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ELM control

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IEF - Plasmaphysik, Theory and Modeling

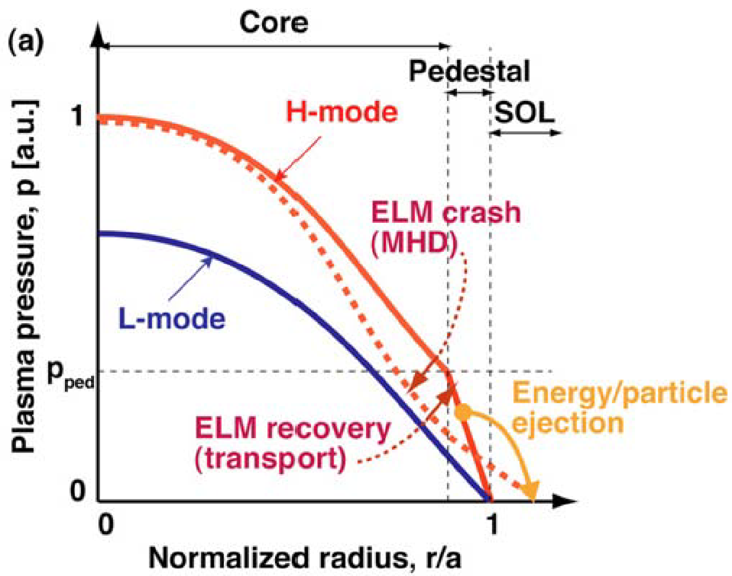
14TH WORKSHOP ON MHD STABILITY CONTROL

Content:

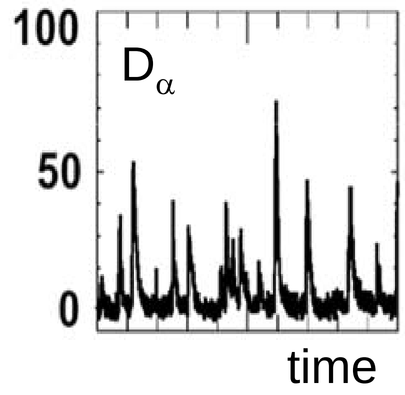
- Introduction
  - Edge Localized Modes
  - Approaches to ELM control
- ELM mitigation with resonant magnetic perturbations
- Magnetic field stochastization
- Particle transport modification with RMP
- Heat conduction paradox
- Conclusions

Edge Localized Modes of Type I in H-mode

• Improved confinement in H-mode in tokamaks is quasi-periodically destroyed by MHD activity called Edge Localized Modes (ELM)

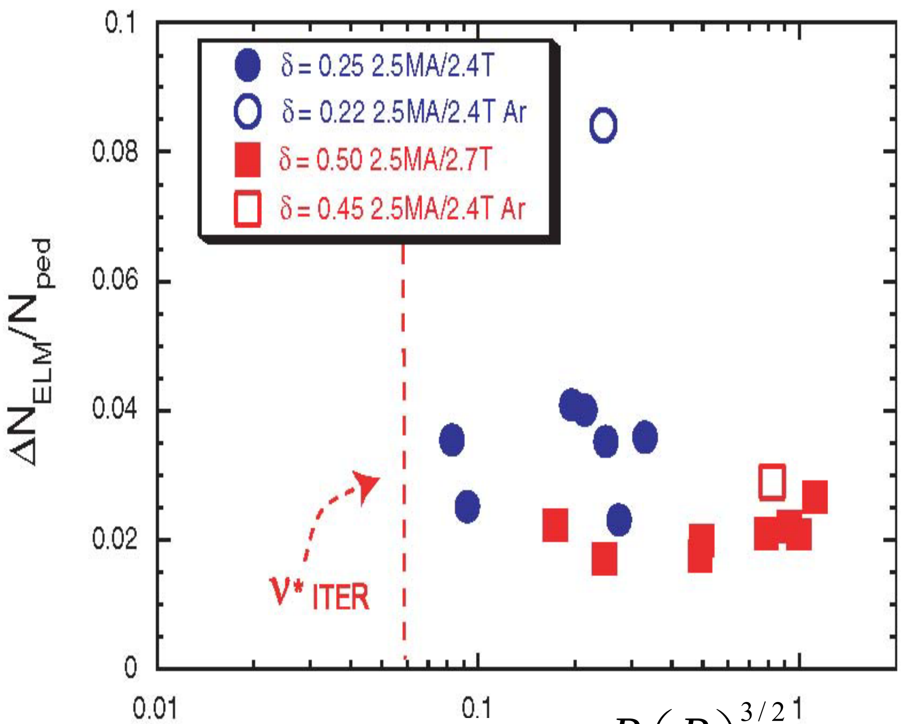


• Type I ELMs are seen as large spikes of radiation from neutrals produced by losses of hot charged particles from plasma



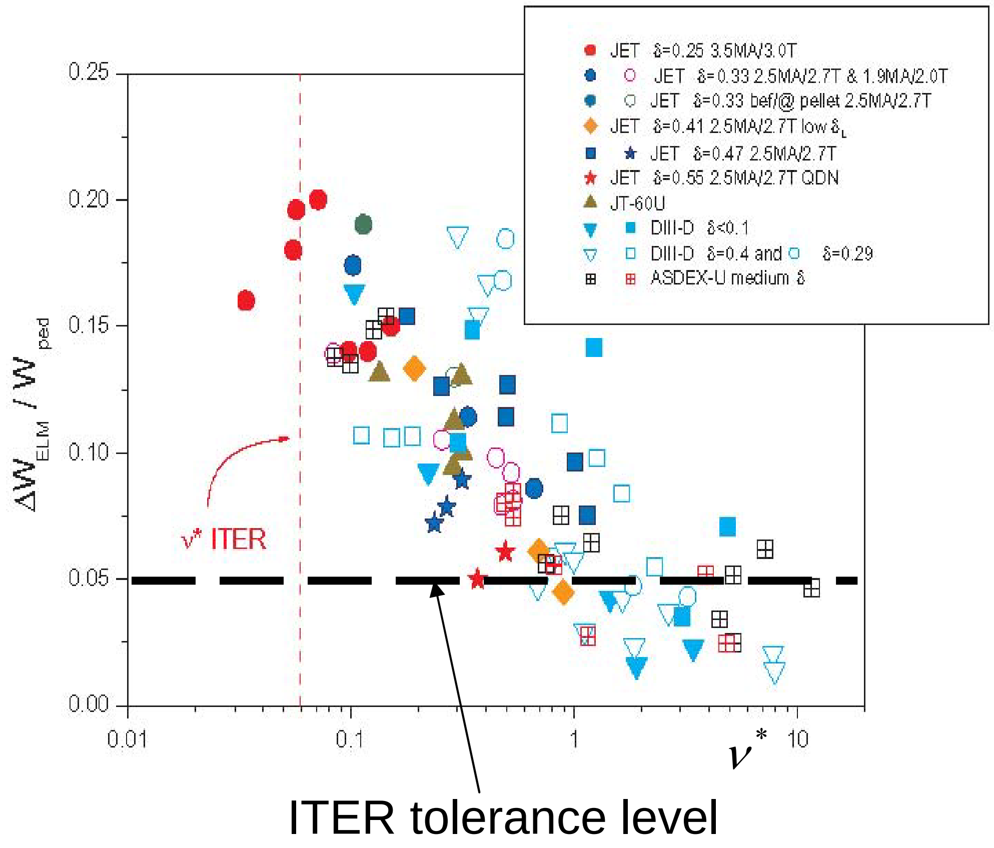
Collisionality dependences of particle and energy losses per ELM crash

