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Role of impurities in fusion plasmas

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Role of impurities in fusion plasmas

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International Workshop on the Frontiers of
Modern Plasma Physics (Trieste, 14 - 25 July 2008)

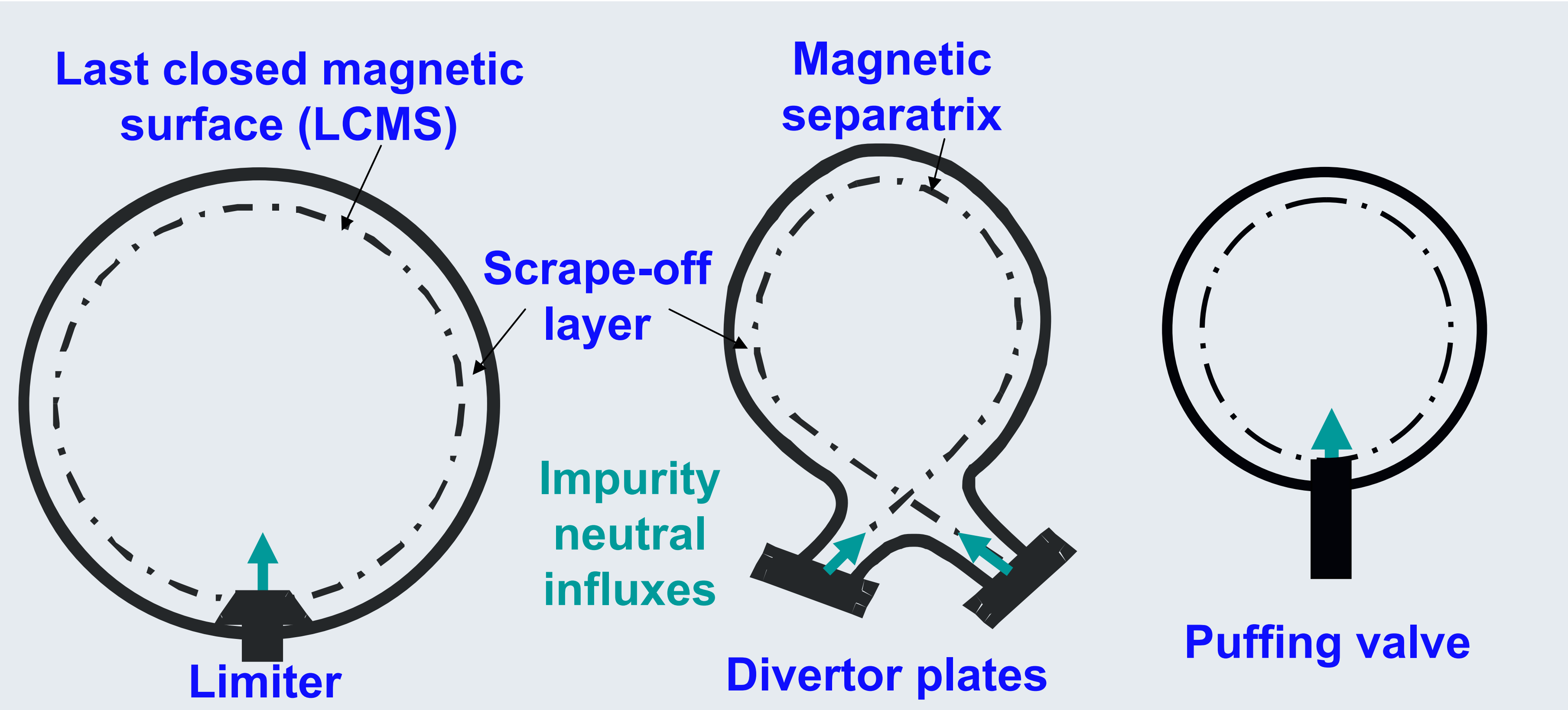
Content:

- **Introduction:** **impurity sources and plasma states strongly affected by impurity radiation**
- **Radiation of impurities:** **line radiation and Bremsstrahlung, cooling rates**
- **Transport of impurities:** **continuity equation, motion along magnetic field, diffusion and convection perpendicular magnetic surfaces, effect of transport on radiation losses**
- **Radiation instability:** **instability threshold, MARFE, stable radiating edge**
- **Impurity influence on anomalous transport:** **suppression of ion temperature gradient instability**
- **Conclusions**

