

Target fabrication and injection activities toward laser fusion reactor with wet wall



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And

Member of Roadmap Committee (Chair, A. Tomabuchi)

Presented at

2nd US-Japan Workshop on IFE target Fabrication, Injection
and Tracking

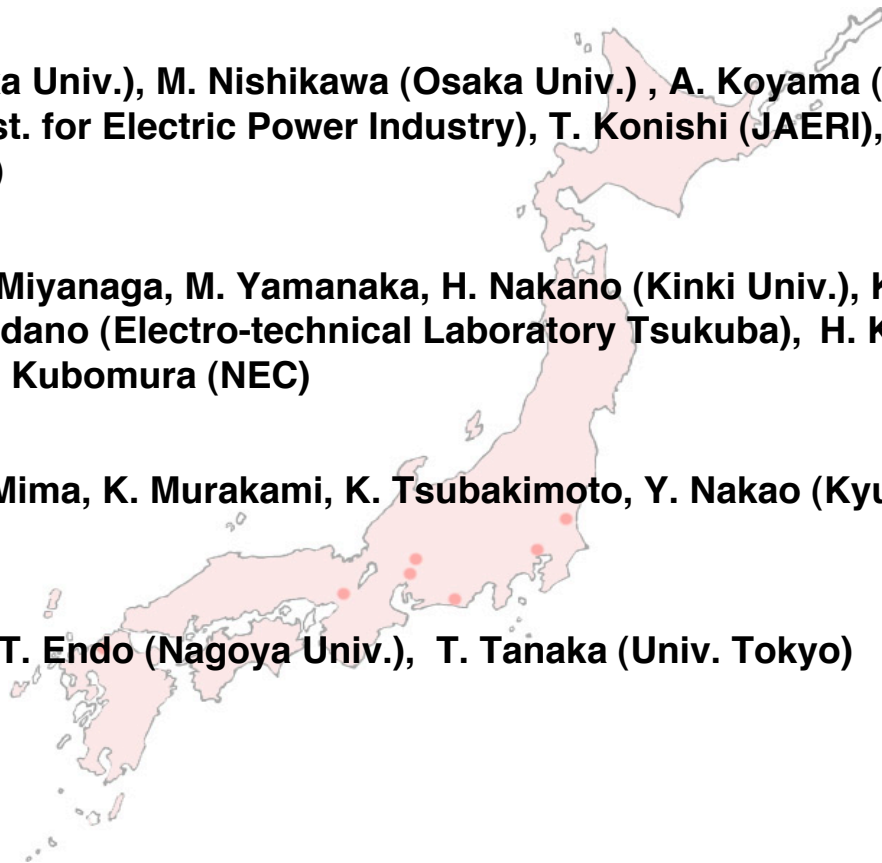
San Diego, Feb. 3-4, 2003.

Roadmap committee of IFE Forum* is working to make proposal for laser fusion research and conceptual design of laser fusion reactor.



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- **Chair A. Tomabuchi** (Cent. Res. Inst. for Electric Power Industry), **Co-chair Y. Kozaki**,
- **Reactor system**
 - Y. Ueda (Osaka Univ.), M. Nishikawa (Osaka Univ.), A. Koyama (Kyoto Univ.), K. Okano (Cent. Res. Inst. for Electric Power Industry), T. Konishi (JAERI), A. Sagara (NIFS), T. Muroga (NIFS)
- **Laser**
 - T. Jitsuno, N. Miyanaga, M. Yamanaka, H. Nakano (Kinki Univ.), K. Ueda (Univ. Electro Com.), Y. Owadano (Electro-technical Laboratory Tsukuba), H. Kan (Hamamatsu Photonics), H. Kubomura (NEC)
- **Plasma**
 - H. Azechi, K. Mima, K. Murakami, K. Tsubakimoto, Y. Nakao (Kyushu Univ.), Y. Ogawa (Univ. Tokyo),
- **Fueling**
 - T. Norimatsu, T. Endo (Nagoya Univ.), T. Tanaka (Univ. Tokyo)





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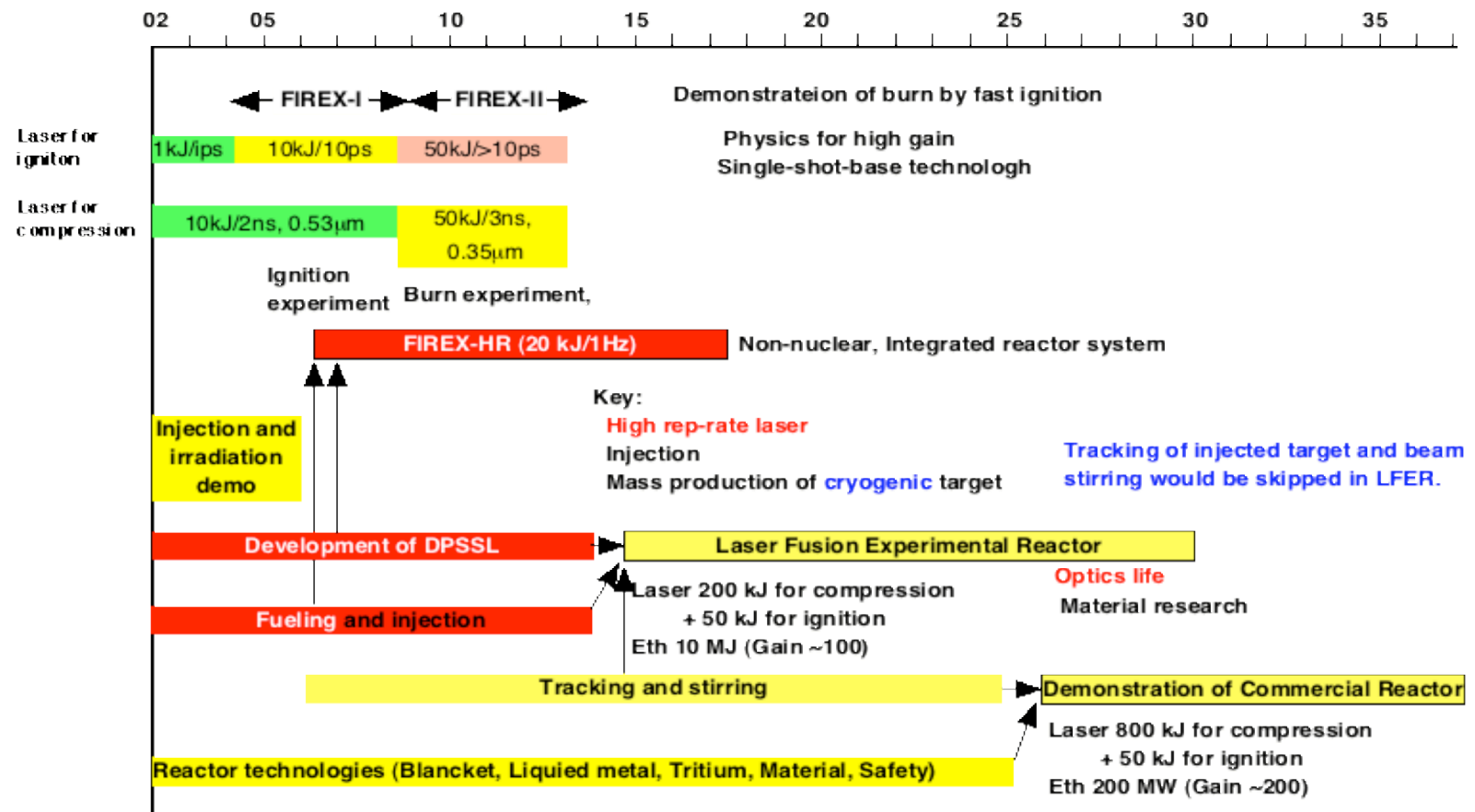
Outline

- ➡ • **Roadmap toward laser fusion reactor**
 - Required targets and the research plan
- **Requirement for injection and tracking for wet wall reactor**
 - Central ignition target
 - Fast ignition target
- **Experimental activities in 2003**
 - Target fabrication
 - Simulator for reactor environment

Roadmap toward laser fusion power plant by fast ignition



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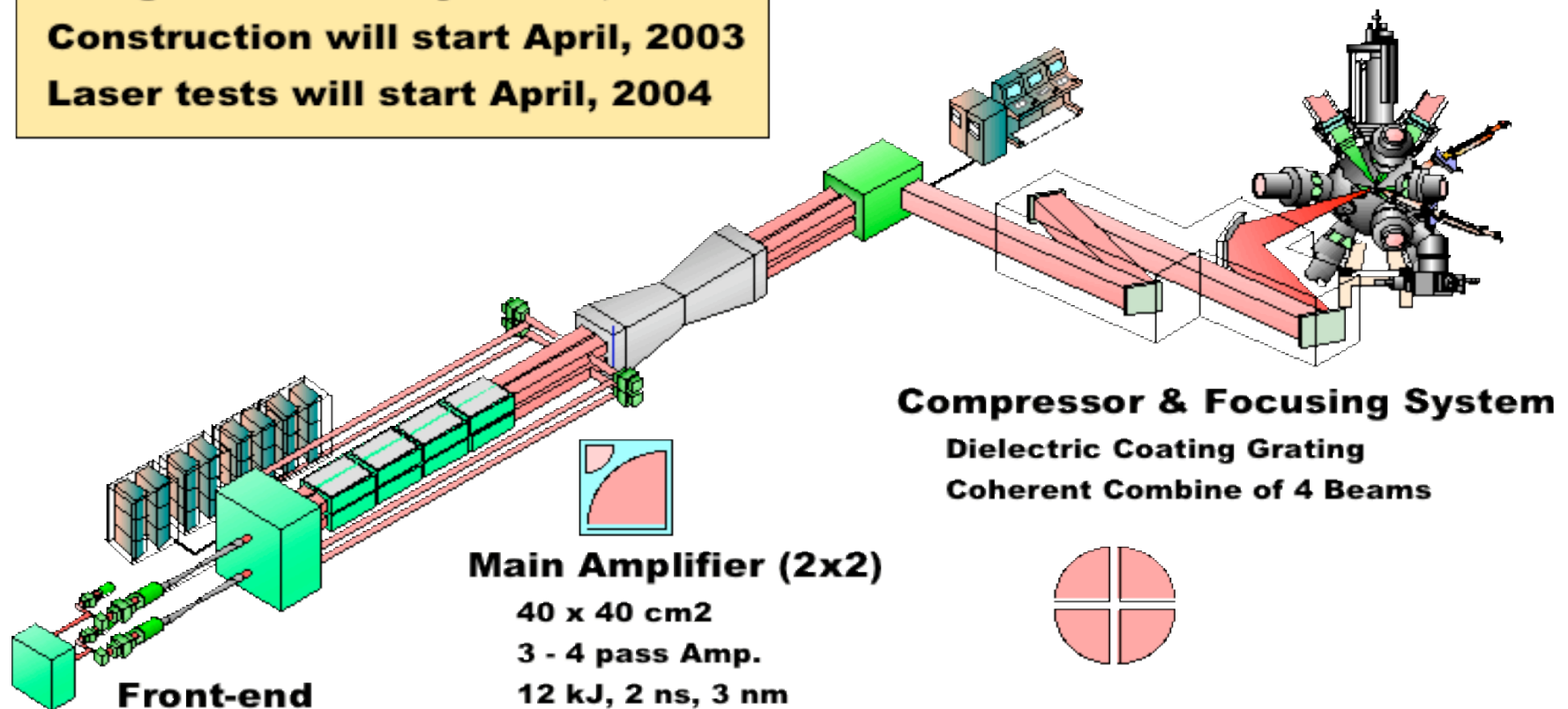


FIREX-I is approved and the design started in 2003.



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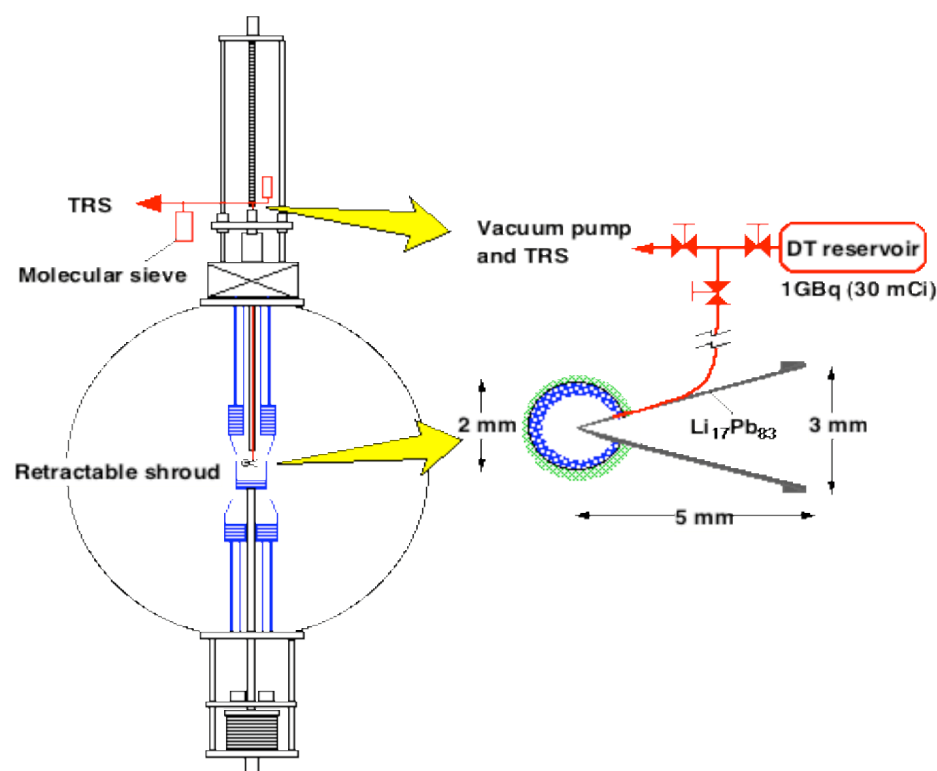
Design will finish by March, 2003
Construction will start April, 2003
Laser tests will start April, 2004





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Research plan of target for FIREX-II



- Cryogenic foam target with gas feeder will be used to demonstrate ignition and burn in FIREX-II.
- Use of the gas feeder reduces the burden of handling high pressure DT gas.
- Foam will sustain the uniformity of fuel layer under non-isothermal condition due to the cone.

