S8-6

Holistic Simulation for FIREX Project with FI^3

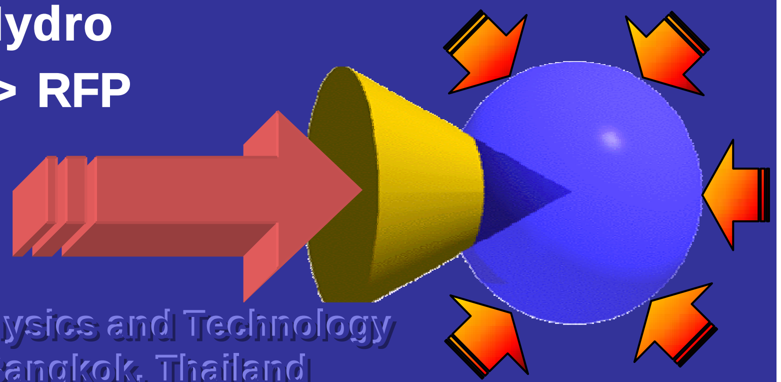
T. Johzaki[1], **H. Sakagami**[2], **H. Nagatomo**[1], **K. Mima**[1]

[1] *Institute of Laser Engineering, Osaka Univ., Japan*

[2] *Theory and Computer Simulation Center, National Institute for Fusion Science, Japan*

Outline

1. Introduction (FI^3, previous works)
2. Fast Electron Generation ... PIC
   a. Effect of Density gap at rear surface of cone tip
   b. Density profile steepening at LPI region
   c. Pre-plasma scale length dependence
3. Core Heating ....RFP-Hydro
4. Fast Ion Contribution .... PIC -> RFP
5. Summary

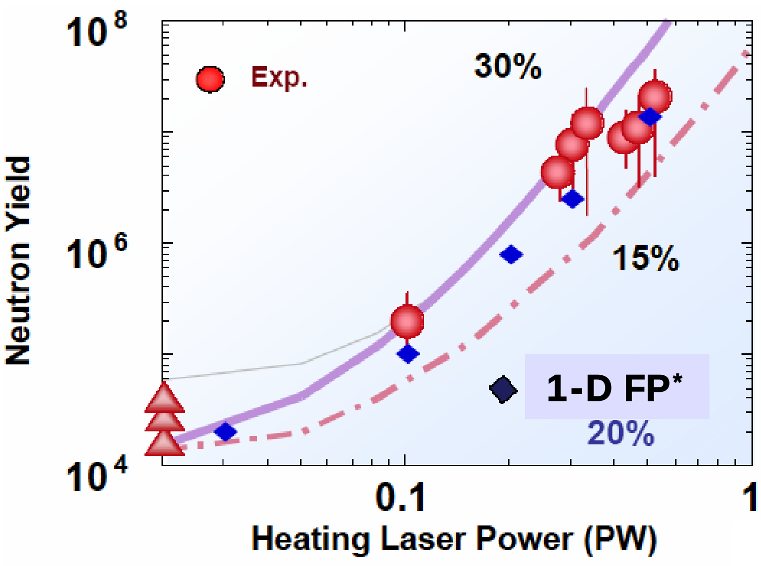


Fast Heating Experiments at ILE

Fast Heating of Cone-Guided CD Targets with GEKKO PW Laser at ILE

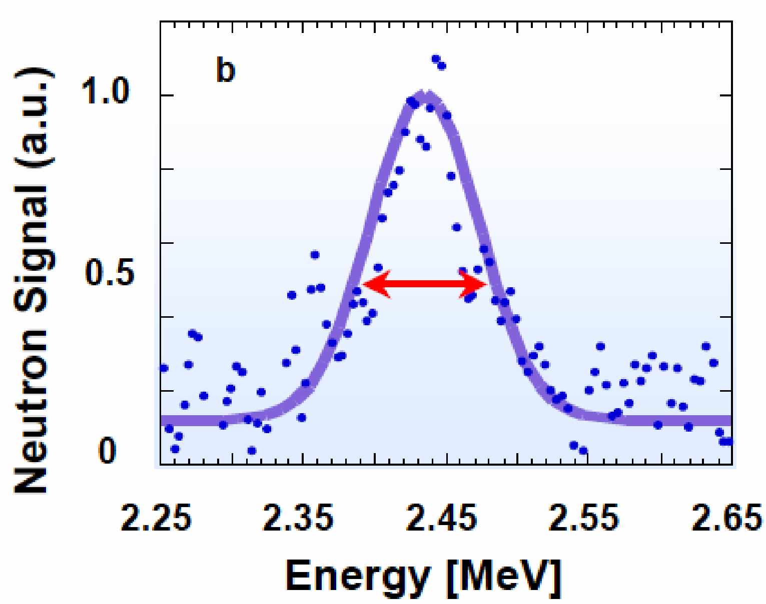
R. Kodama, et al., Nature 418, 933 (2002)

Neutron yield was enhanced by 3 orders of magnitude.



*) 1-D Fokker-Planck simulations results

Heated core up to ~ 0.8keV.

