OV/5-5

Institute of Laser Engineering
The University of Osaka

Strategy to demonstrate heatwave-driven laser fusion with fast ignition scheme

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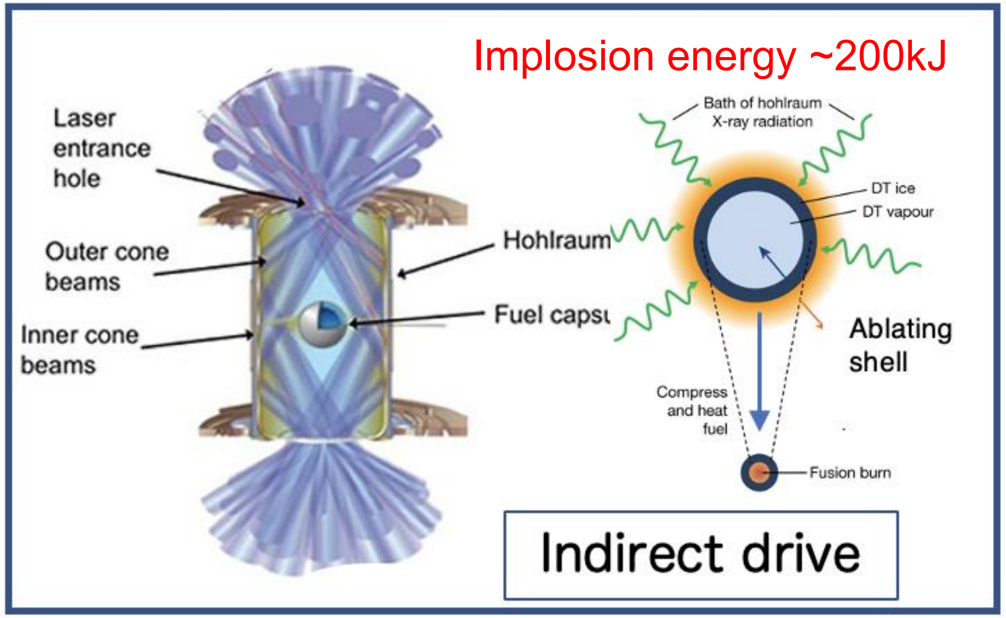
IAEA FEC 2025, Oct. 18@成都, 中国

Laser fusion
– Central Ignition and Fast Ignition -



Laser energy 2MJ ➡ Energy coupled to form the hot core ~ 10kJ (coupling rate ~ 1%)

Fusion yield
~ 8.6MJ (gain > 4, fuel burning rate <10%)

What I talk today

- Introduction of efficient heating “*heatwave*” driven laser fusion with fast ignition scheme.

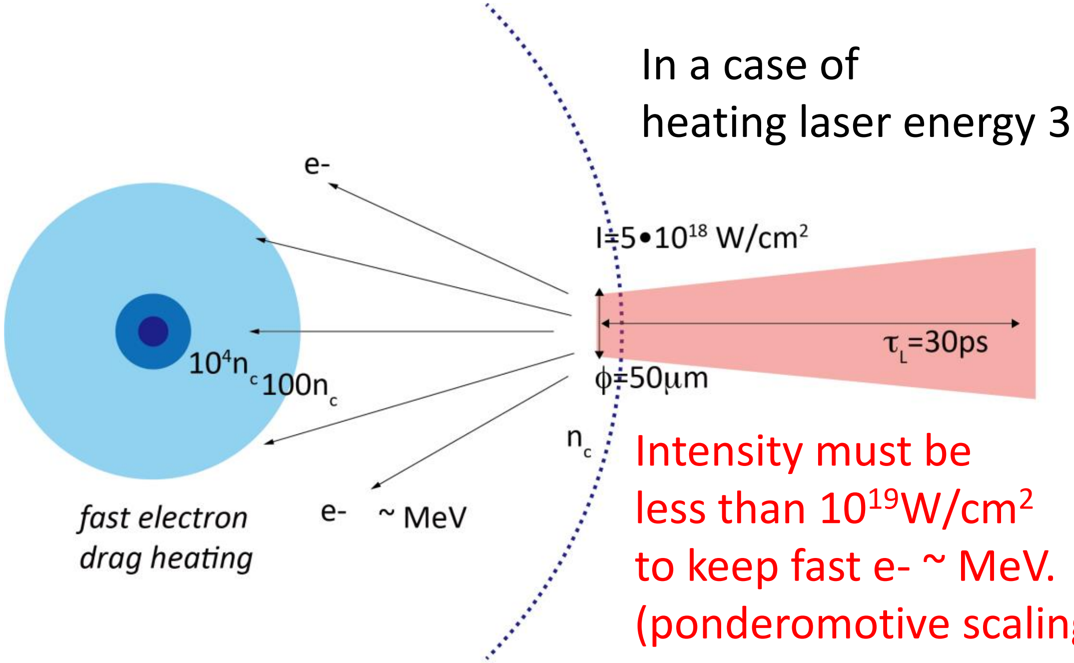
- Two point-designs of laser fusion with the heatwave driven fast ignition. One for IFE scale (gain > 100) and the other for the proof of principle experiment (Gain ~ 1).

- Numerical simulations, particle-in-cell (PIC) code with Coulomb collisions and DT fusion reactions, to estimate the fusion yields.

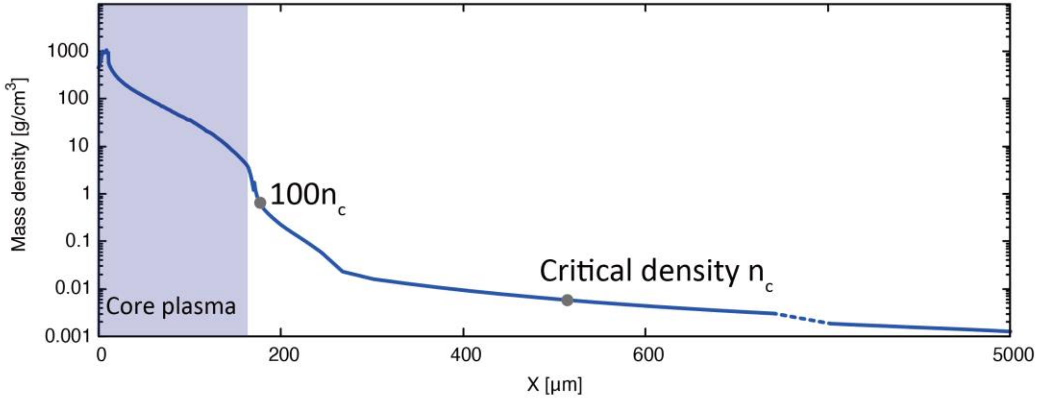
- Strategy of laser fusion research at ILE.

Original concept of fast ignition (core heating by MeV electrons)

In a case of
heating laser energy 3kJ



Intensity must be less than 10^{19}W/cm^2 to keep fast e- ~ MeV.
(ponderomotive scaling)



The core is heated by the following 3 processes.

REB drive heating

Diffusive heating

$$\frac{3}{2} n_e \frac{\partial T_e}{\partial t} = \frac{j_h^2}{\sigma(T_e)} + \frac{3}{2}\frac{n_h T_h}{\tau_e(T_h)} + \frac{\partial}{\partial x}\left(\kappa(T_e)\frac{\partial T_e}{\partial x}\right)$$

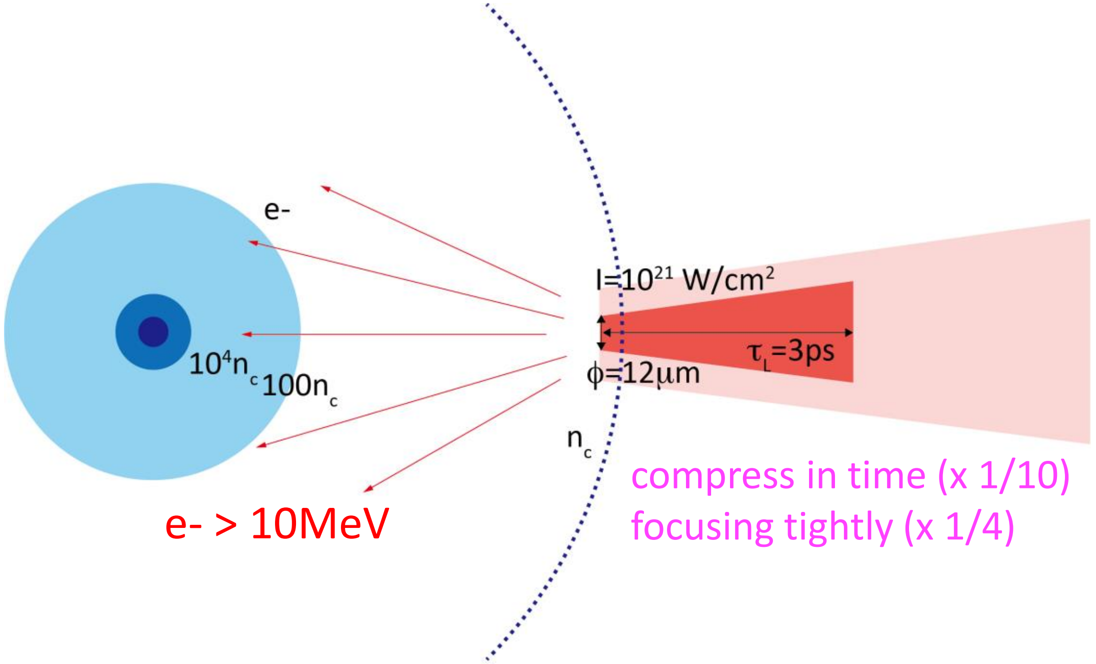
Resistive Heating (collective)
most efficient but quickly saturated

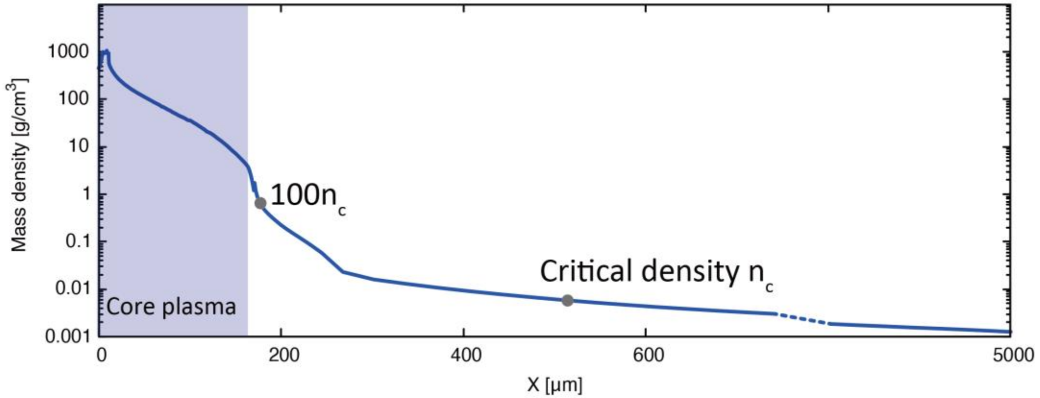
Drag Heating
$\propto 1/T_h^{1/2}$
less effective but long range persistently

Electron must be ~ MeV to be stopped in core.

*M. Tabak, *et al.*, Phys. Plasmas **1**, 1626-1634 (1994).

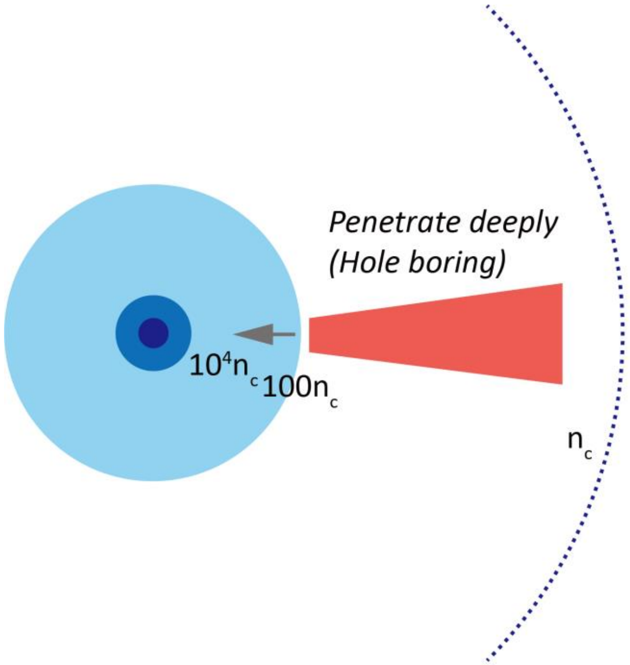
Fast ignition with highly compressed PW laser > 10^{21} W/cm^2

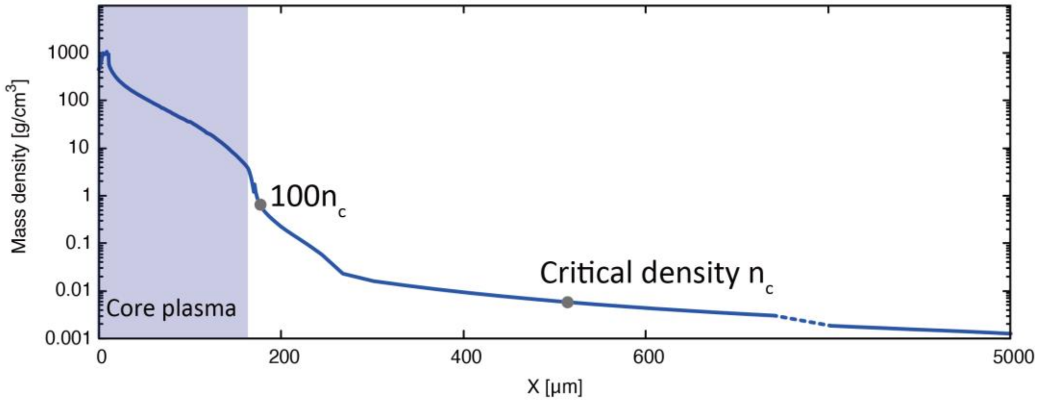




The fast e- energy would be greater than 10MeV.
(too energetic for drag heating)

Ultra-intense PW laser pulse penetrate deeply in corona plasma





The pulse can penetrate deeply in the corona plasma, and converts its energy to electrons in dense plasmas.

Fast electrons' characteristics changes!

