

# Уравнения переноса в упрощенном виде

$$\frac{\partial n_k}{\partial t} = -\frac{1}{r} \frac{\partial}{\partial r} \left( r(D \nabla n_k - V_{p,n} n_k) \right) + S_k$$

$$\frac{3}{2} n_k \frac{\partial T_k}{\partial t} = -\frac{1}{r} \frac{\partial}{\partial r} \left( r[(\chi_k \nabla T_k - V_{p,T} T_k) + \frac{5}{2} \Gamma_k T_k] \right) + P_k$$

$$m_k n_k \frac{dV_{t,k}}{dt} = -\frac{1}{r} \frac{\partial}{\partial r} \left( r \left[ -\chi_{t,k} \frac{\partial V_{t,k}}{\partial r} \right] \right) + M_{t,k}$$

$$\frac{\partial B_p}{\partial t} = \frac{\partial}{\partial r} \left( \frac{\sigma}{\mu_0 r} \frac{\partial (r B_p)}{\partial r} \right) - \frac{\partial}{\partial r} (\sigma J_b)$$

Неоклассический эффект

$$\left. \begin{array}{l} \chi_k \\ \chi_t \\ D \\ V_p \\ \sigma \end{array} \right\} = \text{Par}_{\text{neo}} + \text{Par}_{\text{turb}} + \text{Par}_{\text{MHD}}$$

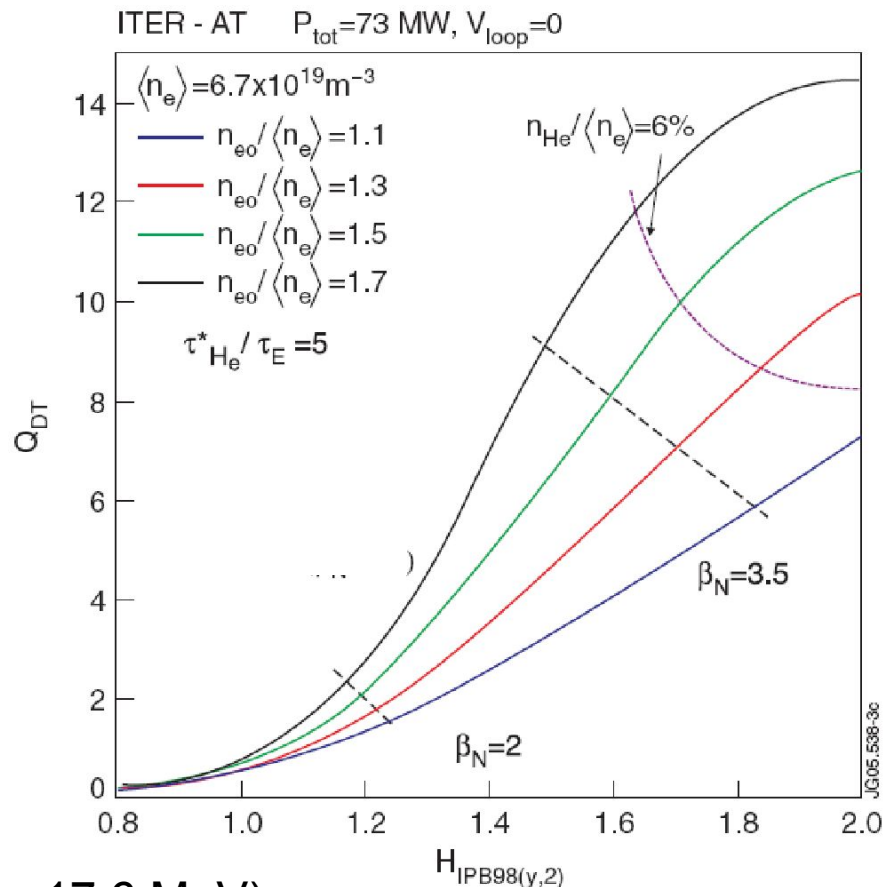
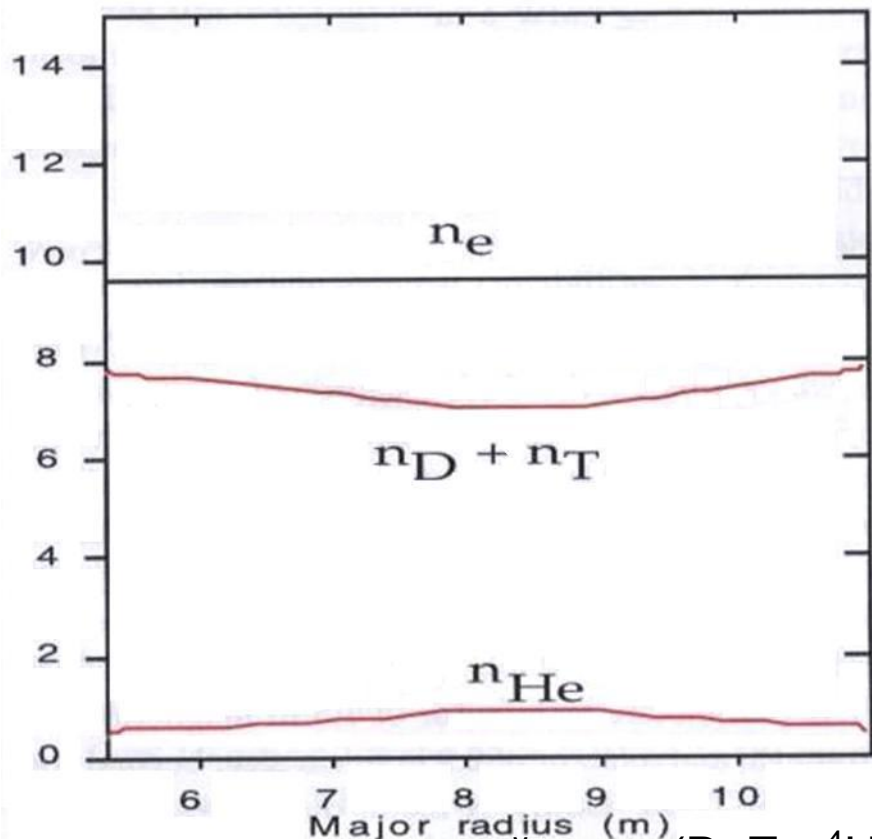
$$\sigma = \sigma_{\text{neo}}$$

# Исследование процессов переноса

- ❖ **Механизм? – Прогноз для реактора (какой профиль можно получить, как и чем определяется эволюция )  
– управление профилем**
- ❖ **Глобальные характеристики; локальные параметры**
- ❖ **Методы:**
  - **анализ с помощью транспортных кодов (анализ баланса тепла/частиц)**
  - **анализ распространения малого возмущения**

# Транспорт частиц

- описание результатов имеющихся экспериментов
- предсказания для ИТЭР, DEMO

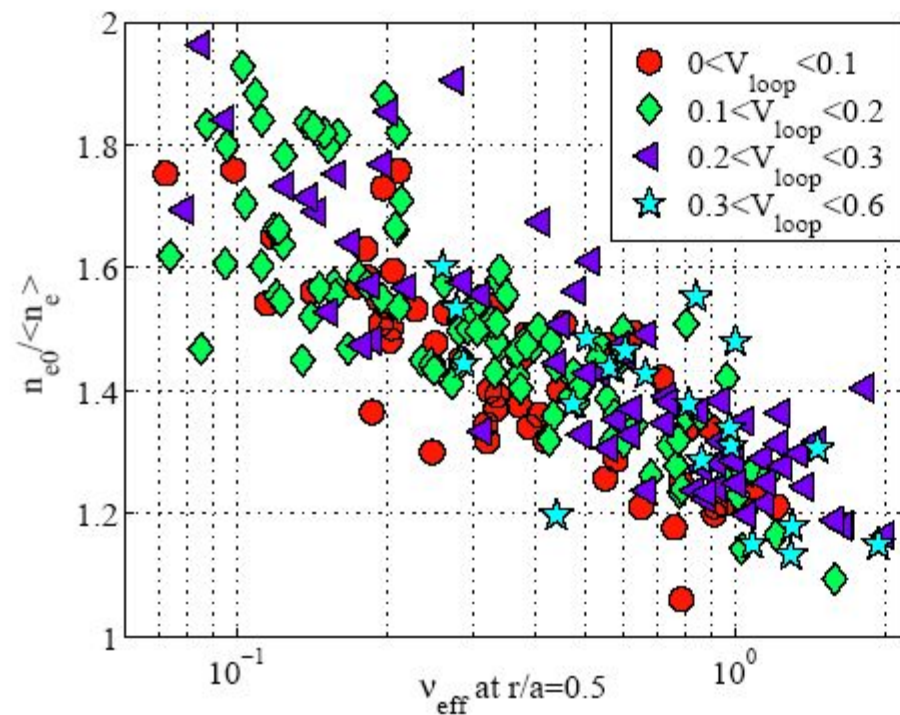


- удаление гелиевой золы ( $D+T \rightarrow {}^4\text{He}+n+17.6 \text{ MeV}$ )
- управление профилями плотности основной плазмы, примесей (включая подпитку топливом)
- поведение трития