Total particle loss per ELM normalized to pedestal particle content (JET):



$$\nu^* = \frac{qR}{\lambda}\left(\frac{R}{r}\right)^{3/2}$$

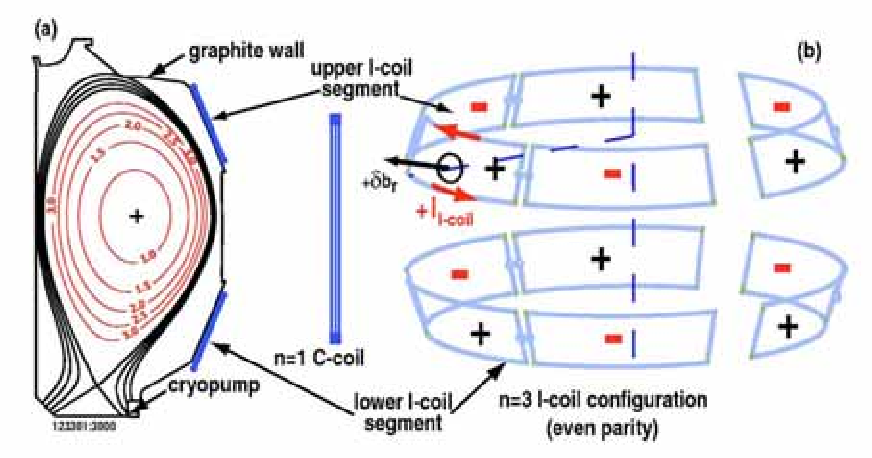
Total energy loss per ELM normalized to pedestal energy content:



Approaches to mitigate ELMs:

- ELM triggering by fast vertical movement of the plasma column (“vertical kicks“)
- ELM pacing using pellet injection in order to split a few strong ones into many sufficiently small ones
- ELM mitigation by noble gas injection by decreasing heat loads on divertor target plates through impurity radiation
- ELM control with resonant magnetic perturbations

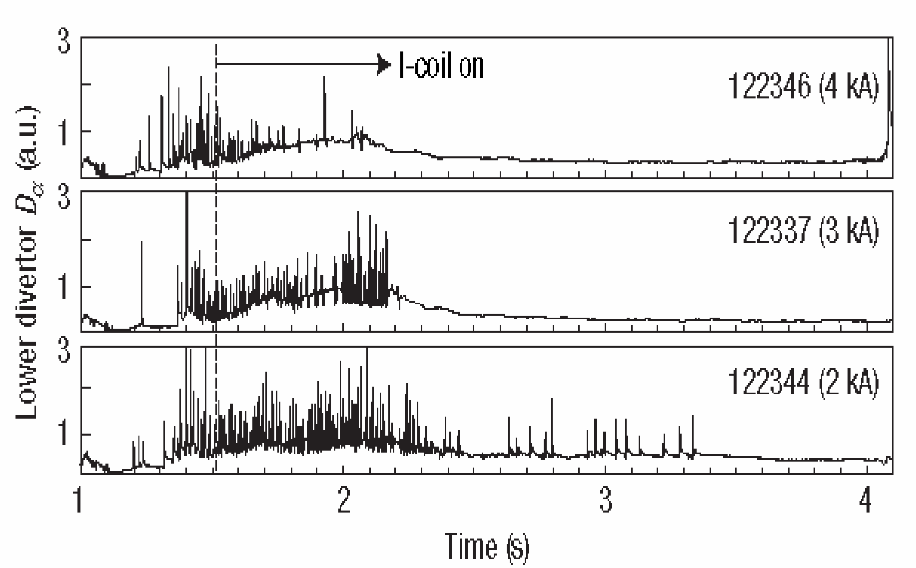
Suppression of ELMs in DIII-D plasmas of low collisionality



I-coils in DIII-D

T. E. Evans ***et al***

Phys. Plasmas 13 (2006) 056121



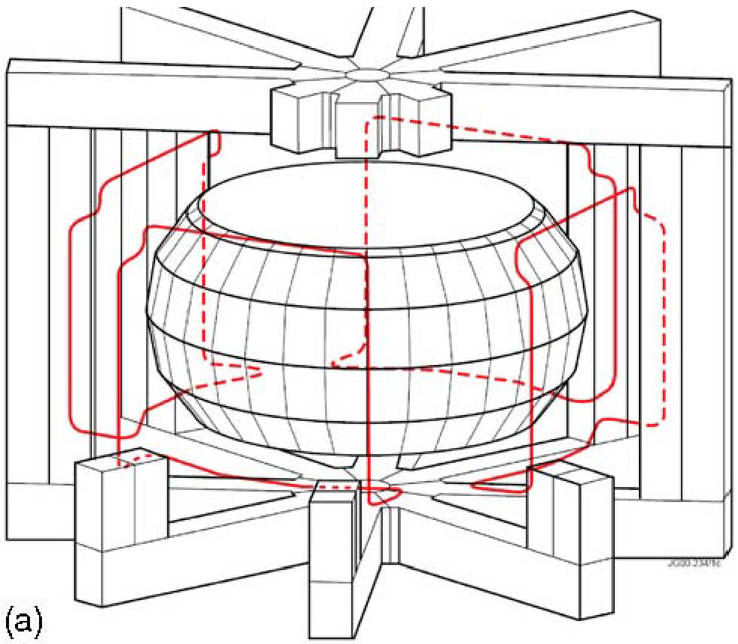
Mitigation and full suppression of D_α-spikes due to ELMs in DIII-D

T. E. Evans ***et al***

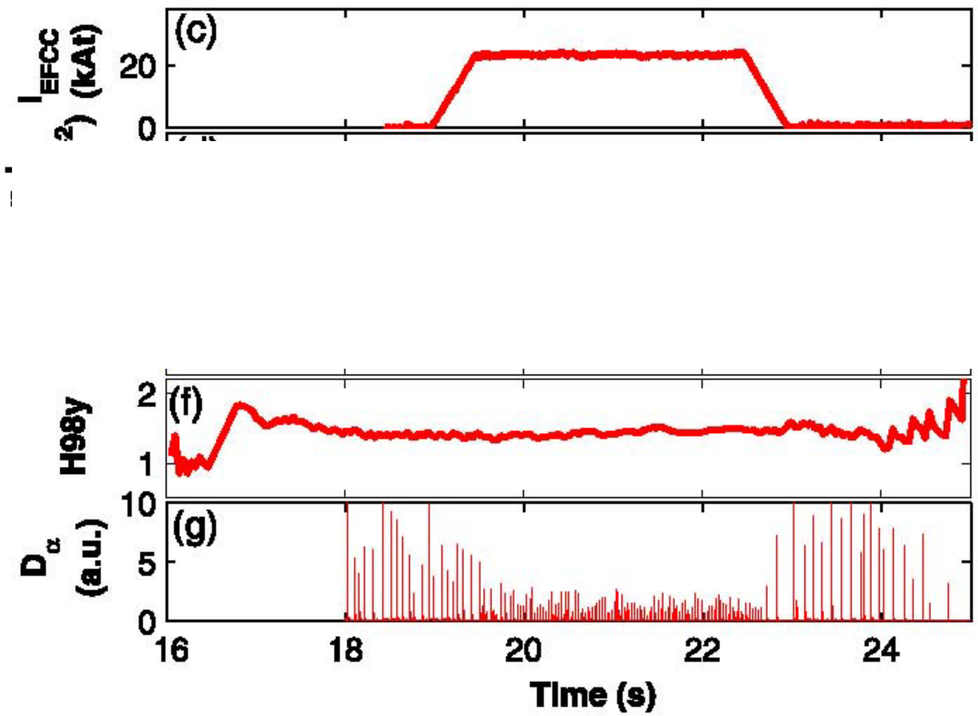
Nature Physics 2 (2006) 419

Mitigation of ELMs in JET

Error Field Correction Coils (EFCC) on JET:



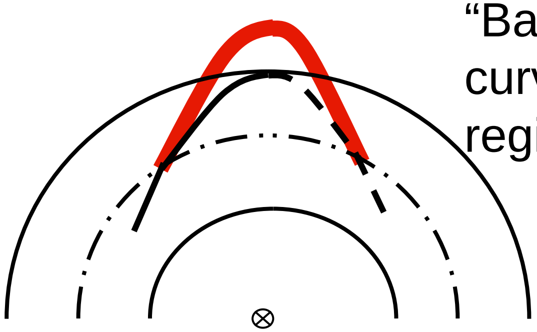
Reduction of ELM amplitude and increase of ELM frequency:



Y Liang *et al*
Plasma Phys. Control. Fusion
49 (2007) B581

Triggers of type I ELMs:
Ideal MHD instabilities

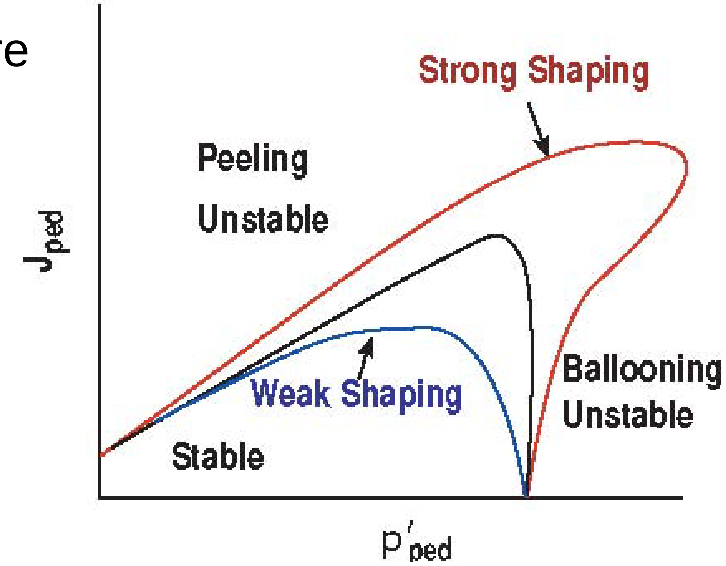
Ballooning instability:



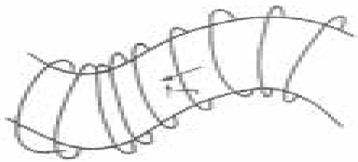
"Bad" curvature region

Instability threshold:

$$\left|\nabla_r P\right| > \frac{B_T^{\,2}}{2\mu_0 q^2 R}\alpha_{cr}$$

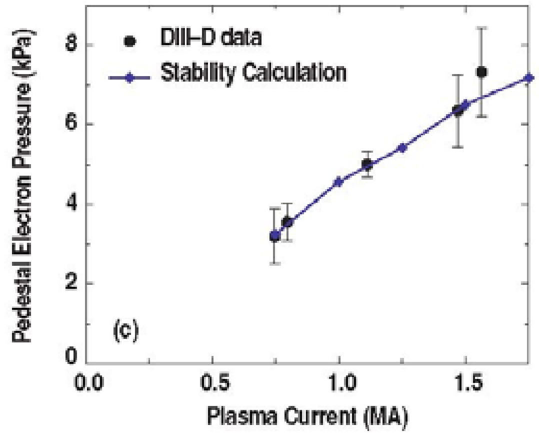


Localized high *n* kink "peeling," instability:



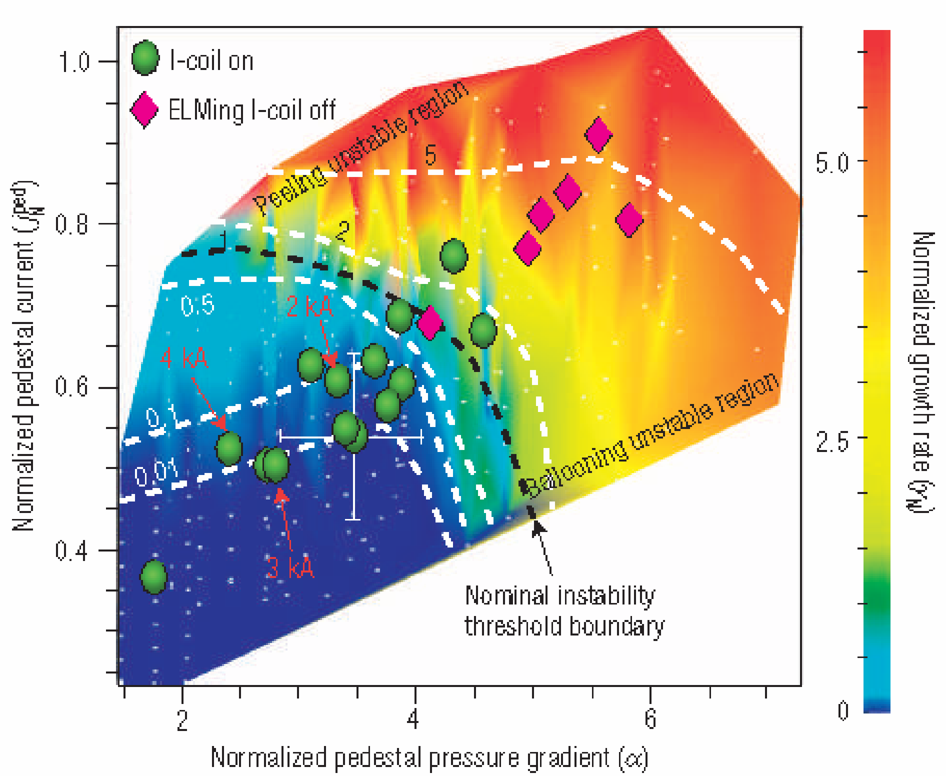
Instability threshold:

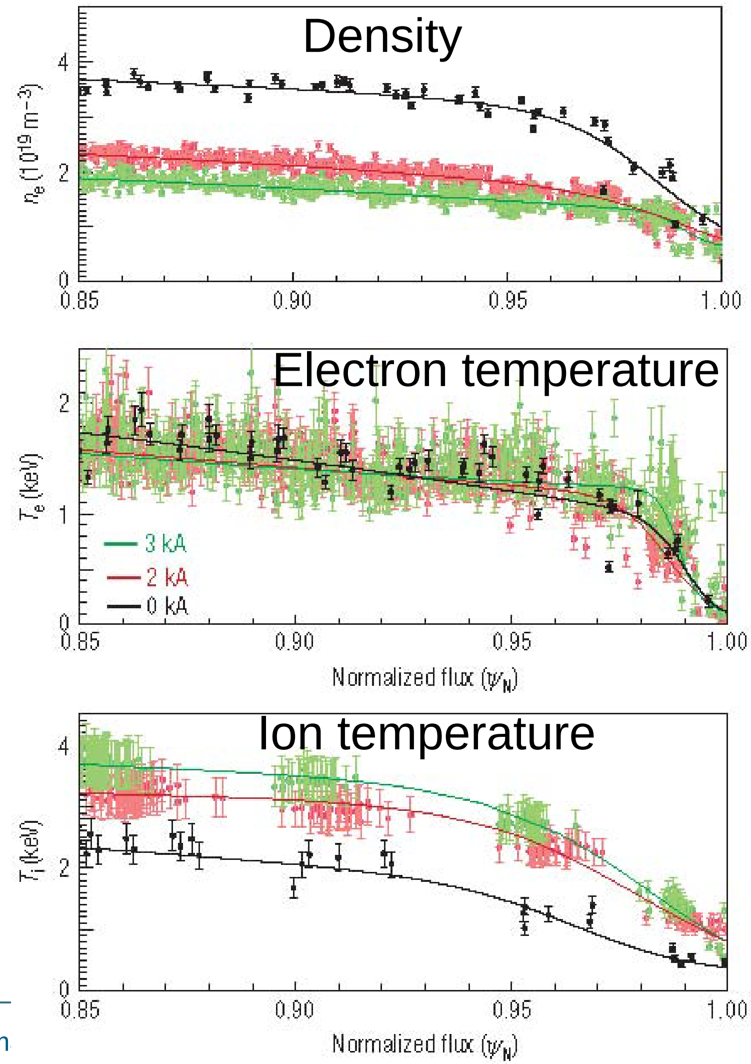
$$j_{\parallel}(a)/\langle j_{\parallel}\rangle > \gamma\left|\nabla_r P(a)\right|$$



P B Snyder *et al*, Plasma Phys. Control. Fusion **46** (2004) A131

Dominant mechanism of ELM suppression in DIII-D: reduction of edge pressure below instability threshold

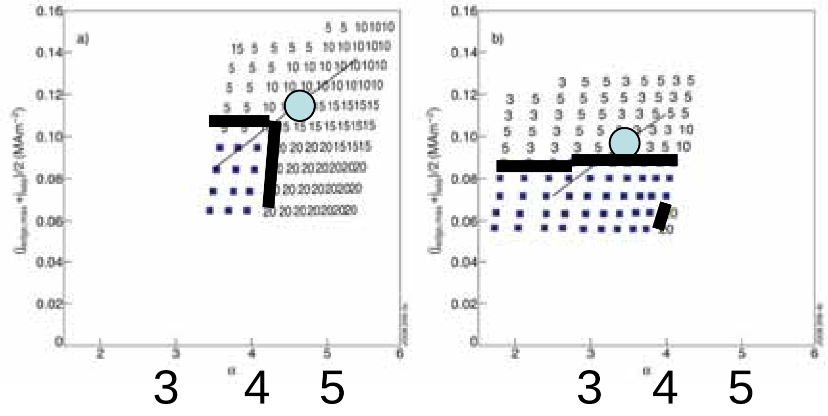




Heat transport is even reduced with RMP

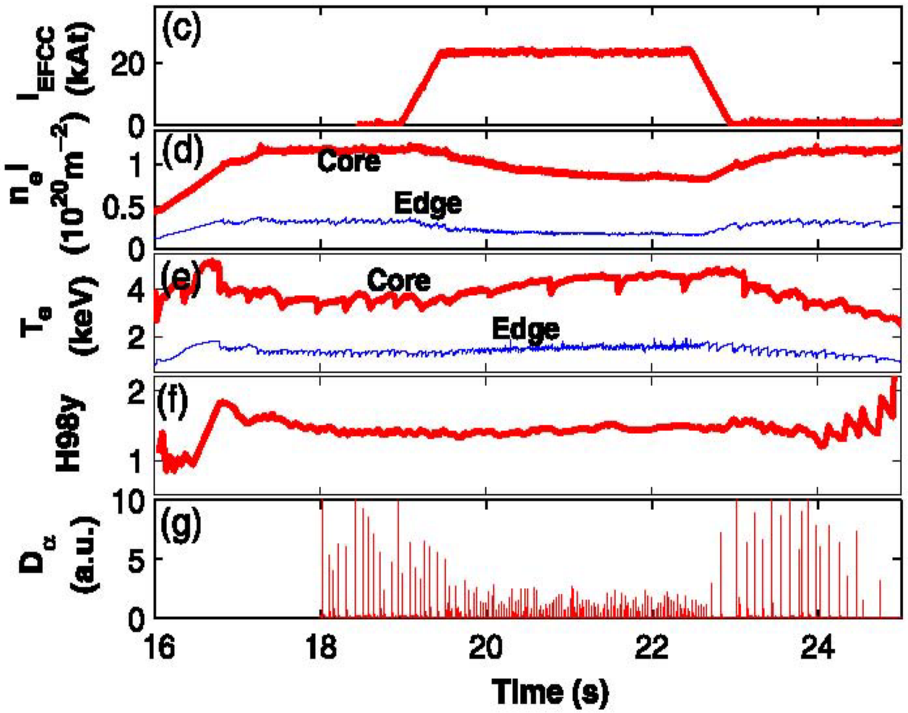
Mitigation of ELMs in JET

ELM are not suppress but amplitude strongly reduced probably due to evolution of working point to peeling stability boundary



S Saarelma, *et al*
Plasma Phys. Control. Fusion
51 (2009) 035001

Modification of plasma parameters:



Y Liang *et al*
Plasma Phys. Control. Fusion
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Effect of RMP on magnetic configuration

Radial magnetic field produced by coil:

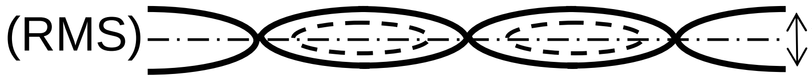
$$B_r = \sum_{\text{integer } M,N} B_r^{M,N}(r)\cdot\cos(M\vartheta - N\varphi)$$

Resonance magnetic surface (RMS):

$$q = M/N$$

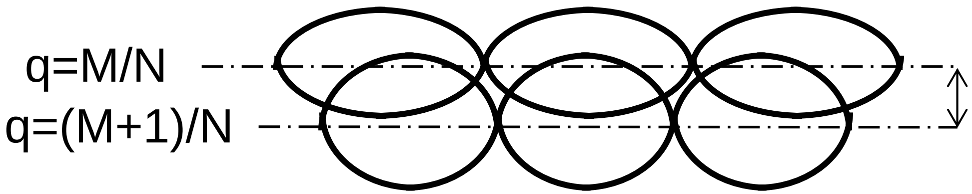
(M,N)-harmonic phase is constant $\Rightarrow$ very small field perturbation can lead to large radial deviation of field lines

Chain of magnetic islands with width **w** increasing with perturbation amplitude



$$w \propto \sqrt{\frac{B_r^{M,N}}{\hat{s}}}$$

By strong enough perturbation σ_{Ch} = **w/Δ >1** and adjacent island chains are overlapped

