*2005/12/13 予備審査

Research on Final Beam Transport and Beam-Target Interaction in Heavy Ion Inertial Confinement Fusion

--- 重イオン慣性核融合における最終段ビーム輸送とビーム-ターゲット相互作用に関する研究 ---

工学研究科　エネルギー環境科学専攻
学籍番号：DT030204　染谷哲勇

Dissertation structure

1. Introduction
    - 1.1 Fusion
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        - 1.1.2 Inertial confinement fusion
        - 1.1.3 Heavy ion fusion
    - 1.2 Lawson criteria
    - 1.3 Purposes of this thesis

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    - 2.1 Beam final transport in heavy ion fusion
    - 2.2 Physical mechanism of insulator guide and simulation model
    - 2.3 Simulation results
    - 2.4 Interaction with background gas
    - 2.5 Discussions

*T.Someya, S.Kawata, et al., Fusion Science and Technology, **43** 282 (2003).

3. HIB-Target Interaction

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  - 3.2.3 Beam particle orbit in the target
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  - 3.3.4 Beam number effect
  - 3.3.5 Target temperature effect
  - 3.3.6 Displacement on fuel pellet position in a reactor
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*T.Someya, A.I.Ogoyski, et al., Physical Review ST-AB, **7** 044701-1 (2004).
*T.Someya, S.Kawata, et al., Nucl. Inst. and Meth. in Phys. Res. A, **544** 406 (2005)

4. Target Hydrodynamics
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        4.2.2 Basic equations
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    4.3 Simulation results
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        4.3.2 With foam case
        4.3.3 Foam thickness effect
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5. Conclusions

*T.Someya, T.Kikuchi, et al., Inertial Fusion Sciences and Applications 2005, Proc. Book, Biarritz, France Sep., 2005.

Chapter 1. Introduction

Introduction

--- fusion and fission ---

Example

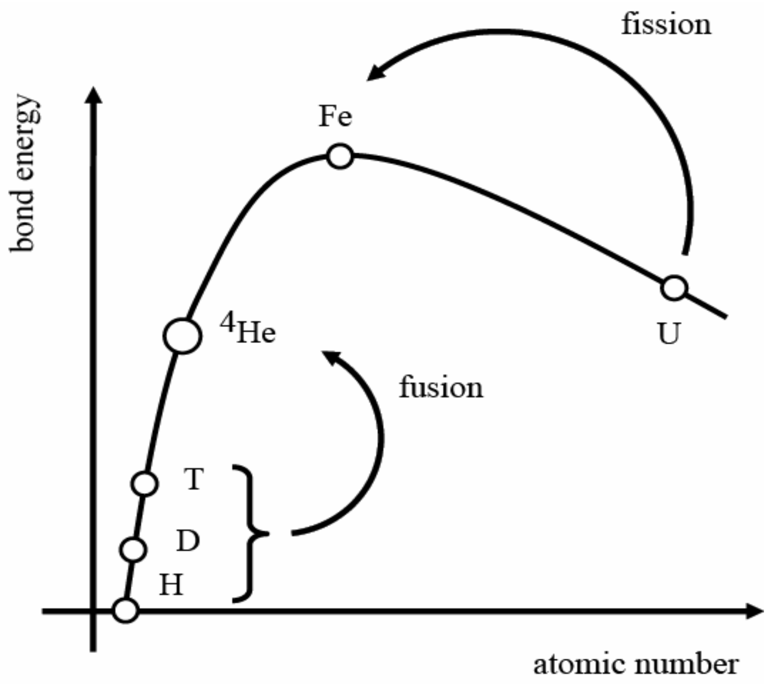
Fission: $\underbrace{{}^{235}\mathrm{U} + \mathrm{n}} \rightarrow \underbrace{{}^{134}\mathrm{Xe} + {}^{100}\mathrm{Sr} + 2\mathrm{n}}$

total mass: $M_{\mathrm{before}} > M_{\mathrm{after}}$

Fusion: $\underbrace{{}^{2}\mathrm{D} + {}^{3}\mathrm{T}} \rightarrow \underbrace{{}^{4}\mathrm{He} + \mathrm{n}}$

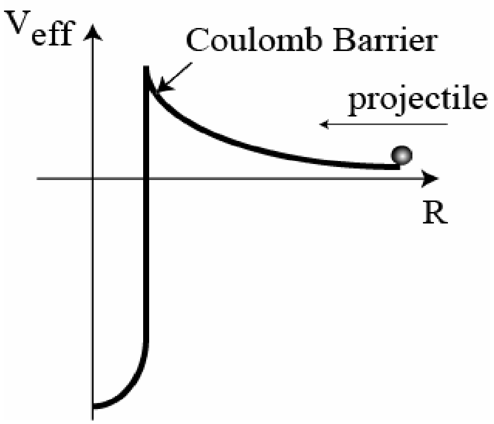
total mass: $M_{\mathrm{before}} > M_{\mathrm{after}}$

$$\mathrm{Energy} = |M_{\mathrm{before}} - M_{\mathrm{after}}| \times c^2$$



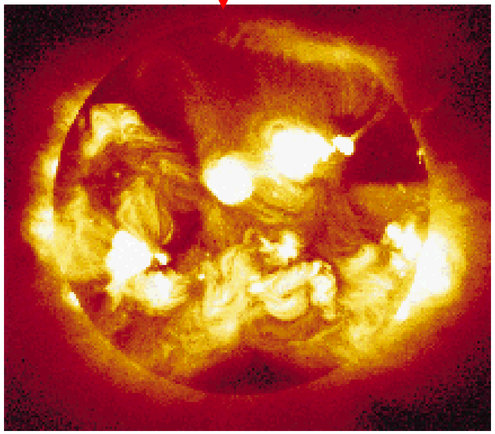
Introduction

--- confinement plasma ---

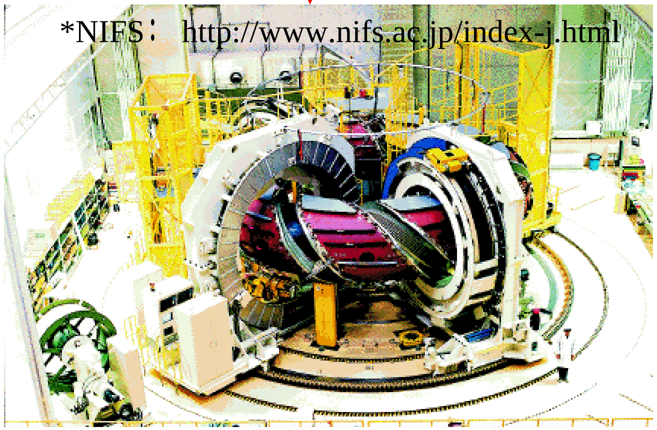


Fusion reaction

Confinement of high density and high temperature plasma

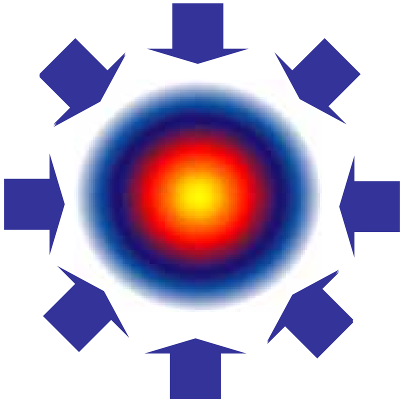


By gravity



*NIFS： http://www.nifs.ac.jp/index-j.html

By magnetic field

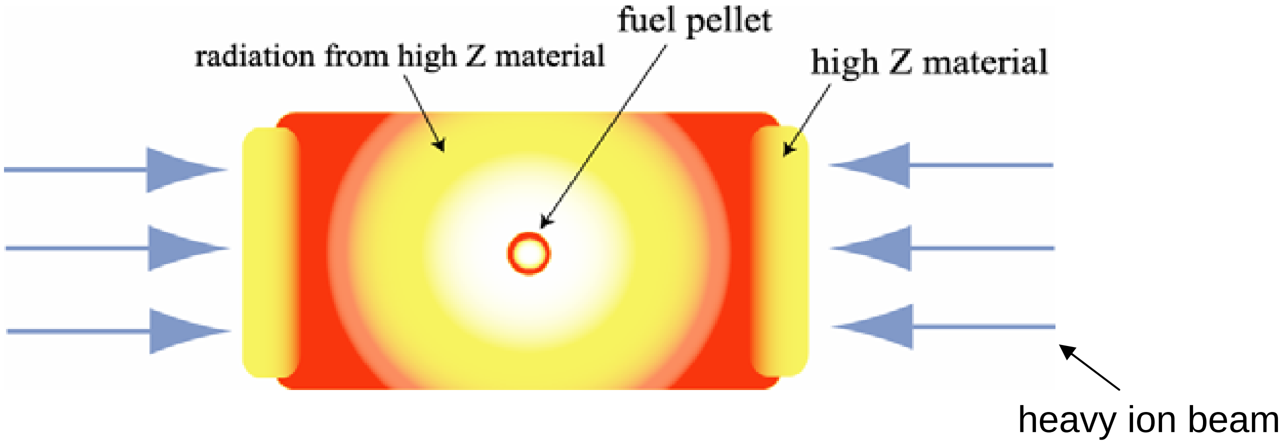


By inertial

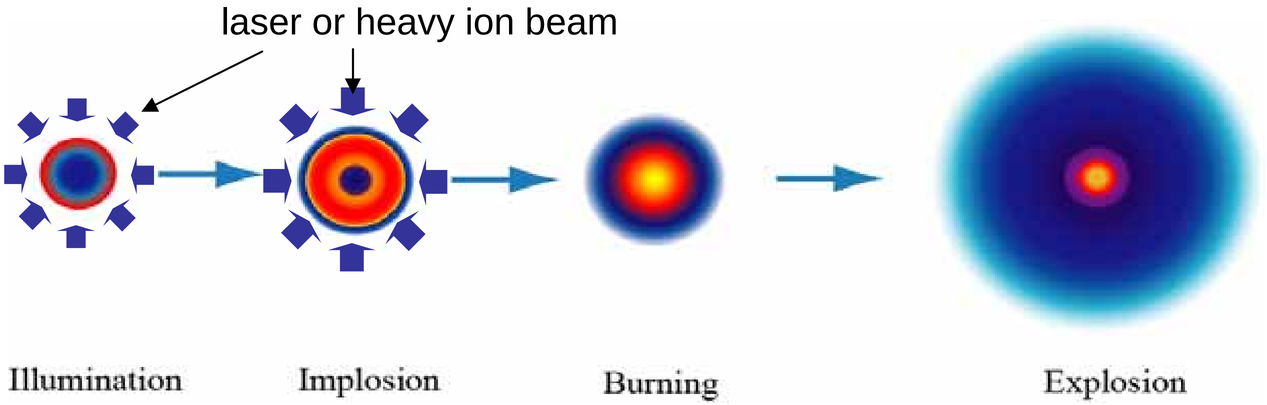
Introduction

--- inertial confinement fusion ---

- *Indirect-driven*

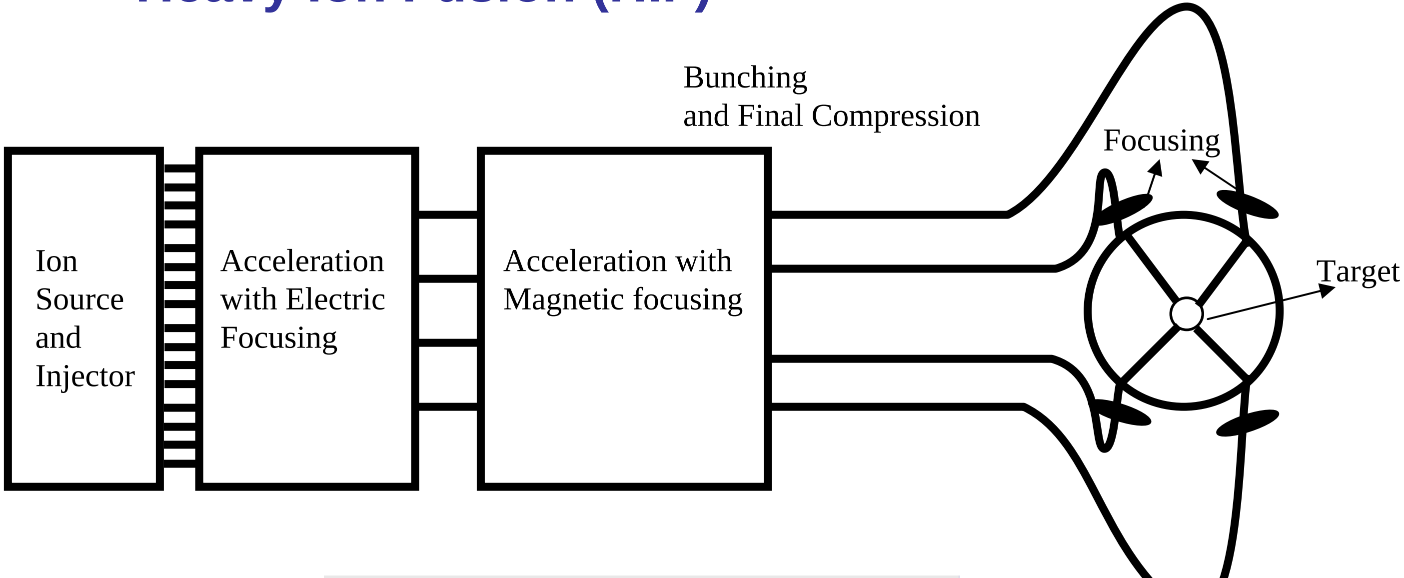


- *direct-driven*



Introduction

--- Heavy Ion Fusion (HIF) ---



Ion Source and Injector

Acceleration with Electric Focusing

Acceleration with Magnetic focusing

Bunching and Final Compression

Focusing

Target

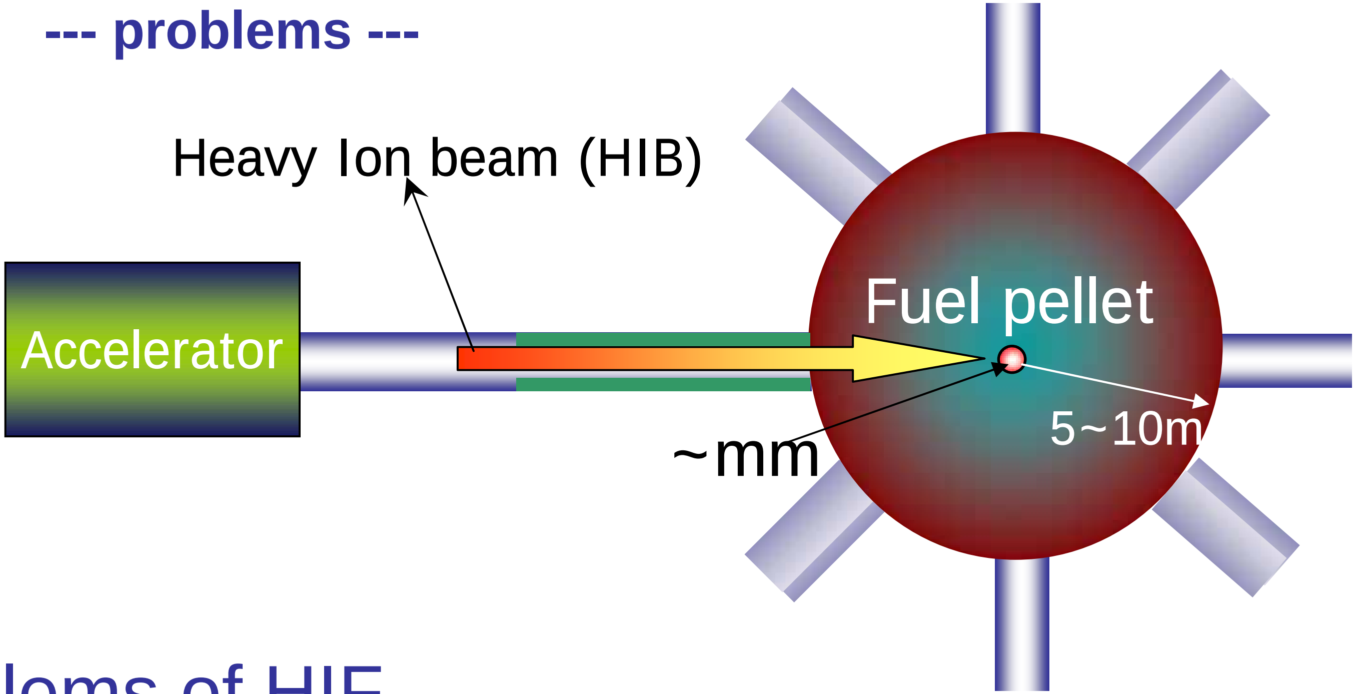
Target Chamber's Dedication Marks a Giant Milestone

Energy Secretary Bill Richardson addresses the crowd that attended the June 11, 1999, dedication of the National Ignition Facility target chamber.

*http://www.llnl.gov/

Introduction

--- problems ---



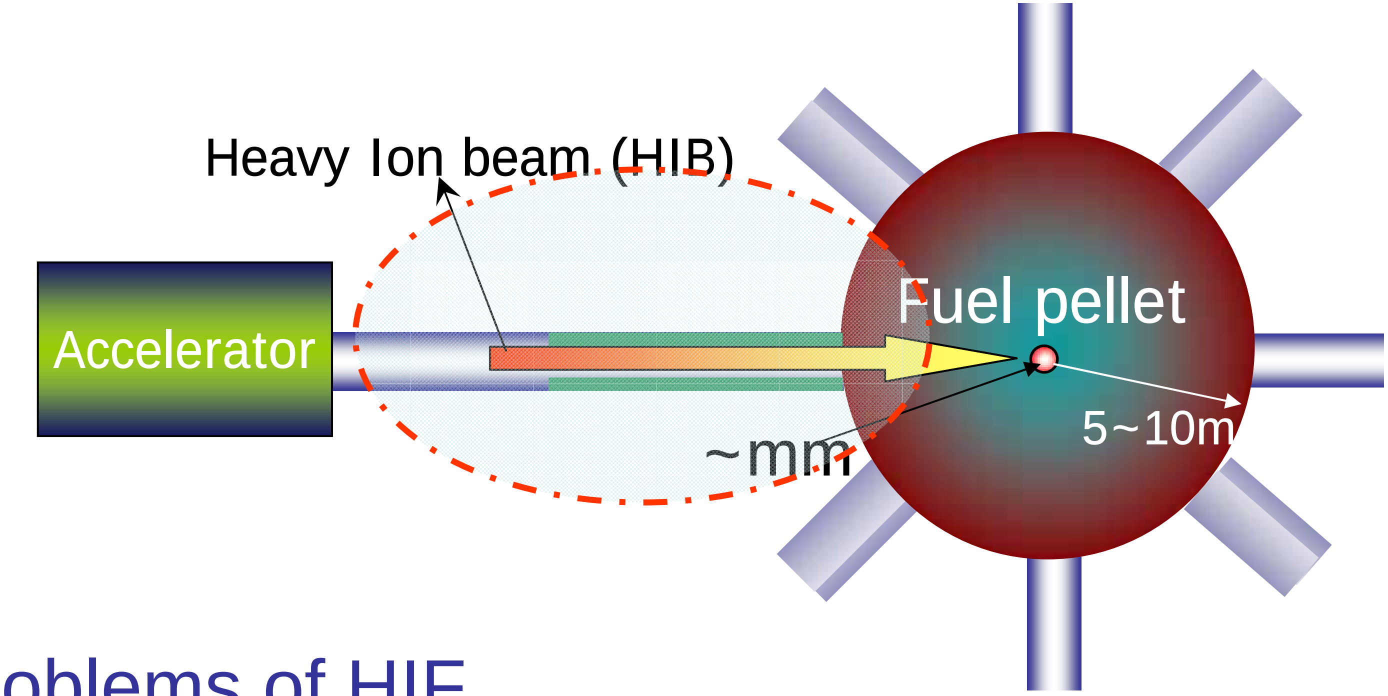
Problems of HIF

- Beam Accelerator (Scale, Cost, Energy, etc..)
- Physics of Intense Beam (Bunching, Emittance growth, etc..)
- Beam Final Transport (Stable transportation, Interaction with gas, etc..)
- Beam-Target Interaction
- Analysis of Target-Plasma Hydrodynamics

etc..

Chapter 2. Final Beam Transport

Introduction



Problems of HIF

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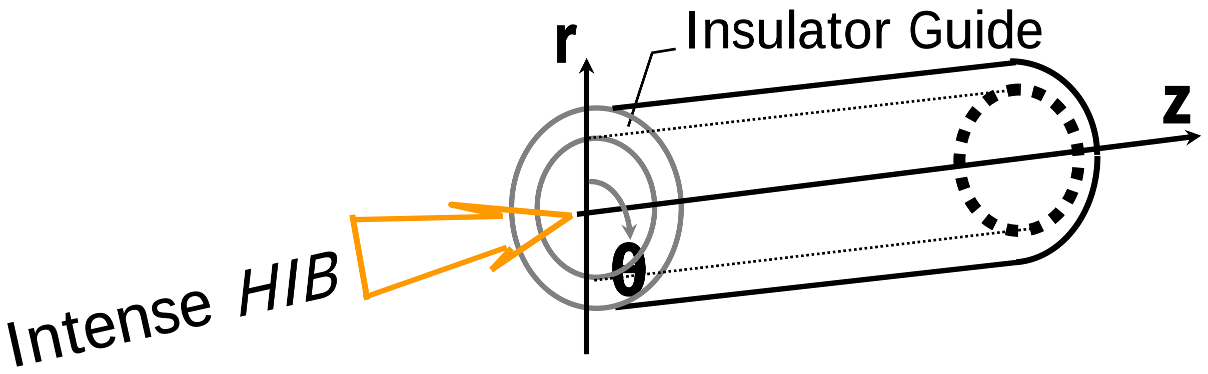
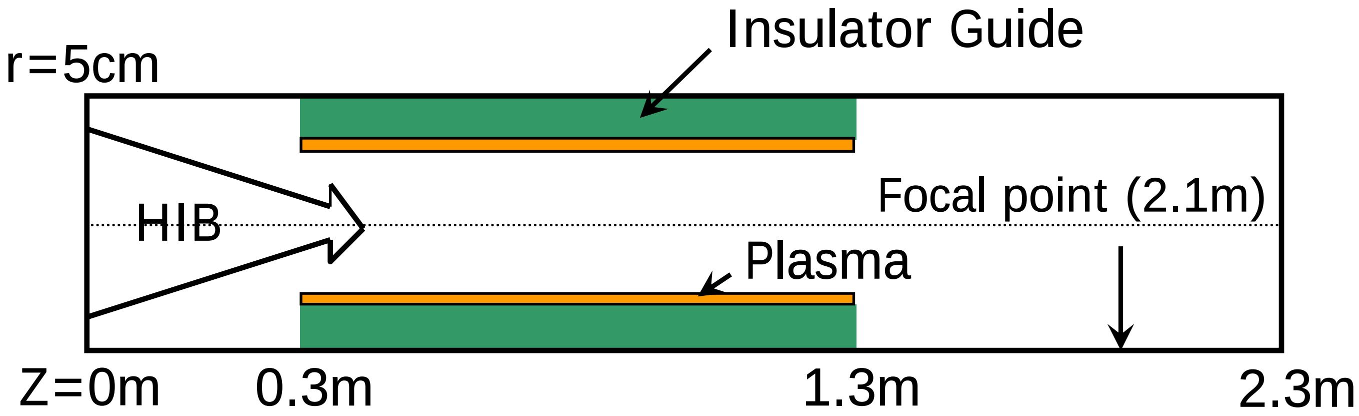
etc..