# H-мода JET с NBI

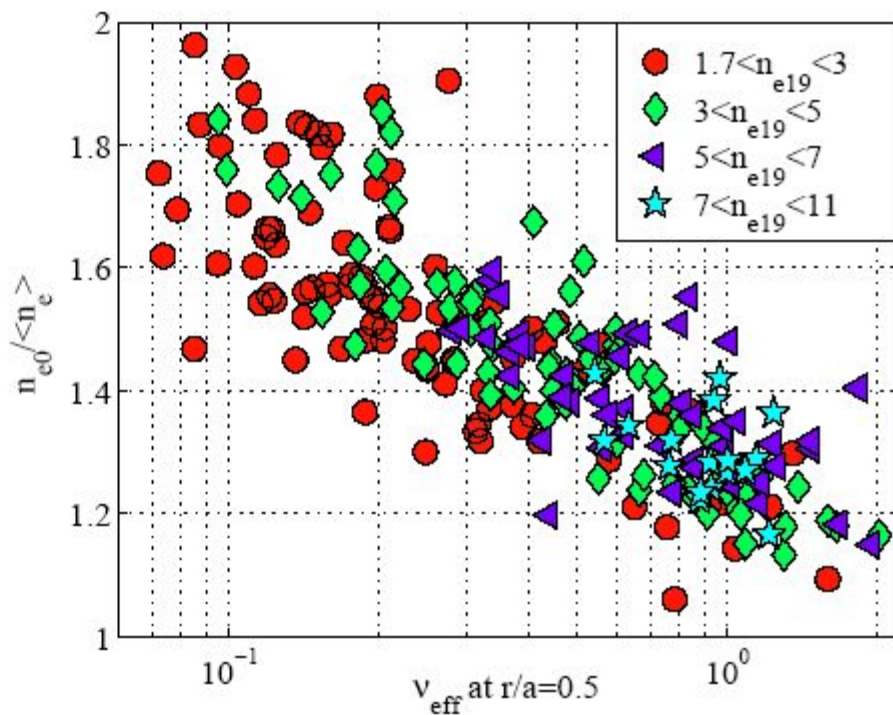
- No dependence on  $V_{loop}$
- Lowest  $V_{loop}$  found at low  $v_{eff}$  when peaking is highest:

**Ware pinch does not determine peaking**



- No dependence on  $\langle n_e \rangle$ , hence not on mean free path of beam and edge neutrals:

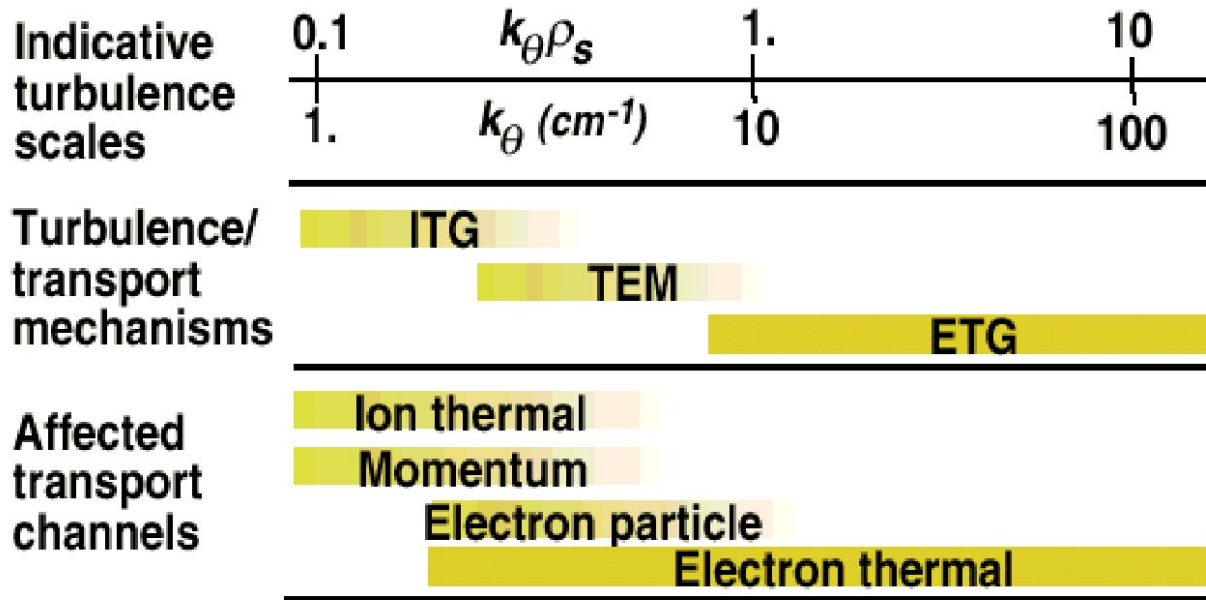
**Fuelling does not determine peaking**



# Методы исследования

1. Импульсный напуск газа
2. Инжекция тестовой пеллеты (основного иона, иона примеси)
3. Laser Blow-off – инжекция материала в плазму с периферии за счет распыления импульсом лазера
4. Ввод малой добавки вещества (третий) с помощью пучка (NBI)
5. Анализ баланса частиц

# Кандидатные механизмы



$$\text{ITG} : \left( -R \frac{\nabla T_i}{T_i} \right)_{\text{crit}} = f \left( -R \frac{\nabla n_e}{n_e}, T_e / T_i, s, \dots \right)$$

$$\text{TEM} : \left( -R \frac{\nabla T_e}{T_e} \right)_{\text{crit}} = f \left( -R \frac{\nabla n_e}{n_e}, f_t, \dots \right)$$

$$\text{ETG} : \left( -R \frac{\nabla T_e}{T_e} \right)_{\text{crit}} = f \left( -R \frac{\nabla n_e}{n_e}, T_e / T_i, s, \dots \right)$$

# Разделение на ионные и электронные моды – идеализация, справедливая для некоторых режимов

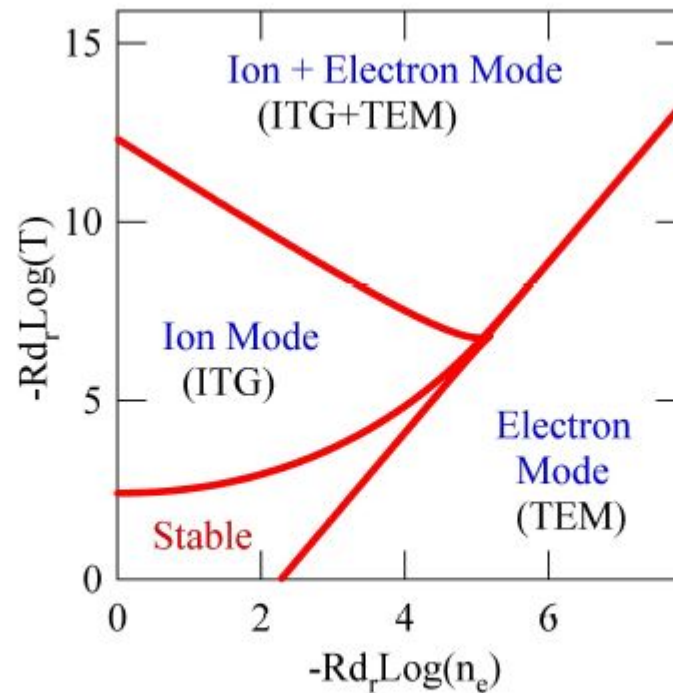


Figure 1: Stability diagram of ITG/TEM modes. Electron and ion temperatures are equal.