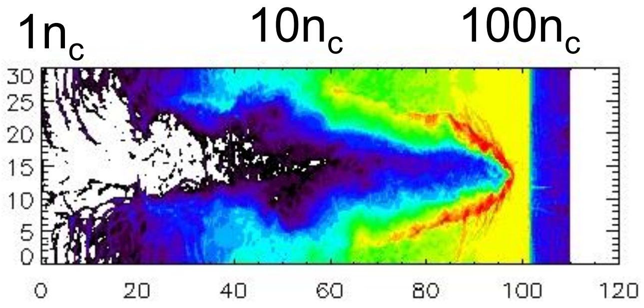
Electrons driven by relativistic laser light (a_0>1)
- Efficient heating requires a large number of MeV electrons -

$$I = m_e c^2 \left(\frac{a_0^2}{2}\right) n_c c$$

n_e

ε_e

absorption η



Ponderomotive scaling

Relativistic critical density

$$n_e = \gamma_{os} n_c \simeq a_0 n_c$$

Ponderomotive energy

$$\epsilon_e = (\gamma_{os} - 1) m_e c^2 \simeq a_0 m_e c$$

$$m_e c^2 = 0.511\ [\mathrm{MeV}]$$

a_0=1 → $\mathrm{I} = 10^{18}$W/cm^2

Scaling at hole-boring front interface

Fast electron density ∝ a_0^2.

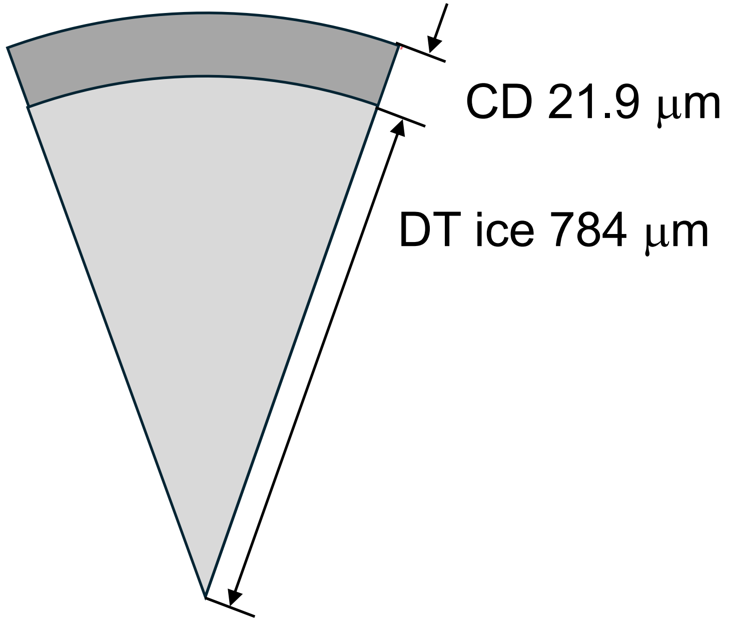
$$n_e = 8 a_0^2 n_c \left(1 - \eta \frac{1 + (\beta_e \alpha)^{-1}}{2}\right)$$

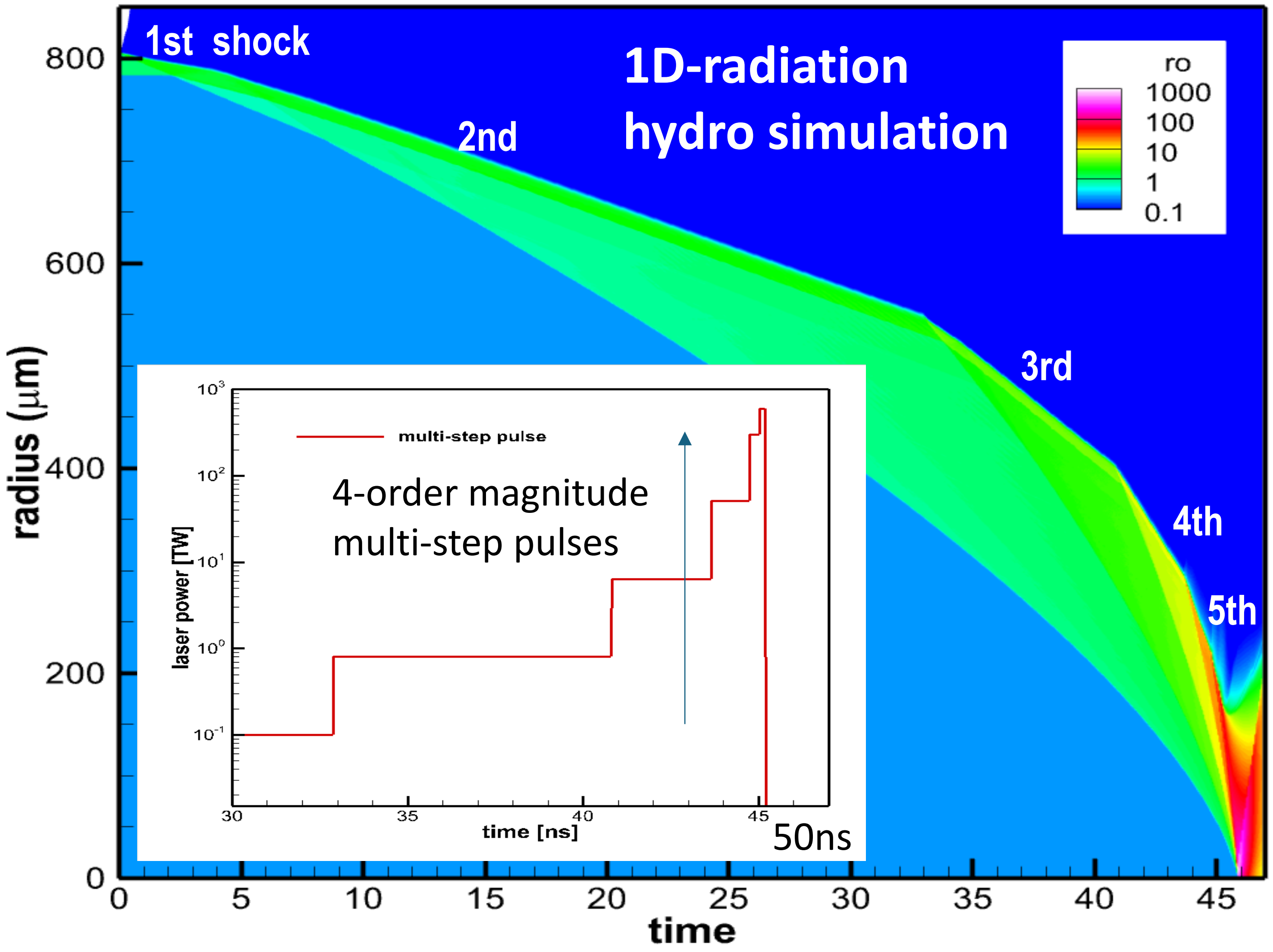
Energy has no explicit dependence on a_0.

$$\epsilon_e = \frac{m_e c^2}{8} \frac{1}{\left(\frac{2}{\eta} - 1\right) \beta_e \alpha - 1}$$ ~ MeV

This characteristic change drive the efficient heating - heatwave-

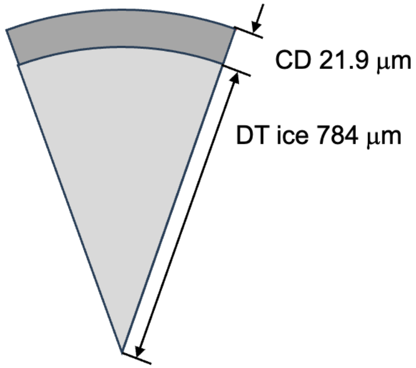
Point design of IFE scale laser fusion
- high-density fuel compression (250 kJ) using a solid-ball target -



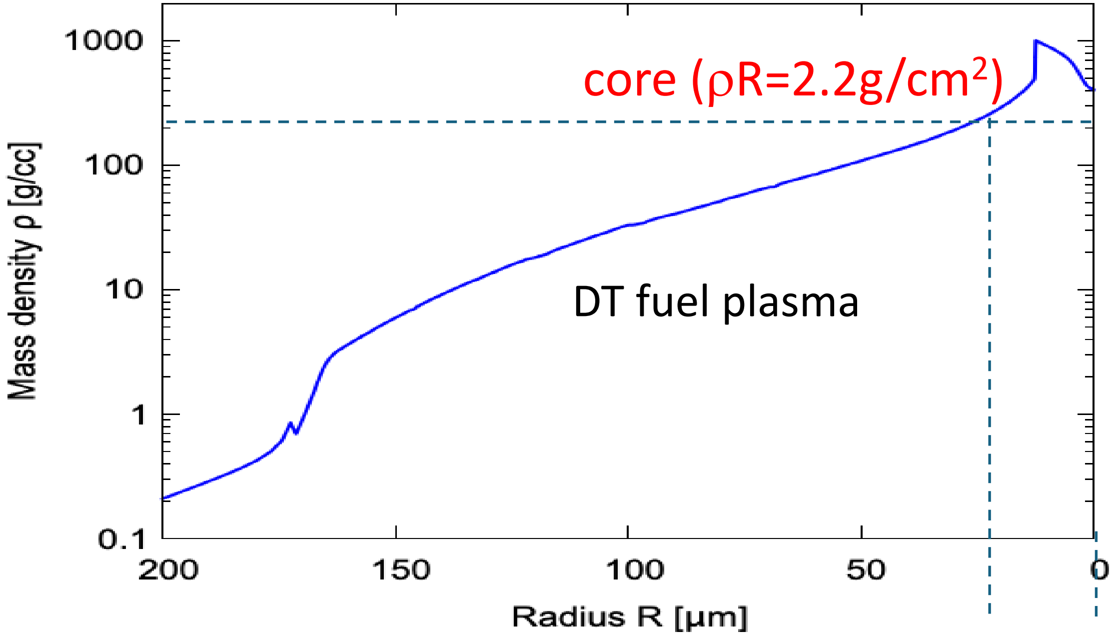


Point design of IFE scale laser fusion with fast ignition scheme (implosion 250kJ + heating laser 30kJ)

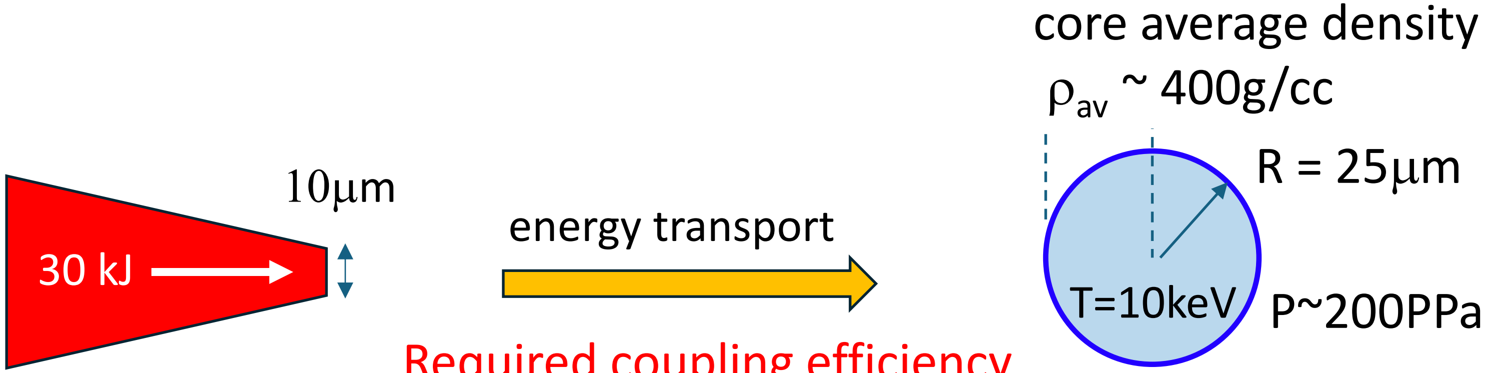
IFE scale laser fusion



Target radius ~ 800μm
Laser energy
implosion 250kJ
heating 50kJ
Gain ~ 100
(30MJ fusion E)



Heating laser 30 kJ/3ps (10PW)
pulse length 1000μm
spot radius 5μm
intensity 10^{22} W/cm^2
normalized amplitude a_0=100
Photon pressure 300PPa

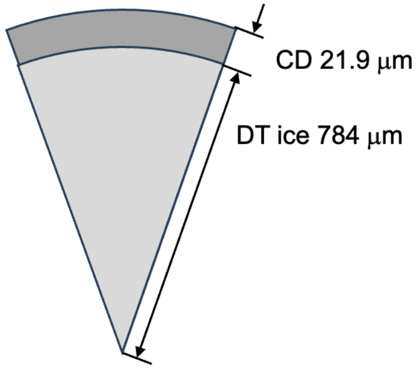


Required coupling efficiency
~ 50%

core energy 16kJ

Point design of IFE scale laser fusion with fast ignition scheme (implosion 250kJ + heating laser 30kJ)

