Impurity effects on the ITB in Alcator C-Mod

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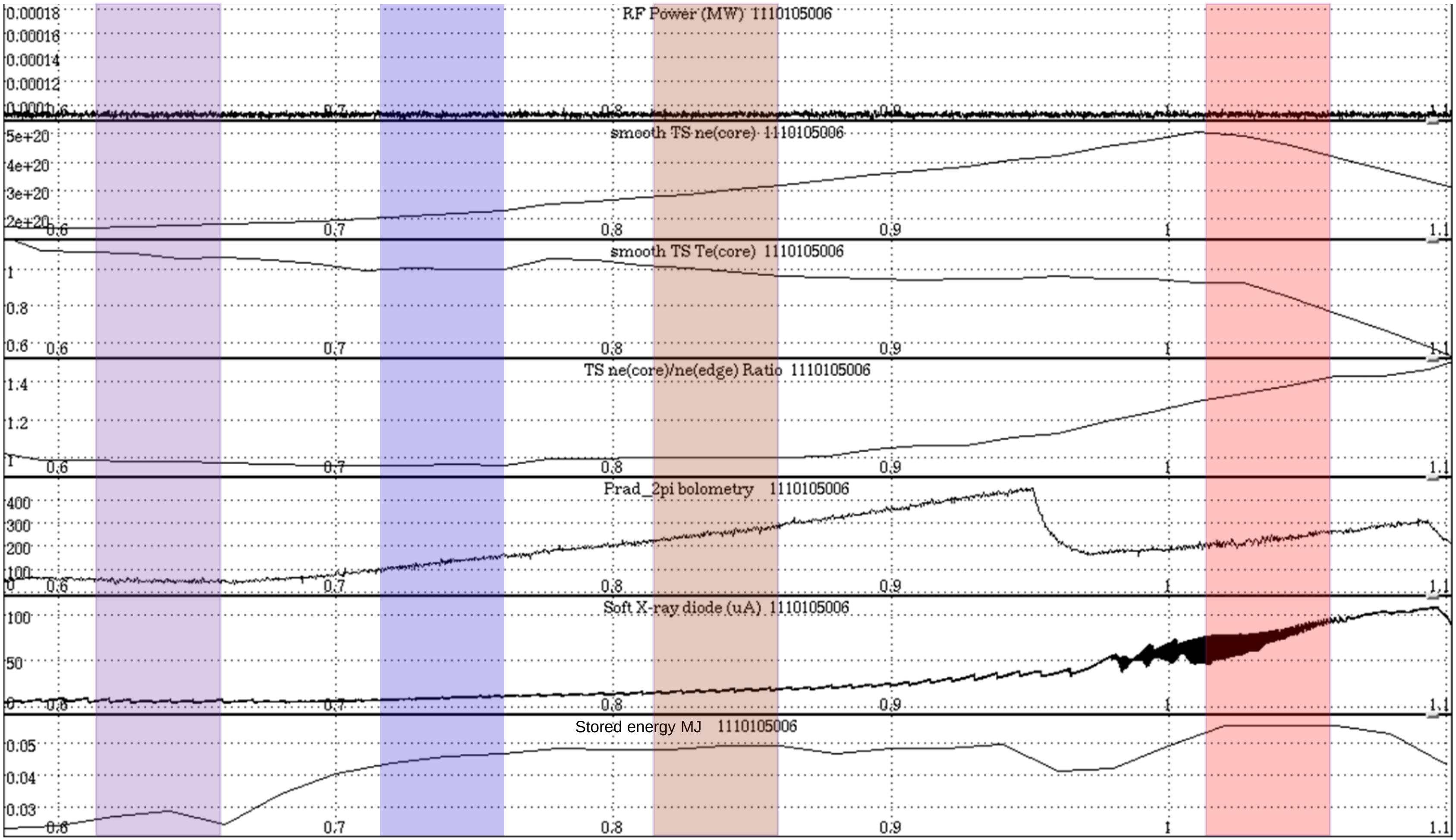
Abstract

We investigate the effects of impurities on ITB sustainability via measurements of ambient and puffed impurities in the Alcator C-Mod tokamak. Impurity peaking is the better known of these effects, and will lead to fuel dilution in and enhanced radiative losses from a burning fusion plasma. Heavy impurities are more effective radiators because even in the core of a fusion plasma they may not be fully stripped. On the other hand, light impurities which are fully stripped can still dilute the fuel. Whether either of these will be relevant for future devices depends on measurement based investigations of impurity transport in current devices which can be used to aid in the formulation of predictions for future devices. In C-mod we investigate impurity peaking and transport for light and heavy impurities in both Ohmic ITBs and RF-induced ITBs and compare those to peaking in a variety of other modes including H-modes, Ohmic and I-modes. The peaking is compared directly among the discharges. Transport fluxes are extracted from the data and compared as well. The correlation of impurity peaking with radiation level and confinement is included. Neoclassical transport is typically not observed but appears in many cases to suggest strongly peaked impurity profiles which would lead to catastrophic consequences in ITBs. The profiles that we observe are less strongly peaked but are compared to the neoclassical profiles as a benchmark. Plasma turbulence is more likely to dominate impurity transport and we include comparisons to a drift wave theory that includes a novel impurity driven drift wave as well as to other turbulence predictions. We will also speculate on the effect of impurities on the ITB trigger using data in which impurities are puffed into the plasma edge. It is clear from our research on C-Mod, that weaker ITBs will not tolerate impurity puffing. Whether this is due to an impurity peaking effect or to some more subtle effect will be discussed.

Summary

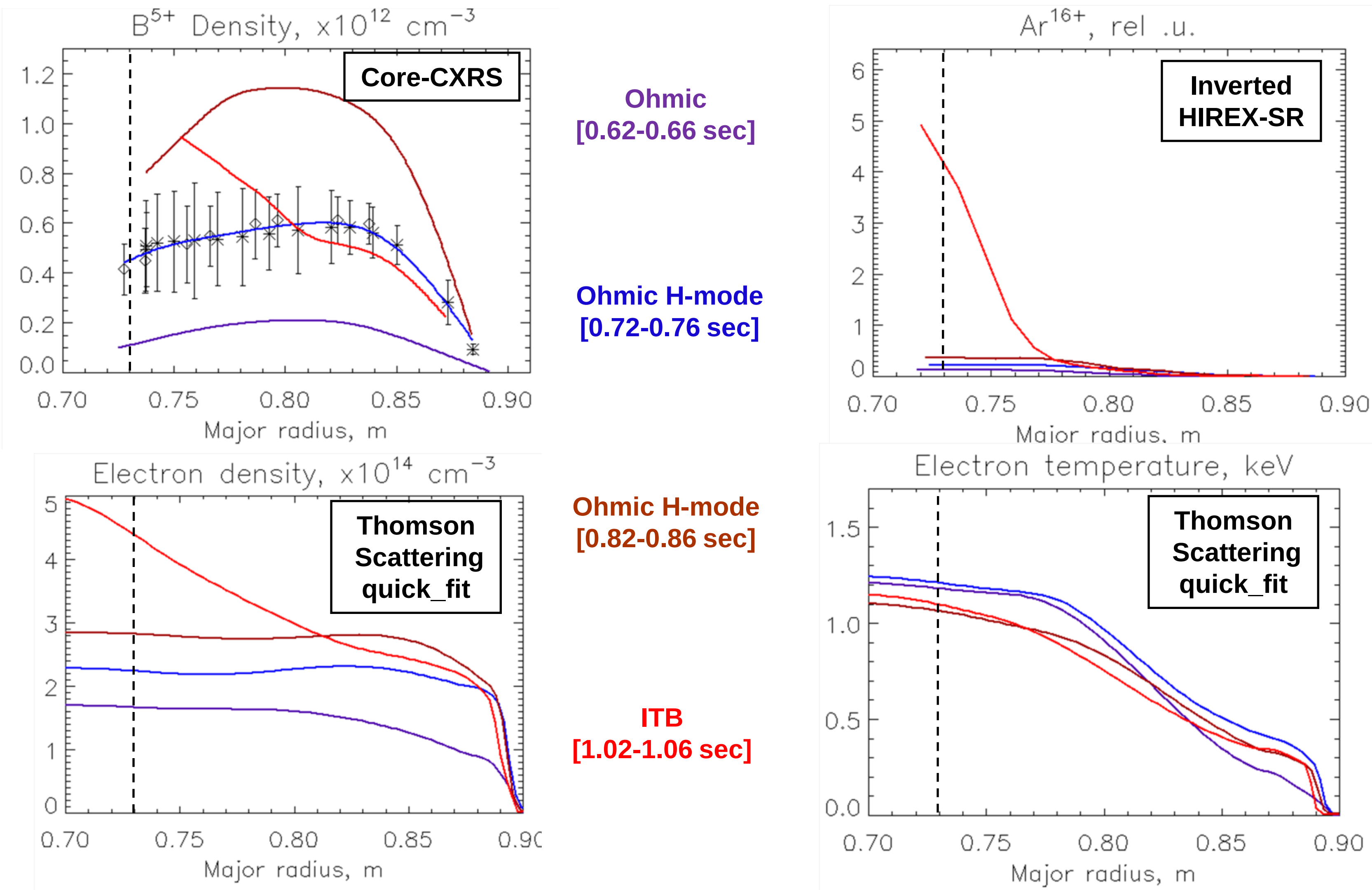
- B^{5+} and Ar^{16+} profiles are routinely measured by CXRS and HIREX-SR diagnostics at C-mod.
- The impurity density profiles are compared among the Ohmic, Ohmic H-mode, Ohmic ITB, I-mode, RF H-mode, RF heated ITB discharges.
- A correlation of impurity peaking with radiation level is observed.
- Absolute density of the seeded argon is estimated based on Z_{eff} measured by a completely different diagnostic and on the CXRS-measured boron density.
- It was found that Ohmic ITBs are very sensitive to levels of Argon in the plasma that that would not affect other modes.
- In the core, argon peaks more strongly than boron for most of the high-confinement modes.
- In the core and during the ITB, boron density peaks more strongly than electron density.
- Boron transport was compared to neoclassical predictions for ICRF H-mode, I-mode and ITB. Boron peaks less than neoclassical theory predicts, although, for ITB modes, transport at some locations can transiently drop to the neoclassical levels.
- Measured (boron) and estimated (argon) absolute densities of impurities in C-mod (for H-mode and ITB) are less than needed to cause plasma radiative collapse or main ion dilution.
- For work on turbulent transport prediction see poster: P27, W. Horton and S. Fu.

