Super Dense Core Ignition Scenario for Helical Device

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OUTLINE

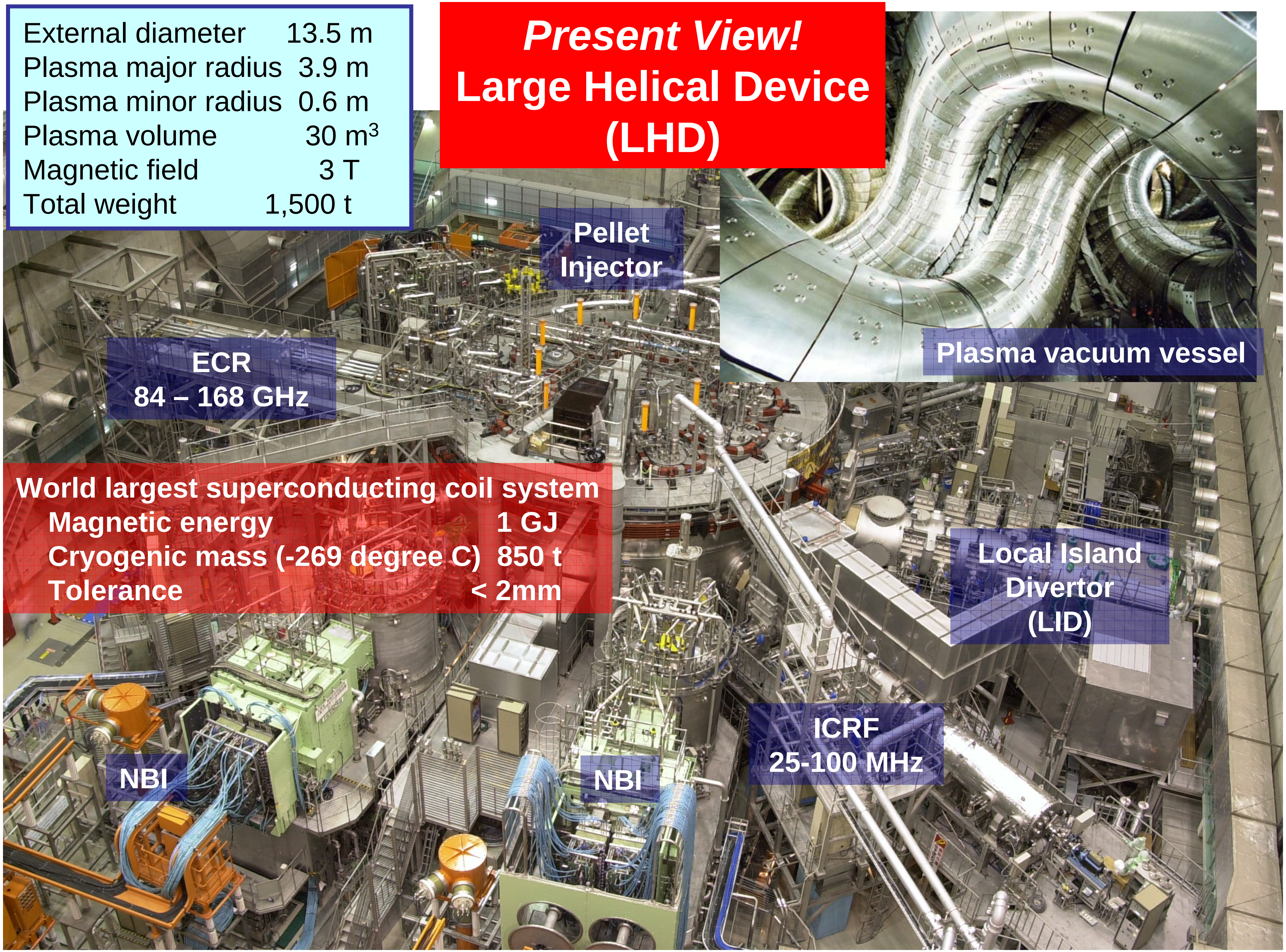
Discovery of Stable Super Dense Core Plasma

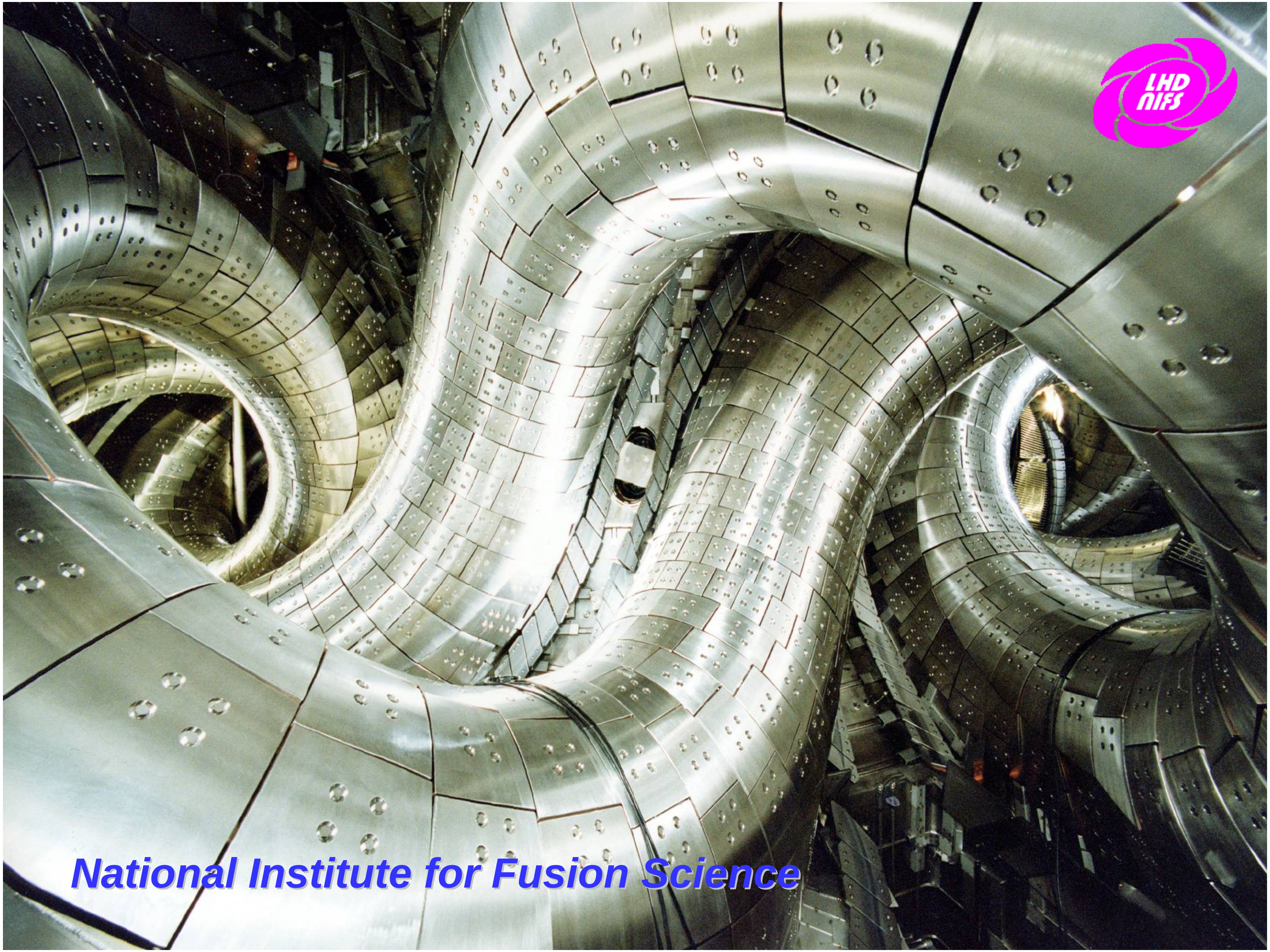
- Internal diffusion barrier.
- Time evolution of SDC discharge.
- Pellet injection.
- Comparison between gas puff and SDC discharges.
- Foot location of IDB
- Quasi-steady operation.

A new Ignition scenario (high density core, relatively low density mantle)

Present View!
Large Helical Device (LHD)

External diameter	13.5 m
Plasma major radius	3.9 m
Plasma minor radius	0.6 m
Plasma volume	30 m^3
Magnetic field	3 T
Total weight	1,500 t




LHD
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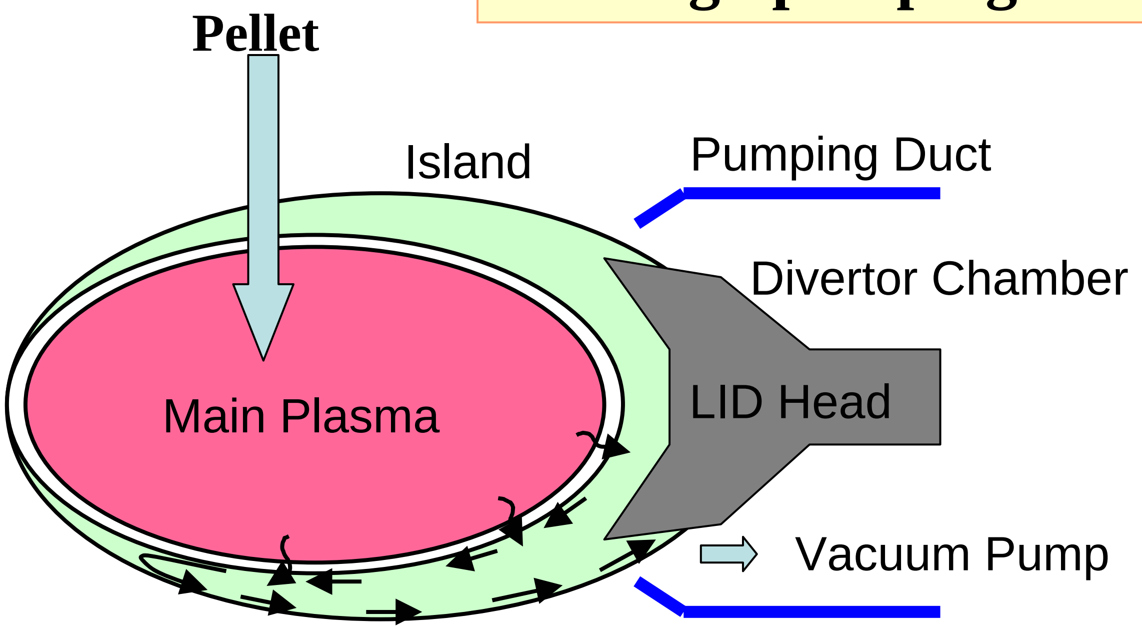
Local Island Divertor

A closed divertor
with high pumping efficiency



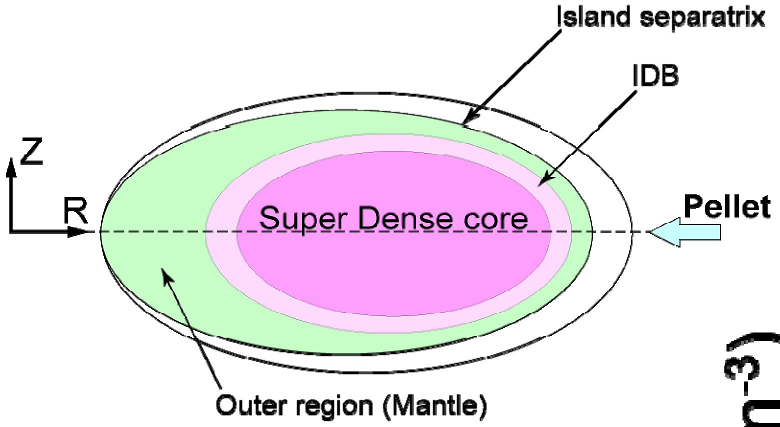
Pellet core fueling

Powerful particle control

Objectives
Of LID experiment

i) to develop island divertor concept.
ii) to study island related physics
iii) to explore confinement enhancement mode.

