Proceedings of the 2nd IAEA Technical Meeting on First Generation of Fusion Power Plants: Design & Technology

PPCA.I-1

Concept of Laser Fusion Power Plant Based on First Ignition

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Reactor Design Committee was organized to clarify the feasibility of Laser Fusion Plant based on Fast Ignition by IFE Forum and ILE, Osaka University

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

Core plasma Working Group

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Purpose

1) to make a reliable scenario for the fast ignition power plant basing on the latest knowledge of elemental technologies,
2) to identify the research goal of the elements
3) to make the critical path clear.

KOYO-F is a commercial or very “close to” commercial power plant.

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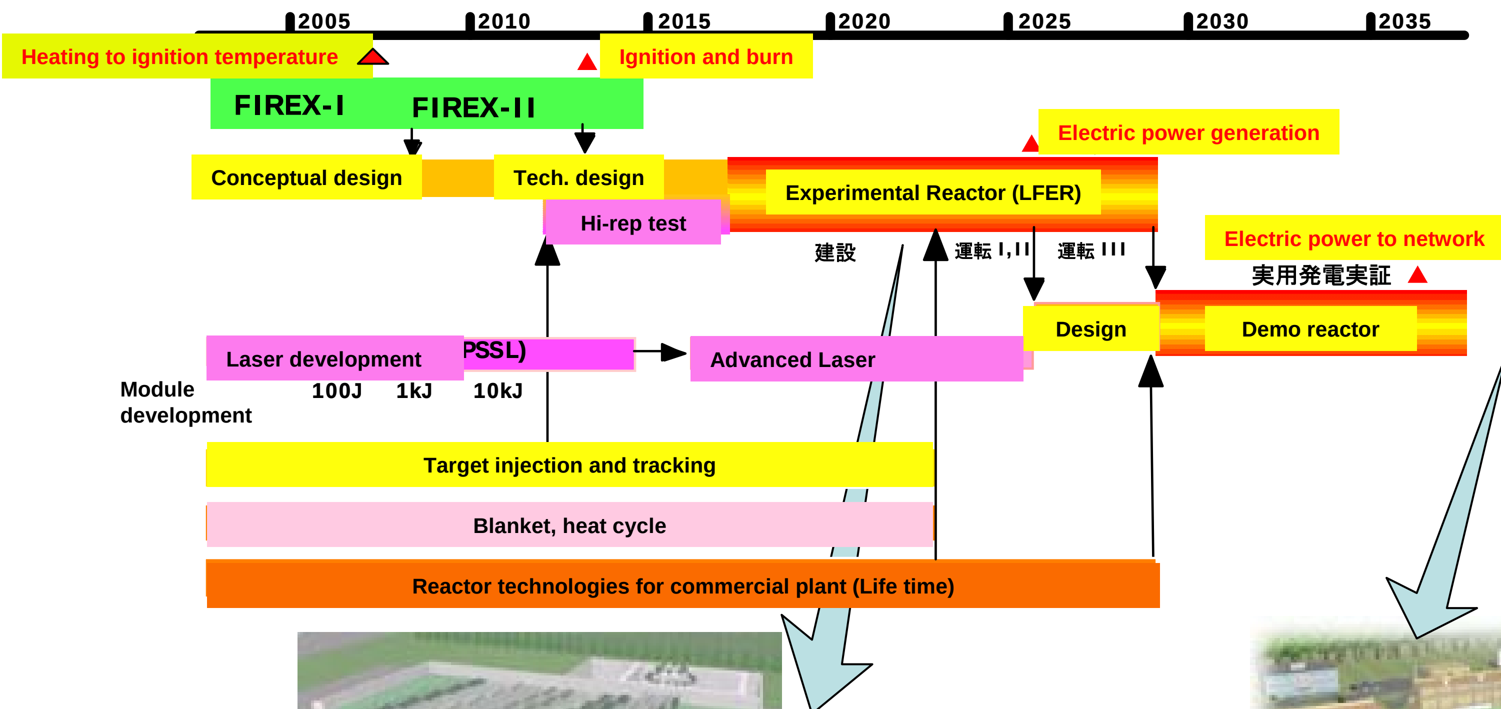
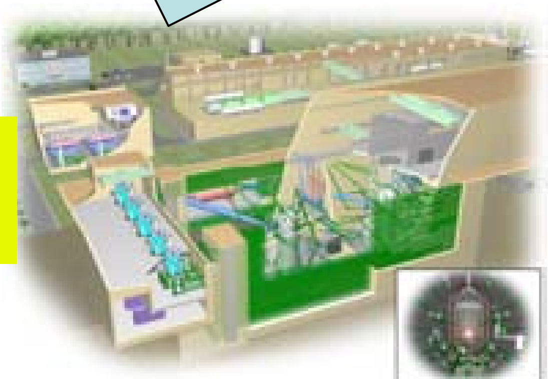
Load map toward Laser Fusion Energy



Laser	200kJ/1Hz
Gain	50
Fusion Yield	10MJ
Electric power	2MW

LFER

Laser	1.2MJ/16Hz
Gain	160
Fusion Yield	200MJ
Electric power	1280 MW



What is new?

- Core plasma
  - Gain estimation and ρR simulation were carried out using latest simulation codes.
- Lasers
  - Cooled Yb:YAG ceramic was newly chosen for both compression and heating lasers
- Target
  - Thermal cavitation technique was employed for fuel loading in batch process.
- Chamber
  - Stagnation-free, liquid wall chamber with cascade flow was proposed for the modular reactors.

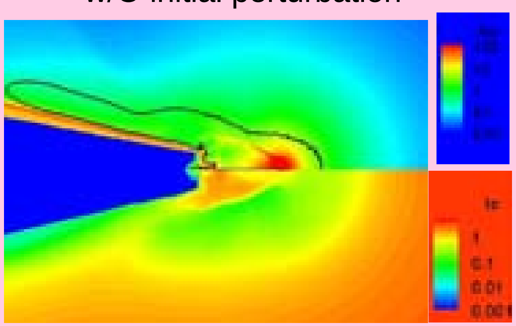
Core plasma

The detail physics of the Fast Ignition are investigated with computational simulations

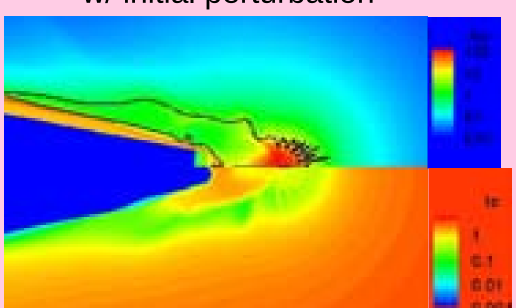
Simulation of non-spherical implosion for FIREX-I experiment (by PINOCO-2D)

CH-DT shell target with gold cone is imploded by GXII laser. Even though, initial perturbation exists on the target surface, high density core plasma is formed.

w/O initial perturbation

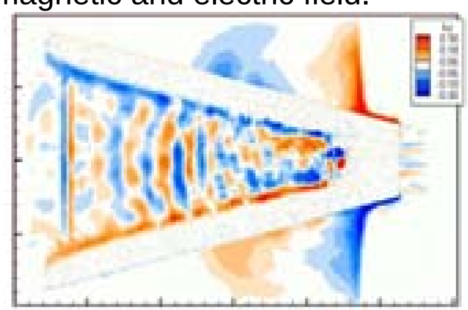


w/ initial perturbation

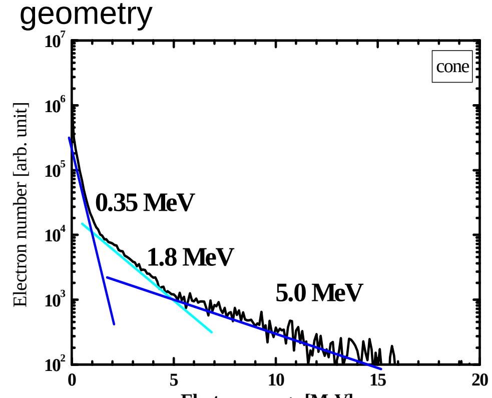


Generation of high energy electron (by FISCOF2D)

Magnetic field in the cone geometry. The hot electrons are transported along cone surface guided by static magnetic and electric field.

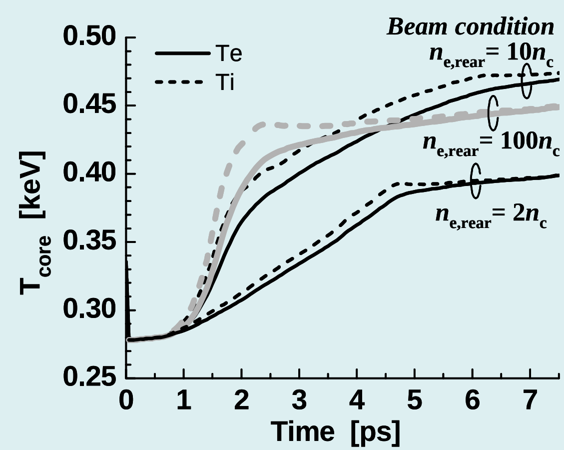


Electron spectrum generated by the laser plasma interaction in the cone geometry

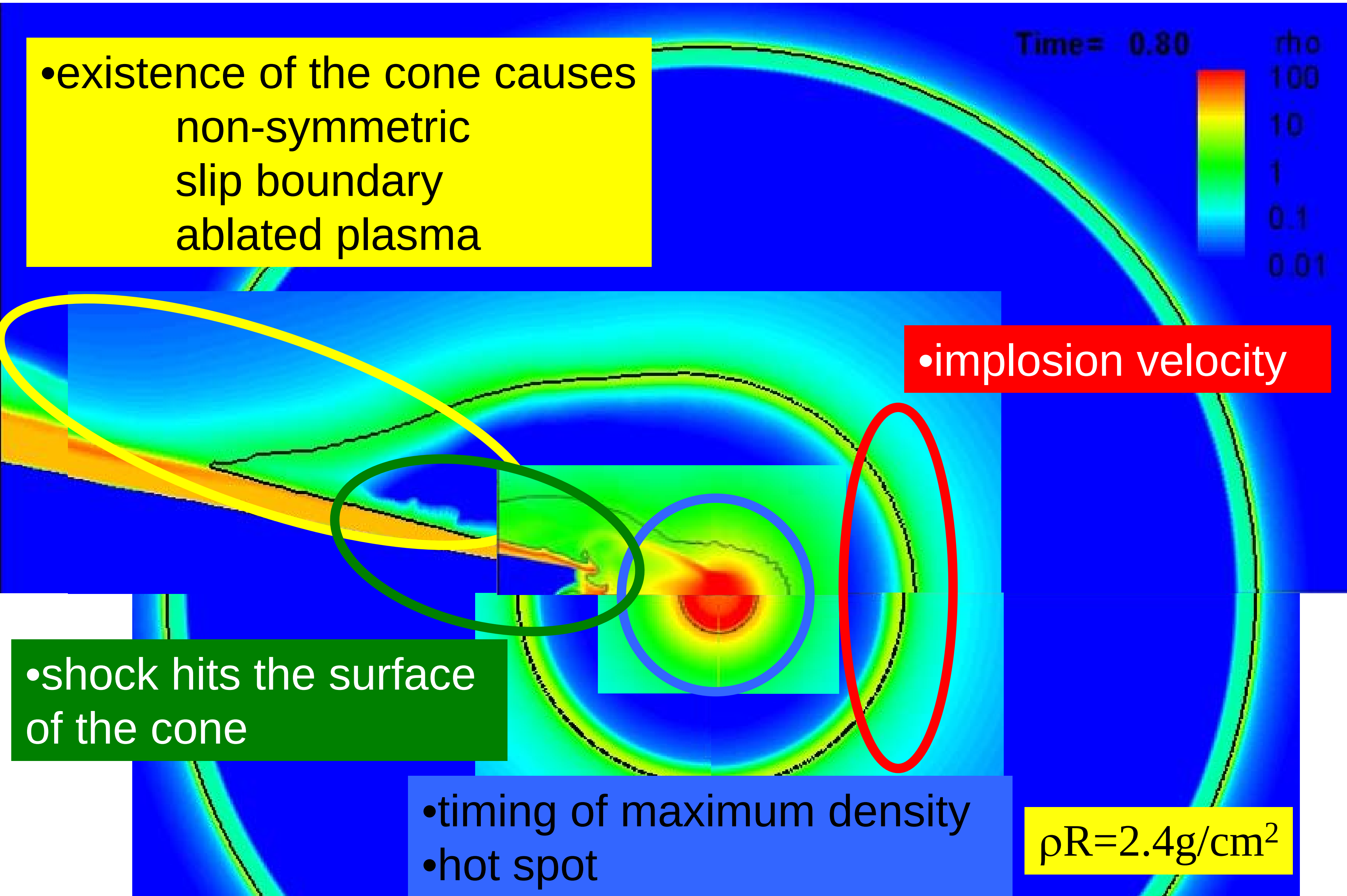


Heating of core plasma by the high energy electrons is simulated (by FIBMET)

In this simulation, initial condition of core plasma is determined by the implosion simulation, PINOCO-2D. Boundary condition of Input hot electron is determined by FISCOF2D. Temporal profiles of bulk-electron and ion temperatures averaged over the dense core region (ρ > 10g/cc) obtained for the three different REB conditions (n_e,rear = 2, 10 and 100 n_c)



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



Actual energy and power of heating laser required for fast ignition after S. Atzeni, (Phy.Plasmas'99)

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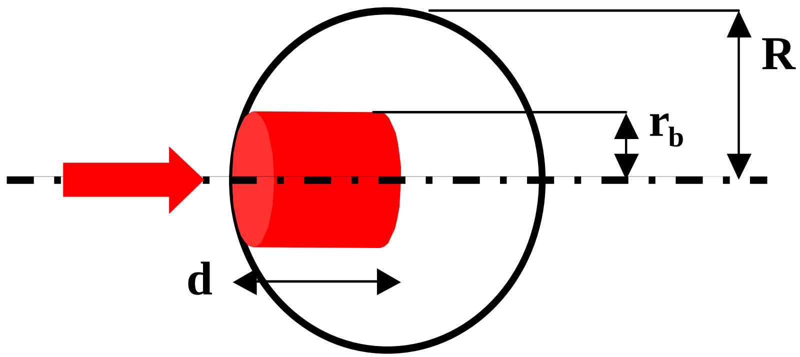

