Impurity Control in Helical Reactor

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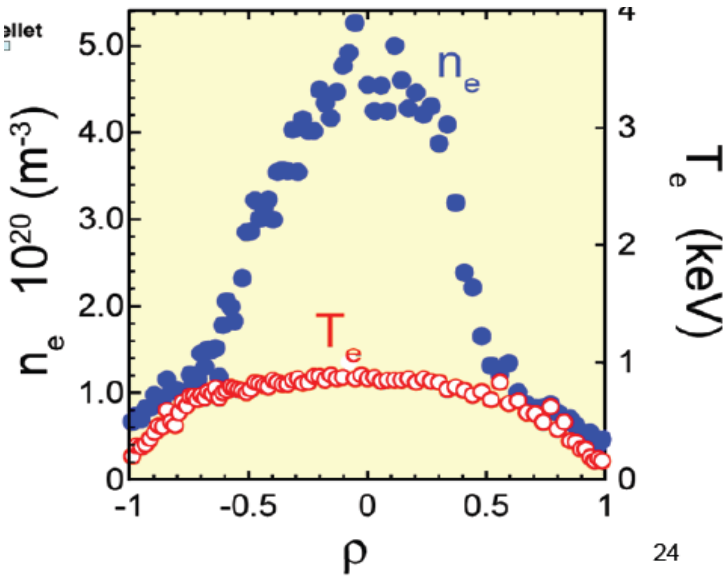
- **High density regimes for FFHR and HSR**
- **“Temperature screening” effect**
- **Screening effect due to poloidal plasma rotation**
- **Screening effect of magnetic perturbation**
- **“Entraining effect” of pellet injection**

High density regimes of improved confinement

- **LHD: SDC plasma**



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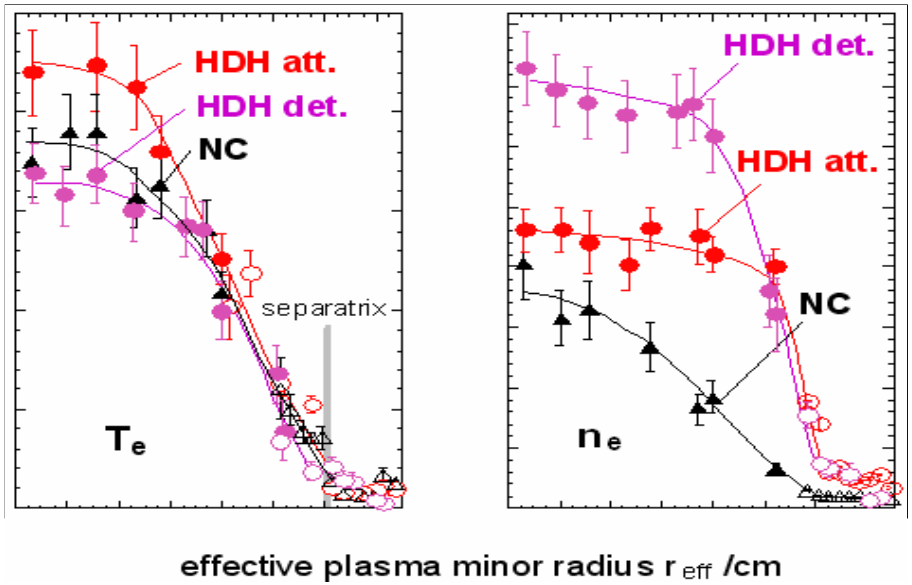
- **W7-AS: HDH mode**



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

$T(0) = 0.85$ keV,

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

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

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

High Density H-mode,

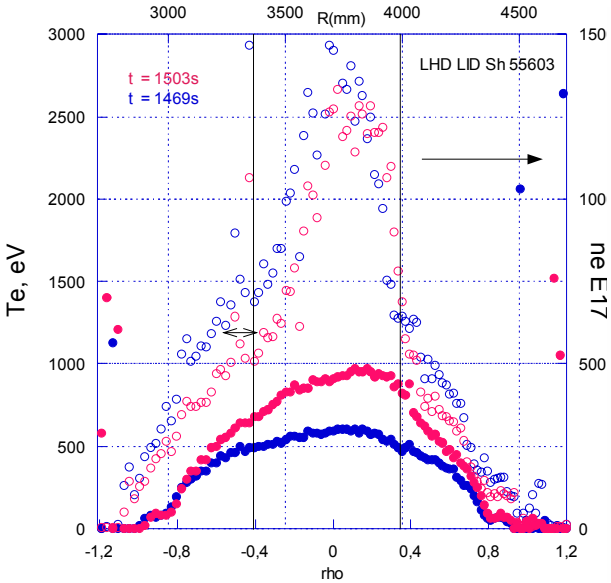
$n(0) = 4 \times 10^{20}$ m^{-3},

high τ_E, extremely low τ_{imp}

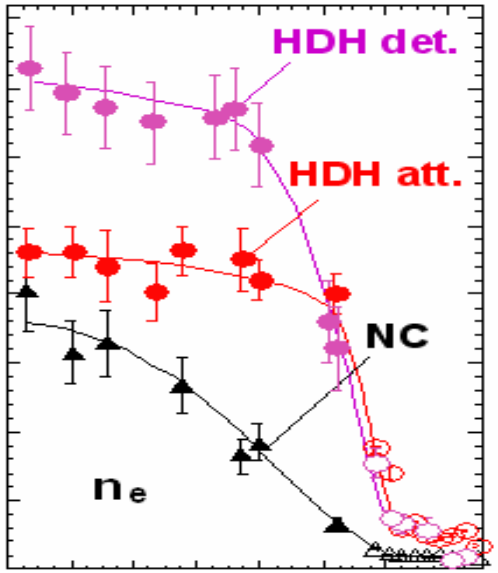
HDH is characterized by flat density profiles with steep gradients at the edge

