Density Limit Studies in LHD

B. J. Peterson, J. Miyazawa, K. Nishimura, S. Masuzaki, Y. Nagayama, N. Ohyabu, H. Yamada, K. Yamazaki, T. Kato, N. Ashikawa, R. Sakamoto, M. Goto, K. Narihara, M. Osakabe, K. Tanaka, T. Tokuzawa, M. Shoji, H. Funaba, S. Morita, T. Morisaki, O. Kaneko, K. Kawahata, A. Komori, S. Sudo, O. Motojima and the LHD Experiment Group

National Institute for Fusion Science, Toki, Japan

20th IAEA Fusion Energy Conference
November 4, 2004
Vilamoura, Portugal

Topics

- Motivation
- Comparison with Sudo scaling
- Maximum achieved densities
    - Gas puff
    - H_2 pellet
- Effect of boronization
- Limitation by Radiative Collapse
    - Evolution of radiative collapse
    - Radiated fraction threshold
    - Critical edge temperature
    - Edge behavior
    - Radiation asymmetry
- Confinement degradation
- Summary

Motivation

- Fusion reaction rate goes as density squared $R_{DT} \sim n^2 <\sigma v>$

- Tokamak density is limited by current disruption and scales with plasma current density:

$$n_{Tok} \sim I_p/a^2 \quad \text{(Greenwald)}$$

but has weak power dependence

- Helical devices have radiative density limit which scales with square root of input power:

$$n_{H\text{-}E} \sim (PB/V)^{0.5} \quad \text{(Sudo)}$$
$$n_{W7AS} \sim (P/V)^{0.4} B^{0.32} \quad \text{(Gianonne-Itoh)}$$

- LHD has a density limit which is more than 1.6 times the Sudo limit

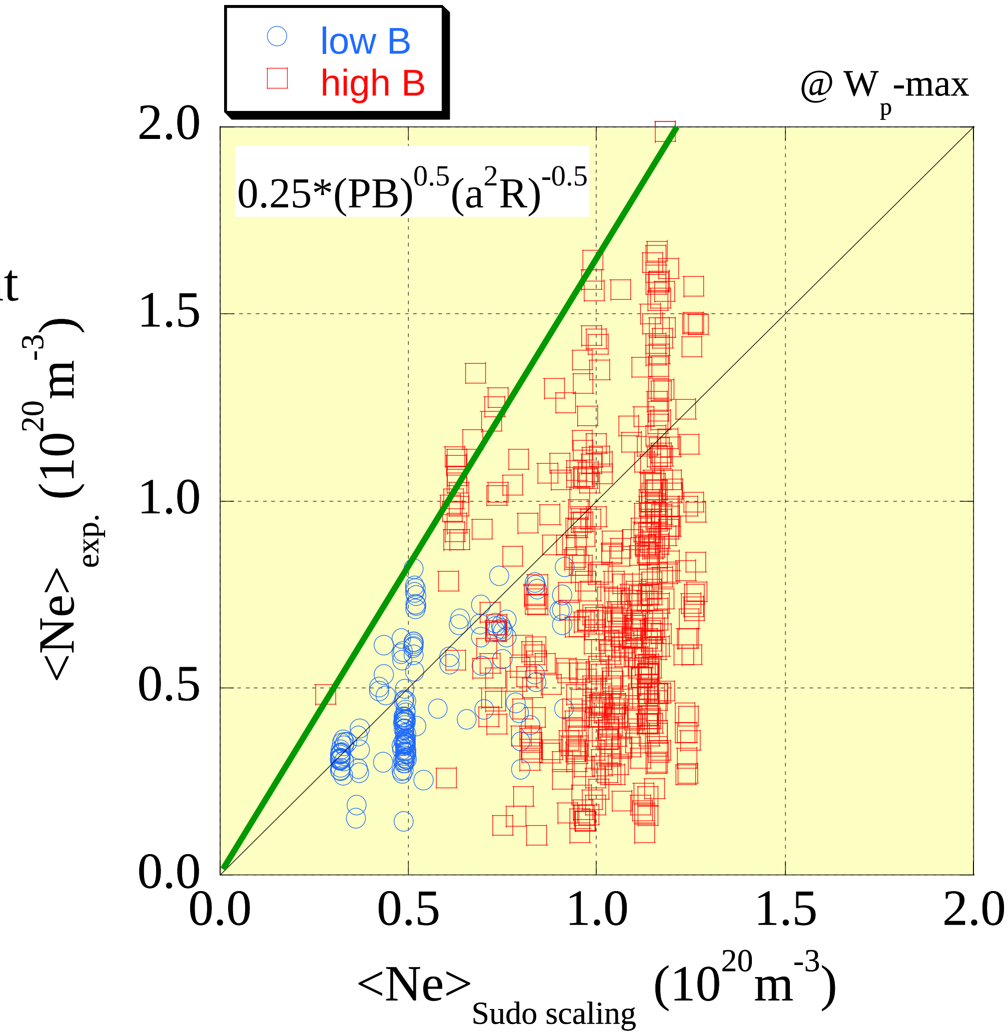
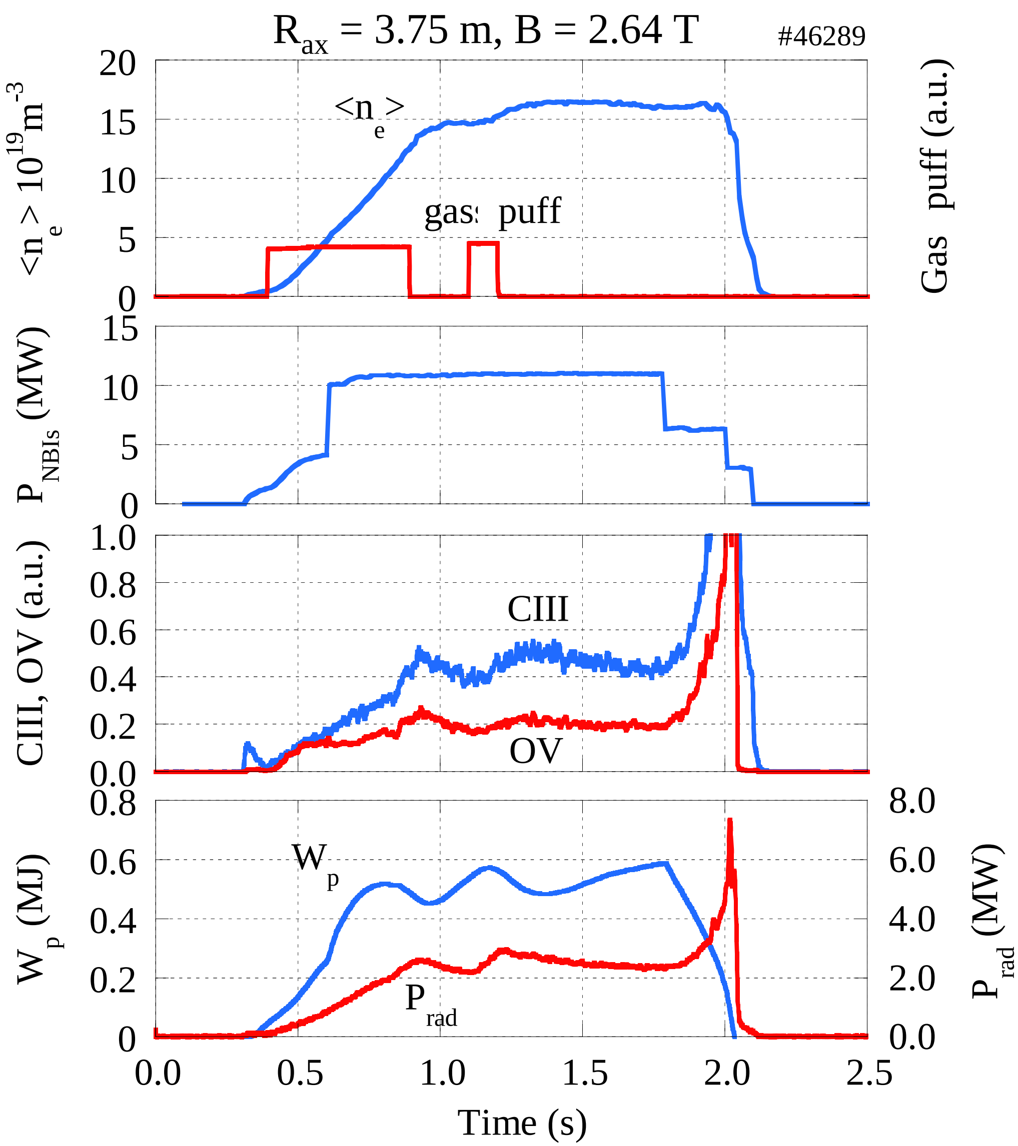


figure by K. Nishimura

Peak Sustained Density

- With He gas puffing
- line-averaged densities of $1.6 \times 10^{20}/m^3$
- $n_e = 1.36\ n_{e\text{-Sudo}}$
- sustained for > 0.7 s
- P_{in} ~ 11MW (3 NBI, -ion, 160-180 keV)
- P_{rad}/P_{in} < 25%
- Plasma collapses after reduction of beam power

figure by K. Nishimura



Higher densities with H_2 pellets

- H_2 pellet into He gas puffing
- Core fuelling @ $\rho \sim 0.7$
- transient line-averaged densities of $> 2.2 \times 10^{20}/m^3$
- $P_{in} \sim 10.5$ MW (3 NBI, -ion, 160-180 keV)
- $P_{rad}/P_{in} < 35\%$
- W_p begins to decay then collapses after reduction of beam power

