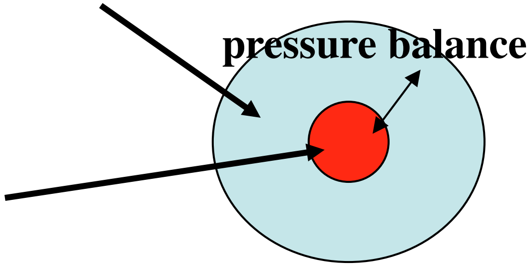
- **Burning fraction** $\phi = (n_0 <\sigma v> t/2) / (1 + n_0 <\sigma v> t/2)$
  for fusion reaction time $t \sim R/4C_s$ **and reaction rate:** $<\sigma v>$

- $\phi = \rho R/(A + \rho R)$, **for DT fuel radius:** R, **sound speed:** C_s, *and*
  $A = 10/(T/\ 10\ keV)^2\ g/cm^2$ **for temperature T**

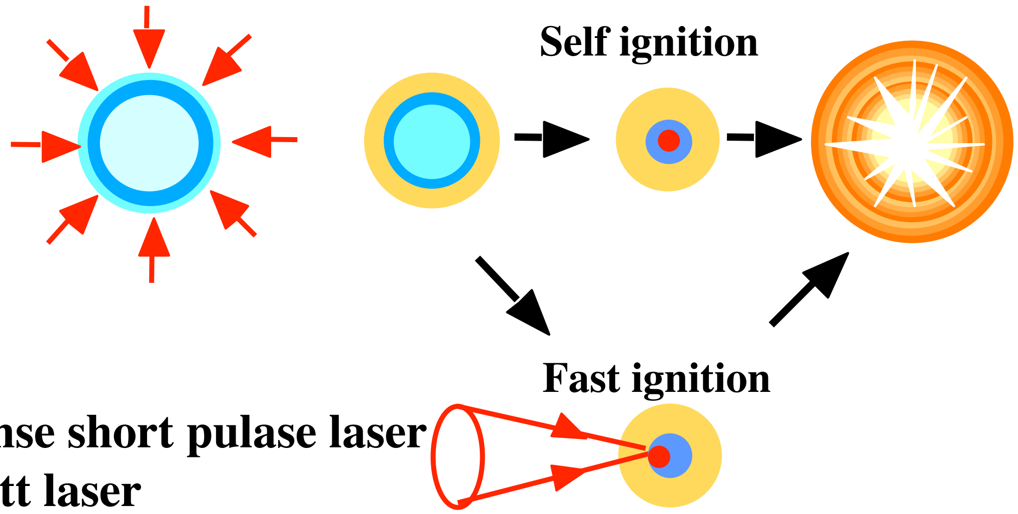
- **" Name of the Game " is compression, because**
  DT mass:$M_f = 4\pi R^3 \rho/3 = 4.19(\rho R)^3/\rho^2 \sim 33/\rho^2\ [g]$,
  when $\rho R = 2 g/cm^2$ **for high gain.**

  $M_f \sim 0.8\ kg$, **for** $\rho = 0.2\ g/cm^3$, **H- bomb!!**
  $M_f \sim 4.5\ mg$, **for** $\rho = 400\ g/cm^3$, $T < 1 keV$ *(2 times fermi energy)*
  (2000times solid density implosion)

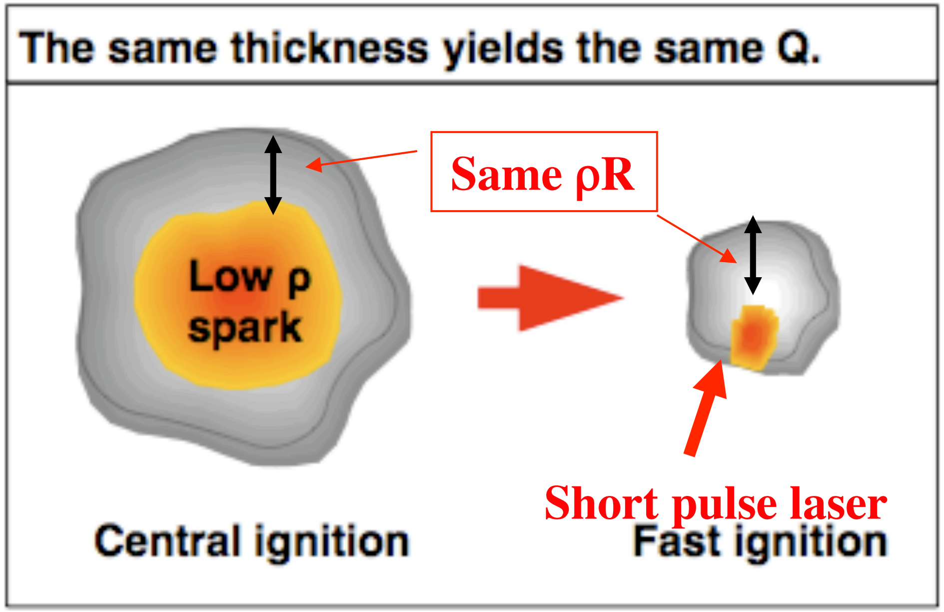
- **Hot spark ignition:** $\rho R = 0.4 g/cm^2$,
  $\rho = 100\ g/cm^3$, $T > 5keV$, *mass 0.6mg*