Ohmic ITB (shot:1110105006)



- In C-Mod, an internal transport barrier (ITB) arises spontaneously from the Ohmic H-mode without application of RF heating but with a well defined toroidal field sweep.
- For this shot, the plasma transits from the initial Ohmic mode (purple) (low confinement) to Ohmic H-mode (blue and brown) (high confinement) and then to Ohmic ITB (red), which is characterized by core peaking of the electron density.

Profiles of impurities and electrons (shot:1110105006)



- Injection of argon (15 msec, 1psi puff)
- Boron is an intrinsic impurity (Boronization), argon (seeded:15 msec, 1psi puff).

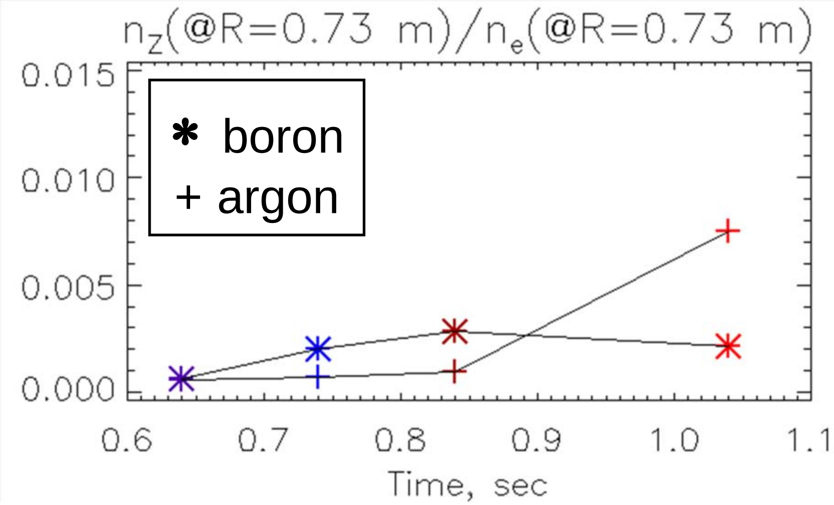
Impurity peaking in the core (shot:1110105006)

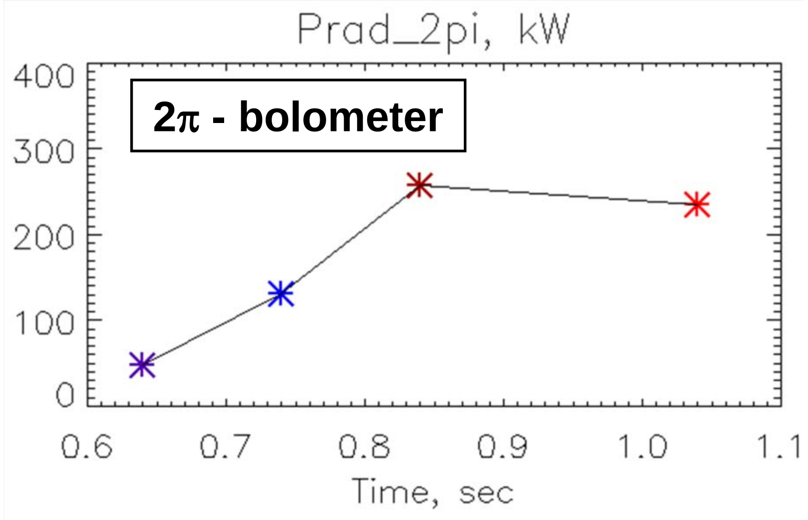
Ohmic **[0.62-0.66 sec]**

Ohmic H-mode **[0.72-0.76 sec]**

Ohmic H-mode **[0.82-0.86 sec]**

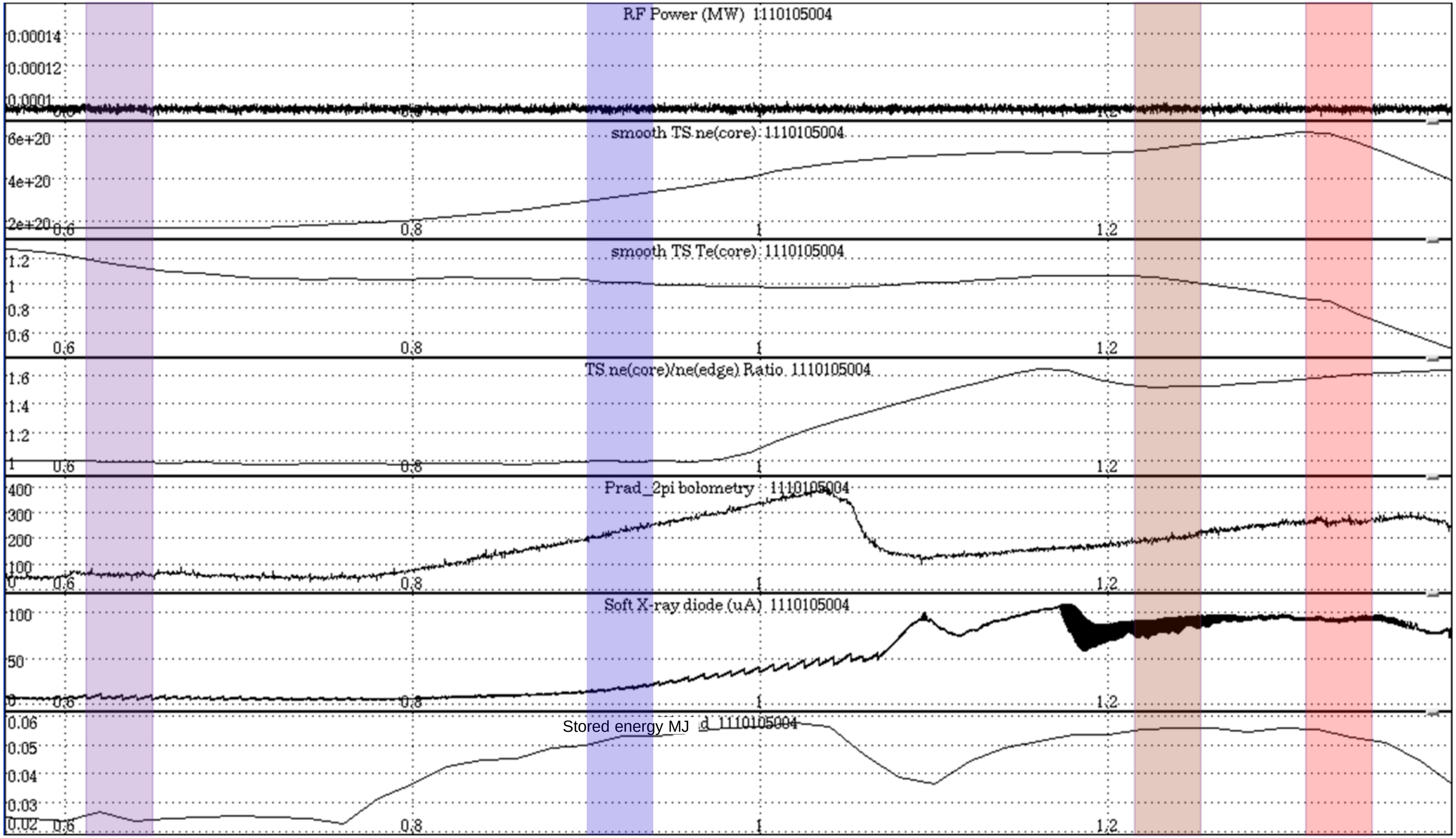
ITB **[1.02-1.06 sec]**





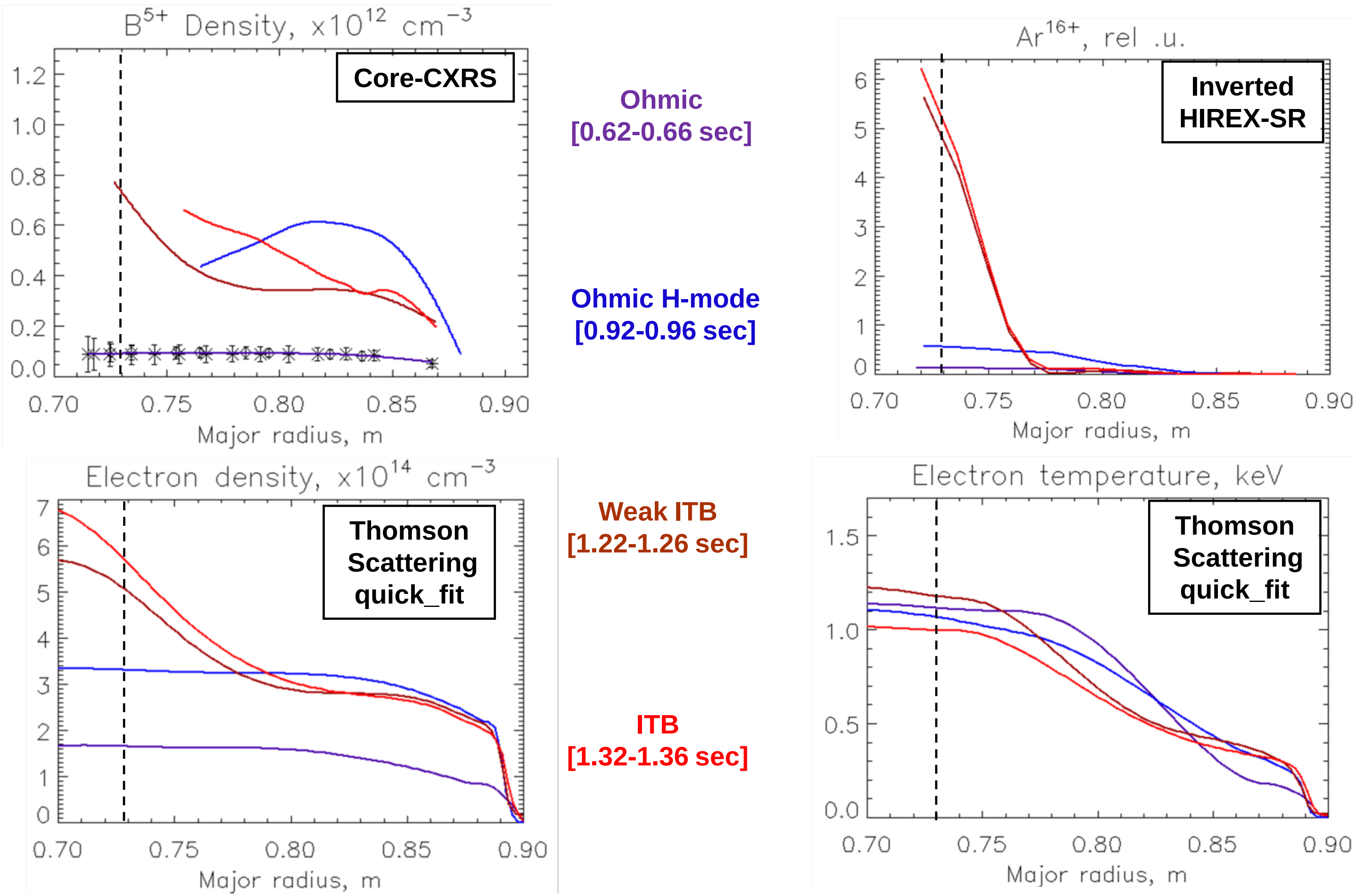
- There is only 0.05% of the boron in the Ohmic plasmas (based on the CXRS measurements)
- Relative density of boron in the core n_{B5+}/n_e (R= 0.73 m) increases by a factor of 2-5 when plasma goes from low confinement mode (Ohmic) to high-confinement modes (H-mode and ITB).
- Relative density of argon in the core n_{Ar16+}/n_e (R= 0.73 m) increases by a factor of 9-10 when plasma goes from H-mode to ITB.
- Argon accumulates in the core more strongly than boron during the ITB.