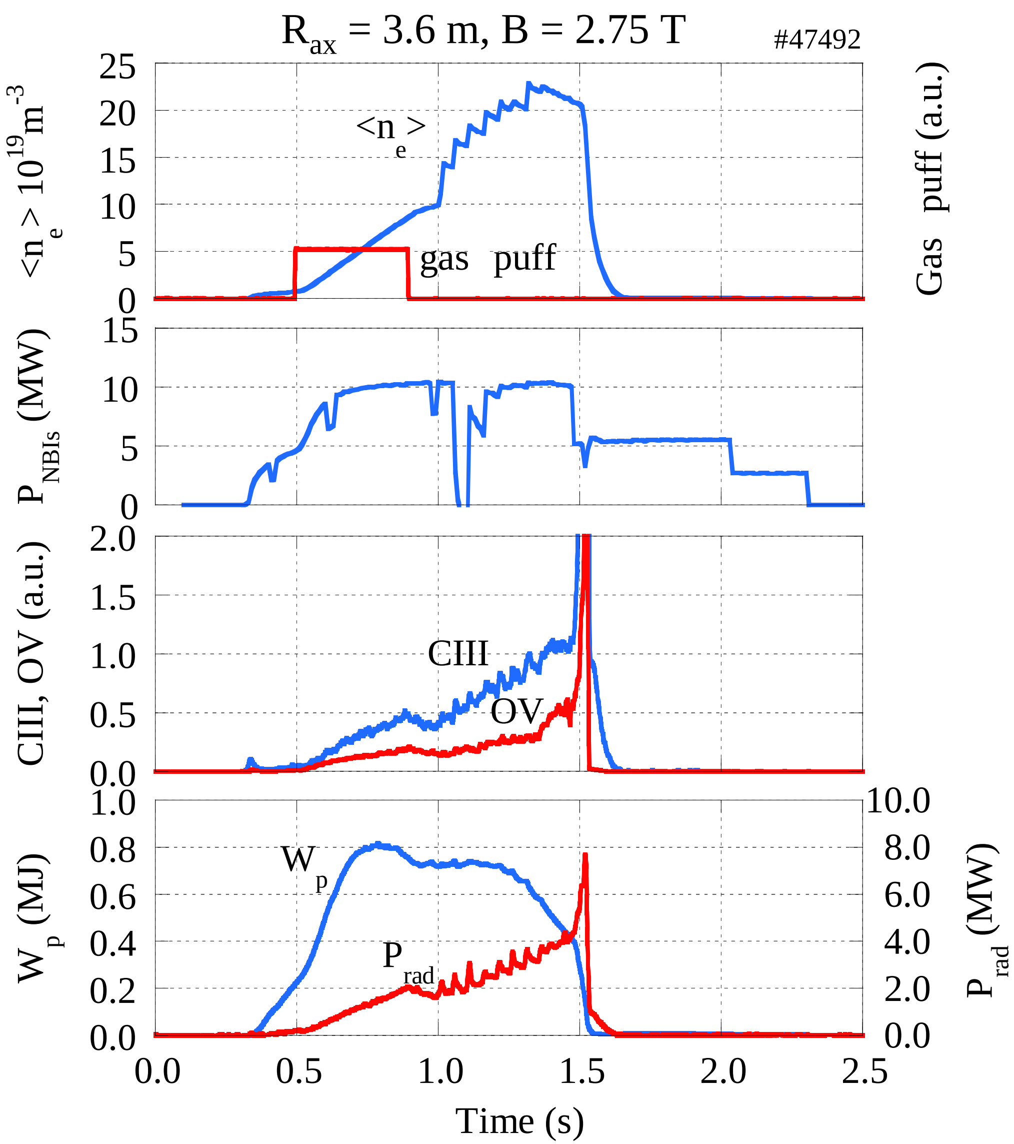
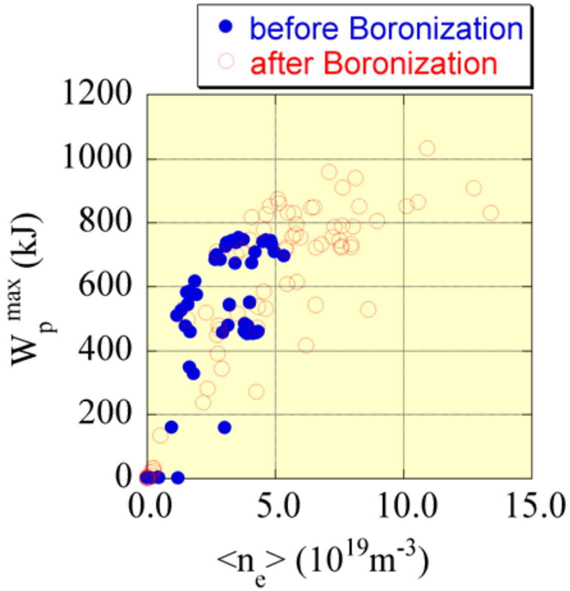
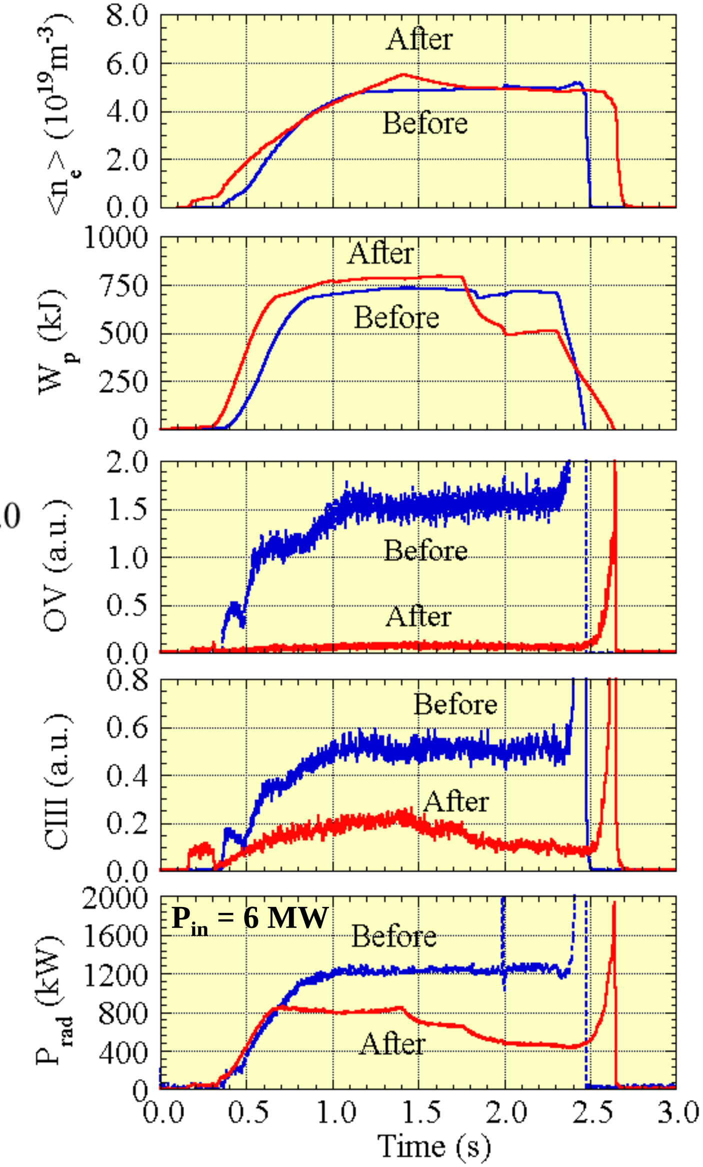


figure by K. Nishimura

Boronization raises density and reveals carbon as dominant radiating impurity

- Using 3 nozzles in LHD
- 60% coverage of vacuum vessel with diborane (B_2H_6)
- Effective in wall conditioning leading to extension of density range





- OV radiation decreases by a factor of >10
- While CIII radiation decreases by factor of 2.5
- Similarly, radiation decreases by factor of 1.5
- Therefore carbon should be dominant light impurity

K. Nishimura et al., J. Plasma Fusion Res. ***79*** *1216 (2003)*

Evolution at Radiative Collapse

- W_p saturates and drops more rapidly due to confinement degradation at high density
- Density and radiation peak as plasma collapses at density limit
- Radiated power is approximately 30% of input at onset of thermal instability
- First OV then CIII increase rapidly at onset of TI
- Edge temperature degrades after TI onset
- Density profile is maintained well beyond onset of TI