How is the influence of the feeder and foam to the implosion performance?

Estimation of Ignition Energy and Gain



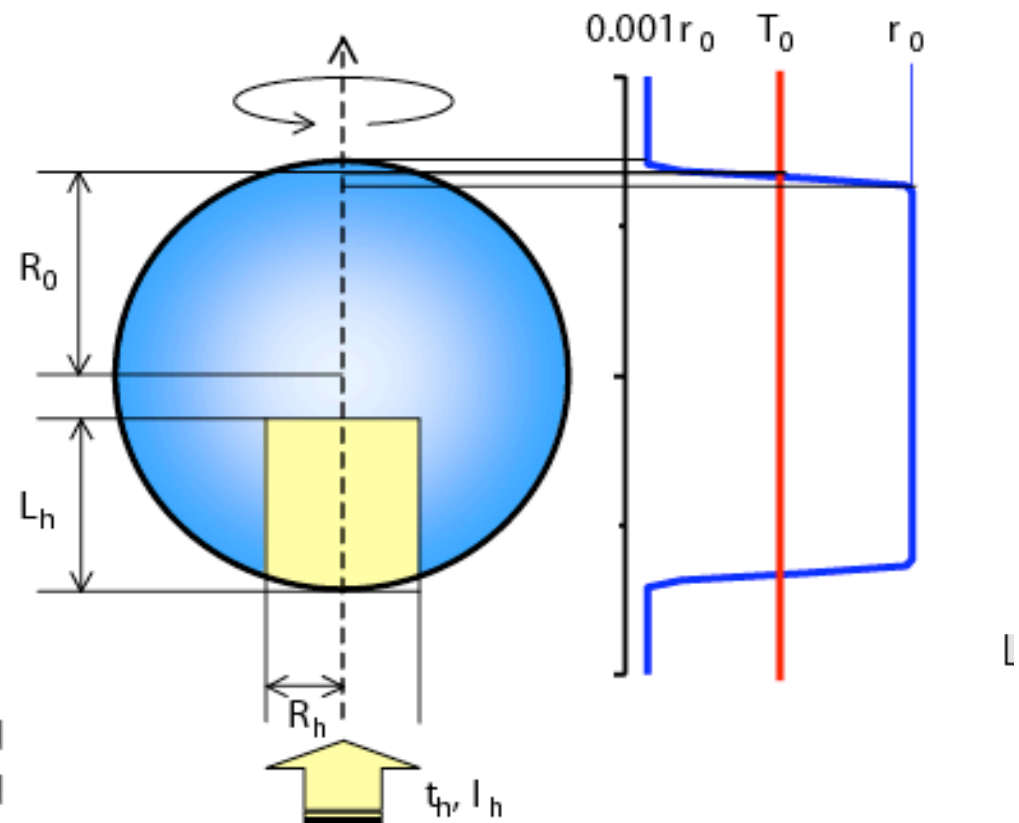
Initial plasma configurations

⇒ Uniformly -compressed plasma sphere
(high gain)

Density, ρ_0	300 g/cc
Temperature, T_0	0.2 keV
(Isentrope α)	2.0
Radius, R_0	90mm
$\rho_0 R_0$	2.7 g/cm ²
Mass, M_f	0.89mg

External Heating

Duration, t_h	10 ps	
Spot radius, R_h	20 mm	fixed
Optical Depth, ρL_h	1.0g/cm ²	fixed
Intensity, I_h	7 - 22E19 W/cm ²	



※ In the heating region, the external heating rate P_h per unit mass is uniform, i.e. $P_h [W/kg] = I_h / \rho L_h$.

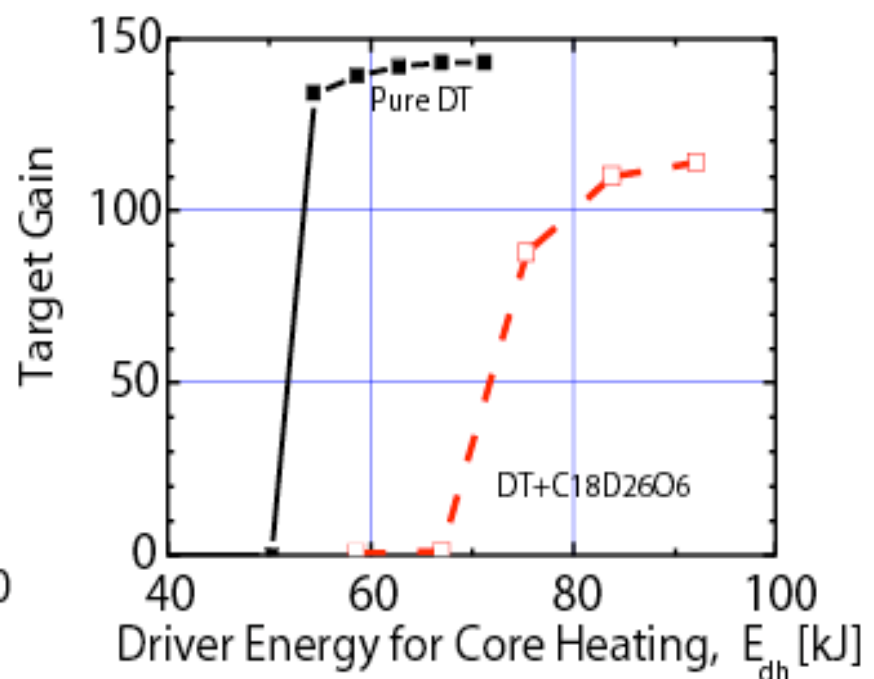
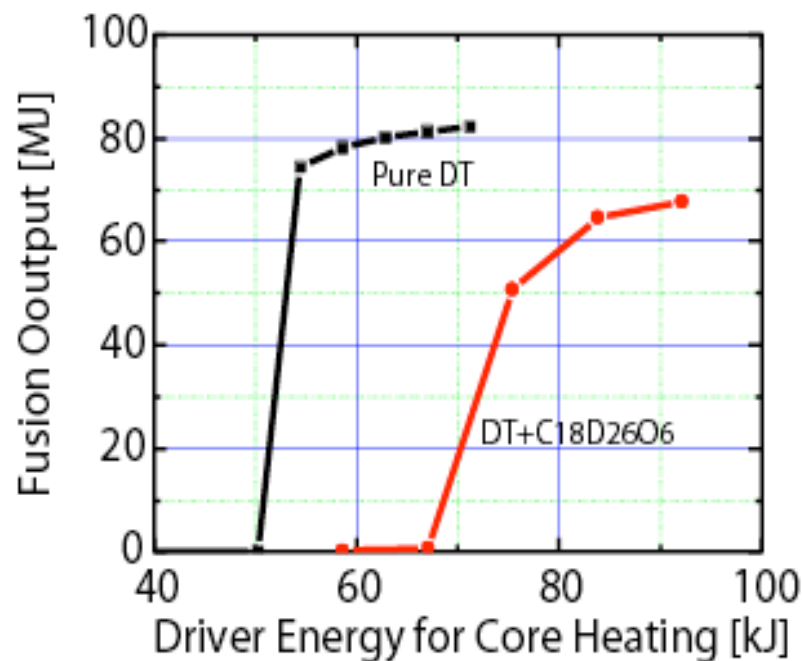
Effect of supporting 30 mg/cc foam ($C_{18}D_{26}O_6$)



High Gain core : $\rho R = 2.7\text{g/cm}^2$, $\rho = 300\text{g/cc}$, $a = 2$, $E_{\text{int}} = 25\text{kJ}$, ($E_{\text{dc}} = 500\text{kJ}$ with 5% coupling for implosion)

Uniform core heating: $I_h = 7 - 22\text{E}19\text{W/cm}^2$ ($t_h = 10\text{ps}$, $r_b = 20\text{mm}$) $E_h = 8.8 - 27.6\text{kJ}$

$\Rightarrow E_{\text{dh}} = 29 - 92\text{kJ}$ with 30% coupling for core heating



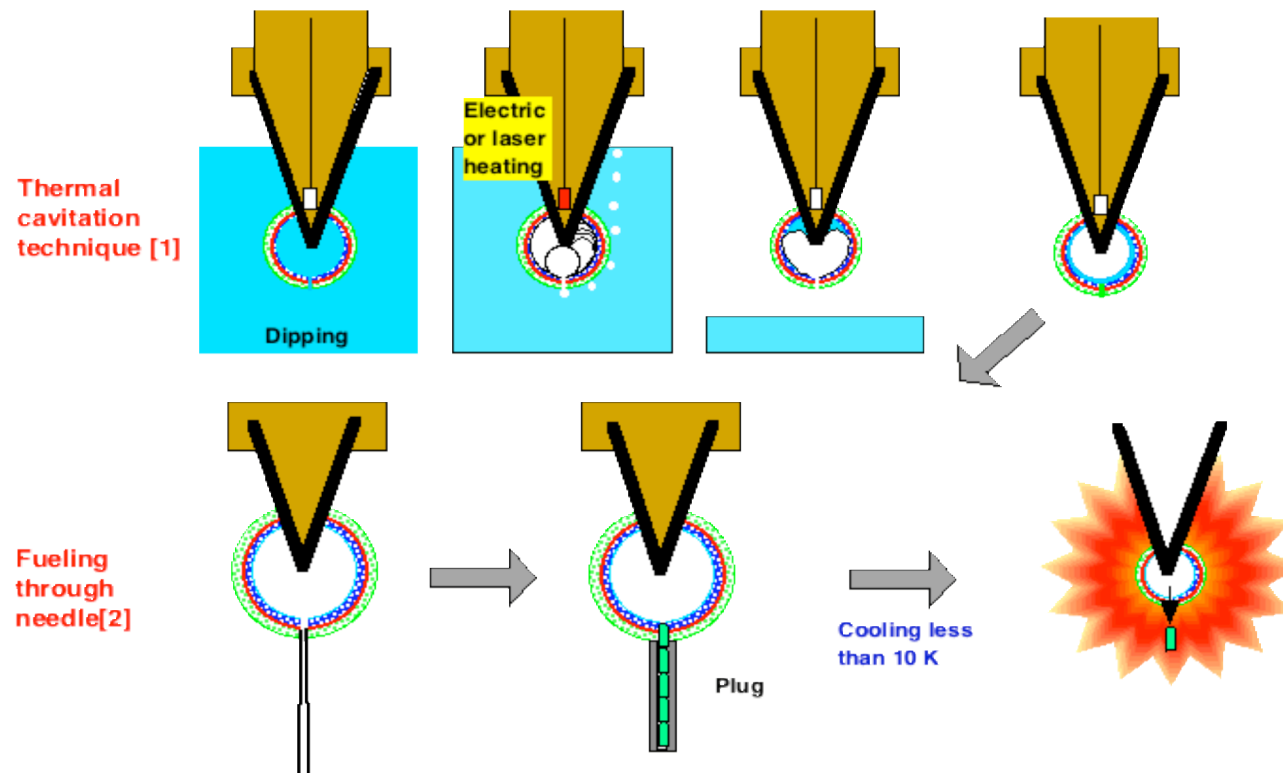
Ignition and high gain are possible but lower density foam is necessary to make FI more attractive.

For FIREX-HR, development of continuous fueling system is the key.



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- Thermal cavitation technique is attractive to fill many shells simultaneously.



[1] H. Katayama, T. Norimatsu, C. Chen, T. Yamanaka, Y. Nishino, and S. Nakai, J. Vac. Sci. Technol., A9(4) 2140 (1991).

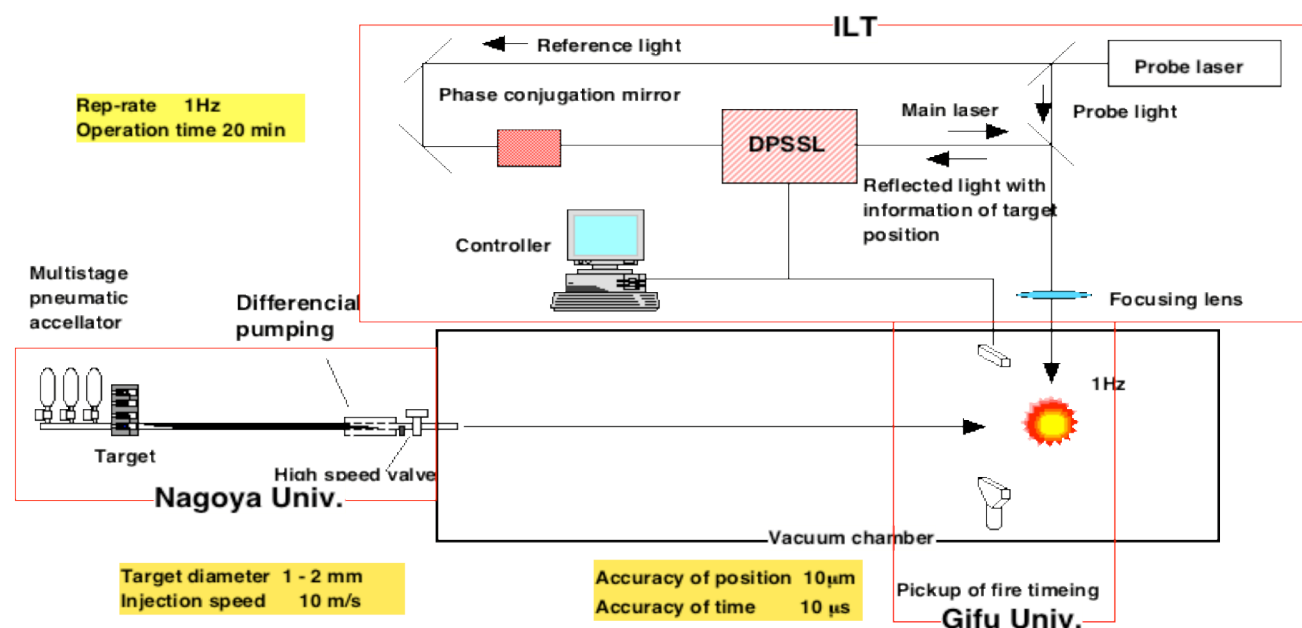
[2] M. J. Monsler, Y. A. Merkul'ev and T. Norimatsu, pp. 151-184 "Energy from Inertial Fusion", IAEA, Vienna (1995) ISBN 92-0-100794-9