Ohmic ITB (shot:1110105004)



- Another characteristic Ohmic ITB shot: 1110105004
- For this shot plasma went from initial Ohmic mode (purple) (low confinement) to Ohmic H-mode (blue) (high confinement) and to Ohmic ITB. (brown and red)

Profiles of impurities and electrons (shot:1110105004)



- Argon is an ambient impurity (no Ar puff), but some amount of argon lingered in the plasma from the previous shot.

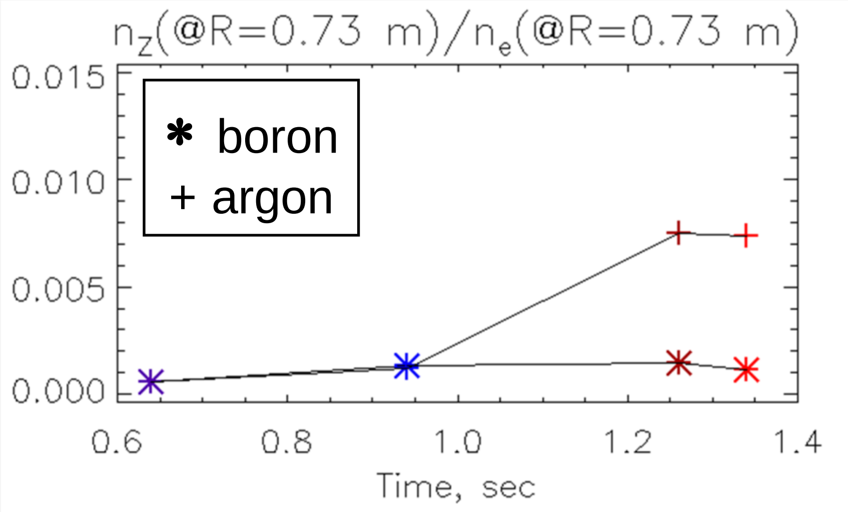
Impurity peaking in the core (1110105004)

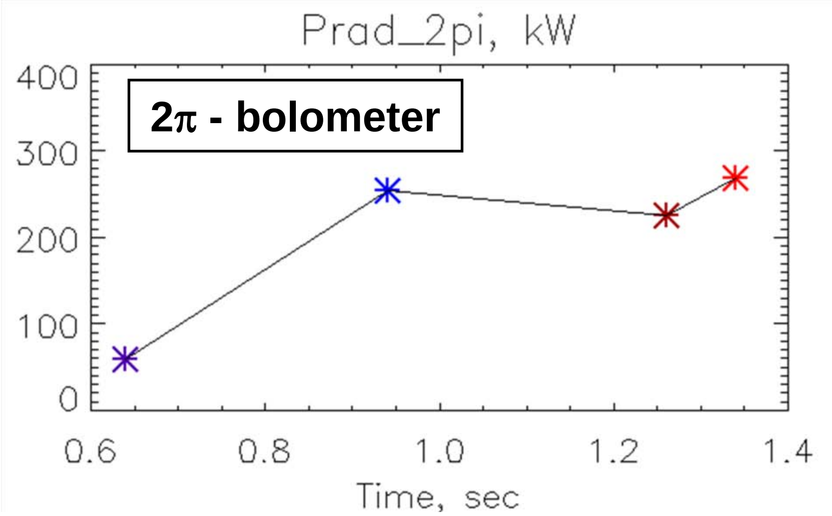
Ohmic [0.62-0.66 sec]

Ohmic H-mode [0.92-0.96 sec]

Weak ITB [1.22-1.26 sec]

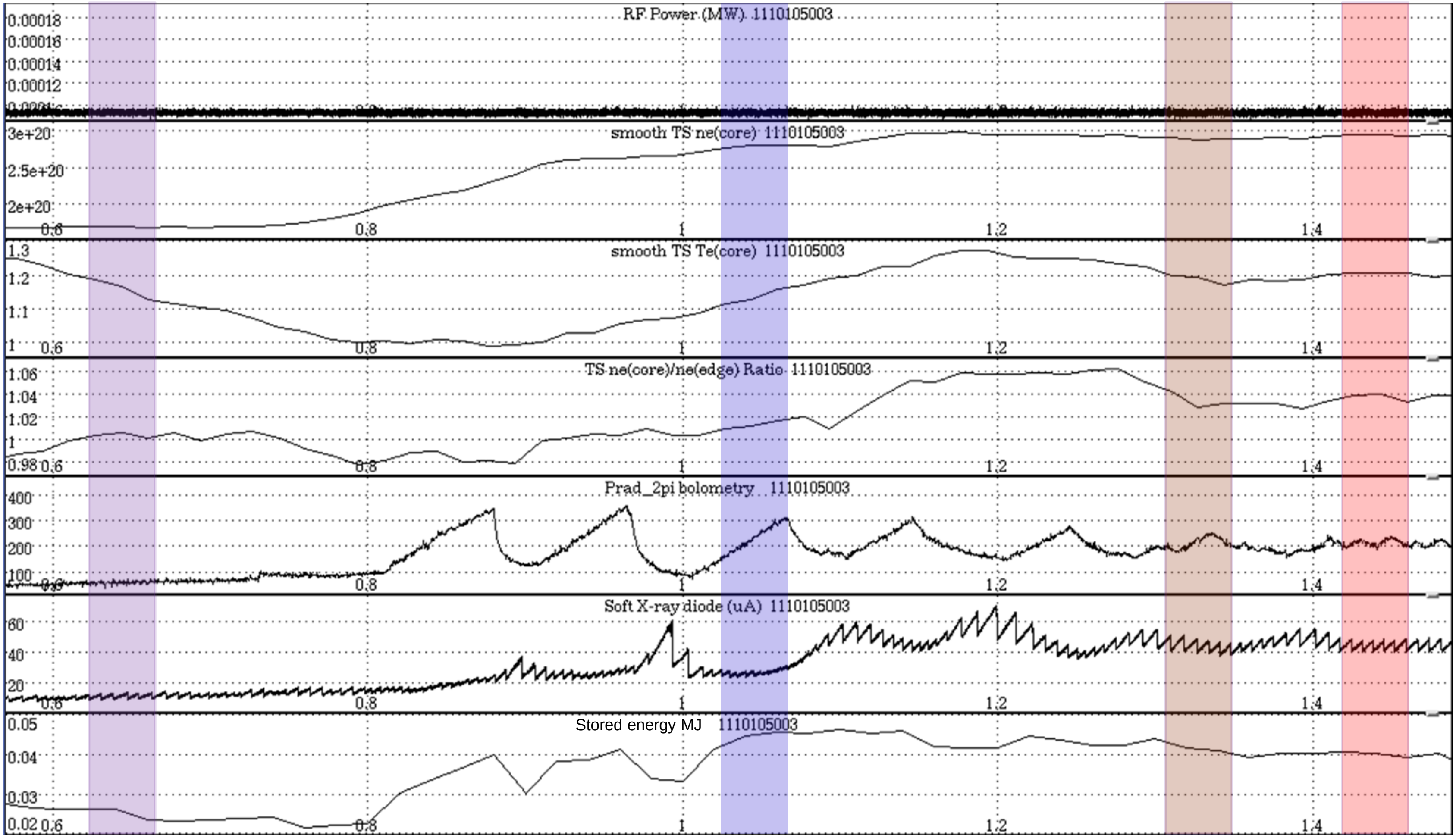
ITB [1.32-1.36 sec]





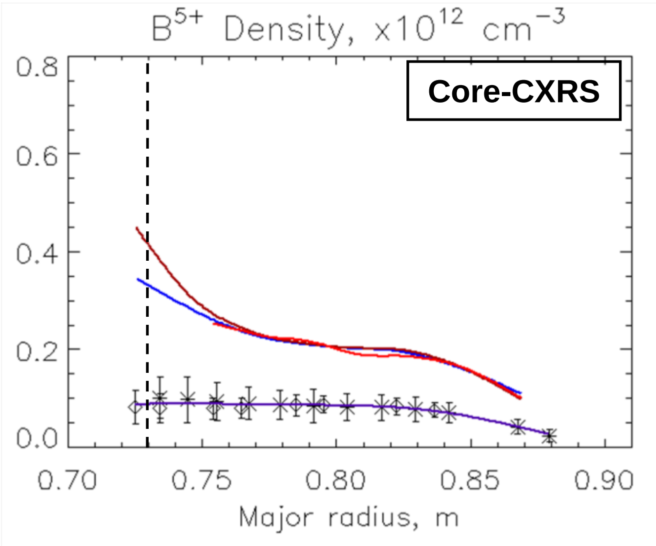
- There is only 0.05% of the boron in the Ohmic plasmas (based on the CXRS measurements)
- Relative density of boron in the core n_{B5+}/n_e (R= 0.73 m) increases by a factor of 2-3 when plasma goes from low confinement mode (Ohmic) to high-confinement modes (H-mode and ITB).
- Relative density of argon in the core n_{Ar16+}/n_e (R= 0.73 m) increases by a factor of 9-10 when plasma goes from H-mode to ITB.
- Argon accumulates in the core more strongly than boron during the ITB.