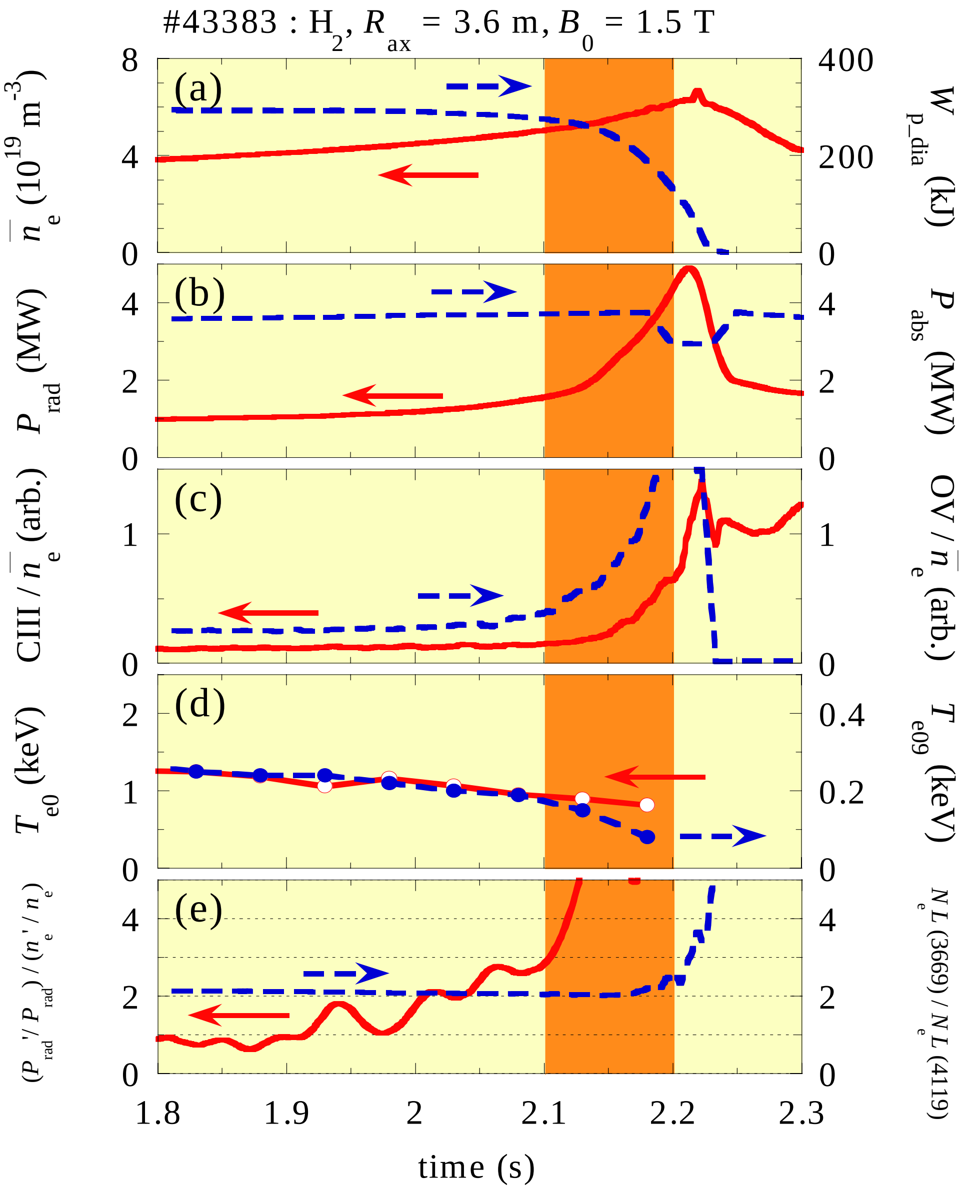


figure by J. Miyazawa

In LHD Radiative Collapse occurs above a certain Radiated Power Fraction

- Collapse occurs for $P_{rad}/P_{abs} > 30\%$

- P_{rad} does not include divertor radiation which is hard to estimate due to helical asymmetry.

- $P_{rad}/P_{abs} = 100\%$ in cases with large core radiation from metallic impurities

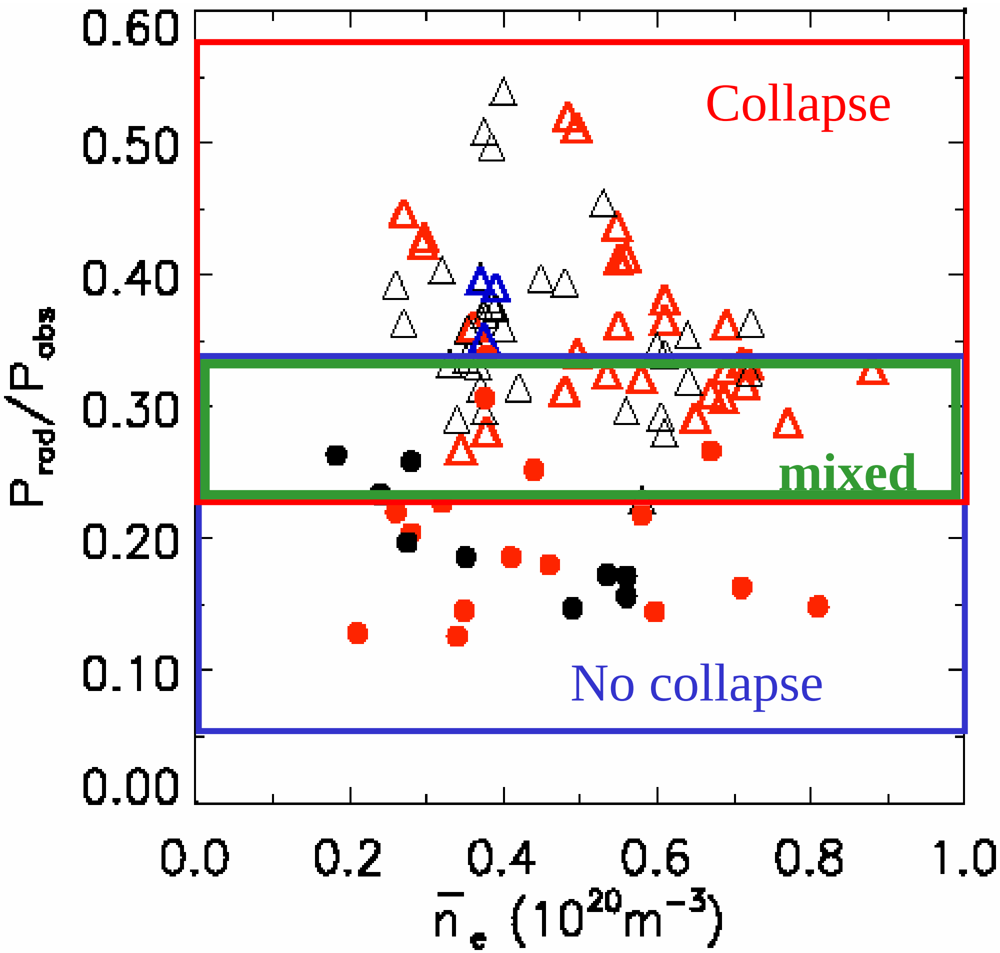


figure by Yuhong Xu

Quantification of thermal instability onset

- Impurity radiation can be written as:

$$P_Z = \int n_Z n_e L_Z(T_e)\,dV$$

- Assuming that n_z and T_e have some dependence on n_e
- The radiated power can be expressed as having a certain power dependence on density

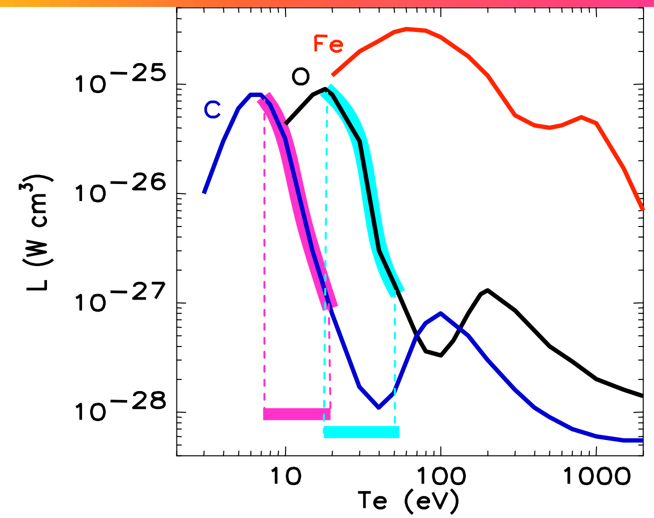
$$P_{\mathrm{rad}} \propto n_e^{\,x} = c\, n_e^{\,x}$$

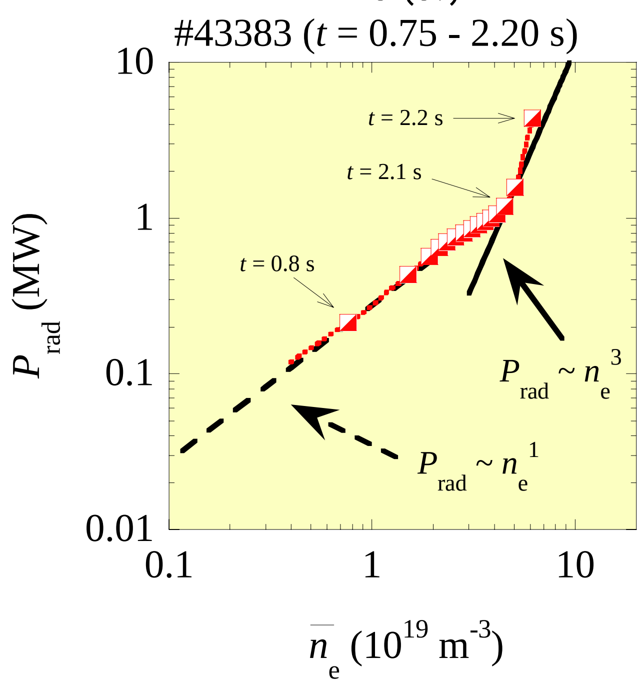
and an expression for x can be derived as

$$\therefore\ x = (P_{\mathrm{rad}}' / P_{\mathrm{rad}}) \,/\, (n_e' / n_e)$$

※ **this is called the <u>density exponent</u>**

- During the steady state portion $x = 1$
- Increases to > 3 after the onset of the thermal instability
- Define onset of thermal instability at $x = 3$