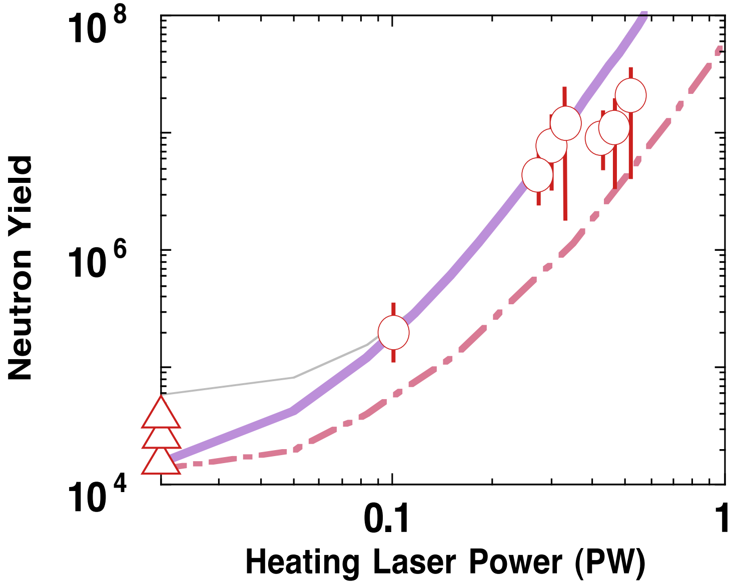
Two ways of Ignition in Laser Fusion



Ultra intense short pulase laser
Peta watt laser
M.Tabak, 1994 POP

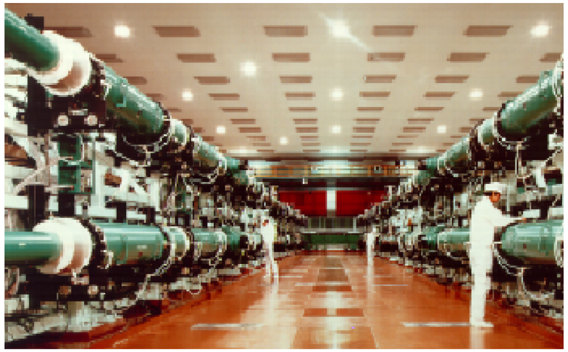


R.Kodama etal, Nature, 2001

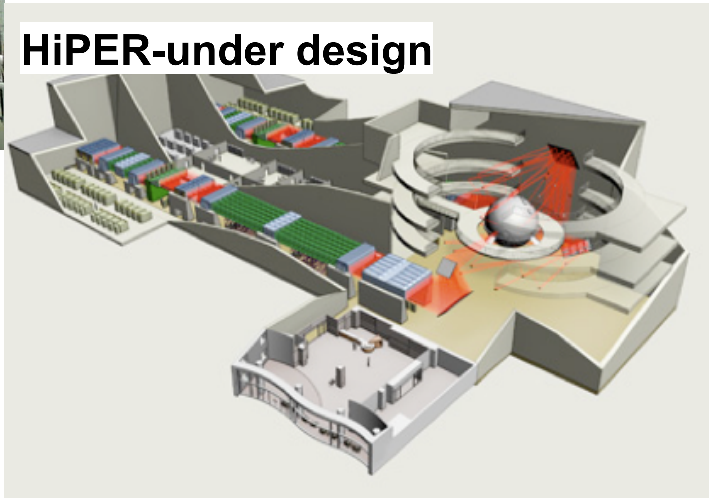


Fast Ignition Facilities.

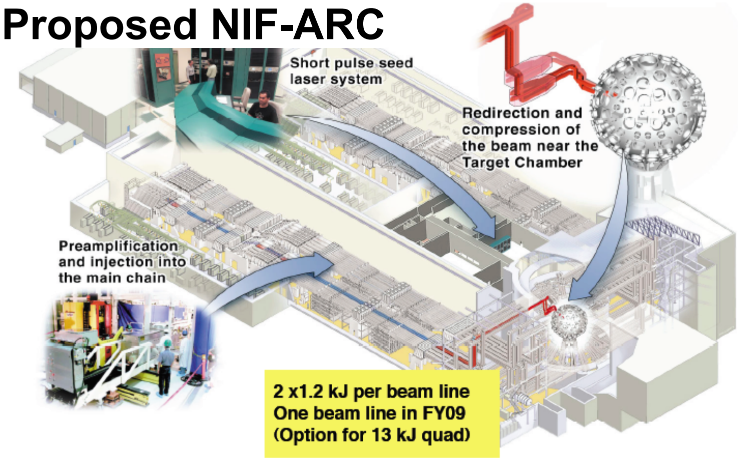

Japan-FIREX-I




Europe-PETAL


HiPER-under design


US-OMEGA EP


Proposed NIF-ARC

Short pulse seed laser system

Redirection and compression of the beam near the Target Chamber

Preamplification and injection into the main chain

2 x1.2 kJ per beam line
One beam line in FY09
(Option for 13 kJ quad)