Internal Diffusion Barrier (IDB)



$n(0) = 4.6 \times 10^{20} m^{-3}$,

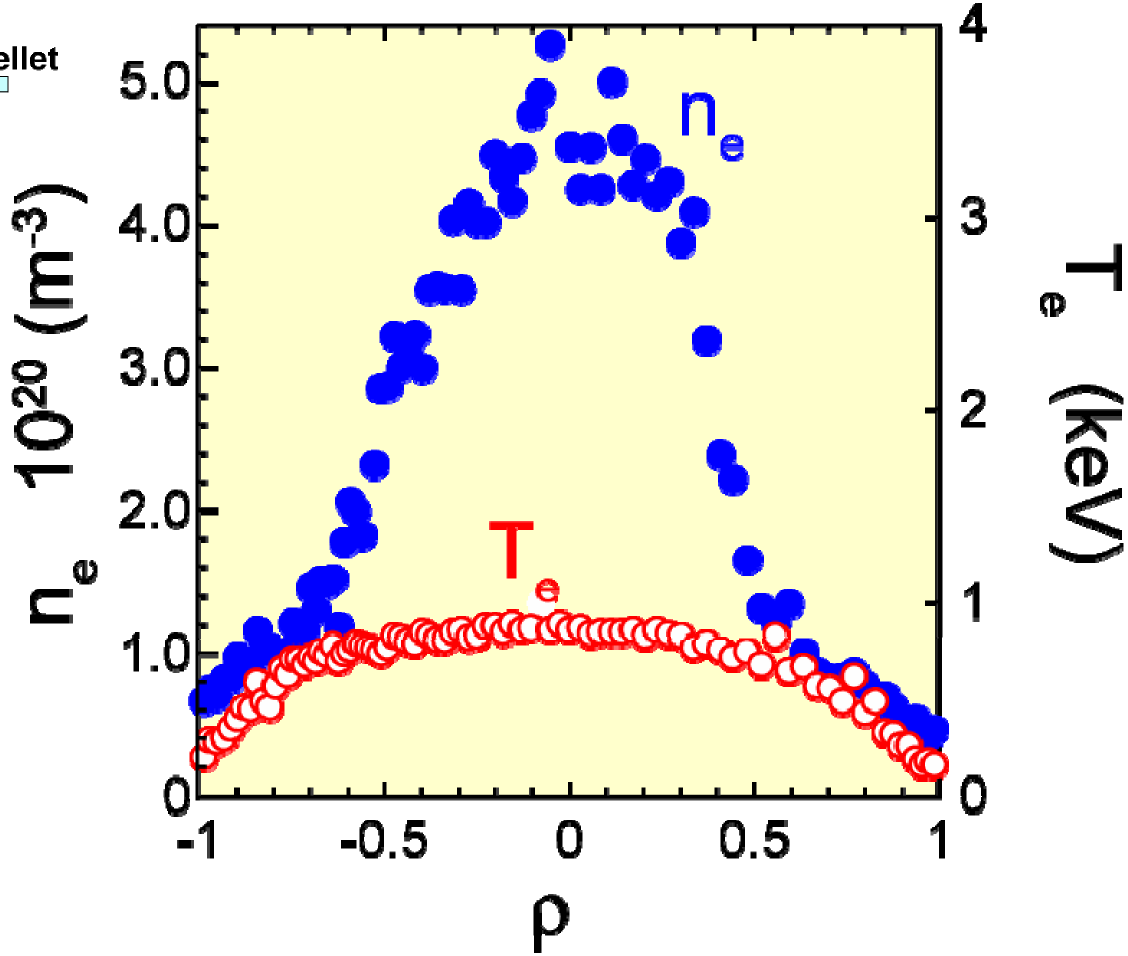
$T(0) = 0.85$ keV,

$W_p = 1.1$ MJ at $P = 10$ MW,

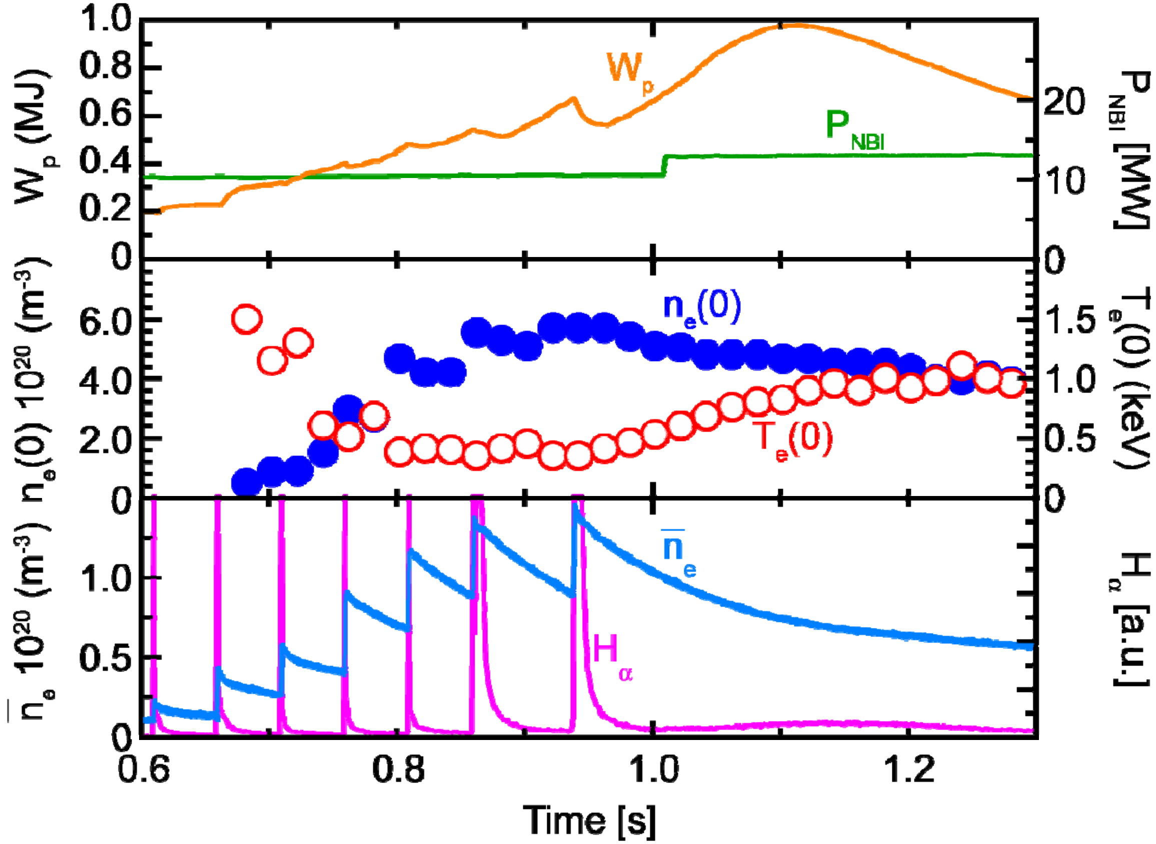
$n^o \tau_E T^o = 0.44 \times 10^{20} m^{-3} keV m^{-3} s$

$(R/a)(d\beta/d\rho) = 0.8$,

$\beta(0) = 4.4$ % at $B = 2.64$ T



Time evolution of IDB

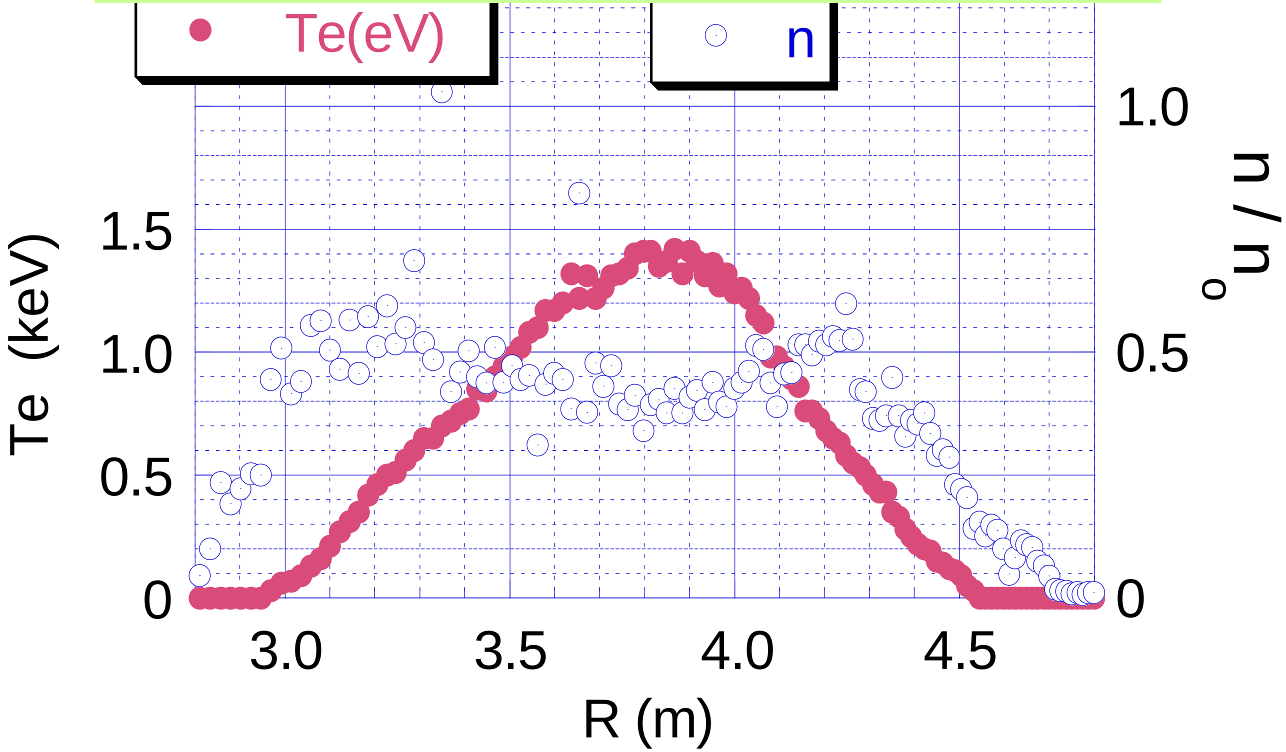


Time constant of n(0) decay is ~1sec, indicating that D is very low (~0.02 m^2s^{-1})..