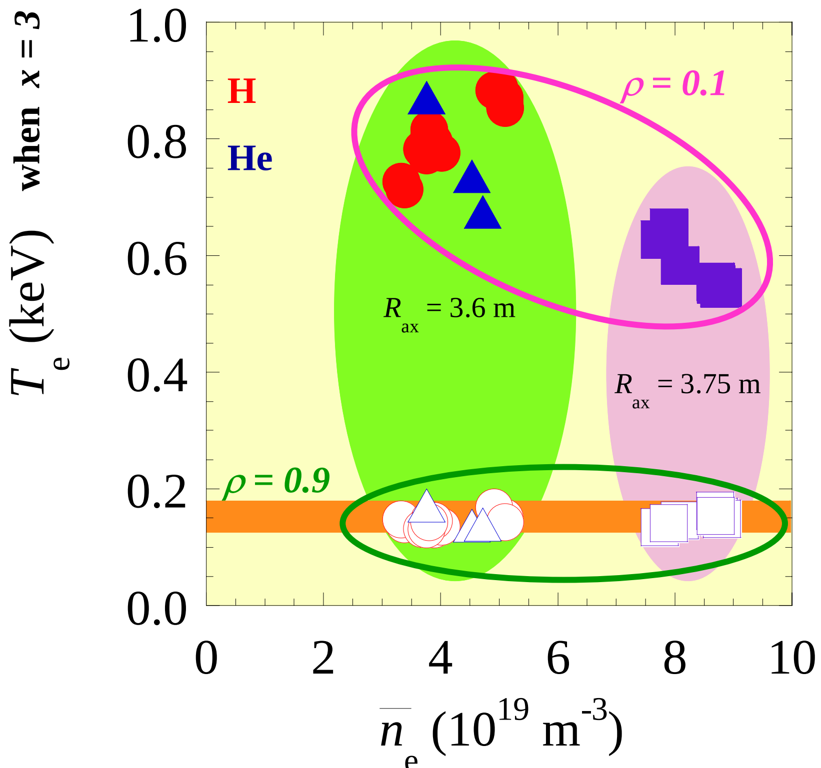


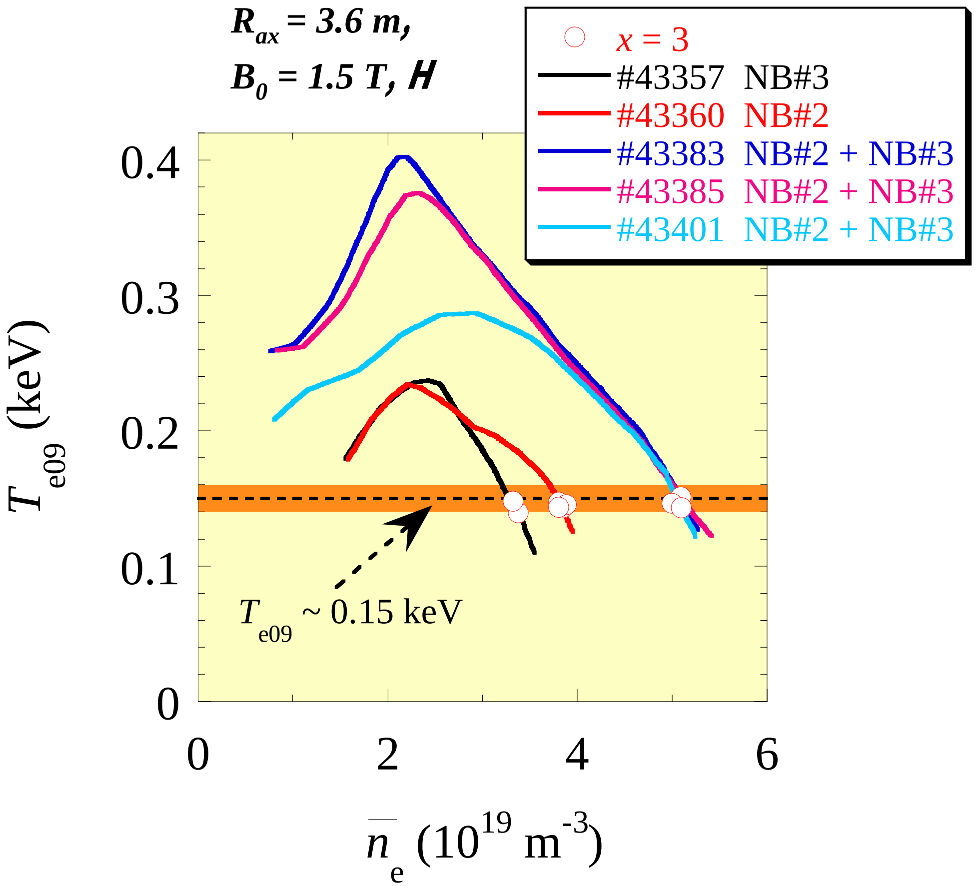


Edge Temperature threshold for density-limiting radiative collapse in LHD

○ $x = 3$ is correlated with T_{e09} ($\rho = 0.9$) **= *150 eV*** independent of the input power, density (right plot), magnetic configuration and gas (left plot)

○ Therefore a certain edge threshold temperature exists for the onset of the thermal instability (but not necessarily at $\rho = 0.9$)





figures by J. Miyazawa

Evolution of Impurity Radiation and Divertor Plasma during Thermal Instability and Collapse

- Radiation asymmetry accompanies onset of thermal instability

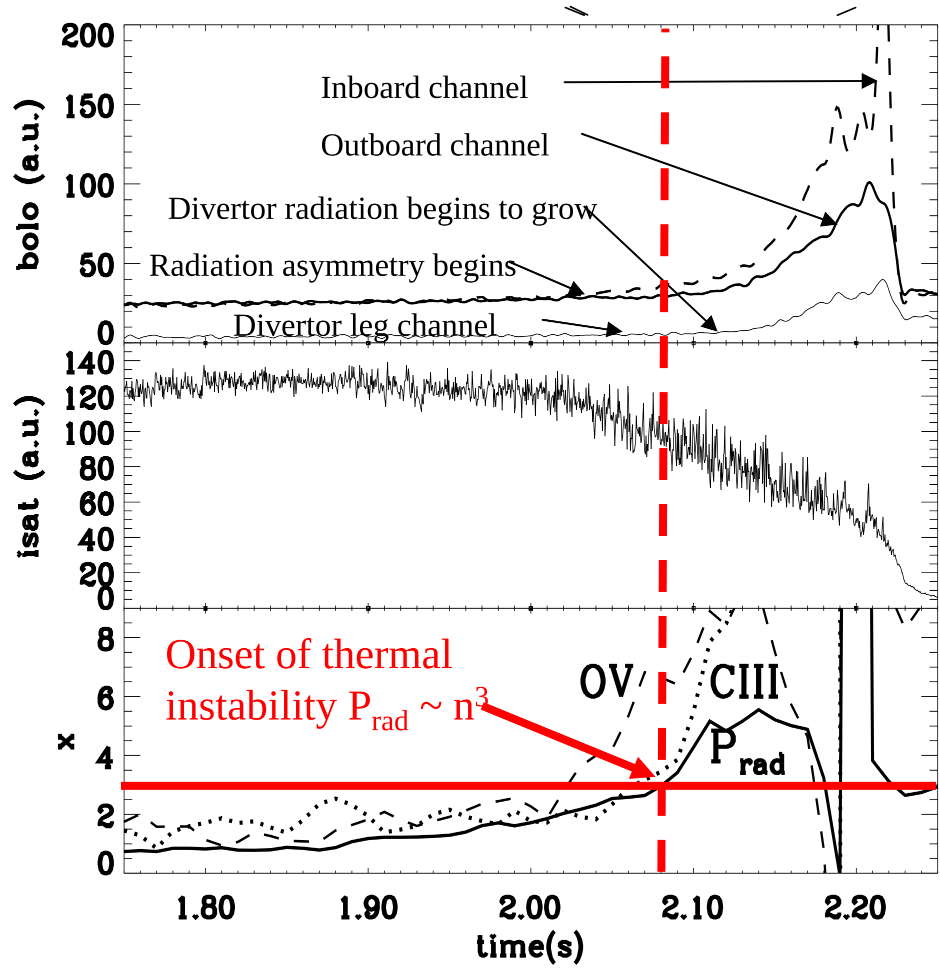
- Divertor radiation increases after thermal instability begins and is less dramatic

- Ion saturation current in divertor decreases

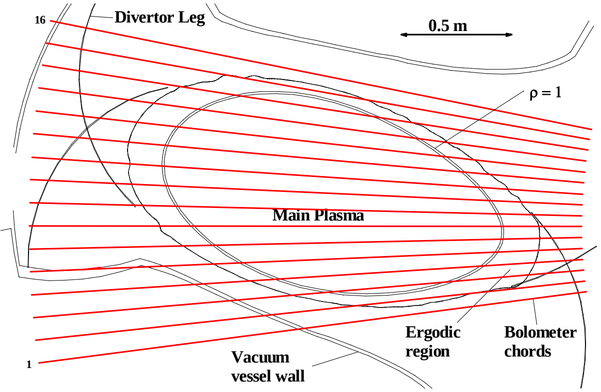
- Thermal instability begins first in OV

