High gain fusion burning in inertial confinement fusion plasma

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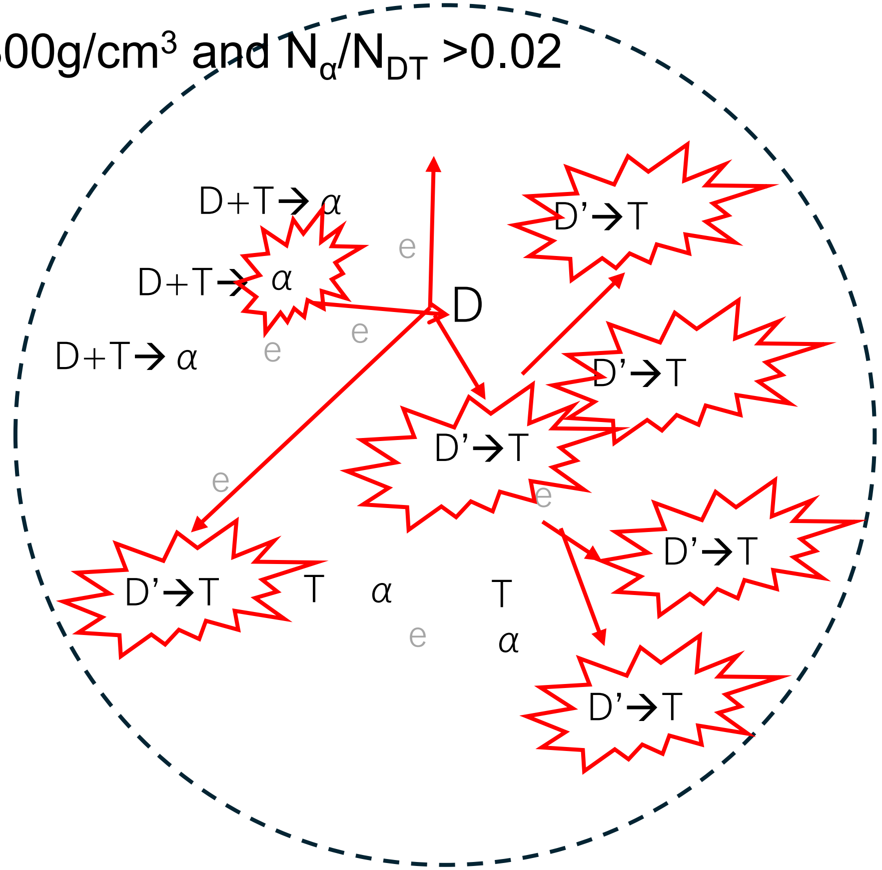
ρ>800g/cm^3 and N_α/N_{DT} >0.02



Avalanche fusion

D+T→ α +n
α +D→ α +nD*
D*+T→ α +n
D*+T→ α +n
α +D→ α +nD*
D*+T→ α +n
D*+T→ α +n
D*+T→ α +n
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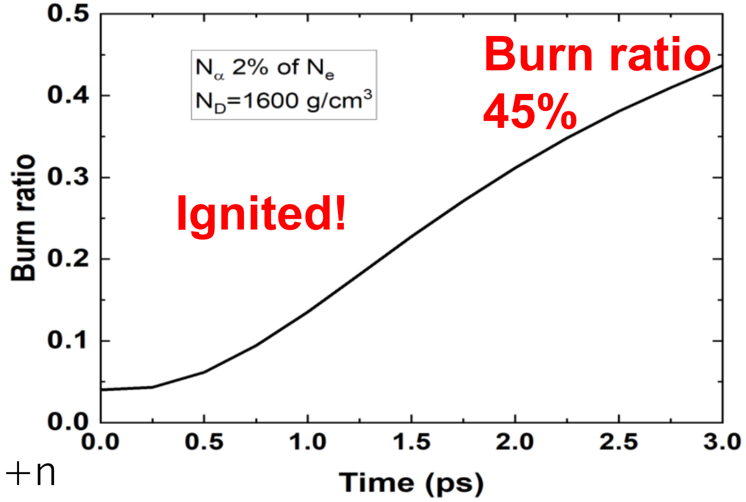

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Summary

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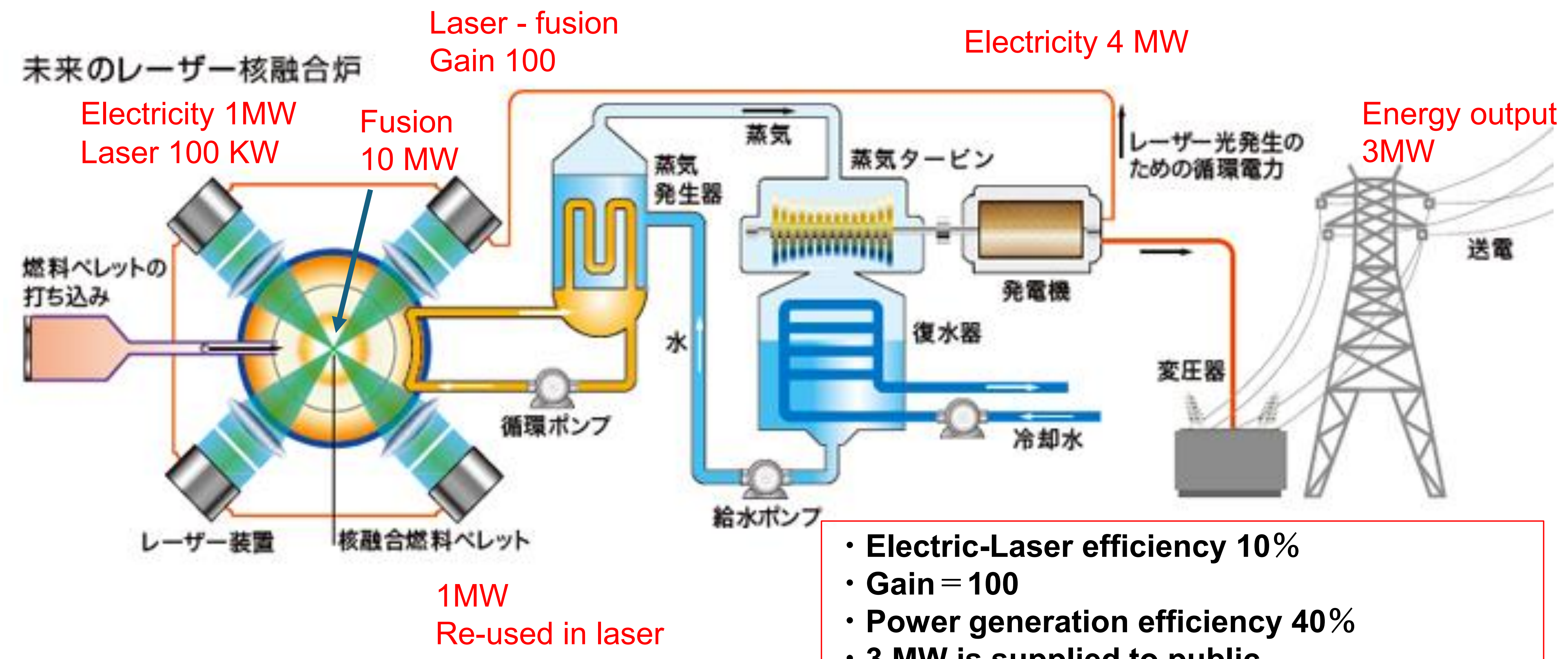
1. A high gain fusion scheme ”avalanche fusion” is proposed.