Without Pellet injection, No SDC Discharge .

Gas puff → particle source in the very edge

→ Flat or slightly hollow density profile

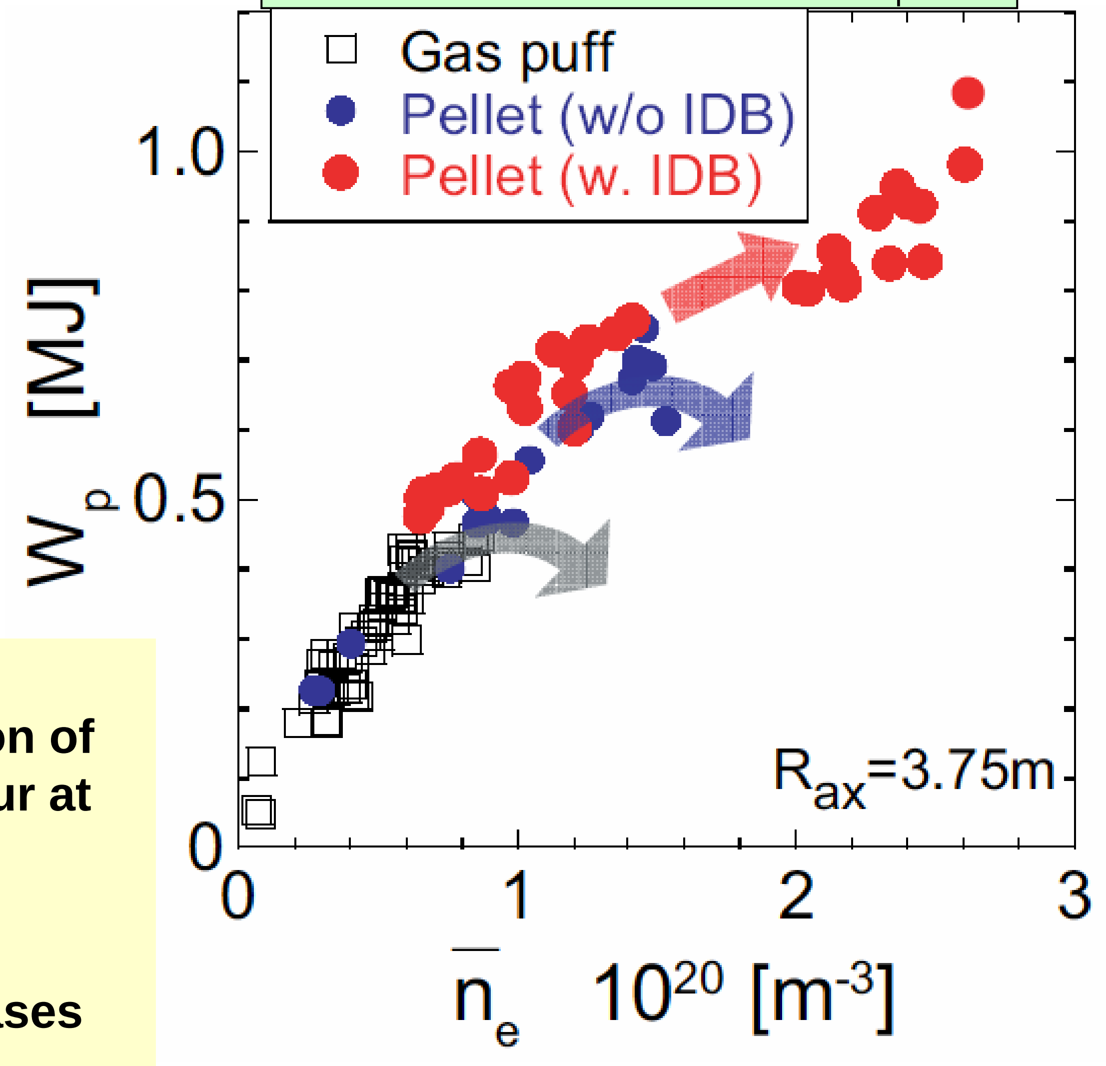


Need Pellet Injection for peaked density profile

For SDC operation

Confinement Improvement

Density dependence of W_p



For gas puff discharges, W_p increases with n_e, but saturation of W_p and radiative collapse occur at higher n.

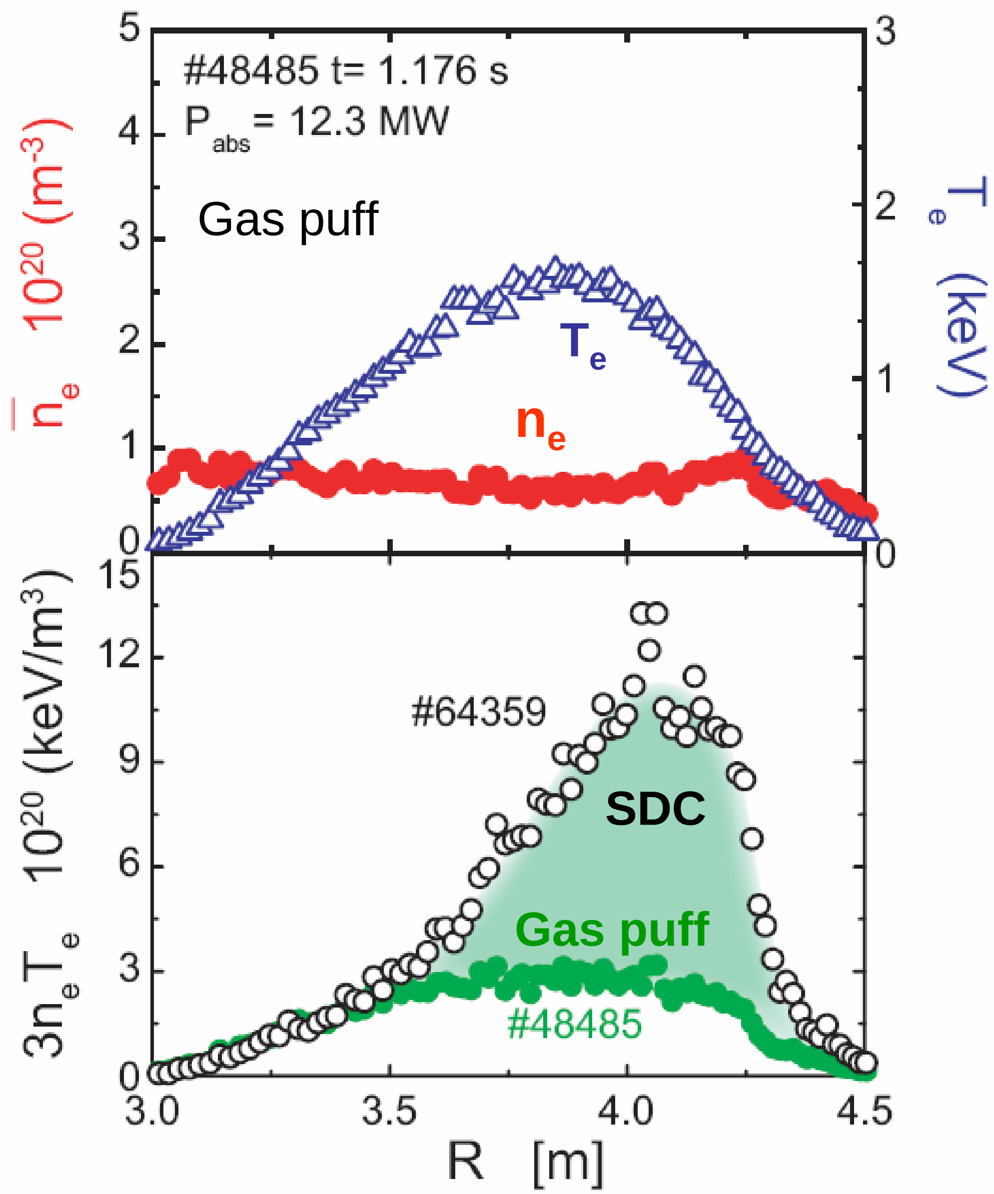
For SDC discharges, W_p increases with n_e even at at higher n.

Comparison between SDC and gas puff discharges

Gas puff → particle source in the very edge

↓

Flat density profile



High core thermal energy is gain for the SDC discharge.