- CIII coincident with P_{rad}

•Indicates C as dominant impurity



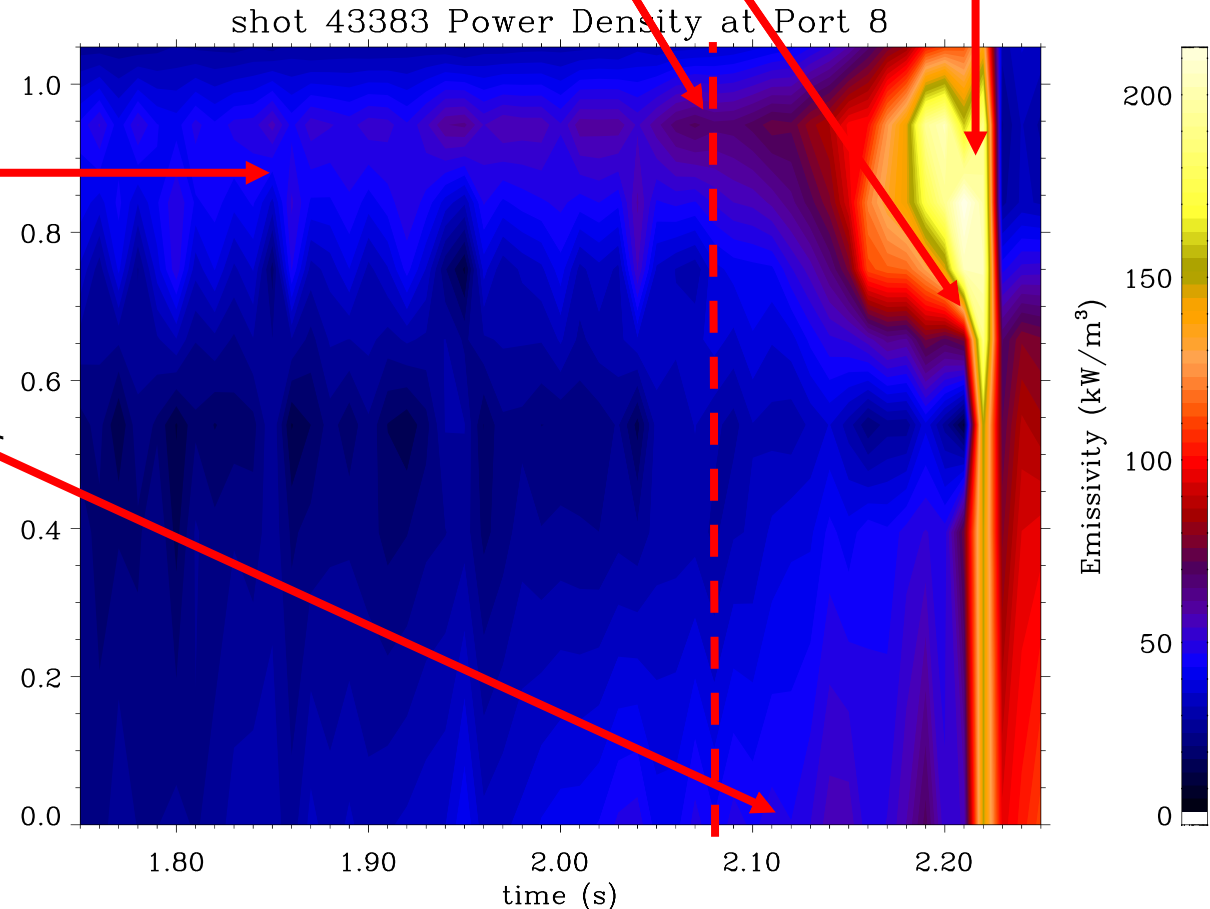
Evolution of Radiation Profile during Thermal Instability and Collapse



Peak moves in as temperature drops

And second peak appears

Onset of thermal instability $P_{rad} \sim n^3$



- Initially hollow
- Slight increase in core radiation
- Extremely hollow during collapse at 2.19 s
- Estimated power density for 3% C, $n_e = 7 \times 10^{19}$, $L = 10^{-33}$ Wm^3 is $150 kW/m^3$

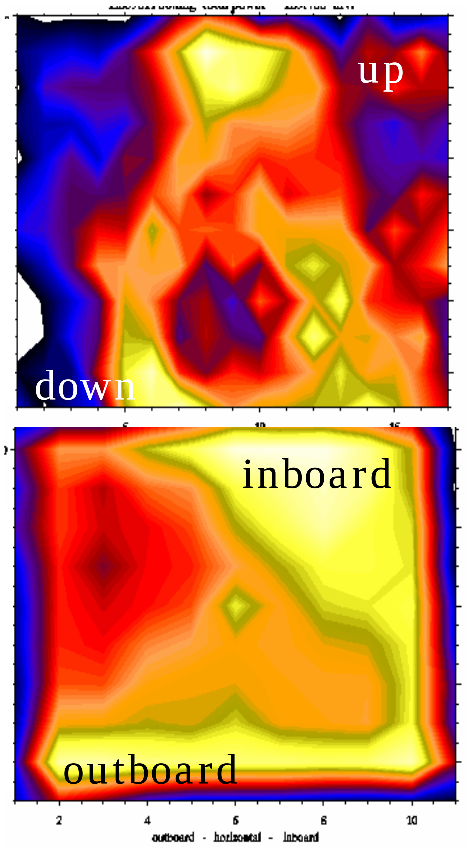
Imaging Bolometers show radiative collapse that is: poloidally asymmetric, toroidally symmetric