IFE scale laser fusion



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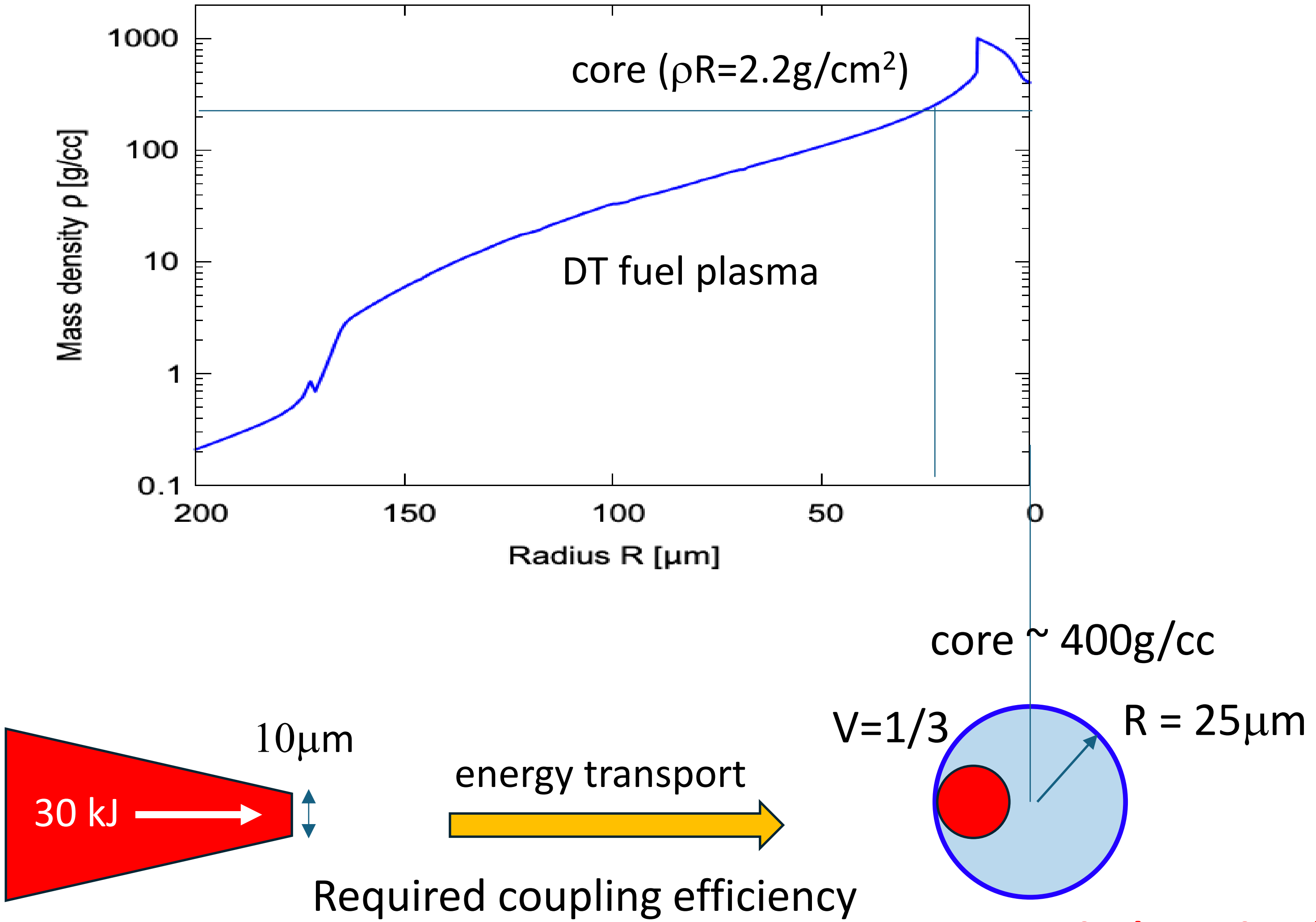
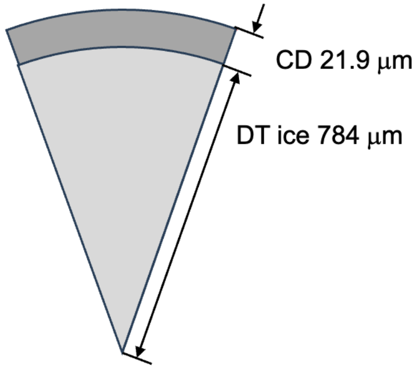


Required coupling efficiency ~ 15%

Hot spot 5 kJ (T=10keV)

Point design of IFE scale laser fusion with fast ignition scheme (heating laser 30kJ/3ps) – collisional PIC simulation

IFE scale laser fusion



Target radius ~ 800μm
Laser energy
implosion 250kJ
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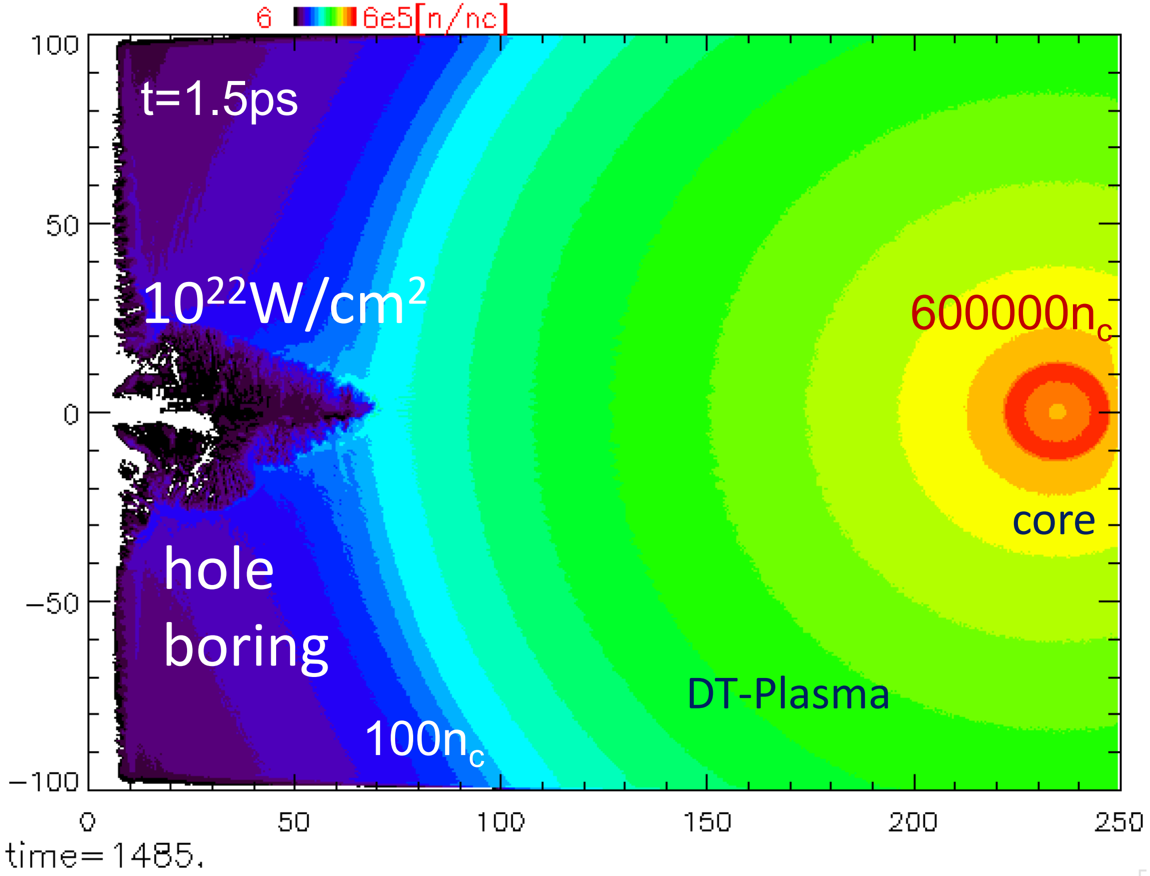
Gain ~ 100
(30MJ fusion E)

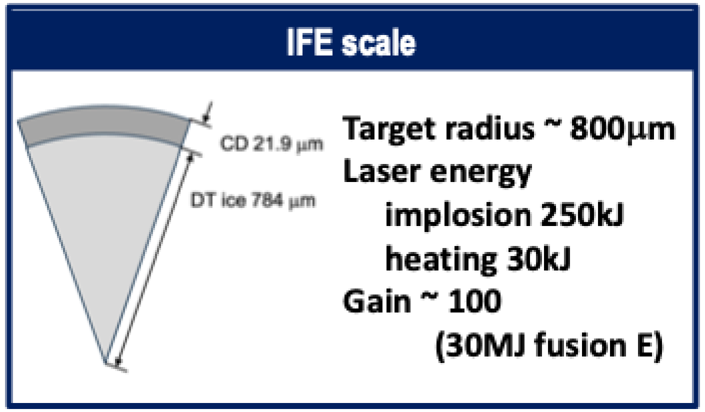
Heating laser 30 kJ/3ps (10PW)
pulse length 1000μm
spot radius 5μm
intensity 10^{22} W/cm^2
normalized amplitude a_0=100
Photon pressure 300PPa

Plasma particle simulation, PICLS, including Coulomb collisions, DT fusions, radiation losses



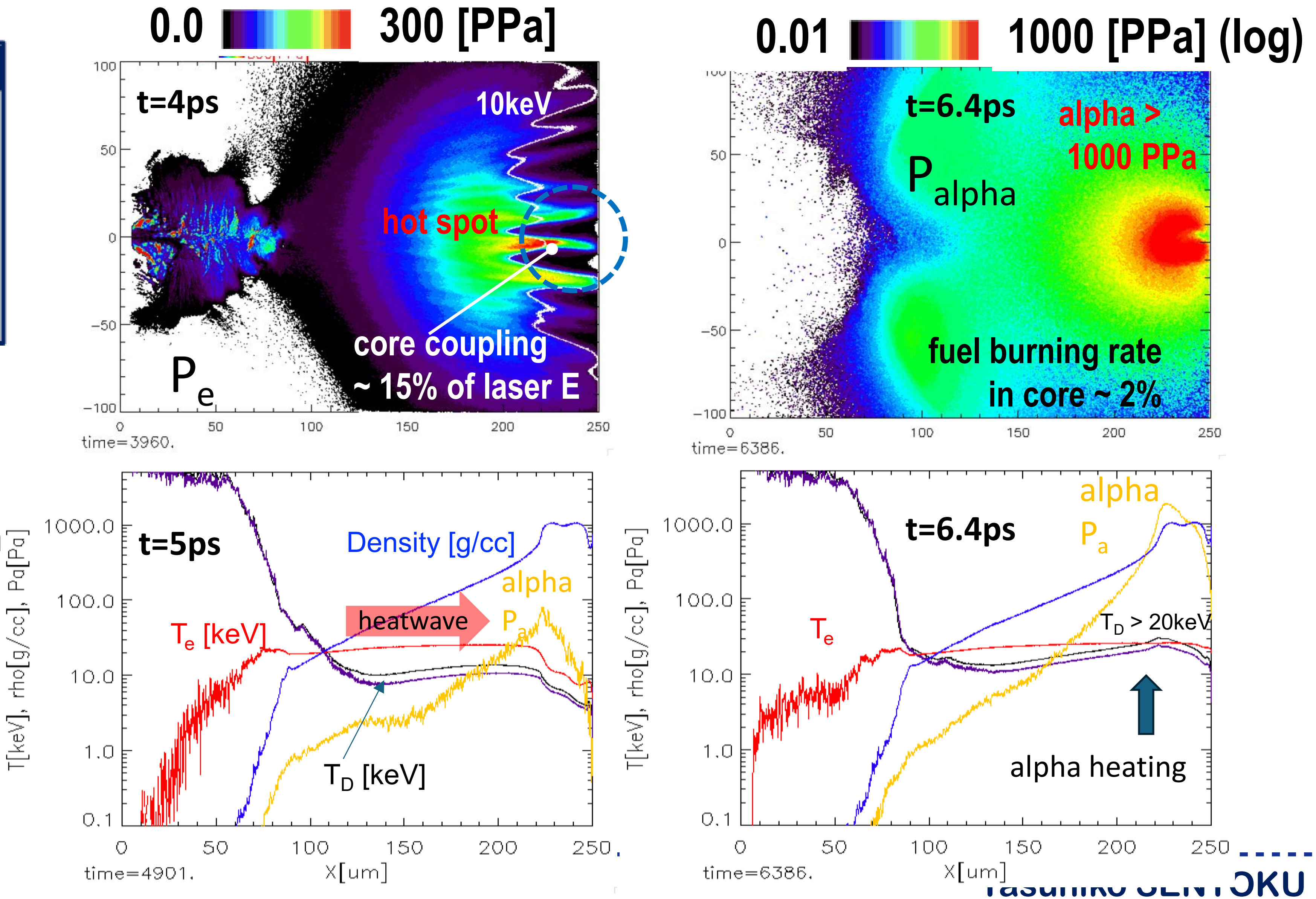
time step 0.025fs simulation time 7ps 2 x 10^9 particles

Heatwave reaches to the core and forms a hot spot, initiating DT fusion burning in the core



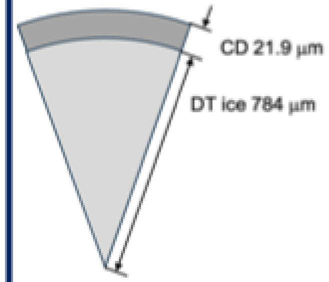
2D-collisional PIC simulation with DT-fusion reactions

after the hot spot formation the core starts burning

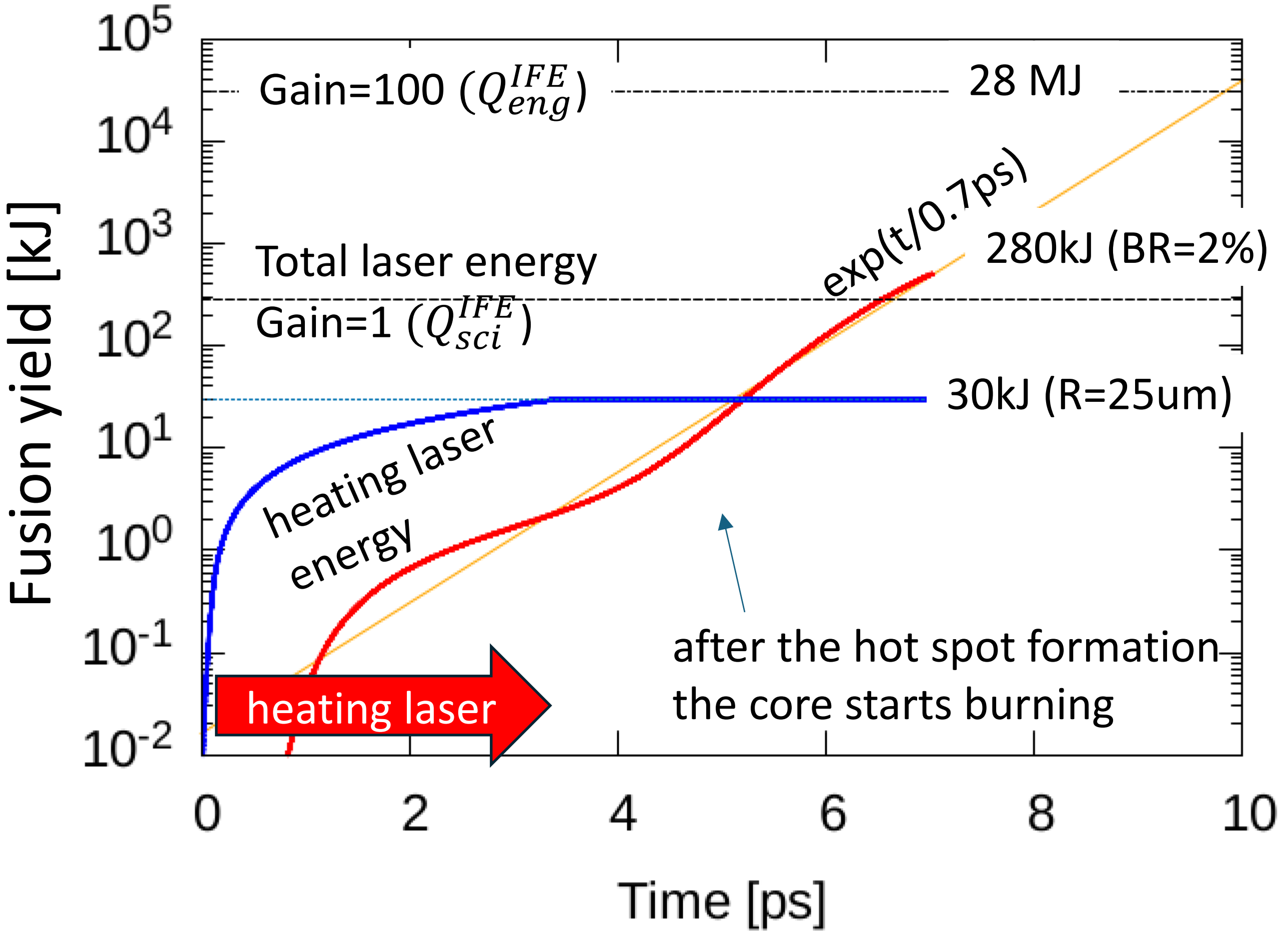


Gain will exceed 100 (about 30MJ yield) in 10ps

IFE scale



Target radius ~ 800μm
Laser energy
implosion 250kJ
heating 30kJ
Gain ~ 100
(30MJ fusion E)



Core can be hold for 10ps with T~10keV.

