# Critical Path to Impact Ignition ––Suppression of the Rayleigh-Taylor Instability––

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**Institute of Laser Engineering**
**Osaka University**
**20th IAEA Fusion Energy Conference**
**1st-6th November 2004**
**Vilamoura, Portugal**

**Collaborators:**
**H. Shiraga, M. Nakai, K. Shigemori, S. Fujioka, T. Sakaiya, Y. Tamari, K. Ohtani, T. Watari, A. Sunahara, H. Nagatomo, K. Nishihara, N. Miyanaga, and Y. Izawa**

## Outline

1. Introduction to impact-ignition

2. Suppression of the RT instability

3. Preliminary exp't

4. Unified theory––RT + KH + Magnetic + Ablation

5. Summary

**Sufficient suppression of the Rayleigh-Taylor instability**

**1. increases compressed density.**

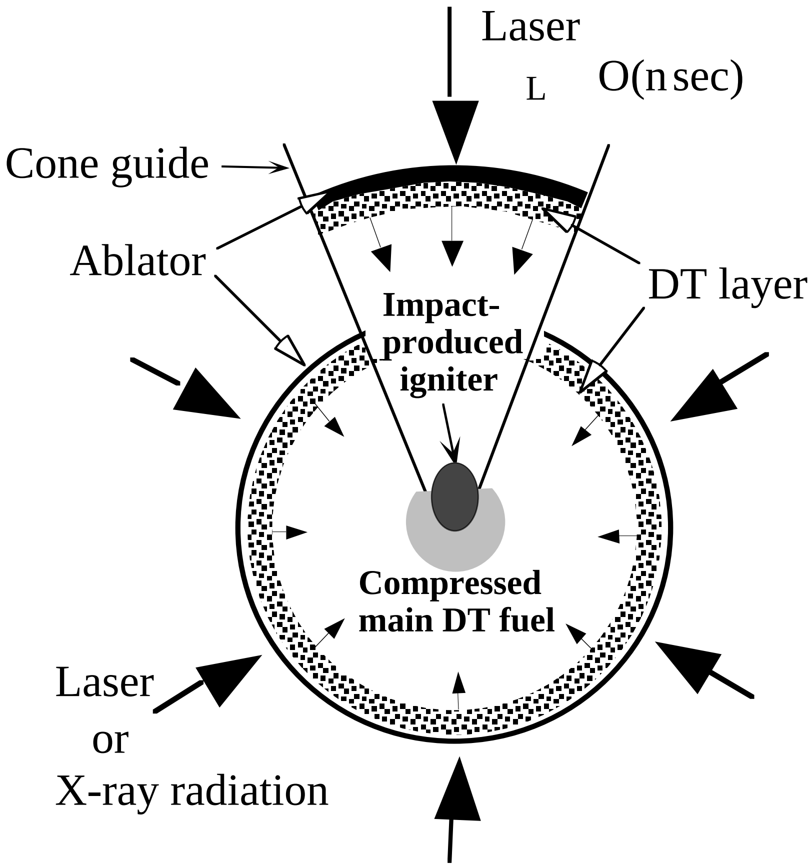
**2. revives an old ignition idea:**

**Super velocity ($10^8$ cm/s) implosion can configurate a hot-spark without a main fuel so as to ignite at very low laser energy (30-100 kJ).**

**This idea was rejected by two major criticisms:**

- **The Rayleigh-Taylor instability limits the maximum implosion velocity.**
- **No pathway towards high gain.**

# A pathway towards high gain
# –– Impact ignition ––



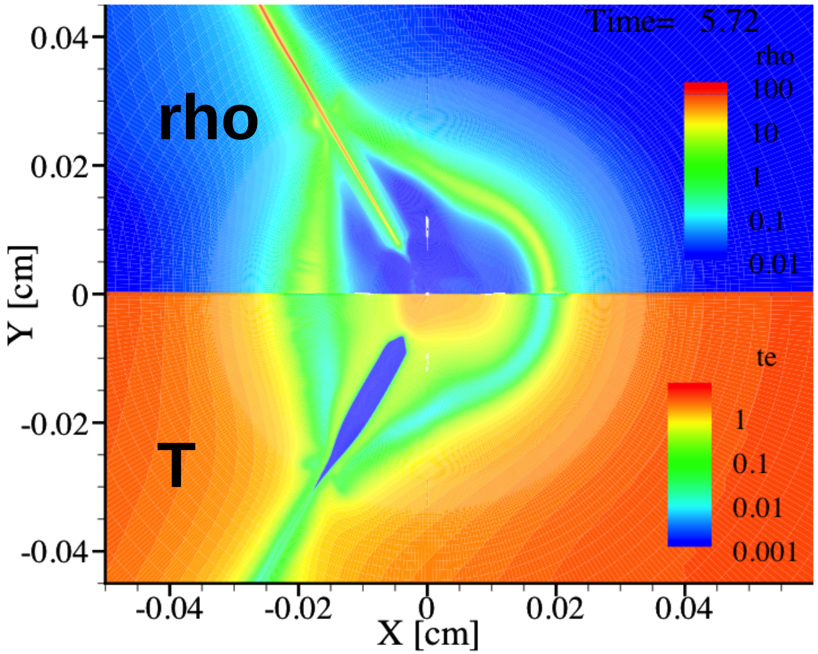

**1) High Gain**

**2) Simple Physics**

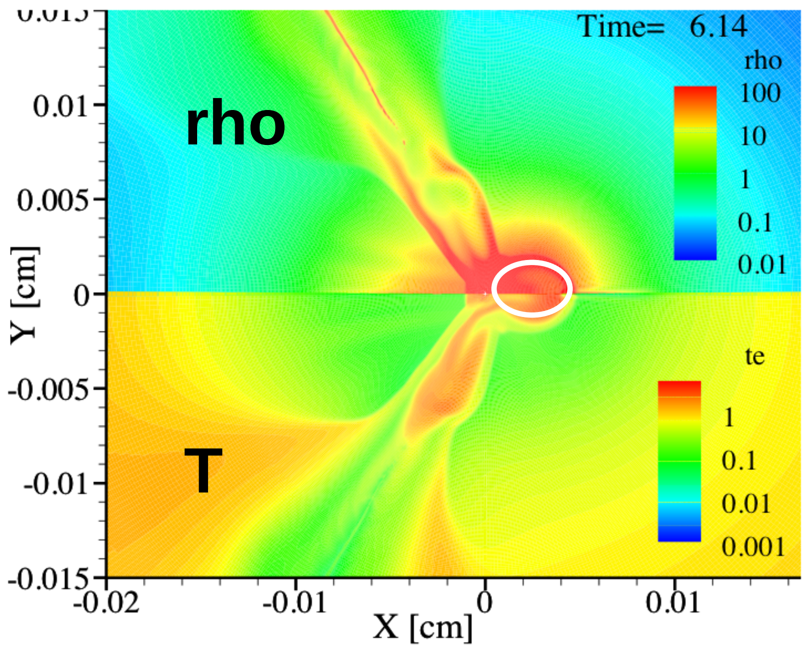
**3) Low Cost**

**Murakami, submitted to PRL**

# 2D Hydrodynamic Simulation



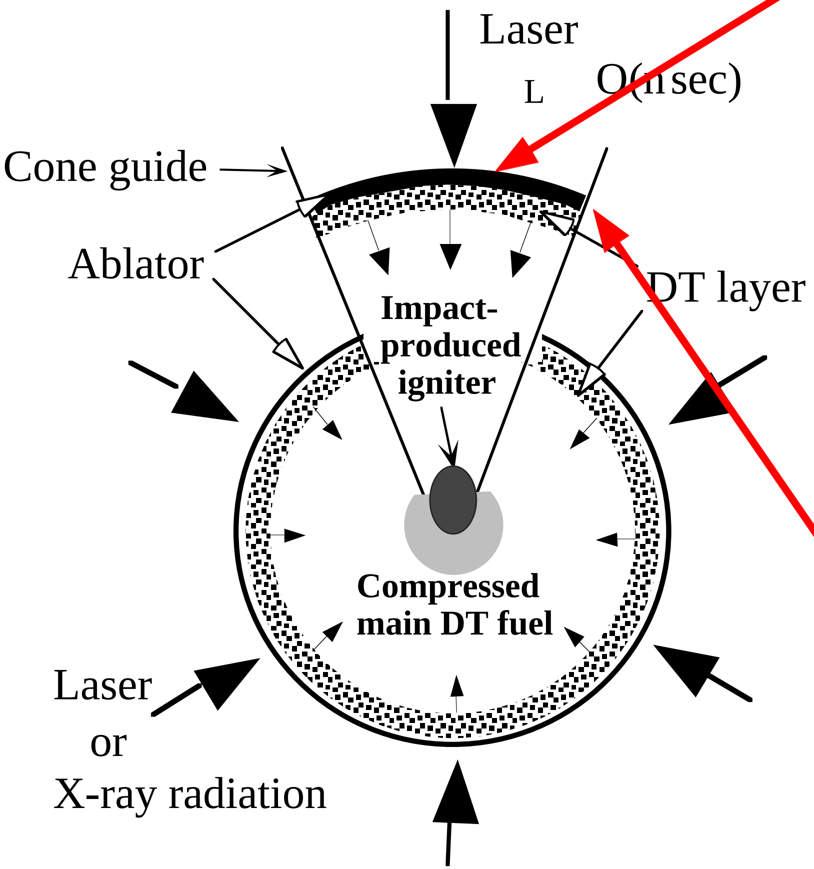

Isocontour map at a time shortly before the impact



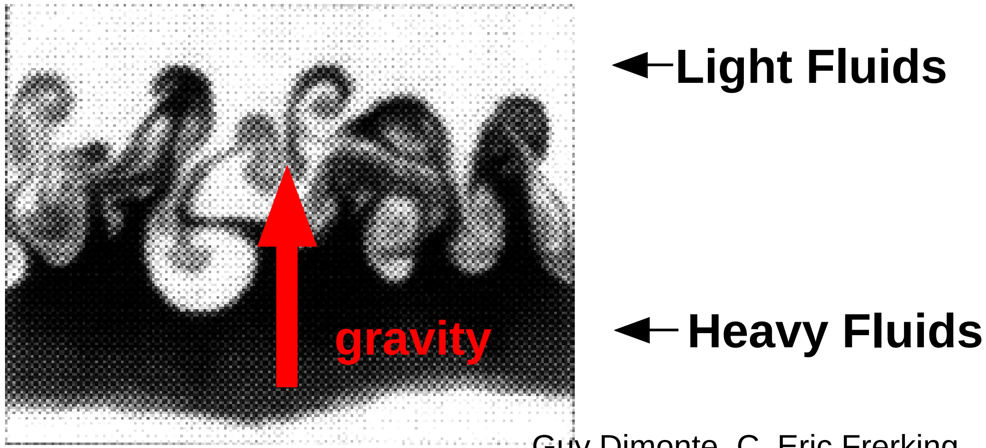

Isocontour map at peak comp-ression shortly after the impact

**A high-density and high-tempertarue spark plug is created by impact ignition.**

# Major obstacle against to super-vilocity acceleration




## Rayleigh-Taylor instability




Guy Dimonte, C. Eric Frerking and Marilyn Schneider, Phys. Rev. Lett. **74**, 4855, (1995)