2. When two conditions are satisfied, (1) N_α:N_e>0.02:1 and (2)N_D>$10^{26}$$cm^3$,
   α collides to D, generates D* (100keV), then the D* +T fusion occurs at max cross section.
   α increases exponentially in much shorter time than inertial confinement time.

3. 1D-PIC simulation shows the avalanche fusion is ignited with >45 % burn ratio.

4. The avalanche fusion is independent to the Generalized Lawson criterion,
   it can be a new path-way to the high gain fusion.

IFE reactor essentially requires gain of 100.



- Electric-Laser efficiency 10％
- Gain＝100
- Power generation efficiency 40％
- 3 MW is supplied to public.
- 1 MW is re-used in laser.

NIF has achieved gain of 4

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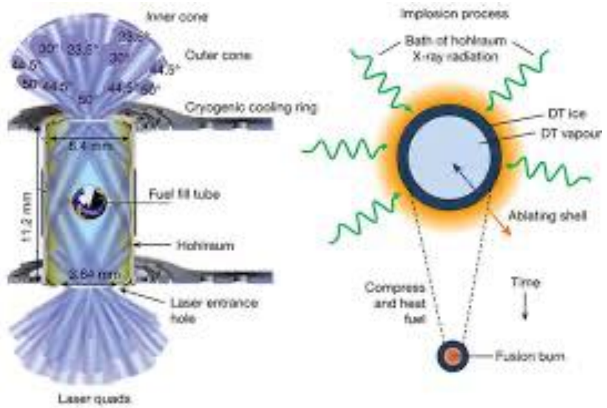
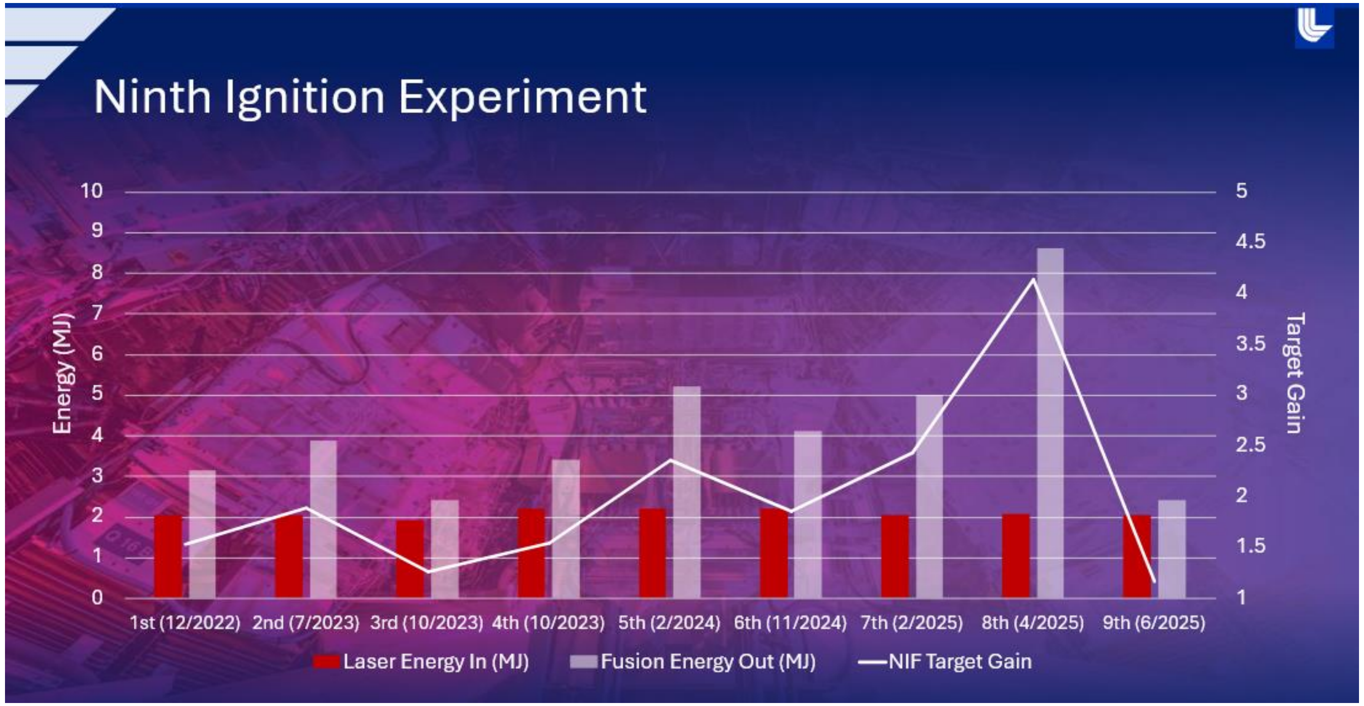
Laser energy input 2MJ →Fusion energy out put 8MJ, burn ratio of ~7%





「How can we increase the gain to 100 ?」

We need to improve laser to plasma coupling,

(by Improving laser, Fast ignition, Direct-drive, improving target design, etc)

Todays talk ; A new fusion approach with "Avalanche fusion"

Thermal fusion and burn wave

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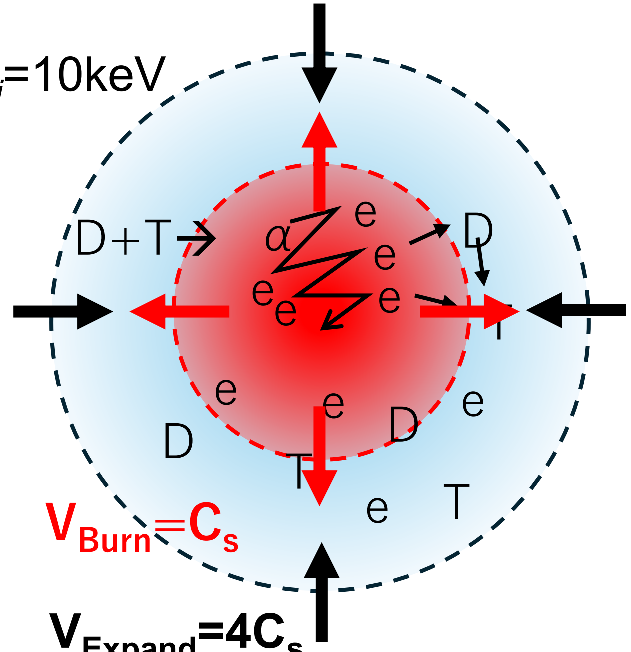
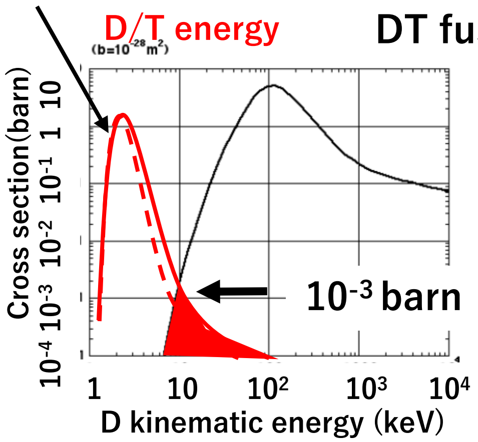
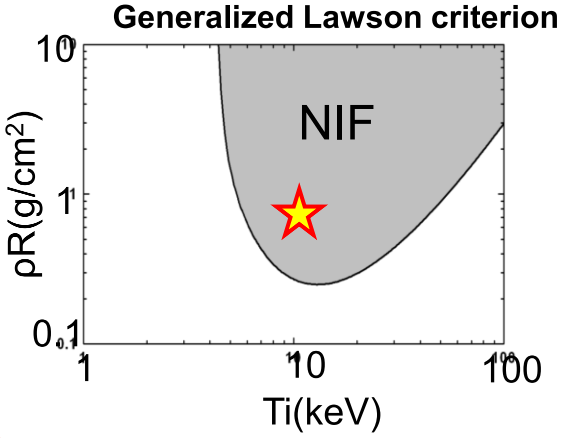
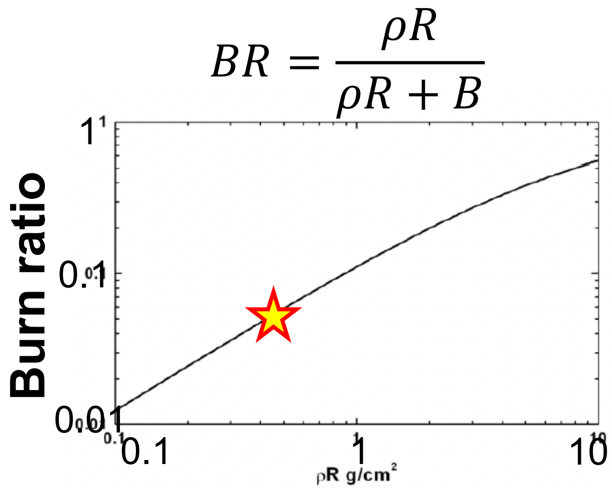
D+T→α(3.5 MeV)+n(14.1 MeV)