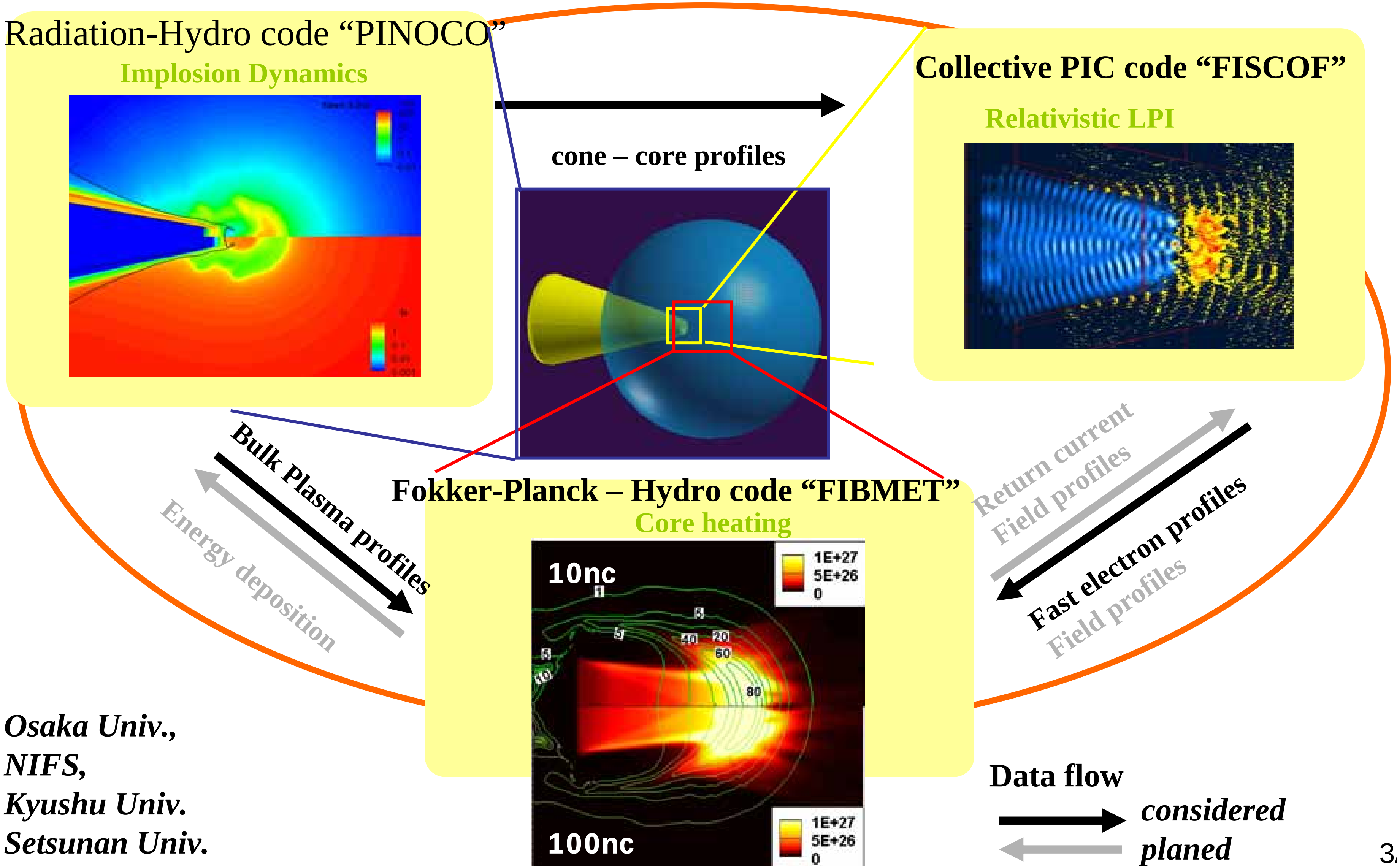


As the next step, FIREX project has been started.
However, efficient heating mechanism is not clarified yet!!

FI^3 Project

Fast Ignition Integrated Interconnecting code Project

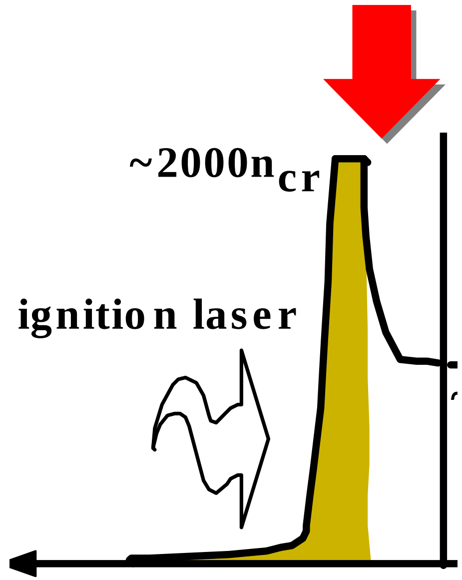
H. Sakagami and K. Mima, Laser Part. Beams, 22 (2004) 41.

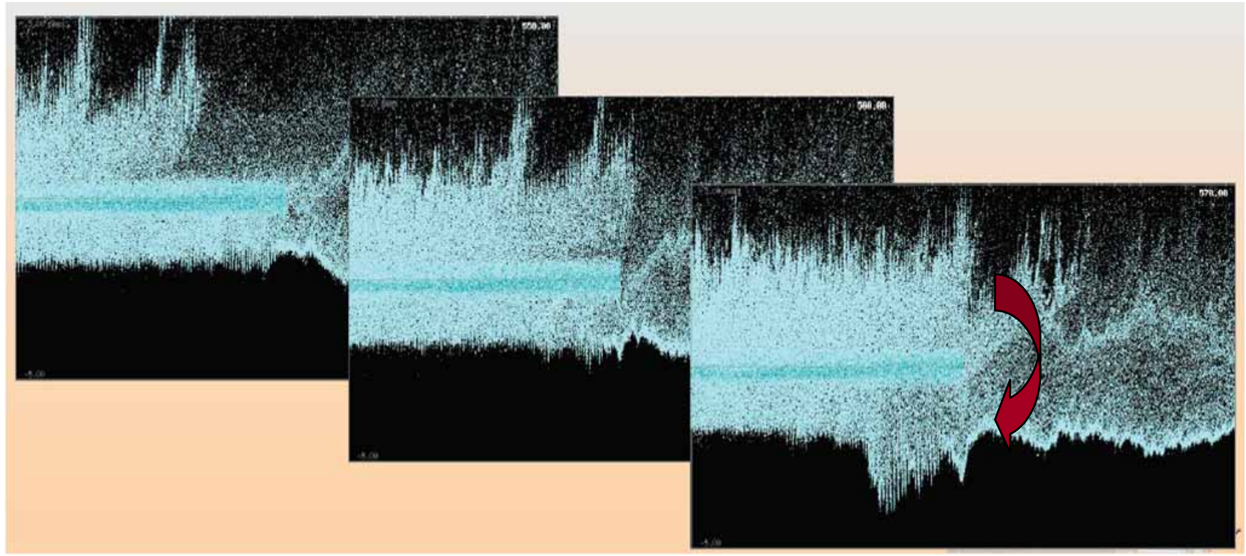


Osaka Univ.,
NIFS,
Kyushu Univ.
Setsunan Univ.

Previous work

Density gap effect at rear surface of cone tip





Fast electron current generates the strong static field, which traps relatively low energy fast electrons inside the cone tip and accelerates the bulk electrons into the cone tip.

=> Fast electron energy is moderated and the beam duration becomes long.

Due to the density gap effects, the dense core is heated more efficiently. But, the heated core temperature is ~ 0.5keV, which is still lower than the experimentally measured value, 0.8keV.