# Транспорт частиц основной плазмы

General model for particle flux:

$$\Gamma = -Dn \left[ \nabla n/n + C_q \nabla q/q - C_T \nabla T_e/T_e \right] + V_{neo} n$$

↓ Anomalous diffusion
↓ Equi-Partition pinch
↓ Thermodiffusion pinch (curvature)
collisional transport

V<sub>neo</sub>n  
 ↓  
 Neoclassical pinch - V<sub>Ware</sub> (∝ E<sub>φ</sub>)

Complex coupling q, T<sub>e</sub> and E<sub>φ</sub> in inductive plasmas  
→ difficult to discriminate among these effects

Ideal conditions now met in Tore Supra plasmas

- ✓ **No central fuelling** (RF heating), Γ=0
- ✓ **V<sub>Ware</sub> completely suppressed over 6 min.** (80-100x resistive time).

V<sub>neo</sub> ~ 0, hence:  $\nabla n/n = - C_q \nabla q/q + C_T \nabla T_e/T_e$

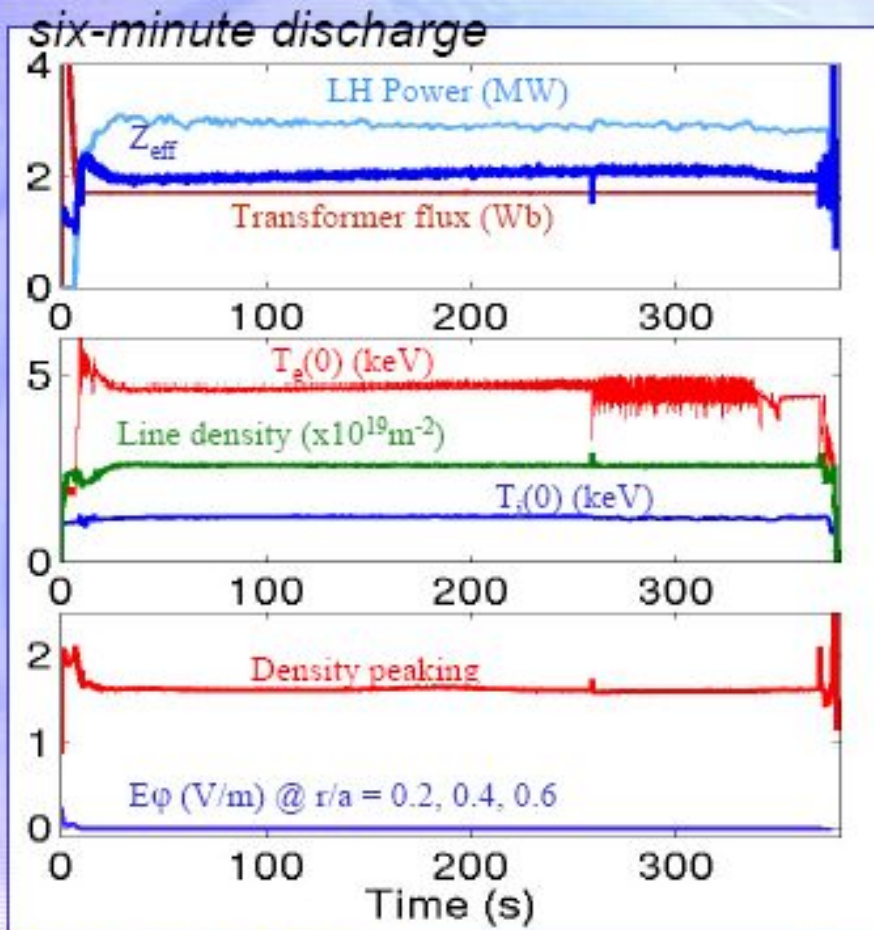
- ✓ Accurate density profiles provided by powerful reflectometry

*See R. Sabot EX/P6-25*

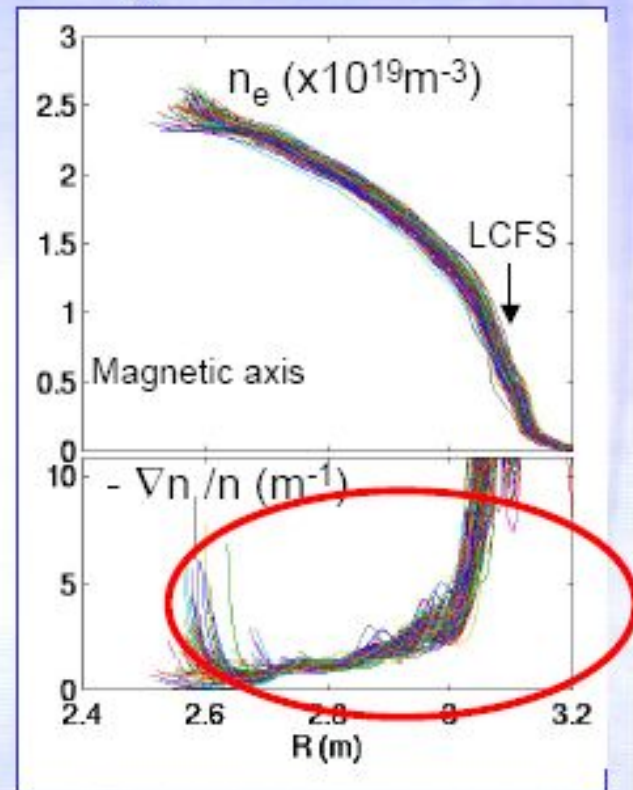




# 1. Пикированный профиль плотности в отсутствие Вееровского пинча и источника частиц в центре



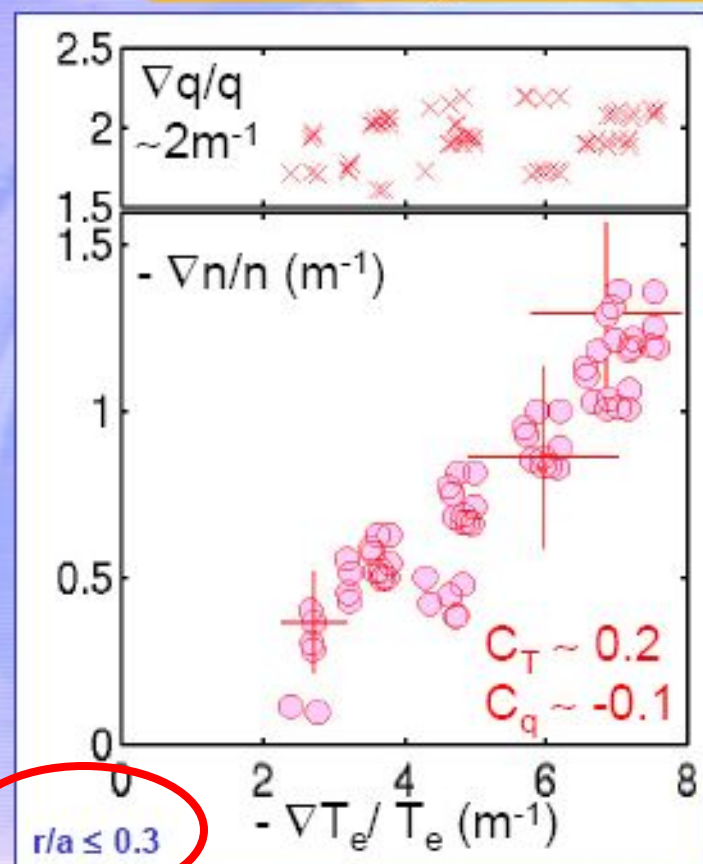
Radial  $n_e$  profiles from 40 – 350s



Inward pinch  $\gg V_{neo}$   
 $V/D = -\nabla n/n \sim 1(m^{-1})$   
 In the gradient region