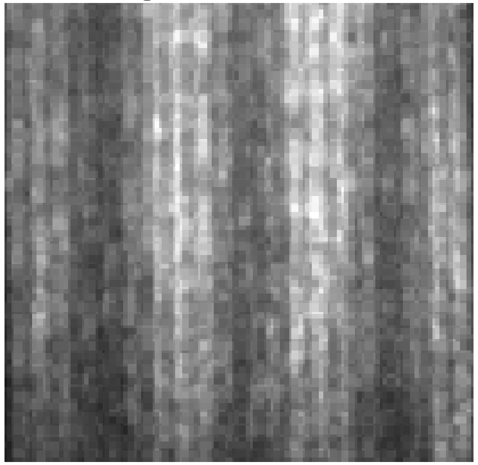
## Effective friction

# Suppression of RT ––Natural ablation

# Our strategy is to measure all physical quantities to test our understanding of ablative RT instability.

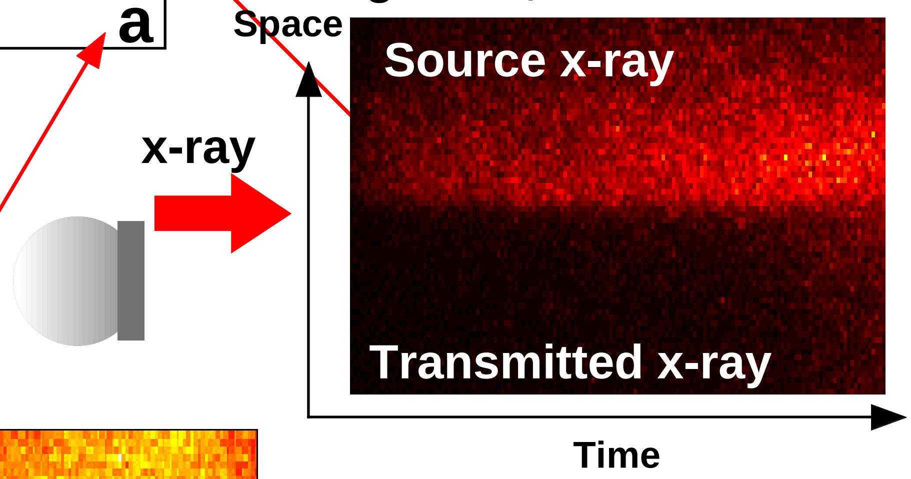
ILE OSAKA

**Moiré Interferometry**
**Sakaiya, PRL 02**

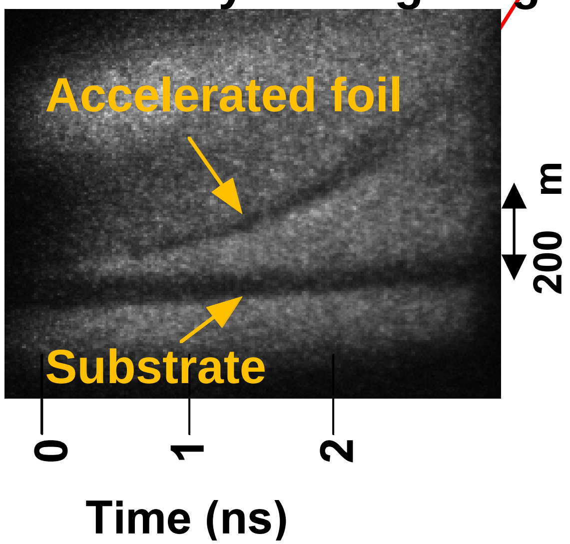


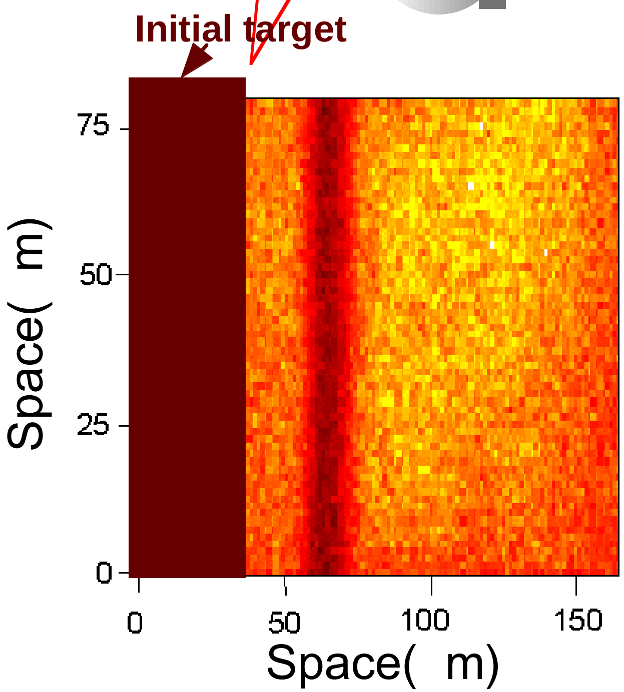
$$= \sqrt{\frac{kg}{1+kL}} \quad k \frac{m}{a}$$

**Target Transmittance**
**Shigemori, RSI 98**




**Side-on x-ray backlighting**




**Super resolution imaging by penumbral imaging**
**Fujioka, RSI 02, 03**
**PRL04, PoP04**
**Fresnel phase zone plate**
**Tamari, RSI submitted**

# Measurements all together determine beta-coefficient.

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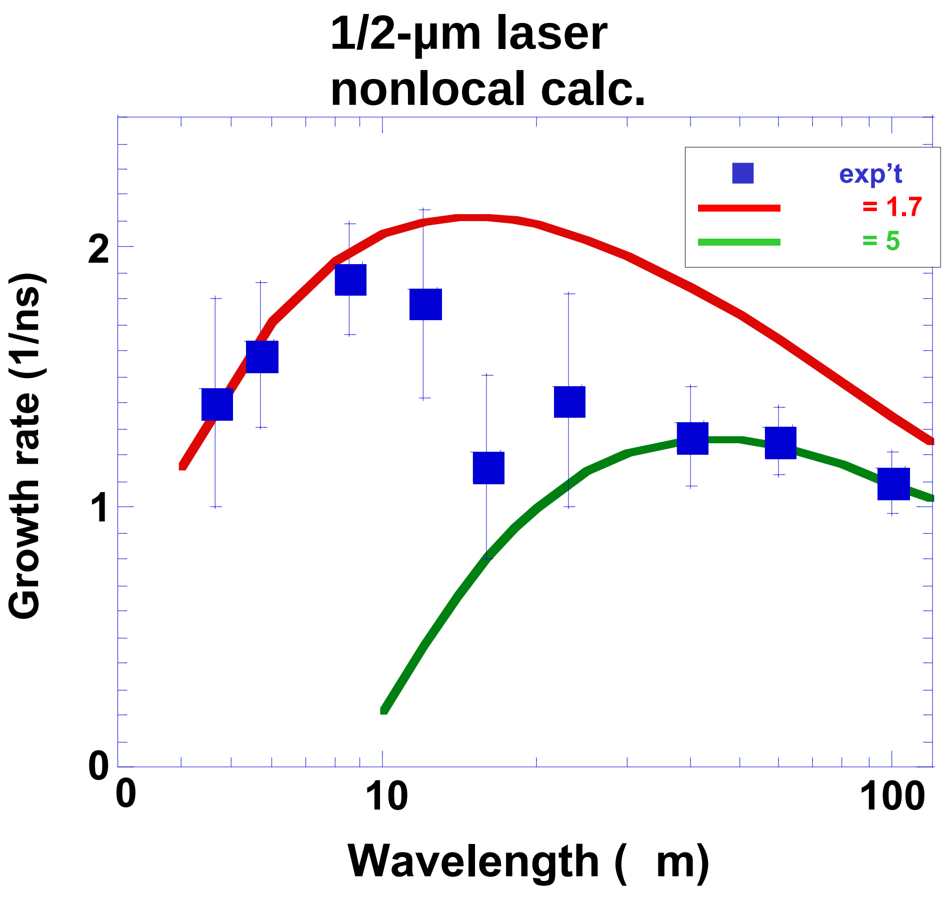
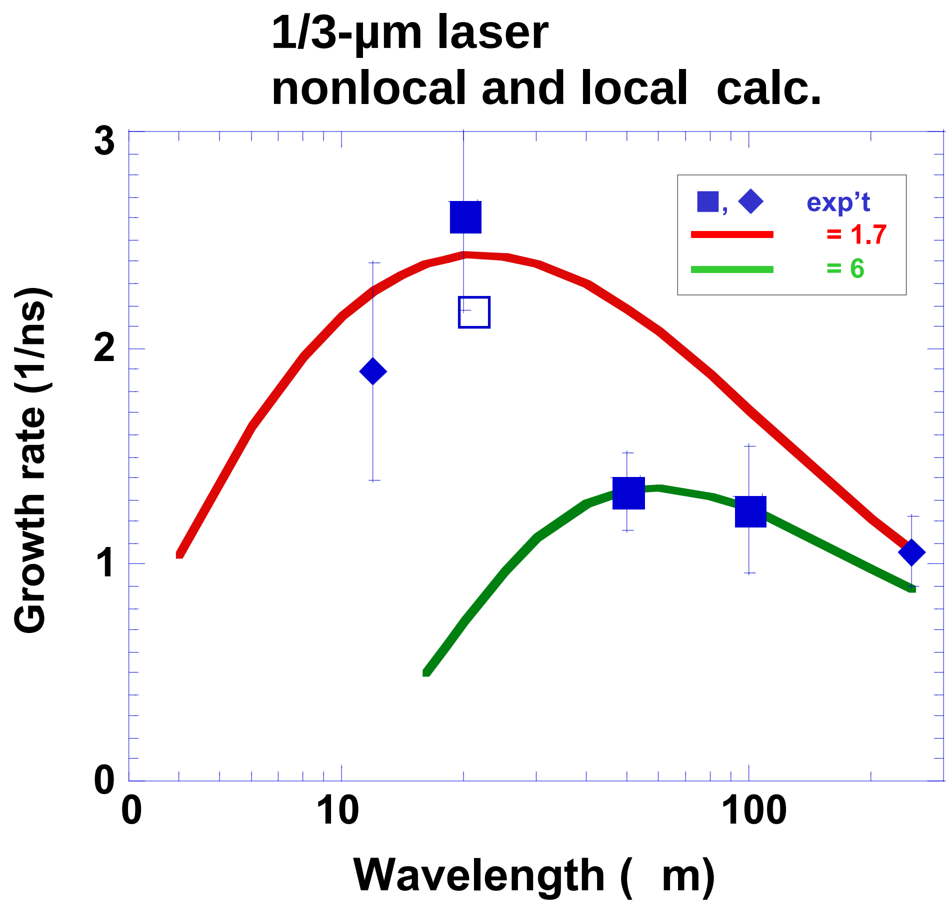



Azechi, PoP 97
Shigemori, PRL 97
Sakaiya, PRL 02

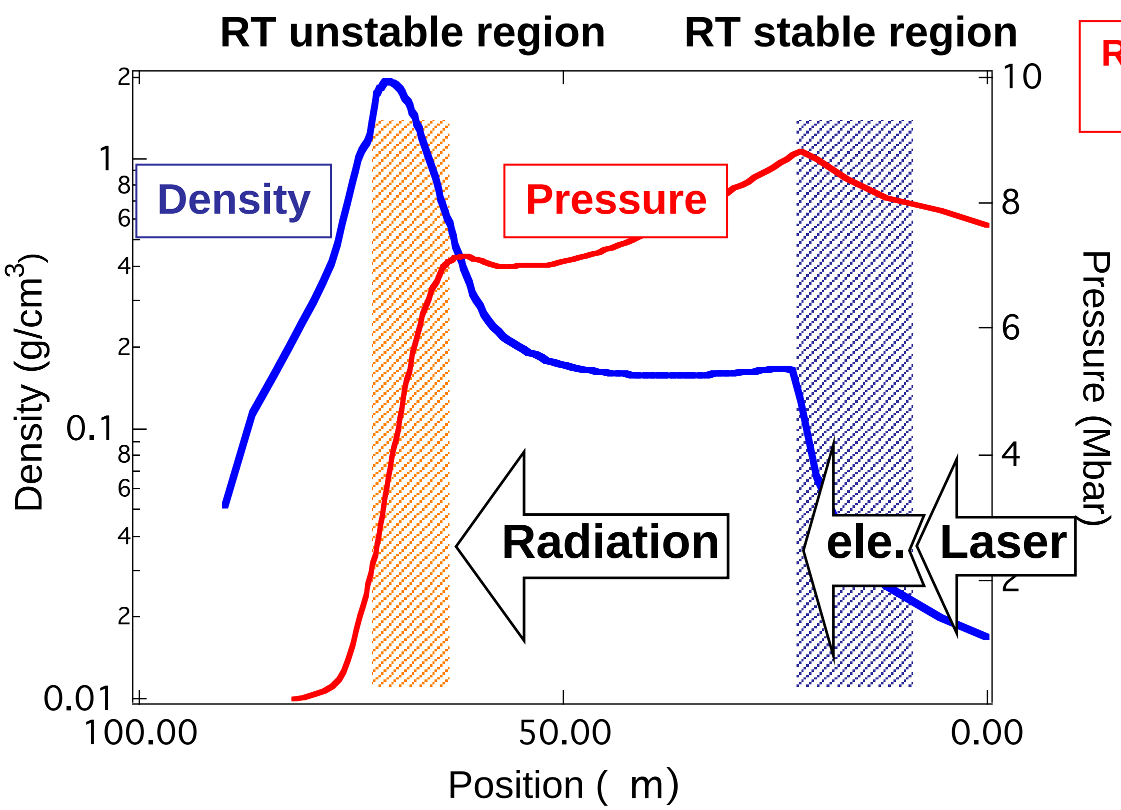
## Suppression of RT ––Double Ablation
## Tow color irradiation

# Double Ablation Target

**We considered the RT growth only at the radiative ablation front, because grad grad *p* is almost positive, namely RT stable, at the electron-conduction ablation front.**