Density gap + Pre-plasma scale length

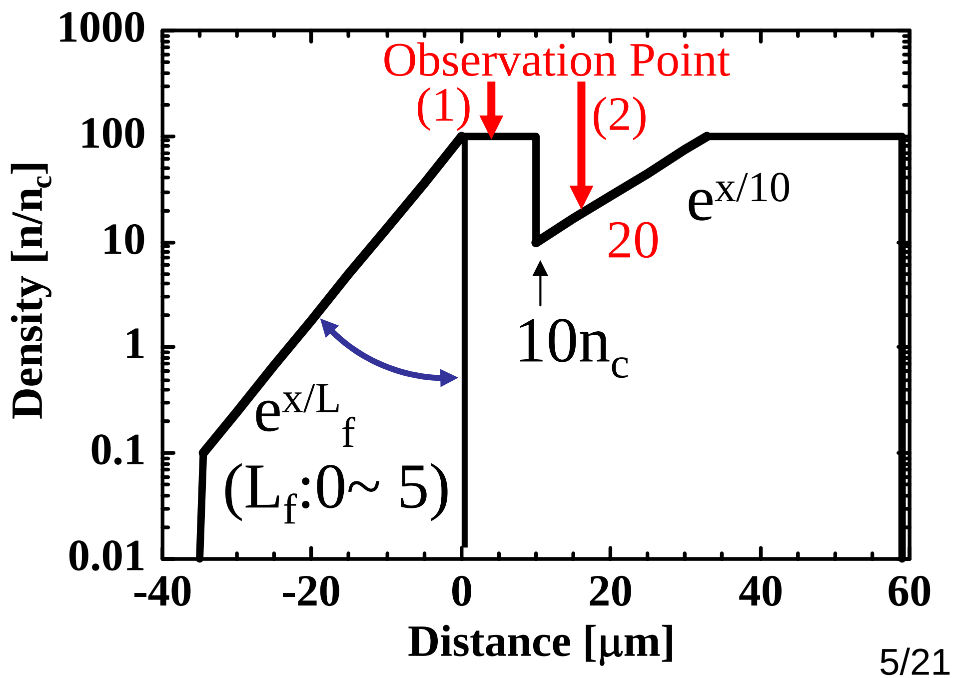
- **The pre-plasma scale length, which is determined by the pre-pulse of heating laser, may strongly affects the laser-plasma interactions. (previously fixed as 5μm)**
- **The effects of density gap + pre-plasma scale length are evaluated by 1D simulations (PIC + RFP-Hydro).**

<u>1D PIC simulations "FISCOF1"</u>

evaluation of effects of density gap and pre-plasma scale length on the fast electron profiles

<u>1D FP-Hydro simulations "FIBMET"</u>

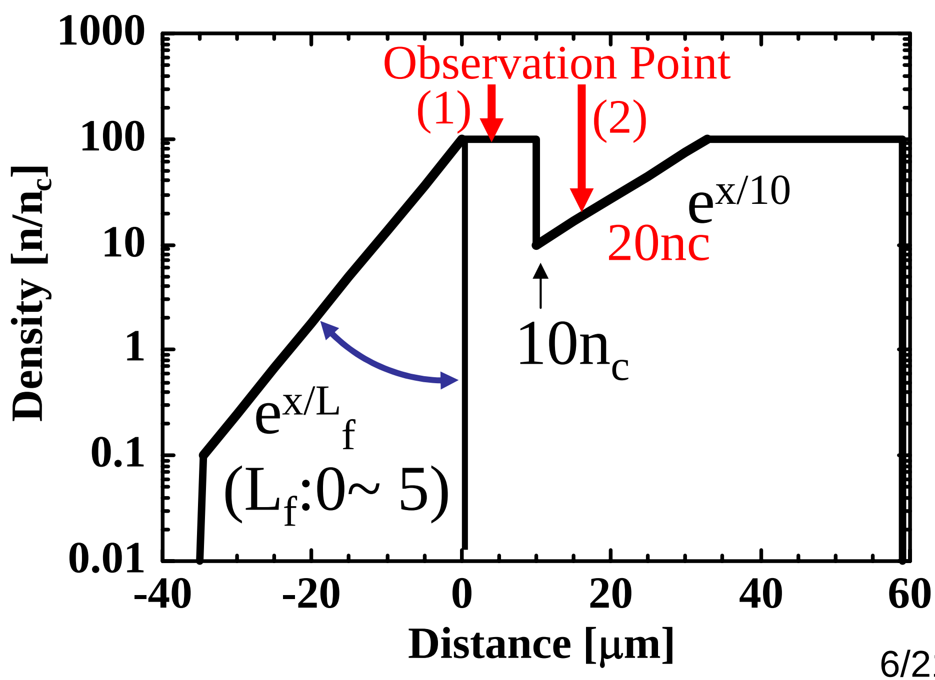
Evaluation of core heating using fast electron profiles obtained by 1D-PIC and bulk plasma profiles obtained by 2-D implosion simulations "PINOCO"



Simulation Condition for 1D "PIC FISCOF1"

Laser-Plasma Interactions at the Cone Inner surface

- **Electrons and ions are mobile.**
- **All the ion are Au with real mass and Z=50**
- **Collision is not included.**
- **Cone tip is modeled by 100nc plasma**
- **Heating laser parameters:**
  - λ_L = 1.06 [μm]
  - Gaussian profile
  - τ_{FWHM}= 750 [fs]
  - $I_L = 10^{20}$ [W/cm^2]



Density Steepening at LPI region

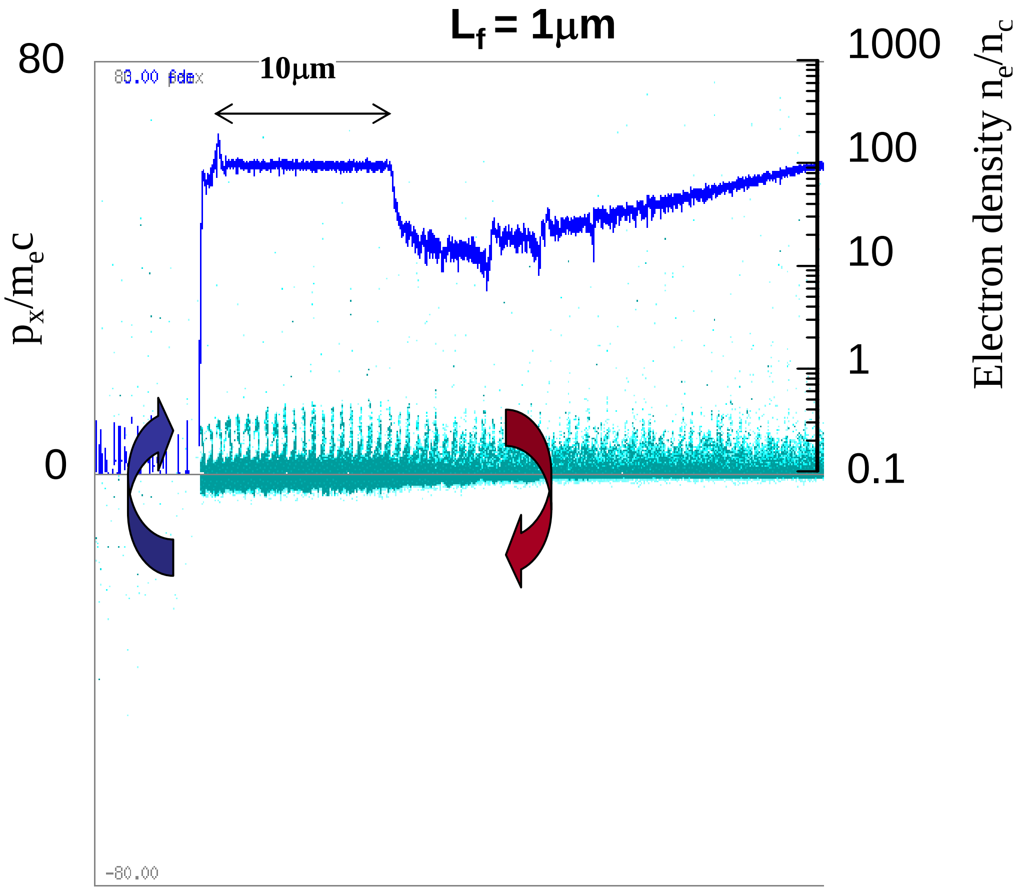
Strong Ponderomotive force steepens the density profile.