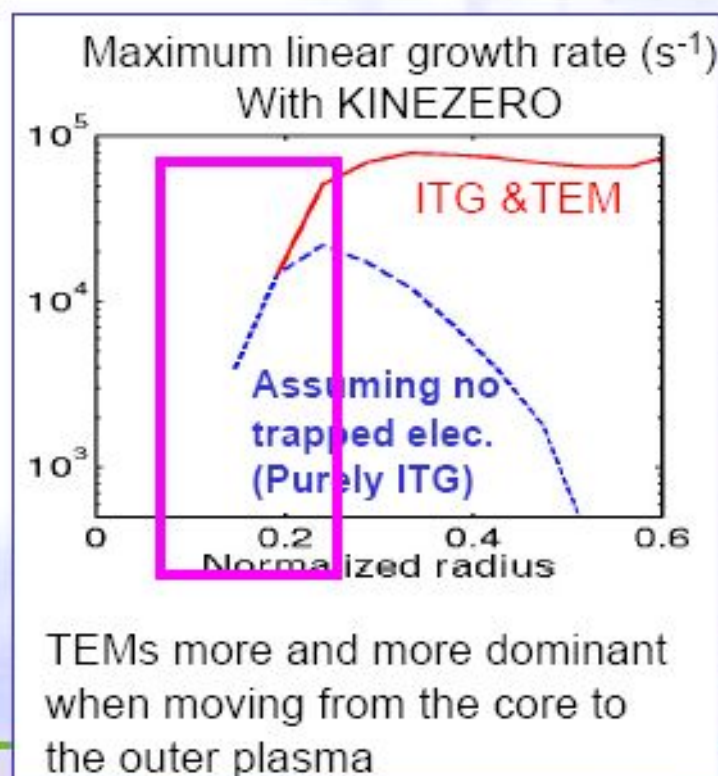
- See D. van Houtte, *pc*
1. Long discharge and peaked profile
  2. No ware
  3. No source

# Density peaking increases when increasing $T_e$ gradient in the plasma center

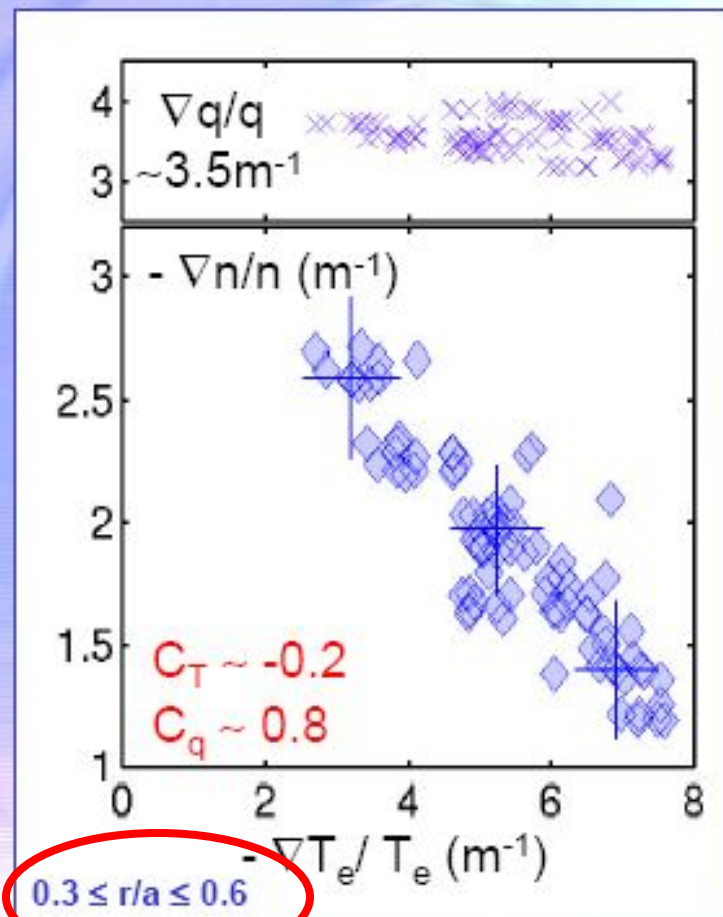


From a set of 7 discharges  
 @ various  $T_e$  ( $T_e(0) = 4\text{-}8\text{keV}$ ), and  $q$   
 ( $q_{\text{edge}} = 8.9\text{-}14$ ), in condition  
 $\nabla n/n = -C_q \nabla q/q + C_T \nabla T_e/T_e$

**Inward thermodiffusion** pinch  
 correlated with pure **ITG** unstable  
 modes, as predicted turbulent  
 simulations Garbet PRL **91**, 035001 (2003)

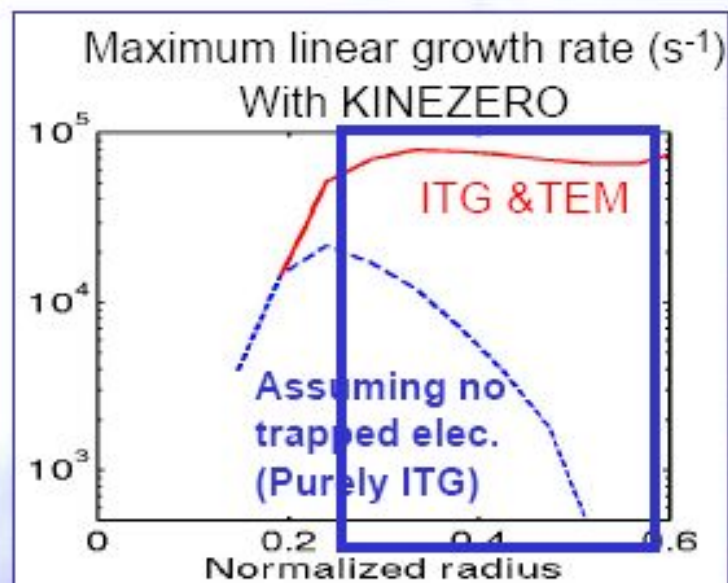


# Density peaking decreases when increasing $T_e$ gradient in the gradient region



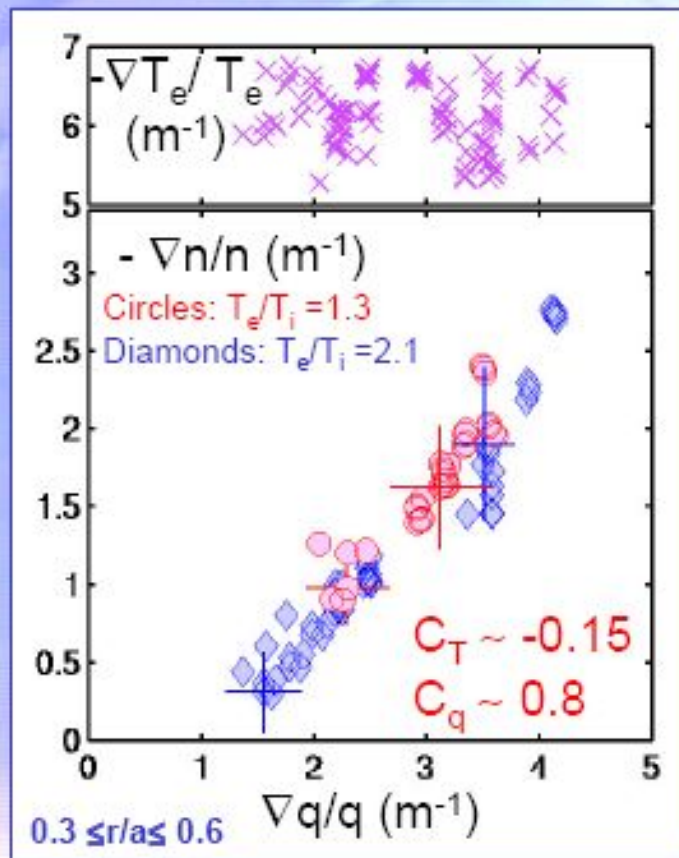
Outward thermodiffusion pinch (weaker than curvature pinch), correlated with dominant TEM as predicted by Garbet's simulations

PRL **91**, 035001 (2003)



TEMs more and more dominant when moving from the core to

# Density peaking increases with magnetic field shear in the gradient region



Similar observation at JET & TCV  
 [H. Weisen, PPCF 46 (2004) 751]

**Dominant inward curvature**  
 pinch correlated with dominant  
**TEM**, consistent with  
 turbulence simulations  
**If curvature pinch dominant**  
 not if thermodiffusion  
**dominant!!!!!!**

e.g., X. Garbet, PRL 91 (2003);  
 C. Angioni, Phys. Plasmas 10 (2003)

