The 4th Yamada Symposium on Advanced Photon Science Evolution 2010

High Energy Density Sciences with Power Lasers

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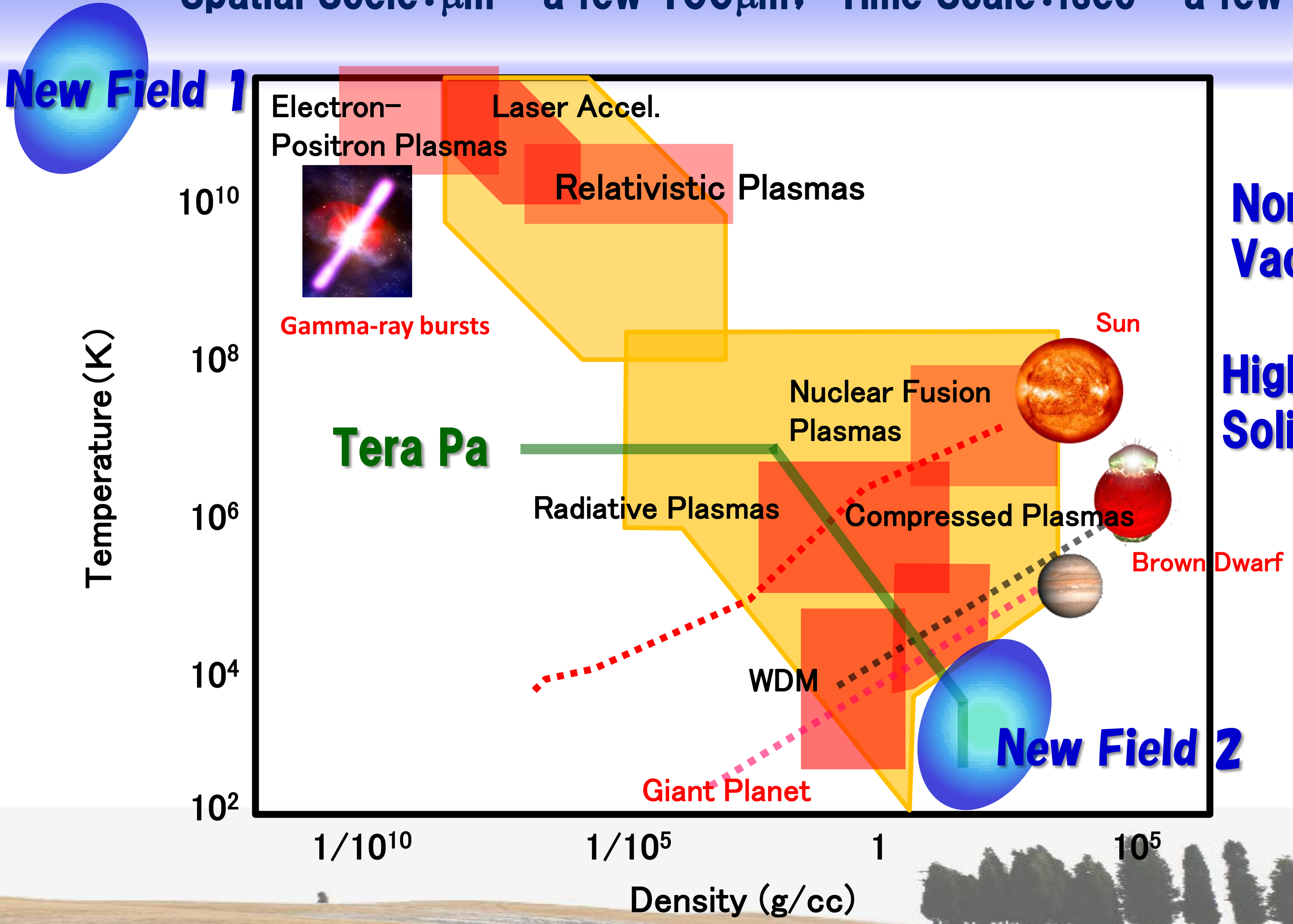
Contents

- High Energy Density Sciences (Introduction)
- High Energy Plasma Photonic Devices for Nonlinear Optics in Vacuum
- High Energy Density Solid Matter

High Energy Density States with High Power Lasers

Spatial Scele:μm - a few 100μm; Time Scale:fsec - a few nsec



Nonlinear Optics in Vacuum

High Energy Density Solid Material

g. 100MA

Contents

☞ High Energy Density Sciences

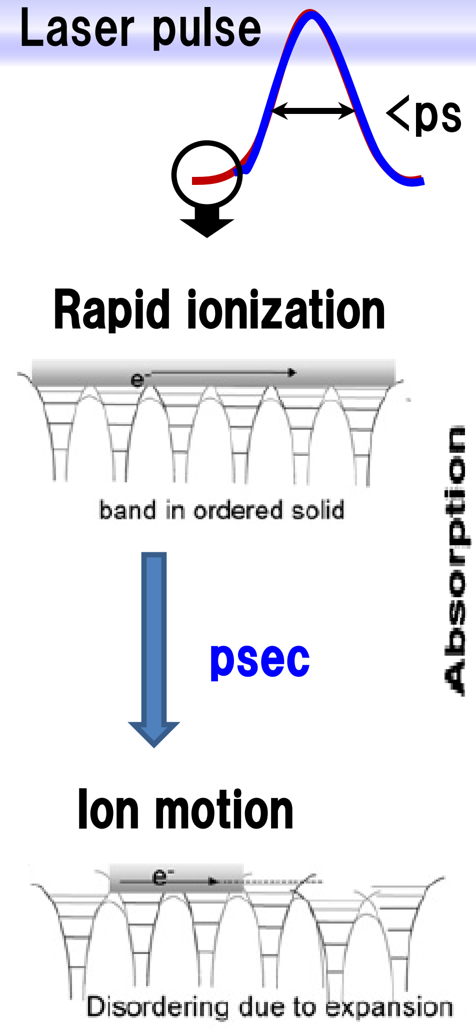
☞ High Energy Plasma Photonic Devices

control of high density (>MA) of charged particles like a light control
control of intense light

Focusing Plasma Mirror
for Nonlinear Optics in Vacuum

☞ High Energy Density Solid Matter

Plasma Mirrors are Most Popular as Plasma Photonic Devices



Laser pulse

<ps

Rapid ionization

band in ordered solid

psec

Ion motion

Disordering due to expansion

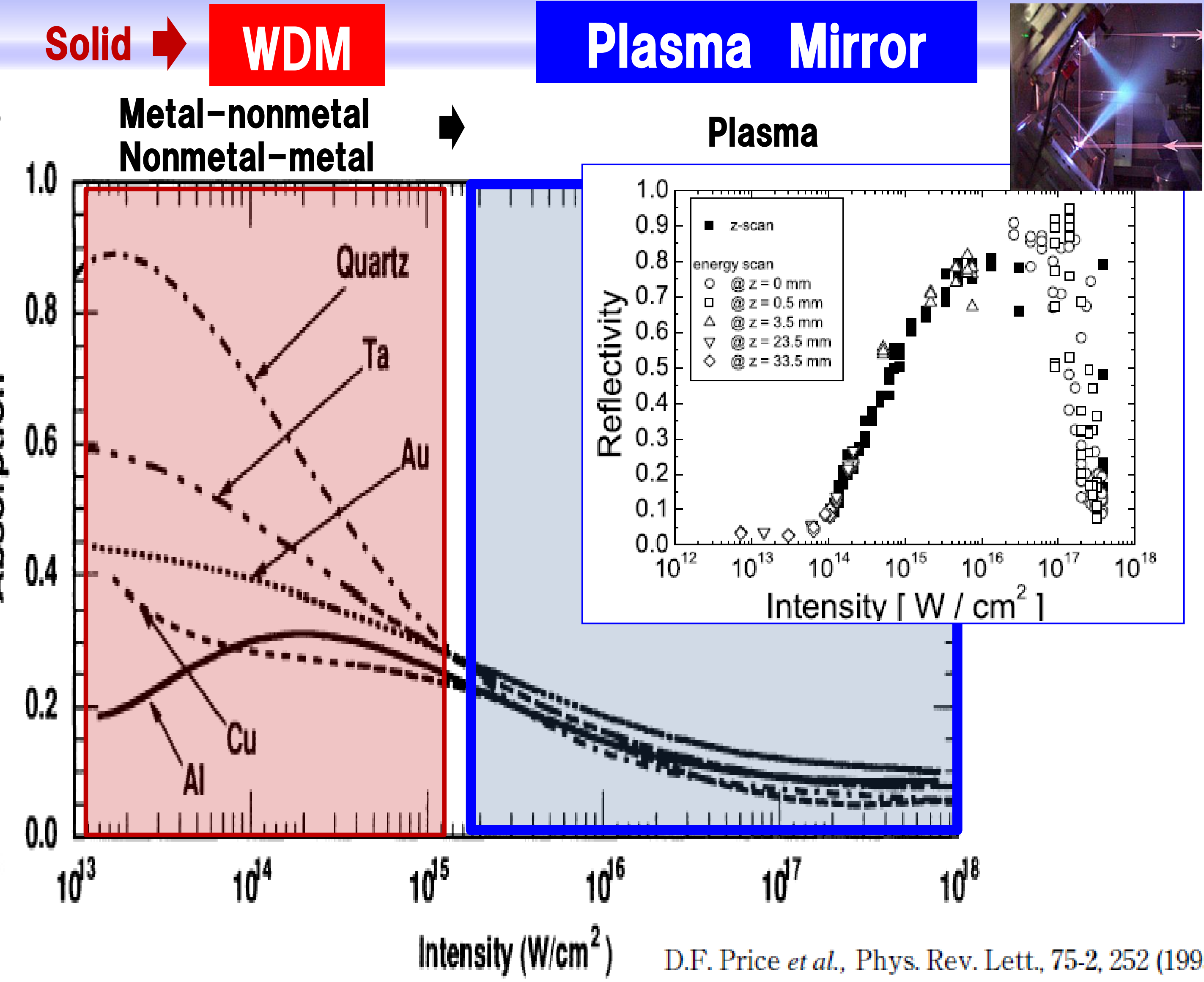
Solid → **WDM**

M. K. Moncur (1977)

Plasma Mirror

Metal–nonmetal
Nonmetal–metal

→ Plasma



D.F. Price *et al.*, Phys. Rev. Lett., 75-2, 252 (1995).