Thus, the core keeps burning in another 5ps.

IFE/1-1 Y. Arikawa, "High gain fusion burning in inertial confinement fusion plasma" (Burning Physics)

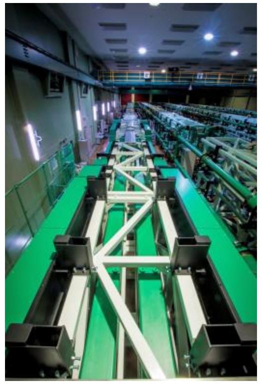
Current GEKKO-XII+LFEX and on-going refinement

GEKKO-XII
Implosion laser

Current
E=2kJ / λ=0.527 μm

E=6kJ / λ=0.351μm
Precise pulse shaping

LFEX
Fast ignition heating PW laser



E=1 kJ

E~3kJ
High reproducibility
High intensity(>10^{21}W/cm^2)

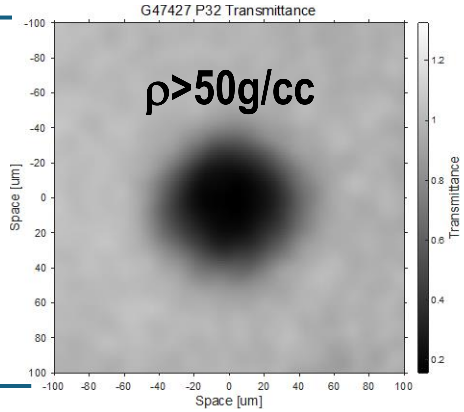
New fast ignition concept

Capsule target

DT liquid target

Solid ball target

Imploded core

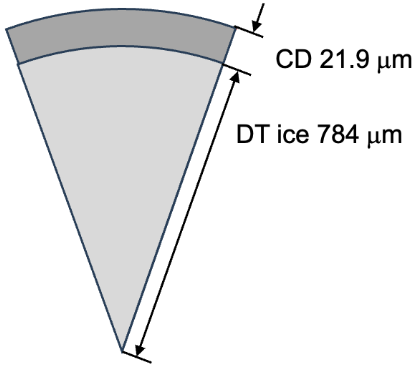


4 keV X-ray backlight image

Poster P-4 R. Takizawa, "Evaluation of solid spherical fuel compression by comparison with simulation" (Implosion)

Scale down the IFE scale to the experimental scale for the refined laser system

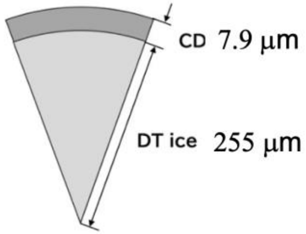
IFE scale



Target radius ~ 800μm
Laser energy
  implosion 250kJ
  heating 30kJ
Gain ~ 100
  (30MJ fusion E)

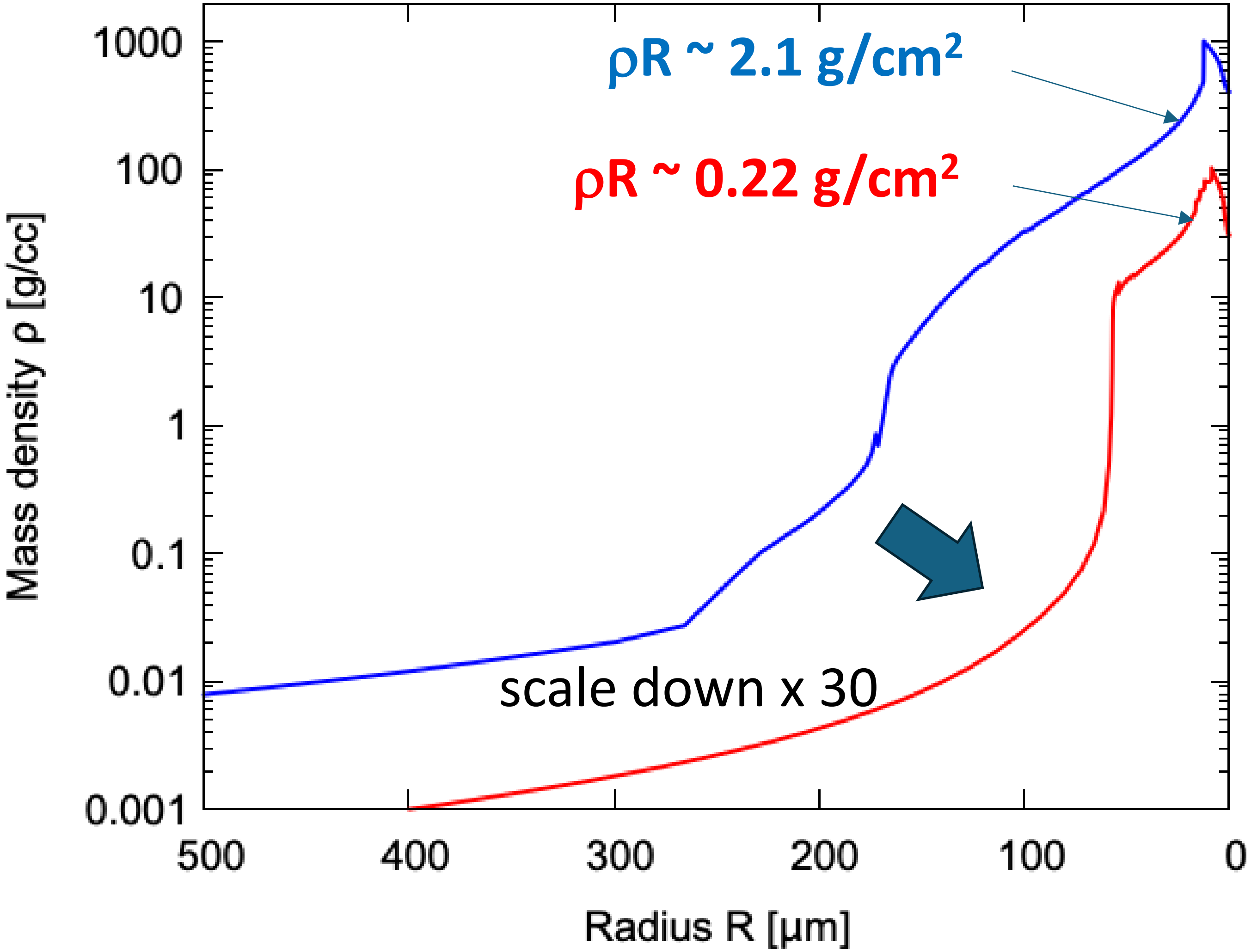
Scale down x 30
(Target mass & Laser energy)

Proof of principle experiment



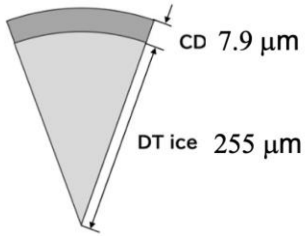
Target radius ~ 260μm
Laser energy
  implosion 6kJ
  heating 3kJ
Gain ~ 1 (10kJ fusion E)

1D-radiation hydro simulation

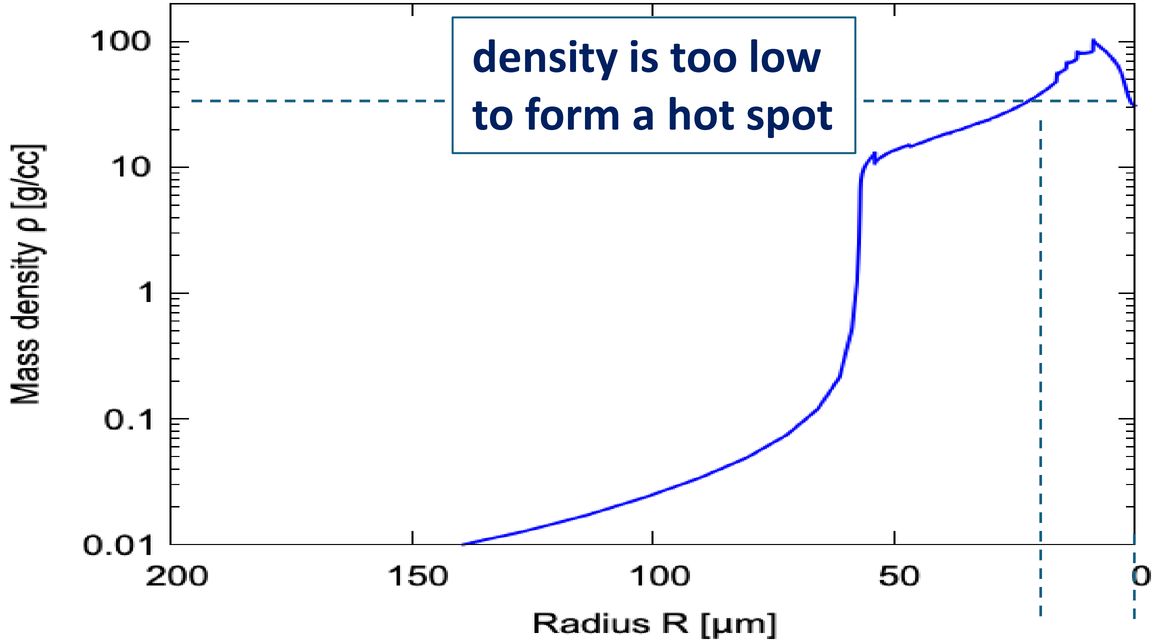


Proof of principle experiment using refurbished laser system
Scale down core x 1/30 with GEKKO-XII (6kJ) + LFEX (3kJ)

Proof of principle experiment

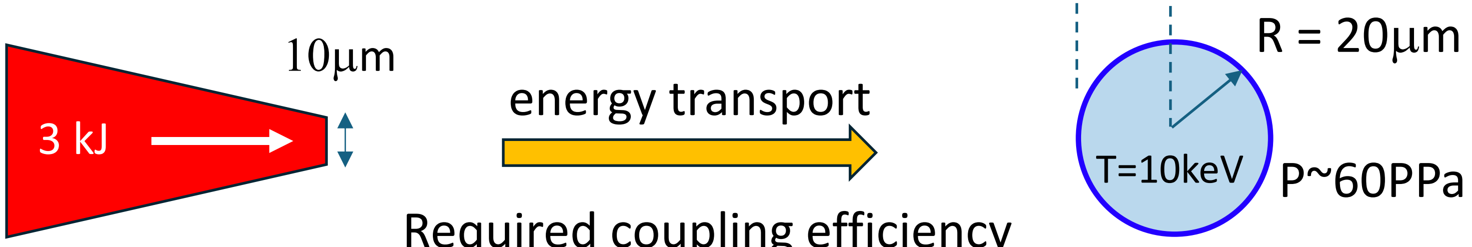


Target radius ~ 260μm
Laser energy
implosion 6kJ
heating 3kJ
Gain ~ 1 (10kJ fusion E)



Heating laser 3 kJ/3ps (1PW)
pulse length 1000μm
spot radius 5μm
intensity 10^{21} W/cm^2
normalized amplitude a_0=30
Energy density 30PPa

