Transport codes for magnetic fusion: ASTRA (overview of applications)

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OUTLINE

- **Objectives and key elements of integrated scenario modelling for tokamaks**

- **Core transport modelling: transport equations and numerical tools**

- **Physics applications: ASTRA**

  - interpretative analysis

  - validation of transport models

  - scenario development

  - plasma control

  - beyond core modelling: integrated core-SOL-divertor simulations

- **Summary, perspectives and open issues**

Objectives of transport modelling

- **Interpretation of existing experiments**
- **Development of empirical models based on experimental observation**
- **Validation of theory-based models – link between experiments and theory**
- **Prediction of future experiments on existing tokamaks and optimisation of operational scenarios in modelling**
- **Prediction for future devices (ITER, DEMO, JT60-SA …)**

Integrated scenario modelling: key physics processes

- **Energy, particle and momentum transport: interaction of charged particles with micro-turbulence, test particles in stochastic magnetic fields, …**
- **MHD events: sawteeth, NTMs, fishbones, ELMs**
- **RF heating and current drive: plasma-wave interaction, fast particle physics**
- **Neutral beam injection, gas puff, pellets: plasma-neutral interaction, atomic physics, fast ion physics**
- **Plasma equilibrium and shape control**
- **Divertor and SOL physics**
- **Impurity and radiation**

Multi-scale time and space, highly non-linear coupling between different processes

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Braginskii (reduced) transport equations

- Based on integration of kinetic equation
- Maxwellian distribution functions with small perturbations

$$\frac{1}{V'}\left(\frac{\partial}{\partial t}-\frac{\dot{B}_0}{2B_0}\frac{\partial}{\partial \rho}\rho\right)(V'n_e)+\frac{1}{V'}\frac{\partial}{\partial \rho}\Gamma_e=$$ **particle sources and sinks**

$$\frac{3}{2}(V')^{-5/3}\left(\frac{\partial}{\partial t}-\frac{\dot{B}_0}{2B_0}\frac{\partial}{\partial \rho}\rho\right)\left[(V')^{5/3}n_eT_e\right]+\frac{1}{V'}\frac{\partial}{\partial \rho}\left(q_e+\frac{5}{2}T_e\Gamma_e\right)=$$ **electron heating (including waves) & heat losses**

$$\frac{3}{2}(V')^{-5/3}\left(\frac{\partial}{\partial t}-\frac{\dot{B}_0}{2B_0}\frac{\partial}{\partial \rho}\rho\right)\left[(V')^{5/3}n_iT_i\right]+\frac{1}{V'}\frac{\partial}{\partial \rho}\left(q_i+\frac{5}{2}T_i\Gamma_i\right)=$$ **ion heating (including waves) & heat losses**

$$\sigma_{\parallel}\left(\frac{\partial \psi}{\partial t}-\frac{\rho\dot{B}_0}{2B_0}\frac{\partial \psi}{\partial \rho}\right)=\frac{J^2R_0}{\mu_0\rho}\frac{\partial}{\partial \rho}\left(\frac{G_2}{J}\frac{\partial \psi}{\partial \rho}\right)-\frac{V'}{2\pi\rho}\times$$ **bootstrap and externally driven current densities (including HF wave driven)**

- System closure via fluxes (Γ_e, q_e, q_i, j_{BS}, j_{CD}) expressed as a functions of n_e, T_e, T_i and their gradients – either from theory or from experimental observations (empirical)

Structure of transport codes

ASTRA

Experimental database

H&CD:
NBI *(Fokker-Planck, Monte-Carlo (NUBEAM))*
ECRH (TORBEAM)
ICRH (TORIC)
LHCD (FRTC, semi-analytical model)

Core transport solver for main species (ne, Ti, Te) and ψ

Equilibrium solvers: *3 moment, SPIDER, ESC*

MHD: *sawteeth (Kadomtsev, Porcelli)*

Impurity and radiation: *coronal*

Transport: NCLASS, neocl. analytics, Bohm-gyroBohm, GLF23, MMM, Weiland, …

Fuelling:
kinetic eq. for neutrals
Pellet module

Modelling database

Presently in use: ASTRA, CORSICA, CRONOS, FASTRAN, JETTO, ONE-TWO, (P)TRANSP, TOPICS, TSC

ASTRA specific characteristics:

- Interactive mode
- Code compiler
- Platform for coupling rather than the code: different combination of modules can be used (w/o transport solver)
- 10 diffusion-type equations built-in (turbulence amplitude, toroidal and poloidal velocity, different plasma species, …)
- Local deployment worldwide:

  - tokamaks: ASDEX Upgrade, CDX-U, COMPASS, DIII-D, FTU, Globus-M, JET, JT-60U, KSTAR, MAST, T-10, TCV, TFTR, Tore Supra, ITER
  - W7-X stellarator
  - RFX
  - State university of Mexico (UNAM), Imperial College (London, UK)

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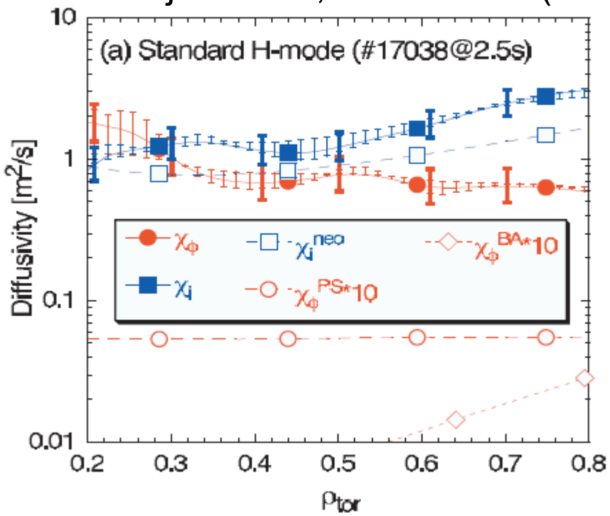
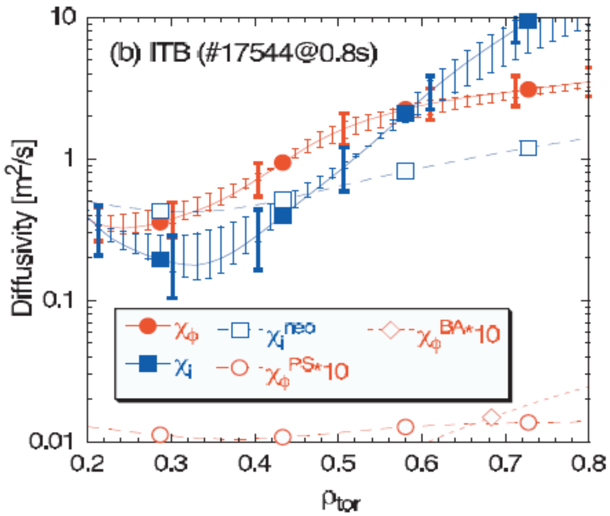
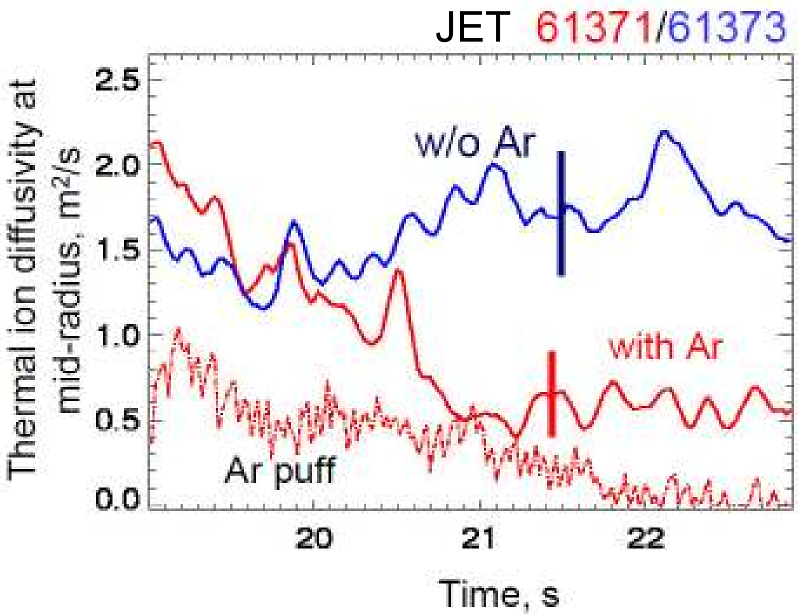
Interpretative transport analysis

Estimation of effective diffusivities: $\chi \sim [\int(P_{heat} - P_{loss})dv - (3/2)dW/dt\,] / (n\nabla T)$

Nishijima et al, PPCF 2005 (AUG)