T_i=10keV Maxwell distribution







Fusion cross section is ~10^{-3} barn at T_I~10 keV

BR ~7%[1]

1. α→e collision creates many electrons (e') with E_e<10keV.
2. e' → D/T collision creates many D'/T' s with $E_{D'}$<10 keV. $E_{D'}$ spectrum becomes Maxwell-dist.
3. D'+T' cross section is increased.
4. When Ti and ρR exceed Lawson Creation threshold, the fusion ignites.
5. Fusion burn wave propagates with V~C_s. BW propagation time is $\tau_{burn}\sim\frac{R}{Cs}$.
6. Plasma confinement time is $\tau_{confine}\sim\frac{R}{4Cs}$.
7. Burn ratio is BR = ρR/(ρR+B) ~0.1ρR.

[1]O. A. Hurricane, PRL, 132, 065103 (2024), and presentations

New concept: Avalanche fusion

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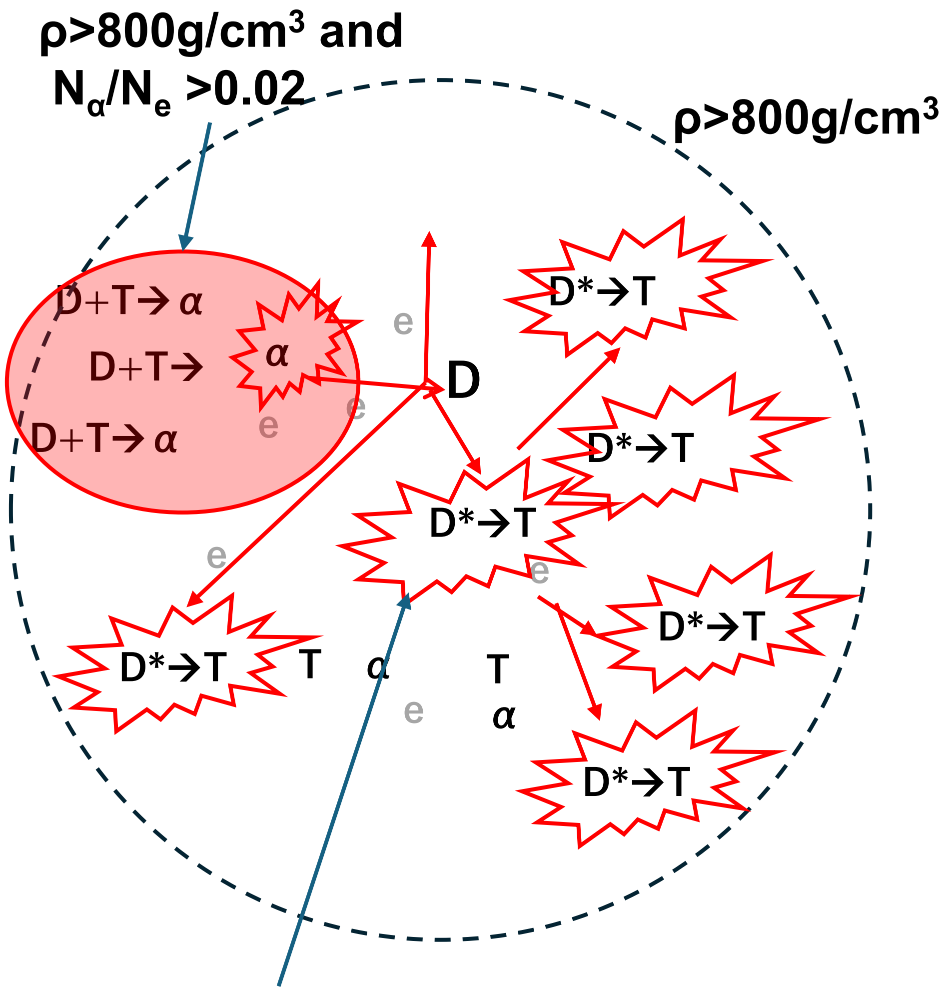
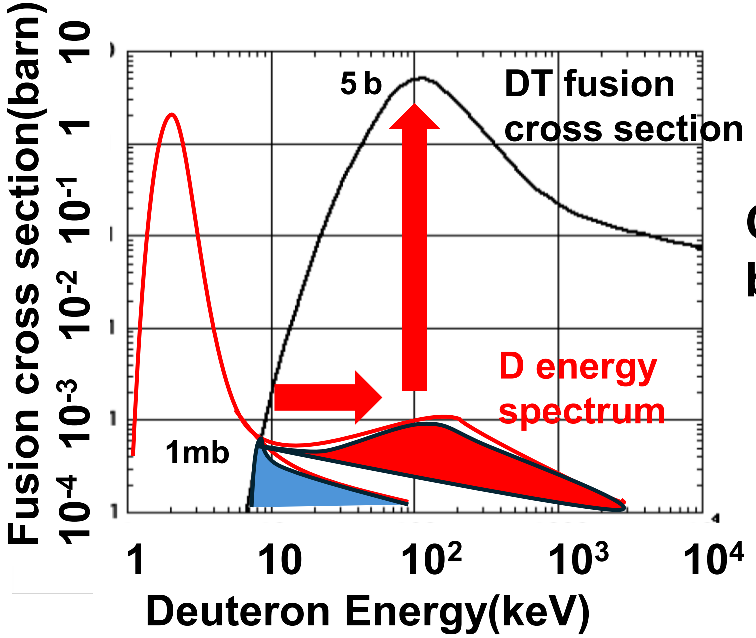


D* (>100keV) is created by direct collision.



Cross section at E_D=100keV becomes maximum (5 barn).

