Laser Fusion Research with GEKKO XII and PW Laser System at Osaka

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Outline

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1) Fast ignition experiment by cone-shell target

2) FIREX project and a new heating laser 10kJ, PW LFEX

3) Toward FIREX
 - code development
 - basic experiments on hot electron transport
 - suppression of Rayleigh-Taylor instability

4) Summary

Fast ignition concept is attractive, because a high gain is expected by small size laser

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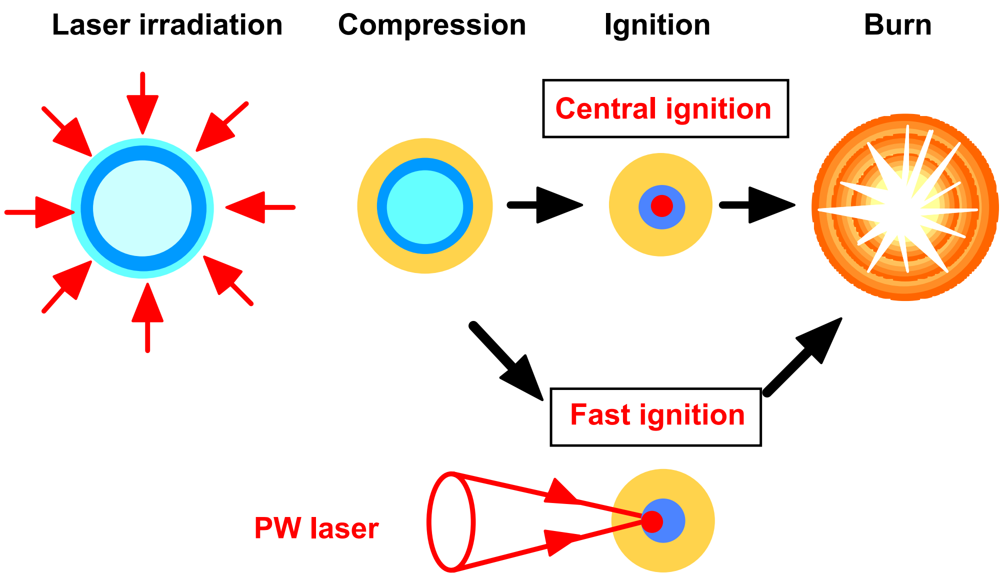
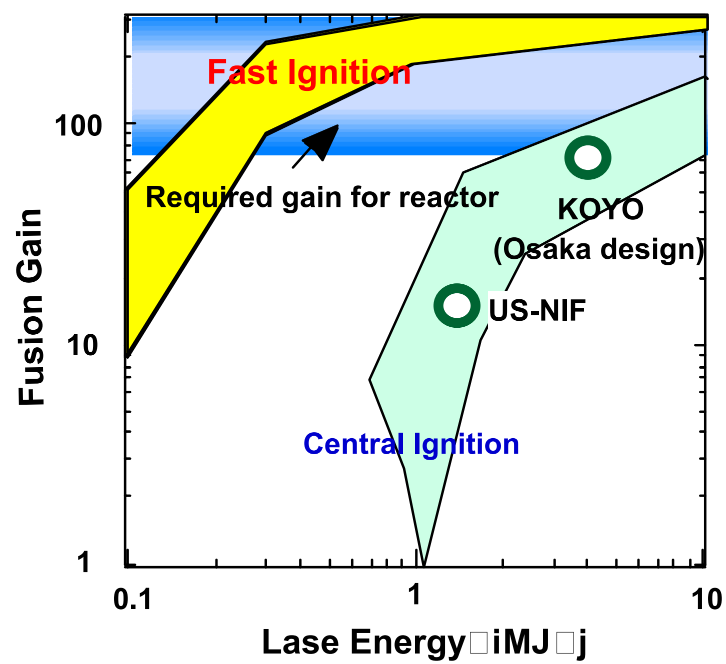
In fast ignition, a highly intense laser is injected into a compressed fuel.



Fast heating of compressed fuel to create a hot spot at its edge



Fast ignition requires to deliver ultra-intense heating pulse close to the core.

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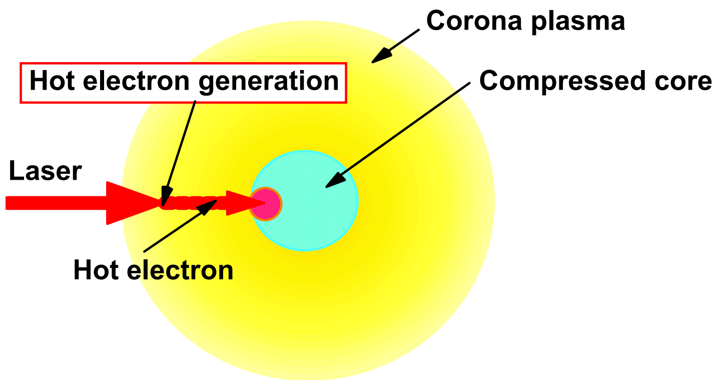
Critical issues in fast ignition: Efficient heating of the core plasmas overcoming the nonlinear interactions with the long scale plasma surrounding the core.

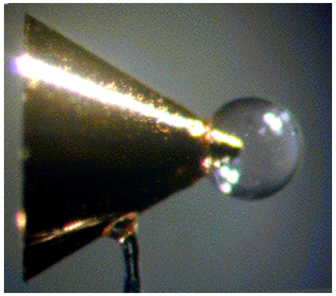
- **Hole boring and heating by separate laser pulses**
  K. Fujita et al., SPIE 4424, 37 (2001)

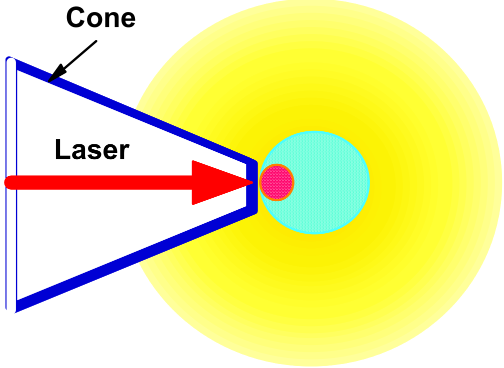
- **Hole boring and heating by one laser pulse**
  Y. Kitagawa et al., submitted to PRL (2004)

- **Cone-guiding: cone-shell target**
  R. Kodama et al., Nature 412, 7989 (2001),
  R. Kodama et al., ibid. 418, 933 (2002)



A hollow cone prevents the heating pulse from nonlinear interactions as well as energy loss in long scale length plasmas. The heating pulse can be injected to the position very near to the compressed core.





Is the high density compression possible by non-symmetry cone-shell target?

High density compression was realized with the cone-shell target.

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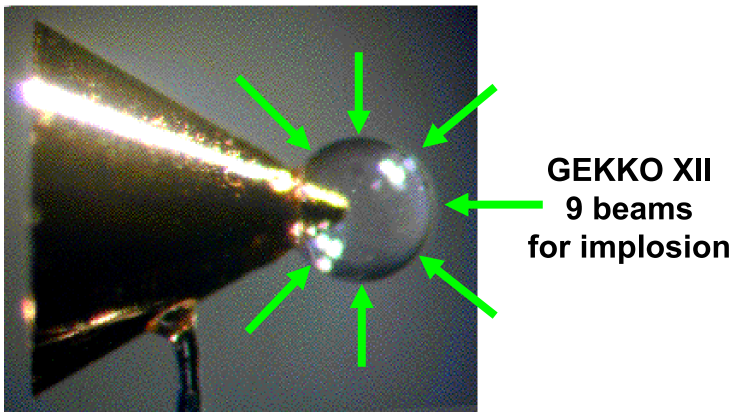
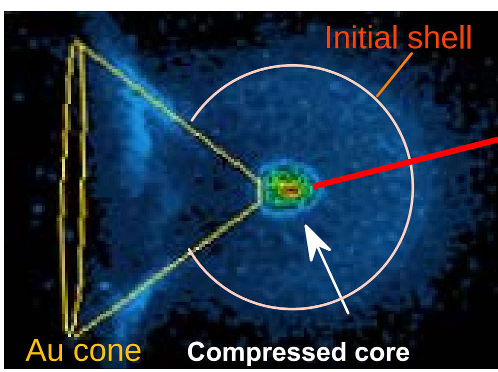
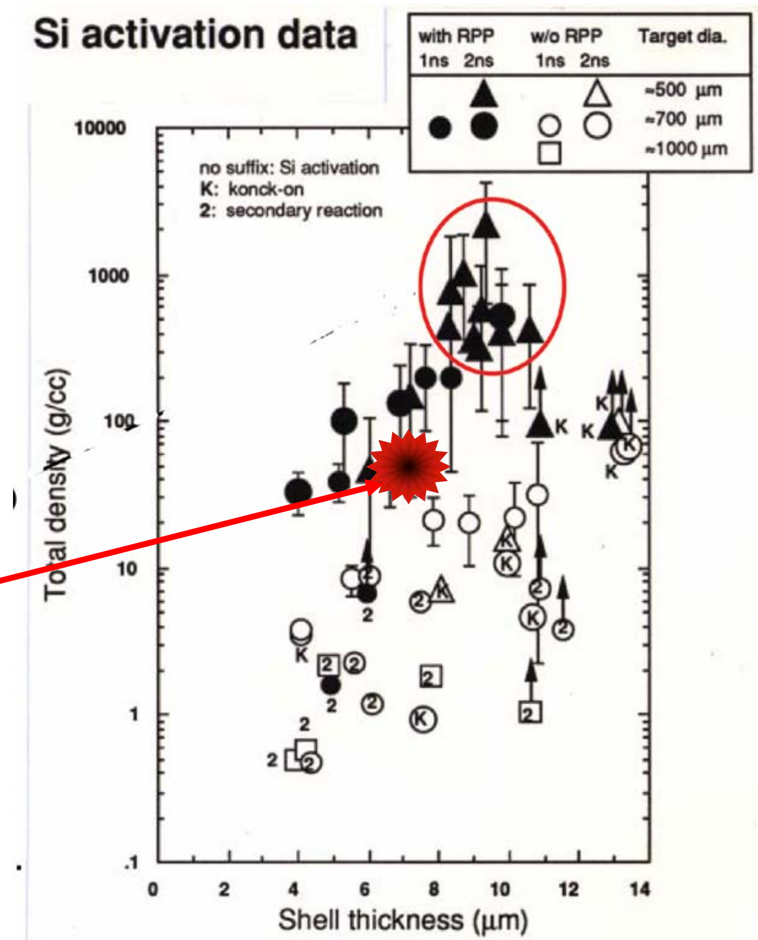
The compressed density obtained with the cone-shell target could be consistent with the scaling of the 1000 times compression with spherical shell targets.



