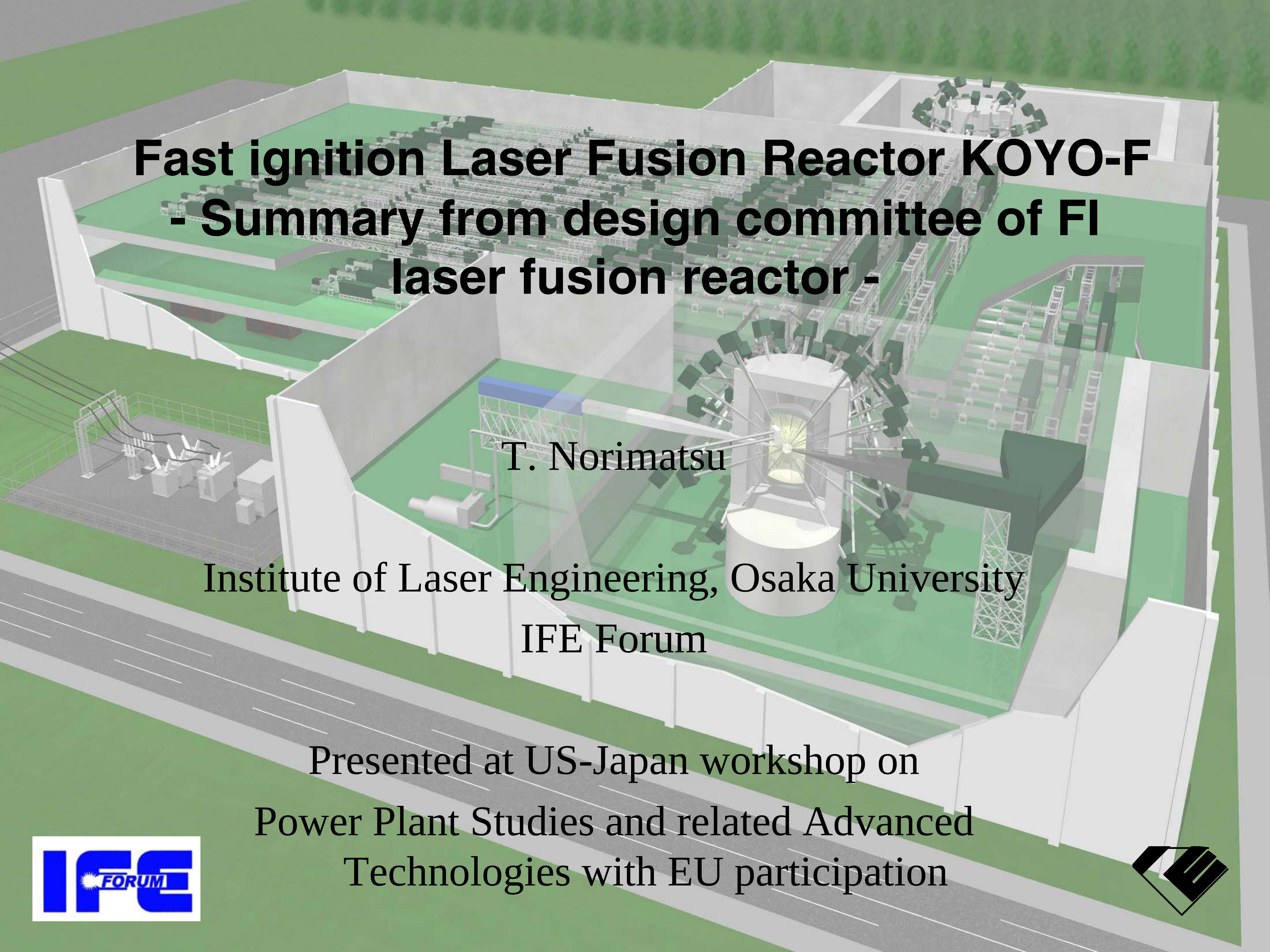

Fast ignition Laser Fusion Reactor KOYO-F - Summary from design committee of FI laser fusion reactor -

T. Norimatsu

Institute of Laser Engineering, Osaka University

IFE Forum

Presented at US-Japan workshop on Power Plant Studies and related Advanced Technologies with EU participation

After the Roadmap committee, we organized a conceptual design committee to make the issue clear. In total, 34 working group meetings were held from March 2004 to Sep. 2005.

ILE, Osaka

- Chair; A. Tomabechi
- Co-chair; Y. Kozaki (IFE, Forum)
  T. Norimatsu (ILE, Osaka)

Core plasma Working Group

H. Azechi	(ILE, Osaka)
K. Mima	(ILE, Osaka)
Y. Nakao	(Kyushu U.)
H. Sakagami	(Hyogo U.)
H. Shiraga	(ILE, Osaka)
R. Kodama	(ILE, Osaka)
H. Nagatomo	(ILE, Osaka)
T. Jhozaki	(ILE, Osaka)

Laser Working Group

N. Miyanaga	(ILE, Osaka)
K. Ueda	(U. Elec.Com.)
Y. Owadano	(Nat. I. Adv. Ind. Sci.)
M. Nakatsuka	(ILE, Osaka.)
K. Yoshida	(Osaka)
H. Nakano	(Kinki U.)
H. Kubomura	(Hamamatsu Co.)
K. Kawashima	(Hamamatsu Co)
Y. Suzuki	(Laser Front Tech.)
T. Jitsuno	(ILE, Osaka)
H. Fujita	(ILE, Osaka)
J. Kawanaka	(ILE, Osaka)
T. Kanabe	(Fukui U.)
Y. Fujimoto	(ILE, Osaka)
K. Tsubakimoto	(ILE, Osaka)
Y. Furukawa	(ILE, Osaka)

Target Working Group

T. Norimatsu	(ILE, Osaka)
A. Iwamoto	(NIFS)
T. Endo	(Hiroshima U.)
H. Yoshida	(Gifu U.)
M. Nishikawa	(Kyushu U.)
S. Konishi	(Kyoto U.)

Plant system Working Group

Y. Kozaki	(IFE, Forum)
Y. Ueda	(Osaka U.)
K. Okano	(Cent. Res. Ins.)
T. Kunugi	(Kyoto U.)
Y. Sakawa	(Nagoya U.)
H. Nakano	(Kinki U.)
A. Sagara	(NIFS)
Y. Soman	(Mitsubishi Co)
M. Nishikawa	(Kyushu U.)
Hayashi	(JAERI)
H. Furukawa	(ILE, Osaka)
M. Nakai	(ILE, Osaka)
T. Kanabe	(Fukui U.)
Y. Fujimoto	(ILE, Osaka)
K. Tsubakimoto	(ILE, Osaka)
Y. Furukawa	(ILE, Osaka)

The committee is supported by IFE Forum and ILE, Osaka Univ.

Outline

- Introduction
  - Fast ignition
  - Gain estimation and the emission
- Chamber and plant system
- Laser system
- Fueling system

Fast ignition is attractive , because the gain is high with a small laser

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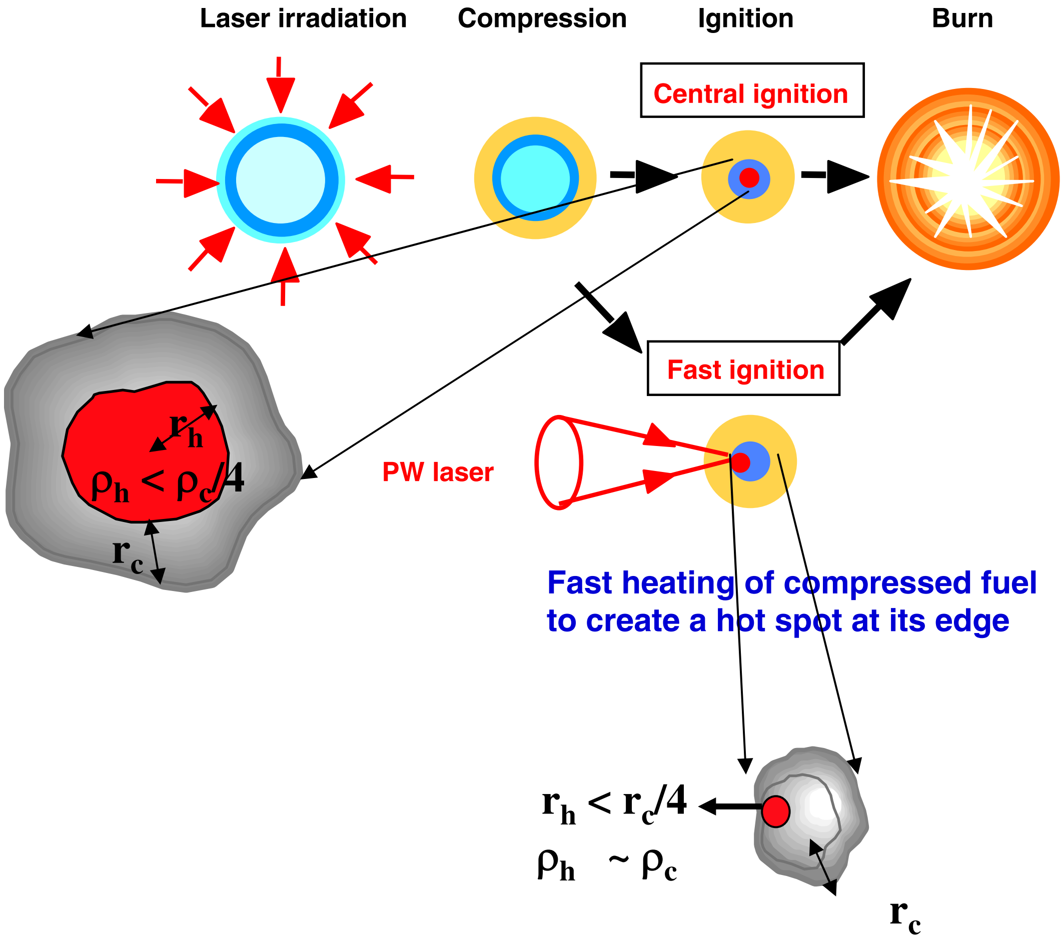
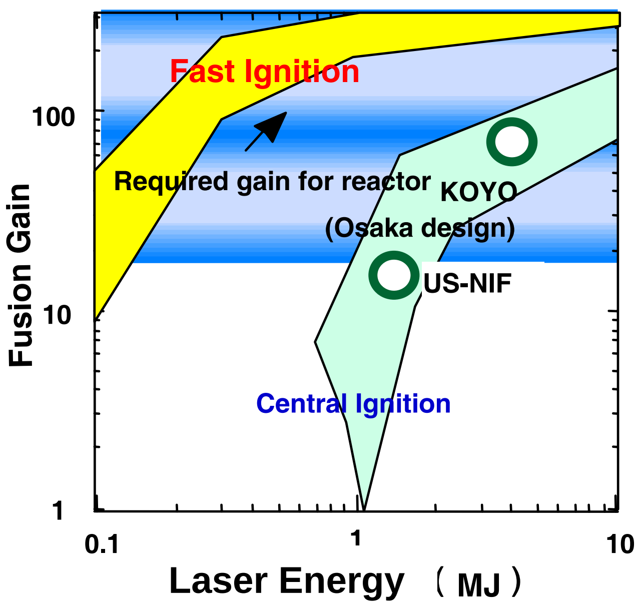
Processes for compression and ignition are separated.





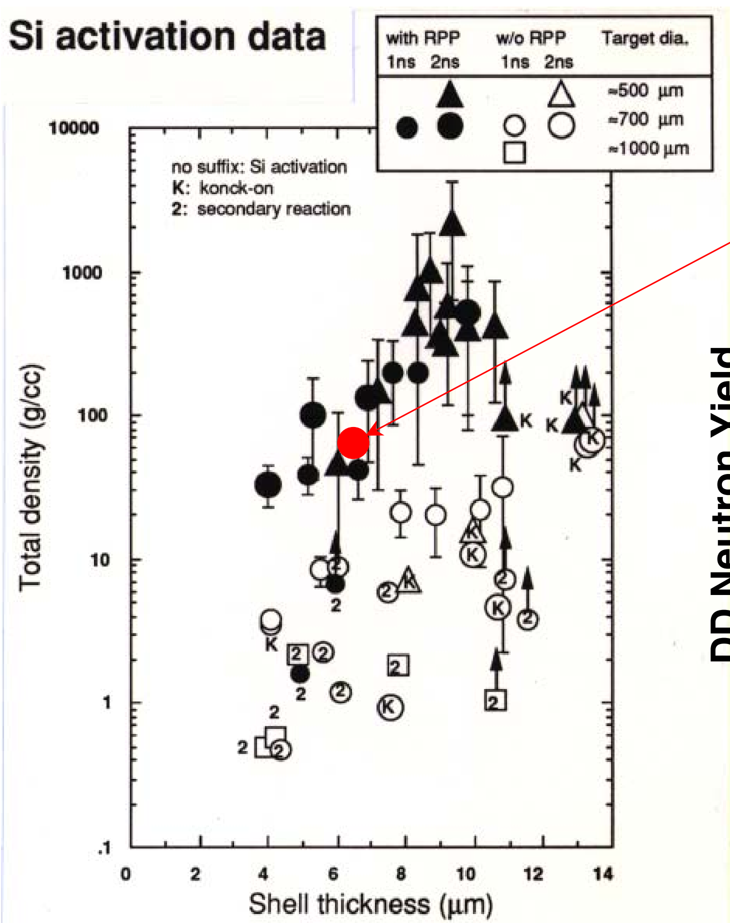
Fast heating needs petawatt laser.
Critical issue is relativistic dense electron dynamics.

FIREX-1 project has been started to demonstrate Ti = 5 keV.

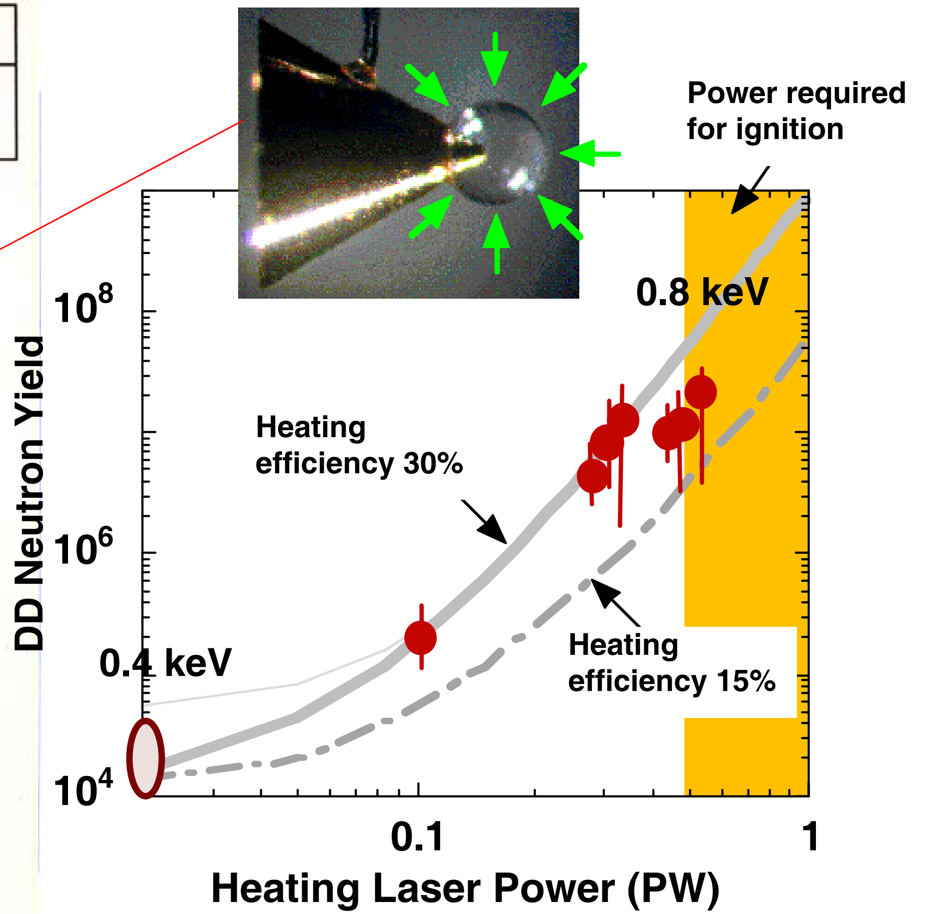
ILE, Osaka

600 times liquid density and 1keV heating have been demonstrated

ILE, Osaka



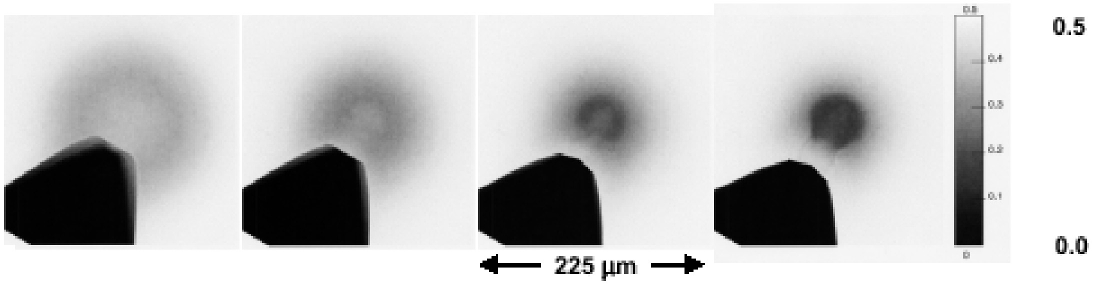
H. Azechi, LPB 91



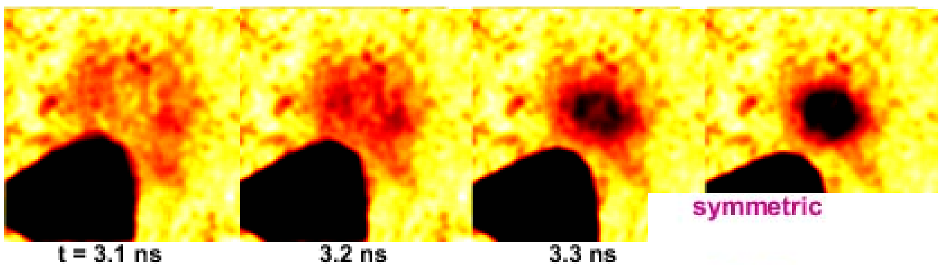
R. Kodama, Nature 01&02

Two-D simulation checked by implosion experiments at Rochester Univ. indicated that high density compression of reactor-scale, cone target is possible.