Relativistic laser plasma physics in Fast ignition

Critical plasma physics in Fast Ignition

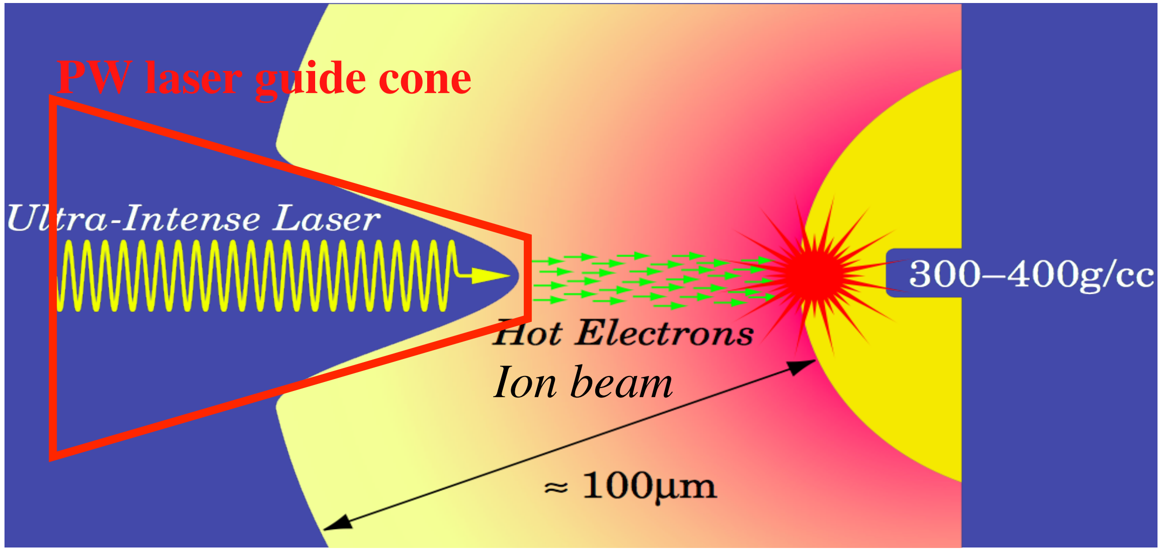
Ultra intense laser - plasma interactions; laser propagation, generations of high energy electron and ions, and transport

Laser intensity; $I_L = 10^{16}\ \mathrm{W}/\ \pi r_h^2 \sim 2\mathrm{x}\ 10^{20}\ \mathrm{W/cm^2}$

Electron energy; $\varepsilon_r = (\gamma\text{-}1)mc^2$,

$\gamma = [1+ (eA/mc)^2]^{1/2} = [1+ I_L/(2.4\mathrm{x}10^{18}\mathrm{W/cm^2})]^{1/2}$

So, $\varepsilon_r \sim$ **3~5 MeV near the cut off.**

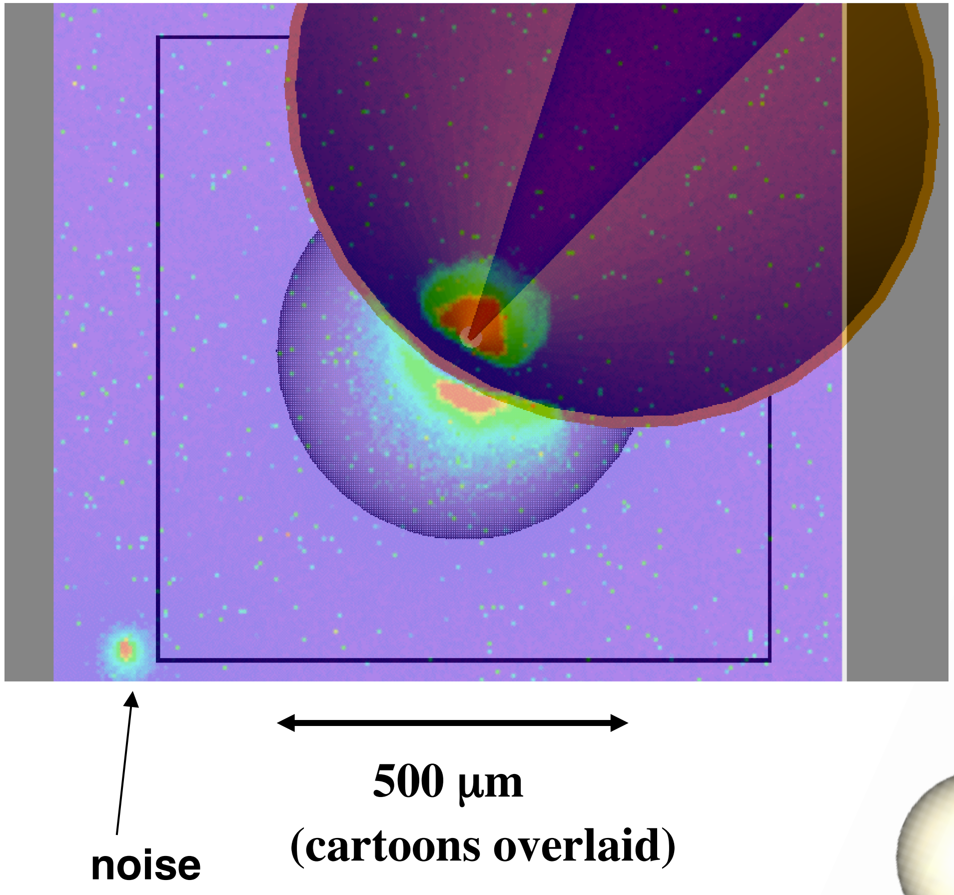


Super dense plasma is heated by relativistic electron beam and/or ion beam.