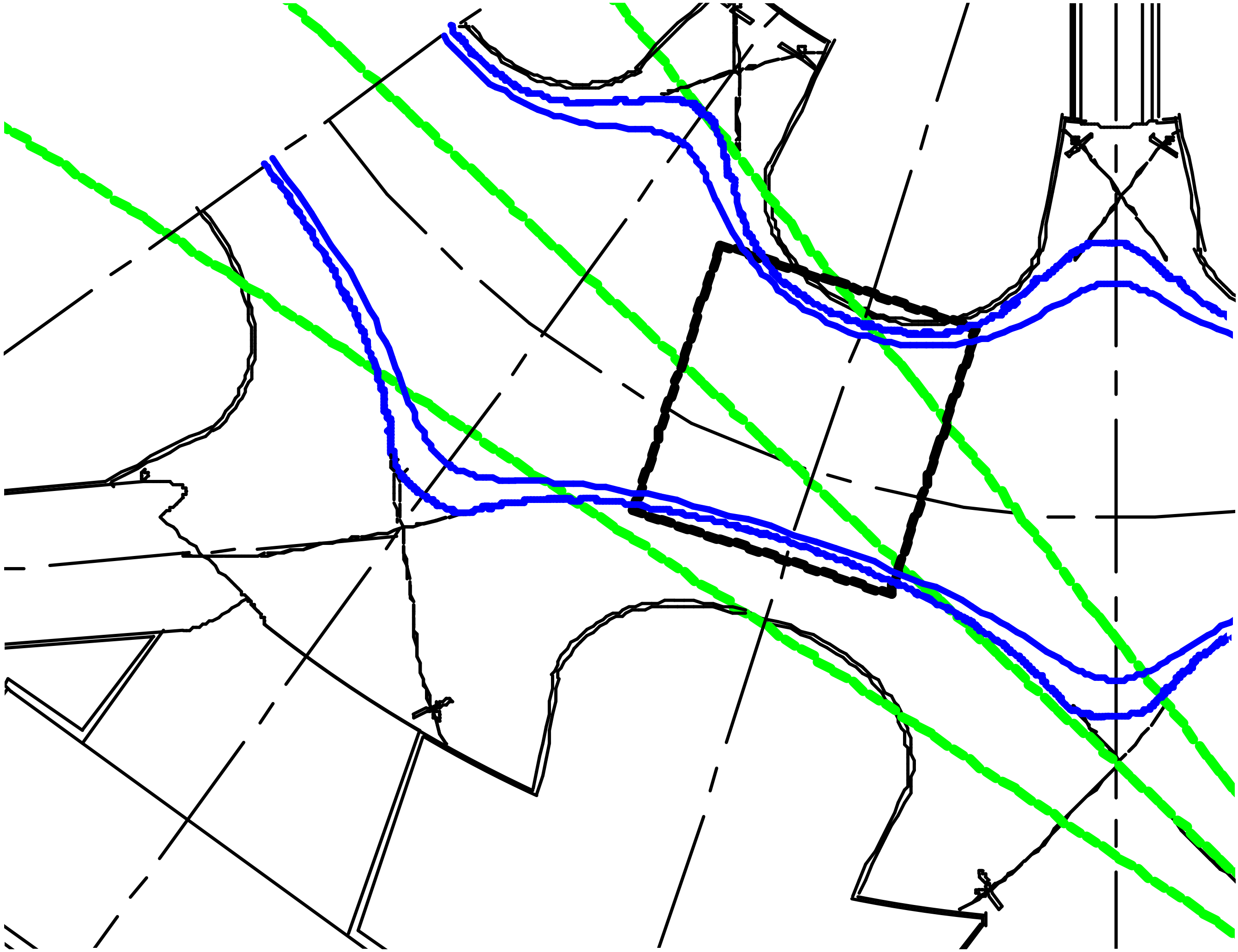
Symmetric Hollow Profile

Experimental data

Tangential view

Top view



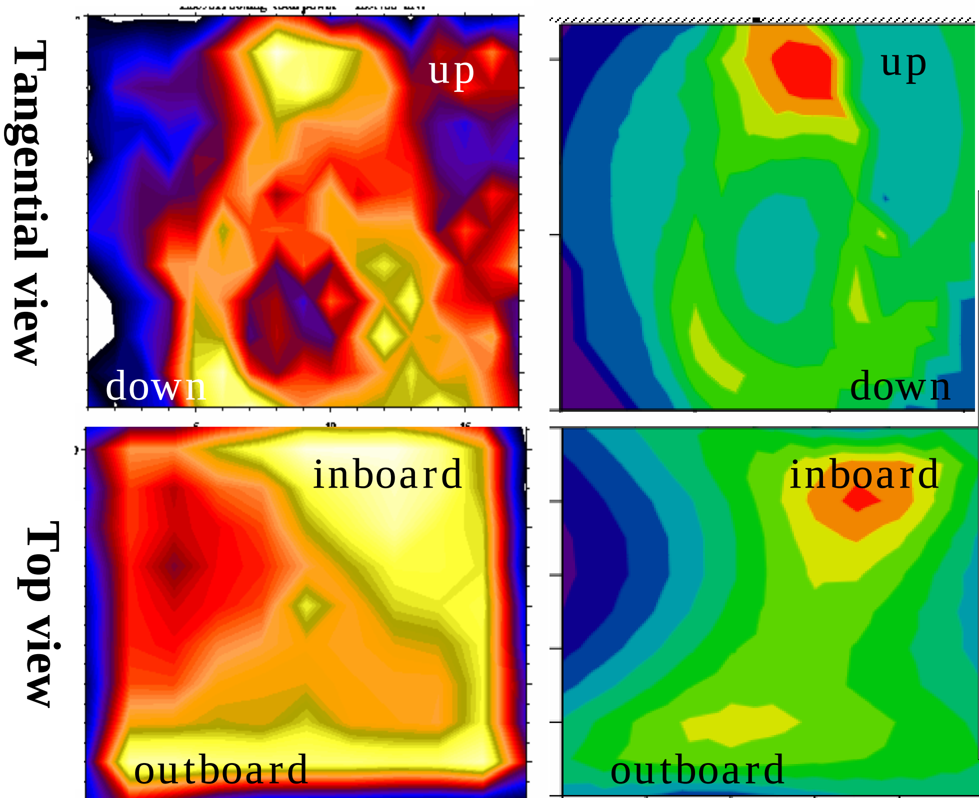


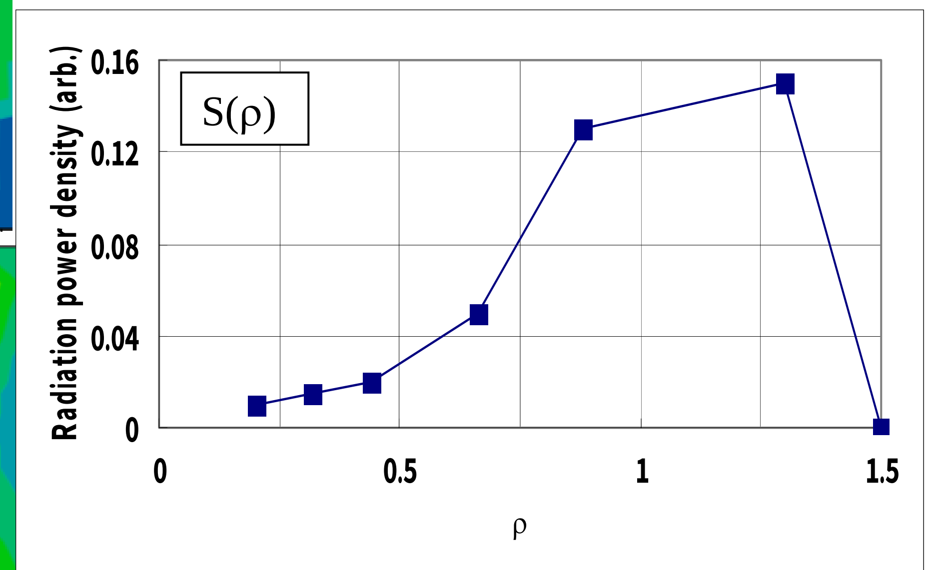
by Peterson and Ashikawa

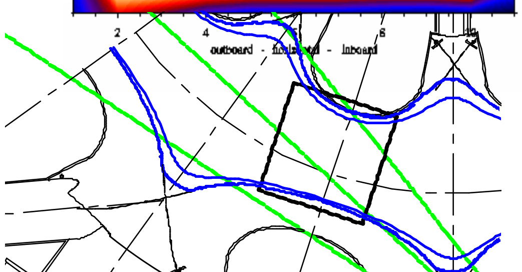
Imaging Bolometers show radiative collapse that is: poloidally asymmetric, toroidally symmetric

Symmetric Hollow Profile

Experimental data Model







$$S(\rho,\theta) = S(\rho)$$

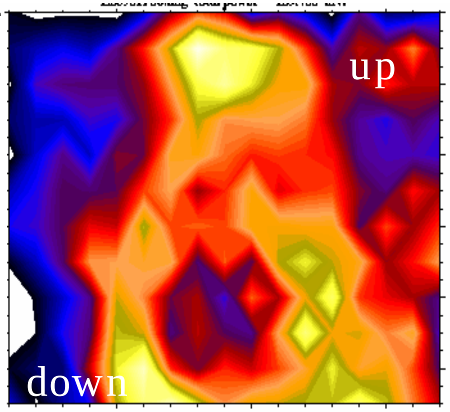
by Peterson and Ashikawa

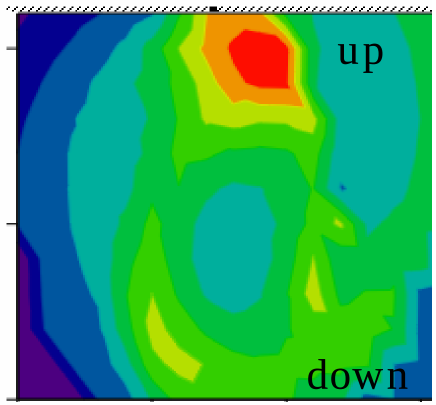
Imaging Bolometers show radiative collapse that is: poloidally asymmetric, toroidally symmetric

Symmetric Hollow Profile

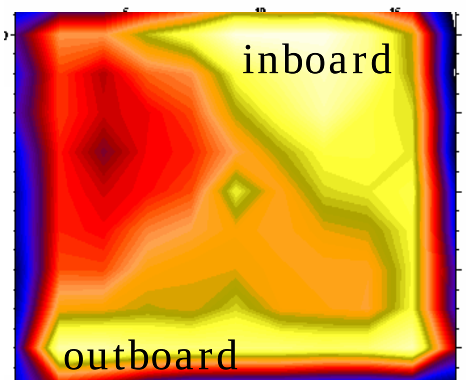
Experimental data | Model $F(\theta) = 0$