core average density
ρ_{av} ~ 60g/cc

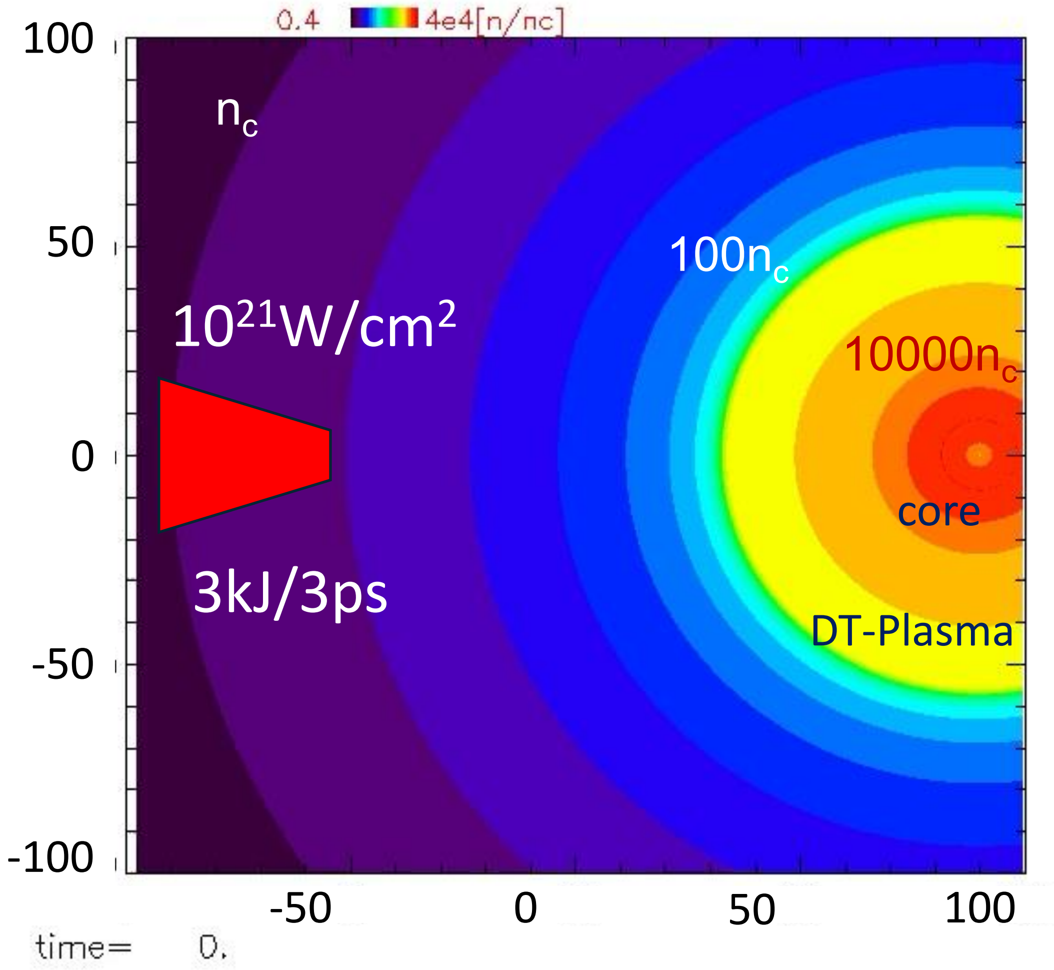


Required coupling efficiency
~ 20%

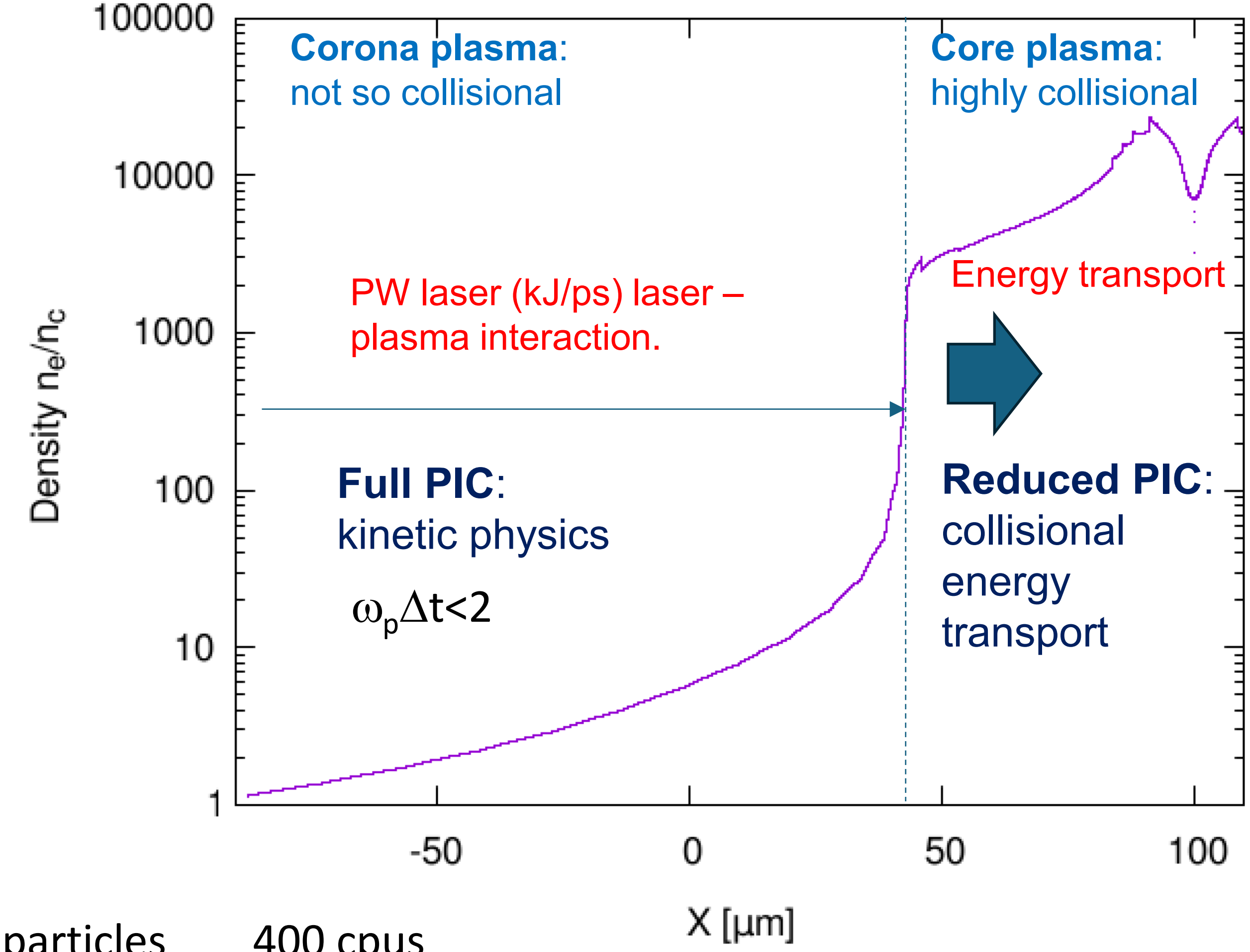
core energy 0.6kJ

Point design of fast ignition scheme for the proof of principle exp. (heating laser 3kJ/3ps) – collisional PIC simulation

Including collisions, DT fusions, radiation losses



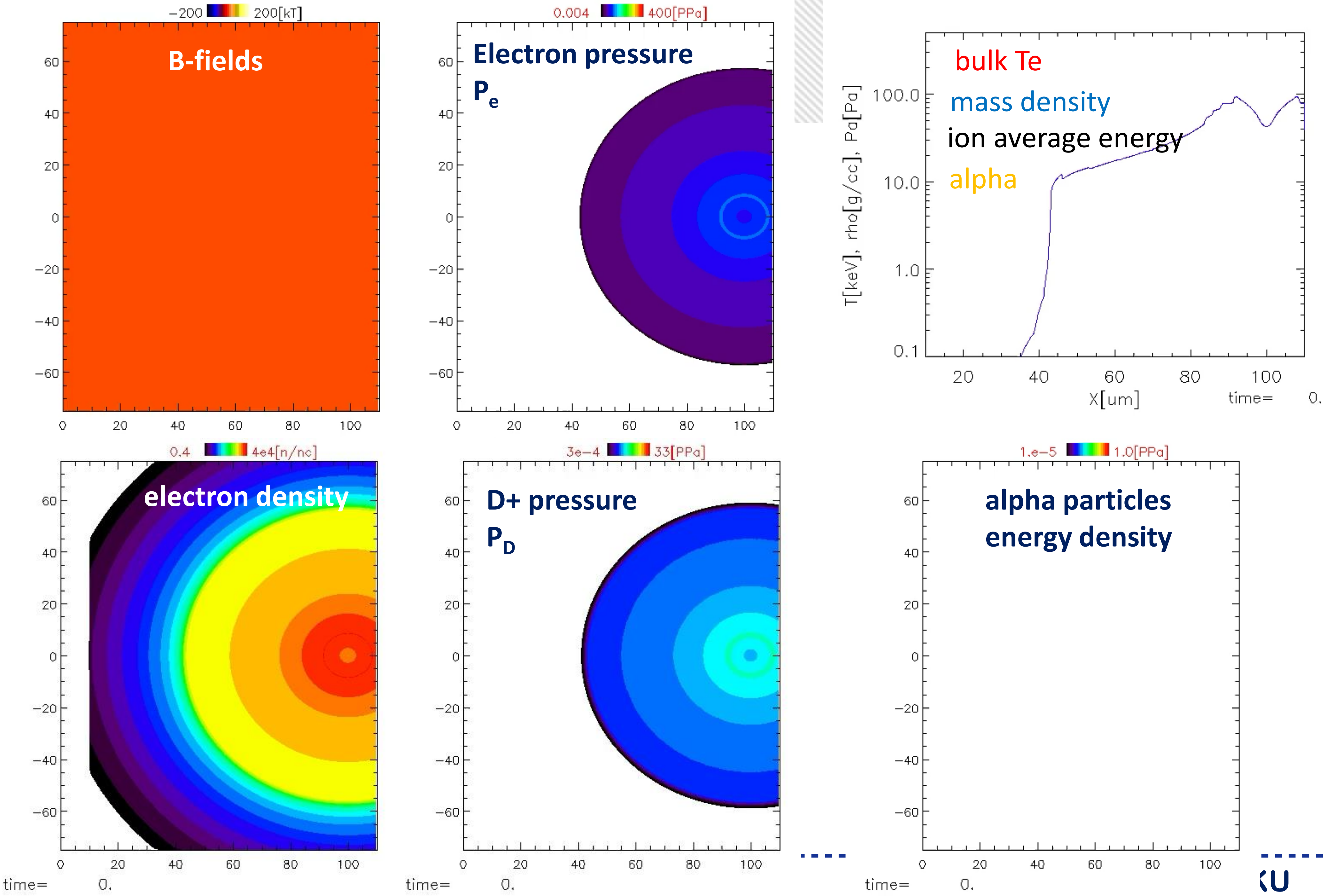
Implosion of a sold ball by 6kJ/3ω
1D-hydro simulation density profile