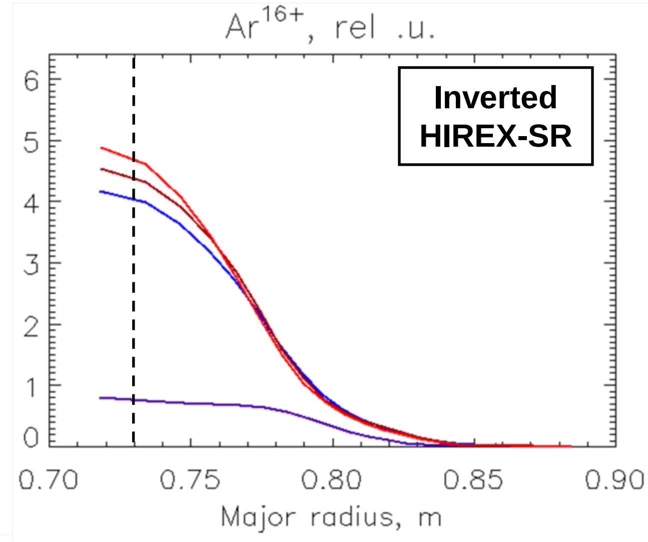
Ohmic ITB (shot:1110105003)



- Another characteristic shot, similar to 1110195004,006, but plasma did not go to Ohmic ITB (possibly due to the large amount of Argon).
- For this shot, the plasma went from initial Ohmic mode (purple) (low confinement) to Ohmic H-modes (blue, brown and red)(high confinement).

Profiles of impurities and electrons (shot:1110105003)



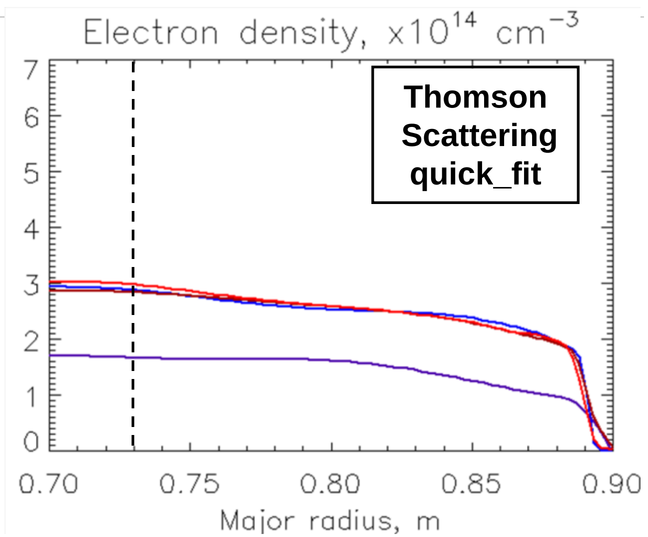


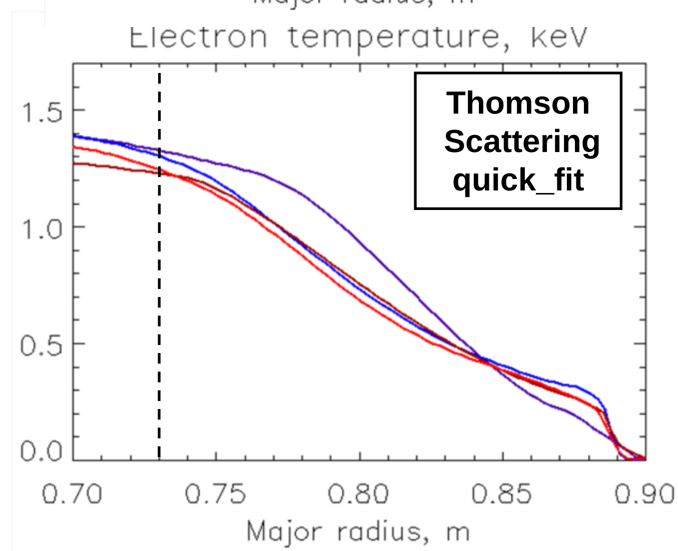
Ohmic [0.62-0.66 sec]

Ohmic H-mode [1.22-1.26 sec]

Ohmic H-mode [1.32-1.36 sec]

Ohmic H-mode [1.42-1.46 sec]

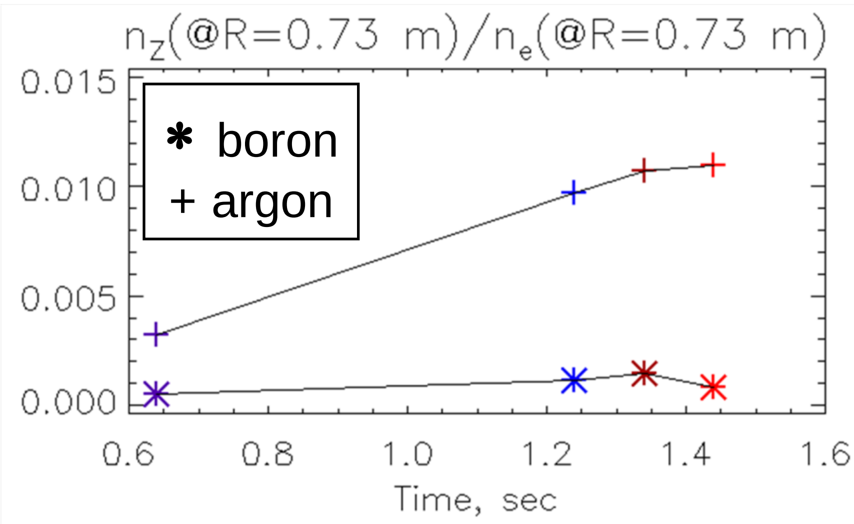


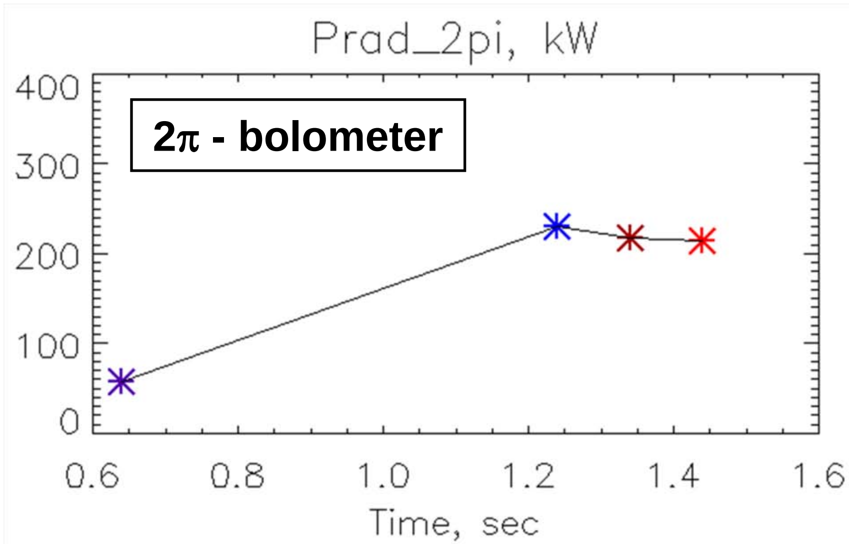


- This shot is characterized by strong argon injection
- Boron is intrinsic impurity (Boronization), argon (seeded:75 msec, 1psi puff).

Impurity peaking in the core (1110105003)

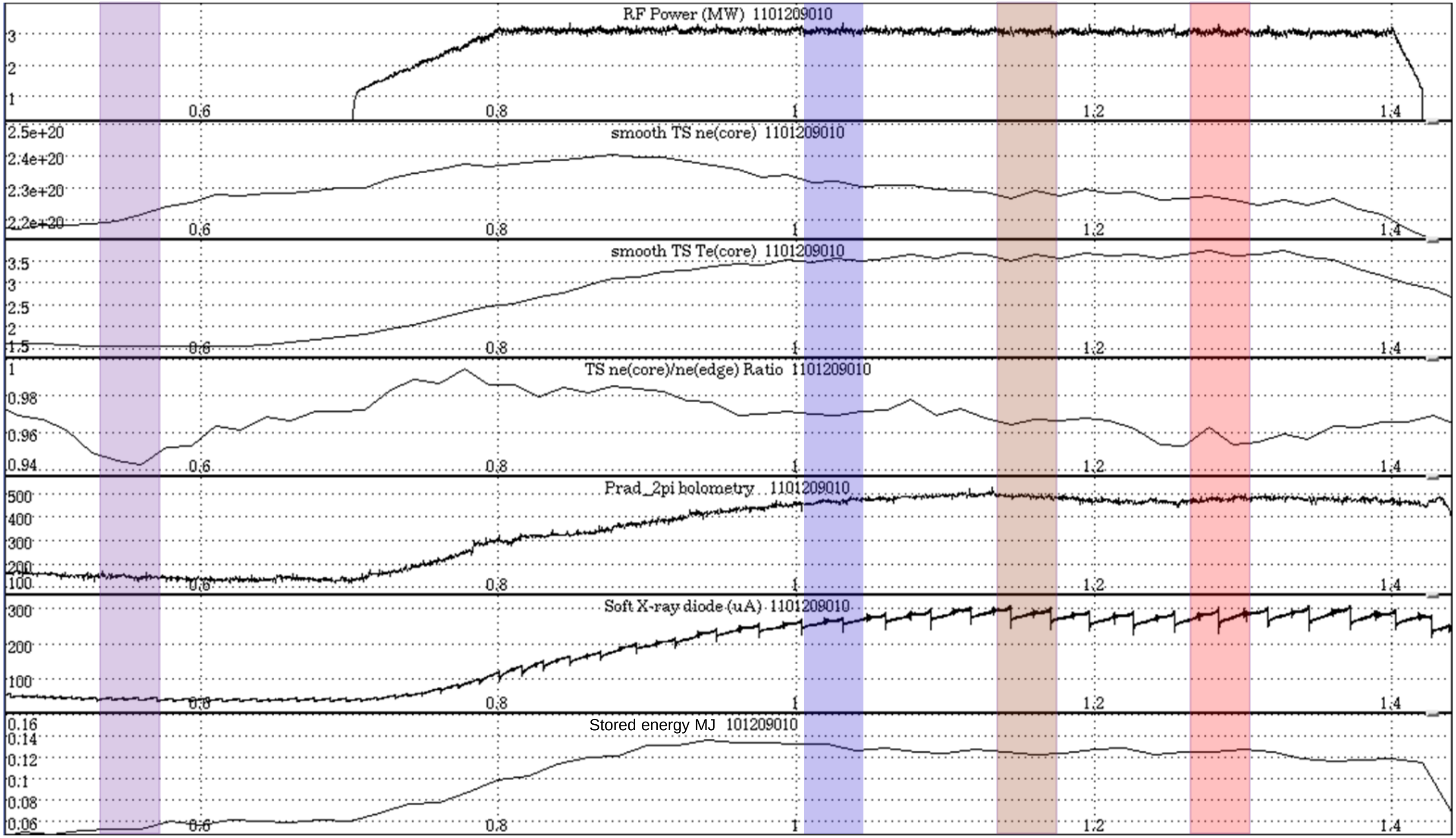
Ohmic [0.62-0.66 sec] | Ohmic H-mode [1.22-1.26 sec] | Ohmic H-mode [1.32-1.36 sec] | Ohmic H-mode [1.42-1.46 sec]