Cone-shell target (CD plastic shell)



X-ray image of compressed core



R. Kodama et al, Nature 412, 798 (2001)

Fast ignition experiments by the PW laser demonstrated the heating efficiency of 20%.

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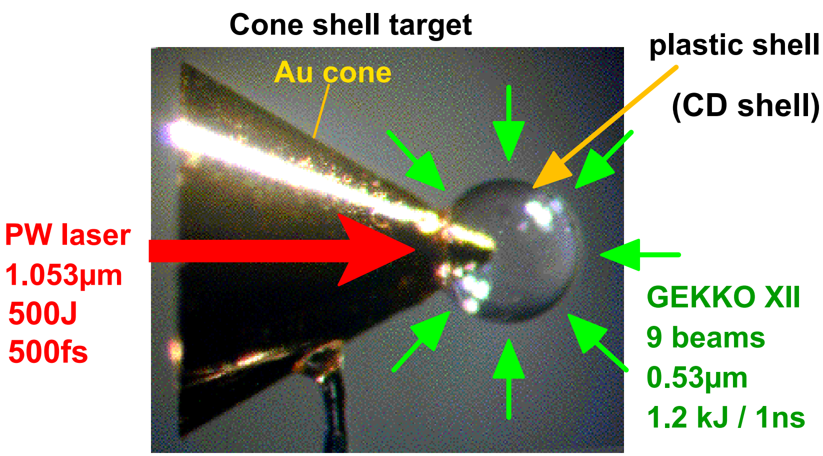
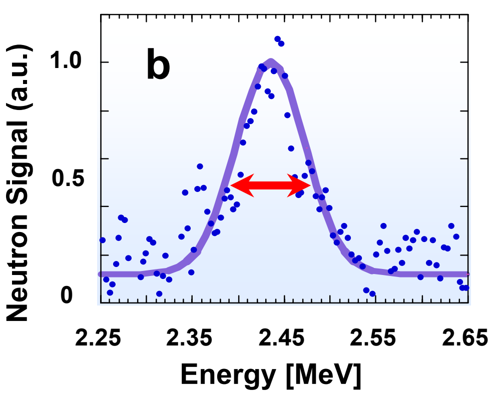
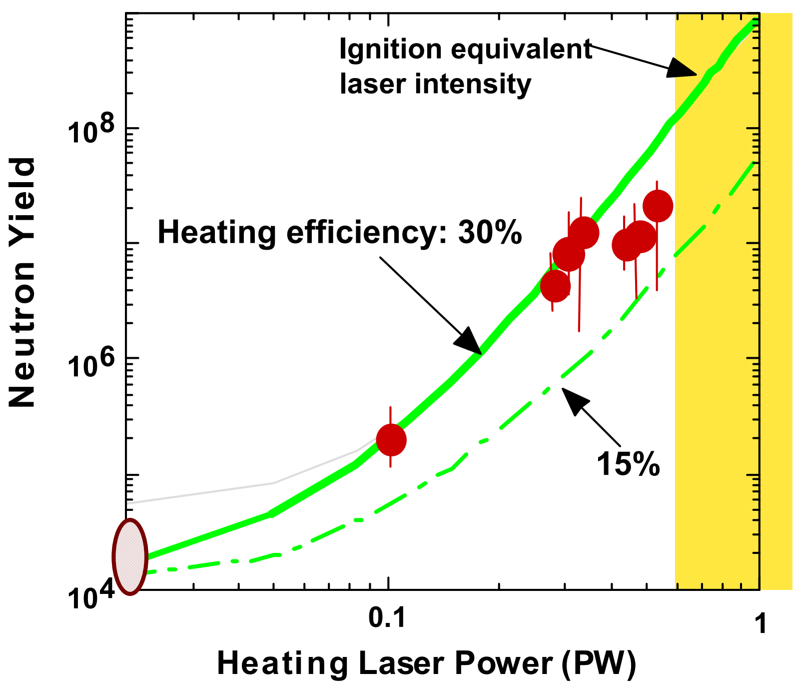




Neutron time-of-flight

Enforced heating was realized at a heating power equivalent to the ignition condition.

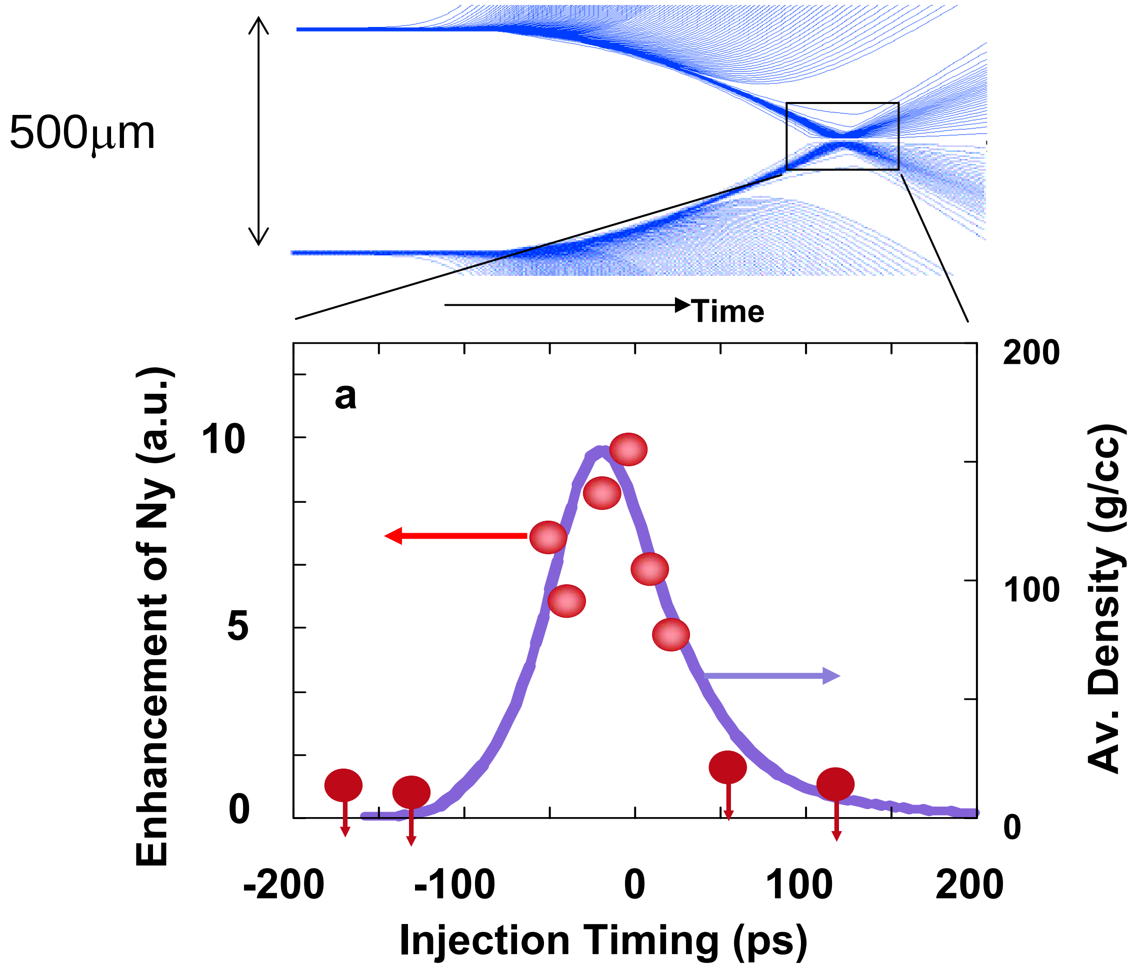


FWHM: 90±5keV keV
Resolution:50 keV

→ **0.86 ±0.1 keV**

Enhancement of neutron yield indicates that the fast heating is possible during the stagnation.

Heating was realized in the time duration of less than 100ps at near the maximum compression.



FIREX : Fast Ignition Realization Experiment

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1995 - 1999
- GEKKO MII CPA (25J, 0.4ps, 60TW)
- PWM laser (70J, 0.7ps, 100TW)

    Elementary physics related to fast ignitor (laser hole boring, super-penetration, MeV electrons, Self-guiding, Cone-guiding)

1999 - 2002
- PW laser (700J, 0.7ps, 1PW) + GEKKO XII

    Heating of imploded plasma up to 1keV by cone-guiding

2003 - 2008 : FIREX-I (Phase 1)
- New heating laser (10kJ, 10ps, 1PW) + GEKKO XII

    Heating of cryogenic target to 5 ~ 10keV

2009 - 2014 : FIREX-II (Phase 2)
- New compression laser (50kJ, 350nm) + Heating laser (50kJ, 10ps)

    Ignition and burn, gain ~ 10

LFEX (10kJ, 1PW) for FIREX-I is under construction.