Negative Radial Electric Field in Reactor Plasma

LHD LID Sh 55603 t =1503s

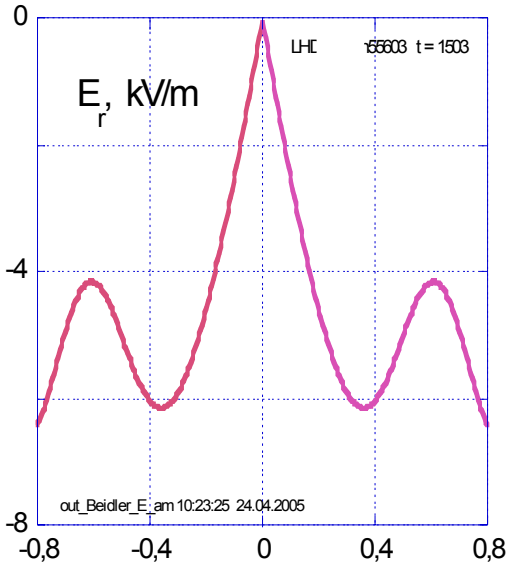


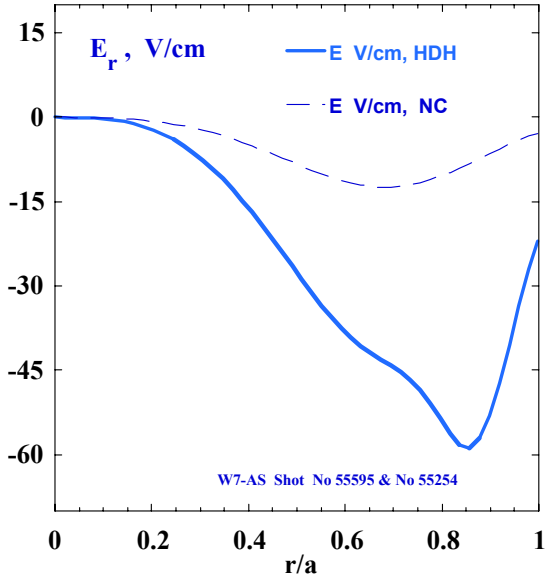
W7-AS Shots # 55595 & 55254



$$V_j^I \equiv \frac{D_1^{I,j}}{T}\left\{Z_I \mathrm{E_r} - \left(\frac{D_2^{I,j}}{D_1^{I,j}} - \frac{3}{2}\right)\nabla T\right\}$$

- under reactor condition, neoclassical theory predicts that only the "ion root" exists for the ambipolar radial electric field Er





- negative Er fields result in a strong inward drift of the high Z impurities and may lead to the problem of impurity accumulation!

Temperature "screening" effect

$$V_j^I \equiv \left\{ Z_I D_1^{I,j} \frac{\mathrm{E_r}}{T} - D_2^{I,j} \frac{\nabla T}{T} \right\} \approx Z_j D_1^{I,j} \left(\frac{\nabla n}{n} + \gamma_T \frac{\nabla T}{T} \right) \sim \gamma_T \frac{\nabla T}{T}$$

- in stellarator configuration

$$D \sim 1/\nu \sim T^{3/2}, \qquad \gamma_T \approx \frac{\partial}{\partial T} D > 0$$

Inward drift (accumulation)

- in tokamak configuration

$$D \sim \nu \sim 1/T^{3/2}, \qquad \gamma_T \approx \frac{\partial}{\partial T} D < 0$$