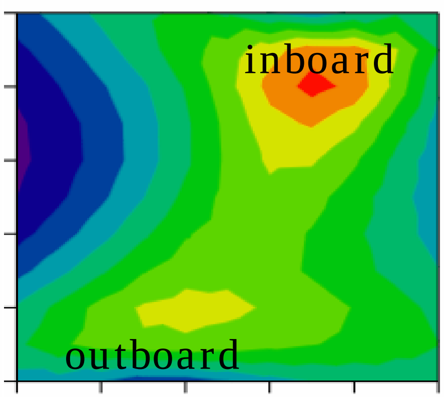
Tangential view

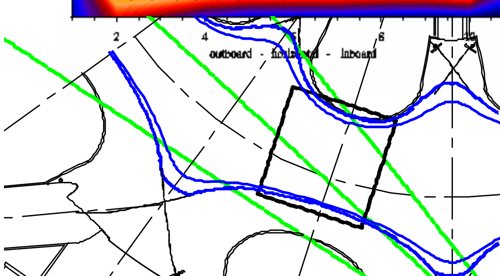




Top view



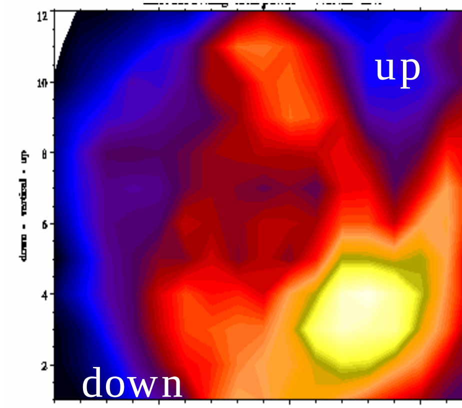


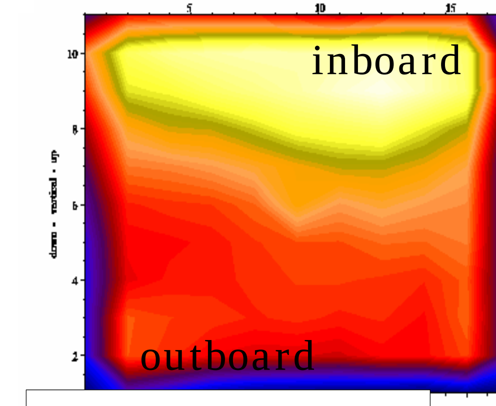


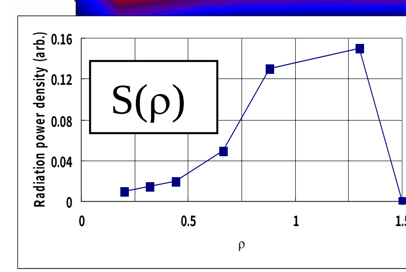
$$S(\rho,\theta) = S(\rho)$$

Asymmetric Collapse

Experimental data







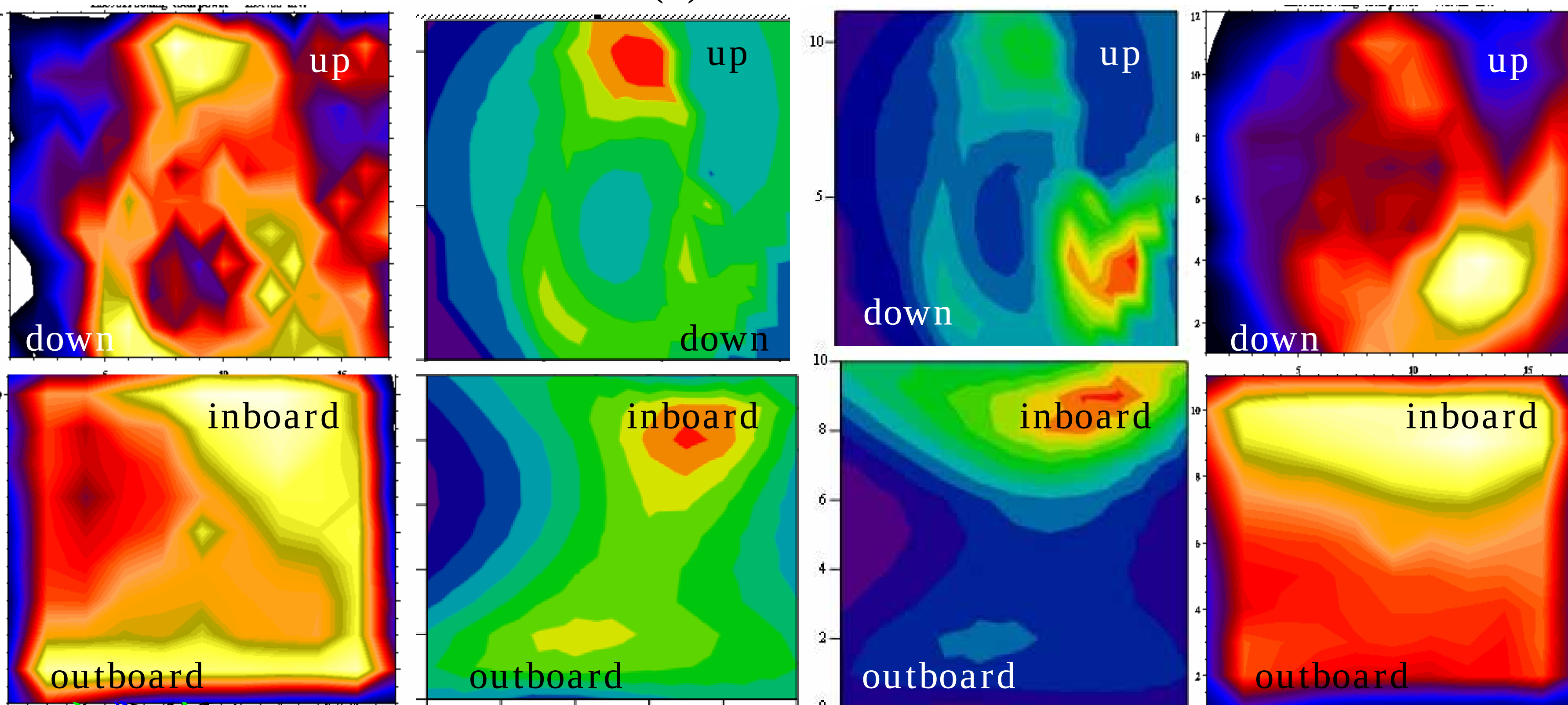
by Peterson and Ashikawa

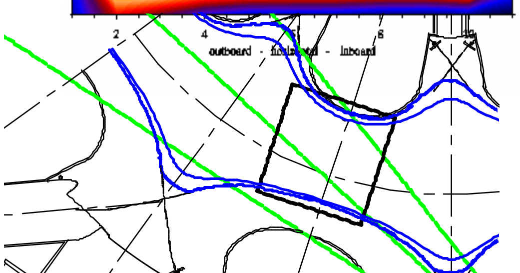
Imaging Bolometers show radiative collapse that is: poloidally asymmetric, toroidally symmetric

Symmetric Hollow Profile — Experimental data | Model $F(\theta)=0$

Asymmetric Collapse — Model $\theta_0=-150°$ | Experimental data

Tangential view / Top view

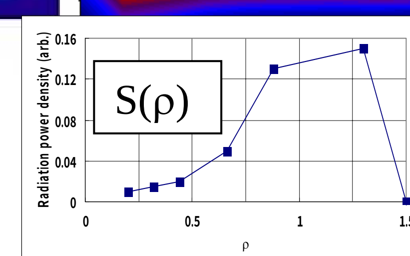




$$S(\rho,\theta)=S(\rho)\cdot[1+F(\theta)]$$

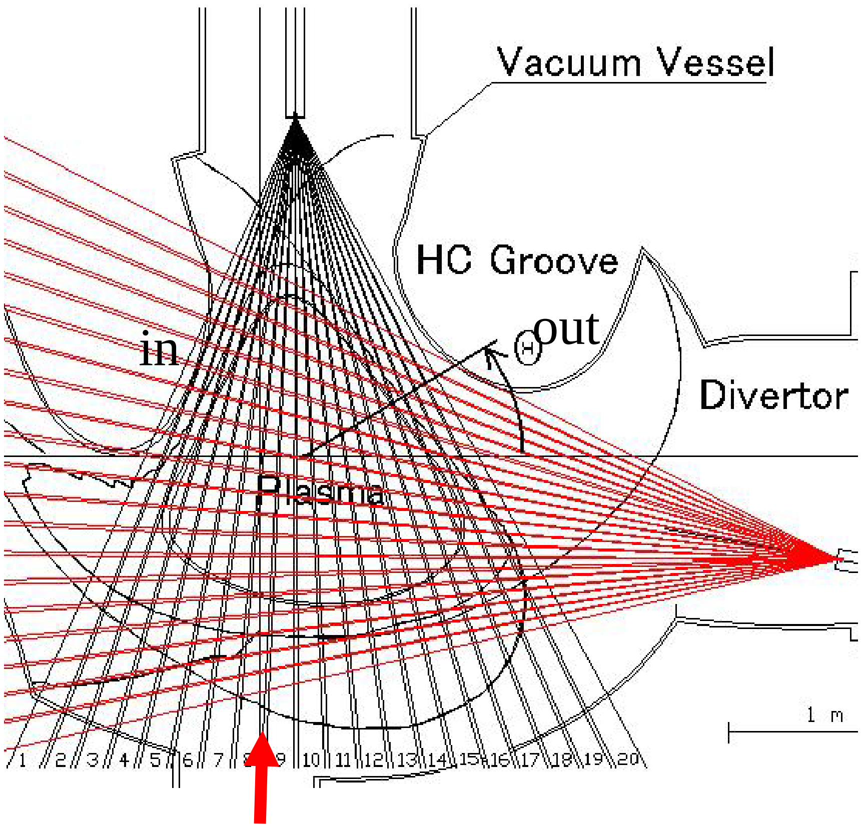
$$F(\theta)=((1+\cos(\theta-\theta_0))/2)^{50}$$

by Peterson and Ashikawa



2-D tomography with AXUV diodes also indicates poloidally asymmetric, toroidally symmetric