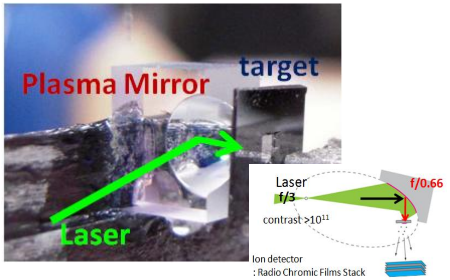
Osaka PhoPs

Plasma Mirror with linear and nonlinear responses

HEDS

10^{16-18}W/cm2

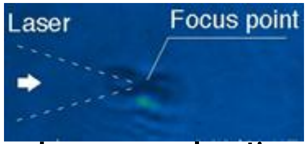
Fast focusing optics (f<1)



High field physics

Submitted to Nature Photonics (2009)

Light guiding optics in plasmas or extreme conditions

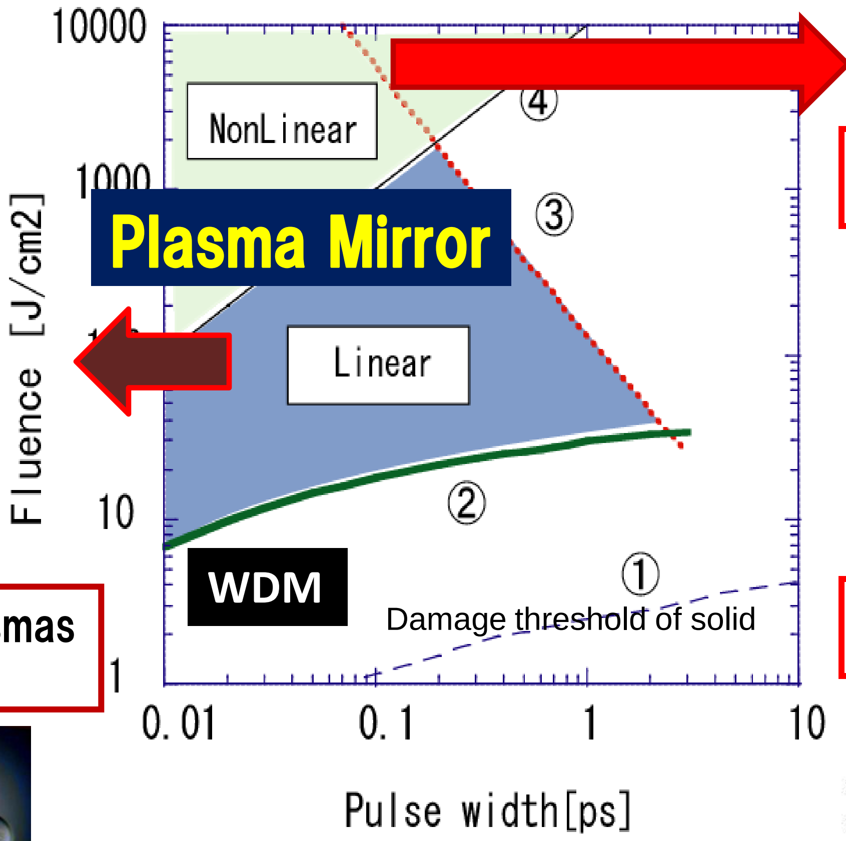


Laser acceleration

Phys Rev. Lett. 97, 075004 (2006)

Laser fusion

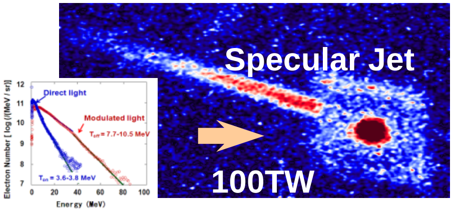
Nature 412, 798 (2001)
Nature 418, 933 (2002)



> 10^{18}W/cm^2

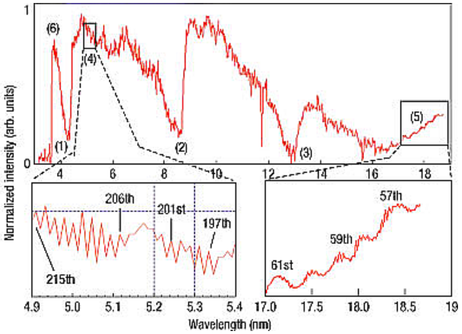
Relativistic Oscillation Mirror

Self phase modulation and particle acceleration



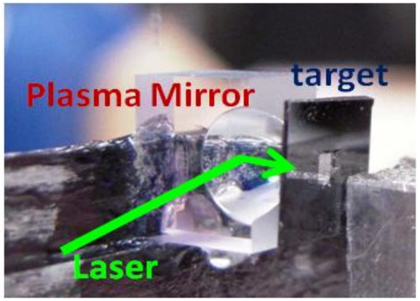
Phys Rev. Lett. 84, 674-877 (2000)
Phys Rev. Lett. 102, 045009 (2009)

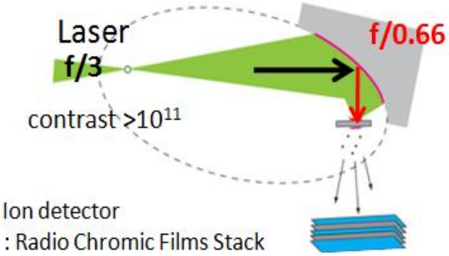
High order harmonic generation in keV region

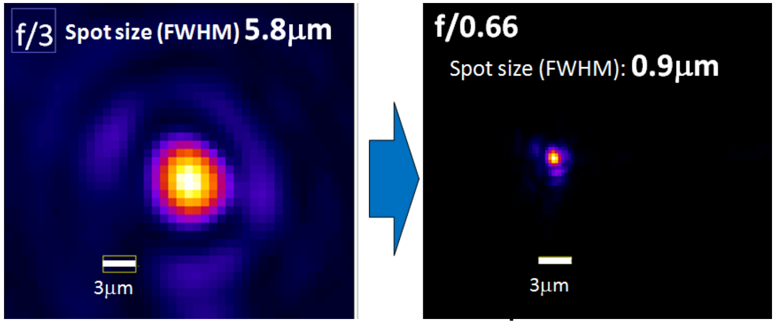


Nature Physics 2, 456 (2006)

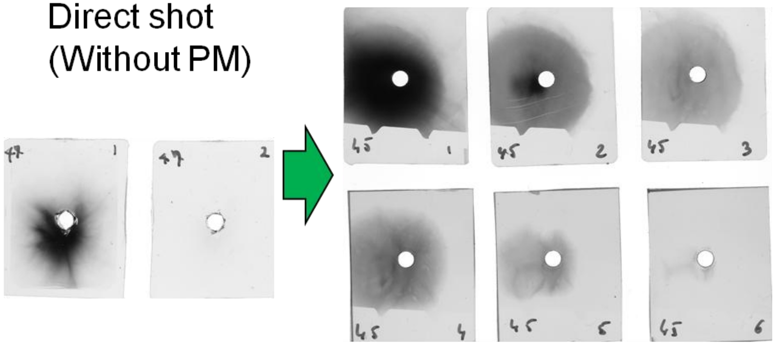
Fast Focusing Optics < 1 can be Realized with a Spheroid Plasma Mirror in a Power Laser System





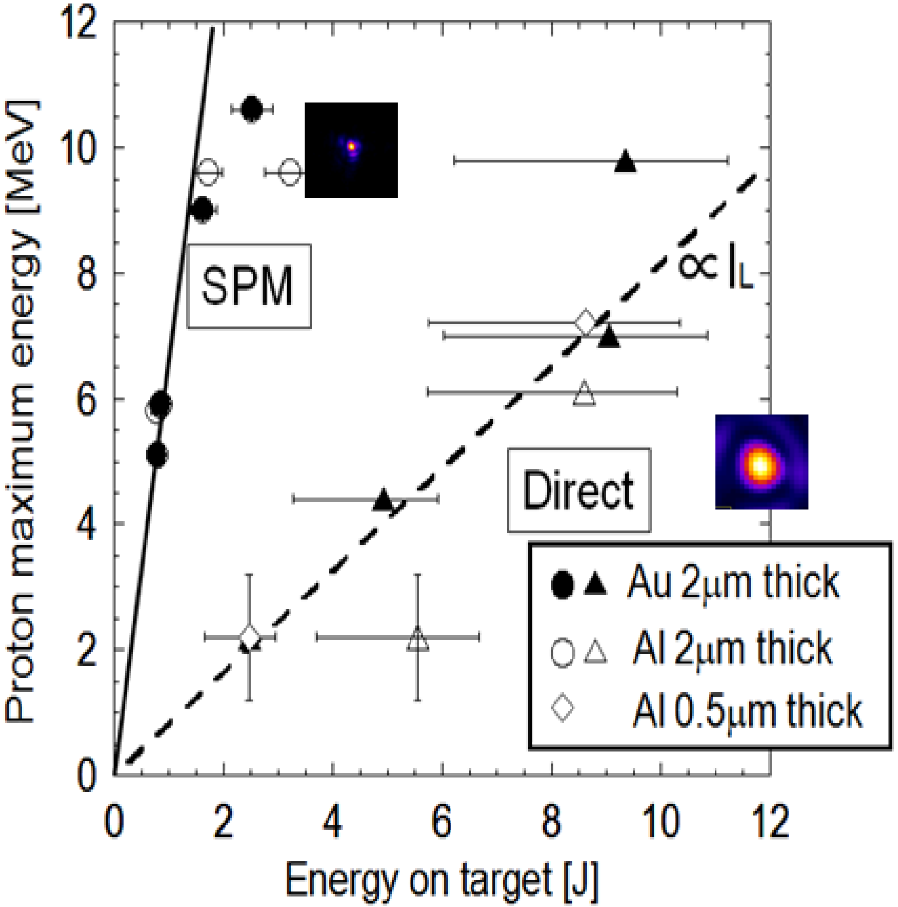


Direct shot
(Without PM)



Maximum proton energy
2 MeV → 11 MeV

Focused laser intensities could be enhanced by 10-20 from increase in the maximum proton energy.