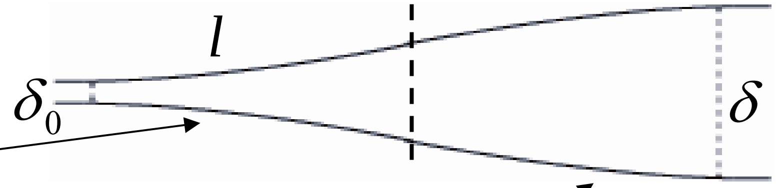


$$\Delta \propto \frac{1}{\hat{s}}$$

$\Rightarrow$ Stochastization of magnetic field lines

Behavior of stochastic field lines

Divergence of neighbouring field lines:



$$l <\approx L_K \Rightarrow \delta = \delta_0 \exp(l/L_K)$$

$$l >> L_K \Rightarrow \delta = \sqrt{2 D_{Fl} l}$$

$$L_K \approx \pi q R \sigma_{Ch}^{-4/3}$$ - Kolmogorov length

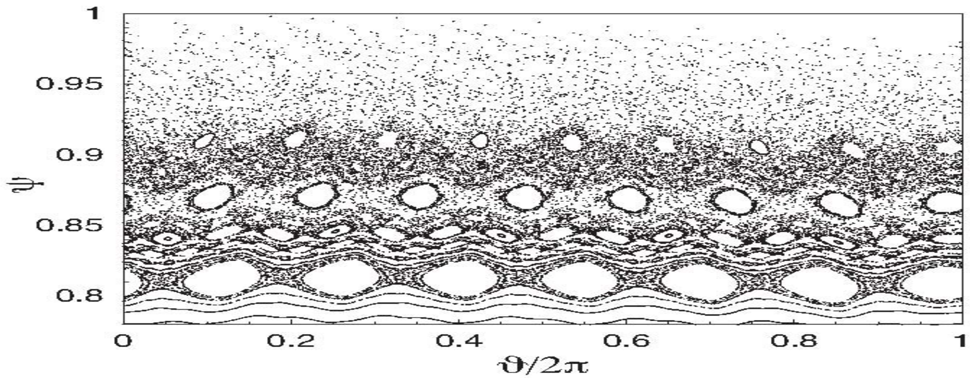
$$D_{Fl} \approx \pi q R \sum \left(B_r^{M,N} / B \right)^2$$ - Field line diffusivity

More exact characterization: solution of field line equations

$$\frac{1}{R}\frac{dr}{d\varphi} = \frac{B_r}{B_T}, \qquad \frac{r}{R}\frac{d\vartheta}{d\varphi} = \frac{B_\vartheta}{B_T}$$

by diverse approaches: field line tracing, mapping

Intersection points of field lines with poloidal plane, φ =const, provide Poincaré plots:



S. S. Abdullaev, PoP, **16 (**2009) 030701

RMP amplitude in plasma:

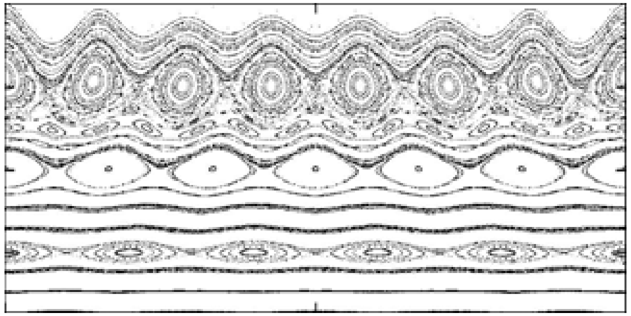
$$B_r^{M,N}(r) \propto I_{coil} \times \left(\frac{r}{a}\right)^{M-1} \times f_{scr}$$

Effect of flows in plasma close to RMS

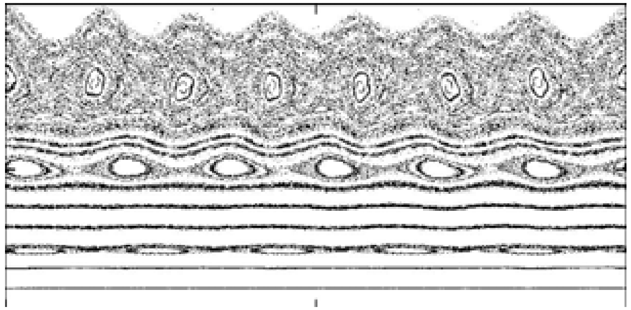
Cylindrical geometry

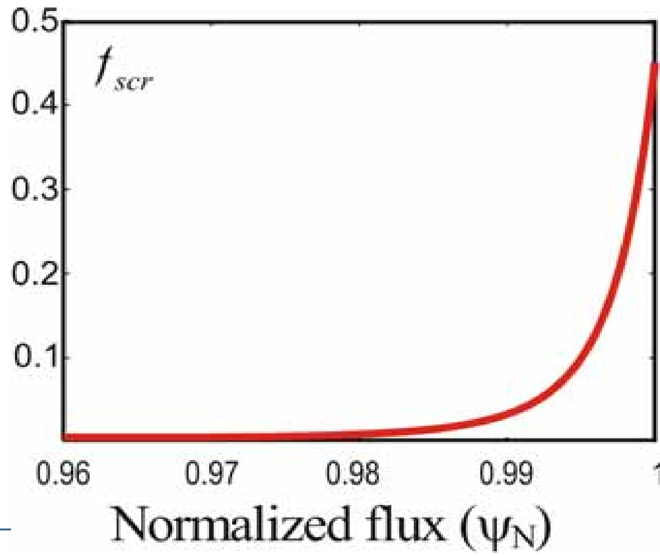
Screening effect in collisional plasma edge (TEXTOR) D.Reiser *et al*, PoP **16** (2009) 042317

Vacuum RMP



Screened RMP





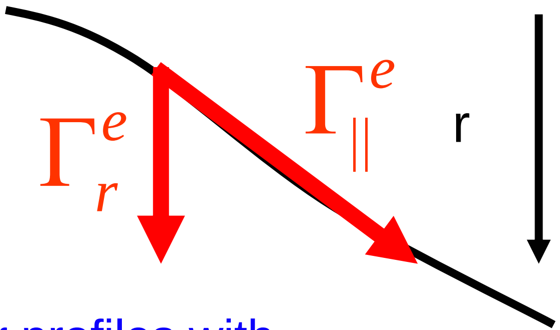
Edge Transport Barrier (ETB): diamagnetic electron rotation is of most importance

Kinetic description of RMP penetration in plasma of low collisionality
M.F.Heyn *et al*, Nucl. Fusion 48 (2008) 024005.

Effect of stochastization on particle transport (II): ion perpendicular transport

• Escape of light electrons along field lines is retarded by radial electric field:
R.W. Harvey *et al* PRL 47 (1981) 102

$$\Gamma_{\|,r}^{e} = -nV_{th,e}D_{FL}\left(\frac{\nabla_r n}{n} + \frac{1}{2}\frac{\nabla_r T_e}{T_e} + \frac{eE_r}{T_e}\right)$$



• E_r has to be positive for normally peaked plasma parameter profiles with $\nabla_r n,\ \nabla_r T_{e,i} > 0$

• Contradicts to negative E_r necessary to maintain balance of radial forces for ions:

$$enE_r = \nabla_r(nT_i) - en(V_\vartheta B_\varphi - V_\varphi B_\varphi)$$

• New equilibrium with E_r >0 is achieved if ion rotation velocity is significantly changed

Effect of stochastization on particle transport (II): ion perpendicular transport

- Deviation of V_ϑ from neoclassical value results in poloidal viscous force leading to enhanced radial drift of ions

$$\Gamma^{i}_{\perp,r} = \Gamma^{e}_{\perp,r} + \frac{q\rho_i}{R} n\left(V_\vartheta - V_{neo}\right)$$