Avalanche fusion*

*Number of α increases exponentially

D+T→α+n

α+D→α+εD* 【number of D* = ε=~20】

D*+T→α+n

D*+T→α+n

α+D→α+εD* 【ε=~20】

D*+T→α+n

D*+T→α+n

D*+T→α+n

D*+T→α+n

Key physics 1: Collision frequency changes

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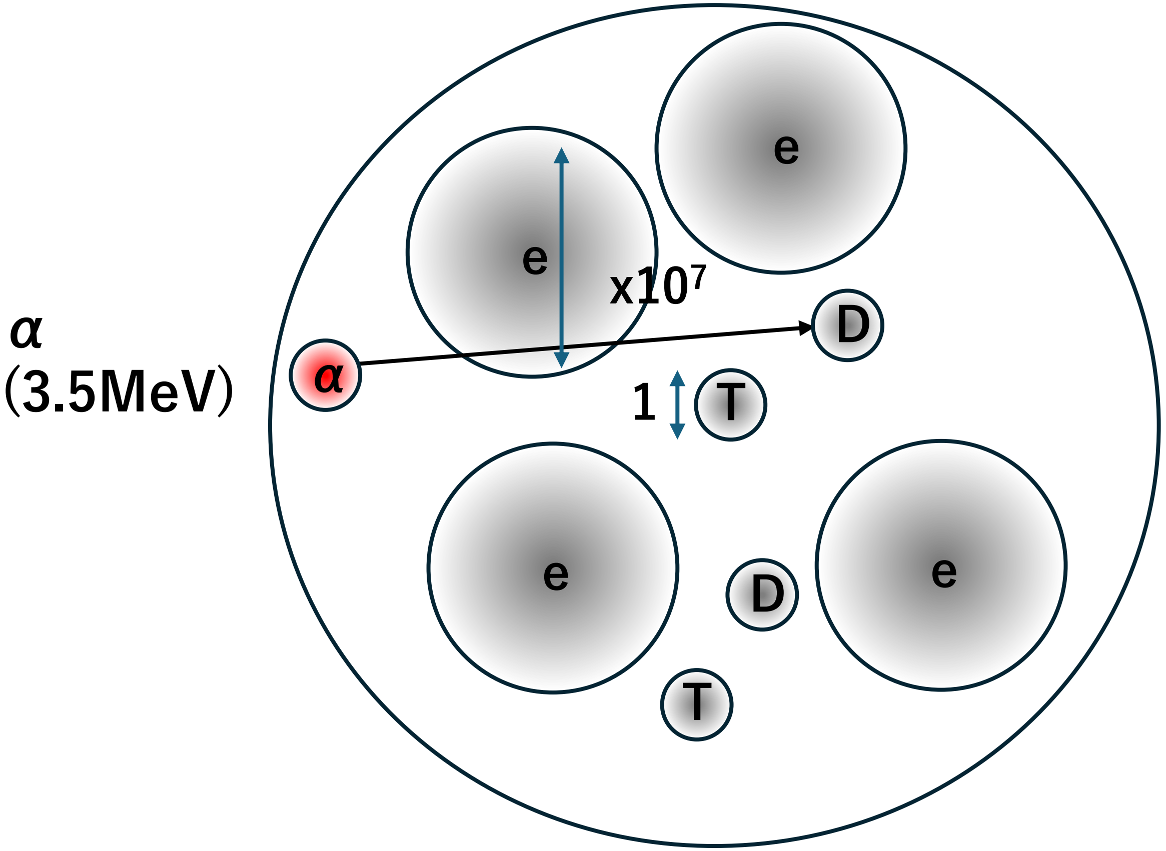


Coulomb collision frequency

$$\nu_{1-2} = \frac{8\pi n_2 (q_1 q_2)^2 ln\Lambda}{m_2 \mu |v_1 - v_2|^3} \frac{1}{(4\pi\varepsilon_0)^2}$$

1 = α , 2= e, D,T

In DT plasma (T_e=10keV)

$\nu_{\alpha\text{-}e} : \nu_{\alpha\text{-}D} = 10^7:1$

If E_e exceeds > 30 keV, $v_\alpha < v_e$, then $\nu_{\alpha\text{-}e}$ decreases.
When $v_\alpha \ll v_e$ $\nu_{\alpha\text{-}e}$ becomes → 0 .

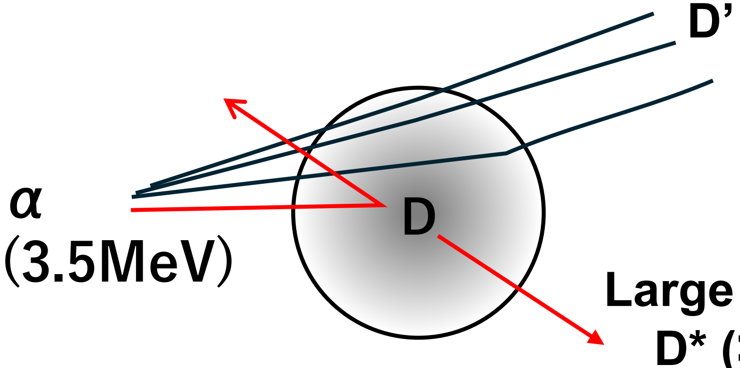
Next, α→D and T occurs.
The dominant reaction is changed from α-e to α-D.

$N_\alpha E_\alpha$ needs to be larger than $N_e E_e$,
thus $N_\alpha E_\alpha$(3.5 MeV) > $N_e E_e$ (30 keV)
N_α:N_e =>0.0085:1.
We defined as N_α:N_e=>0.02:1.

Condition 1; N_α/N_e >0.02

Key physics2: Large angle scattering

Small angle scattering (~0.999)
D' ~10keV



Large angle scattering (10^{-3})
D* (>100keV)

$$\nu_{1-2} = \frac{8\pi n_2 (q_1 q_2)^2 ln\Lambda}{m_2 \mu |v_1 - v_2|^3} \frac{1}{(4\pi\varepsilon_0)^2}$$

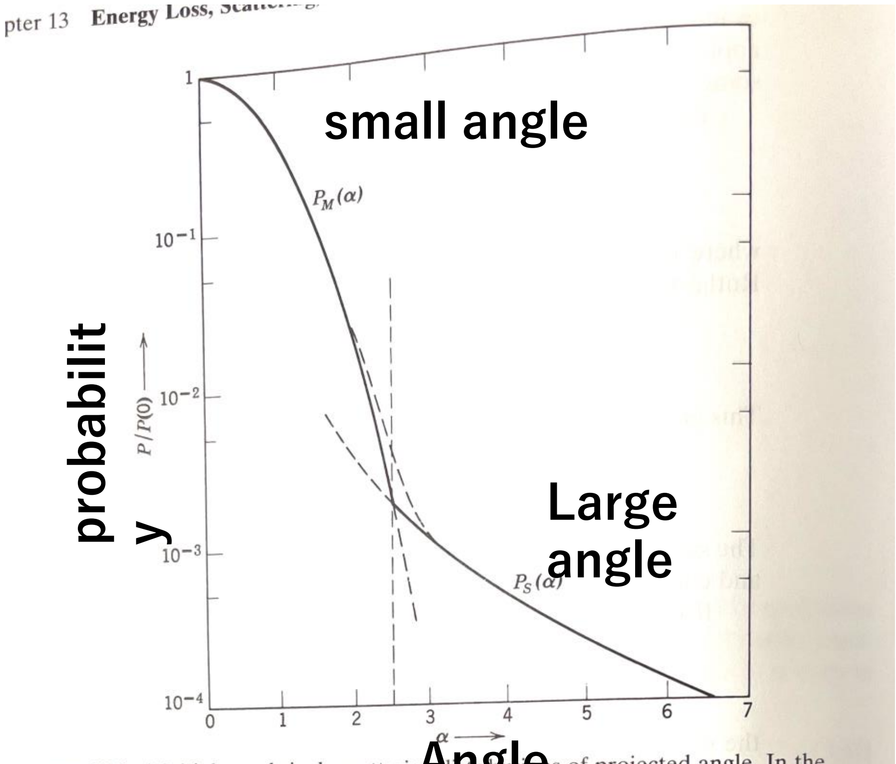


Figure 13.8 Multiple- and single-scattering distributions of projected angle. In the region of plural scattering ($\alpha \sim 2$–3) the dashed curve indicates the smooth transition from the small-angle multiple scattering (approximately Gaussian in shape) to the wide-angle single scattering (proportional to α^{-3}).