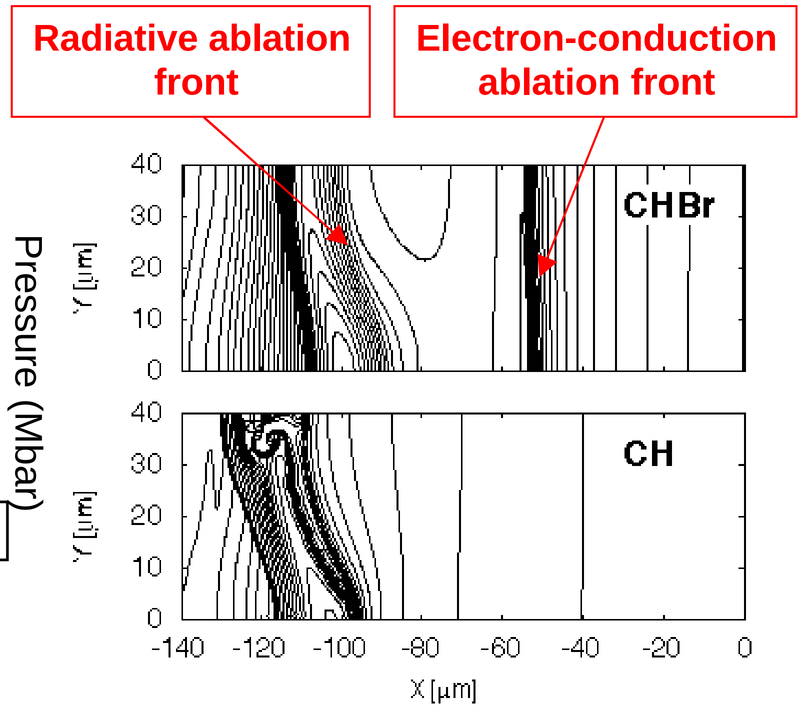
S. Fujioka
(ILE. Osaka)

## 1D simulation (ILESTA-1D)




## 2D simulation (RAICHO*)

* N. Ohnishi *et al.*, JQSRT **71**, 551 (2001)

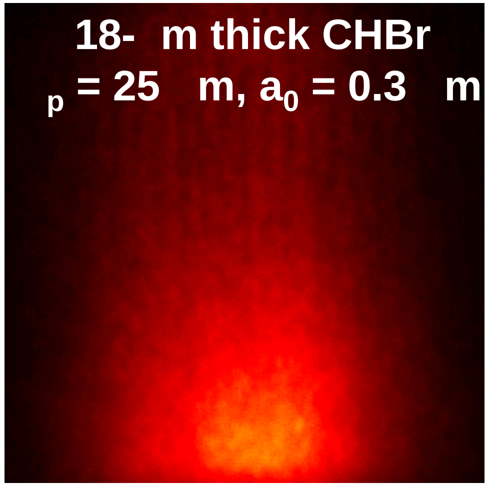



**Physical mechanism which makes the electron-conduction ablation front to be RT stable is now under investigation.**

## *RT exp. with shorter wavelength perturbation*

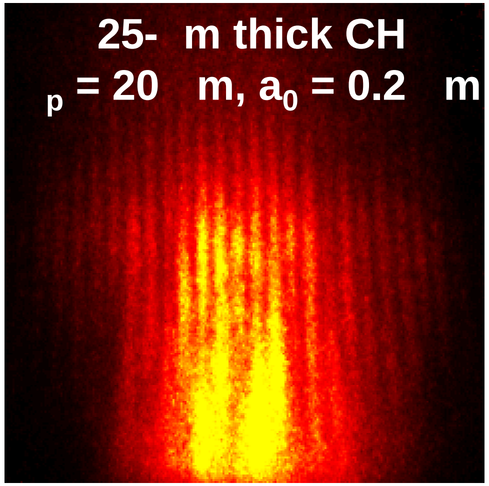
**Growth of the perturbations in the CHBr target is strongly suppressed in comparison with that in the CH target.**

S. Fujioka
(ILE. Osaka)




1 ns

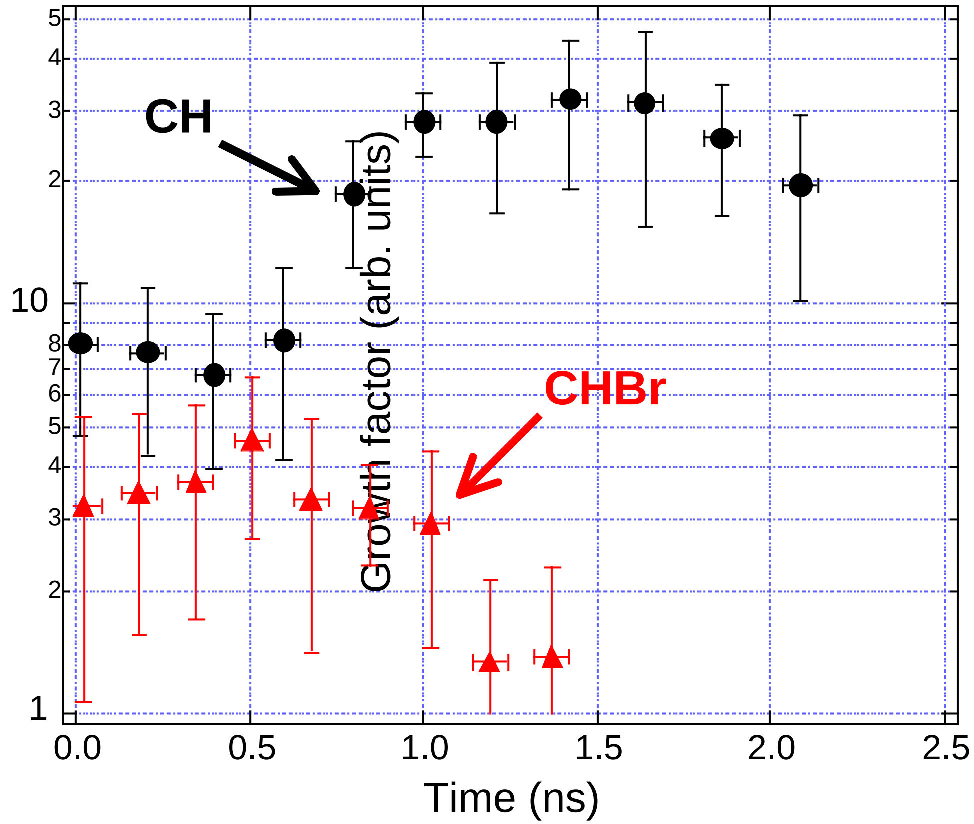
300 m




1 ns

300 m

**Temporal evolution of growth factor**



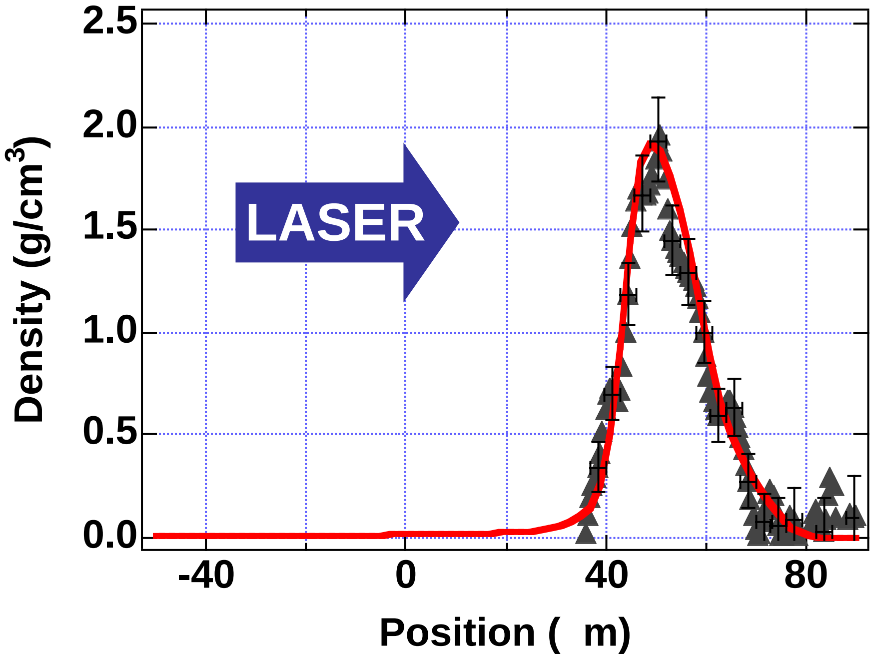

**The theory predicts the RT growth rate to be 1.5 $ns^{-1}$ in the CHBr target. This value is large enough to amplify the perturbation to be observable.**

## *Density profile*

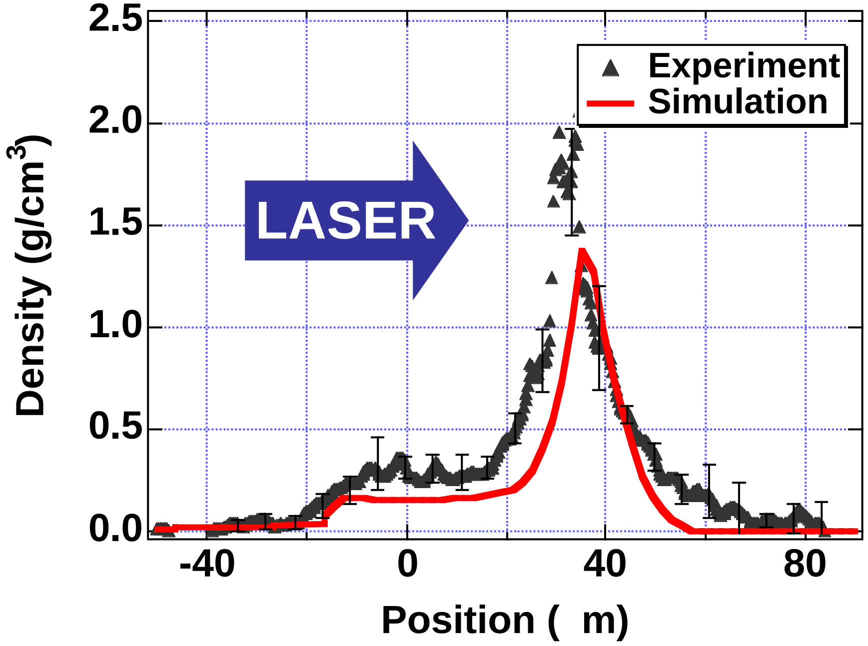
**Peak density of the CHBr target is not lowered drastically in comparison with that of the CH target.**

S. Fujioka
(ILE. Osaka)

**CH @1.6 ns**



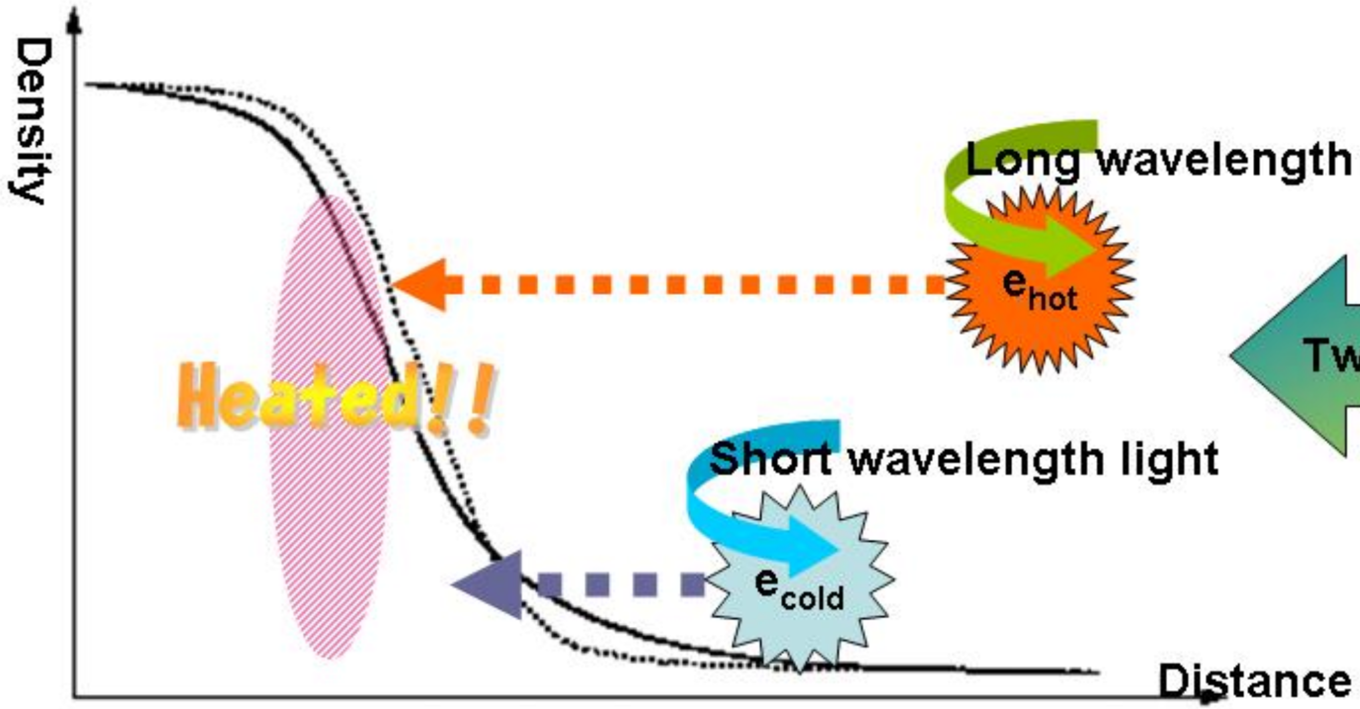

**CHBr @1.4 ns**




**Differences between the experimental result and the simulation may indicate a more detail atomic model is required for reproducing the full characteristics of the density profile in a CHBr target**