↓

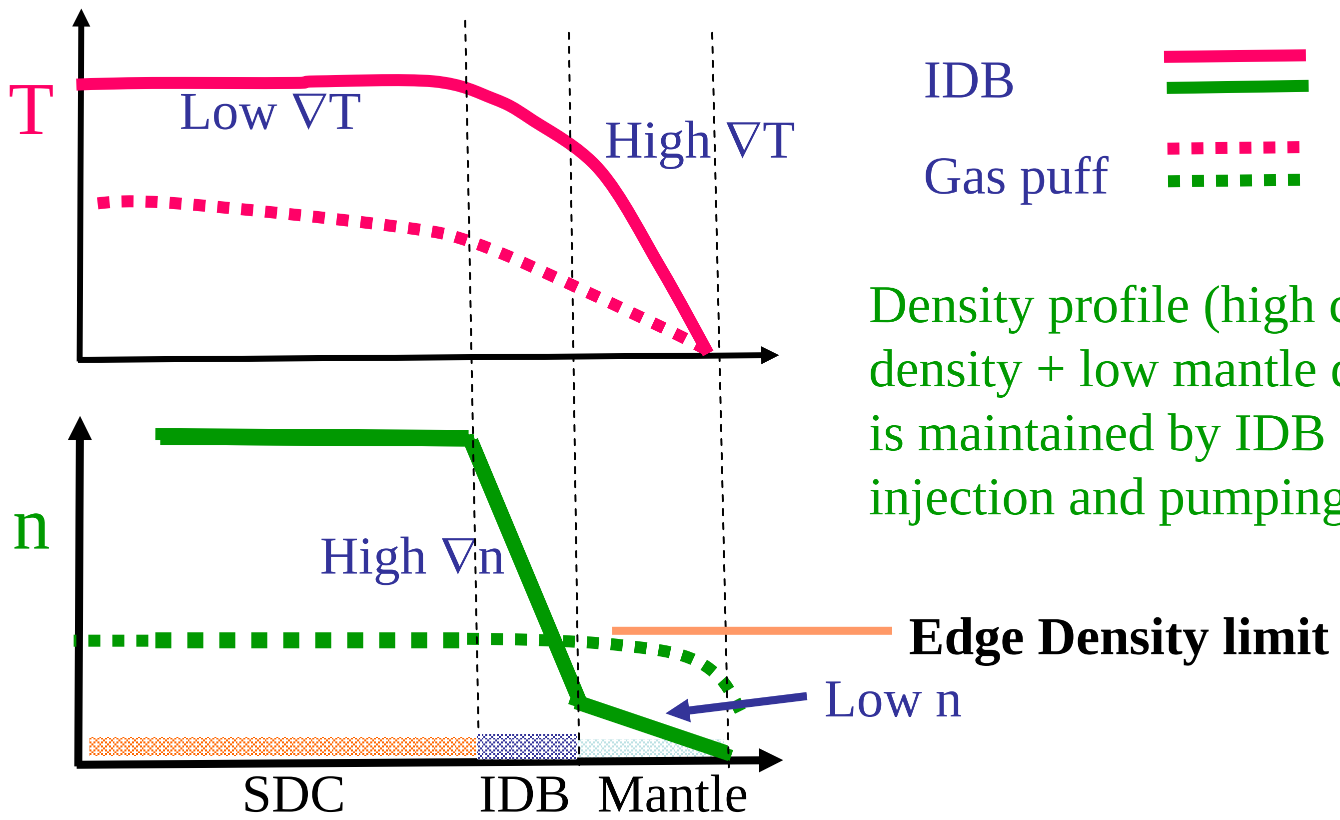
high $n_0\tau_E T_0$

Confinement Improvement Mechanisms in SDC discharges

IDB + Pellet injection → dense core plasma → High confinement

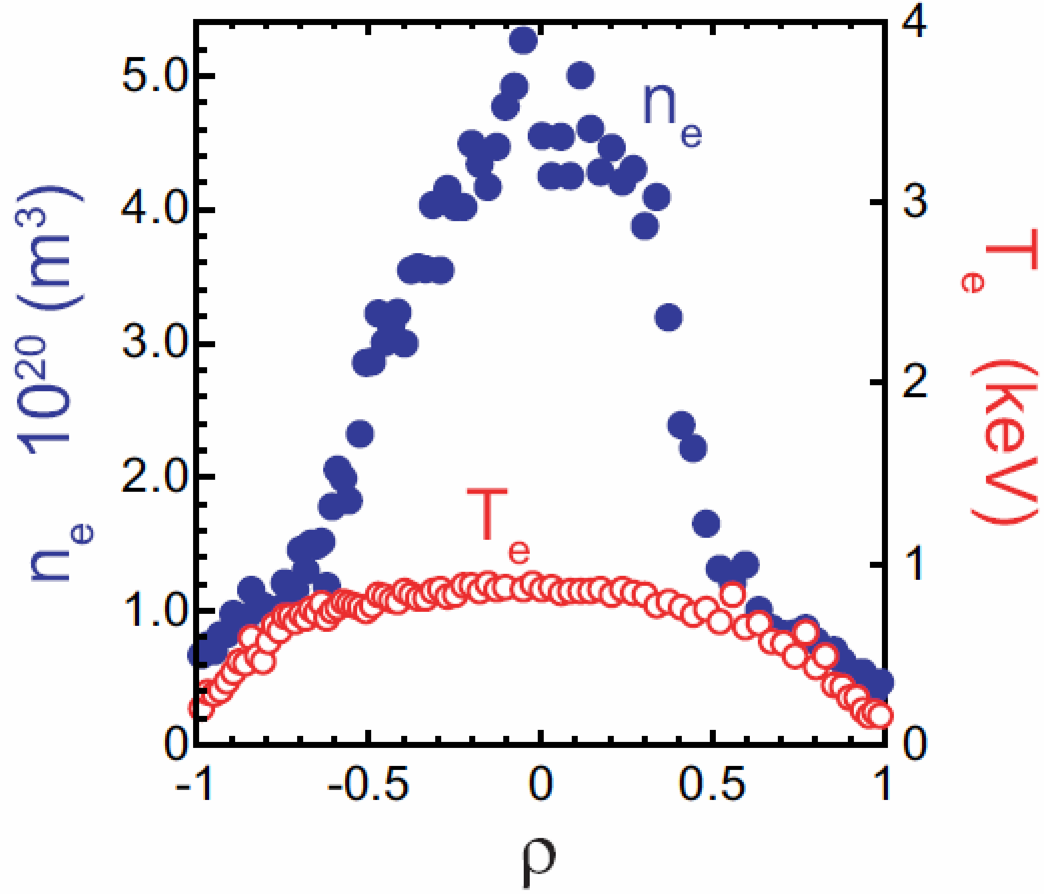
Pumping → Low mantle density → High ∇T in the mantle → High core temperature ↑ (High confinement)

Low mantle density → Avoidance of radiative collapse

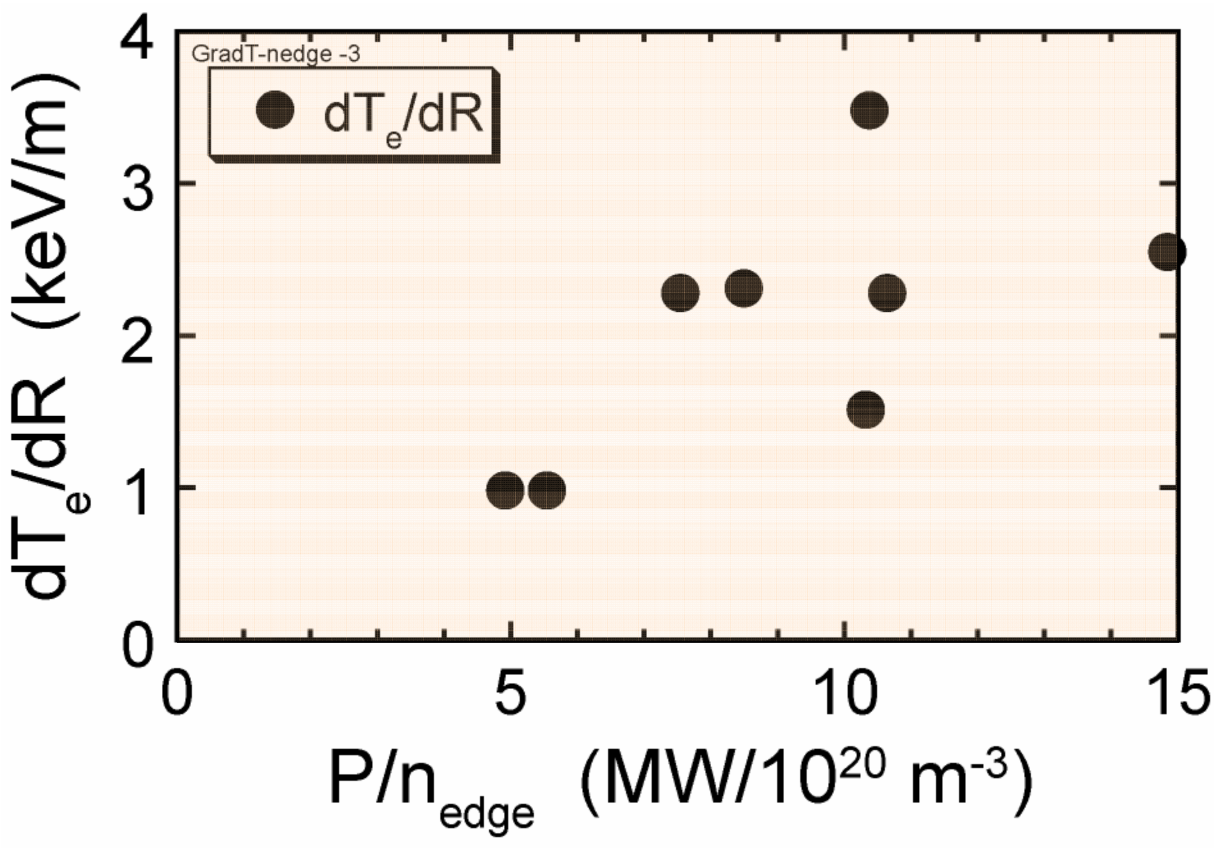


Density profile (high core density + low mantle density) is maintained by IDB ,pellet injection and pumping.

SDC Mode



In the outer region (mantle), ∇T tends to increase with P/n_{edge}

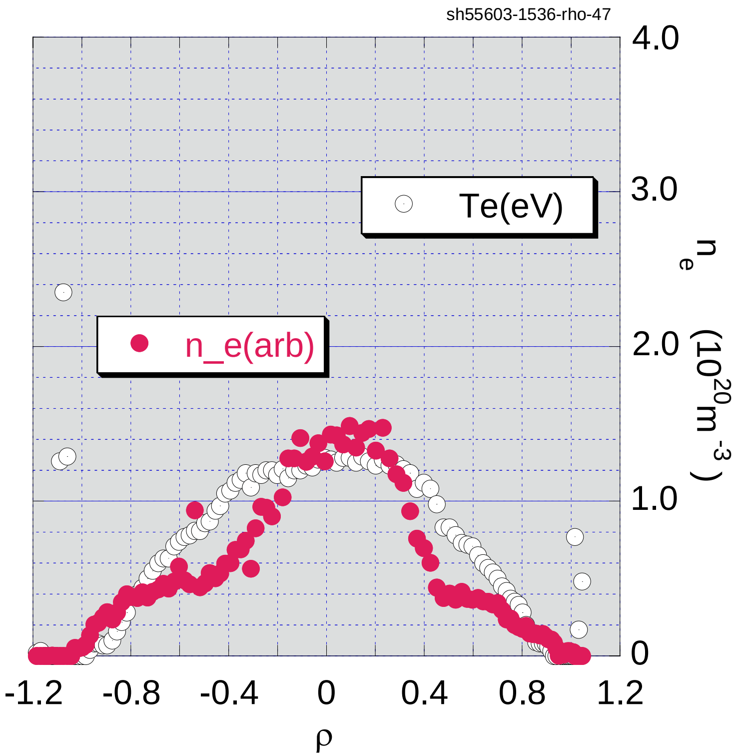


$$q = - n\chi \nabla T$$

Location of IDB Foot depends on R_{ax}

Inward shifted configuration (R_{ax}=3.65m).