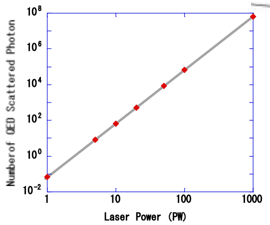
Probing of Vacuum with Photon

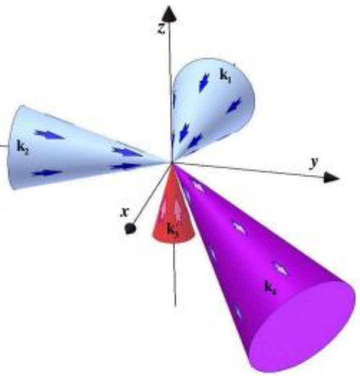
Laser interaction with vacuum

Nonlinear Optics in Vacuum
10^{24-26}W/cm^2

Vacuum Breaking
10^{29}W/cm^2
(matter・anti mater)

Propagation in Vacuum
10^{23}W/cm^2





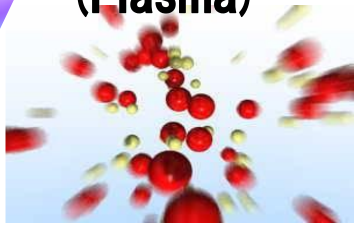
Understanding of Vacuum without breaking of Vacuum

PW

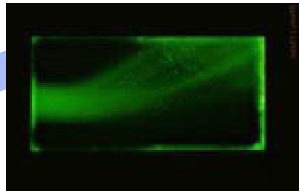
0.1−1EW

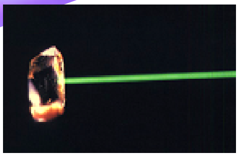
Ultra-Intense Laser

Material Breaking (Plasma)



Nonlinear Optics in Material

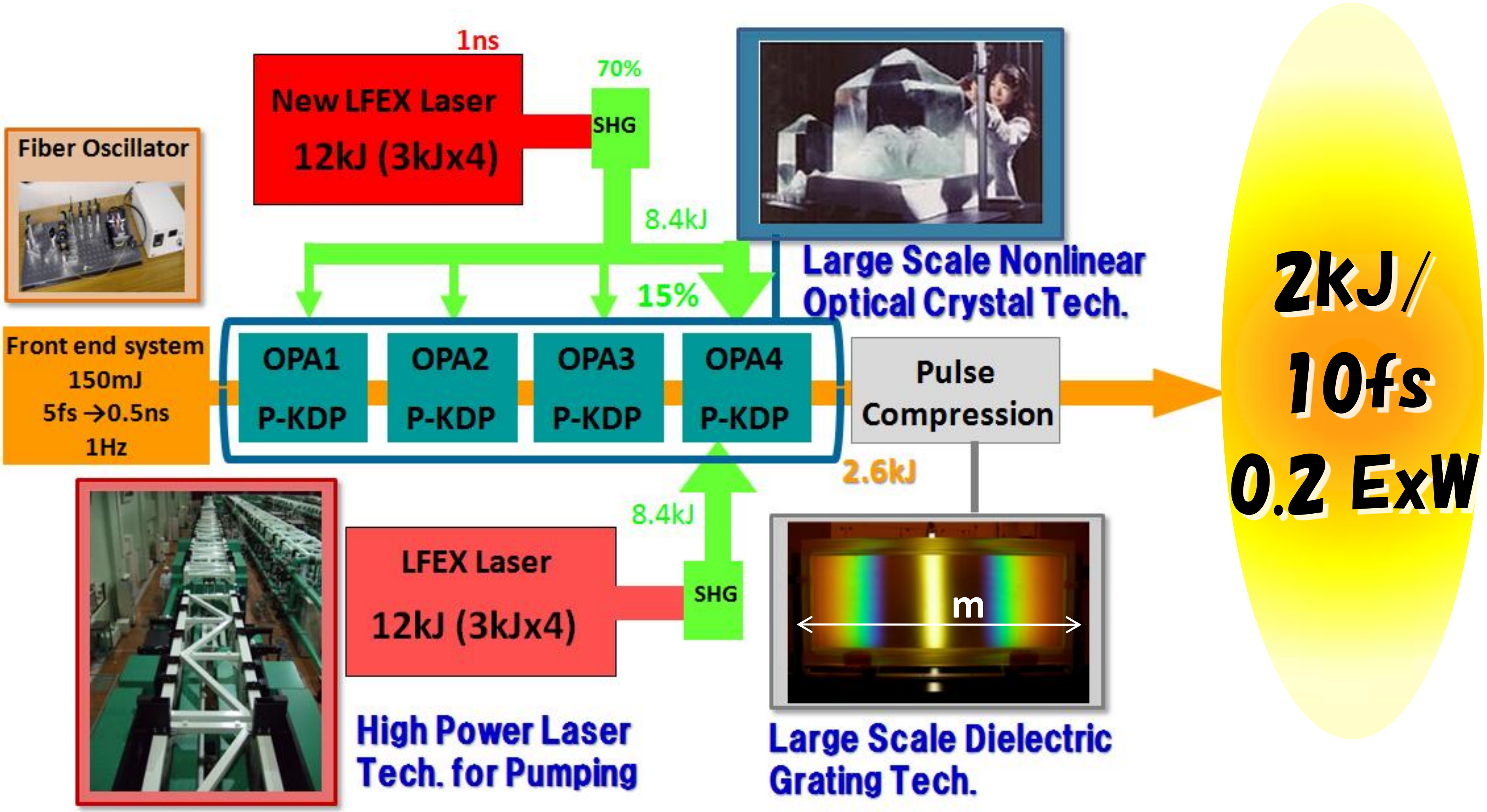




Laser

Propagation in material

Key Technologies to realize Ex watt Laser



Large Scale Nonlinear Optical Crystal Tech.

High Power Laser Tech. for Pumping

Large Scale Dielectric Grating Tech.

Simple Plane Wave can not Create the Polarization in Vacuum: Non symmetry is required.

Lagrangian density *L* (F,g) of electromagnetic fields in a vacuum is represented by the sum of the densities due to the classical L_{class} and QED *L'* (F,g) terms.

$$\begin{aligned} L(F,g) &= L_{class} + L'(F,g) \\ &= L_{class} + L_1(F,g) + L_2(F,g) + \cdots \\ &= L_{class} + \underbrace{\frac{\alpha(4F^2+7g^2)}{360\pi^2 E_{cr}^2} - \frac{\alpha F(8F^2+13g^2)}{630\pi^2 E_{cr}^4} + \cdots}_{\text{Nonlinear term}} \end{aligned}$$

where $\alpha = e^2/\hbar c$ is fine-structure constant, $F = (\mathrm{B}^2 - \mathrm{E}^2)/2$, and $g = \mathrm{E}\cdot\mathrm{B}$ are the invariants of the electromagnetic field, and $E_{cr} = m^2c^3/e\hbar$ is called critical electric field.

$$\mathbf{P} = \frac{1}{4\pi}\left[-\frac{\partial L'}{\partial F}\mathbf{E} + 2g\frac{\partial L'}{\partial G}\mathbf{B}\right], \quad \mathbf{M} = \frac{1}{4\pi}\left[\frac{\partial L'}{\partial F}\mathbf{B} + 2g\frac{\partial L'}{\partial G}\mathbf{E}\right] \qquad G = g^2$$

$$F = \frac{1}{2}\left(\mathbf{B}^2 - \mathbf{E}^2\right) \neq 0$$

$$g = \mathbf{E}\cdot\mathbf{B} \neq 0$$

Non Symmetry

- **Multi beam interactions**
- **External fields**
- **Focusing with a large angle**

The 1st of the QED term is Taken into Account in the Calculation at less than the Schwinger Limit.

Lagrangian density *L* (F,g) of electromagnetic fields in a vacuum is represented by the sum of the density in classical L_{class} (F,g) and QED *L'* (F,g) terms.

$$
\begin{aligned}
L(F,g) &= L_{class} + L'(F,g) \\
&= L_{class} + L_1(F,g) + L_2(F,g) + \cdots
\end{aligned}
$$

Nonlinear term

L_1 → (ω' , 3ω)

L_2 → (ω' , 3ω , 5ω)

$P_m(n\omega)$:polarization for nω due to L_m term

$$P_1(3\omega)/P_1(\omega') \sim 10^{-1}$$

$$P_2(\omega')/P_1(\omega') \leq 10^{-2}$$

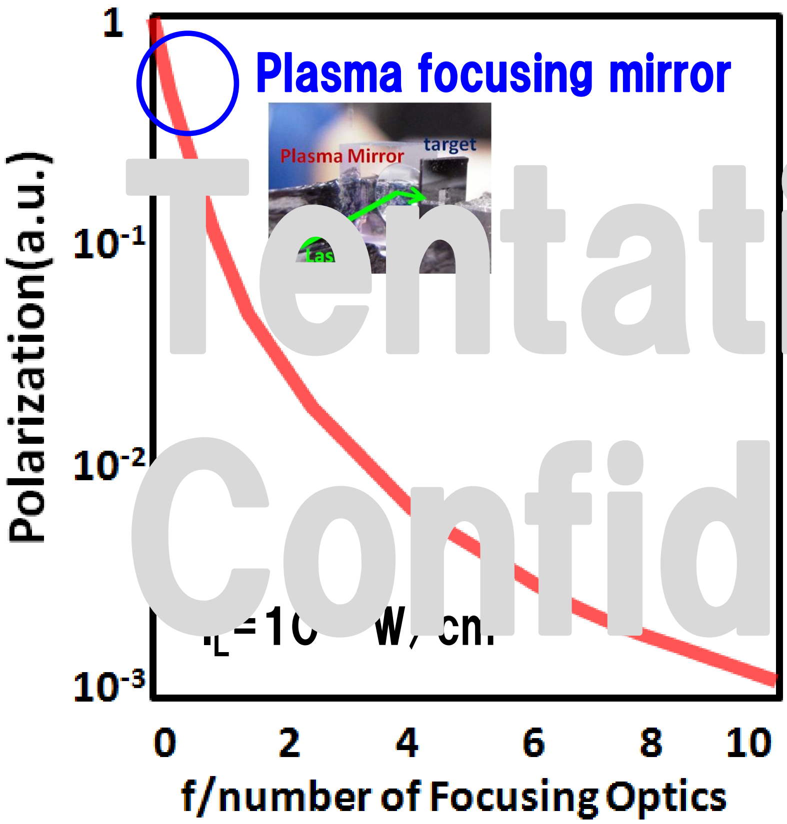
$$P_2(3\omega)/P_1(3\omega) \leq 10^{-2}$$

Calculation:

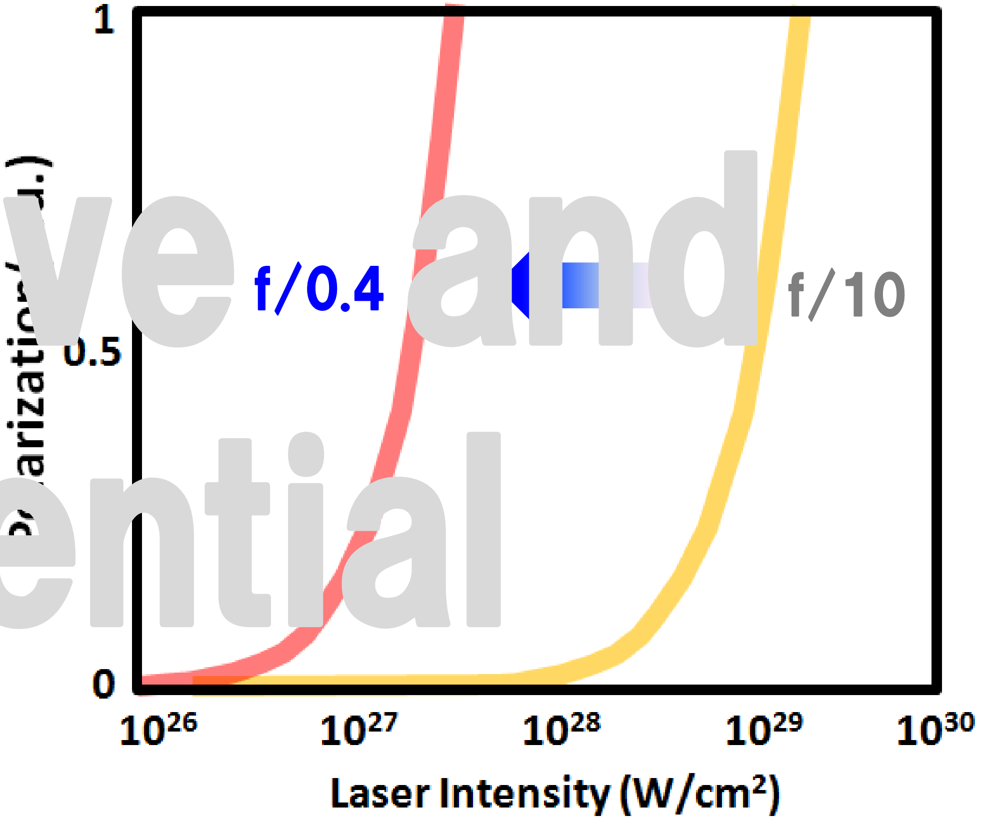
P_1 (ω') ; M_1 (ω')
and
P_1 (3ω) ; M_1 (3ω)

Polarization due to the nonlinear process in Vacuum Depends on the Focusing Optics

f/number Dependence



Intensity Dependence



Photon Number（ω: Optical Rotation and 3ω : harmonic generation）in Vacuum with High Fields

Wave equations taking account of the polarization and the magnetization due to the QED correction term in vacuum

$$\Box\mathbf{E} = -4\pi\nabla(\nabla\cdot\mathbf{P}) + \frac{4\pi}{c^2}\frac{\partial^2\mathbf{P}}{\partial t^2} + \frac{4\pi}{c}\nabla\times\frac{\partial\mathbf{M}}{\partial t},$$

$$\Box\mathbf{B} = -\frac{4\pi}{c}\nabla\times\frac{\partial\mathbf{P}}{\partial t} - 4\pi\nabla\times(\nabla\times\mathbf{M}), \qquad \Box = \nabla^2 - \frac{1}{c^2\partial_t^2}$$

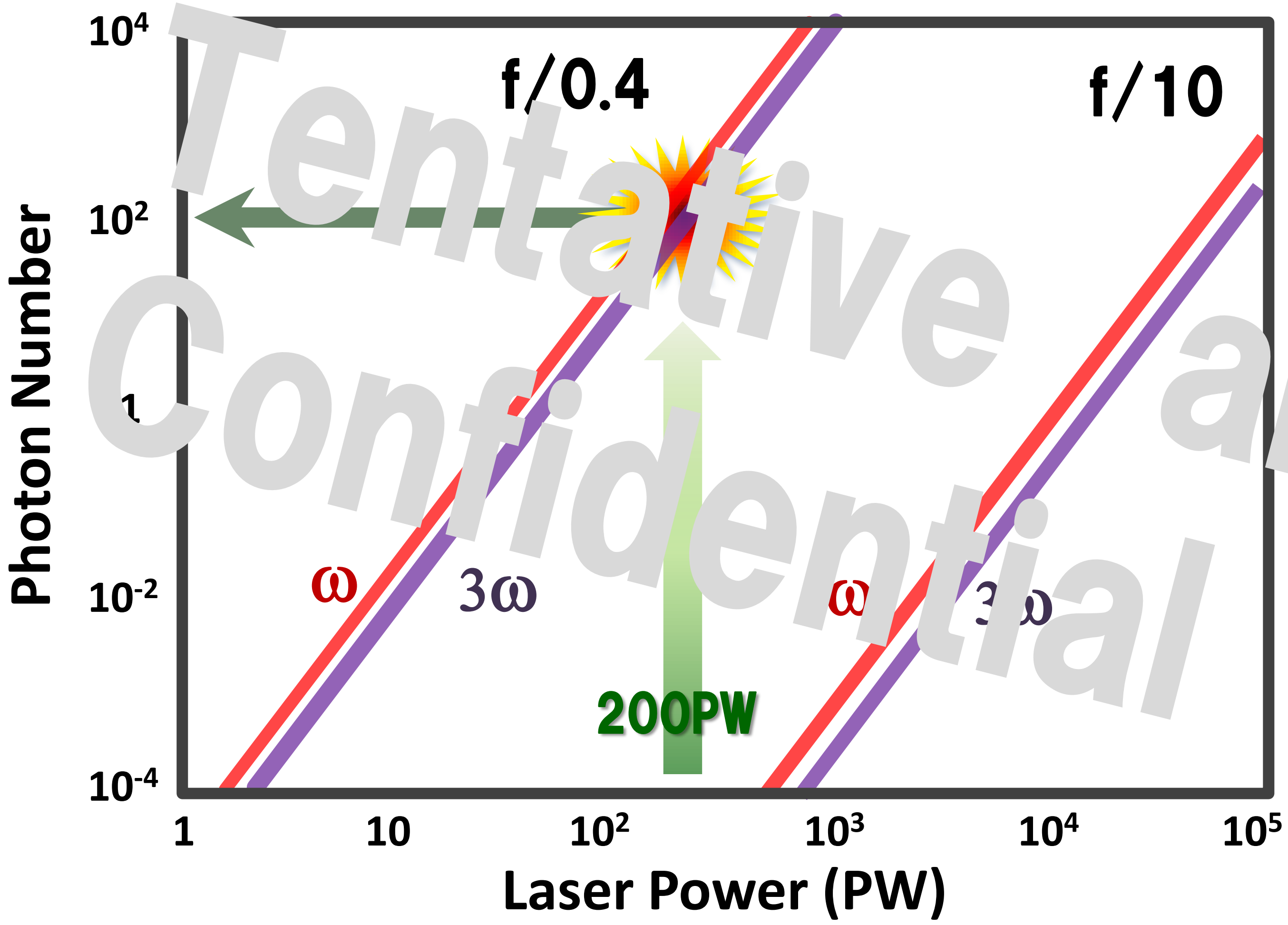
Photon Number N:

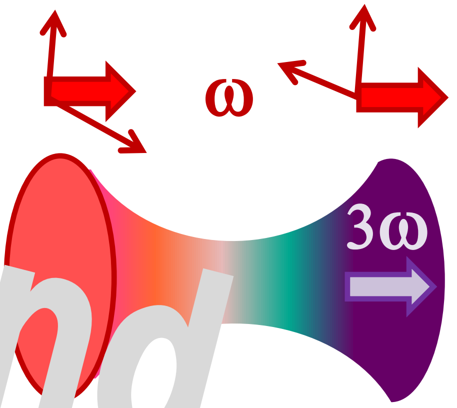
$$N \cong \frac{\tau}{\hbar\omega}\int\frac{c}{4\pi}\left|\left\langle\mathbf{E}_g \times \mathbf{B}_g\right\rangle\right| dS$$

Where E_g and B_g are solutions of the wave equations,
τ the pulse duration of the square pulse.
The area S is give by the spot size.

3ω Generated in Vacuum could be Observed with a Fast Focusing Optics and a 200PW Laser

Photon number of the ω light is counted in a focal depth, which is optically rotated in vacuum by 90 deg. Total number of 3 ω photons is counted taking account of the propagation in a focal depth.