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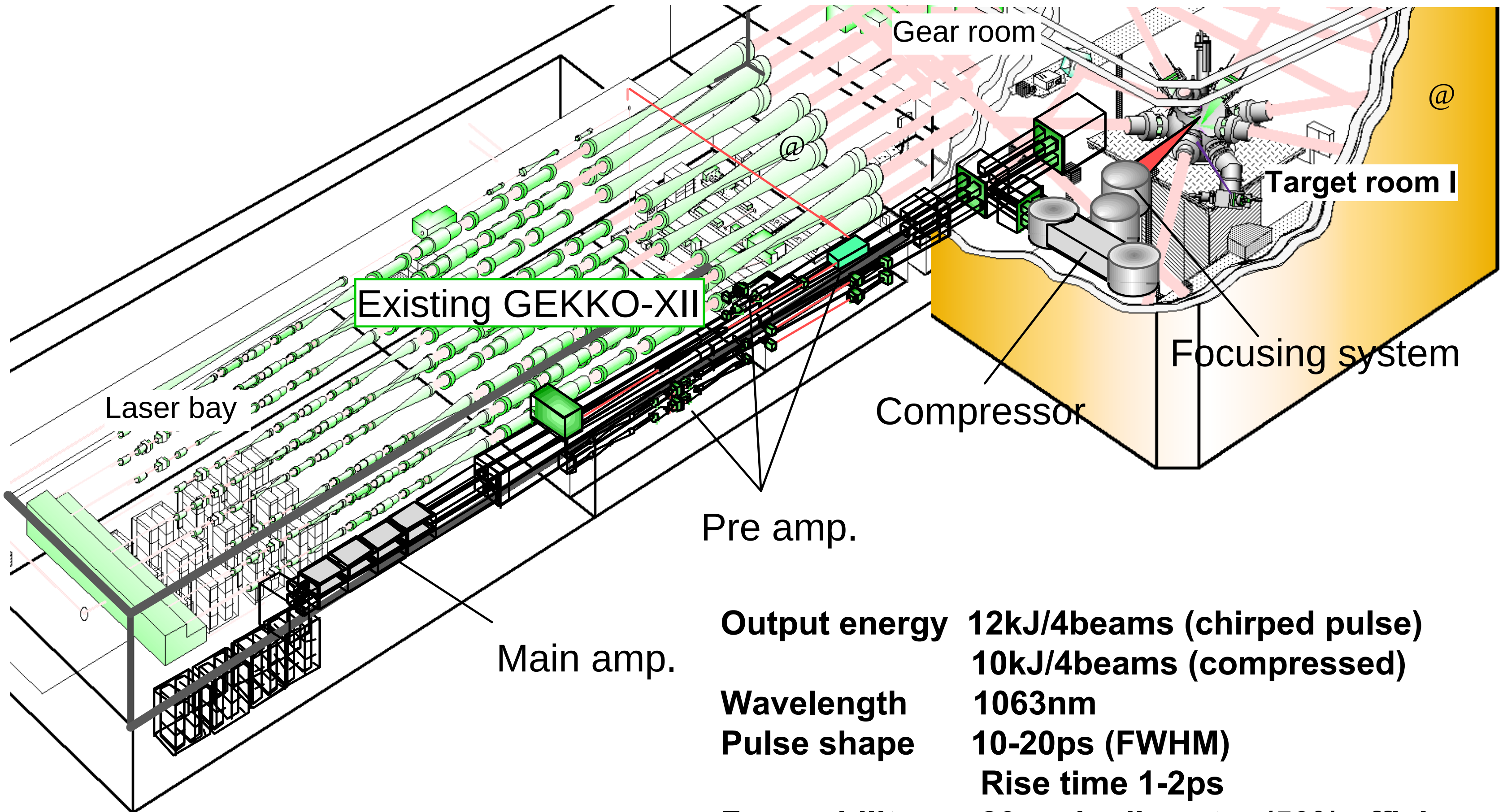

Output energy	**12kJ/4beams (chirped pulse)**
	10kJ/4beams (compressed)
Wavelength	**1063nm**
Pulse shape	**10-20ps (FWHM)**
	Rise time 1-2ps
Focusability	**20μm in diameter (50% efficiency)**
Prepulse	**$< 10^{-8}$**

Basic configuration of 10 kJ, PW laser

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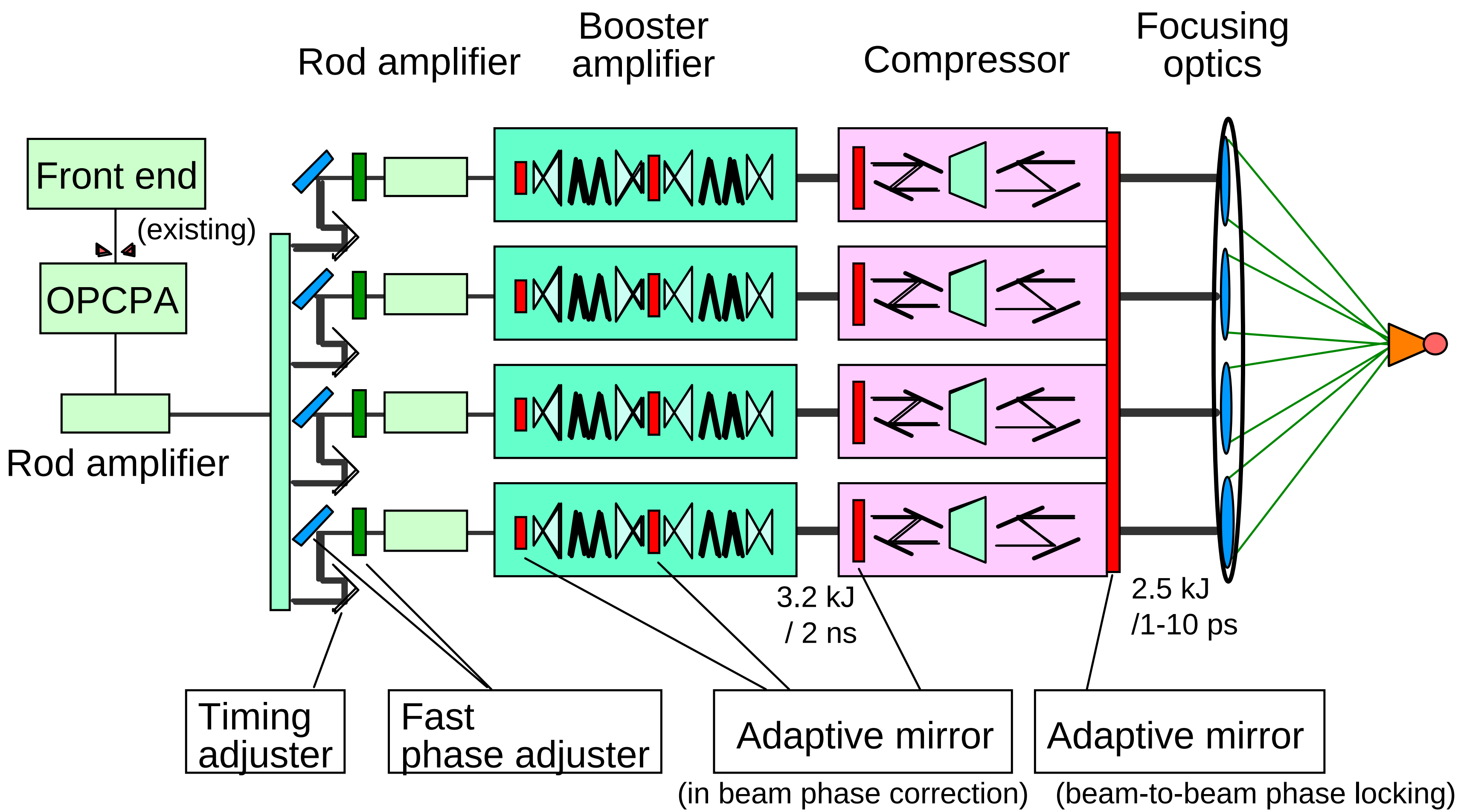
- 4 pass booster amplifier with angular multiplexing
- adaptive optics for precise phase control
- arrayed dielectric grating in large scale
- 4 beam combining to a single focal spot



Beam path of 4-pass amplifier by angular-longitudinal multiplexing

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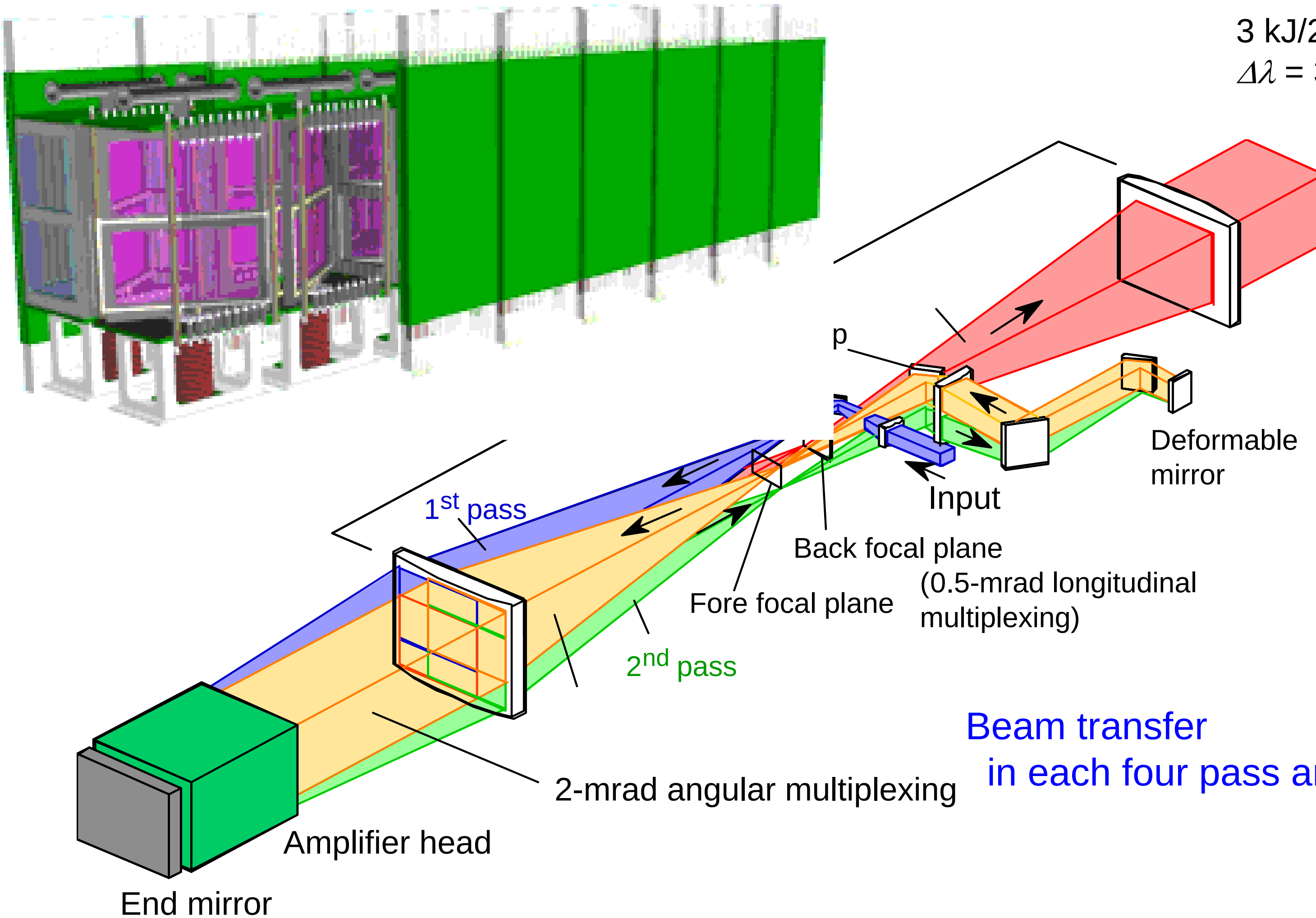
2x2x8 disk amplifiers
Beam size: 40 x 40 cm in each beam