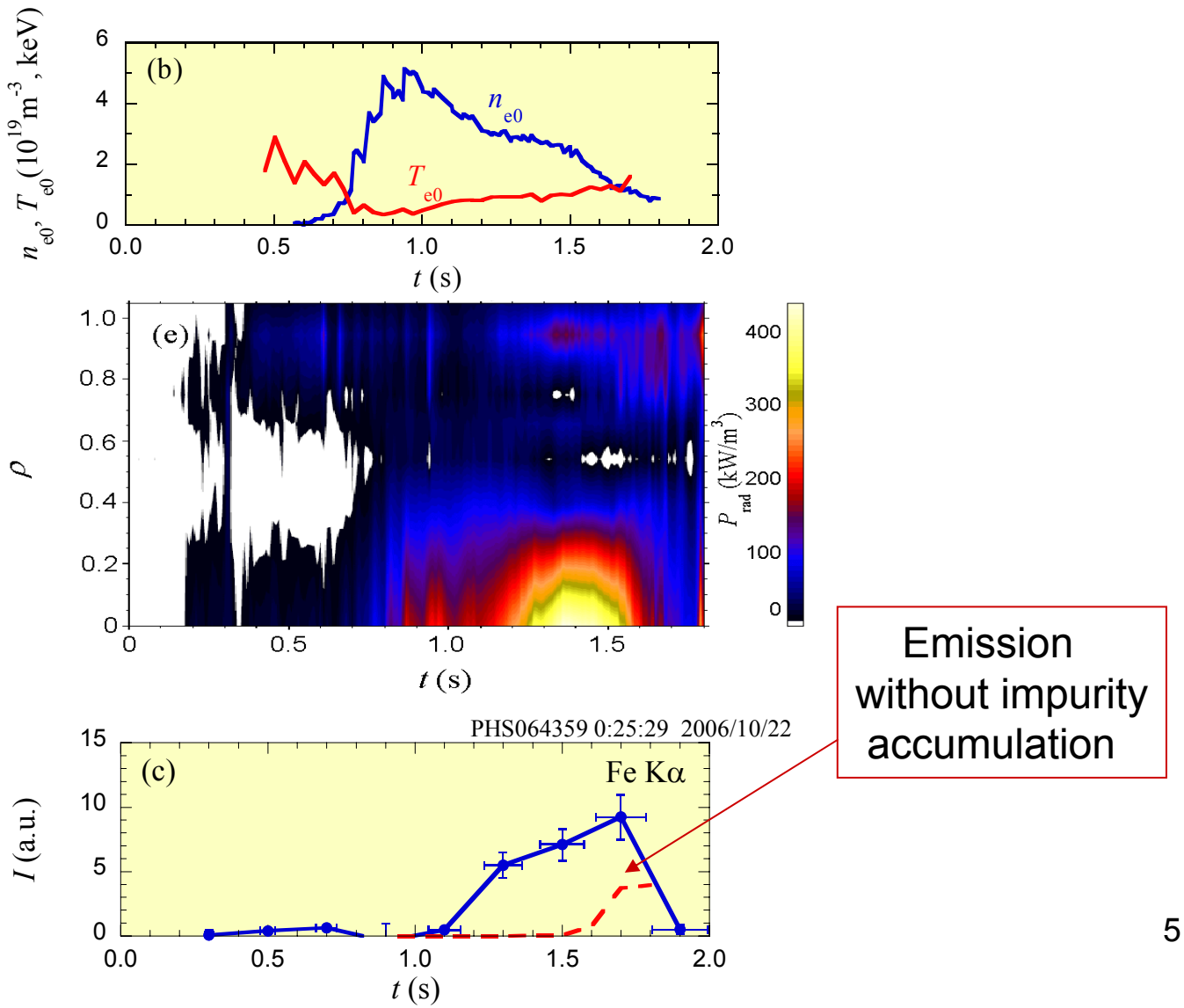
Outward drift ("screening" effect)

- **in stellarator plasmas thermal force pulls impurities inwards (in contrast to tokamaks) : no "temperature screening" effect is expected!**
- **impurity accumulation is expected in core of FFH & HD Reactor plasmas!**

Yu. Igitkhanov

Impurity behavior in LHD SDC Discharges

* **Fe Kα** line emission from the center increases gradually in the latter half of the discharge.



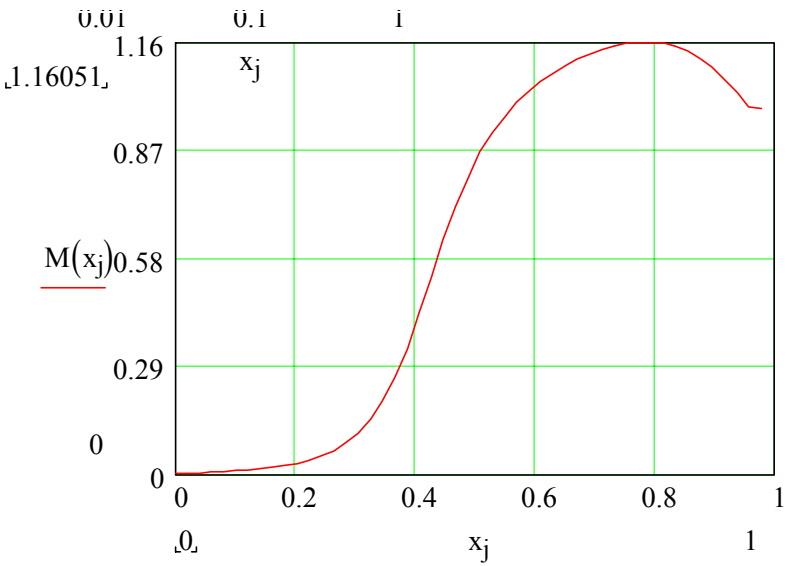
Screening effect due to poloidal plasma rotation