High resolution prediction for 8 keV backlit images

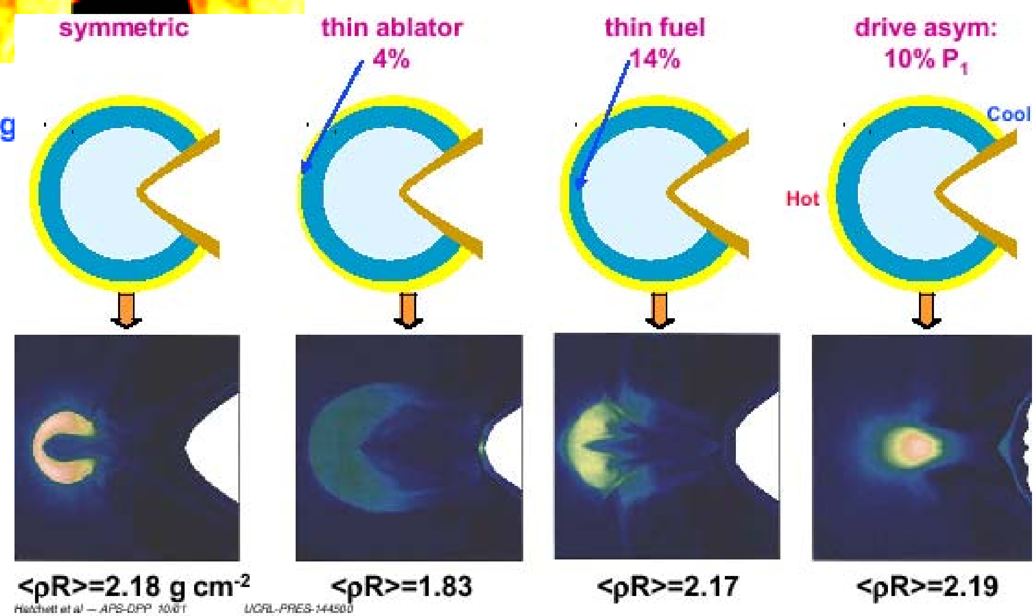


ILE, GA, Rochester collaboration



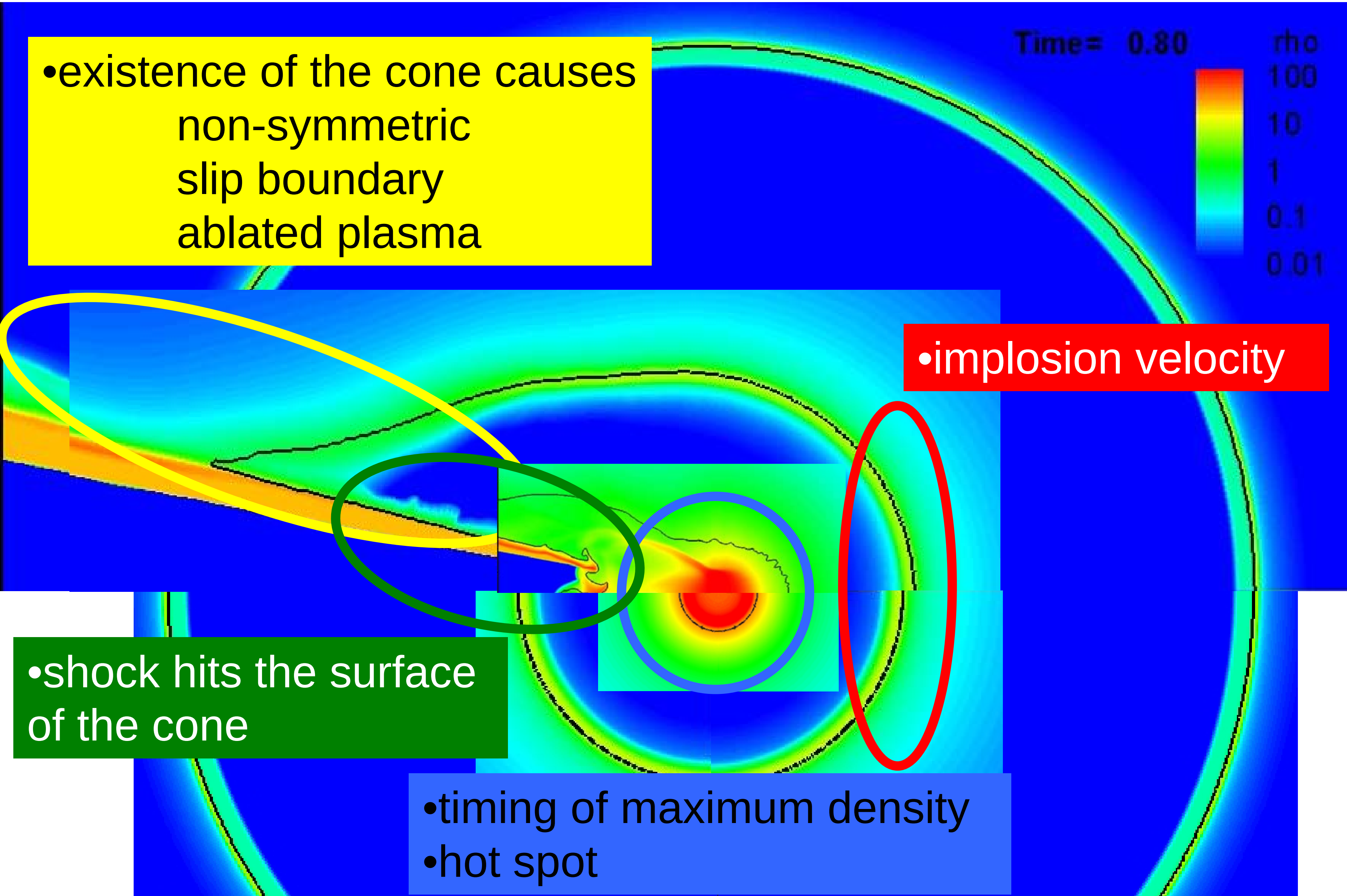
Prediction — with pixelation, noise, and smoothing

S. Hatchet LLNL, APS/DPP '01



One of key requirements to start FIREX-II is satisfied.

Although dynamics of cone-guided implosion is quite different from conventional spherical one, high ρR for ignition can be achieved



High gain will be achieved by increasing the laser energy at the same intensity.

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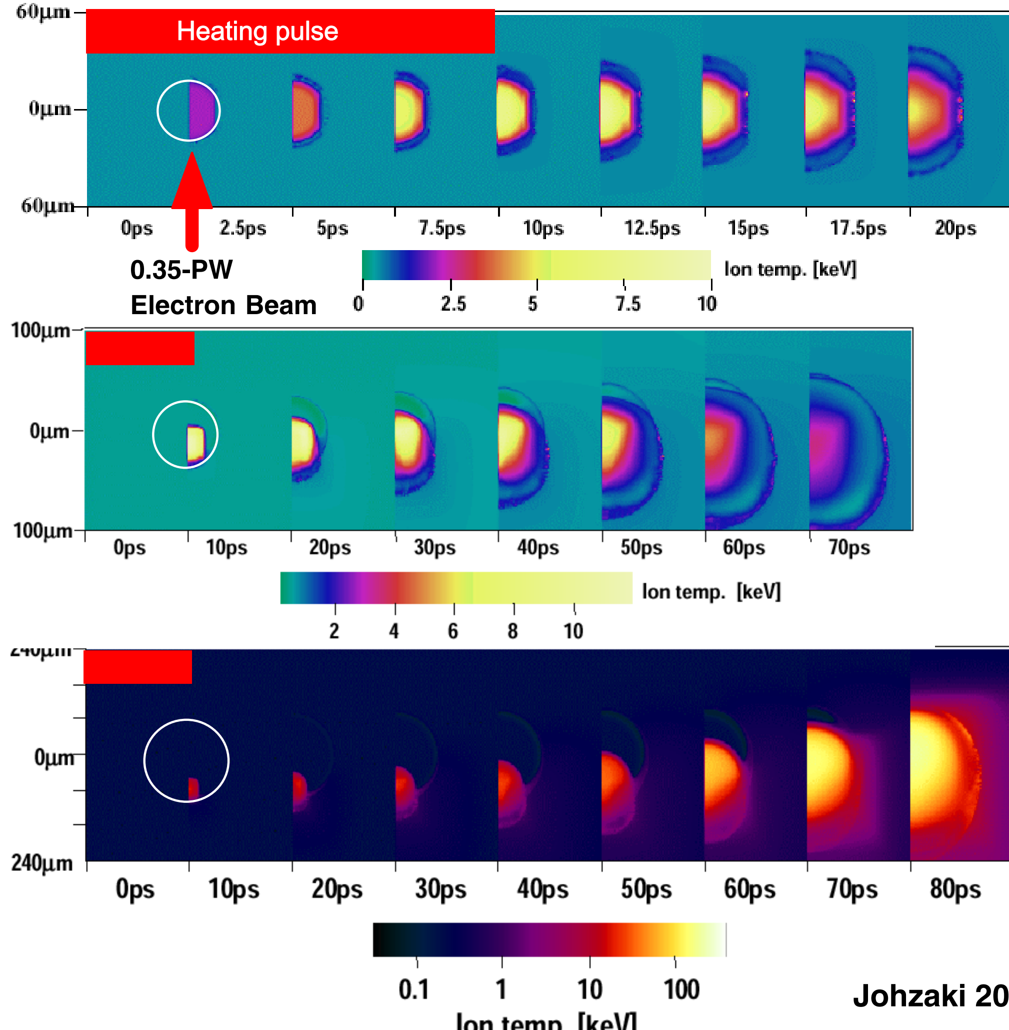
FIREX-I Q~ 0.1

FIREX-II Q~8

Demo Q~150
By increaseing the core size, high gain will be achieved.



Johzaki 2003

Fast Ignition Gain Performance

ρ = 300g/cc, α = 2 and 3

Energy coupling; η_{imp} = 5% for implosion & η_{heat} = 30% for core heating

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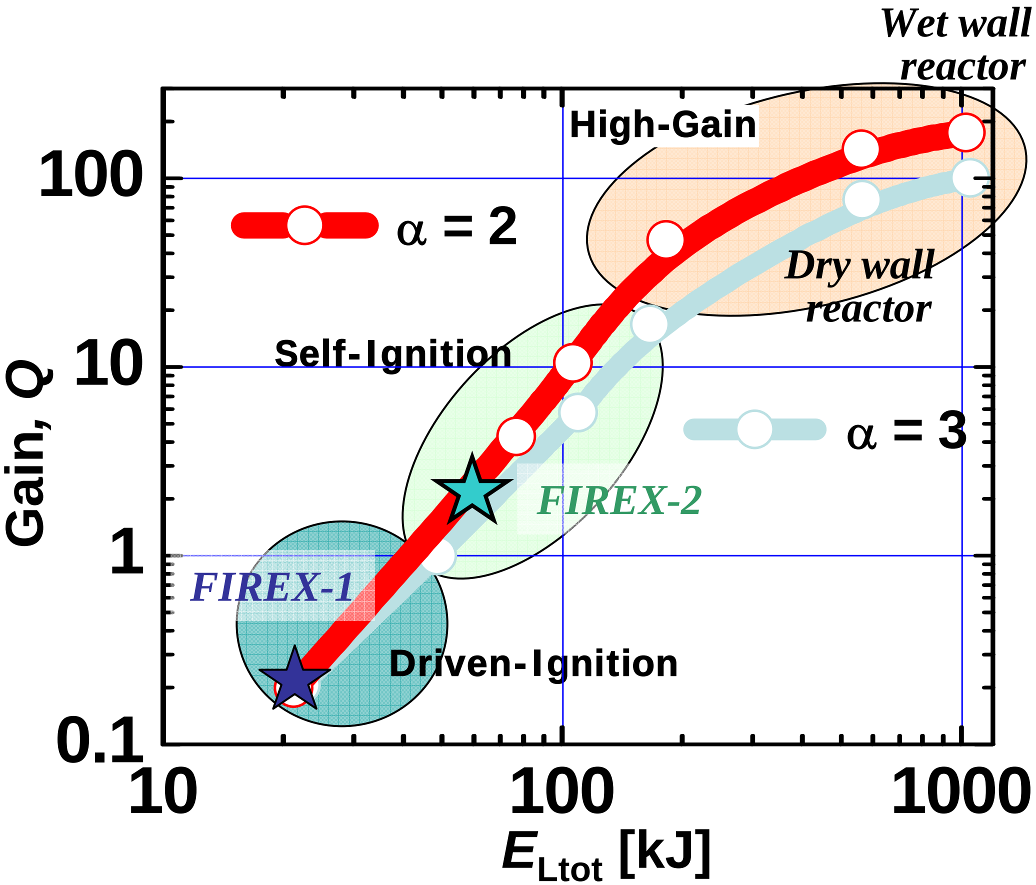
In high gain region, target gain considerably decreases with increasing adiabat α.



Outline

- Introduction
- Chamber and plant system
  - Chamber structure
  - Pumping
  - Protection of final optics
- Laser system
- Fueling system

KOYO-F with 32 beams for compression and one heating beam

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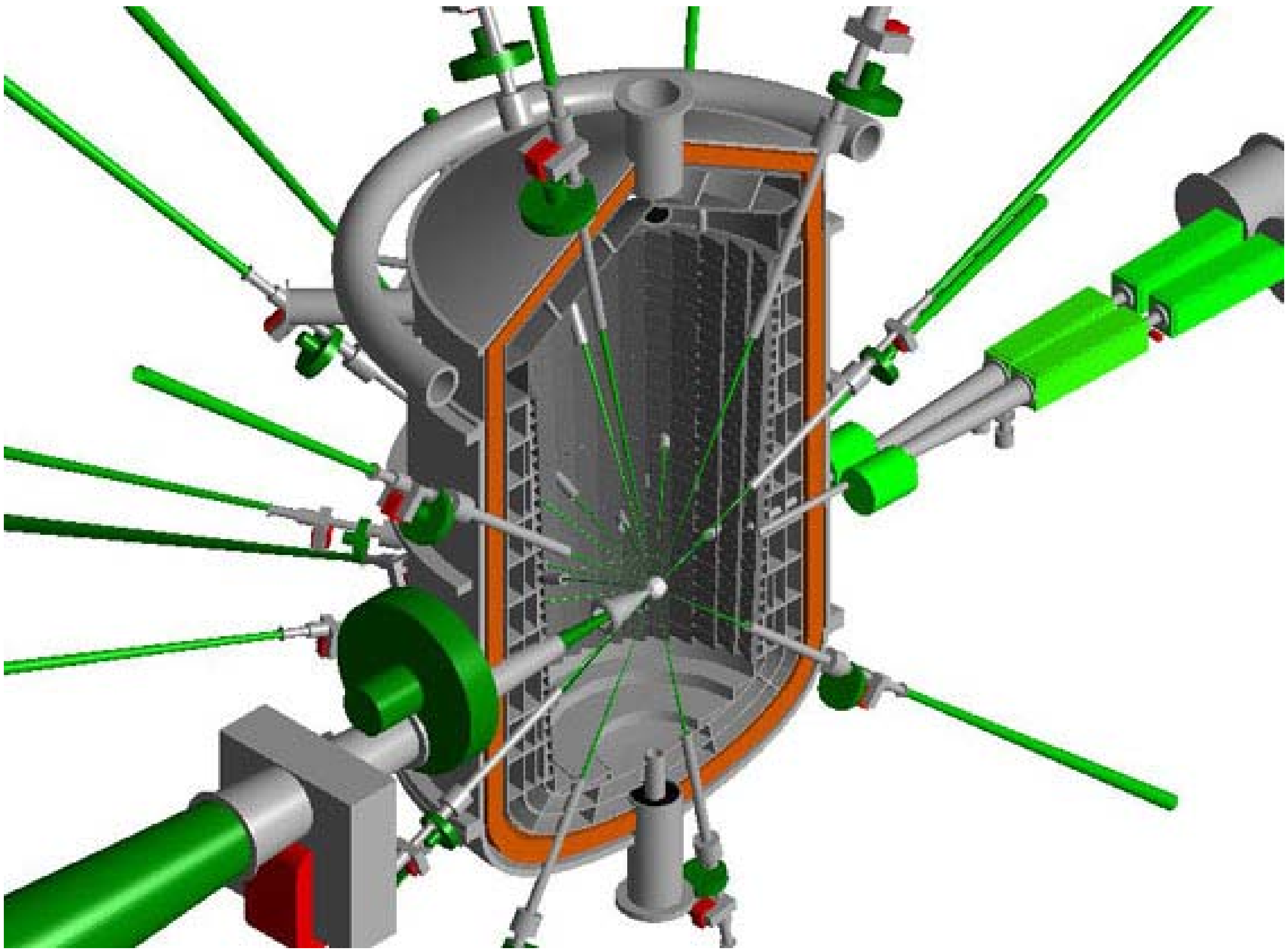

- Vertically off-set irradiation
- Cascade surface flow with mixing channel
- SiC panels coated with wetable metal
- Tilted first panels to make no stagnation point of ablated vapor
- Compact rotary shutters with 3 synchronized disks

The surface flow is mixed with inner cold flow step by step to reduce the surface temperature.

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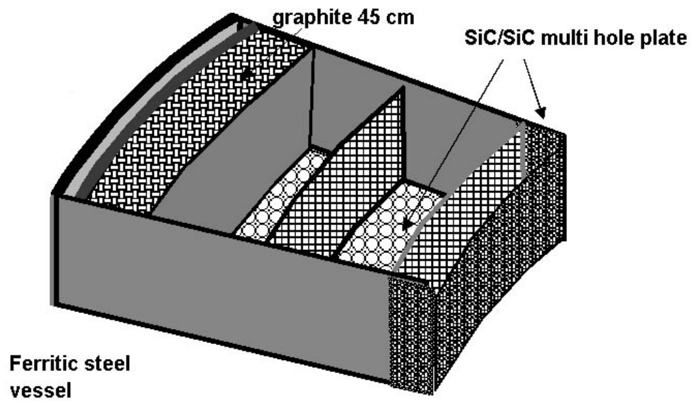

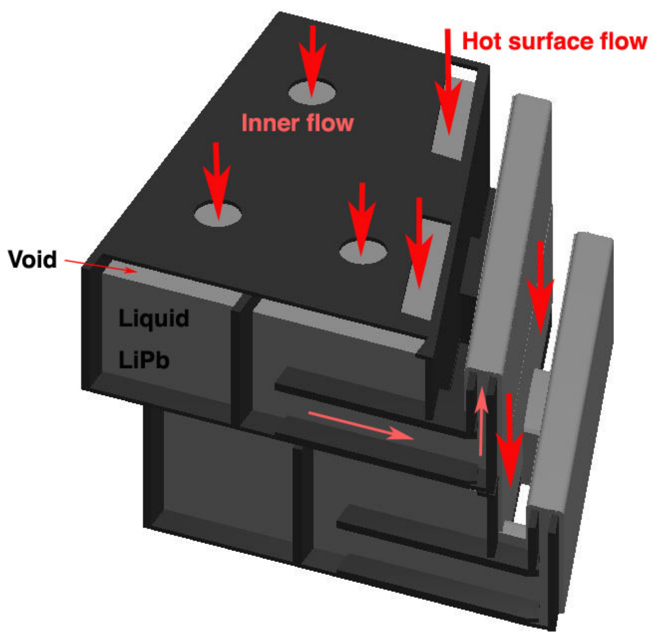

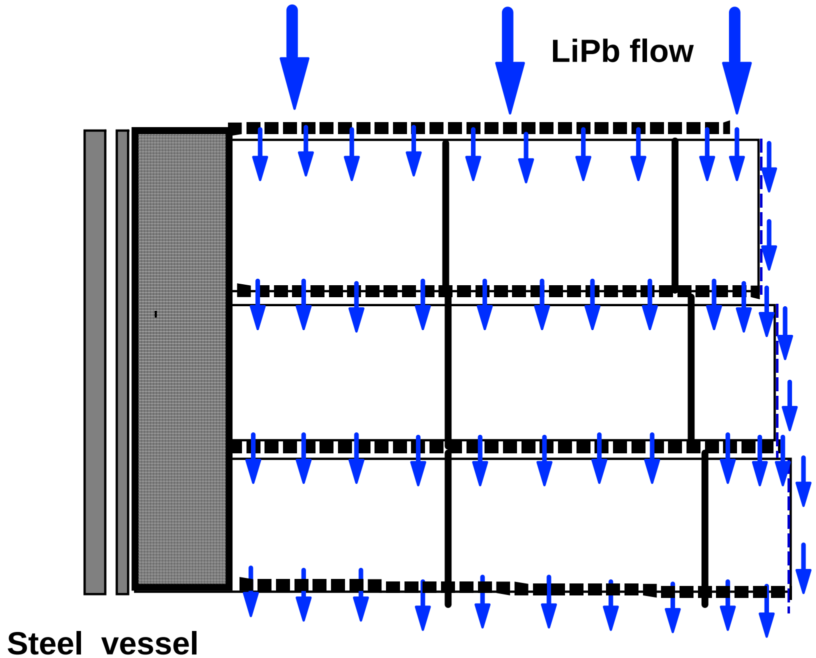

Not to scale

Thermal flow of KOYO-F
(One module)