Assuming high energy electron range ; ρ ***d = 0.6 g/cm²***

- $E_h = 140\{\rho/(100g/cc)\}^{-1.85}$ kJ
- $P_b = 2.6\{\rho/(100g/cc)\}^{-1.0}$ PW
- $I_b = 2.4X10^{19}\{\rho/(100g/cc)\}^{0.95}$ W/cm²
- $r_b = 60\{\rho/(100g/cc)\}^{-0.975}$ μm

E_L = 60 - 100 kJ

Core plasma

Fast Ignition Gain Performance

ρ = 300g/cc,

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

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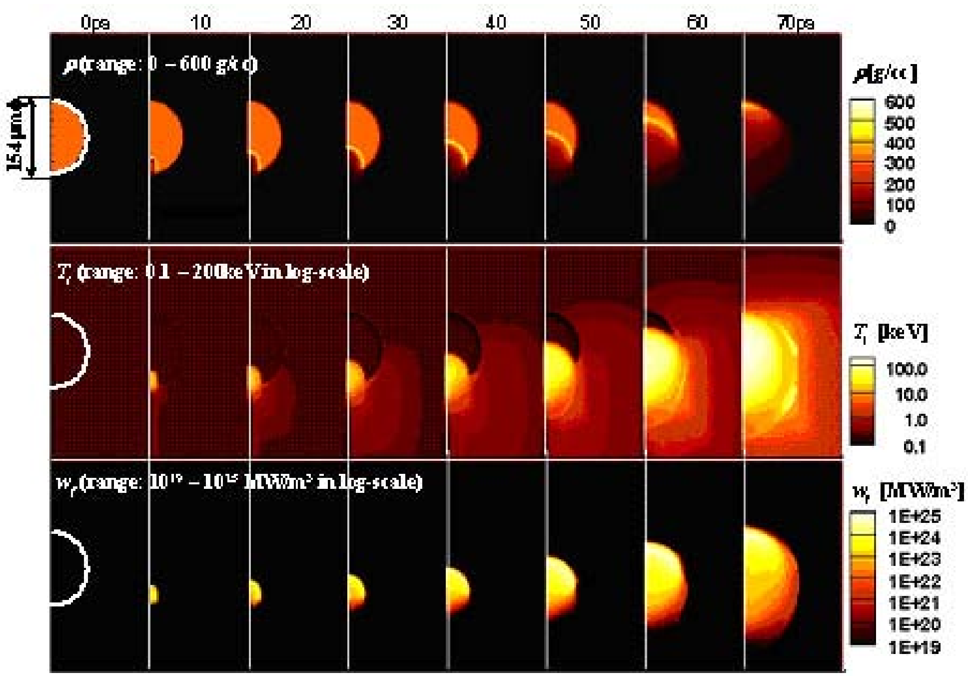
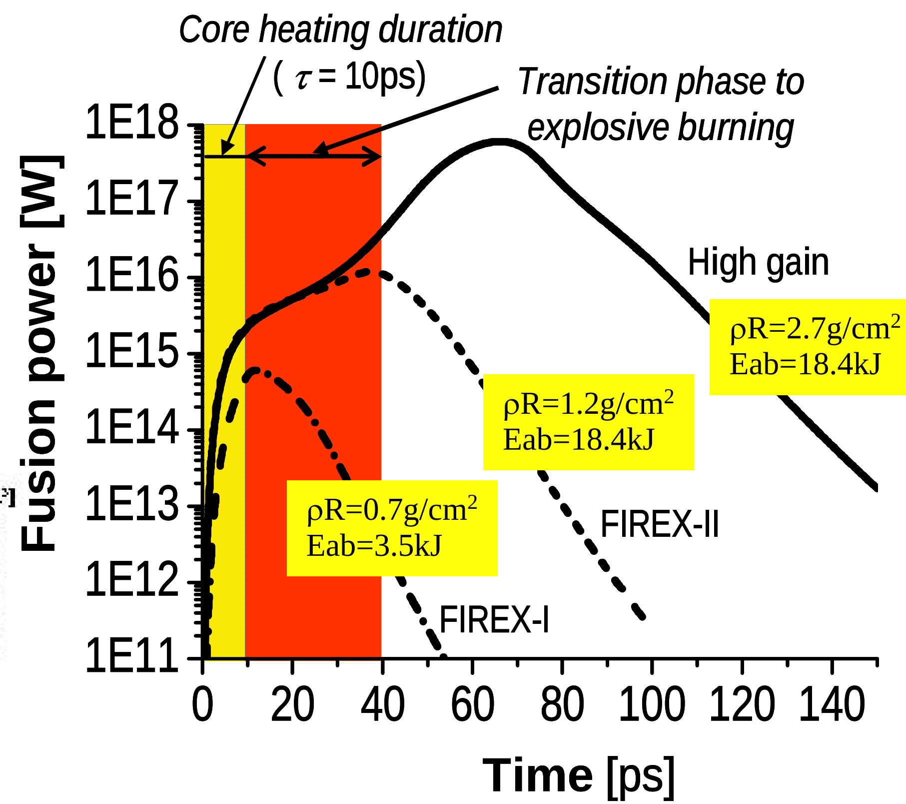
Pulse width of >10 ps would be accepted for the heating laser. This result relaxes requirements for heating laser. We can use transmitting optics.

This is a good news. We can use conventional transmitting optics.





Core plasma

Target for KOYO-F

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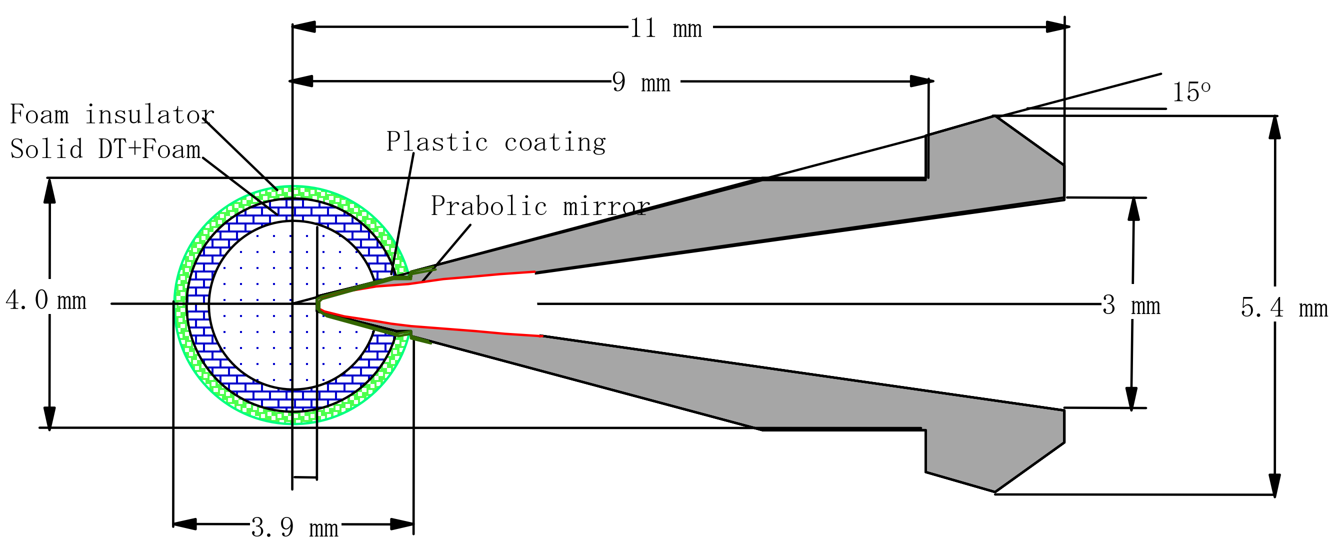
Basic specification	
Compression laser	1.1 MJ
Heating laser	70kJ
Gain	165
Fusion yield	200MJ

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



Critical issues toward high gain

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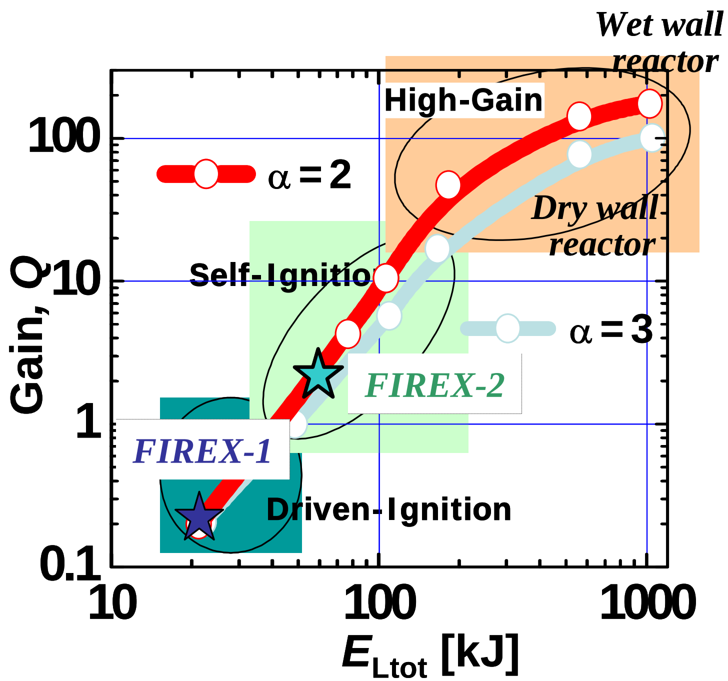
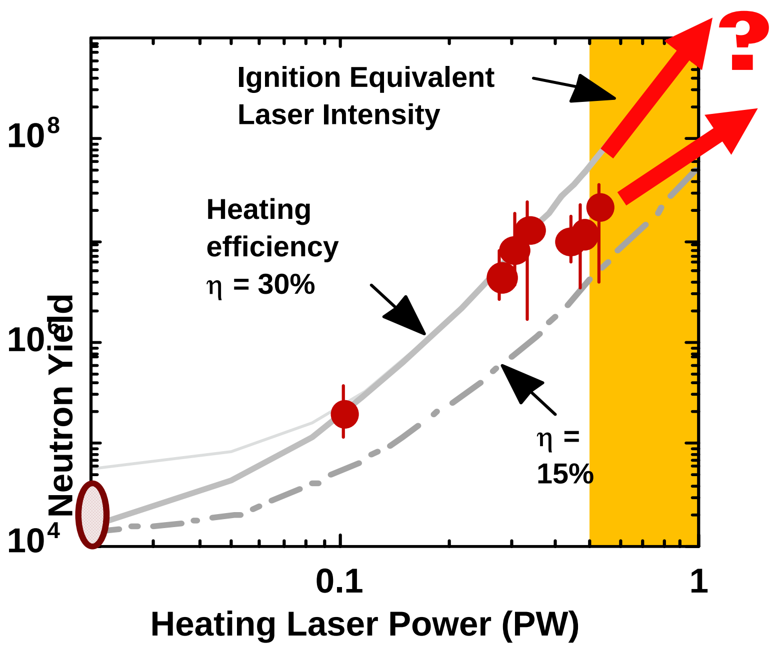
- Can we achieve low adiabat α ?
  - Current experiments α >2.5

    Pulse control, target design are the key.





•Can we deposit 20-30% heating laser energy in a 60 μm diameter x 100 μm area?

The Answer will be obtained with FIREX projects.

Lasers

Compression and heating lasers based on identical amplifier architecture

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	Compression laser		Heating laser
	Main pulse	Foot pulse	
Energy/pulse	1.1 MJ	TBD	100 kJ
Wavelength	UV (3ω) 343 nm	Visible (2ω) 515 nm	1030 nm
Band width	Narrow band	Broad band 1.6 THz	Broad band (rectangular pulse) ~3 nm
Efficiency	Efficient	Sacrifice of efficiency	（Sacrifice of efficiency）
Laser material	Cooled Yb:YAG ceramic		
Method for broad band	Arrayed beam with different wavelength ~0.1 nm@1030 nm (0.08 THz@343 nm)	Broad-band OPA pumped by 3ω, Spectral angular dispersion	Broad-band OPCPA pumped by 2ω

OPA: optical parametric amplifier
OPCPA : optical parametric chirped pulse amplifier

Lasers

Originally Yb:YAG has high quantum efficiency of 90%. Why Cooled Yb:YAG now ?

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Because there are dramatic Improvements in;

1. Wide Tuning Range of Emission Cross Section (Saturation Fluence)

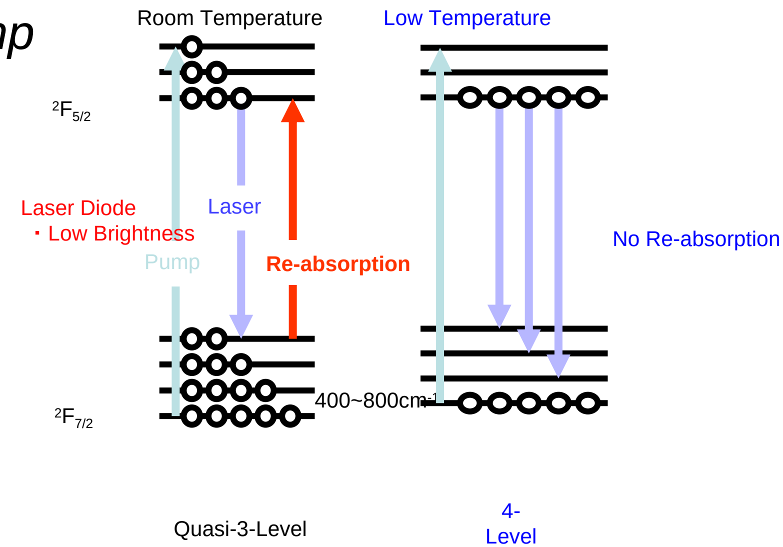
Realize an efficient energy extraction without optics damages