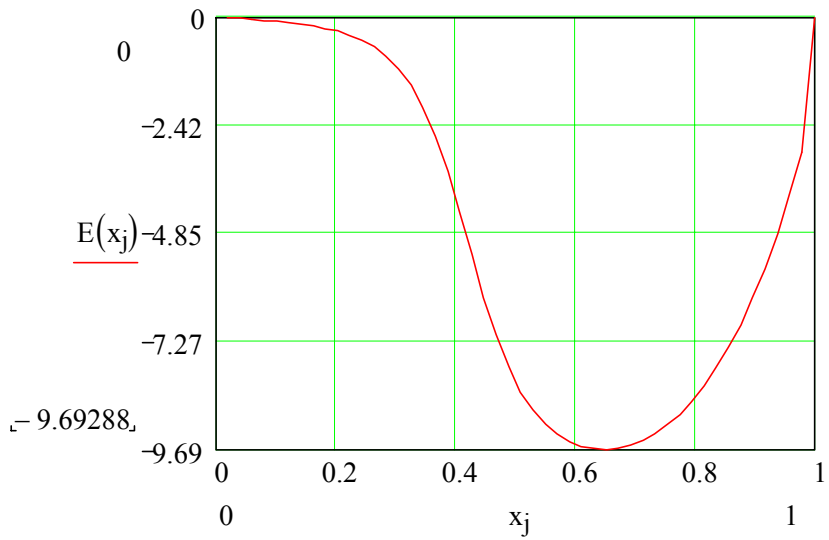
FFHR2 R=10m, a=1.2m B=10T

$$n_I / n_i \propto n_i^{Z-1} \; T^{F(A,Z)} \; \exp - I(A,Z) \int_r M_\theta^2 dr / r$$

$$M_\theta = \frac{cT}{eBv_{Ti}} \frac{\partial \ln p_i}{\partial r}$$

Poloidal mach number & Er:

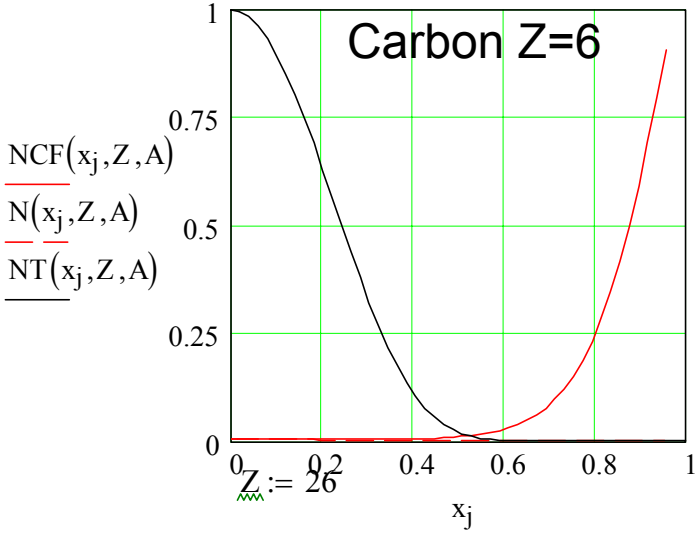




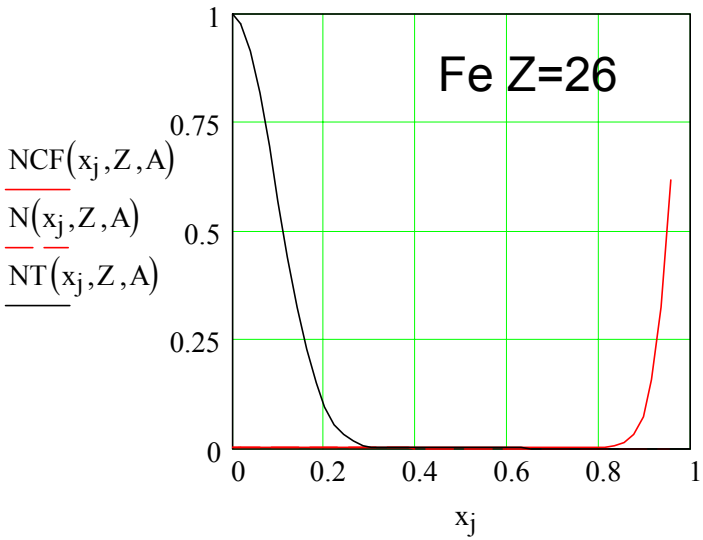
Screening effect due to poloidal plasma rotation

FFHR2 R=10m, a=1.2m B=10T

$Z := 6$



$Z := 26$



$$NT(x) := \left(\frac{n(x,\theta,\mu)}{n(0,\theta,\mu)}\right)^{Z-1} \cdot \left(\frac{TT(x,\alpha)}{TT(0,\alpha)}\right)^{Z-1+\frac{3\cdot(1-A\cdot Z)}{2\cdot(1+A)}}$$