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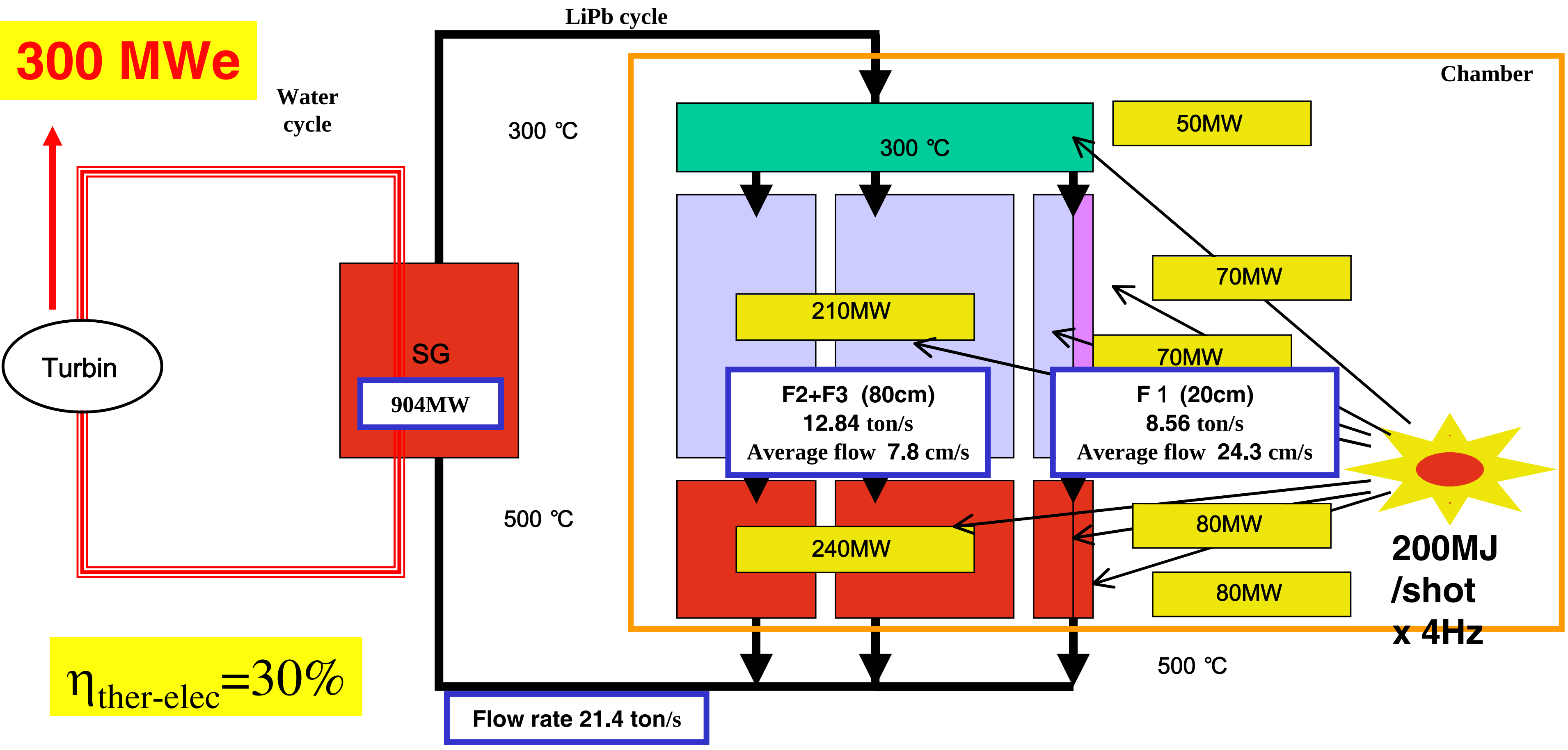

$\eta_{ther\text{-}elec}=30\%$

Specification of KOYO-F

ILE, Osaka

Net output	1200 MWe (300 MWe × 4)
Laser energy	1.1 MJ
Target gain	165
Fusion pulse out put	200 MJ
Reactor pulse rep-rate	4 Hz
Blanket energy multiplication	1.2
Reactor thermal output	916 MWth
Total plant thermal output	3664 MWth (916 MWth × 4)
Thermal electric efficiency	41.5 % (LiPb Temperature ~500 C)
Total electric output	1519 MWe
laser efficiency	11.4 % (implosion) , 4.2 % (heating), total 8%
Laser pulse rep-rate	16 Hz
Laser recirculating power	240 MWe (1.2 MJ × 16 Hz / 0.08) Yb-YAG laser operating 150K or 220K)
Total plant efficiency	32.8 %(1200 MWe/ 3664 MWth)

Estimation of Output Energy Structure 200MJ output (~1.2MJ driver; 1.14MJ imp + 71.5kJ heat) Case

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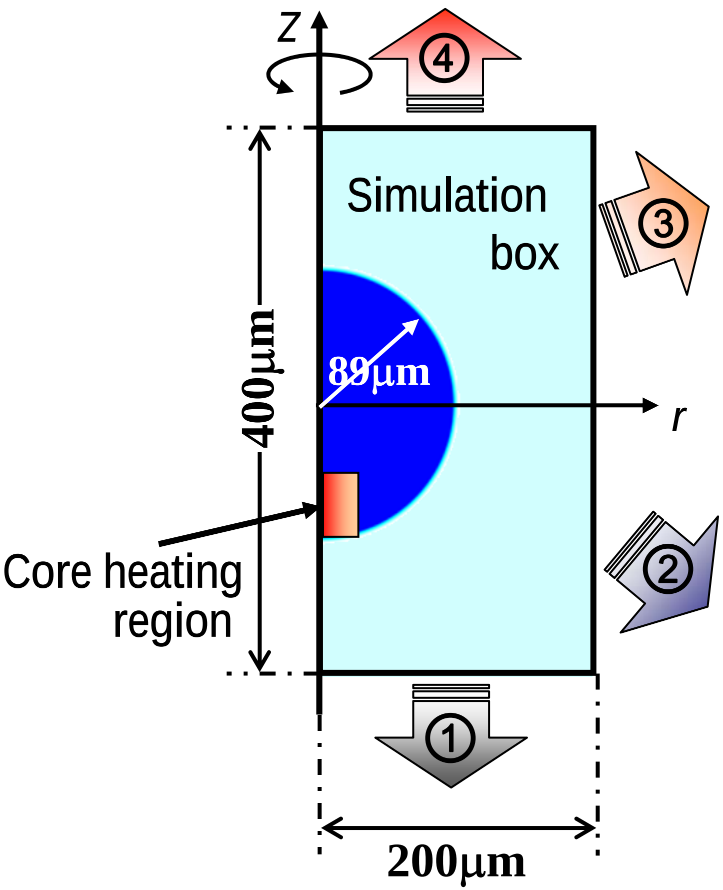
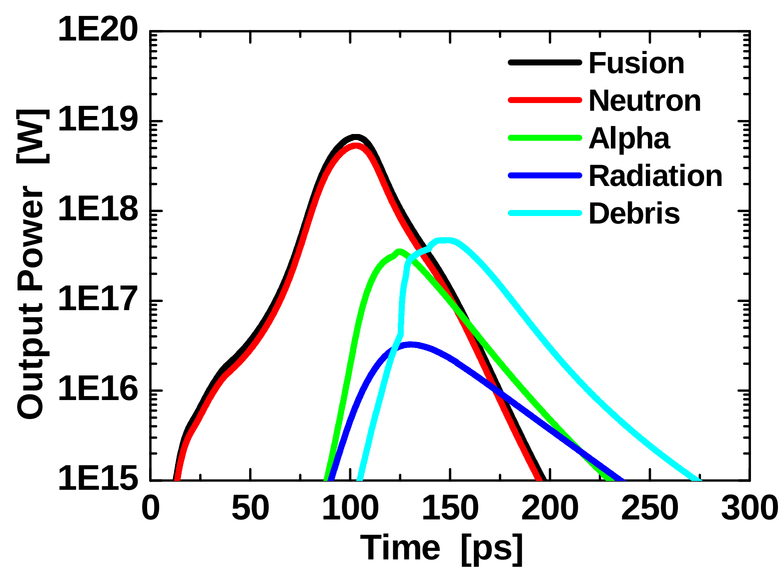


(a) **Output Power** and **Energy Spectrum** of of α-particles leaking from each boundary (① ~ ④)

(b) **Output Power** of Radiation leaking from each boundary (① ~ ④)

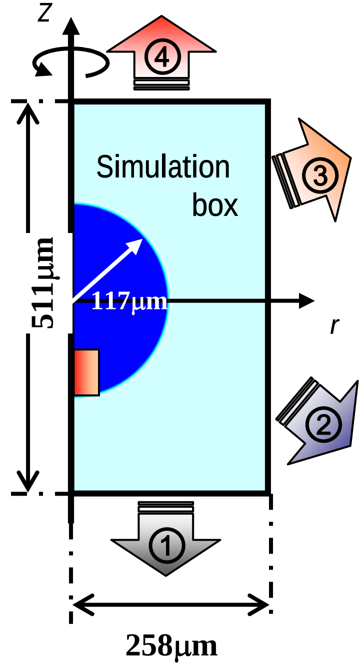
(c) **Output Power** of Debris (thermal + Kinetic) leaking from each boundary (① ~ ④)



Summary of Burn Properties
Input and output energies [MJ] for ~ 200MJ output case

ILE, Osaka

	Energy [MJ]	Heating side (①)	Opposite side (④)
Driver Energy※1	1.12		
Implosion	1.14		
Heating	0.0715		
Fusion [MJ]	200		
Carried out by			
Neutron※2	160 (80.0%)	12.7 MJ/str	12.7 MJ/str
Alpha※3	11.8 (5.9%)	1.31 MJ/str	0.67 MJ/str
Debris※4	19.4 (9.7%)	2.26 MJ/str	1.34 MJ/str
Radiation	1.85 (0.9%)	0.12 MJ/str	0.15 MJ/str
~~*error*~~	~~6.9 (3.4%)~~		
Gain	165		



※1 The energy coupling efficiencies of 5% and 30% were assumed for implosion and core heating, respectively.
※2 Neutrons were assumed to be freely and isotropically escaped from the core.
※3 Alpha particle: Leakage/Source = 29.8% (70.2% is deposited inside the core.)
※4 Constitution (energy D:35.5%, T:49.9%, α:14.3% / Number D:43.6%, T:44.5%, α:11.5%)

The speed of ablated vapor 500 m/s at higher density region and 4000 m/s at the front.

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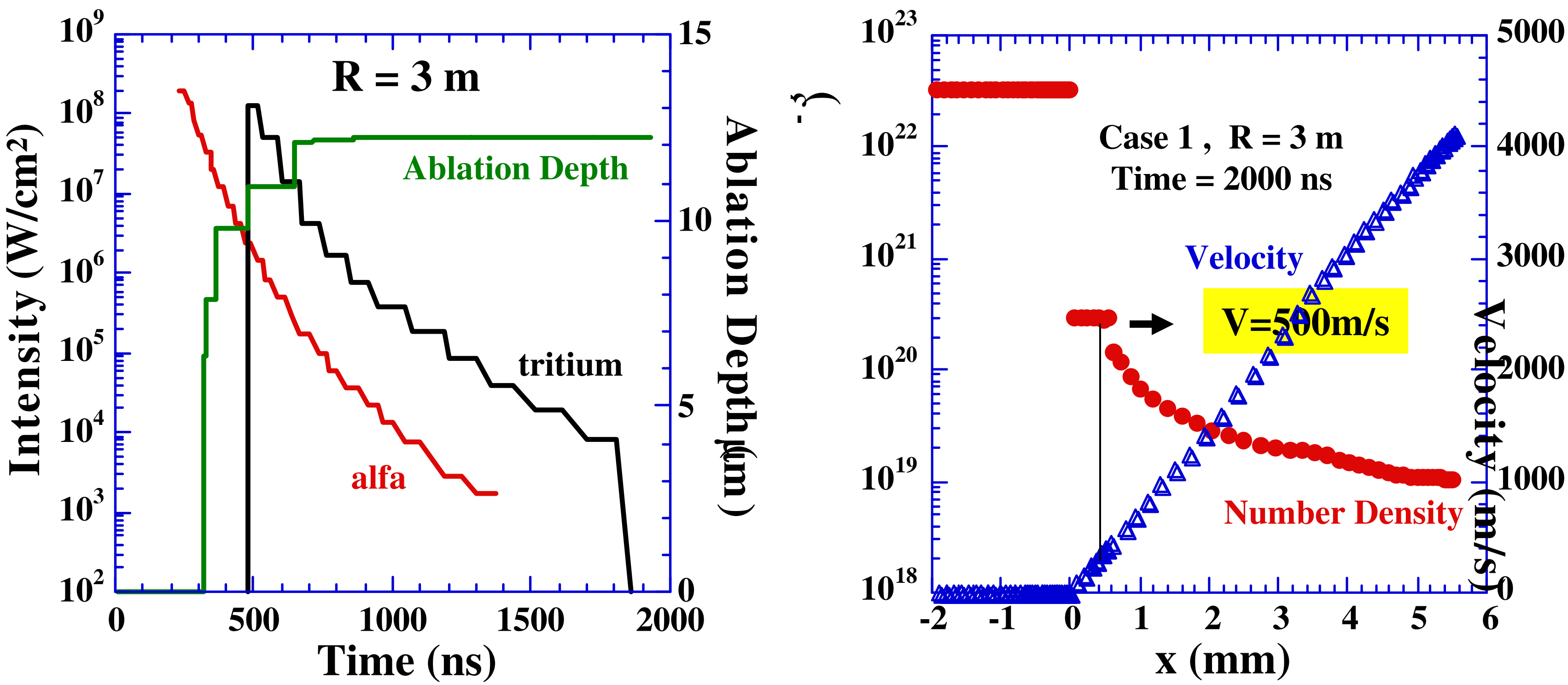
(This work is on the way. Depends on the model for stoping range.)



Total mass of ablated materials was 6.2 kg/shot including oblique-incidence effect.

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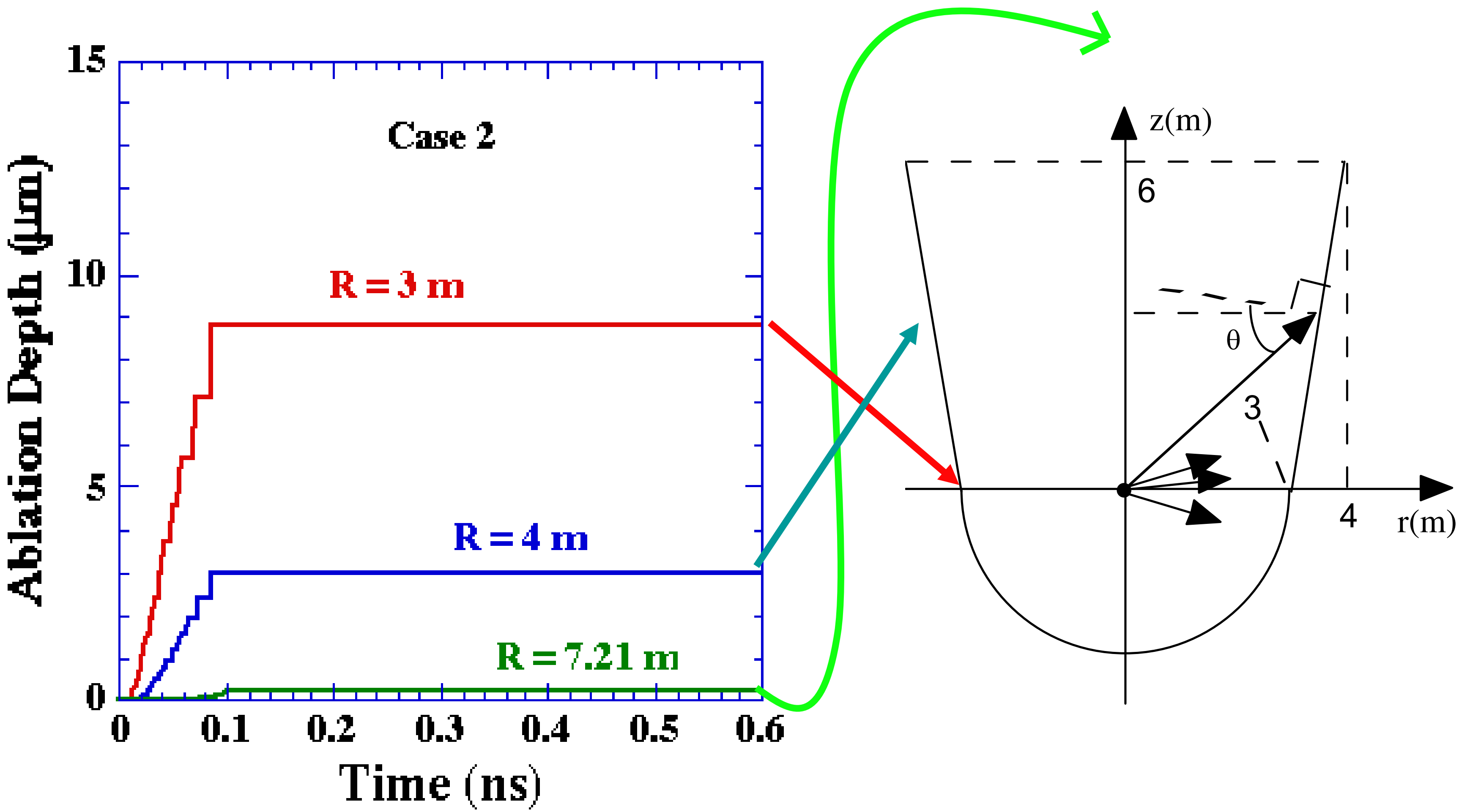

Lot of 0.1 μm radius clusters are formed after adiabatic expansion.