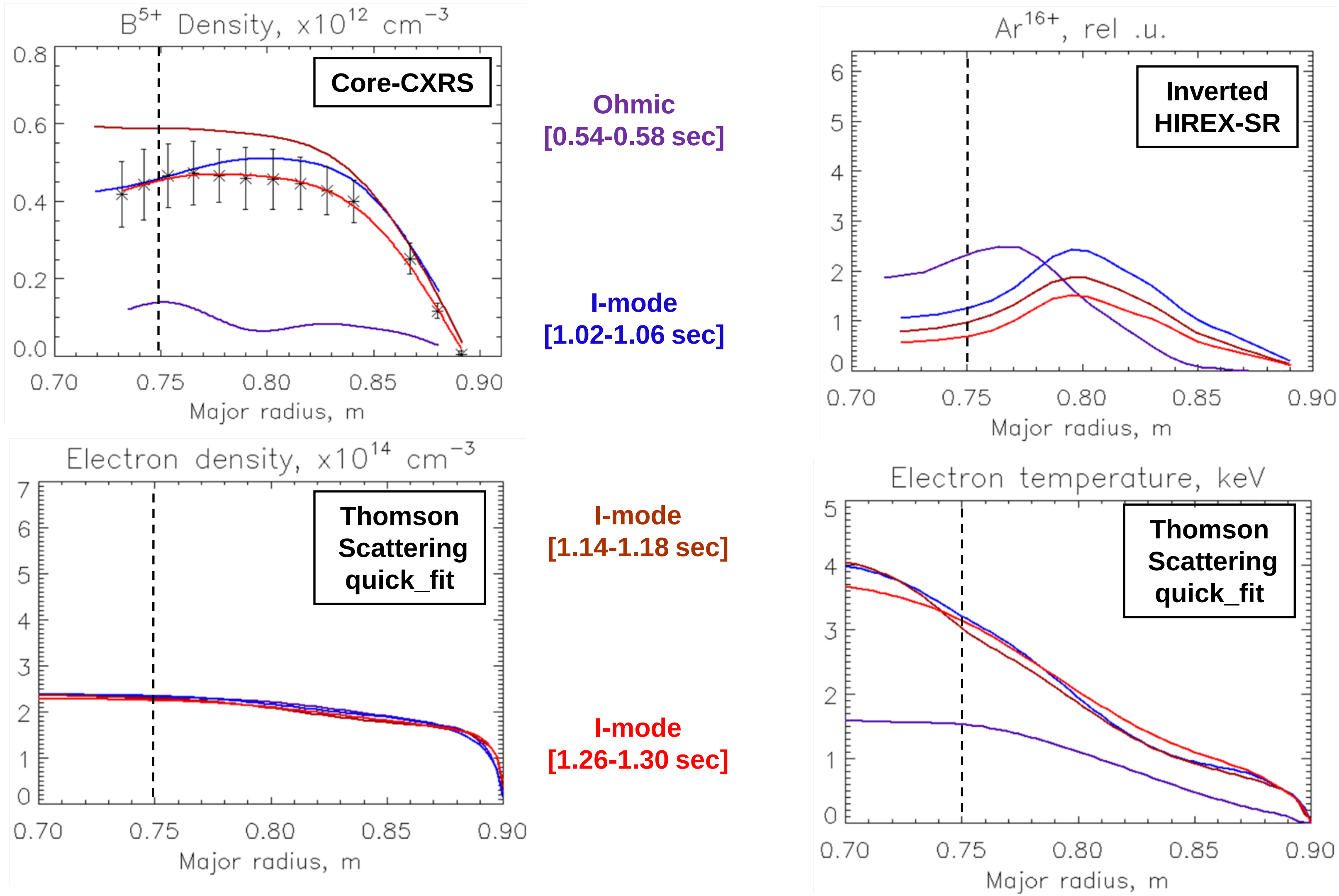
- There is only 0.05% of the boron in the Ohmic plasmas (based on the CXRS measurements)
- Relative density of boron in the core n_{B5+}/n_e (R= 0.73 m) increases by a factor of 2-3 when plasma goes from low confinement mode (Ohmic) to high-confinement modes (H-mode).
- Density of argon for Ohmic mode is 5-7 times higher than for Ohmic modes from shot: 004,006.
- Relative density of argon in the core n_{Ar16+}/n_e (R= 0.73 m) increases by a factor of 3-4 when plasma goes from Ohmic to H-modes.
- Argon accumulates in the core more strongly than boron during the H-modes.

I-mode (improved L-mode) (shot:1101209010)



- C-mod I-modes are characterized by strong peaking of electron temperature and flat (H-mode like) electron density profiles. I-mode is a high confinement mode.
- For this shot plasma transits from initial Ohmic mode (purple) (low confinement) to I-mode (blue, brown and red) (high confinement), which was sustained for 400 msec.

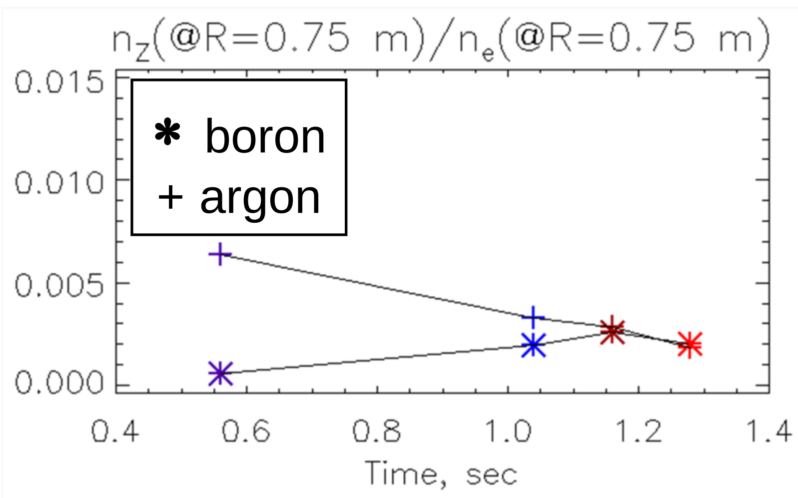
Profiles of impurities and electrons (shot:1101209010)

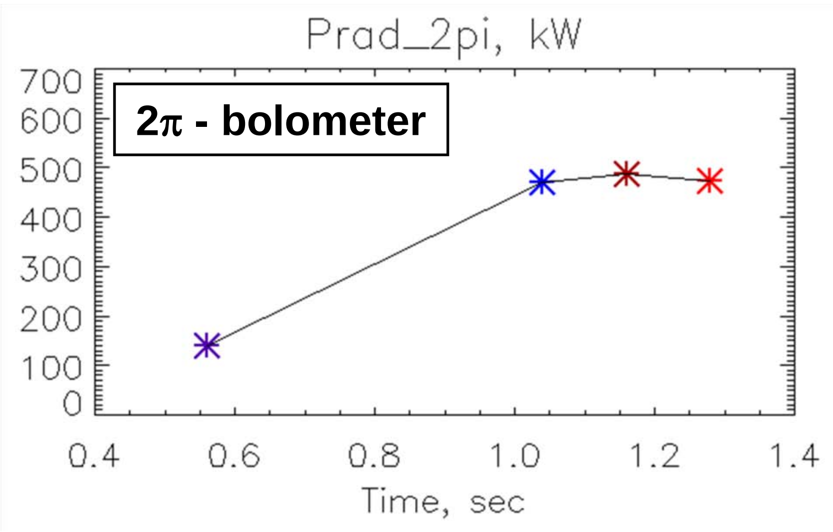


- Ar is injected (20 msec puff at 0.3 sec, 20 msec puff at 0.75 sec)
- Boron is intrinsic impurity (Boronization), argon (seeded: total 40msec, 1psi puff).

Impurity peaking in the core (shot:1101209010)