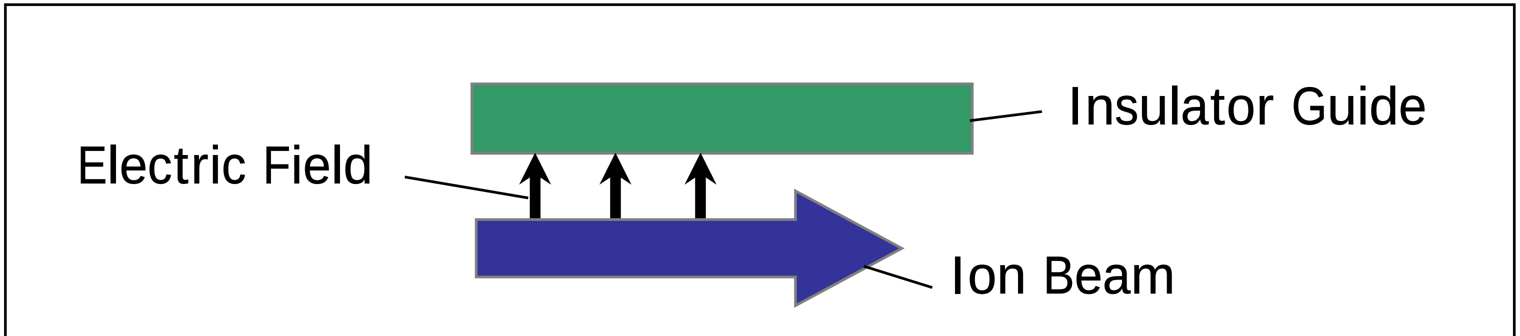
Simulation model





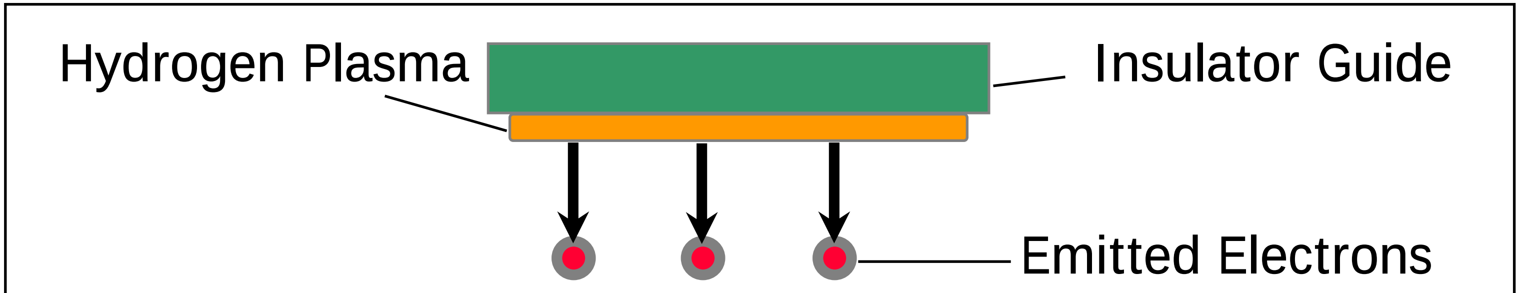
Initial Beam radius: 4cm

Physical mechanism of Insulator guide



1. Local electric field creation

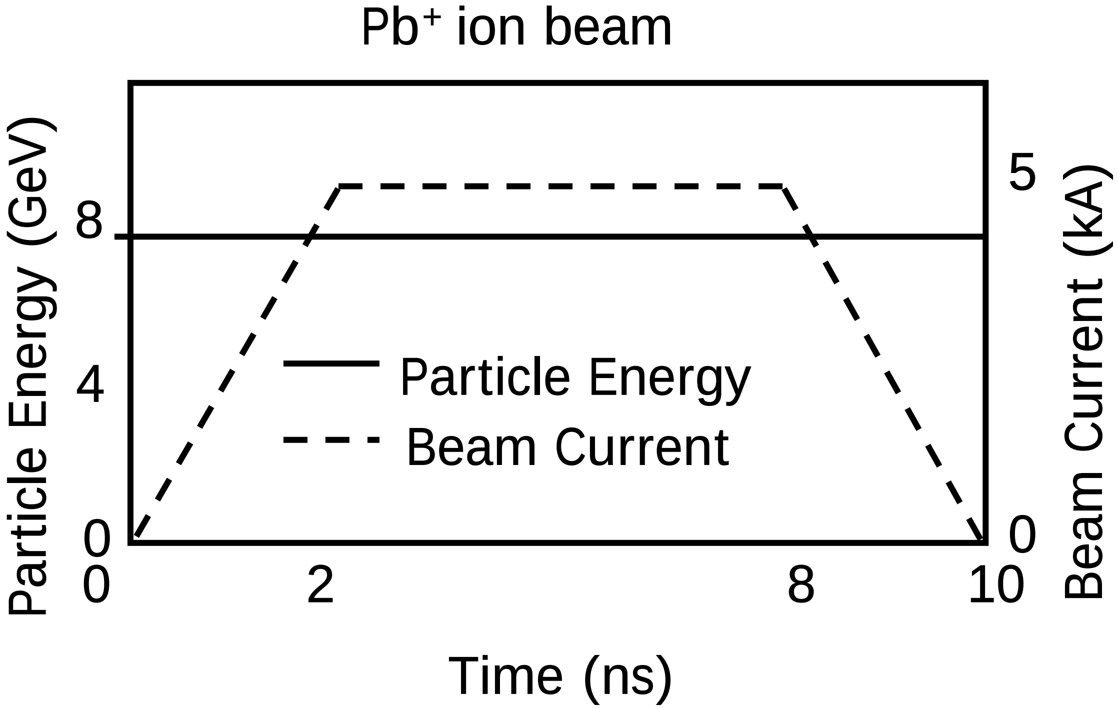
2. Discharges and plasma production



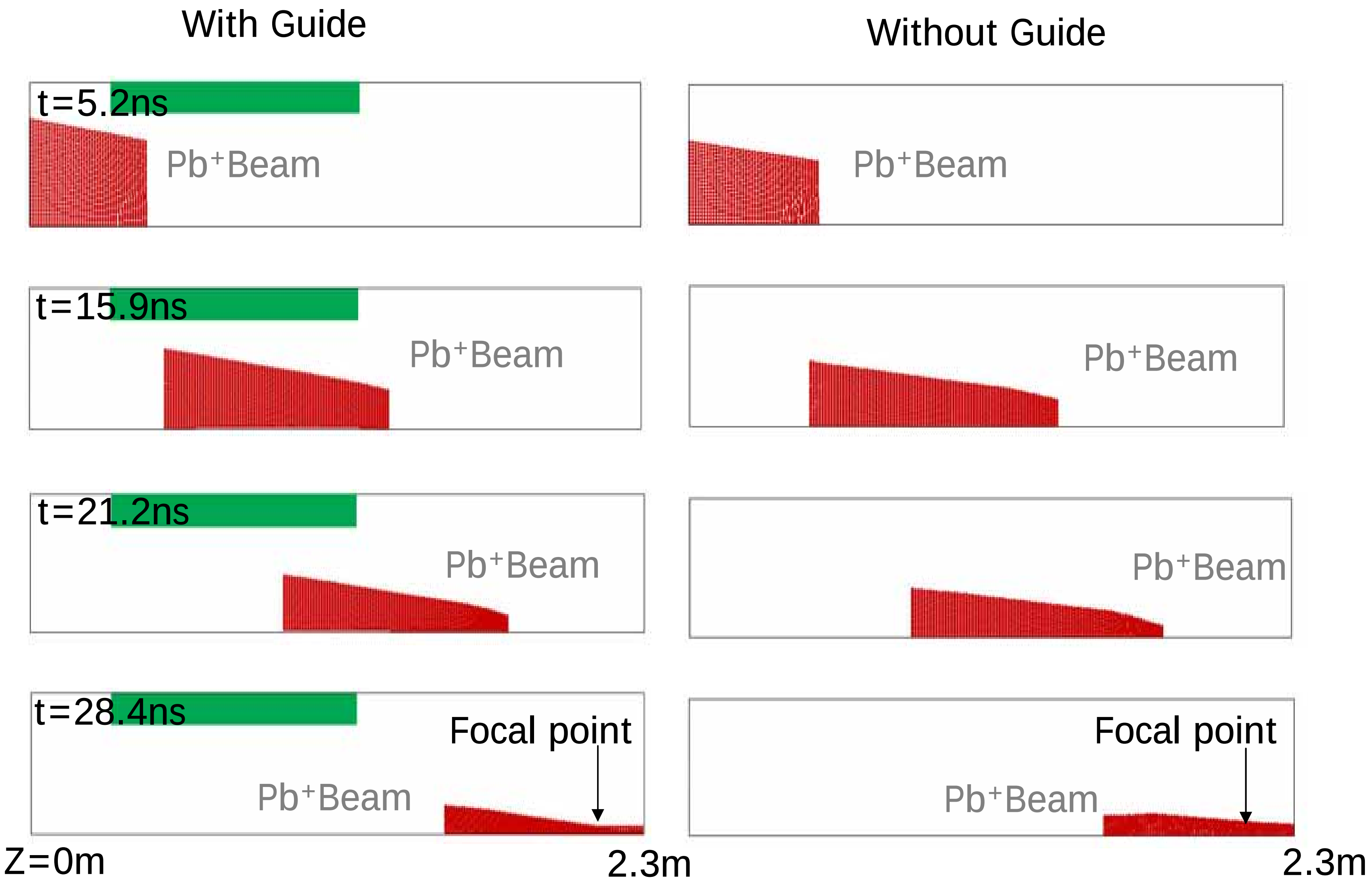
3. Electrons extraction

Input HIB parameter

- Maximal beam current: 5 kA
- Particle energy: 8 GeV
- Pulse width: 10 nsec
- Beam particle temperature: 10 eV

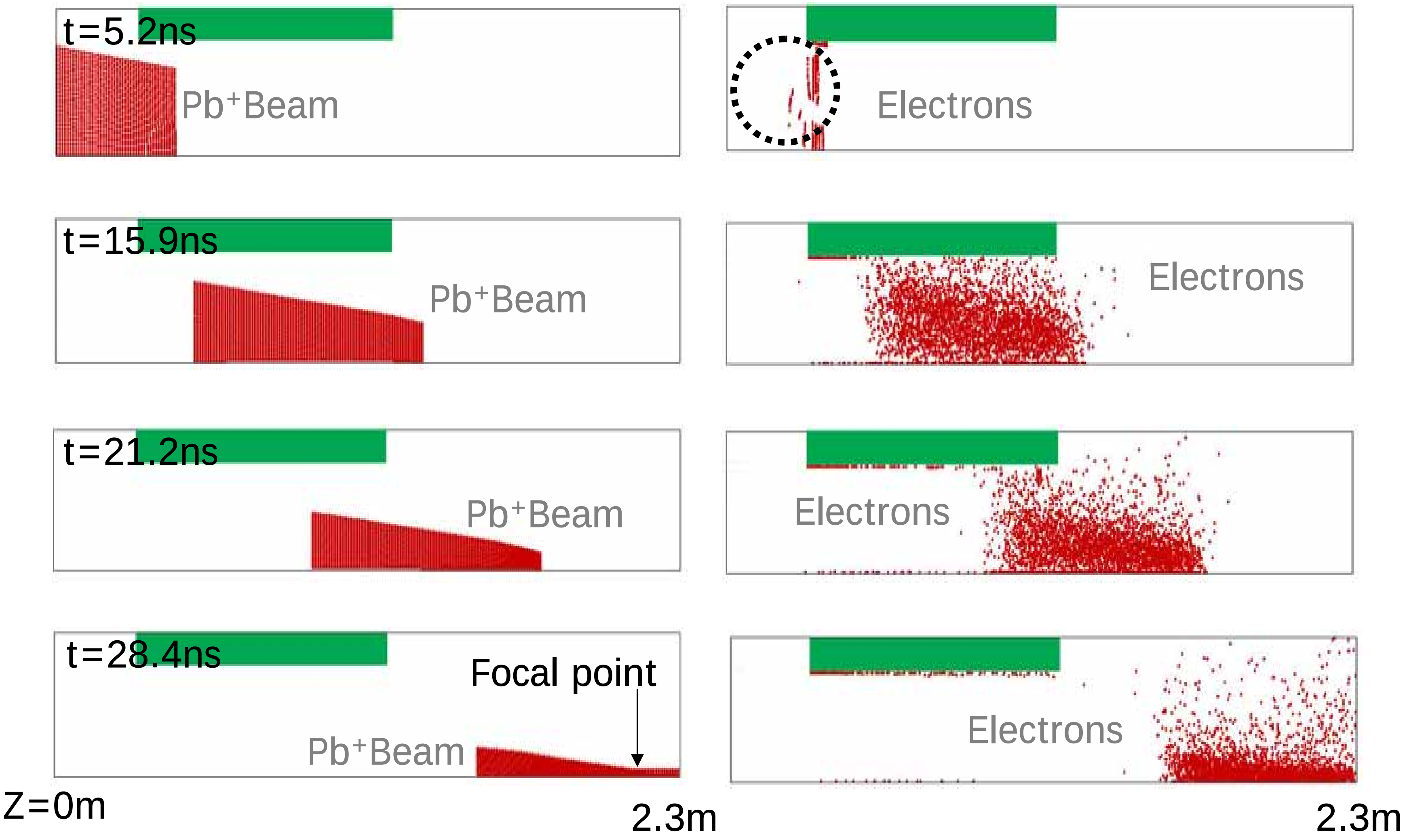


Simulation results



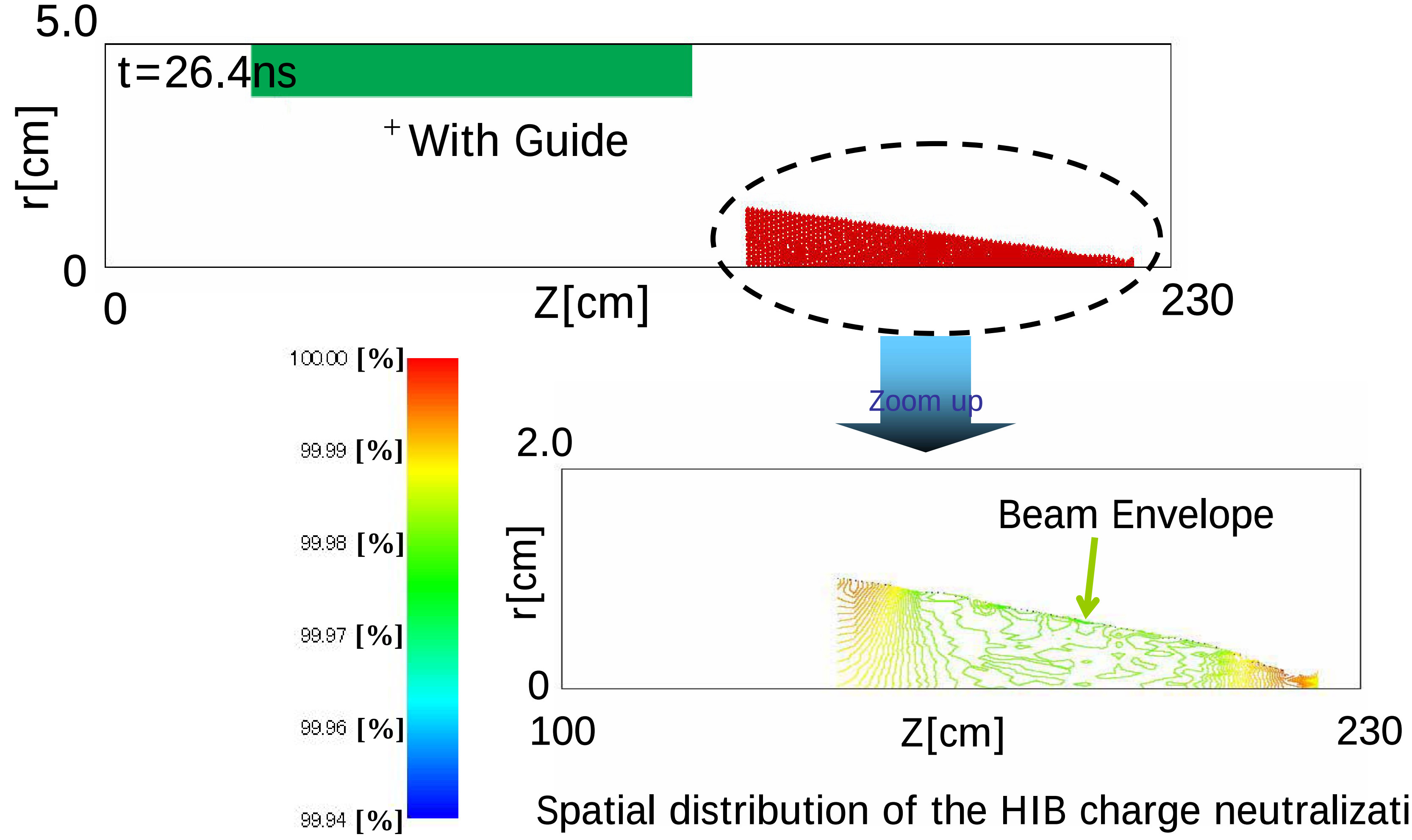
Ion beam particles

Simulation results



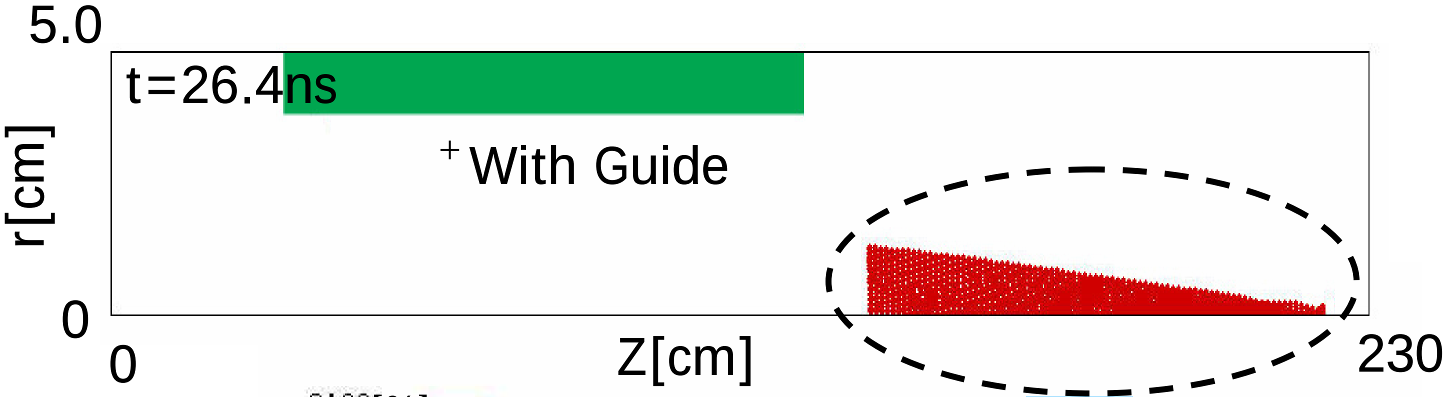
Ion beam and generated electrons from the plasma

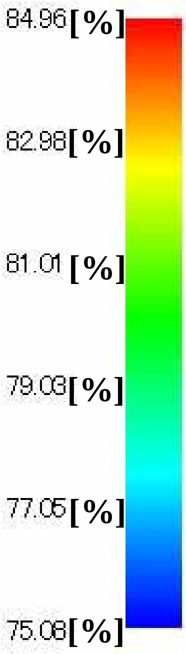
Spatial Distribution of the HIB Charge Neutralization

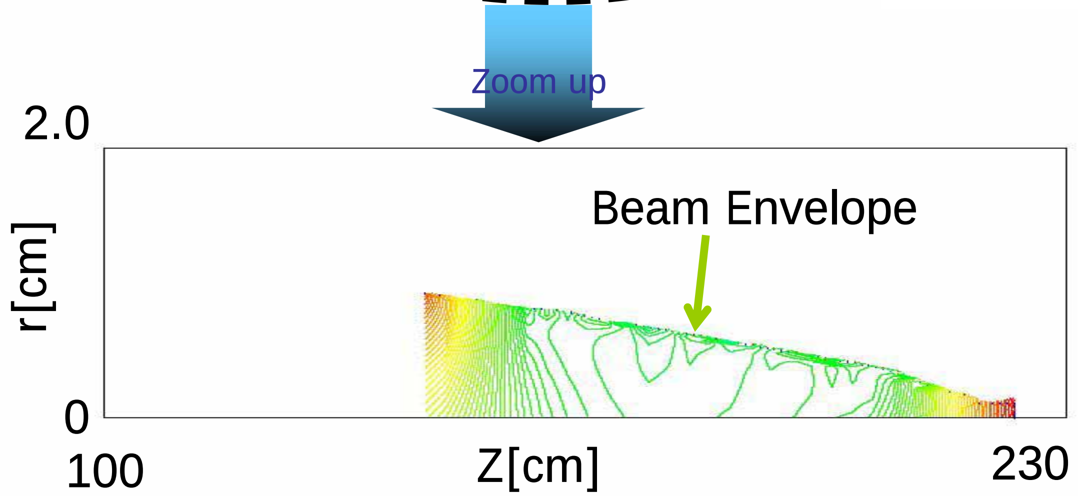


Spatial distribution of the HIB charge neutralization

Spatial Distribution of the HIB Current Neutralization

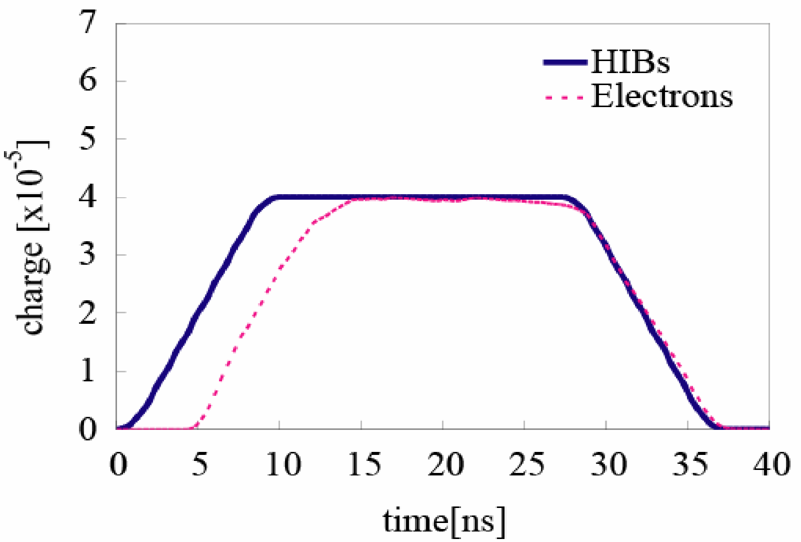




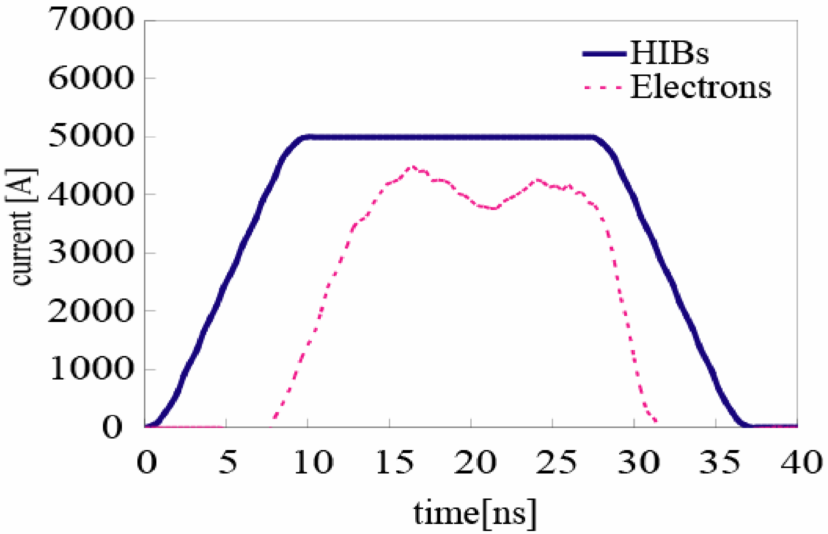


Spatial distribution of the HIB net current neutralization

Charge & current neutralization



Total space charge in the chamber

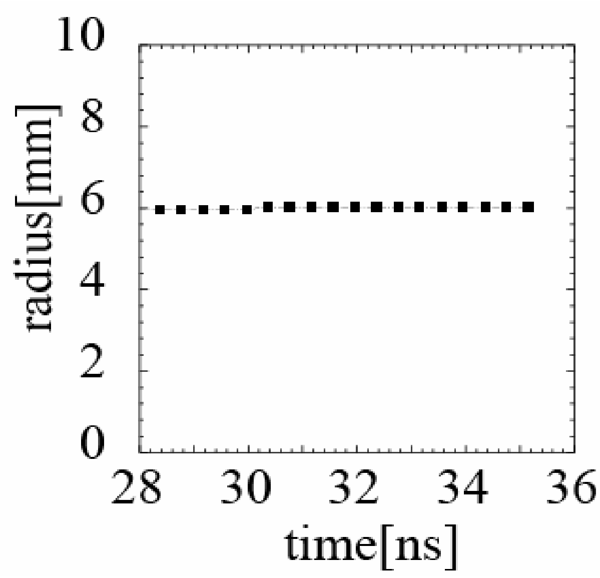


Beam net current

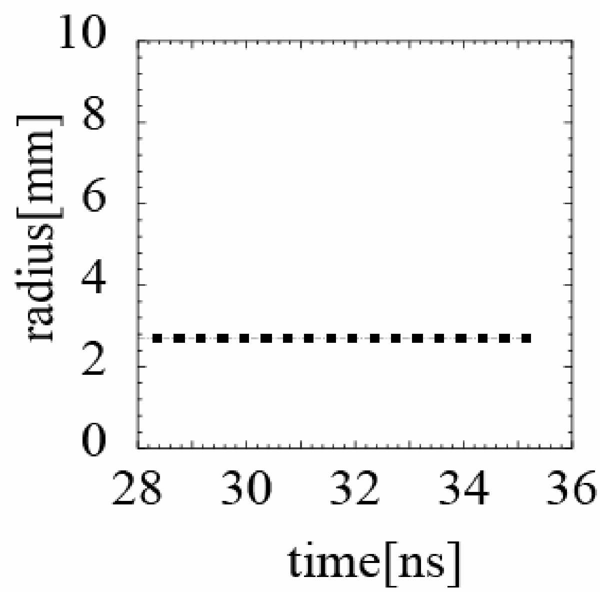
Charge and Current neutralization are self-regulated