time step 0.025fs simulation time 6ps 1.3×10^9 particles 400 cpus

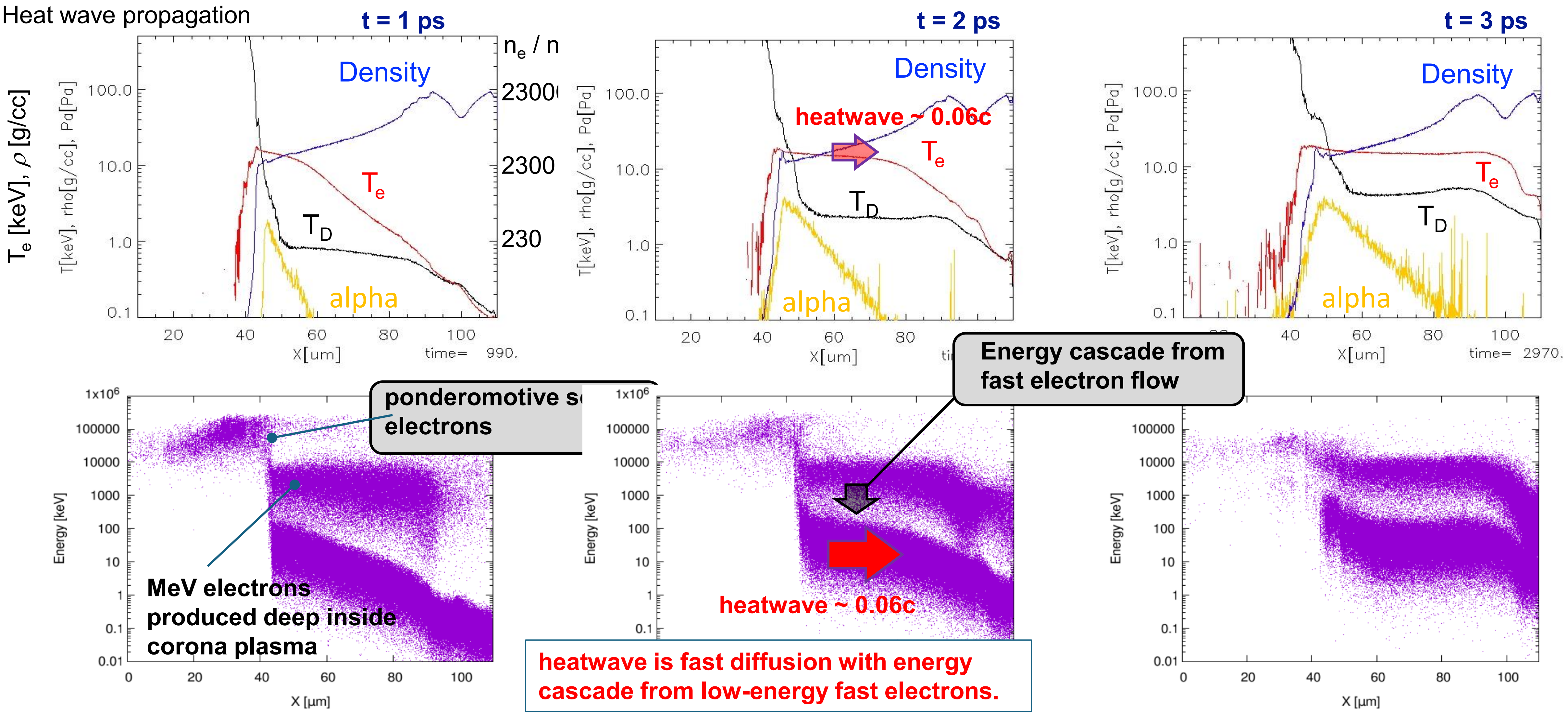
movies

Heating laser
$I=10^{21}$ W/cm^2
1PW (kJ/ps)
duration 3ps
E_L ~ 3kJ



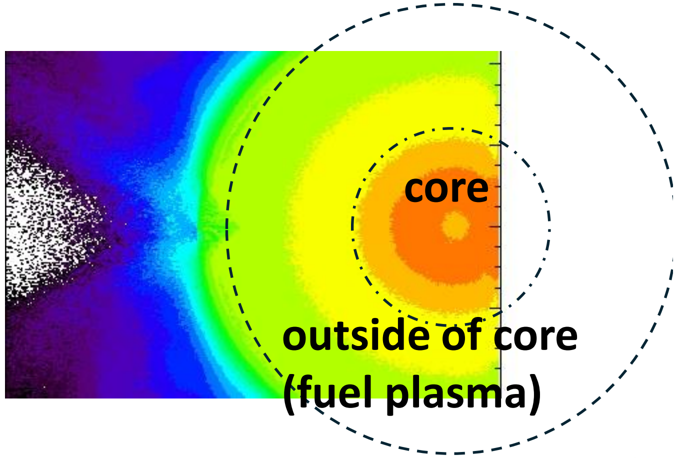
Stage (1~3ps) heatwave

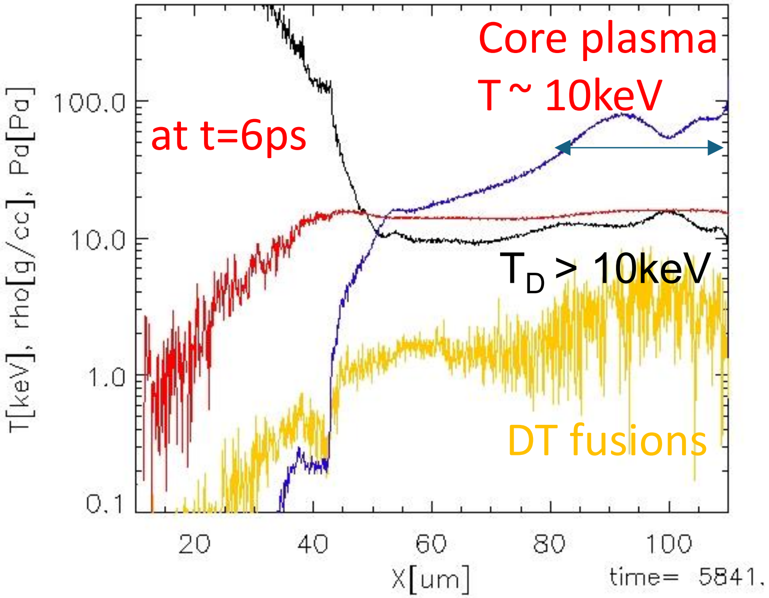
Heatwave propagation to the core

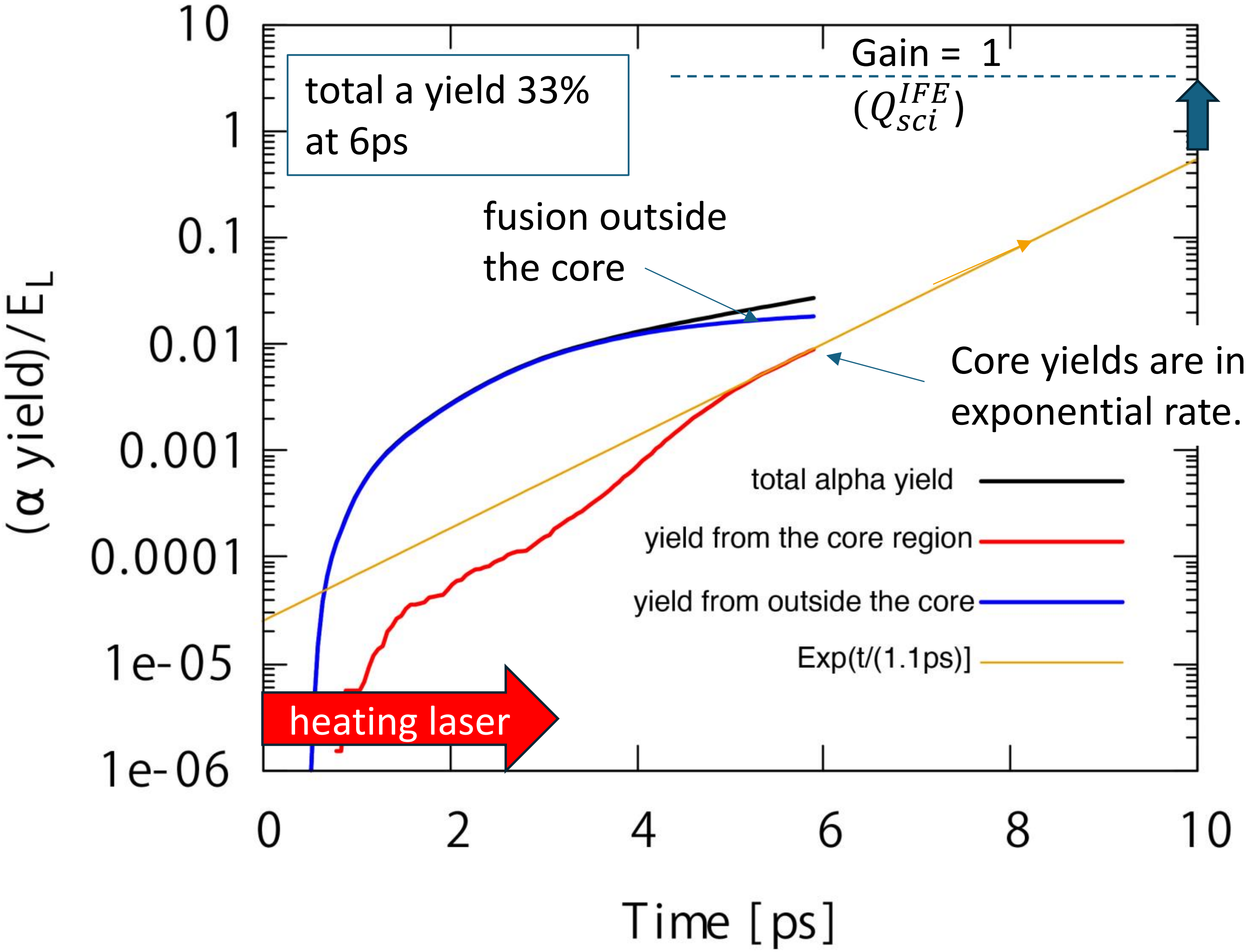


heatwave is fast diffusion with energy cascade from low-energy fast electrons.

The core continues burning for another 4ps, the total yield will exceed 6kJ (Gain ~1) – the proof of principle of the heatwave FI







with neutron yields (x5)

Core can be hold for 10ps with T~10keV.

ILE's strategy: We are refurbishing GEKKO-XII & LFEX lasers. Our facility will demonstrate the heatwave fast ignition with gain ~ 1

Current — 2026年 — 2029年

Proof of Principle：
NIF

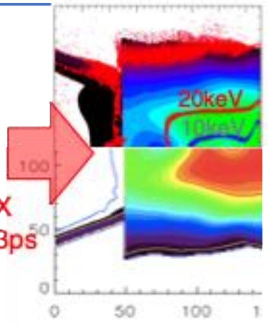
Refinement

High-efficiency demonstration
FIREX
PRL2020

GEKKO-XII
6kJ/3ω
pulse shaping

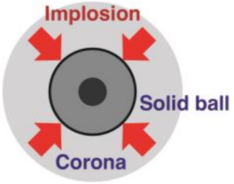
LFEX（4 beam）
3kJ/1.5-6ps
deformable

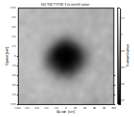
I. Demonstrate heatwave heating & hole boring over critical density



II. Achieve high-density implosion for solid ball explosion
core density 10g/cc → >100g/cc

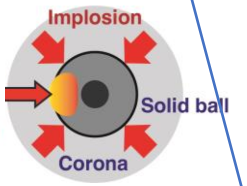
GEKKO-XII
6kJ
Tailored pulses





III. Integrated Experiment solid ball implosion + LFEX heating
core density >100g/cc
Demonstration of efficient heating
Ion temperature ~ 10keV + neutron diagnostics

PW Laser
3kJ/3ps



GEKKO-XII
6kJ
Tailored pulses

Gain ~ 1

Design a compact laser fusion with about 100kJ laser energy and with gain > 100.

High rep laser development

Senju-Lite (10J/100Hz)   Senju (100J/100Hz)   J-EPoCH

IFE/1-5 J. Ogino, "Development of innovative repeatable power laser for laser fusion" (High-rep laser system)

Advanced DT Target Development Research

Measurement and improvement of DT mixing ratio   Development of high-quality DT target

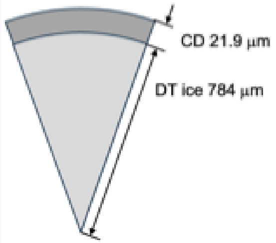
Summary

- Introduce heatwave driven laser fusion with fast ignition scheme by increasing the heating laser intensity > 10^{20}W/cm^2.

- Two point-designs of laser fusion with heatwave driven fast ignition (1) for IFE (gain > 100)
(2) for the proof of principle experiment (Gain ~ 1).

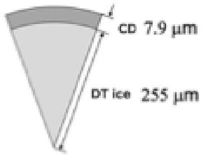
- Strategy for laser fusion research at ILE for the next five years, including the proof of principle experiment of heatwave fast ignition (Gain~1) and the high-rep laser system development.

IFE scale



Target radius ~ 800μm
Laser energy
implosion 250kJ
heating 30kJ
Gain ~ 100
(30MJ fusion E)

Proof of principle experiment



Target radius ~ 260μm
Laser energy
implosion 6kJ
heating 3kJ
Gain ~ 1 (10kJ fusion E)

Acknowledgements

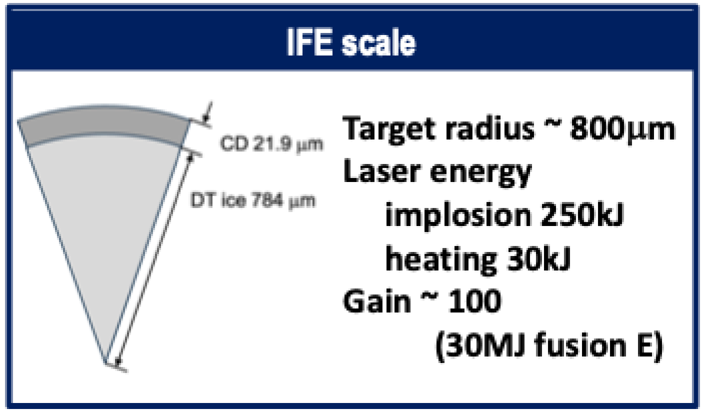
(Theory & Simulations) Natsumi Iwata, Hideo Nagatomo, Tomoyuki Johzaki, Naok,I Okuda, Hayato Yanagawa, Masakatsu Murakami
(Experiments) Yasunobu Arikawa, Ryunosuke Takizawa, Koji Tsubakimoto, Keisuke Shigemori, Takayoshi Sano, Yuki Tamaru, Kohei Yamanoi, Alessio Morace, Yoshiki Nakata, Jumpei Ogino, Akifumi Yogo, Akifumi Iwamoto, Shinsuke Fujioka
(Director) Ryosuke Kodama

LFEX and Gekko XII group, Plasma diagnostics group, Target fabrication group.

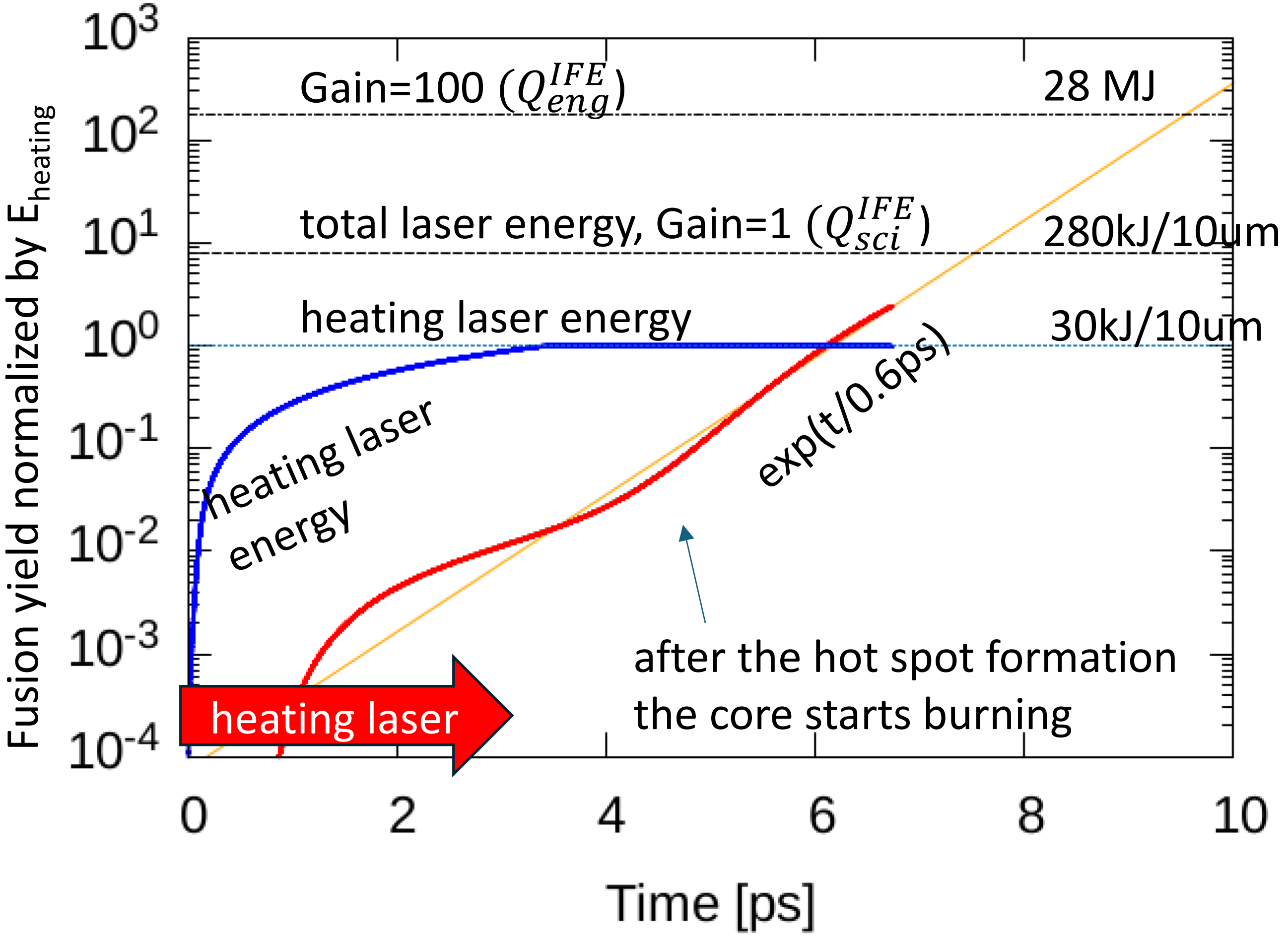
Supplemental budget year 2025 from Japanese government
JSPS KAKENHI JP20H00140, JP24H00204.

科研費 KAKENHI

Gain exceeds 100 (~30MJ yield) in 10ps



2次元換算



Core can be hold for 10ps with T~10keV.

10ps is a time for 10um expansion

Other presentations for IFE

- Poster P-4 R. Takizawa, "*Evaluation of solid spherical fuel compression by comparison with simulation*" (Implosion)
- IFE/1-1 Y. Arikawa, "*High gain fusion burning in inertial confinement fusion plasma*" (Burning Physics)
- IFE/1-5 J. Ogino, "*Development of innovative repeatable power laser for laser fusion*" (High-rep laser system)

Key to demonstrate gain 1 with lasers 6kJ (implosion) and 3kJ (heating)

[Implosion]

- High-precision pulse tailoring with 4-5 orders magnitude, and well-balanced laser energy among the beams.
- Fabrication of solid/liquid DT fuel target.