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Demonstration of repetitive laser irradiation

- To persuade suspicious people, we are going to make a small integrated reactor system that demonstrate repetitive laser irradiation of injected targets. (2003-2006)



Scientific interest;
Power distribution on target
Reflectivity of phase conjugation mirror
Influence of heat generation in the mirror



Collaborations

- **We are going to collaborating with;**
 - **On target material**
 - GA
 - Hirosaki Univ. (Photo-voltaic material)
 - Nihon Univ. , Tokyo Inst. Technol. (Dopant, Monomer)
 - Ibaraki Univ.(Dopant)
 - **On Cryogenic technology;**
 - NIFS (D-³He)
 - LPI (Characterization)
 - **Injection and tracking**
 - GA
 - Nagoya Univ. (Pneumatic gun), Gifu Univ. (Tracking), ILT (Tracking and Stirring)
 - **Reactor material**
 - Tokyo Inst. Technol. (Irradiation with pulse power)



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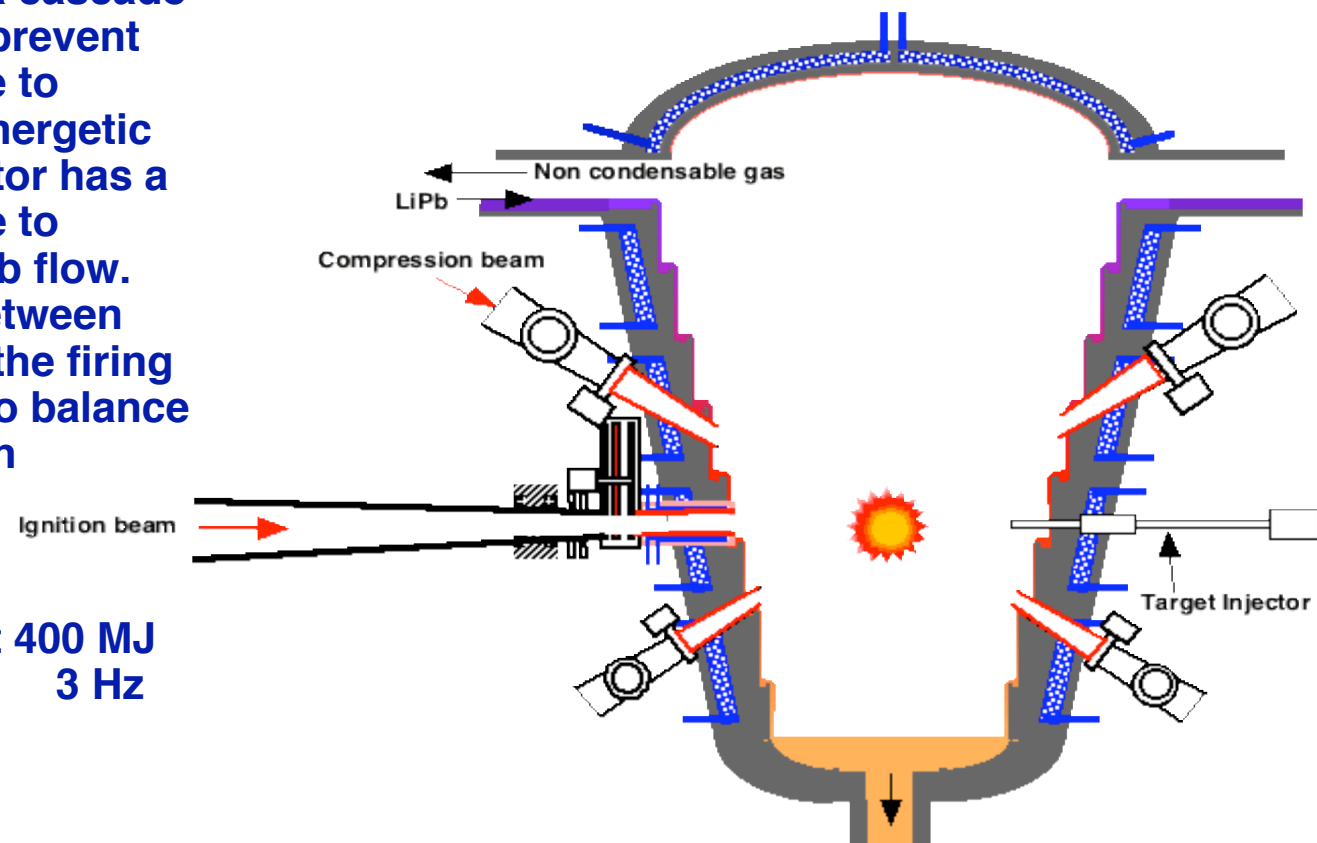


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Cascade reactor for fast ignition scheme

- New Koyo has a cascade flow of LiPb to prevent the ablation due to sputtering by energetic ions. The reactor has a hybrid structure to simplify the LiPb flow. The distance between the ceiling and the firing position is set to balance the ablation with condensation.

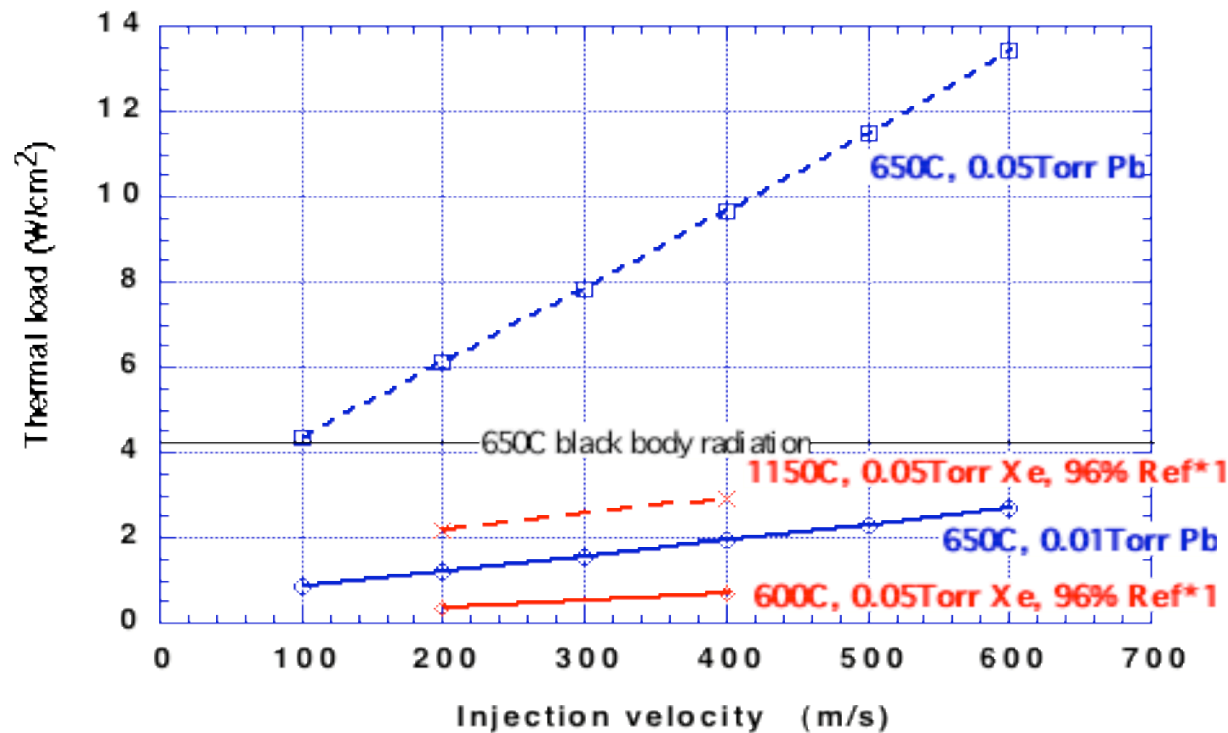
Thermal out put 400 MJ
Rep-rate 3 Hz



Some protection scheme is necessary to use a cryogenic target in a wet wall reactor.



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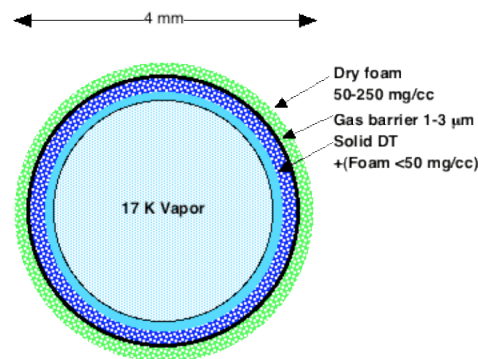
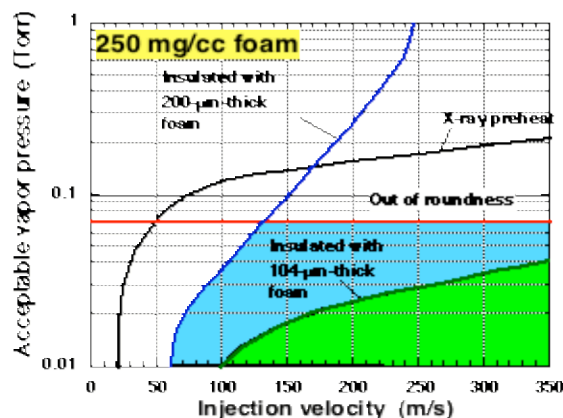
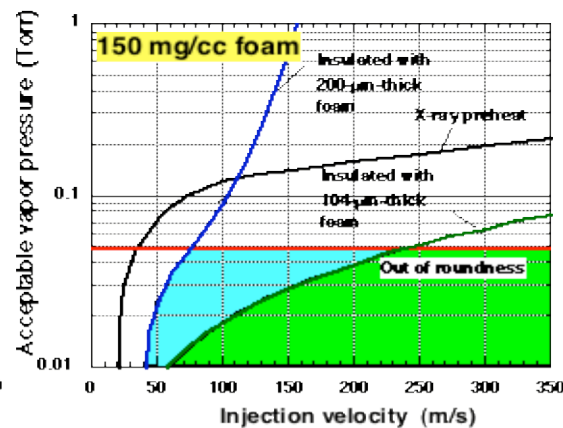
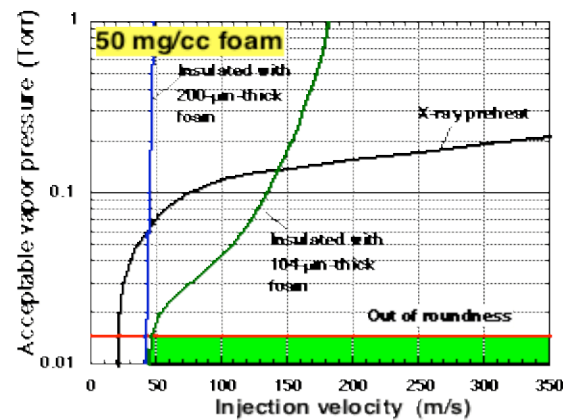


- Because of large latent heat of condensation, the thermal load in a wet wall reactor is 10 times as large as that in a dry wall reactor.
- Ref*1, D. Goodin to be published in Fusion Technology.

Design space for foam insulated central ignition targets



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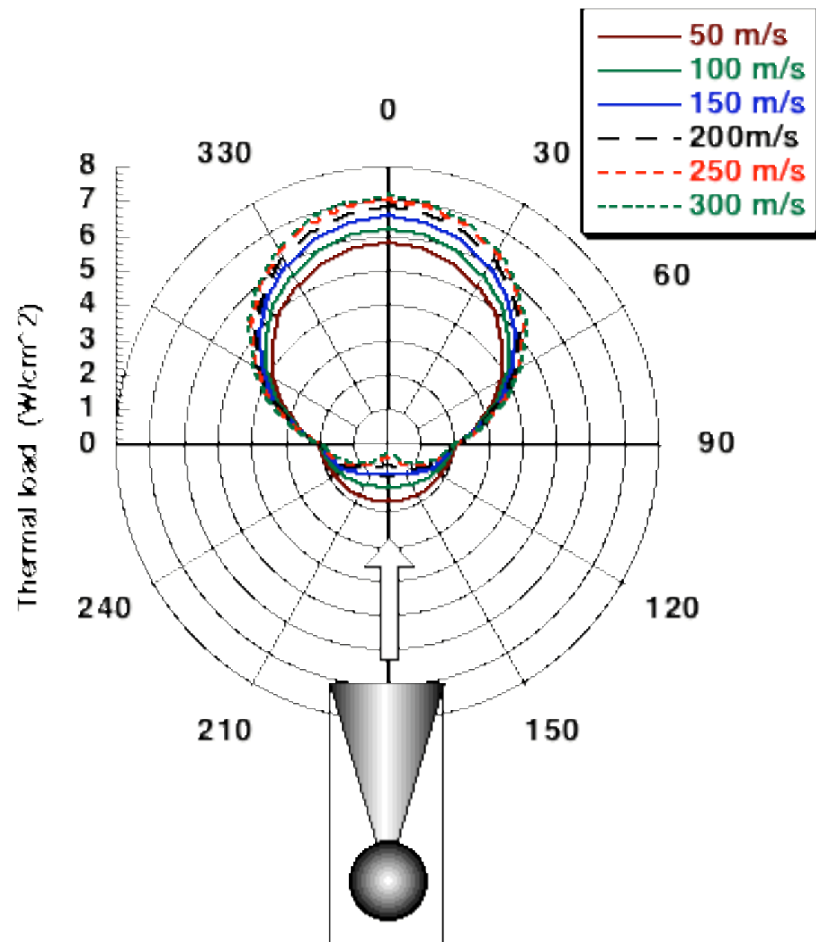
- When the density of foam layer is 50 mg/cc, the out-of-roundness is the critical issue because of large density jump. Melting occurs mainly by thermal radiation.