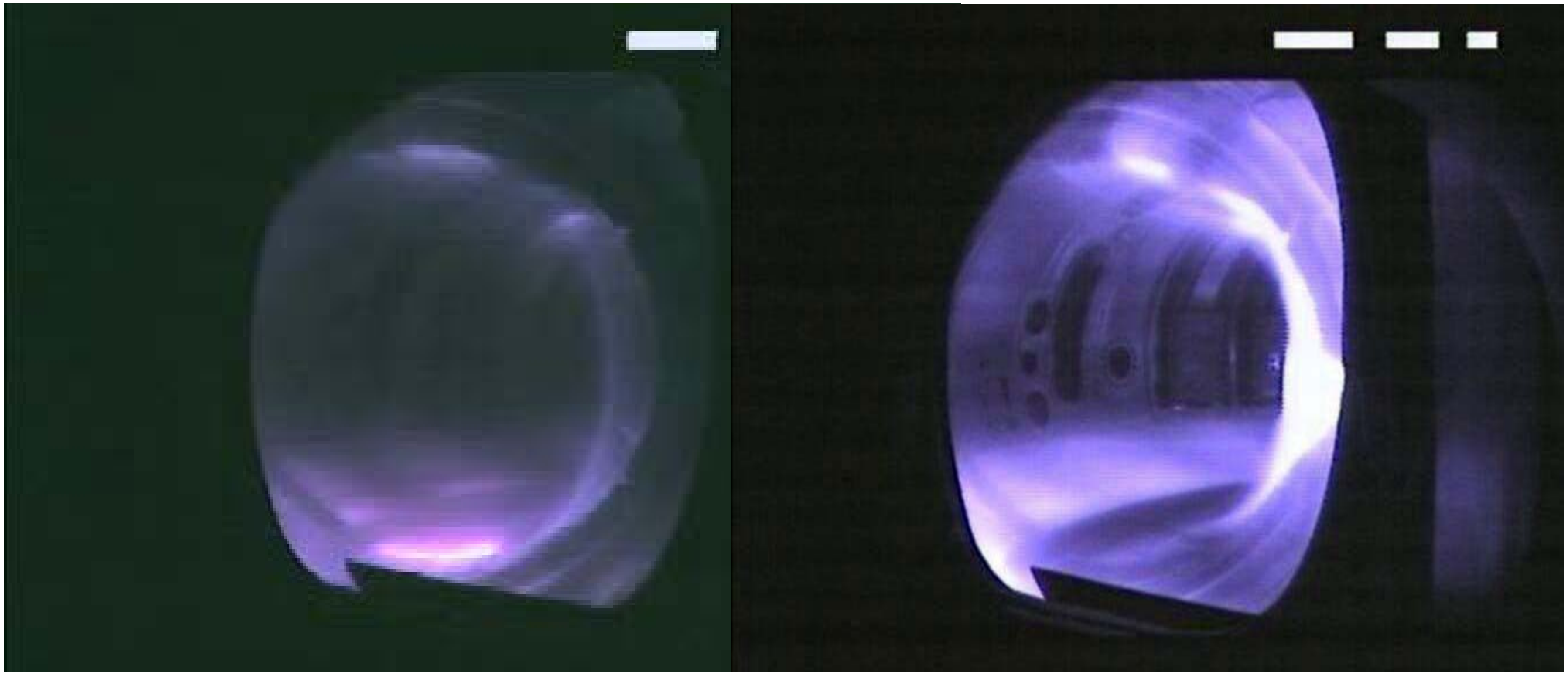
Impurity sources in fusion plasmas

Intrinsic impurities eroded from material surfaces

Seeded impurities



MARFE (Multi-Facetted Asymmetric Radiation From the Edge) in TEXTOR

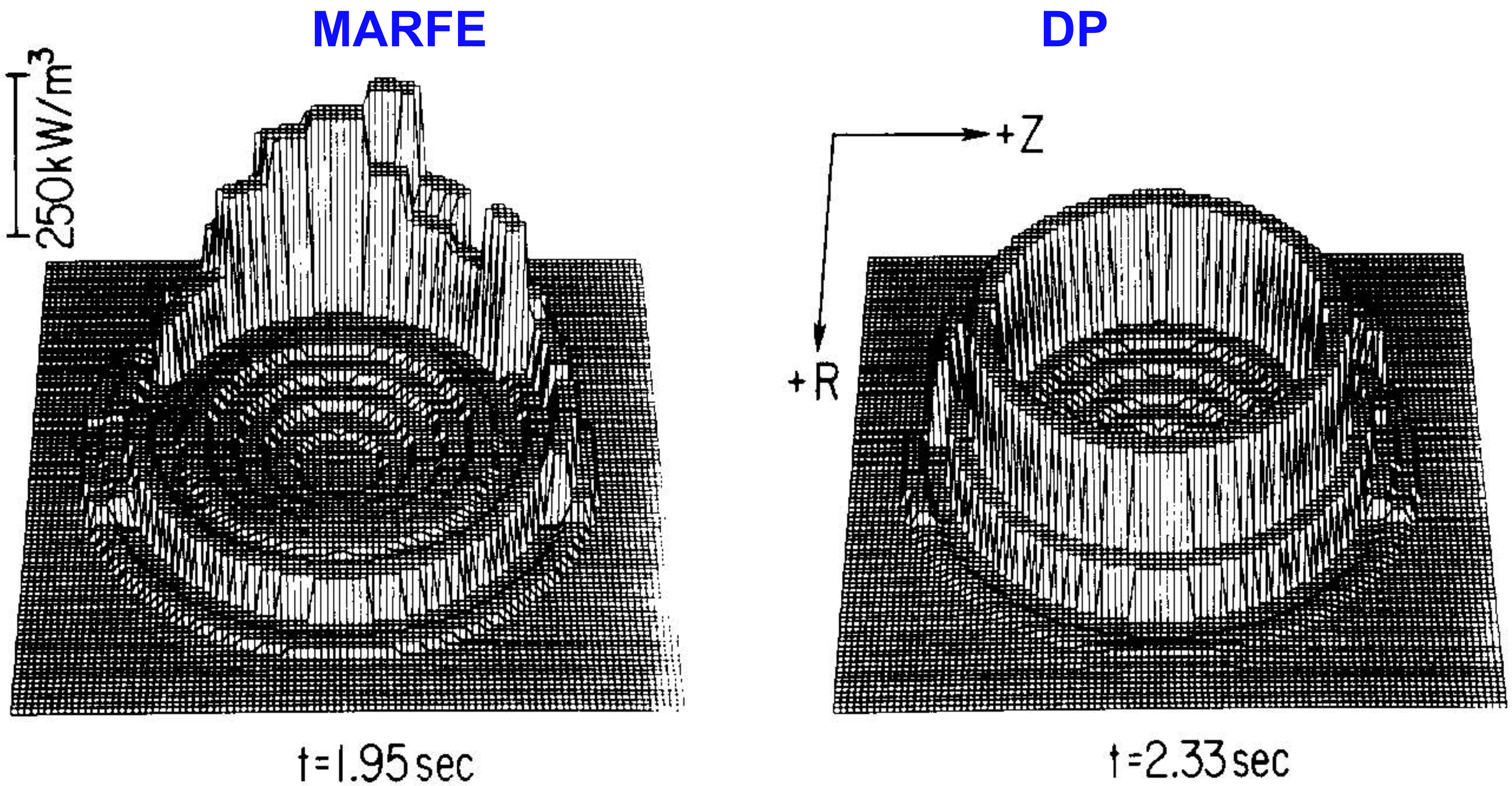


MARFE develops when plasma density is increased above a limit

Radiation losses from low-Z impurity (C, O) and plasma density are **much higher** and

Temperature is **much lower in MARFE** than in surrounding plasma

Development of Detached Plasma (DP) from MARFE in TFTR

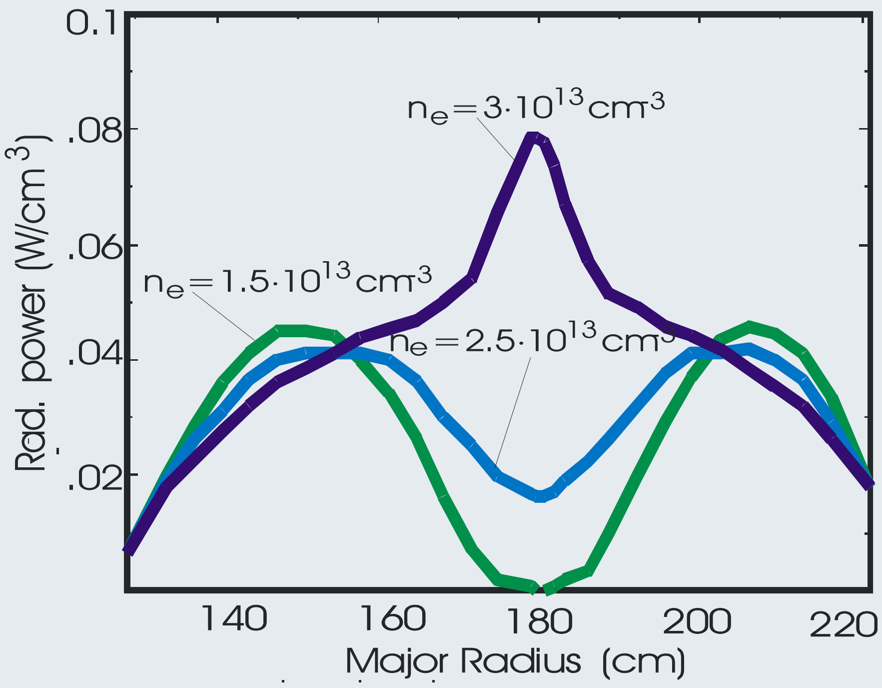


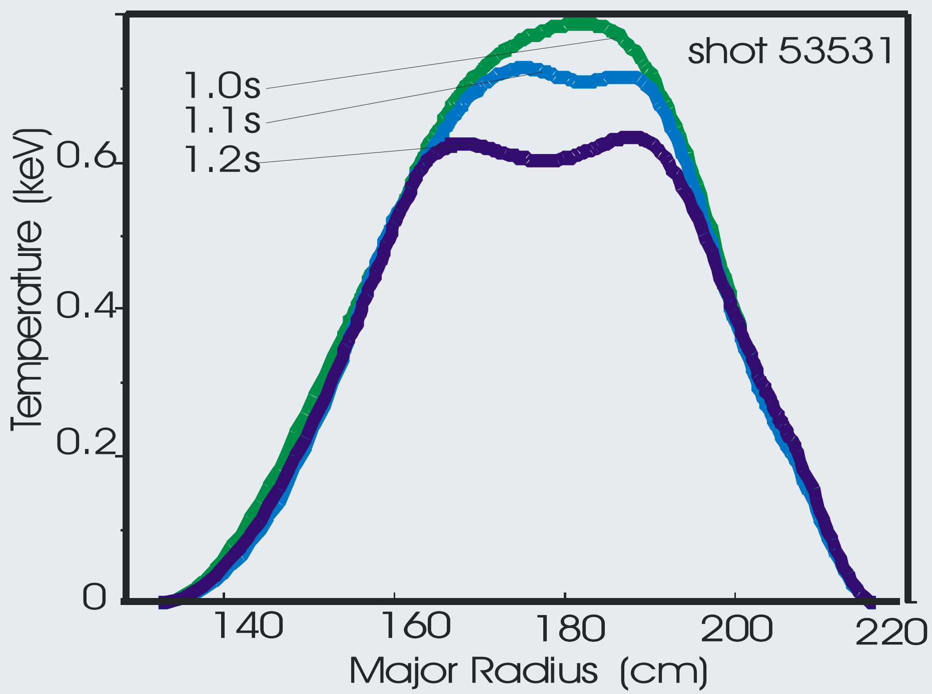
In DP radiation losses are poloidally symmetric

In Ohmic discharges in TEXTOR DP develops without MARFE stage

High-Z impurity accumulation and cooling of plasma core

(Mo impurity from test limiter in TEXTOR)