HIB radius at focal spot

Without Guide

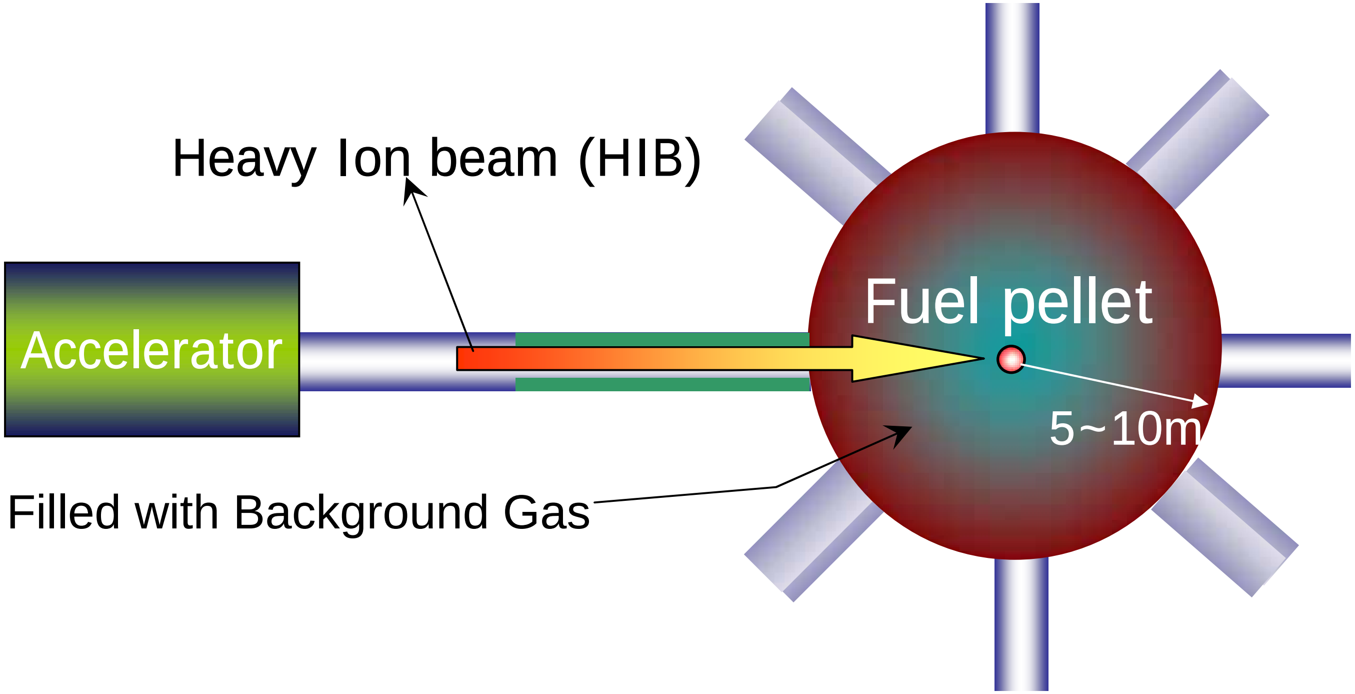


With Guide



HIB radius at focal spot is suppressed to about 1/3

Instability



Ion beam and background gas

◎Two stream instability

$$\gamma_{\max} = -\frac{\nu_e}{2} + \sqrt{\frac{\pi}{2}}\,\frac{\omega_b^2}{\omega_e}\,\frac{V_b^2}{u_b^2}\exp(-\frac{1}{2})$$

$\gamma_{\max}$: Maximum growth rate
u_b : Beam thermal velocity
V_b : Beam velocity

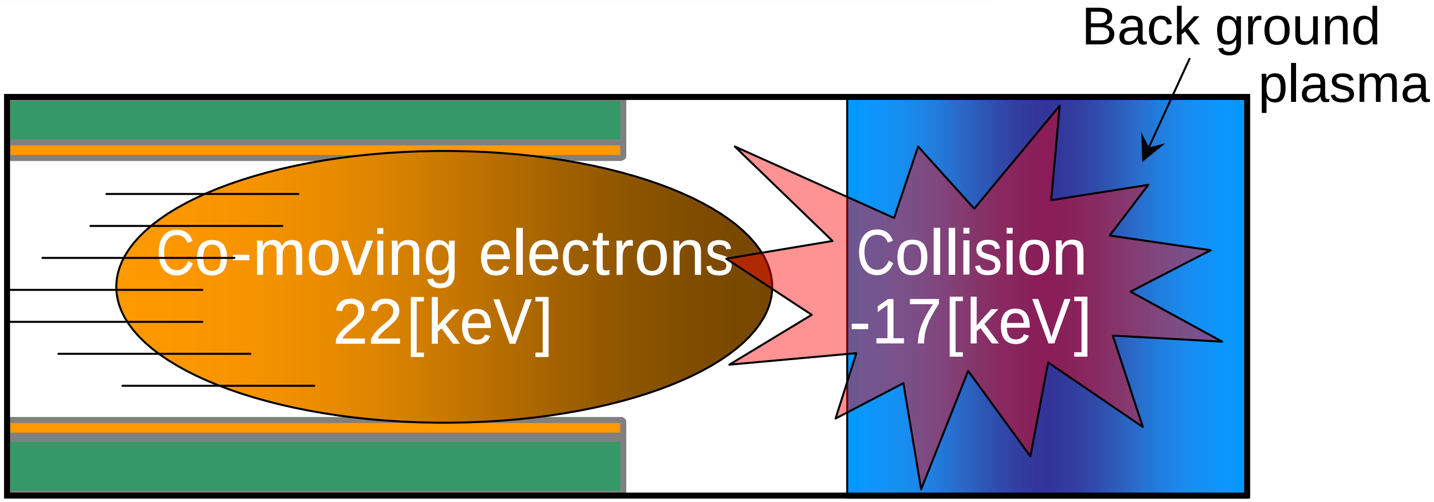
◎Filamentation instability

$$\gamma_{\max} = 2\,\frac{\omega_b^2}{\omega_p^2}\,\frac{V_b^2}{u_b^2}\,\nu_e$$

ν_e : Collosion frequency
ω_b : Beam plasma frequency
ω_e : Electron plasma frequency

Interaction between the Guide Electrons & Background Electrons

Calculation Result $\gamma_e \tau < 0$ ⇒ Collision

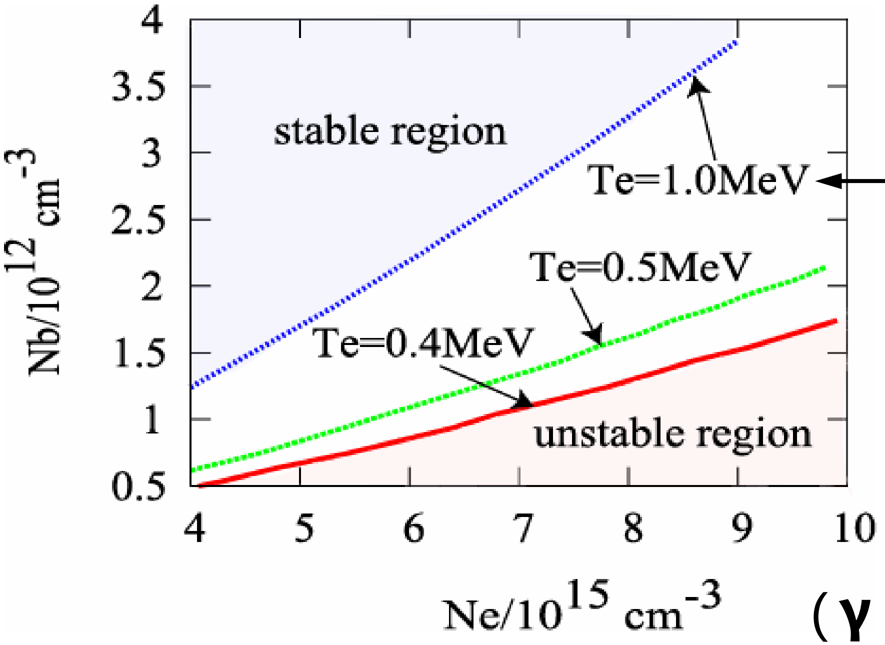


scattering co-moving electron by collision

HIB space charge is neutralized by background gas

Two-Stream Instability

Between the Beam Ions and Background Electrons



HIB Temperature at focal spot

Nb: Beam ion density
Ne: Background electron density

(**γ τ** <5 for the two-stream instability)

Estimated stability boundaries

Safe from the Two-stream instability

Filamentation Instability

$$\boxed{\gamma_{\max} = 2\frac{\omega_b^2}{\omega_p^2}\frac{V_b^2}{u_b^2}\nu_e}$$

Parameters

$\mathrm{Nb} = 1.38\times10^{11} \sim 2.00\times10^{12}\ \mathrm{cm}^{-3}$ $\mathrm{Tb} = 0.1 \sim 1.0\,\mathrm{MeV}$

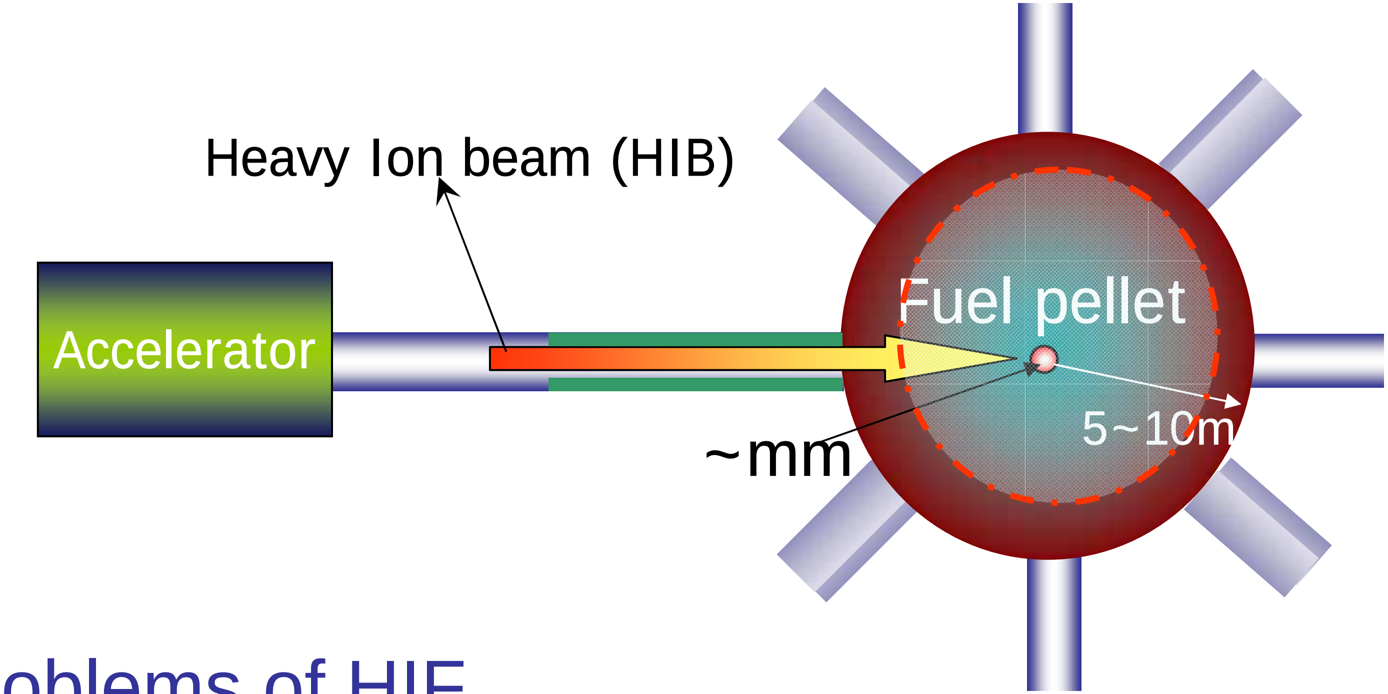
$\mathrm{Ne} = 1.00\times10^{5} \sim 1.00\times10^{16}\ \mathrm{cm}^{-3}$ $\mathrm{Te} = 10\,\mathrm{MeV}$

Always $\gamma\ \tau < 5$

Safe from the Filamentation instability

Chapter 3. HIB-Target Interaction

Introduction



Problems of HIF

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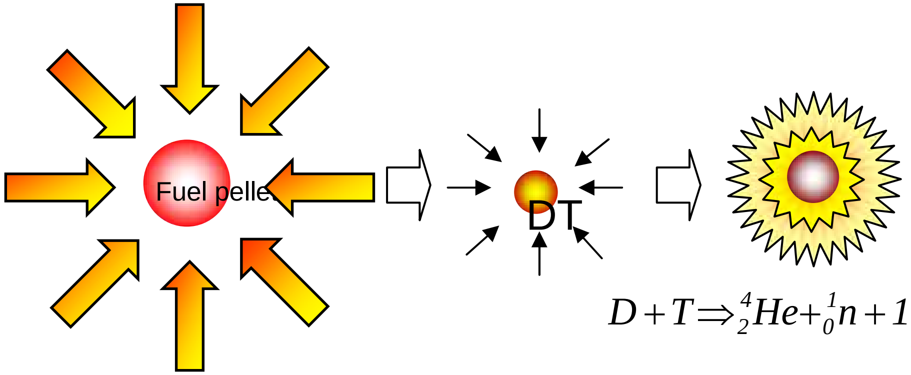
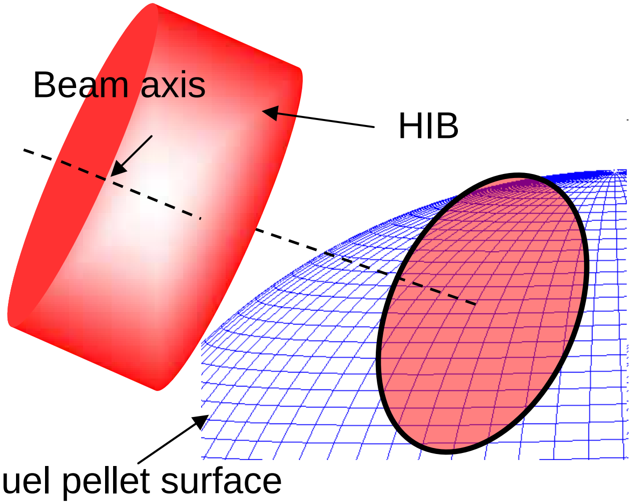
etc..

Purposes



$D+T \Rightarrow {}_{2}^{4}He + {}_{0}^{1}n + 17.6 MeV$

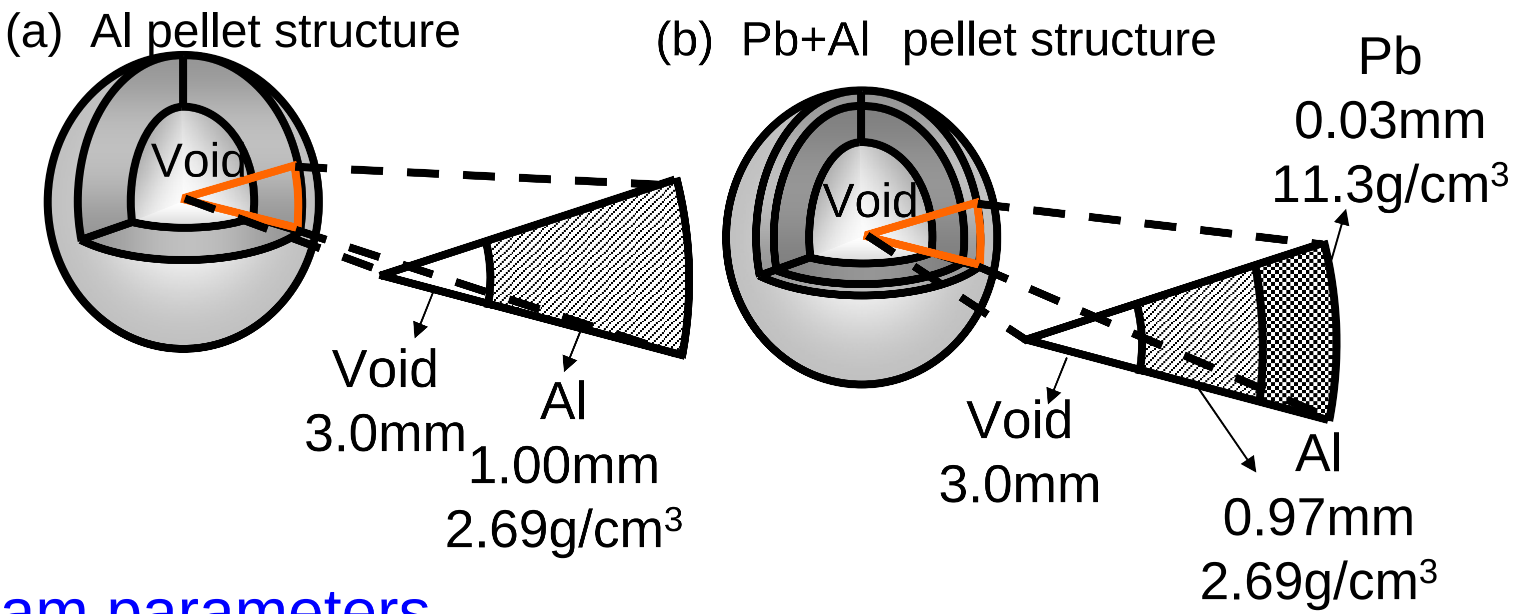


Effective Implosion

Non-uniformity (< few %)

- Calculate deposition energy on the target surface
- Illumination scheme to suppress deposition energy non-uniformity

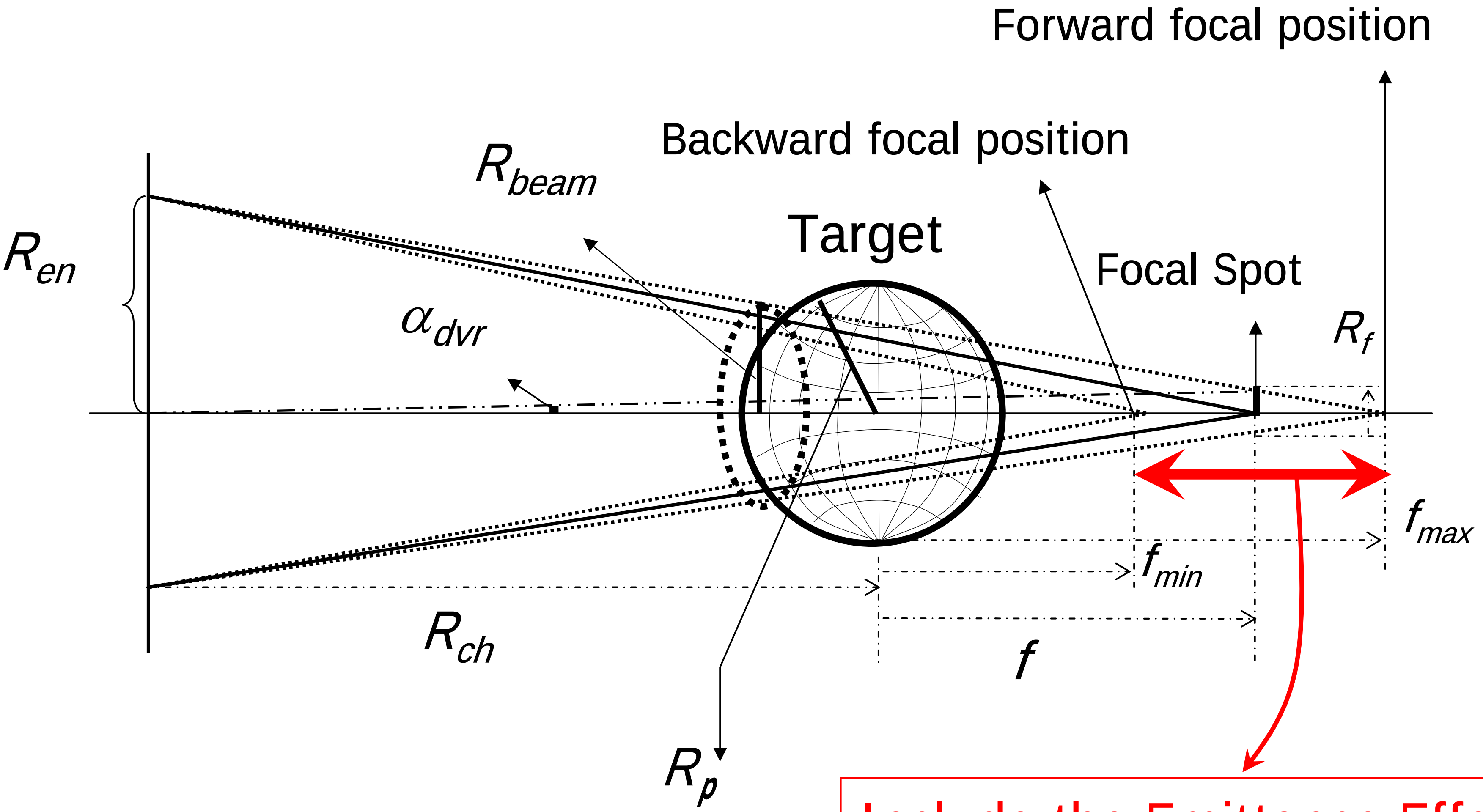
Simulation Model



Beam parameters

*Heavy ion beam:	Pb$^+$
*Particle energy:	8GeV
*Beam temperature:	0MeV,100MeV
*Beam number density:	1.3X10^{11} 1/cc
*Beam number:	12,20,32,60,92,120
*Beam distribution:	Semi-Gaussian,Gaussian

Beam Transverse Emittance & Beam Temperature



Include the Emittance Effect by changing the Focal Spot

Non-uniformity

$$\sigma_{\mathrm{RMS}} = \sum_{i}^{n_r} w_i \sigma_i$$

$$\sigma_{RMSi} = \frac{1}{\langle E \rangle_i} \sqrt{\frac{\sum_{j}^{n_\theta} \sum_{k}^{n_\phi} \left(\langle E \rangle_i - E_{ijk} \right)^2}{n_\theta n_\phi}}$$

$$w_i = \frac{E_i}{E}$$

$$\sigma_{PTV} = \sum_{i}^{n_r} w_i \sigma_{PTVi}$$

$$\sigma_{PTVi} = \frac{E_i^{\max} - E_i^{\min}}{2 \langle E \rangle_i}$$

σ_{rms}:root mean square(RMS) non-uniformity

σ_i:non-uniformity at a surface

$\langle E_i \rangle$:mean deposition energy at a surface

E_{ijk}:deposition energy at each point

n_r, n_θ, n_ϕ:each mesh number

E:total deposition energy

E_i:total deposition energy at a surface

w_i:weight function include the Bragg peak effect

σ_{ptv}:peak to valley(PTV) non-uniformity

σ_{PTVi}:PTV non-uniformity at a surface

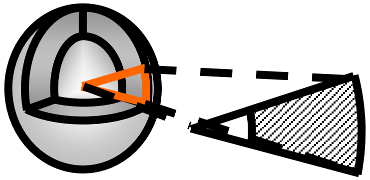
E_i^{max}:the Maximum deposition energy at a surface