Jakson, Classical Electrodynamics,

In ultra high-density, $N_D=10^{26}$ /cm^3,
α(3.5MeV) → D*(100keV): Collision frequency becomes ~10^{12} /s (t=1ps)
which is faster than confinement time and thermalization time.

Condition 2 : $N_D>10^{26}$ /cm^3, ρ~800g/cm^3

Condition 1 N_{α}/N_D > 0.02 also helps to accelerate D* generation time.

Key physics 3: Temporal evolution of N_α

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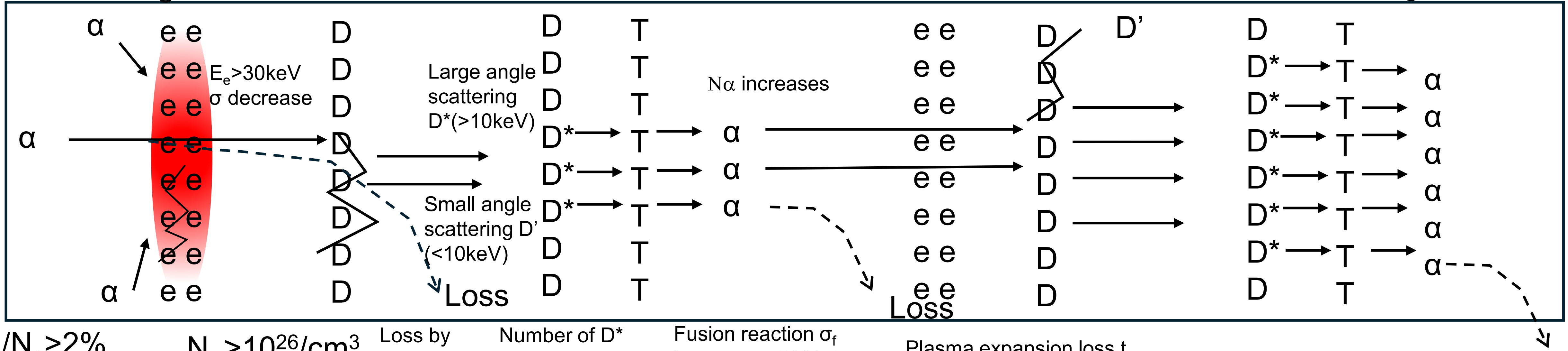
time

1st generation 2nd generation 3rd generation



N_α/N_e>2%, N_D>10^{26}/cm^3

Loss by Stopping

Number of D* ε~20

Fusion reaction σ_f increases x5000 time

Plasma expansion loss t_c

$$+\frac{dN_\alpha}{dt}(increase) = (N_\alpha \quad \sigma_{D*}N_D L \quad \varepsilon_{D*} \quad \sigma_{f*}N_T L \quad)t/\tau_{D*}$$

$$-\frac{dN_\alpha}{dt}(energy\ loss) = (N_\alpha \quad \sigma_{D'}N_D \mathrm{L}) \quad t/\tau_{scat}$$

$$+) \quad -\frac{dN_\alpha}{dt}(expansion\ loss) = N_\alpha \exp(\frac{-t}{t_c})$$

τ_{D*} ~1 ps (∝1/N_D) (estimated by sim)

τ_{scat} ~3 ps (∝1/N_D)

$t_{confinement}$~ 50 ps

If $\frac{dN_\alpha}{dt}_{total} \gg 1$ **N_α increases exponentially,**
become avalanche fusion.

$\frac{dN_\alpha}{dt} \propto {N_{DT}}^3$ **Density perturbation create an instability,**
and create an explosive ignition.

1D-PIC simulation without fusion

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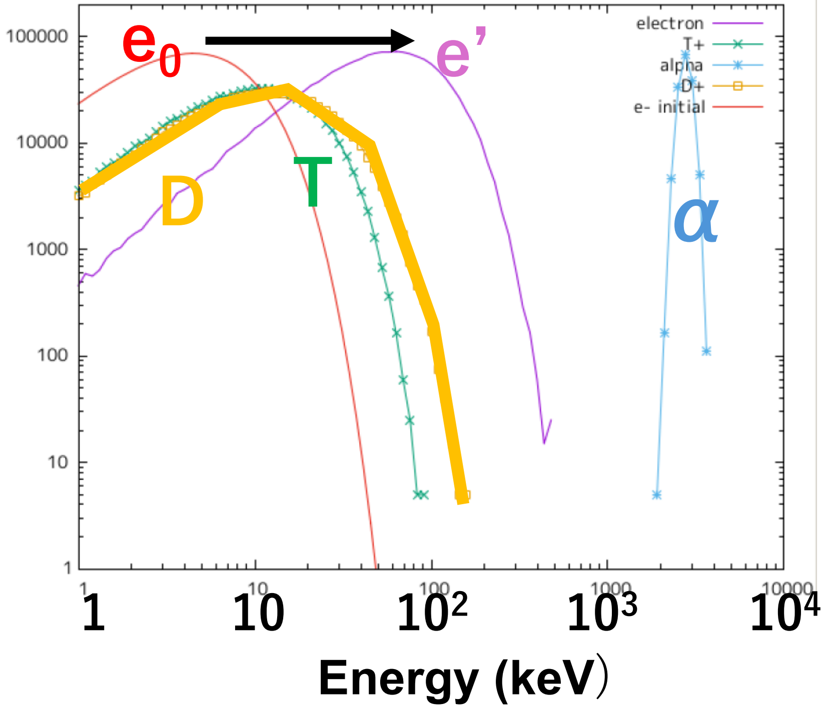
Size R= 10 nm, cell size 2.5 nm
N_α = 2x10^{25} /cm^3 (10% of N_e)
N_D, N_T = 1x10^{26} /cm^3
N_e=2x10^{26}/cm^3
E_α=3.5 MeV
Initial Te =Ti = 10 keV