Beam current ~ 1GA

Experimental Results and Issues

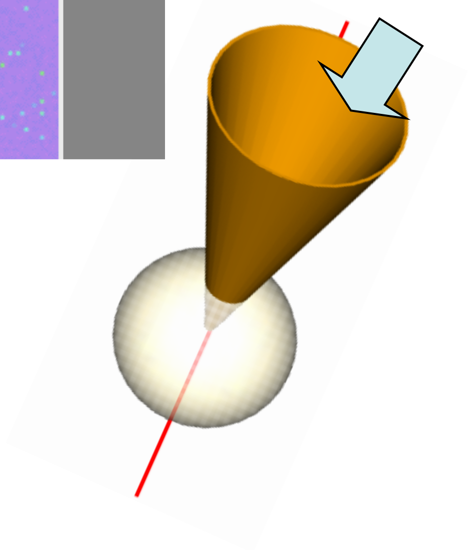
X-ray pinhole camera observing from the cone side (time integrated)



(cartoons overlaid)

Laser pre-pulse of ~100mJ with 3ns duration produces pre-plasmas

- **High electron slope T_h**
- **Large spot size of electron beam**



Requirements for fast heating

Assume hot spark area density: ρr_h: 0.6 g/cm^2

[Electron heat deposition range]

Imploded plasma density : 1000times solid density

$\rho_h \sim 200 g/cm^3$

Hot spark radius: $r_h \sim 30 \mu m$

$2 \rho r_h \sim 1.2\ g/cm^2$ >range -> $\varepsilon_h < 3 MeV$,

ie. not too high energy

- Total energy of DT hot spark : $3 N_h T_h \sim 5 kJ$ -> 10kJ
- where $N_h \sim 2 \times 10^{18}$, $T_h \sim 10 keV$
- Heating efficiency of 10 % then: total laser energy: 100kJ

[Electron beam geometry]

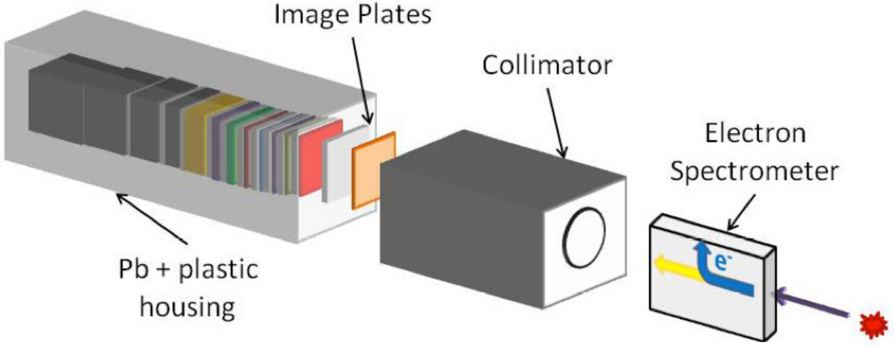
Heating e-beam diameter: $60\ \mu m^{\phi}$

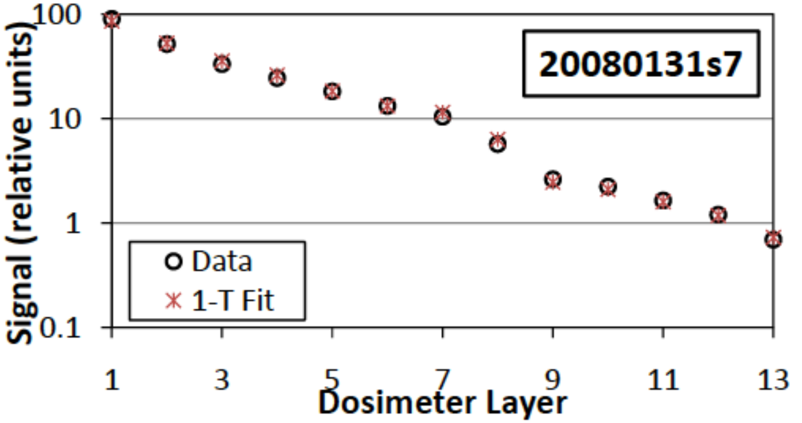
Distance from heat deposition point to hot spark: 100μm

Beam divergence full angle: 0.6 radian ~ 30^o

Bremsstrahlung diagnostic* confirms low hot electron temperature

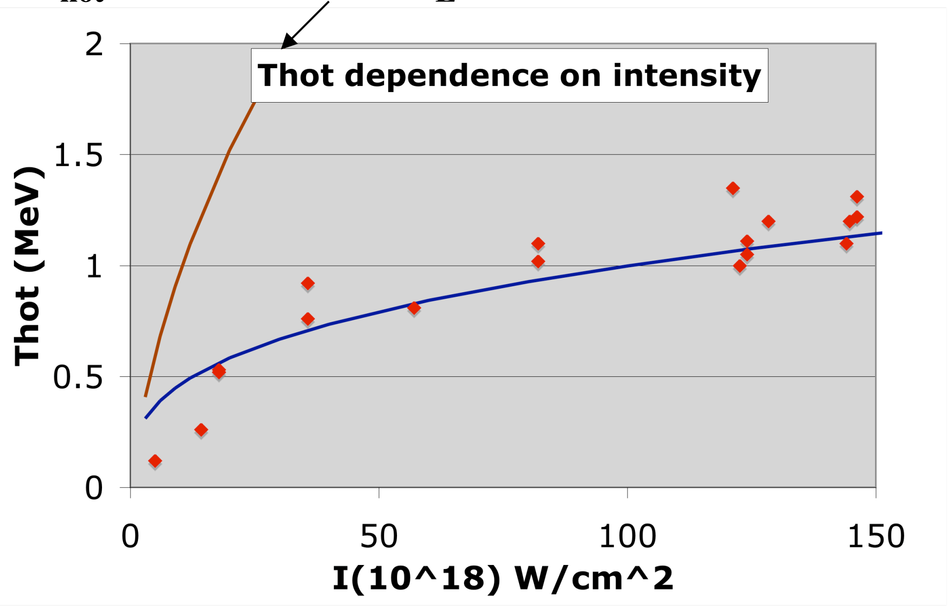
- Fast electrons produce bremsstrahlung in target
- Detected with image plates interleaved with filters
- Detector response modeled with T_h and n_e as variables