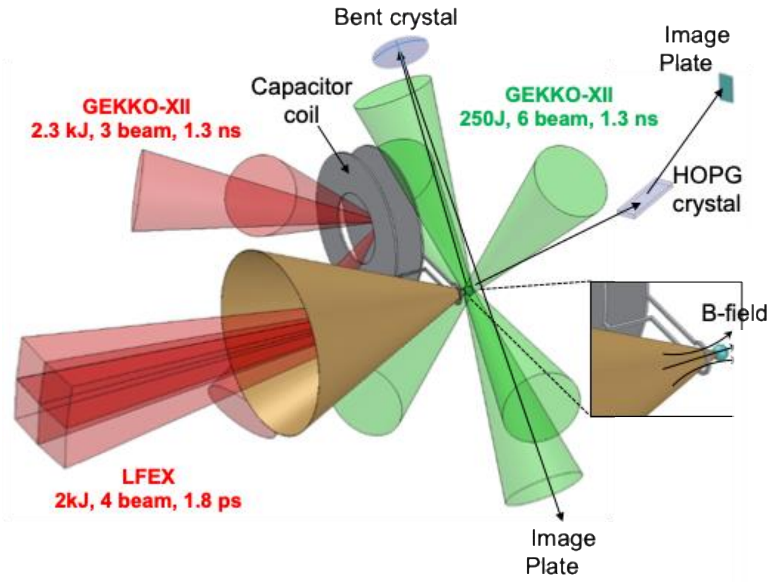
[Heating]

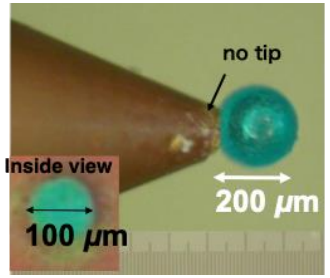
- High intensity > 10^{20} W/cm^2 to deeply penetrate in coronal plasma (hole-boring and heatwave heating)
- 1kJ for hole boring, 2kJ for heatwave heating to initiate the DT fusion burn in the core.
- The alpha heating started, but they are still small. Need denser core (challenge of implosion).

Experimental demonstration of fast heating with 3.5kJ (1.5kJ implosion + 2kJ PW laser)

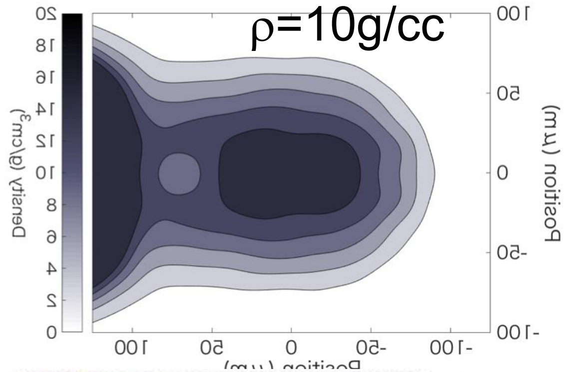
ILE, Osaka

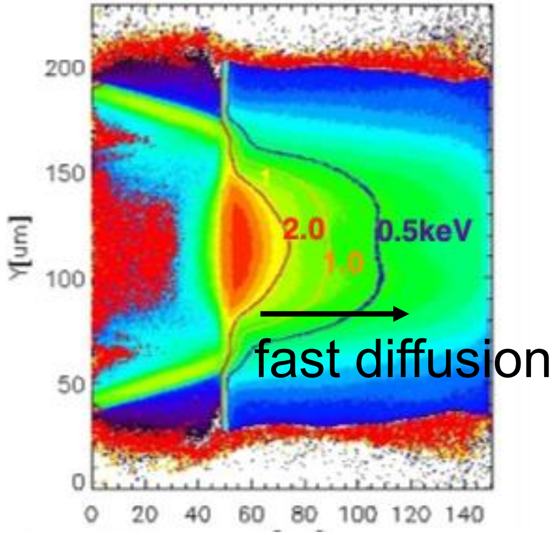
Experimental set up





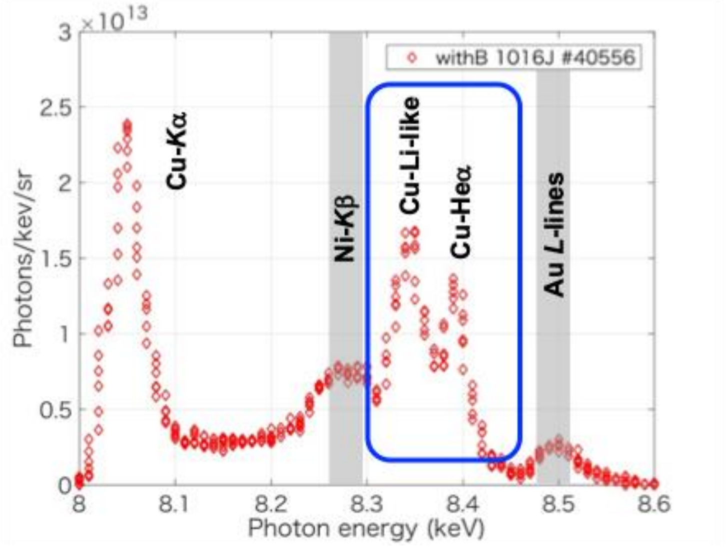
copper dopped solid CH ball





X-ray spectrum @0.72ns

X-ray spectrum contains also emissions from a Ni coil and Au cone.



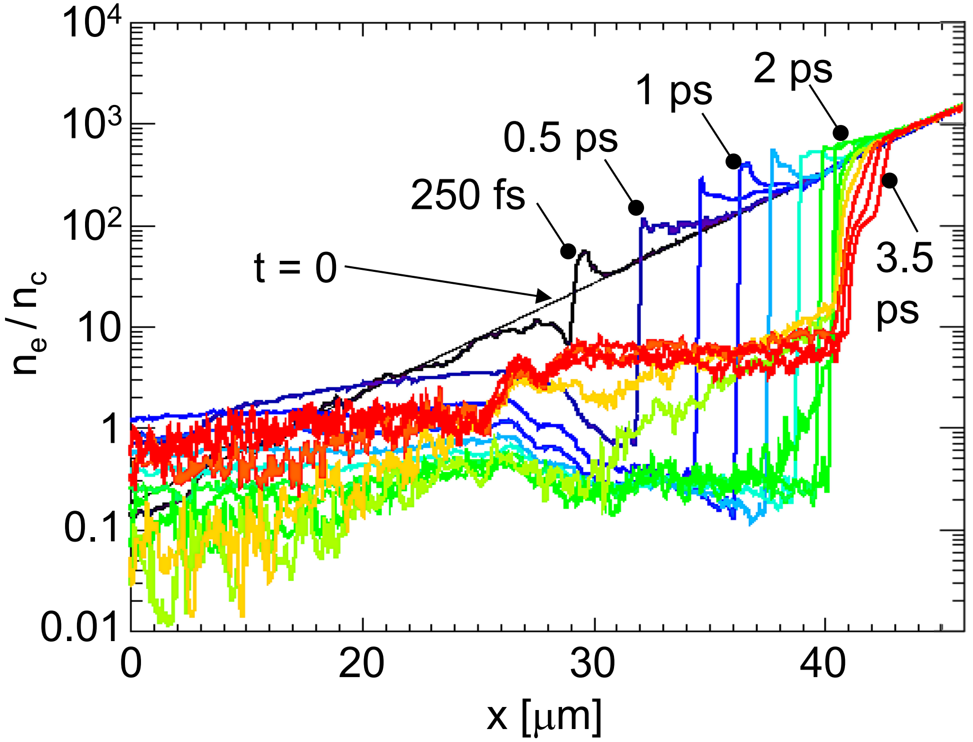
By fitting the spectrum with FLYCHK, the core temperature ~ 1keV and 2PPa.

[1] K. Matsuo, N. Higashi, N. Iwata et al., Phys. Rev. Lett. 124 (2020), 035001.

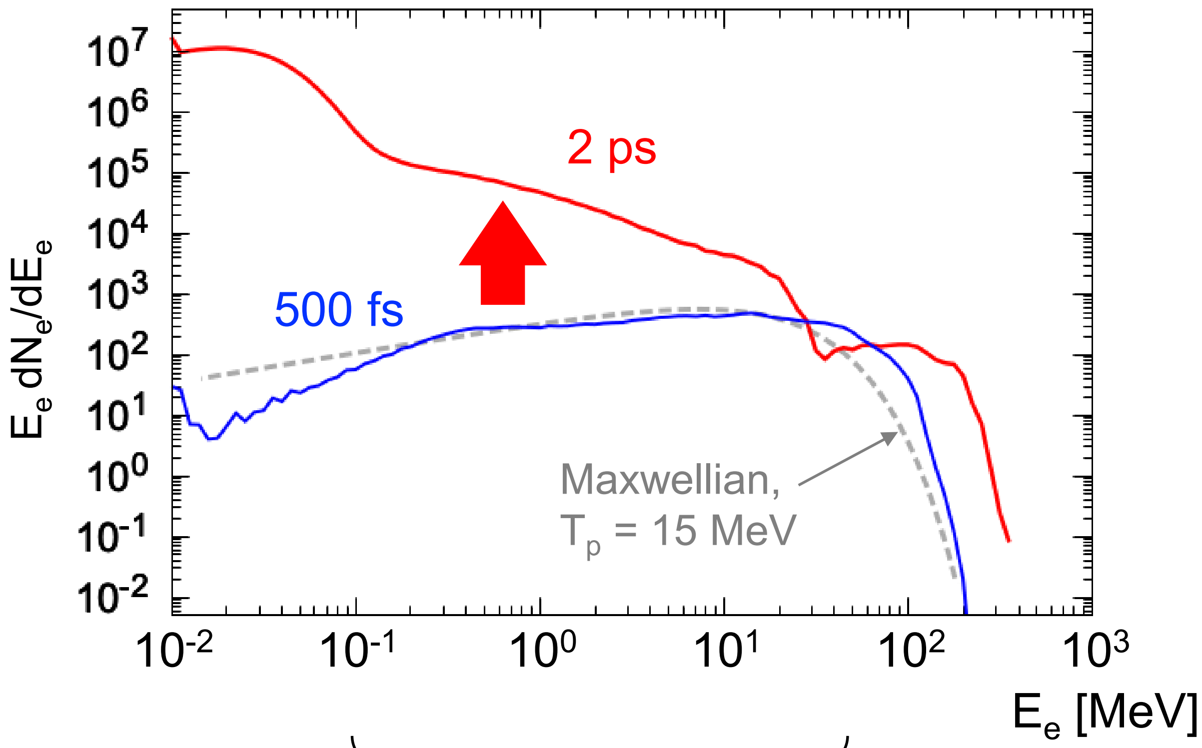
[2] N. Higashi, N. Iwata, T. Sano et al., Phys. Rev. E 105 (2022) 055202.

After the interface steepens, changes in the properties of fast electrons drive thermal waves

Temporal evolution of plasma density



Electron energy spectrum observed in x > 40 μm



Average energy (100 keV < E_e < 50 MeV, t = 2 ps)

E_{av} = 620 keV << Ponderomotive energy T_p

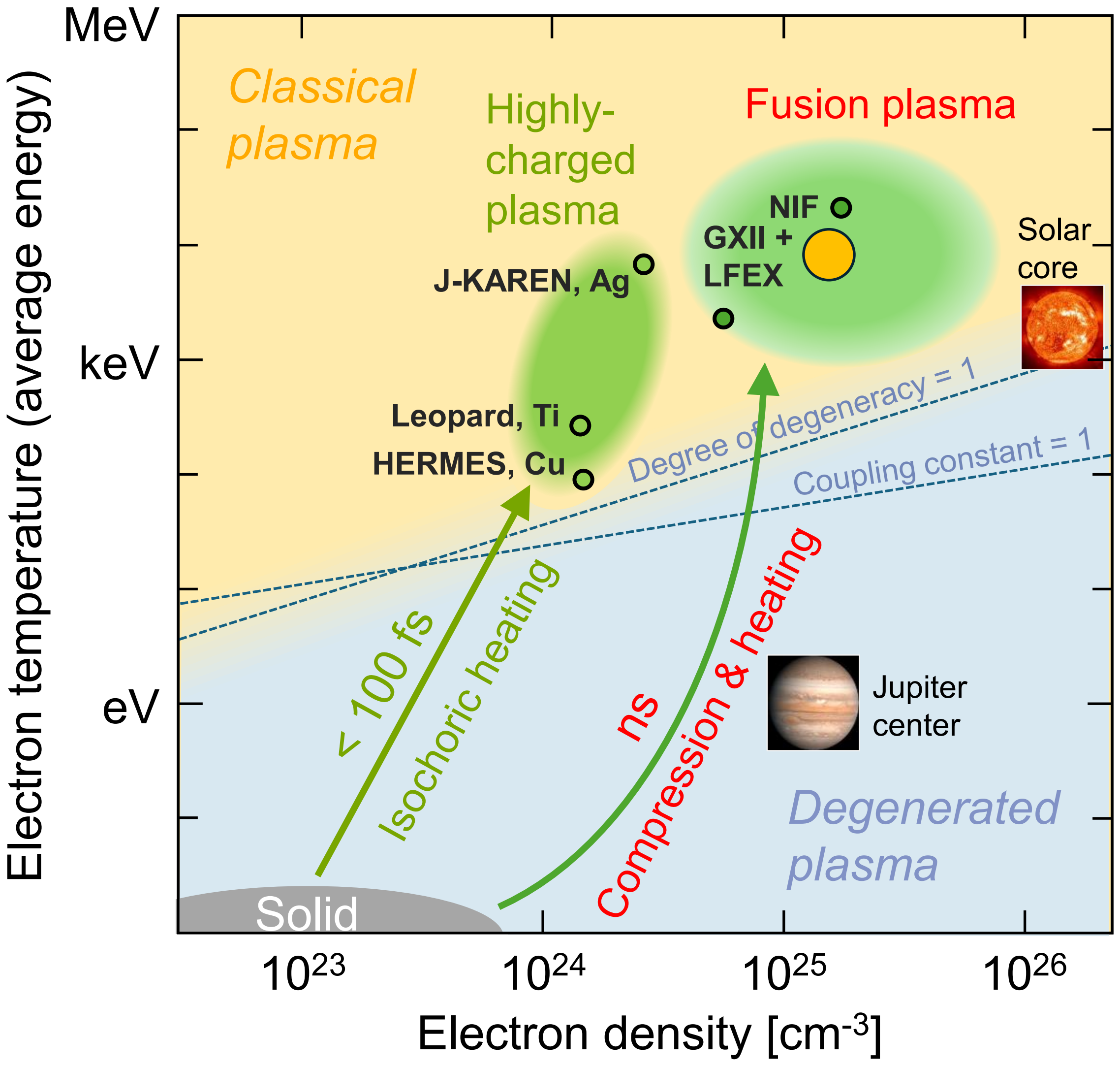
N. Iwata, Invited talk, Mon Afternoon

Heating of high-density plasmas by high power lasers

fs high-power lasers
Energy 0.1-1 J
Pulse length 10-100 fs

Generate highly-charged hot plasmas with energy densities equivalent to the laser light pressure.
($T_e << T_i$)

Application to radiation source, highly-charged heavy ion source, etc.



ps-ns high-power lasers
Energy kJ-MJ
Pulse length ps-ns

Generate large-volume dense hot plasmas with energy densities exceeding the laser light pressure.