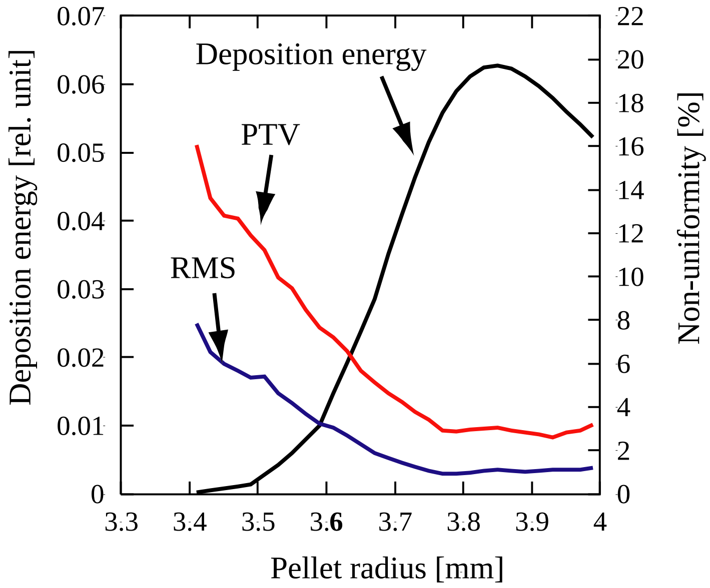
E_i^{min}:the minimum deposition energy at a surface

Simulation results

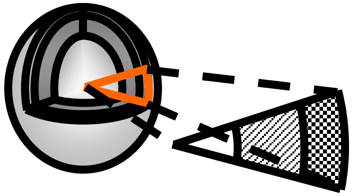
--- 32HIBs illumination ---

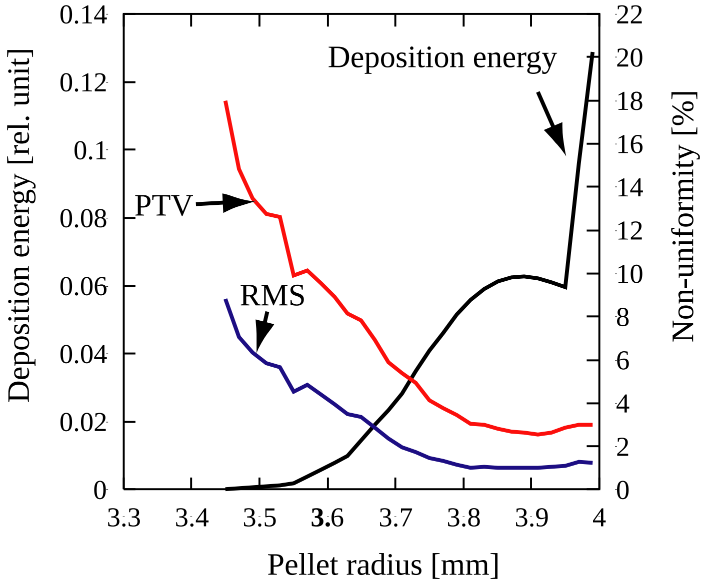
Al target





Pb + Al target



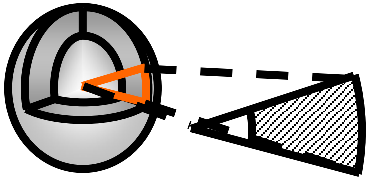


non-uniformity = 1.86 %

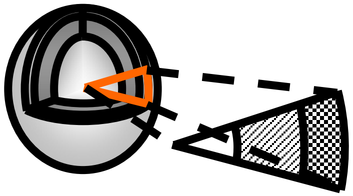
non-uniformity = 1.98 %

Mode Analysis

Al target

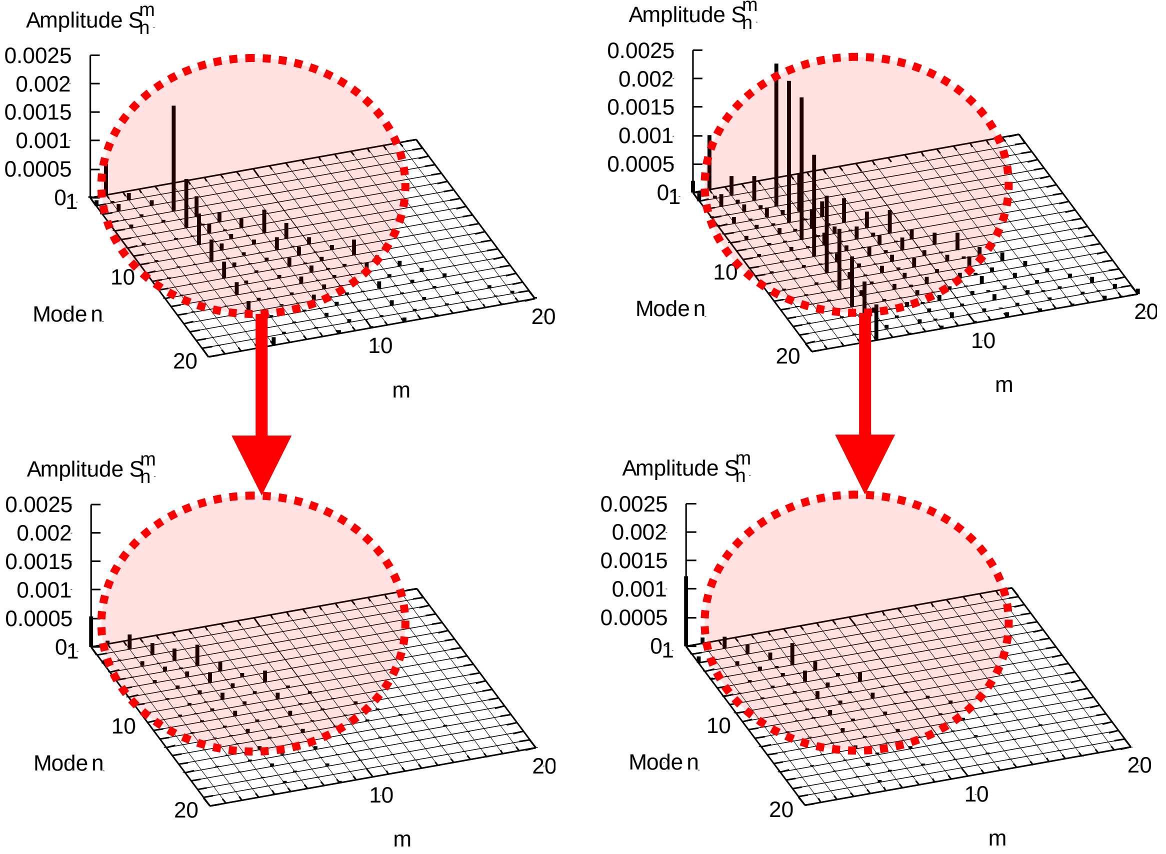


Pb + Al target



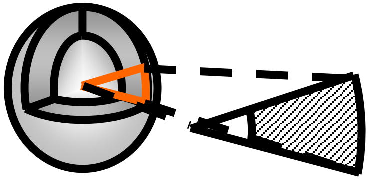
Global

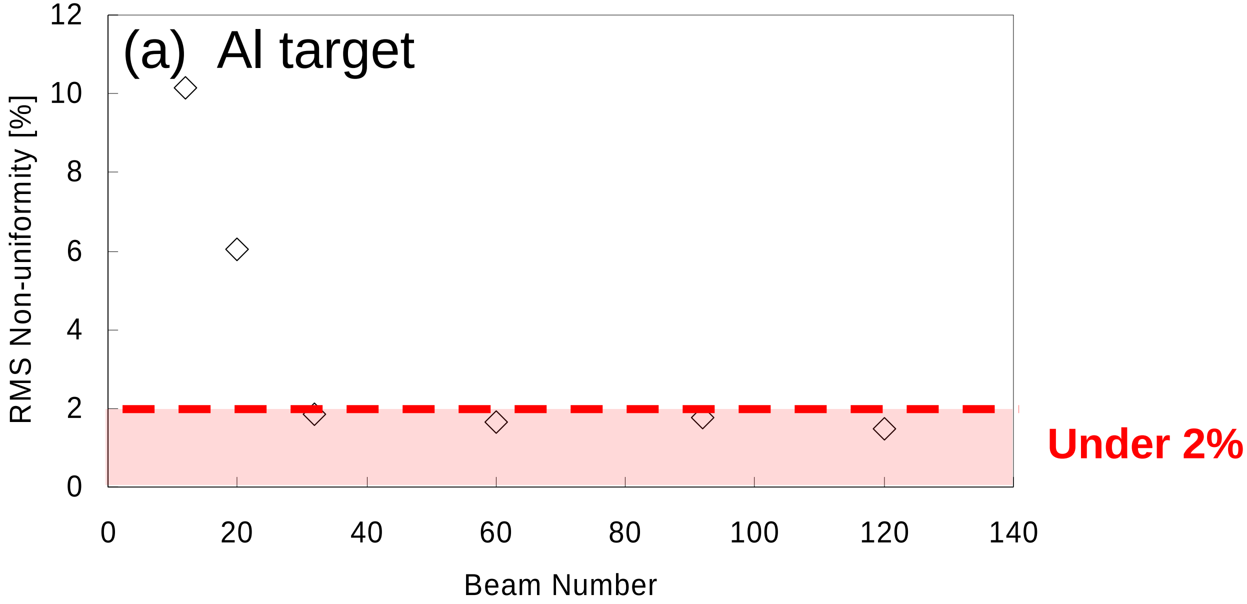
At the Bragg peak



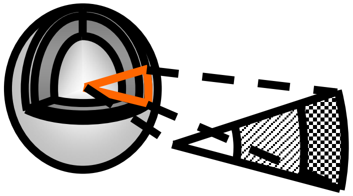
- Reduction of noise mode

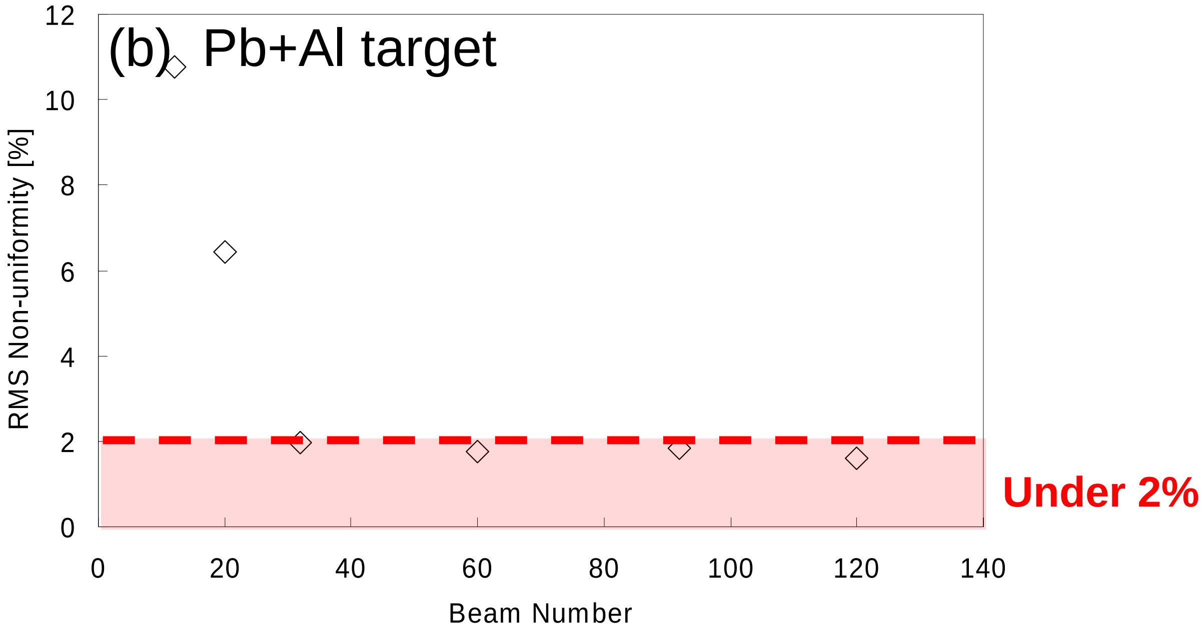
Beam Number Effect





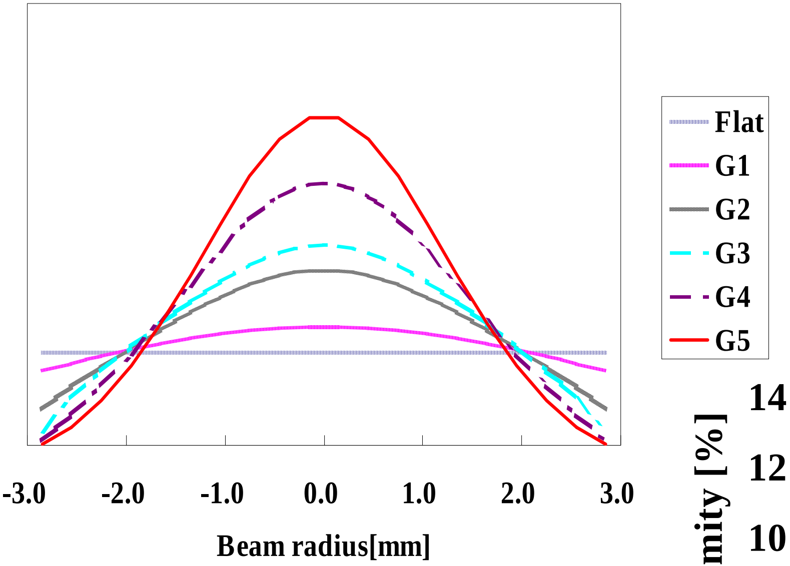
(a) Al target





(b) Pb+Al target

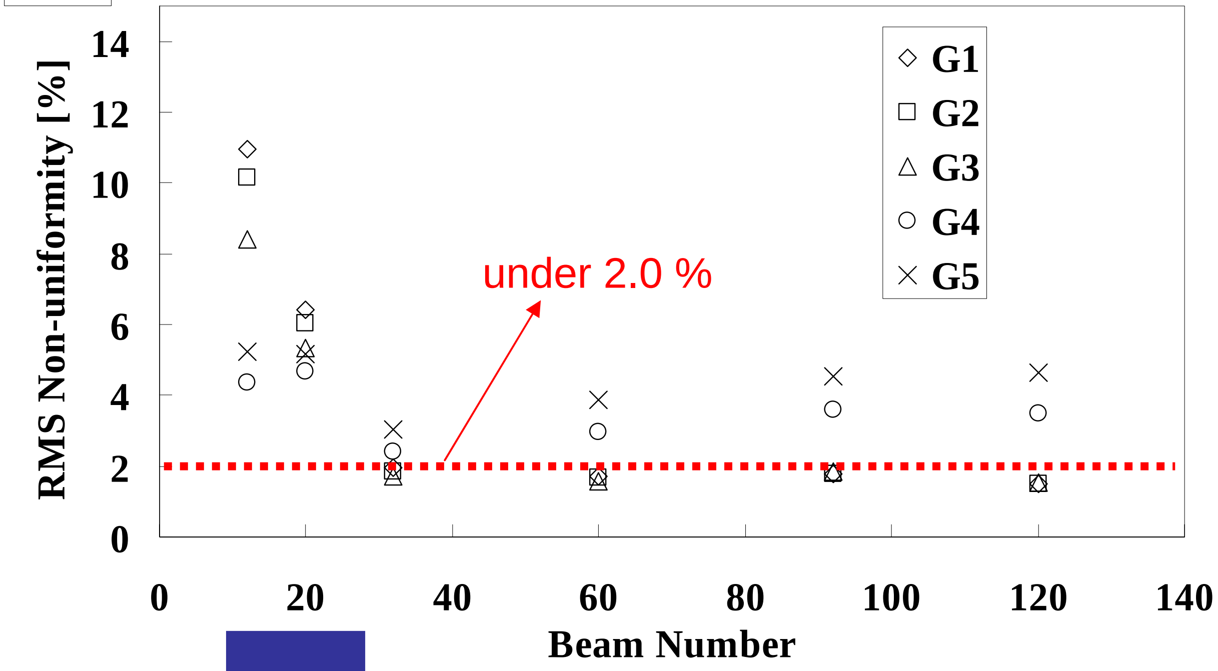
Gauss Distribution Effect



G1: **σ** =1.20R$_b$
G2: **σ** =1.00R$_b$
G3: **σ** =0.80R$_b$
G4: **σ** =0.55R$_b$
G5: **σ** =0.50R$_b$
*R$_b$ is beam radius

The Gauss distribution

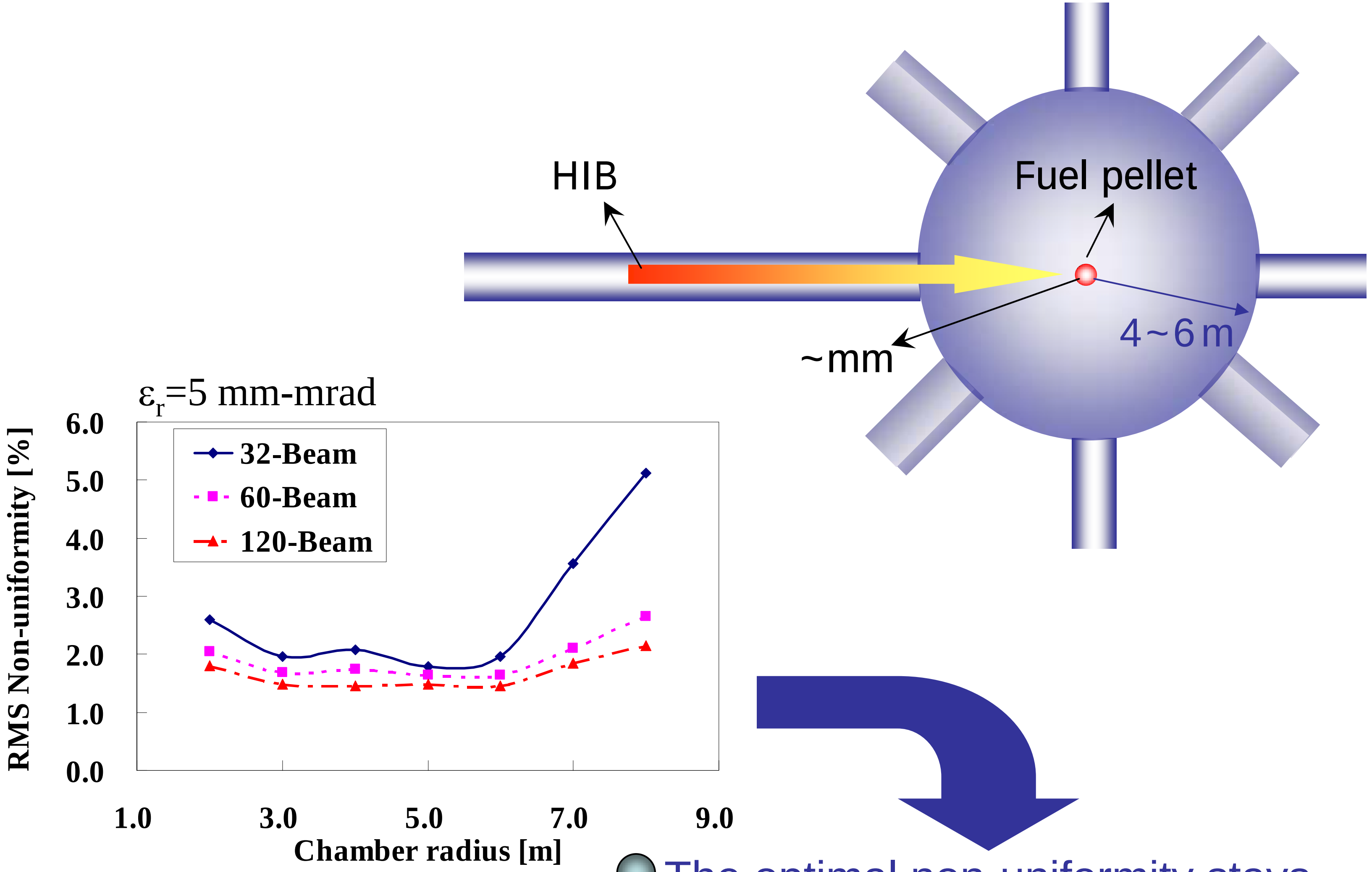
$$n(R_b)=\frac{1}{\sqrt{2\pi\sigma^2}}\exp\left(-\frac{R_b^2}{2\sigma^2}\right)$$



under 2.0 %

● The non-uniformities are suppressed low in the cases of G1 ~ G3 for the lager number of beams (>32)

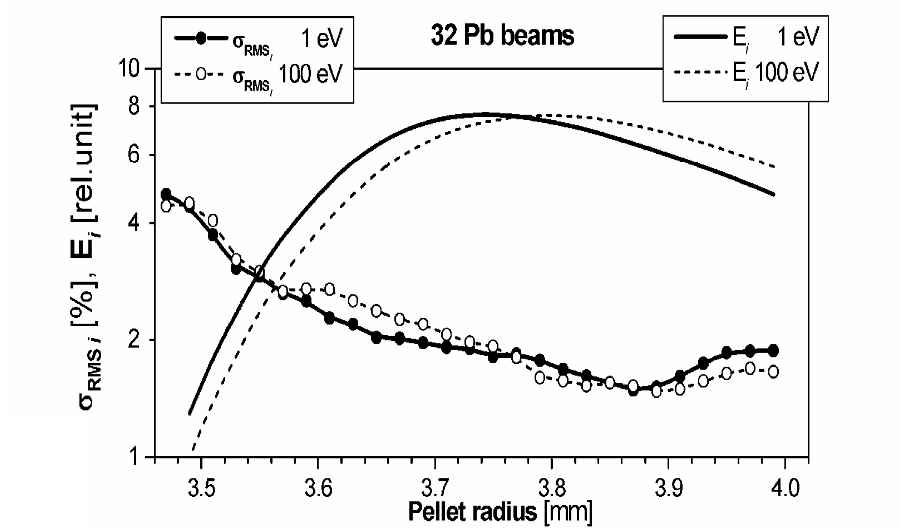
Chamber Effect



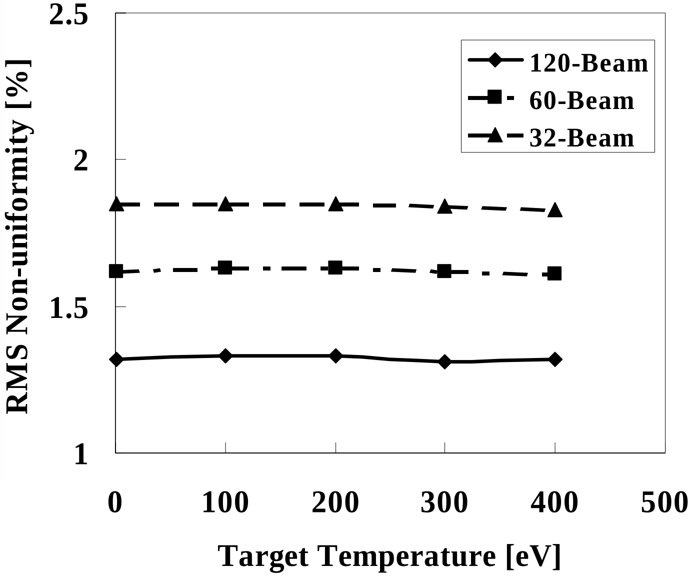
- The optimal non-uniformity stays at around the 3.0 ~ 6.0 m chamber radius in the 32, 60 and 120-beam systems