<u>At the front surface (LPI region)</u>

- The pre-plasma is pushed by the strong Ponderomotive force and then the density profile steepening occurs.
- Periodically lunched electron bunches are observed, and returned electrons are completely kicked back.

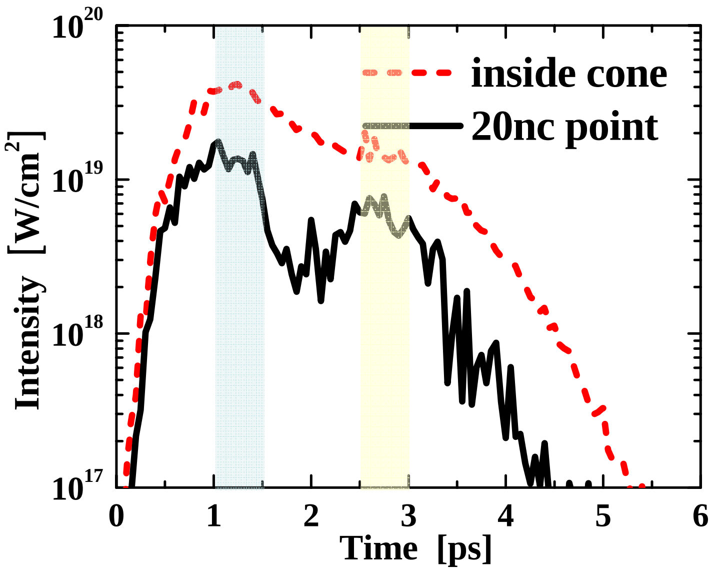
<u>At the rear surface (density gap)</u>

- The static field built up due to fast electron current, which reflects the relatively low-energy fast electrons and accelerates the bulk electrons into the cone tip.

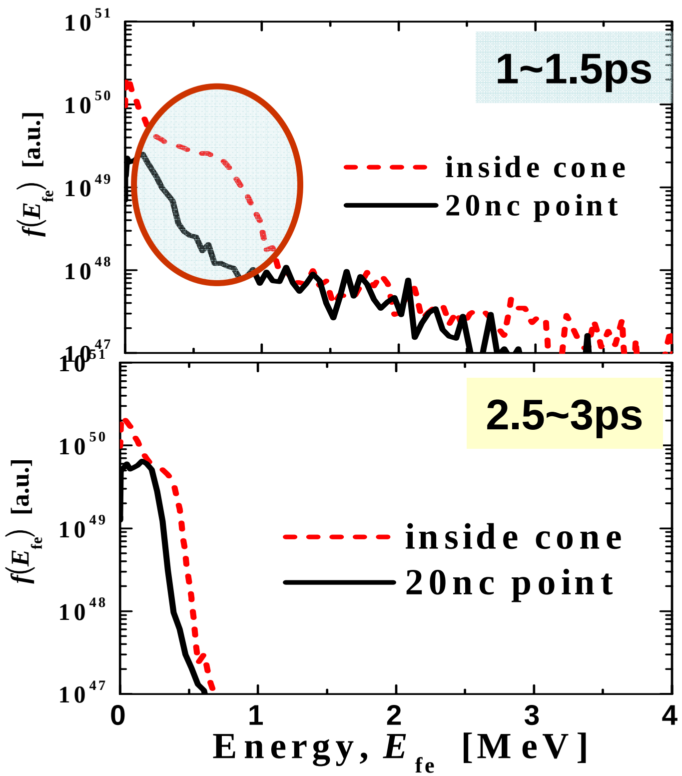


at t = 1ps

Effects of density gap & profile steepening (Lf = 1μm)



Energy Spectra



- The relatively low energy fast electrons are trapped inside the cone tip due to the static fields generated at the front and rear surfaces of cone tip.
- These trapped electrons are released from the tip even after finishing laser irradiation.

Scale length dependence 1

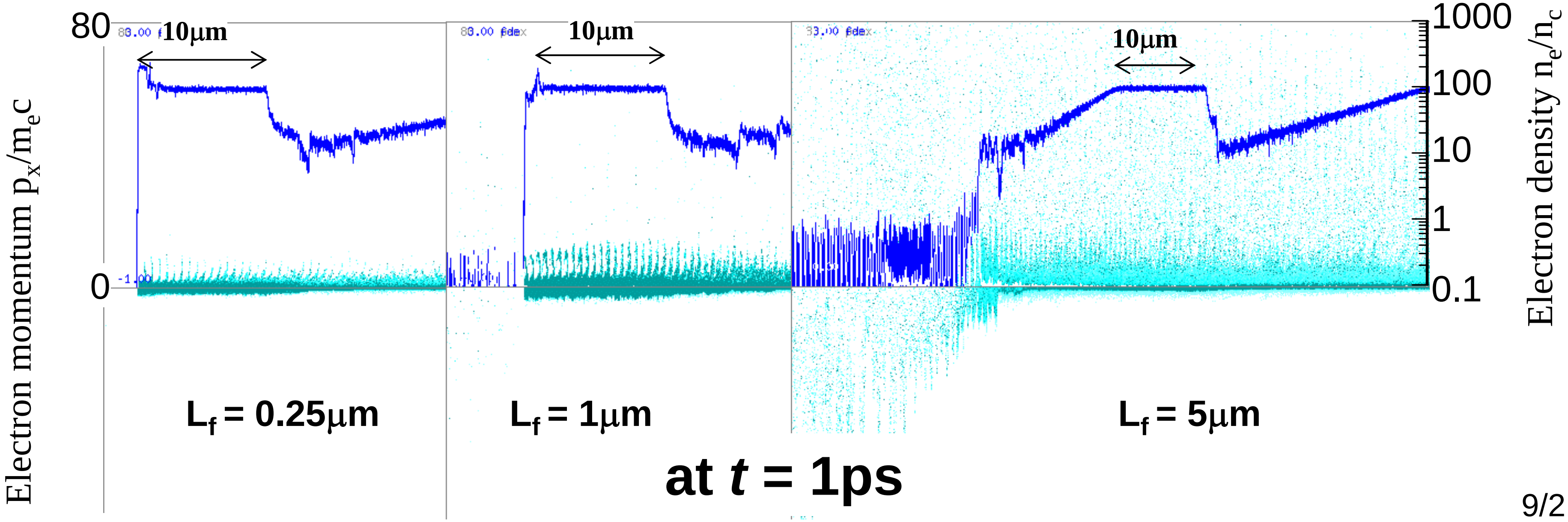
Strong Ponderomotive force steepens the density profile.