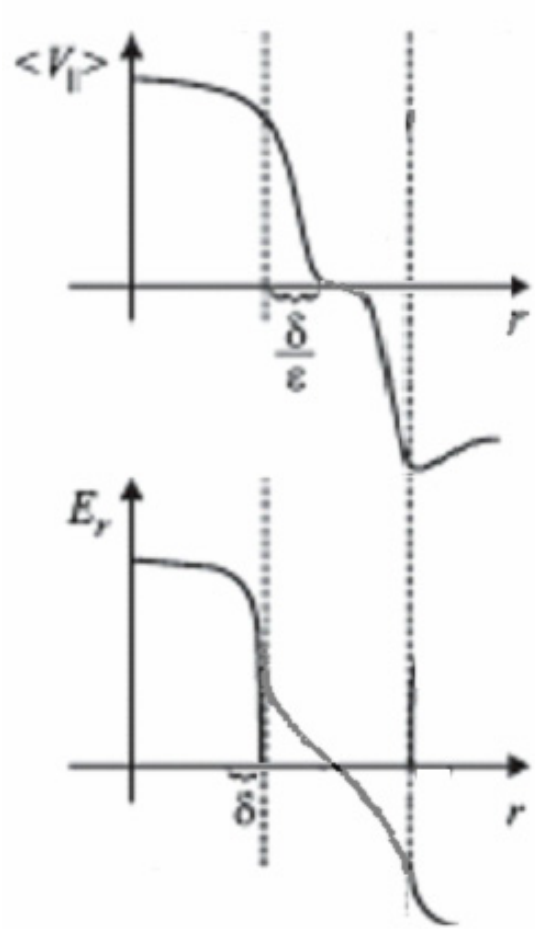
$$NCF(x) := e^{-(A-Z)\cdot\int_x^1 \frac{1}{t}\cdot M(t)^2\,dt}$$

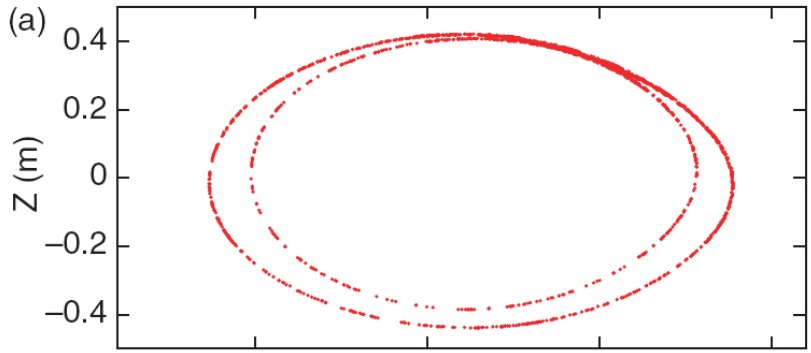
- **strong poloidal plasma rotation (M~1) could prevent accumulation of high Z impurities**
- **when their rotation energy exceed thermal energy**
- **CF effect is effective for impurities of high Z and low T**
- **impurity localization depends on CF and Er**
- **in FFHR plasmas expecting M~0.6 seems to be insufficient for effective shielding**

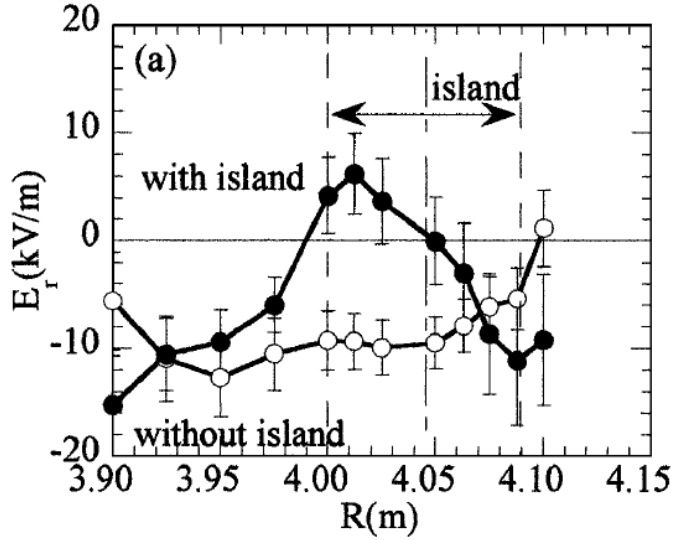
Screening effect of externally induced island

$$E_r \approx T_i\left(\frac{\partial \ln n}{h\partial r} + k\frac{\partial \ln T_i}{h\partial r}\right) + \langle V_\theta B_{//} \rangle$$