D, T, e, α plasma

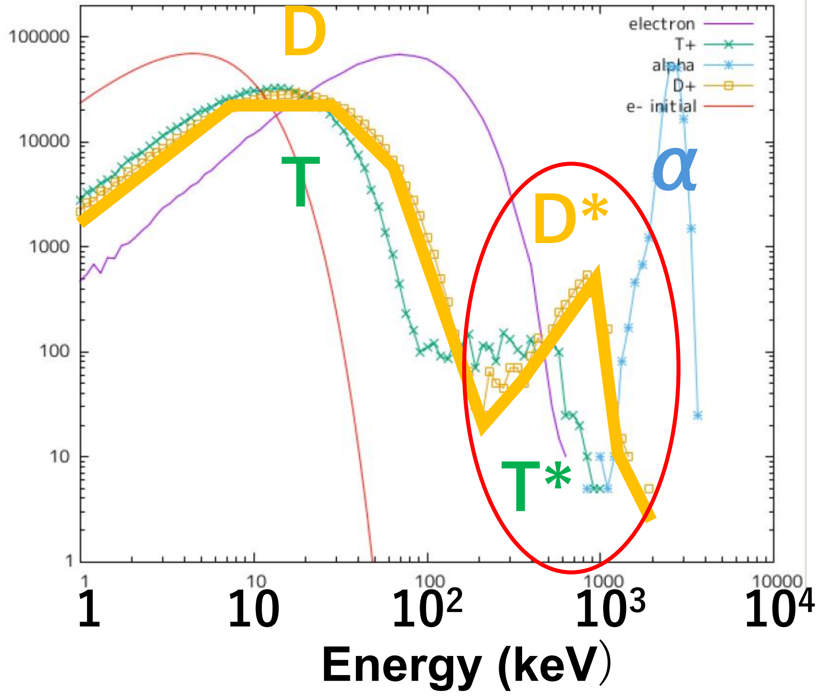
Time evolution of the energy spectrum of particles are simulated.

0.01 ps



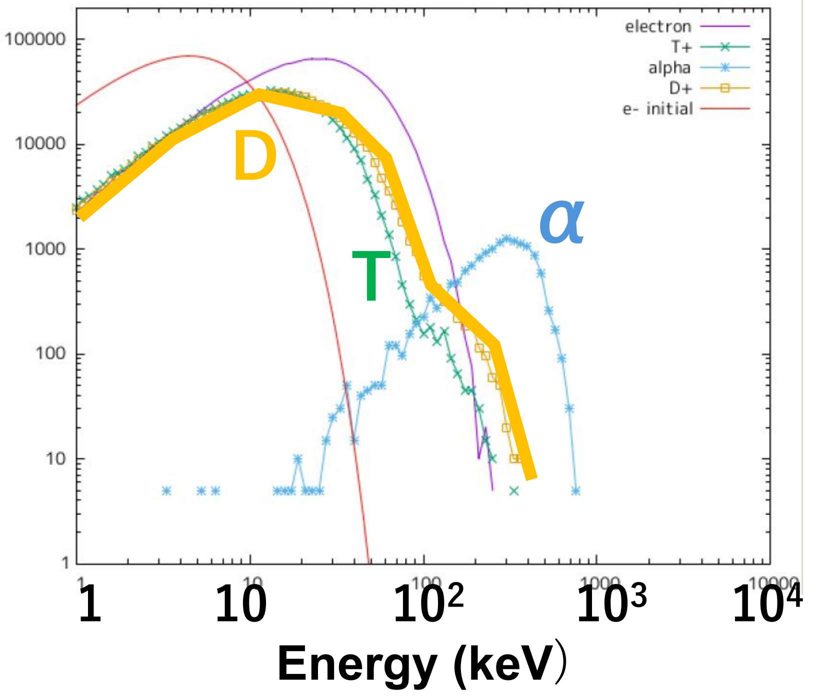
e is heated >30 keV within 10fs

1 ps



α→ D collision
generates D* (100keV- 1MeV)

3 ps



Thermalized at 3ps
if without fusion

1D-PIC simulation with fusion

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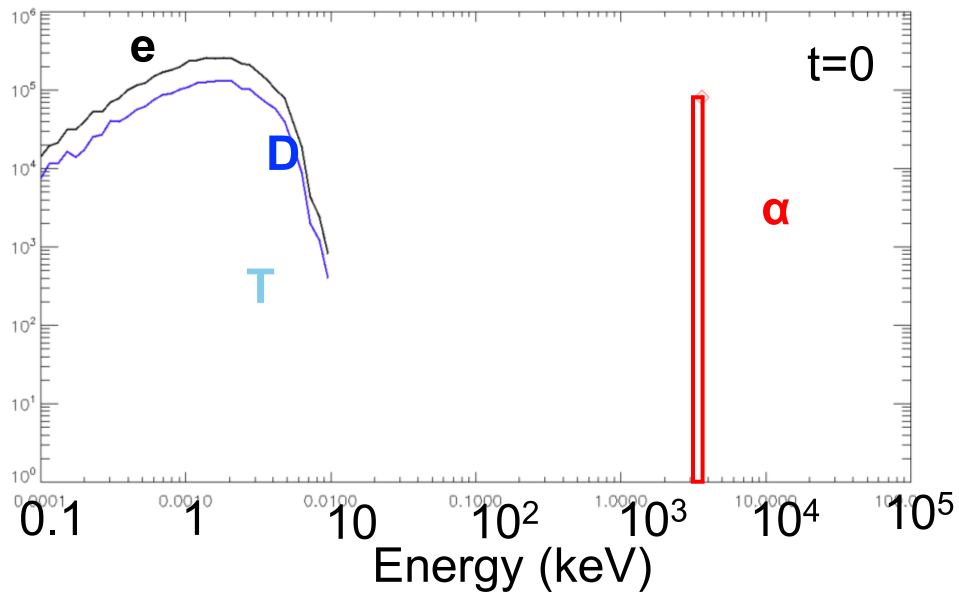
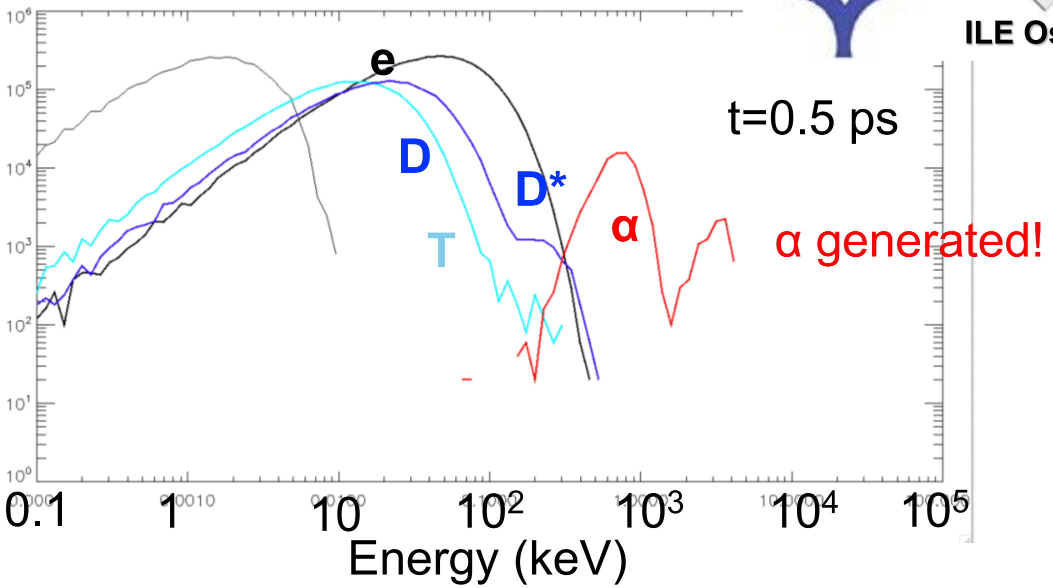
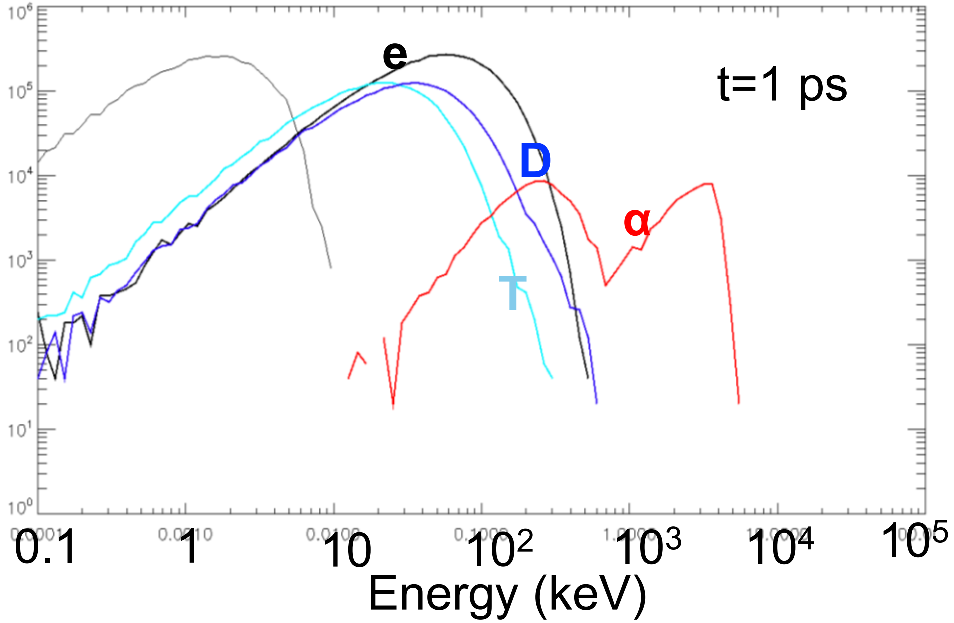
N_D, N_T = 1x10^{26} /cm^3