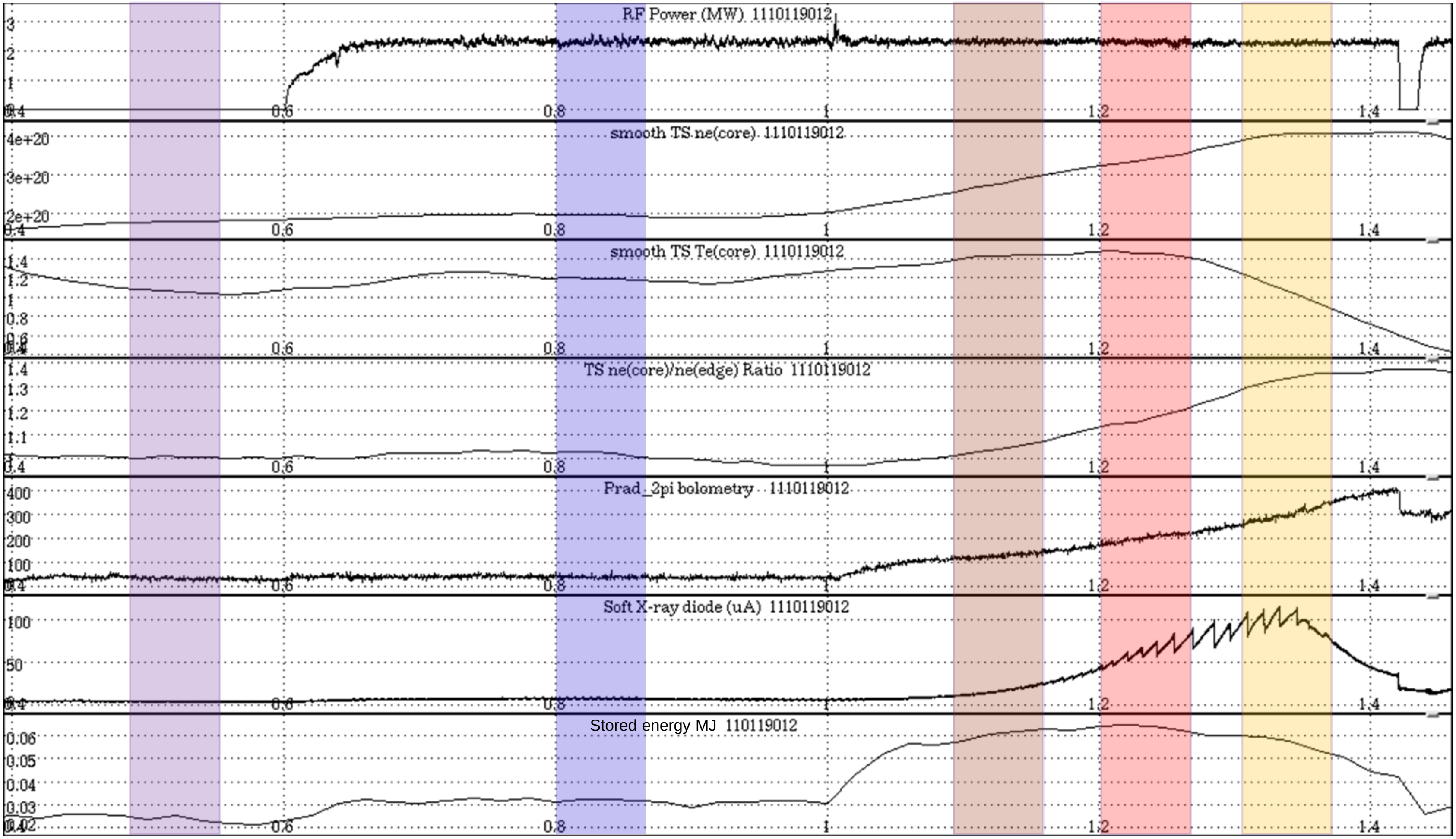
Ohmic [0.54-0.58 sec] | **I-mode [1.02-1.06 sec]** | **I-mode [1.14-1.18 sec]** | **I-mode [1.26-1.30 sec]**





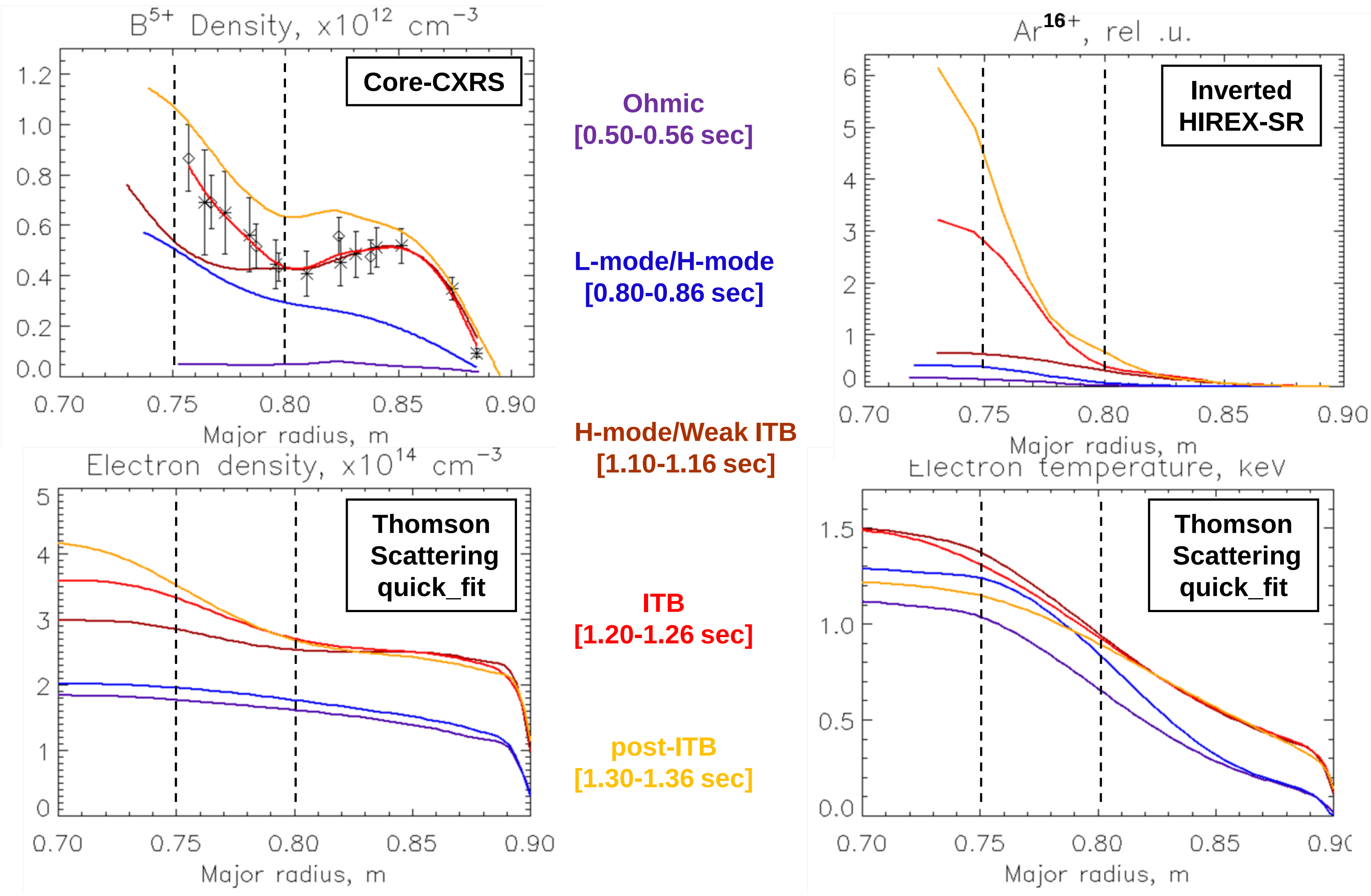
- There is only 0.05% of boron in the Ohmic plasmas (based on the CXRS measurements)
- Relative density of boron in the core n_{B5+}/n_e (R= 0.75 m) increases by a factor of 4-6 when plasma goes from low confinement mode (Ohmic) to high-confinement mode (I-mode).
- Ar^{16+} does not show the peaking pattern needed for heavy impurities. The ionization energy for Ar^{16+} is 4120eV so it is ionized to Ar^{17+}. So it is (Ar^{17+} and Ar^{18+}) (not measured) plus Ar^{16+} that would carry the peaking information.

ICRF heated ITB (1110119012)



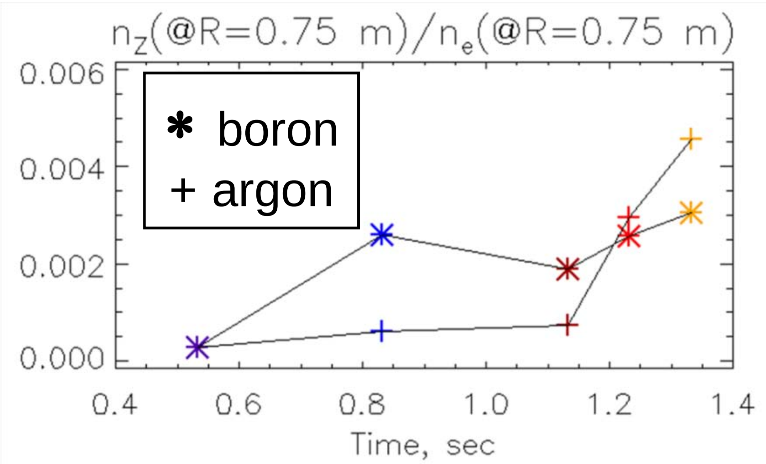
- Internal transport barriers can be routinely produced on C-Mod in EDA H-mode plasmas by placing the ICRF resonance location outside |r/a| ~ 0.5
- For this shot, plasma transits from initial Ohmic mode (purple) (low confinement) to H-mode (blue) (high confinement), and then at about 1.0 sec ITB develops into three phases: weak ITB (brown), strong ITB (red) and post-ITB (yellow) phases (post-ITB is characterized by the drop of the core electron temperature)

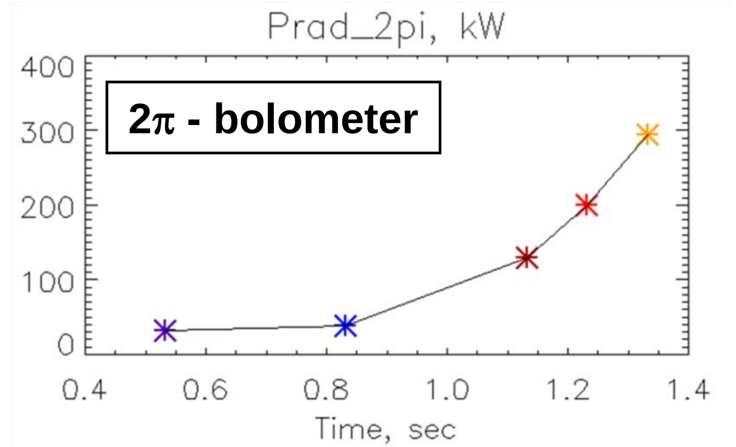
Profiles of impurities and electrons (shot:1110119012)

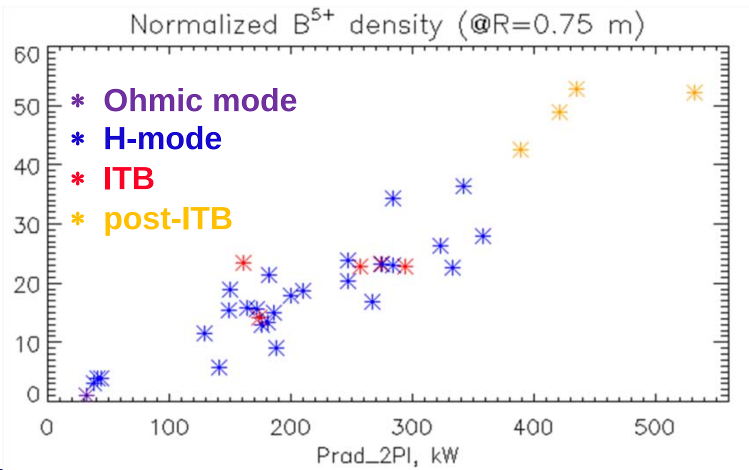


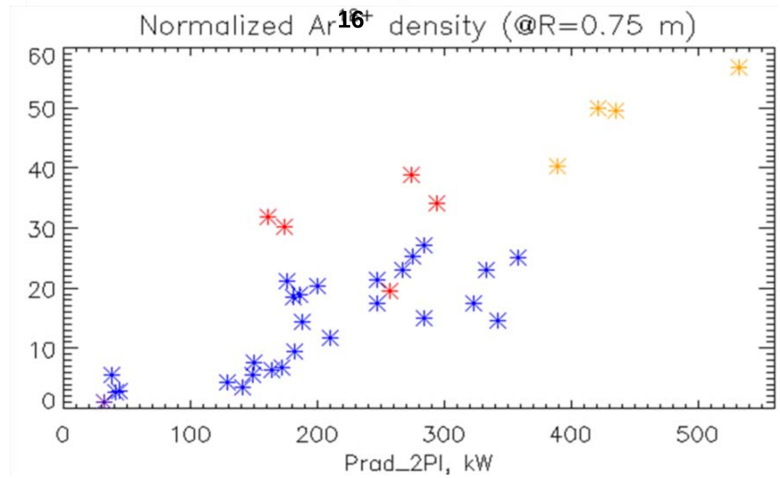
- Ar is injected (40 msec puff at 0.3 sec)
- Boron is intrinsic impurity (Boronization), argon (seeded: 40msec, 1psi puff).