3 kJ/2.3 ns
$\Delta\lambda$ = 3 nm

Beam transfer
in each four pass amplifier

Main amplifier chain for LFEX

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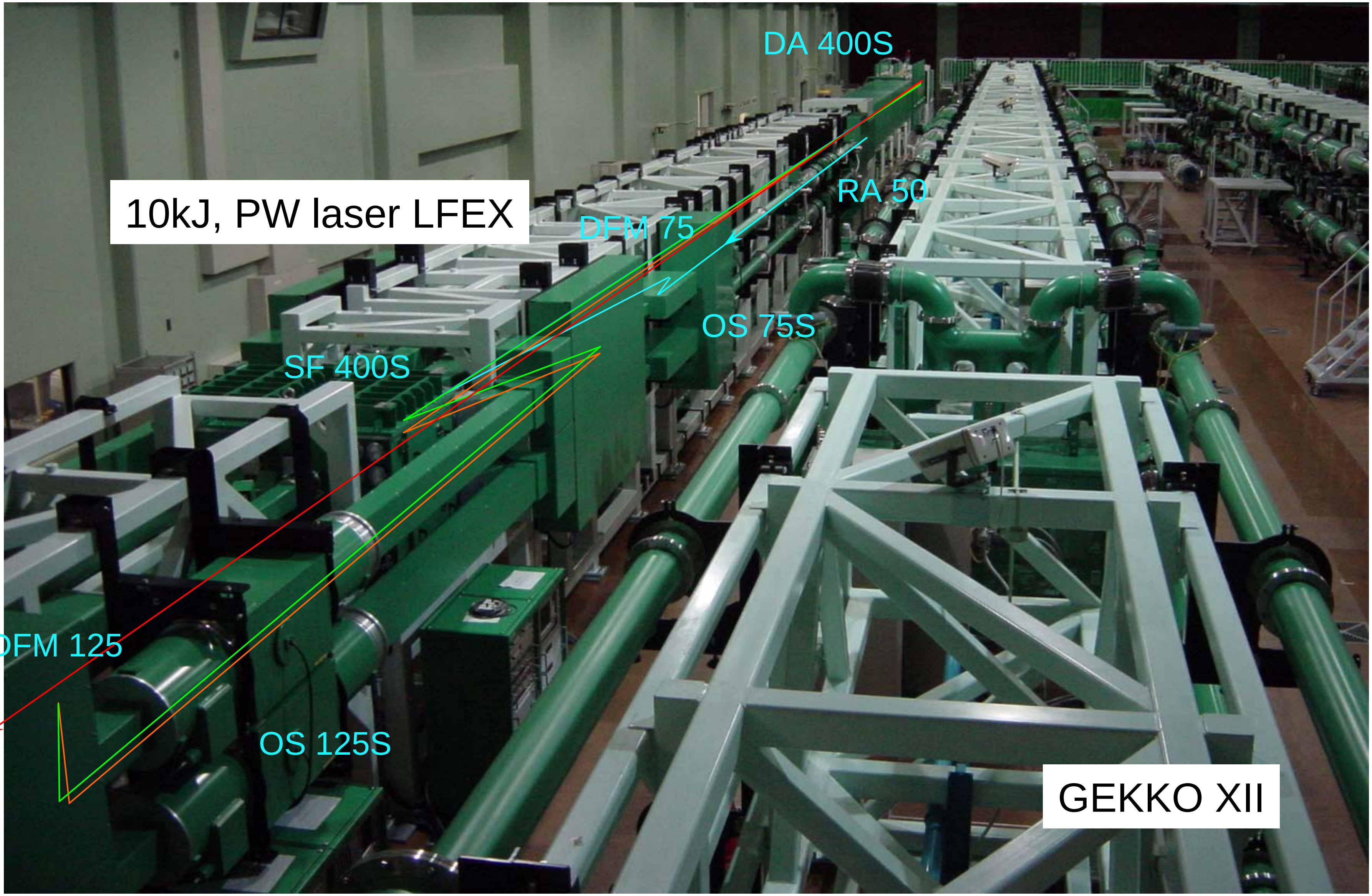
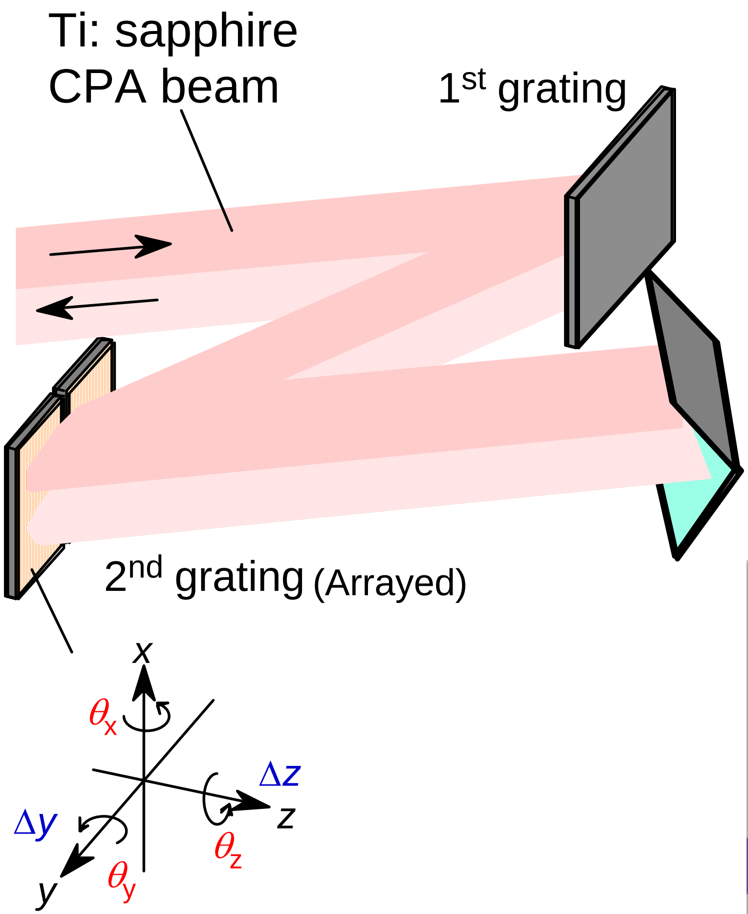


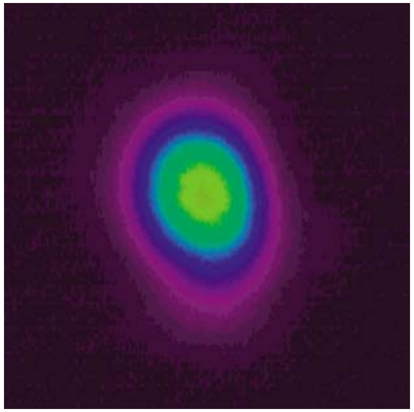
Test of arrayed grating started.

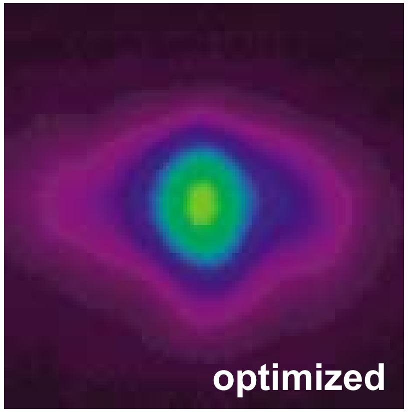
Preliminary experiment



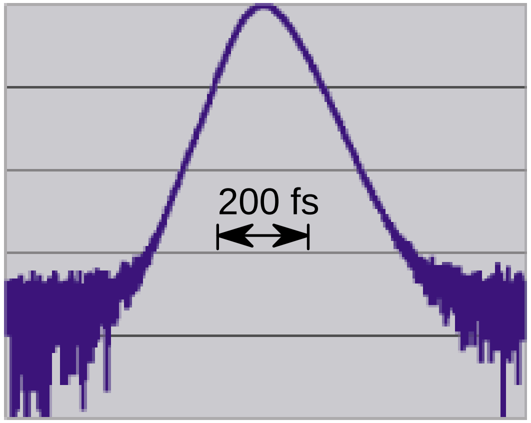
Monolithic grating | **Arrayed grating**