Wilks scaling

T_{hot} (MeV)= $0.5(1+I_L/(2.3\text{x}10^{18}\text{W/cm}^2))^{1/2}$-1



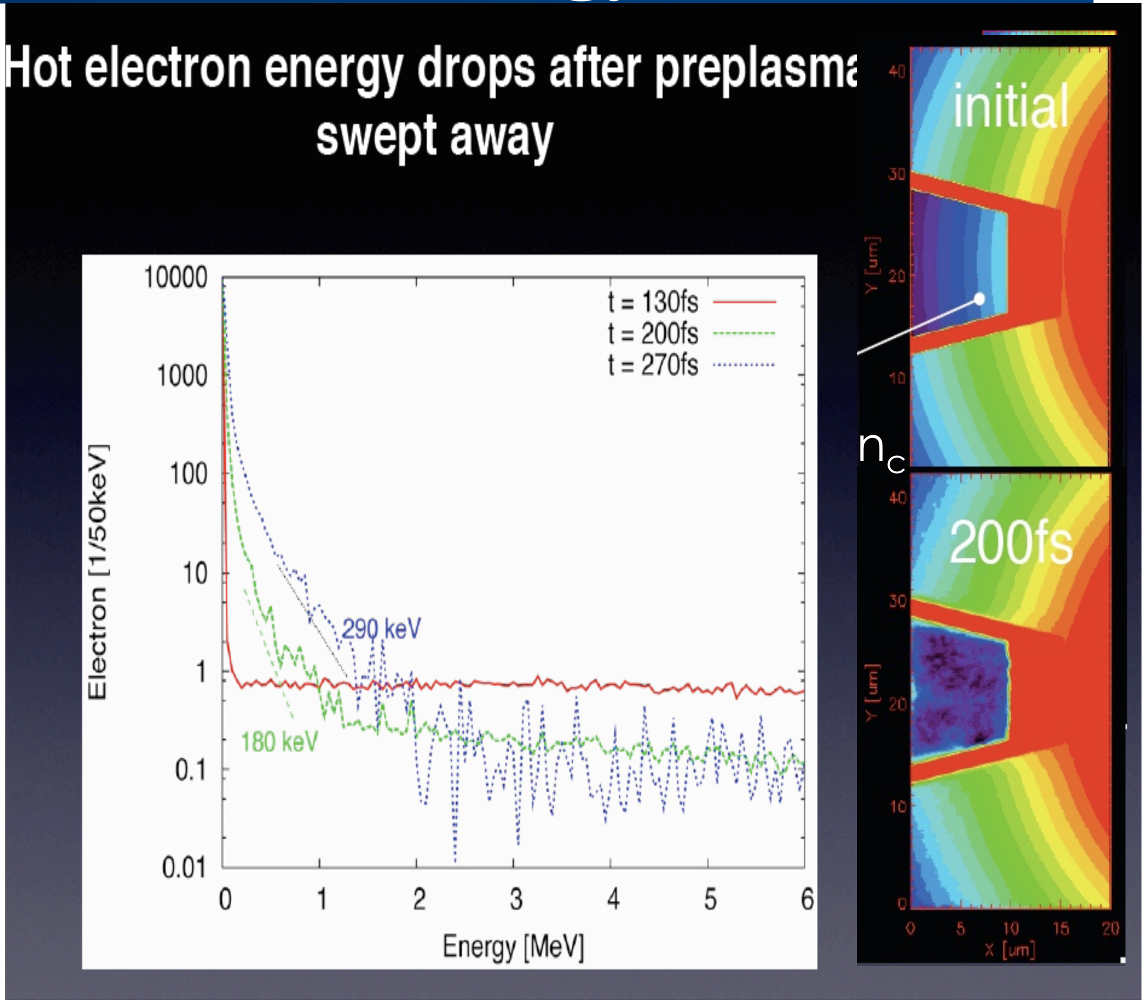
Single temperature fit shows hot electron temperature follows Beg's scaling†: T(MeV) = $0.215(I_{18})^{1/3}$

*C. Chen et al., HTPD conference 2008
†F.N. Beg *et al.*, Phys. Plasmas **4**, 447 (1997)

Model predicts intense laser pulse moderates electron energy

- **Simulations show high intensity beams compress the laser plasma interface**
- **So electrons escape EM field before attaining ponderomotive energy**[†‡]
- **Energy reduction:**

$$\propto \frac{skin\_depth}{acceleration\_length}$$



Hot electron energy drops after preplasma swept away

=> Good coupling to compressed target

After R.Stephens, 2008 US-Japan

[§] B. Chrisman et al., PoP 15, 056309 (2008)

[†] M. Haines et al., submitted to PRL (2008)

[‡] P. Mulser arXiv 0805.1815v1 13May 2008

Hot electron generation

Collisionless absorption mechanisms:

1) Stimulated Raman Scattering (forward Raman:wake filed), and Two Plasmon deacy:

em wave -> epw + emw -> hot electron

[Long scale under density plasma, fast process]

2) Parametric decay instability:

em wave -> epw+iw -> hot electron

[Long scale critical density plasma, slow process, but if $> 10^{24}$W/cm^2 , fast ?]