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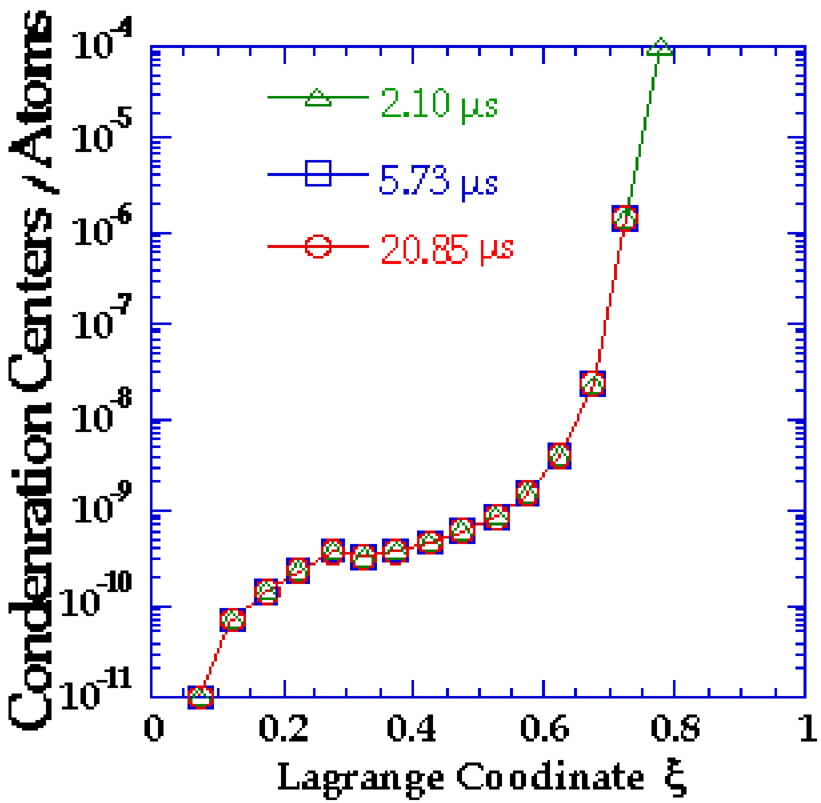
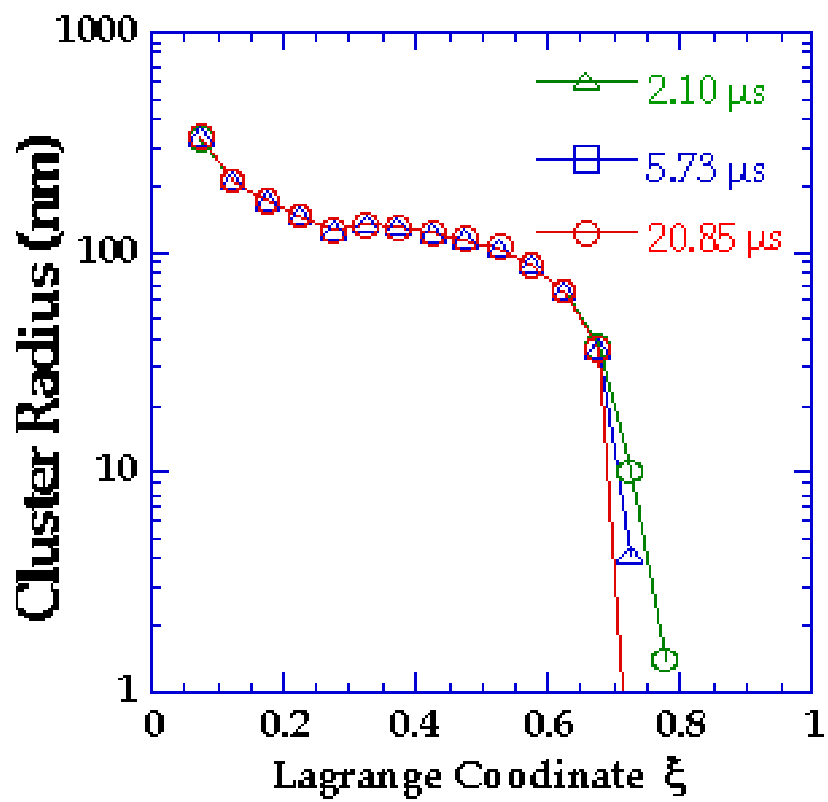
(Luk'yanchuk, Zeldovich-Raizer Model)





Future work: Hydrodynamic simulation including phase change is necessary to discuss the formation of aerosol.

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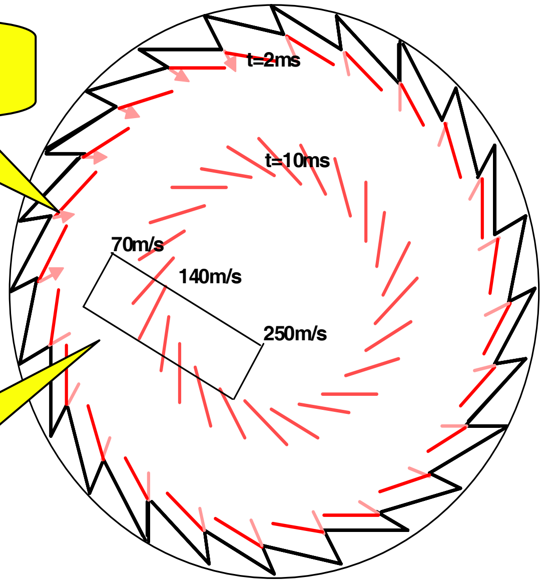
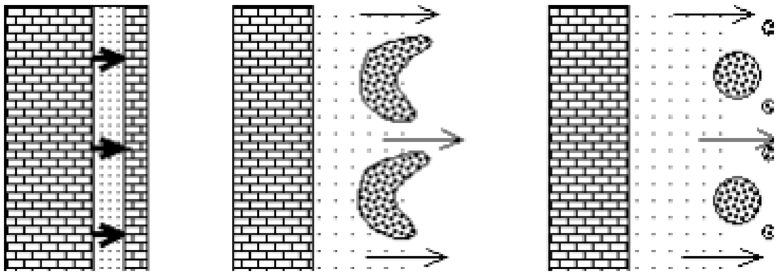
Jet formation



Size of evaporated vapor in flight



RT instabilities would form larger particles. -->

Four Pb diffusion pumps will be used to keep the chamber less than 5 Pa

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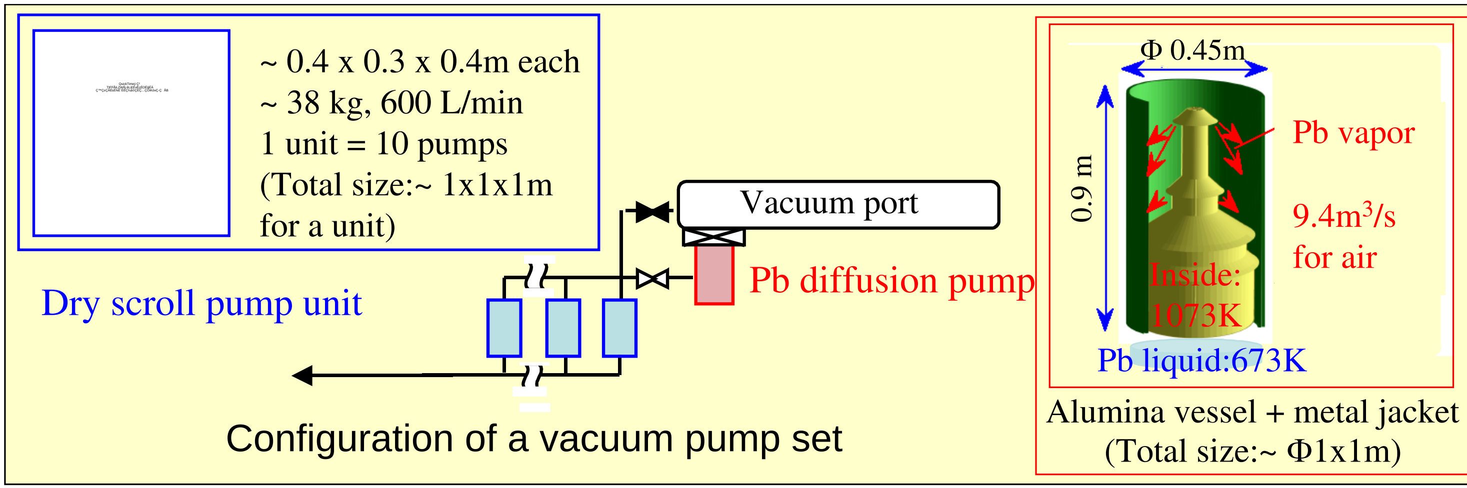
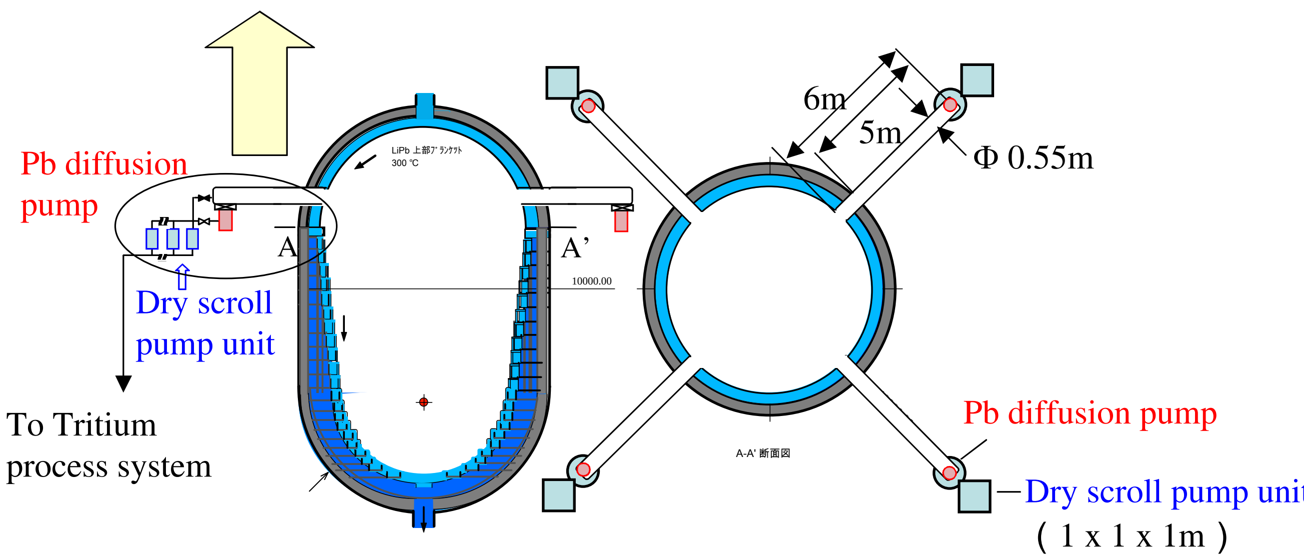


Configuration of a vacuum pump set



A set of 3 rotary shutters and buffer gas will be used to protect the final optics from the bluster wave.

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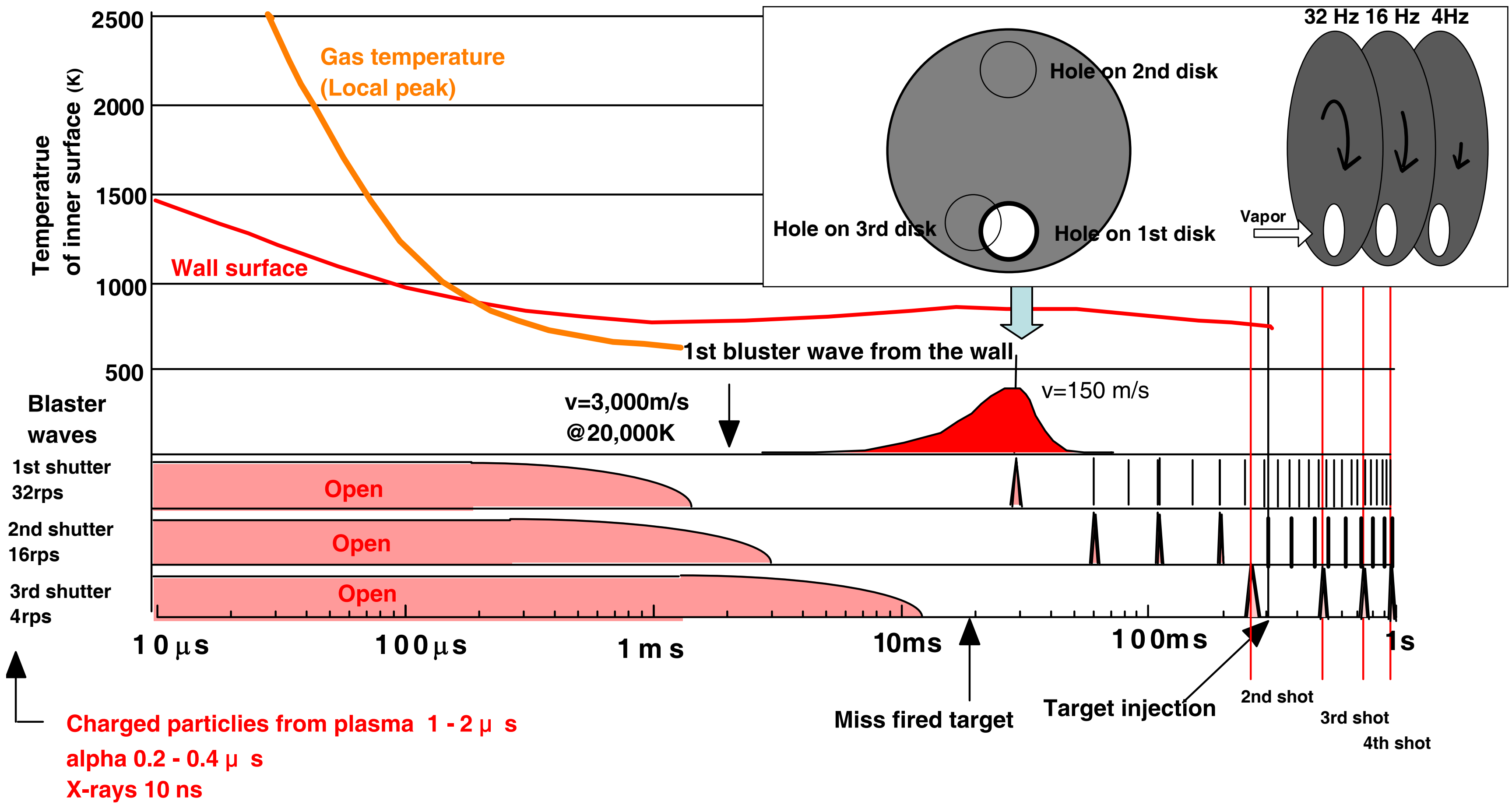

Vapor coming into the beam duct can be stopped with 0.1Torr D_2 buffer gas.

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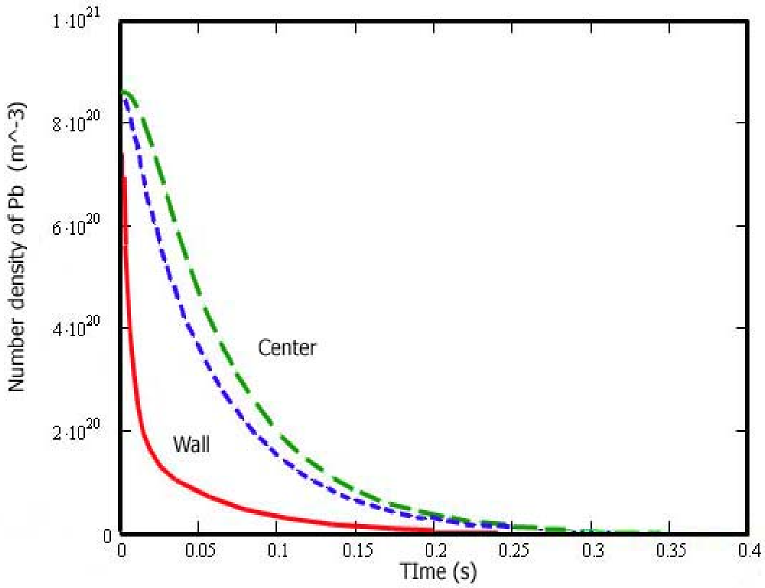
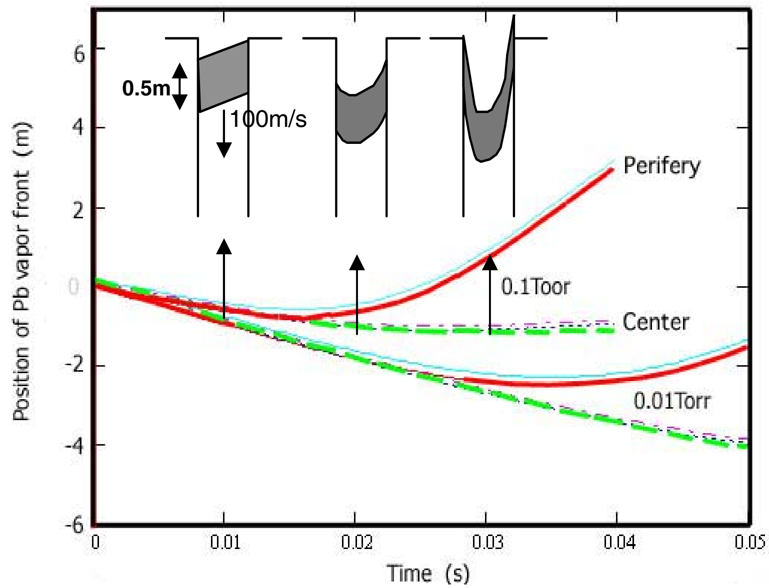




- The speed of vapor is decelerated from 100 m/s to 30 m/s before the plume breaks due to RT instabilities.
- Mass of Pb vapor coming into the beam duct is10mg/shot, that means 1 ton/year ! Periodic cleaning in necessary.

Outline

- Introduction
  - Fast ignition
  - Core plasma
- Chamber and plant
- Laser system
  - Cooled, ceramic Yb:YAG
  - Beam distributor
- Fueling system

Key technologies of laser for FI fusion plant

ILE, Osaka

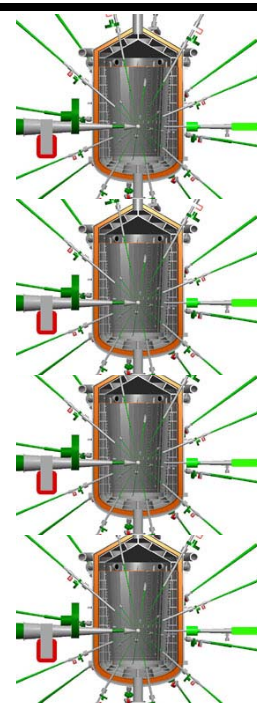
Foot pulse to form pre-plasma
- 32 beams
  - Controlled focus pattern
- 2 ω
- wide band
- coherent during amplification
  - in-coherent at focus point

Main pulse for compression
- 32 beams
  - Controlled focus pattern
- 3ω
- wide band
- coherent during amplification
  - low-coherent at focus point

Lasers

16Hz

Distributor



Heating pulse
- 1 beam
  - coherently bundled
- ω
- wide band
  - OPCPA
- Pulse compression
  - Grating

Common technologies for compression and heating lasers
- main amplifier
  - laser material, LD
  - Structure, optical shutter
- beam switching
  - Laser : 16Hz, reactor : 4Hz
- Optics with multi-coating

Basic specification of lasers for reactor

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	Compression laser	Heating laser
Wave length	3ω	ω
Energy/pulse	1.1 MJ	100 kJ
Pulth width	TBD	30 ps
Pulse shape	Foot pulse + Main pulse	Flat top (2 ps reise time)
Beam number	32	1 bundle
F number	depends on plant design	F/10～20
Uniformity	1 % (foot pulse)	-----
Spot size	Controlled focusing pattern	≤ 50 μm
Rep-rate	16 Hz	16 Hz

Cooled Yb:YAG was chosen for the laser material.