<u>Short scale length case</u>

- **The pre-plasma is swapped away.**
- **Periodically lunched electron bunches are observed, and returned electrons are completely kicked back.**

<u>Long scale length case</u>

- **The pre-plasma still remains at LPI region.**
- **Very high energy fast electrons are generated and part of the returned electrons are pulled into the vacuum region.**



at t = 1ps

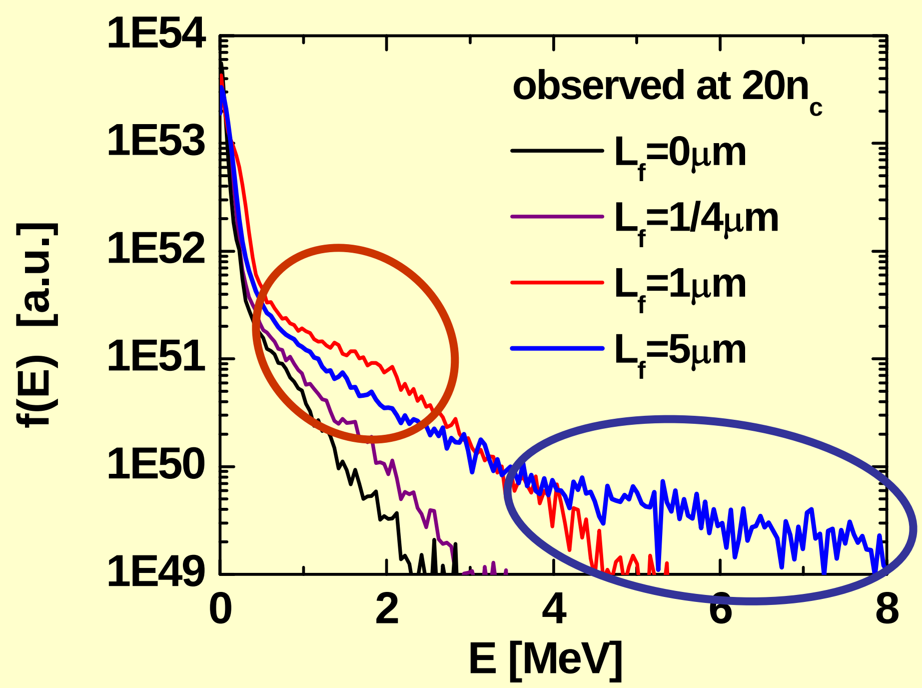
Scale length dependence 2

With increasing the scale length, higher energy electrons generated.

- **L_f = 5μm; very high energy electrons are not trapped and trapped effect due to density gap and profile steepening is weaker. So the fraction of high energy electrons is large. They can not heat the core efficiently due to long range.**

- **L_f = 1μm; the relatively low energy electrons, which are favorable to core heating, are increased due to the gap and steepening effects.**

Time-integrated Fast electron spectrum

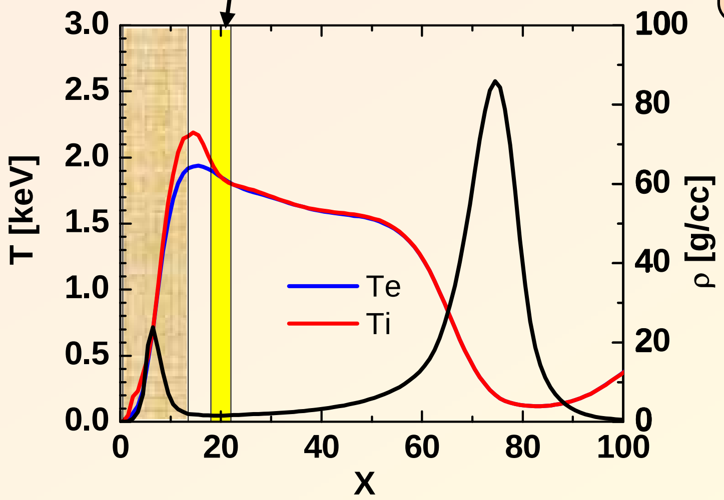


Optimum scale length for core heating will exist!!

1D Fokker-Planck Simulation Model

Fast Electron & Ion Profiles
(PIC Code)

Fast electrons were injected at outer surface of a gold cone.



Imploded Core Profiles
(ALE Rad-Hydro Code)

Fast Electron & Ion Transport

Relativistic Fokker-Planck transport
Electric Fields

(x) – CIP (85x161 mesh)

(p) – Discontinuous Linear FEM (25 groups)

(μ) – Discrete Ordinate Sn method (36 directions)

n_i, T_i, T_e, Z

Energy(fast electron, ion) & Momentum(fast ion) deposition rates

Radiation-Hydrodynamics

Bulk Plasma
- **1-fluid 2-temp. CIP code**

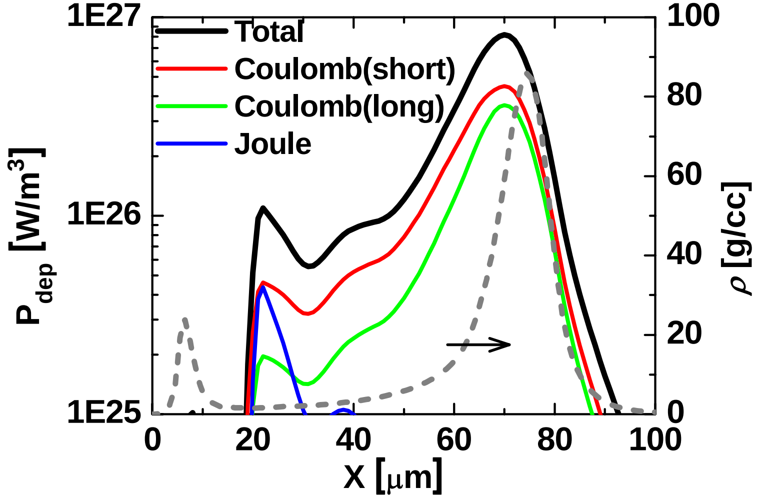
Radiation
- **Flux-limited diffusion**

Core Heating Properties (1D RFP)

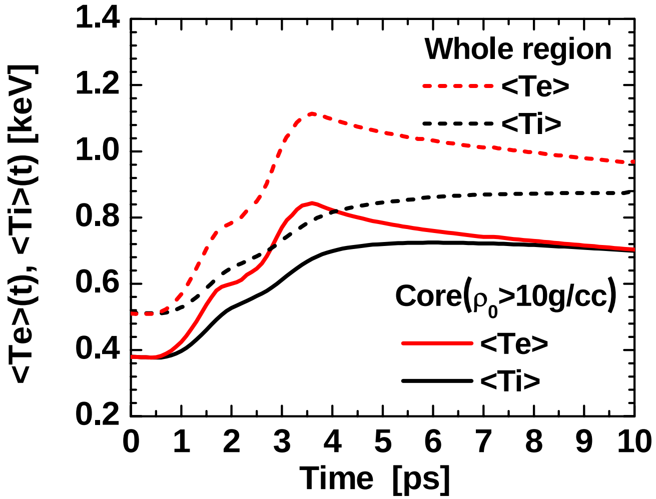
Core Heating Properties…1D FP

source: L_f = 1μm, n_{erear} = 10n_c

Heating rate (at t = 2.5ps)