# Non-local electron heats the ablation surface and lengthen density scale length

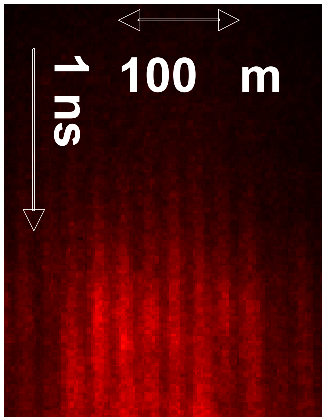
Growth rate of Rayleigh-Taylor instability $\gamma = \sqrt{\frac{kg}{1+kL}} - \beta k v_a \quad \left( v_a = \frac{\dot{m}}{\rho_a} \right)$

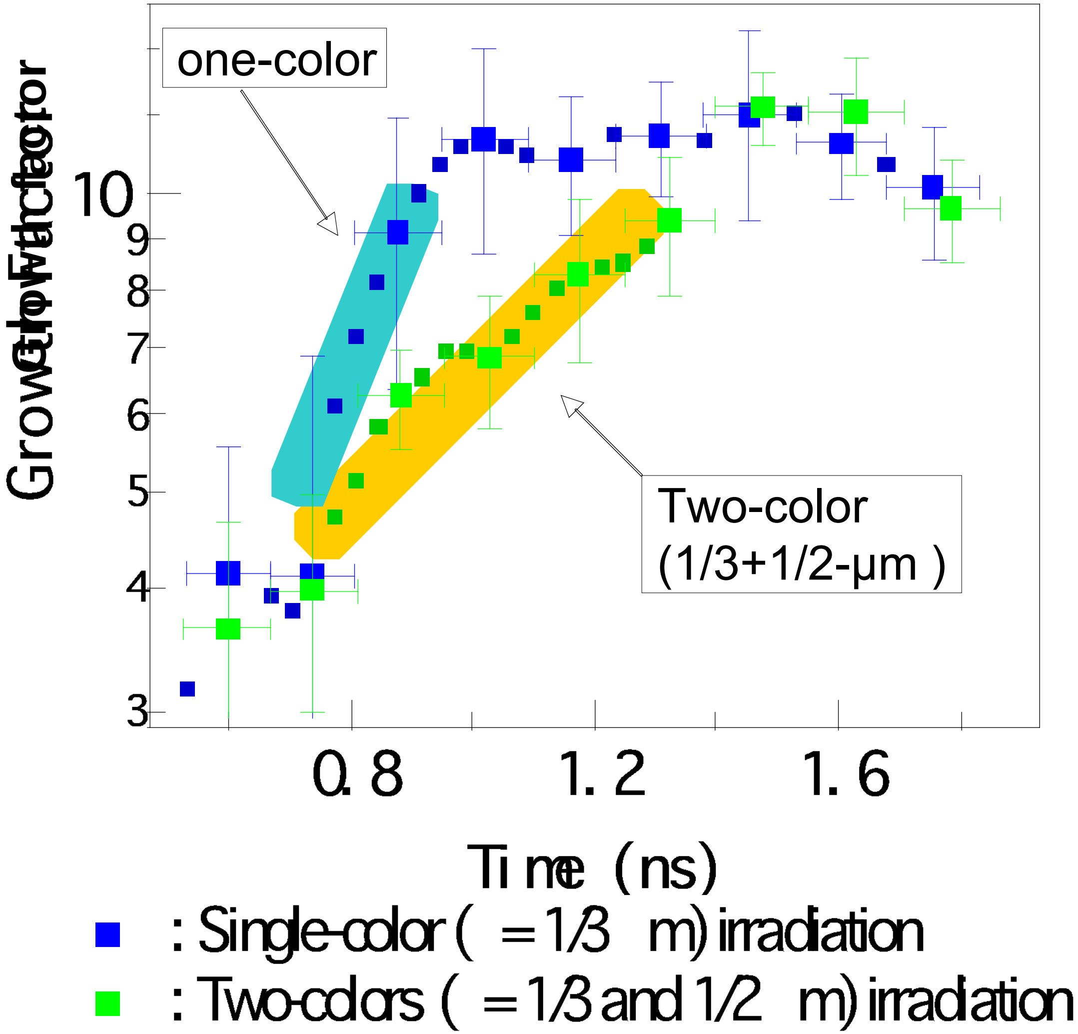



Dotted line: Single-color (short wavelength) density profile
Solid line: Multi-color density profile

# Rayleigh-Taylor growth rate is reduced by two-color laser irradiation.

**Streaked image**

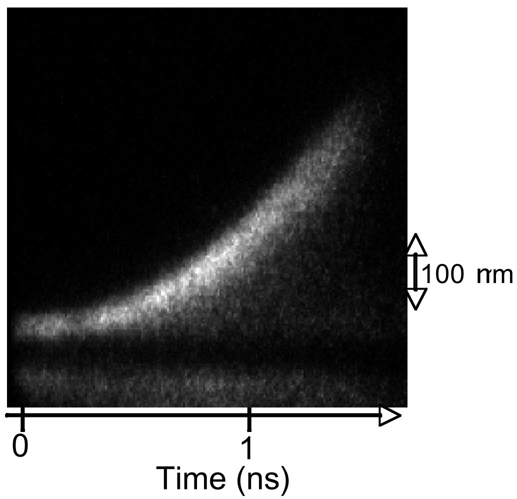


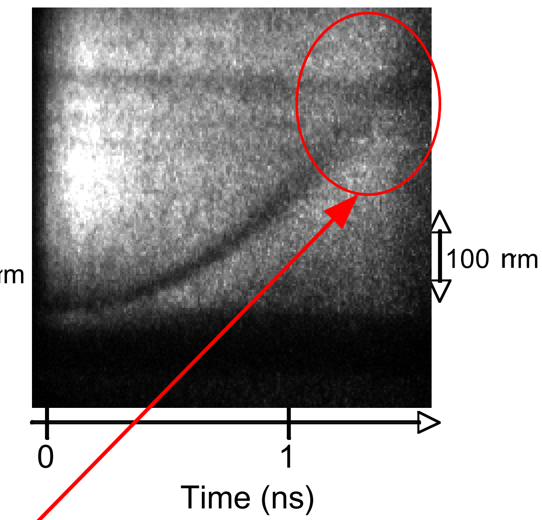
# Preliminary experiments for super velocity

# 4 x $10^7$-cm/s velocity has been achieved even at moderate irradiance.

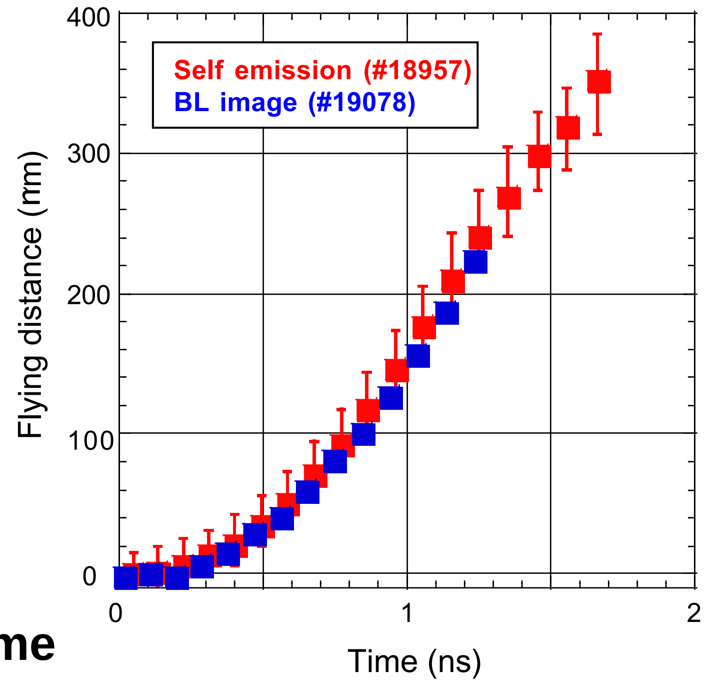
**Self emission**




**x-ray backlighting**




**10-μm CH @$10^{14}$ W/cm$^2$**




**Foil disassembly is observed at late time**

**$10^8$ cm/s-velocity must be achieve, if**

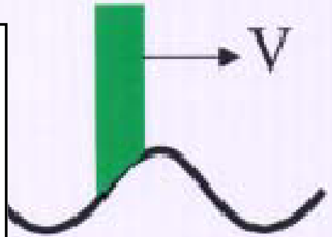
- **RT-reduced targets**
- **higher irradiance .**

# Dissipation by wall roughness exceeds PdV work

I F A

**Effective friction**
- **tilt**
- **roughness**
- **KH instability**

- A sinusoidal pertubation acts on the foil as an alternated piston.

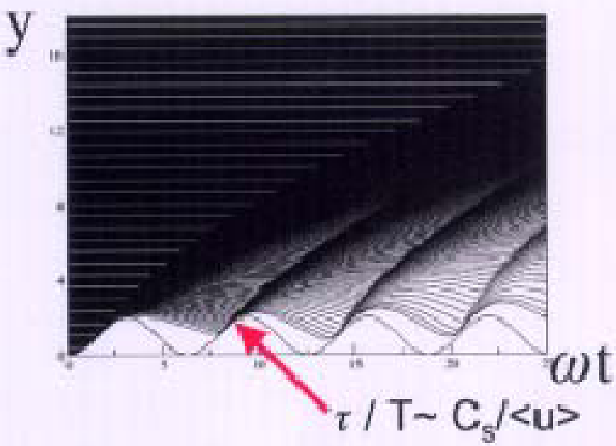



$y = a \cos wt$

$\omega = \frac{2\pi V}{\lambda}$

$U = -\omega a \sin \omega t$

1D piston (CHIC code)




- Each period launches a wave in the foil
  - a/λ << 1 : acoustic wave with energy flux $0.5\rho c_s u^2$
  - a/λ > 1 : rarefaction waves are slower than u : shock waves are launched during a short fraction of the period: $\Phi = \frac{1}{2}\rho u^3 \frac{\tau}{T} \approx \frac{1}{2}\rho c_s u^2 \approx \frac{1}{2}\rho\, c_s \omega^2 a^2$
- Roughness friction equation is ~ 5 x hydro friction for a/λ =0.1

$$\dot{V} = -\gamma \frac{P_0}{\rho h}\pi^2\left(\frac{a}{\lambda}\right)^2 \frac{V}{C_s}$$

**work by Euro group**

CELIA


2004.5.18
FIREX-I laser can also be used for impact ignition

# Effects of Magnetic Field, Sheared Flow and Ablative Velocity on the Rayleigh - Taylor Instability

**D. Li, W. L. Zhang, Z. W. Wu**
**Department of Modern Physics**
**University of Science and Technology of China**

# Prof. Li *et al*. have found a new formula of the RT growth rate.

$$\gamma = [gkA_T + k^2\delta_u^2(1 - A_T^2) - k^2u_{rA}^2]^{1/2}$$

**Rayleigh-Taylor**
$A_T$ = Atwood #

**Kelvin-Helmholtz**
$u$ = relative speed

**B-friction**
$u_{rA}$ = Alfvén speed

**This formula must be useful for good understanding of the RT instability at the deceleration phase, where large shear flow and strong magnetic fields interfere with short-wavelength RT instability.**

# summary

• New suppression schemes
  – Double Ablation
  – Two Color Irradiation

are the key element not only for higher density compression but for new impact-ignition.