$$\delta = \left(\frac{2}{3}\frac{\eta_{an} r^2}{\eta_0 B_p / B}\right)^{1/2}$$



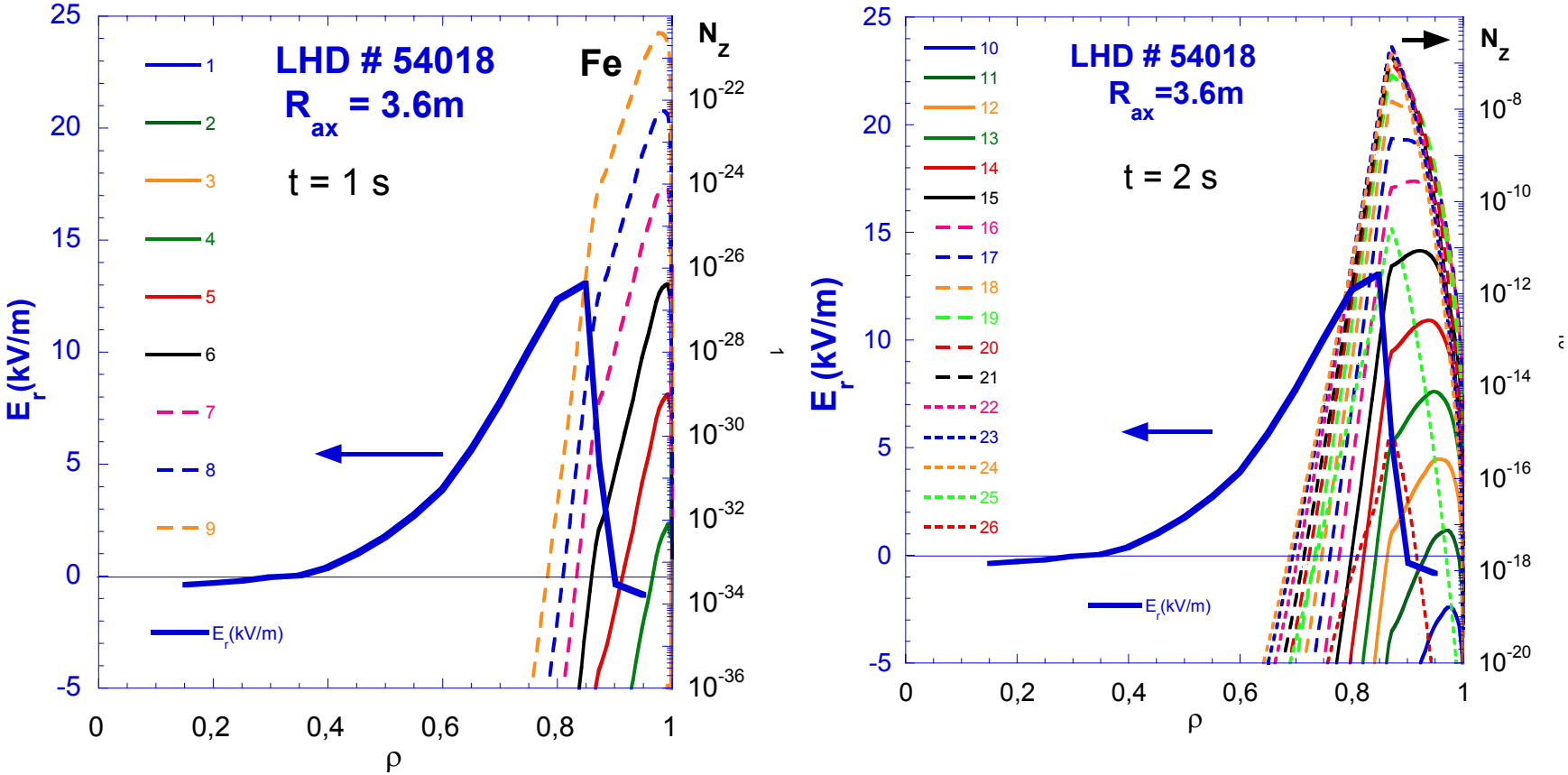




K. Ida, 2002

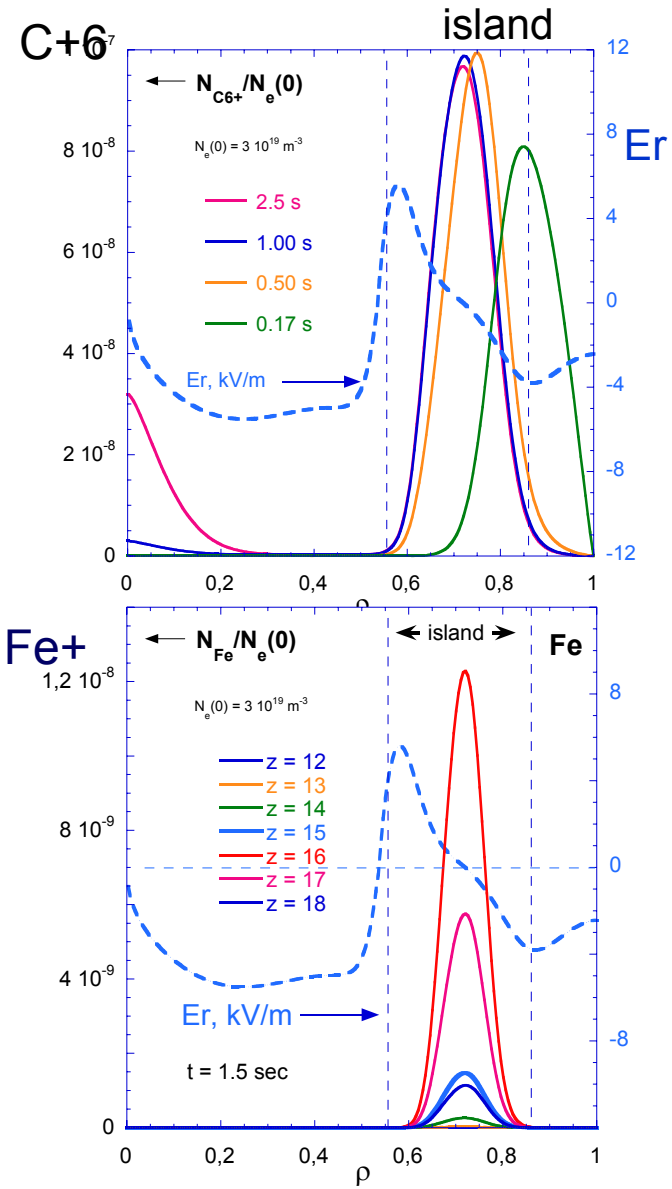
Screening effect of positive electric field

LHD Shot # 54018 low density case



- **Fe** radial distribution at t=1s and t=2s. The source at the separatrix (ρ=1) was turned off at t=0.1s. Impurities different charge states are completely screened by positive electric field.