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	Compression laser		Heating laser
	Main pulse	Foot pulse	
Wavelength	UV (3ω) 343 nm	Visible (2ω) 515 nm	IR,1030 nm
Bund width	Narrow band	Wide band 1.6 THz	Wide band (Flat top pulse) ~3 nm
Efficiency	8 - 10 %	Not so important	~ 4%
Laser material	Cooled Yb:YAG ceramic		
Method for wide bund	Arrayed beams with different wave length ~0.1 nm@1030 nm (0.08 THz@343 nm)	One beam of arrayed beams Wide band OPA pump light: 3w	Wide band OPCPA Large KDP pump light: 2w band width≈100nm

OPA: Optical Parametric Amplification
OPCPA : Optical Parametric Chirp Pulse Amplification

Characteristics of Nd:YAG and Yb:YAG as materials for high power laser

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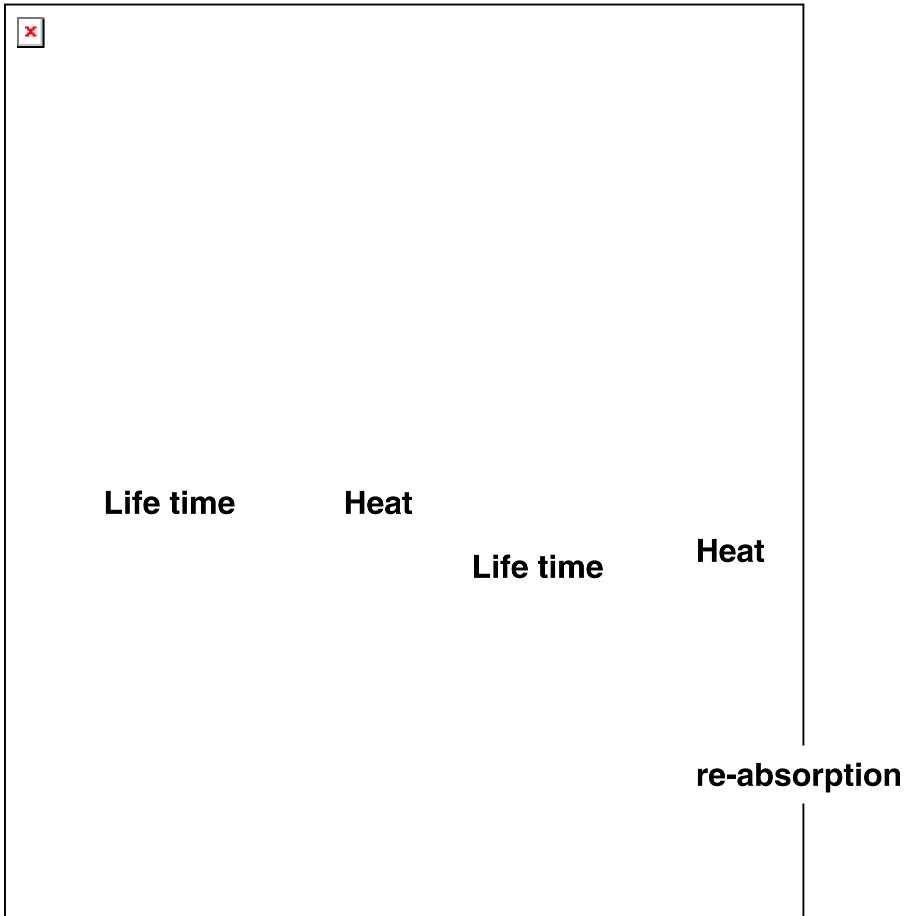

Advantage of Yb:YAG

Close wavelength of oscillating light to pumping light
⇒low heat generation

Long fluorescent life time of upper level
⇒easy to store energy

Wide absorption spectrum
⇒ easy to pump with LD

Wide fluorescent spectrum
⇒short pulse amplification

Disadvantage

Small cross section for stimulated emission
⇒high saturation flounce

Quasi three level system
⇒energy loss due to re-absorption

Why cooled Yb:YAG?

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Disadvantage

~~Small cross section for stimulated emission~~

~~⇒high saturation fluencies~~

~~Quasi 3 level system~~

~~⇒Gain loss due to reabsorption~~

Larger cross section for stimulated emission

⇒Lower saturation flounce

Four level system

⇒Higher efficiency with low pumping

Higher thermal conductivity

⇒Smaller thermal strength

⇒Appropriate characteristics for high intensity, average power laser

Cooled Yb:YAG ceramic is promising as the laser driver material

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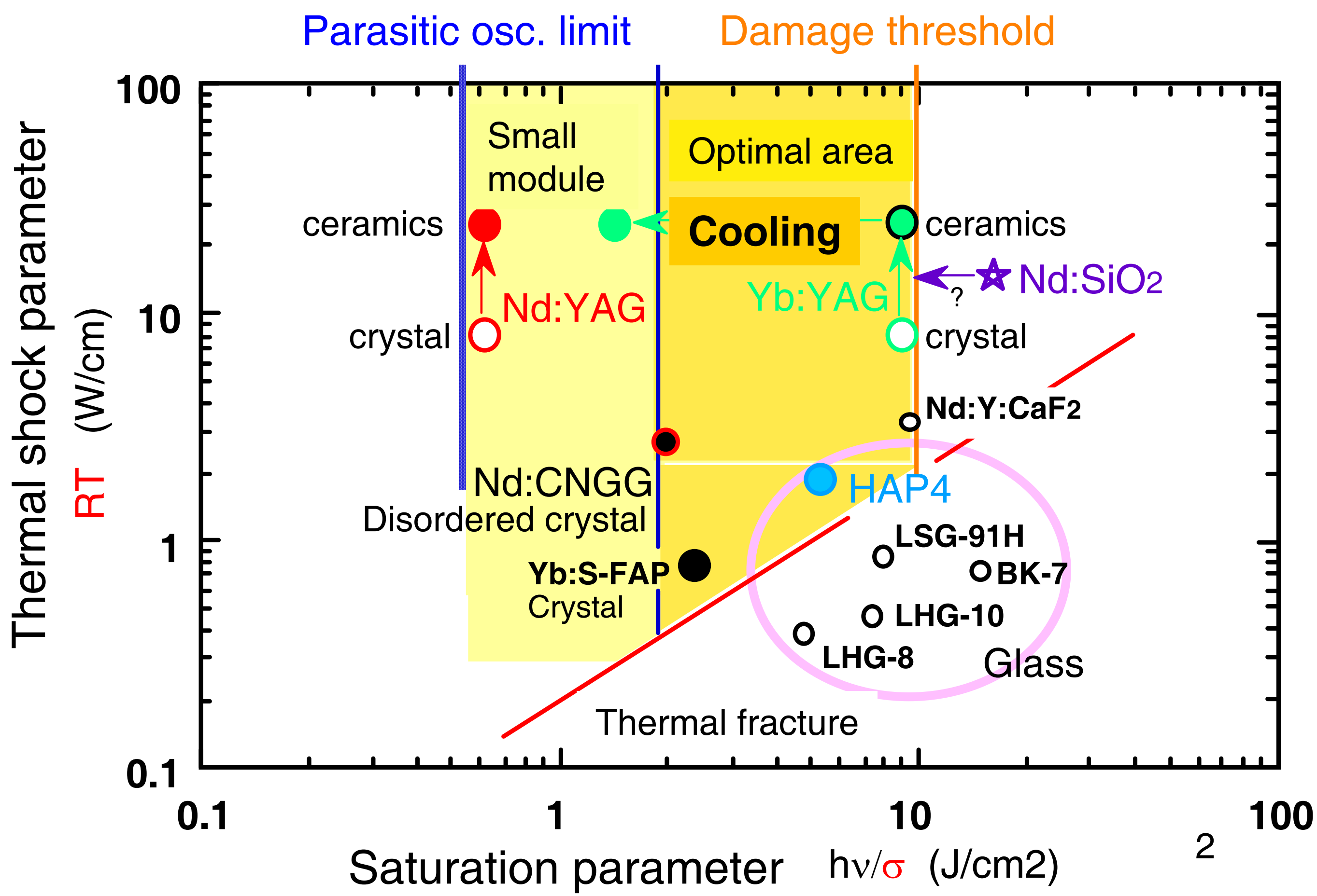

Artificial control of emission cross section → **Cooled Yb:YAG ceramic** ← Practical use of ceramic technology

Demonstration of high efficiency by cooling

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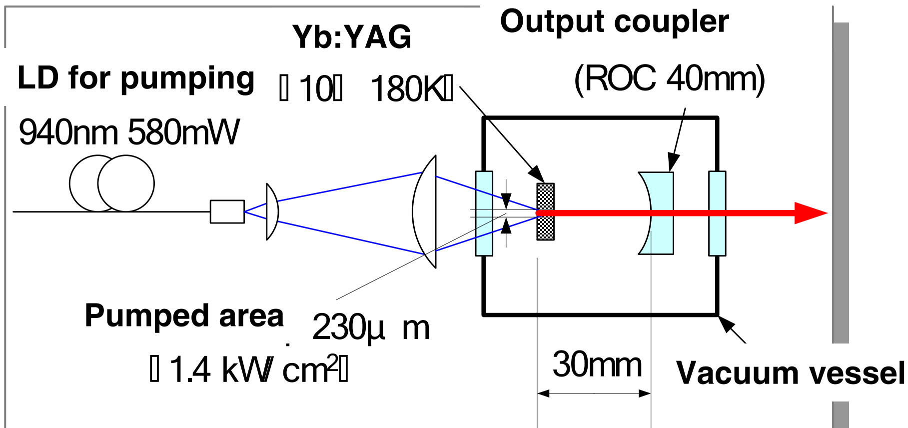

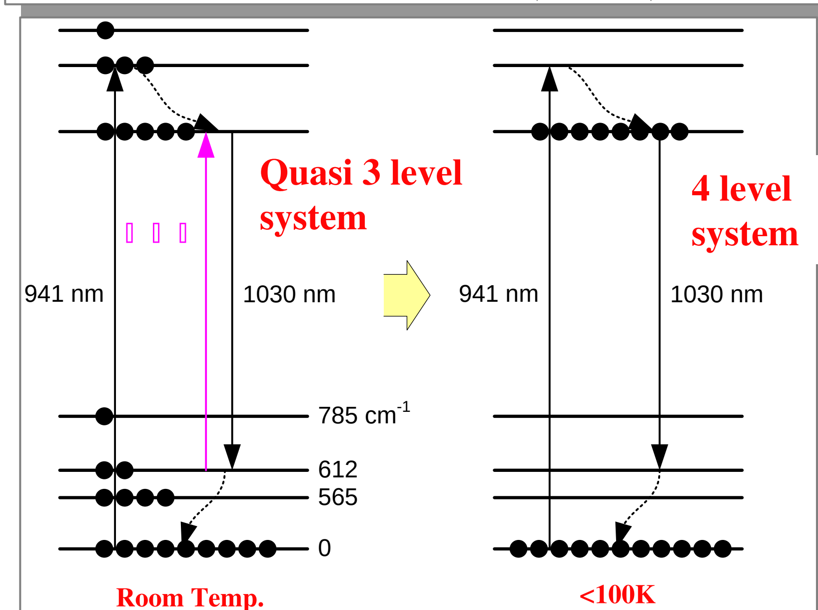

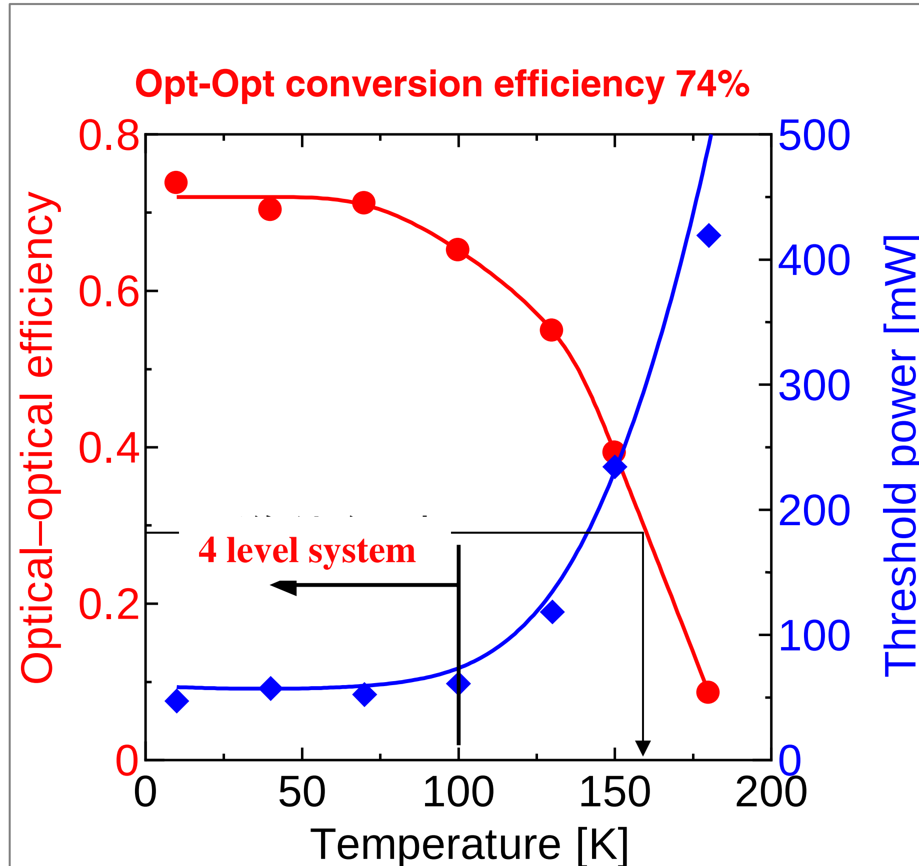

We demonstrated high beam quality (M^2<1.4).

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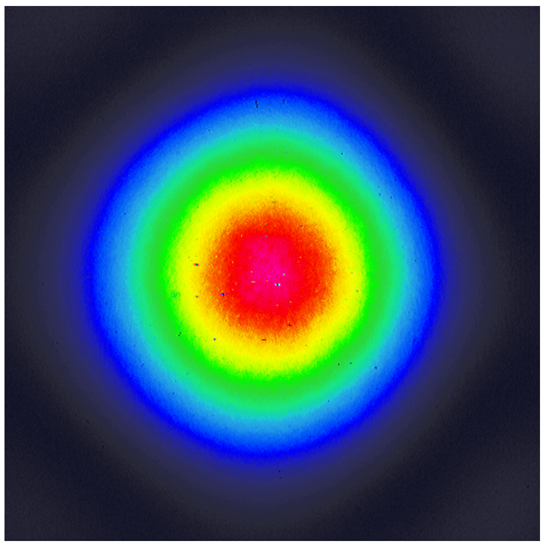
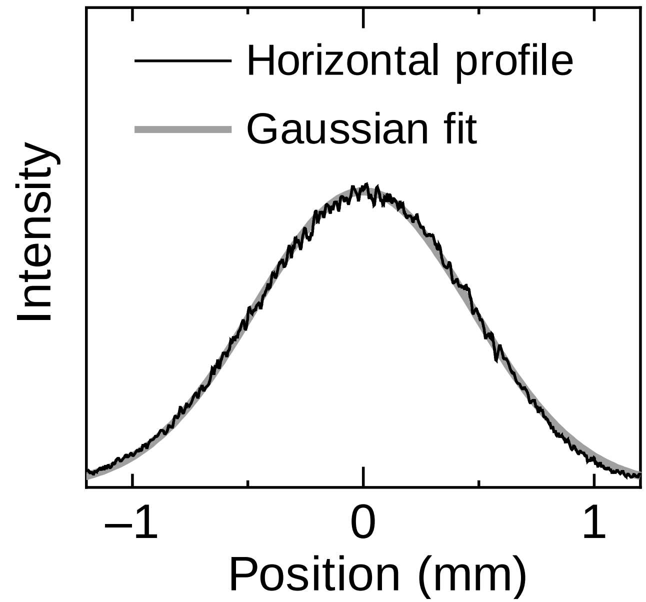
Beam quality $M^2<1.4$





$$M = \frac{\textbf{Experimental focusable spot size}}{\textbf{Ideal focusable spot size of Gaussian beam}}$$

Estimation of laser efficiency

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Implosion laser :

Total efficiency : 11.4%

LD eff. = 60%, optical-optical eff. = 30%, (@160K)

THG eff. = 70%, transfer eff. = 90%

Heating laser:

Total efficiency : 4.2%

LD eff. = 60%, optical-optical eff. = 30%, (@160K)

SHG eff. = 80%, OPCPA eff. = 40%,

compressor eff. 80%, transfer eff. = 90%

Cooling of amplifier :

Thermal load of 5% of electric input power to LD

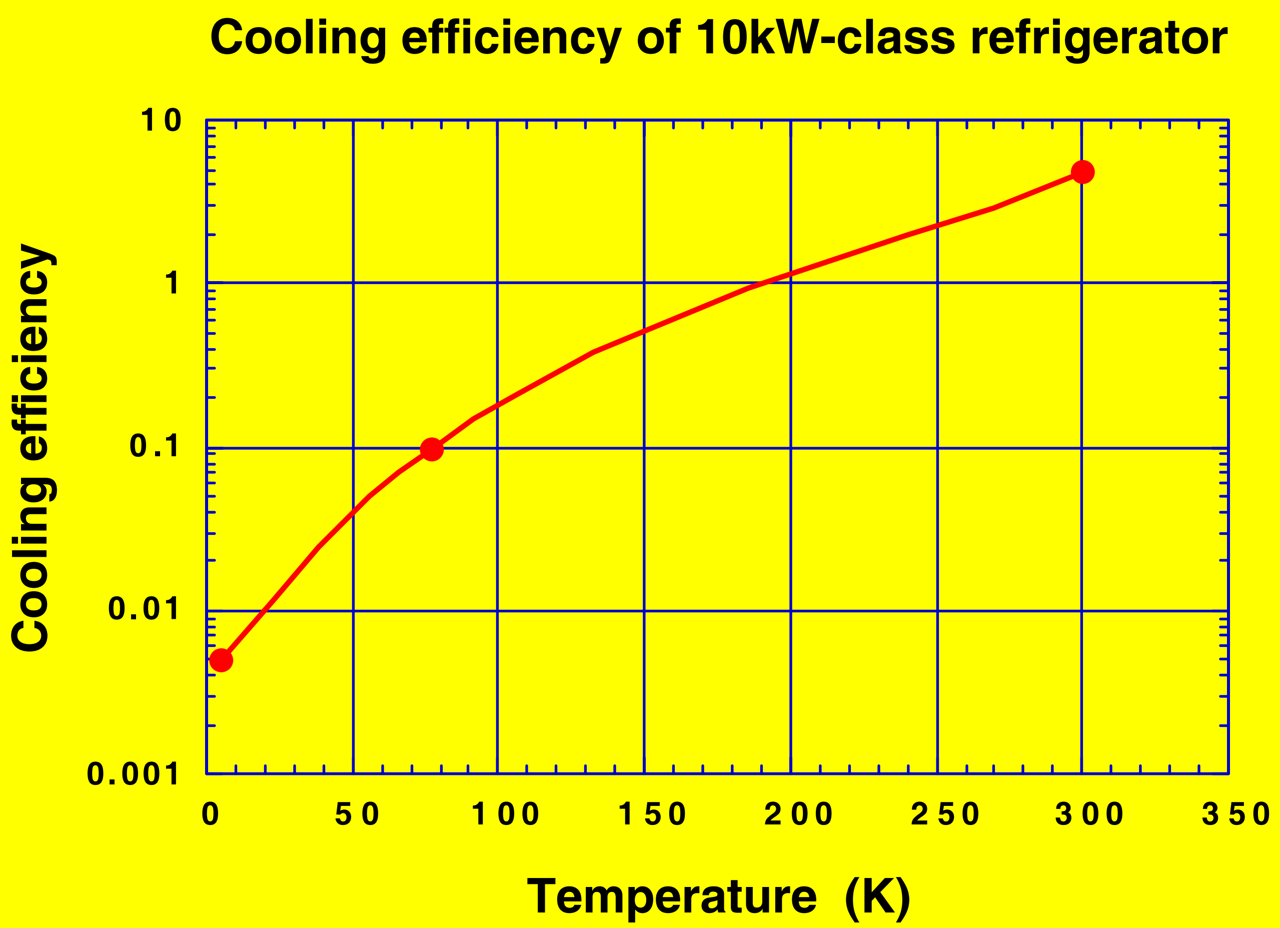
Cooling efficiency = 30% (safely assumed, 60%@160K)

Total efficiency of laser system includig refriierator= 8.7% (9.2%)

- **Supplementary power supply (air conditioner, etc.) is excluded in this estimation.**
- **Improvement of optical-optical eff. is needed.**

Cooling efficiency of large, industrial refrigerator

Osaka



Cooled Yb:YAG has potential to achieve 20% in electricity to laser efficiency.