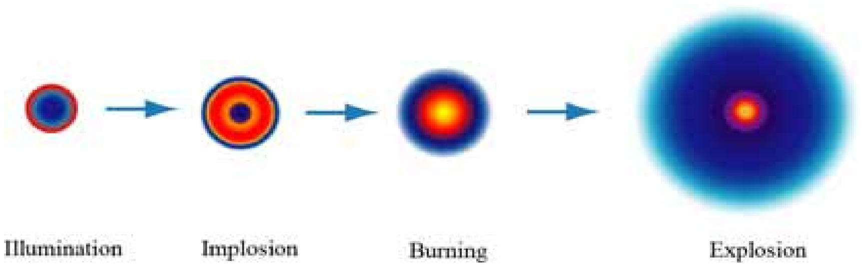
Target Temperature Effect

Changes of stopping range



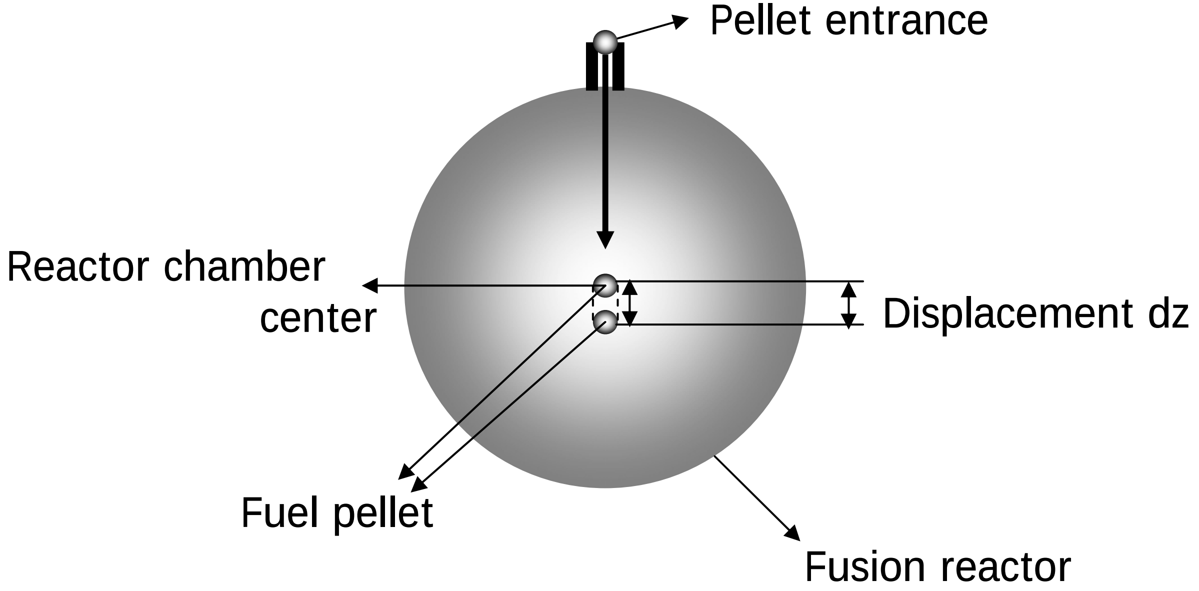
Target temperature v.s. RMS non-uniformity





- HIB illumination non-uniformity is kept low during the HIB pulse duration

Pellet Displacement



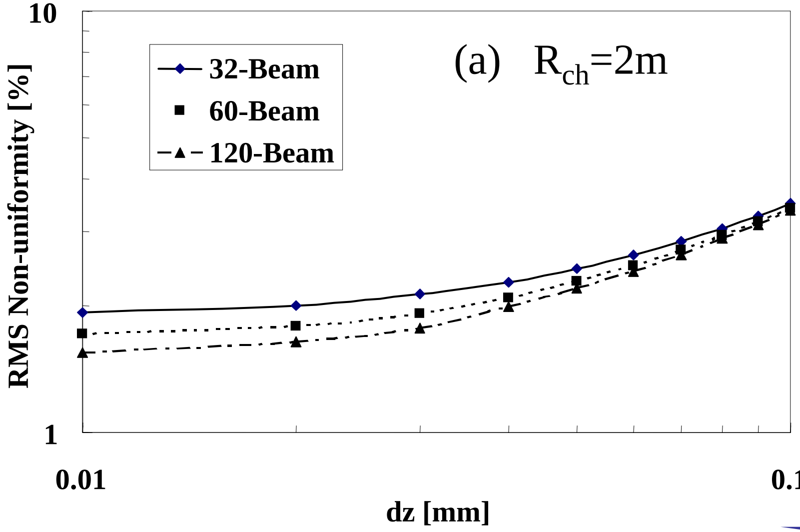
Pellet entrance

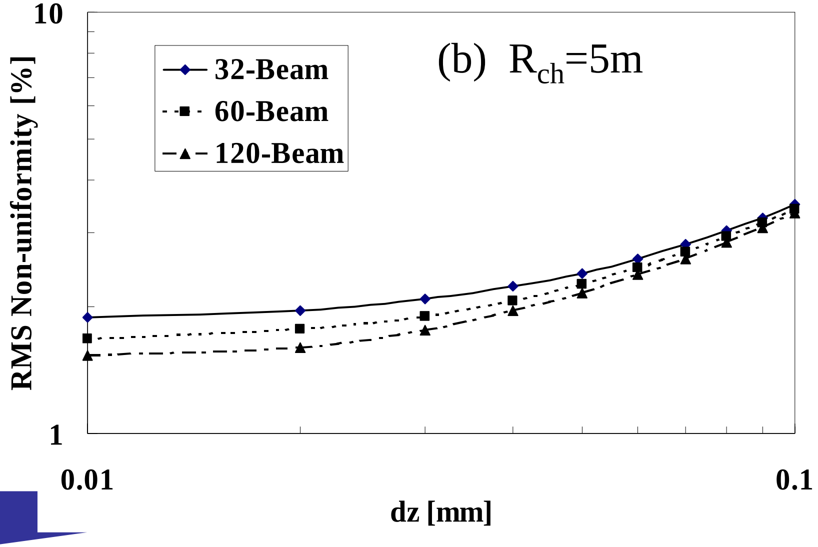
Reactor chamber center

Displacement dz

Fuel pellet

Fusion reactor

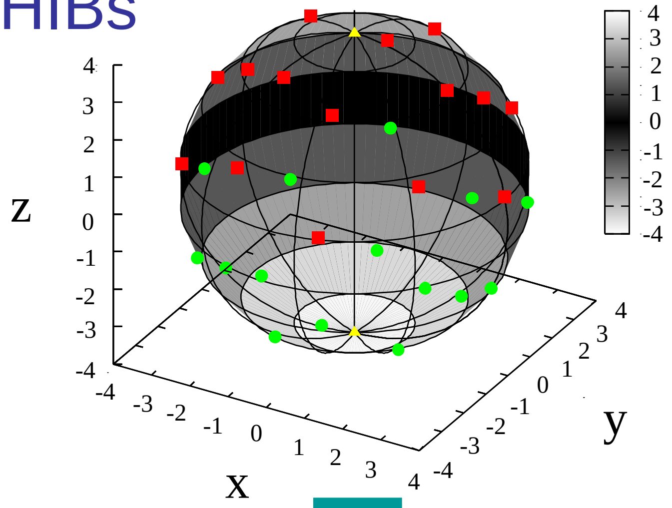




Serious problem

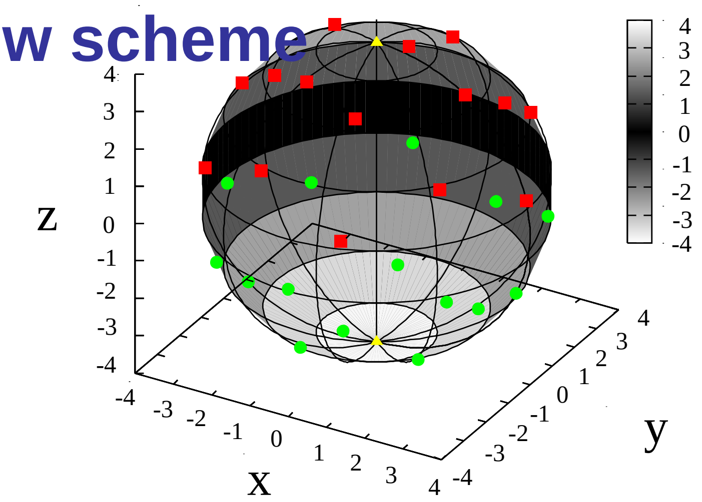
Reduce the Non-uniformity for the Pellet Displacement

32-HIBs

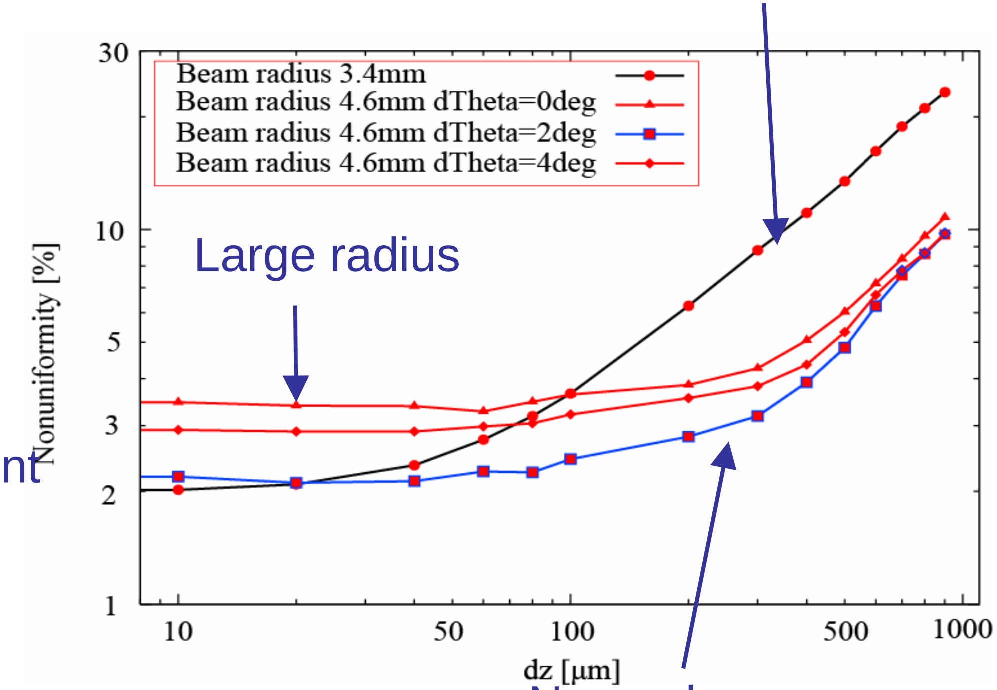


Displace the HIB illumination point for the theta-direction (2 deg.)

New scheme



32-HIBs system

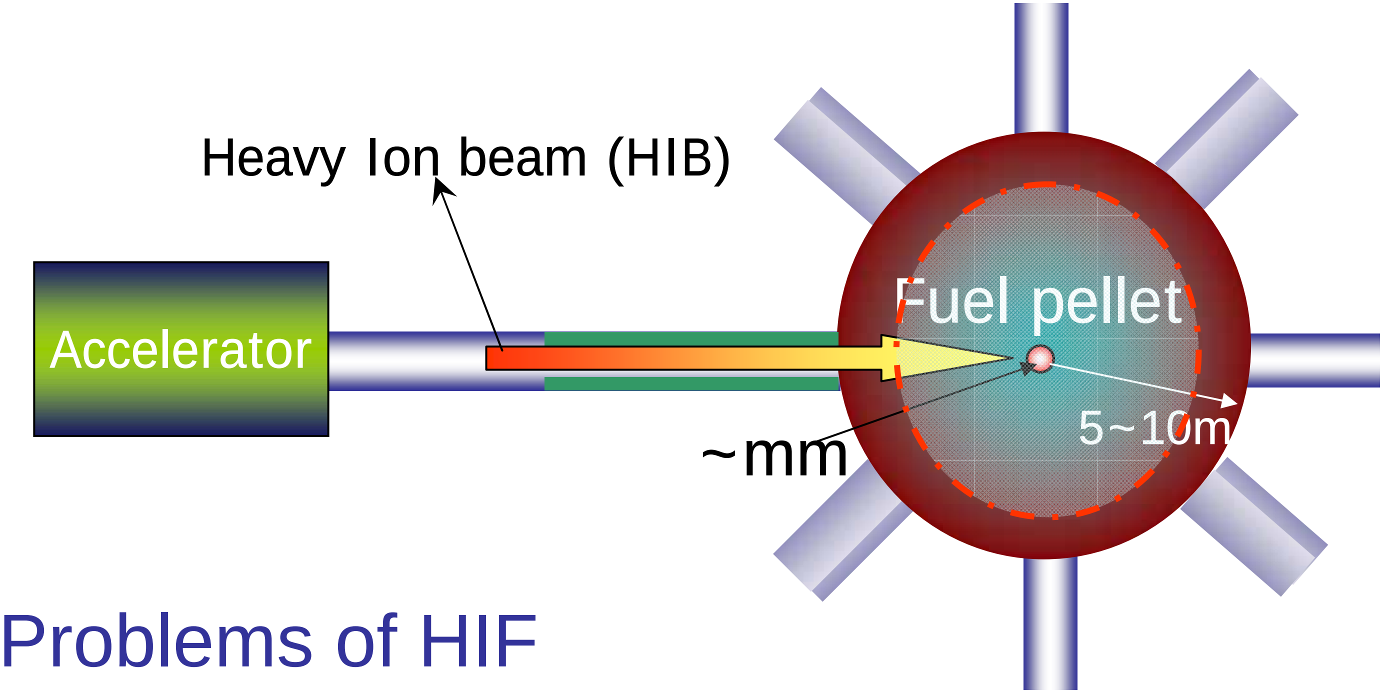


Large radius

New scheme
&
Large radius

Chapter 4. Target Hydrodynamics

Introduction



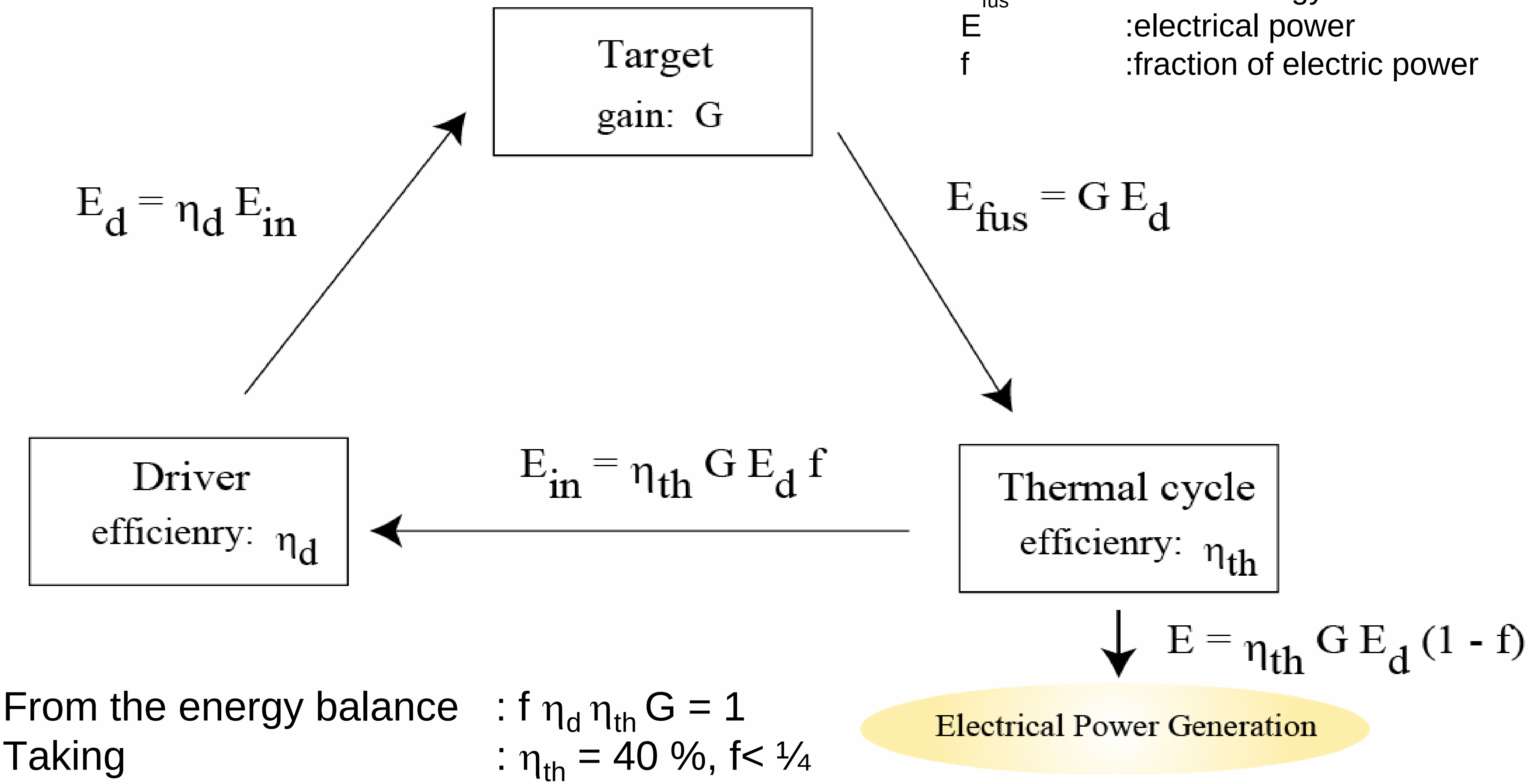
Problems of HIF

- Beam Accelerator (Scale, Cost, etc..)
- Physics of Intense Beam (Bunching, Emittance growth, etc..)
- Beam Final Transport (Stable transportation, Interaction with gas, etc..)
- Beam-Target Interaction
- Analysis of Target-Plasma Hydrodynamics

etc..

Required gain

E_d : driver energy
E_{in} :energize driver
E_{fus} :fusion energy
E :electrical power
f :fraction of electric power



Target

gain: G

$E_d = \eta_d E_{in}$

$E_{fus} = G E_d$

Driver

efficienry: η_d

$E_{in} = \eta_{th} G E_d f$

Thermal cycle

efficienry: η_{th}

$E = \eta_{th} G E_d (1 - f)$

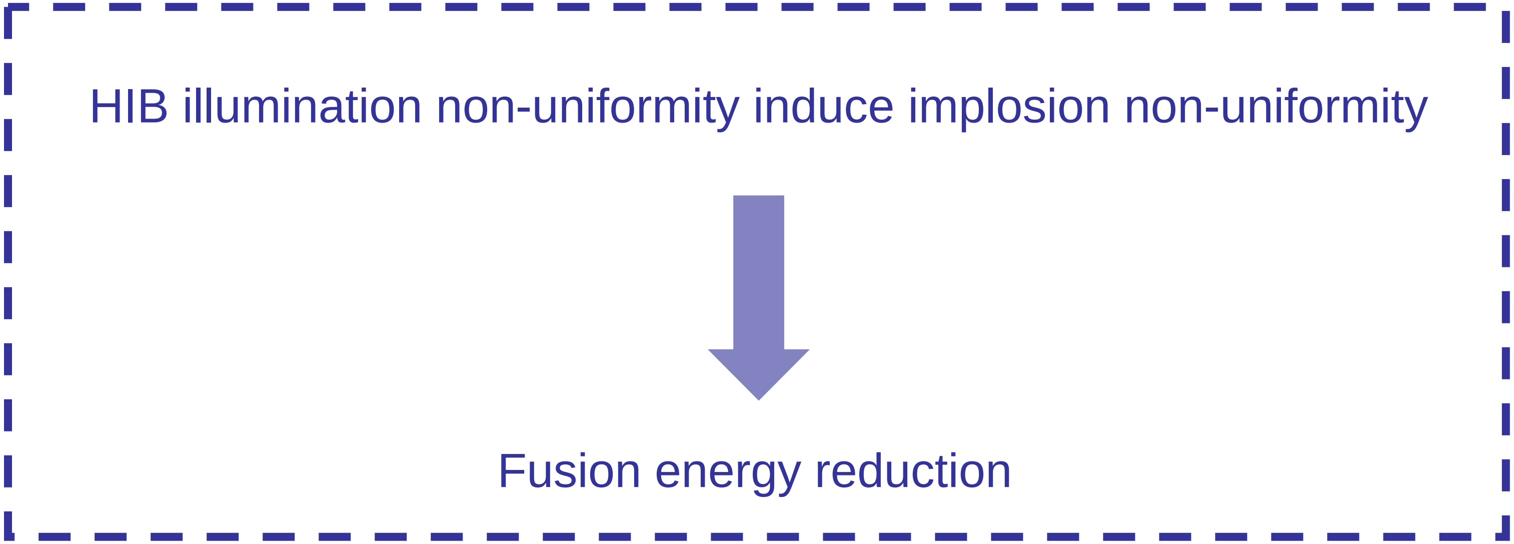
Electrical Power Generation

- From the energy balance : $f \eta_d \eta_{th} G = 1$
- Taking : η_{th} = 40 %, $f< 1/4$

  → $\eta_d G > 10$
- Suppose: η_d = 10 ~33 %

→ Rquirement gain G > 30 ~ 100 → **G > 30 for HIB driver**

Purposes



HIB illumination non-uniformity induce implosion non-uniformity

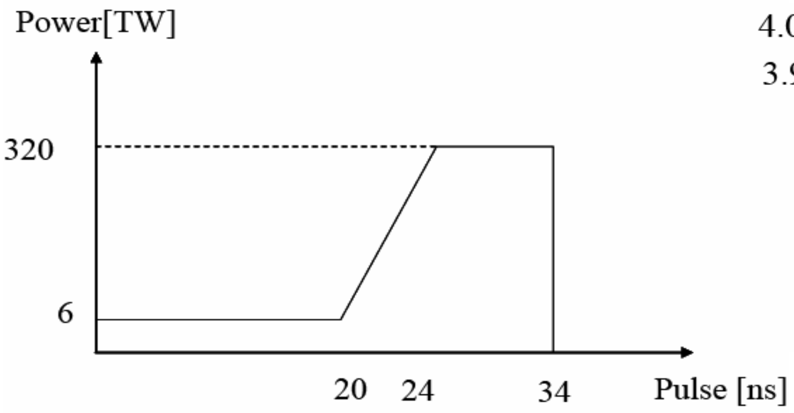
Fusion energy reduction

- Find the target structure and HIB parameters to suppress the implosion non-uniformity and achieve required gain
- Investigate radiation transport effect on the implosion non-uniformity
- Find robust parameters over a large pellet displacement

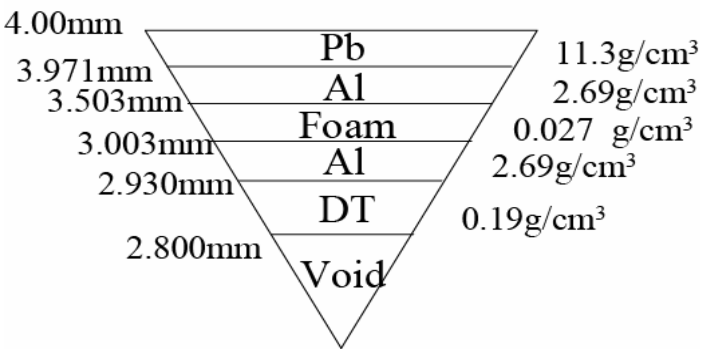
Foam and radiation transport effect

Initial condition

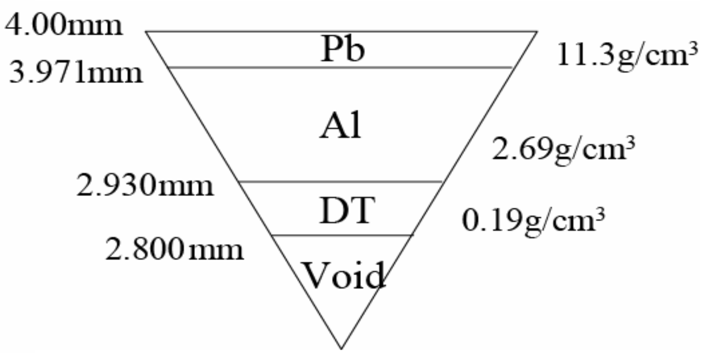
- target
  - With foam (0.5 mm thickness)
  - Without foam
- pulse
- Radiation transport
  - ON
  - OFF
- 32-HIBs illumination