08:15

# Density peaking varies with q-profile

Slightly under estimated using  
Isichenko's formula based on  
ITGs

$$\frac{n(r)}{n(0)} = 1 - \frac{1}{R_0} \int_0^r \left( \frac{1}{2} + \frac{4}{3} r \frac{\nabla q}{q} \right) dr$$

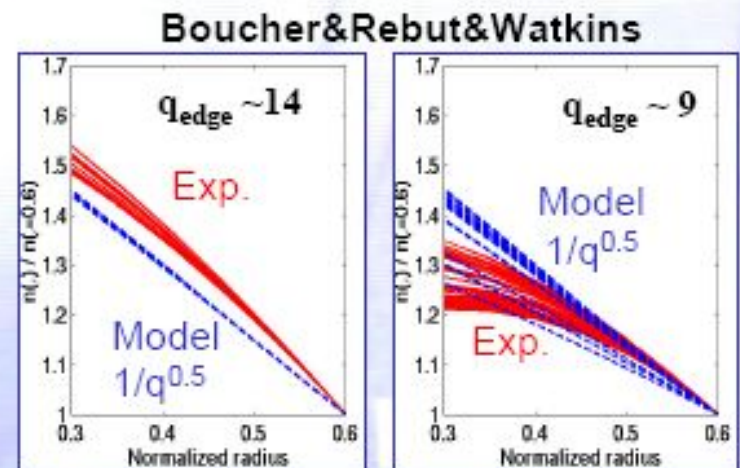
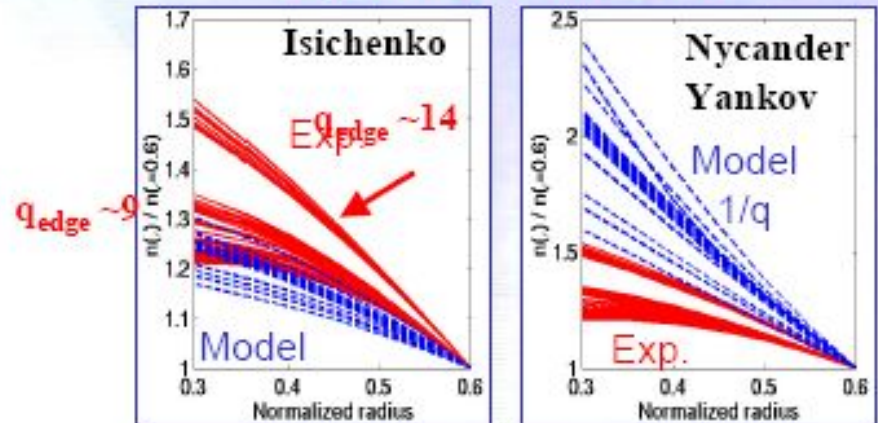
(fits TFTR L-mode) *PRL* **74**, 1995

Over estimated by model 1/q  
(fits TFTR supershots) *PoP* **2** 1995

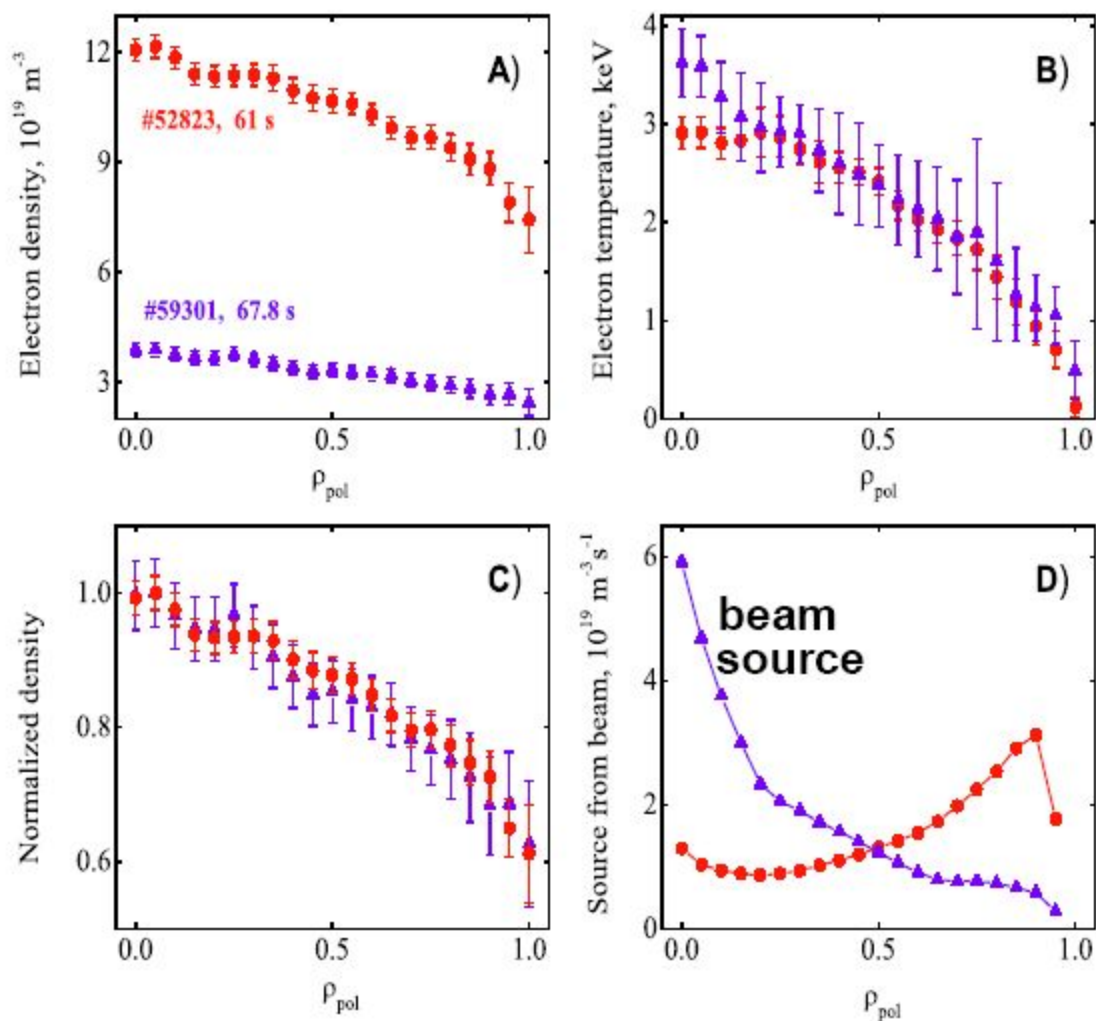
Empirical model,  $n \sim 1/q^{0.5}$ ,  
reproduces **better** experiments  
also fits JET and ITER database