Shielding effect of **island**



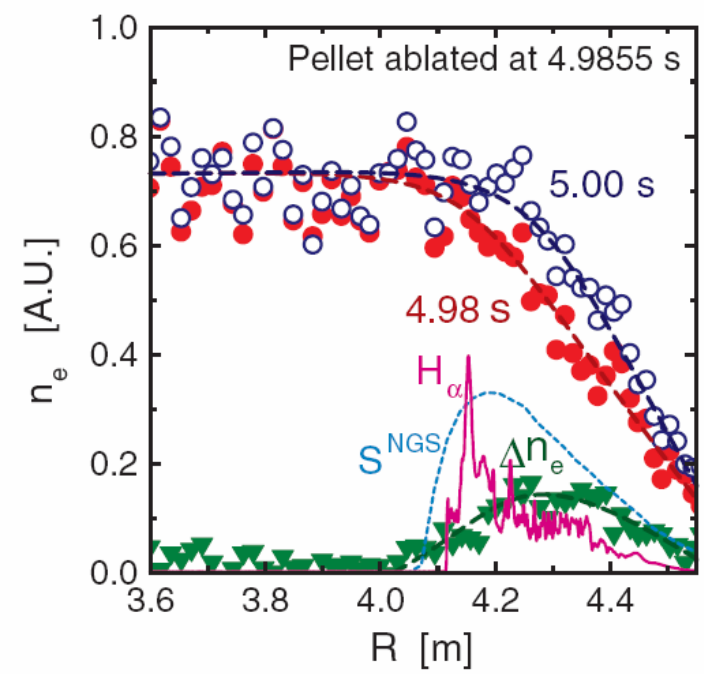
- Impurity ions can be retained within an externally induced magnetic island if the radial electric field changes the sign within the island.

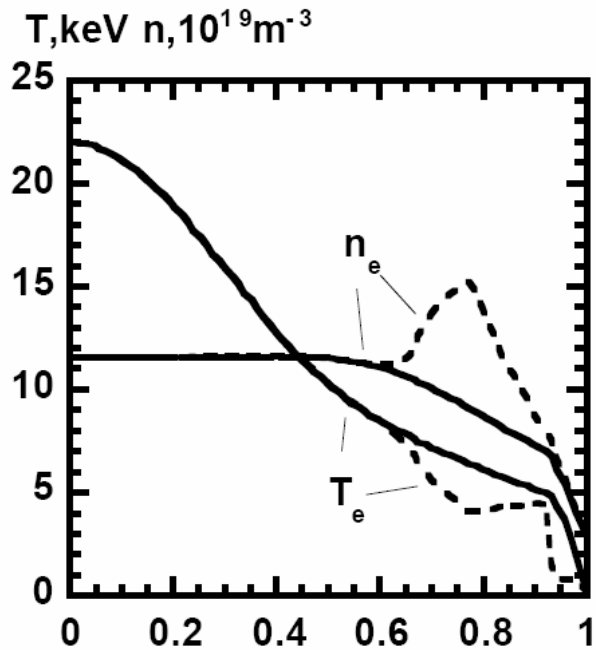
- In long pulse discharges at high ion temperature at the edge, impurities can slowly diffuse through the island overcoming an “electric barrier”. This can eventually could bring to accumulation.

- Healing effect at high beta makes this effect less effective!

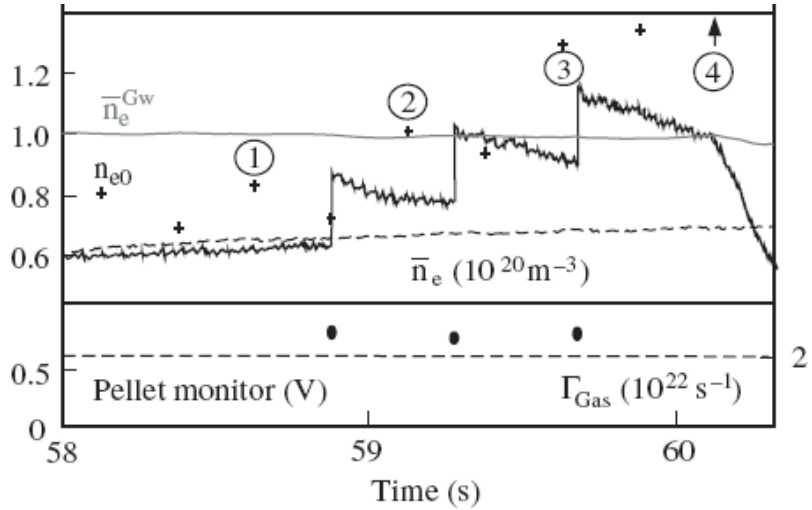
Impurity Control by Pellet Injection

- The repetitive small pellet injection at the plasma edge acts similar to ELMs, e.g. screening bulk plasma from impurities