τ_L=50fs

Contents

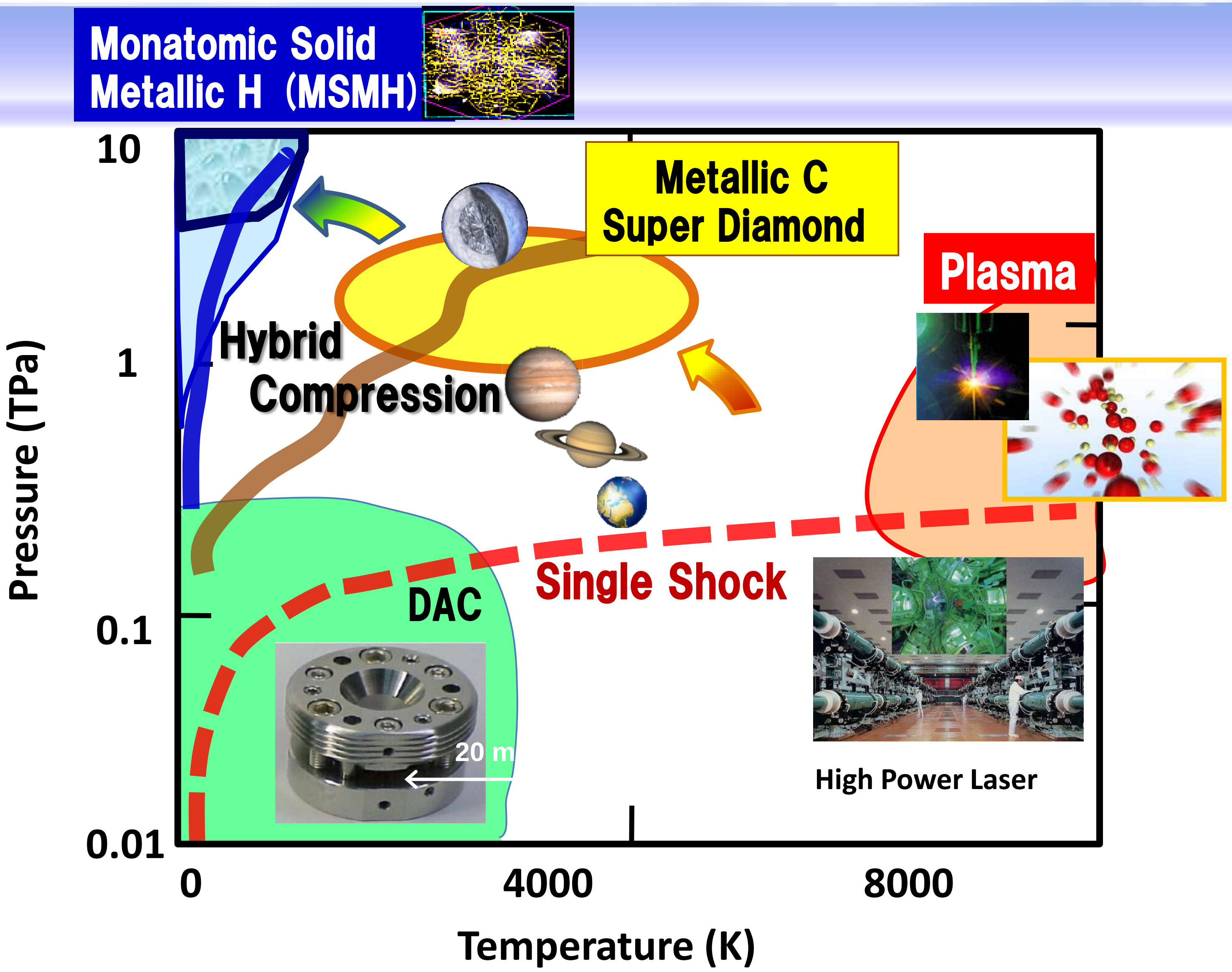
☞ High Energy Density Sciences

☞ High Energy Plasma Photonic Devices for Nonlinear Optics in Vacuum

☞ **High Energy Density Solid Matter**

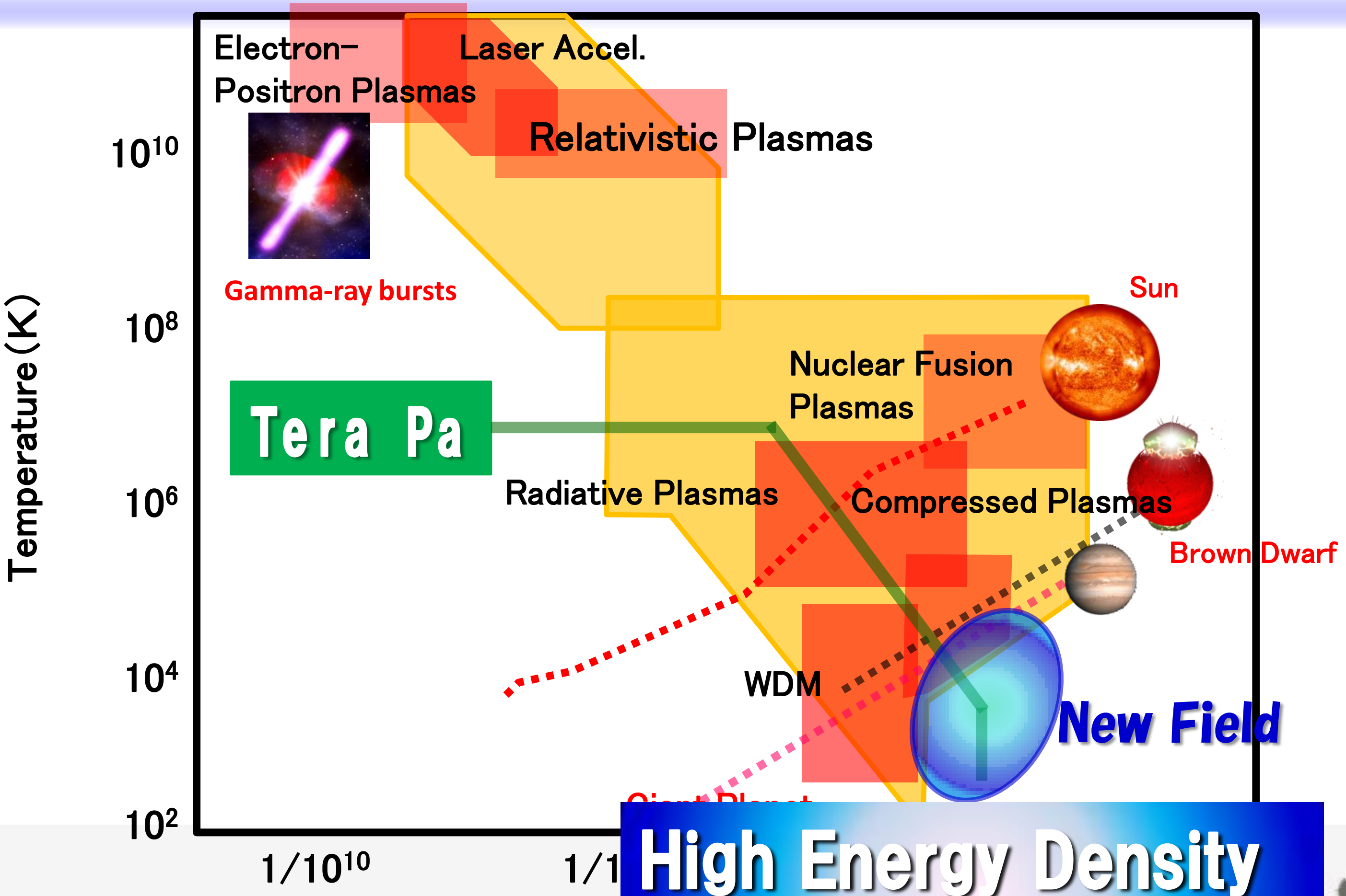
- Super-Diamond & Solid Metallic Hydrogen
- Compression and Probe Techniques

Approach to Higher Pressures with Lower Temperature for Novel Matter States



Exploring of High Energy Density Solid States with High Power Lasers

Spatial Scele:μm – a few 100μm; Time Scale:fsec – a few nsec



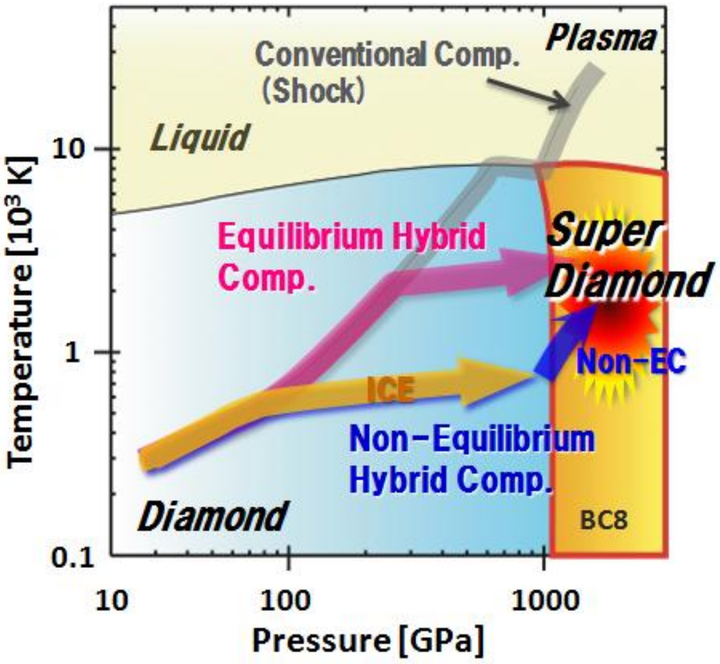
High Energy Density Matter and Material

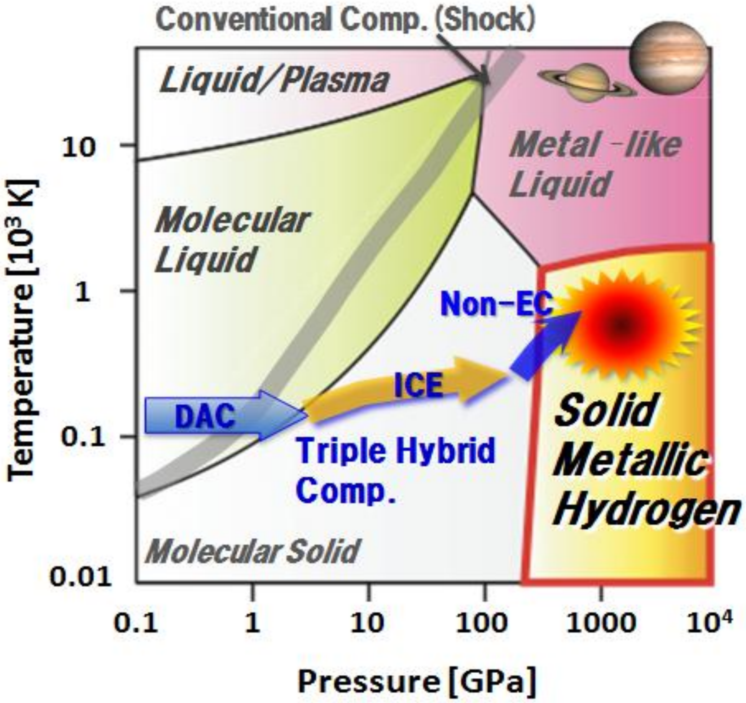
e. g. 100MA

Exploring of High Energy Density Matter as New Material

- **Super Diamond, which is harder than Diamond**
- **Solid Metallic Hydrogen（quantum solid, superconductor)**

Those material have never been observed on the earth, whereas the metallic hydrogen have been predicted end of 19th century.