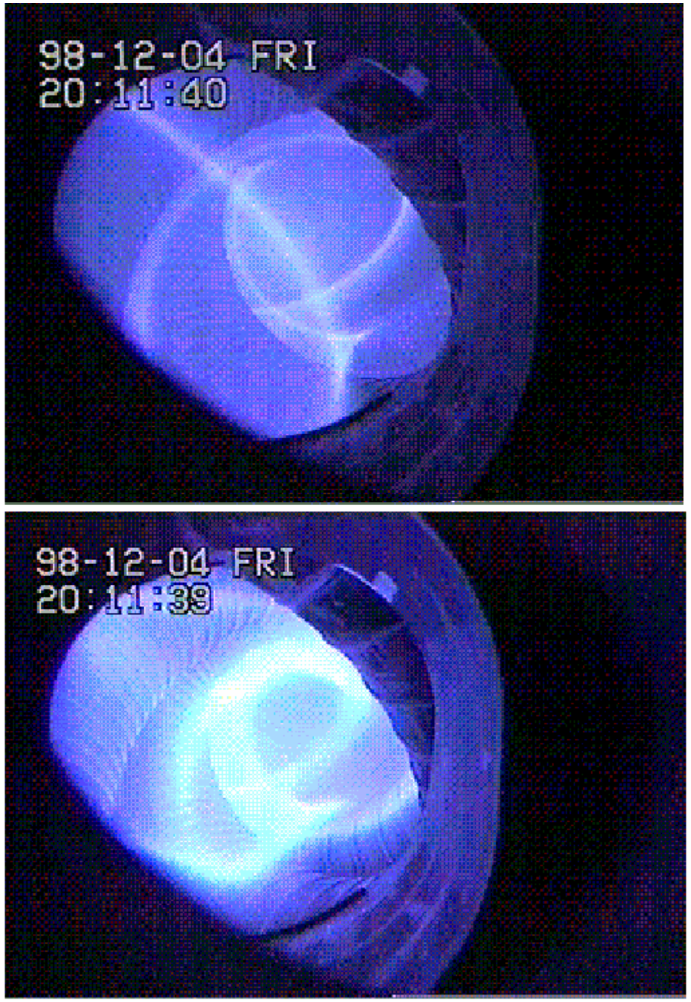


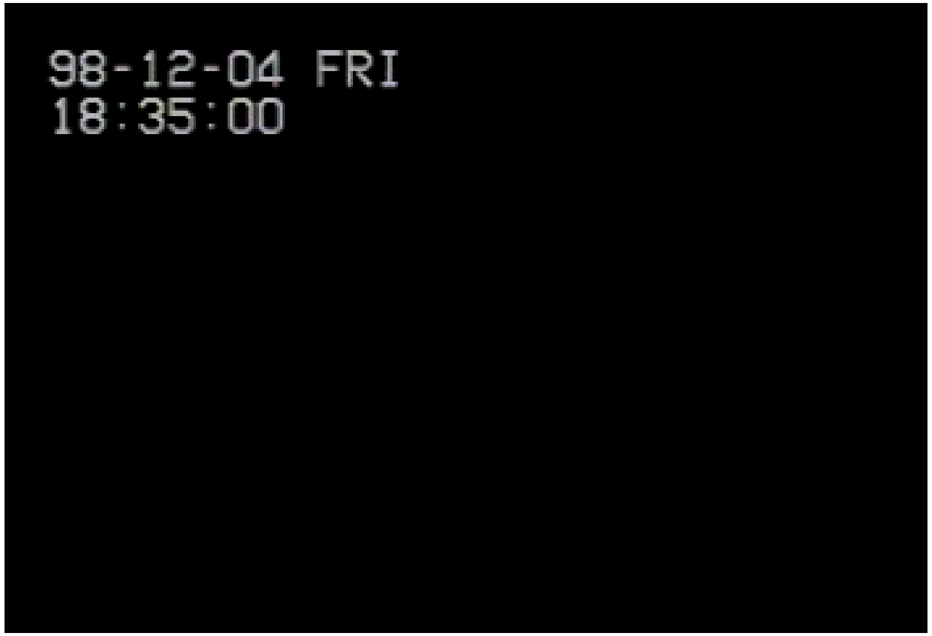


Radiation losses peak in plasma core

Plasma temperature drops in core

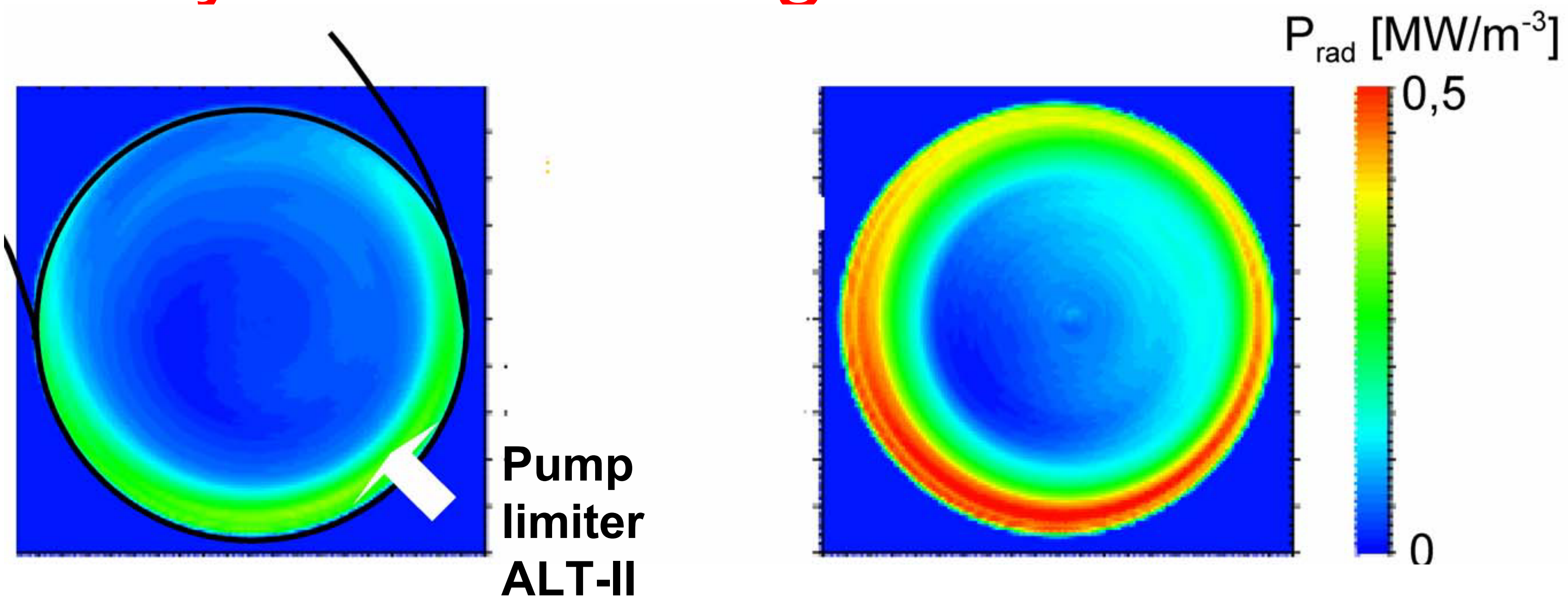
Breathing oscillations in Large Helical Device (LHD)





- Radiating plasma boundary oscillates
- Synergy of low-Z impurity radiation from the edge and high-Z impurity from core

Stationary cooling of plasma edge by neon seeding in TEXTOR



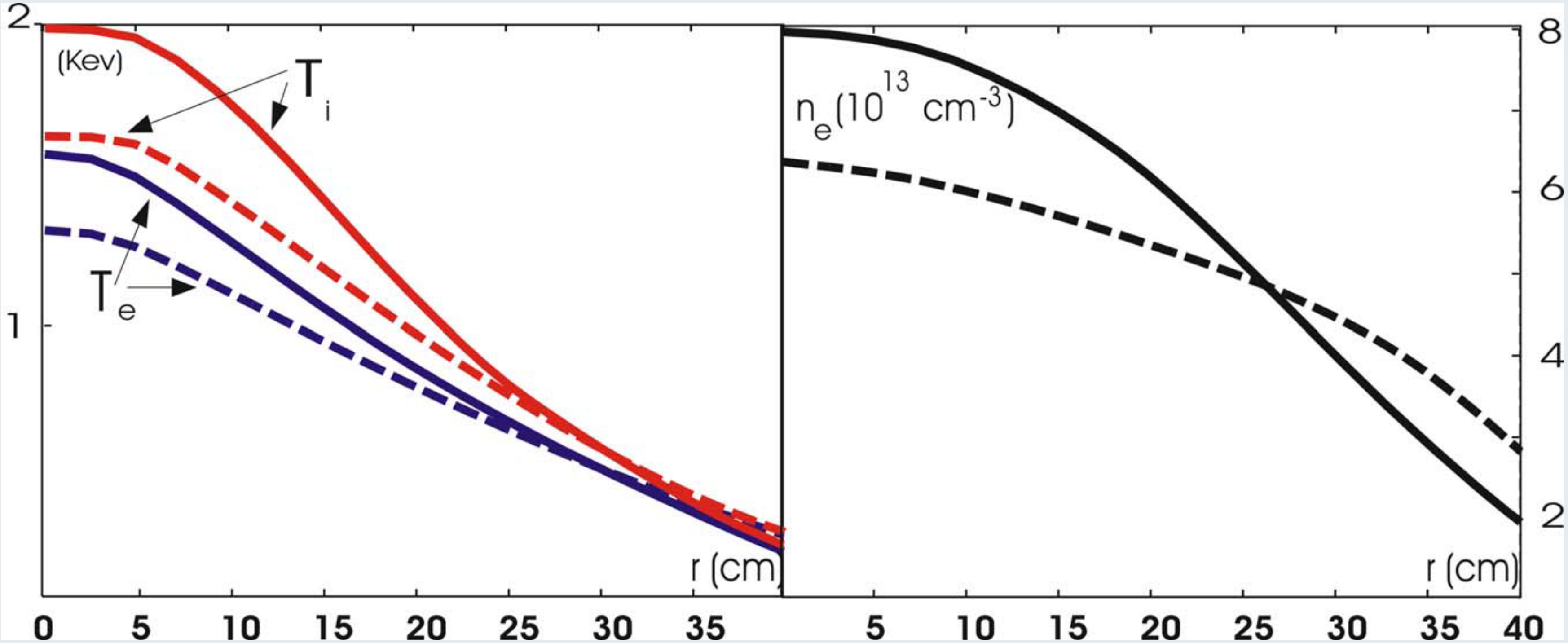
W/o neon seeding:

65% of heating power goes to limiter

With neon seeding:
85% of power is radiated, plasma-wall interaction is strongly **reduced**

Cooling by impurity radiation will be unavoidably needed in ITER!