- Melting is the critical issue for 250 mg/cc foam shells because of poor insulation effect.

In the case of a fast ignition target, thermal load is concentrated on the leading side.



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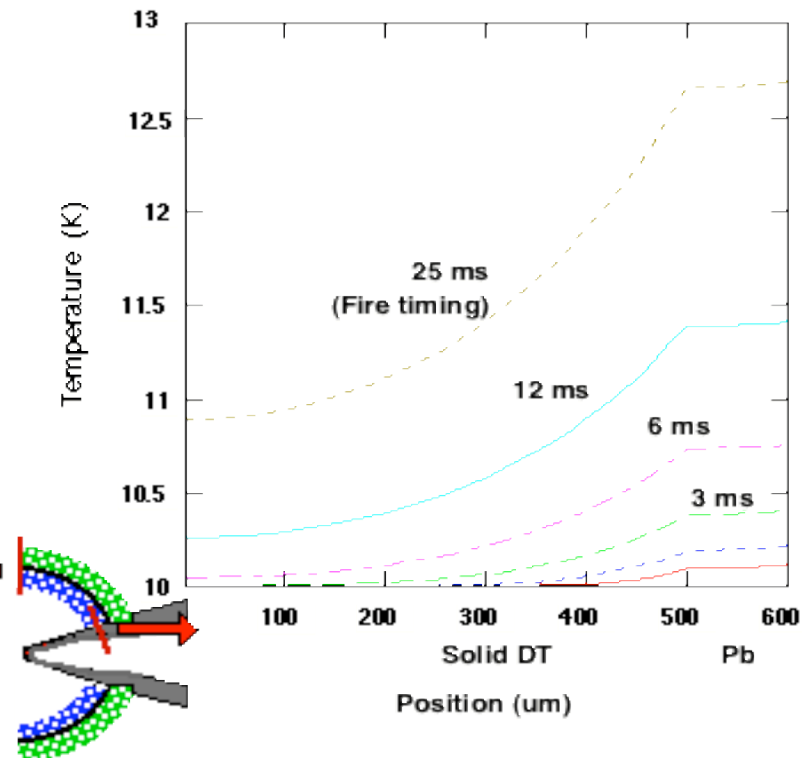
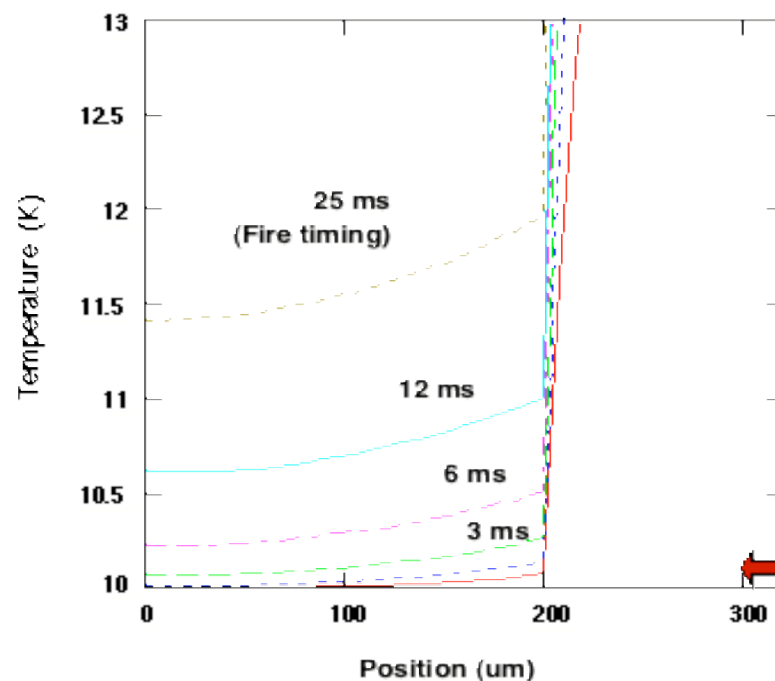
- When a target is injected into 650 C, 0.05 Torr Pb vapor at 300 m/s, the thermal load on the leading side exceeds Black body radiation.
- The cone works as a wake shield that reduces the thermal load due to the dynamic component.
- Because of large thermal conductivity of lead, the cryogenic layer would melt away.

Due to large heat capacity of the cone and lower initial temperature, foam-insulated cone target can survive in the wet wall reactor.



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- Vapor pressure, 0.05 Torr, Chamber temperature 650 C
- The injection velocity, 200 m/s
- Foam density 250 mg/cc, Foam thickness, 100 μm

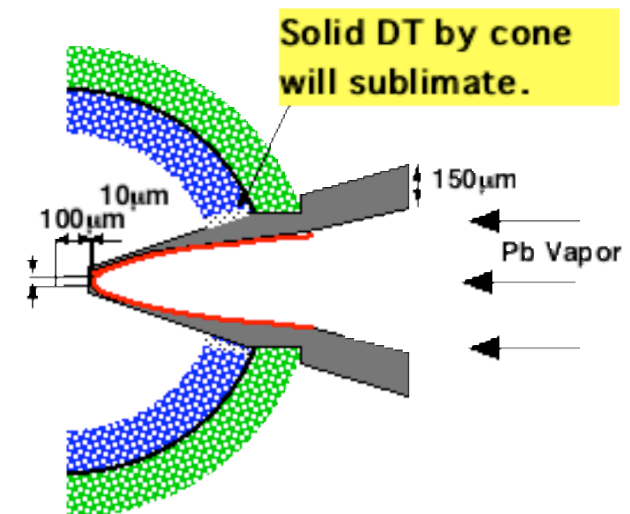
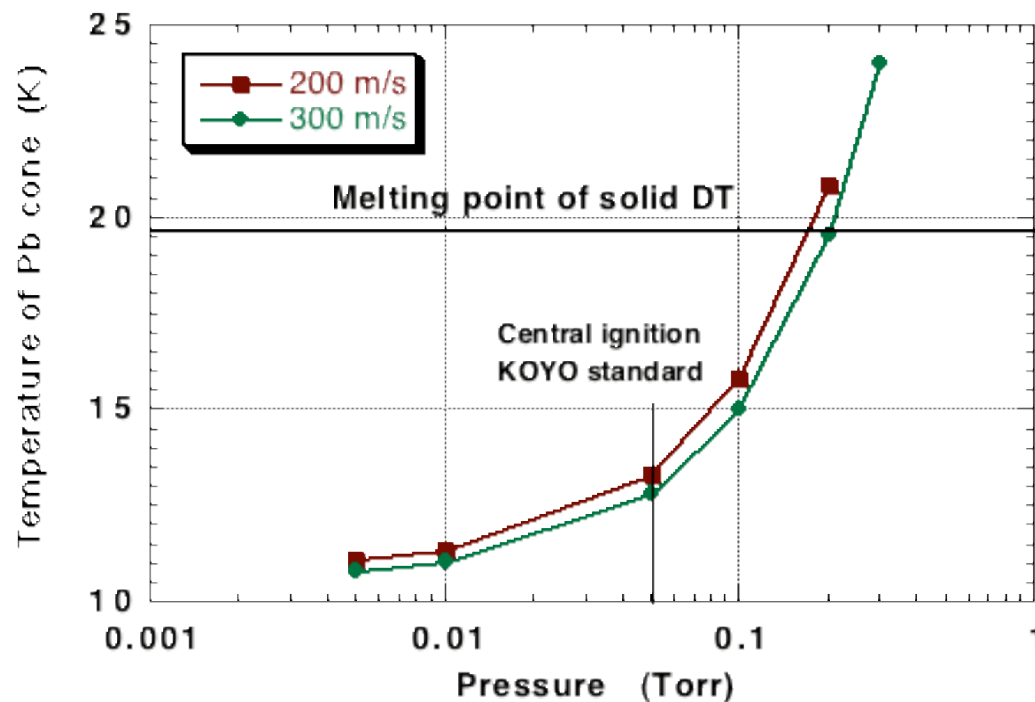


Because of the large heat capacity of the cone, the temperature of the cone is representative of the target.



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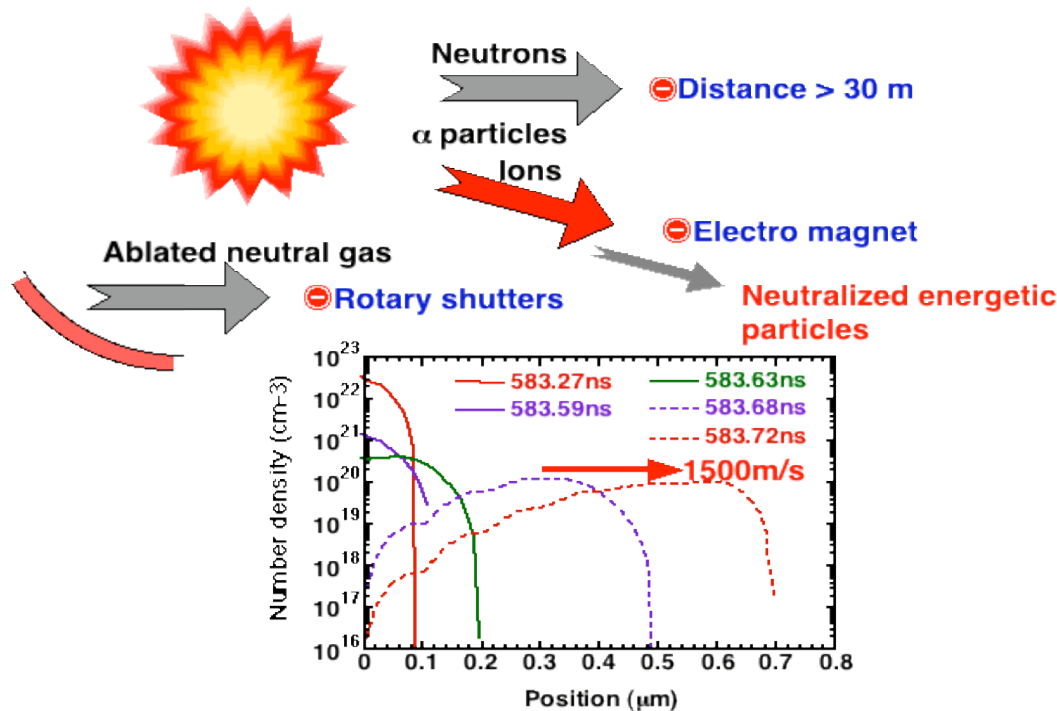
- Since there is no gas barrier inside, solid DT layer contacting with the cone will sublime and be redistributed toward lower temperature zone.
- Influence of dry zone on the high density compression is future issue.



In wet-wall reactor, protection of final optics from neutralized particles seems most critical.



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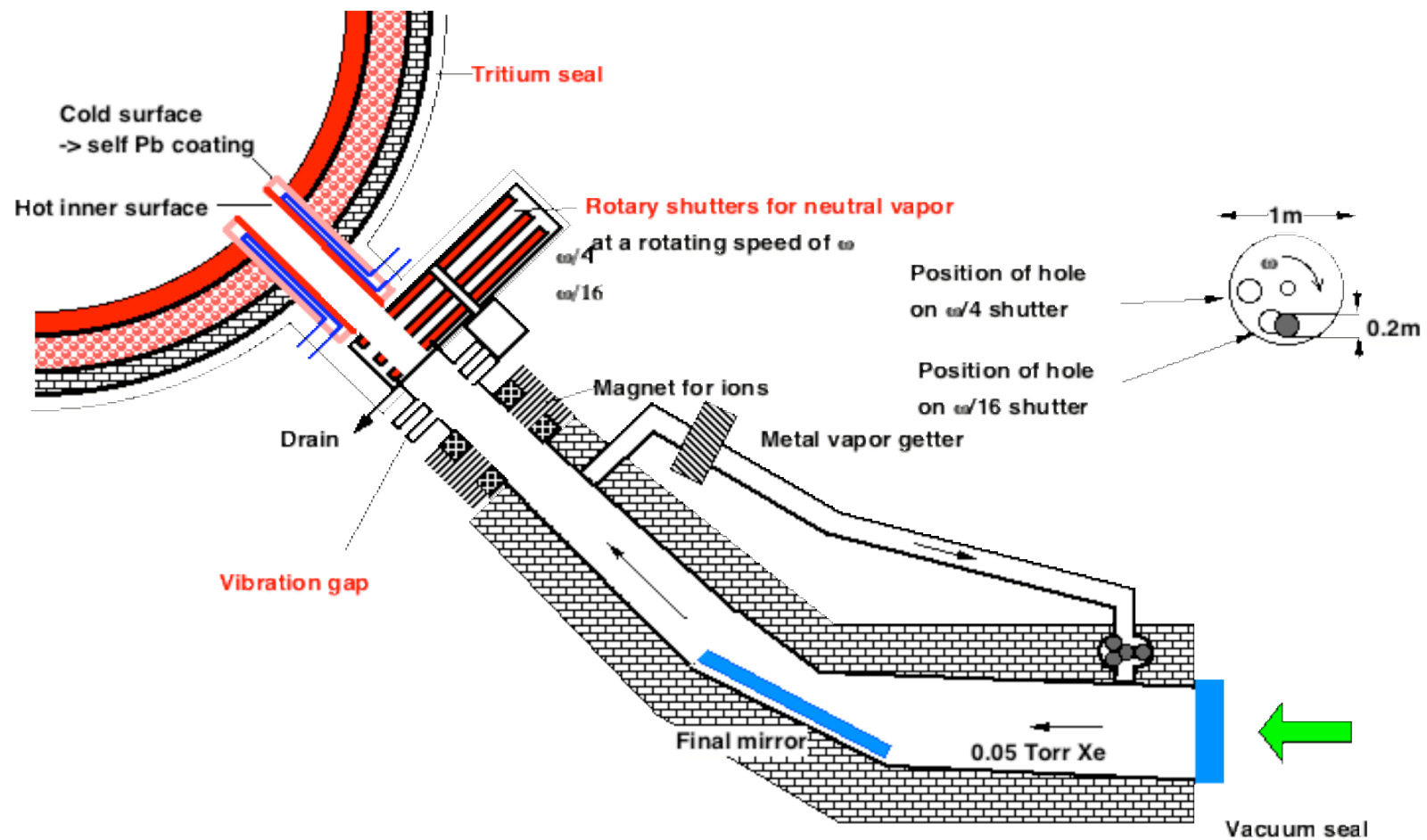


- Metal vapor on final optics makes plasma that damages the surface of optics.
- Neutrons can be ignored by locating the optics 30 m apart.
- Alpha particles and ions can be removed by a Magnetic field.
- Ablated metal from inner surface can be shielded by rotary shutters.