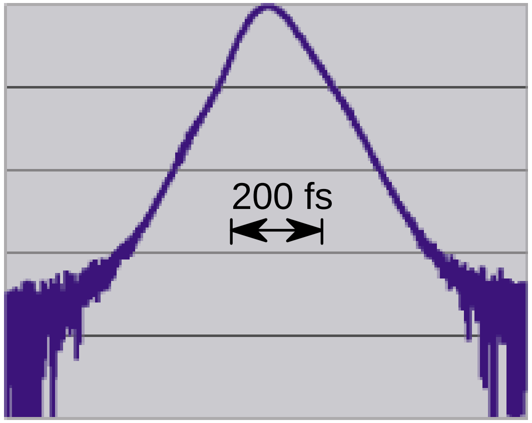
Far-field pattern





2nd order auto correlation trace





Layout of beam combining / focusing optics

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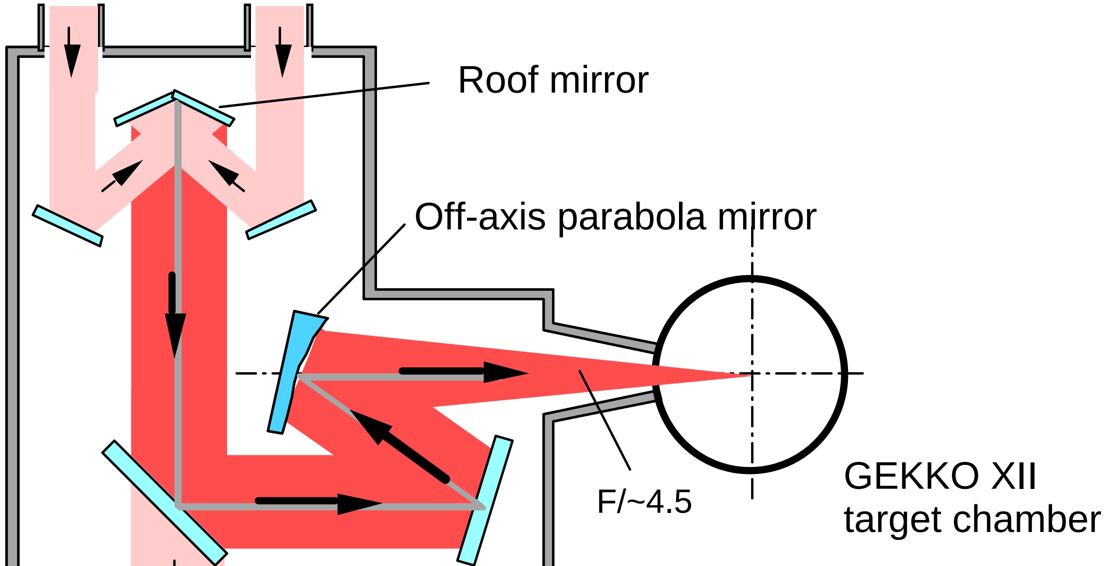
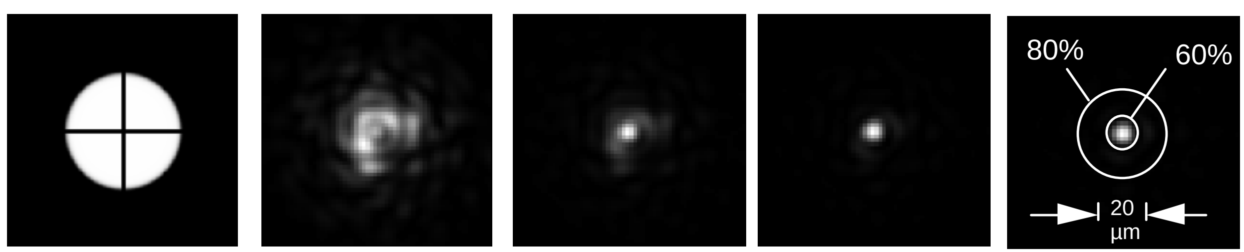


Beam monitor

Beam combining/focusing geometry depends on the possible performance of a large-aperture parabola mirror.

Single-beam phase aberration
$\lambda/5$
Beam-to-beam phase jump
$\lambda/5$



d = -160 µm | -110 µm | -55 µm | 0 µm

□**Phase control less than $\lambda/5$ is required for high focusability.**

FI³ (Fast Ignition Integrated Interconnecting) Code was newly developed. (→ IF/P7-29)

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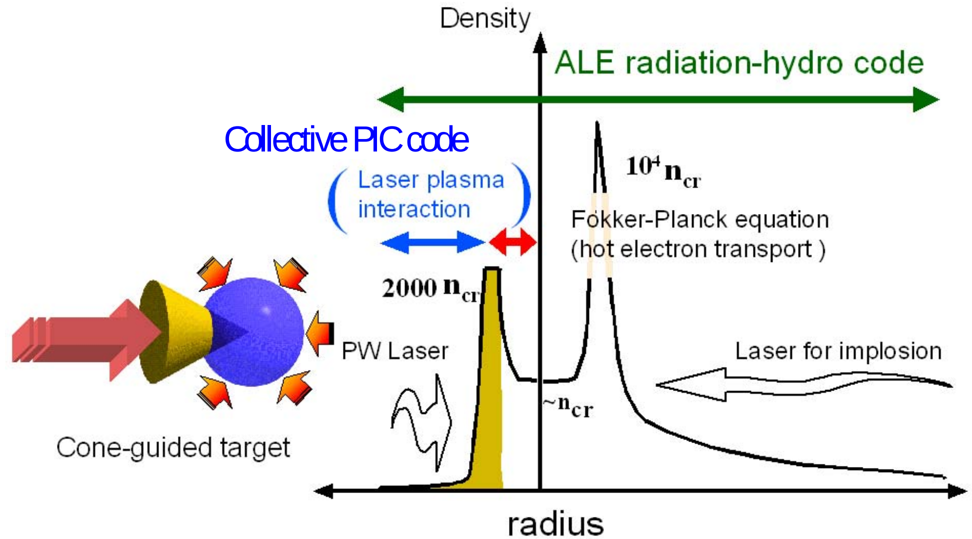
• The cone-guided implosion dynamics is calculated by PINOCO. and the mass density, temperatures, and other profiles calculated by PINOCO are exported to both collective PIC and RFP-hydro code for their initial and boundary conditions.

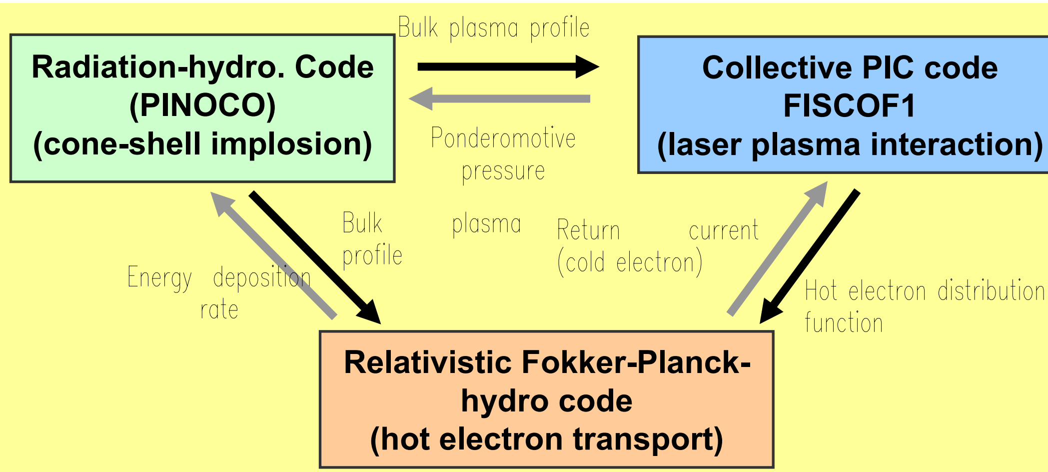
•The relativistic laser plasma interaction inside the cone target is simulated by collective PIC code FISCOF1, which exports the time-dependent energy distribution of fast electron to REP-hydro code.

• The fast electrons calculated by the FISCOF1 are exported to the RFP-hydro code. Therefore, the core heating process is simulated using both physical profiles of imploded core plasma and fast electron as the boundary conditions.

•Those numerical codes are executed on the different computers via DCCP, TCP/IP network communication tools.

The first numerical fast ignition simulation was performed to demonstrate the FI³ and to investigate the GXII experiment.





Data flow in FI³ system. (Black arrows are already executable data flows, and gray arrows are next plan to be considered.)

H. Nagatomo et al., IAEA-CN-94/IF/P7-29

Imploded core plasma ρR is higher for cone target than for spherical target in PINOCO-2D simulations.

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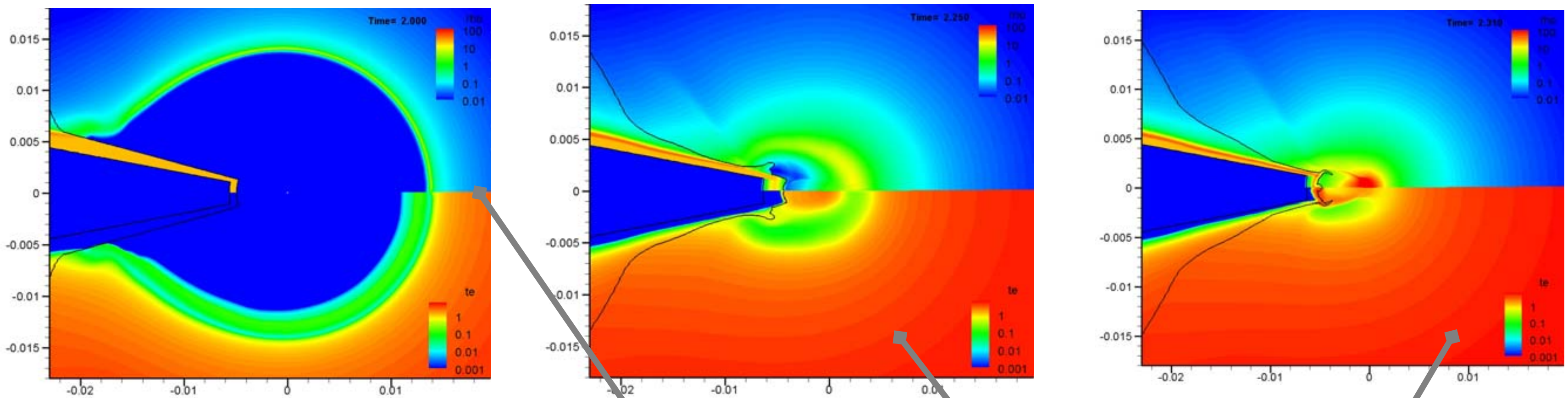
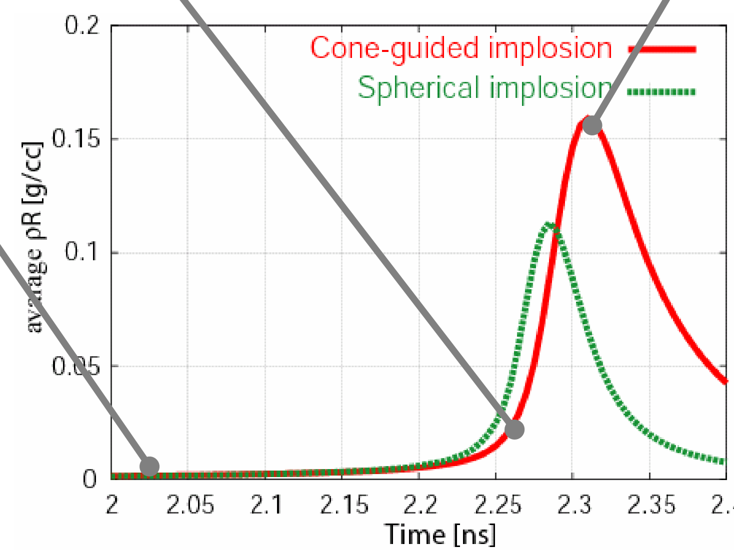
mass density



electron temperature

Time dependence of angular average ρR in gold cone-guided implosion (GXII scale CH target).