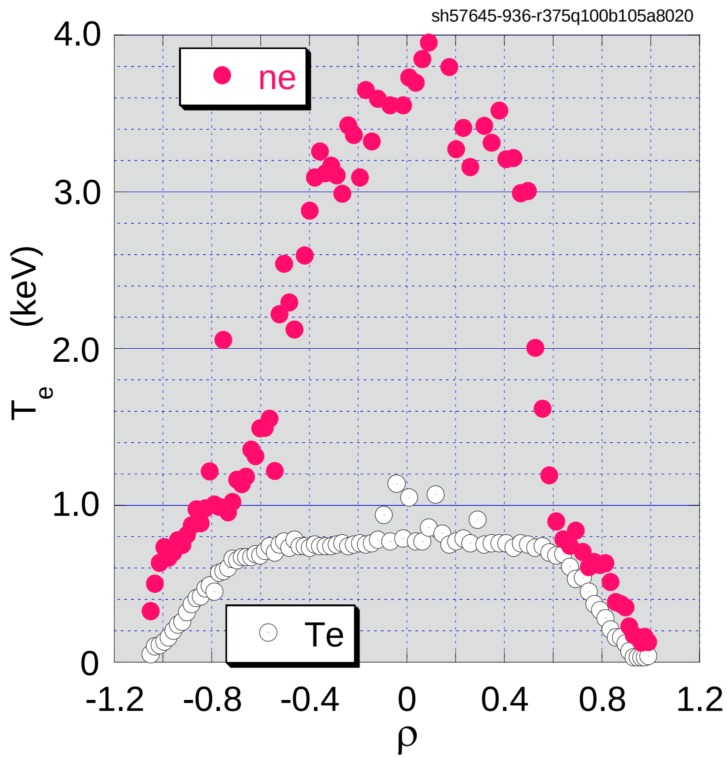
Small, but clear core



ν^*_{foot}=0.03, $\nu^*_{shoulder}$=0.07, $\beta(0)$=1.7%

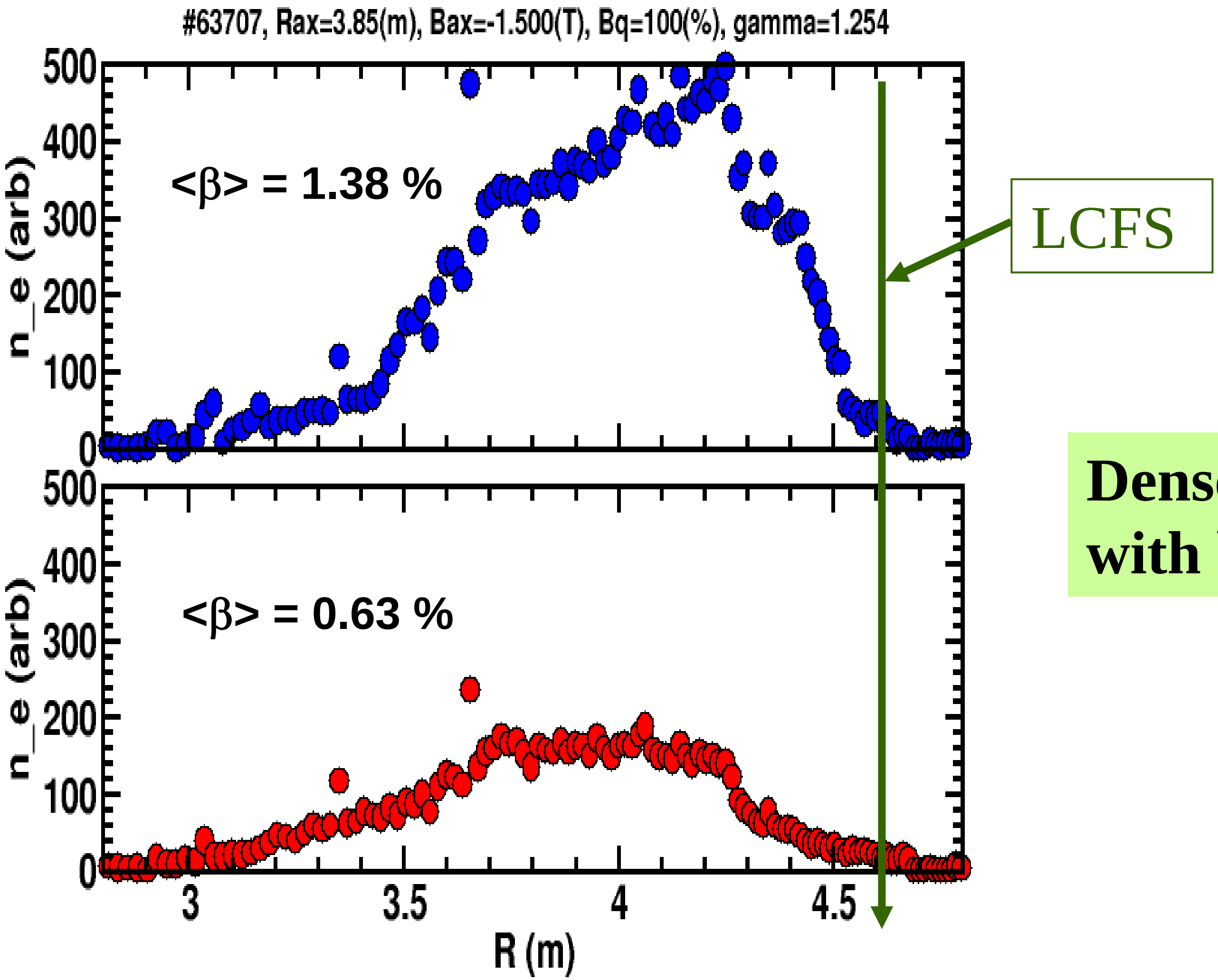
Standard configuration (R_{ax}=3.75m)

Optimum core



ν^*_{foot}=0.12, $\nu^*_{shoulder}$=0.35,

Dense core expands up to LCFS for outward shifted configuration (R_{ax} = 3.85m).



Dense core expands with beta

Role of LID ➔ pumping

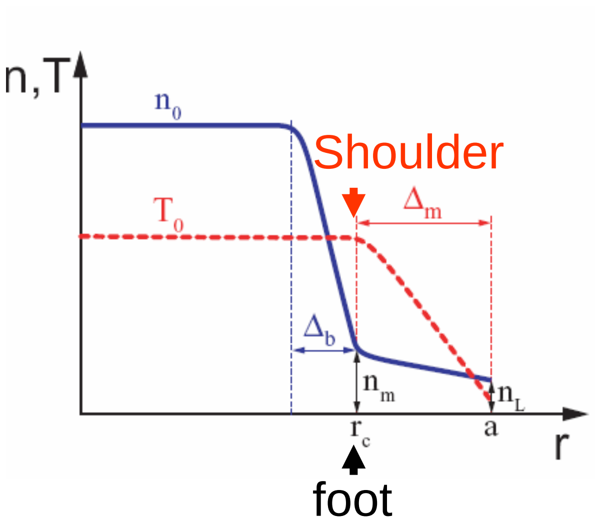
- For inward shifted configuration, LID (possibly its pumping capability) is needed.
- For outward shifted configuration, it is not needed. The mantle density is low.

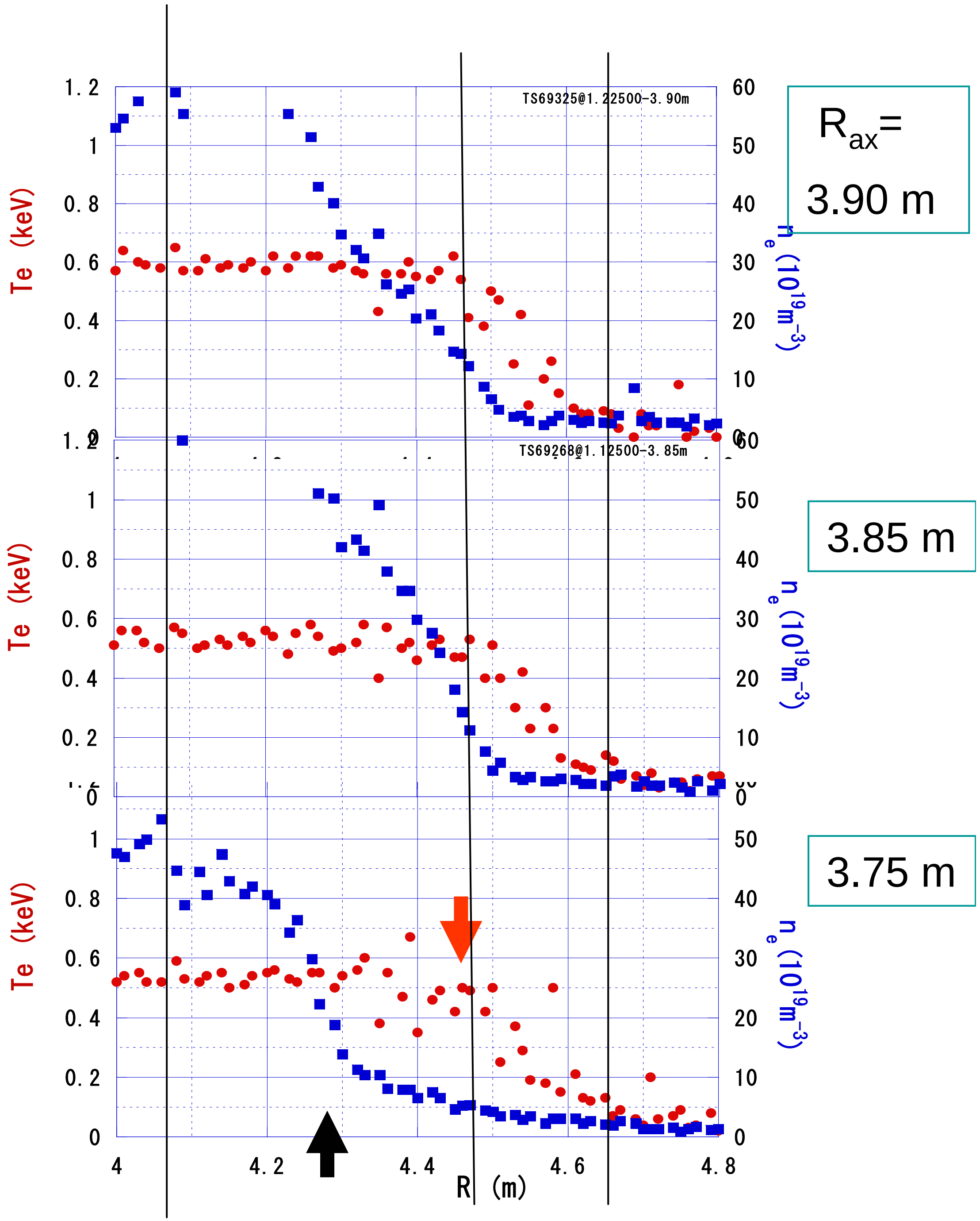
  Wall pumping is effective or D_{mantle} is high (we do not know why so).
- For steady state operation of SDC mode, active pumping such as LID is essential.