2. 4-Level Laser System

Enough Laser gain even in diode-pump

3. Improved Thermal Characteristics

High average power operation



Lasers

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

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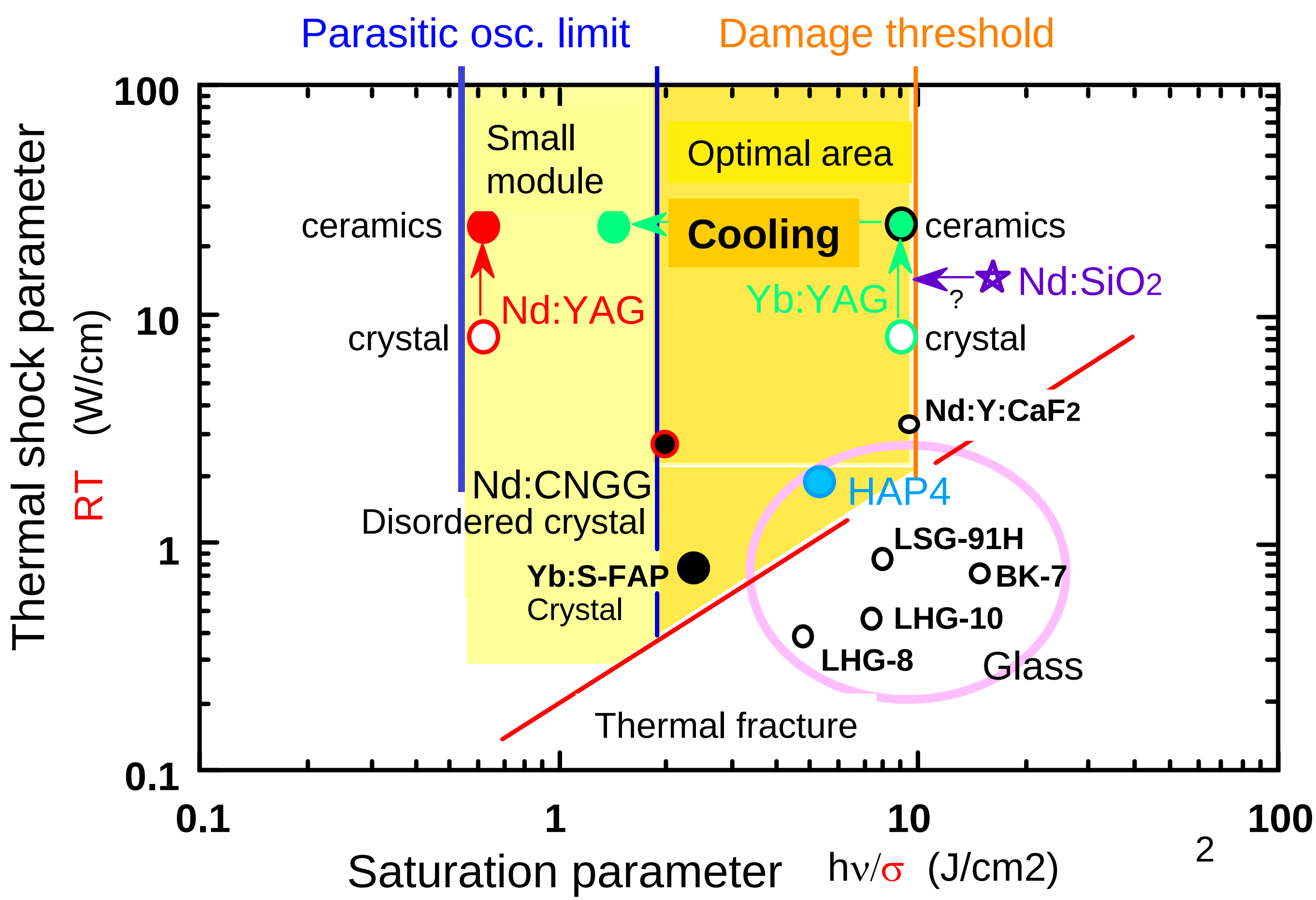

Artificial control of emission cross section → **Cooled Yb:YAG ceramic** ← Practical use of ceramic technology

We experimentally confirmed performance of cooled Yb;YAG

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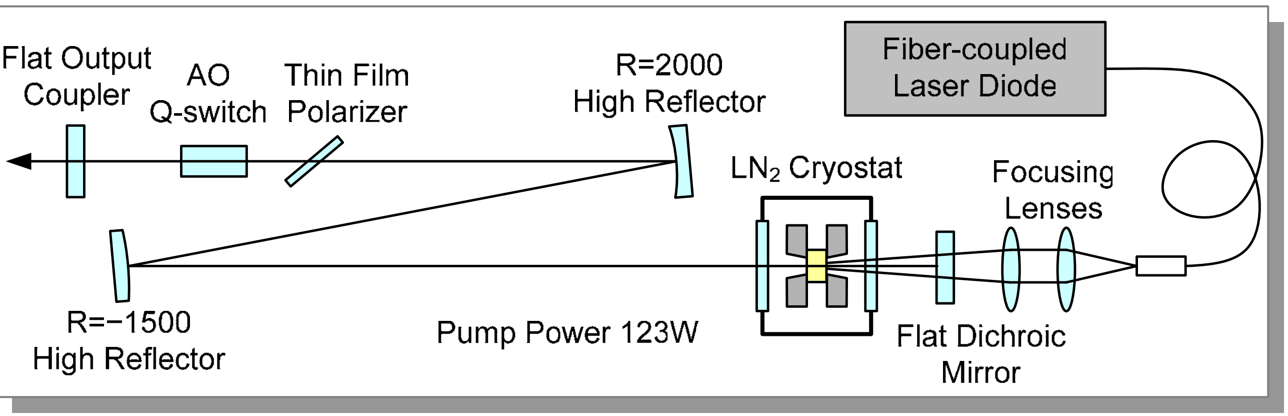

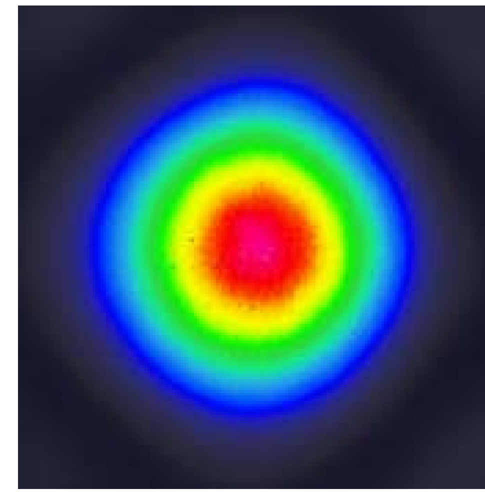

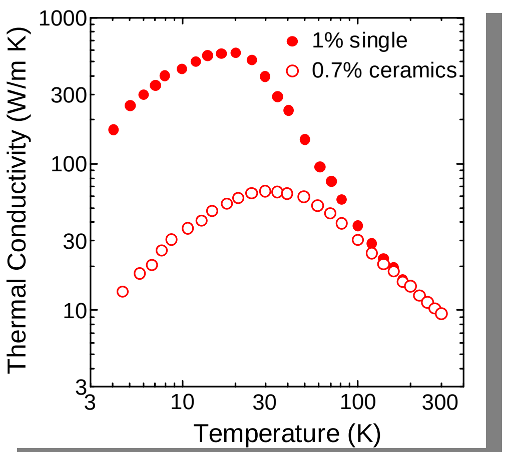

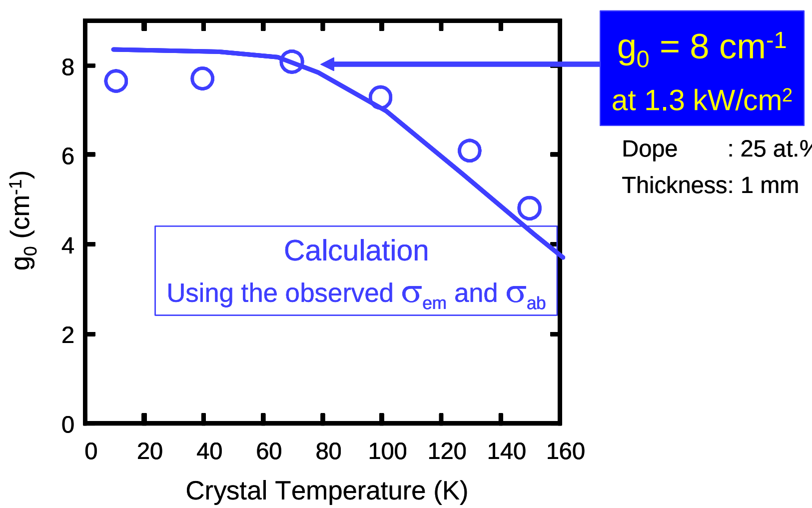

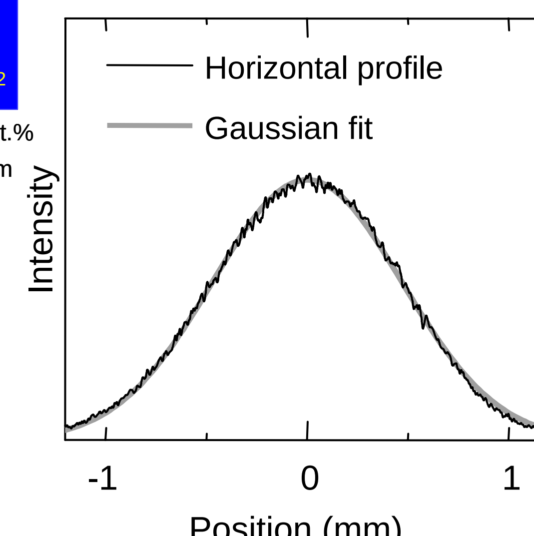

Overall Efficiency from Electricity to Laser

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	Implosion Laser	Heating Laser
Laser Power	17.6 MW(1.1MJ, 16 Hz)	1.6 MW(0.1MJ, 16Hz)
LD Electrical – LD Optical	60%	
LD Optical – 1ω	42%	
LD Electrical – 1ω	25.2% (= 0.6 x 0.42)	
1ω – 3ω	70%	-
1ω – 2ω	-	80%
OPCPA Eff.	-	40%
Pulse Compression Eff.	-	80%
Transportation Eff.	90%	90%
Harmonic Generation and Transportation	63%	23%
Electric Input Power	111 MW	27.6 W
Crystal Heating Power	7 MW	0.7MW
Cooler Electric Power	23 MW	2.1 MW
Electric Power Demands	134 MW	30 MW
Total Electric Power	164 MW	
Overall Efficiency	12% (13% + 5.4%)	

Lasers

Beam arrays of implosion and hearting lasers

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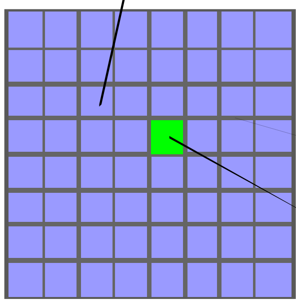
Compression laser beam (343 nm)



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

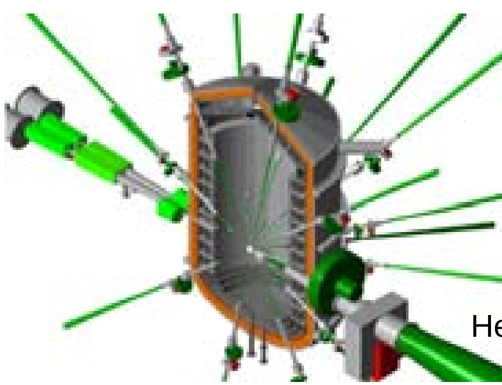
Absorber

Foot pulse beam (515nm)

8x8 incoherent arrays

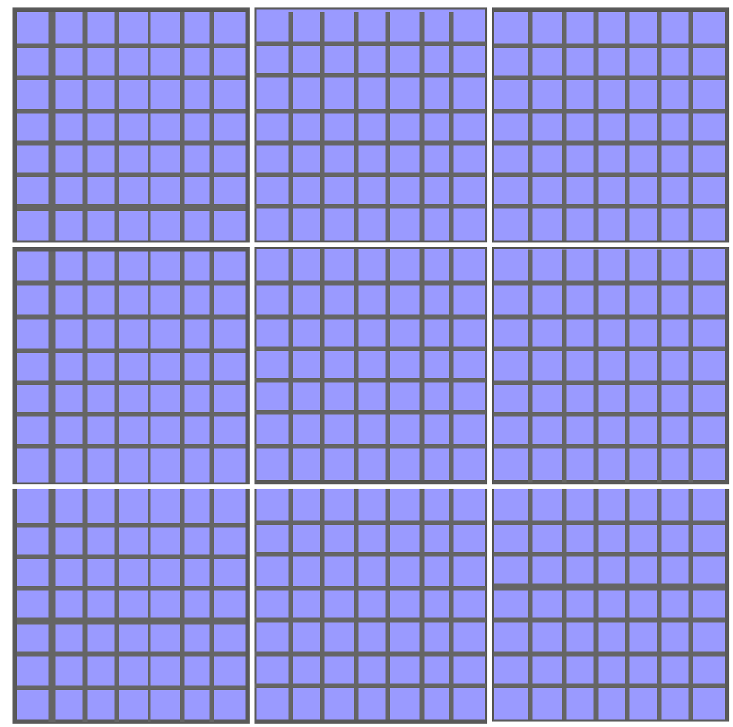
80cm×80cm,
32 beams

(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)

Illustration of main amplifier using active mirror concept

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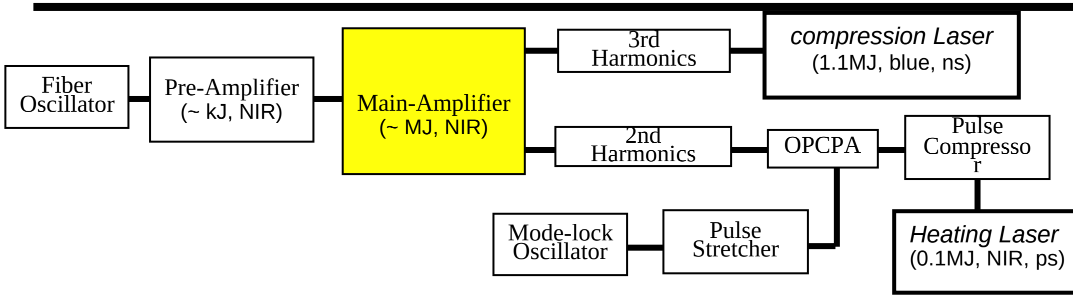