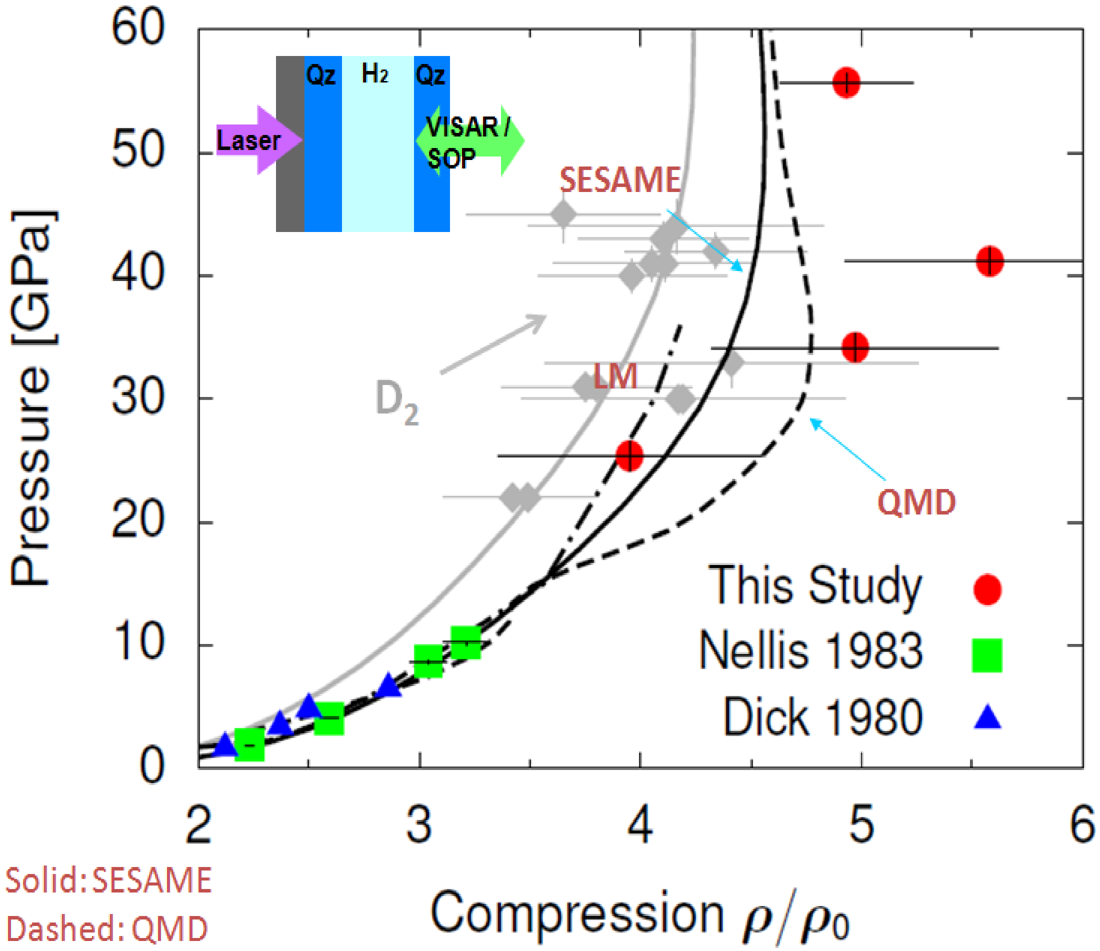




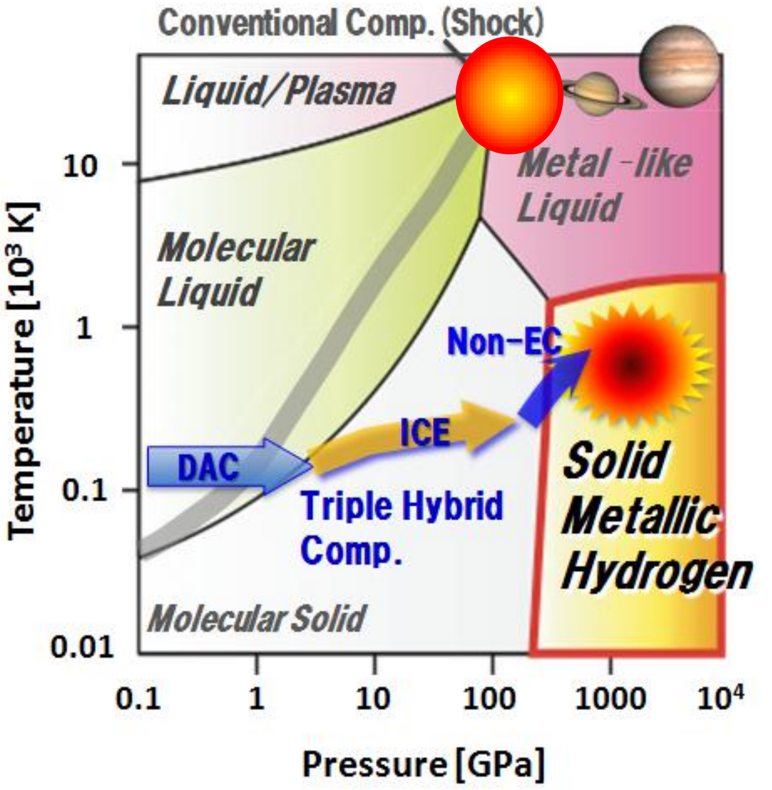
**High power laser can easily create high pressures of more than TPa.
Only a plasma or liquid phase has been produced at such high pressures.
Now we are approaching the solid phase in the TPas regime.**

Isotope effect is probed in High Pressured Phase between H_2 and D_2

Principal shock compression curve for Liquid H_2



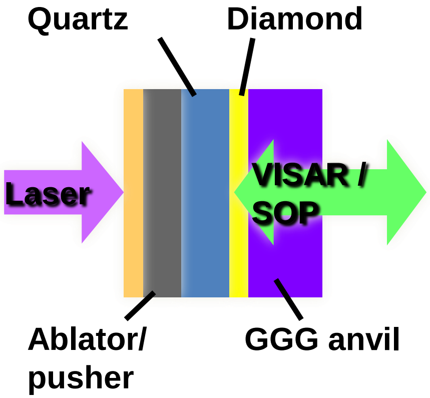
Solid: SESAME
Dashed: QMD
Dot-dashed: Linear Mixing

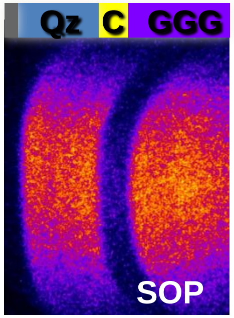


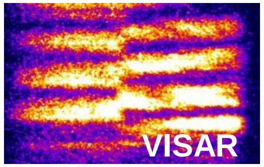
Submitted to PRL

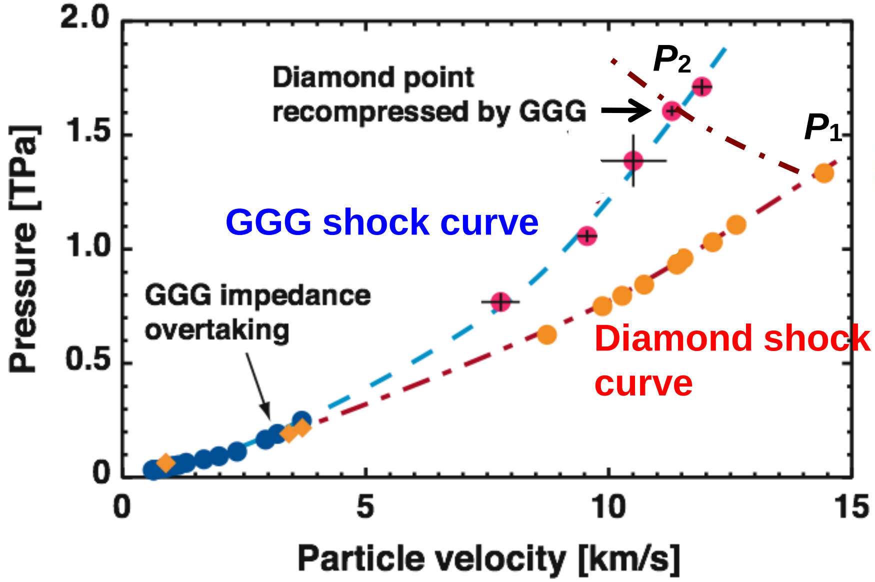
Re-shock with New High Impedance Material (GGG) could Access Super-Diamond i.e. >TPa with < 10,000 K

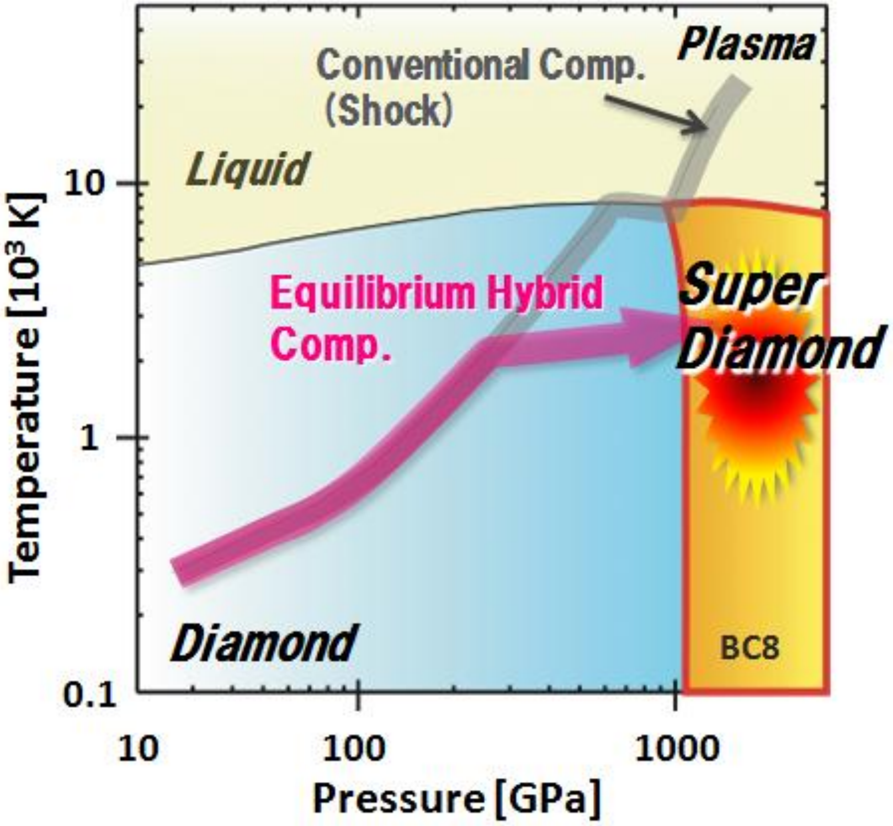
Diamond was re-compressed with an higher impedance material (GGG) than diamond to be > TPa, for the fist time.







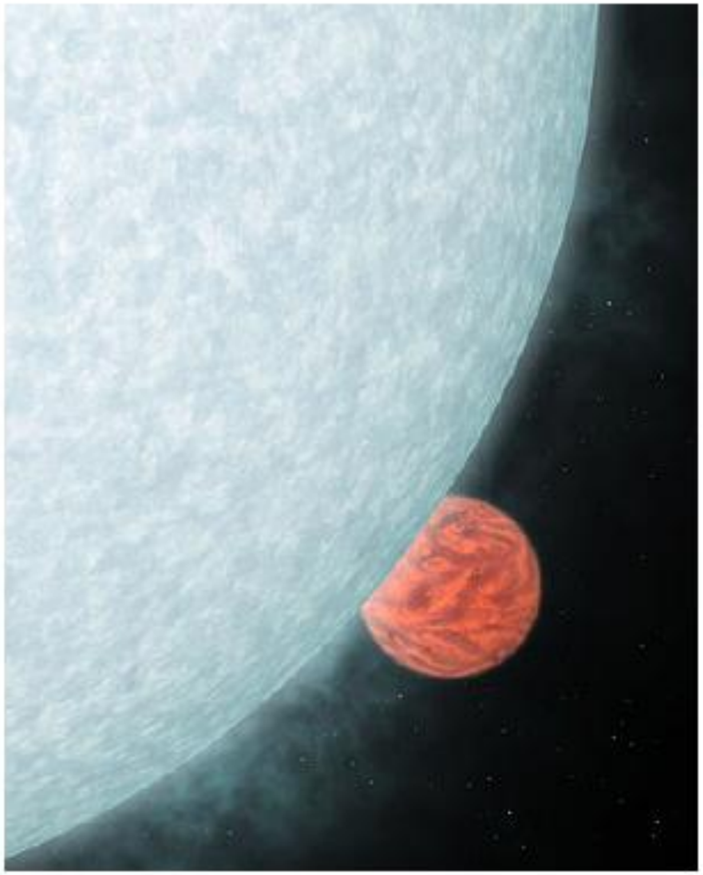




Super-Terra on the Earth

Super-Terra ex GJ 876d M = 7.5M_{Earth}

Rivera et al. 2005, Valencia et al. 2007



Artist's concept of an extra-solar planet moving behind its parent star. *Credit: NASA/JPL-Caltech/R. Hurt (SSC)*

Massive extrasolar Earth-like planet (GJ 876d)

CMB P =1100 GPa T = 5000K

Center P = 3400 GPa T = 7000 K

New dense structures ?