Edge Density and Temperature profiles for SDC discharge

- Foot location (n) moves outwards with Rax.
- Shoulder location (T)

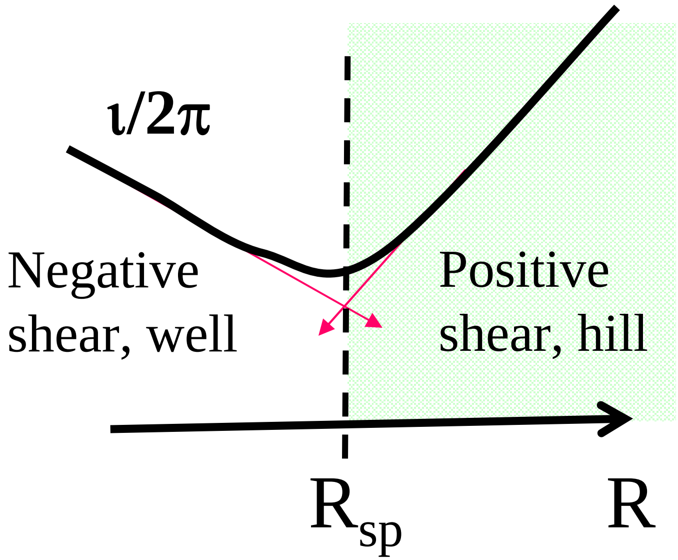
  R ~ 4.5 m independent of Rax

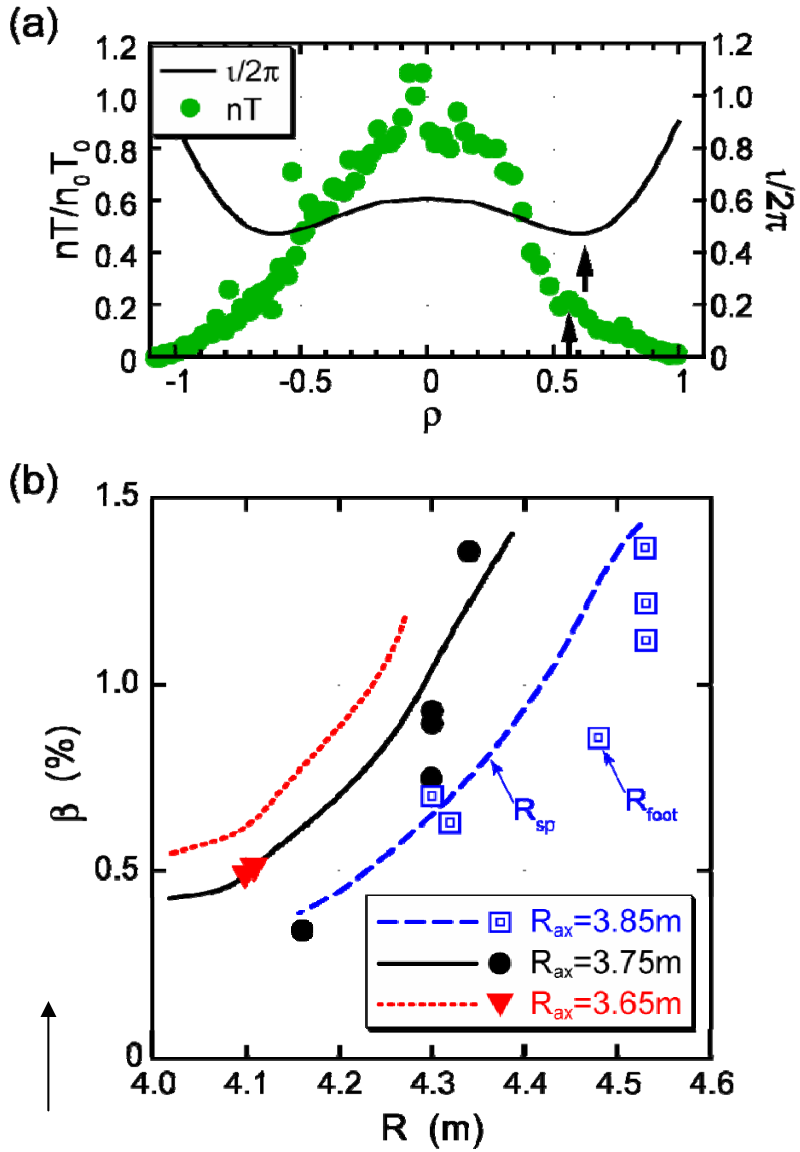




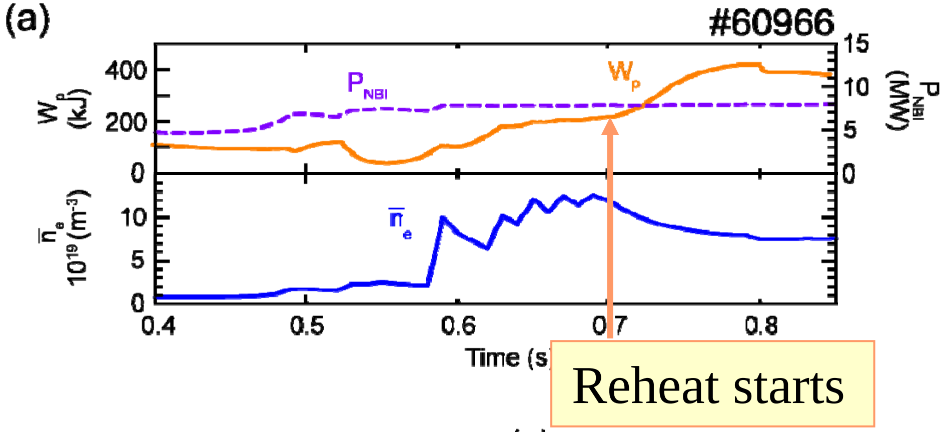
IDB foot (R_{foot}) increases with R_{ax} and β.

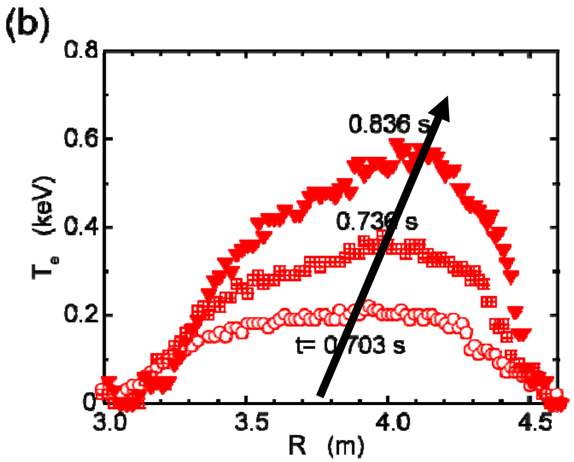
Foot location is close to those of "zero shear" and boundary between well and hill.



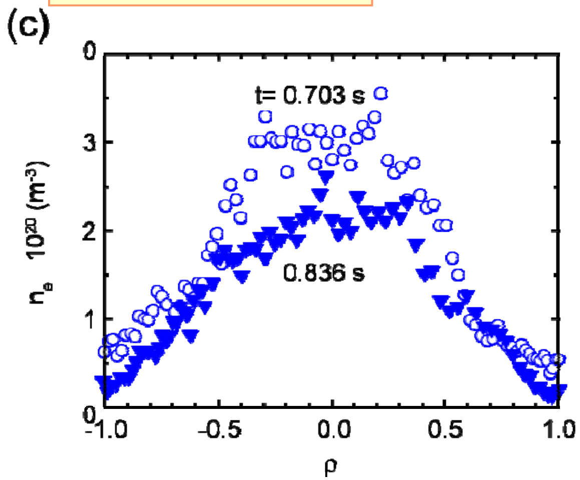


“Reheat” raises the core beta up to 5.1 % (B=1.5T)