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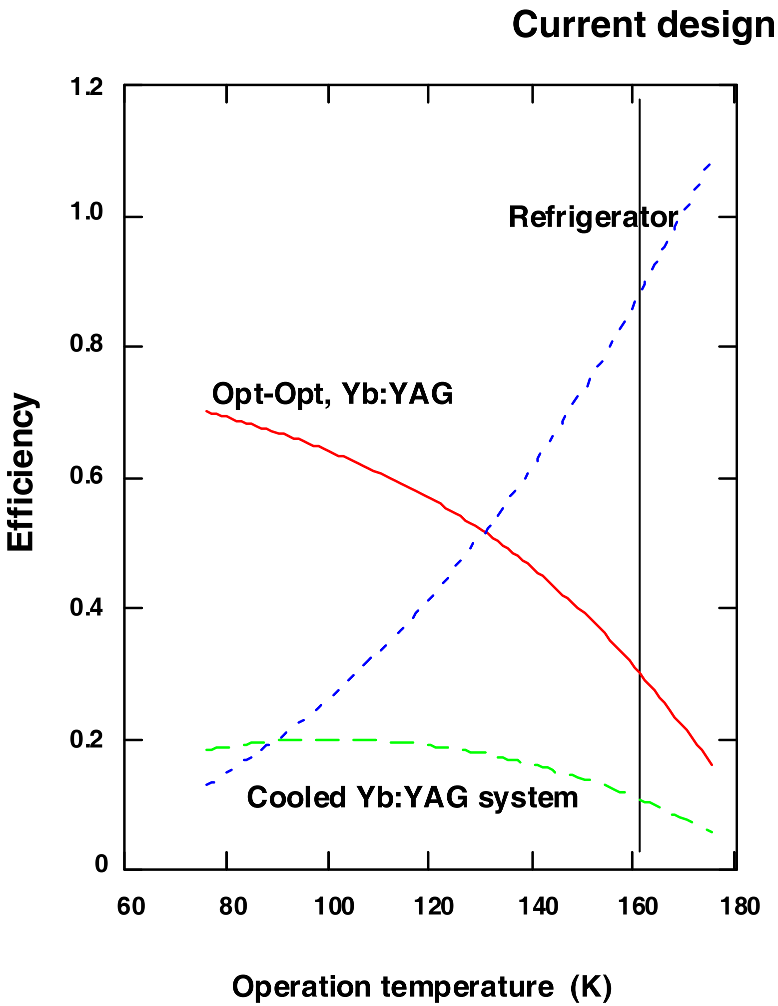

More explore is necessary in;

efficiency of refrigerator,
coolant,
cross section for stimulated emission,
$\delta T/T$
total cost of optics.

Candidates for amplifier architecture

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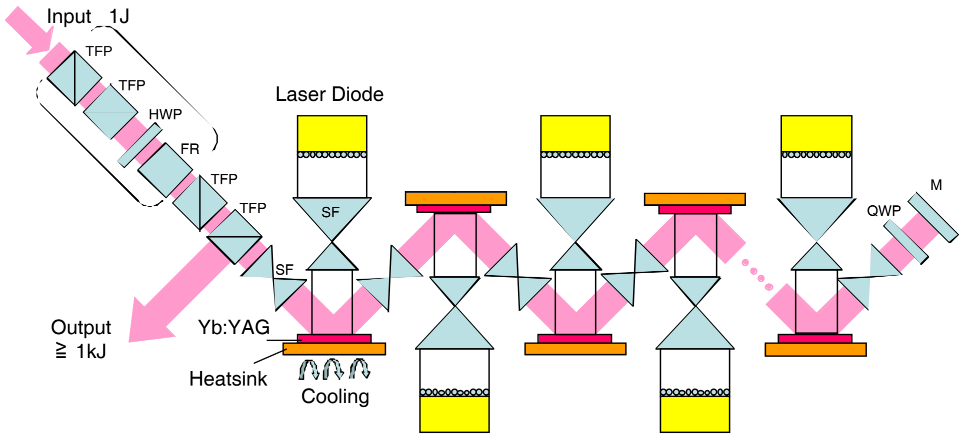
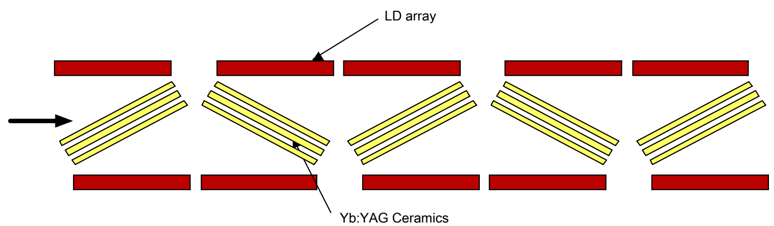
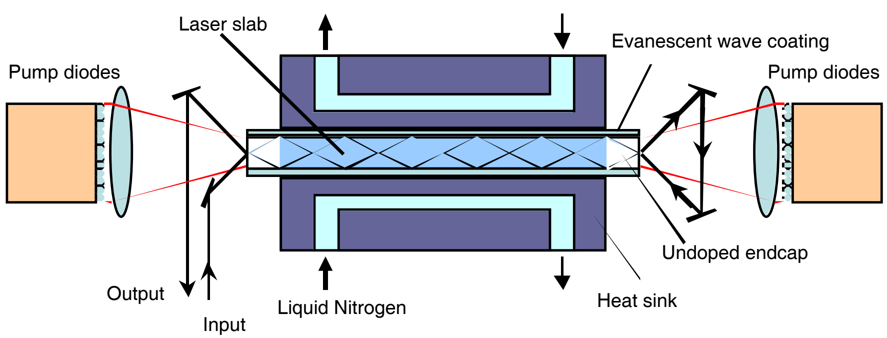
Active mirror



Thin disk



Zigzag slab



Active mirror is practical for arrayed large-aperture amplifier.

Illustration of main amplifier using active mirror concept

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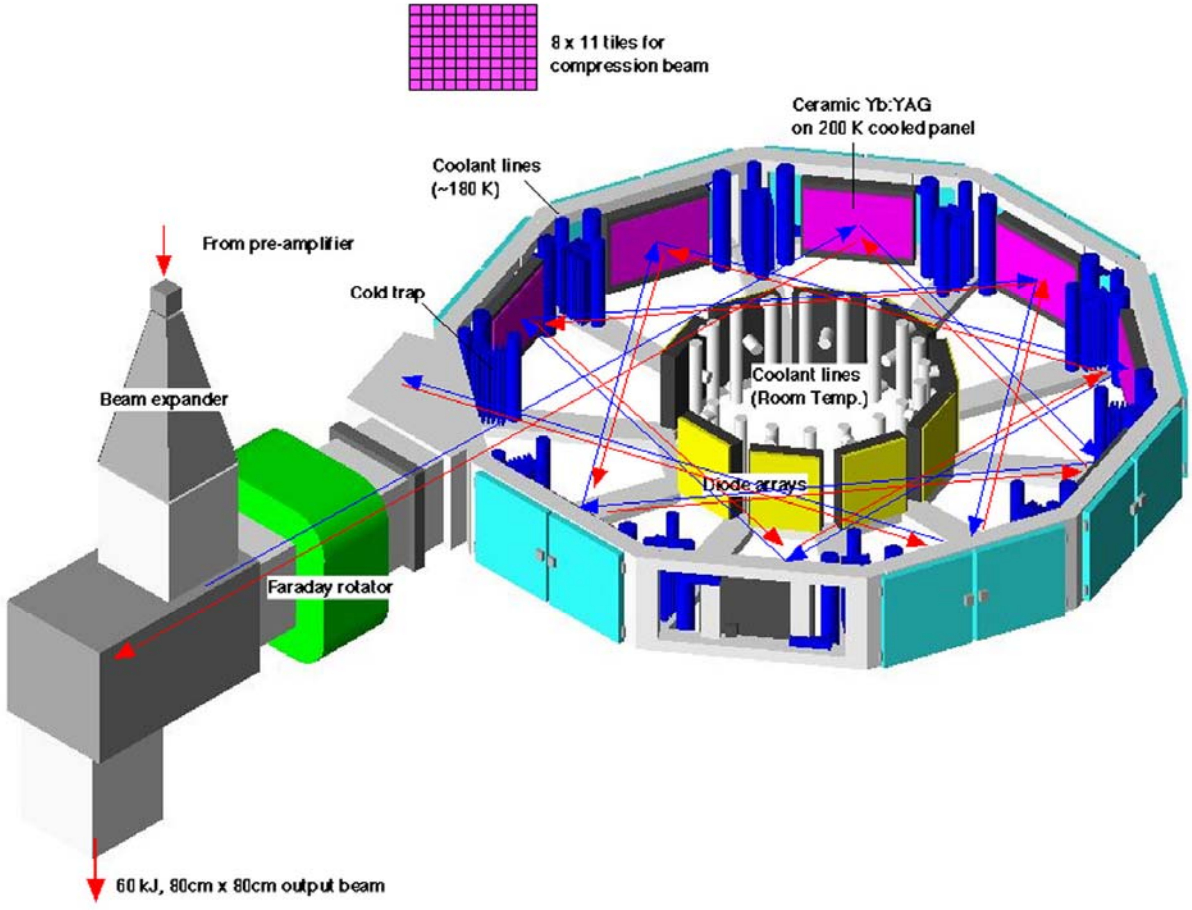
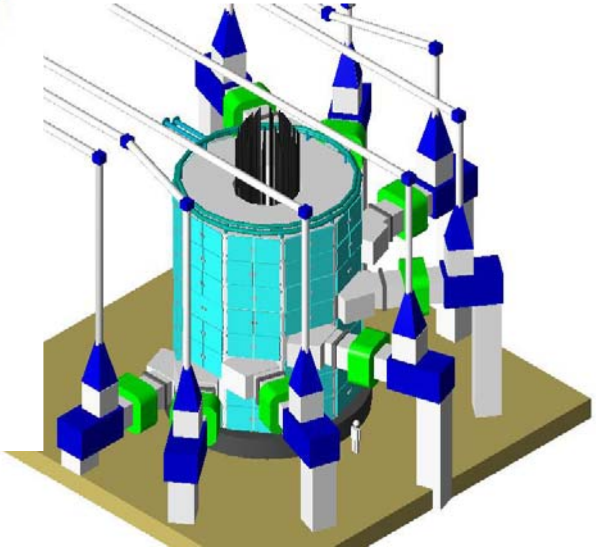


8 beams

(1/4 of a plant)



Beam arrays of implosion and hearting lasers

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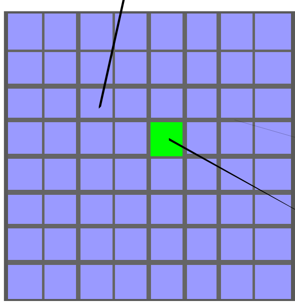
Compression laser beam (343 nm)



$\Delta\lambda$ = 0.1 nm @fundamental ($\Delta\nu$ = 0.08 THz)

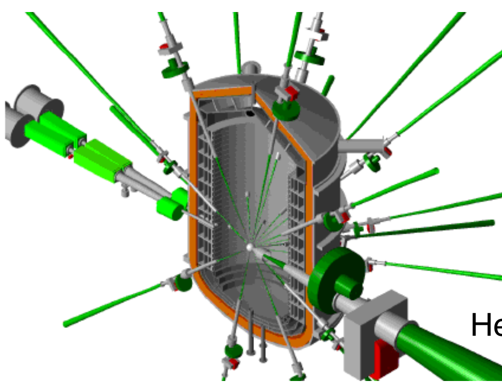
Absorber

Foot pulse beam (515 nm)

8x8 incoherent arrays

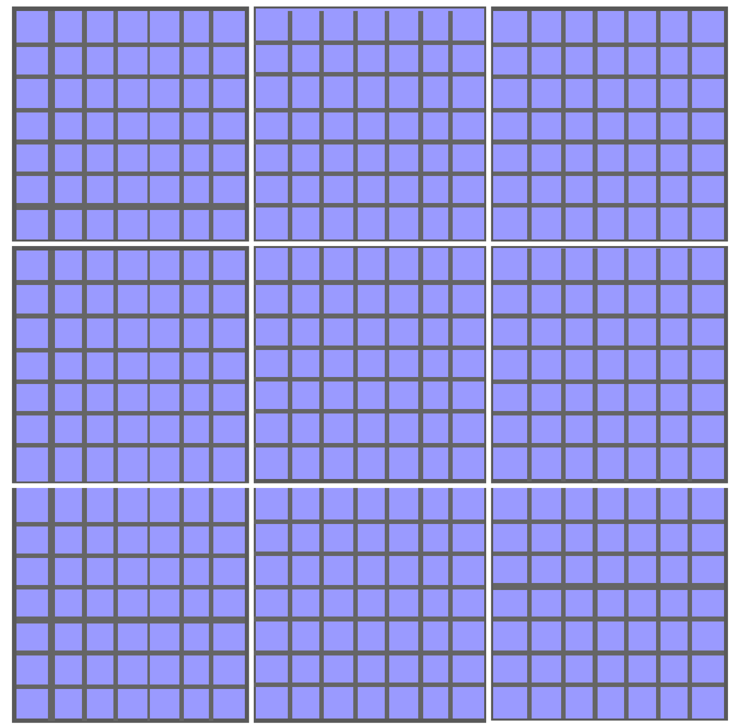
80cm× 80cm,
32 beams

(DT = 10 J/cm^2)



Heating laser beam

Heating laser beam (1030 nm)



210cm× 210cm,
21x21 coherent arrays or
9 bundles of 7x7 coherent arrays

(Grating DT = 3 J/cm^2)

Beam distributor

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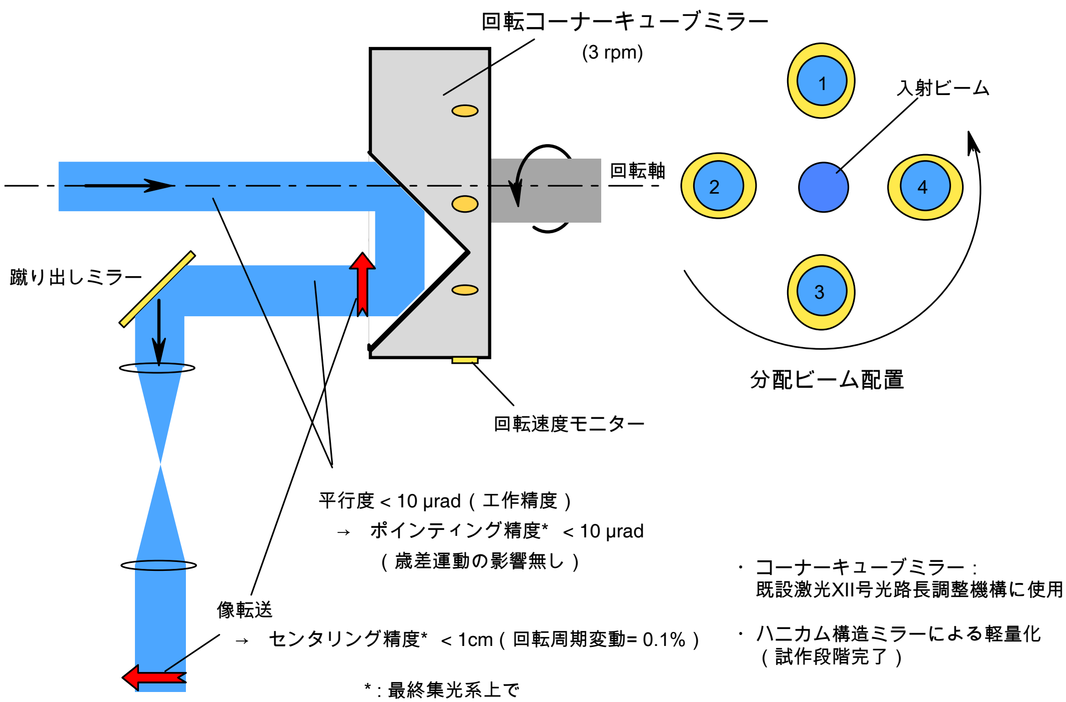
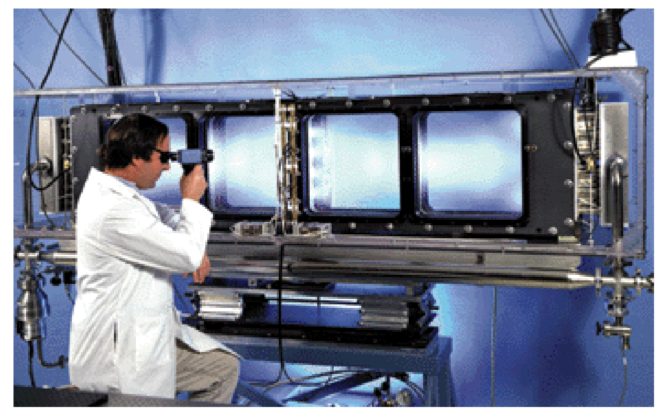
Laser beams will be distributed into 4 module reactors using either rotating corner cubes or plasma electorode optical switchs.



Rotating corner cube



Plasma-electrode optical switch (LLNL)

Outline

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- Introduction
- Chamber and plant
- Laser system
- Fueling system
  - Target design
  - Status of fabrication
  - Batch process

Target for KOYO-F

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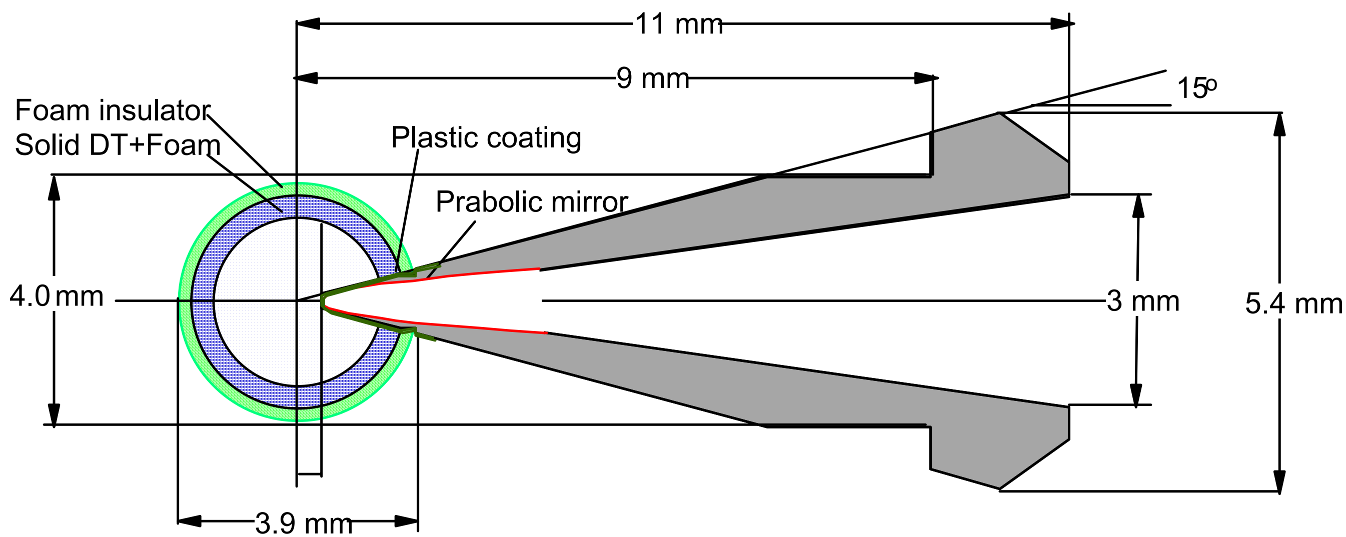
Basic specification	
Compression laser	1.1 MJ
Heating laser	70kJ
Gain	165
Fusion yield	200MJ

Fuel shell	
DT(gas) (<0.01mg/cc)	1,500μm
DT(Solid) (250mg/cc+10mg/cc Foam)	300μm
Gas barrier (CHO, 1.07g/cc)	2 μm
CH foam insulator (250mg/cc)	150 μm
Outer diameter	1,952 μm
Mas of fuel	2.57mg
Total Mas of shell	4.45mg

Cone	
Material	Li17Pb83
Length	11mm
Diameter	5.4 mm
Mas	520 mg



The cone works as a focusing device of the heating laser.