In the spherical implosion, the shell target reach the maximum compression at 2.285 ns.
In non-spherical implosion case, the shell continued to be compressed since a hot spot is not formed and an average ρR reached a higher value (0.15 g/cm^2).

H. Nagatomo et al., IAEA-CN-94/IF/P7-29

Compressed-core profile by PINOCO

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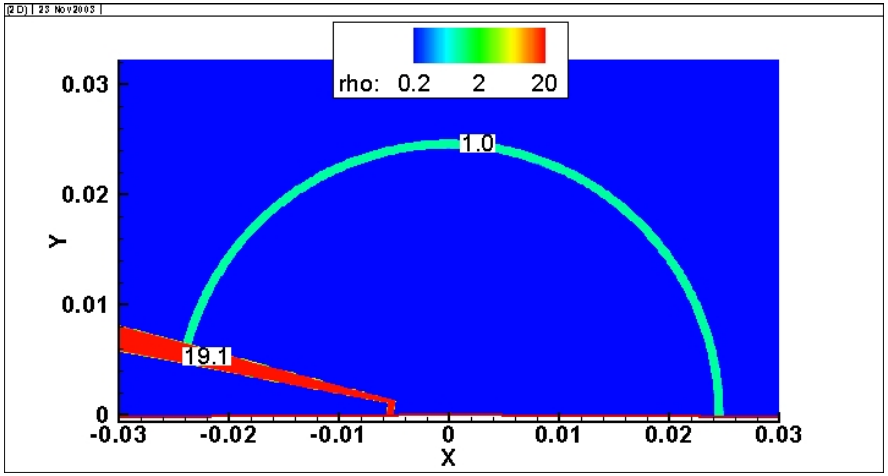
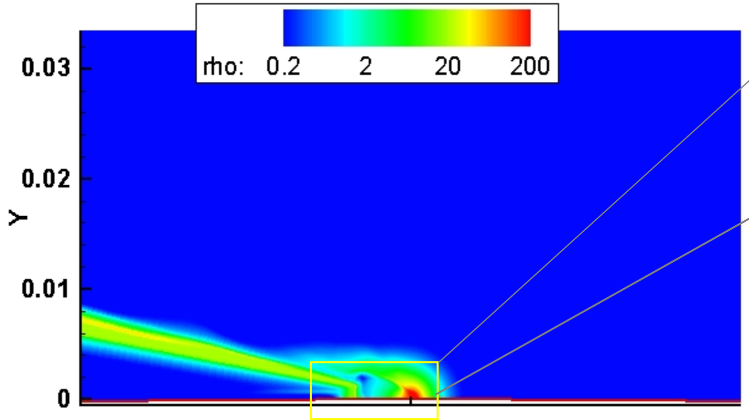
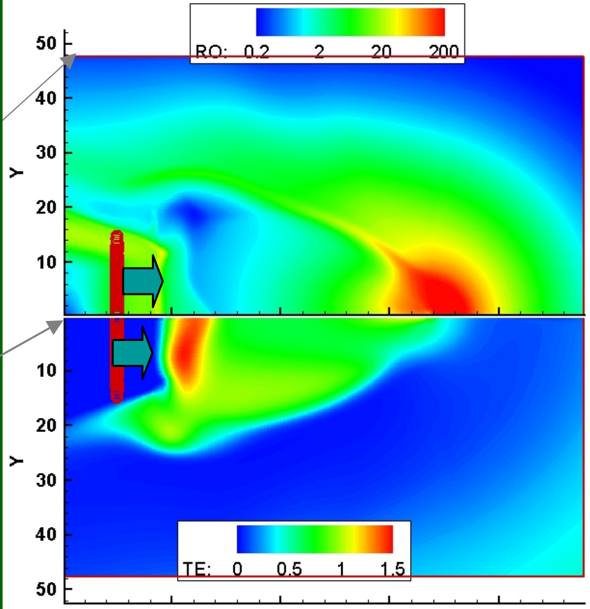
Implosion simulation of a cone-shell target (2D ALE code "PINOCO" by Nagatomo)





RFP-Hydro simulations

REB was injected at inner surface of a gold cone.



H. Nagatomo et al., IAEA-CN-94/IF/P7-29

Hot spot appears to flow out toward the cone tip.

10 ps X-ray frame Image (MIXS)

CH shell:1000 μmϕ
25 μmt, D_2 0, 5 atm

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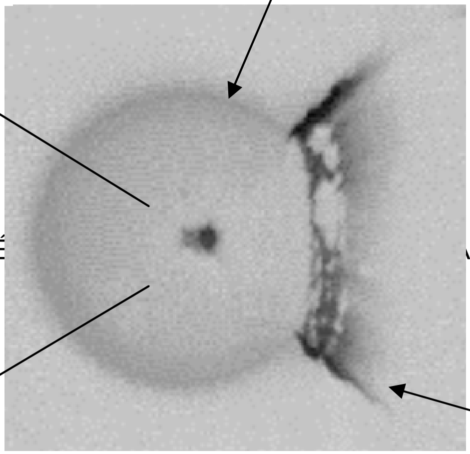

Laser:
35 beams
15 kJ/1 ns SQ
($8x10^{15}$W/cm^2)

70deg Au cone

Plasma streams out of hot spot.

Fast electron energy distribution at a top of cone.
This result is used for Fokke- Planck simulation

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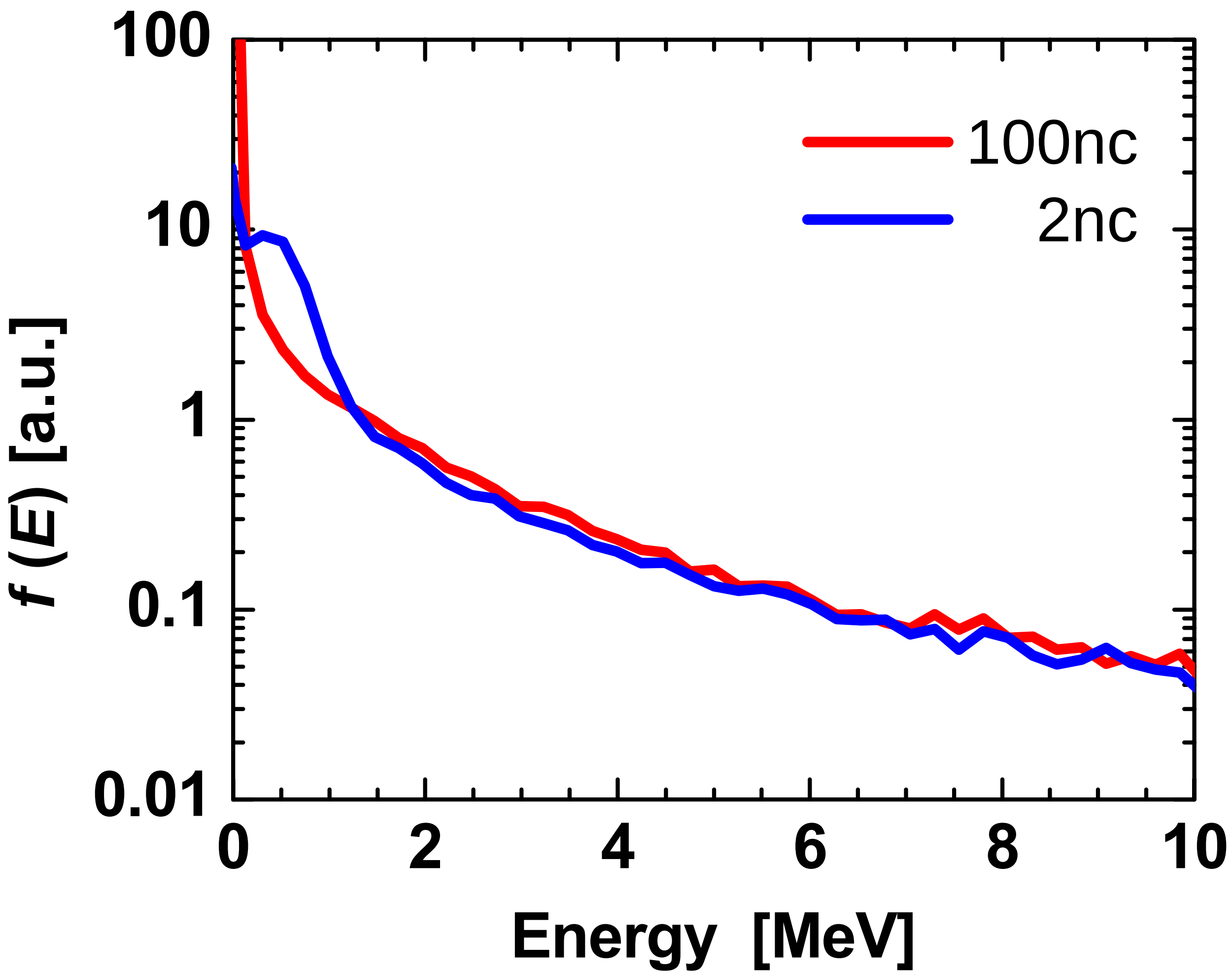