3) Resonance absorption: sharp density gradient.

em wave -> epw -> hot electron

[finite scale length plasma, non relativisic]

4) Brunel absorption/JXB absorption(Brunel,1987, PRL), Vacuum heating (stochastic heating)(Gibon 1992), so on

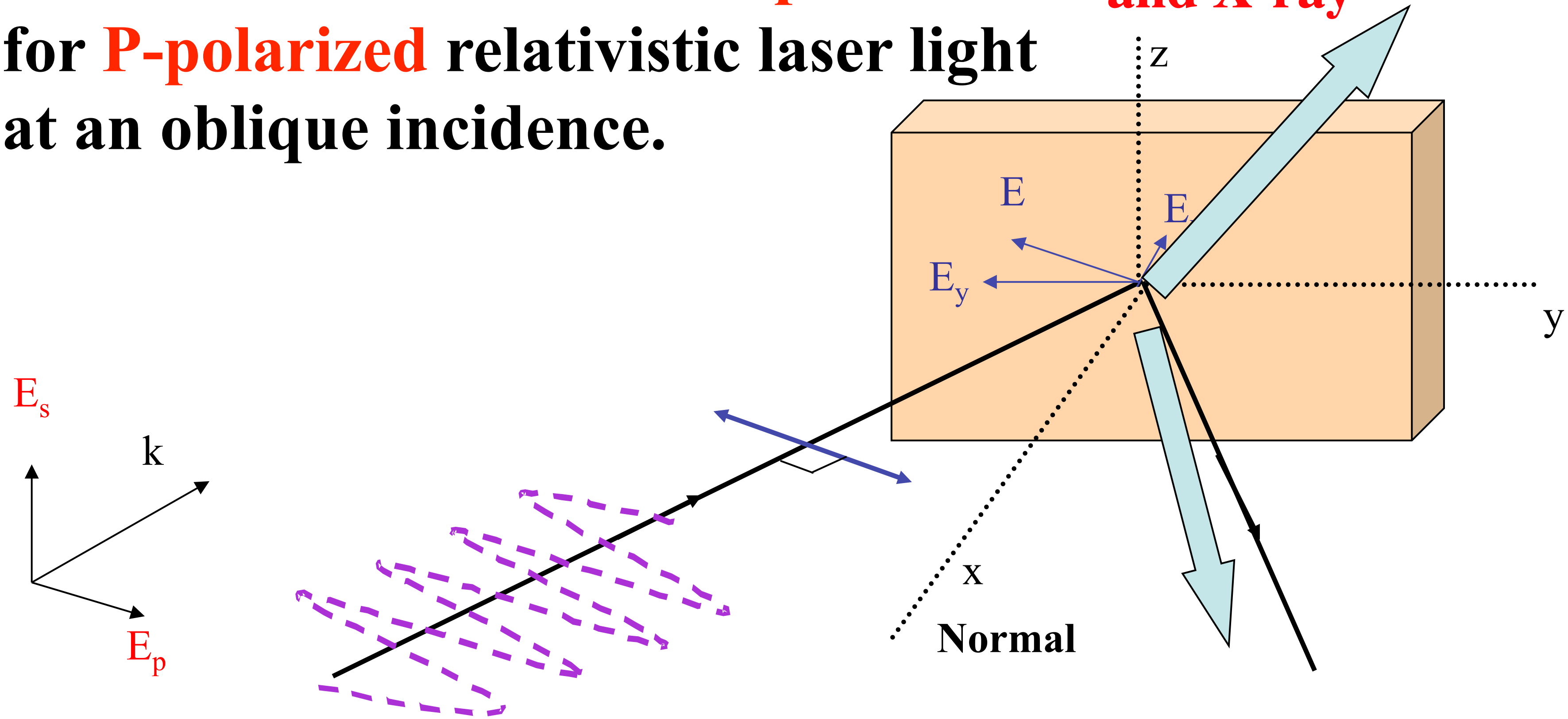
particle oscillation <-> laser oscillation (ω_0 and/or $2\omega_0$ fields) are de-phase.

emw -> hot electron

[relativistic, short scale length $L < \lambda$] (P.Mulser etal, PRL, 2008)

Collective laser absorption of short pulse laser

Revisit the resonance absorption
for P-polarized relativistic laser light
at an oblique incidence.

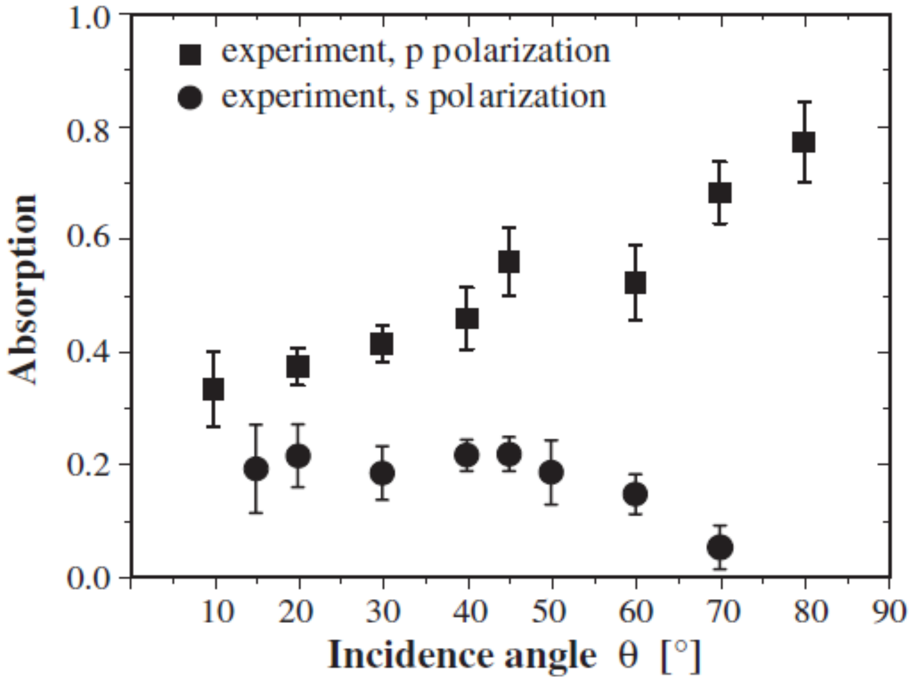


Realtivistic electron and X-ray

higher harmonics

Component E_x along density gradient drives Plasma Oscillations. **After Rav.Kumar,TIFER, January, 2010 Kaw fest.**