Application to fusion energy
($T_e \sim T_i$)

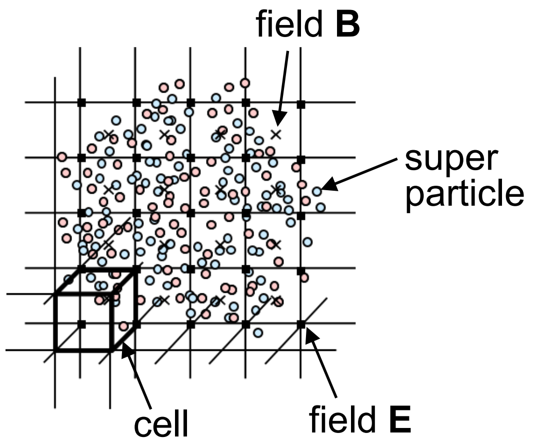
H. Sawada *et al*., Nat. Commun. **15**, 7528 (2024); H. Abu-Shawareb *et al*., PRL **132**, 065102 (2024), K. Matsuo et al., Phys. Rev. 124, 035001 (2020)

Plasma particle (particle-in-cell, PICLS) simulation with Coulomb collisions and DT fusions

First-principles calculation

PIC solving the basic equations of kinetic equations and the Maxwell's equations

e.g.,
solid density
10^{23} cm^{-3} x target size
(100 μm)^3 = 10^{17}, too much!



Typical number of super particles in a PIC simulation
2D simulation ~ 10,000,000
3D simulation ~ 100,000,000

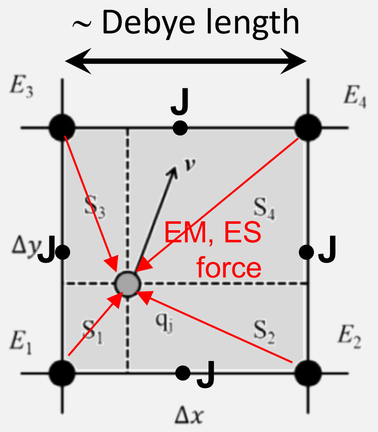
Basic loop of PIC simulation

For each super particle
Eq. of motion

$$\frac{d\mathbf{p}_j}{dt} = q_j\left(\mathbf{E} + \frac{\mathbf{v}_j}{c}\times\mathbf{B}\right)$$

$$\frac{d\mathbf{x}_j}{dt} = \mathbf{v}_j$$

Current density **J** ↓ ↑ **E, B**



Maxwell eqs.

$$\nabla\times\mathbf{E} = -\frac{1}{c}\frac{\partial\mathbf{B}}{\partial t}$$

$$\nabla\times\mathbf{B} = \frac{1}{c}\frac{\partial\mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{J}$$

＋ **Monte Carlo processes** such as Coulomb collisions, ionizations, radiations, QED processes, and fusions

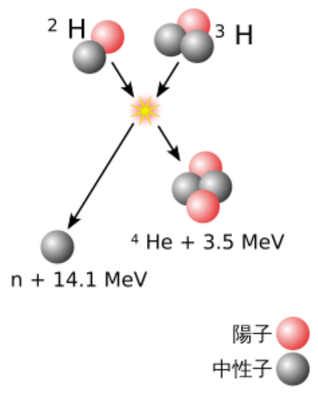
PIC scheme

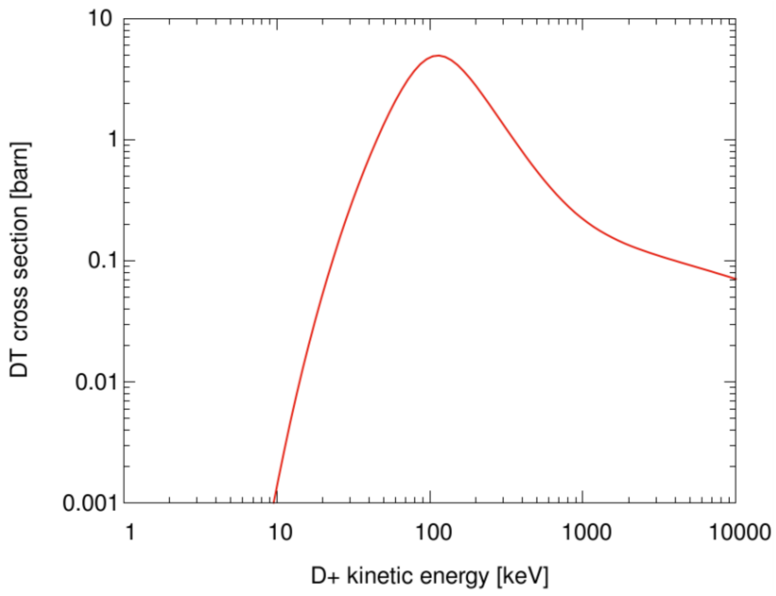
One PIC particle (super particle), which has a size of Debye length, has a weight of 10^{10} real particles.

Distribute super particles and solve the kinetic equation for each.

Super particles move based on the average electromagnetic field at a distance equivalent to the the Debye length.

PICLS binary collision model for DT fusion reactions





Binary collision calculation for fusion reaction

Binary collision

Random sampling

Scattering angle ϑ_{cm}

Laboratory frame

Lorentz transform

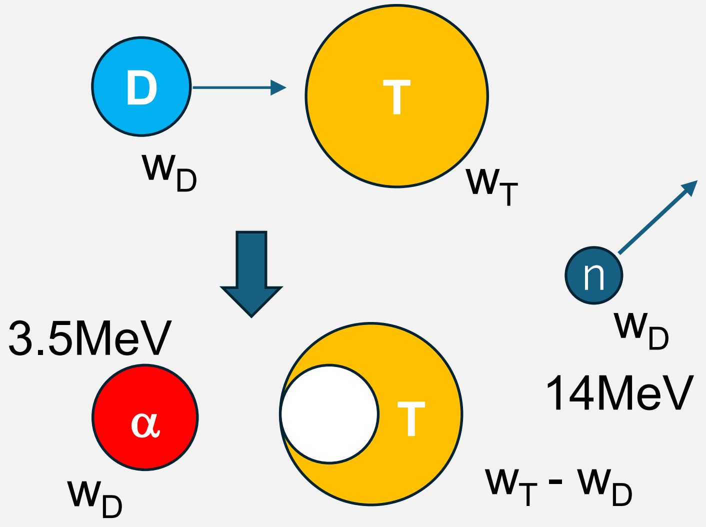
Center of momentum frame

DT fusion frequency

$$\nu_{DT} = \sigma_{DT}(\epsilon_D) n_T v_{rel}$$

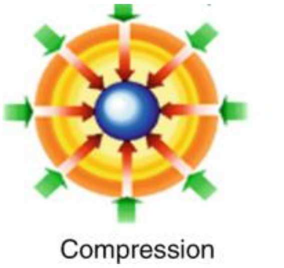
Do fusion in CoM frame and transfer back to lab frame

Fusion between different weights ➔ adjust the timestep as weighted collisions



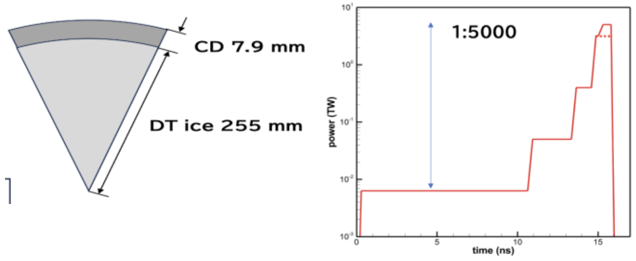
see Sentoku and Kemp, JCP 227, 6846 (2008) for weighted particles collisions.

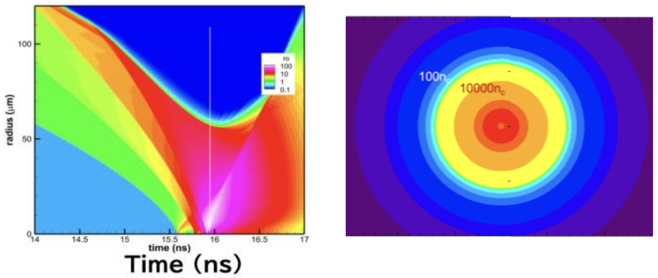
Establishing integrated simulation platform for laser fusion (FIREX-NEO project)



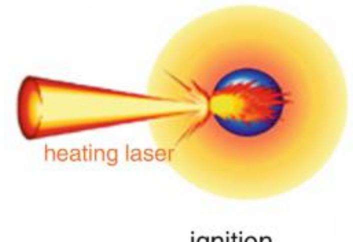
Rad-Hydro

10 nanoseconds



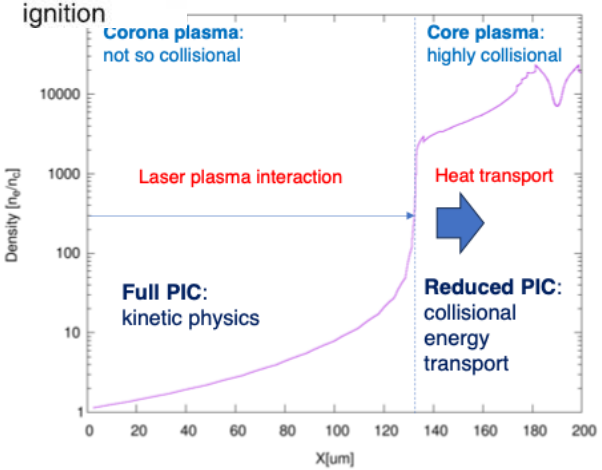


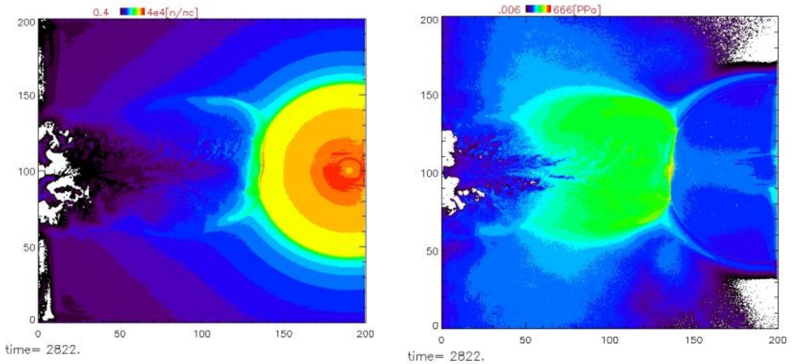
n, T



Fusion PIC

10 picoseconds



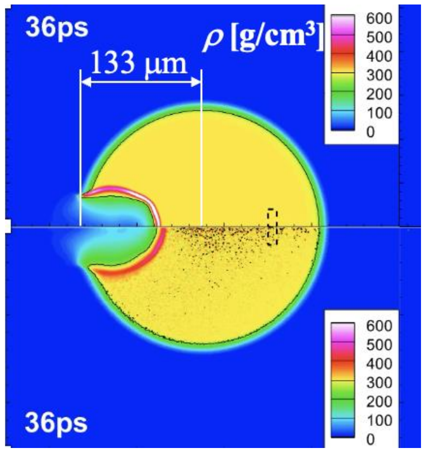


n, P, v_{flow}

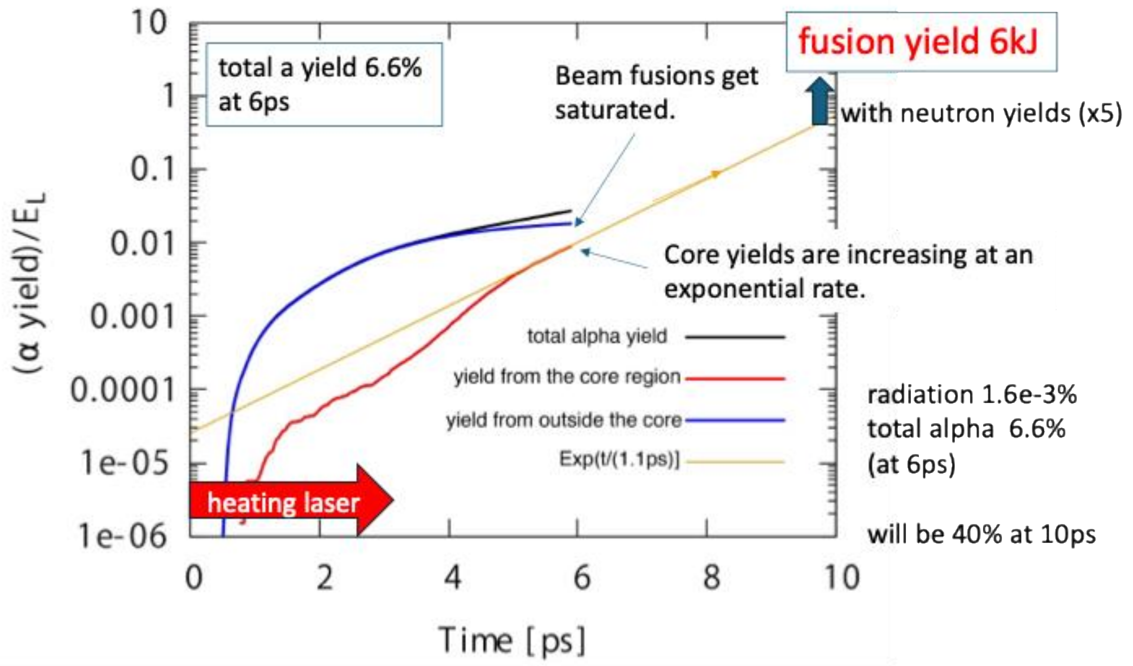
burning

Burning FP

50 picoseconds



Fuel gain



R=60um
T=100eV
ρ=40g/cc

E(fuel) = 0.34×10^7 J/m (155J in 3D)

R=20um
Ti=10keV
Te=20keV
ρ=100g/cc

E(hotspot) = 4.8×10^7 (ions) + 10×10^7 (eons)
~ 14.8×10^7 J/m (2.16kJ in 3D)

at 6ps
6.6%x5xE_L

E(fusion) ~10×10^7 J/m (6kJ in 3D)

at 10ps
40%x5xE_L

E(fusion) ~60×10^7 J/m (6kJ in 3D)

$$G_{fuel} = \frac{E_{fusion}}{E_{fuel} + E_{hotspot}}$$
$$= \frac{60}{0.34 + 14.8} = 3.96\ (2D)$$
$$= \frac{6}{0.155 + 2.16} = 2.59\ (3D)$$