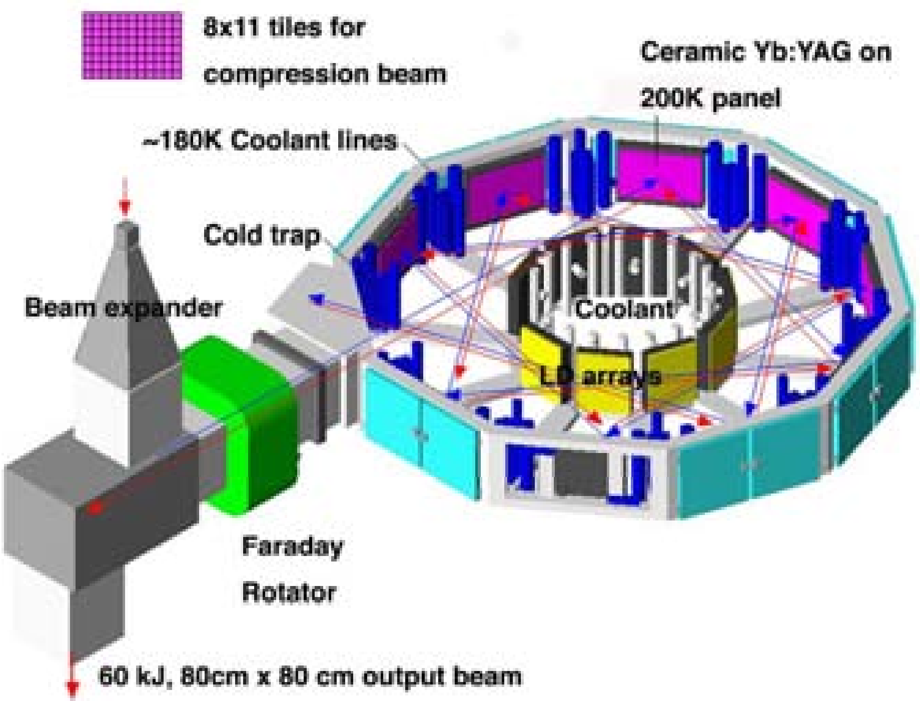

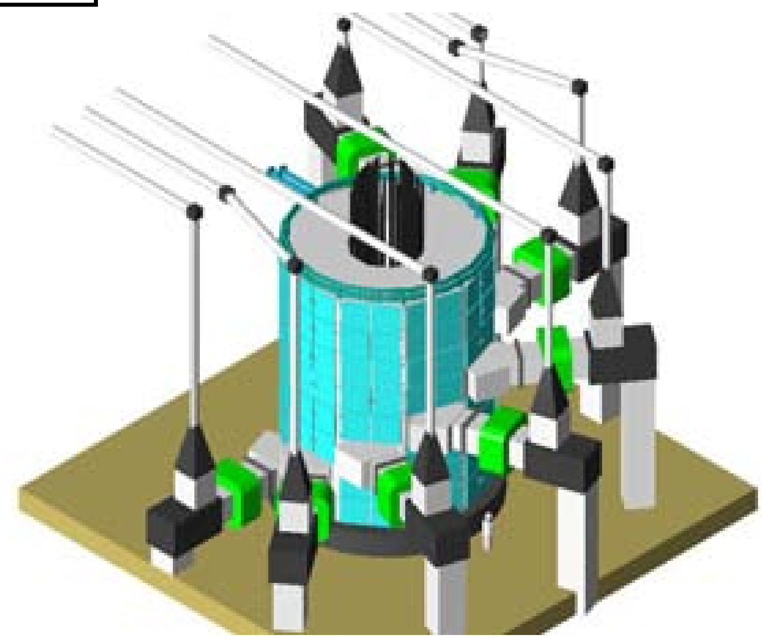

60kJ x 8 beams

Large diameter laser beams will be distributed to 4 modular reactors using rotating corner cubes.

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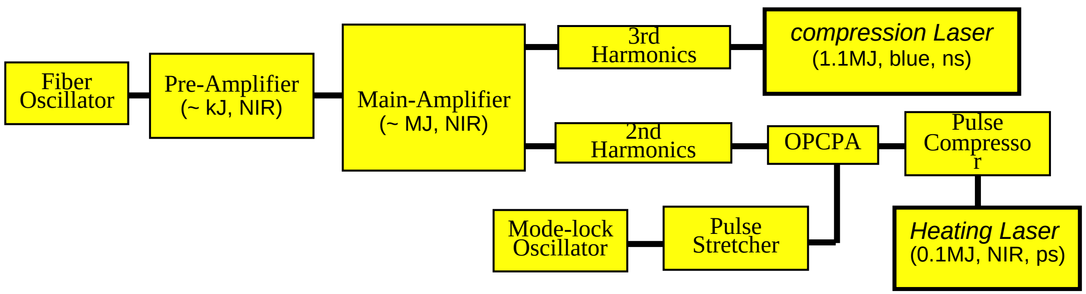

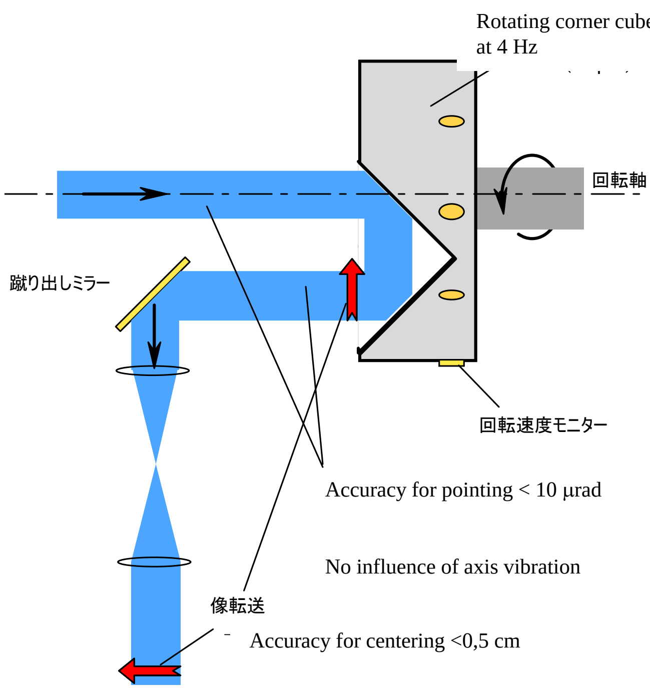

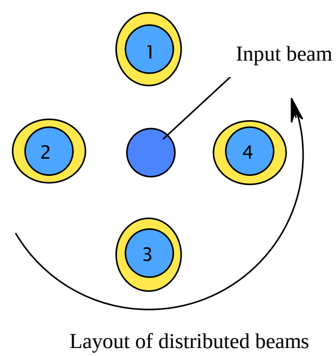

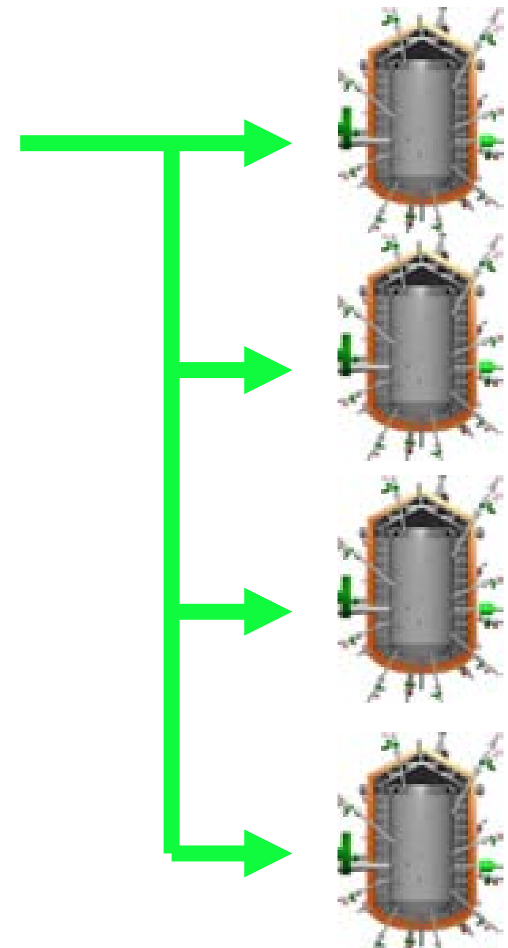

・コーナーキューブミラー：
既設激光XII号光路長調整機構に使用

・ハニカム構造ミラーによる軽量化
（試作段階完了）

Cooling system with 2MW at 200K can be constructed with existing technology.

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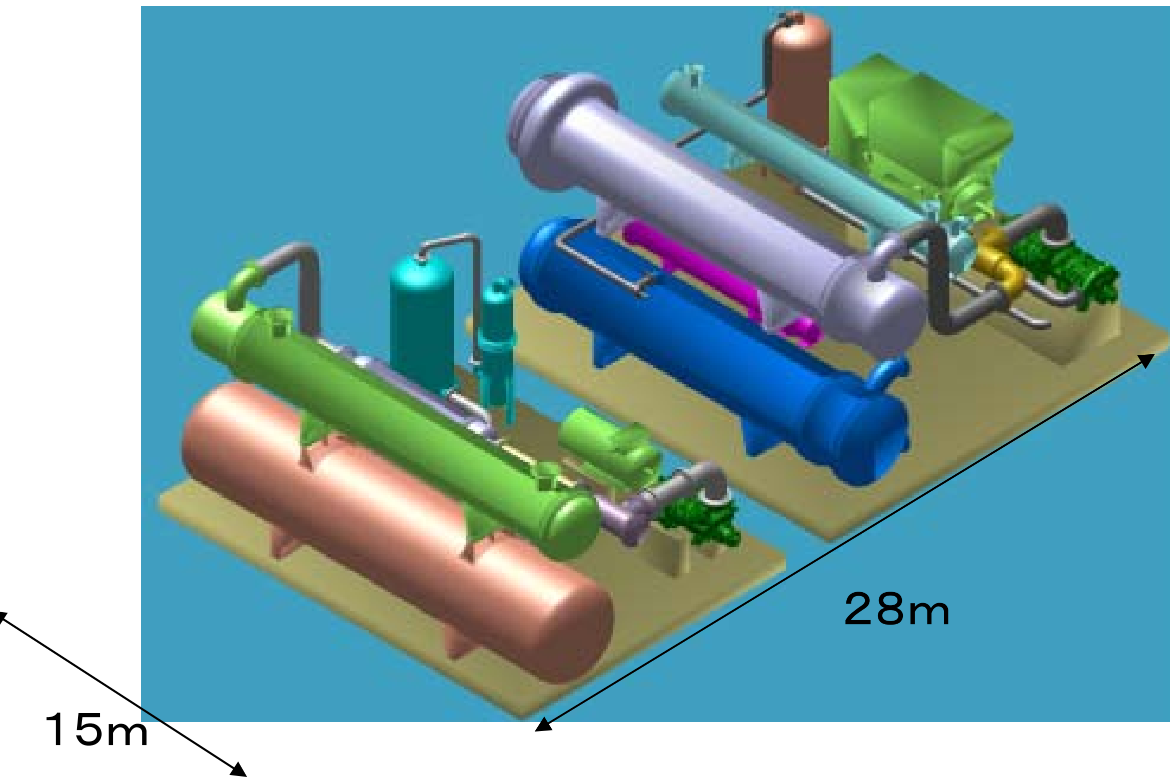

Image of 600kW, two coolants refrigerator*

This image was produced by Maekawa MFG. Co. LTD.

Electric input power 3600+1500kW
Cooling water 1300m^3/h (32-37^{o}C)
Cooling power 2MW at 200K (δT=5K)
Efficiency >30%
Coolant R507A（High）＋ R23(Low)

After fast ignition, share of lasers in the construction cost became minor.

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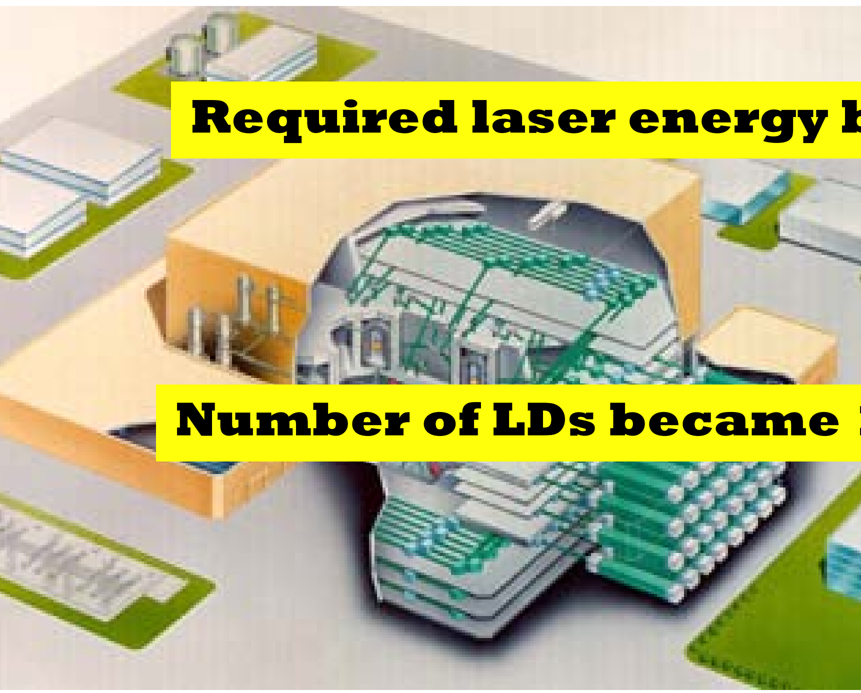
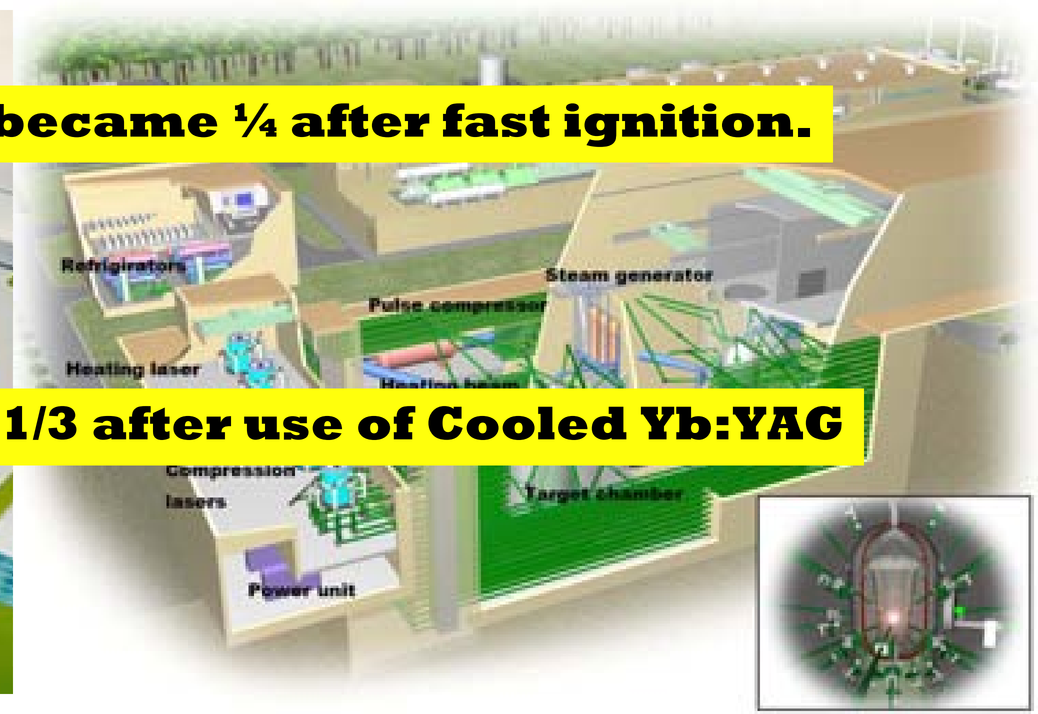
Required laser energy became ¼ after fast ignition.