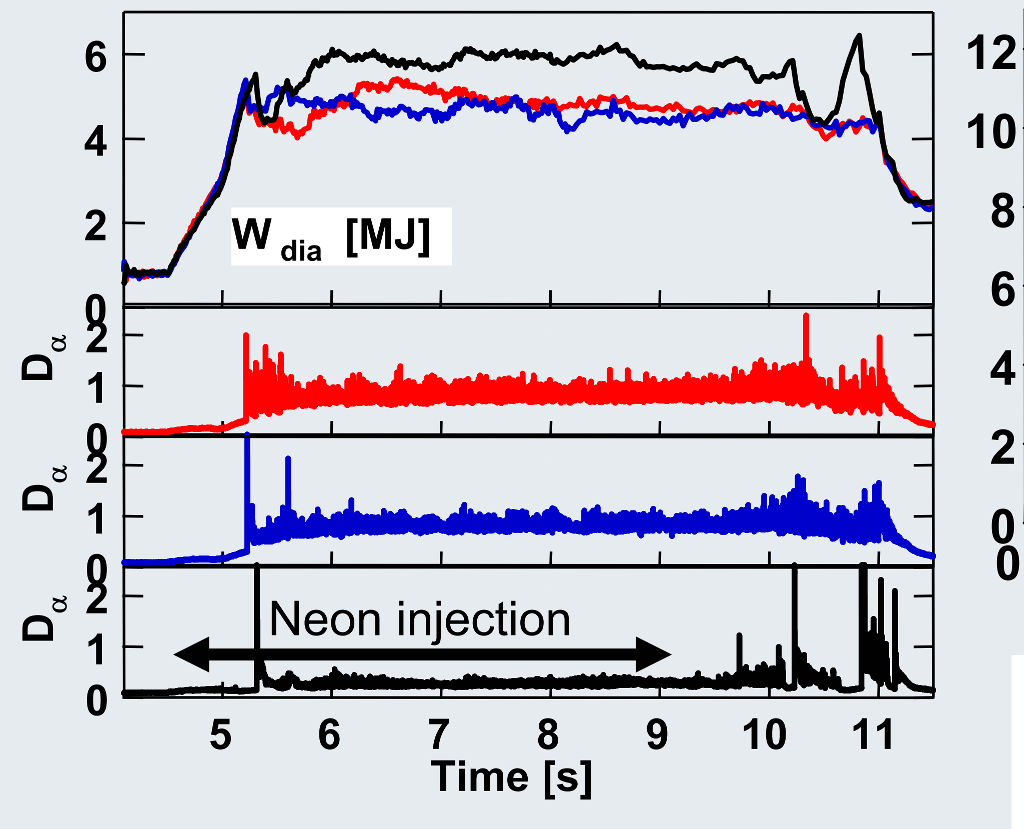
Radiation improved mode in TEXTOR

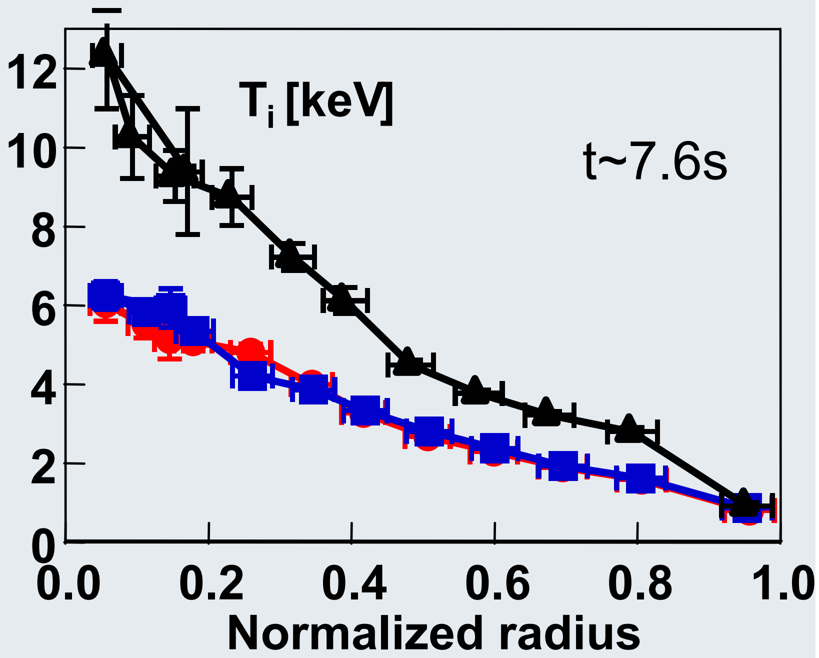


Temperature and density profiles peak by neon seeding triggering transition from L-mode (– – – -) to RI-mode (———)

Optimisation of Neon seeding in JET

#69091 ($Ne+D_2$), #69092 ($Ne+D_2$), #69093 (mainly Ne)





- Edge pedestal in T_i
- T_i peaks in plasma core
- No neon accumulation in core

- Heat losses on divertor target, both during ELM and time averaged, are strongly reduced

Most important mechanisms of impurity impact on plasma behaviour:

- Radiation energy losses
- Effect on anomalous transport due to plasma instabilities

Power density of impurity radiation

$$Q_{rad} = n \sum_Z L_Z n_Z$$

n **- density of electrons, exciting impurities**

L_Z*, *n_Z* – "cooling rate" and density of impurity ions with charge *Z

$$Q_{rad} = n L_I n_I$$

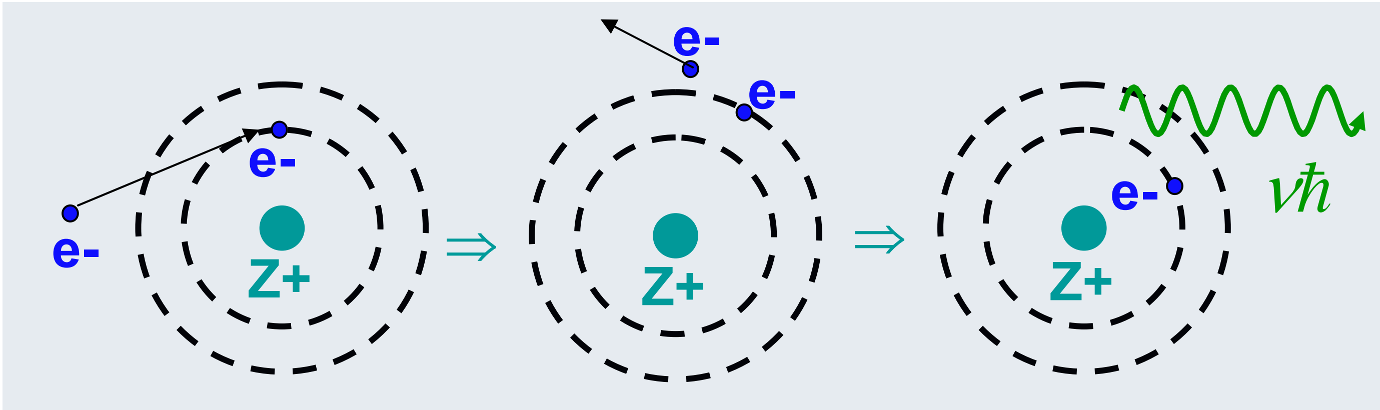
$$L_I = \sum_Z \zeta_Z L_Z$$ **- effective impurity cooling rate**

$$n_I = \sum_Z n_Z$$ **- total impurity density**

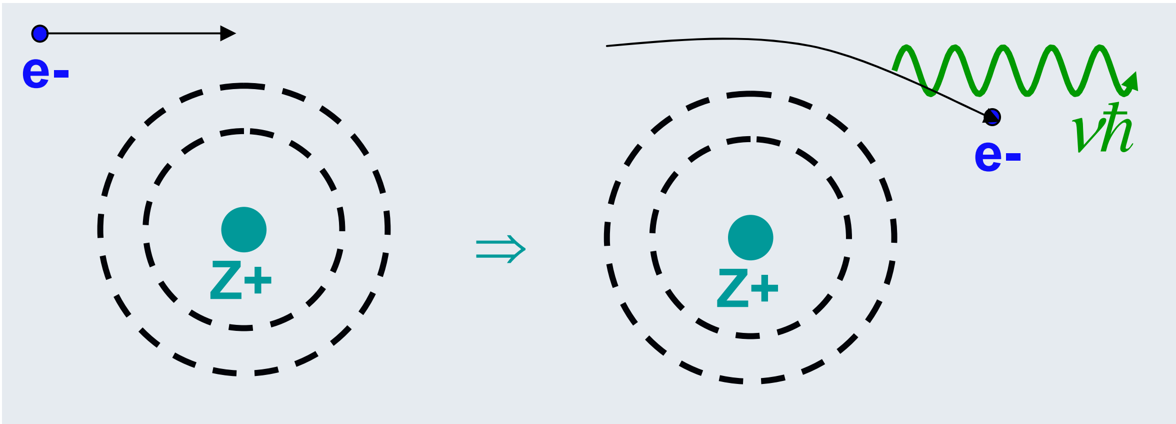
$$\zeta_Z = n_z / n_I$$ **- relative concentration of *Z*-ions**