• Super velocity of $10^8$ cm/s should be demonstrated using these RT-suppression schemes.

• You are welcom to discuss at a poster
  IF/P7-31 (Sat.) for impact-ignition
  IF/1-1Rb (Sat.) for the magnetic-sheared-ablative RT.

New concepts have been generated every 10 years.

1. Early 60's: Birth of laser fusion

2. Early 70's: Implosion

3. Late 70's:  Hot spark ignition

4. Early 90's: Fast ignition

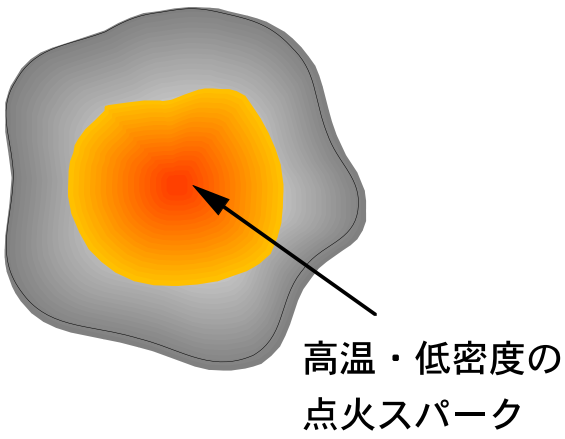
5. Early 2000's: Impact ignition?

# Spare Viewgraphs

**Confinement time = Fuel thick / sound velocity**

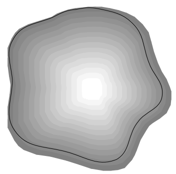
**The following two kinds of structure have the same fusion gain.**

Central Ignition

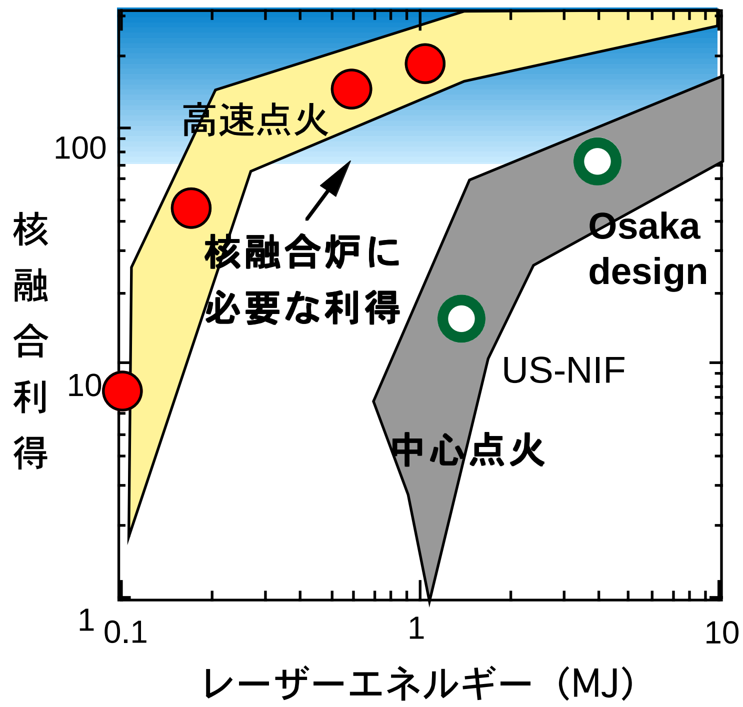



燃料が中空構造となるために，燃料の体積が大きい．このため大きなエネルギーが必要となる．

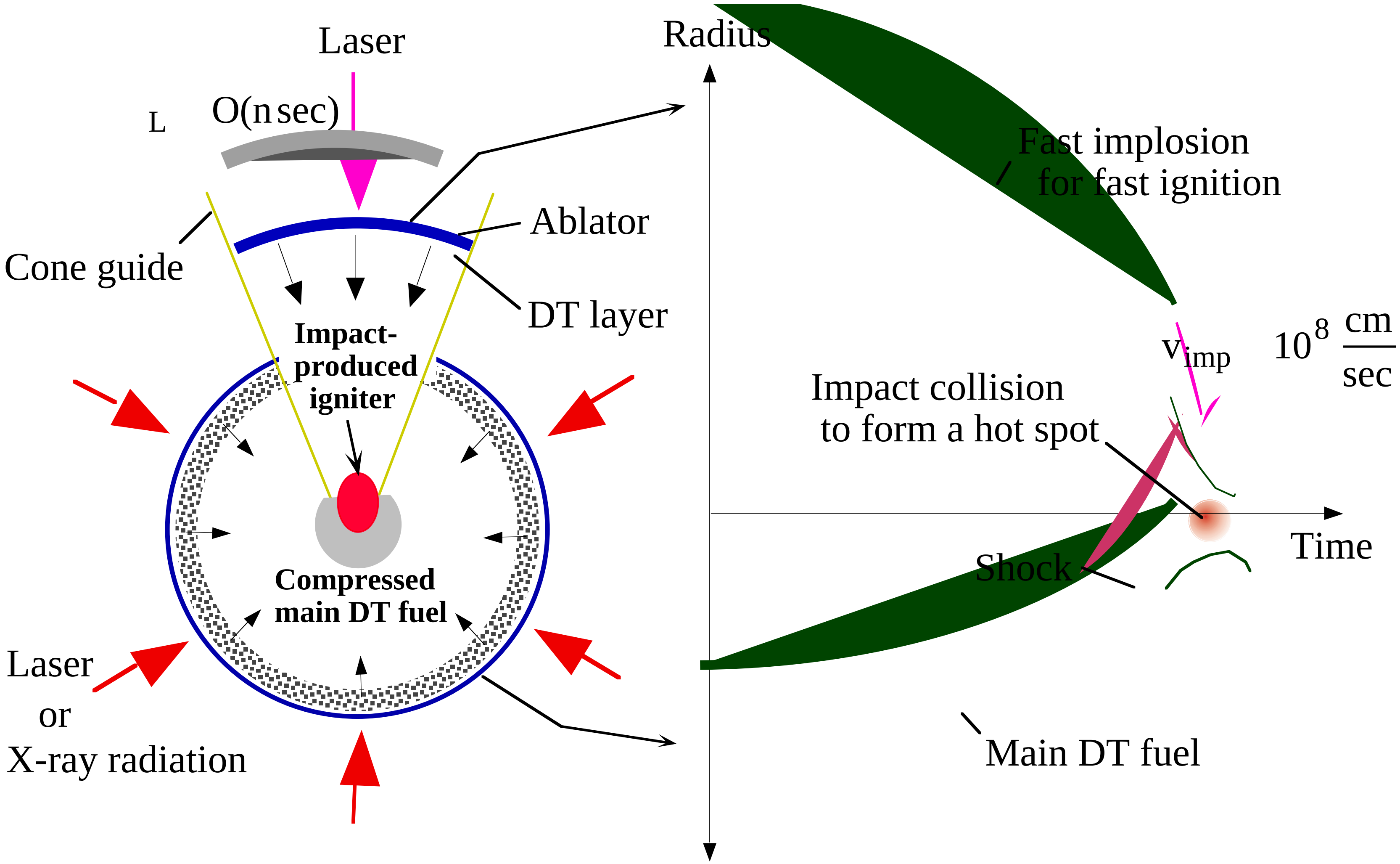
Fast Ignition
Impact Ignition



中空部が無いので，体積が小さい．このため小さなエネルギー（約１０分の１）でよい．

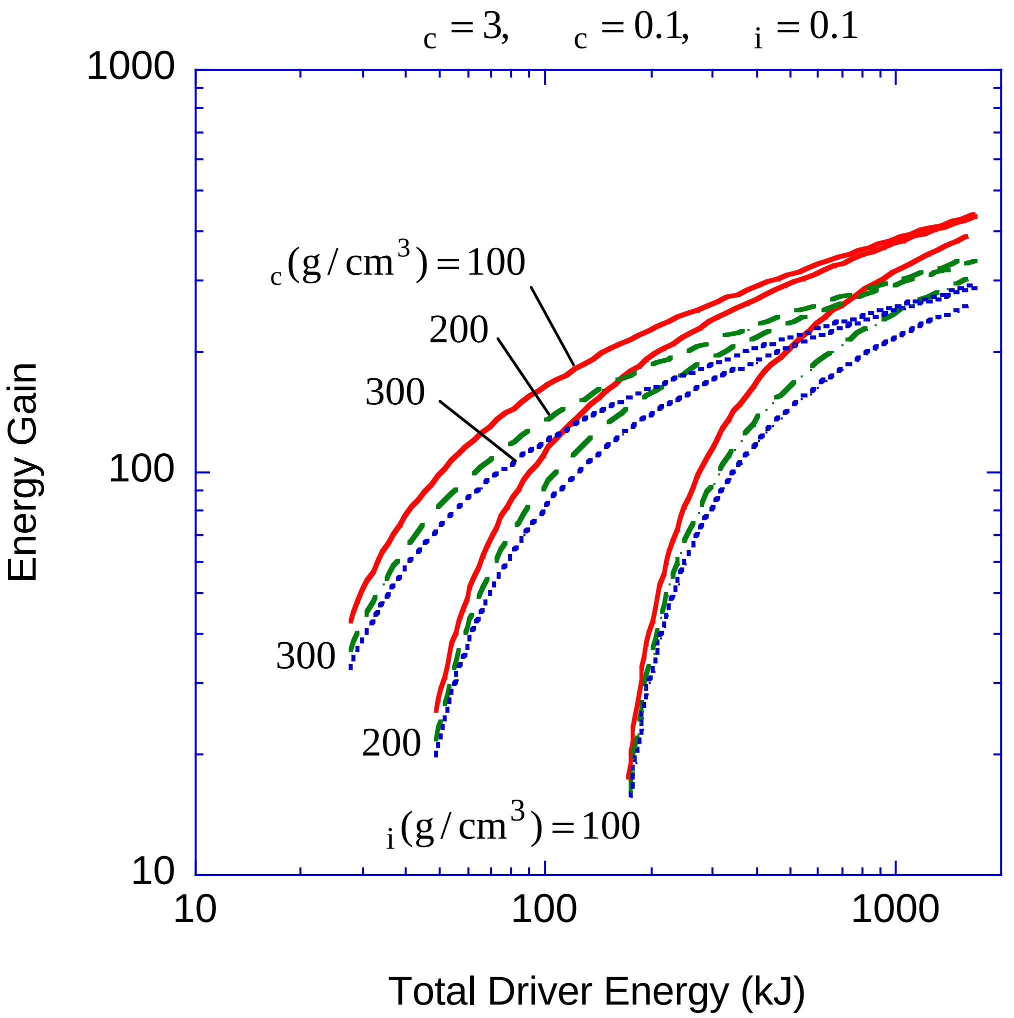


# New Ignition Scheme: Impact Ignition Makes A Pathway towards High Gain.




**Murakami, submitted to PRL**

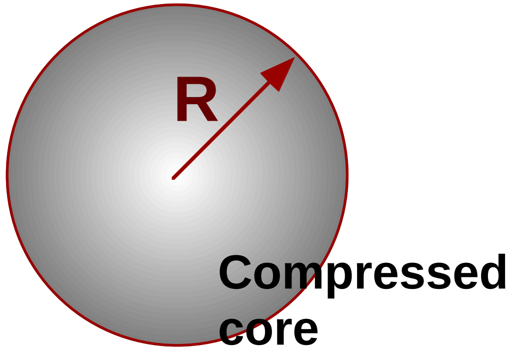
# Gain curves for Impact Ignition Targets