0.5 mm foam



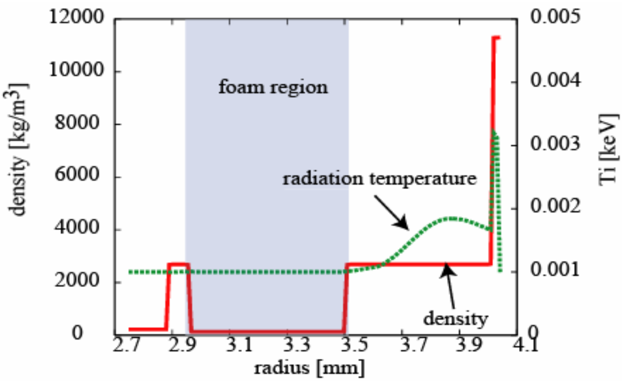
Without foam



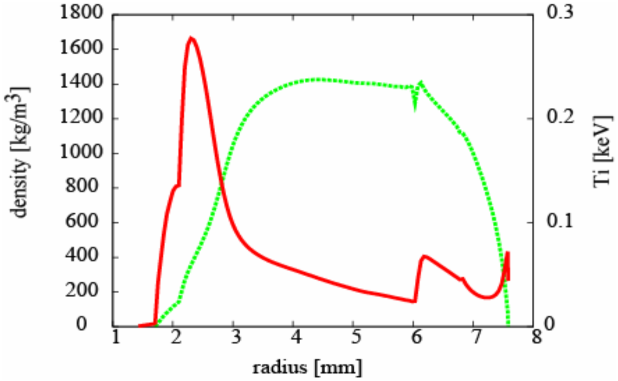
Mean profile of radiation temperature and density

0.5mm foam

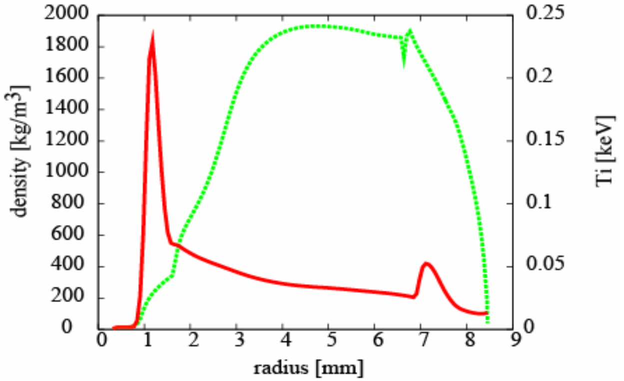
t=0.29ns



t=40.4ns

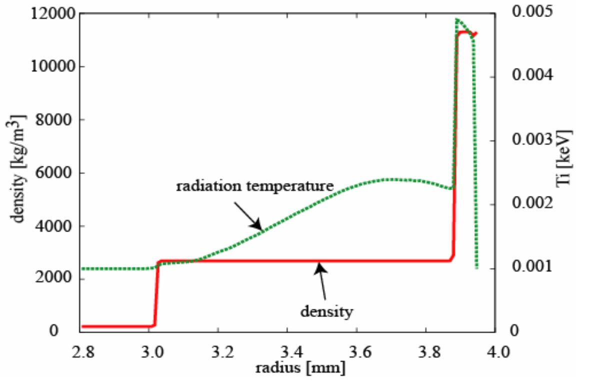


t=44.6ns

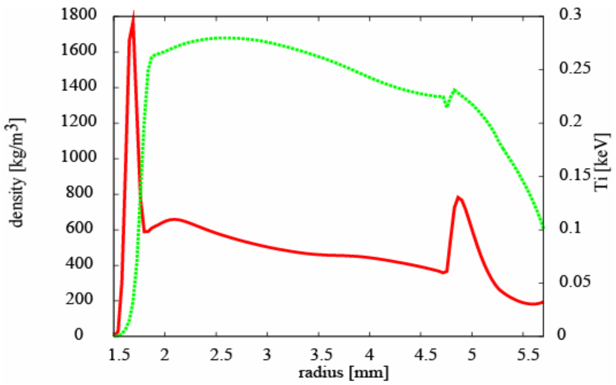


w/o foam

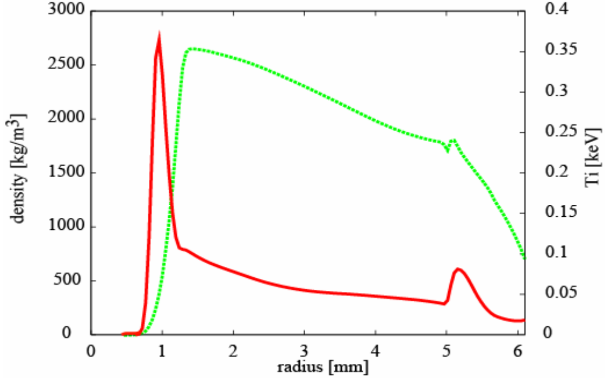
t=0.37ns



t=34.9ns

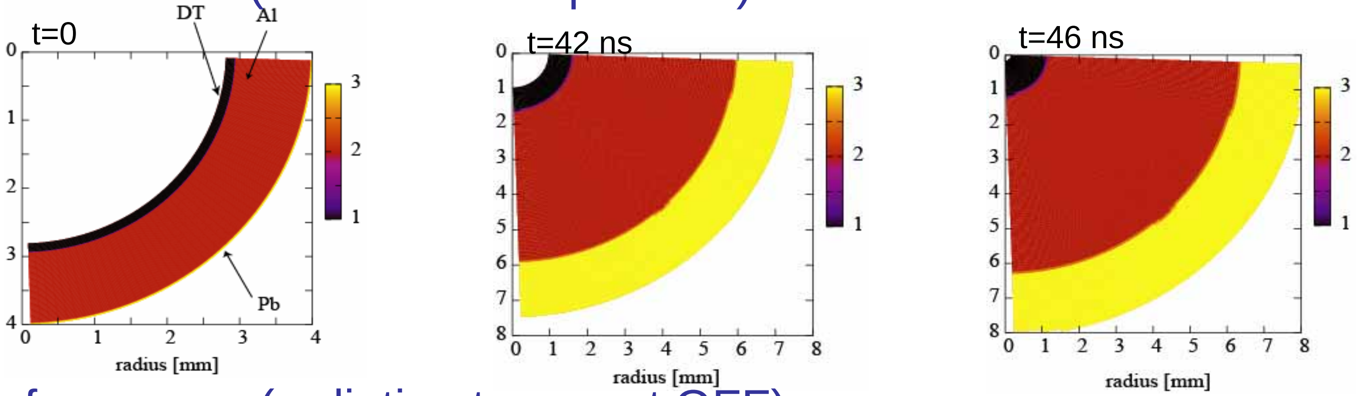


t=36.2ns

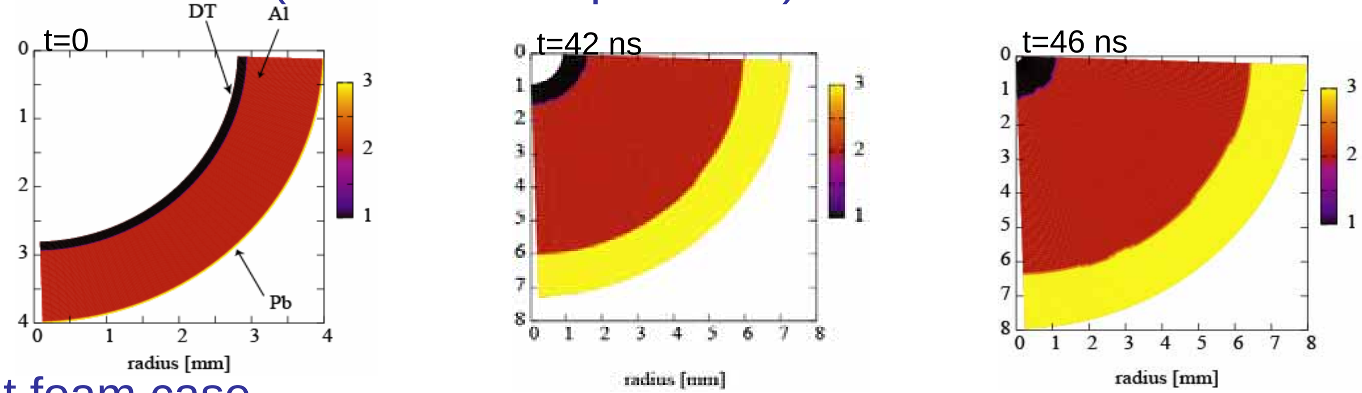


Profile of target materials

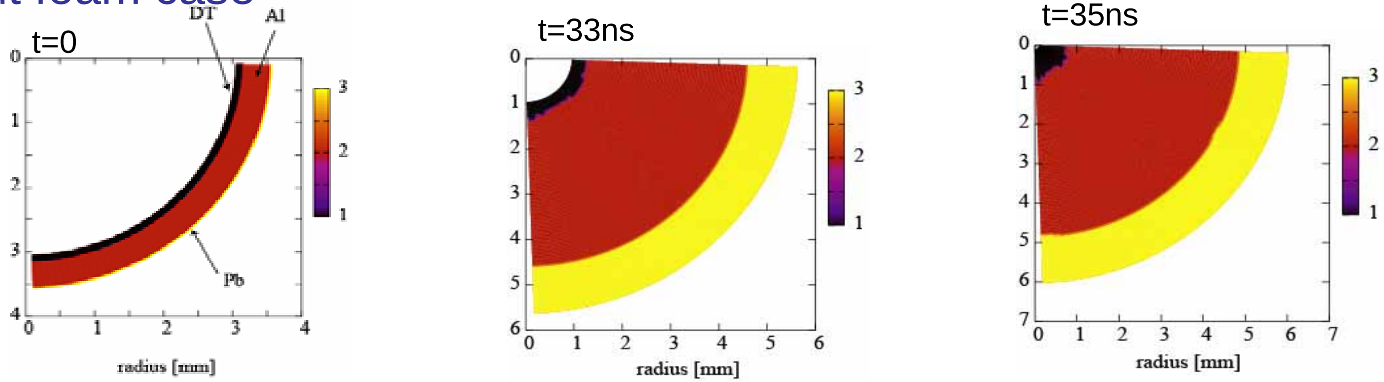
- 0.5 mm foam case (radiation transport ON)



- 0.5 mm foam case (radiation transport OFF)

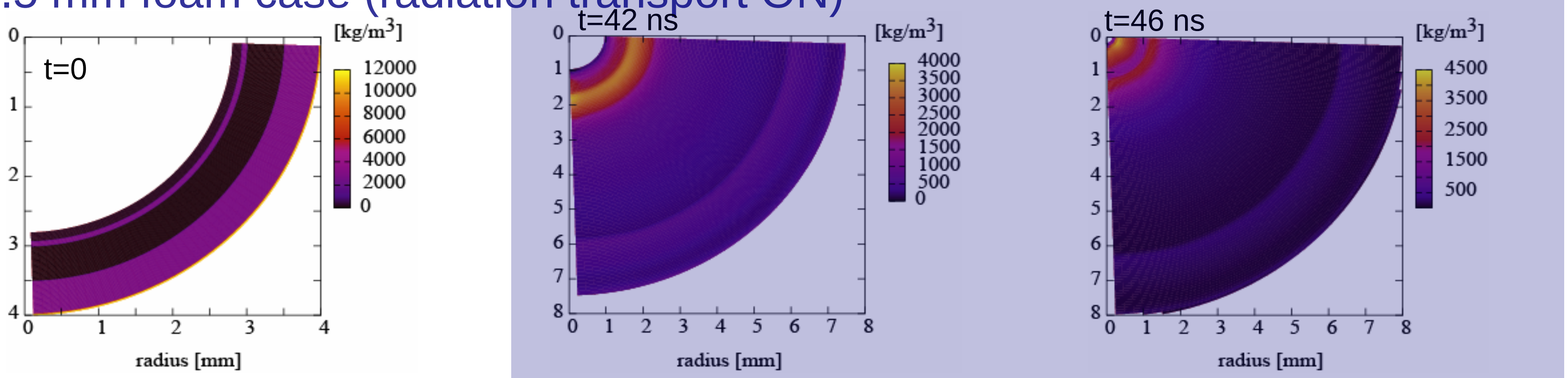


- without foam case

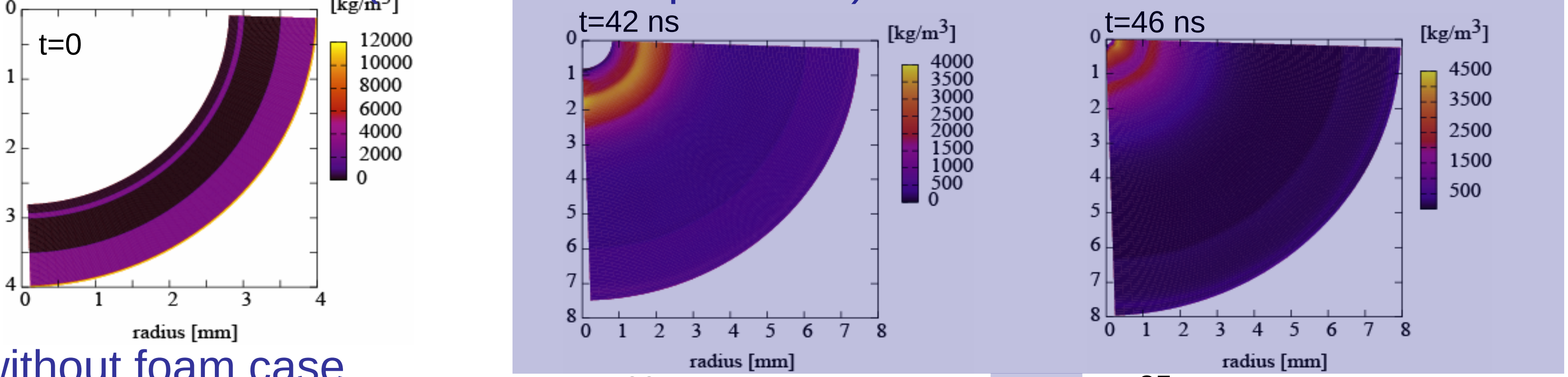


Profile of target density

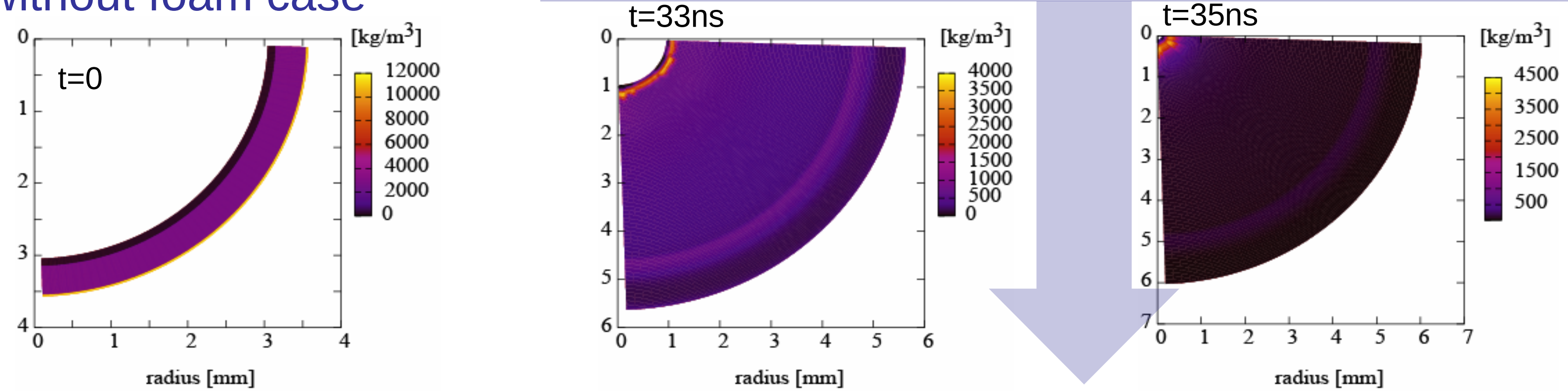
- 0.5 mm foam case (radiation transport ON)



- 0.5 mm foam case (radiation transport OFF)

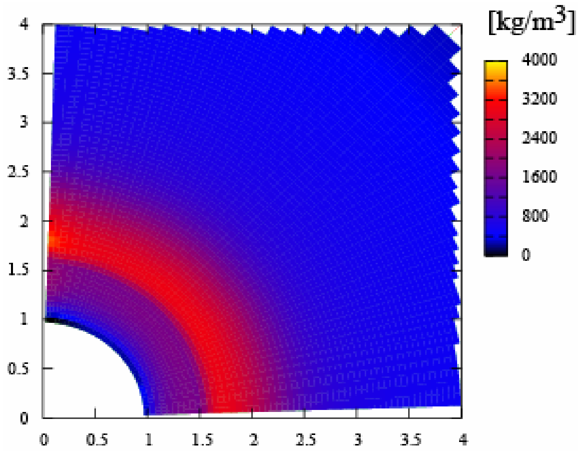


- without foam case

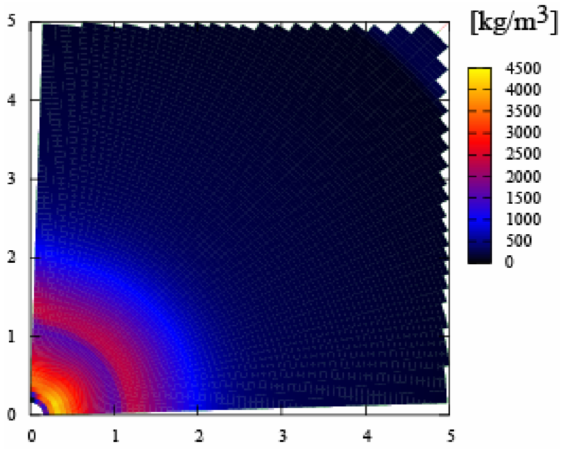


Focused profile of target density (rad. tra. ON & OFF)

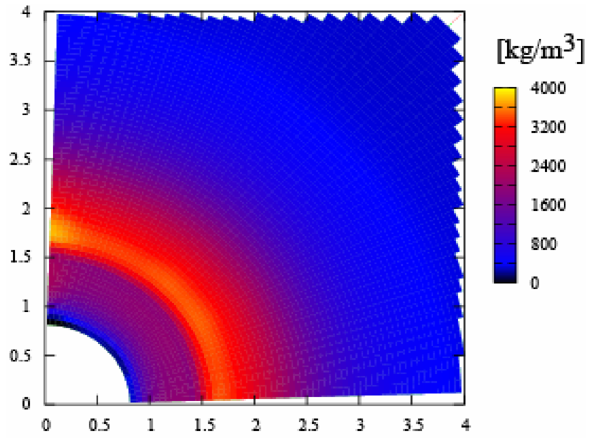
t=42ns rad. tra. ON



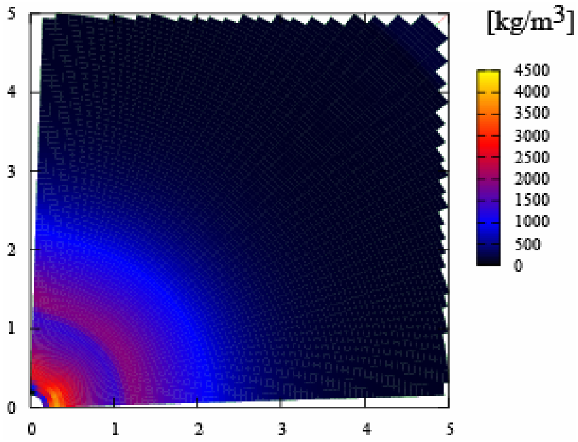
t=46ns ON



t=42ns rad. tra. OFF

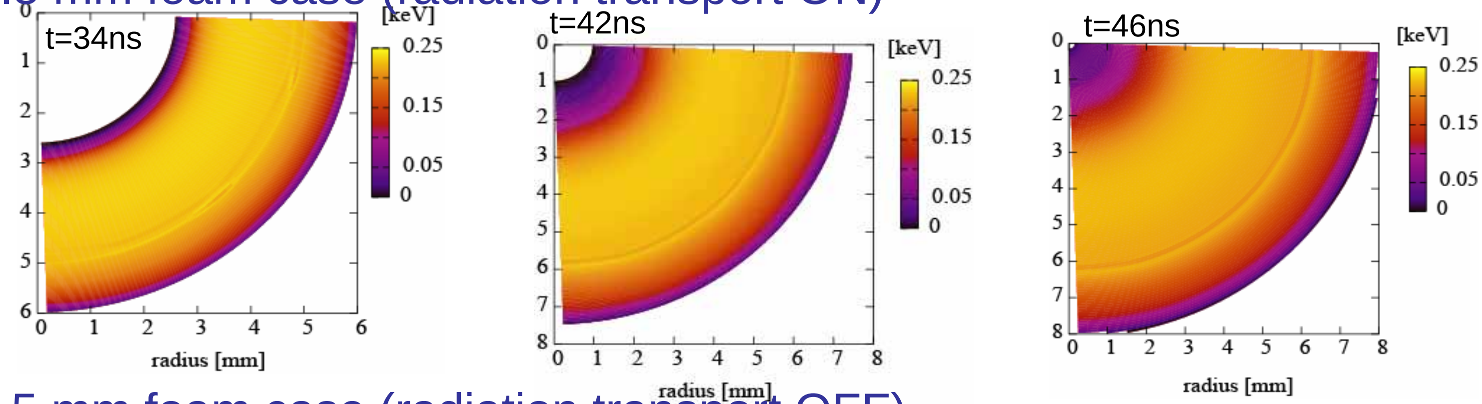


t=46ns rad. OFF

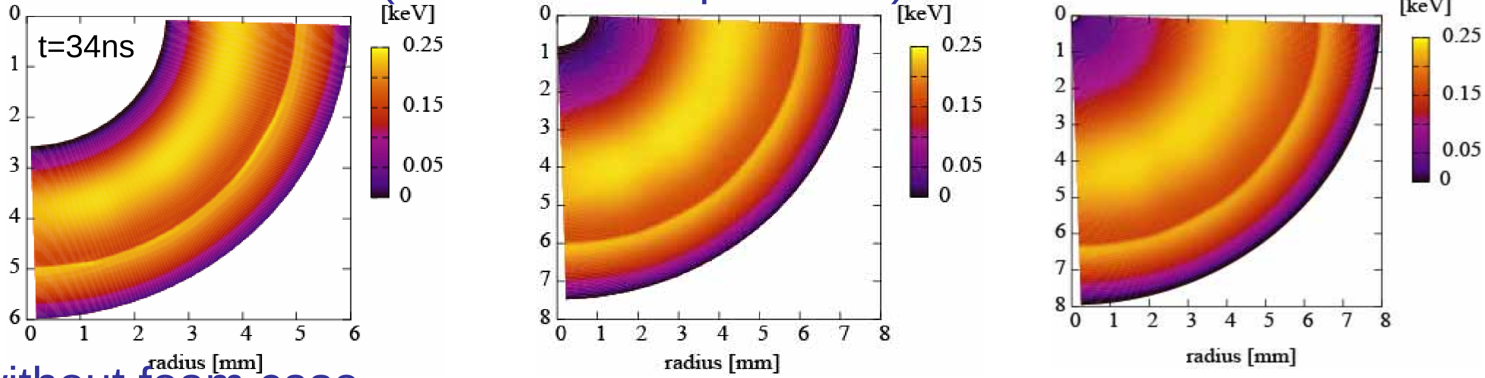


Profile of target ion temperature

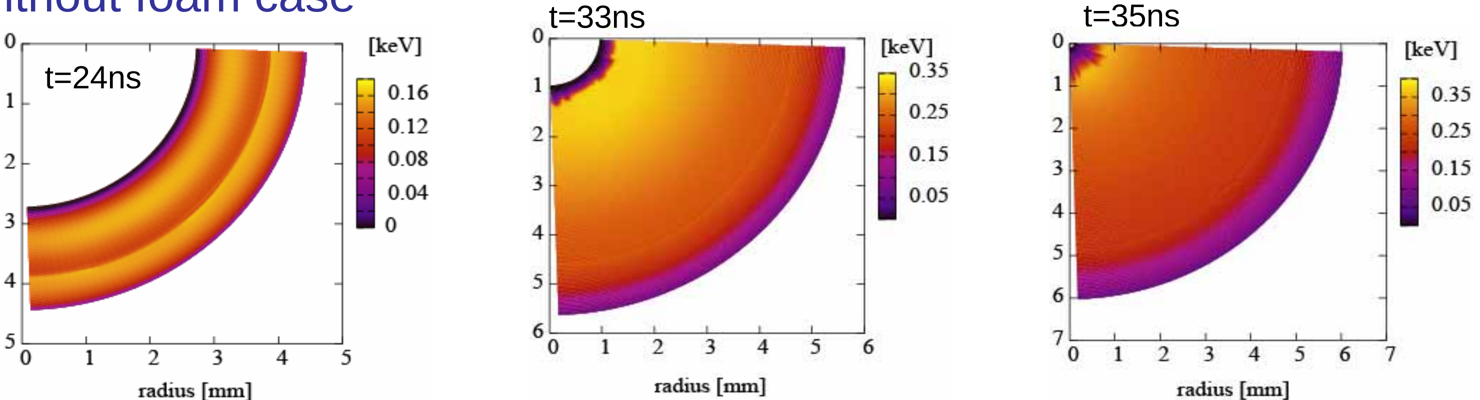
- 0.5 mm foam case (radiation transport ON)