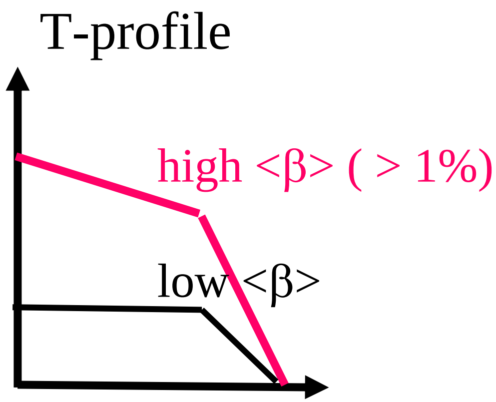




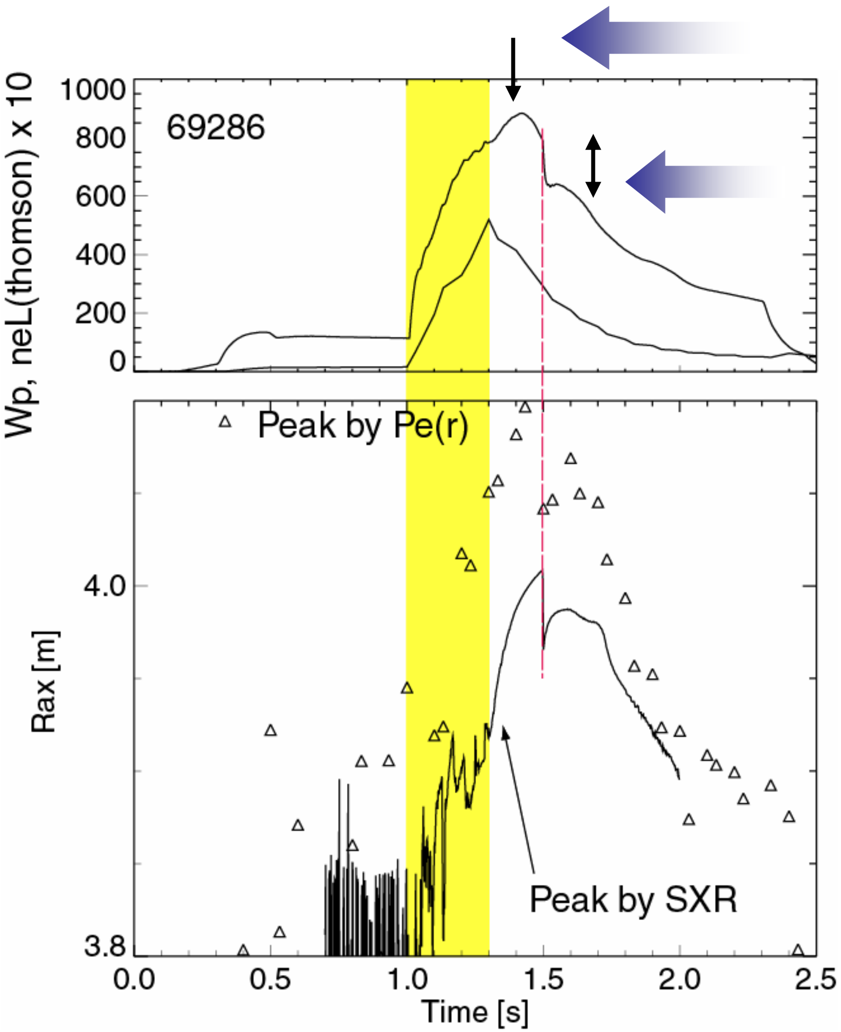
Large Shafranov shift.



Density profiles before and during “Reheat” event.

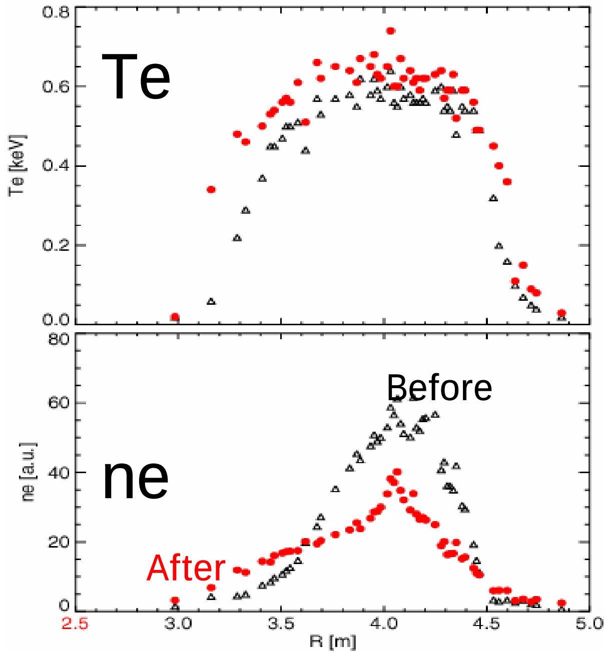


Density collapse at high beta



Occurs after the maximum of the store energy

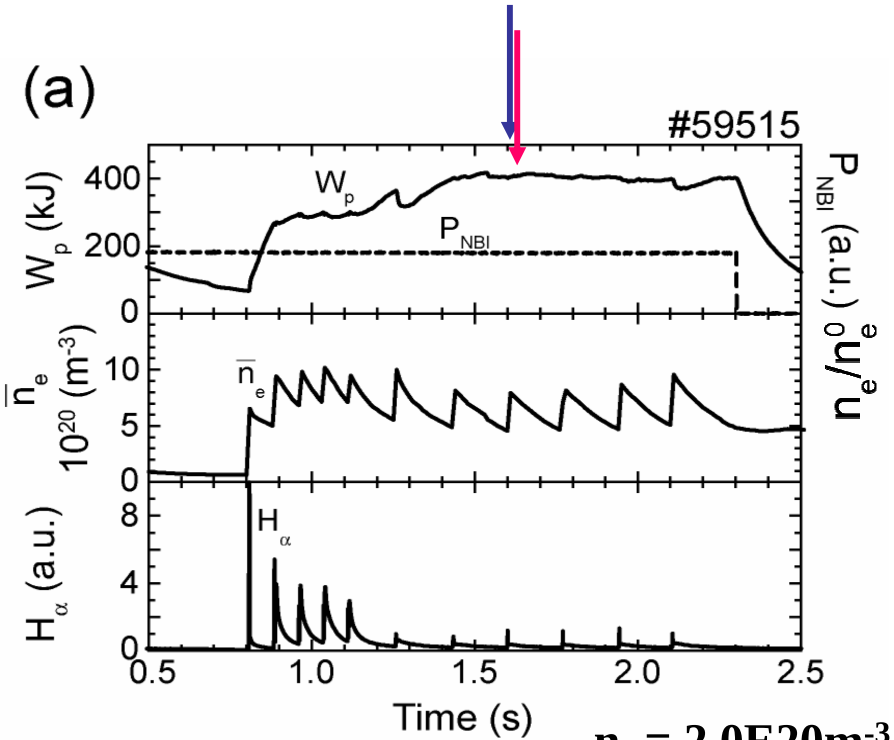
Large decrease in stored energy (by ~30%)



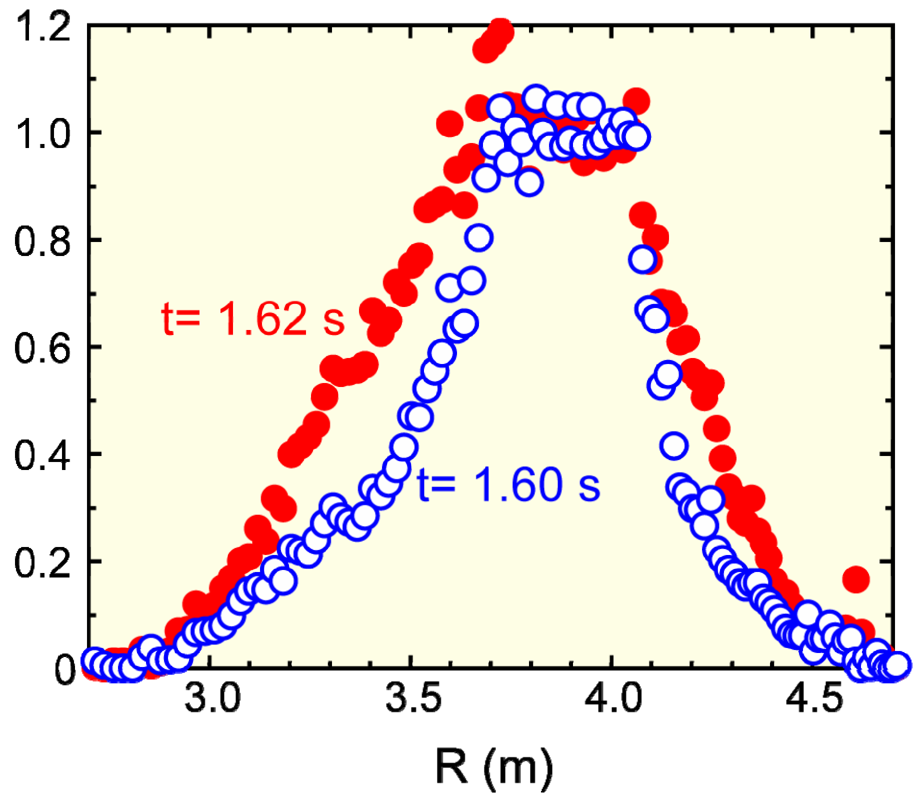
- It is a very rapid event where the core plasma is lost with a time scale of several hundred micro sec.

Quasi-steady state operation of SDC mode has been demonstrated.

Pellet injection tends to fuel the particle in the region with high ∇n.



n_o = 2.0E20m^{-3}

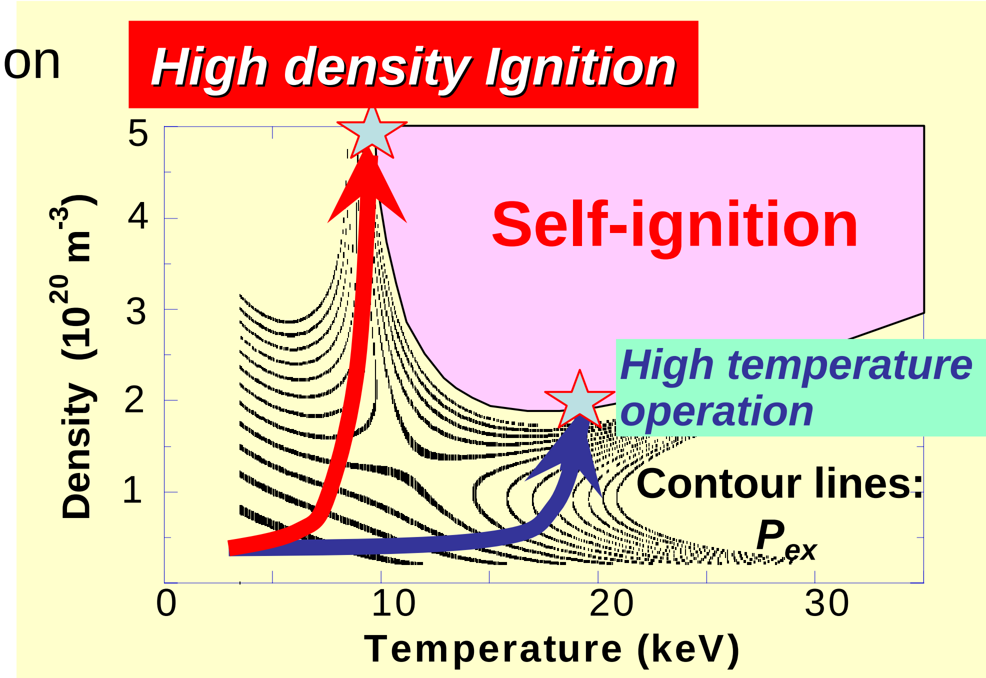


Continuous pellet injection

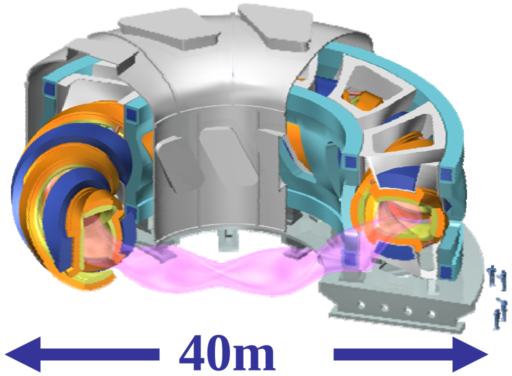
Observation of Internal Diffusion Barrier (IDB) Enabling New Scenario of Super Dense Core Reactor