## We need high density compression as well as efficient heating.

Required energy for ignition is given by

$$E_{laser} = \frac{4}{3} R^3 \;\Diamond\, h = \frac{4}{3} \frac{(\;R)^3}{2} \; h$$




where

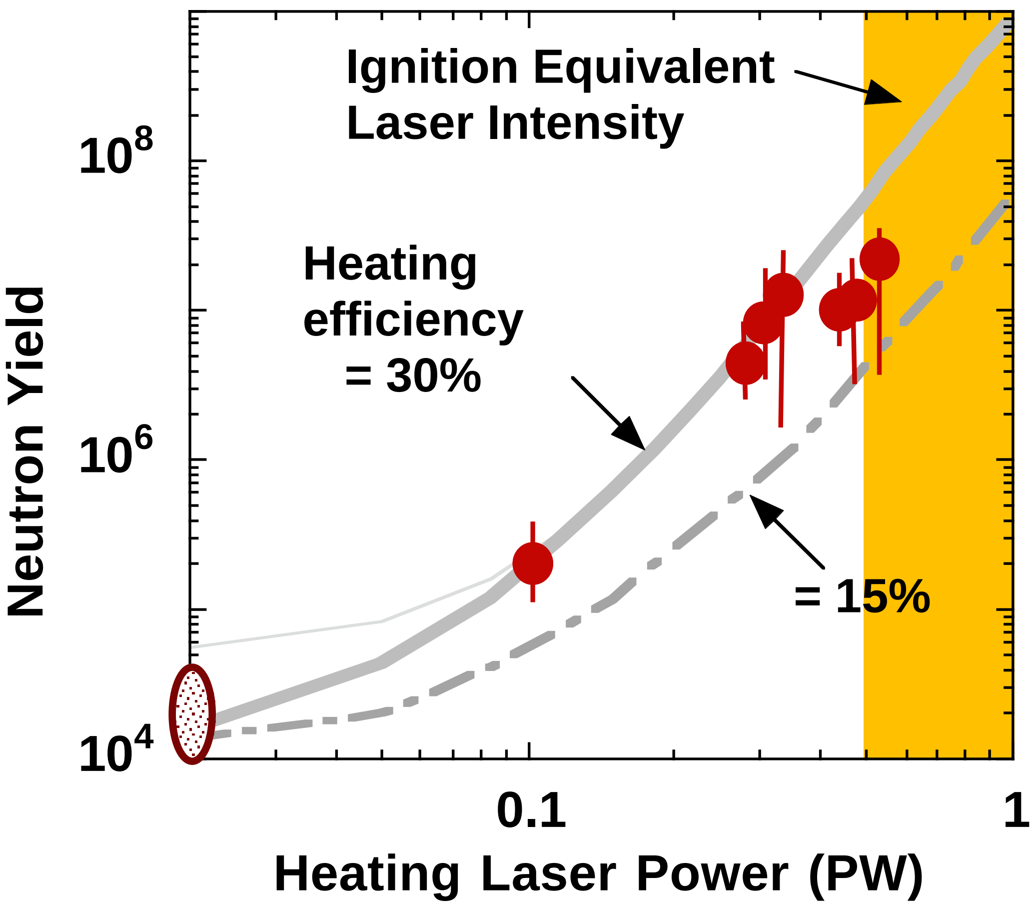
R particle range = 0.3 $g/cm^2$

$h$ = 2(3/2)$T/m_{dt}$=1.15 GJ/g @T=10 keV.

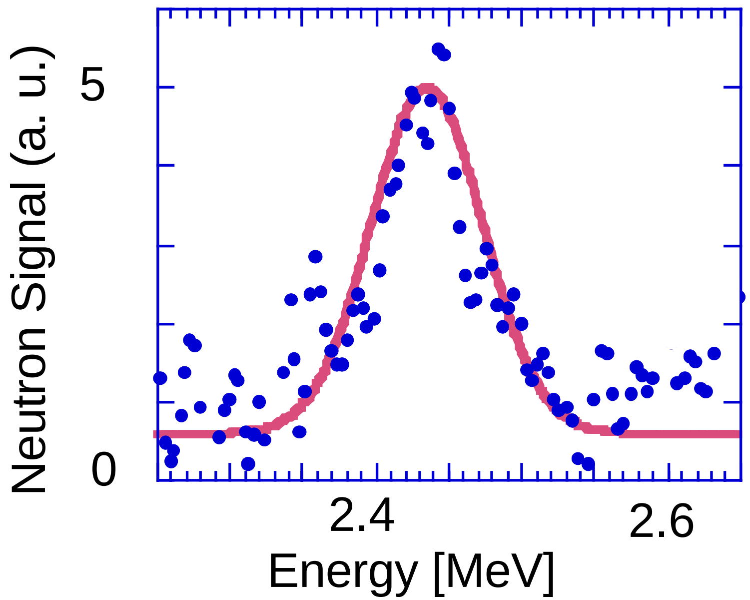
To achieve fast ignition with reasonable size of $E_{laser}$ 10's kJ, we need

- efficient heating of 0.2-0.3
- high density of 1000-1500 times liquid density.

# Recent fast ignition exp't has demonstrated efficient heating of 0.2 at the ignition equivalent laser intensity.




Neutron time-of-flight spectra showing Ti 1kev




R. Kodama et al., Nature 2002

# High density compression of 1500 times liquid density needs to be demonstrated.

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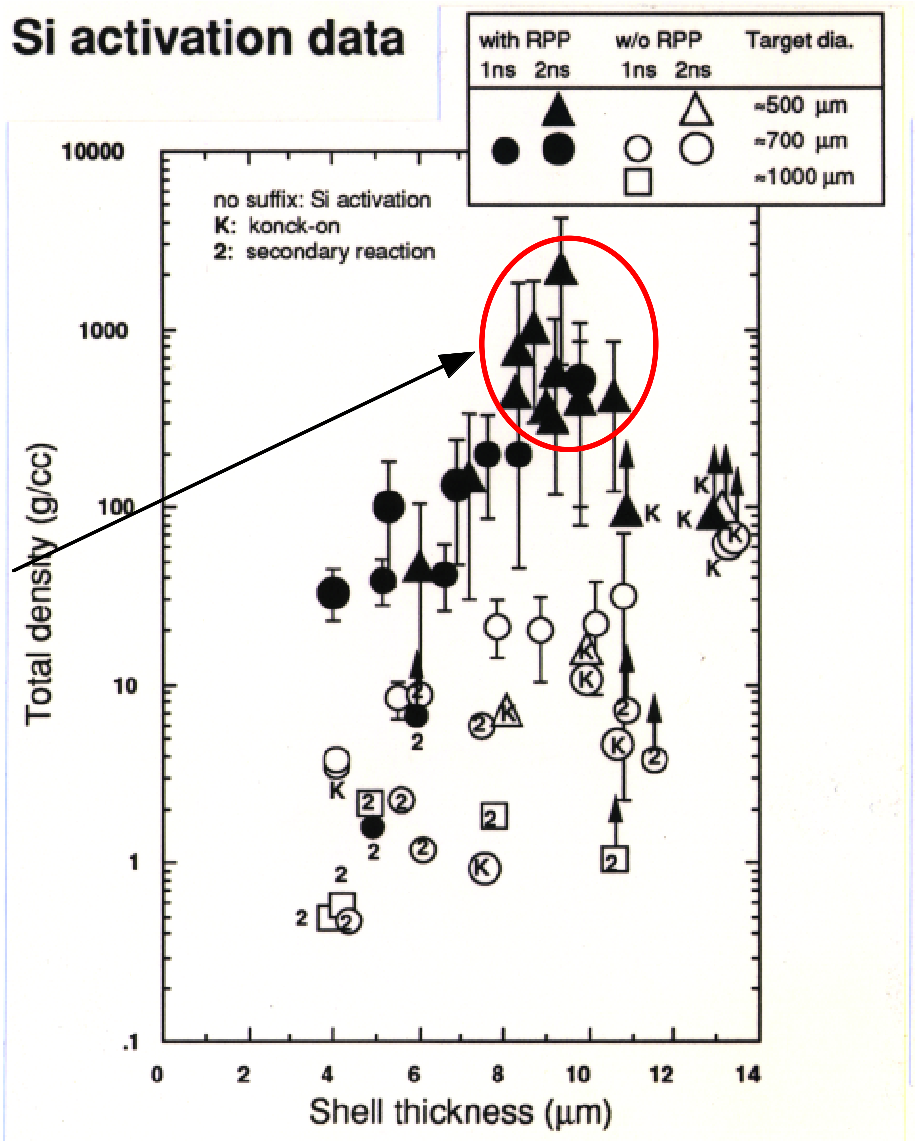
**This is about three times higher density than that ever achieved.**

**Average density 600 XLD**



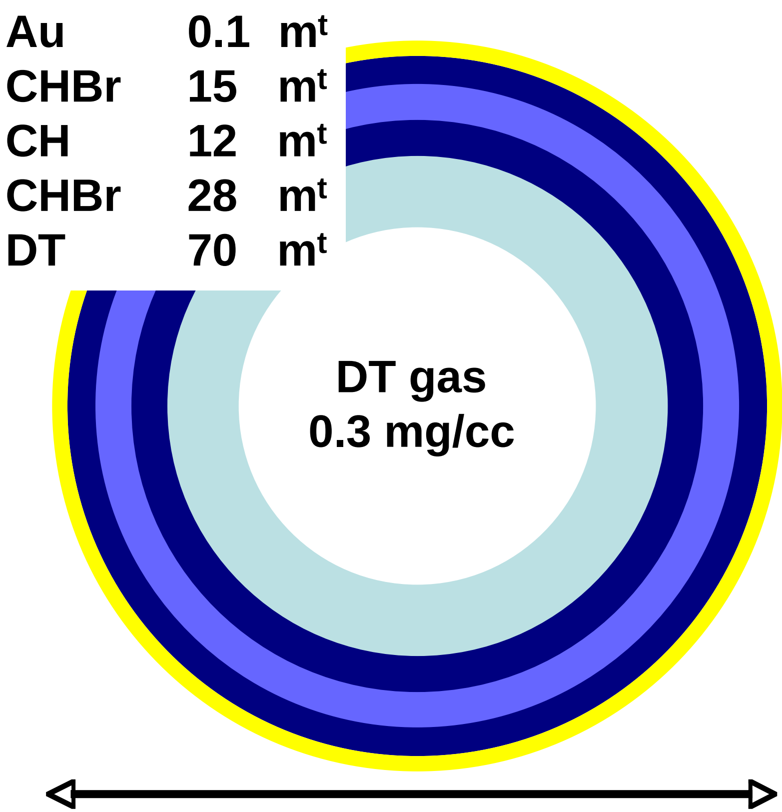

**Azechi et al., Laser Part. Beam 1991.**

*Ignition target design*

## Target consists of 3 layered ablator (CHBr/CH/CHBr) yields thermonuclear energy of 41 MJ in the NIF-direct (1.8 MJ).

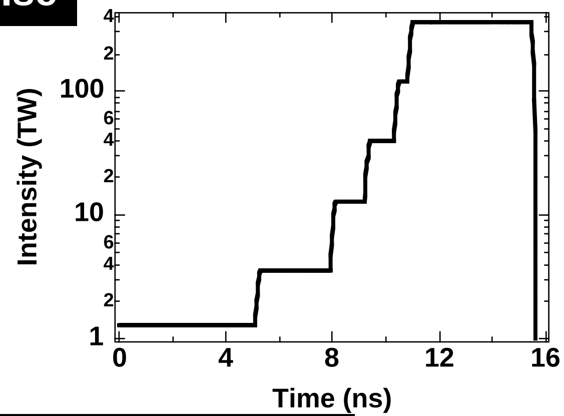
S. Fujioka
(ILE. Osaka)

**Target**

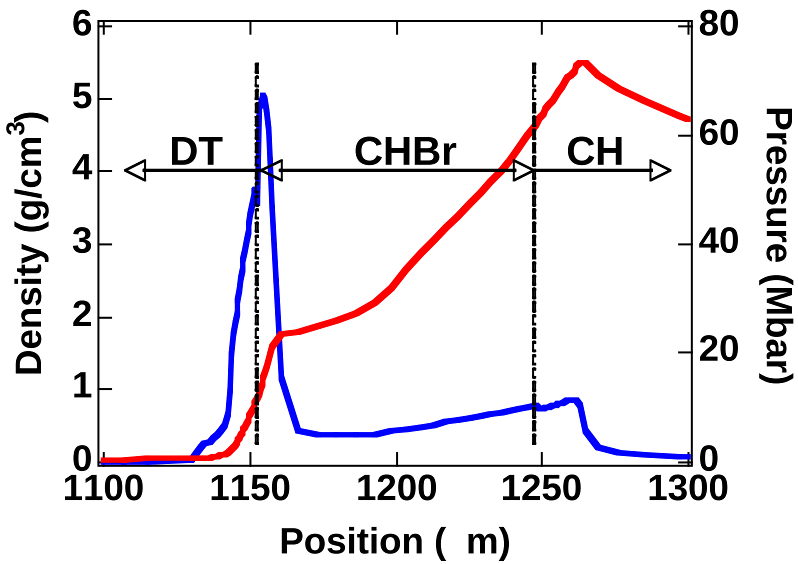



Diameter: 3500 ɱm

**Laser pulse**



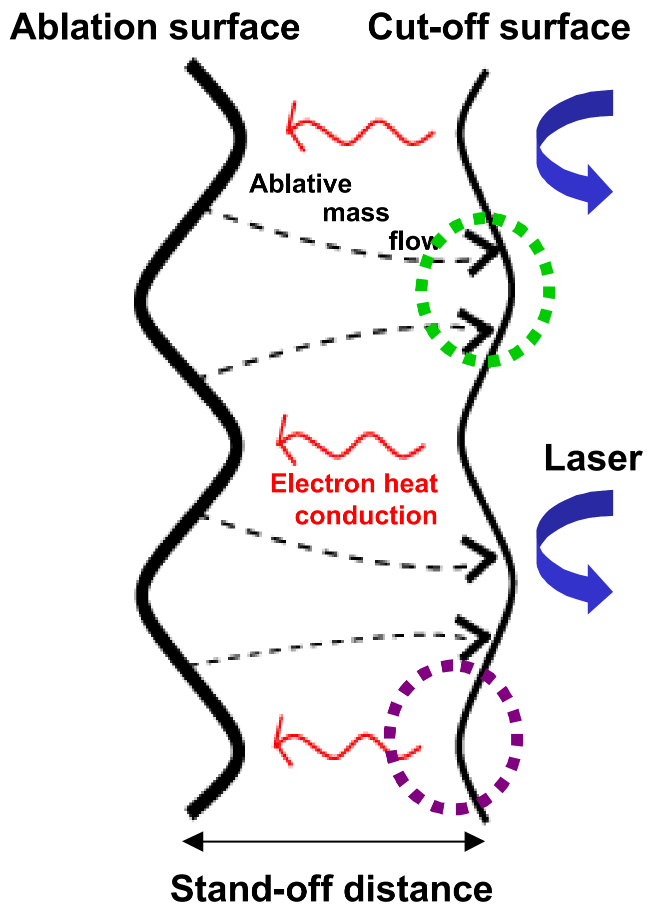

**Density profile @ 14.0 ns**



# The dynamic overpressure is enhanced by modulation of cut-off surface.

ILE Osaka

## The laser-absorption region is modulated by the ablative flow.




In the concave region,

- The concentration of the ablative flow.
- The stand-off distance becomes long.