Number of LDs became 1/3 after use of Cooled Yb:YAG



Central ignition KOYO



Fast ignition KOYO-F

Chamber

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

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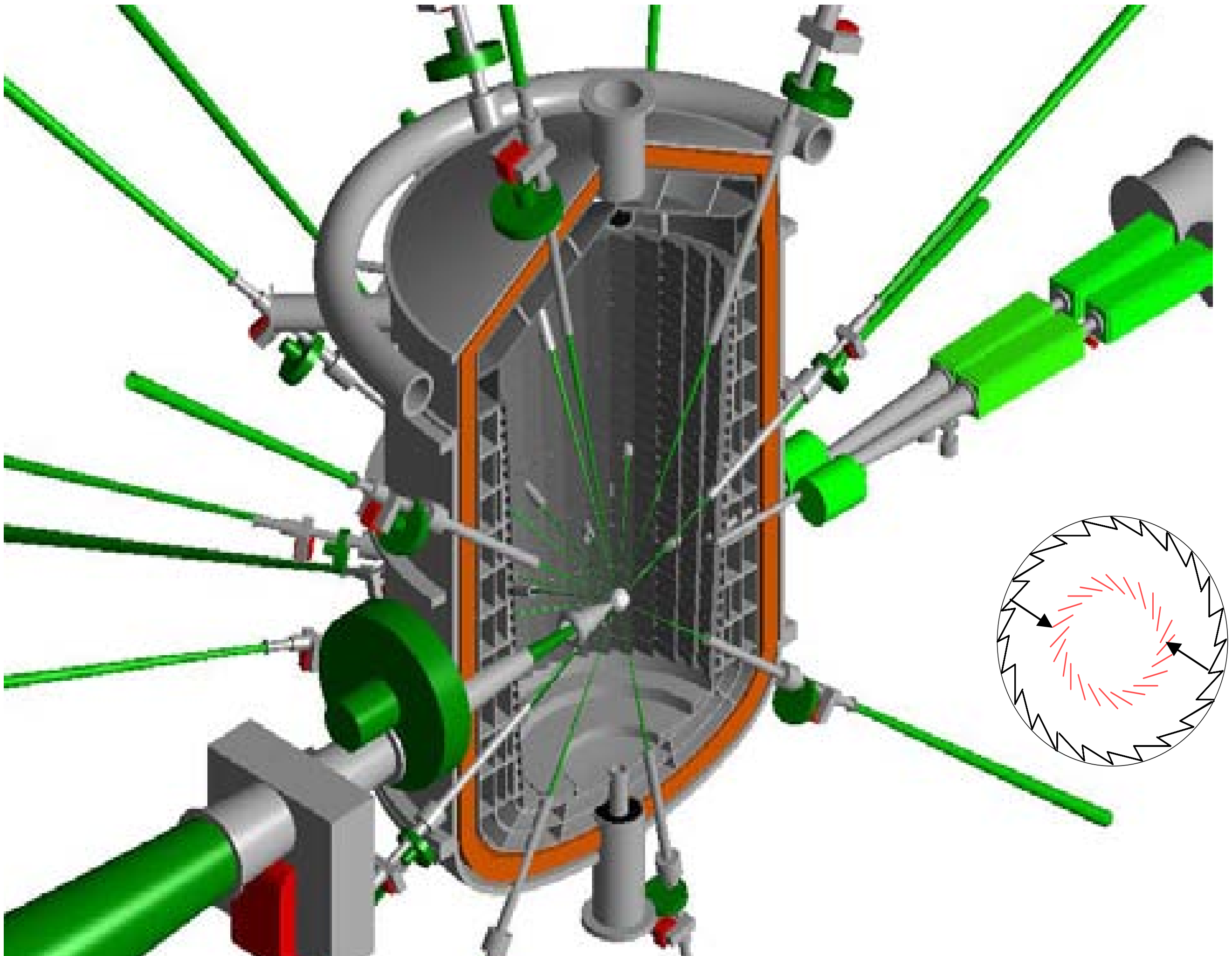

- Vertically off-set irradiation
- Cascade surface flow with mixing channel
- SiC panels coated with wetable metal
- Tilted first panel to make no stagnation point of ablated vapor
- Compact rotary shutters with 3 synchronized disks

Chamber

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

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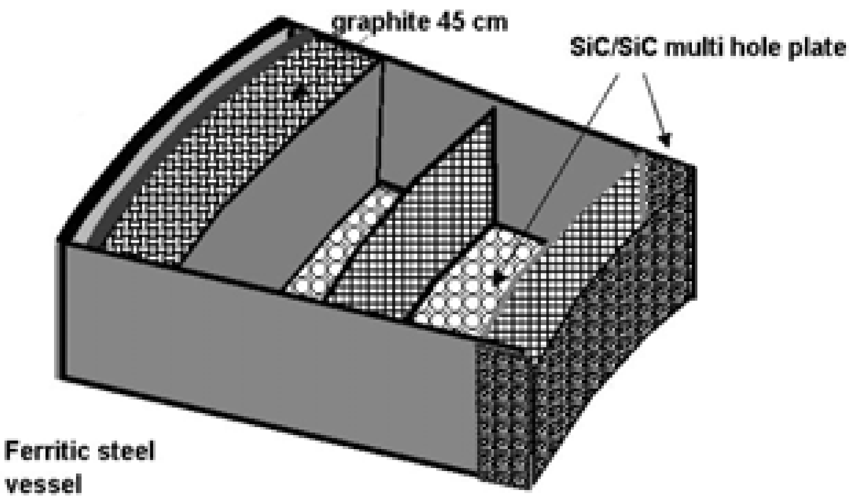
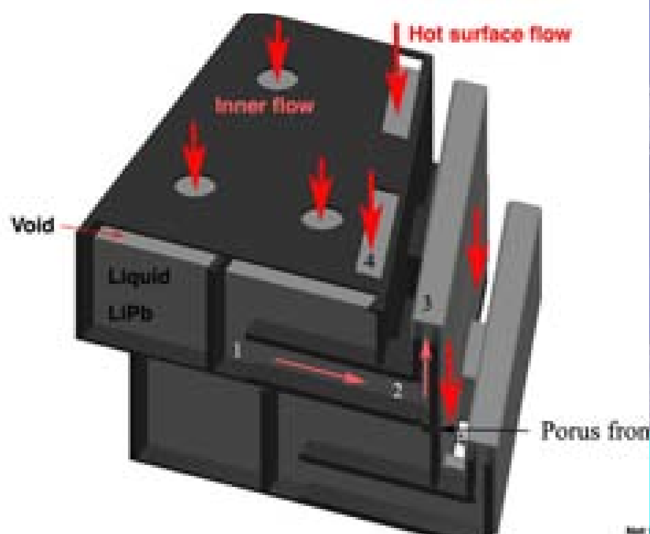
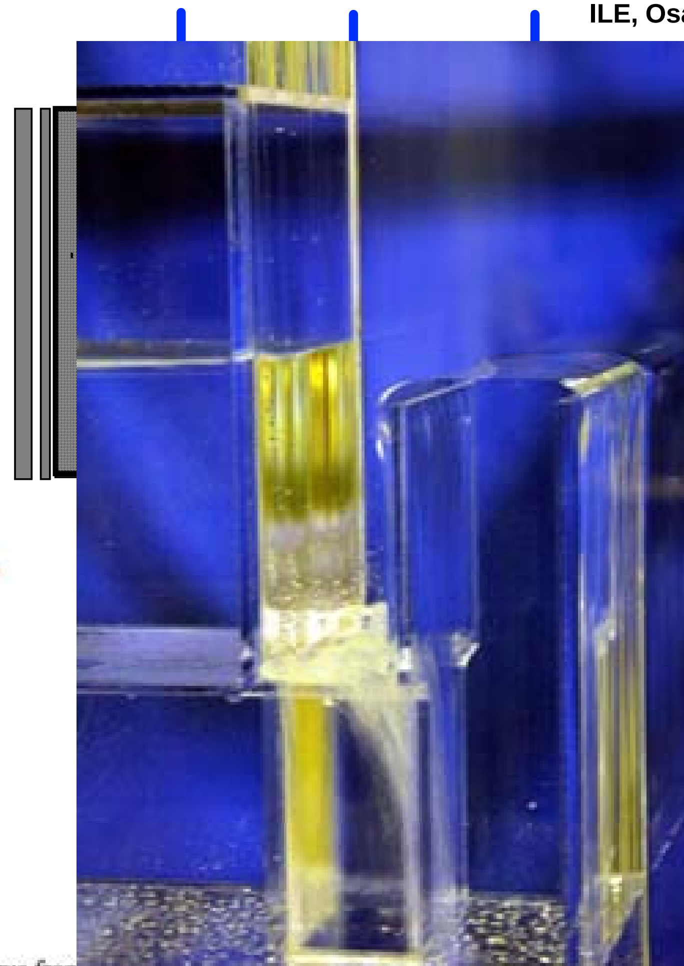


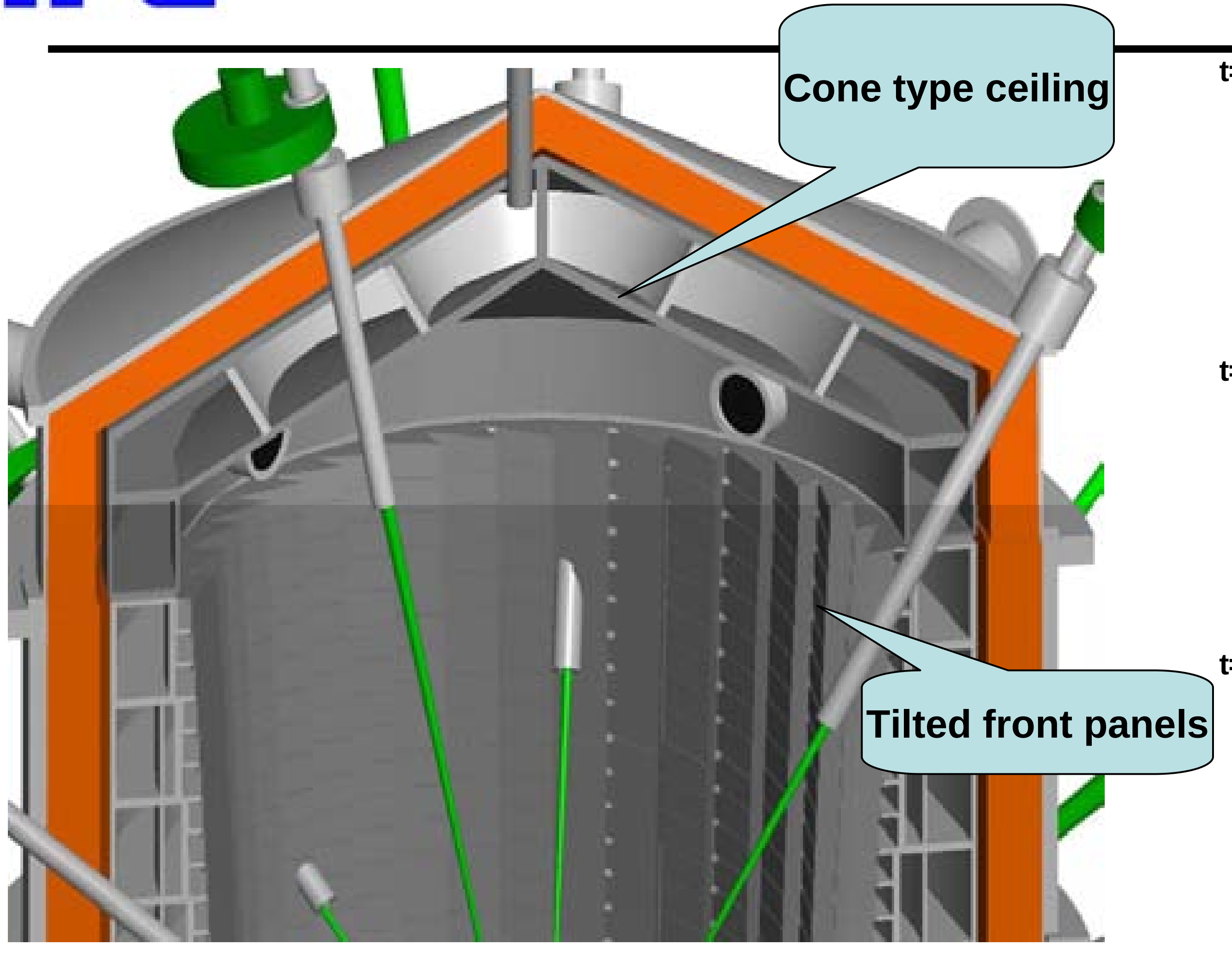


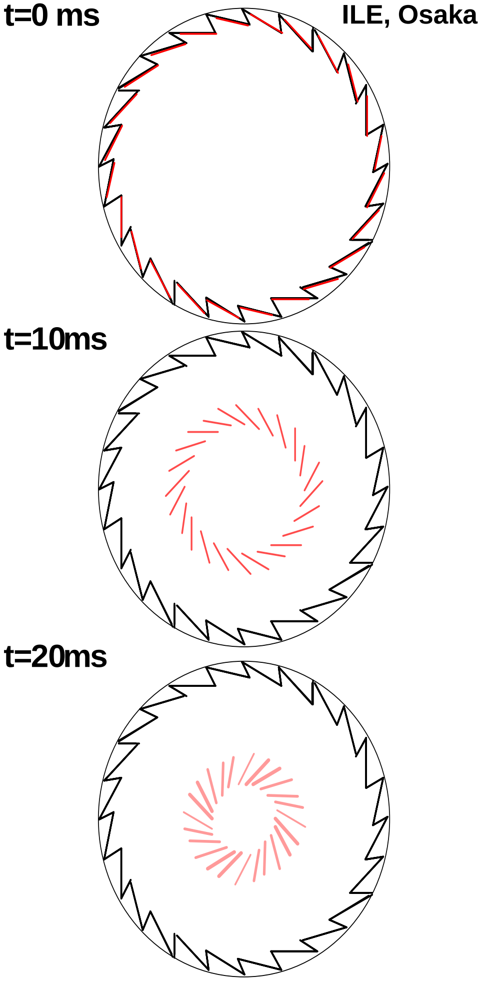


This concept was experimentally confirmed by Dr. Kunugi.