HEDS – T³: Hot electron generation



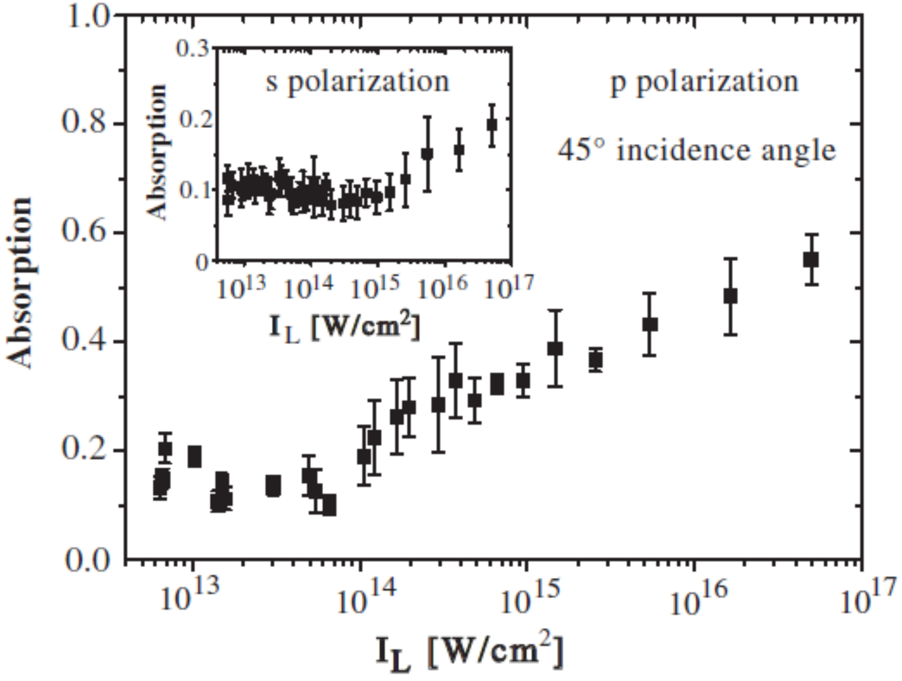
8 fs, 5 x 10^{16} W cm^{-2}

10^{-5} picosecond contrast

Steep, highly overdense plasma.

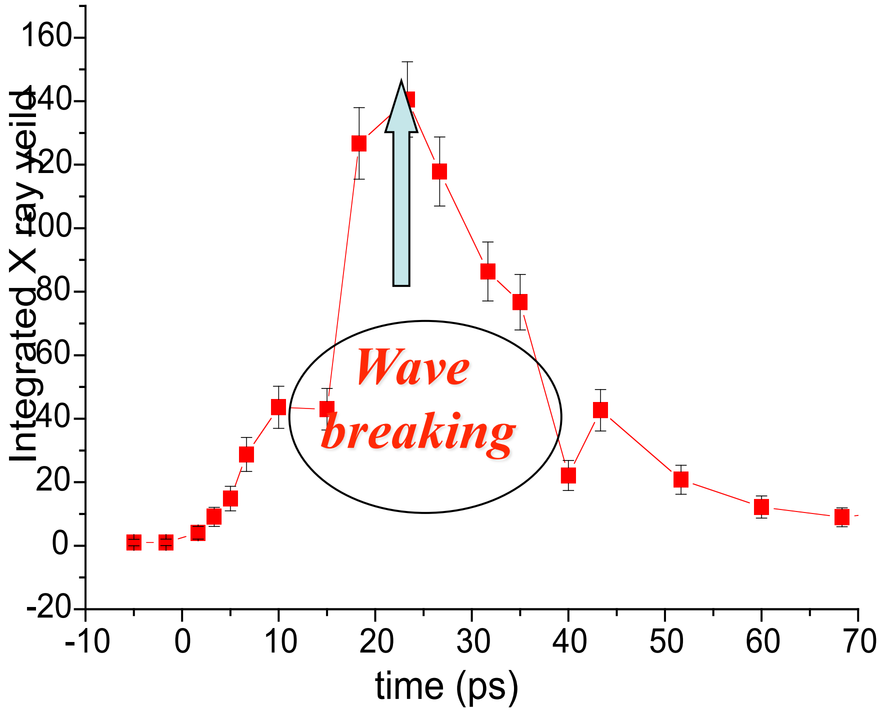
Absorption up to 80% !