Temporal evolution of spatially-averaged Temp



- **The Coulomb interaction with bulk electron is dominant energy deposition mechanism of fast electron in dense core.**
- **The bulk ion is heated through the temperature relaxation with bulk electron, so Ti reaches maximum by 3ps delay from Te,max time.**

Averaged ion temperature reaches

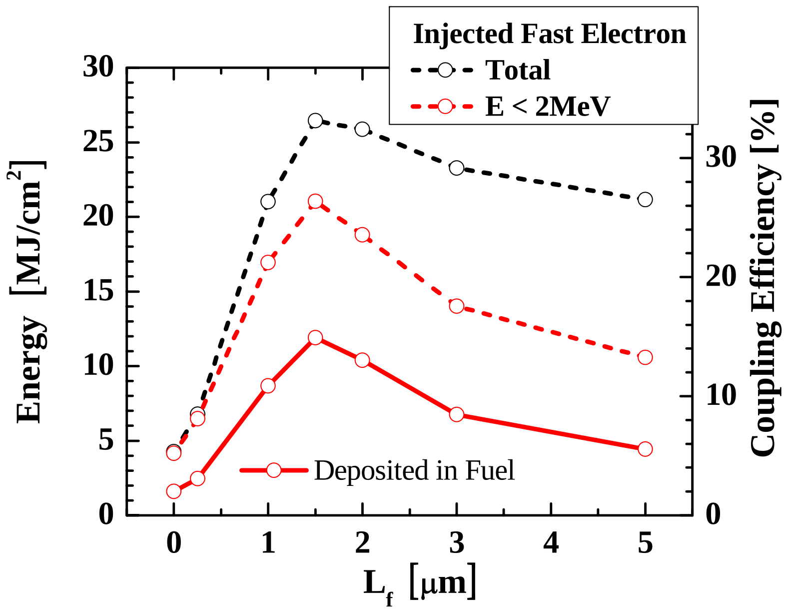
- **0.87keV at 9,0ps in the whole fuel region,**
- **0.72keV at 6.5ps in dense core (ρ>10g/cc) .**

→ ΔT_i ～0.35keV

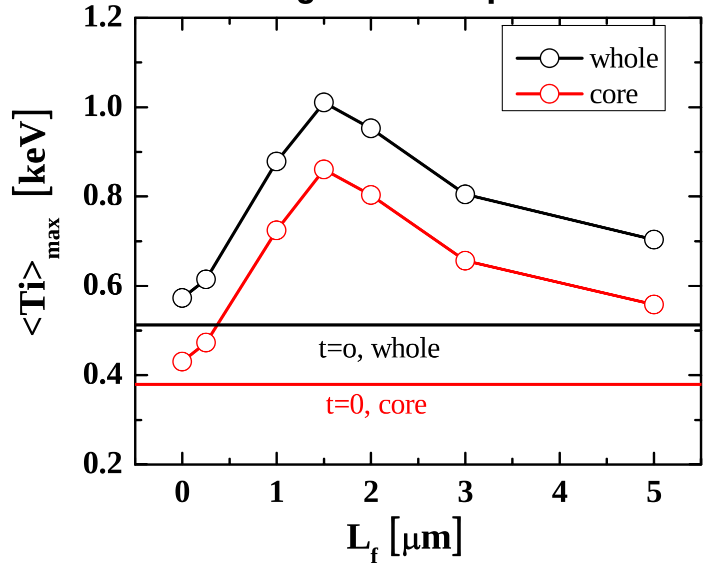
Pre-plasma scale length dependence : $L_f = 0 \sim 5\ \mu m$

Core Heating Properties…1D FP

Irradiated Laser Energy = 79.8 MJ/cm^2



Maximum values of Spatially averaged ion temperature

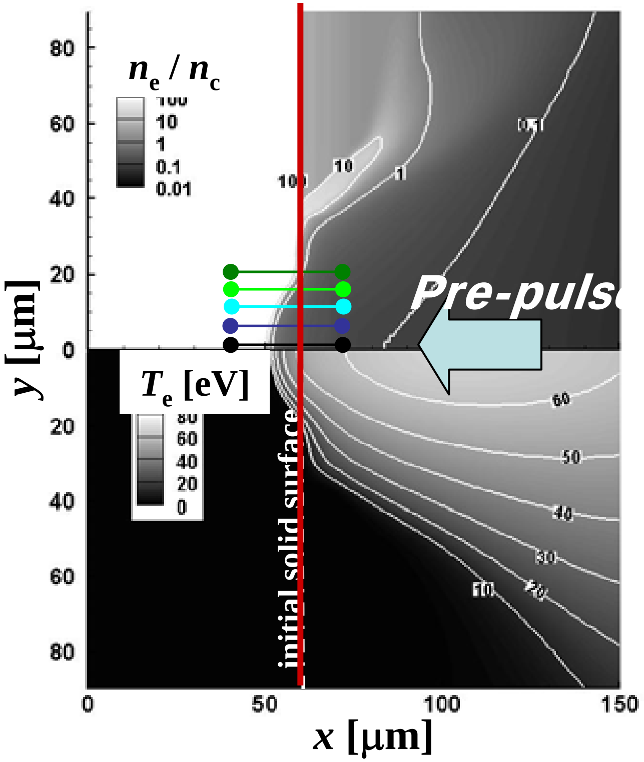


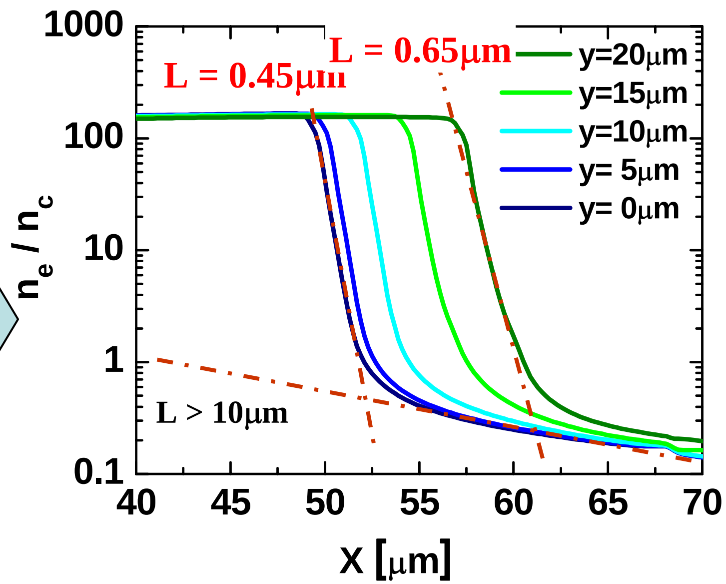
- **L_f < 1μm; $\eta_{L\rightarrow e}$ is small, so that the core heating efficiency is low.**
- **L_f > 2μm; with increasing L_f, $\eta_{L\rightarrow e}$ gradually decreases, but the low energy component (*E* < 2MeV) decreases faster, which lowers the core heating efficiency.**

In the present simulations, the optimum L_f for core heating is 1.5μm. The energy coupling from laser to core is 14.9%, and the core temperature reaches 0.86keV (ΔT_i = 0.48keV).