AXUV Diode Arrays in semi-tangential cross-section

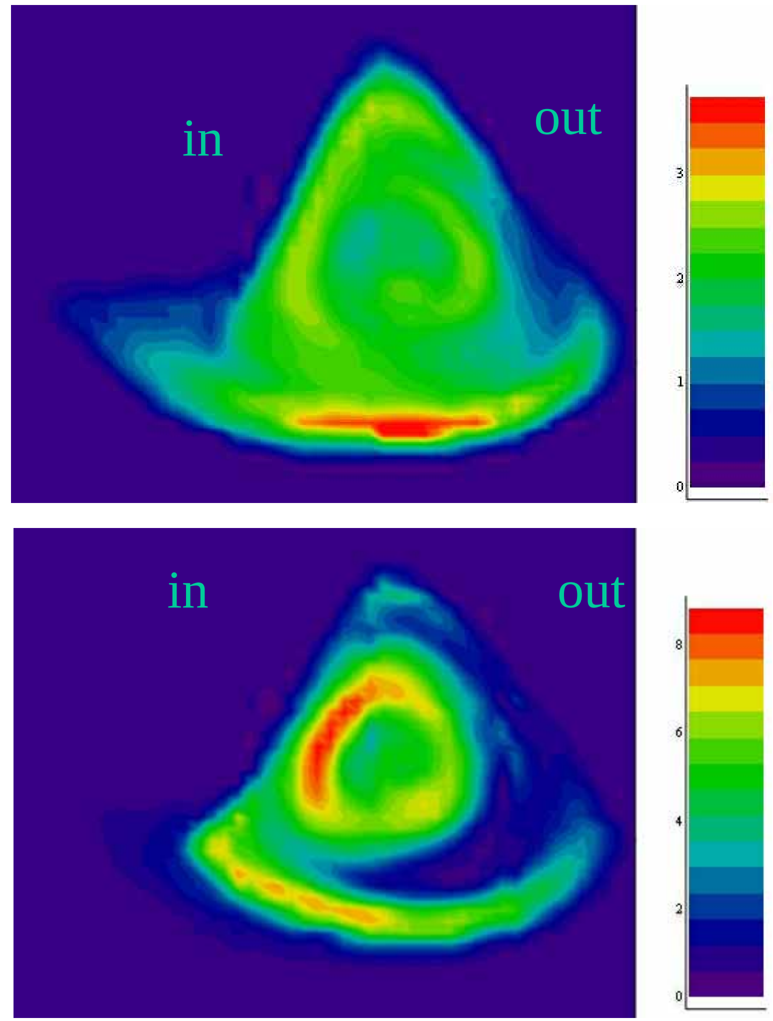


Gas Puff

*Peterson et al., PPCF **45** (2003) 1167.*

Reconstructed 2-D Images

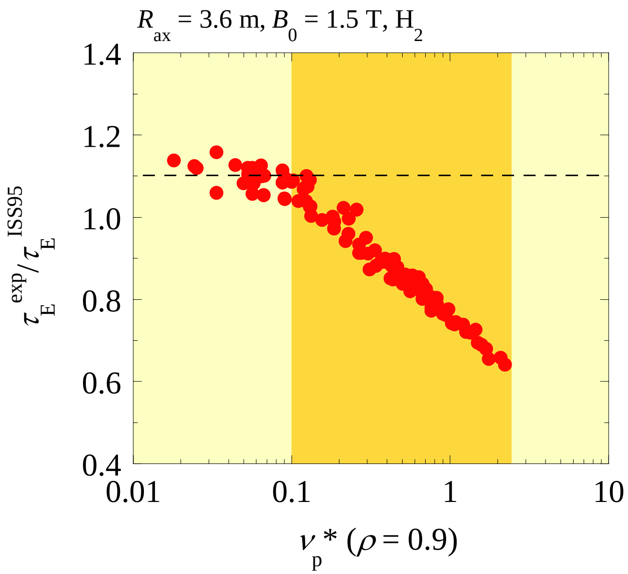
(tomography courtesy Y.Liu, SWIPP, China)

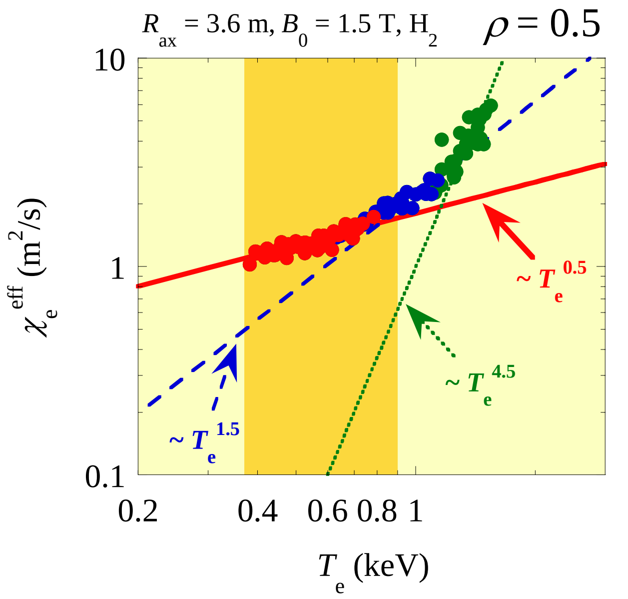


Symmetric radiation with gas puff

Asymmetric collapse

Confinement degradation at high density





τ_E compared with ISS95 declines in high-density (high-collisionality) regime, however χ_e^{eff} still is lower in this regime (yellow band).

This "confinement limit" appears at lower density than the operational density limit by radiative collapse and leads to an earlier saturation of and accelerated decay of W_p and thus T_e as n_e increases.

Shallow penetration of heating beams at high density is not sufficient to explain degradation.

The effective thermal diffusivity shows weaker temperature dependence of $\chi_e^{eff} \propto T_e^{0.5}$ at low T_e (corresponds to $\tau_E \propto n_e^{1/3}$).

As temperature increases, temperature dependence becomes stronger, gyro-Bohm (blue) and/or neo-classical theory (green).

Degradation from ISS95 in high-density regime attributed to change in temperature dependence of thermal diffusivity.

Weaker temperature dependence is less favorable (and thus leads to lower density limit) as higher temperature dependence inhibits collapse by giving weaker transport as temperature drops.

However, higher power is expected to raise temperature returning to regime of favorable density and temperature dependences.

Summary

• Maximum line-averaged densities of 1.6 x 10^{20} /m^3 have been sustained in LHD which is 1.36 times the value expected from scaling laws for smaller helical devices.

• Boronization of 60% of vacuum vessel effectively conditions wall and can lead to lower radiation and higher density limits.

• LHD plasmas are limited at high density by a radiative thermal instability leading to radiative collapse of the plasma when core radiated power fraction is > ~30%.

• Onset of the radiative thermal instability at a certain edge temperature indicates temperature threshold.

• Comparison of CIII and OV signals with P_{rad} before and after boronization and during radiative collapse indicate C is dominantly radiating impurity.

• A poloidally asymmetric, toroidally symmetric radiation structure accompanies the collaspse of the plasma similar to a MARFE in tokamak.

• Degradation from ISS95 in high-density regime due to weak temperature dependence of thermal diffusivity should accelerate the decrease in the electron temperature leading to a lower density limit at the collapse.

Loss of edge profile stiffness at high density

- In the high density range, the scale length of the electron pressure gradient is sustained except at the periphery where it increases with density in the shaded region.

- Pressure itself is found to increase with P_{abs}, $p_e \propto P_{abs}^{0.51}$

- The electron pressure profile can be fitted with a model equation in the plateau regime:

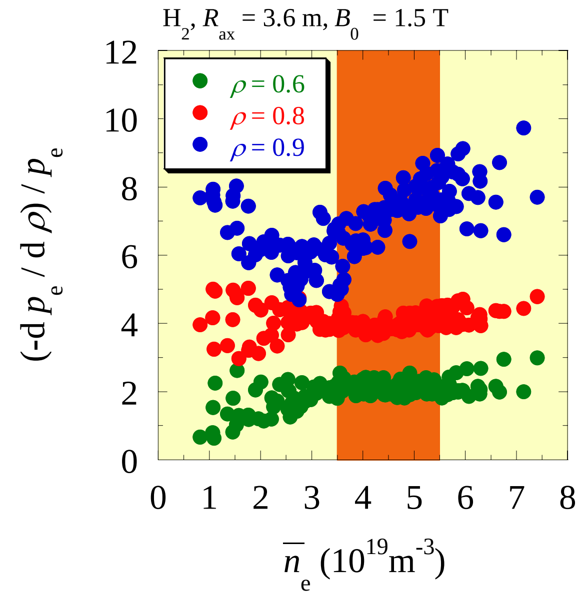
$$p_e^{plt}(\rho) = 3.4 P_{abs}^{0.51} \exp(-(1.5\rho^2 + 1.5\rho^{10}))$$

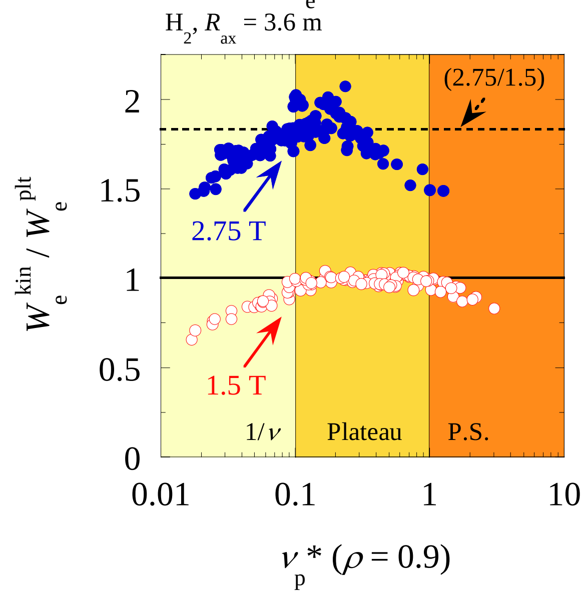
- This can be integrated over ρ to give W_e^{plt}

- At low B the dgradation of the We kin compared to themodel in the P-S regime is due to deterioration in the edge as seen above.

- At high B hovevfer the deterioration happens at lower collisionaltiy and occurs in the core.

- Loss of profile stiffness at high collisionality should limit the density which can be obtained before the raditive collapse





figures by J. Miyazawa

Role of electric field on radiative collapse

positive radial electric field contributes to avoid radiation collapses