Protection scheme of final optics by rotary shutters



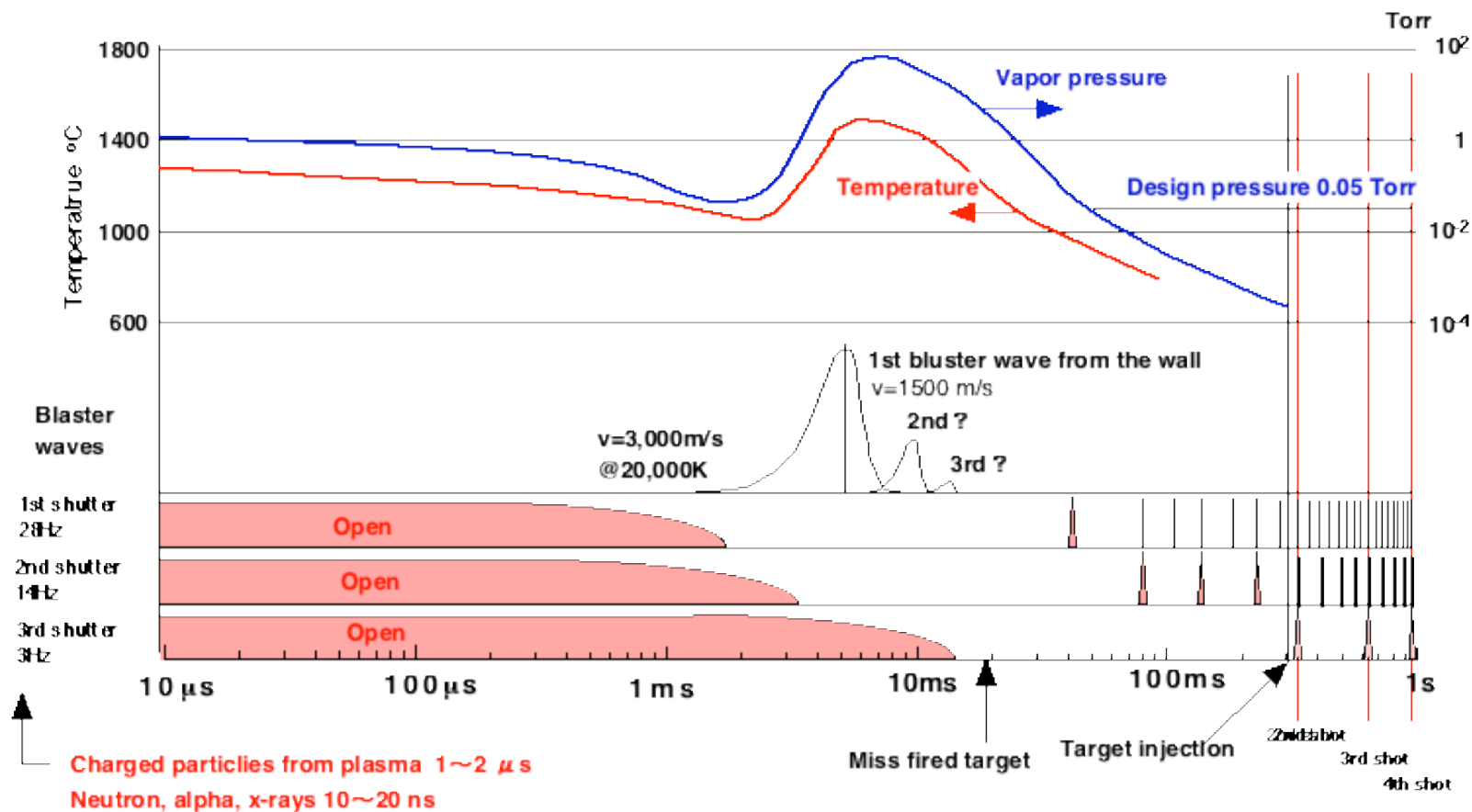
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Timing chart for bluster wave and rotary shutters



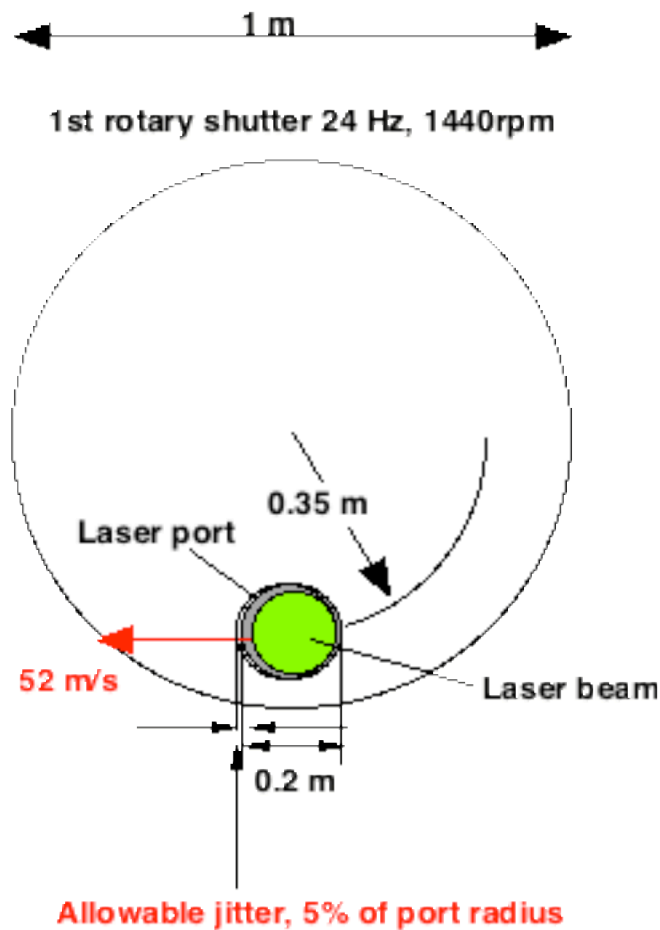
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Rotary shutters impose severe accuracy for the injection velocity.

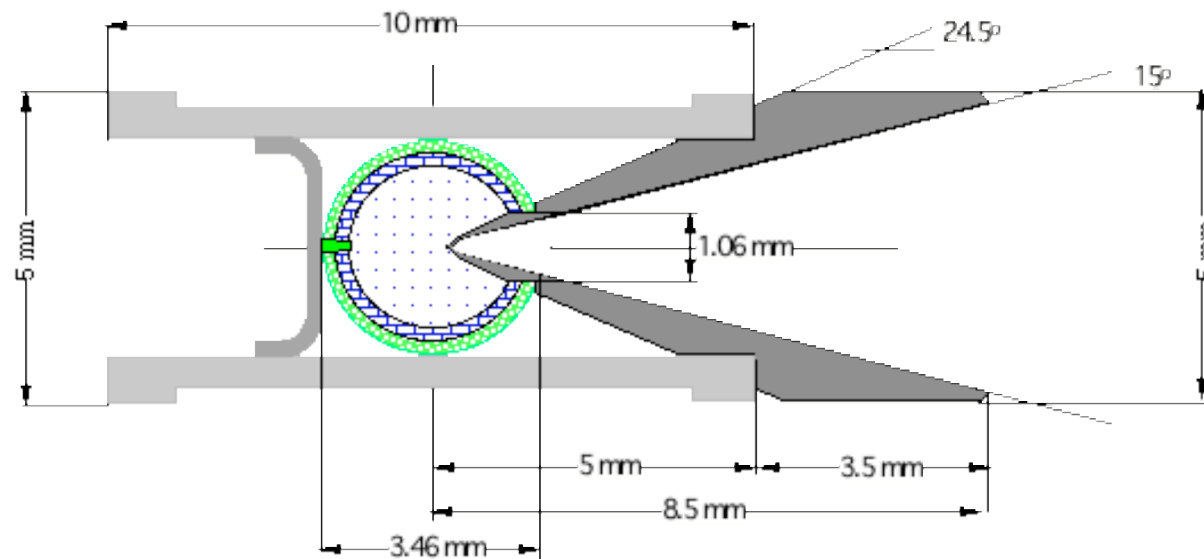


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- Fire timing of the target and open time of the rotary shutters must be synchronized with accuracy of 0.2 ms.
- This requires the injection velocity of **200 +/- 2 m/s**.