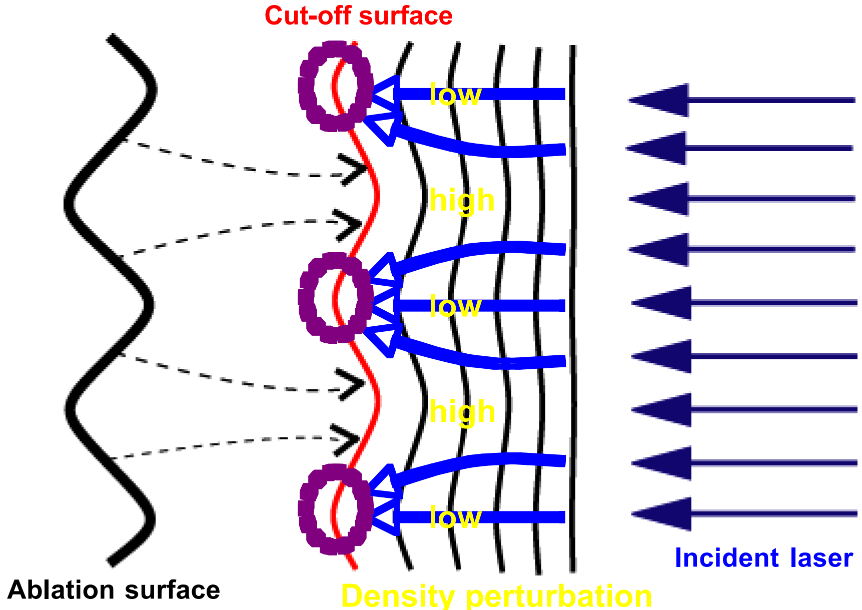
In the convex region,

- The stand-off distance is shorter than that in the concave region.
- The increase of dynamic overpressure.

# The stabilization of RT growth by the convergence effect of incident laser

ILE Osaka

## Modulation distribution of perturbation




- Focusing laser in the purturbed density region.
- Others, such as B field

*Discussion*

# The calculation result of model suggests the stabilization of RT growth on the medium perturbation wavelengths.

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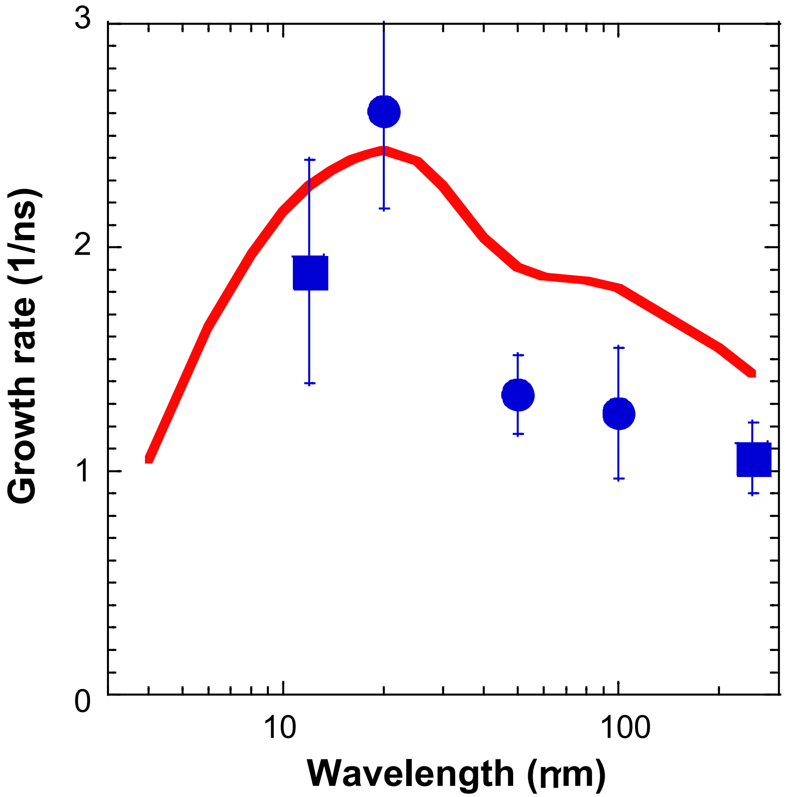



**Model**

$$^2 = {}_{TB}^{\;2} + kgd \frac{}{L'} e^{kL'} + \frac{k^2L^2}{L_0} \frac{n_e}{n_c} e^{kL_0} f(z)$$

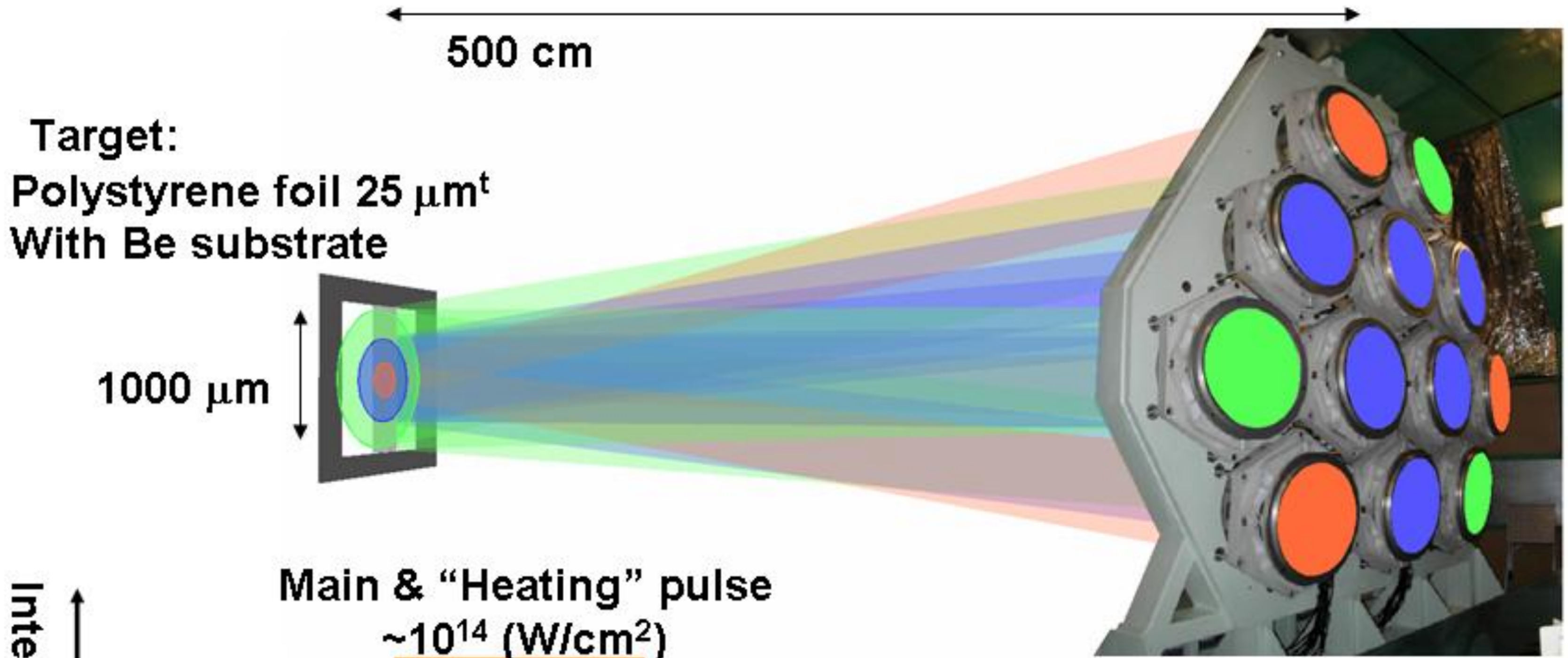
$$_{TB} = \sqrt{kg/(1 + kL_m)} \quad kv_a$$

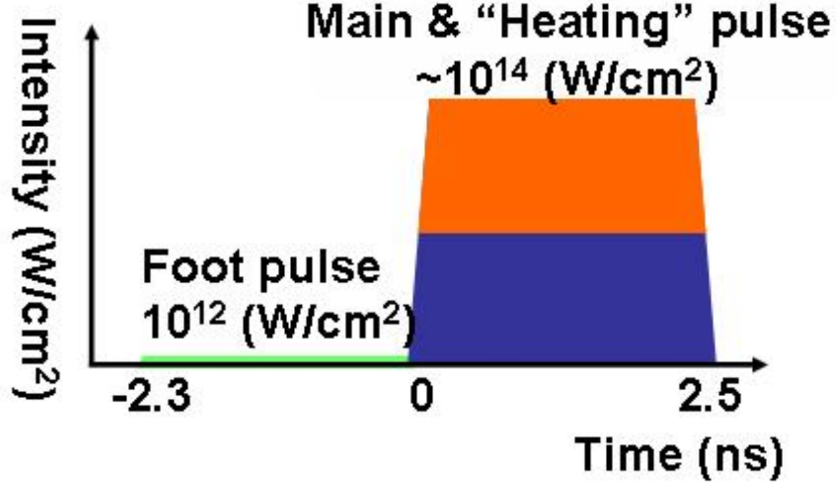
**Substitution of typical value from the result of 2D simulation,**

$g = 4\times10^{15}$ cm/s$^2$,
$L_m$ = 2 µm,
$b$ = 1.7,
$v_a$ = $1\times10^5$ cm/s

$L \sim L_0$ = 20 µm,
$d$ = 25 µm,
$n_e$ = $5\times10^{21}$ cm$^{-3}$,
$n_c$ = $9\times10^{21}$ cm$^{-3}$,
$L'$ = 20 µm

# - Experimental setup -
# GEKKO-XII HIPER facility



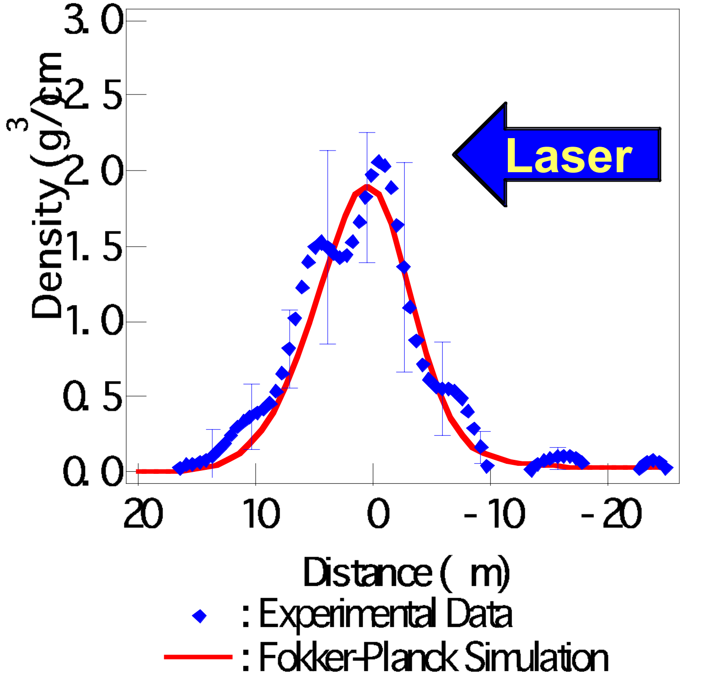

Wavelength:
Foot Pulse: 0.53 μm
Main Pulse: 0.35 μm
Heating Pulse: 1.05 μm or 0.53 μm