Rozhanski V and Tendler M, 1991
Reviews of Plasma Physics Vol.19 147

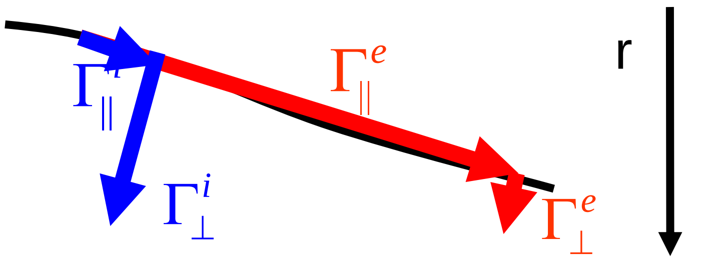
- Ambipolarity of total radial fluxes ⇒ Stochastic diffusivity:

$$D_{st} = \frac{D_i^{\perp} D_e^{\parallel}}{D_i^{\perp} + D_e^{\parallel}} \frac{T_e + T_i}{T_e}, \quad D_i^{\perp} = \frac{T_e}{eB}\frac{q\rho_i}{R}, \quad D_e^{\parallel} = D_{FL} V_{the}$$

- In ETB with T_e ~ 1 keV:

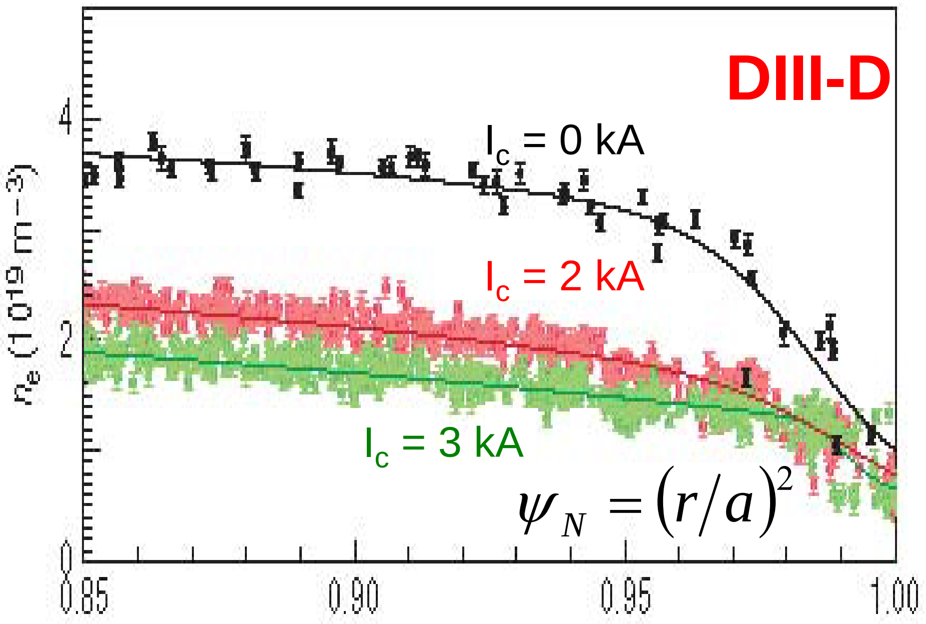
$$D_i^{\perp} \approx 1\, m^2/s \Rightarrow D_{st} \approx D_e^{\parallel} \Rightarrow \Gamma^{i}_{\perp,r} >> \Gamma^{i}_{\parallel,r}$$

- Total particle transport is comparable to free stream of electrons along field lines but ions go perpendicular!

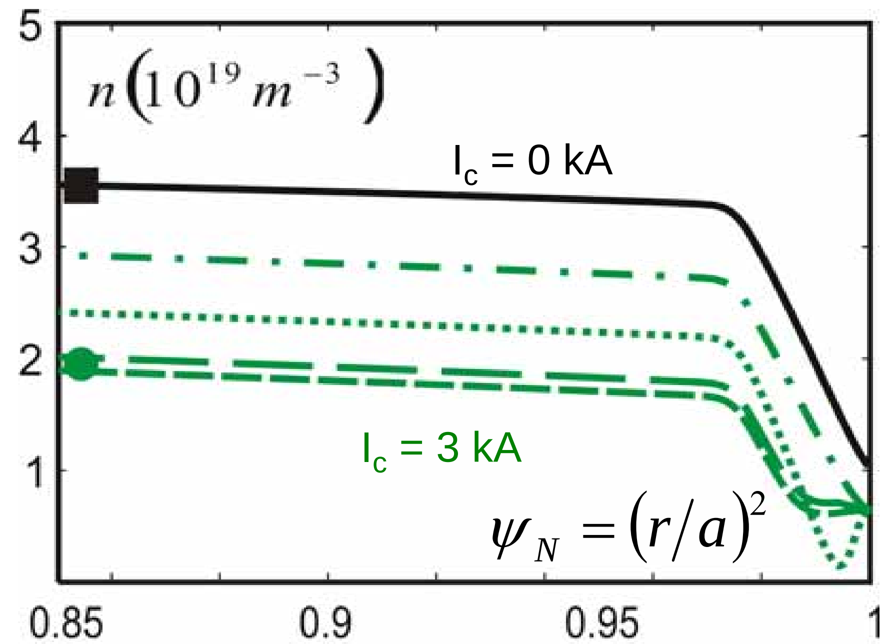


Radial density profile

Measured



Calculated with measured temperatures and RMP screening



w/o RMP

With RMP: all flux components included

with perpendicular ion flow only

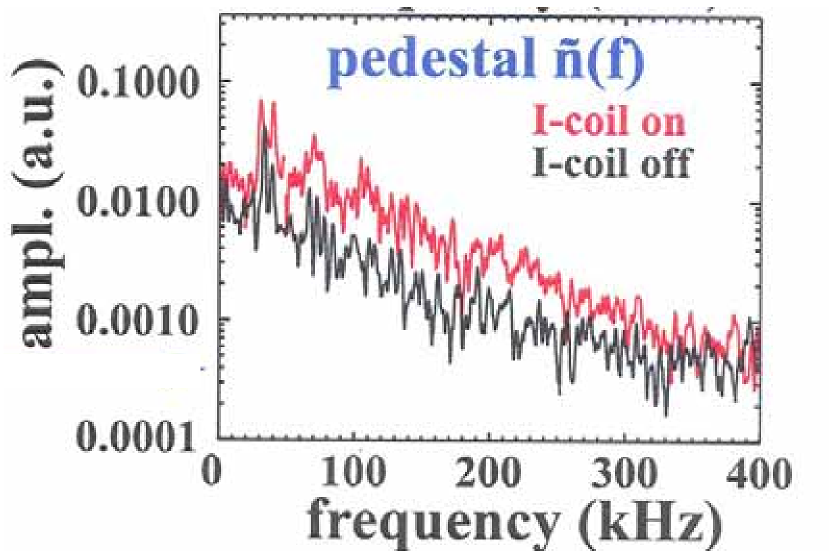
with parallel ion flow only

temperatures are modified only

M.Z.Tokar *et al*, PoP 15 (2008) 072515

Effect of stochastization on particle transport (III): increased plasma fluctuations