Main channels for radiation losses from impurity ions

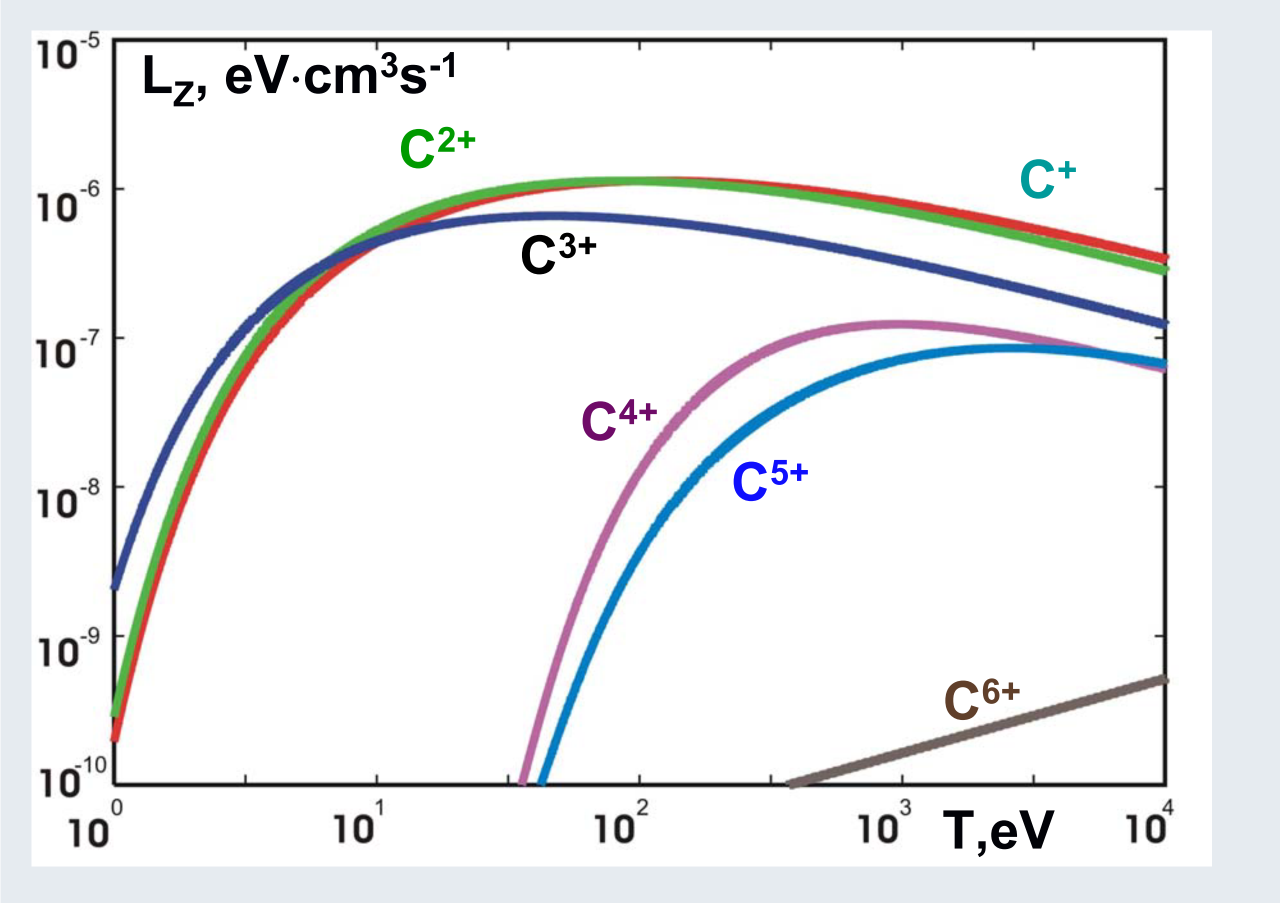
Line radiation:



Bremsstrahlung:



Cooling rates of carbon ions



$C^{+,2+,3+}$ **(Be, B, Li-like ions with E_{ex}~ 5-10eV) - easy to excite**

$C^{4+,5+}$ **(He, H-like ions with E_{ex}~ E_{ion}~ 300eV) - difficult to excite**

C^{6+} **(nuclei) - Bremsstrahlung only**

Density of impurity ions

governed by continuity equation:

$$\partial_t n_Z + \nabla_{\|}\left(n_Z V_Z^{\|}\right) + \nabla_{\perp}\Gamma_Z^{\perp} = S_Z$$

Divergence of fluxes
II and ⊥ magnetic field

Source density:

$$S_Z = k_{ion}^{Z-1} n n_{Z-1} - k_{ion}^{Z} n n_Z + R_{Z+1} n_{Z+1} - R_Z n_Z$$

Ionization by electrons

Electron capture rate:

$$R = k_{rec}^{rad} n + k_{rec}^{diel} n + k_{c-ex} n_a$$

Radiative **Dielectronic recombination**

Charge-exchange with atoms of working gas

Corona approximation

Sun corona:

processes of ionization and recombination are of importance only

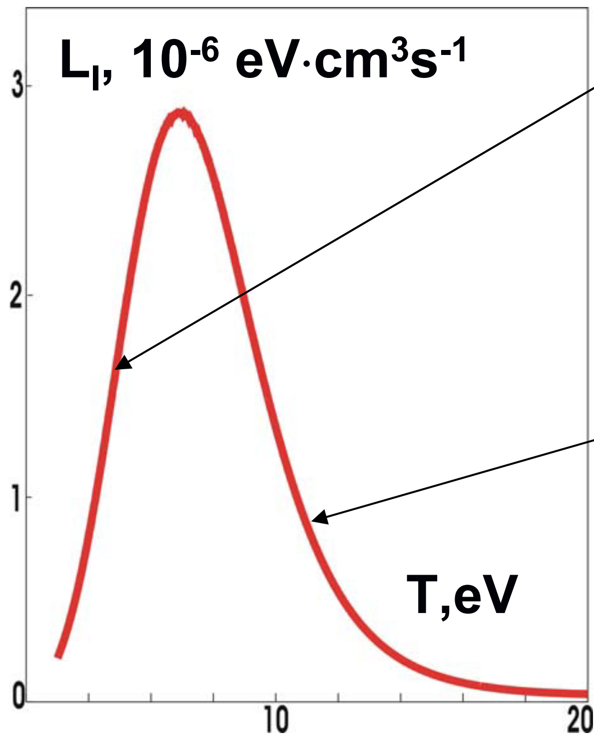
Particle balances for different charge states:

$$\left(k_{ion}^{Z}+k_{rec}^{Z}\right)n_Z=k_{ion}^{Z-1}\,n_{Z-1}+k_{rec}^{Z+1}\,n_{Z+1}$$

Relative concentrations of different impurity charge states and effective cooling rate depend on local temperature only:

$$L_I\equiv\sum_Z\zeta_Z L_Z=L_I(T)$$

Carbon cooling rate:



Behavior of L_Z:
$T\uparrow\rightarrow$ electrons excite more often brilliant low-Z impurity ions

Behavior of ζ_Z:
$T\uparrow\rightarrow$ impurity is ionized into dim high-Z states

In fusion devices impurity transport, both parallel and perpendicular to magnetic field, is very important

Impurity transport along magnetic field

is controlled by forces acting on ions mostly due to

Parallel electric field: $F_{El} = ZeE_{||}$

Coulomb collisions with background plasma particles resulting in:

- **friction with ions** $F_{Fr} = m_Z \nu_{Zi} \left(V_i^{||} - V_Z^{||} \right)$
- **thermal force** $F_{Th} = \xi \nabla_{||} T$

because of $\nu \propto 1/T^{1.5}$

Impurity transport across magnetic surfaces

Density of perpendicular ion flux :

$$\Gamma_Z^{\perp} = -D_{\perp} \nabla_{\perp} n_Z + V_{\perp} n_Z$$

Diffusion **Convection**

Contributions to transport coefficients:

$$\begin{Bmatrix} D_{\perp} \\ V_{\perp} \end{Bmatrix} = \begin{Bmatrix} D_{\perp}^{neo} \\ V_{\perp}^{neo} \end{Bmatrix} + \begin{Bmatrix} D_{\perp}^{an} \\ V_{\perp}^{an} \end{Bmatrix}$$

Neoclassical transport due to collisions with main ions

Anomalous transport due to drift micro-instabilities in plasma

Neoclassical convection:

$$V_{\perp}^{neo} = \alpha \nabla_{\perp} n + \beta \nabla_{\perp} T$$

α and β are different in Pfirsch-Schlüter, Plateau and Banana regimes

Anomalous convection:

$$V_{\perp}^{an} = \gamma \nabla_{\perp} q + \delta \nabla_{\perp} T$$

due to toroidal geometry and thermal force

Effect of impurity transport on radiation losses

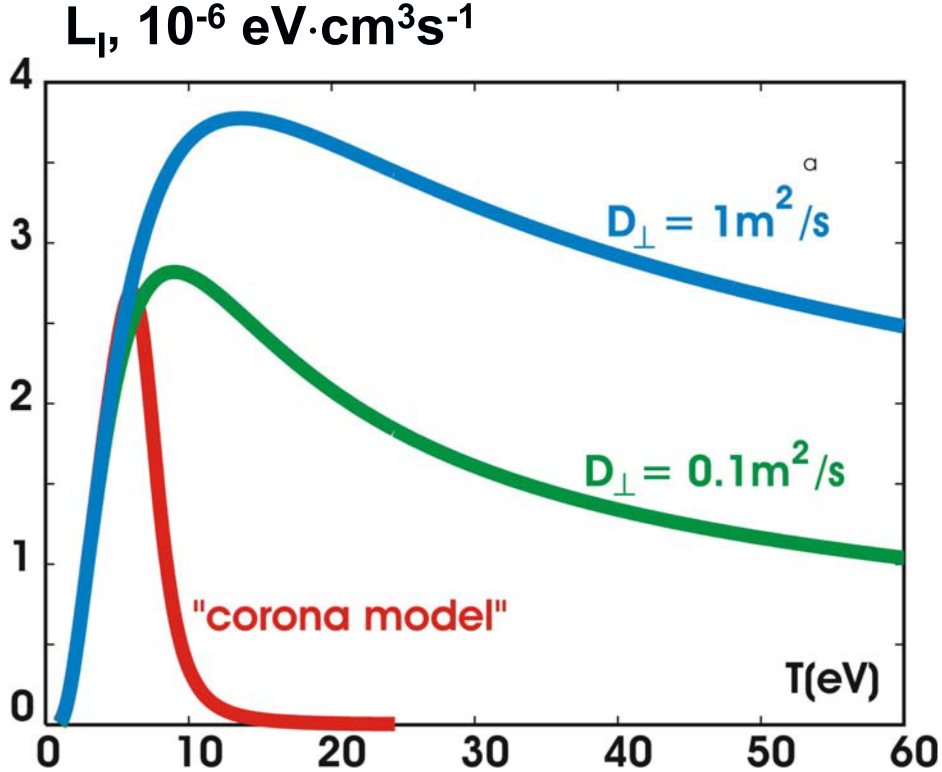
- **Impurities enter plasma where its temperature is low**

- **Low-Z impurity ions are transferred into hot regions where according to corona model they should be ionized into dim high-Z states**

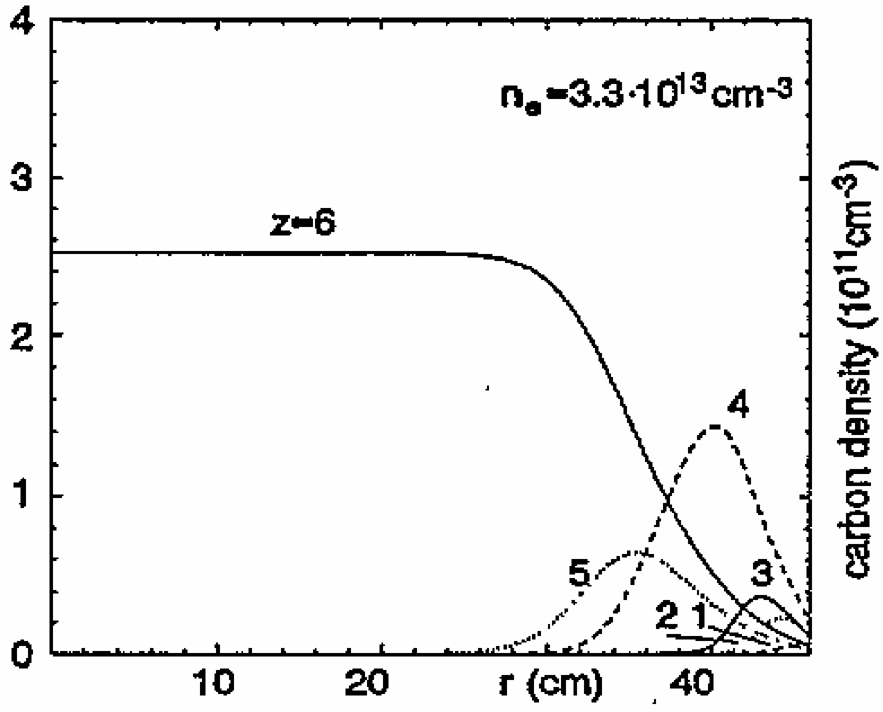
- **Transport increases effective cooling rate and makes it less temperature sensitive**

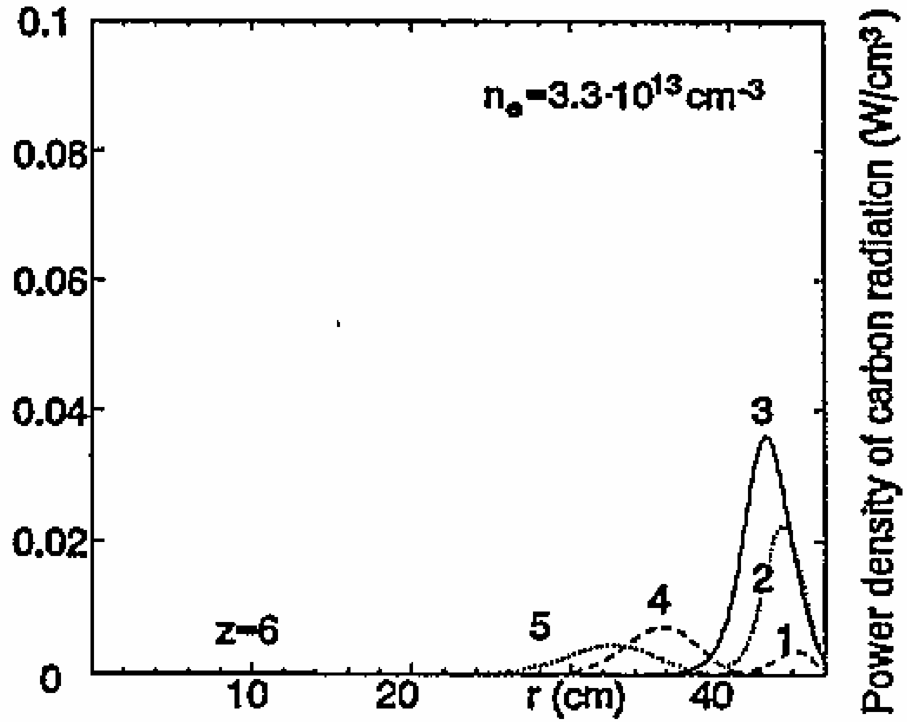
- **Similar effect is due to charge-exchange with neutrals**

Carbon cooling rate:



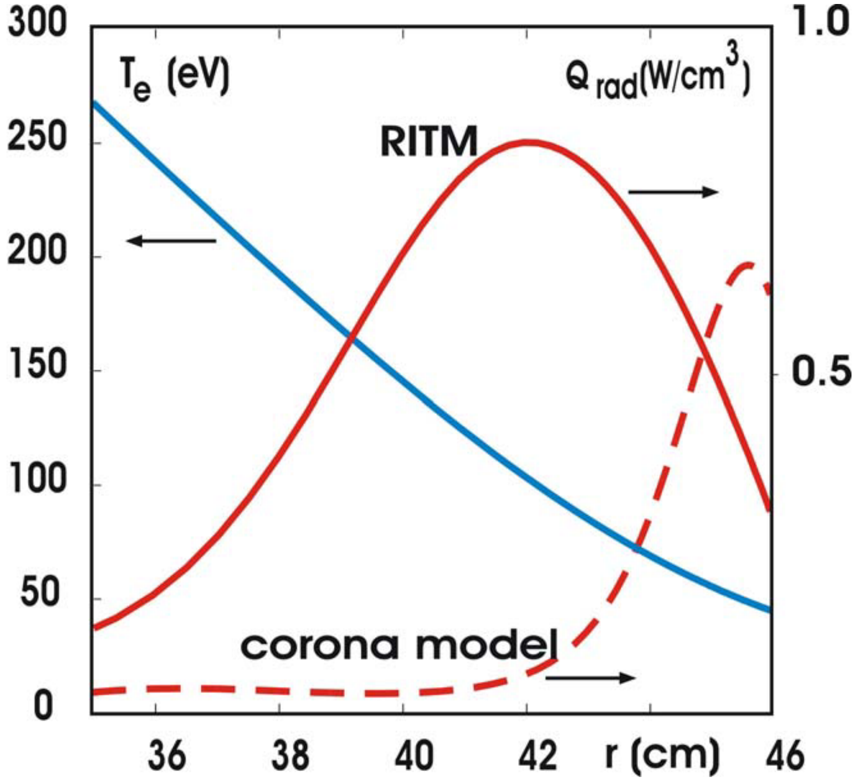
Densities and radiation contributions of different carbon charged states in TEXTOR computed by code RITM





Main contributor to radiation losses: Li-like C^{3+} ions

Neon radiation in TEXTOR computed by code RITM



Broadening of radiating layer due to transport allows to get high radiation at relatively low neon concentration

Impact from radiation losses on plasma density *n* and temperature *T*

is governed by:

Plasma energy balance governs temperature

$$5n\partial_t T - \kappa_{||}\Delta_{||}T - \kappa_{\perp}\Delta_{\perp}T = -Q_{rad}$$

Components of plasma heat conduction II and ⊥ magnetic field

$$\kappa_{||} \text{ and } \kappa_{\perp}$$

Pressure balance II magnetic field governs density

$$\nabla_{||}(nT) = 0$$

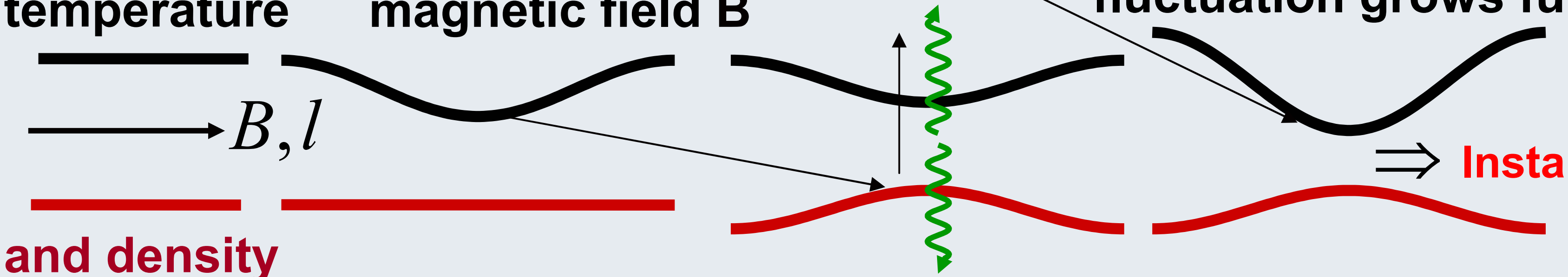
Radiation instability

Homogeneous plasma temperature

Temperature fluctuates along magnetic field B

Radiation losses grow

Plasma is cooled down by radiation ⇒ Temperature fluctuation grows further



and density

Density locally increases due to pressure equilibration

Perturbed parameters $T, n = \overline{T}, \overline{n} + \widetilde{T}, \widetilde{n} \quad \Rightarrow$

Form of fluctuations $\widetilde{T}, \widetilde{n} \sim \exp\left(ikl + \gamma t\right) \quad \Rightarrow$

put into pressure and heat balances:

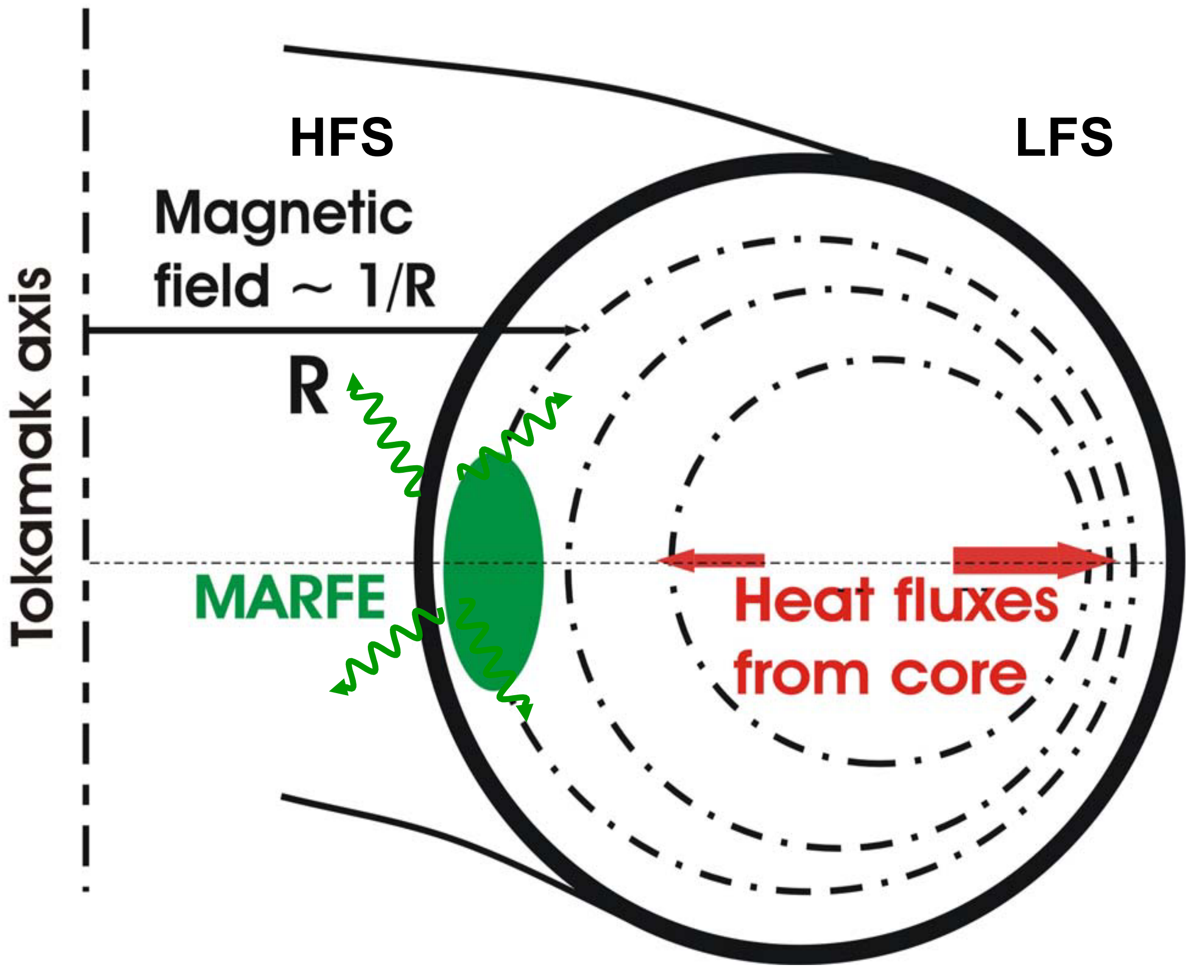
Instability condition

$\mathrm{Re}\,\gamma > 0$ $\Rightarrow$

$$Q_{rad} > Q_{rad}^{crit} \equiv \frac{\kappa_{\parallel} k^2 T}{1 - \partial \ln\left(n_I L_I\right) / \partial \ln T}$$

Parallel heat conduction is stabilizing, $\partial L_I / \partial T < 0$ - destabilizing

MARFE as result of RI: why it develops at HFS?