H. Nagatomo et al., IAEA-CN-94/IF/P7-29

Integrated simulation results on core heating rate and temperature

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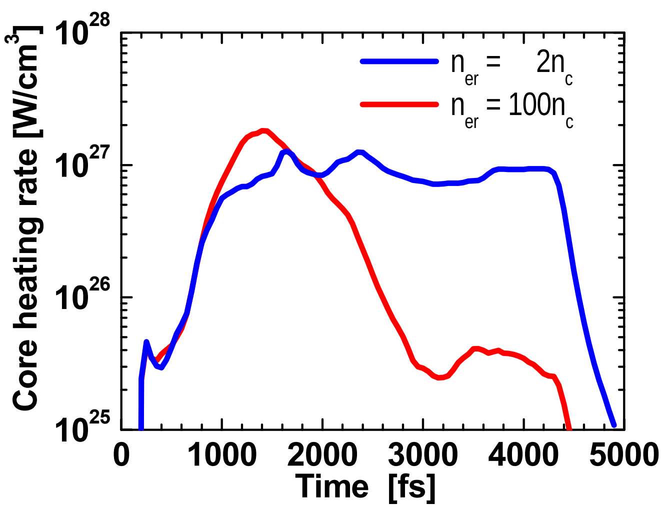
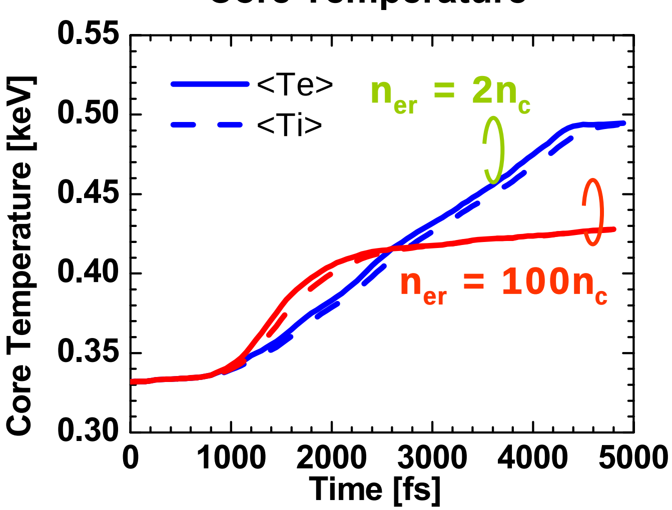
$I_{L,max} = 1\text{x}10^{20}$ [W/cm²]





	$n = 100n_c$	$n = 2n_c$
Resultant core temp., <Ti>	0.43keV	0.50keV

Coupling efficiency in the case of $n = 2n_c$
from fast electrons to core is 25%, and from laser to core is 5.4%.

Y. Nakao et al., IAEA-CN-94/IF/1-5

Heated blackbody emission was observed by HISAC.

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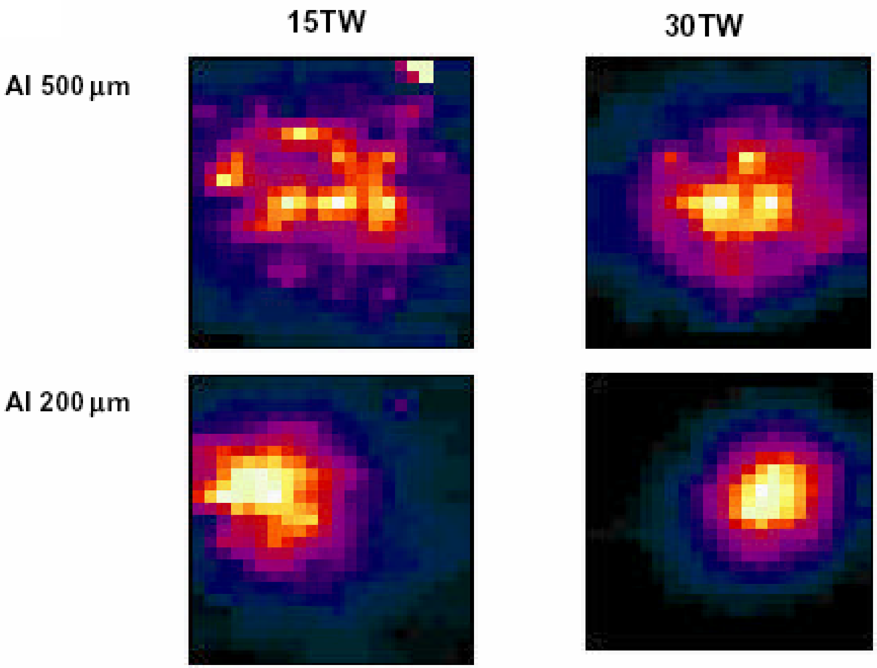
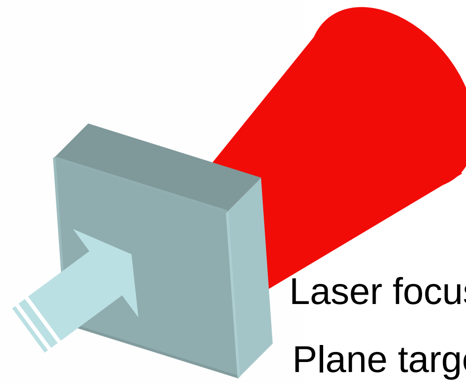
Rear of the target is heated up by hot electrons.
Black body emission was observed with time and spatial resolution.





Number of filaments decreases with increase of laser intensity and also with decrease of target thickness.

HISAC: Framing camera with Δt = 30 psec and Δx = 30 micron.

Y. Tohyama, R. Kodama et al., submitted to PRL (2004)

K. A. Tanaka et al., IAEA-CN-94/IF/1-4Ra

Number of filament decreases quickly with increasing laser intensity.

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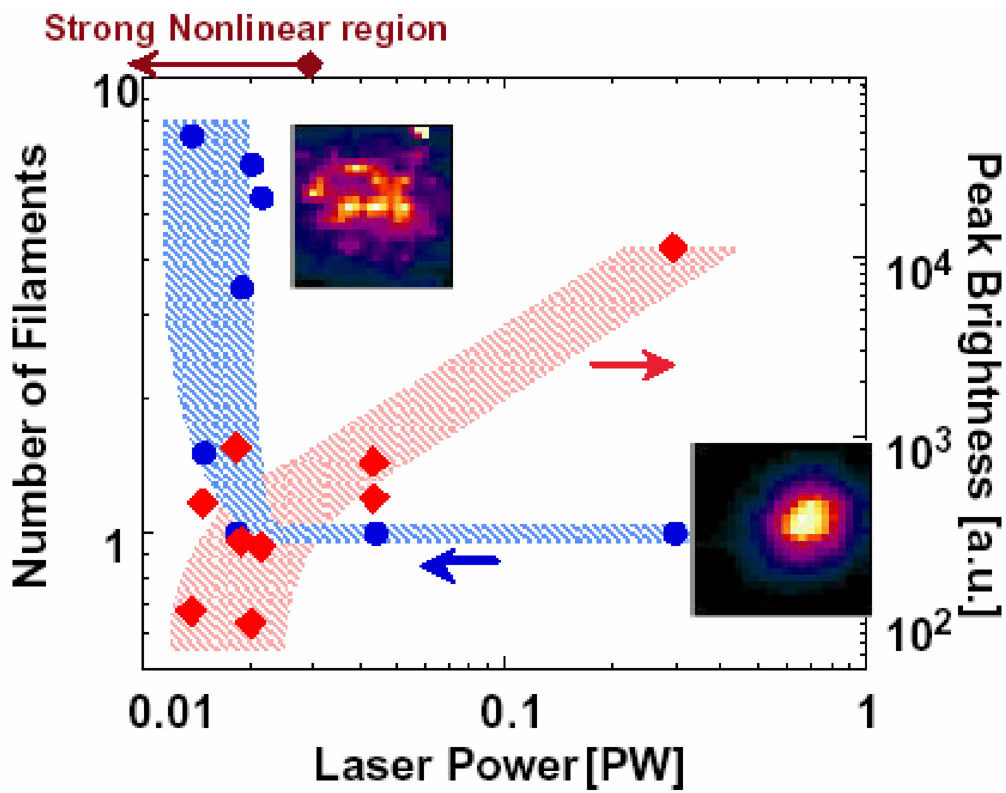
Number of filament and peak brightness in rear emission were measured by 200 μm Al target changing the laser power up to near PW.
The filament could merge due to magnetic field generated by inhomogeneous conductivity, which depends on the temperature and/or heating power.



Hot electrons can be transported not breaking into filaments at the laser power of ~PW and be maintained in a flux to heat the core.

K. A. Tanaka et al., IAEA-CN-94/IF/1-4Ra

β was estimated by measuring all parameters.

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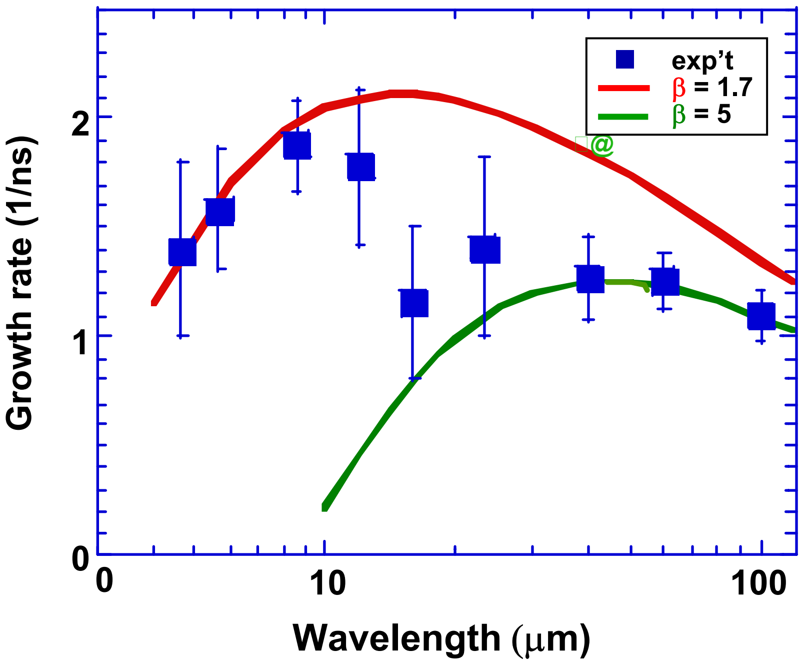
RT growth rate by Takabe formula

$$\gamma = \sqrt{\frac{kg}{1+kL}} - \beta k \frac{\dot{m}}{\rho_a}$$

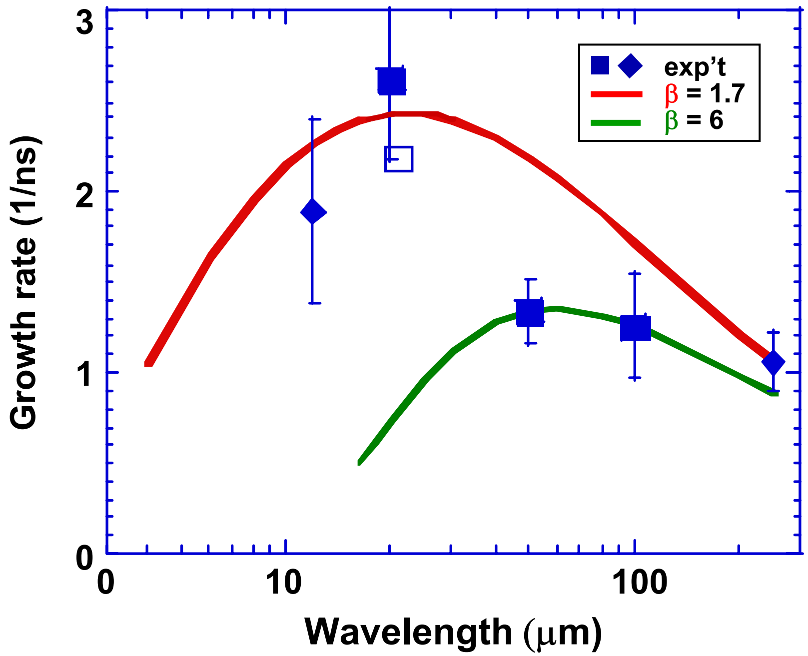
k: wavenumber of perturbation
g: gravity
L: density scale length

m: mass ablation rate
ρ_a: mass density
β: numerical coefficient

0.53 μm laser



0.35 μm laser



β = 1.7 for shorter wavelength of perturbation.
β ~ 5 for longer wavelength.