Impurity peaking in the core (shot: 1110119012)



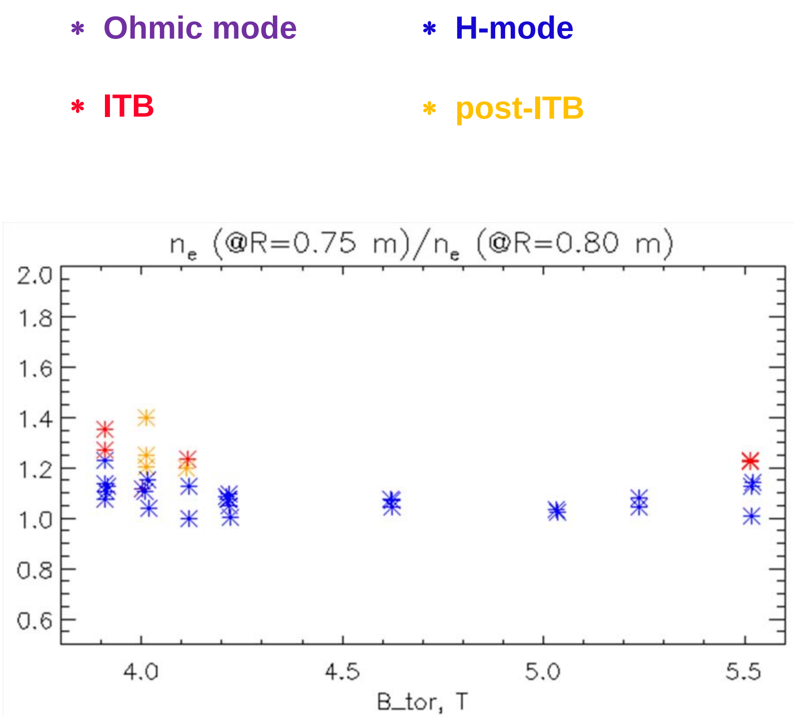


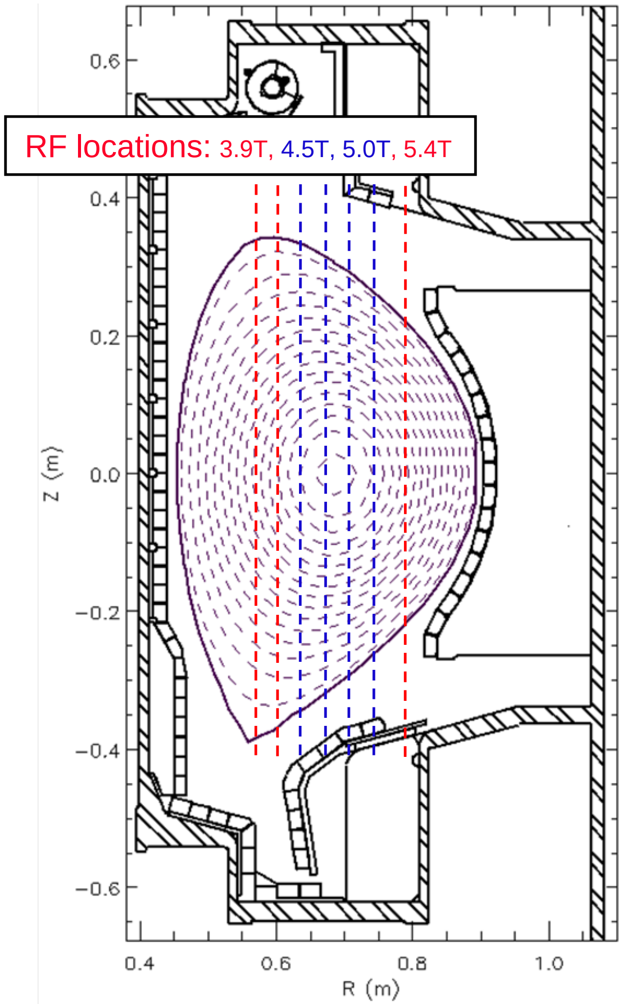




- Relative density of boron in the core n_{B5+}/n_e (R= 0.73 m) increases by a factor of 4-6 when plasma goes from low confinement mode (Ohmic) to high-confinement modes (H-mode and ITB).
- Relative density of argon in the core n_{Ar16+}/n_e (R= 0.73 m) increases by a factor of 6-10 when plasma goes from H-mode to ITB.
- Densities of B^{5+} and Ar^{16+} scales linearly with radiative power measured by bolometer foils (scan using 11 shots from 1110119 run). All densities are normalized to the densities during Ohmic mode (purple)

Impurity peaking: B_{tor} scan (shot: 1110119012)



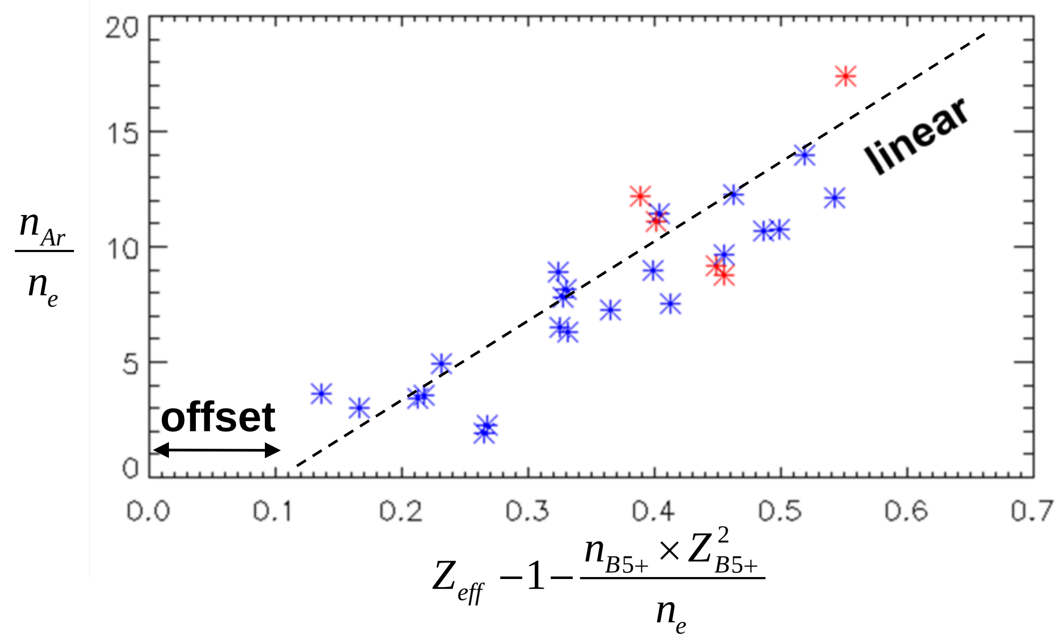


- Internal transport barriers are produced on C-Mod in EDA H-mode plasmas by placing the ICRF resonance location outside |r/a| ~ 0.5.
- ITBs were not developed for shots when ICRF power was deposited inside |r/a| ~ 0.5, when (B_{tor}: [4.2-5.3T]).

Comparison to Z_eff

Z_{eff} model

$$Z_{eff} \approx 1 + \frac{n_{B5+} \times Z_{B5+}^2 + n_{Ar} \times Z_{Ar}^2}{n_e}$$



- Here we select a set of shots from 1110119 when ITB was developed. Each symbol represents a value measured at a specific characteristic time for H-mode or ITB.
- Boron density was measured and changes from: 0.1-0.4%.
- Since argon density linearly depends on Z_{eff}, argon is possibly one of the main contributors to Z_{eff}.
- Absolute density of the seeded Argon is estimated based on the CXRS-measured boron density and linear contribution to Z_{eff}. Argon density changes from: 0.03-0.2% (15 msec -75 msec, 1psi puffs)
- 0.1 of Z_eff are due to some third impurity. Possibility for third impurity is Tungsten (C-mod divertor tiles), which would constitute about 1.8e-3% of n_e.