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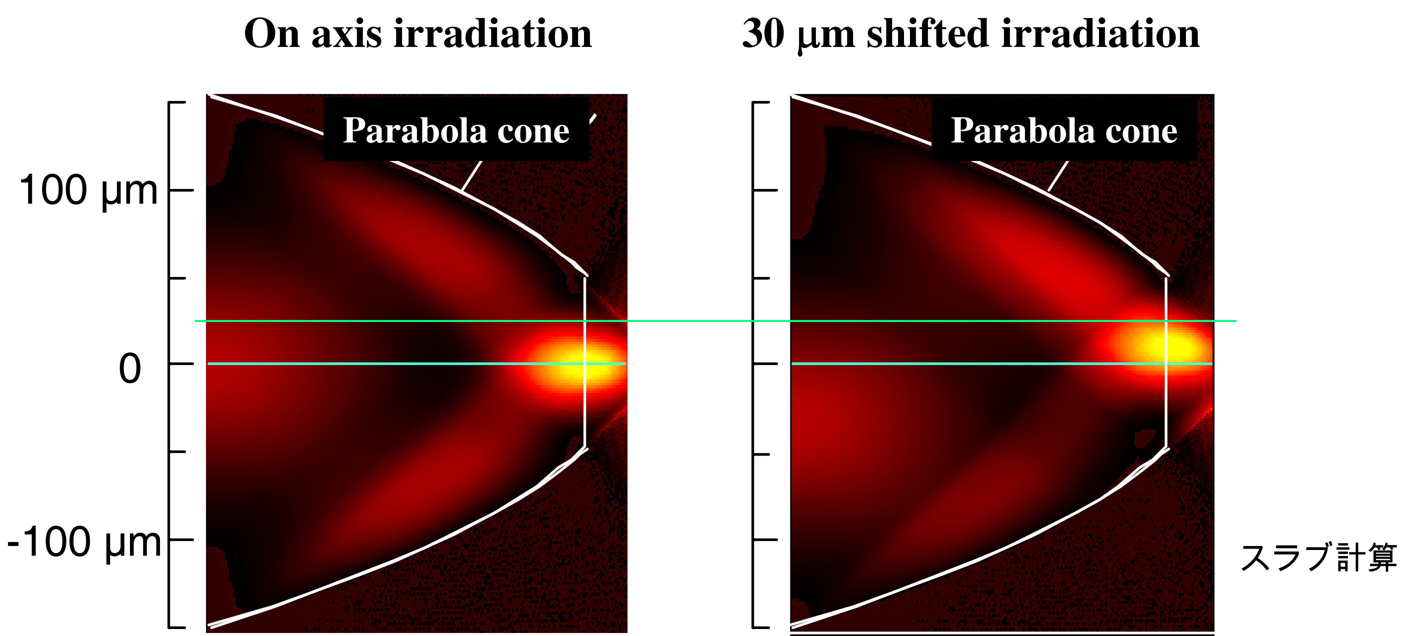
- Heating laser must be focused on a 30μm diameter spot.
- Heating laser
  - Beam size : 2 m×2 m
  - Distance between target and focusing mirror ≈ 50 m
- Accuracy of target injection is not known.

→ **Assistant focusing mechanism is necessary.**



Mass production of target is remaining issue but the elemental researches are promising.

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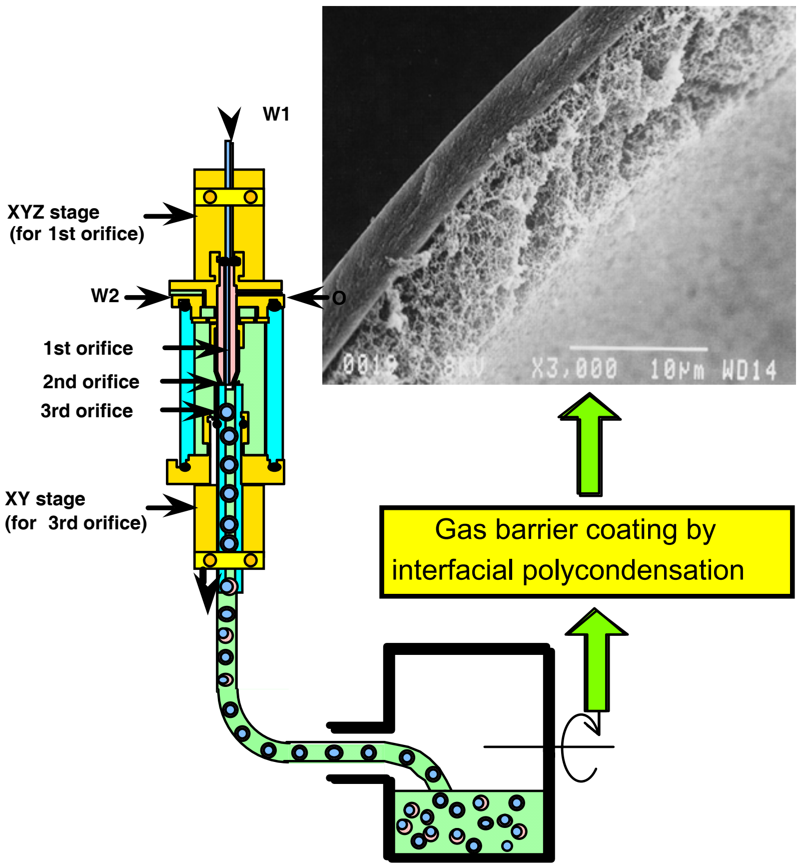
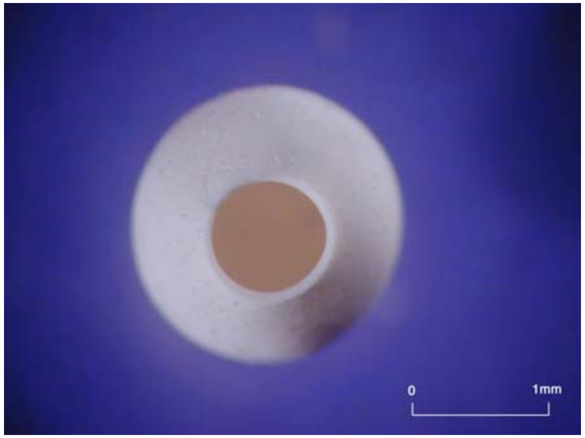
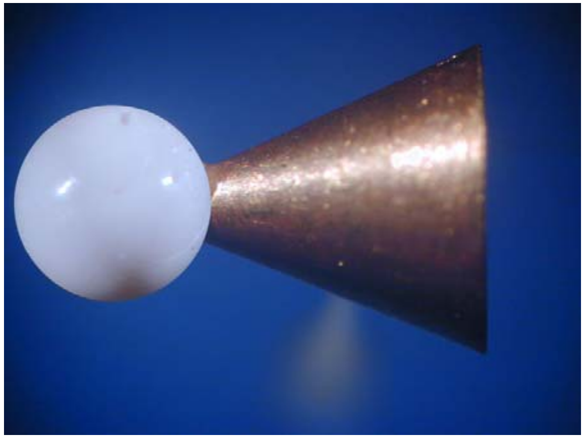
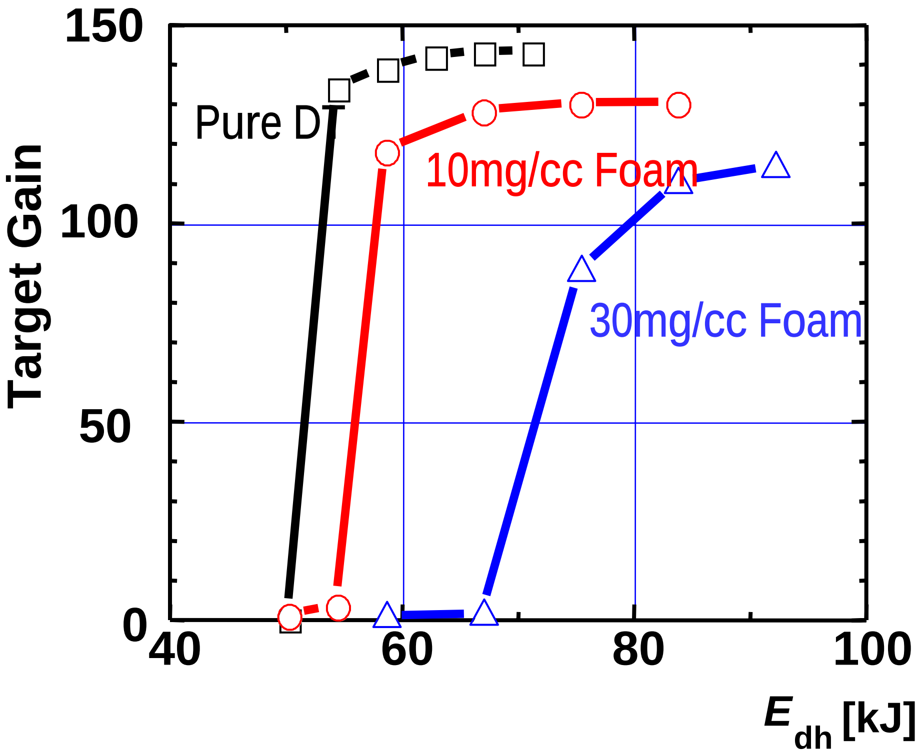






Low density foam is the key of FI target.



Driver Energy for Core Heating,

(By Dr. Johzaki et al)

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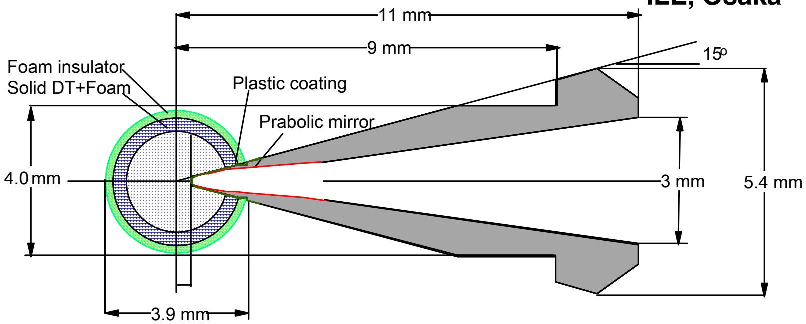

- **When the foam density is 10 mg/cc, the energy of heating laser is increased from 50 kJ to 55 kJ.**
- **Our final goal is to develop 10mg/cc foam shells. (Our achieved data, 43 mg/cc for shell and 5 mg for block)**

Fuel loading system by thermal cavitation method.

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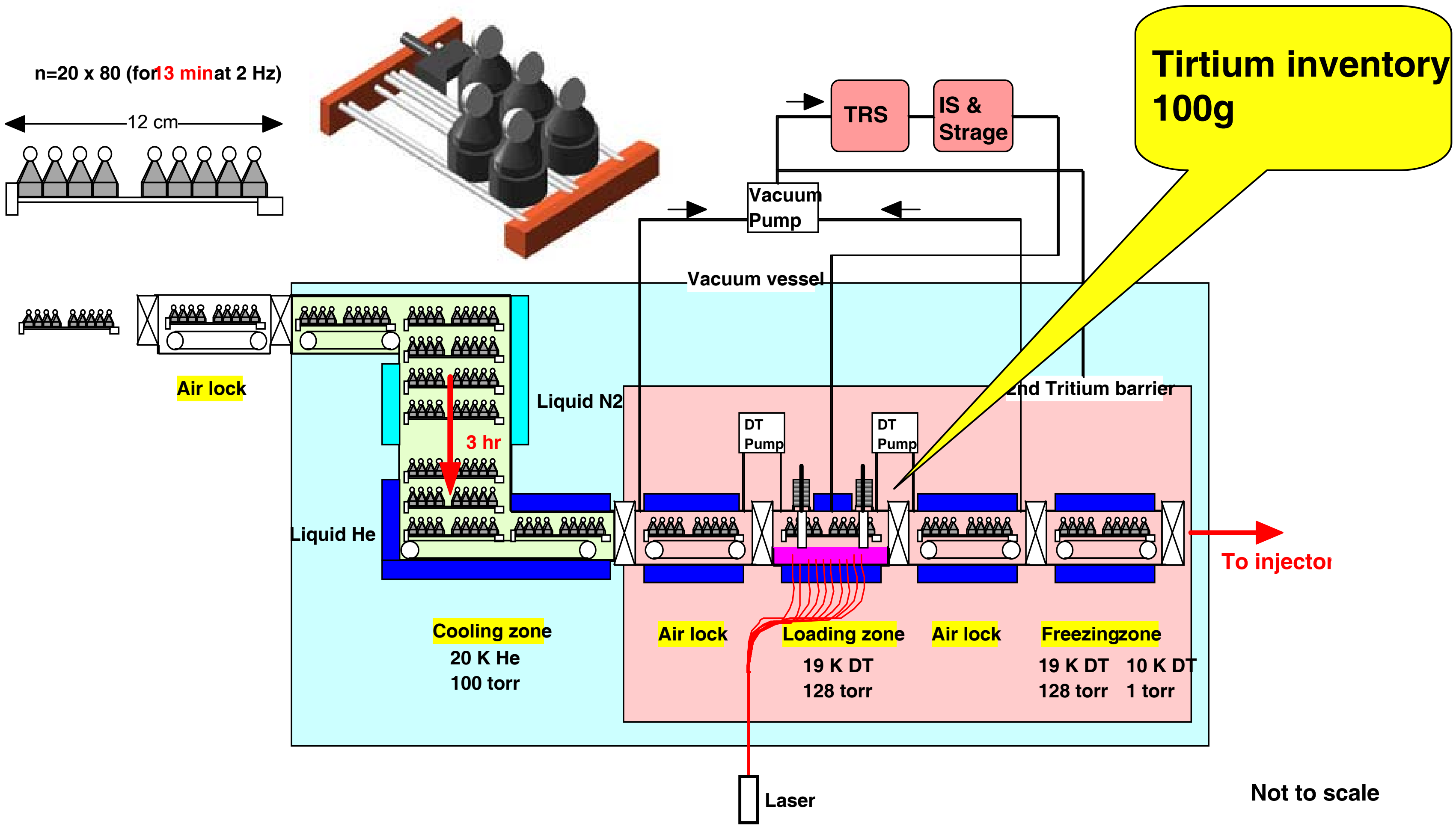

Not to scale

Step 1 Saturation of foam with liquid DT

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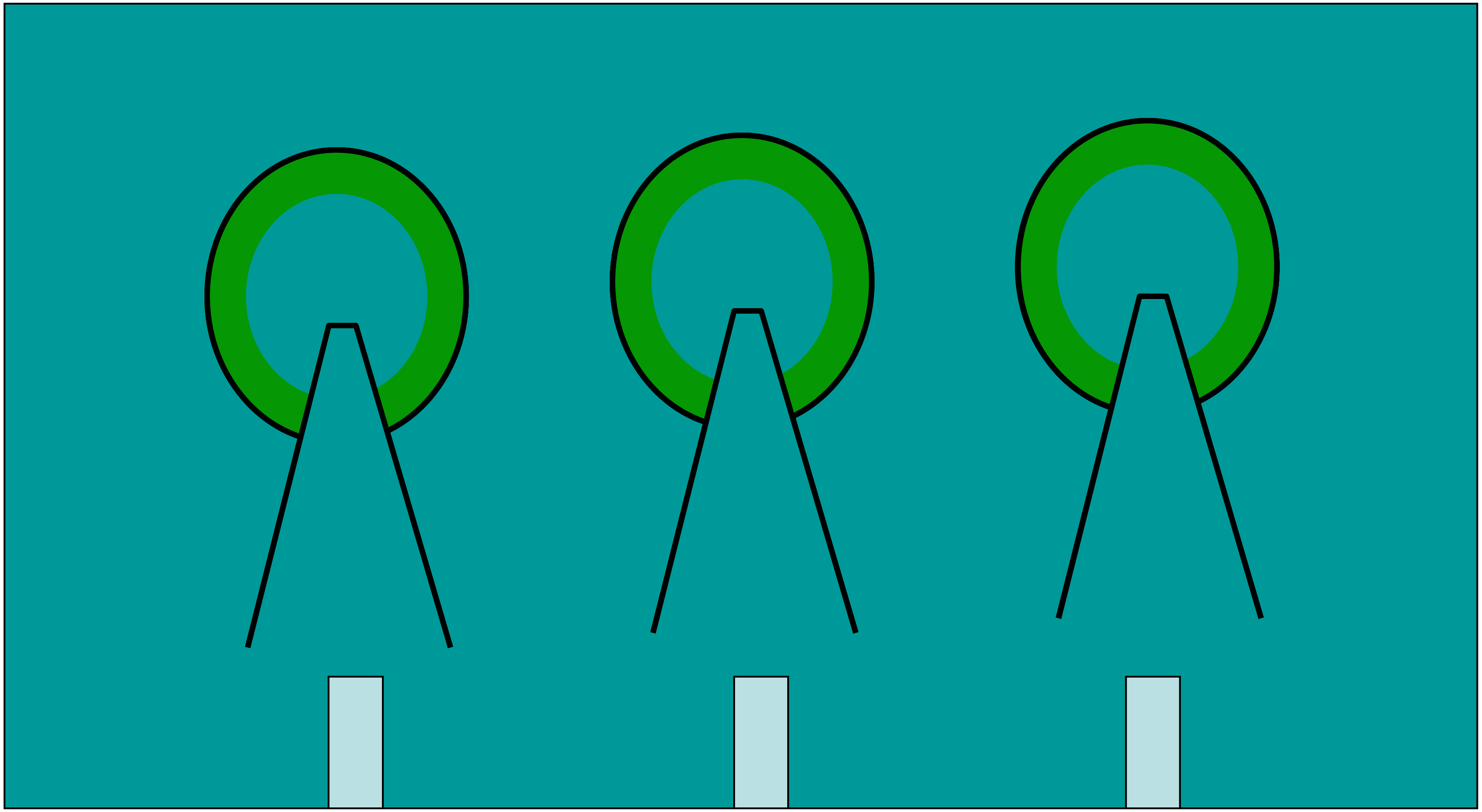