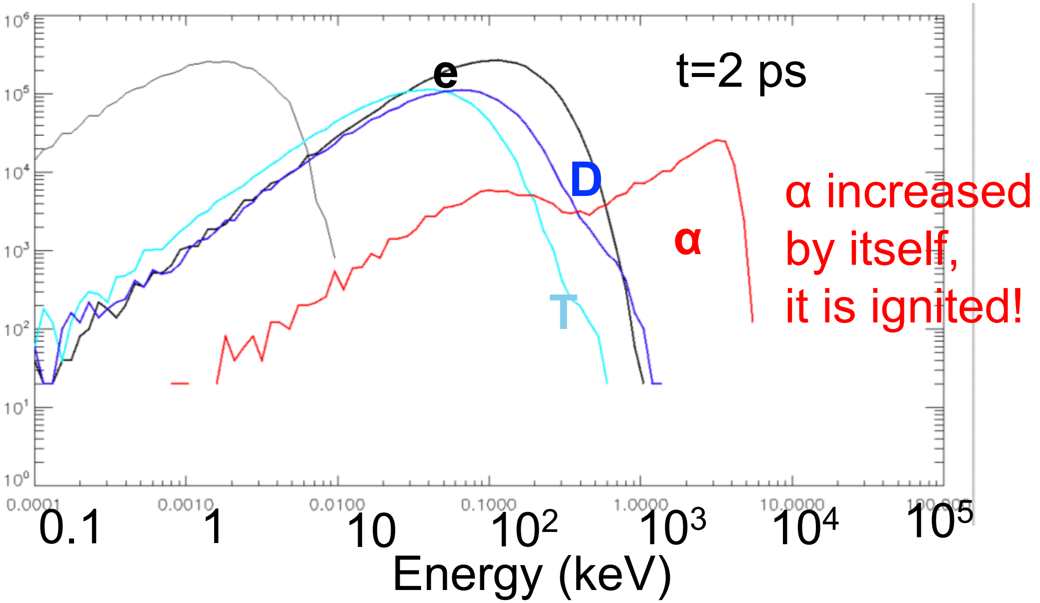
ρ 800/cm^3

Nα:Ne=2%



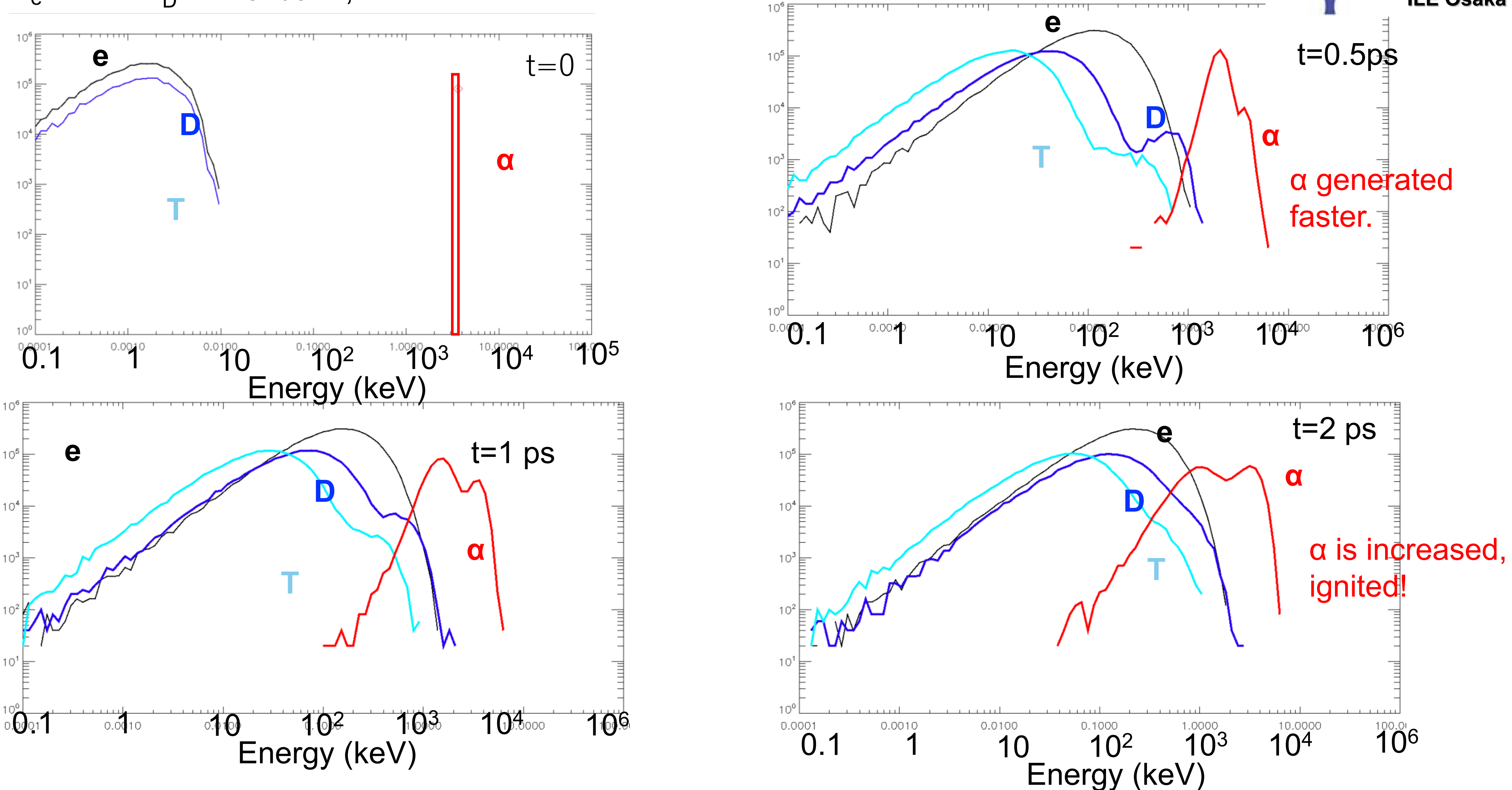






1D-PIC simulation with fusion

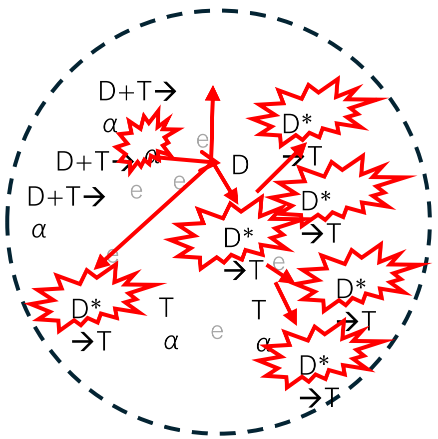
$N_\alpha:N_e=10\%$ $N_D=1\times10^{26}/cm^3$,

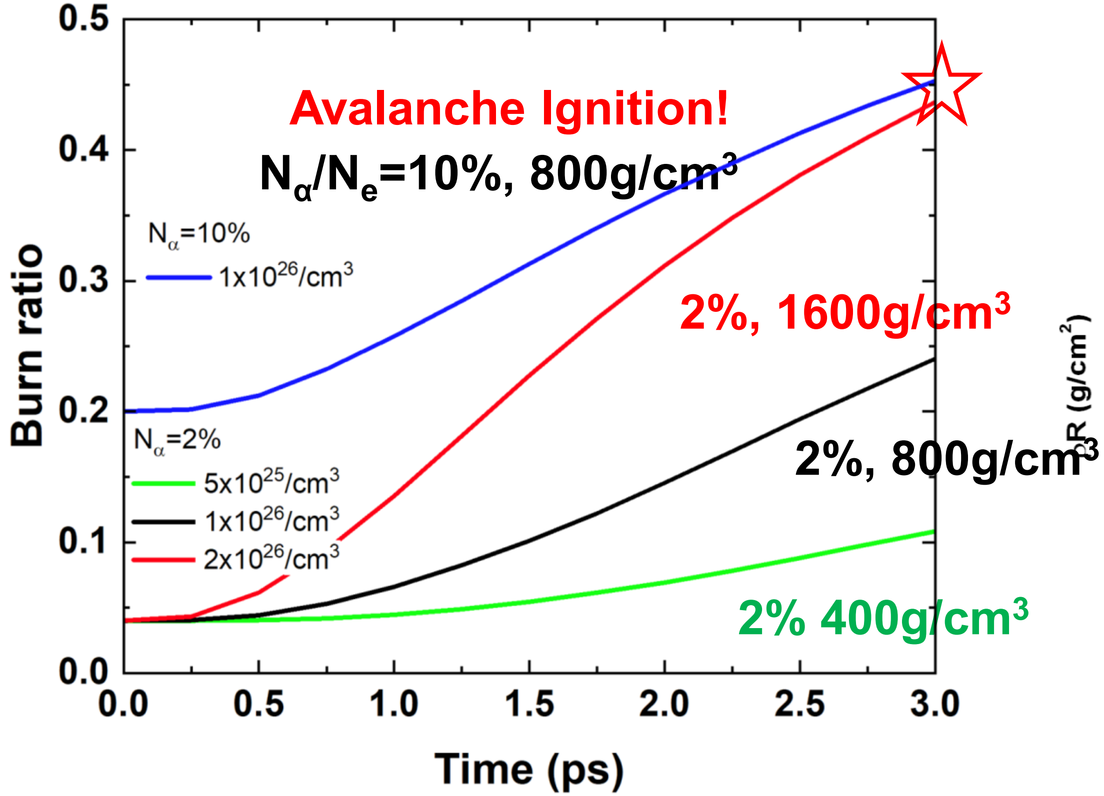


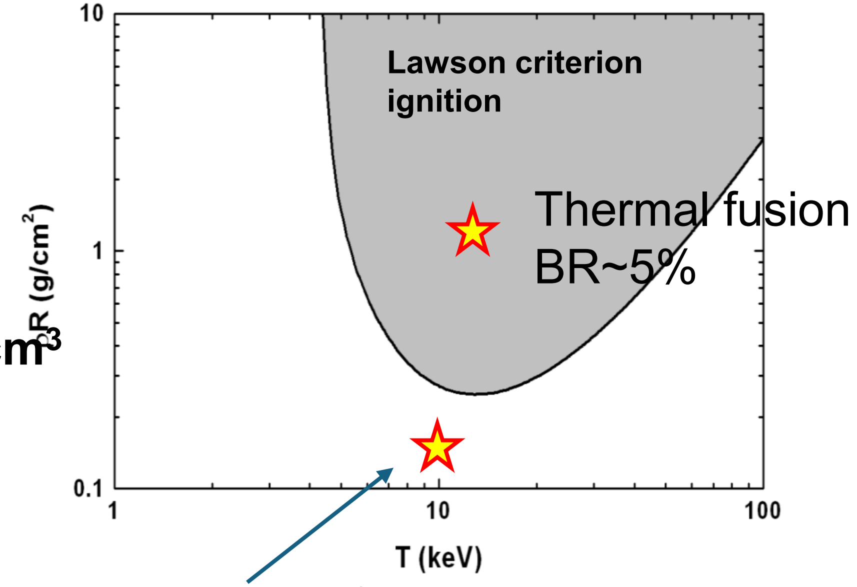
Larger N_α/N_e makes the fusion reaction faster and larger in burn ratio.

The avalanche fusion resulted a high burn ratio.

PIC-1D with fusion







ρ=1600g/cm³ R=1μm
Avalanche ignition, BR >45 %

- **Burn ratio reaches to 45% within 3 ps, at ρ=1600g/cm³ ,R=0.01μm.**
- **The burn ratio is dependent to ρ, but independent to R,**
  it does not follow the Generalized Lawson Criterion.
  e.g. R=1 μm ρ=1600g/cm³, ρR =0.16 g/cm², it will ignite with BR >45% (~10 bigger than the thermal fusion) .
- **A small ignition volume propagates to the entire fuel as detonation associated with an instability.**

The avalanche fusion can be a new path to the high gain fusion.

Summary

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1. A high gain fusion scheme ”avalanche fusion” is proposed.

2. When two conditions are satisfied, (1) $N_\alpha:N_e>0.02:1$ and (2)$N_D>10^{26}cm^3$,
   α collides to D, generates D* (100keV), then the D* +T fusion occurs at max cross section.
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4. The avalanche fusion is independent to the Generalized Lawson criterion,
   it can be a new path-way to the high gain fusion.

Thank you for your attention!

Four pandas from Wakayama adventure world (Osaka area zoo) are living very happily at Chengdu research base of Giant Panda Bleeding now. Thank you!

Acknowledgement
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