Advantages of the High Density Ignition

- Raising the density is easier.
- Lower neoclassical ripple transport
- Smaller effects of Alpha particle



FFHR
1,000 MW
6Tesla



A New Ignition SDC Scenario

- **Internal Diffusion Barrier +Pellet maintain high density core.**
- **Achievement of ignition with core temperature as low as possible.**

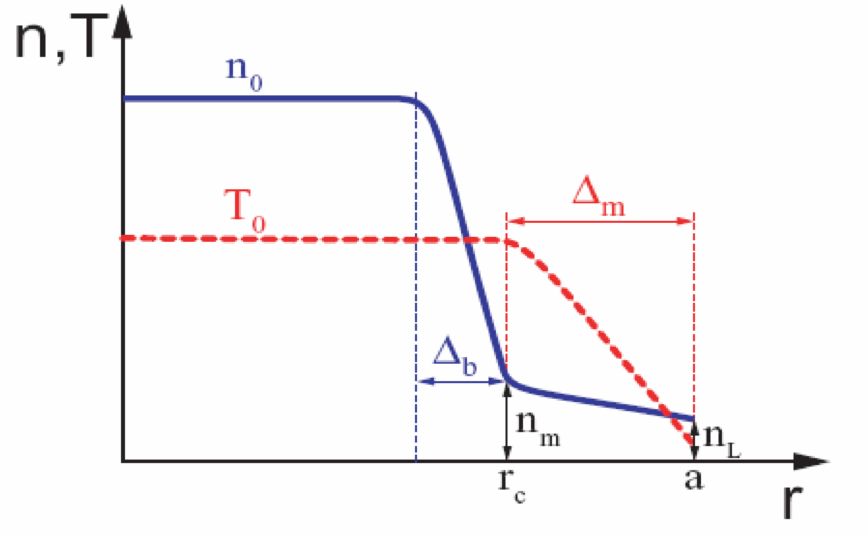
Low density mantle maintain the reasonably high ∇T.

SDC reactor design

$n^o = 5 \times 10^{20} m^{-3}$, $T^o = 8$ keV

Conventional reactor

$n^o = 1.5 \times 10^{20} m^{-3}$, $T^o = 30$ keV

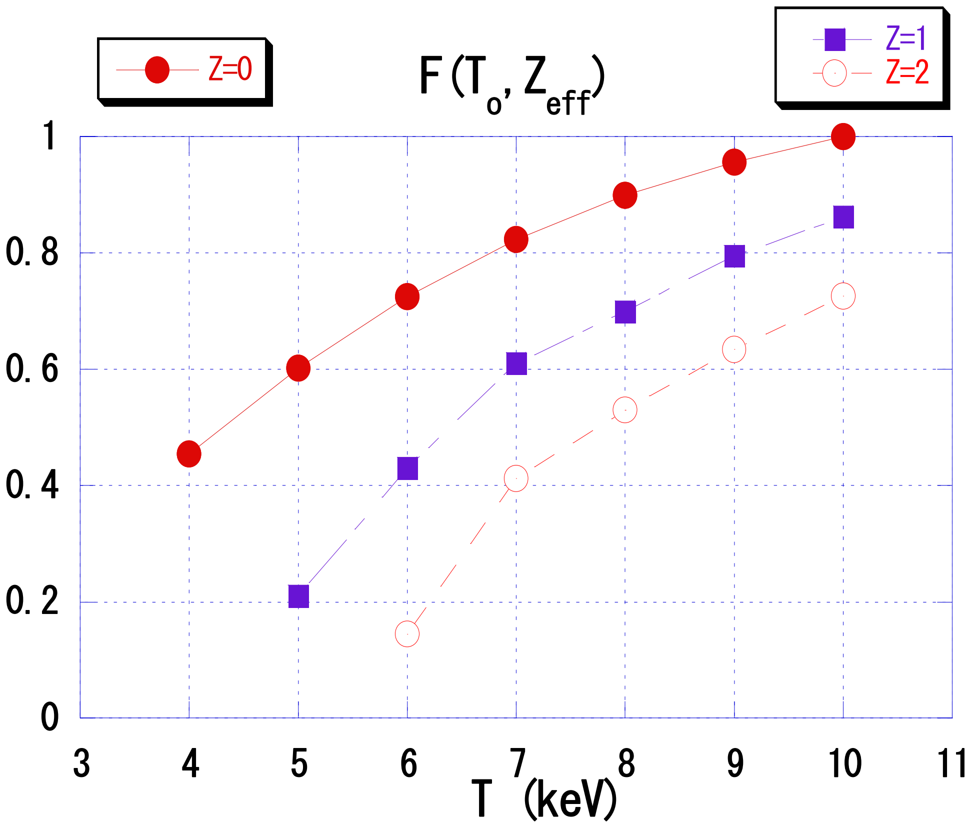


Ignition Condition　I

Alpha Power density - Bremsstrahlung

$$P = 0.14\,(nT)^2\,F(T)\left[1 - 0.134\cdot Z_{eff}\,/\,T^{3/2}F(T)\right]$$

$$where\ \ P(MWm^{-3}), n(10E20m^{-3}), T(10keV), F(10keV) = 1$$



Minimum Temperature for Ignition：

～7 keV　for　Z_{eff}=2

Ignition Conditions II

Fusion power density $C \cdot (n_o T_o)^2 \cdot F(T_o, Z_{eff})$

where n_o,T_o are core density and core temperature, respectively (. C is 0.14 MWm^{-3} with f (T=10keV) = 1. F (T_o, Z_{eff}) = f(T_o)[1-g(T_o,Z_{eff})]

$$q_{cond}(r_c) + q_{conv}(r_c) < q_{self}(r_c)$$

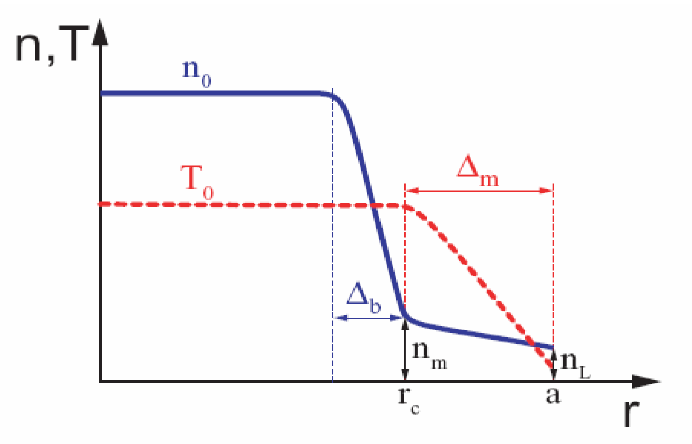
where

$$q_{self} = C \cdot n_o^{\,2} \cdot T_o^{\,2} \cdot F(T_o, Z_{eff})(r_c/2)$$

$$q_{cond}(r_c) = C^*(C_m\ n_m \chi_m / n_o \Delta_m) \cdot n_o T_o$$

$$q_{conv}(r_c) = C^*\left(5 C_b D_b\ / \Delta_b\right) n_o T_o$$

Where C*=0.16MJm^{-3}, Units of n_o, T_o, χ_m, Δ_m are 10^{20} m^{-3}, 10keV, m^2s^{-1}, m



Ignition Conditions III

In the IDB discharge, the convective heat flux is small in the mantle i.e.,

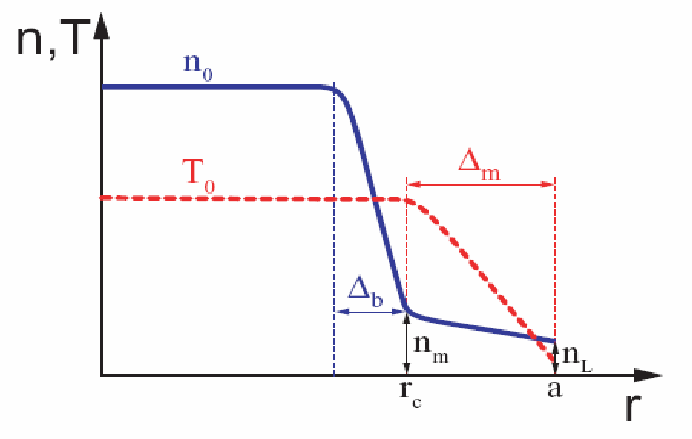
$$(\Delta_b / 5\Delta_m)\cdot(n_m / n_o)\cdot C_m \chi_m >> C_b D_b$$

In such a case, the ignition condition is expressed by

$$n_m T_o \tau_E^* > \cdot (n_m / n_o)^2 / F$$

where $\tau_E^* = 0.43\ r_c \cdot \Delta_m / C_m \cdot \chi_m$

almost the energy confinement without SDC.



Reactor Parameters

Ignition Condition

$D_b < 0.15\ m^2s^{-1}$

$\chi_m < 5\ m^2s^{-1}$

↓

$\tau^*_E > 100$ ms

- Minor radius 2.3 m
- Major radius 15.0 m
- Magnetic field 8 T
- Core density $5 \times 10^{20}\ m^{-3}$
- Mantle density $1 \times 10^{20}\ m^{-3}$
- Core temperature 8 keV
- Core beta 5 %
- Effective Z 2.0
- Mantle width (Δ_m) 0.70 m
- Barrier width (Δ_b) 0.45 m

Summary

Observation of Stable Super dense Core Plasma

- **Internal diffusion barrier.**
- **Pellet injection.**
- **Foot location of IDB shearless**
- **Quasi-steady operation.**

New Ignition scenario {high density core ($5\times10^{20}m^{-3}$), relatively low density mantle (8keV)}