Step 2 Evacuation by laser heating

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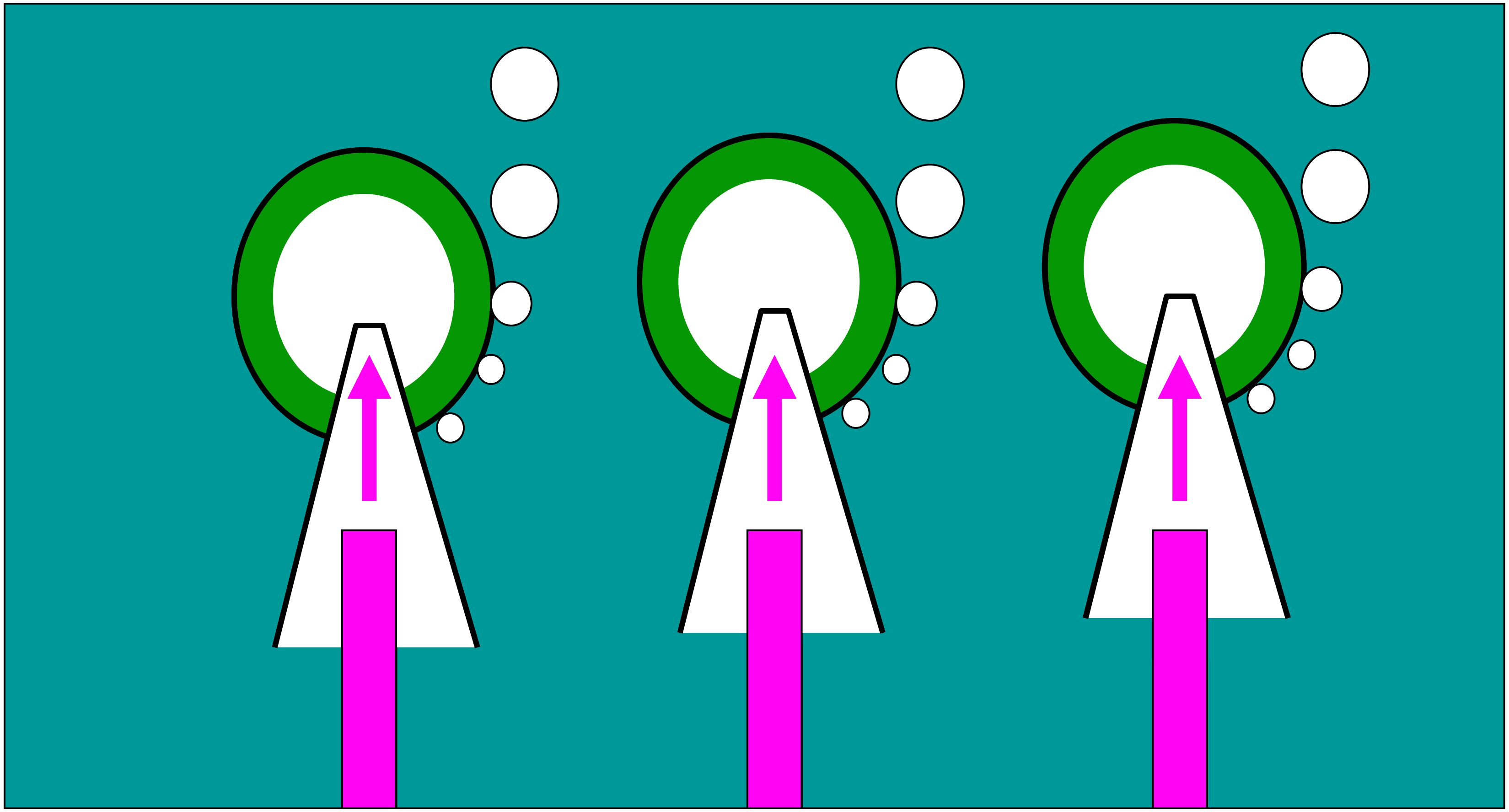

Step 3 Finish

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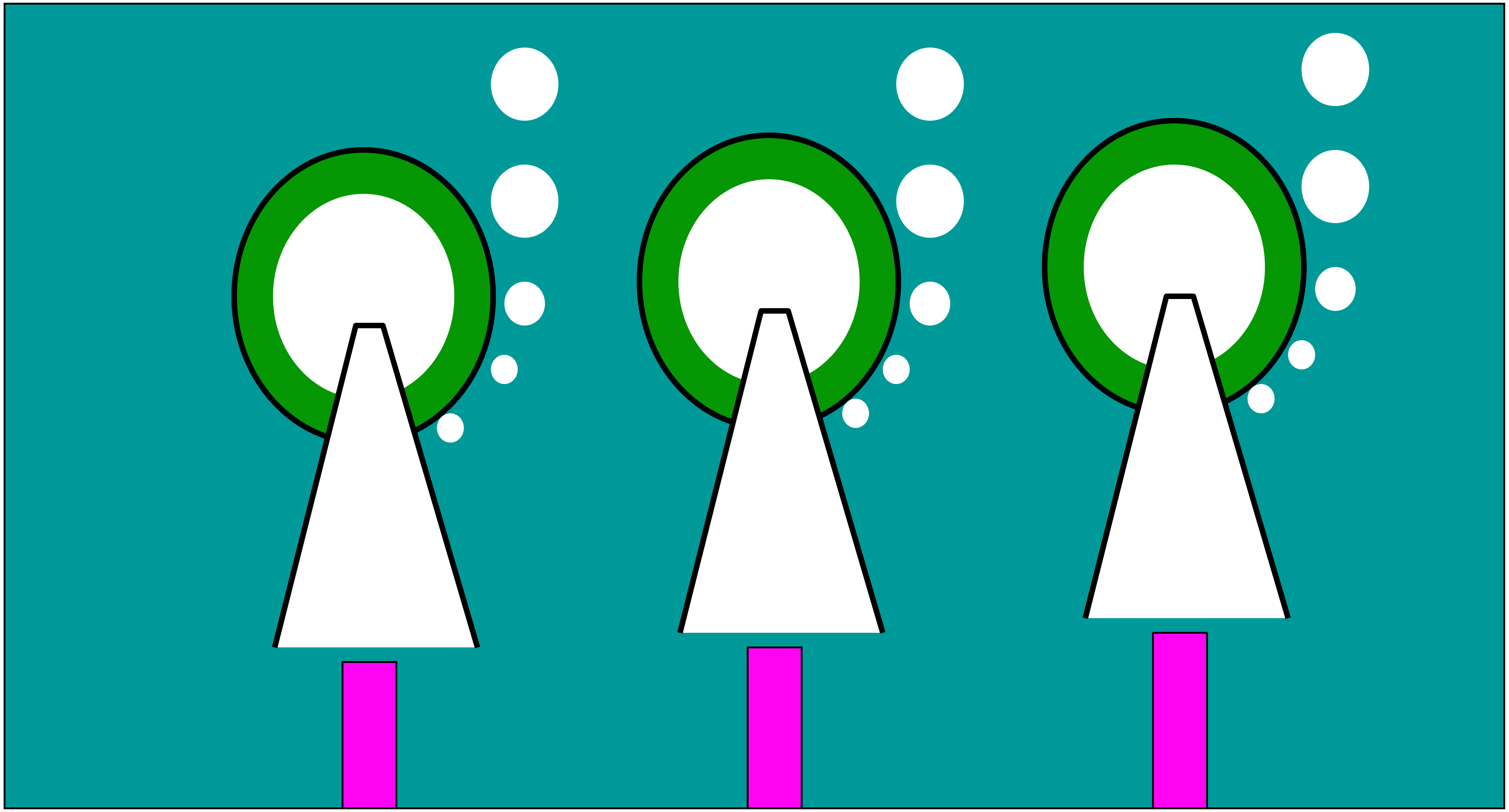

Hybrid injector for KOYO-F

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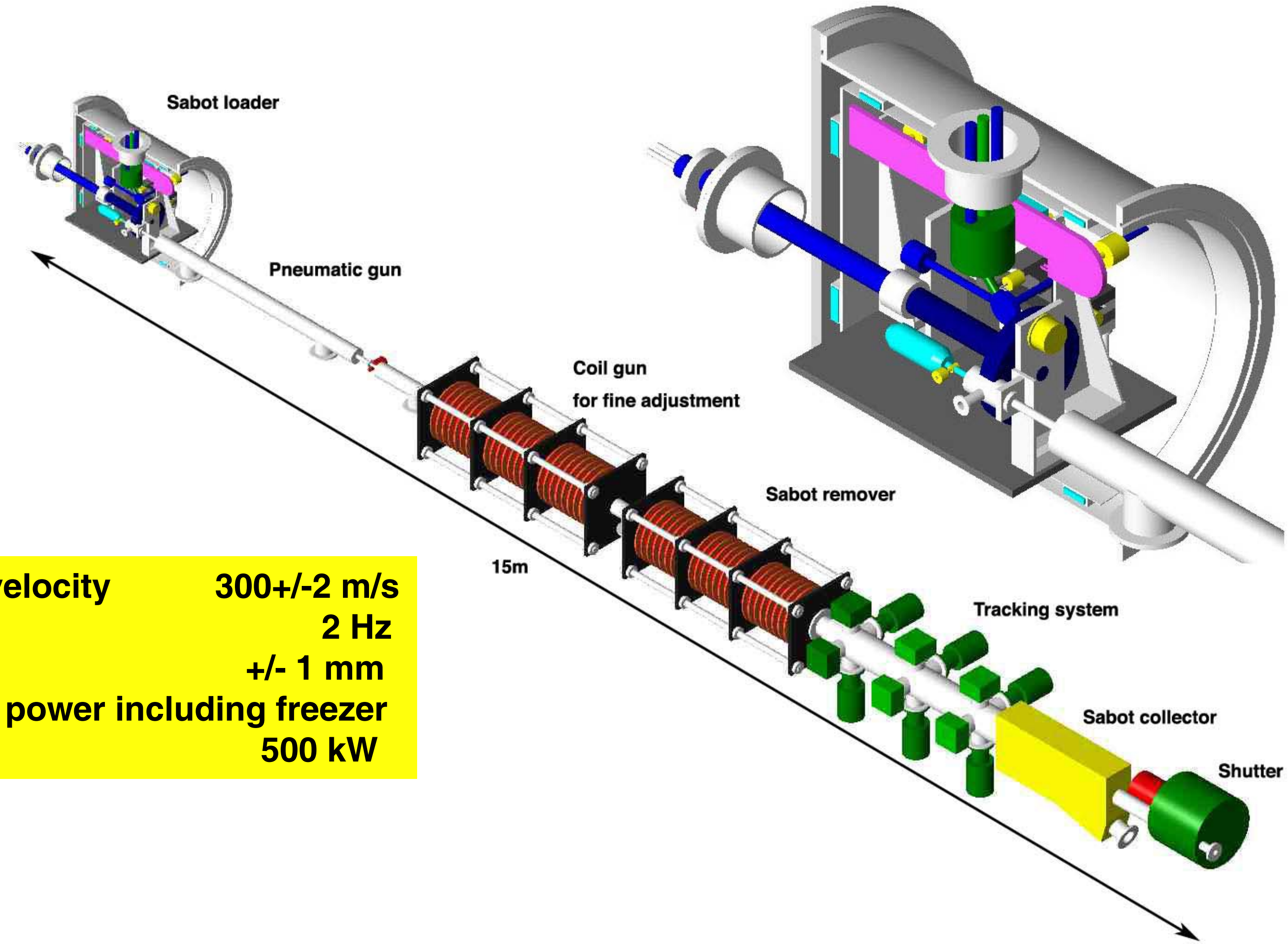

Injection velocity	300+/-2 m/s
Rep rate	2 Hz
Pointing	+/- 1 mm
Operation power including freezer	500 kW

Correlational detection by matched filter

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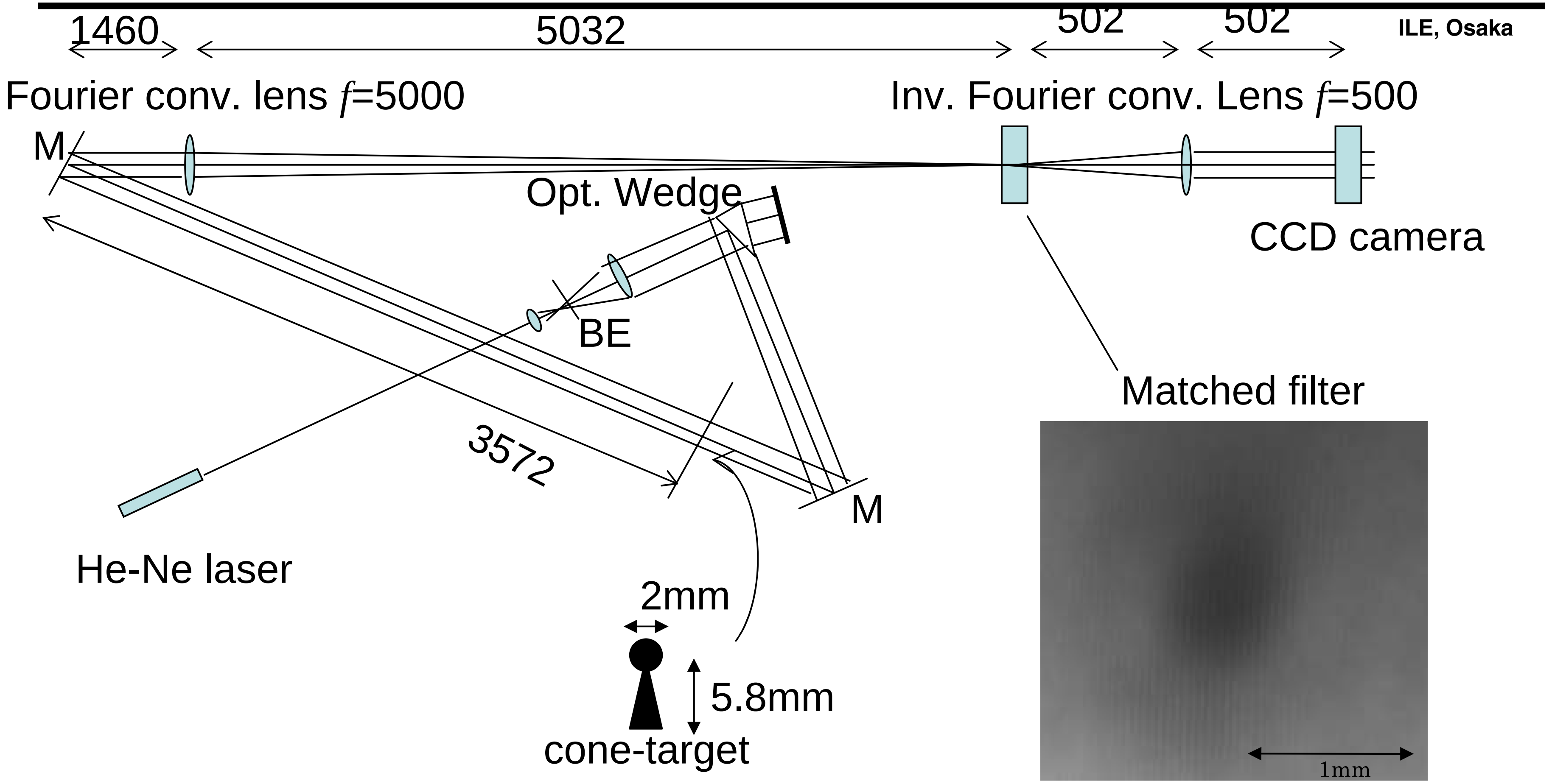

Accuracy of detection was 140 μm at 5 m apart.

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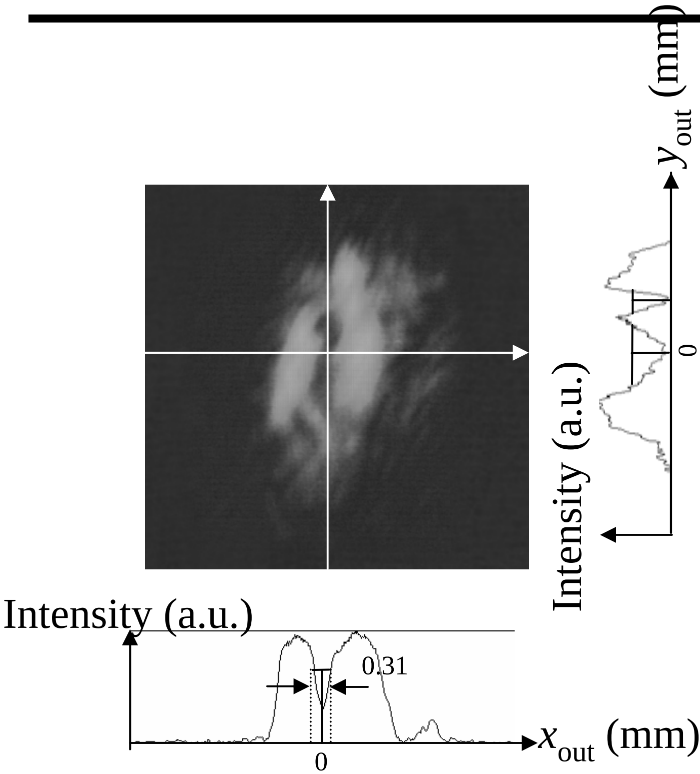

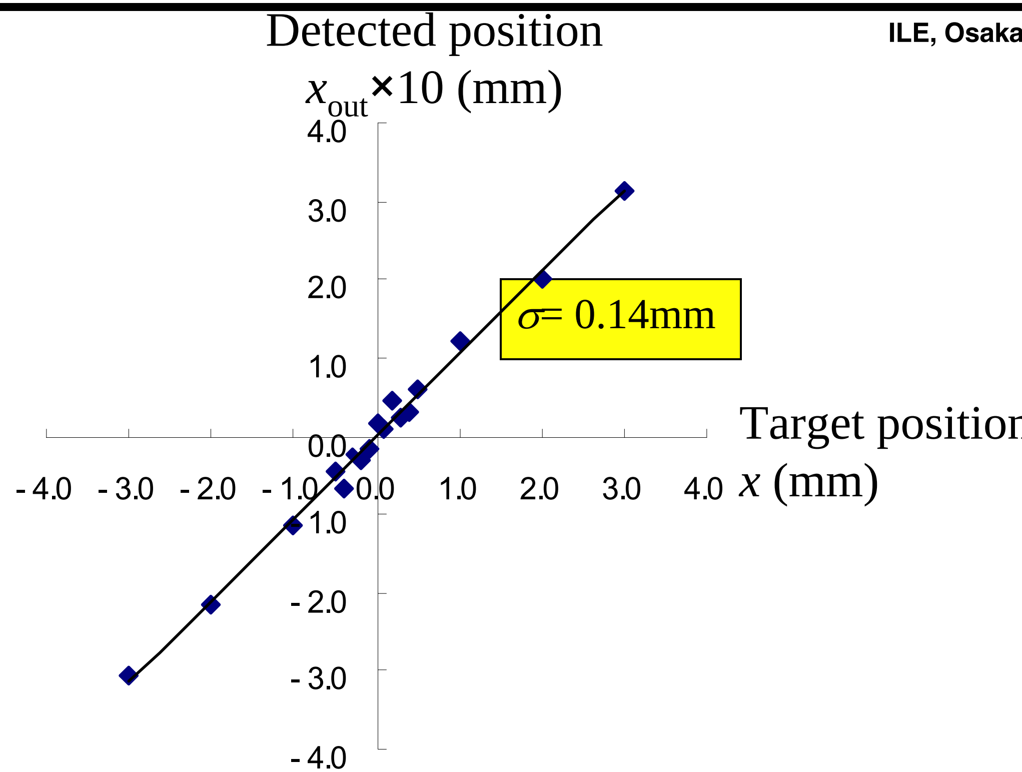

The accuracy will be improved with

- uniform irradiation,
- f-number,
- linearity of film to make filter.

Summary

- 1) We have examined the design windows and the issues of the fast ignition laser fusion power plants. ~1200 MWe modular power plants driven at ~16 Hz
- 2) For laser driver we have considered the DPSSL design using the Yb:YAG ceramic operating at low temperature (100~200K).
- 3) We have proposed the free fall cascade liquid chamber for cooling surface quickly enough to several Hz pulses operation by short flow path. The chamber ceiling and laser beam port are protected from the thermal load by keeping the surface colder to enhance condensation of LiPb vapor.
- 4)For exhausting DT gas mixed with LiPb vapor we have designed diffusion pumps using Pb (or LiPb) vapor with effective exhaust velocity about 8 m^3/s DT gas.
- 5) For protecting final optics we have considered the combinations of rotary shutters for stopping neutral vapors and magnets for eliminating ions.

Future work

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- Core plasma
  - Specification for lasers
  - Control of isentrope
- Laser
  - Frequency conversion
  - Phase control
- Reactor system
  - Stability of surface flow
  - Accuracy of injection
  - Tracking and beam steering
  - System integration
- Target
  - Low density foam
  - Accuracy ± 1 %