Cone	
Material	Li17Pb83
Length	8.5 mm
Diameter	5 mm
Mass	429 mg

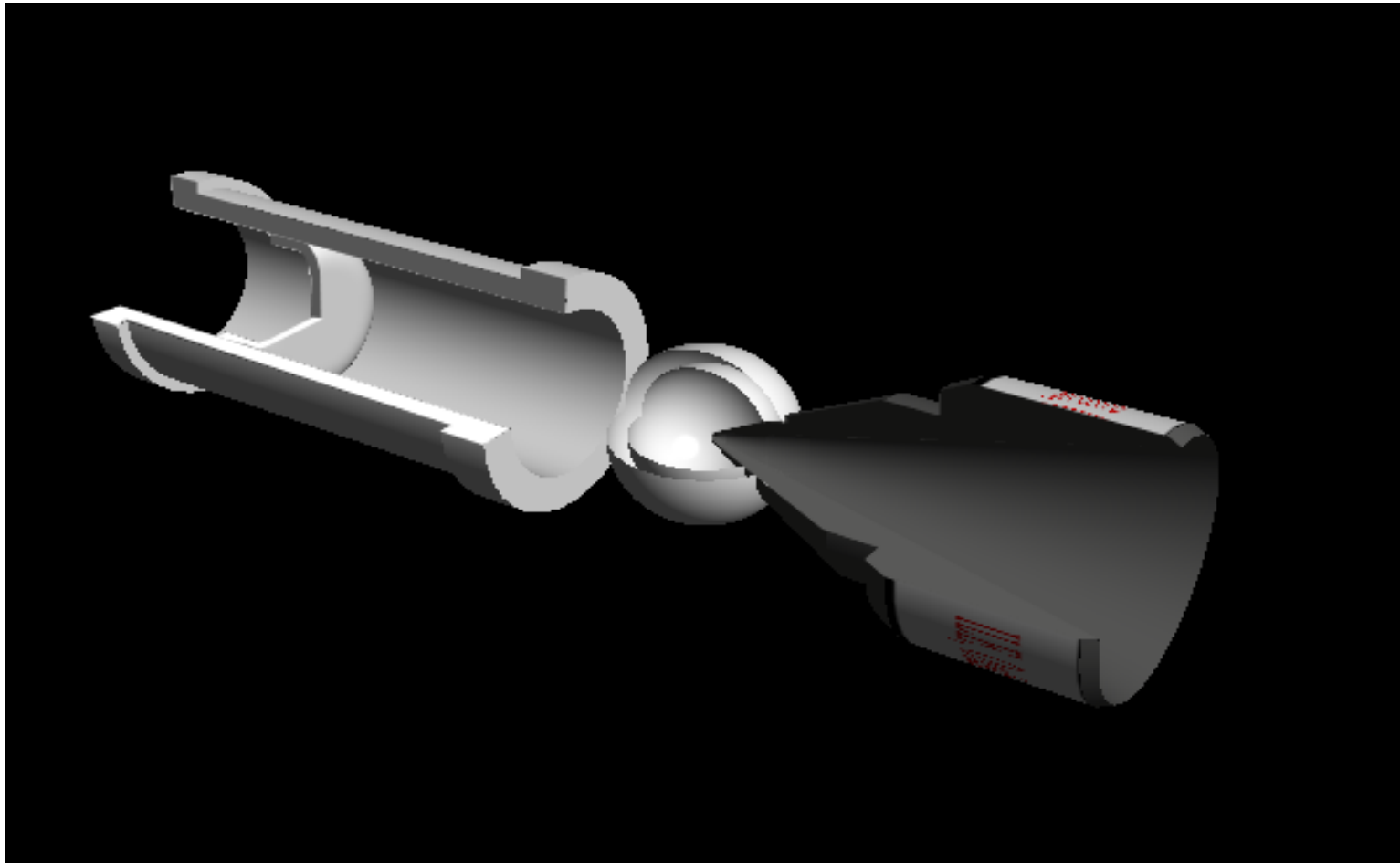


Sabot	
Material	Al
Mass	200mg

Cut view of cryogenic cone target and the sabot



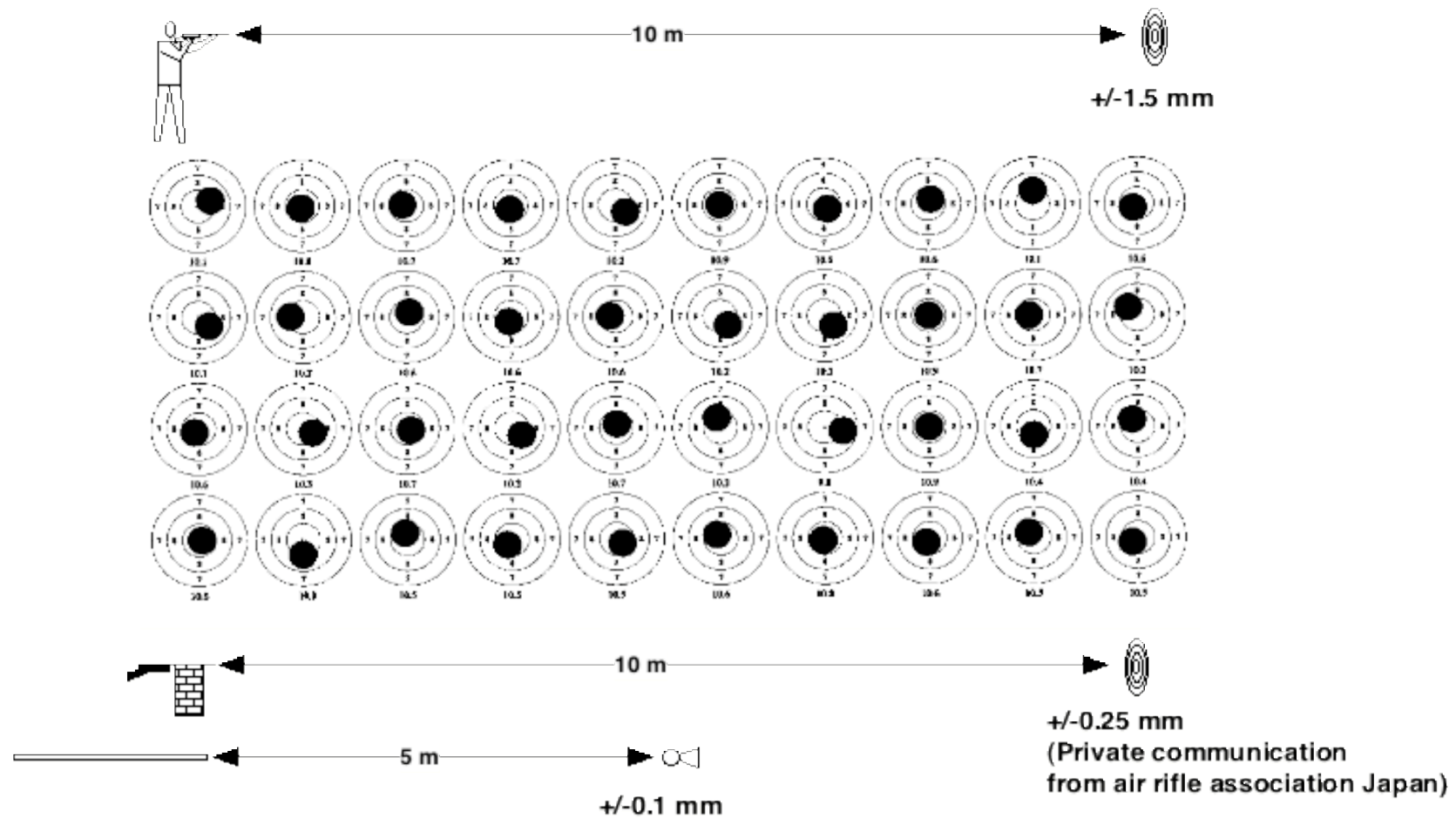
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Ideally we can expect pointing accuracy of ± 0.1 mm at 5m apart.



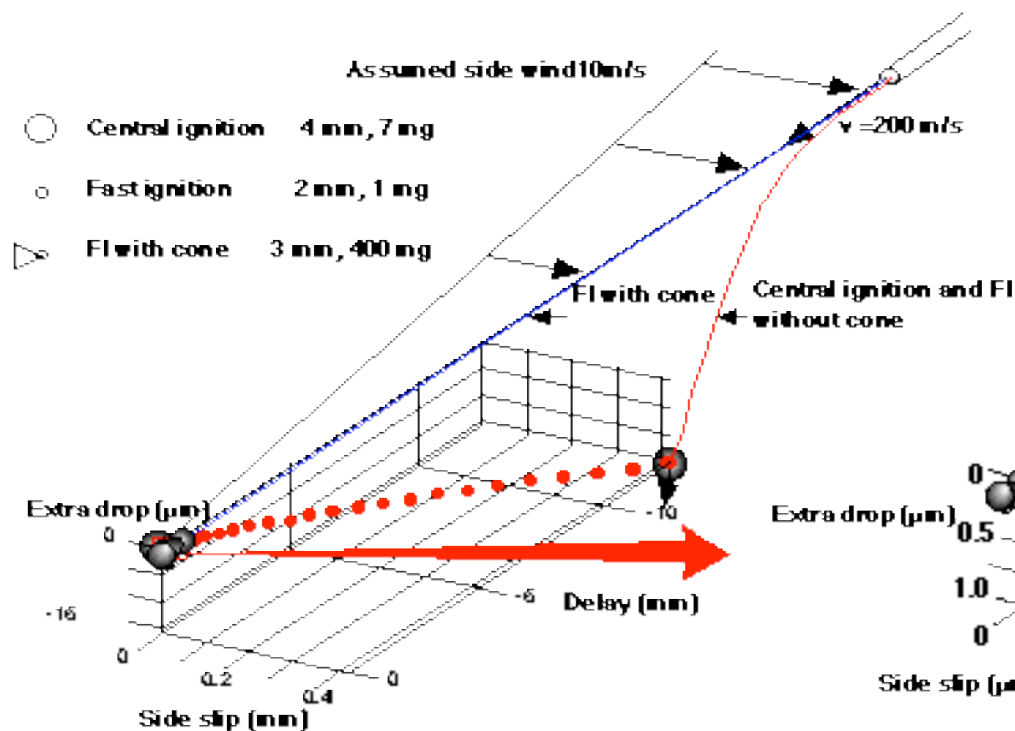
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Trajectory of fast ignition target with heavy cone.

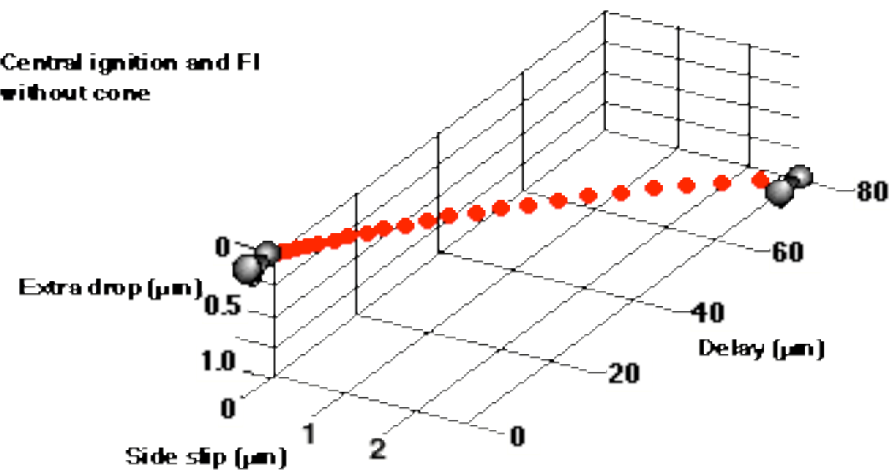


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In the case of a fast ignition target with cone, estimated variation is $\pm 8 \mu\text{m}$ because of its large mass.

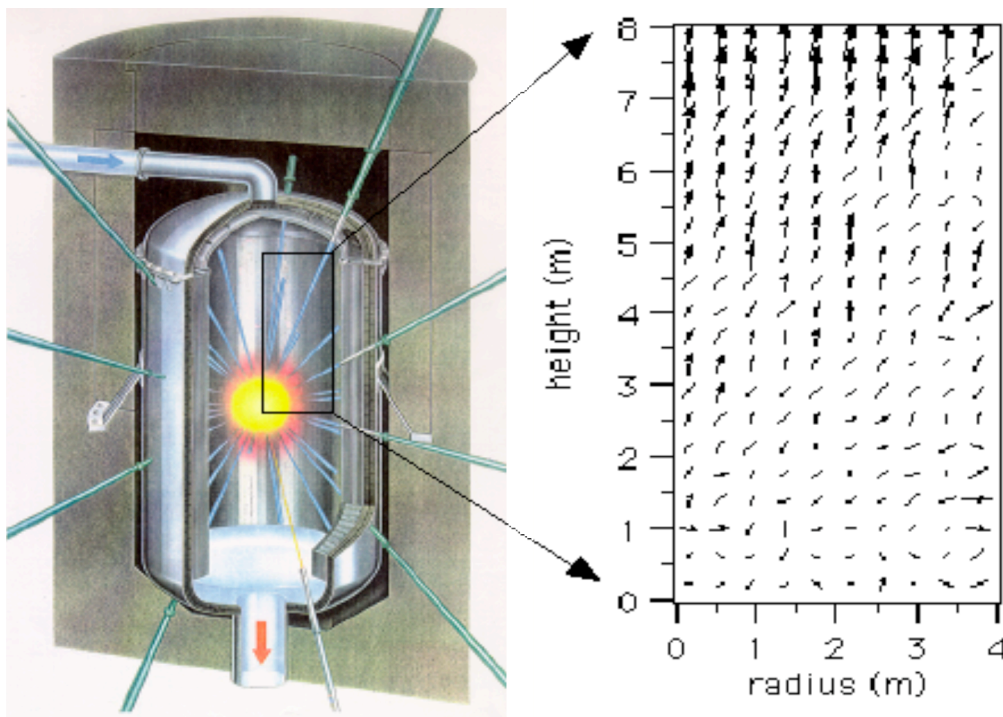
Tracking in chamber could be skipped depending on the requirements.



In future wet-wall reactor, the speed of vapor flow is estimated to be 170 m/s at the periphery.



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→ = 1.718e+02

case3 (60msec)

- When the fusion yields varies 10 % for shot to shot, the speed of vapor will also vary 10 % since the ablated mass is proportional to the fusion yield.
- The variation of the vapor was estimated to be 20 m/s.
- This estimation indicates that the shot to shot variation in the target position at the center due to cross wind is 5 μ m for the FI target with heavy cone.



Necessity of tracking

	Tracking at muzzle	Tracking in chamber	Detection of firetiming	Beam stirring
Central ignition target	Necessary	Necessary	Necessary	Necessary
FI target (without cone)	Necessary	Necessary	Necessary	Necessary
FI target (with right cone)	Depends on conditions	Depends on conditions	Necessary	Depends on conditions
FI target (with heavy cone)	Could be skipped depending on injector performance 1×10^{-5} rad	Could be skipped	Necessary	Could be skipped depending on injector performance $\pm 100 \mu\text{m}$



Key technologies related to target toward IFE

- **Fabrication of low density foam shell with gas barrier and (insulator for wet wall reactor)**
 - Density 10 mg/cc (Gain reduction)
 - Cell size 1 μ m (To allow optical characterization)
 - Coating of gas barrier (Maybe interfacial polycondensation technique)
 - Coating of insulation layer (for mainly wet wall reactor)
- **Direct fueling system**
 - Thermal cavitation (controllability, cracks, tritium inventory)
 - Needle injection (Currently no demonstration)
- **Injection**
 - Speed control
 - Rifling



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Outline

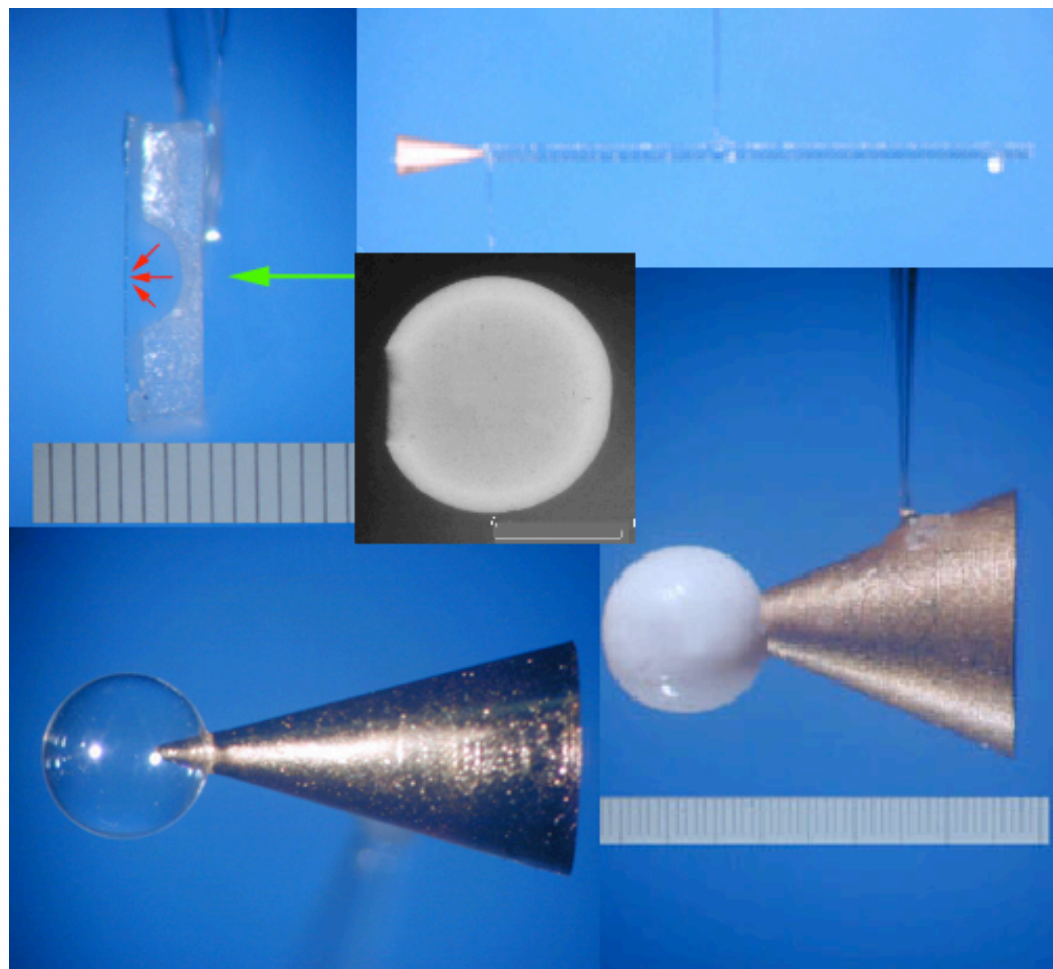
- **Roadmap toward laser fusion reactor**
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Experimental activity of 2002 at ILE