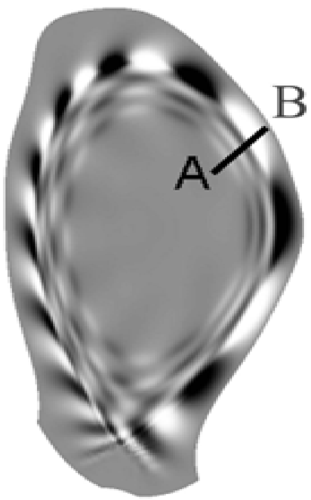
- Amplitude of density fluctuations in pedestal is increased with RMP by factor of 2
- Modelling: Necessary pump out could be achieved due to enhanced $D_\perp$ only if is increased by a factor of 40-100 over neoclassical level
- Negative consequences to heat transport have to be also seen



R.A.Moyer *et al,* 21st IAEA Fusion Energy Conference, Chengdu, 2006, EX/9-3

Effect of stochastization on particle transport (IV): convective cells

JOREK-code: perturbation in plasma induced by RMP

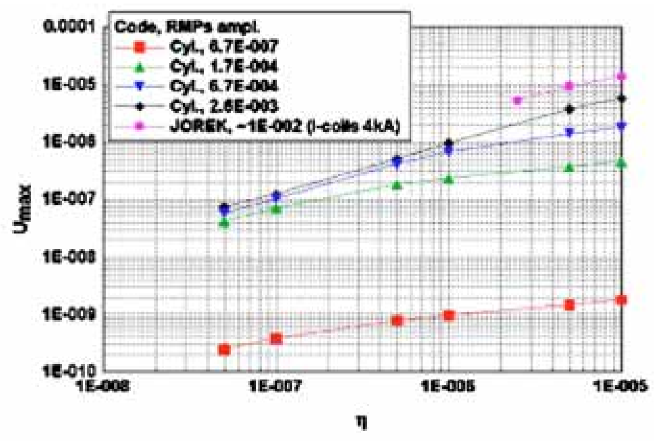


Electric potential

Plasma density

E.Nardon *et al,* PoP 14 (2007) 092501

Effect is reducing with decreasing collisionality, opposite to observations



Amplitude of electric potential vs. plasma resistivity

Heat conduction paradox

Heat flux densities:

$$q_r^{e,i} = \alpha \Gamma_r T_{e,i} - \kappa_r^{e,i} \nabla_r T_{e,i}$$

Defined by heat sources – RMP indep.

Defined by particle sources – RMP indep.?

Increased at very edge with RMP

Effective radial heat conduction are most probably reduced with RMP

$$\kappa_r^{e,i} = \frac{q_r^{e,i} - \alpha \Gamma_r T_{e,i}}{-\nabla_r T_{e,i}}$$

Rough estimate for heat conduction in stochastic field

$$\kappa_r^{e,i} \approx \kappa_\perp^{e,i} + \kappa_{st}^{e,i}, \quad \kappa_{st}^{e,i} \approx \kappa_\parallel B_r^2 / B^2$$

$\kappa_\perp$: in ETB ion neoclassical and electron anomalous perpendicular heat conductions decrease with dropping plasma density

κ^e_{st}: contribution of 50 m^2/s is expected

A.B.Rechester and M.N.Rosenbluth, PRL 40 (1978) 833

R.W.Harvey *et al*, PRL 47 (1981) 102

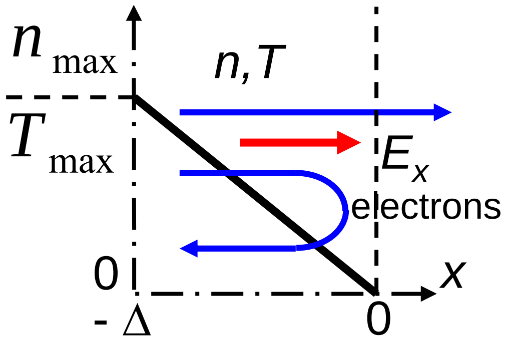
$$\kappa_{st}^e \approx nD_{FL} V_{the}$$

Heat flux limit concept: conductive heat flow along perturbed field lines is strongly reduced compared to free stream flow

$$q_\parallel^e \approx \beta n V_{the} T$$

$$0.03 \le \beta \le 0.1$$

Parallel heat flux in collisionless plasma



Electric field E_x:

- normally from $\Gamma_x(\partial_x n, \partial_x T_e, E_x) = 0$
- Γ_x - from 2nd – order correct. to Maxwell distribution f_M
- but 1st – order results in force balance:

$$0 = -\partial_x (nT_e) - enE_x$$

Moreover: in collisionless plasma distribution at x=0 is a mixture of particles from different positions with different temperatures ⇒ any expansion $f = f_M + f_1 + f_2$ is questionable ⇒ particle modeling, e.g., with XGC0 code ⇒ $\beta << 1$

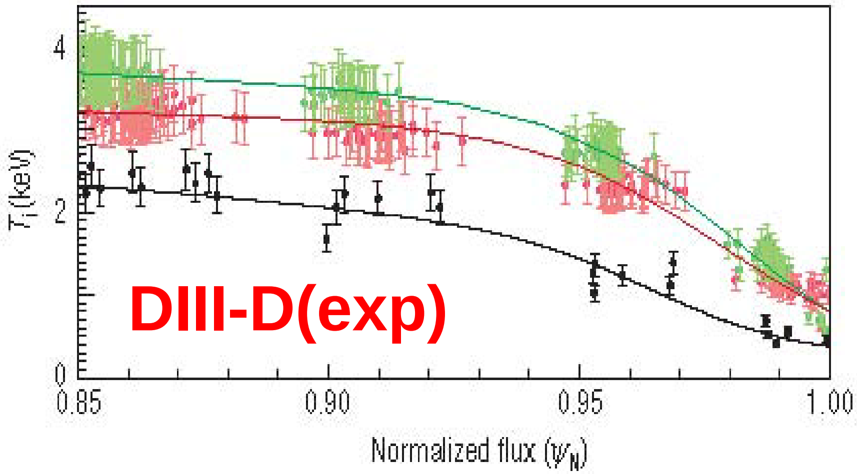
G. Park *et al*., J. Physics: Conference Series **78** (2007) 012087

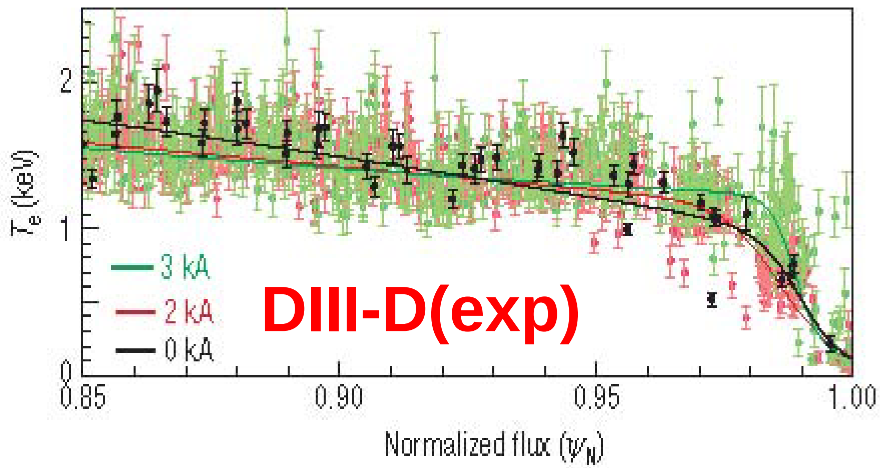
Simple estimate: plasma decay in layer $-\Delta \le x \le 0$ with initial linear profiles of n(x) and T(x)