Chamber

To prevent stagnation of ablated LiPb, front panels were tilted by 30 degree.





Position of mass center of ablated vapor

Beam port will be protected using a magnetic field.

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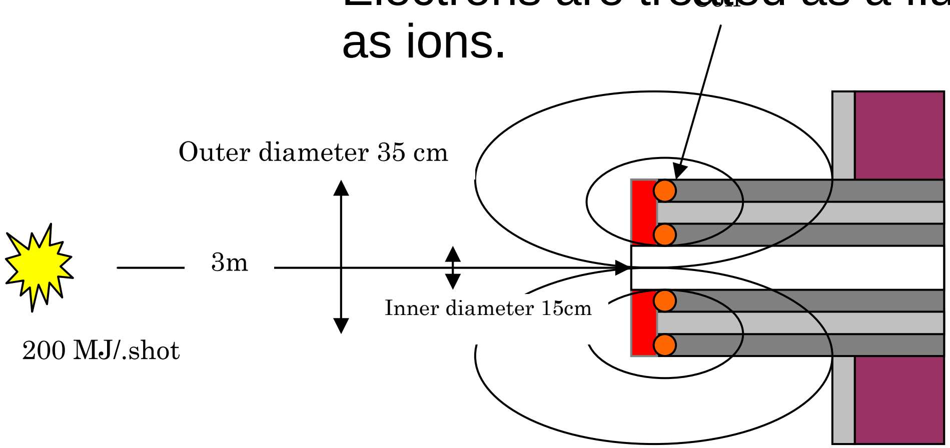
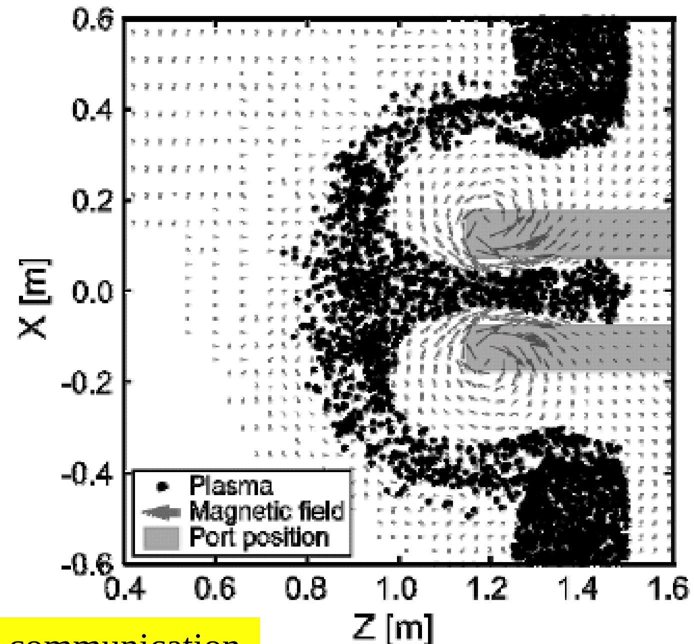
- Preliminary numerical simulation indicates that the tip of beam port can be protected from alpha particles.
  - B=1 T, pulse operation.
  - Alpha, 6.3×10^{17} n/m^2, τ=0.18 μs
    - Electrons are treated as a fluid as ions.





H. Nakajima and Y. Kajimura, Private communication

Final optics will be protected with synchronized rotary shutter, magnetic field, and buffer gas.

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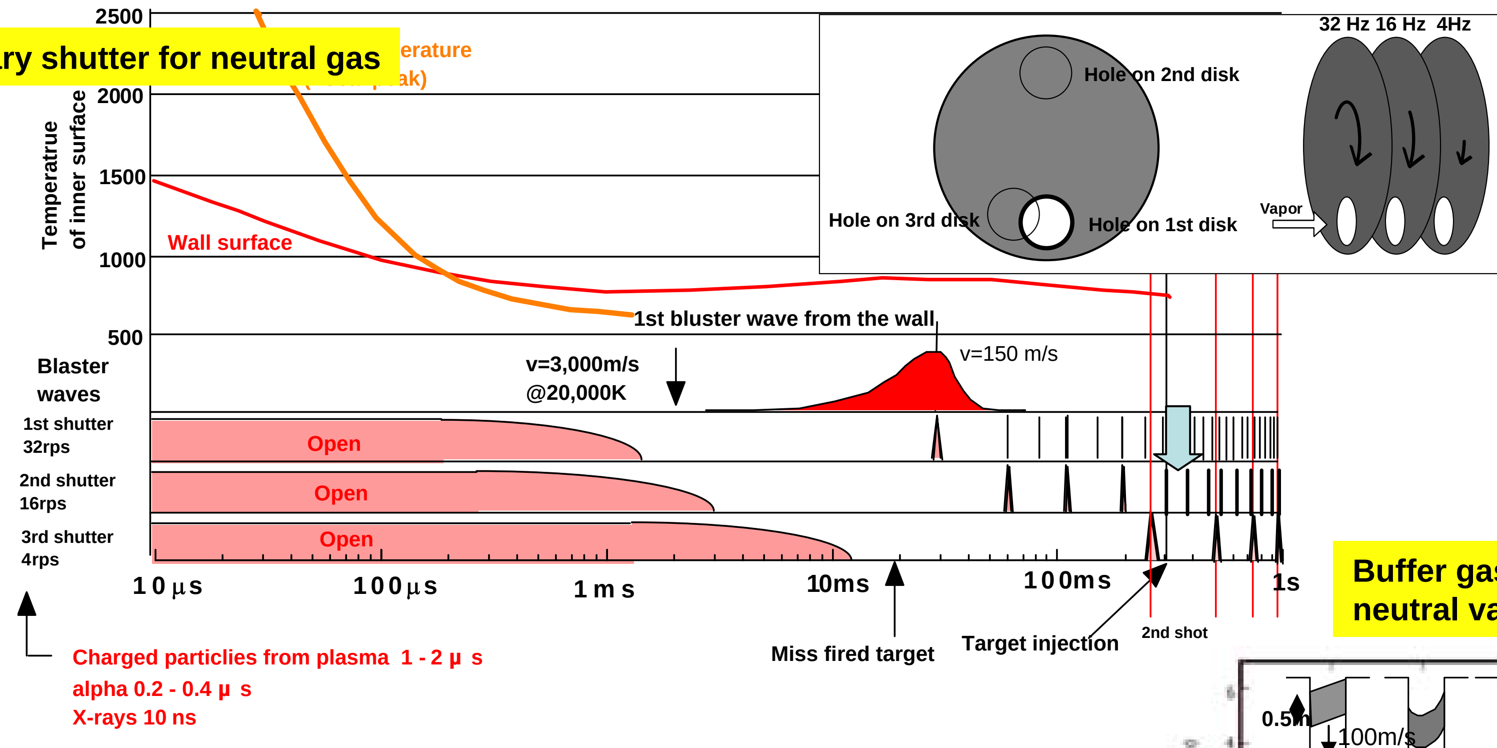
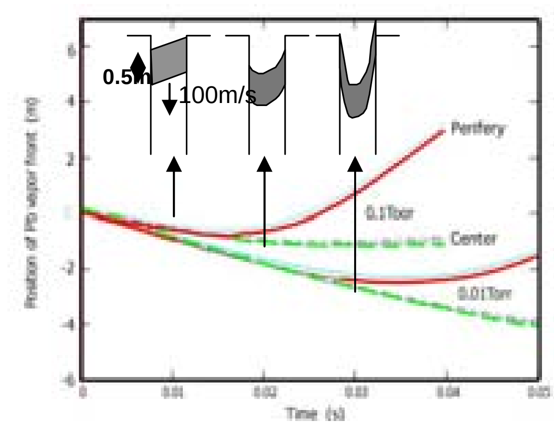
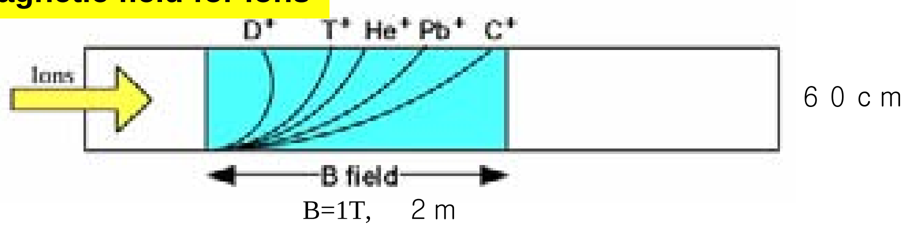
Rotary shutter for neutral gas



Buffer gas for slow neutral vapor



Magnetic field for ions



Chamber

Thermal flow of KOYO-F

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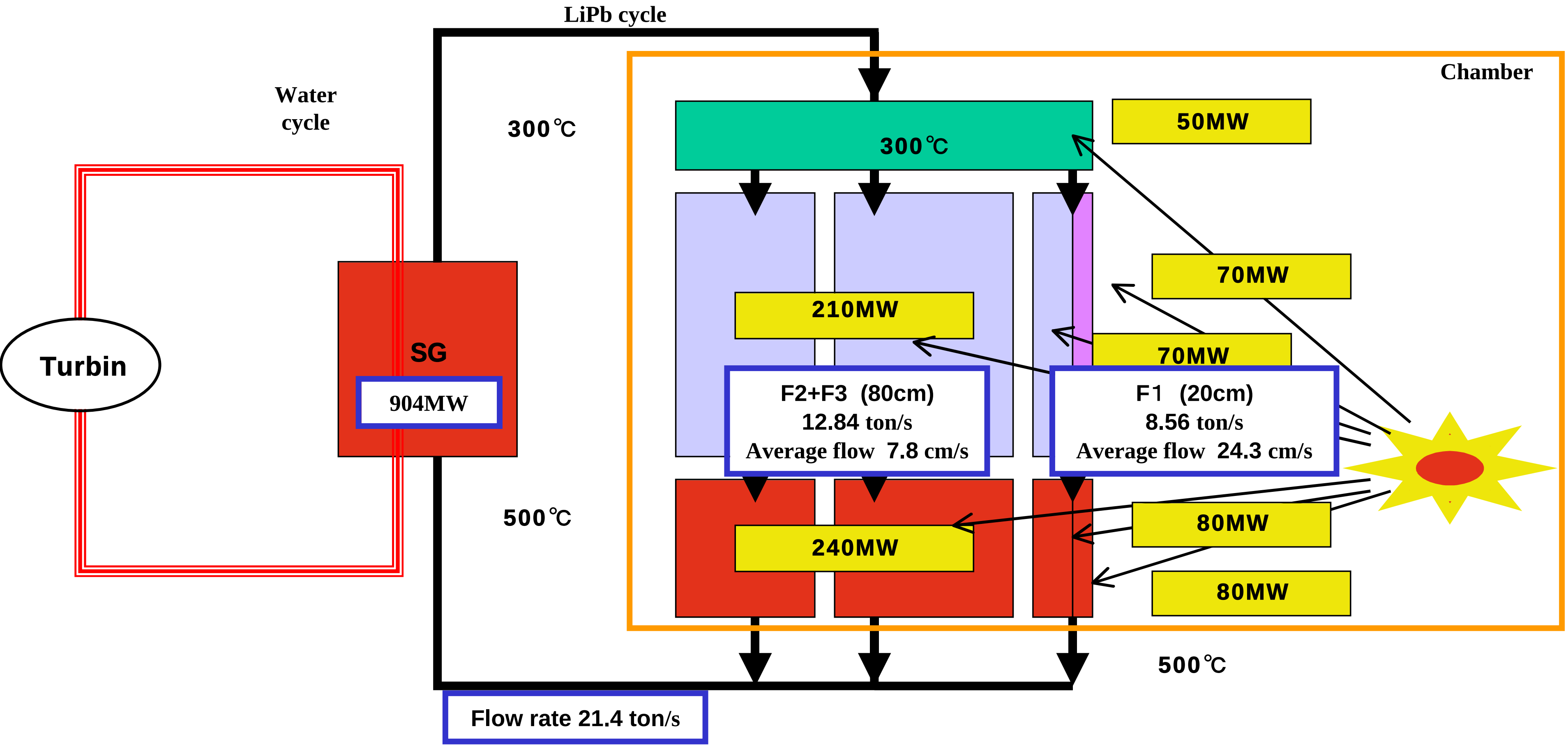

δt=0.5 ^{o}C/shot δt=1.3 ^{o}C/shot

Residual gases can be evacuated with lead diffusion pumps.