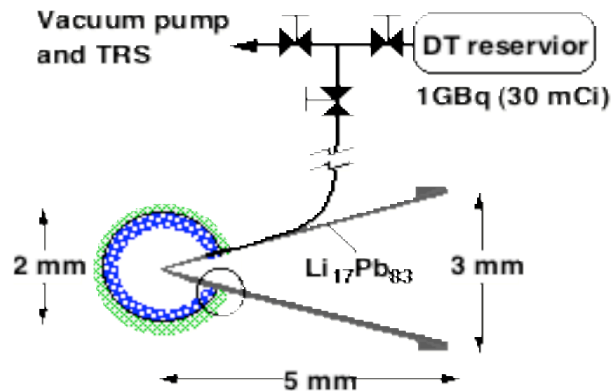
- Target fabrication
 - Fast ignition targets
 - PS, Foam
 - Ion focusing
 - Beat wave acceleration
 - Polyimide shell
- Material development
 - Low density foam
 - Photo-voltaic polymer
 - Polymer with high Z
- Injection and tracking
 - Reactor simulator



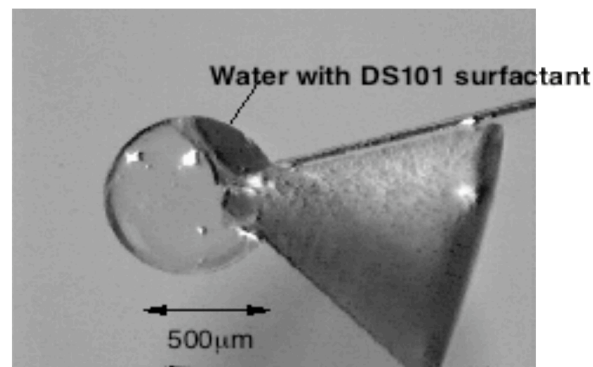
We are going to use foam technique to make solid hydrogen layer in FI target with cone.



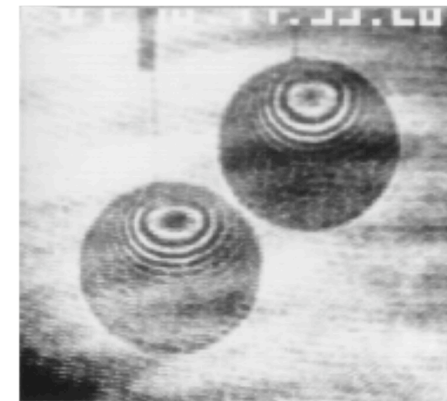
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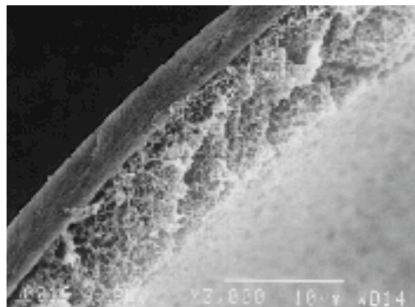
Fuel will be loaded through a gas feeder



Demonstration of feeder at room temperature



Without foam layer



With use of the foam layer, a uniform solid hydrogen layer will be produced in a shell with a optical guide cone.

Foam shell with gas barrier was already fabricated by emulsion process followed with interfacial polycondensation technique.

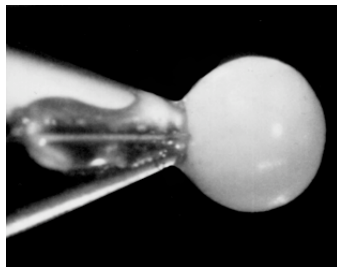


With foam layer

The first try was failure because of puncture of shell

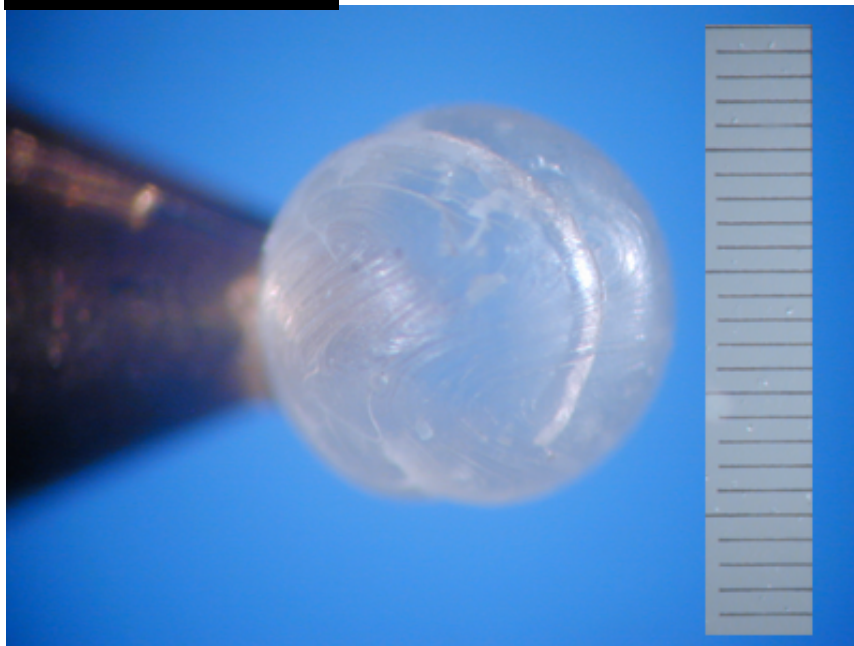


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← Before injection

After injection



- The foam layer becomes transparent, which revealed new issue, many micro-structures in the gas barrier coated with interfacial polycondensation technique.

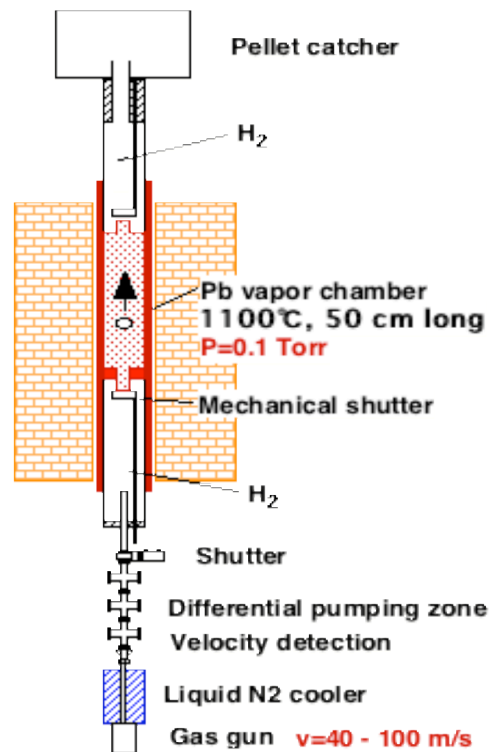
Simulation of liquid wall reactor started.



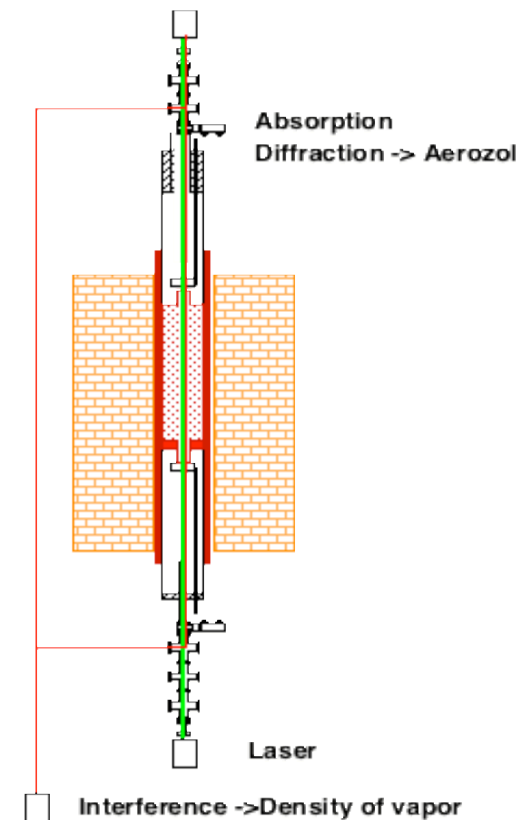
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For injection experiment



For laser propagation experiment

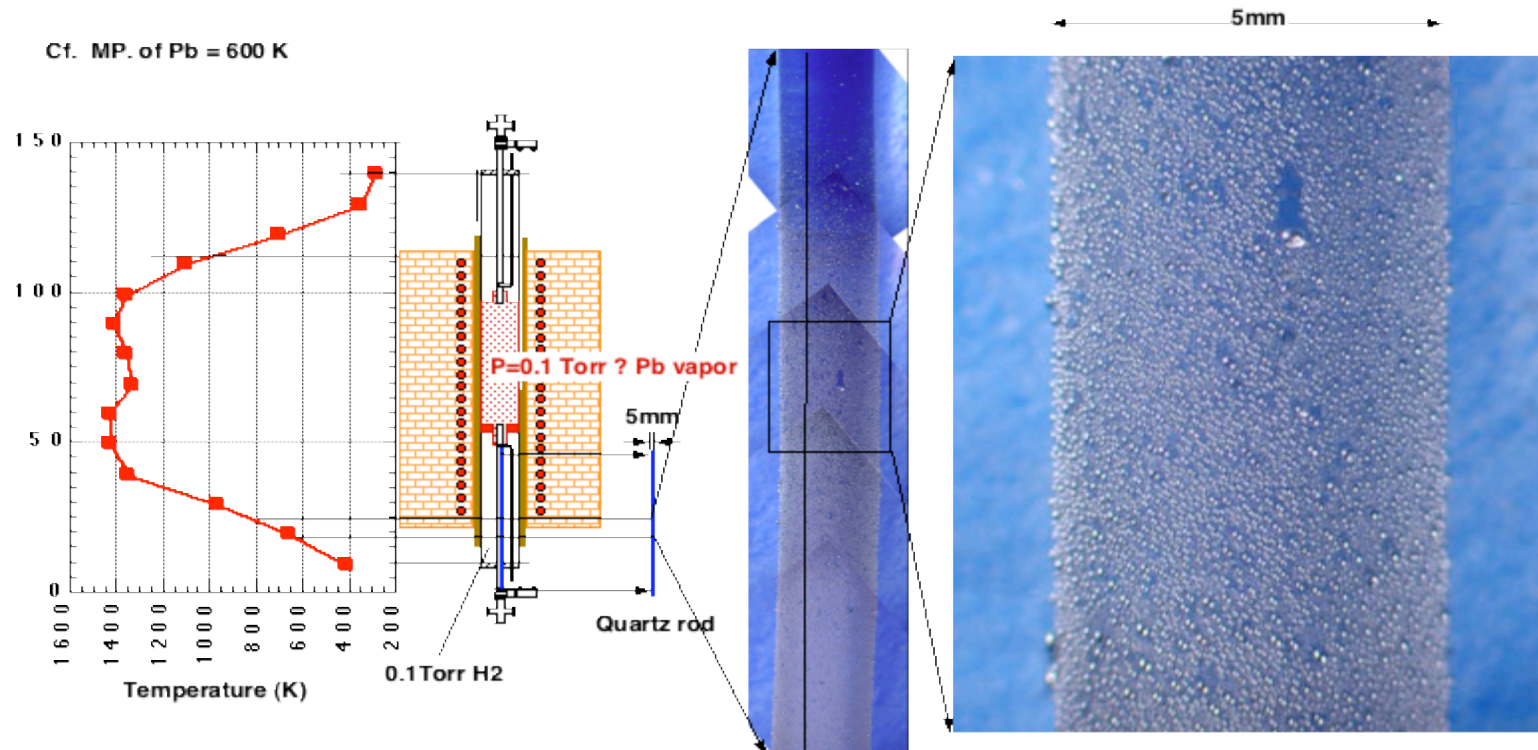


A lot of Pb particles, drops of dew, was observed on the surface of a quartz rod during a **H₂ 10 Torr, 1400K, 1hr operation.**