Pre-plasma estimation by PINIOCO

An Example of PINOCO Simulation for pre-plasma formation due to pre-pulse irradiation (~10^{11}W/cm^2)

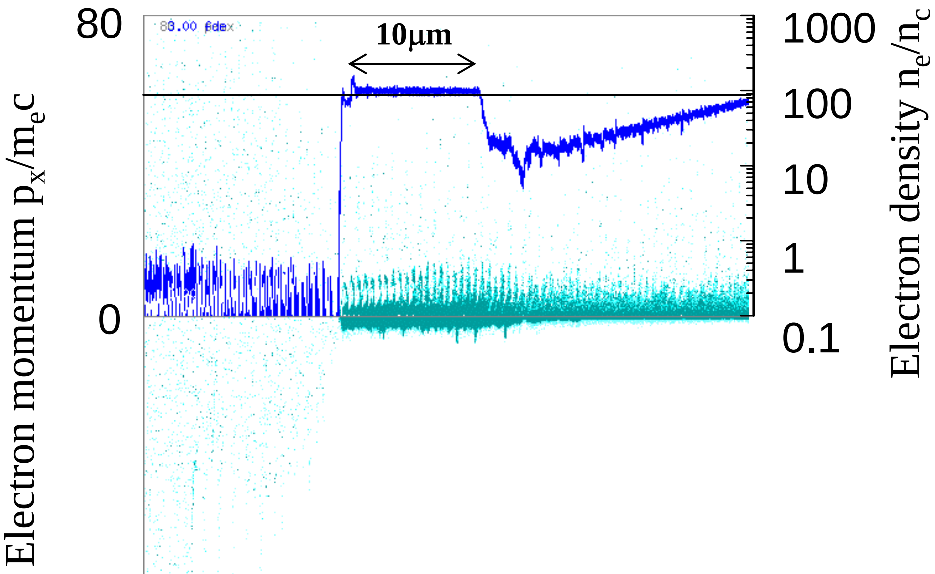


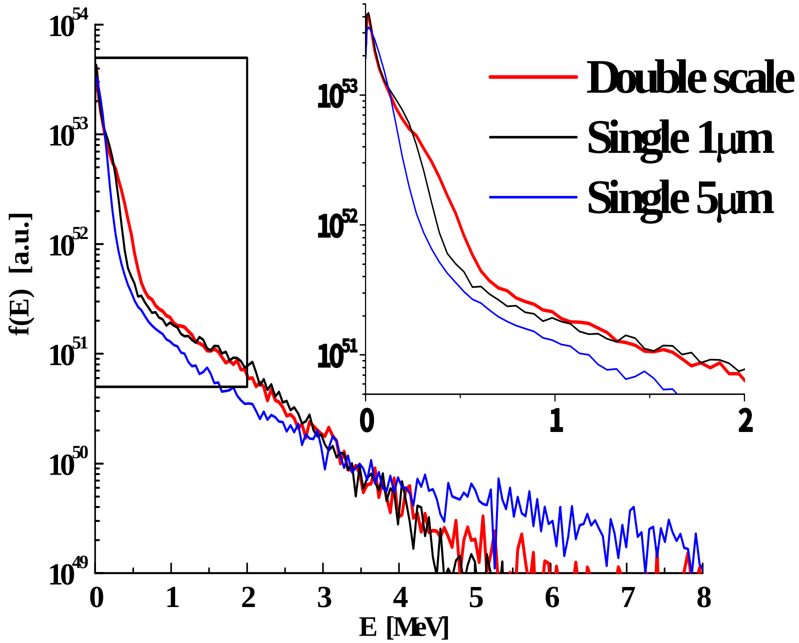


Pre-plasma has double scale length, *i.e.* $L_{f1} \leq 1\mu m$ at $n_e > n_c$ and $L_{f2} >> 1\mu m$ at $n_e < n_c$.

Double Scale Length;
$(L_{f1}=1\mu m\ (n_e>n_c)+L_{f2}=5\mu m(n_e<n_c))$

Fast electron profiles …… 1D PIC



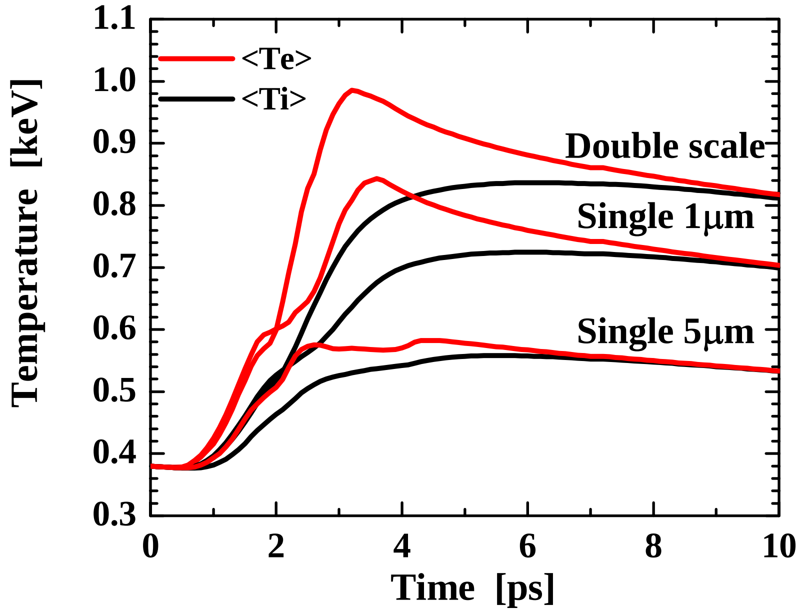


	Electron beam	Low energy (2MeV) Comp.
Lf = 1µm	21.0 MJ/cm² (26.3%*)	16.9 (21.1%*)
Lf = 5µm	21.2 MJ/cm² (26.6%*)	10.6 (13.3%*)
Double scale	24.6 MJ/cm² (30.8%*)	19.8 (24.8%*)