# Multi-color irradiation sustains the peak density of the ablating target

**The density profile of laser-driven polystyrene**

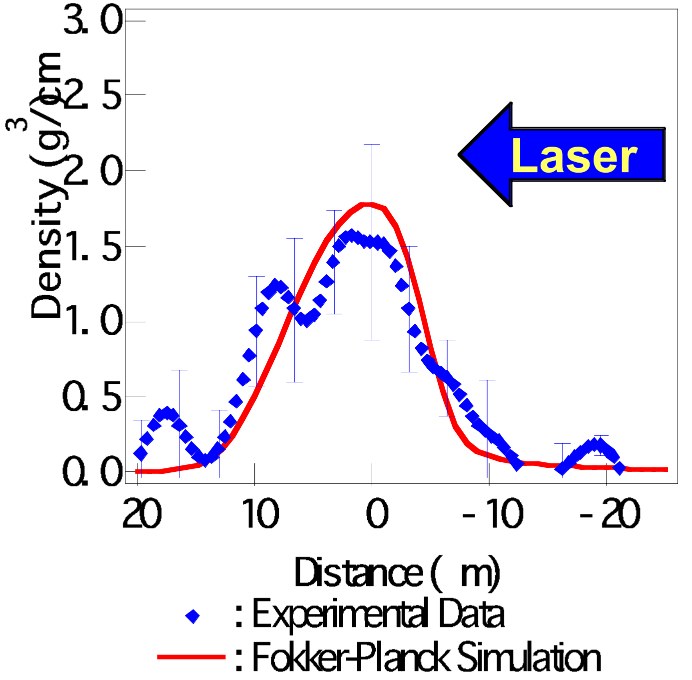
**1/3 m wavelength single-color laser irradiation**

**t= 1.0 ns**




**1/3 m and 1 m wavelength two-color laser irradiation**

**t= 1.3 ns**



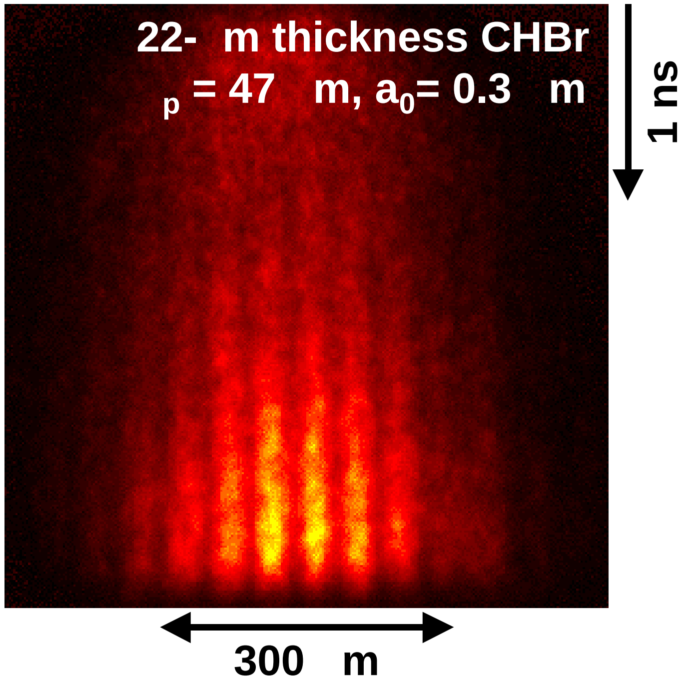
## *RT exp't with perturbed CHBr target*

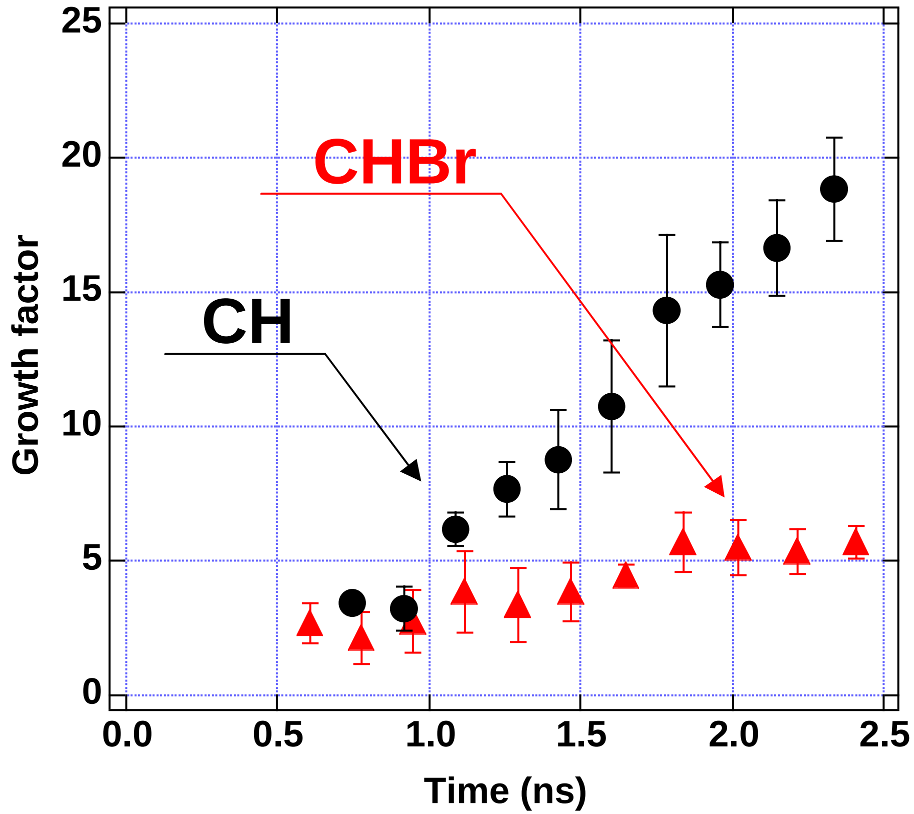
# Growth of perturbations in a CHBr target is lower than that of the CH target.

S. Fujioka
(ILE. Osaka)

* R. Betti *et al.*, PoP **5**, 1446 (1998)

| | $I_L$ (TW/cm$^2$) | $g$ ( m/ns$^2$) | $L_m$ ( m) | $_a$ (g/cm$^3$) | $m$ (g/cm$^2$ s$^{-1}$) | $V_a$ ( m/ns) | $Fr$ |
|---|---|---|---|---|---|---|---|
| CHBr | 61 | 42 | 2.6 | 2.4 | 6.9 x 10$^5$ | 2.9 | 0.36 |



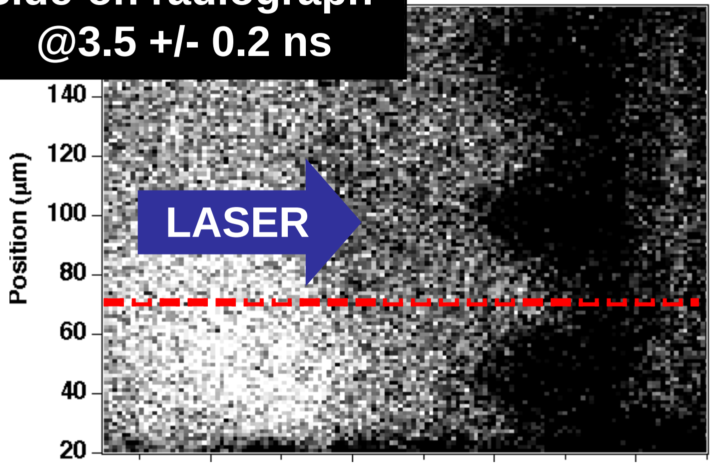



## *RT exp't with perturbed CHBr target*

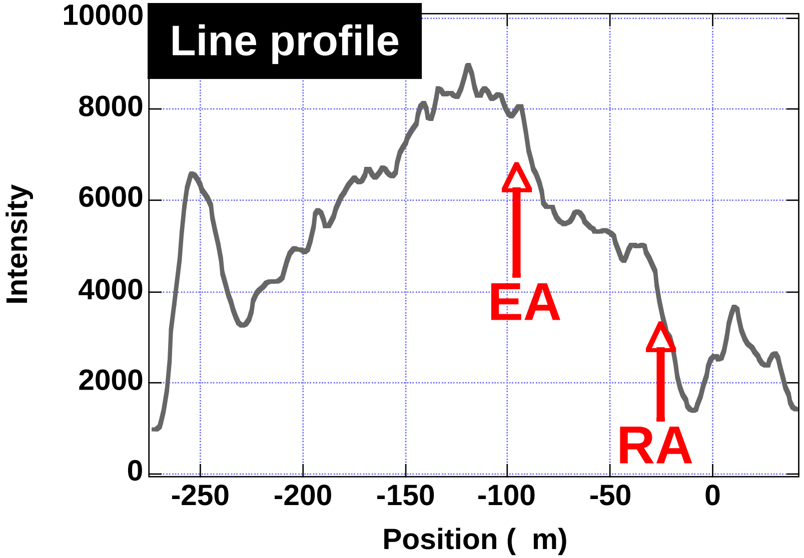
**The electron-conduction ablation front is almost RT stable, while averaged amplitude of perturbations (  = 50  m, $a_0$ = 0.3  m) is 12  m at the radiative ablation front.**

S. Fujioka
(ILE. Osaka)

**Side-on radiograph @3.5 +/- 0.2 ns**

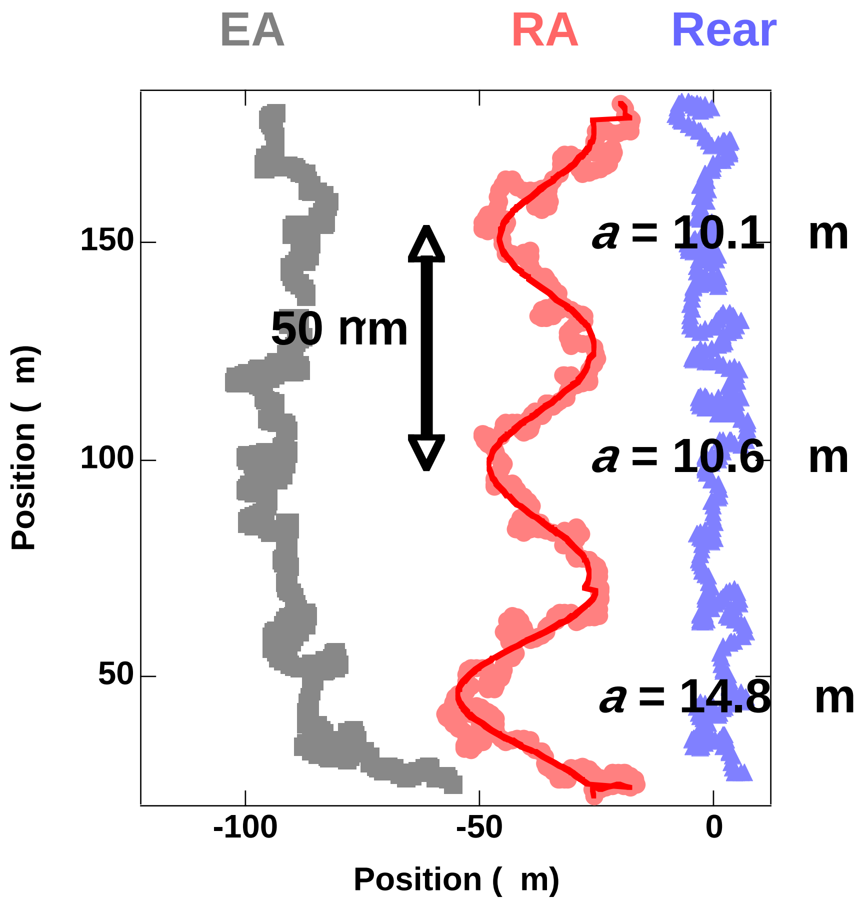



**Line profile**




**Density contour plot**

*GF* = 40
(GR = 1.2 /ns)



# 1D Radiation-hydrodynamic simulation shows that hyper velocities ~ $10^8$ cm/s can be achieved under proper conditions.