*CR Acad. Sci. T315, Ser. II, 273 (92)*

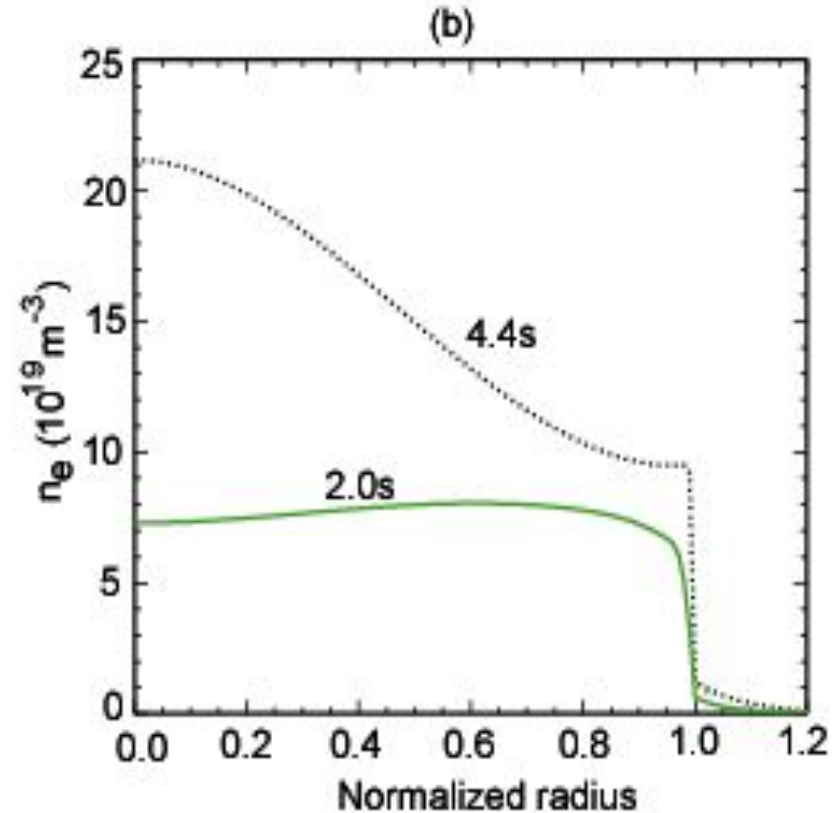
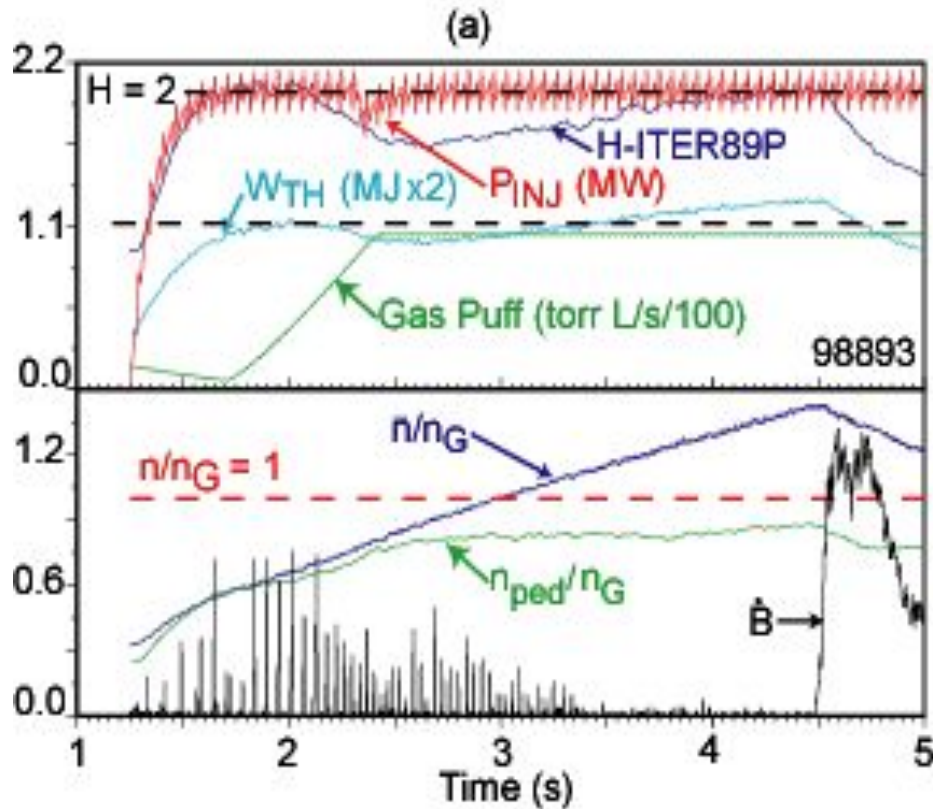
Normalized profile to the value @  $r/a = 0.6$   
**50 profiles from 10 shots.**



Very different neutral transparencies, same profile shapes,  
same collisionality ( $n_e Z_{\text{eff}}$  is  $\sim$ same)



# Влияние пикирования плотности на удержание



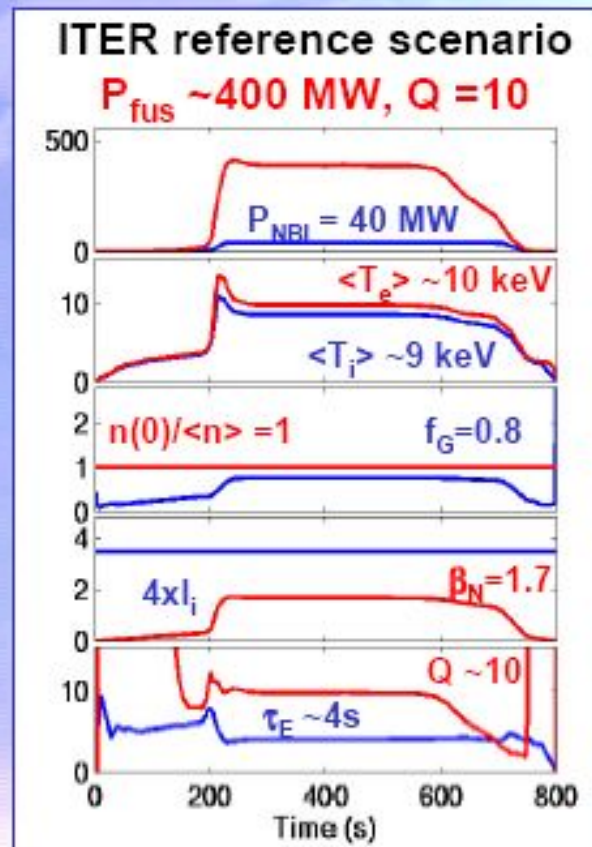
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ИТЭР - ?

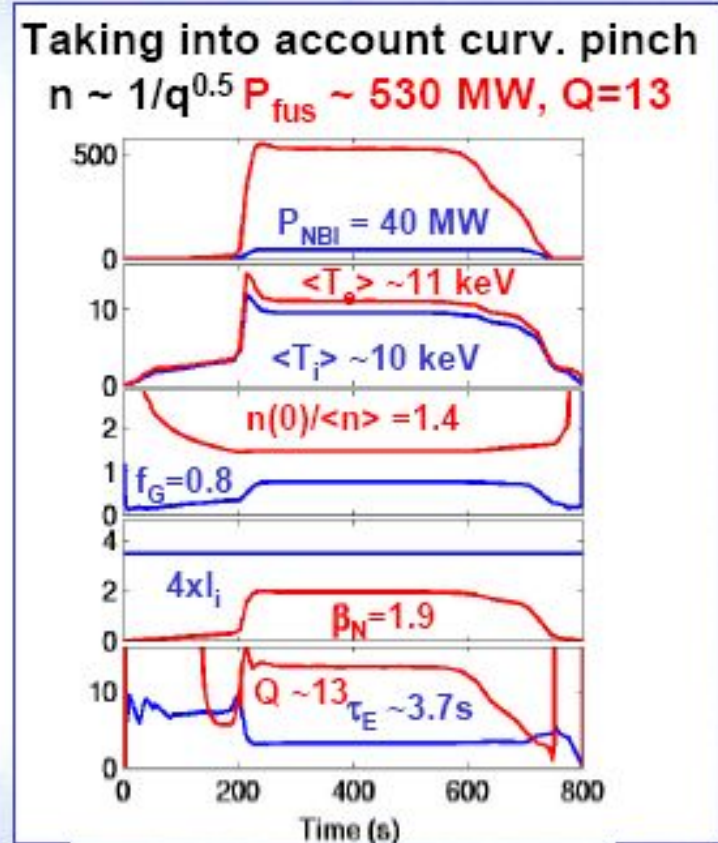
Правильность подхода - ?

# Possible gain of 30% in fusion power on ITER taking into account curvature pinch

Simulation with 0D module of *CRONOS*



Simulation performed in a consistent manner using 0D scaling laws, namely ITERH-98P(y,2)



No Impurity transport. But, scalings include an increase of  $Z_{\text{eff}}$  (1.5 to 1.7)