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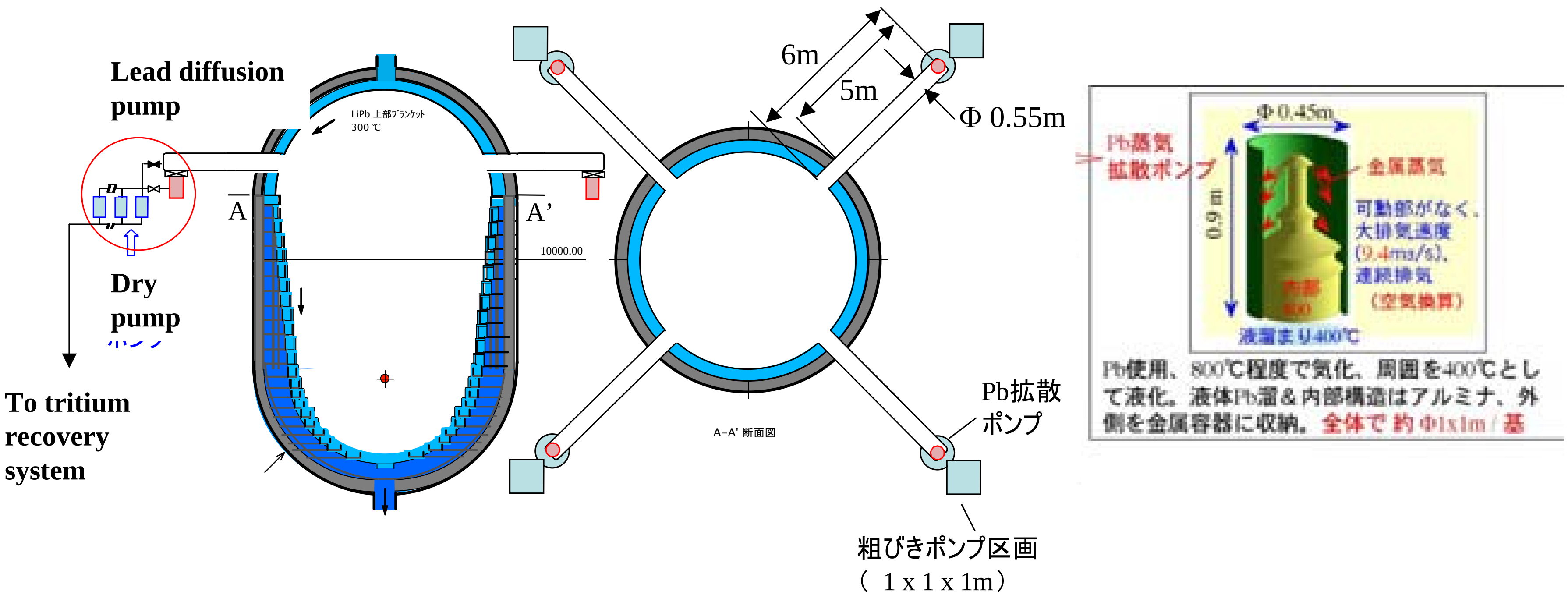

Tritium necessary for one fuel loading system is about 100g

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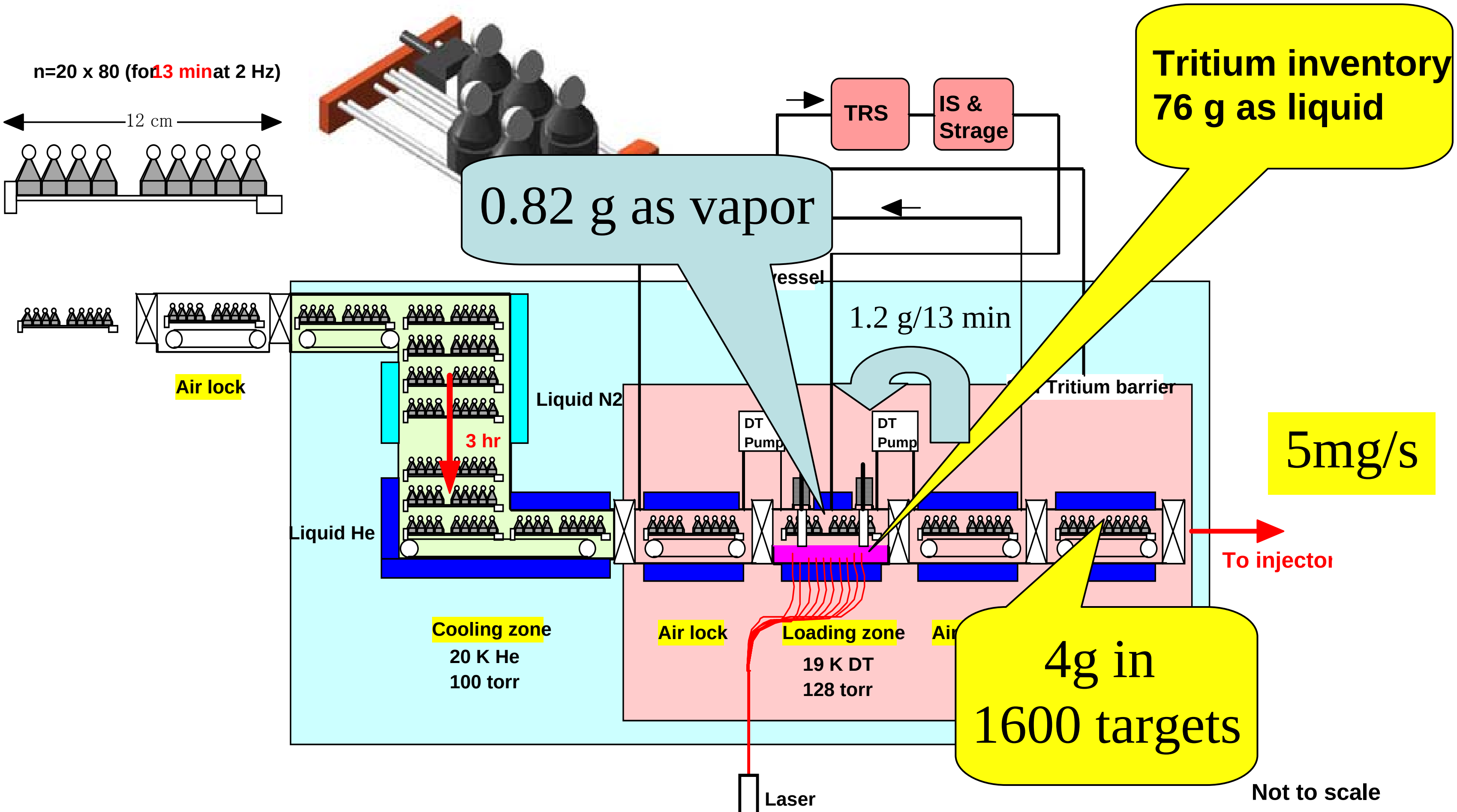

Tritium in gas phase and LiPb leach their ultimate concentrations in 30 sec 6 hr, respectively.

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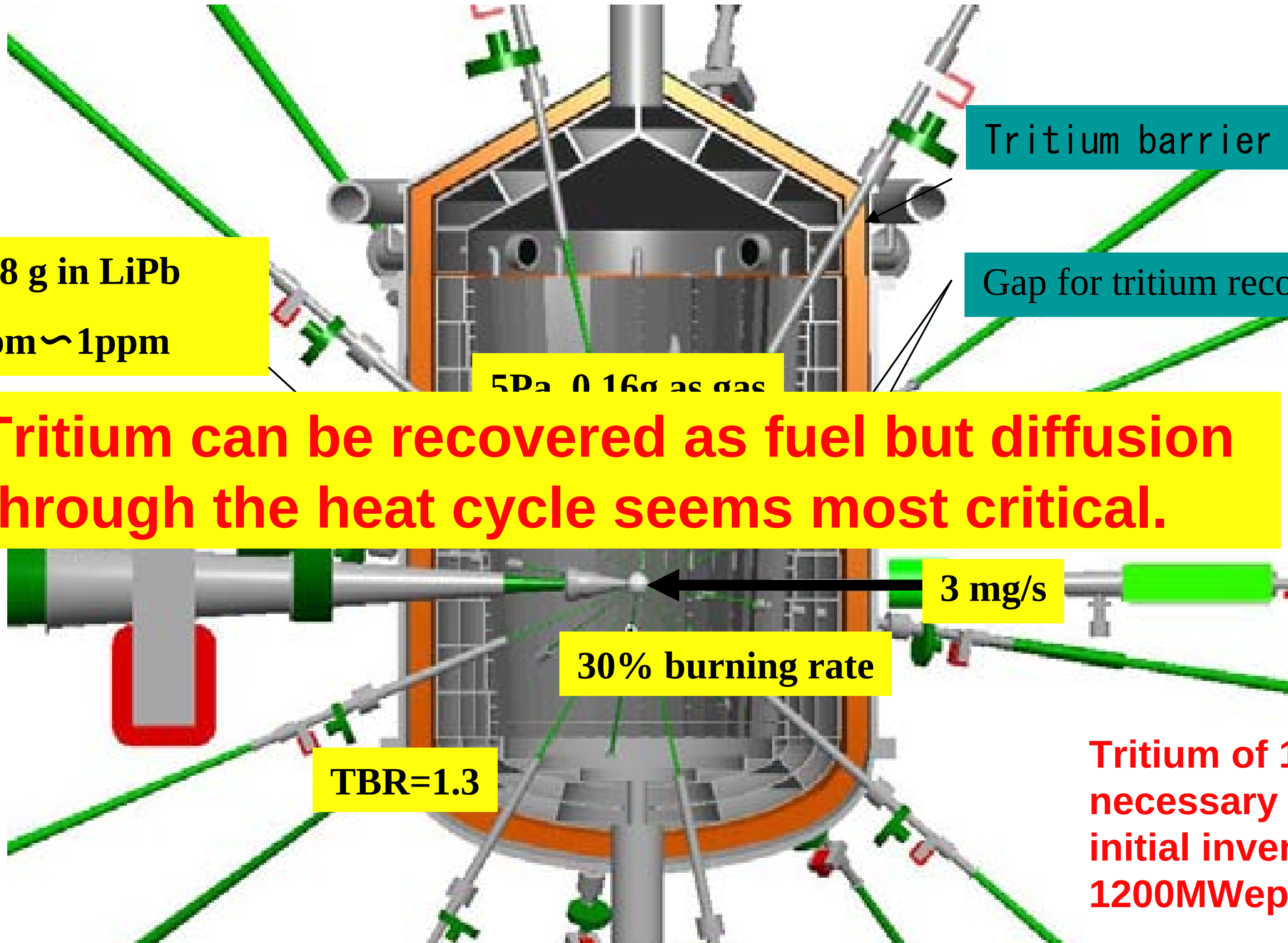

Tritium can be recovered as fuel but diffusion through the heat cycle seems most critical.

Tritium of 1 kg is necessary as the initial inventory for 1200MWeplant.

Chamber

We estimated the ablation process using ACORE. Stopping power in ionized vapor was calculated.

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Atomic Process Code

↓

Ionization Degree, Population, Energy Level

↓

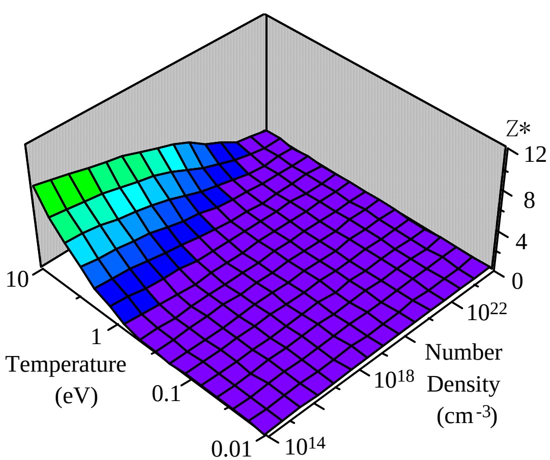
Stopping Power Code | EOS Code | Emissivity and Opacity Code

↓

Stopping power | Ionization Degree, Pressure, Specifiic heat | Emissivity, Opacity

↓

ACORE (Ablation COde for REactor)



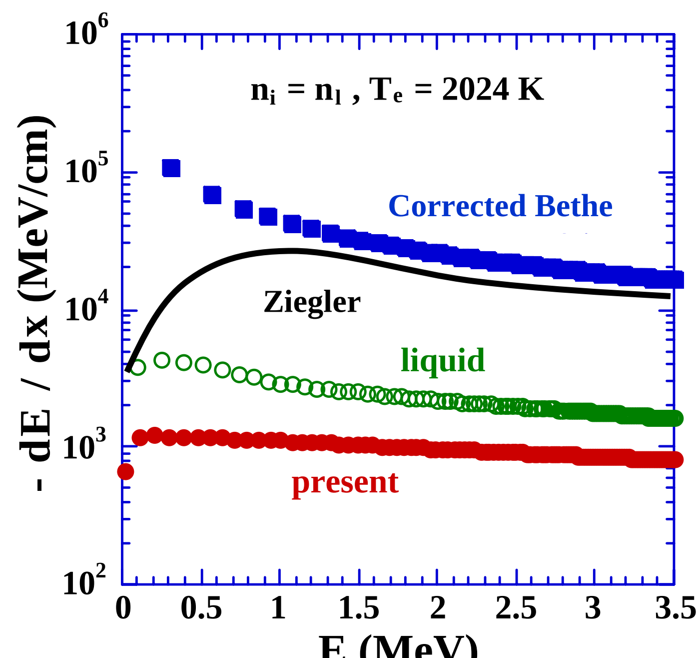
Ionization rate of Pb

Ziegler's model

$$-\frac{dE}{dx} = \frac{4\pi e^4 Z_0^2 n_e}{m_e v^2} K_0\left(\frac{h}{n_e v^2}\sqrt{\frac{4\pi n_e e^2}{m_e}}\right)$$

Present model

$$-\frac{dE}{dx} = n_i \sum_n \sum_l I_{nl} P_{nl}\, \pi \left(\frac{Z_0 e^2}{I_{nl}}\right)^2 G\left(\frac{v}{v_{nl}}\right) \qquad G(V) = \frac{\alpha^{3/2}}{V^2}\left[\alpha + \frac{2}{3}(1+\beta)\ln(2.7+V)\right]$$



Density, Temperature and velocity profile of ablated material.