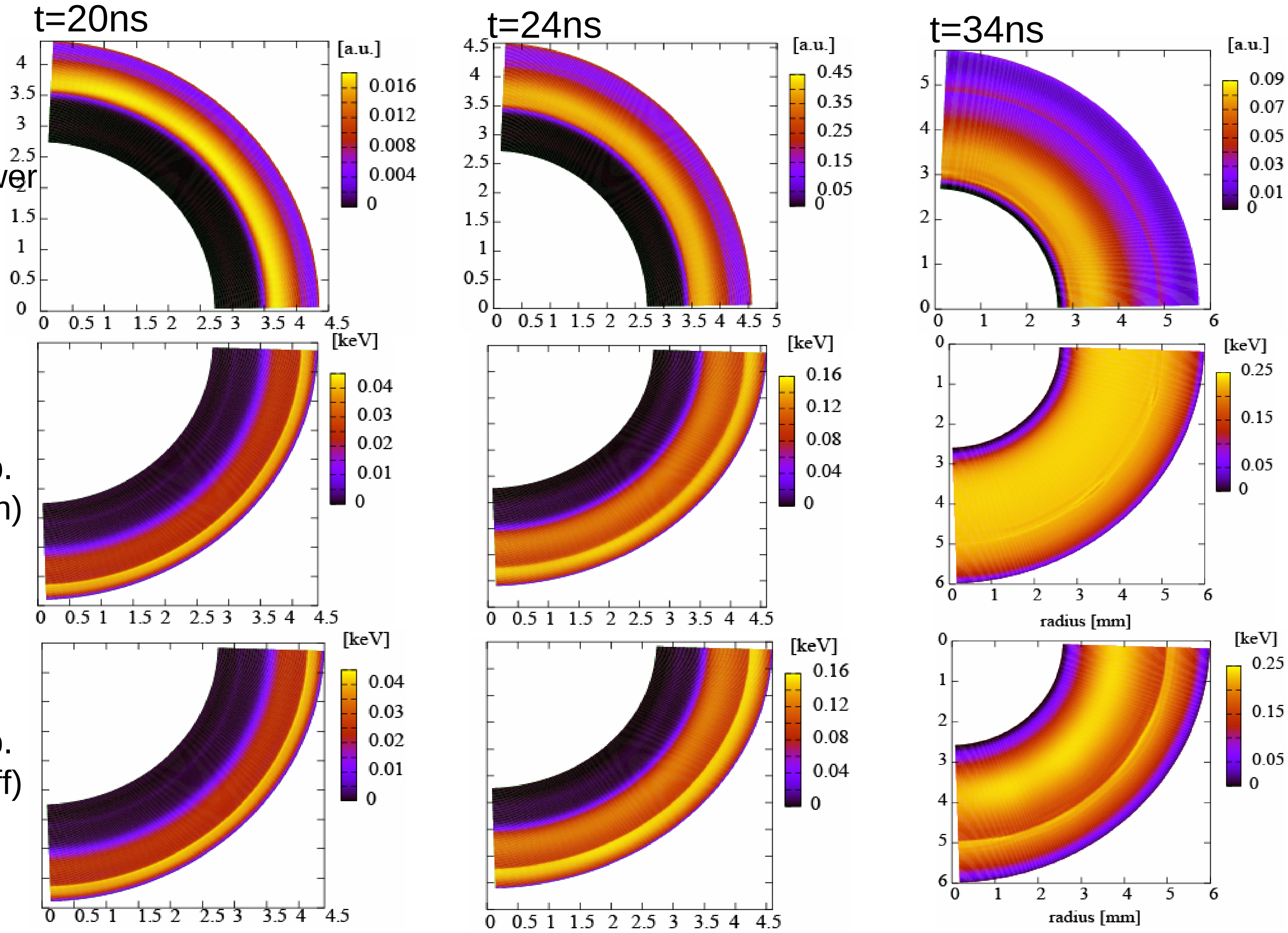
- 0.5 mm foam case (radiation transport OFF)



- without foam case



Deposition energy and target temperature



t=20ns

t=24ns

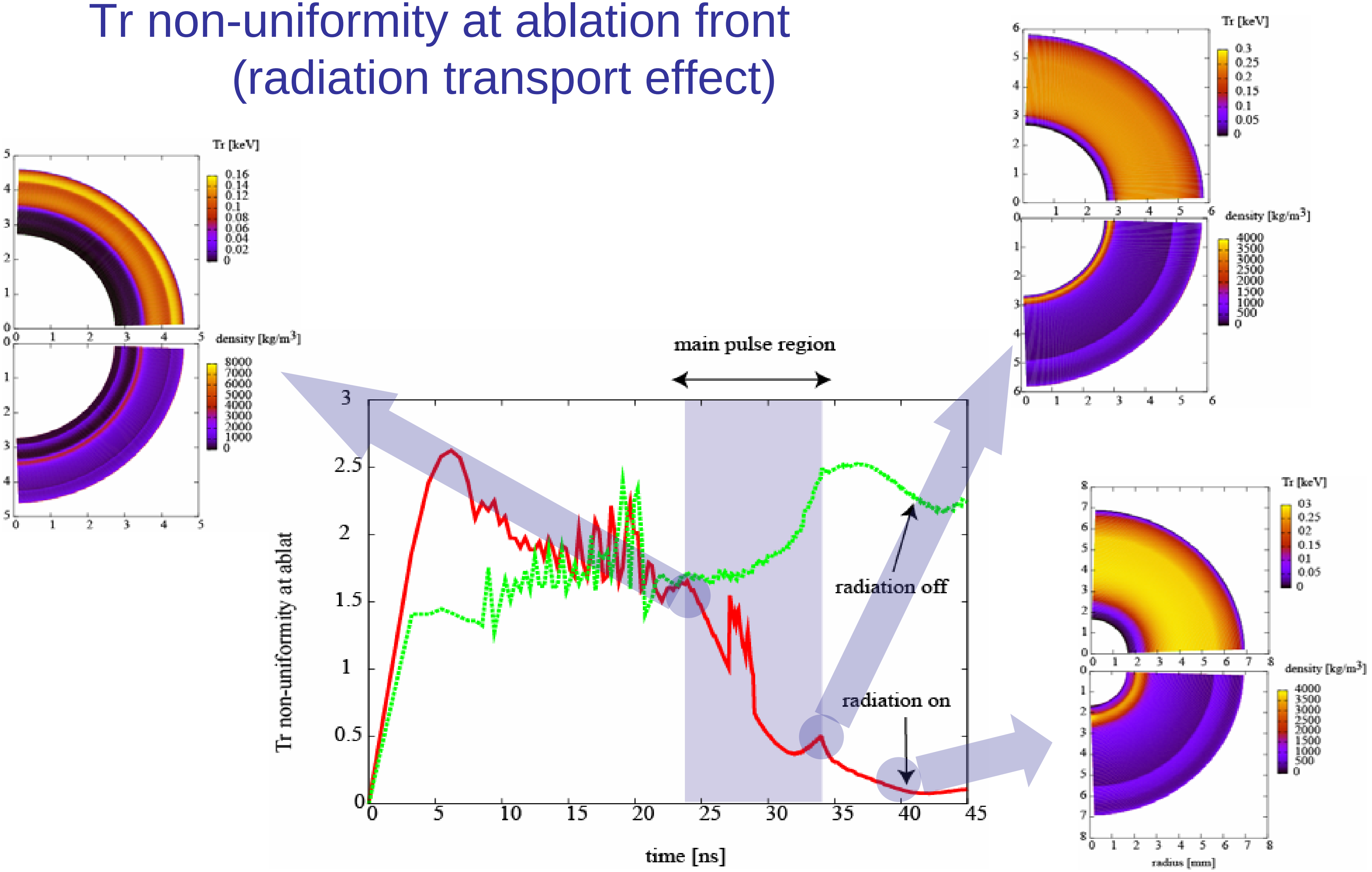
t=34ns

Stopping power

Target temp.
(Radiation on)

Target temp.
(Radiation off)

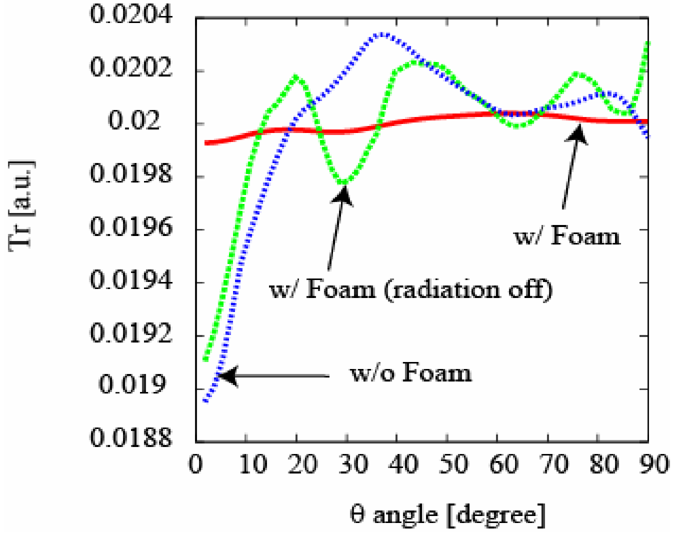
Tr non-uniformity at ablation front (radiation transport effect)



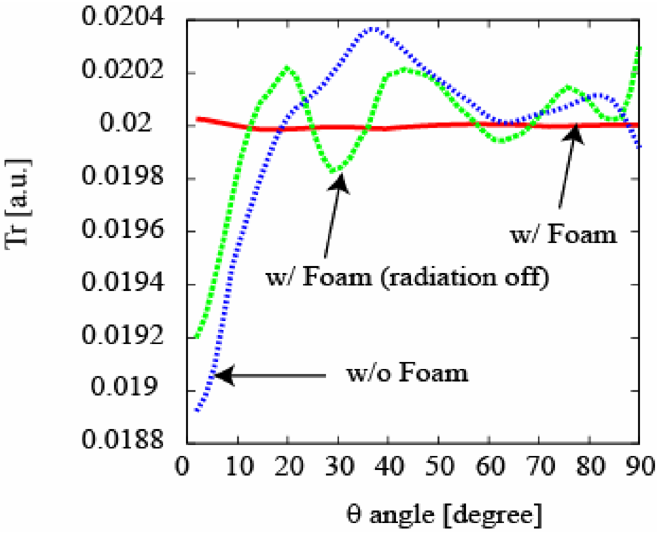
- non-uniformity is suppressed effectively at the main pulse region by the radiation transport effect

Non-uniformity at ablation front

t=34 ns



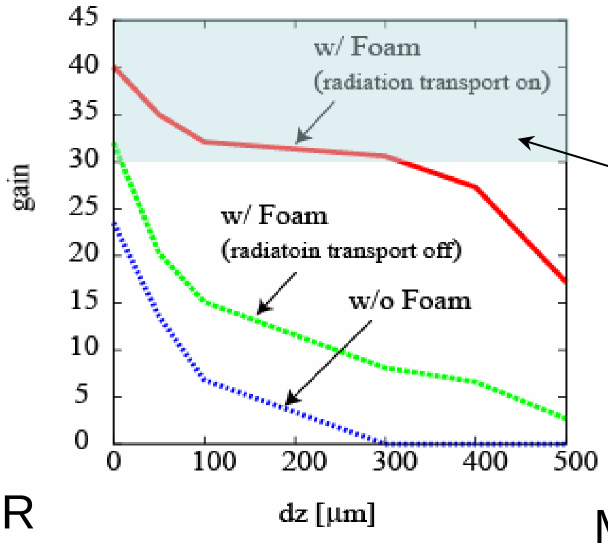
t = 42 ns



- non-uniformity is smoothed by the radiation transport effect

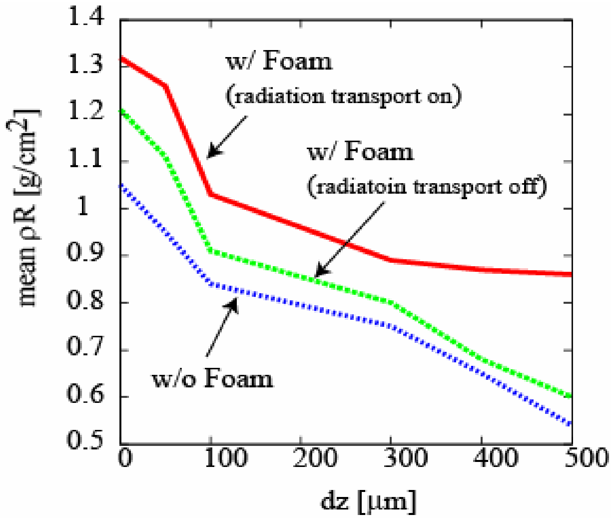
Radiation transport effect on pellet displacement

Gain curve

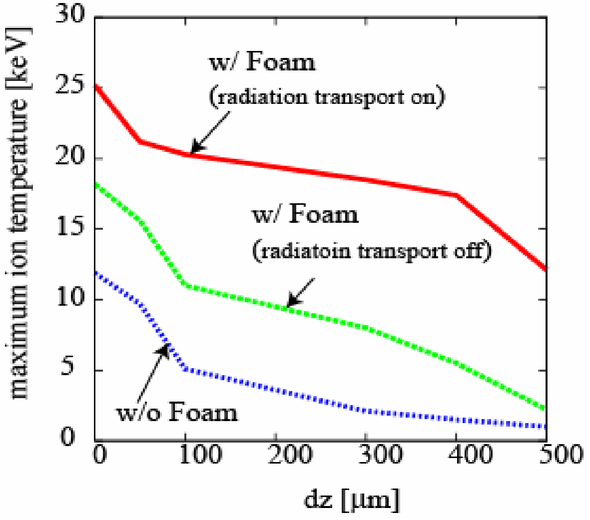


Requirement gain region

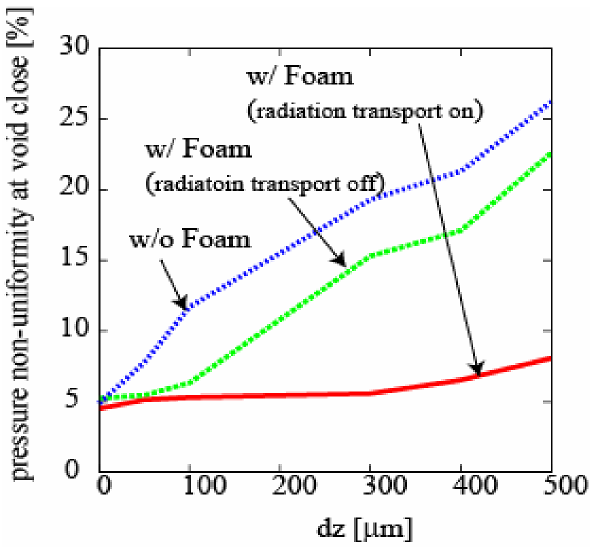
Mean ρR

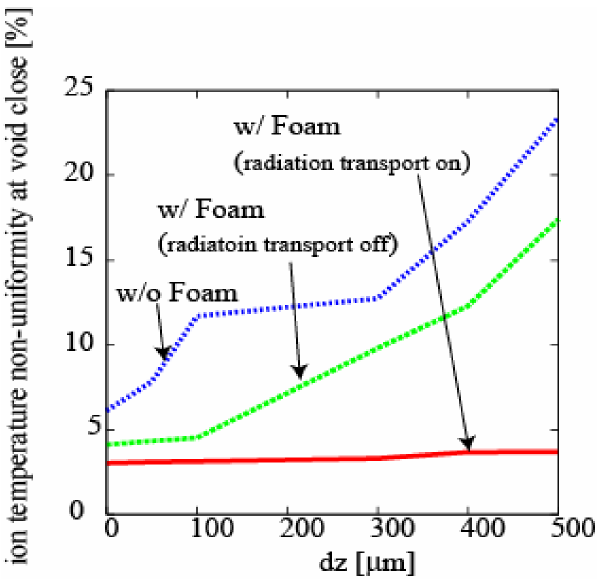


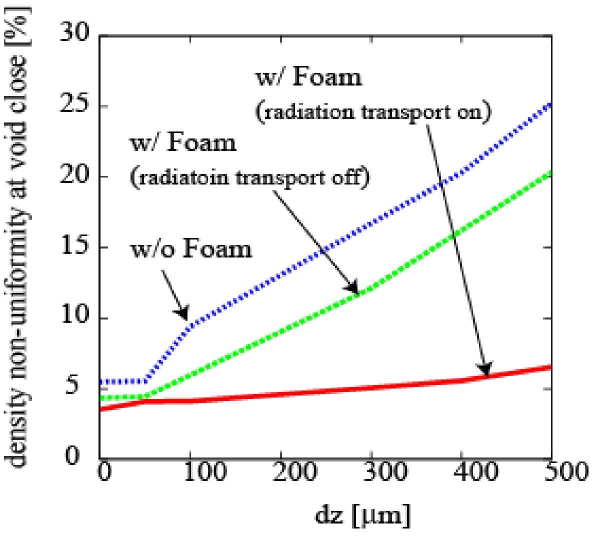
Maximum ion temperature

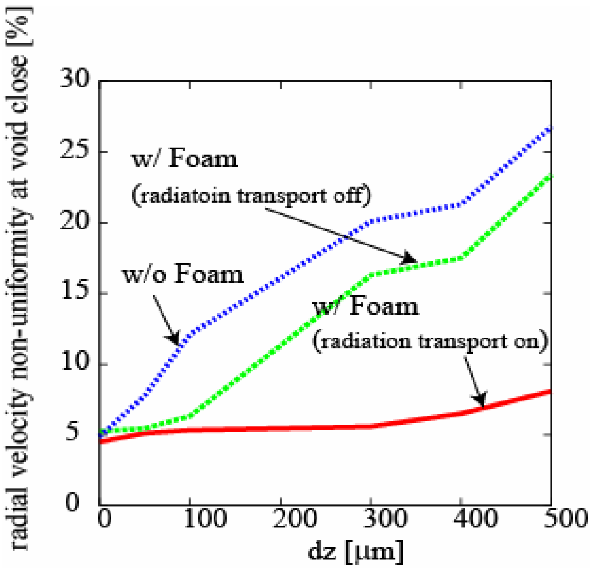


Non-uniformity at void close

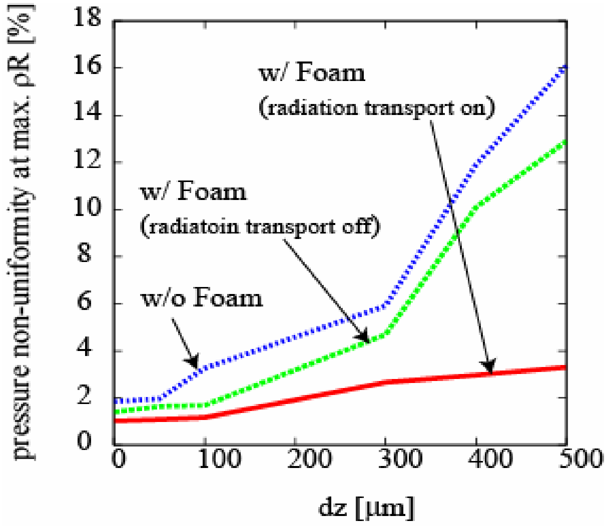


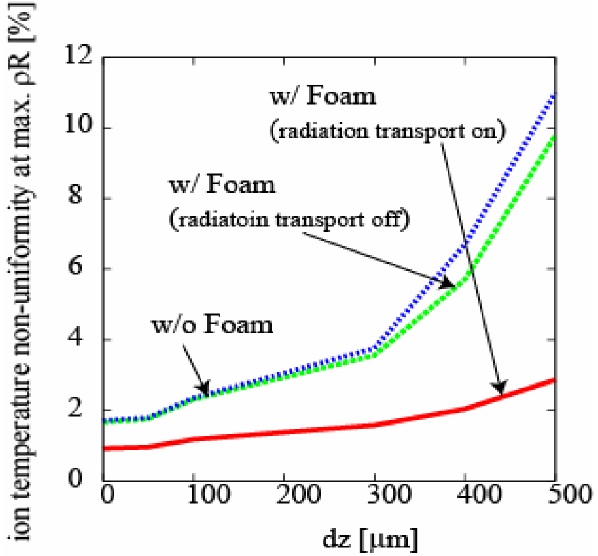


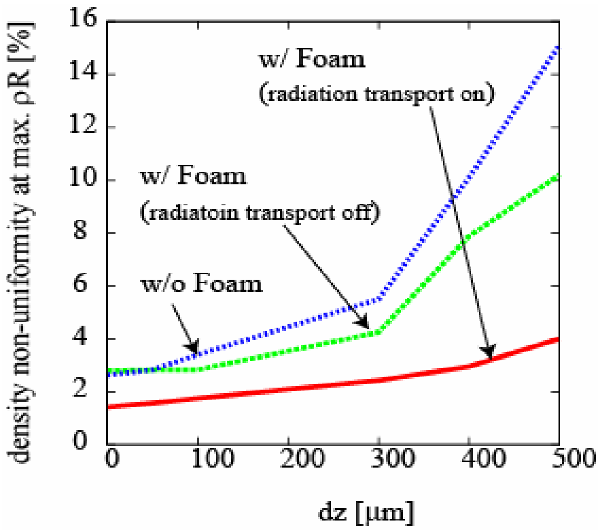


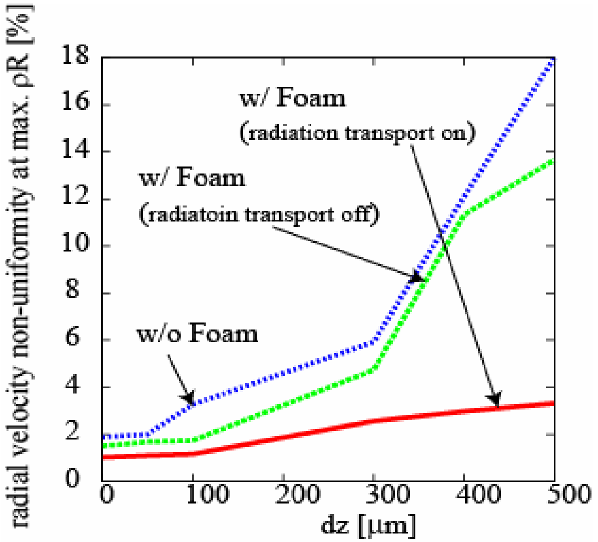


Non-uniformity at max ρR





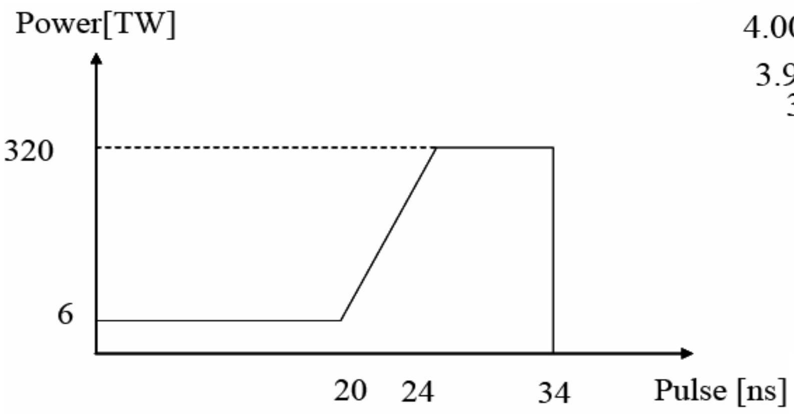




Foam thickness effect

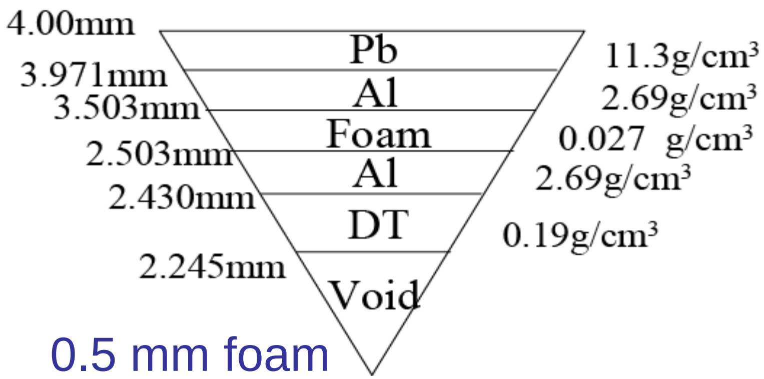
Initial condition

- target
  - 1.0 mm thickness foam
  - 0.5 mm thickness foam
- pulse

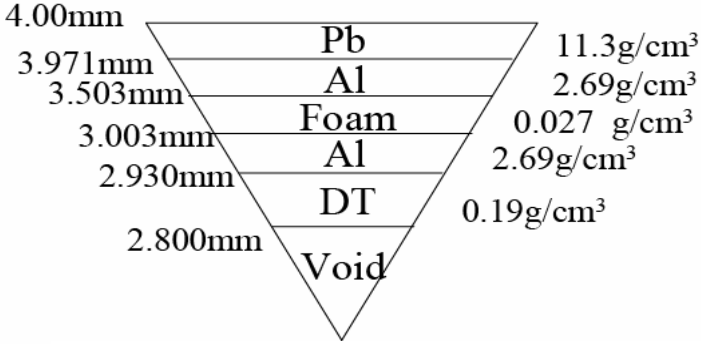


- Radiation transport
  - ON
- 32-HIBs illumination

1.0 mm foam



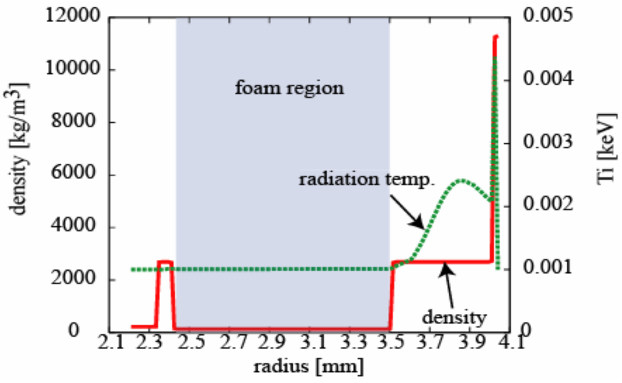
0.5 mm foam



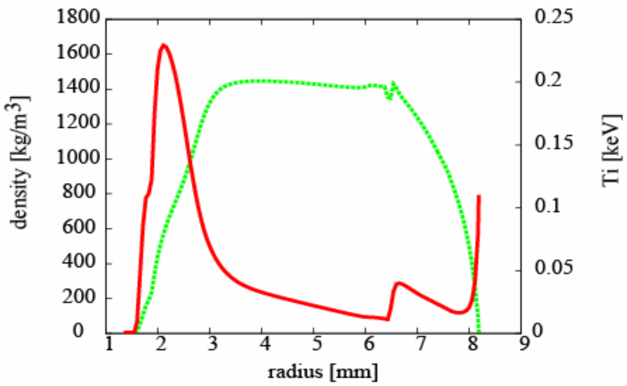
Mean profile of radiation temperature and density