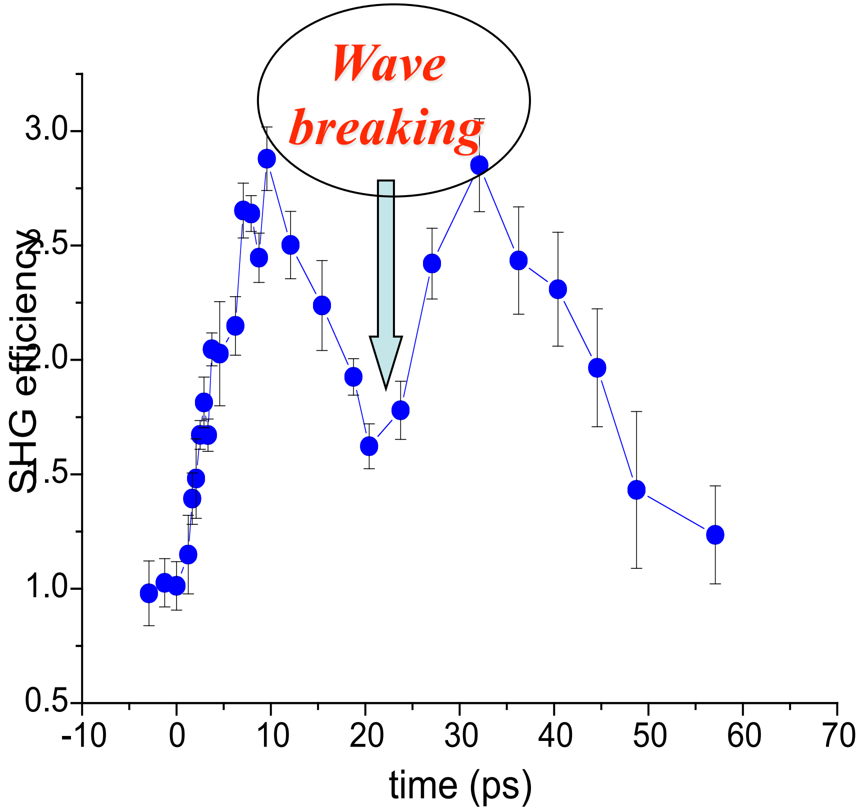
New mechanism ?



After R.Kumar, TIFER: Cherchez et al.PRL,100, 245001 (2008)

Hard X-Ray Yield and Second Harmonic signals vs. Plasma scale length (time delay of main pulse)





Observe dip in second harmonic and peak in X-ray Yield at ~ 24 ps

X-ray yield is enhanced by two orders of magnitude

Second Harmonic dips to half its maximum value

Plasma waves couple light to itself

Higher harmonic generation
(SHG) via the *plasma density oscilation*…..

$\omega_{\text{light}} + \omega_{\text{pl}} = 2\,\omega_{\text{light}},\ 3\,\omega_{\text{light}}$

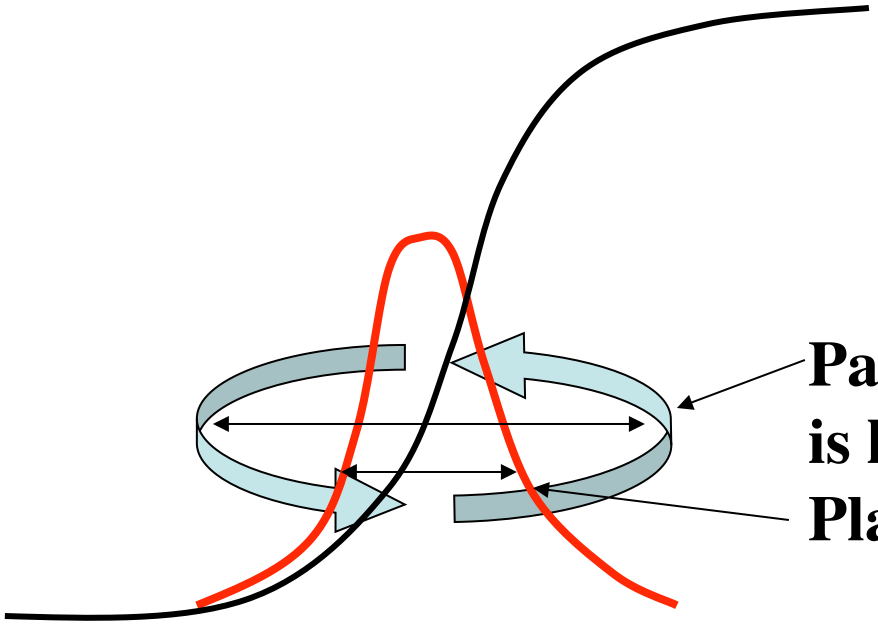
($\omega_{\text{pl}} = \omega_{\text{light}}$ or $2\omega_{\text{light}}$ at critical layer)

The **stronger** the plasma wave, the stronger the HHG

HHG - essentially at the relativisic critical layer

The mechanism of collisionless absorption

Plasma wave breaking accelerates (heating) hot electrons, since phase relation of field oscillation and electron oscillation is no more π/2



Particle excursion length is longer than Plasma and filed scale length

When all electrons satisfy the above condition, it is " wave breaking".

PRL **95,** 025005 (2005) PHYSICAL REVIEW LETTERS week ending 8 JULY 2005

Laser-Pulse-Induced Second-Harmonic and Hard X-Ray Emission: Role of Plasma-Wave Breaking

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Tata Institute of Fundamental Research, 1 Homi Bhabha Road, Mumbai 400 005, India

S. Sengupta, A. Das, and P. K. Kaw
Institute for Plasma Research, Bhat, Gandhinagar 382 428, India

(Received 29 August 2004; published 8 July 2005)

TIFR+IPR

Collision-less absorption in highly relativistic regime is relevant to Fast Ignition

- **There are very many experiments and simulations, but not well understood yet!**
- **In this regime, density profile steepening is essential --> polarization dependent**
- **Steep plasma-vacuum surface oscillates by $2\omega_0$ oscillating ponderomotive force.--> Oscillating piston**
- **The oscillating mirror producing many higher harmonics---> many observation (Gibon etal, Gibbon, 1992)**