# Глобальные характеристики удержания частиц

- Время жизни частиц

$$\tau_p = \frac{N}{\Gamma - \frac{dN}{dt}}$$

$$\tau_p^* = \frac{\tau_p}{(1 - R_{\text{eff}})}$$

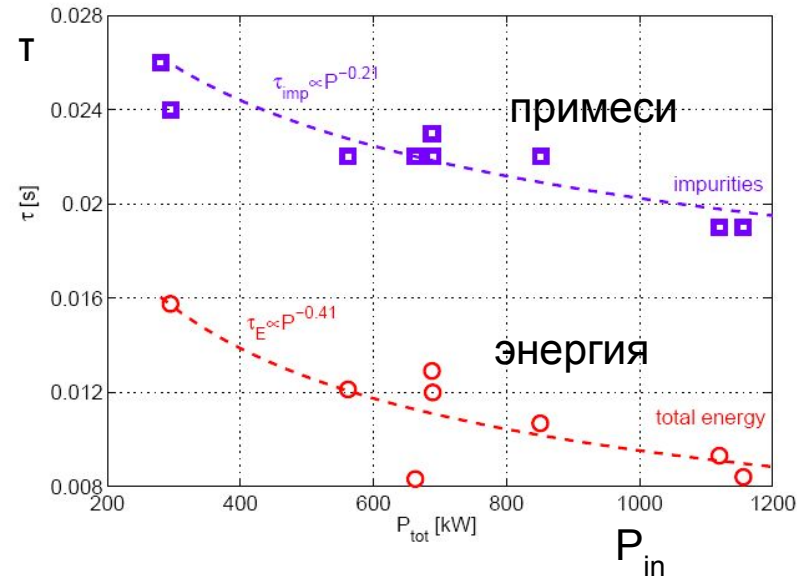
$$\tau_{\text{imp}} = 0.75 a R^{3/4} \frac{Z_{\text{eff}} M_{\text{bg}}}{q Z_{\text{bg}}} -$$

$$\tau_{\text{imp}} = 0.4 \mu L^{0.7} I^{0.31} \left( \frac{P_{\text{int}}}{n_e} \right)^{-0.57} -$$

# Сравнение транспорта ионов основной компоненты и примесей с переносом энергии

- Some transport models (RITM, JETTO) assume fixed relationships, such as  $\chi_e = \chi_i = D_e = D_i = D_z$
- However experimental ratios  $\tau_z/\tau_E$  and  $D/\chi$  vary widely in published literature and can depend on discharge conditions such as power and plasma shape.
- Example: Impurities can experience power degradation more or less strongly. Dependent on heating method & electron-ion coupling?

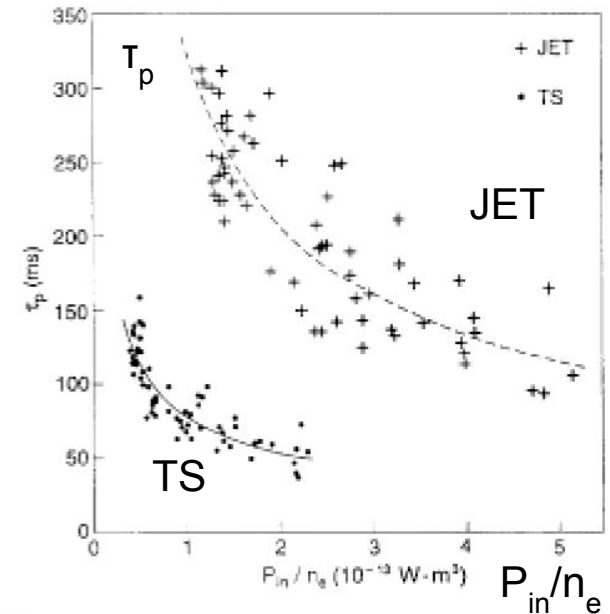
Scavino et al, subm. PPCF 2004



← TCV:  
 Si from LBO with  
 ECH, L-mode  
 $\tau_E < \tau_Z \propto P^{-0.2}$

JET, TS →  
 High Z with RF,  
 NBI, LH, L-mode  
 $0.4 \tau_E \sim \tau_Z \propto P^{-0.6}$

Mattioli et al, NF 35 (1995) 1115



Message: No picture of systematic behaviour so far.

# Неоклассический эффект – накопление примесей

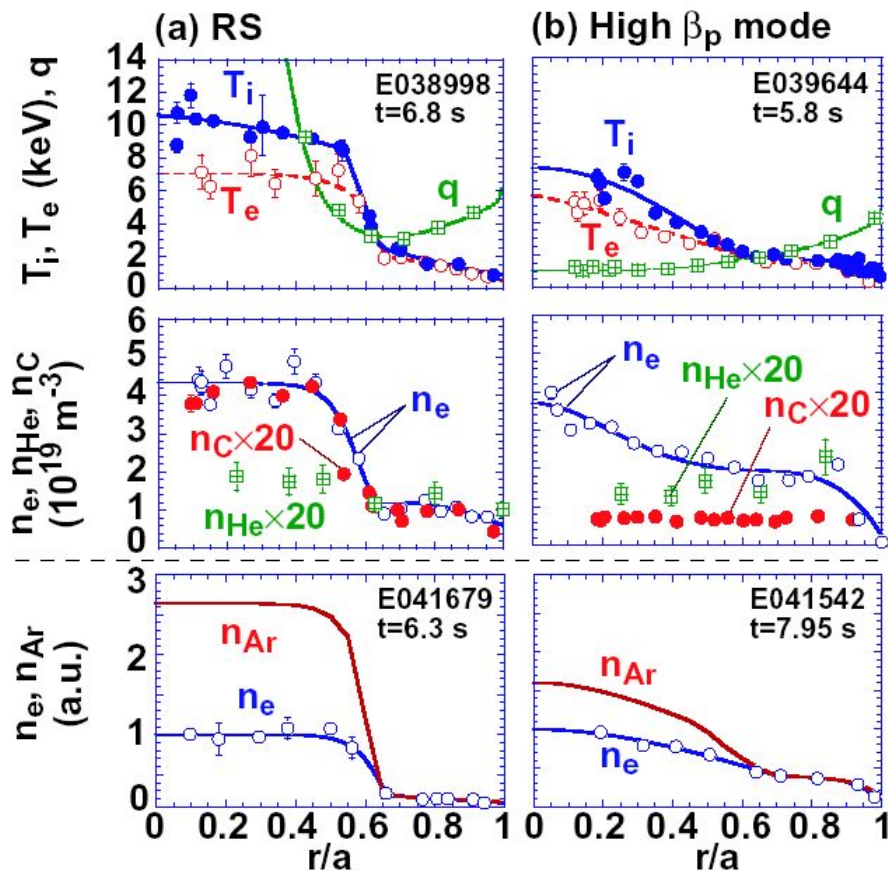
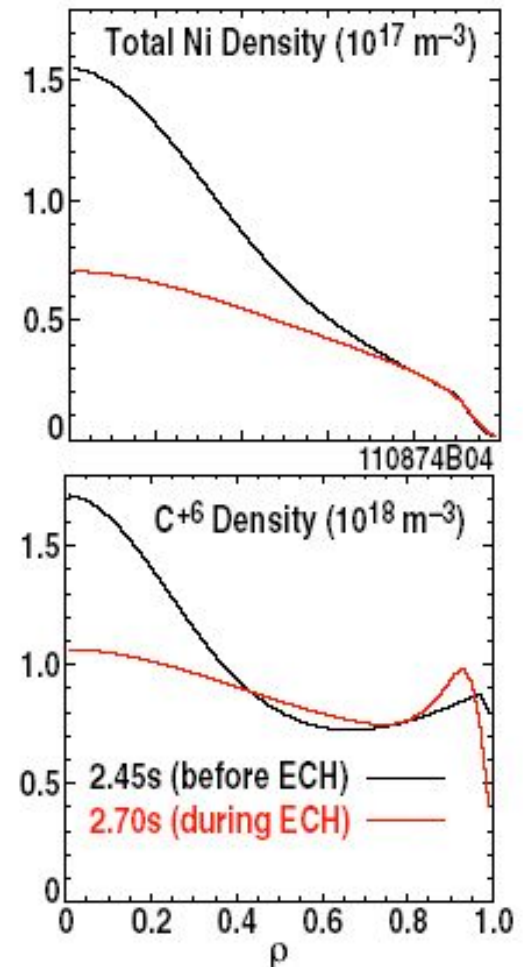
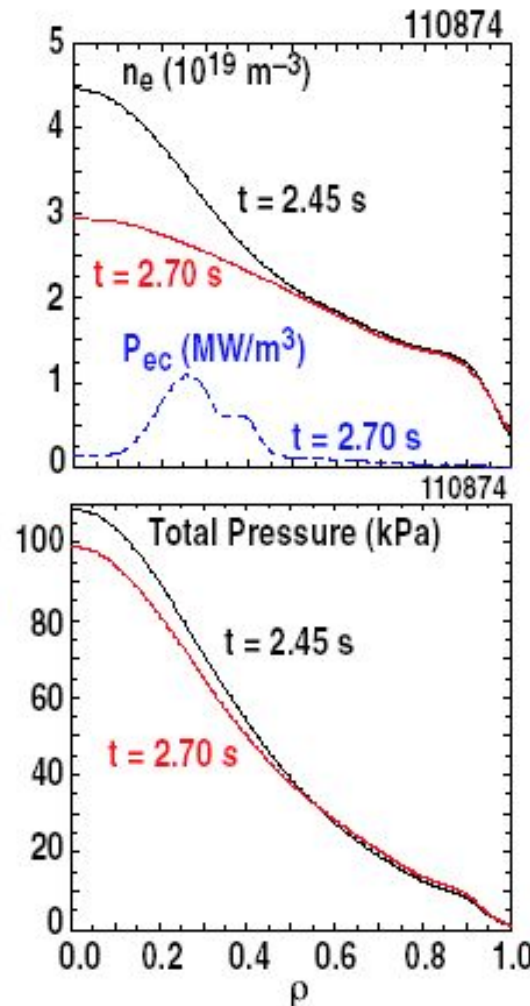


Fig. 1 Profiles of temperatures, safety factor, and densities of electrons, He, C and Ar in (a) RS and (b) high  $\beta_p$  mode plasmas. In the bottom figures,  $n_e(r)$  is normalized at  $r/a=0$  and  $n_{Ar}(r)$  is adjusted to  $n_e(r)$  outside the ITB.