Without E_x : $$\bar{q}_x = 0.32\, n_{max} T_{max} \sqrt{T_{max}/m_e}$$

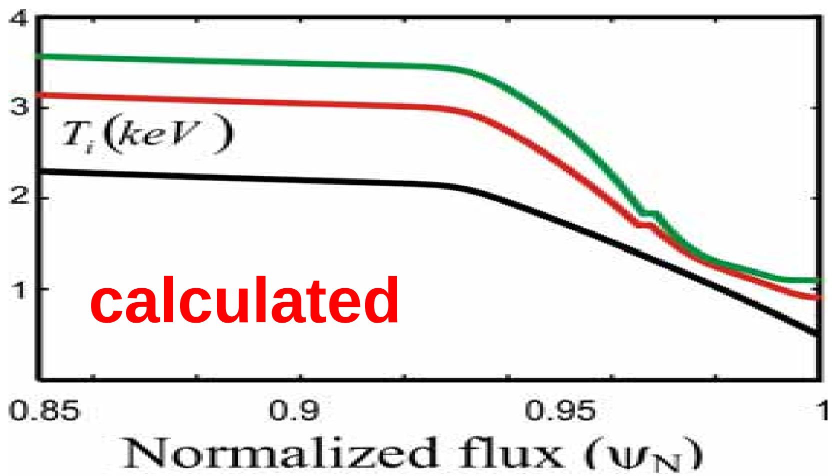
With E_x : $$\bar{q}_x = 0.034\, n_{max} T_{max} \sqrt{T_{max}/m_e}$$

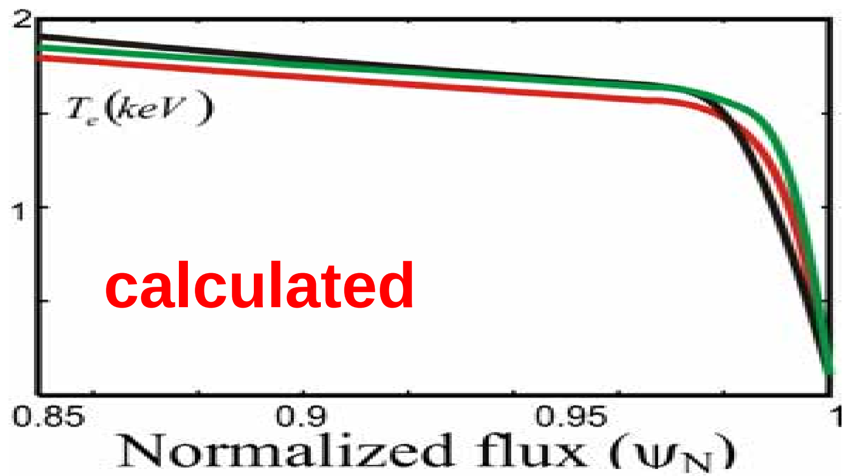
Modification of temperatures with RMP



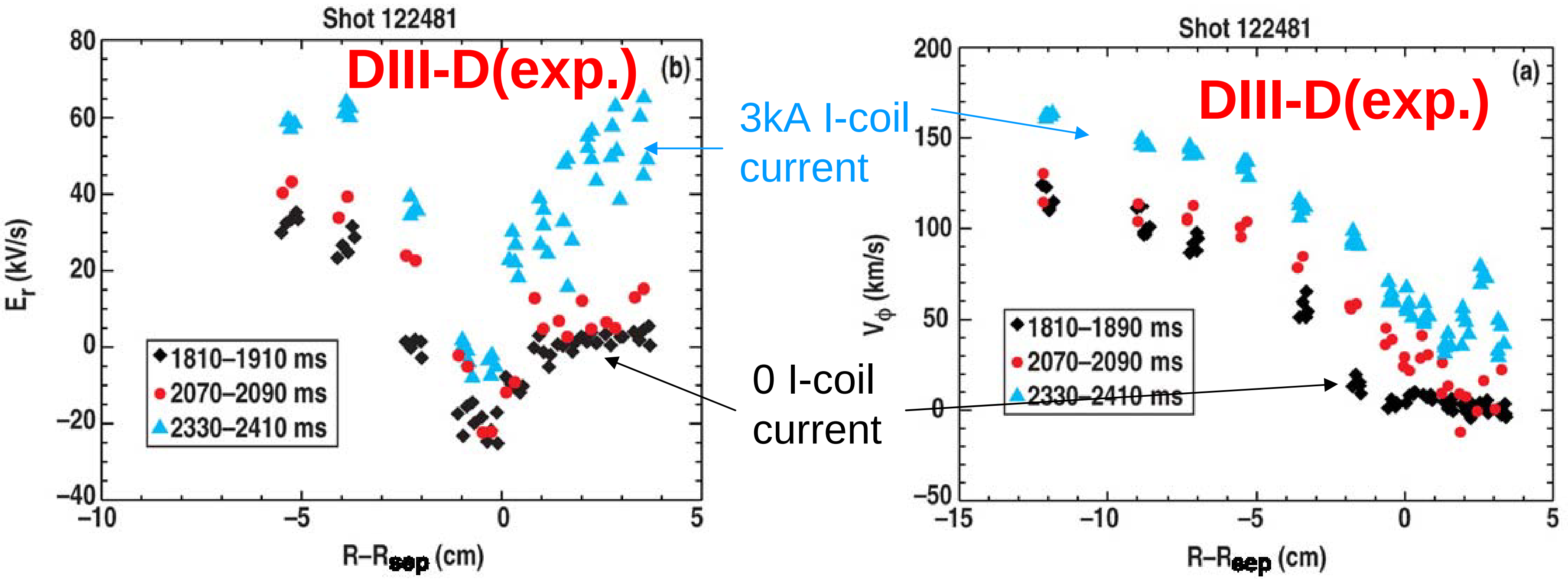


- ion neoclassical and electron anomalous perpendicular heat conductions in ETB decrease with dropping plasma density
- electron parallel heat conduction is restrained by heat flux limit





Electric field and rotation



$$E_r = E_r^{neo} \cdot \frac{D_i^{\perp}}{D_i^{\perp} + D_e^{\parallel}} + E_r^{amb} \cdot \frac{D_e^{\parallel}}{D_i^{\perp} + D_e^{\parallel}}$$

Radial ion flow in stochastic field provides Lorenz force:

$$F_L^T = e\Gamma^i_{\perp,r} B_P$$

W/o RMP: $D_e^{\parallel} = 0 \Rightarrow E_r = E_r^{neo} < 0$

With RMP: $D_e^{\parallel} > 0 \Rightarrow E_r^{amb} > 0$ contributes to E_r

which affects plasma rotation

Conclusions

- External resonant magnetic perturbations (RMP) are efficient tool for mitigation and even complete suppression of edge localized modes (ELM)

- Magnetic field stochastization produced by RMP modifies essentially transport properties in the edge transport barrier, reducing the pressure gradient below the threshold of MHD instabilities

- This happens mostly because of pump out effect leading to plasma density reduction and several mechanisms for increased particle transport have been identified: flows along perturbed field lines, perpendicular ion transport due to deviation from neoclassical equilibrium, enhancement of plasma fluctuations, convective cells

- Reduction of perpendicular heat conduction with decreased density and restrain of parallel heat losses due to heat flux limit preserve good energy confinement in ETB with RMP

- Complexity of RMP impacts on processes both in the edge and in the central plasma regions necessitates an adequate and coherent approach for understanding the physics and making predictions for ITER, as, e.g., in the CPES, EMC3-EIRENE projects