Silicates or oxides metallization ?

Structure and physical properties of iron and alloys

Diamond cores

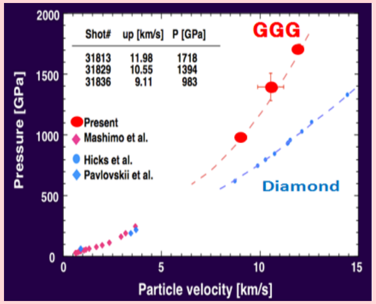
Osaka PhoPs

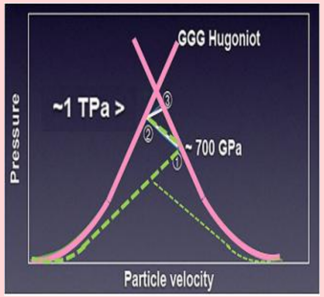
2 Ways for Super Diamond : Re-shock comp. and Equilibrium/non equilibrium hybrid comp.

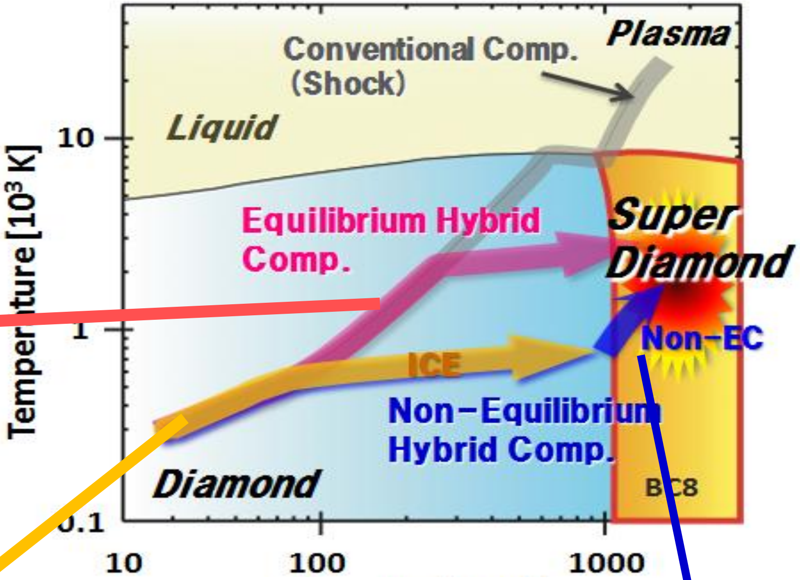
HEDS

1. Dynamic Compression with Multiple Shock

Demonstration of a GGG Anvil to Compress Diamond (higher impedance)

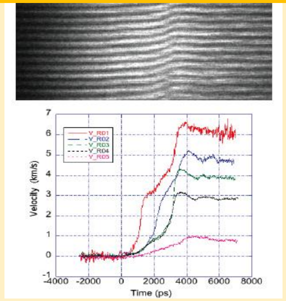


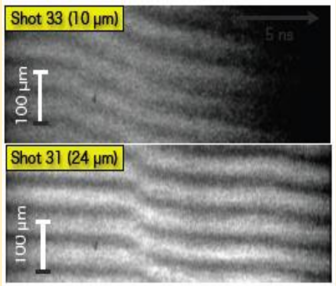




2. Pre compression to the phase transition region keeping low entropy + Non Equilibrium Compression for the phase transition

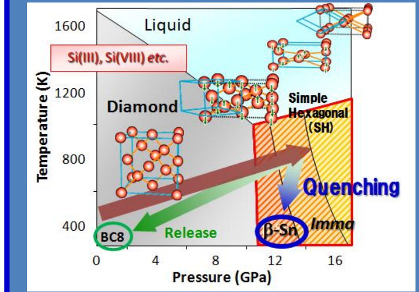
ICE: Dynamic Isentropic Compression with pulse tailering(a fe 100GPa)

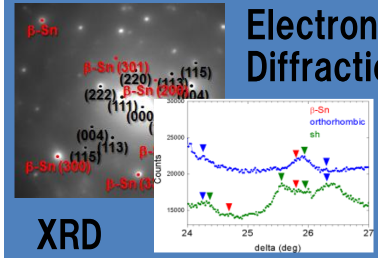




+

NEC: Non Equilibrium Compression for Quenching (Metallic Si)

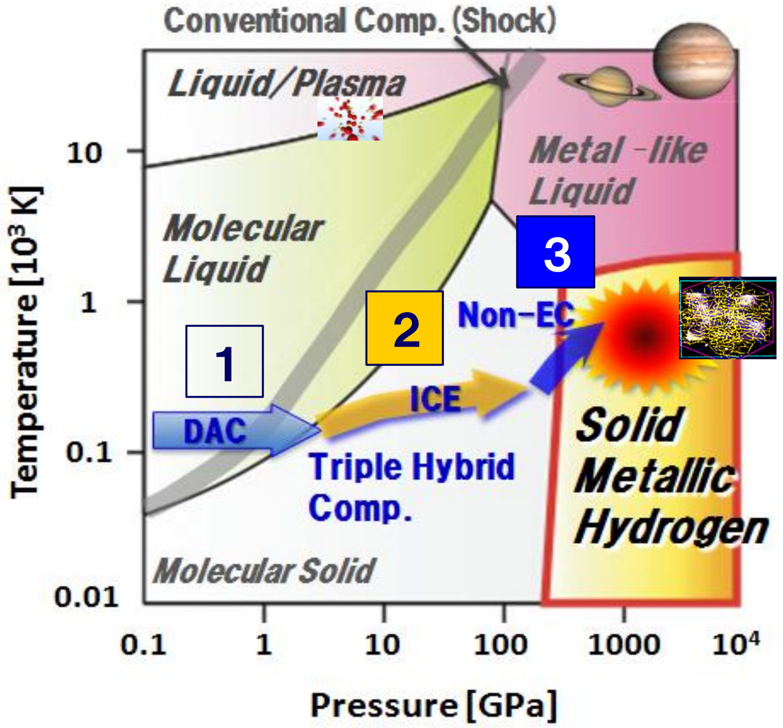




Electron Diffraction

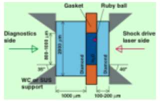
XRD

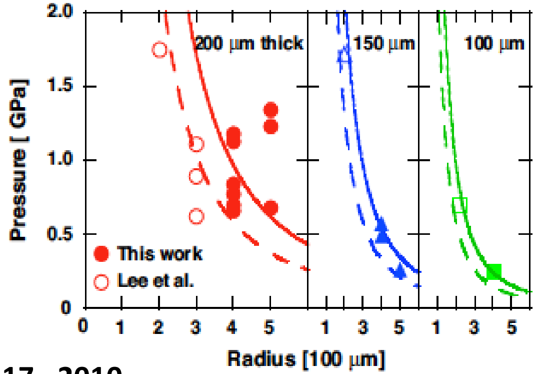
3 step Hybrid Compression to realize solid Metallic H
: static-Isentropic dynamic-non equilibrium comp.

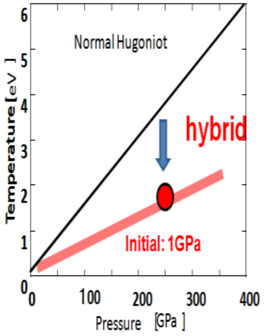


1. Static compression Tech. for Laser comp.

Development f DAC with wide irradiation area





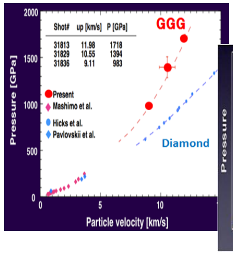


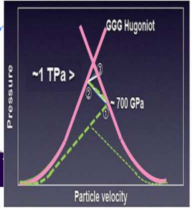
Phy. Plasma 17, 2010

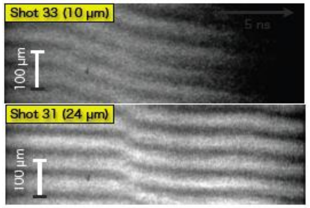
2. Isentropic dynamic comp.

Re shock comp.

Tailored pulse laser and Ramp comp.





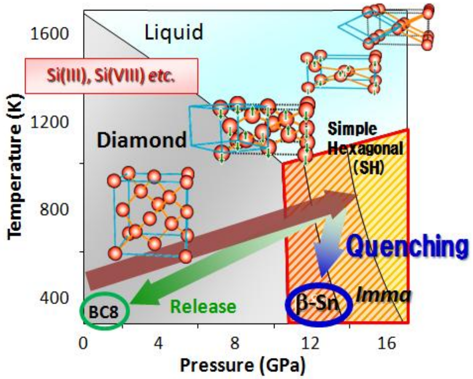


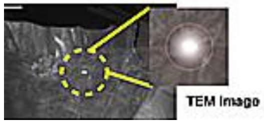
Phys. Rev. Lett. (2006).

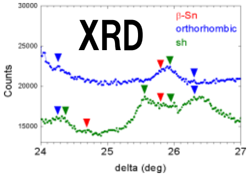
J. Phys. (2010).

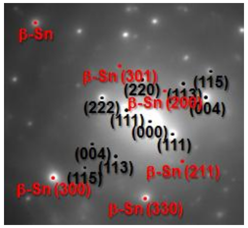
3. Non Equilibrium Comp. for Quenching

Demonstration of Quenching of Metallic Si







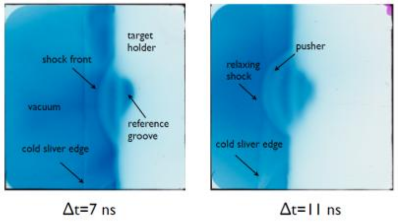


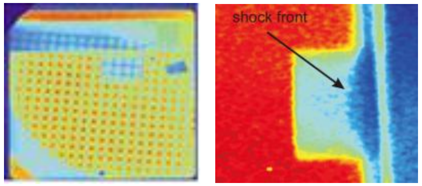
E-Diffraction

Investigation of Phase Transition under High Pressure with Micro-Macro Dynamic Probing

Dynamic Probing of Macro Phenomena

- Dynamic shadow imaging of a compressed region with a pulse x-ray and proton beam using laser and PPD

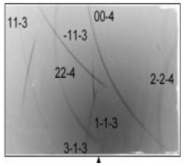


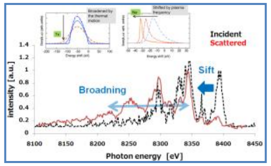


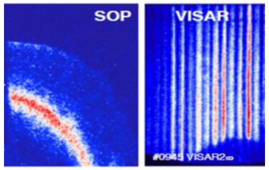
Phys. Plasmas **16**, 033101 (2009)

Dynamic Probing of Micro Phenomena in Macroscopic.