→ H. Azechi et al., IAEA-CN-94/IF/1-1Ra

Two suppression schemes for RT growth were proposed.

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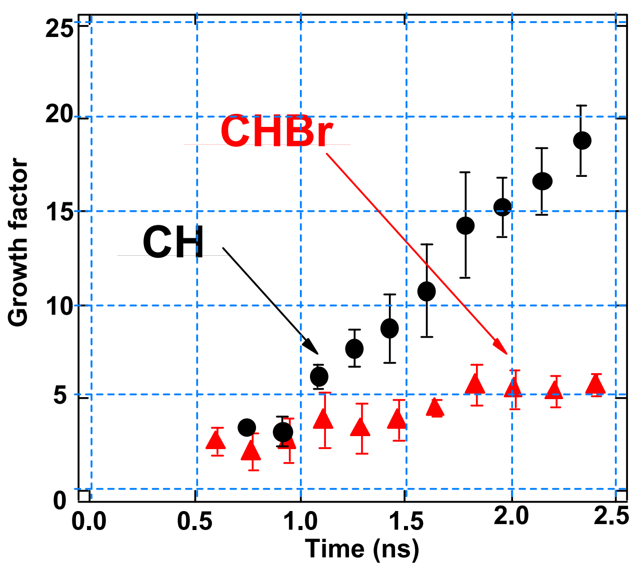
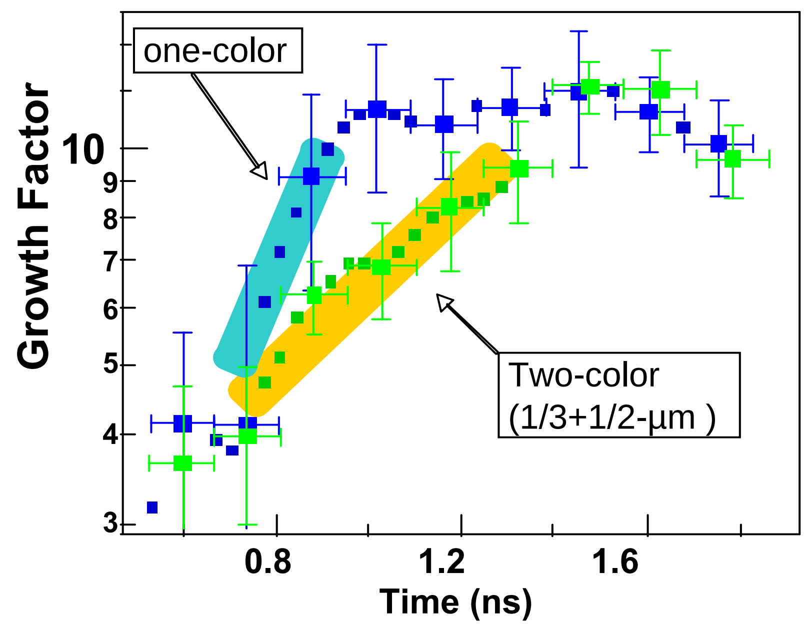
- Double ablation by high-Z doping: ablations by electron and radiation
  → increase of ablation velocity
- Two-color irradiation: enhancement of nonlocal heat transport of electron
  → increase of density scale length





→ H. Azechi et al., IAEA-CN-94/IF/1-1Ra

Summary

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1. Enforced heating of imploded plasmas has been demonstrated by using cone-shell targets.

2. We have started the FIREX project towards ignition and burn of laser fusion.
   - FI^3 (Fast Ignition Integrated Interconnecting) code was developed for target design.
   - Cone-target implosion and hot electron transport have been studied by the experiment and simulation.
   - New stabilization schemes for R-T instability were proposed and significant suppression of instability were demonstrated.
   - A new heating laser LFEX,10kJ/10ps PW laser,is under construction. Technical issues should be solved such as segmented grating and phase coupling.
   - Foam cryogenic cone-shell target is under development.

3. FIREX-I experiment will start before 2007. Gain of up to 0.1 will be expected at FIREX-I.

Laser fusion research is progressing toward ignition and burn.

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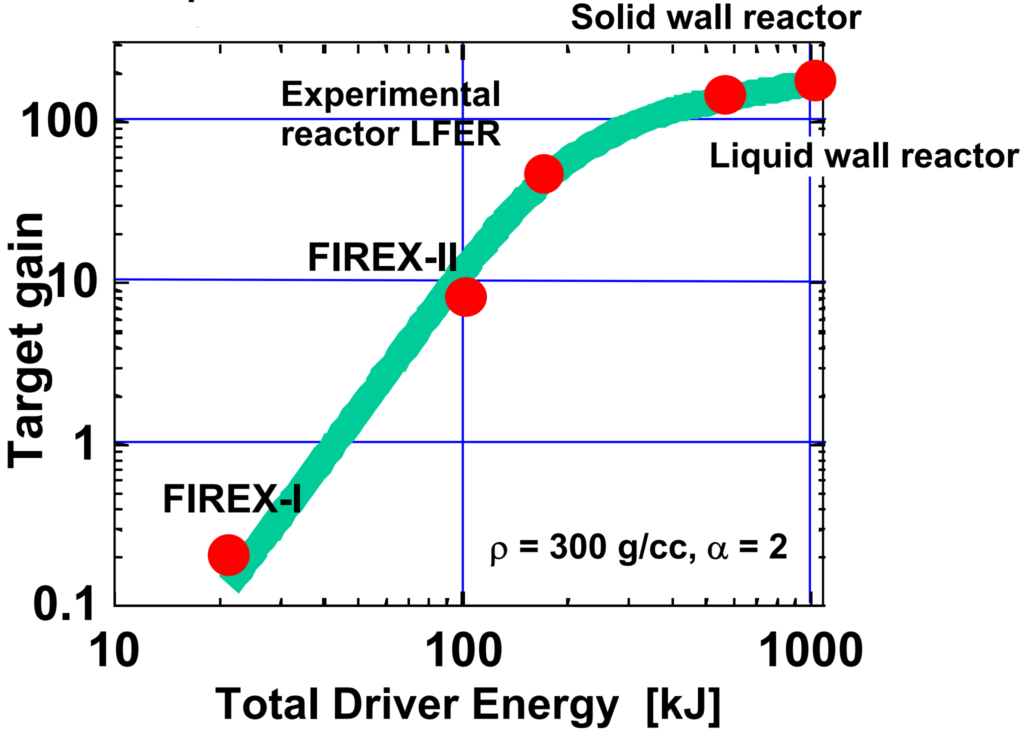
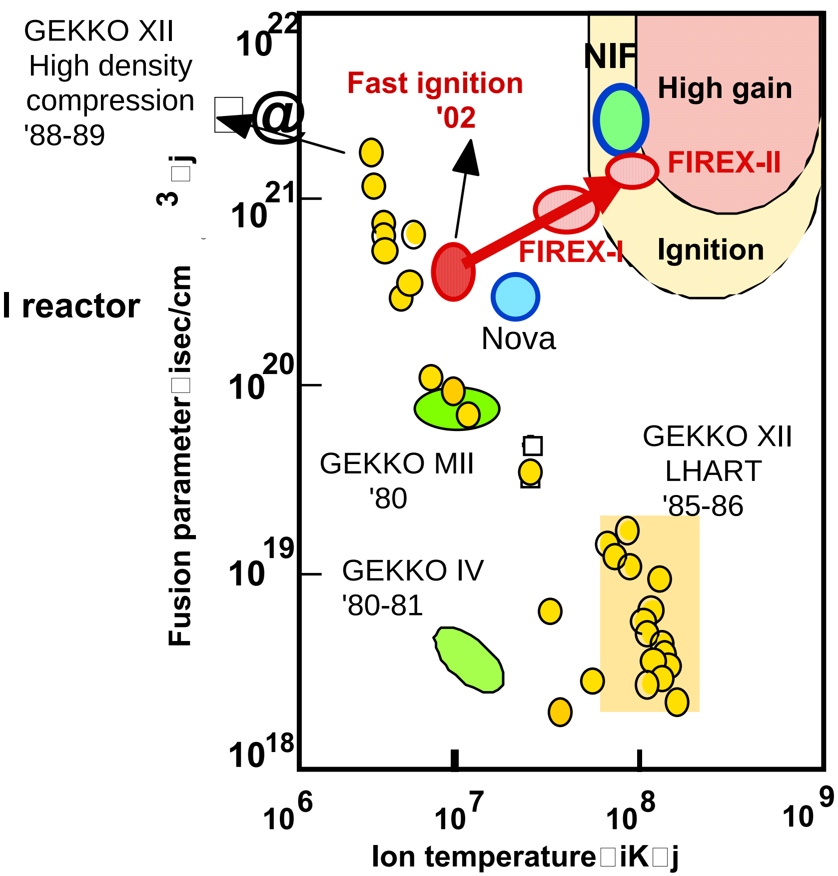
I_{REB} (10^{20}W/cm^2)	
FIREX-II	1.4
IFER	1.4
Solid	2.6
Liquid	2.6





Reactor technology: see Y. Kozaki et al., IAEA-CN-94/IF/P7-5