1.0mm foam

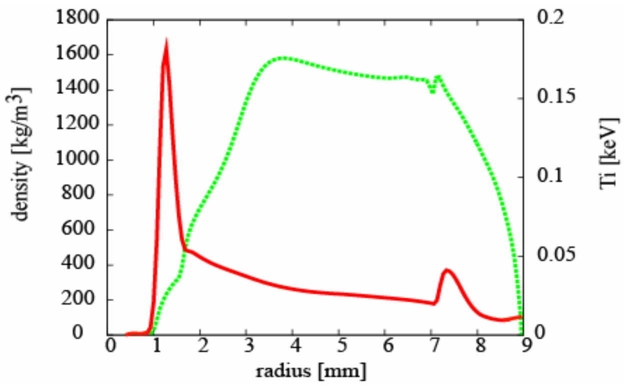
t=0.50ns



t=43.57ns

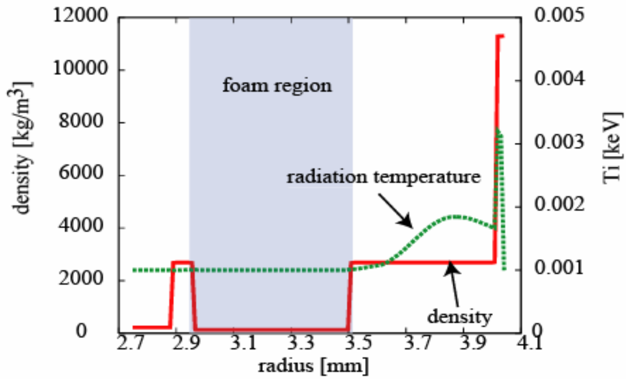


t=47.27ns

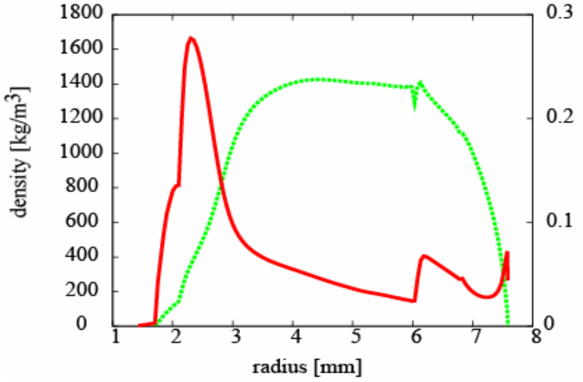


0.5mm foam

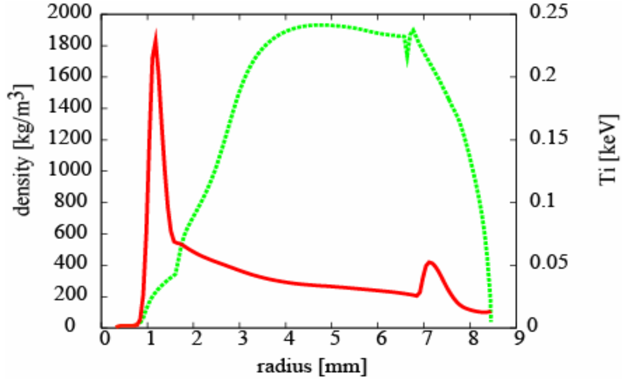
t=0.29ns



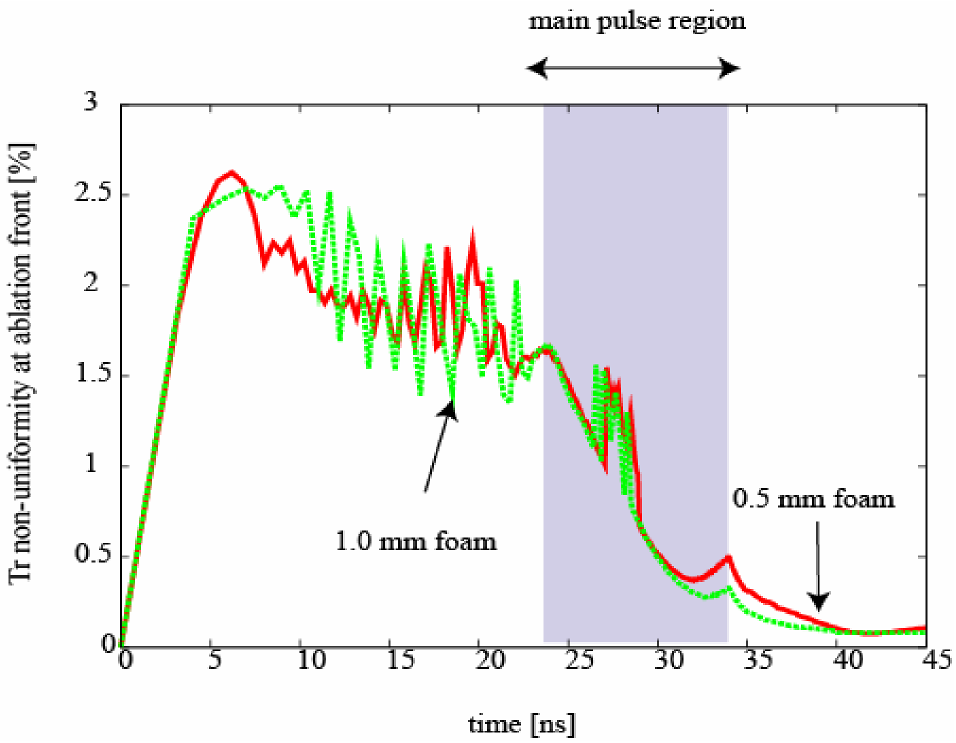
t=40.4ns



t=44.6ns



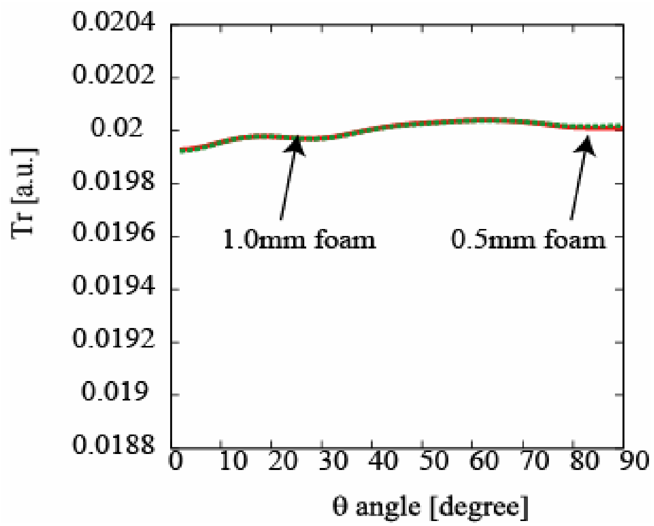
Tr non-uniformity at ablation front



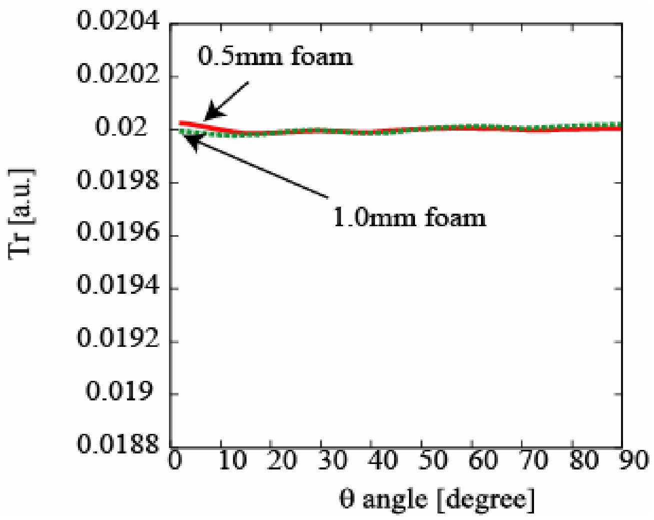
- non-uniformity in the case of 1mm foam thickness is also suppressed

Non-uniformity at ablation front

t=34 ns

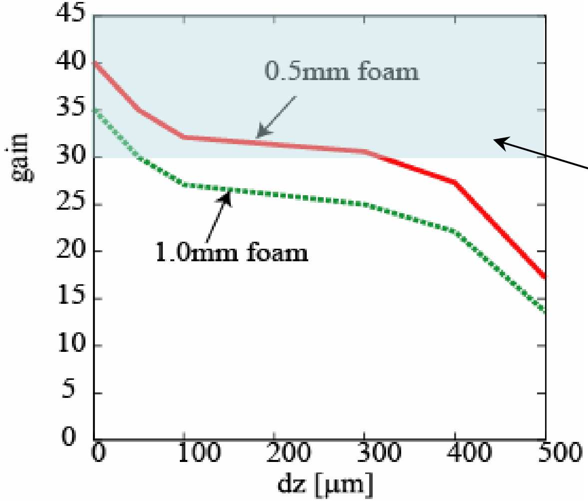


t=42 ns



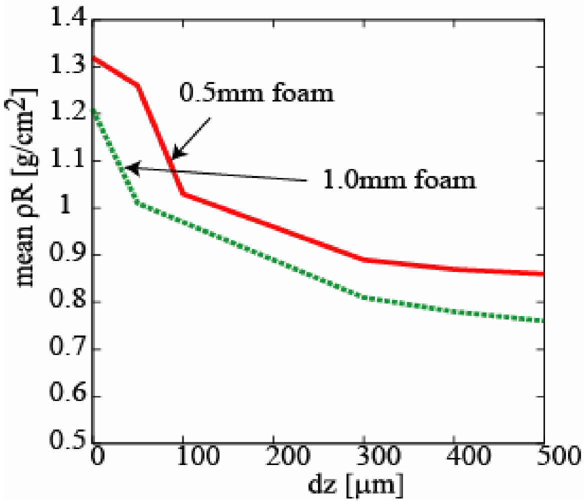
Foam thickness effect on pellet displacement

Gain curve

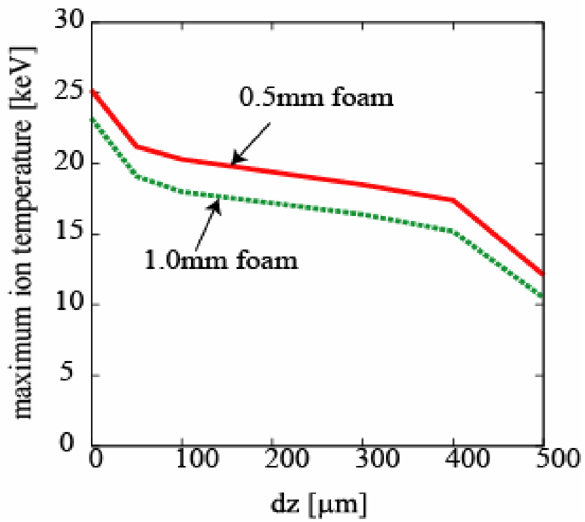


Requirement gain region

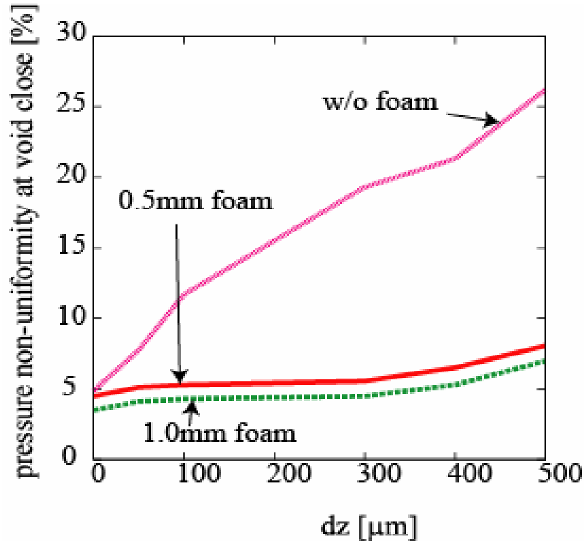
Mean ρR

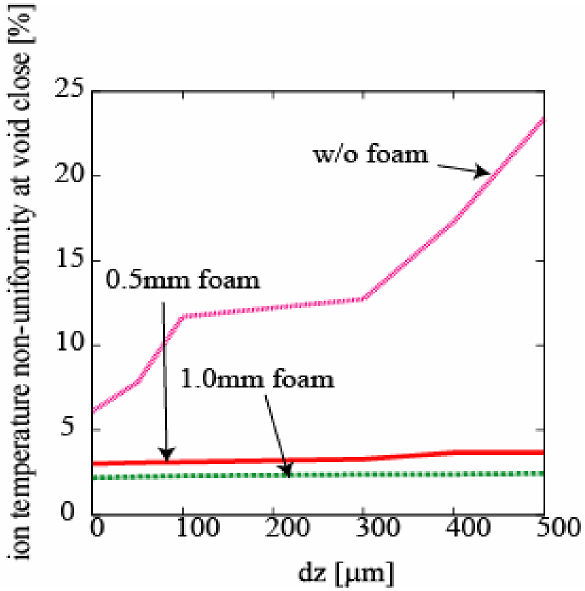


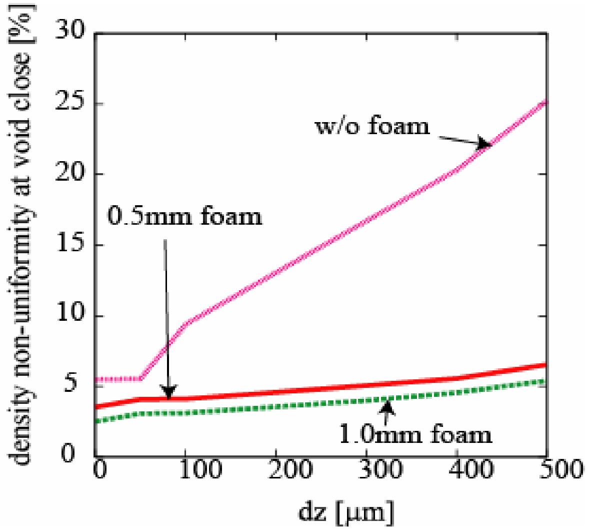
Maximum ion temperature

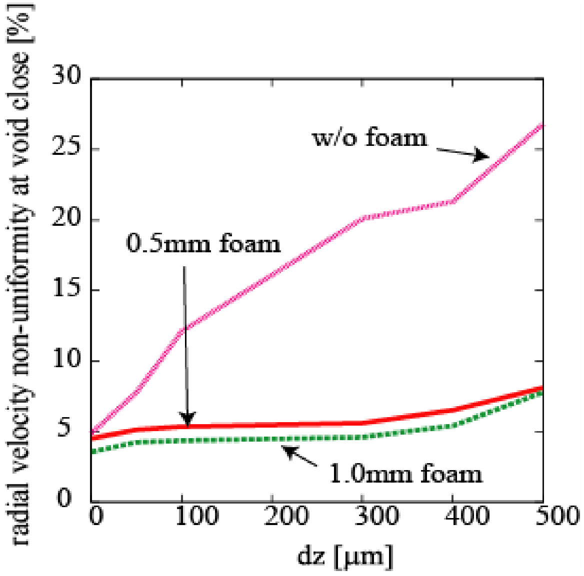


Non-uniformity at void close

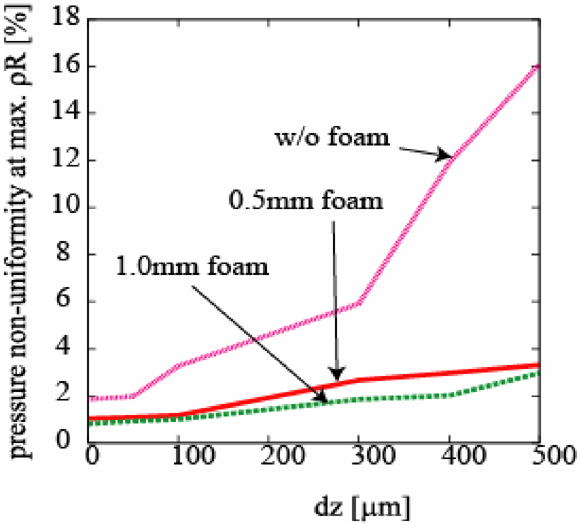


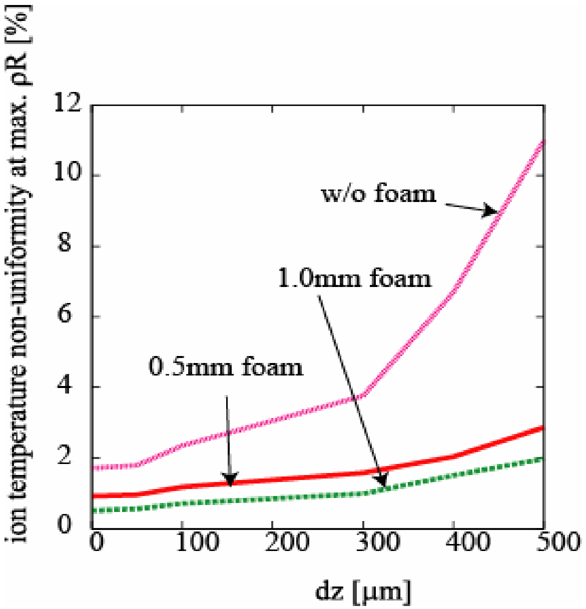


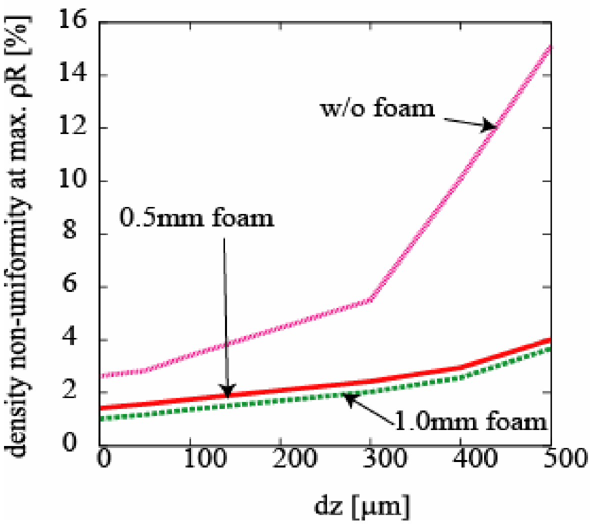


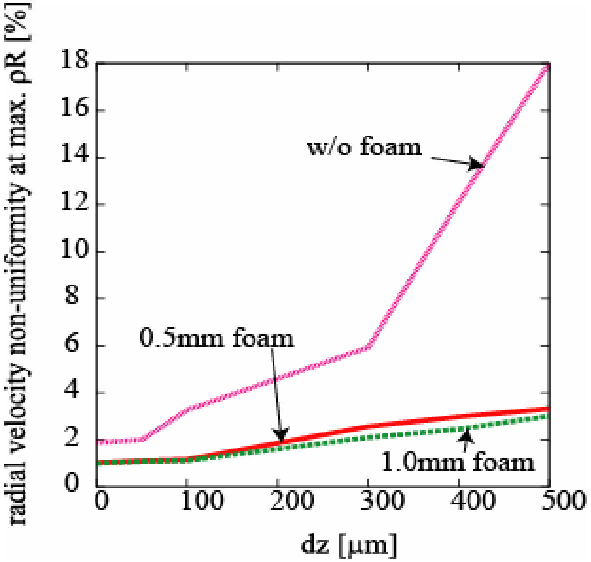


Non-uniformity at max ρR









Chapter 5. Conclusions

Conclusions

Beam Final Transport

- The HIB space charge and current are neutralized effectively
- Beam divergence is suppressed using the insulator guide
- Two stream and filamentation instabilities are not problem in our parameters

Beam Illumination

- Illumination non-uniformity is suppressed using 32 or more illumination system
- The non-uniformity is most suppressed for the 3 ~ 6 m chamber radius
- Target temperature is minor effect on the illumination non-uniformity
- The non-uniformity is kept small for the pellet displacement using out new illumination scheme

Target hydrodynamics

- The radiation energy is trapped at the low density region
- The implosion non-uniformity is suppressed by the radiation transport effect
- For the large pellet displacement, we can product the effective fusion energy using the 0.5 mm foamed target

Achievement

Journals

1. T.Someya, S.Kawata, T.Nakamura, A.I.Ogoyski, K.Shimizu and J.Sasaki, "Beam final transport and direct drive pellet implosion in heavy ion fusion", Fusion Science and Technology, **43** 282 (2003).
2. T.Someya, A.I.Ogoyski, S.Kawata and T.Sasaki, "Heavy ion beam illumination on a direct-driven pellet in heavy-ion inertial fusion", Physical Review ST-AB, **7** 044701-1 (2004).
3. T.Someya, S.Kawata, T.Kikuchi and A.I.Ogoyski, "HIB illumination on a target in HIF", Nucl. Inst. and Meth. in Phys. Res. A, **544** 406 (2005).

International conferences

1. A.I.Ogoyski, T.Someya, T.Sasaki and S,Kawata, "Heavy ion beam illumination non-uniformity", Inertial Fusion Sciences and Applications 2003, Proc. Book p.694, Monterey, USA, Sep., 2003.
2. T.Someya, T,Kikuchi, K.Miyazaki, S.Kawata and A.I.Ogoyski, "HIB irradiation on direct-driven fuel target in heavy ion fusion", IEEE International Conference on Plasma Science, Abst. Book p.88, Monterey, USA, Jun., 2005.
3. T.Someya, T.Kikuchi, K.Miyazawa, S.Kawata and A.I.Ogoyski, "Heavy ion beam interaction with a direct-driven pellet", Inertial Fusion Sciences and Applications 2005, Proc. Book, Biarritz, France Sep., 2005.