- Lattice structure, Grain size, Electron distribution function from XRD, WAXS and SAXS using radiation sources with laser and PPD





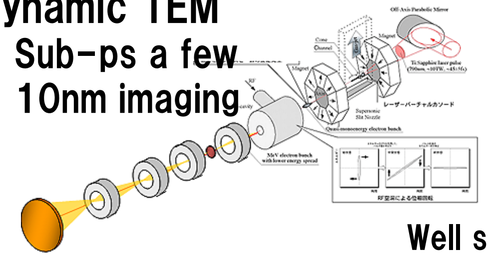


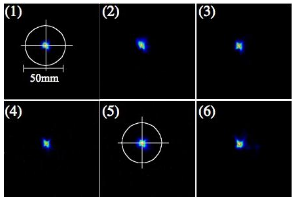
Dynamic Direct Probing of Micro Phenomena

(under developing)

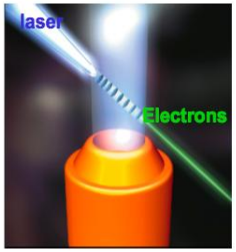
Dynamic TEM

Sub-ps a few 10nm imaging



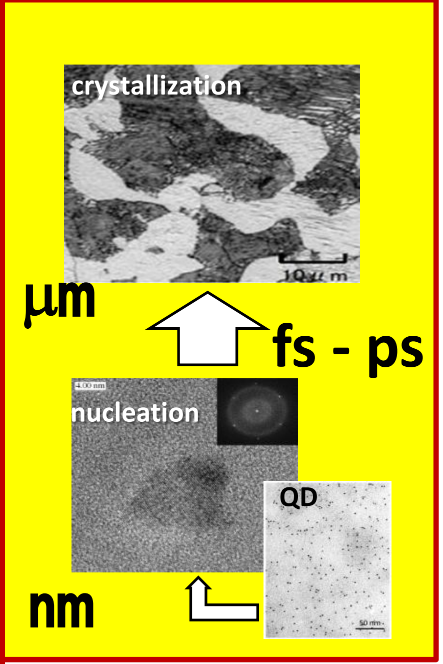


Well stable laser acceleration



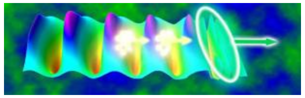
Micro/Macro Dynamic Probing

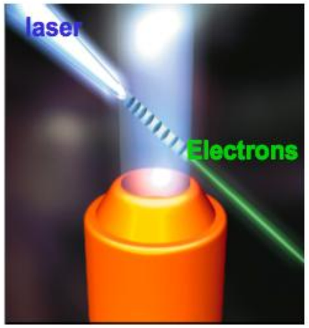
Phase transition dynamics under high pressures

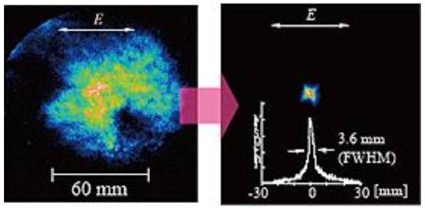


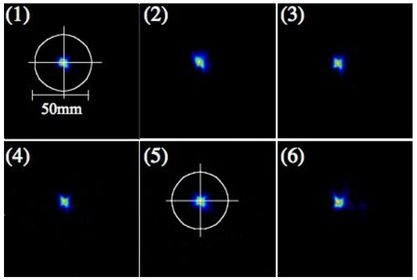
Dynamic Direct Probing of Micro Phenomena with Super TEM (under deveopling)

(DyTEMSHI: Dynamic Transition Electron Microscope Innovation System)



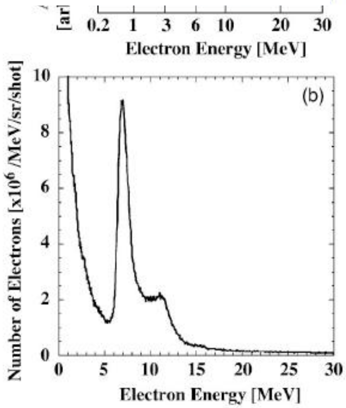




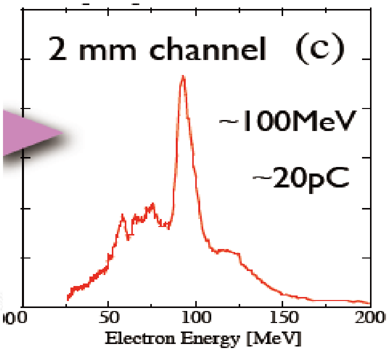


Well-stable and bright monochromatic MeV Electron-beam

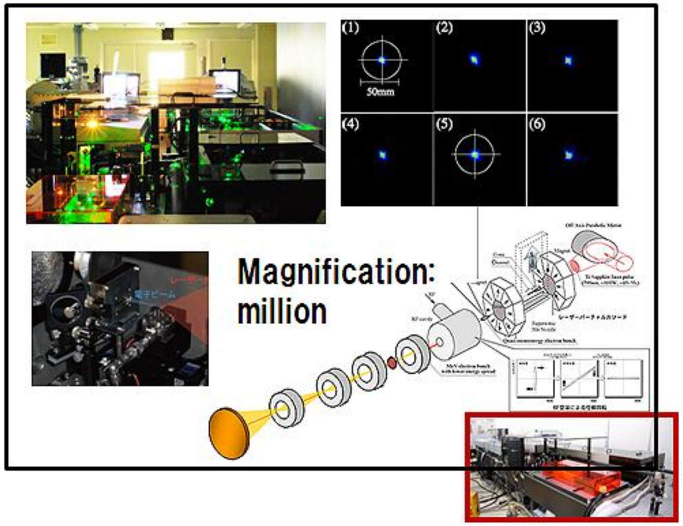
Small Dynamic TEM (a few 10 nm)
+ α (high speed phenomena: a few 10fs)
+ β (random transient phenomena)



E. Miura (AIST)et al.,
Appl. Phys. Lett. (2005)



T. Hosokai et al.,
Phys. Rev. Lett. (2006)



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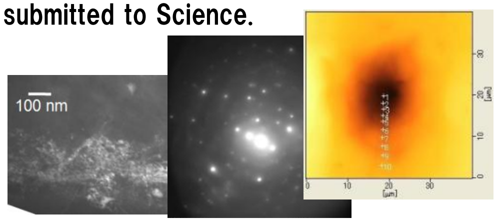
Large Scale TEM
(MeV e-beam)

Creation of High Energy Density New Material with Laser-Dynamic Compression

2010 2015 2020

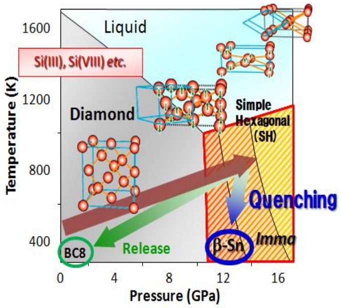
Quenching Model of High Pressure States

Demonstration of Metallic Si
submitted to Science.



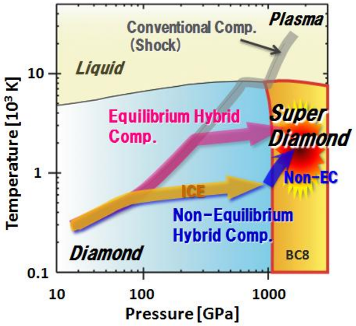
Quenching Mechanism

Si



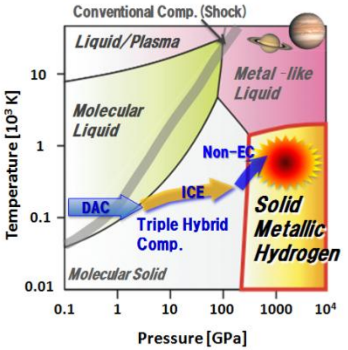
Super Diamond

C: diamond



Solid Metallic Hydro.

H



Non Equilibrium Hybrid Compression

Compression ratio ρ/ρ_0 ~1.2 > ~2 > ~4 (20)

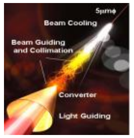
~10 GPa
< 1000 K

~1 TPa
< 5000 K

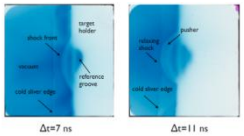
~1 TPa
< 1000 K

Micro-Macro Dynamic Probing with Radiation Sources

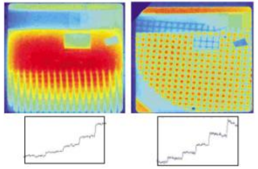
Electron Beam



Proton Beam



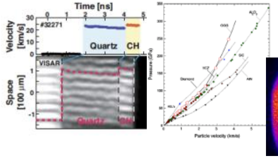
Pulse X-ray



Nature 2004
Phys. Rev. E 2009
Phys. Plasmas 2009
Phys. Rev. E 2010

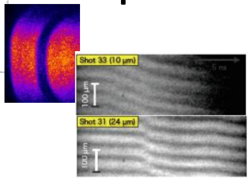
with Isentropic Comp. (ICE)

Multiple shock



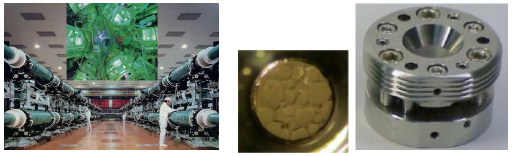
Phys. Rev. Lett. 2006
Phys. Plasmas 2009
accepted in J. Phys. 2009
Phys. Rev. Lett. 2010

Isentropic Compression



with Diamond Anvil cell Comp.

Large area Anvil cell for laser comp.



Phys. Plasmas 2009
Rev. Sci. Instrum. 2010

Summary

Two topics has been presented as a front edge of the high energy density sciences with high power lasers

☞ **Nonlinear optics in vacuum** using plasma photonic devices such as a plasma focusing mirror.

- Study on nonlinear optics in vacuum would be realized with a few 100PW laser and plasma focusing mirror in 10 years.

☞ **High Energy Density Solid Material** such as super diamond and solid metallic H, which is realized in high pressure (Tera Pa) at relatively low temp. (< a few1000K).

- We have all technologies such as compression, quenching and probing to realize the new material.
- In 10 years, we are approaching the solid metallic hydrogen or the ultimate metal with high power laser.