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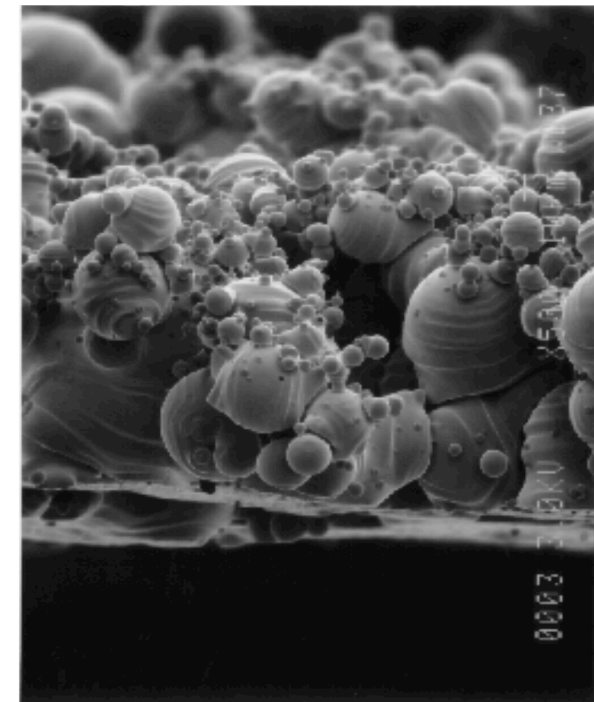
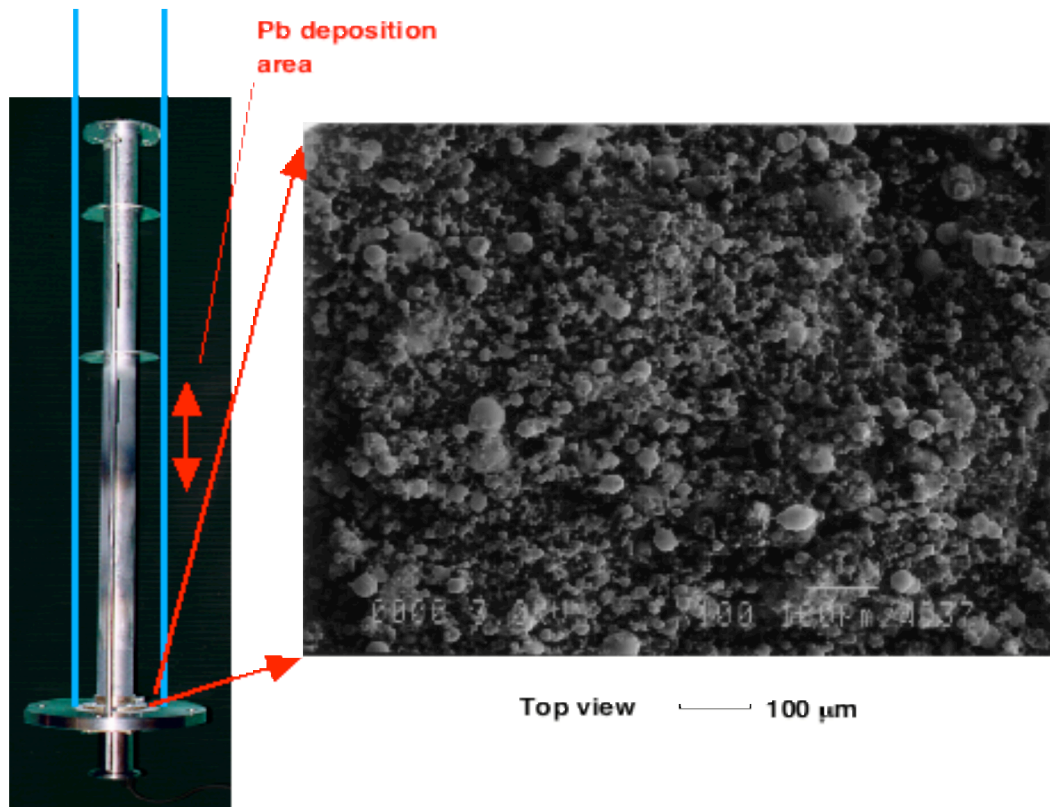
- To simulate diffusion of Pb vapor from wet-wall-reactor to the final optics, 25 g Pb was evaporated.
- No deposition of Pb at areas of $T > 800\text{K}$ and $T < 600\text{K}$.
- A lot of Pb particles ranging $< 300\text{ }\mu\text{m}$ at the area of $650\text{K} < T < 750\text{K}$.



Many Pb particles ranging 0.1 to 30 μm were deposited on the bottom of furnace filled with **10 Torr H_2** .



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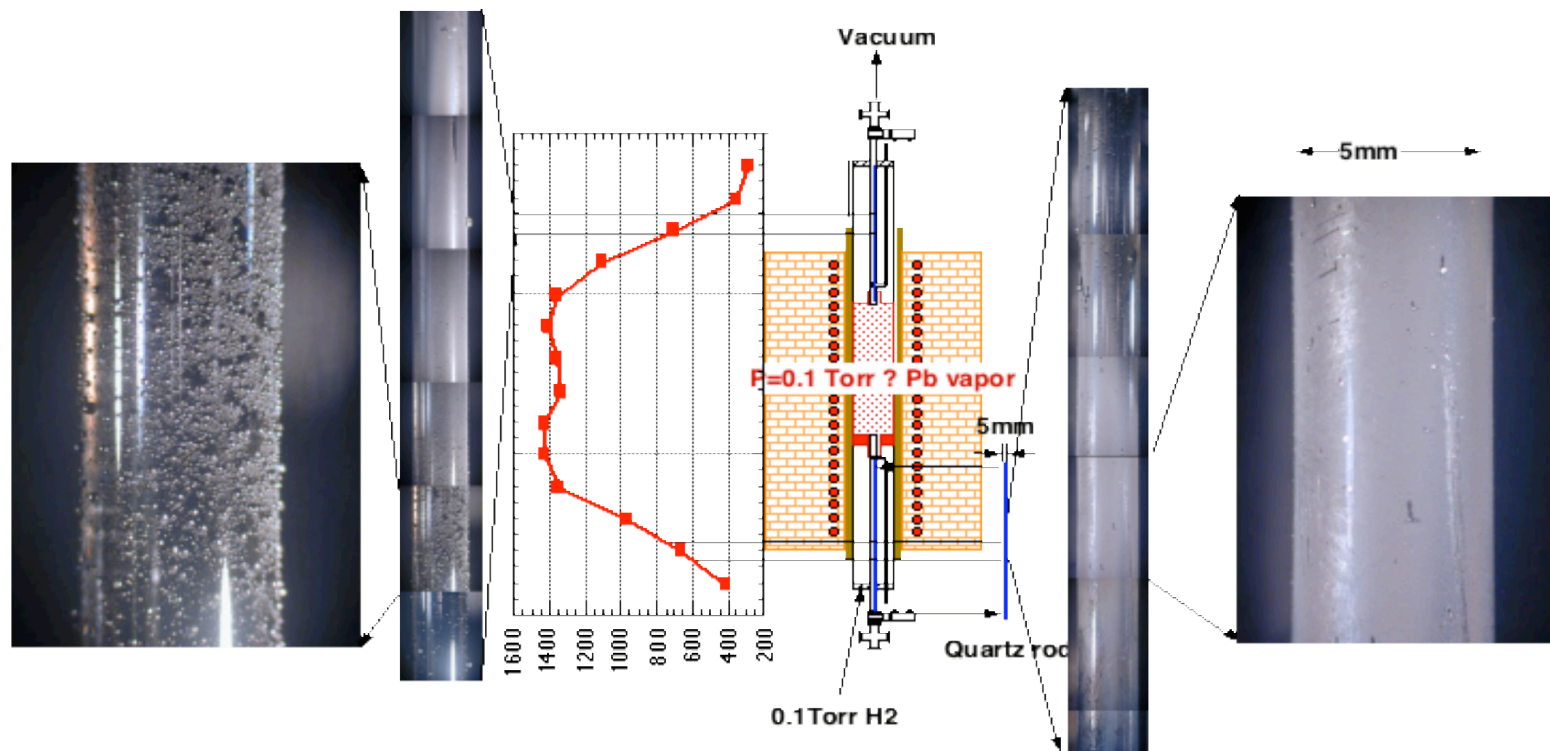
Cross sectional view $\text{1 } \mu\text{m}$

Lead deposited on the 500K to 800K surface during a H_2 0.1 Torr, 1400K, 1hr run. No dew on the bottom rod.



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- To simulate diffusion of Pb vapor from wet-wall-reactor to the final optics, 14 g Pb was evaporated.
- No deposition of Pb at bottom area of $T > 800\text{K}$ and $T < 600\text{K}$ and at top area of $T > 750\text{K}$ and $T < 500\text{K}$. Hydrogen gas flow from bottom to top carried the Pb vapor toward colder region.

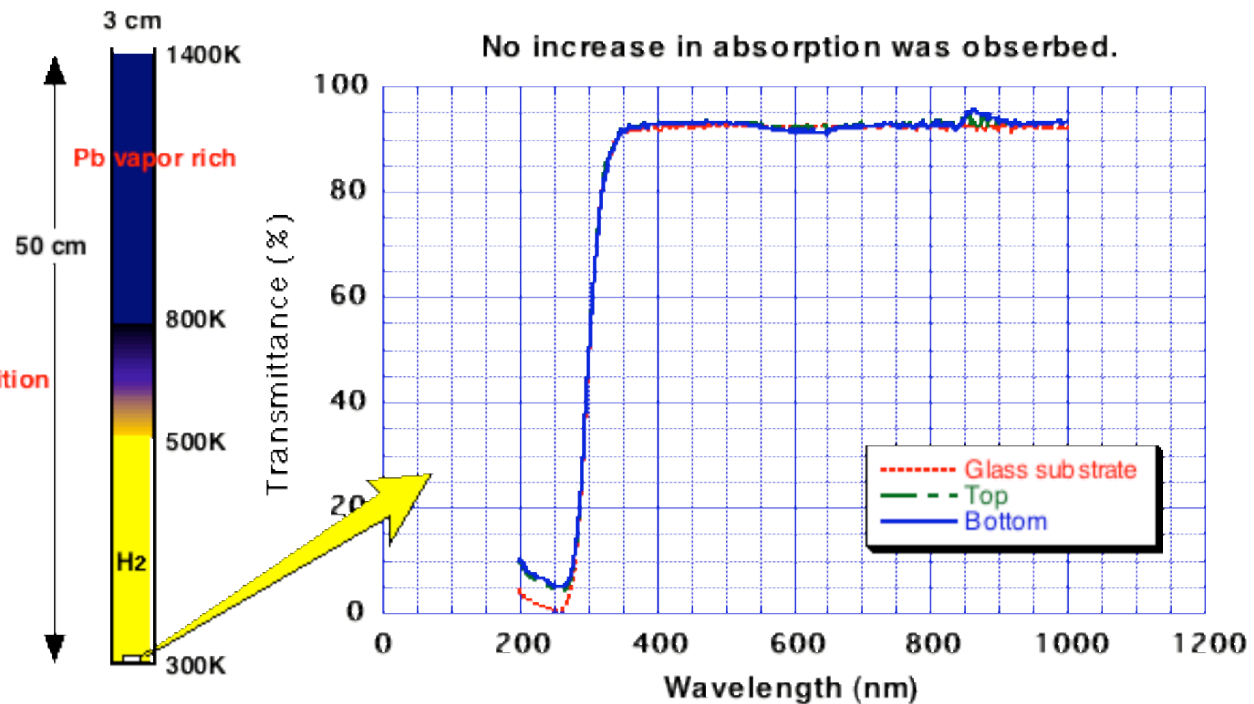
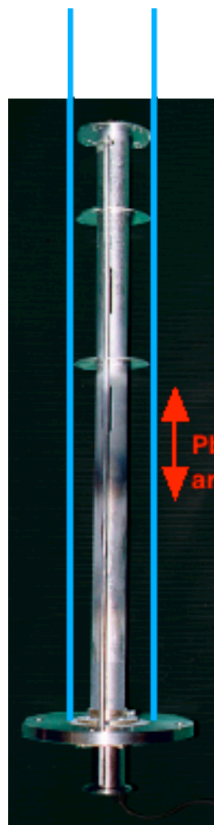


No deposition of Pb was observed on witness plate in 0.1 Torr H_2 .



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It seems that Pb vapor condenses on cold surface before forming aerosol.

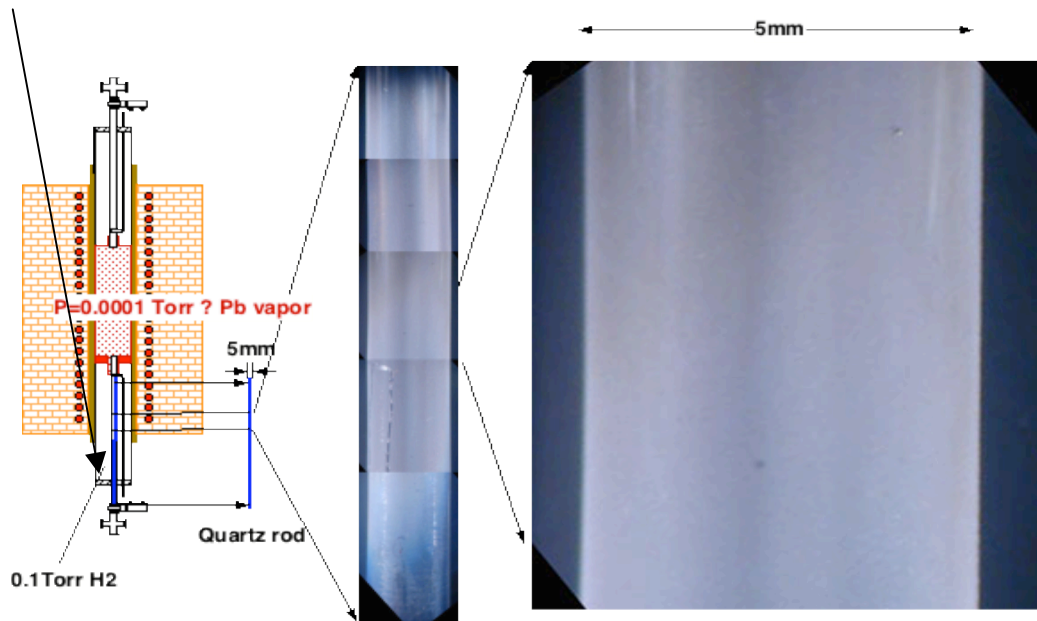


Deposition of Pb was observed on the surface of a quartz rod during a H_2 0.1 Torr, 780K, 1hr run.



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No deposition on a witness plate



- 9.5 g of Pb (1/3 of previous case) was evaporated during 1hr run.
- Deposition area moved inward.
- No drop of dew was observed.
- **No deposition on bottom**
- **This result indicates that contamination of final optics can be avoided if the first bluster wave is blocked.**



Summary

- **A set of rotary shutters was proposed to protect the final optics from neutral Pb vapor. This scheme, however, imposes severe requirement on the injection velocity. (For example, 200+/- 1 m/s)**
- **FI target with heavy cone was proposed, which may allow no tracking and beam stirring.**
- **Wet-wall simulator in operation.**
 - Preliminary result indicates no deposition on the surface $T > 800\text{ C}$ and $T < 500\text{ K}$.
 - Lot of aerosol in 10 Torr H_2 run, but no visible aerosol in 0.1 Torr H_2 run.