Due to Shafranov shift distance between magnetic surfaces is larger at HFS than at LFS

⇒

Radial temperature gradient and heat flux from plasma core are weaker at HFS

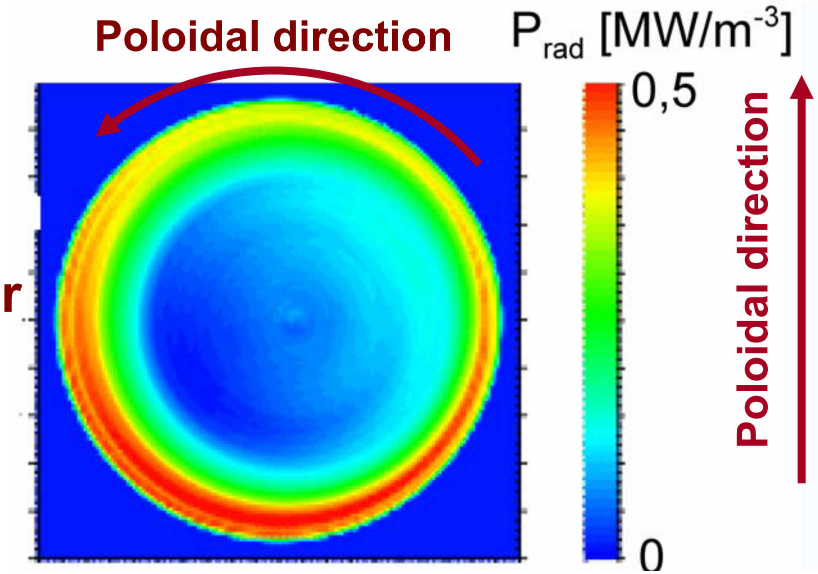
⇒

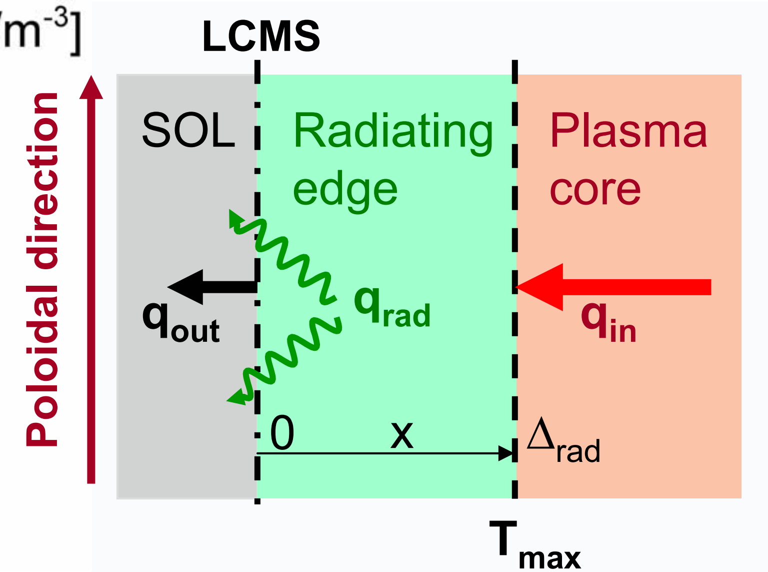
Radiation overcomes heating and instability develops first at HFS

Stable radiating edge (I)

With neon seeding:

85% of power is radiated





Radiating edge is homogeneous along magnetic field ⇒ parallel heat conduction is unimportant

$$-\kappa_\perp \frac{d^2T}{dx^2} = -Q_{rad}$$

Plasma boundary x = 0:

$$\kappa_\perp dT/dx = q_{out} \equiv \alpha T$$

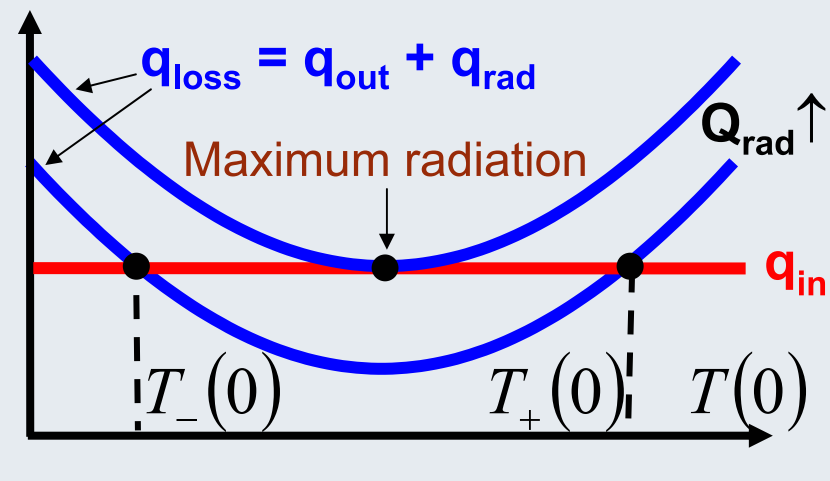
Interface with hot core x = Δ_{rad}:

$$T = T^I_{\max} \approx E^{Li-like}_{ion}$$

$$\kappa_\perp dT/dx = q_{in}$$

Stable radiating edge (II)

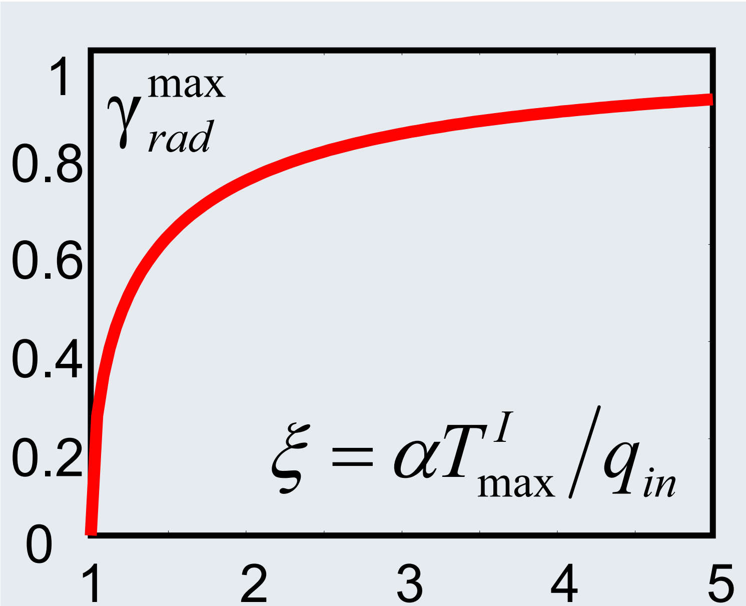
Edge power balance



- **State with $T_-(0)$ is unstable:**
  $T(0)\downarrow \Rightarrow q_{loss} \uparrow \Rightarrow T(0)\downarrow$

- **Maximally achievable radiation level, $\gamma_{rad} \equiv q_{rad}/q_{in}$, corresponds to merging of stable and unstable states, $T_-(0) = T_+(0)$ $\Rightarrow$**

$$\gamma_{rad}^{max} = 1 + \sqrt{\xi^2 - 1} - \xi$$



- **Impurities with higher T^I_{max} provide higher stable $\gamma_{rad} \Rightarrow$**

- **Neon, $T^I_{max} \approx 200$eV, is better to create radiating edge than intrinsic carbon impurity, $T^I_{max} \approx 60$eV**

Suppression of anomalous transport (AT) through impurities (I)

Main contributor to AT in plasma core:

Ion Temperature Gradient (ITG) Instability with typical growth rate:

$$\gamma_{ITG} \approx \frac{k_\perp c T_e}{eB} \sqrt{\frac{2}{R}\left(\frac{1}{L_{T_i} Z_i} - \frac{1}{L_{T_i}^{cr}}\right)}, \quad \frac{1}{L_{T_i}} = -\frac{d \ln T_i}{dr}$$

Critical ion temperature e - folding length:

$$\frac{1}{L_{T_i}^{cr}} \approx \frac{\beta}{R} + \frac{R}{8L_n^2}, \quad \frac{1}{L_{n_i}} = -\frac{d \ln n}{dr}$$

Effect of ion charge Z_i: supporter of ITG, ion diamagnetic flow induced by temperature perturbations, reduces as $1/Z_i$

Suppression of AT through impurities (II)

Very plasma edge: density gradient is very sharp and ITG is suppressed

L-mode: other instabilities, e.g., drift-Alfven waves govern AT

H-mode: no AT, Edge Transport Barrier with low neoclassical transport is sustained

Width of ITG-free region: $\gamma_{ITG} = 0 \Rightarrow$

$$\frac{1}{L_{T_i} Z_i} \approx \frac{R}{8 L_n^2}$$

With increasing Z_i this condition can be satisfied by larger L_n, i.e., deeper in plasma and ITG-free region broadens

Conclusions

- **Impurities plays crucial role in fusion plasmas, both negative and positive**
- **Line radiation due to excitation of bounded electrons in impurity ions and Bremsstrahlung due to elastic scattering by impurity ions are the main radiation loss channels**
- **Diverse transport processes, such as motion along magnetic field lines, diffusion and convection perpendicular to magnetic surfaces, control the density of impurity ions of different charges and radiation**
- **Due to impact on plasma parameters radiation instabilities can develop and lead to structure formation, e.g., MARFE**
- **More stable radiating edge can be created by using impurities radiating up to higher temperature, e.g., neon instead of intrinsic carbon impurity**
- **Impurity affect drift instabilities, in particular ITG, through the ion charge and have influence on anomalous transport**