** Energy carried by fast particles / laser energy*(79.8MJ/cm²) [%]

Double Scale Length; $(L_{f1}=1\mu m\ (n_e>n_c) + L_{f2}=5\mu m(n_e<n_c))$

Core Heating Properties…1D FP



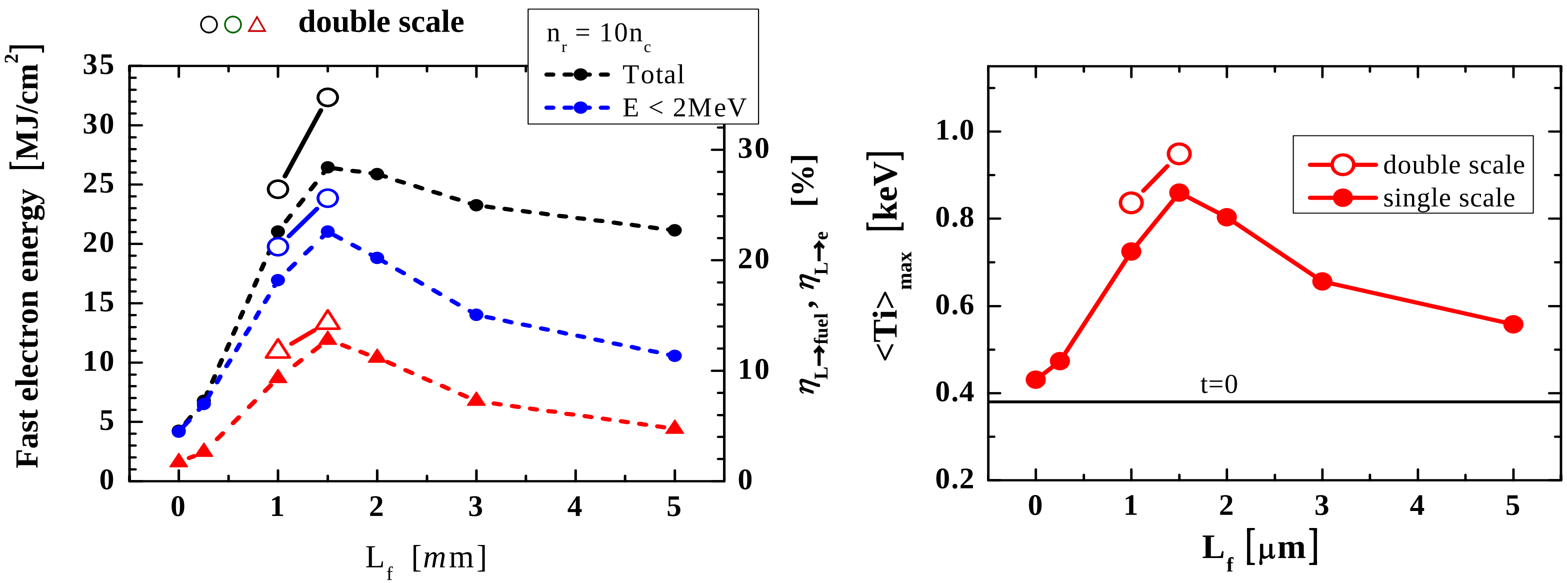
Irradiated Laser Energy = 79.8 MJ/cm^2

	Single scale		*Double scale*
L_f[μm]	1.0	5.0	1.0+5.0
E_{beam}[MJ/m^2]	21.0	21.2	24.6
$\eta_{L\to e}$ [%]	26.3	26.6	30.8
E_{dep} [MJ/m^2]	8.68	4.42	10.94
$\eta_{e\to fuel}$ [%]	41.3	20.8	44.5
$\eta_{L\to fuel}$ [%]	10.9	5.5	13.7
$\Delta\langle Ti\rangle_{max}$[keV]	0.34	0.17	0.46

In the double scale case, the number of relatively low energy electrons (E<2MeV) is increased, so that the heated core temperature becomes higher ($\langle T_i\rangle_{max}$ = 0.84keV) than that in 1μm single scale case ($\langle T_i\rangle_{max}$ = 0.72keV) .

Double Scale Length

Core Heating Properties…1D FP L_{f1} = 1 or 1.5μm ($n_e>n_c$) + L_{f2} = 5μm ($n_e<n_c$)



In the double scale case, low energy component (E< 2MeV) is increased, so that the energy coupling from laser to core and resultant core temperature become high compared with the single scale length cases.

L_{f1} = 1.5μm + L_{f2} = 5μm ⇒ $\eta_{L\to fuel}$ = 16.7% and $<T_i>_{max}$ = 0.95keV.

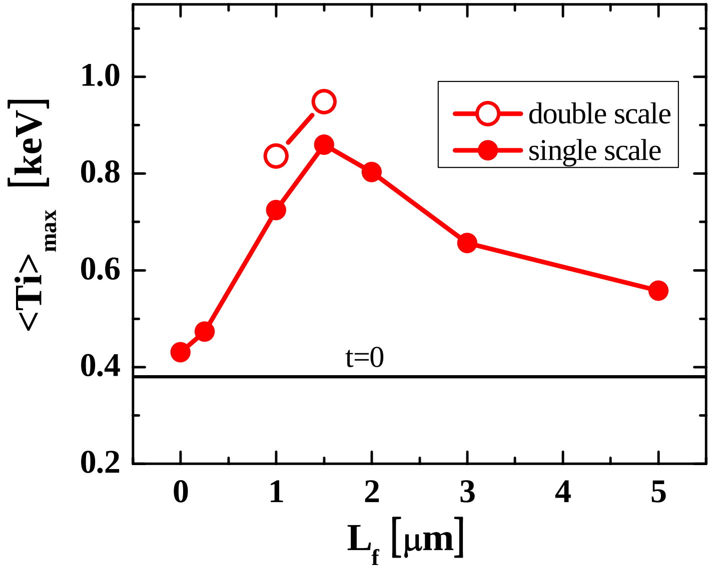
Summary

Pre-plasma scale-length dependence of core heating;

….. 10^{20}W/cm^2 / 750fs / 1.06μm pulse

- **When scale length is too short (L_f <1μm), the energy coupling from laser to fast electron is small and then the core heating efficiency is low.**
- **In the longer scale length region (L_f >>1μm), with increasing L_f, the low energy component of fast electron, that mainly contributes to the core heating, becomes small, so that the heating efficiency also becomes low.**
- **Optimum scale length is 1.5μm**

→ $\eta_{L\rightarrow fuel}$ ~15%, $\langle T_i \rangle$ reaches 0.86keV



Double scale length case;

- **Energy coupling from laser to fast electron is higher than that in the single scale length case and low energy component of fast electron also increases.**

⇒ Core heating efficiency becomes high.

L_{f1} = 1.5μm ($n_e > n_c$) + L_{f2} = 5μm ($n_e < n_c$); $\eta_{L\rightarrow fuel}$ ~17%, $\langle T_i \rangle_{max}$ = 0.95keV

Others

Longer & Higher energy Laser Case (>10ps, >10^{20}W/cm^2)
- **In FIREX-I, heating laser is 10kJ/10ps. For ignition, 100kJ (or more?) heating laser is required. What's happen? Can we Extrapolate the short & relatively low energy shot results?**

Additional Heating due to Fast Ion ?
- **Accelerated ions (Au, Z=50) does not contribute to the core heating because of their short range.**
- **But, how about the different ion species (C, P, D, T)?**

Geometrical effects in laser-cone interactions (*e.g. laser-cone wall interaction, laser focusing, fast electron accumulation)*

‥‥ On going by T. Nakamura

Collision processes in the cone

‥‥ reduced model is under construction.

Effects of Microscopic instabilities on fast particle transport
- **In ps-order 1D PIC simulations, we observed ion heating (or acceleration) in the medium-density propagation region (between cone tip and core, n ~ a few 10n_c region) due to the instability.**