# Управление поведением примесей

## DENSITY AND IMPURITY PROFILES MODIFIED WITH ECH AND ECCD IN QUIESCENT DOUBLE BARRIER PLASMAS

- EC power applied near  $\rho = 0.2$  in plasma with core transport barrier already formed
- Density peaking reduced, leading to much reduced central impurity densities and factor 1.3 reduction in  $Z_{\text{eff}}$
- More information in E.J. Doyle, et al., EX/C3-2



# Управление поведением примесей- II

JT-60U

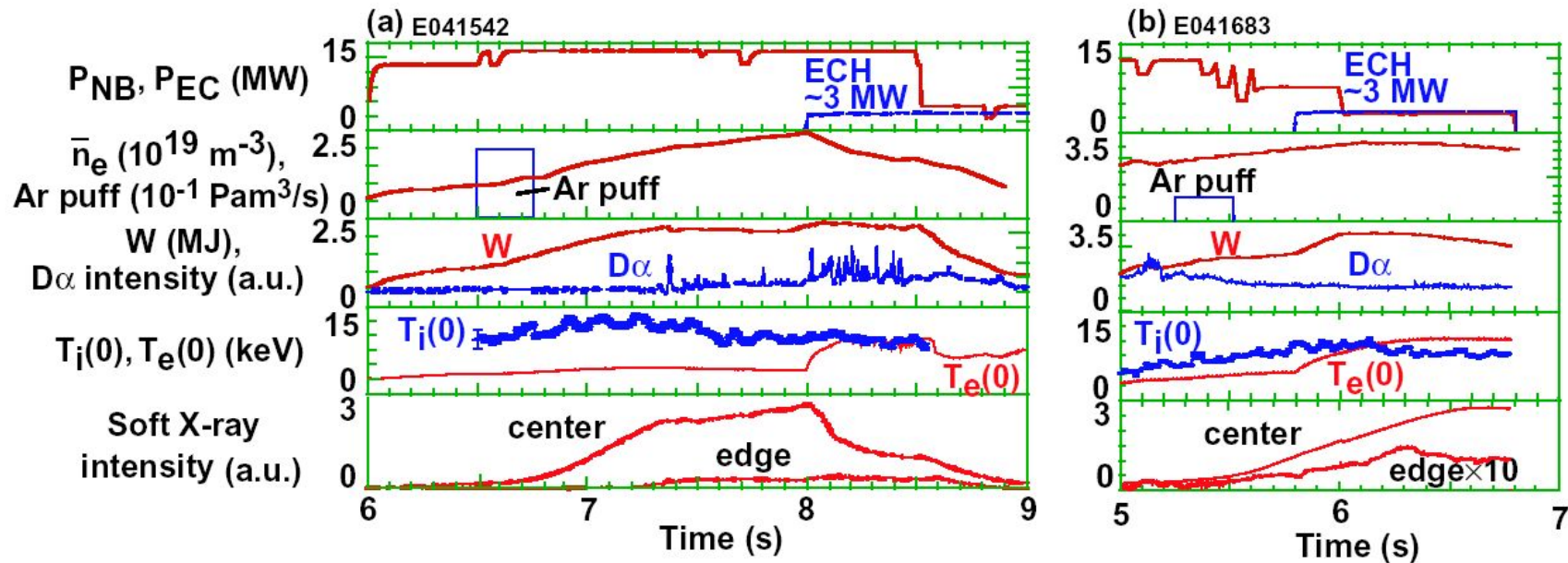


Fig. 4 Wave-forms in (a) high  $\beta_p$  mode and (b) RS plasmas with central ECH and Ar puffing.

# Уплотнение профиля плотности при доминирующем электронном нагреве

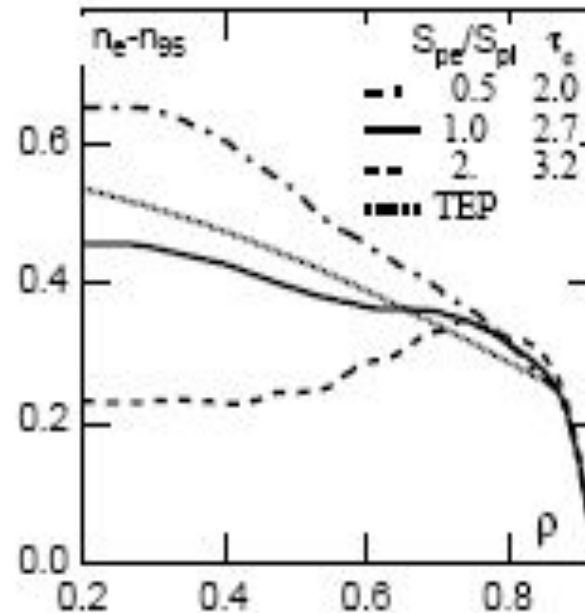


Fig.2: Density profiles when varying the ratio of electron to ion heating  $S_{pe}/S_{pi}=0.5, 1$  and  $2$ .

The corresponding values of  $\tau_e = \sqrt{V}T_e/\sqrt{V}T_i$  at  $r/a=0.5$  are indicated [14].

# Бомовская диффузия

1. 'Bohm diffusion' causes the electrons to diffuse perpendicularly to the magnetic field lines. However, its origin is not yet completely understood: low and high frequency electric field fluctuations are both named to cause Bohm diffusion.

E Bultinck *et al* 2010 *J. Phys. D: Appl. Phys.* **43** 292001

## 2. Wikipedia:

Классическая диффузия максимальна, если  $v_{ei} = \omega_c$

$$D = \lambda^2 / \tau = \rho^2 \omega_c = (v_{th} / \omega_c)^2 \omega_c = v_{th}^2 / \omega_c$$

$$v_{th} = (kT/m)^{1/2}$$

$$\omega_c = eH/mc$$

$$D = \frac{kT}{m} \frac{mc}{eH} = c \frac{kT}{eH}$$

$$D_B = \frac{c}{16} \frac{kT}{eH}$$

# Бомовская диффузия

## 3. С.Ю. Лукьянов, Н.Г. Ковальский Горячая плазма и УТС

Редкая замагниченная плазма

Вихрь с пространственным масштабом  $L$  :  $e\phi \sim kT \Rightarrow E \sim \phi/L$

Дрейф плазмы и вихря на длине  $L$ :

$$u = cE/B$$

$t = L/u$  – среднее время пробега вихря

Тогда  $D_{\text{turb}} \sim L^2/t$

$$D_{\text{turb}} \sim Lu \sim \frac{kT}{eEL} \frac{cE}{B} \sim c \frac{kT}{eLB}$$

## 4. К. Миямото Основы физики плазмы и управляемого синтеза

Коэффициент аномальной диффузии, обусловленный флуктуационными потерями – дрейф в скрещенных магнитном поле и флуктуирующем электрическом поле

$$D_{\text{turb}} = \left( \sum_k \frac{k_y}{k_n} A_k \sin \alpha_k \left| \frac{\mathbf{n}_k}{\mathbf{n}_0} \right|^2 \right) \frac{kT_e}{eB}$$

$$\max(\dots) = 1/16$$