Radiation losses and fuel dilution

Confinement time ratio

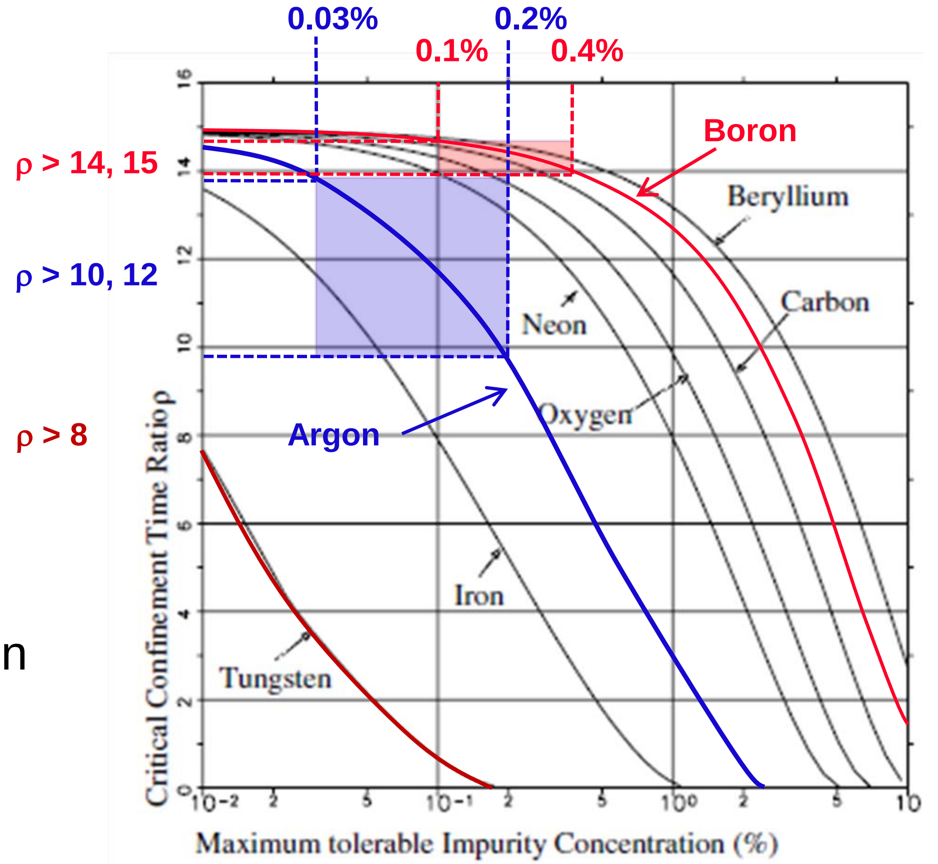
$$\rho = \frac{\tau_Z}{\tau_E}$$

Impurity fractional density

$$f_z = \frac{n_Z}{n_e}$$

Radiation losses and fuel dilution criterion

$$\rho > \rho_{crit}(Z, f_z)$$



D. Reiter and S. Weisen, Helium removal and recycling, Transactions of FST, 49, 2006

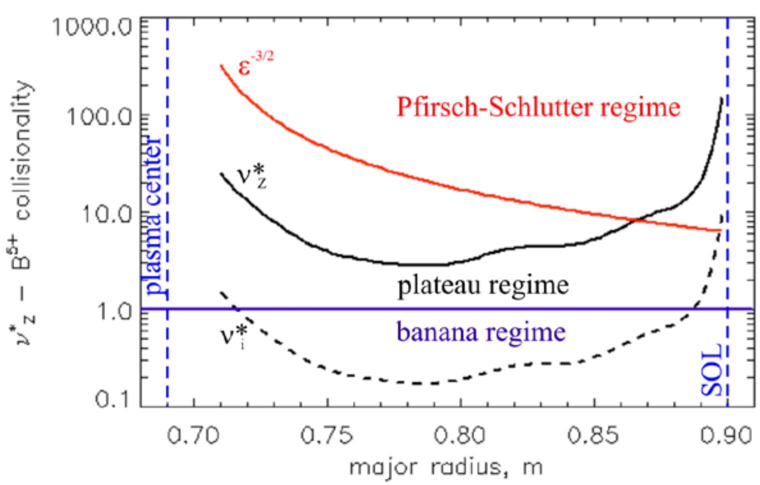
- For C-mod ρ is in the range: 0.5-4. Nathan Howard poster, TTF 2010. Note: estimated only for Ca.
- Based on the these estimates, C-mod's plasma (in H-mode or ITB phase) should be stable with regards to radiative collapse or main ion dilution caused by core impurities.
- Although, for plasmas with ρ ~ 10, core argon peaking up to 0.2% of n_e might be a reason for radiative collapse of the ITB.

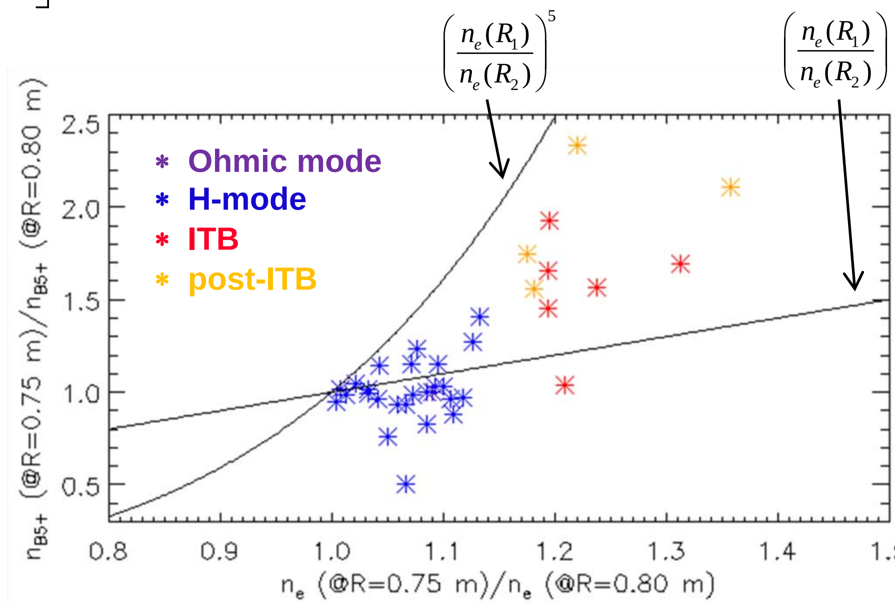
Comparison to neoclassical peaking

$$\nu_Z^* = \frac{\nu_Z R q \varepsilon^{-3/2}}{V_{ZT}} \qquad \nu_Z \equiv \frac{16\sqrt{\pi} e^4 Z^2 \ln\Lambda}{3 m_Z} \times \left[\frac{n_i}{m_i V_{iT}^3} + \frac{n_Z Z^2}{\sqrt{2} m_Z V_{ZT}^3}\right]$$

$$\frac{n_Z(R_1)}{n_Z(R_2)} = \left(\frac{n_i(R_1)}{n_i(R_2)}\right)^Z \left(\frac{T_Z(R_1)}{T_Z(R_2)}\right)^{-H\times Z}$$

$$\Gamma_z^P = 1.25\frac{q}{R}\sqrt{m_z}\,\frac{T_Z^{1.5} c^2 n_i}{e^2 B_T^2 Z} \times \left[\frac{1}{n_i}\frac{\partial n_i}{\partial r} - \frac{1}{Z n_Z}\frac{\partial n_Z}{\partial r} - H\frac{1}{T_Z}\frac{\partial T_Z}{\partial r}\right]$$





- Main ions are mostly in the banana regime, boron ions are in the plateau.
- For most of the high-confinement modes B^{5+} density peaks stronger that electron density, but weaker than neoclassical theory predicts.
- For this example impurity particle transport is calculated by averaging of profile gradients in the range of R=[0.75,0.5] m. Average impurity transport doesn't drop entirely to the neoclassical level, but has some anomalous component.

Nearness to neoclassical

- The transport equation is

$$\frac{\partial n_j^z}{\partial t} + \square \bullet \Gamma_j^z = S_j^z$$

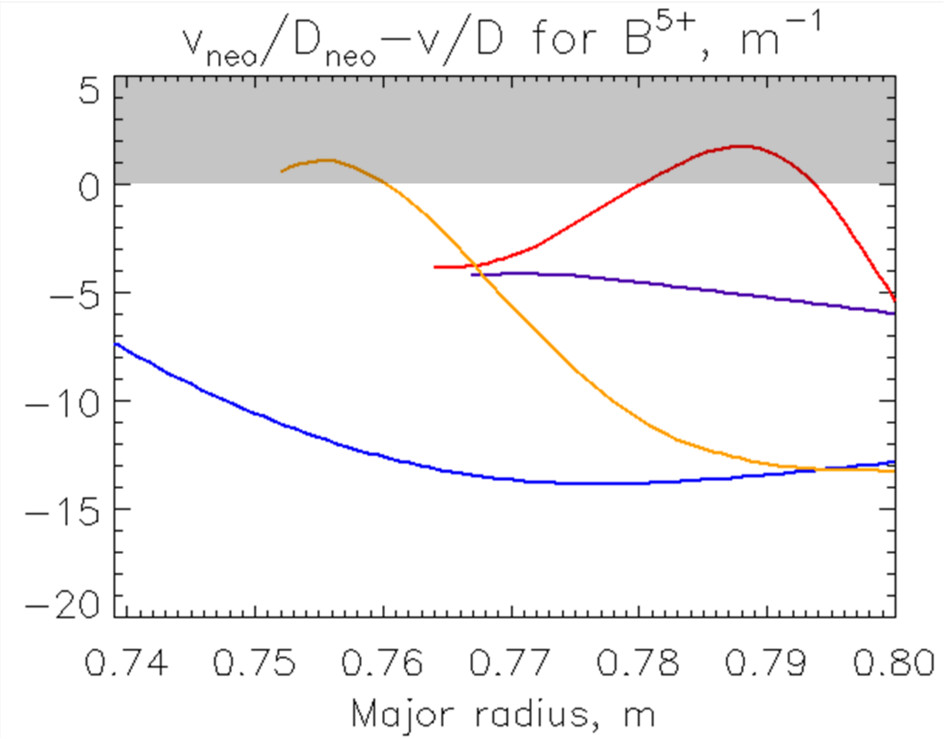
- For quasi-linear or neoclassical descriptions of impurity transport transport

$$\Gamma_j^z = -D\frac{\partial n_j^z}{\partial r} + v n_j^z$$

- Dynamic equilibrium $\frac{\partial n_j^z}{\partial t} = 0$
- For fully-stripped boron (B^{5+}) R < 0.85 m $S_j^z = 0$
- That region is "source free" so that $\frac{1}{n_j^z}\frac{\partial n_j^z}{\partial r} = \frac{v}{D}$

$$D_{neo} = 1.25\frac{q}{R}\sqrt{m_Z}\frac{T_Z^{1.5}c^2}{e^2 B_T^2 Z^2}$$

$$\frac{V_{neo}}{D_{neo}} = Z\left[\frac{1}{n_i}\frac{\partial n_i}{\partial r} + H\frac{1}{T_Z}\frac{\partial T_Z}{\partial r}\right]$$



ICRF H-mode	1110119013	[0.70-0.76 sec]
I-mode	1101209010	[1.02-1.06 sec]
ITB	1110119012	[1.20-1.26 sec]
post-ITB	1110119012	[1.30-1.36 sec]

- For H-mode and I-mode impurity transport is higher than neoclassical.
- For ITB phases impurity particle transport, at some of the locations, may occasionally drop to the neoclassical levels. (it is assumed for this calculation that H=0, no temperature screening)