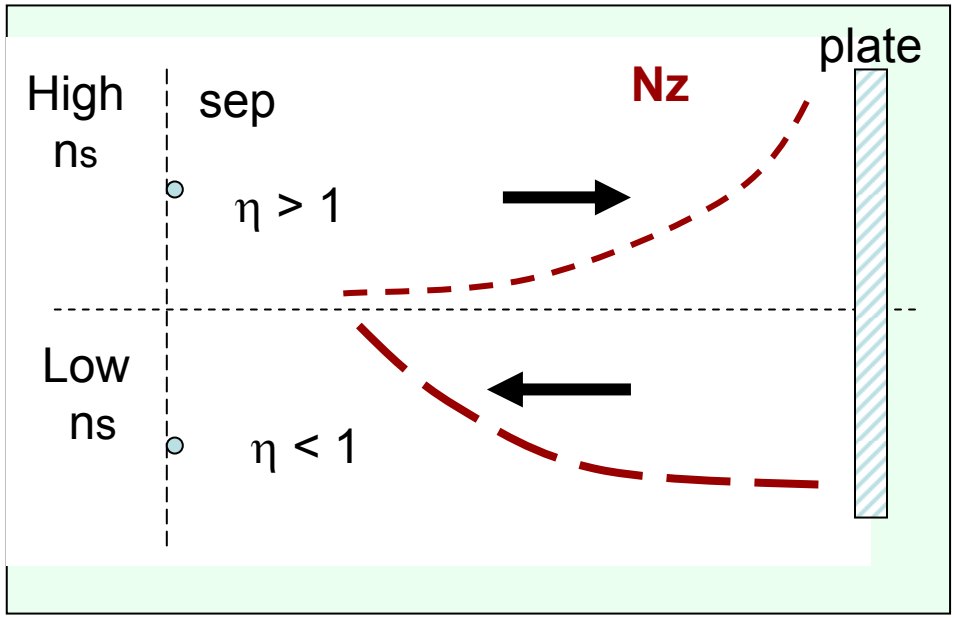
Screening of impurities in the SOL



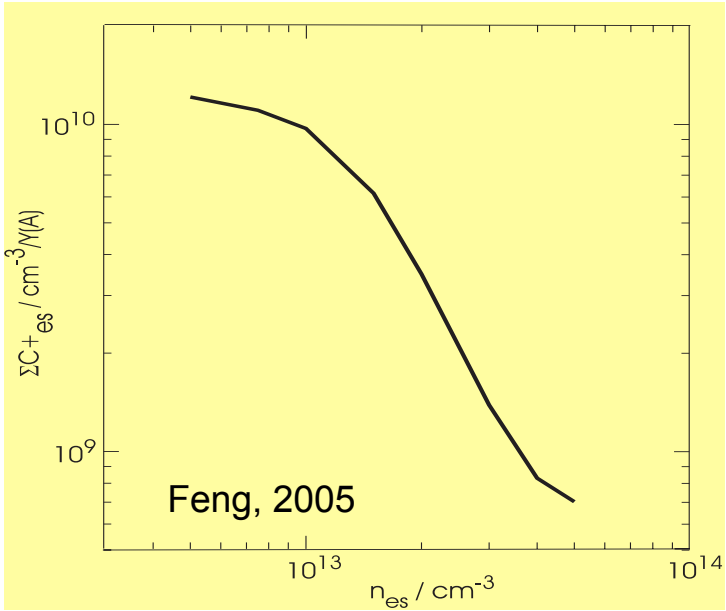
$$N_Z \cong T^{\alpha(1-\eta)}$$

Igitkhanov 1996

$$\eta \equiv \frac{Friction\ force}{Ion\ thermal\ force} \equiv \frac{q^C_{//}(convective)}{q^T_{//}(conductive)}$$



Impurity flux vs. n_{sep}



Resume

- **Under reactor condition neoclassical theory predicts that only the "ion root" exists for the ambipolar radial electric field Er, and this negative Er fields may lead to the problem of impurity accumulation!**

- **Poloidal plasma rotation may retained of high Z impurities at the edge when their rotation energy exceeds thermal energy. For FFHR & HSR expecting M~0.6 seems insufficient for an effective shielding: inward drift due to negative Er is stronger.**

- **Impurity ions can be retained by externally induced magnetic island. However, this method seems to be unreliable due to strong healing effect at high beta observed in LHD SDC plasmas!**

- **A new method of impurity screening in LHD and FFHR is suggested : to induced ELMs type perturbation by launching repetitively small pellets at the plasma edge (10Hz, 1021s**-1 for HSR and FFHR **)!**

Resume

- calculations show that for proper frequency and amount of pellets, impurity ions be can effectively captured and pulled from the edge to the SOL. The resulting screening is similar to that seen in ELMing H-mode tokamak.

- periodic plasma & energy outflow of the plasma to the SOL changes the impurity behavior along the open magnetic field lines, where the conduction and convection alternate to enhance the screening efficiency.

- the amount of pellets, which should be injected continuously, are supplemental to the larger pellets needed to initiate the SDC regime in FFHR and are not detrimental to the achievement of the internal diffusion barrier and do not deteriorate the confinement time.

Resume

- For the helical reactor these small pellets should pose no threat to ignition due to the lack of a density limit in non-axisymmetric configurations

- In a tokamak pace making ELMs are used to reduce the power load to the divertor. In contrast we propose these artificially induced plasma perturbation as a means of impurity control without a threatening increase of the power loading of the divertor in a helical reactor