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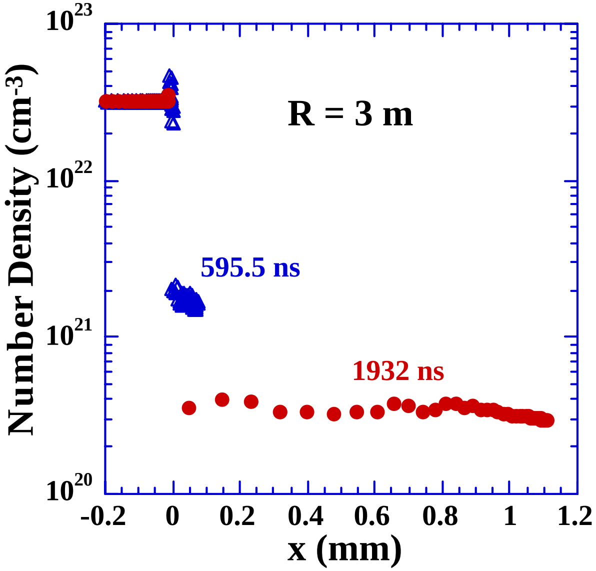

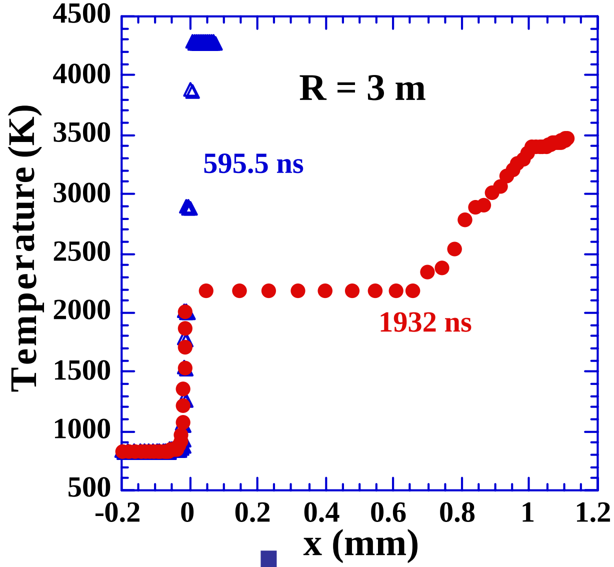

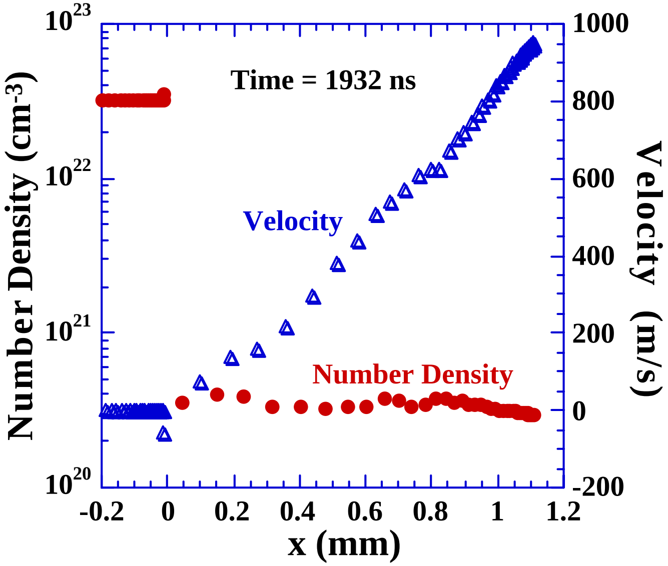

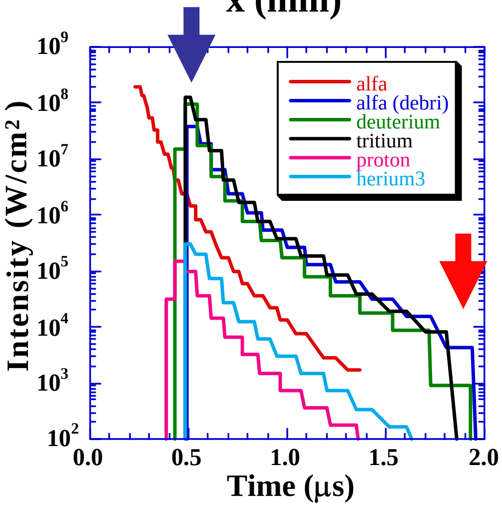

Chamber

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

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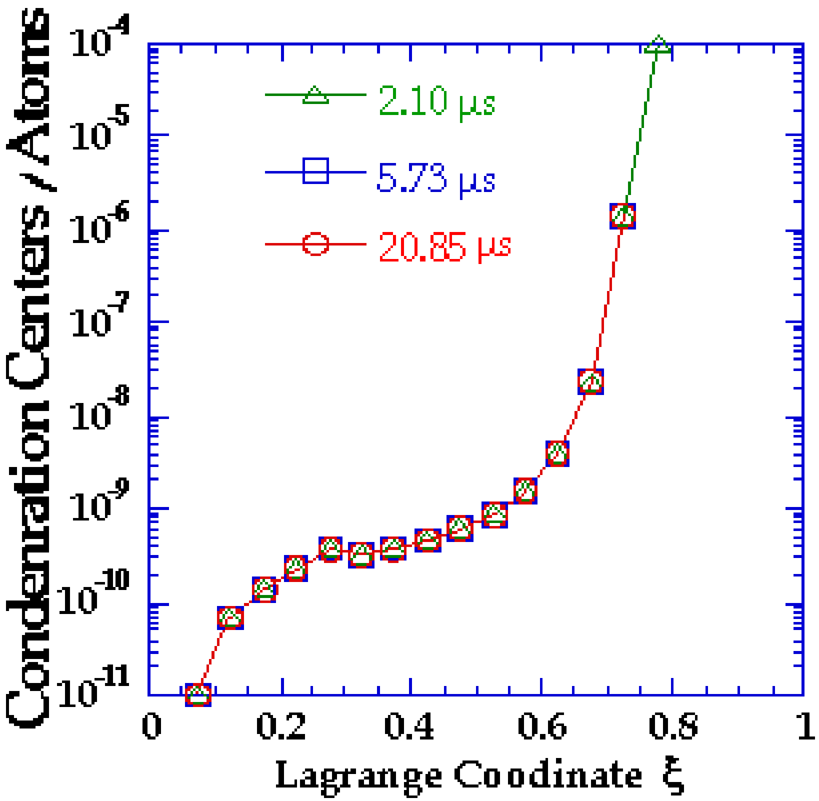
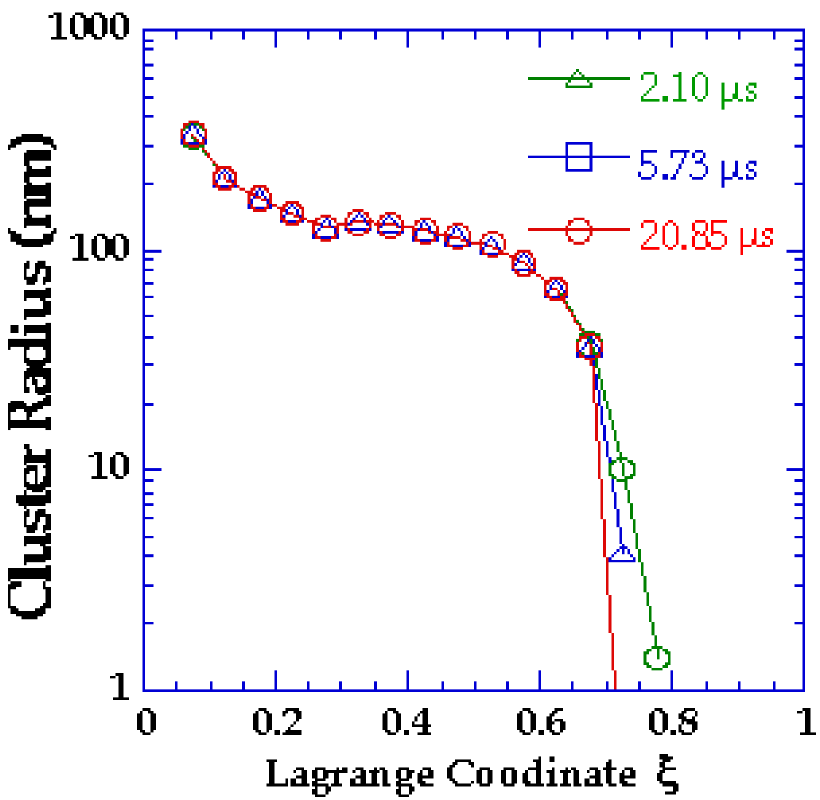
(Luk'yanchuk, Zeldovich-Raizer Model)





20% of ablated vapor becomes aerosol.

Chamber

Beam ports and ceiling will be made with porous metal and followed by condensation of vapor ablated by previous shot.

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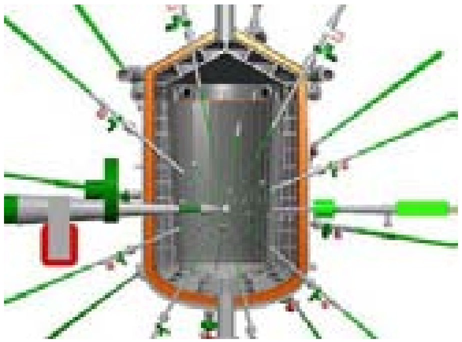
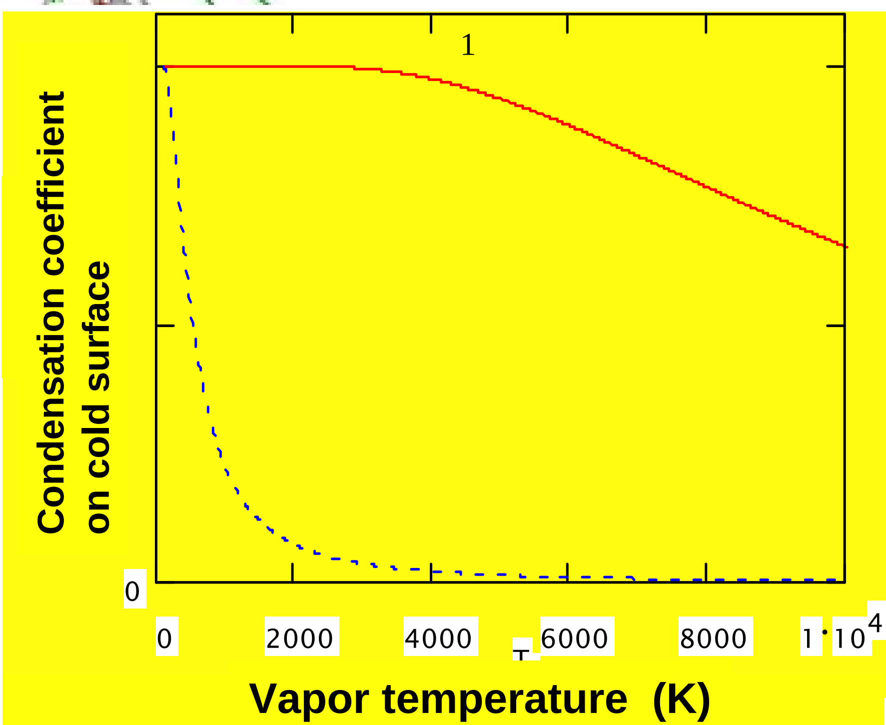
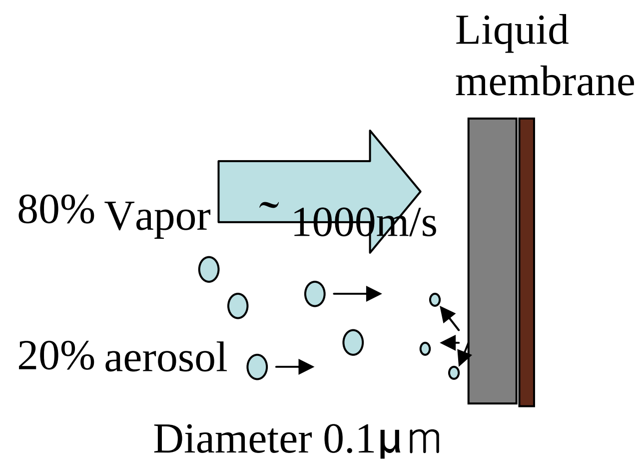


Condensation rates of the fast and slow component at the first bounce are about 60% and 100%, respectively.

These rates are sufficient to keep the vapor pressure < 5 Pa

and to form a 2 μm-hick, protective layer before the next laser shot.





Aerosol mainly appears in slow component.
Now secondary particles because the surface energy > kinetic energy

Critical issue in chamber

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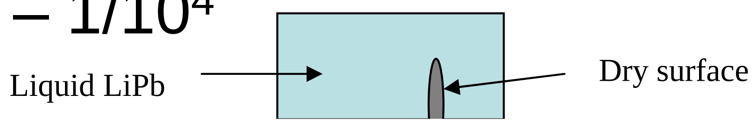
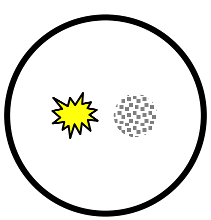
- Probability for direct exposure of the same place $<1/10^3 - 1/10^4$



  - If we assume maintenance period of 2 years and acceptable erosion of 3mm, the probability for direct exposure of the same place with α particles must be less than $1/10^4$.
  - The answer would be improve flow control, material selection, and chamber radius
- Although tilted front panels will reduce the stagnation to $1/10^3$, few gram of LiPb vapor will stagnate at the center.
  - Off set irradiation would be the answer.



Summary 1

- 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 (~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.

Summary 2

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- Core plasma,
  - High density compression of cone target
  - Heating efficiency of 30%
  - Adiabat a <2.5
- In the laser system
  - Construction of laser itself seems possible with existing technology.
  - Beam steering of ignition beam may be critical.
- Chamber system
  - Chamber clearance
  - Tritium confinement

Basic specification of KOYO-F

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Net electric output	1283 MWe (320 MWe x 4)
Electric output from one module	320 MWe
Target gain	167
Fusion Yield	200 MJ
Laser energy/Beam number	1.2 MJ（Compression=1.1MJ/32beams, Heating=100kJ 1beam）
Laser material / Rep-rate	Cooled Yb:YAG ceramics at 150 ~ 220K /16 Hz
Chamber structure/Rep-rate at module	Cascade-type, free-fall liquid LiPb wall/4 Hz
Fusion power from a module	800 MWth
Blanket gain	1.2（design goal）
Total thermal output from a module	916 MWth
Total thermal output from a plant	3664 MWth (916 MWth x 4)
Heat-electricity conversion efficiency	41.5 %（LiPb Temperature 500℃）
Gross electric output	1519 MWe
Laser efficiencies	13.1% (compression), 5.4% (heating)、Total 11.8%（including cooling power）
Recirculating power for laser	164 MWe（1.2 MJ x 16 Hz / 0.118)
Net electric output/efficiency	1283 MWe(1519 MWe - 164 MWe - 72 MWe Aux.)/32.7%

Plant size is 303mlong x 110mwidth x 50mhigh.