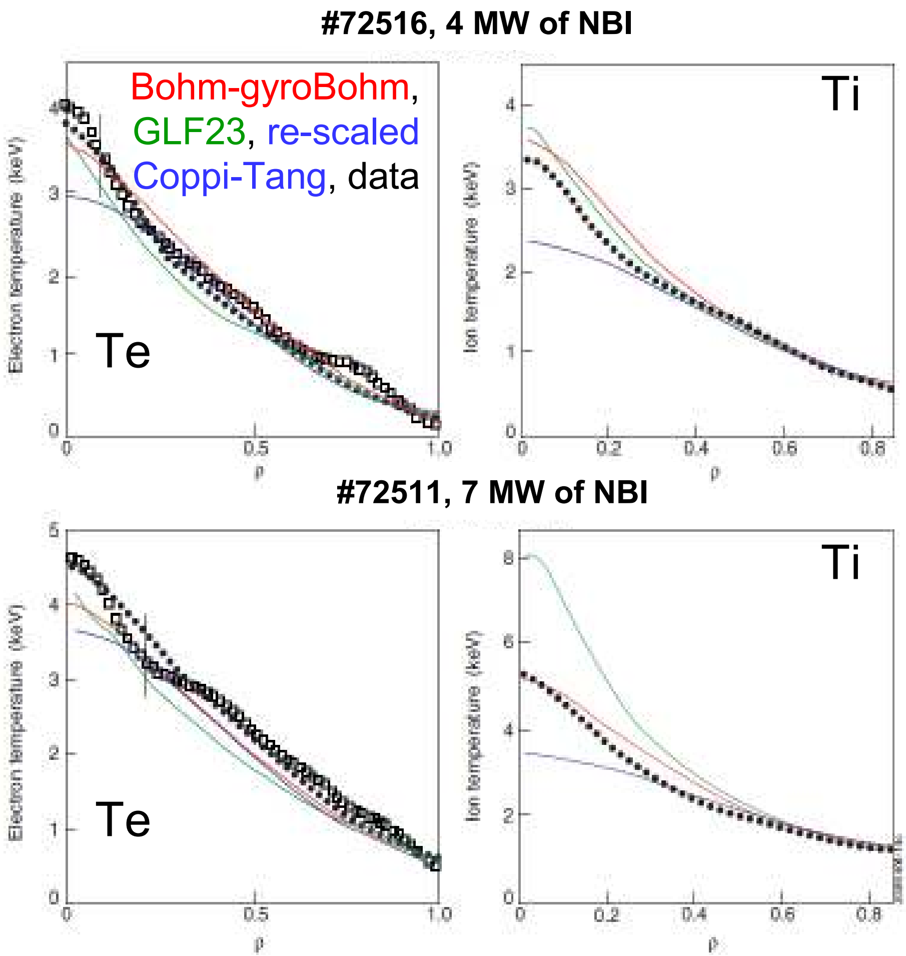


-similar heating power (17 MW), toroidal field (2.7 T), plasma current (2.5 MA), initial density in discharge with and without Ar seeding

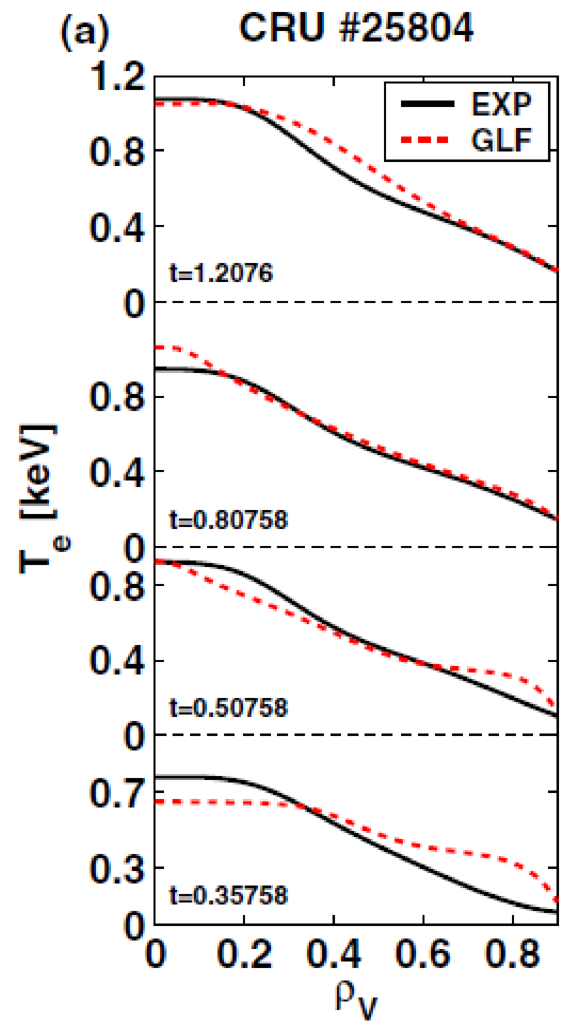
- thermal ion diffusivity reduces with Ar seeding

Validation of core theory-based transport models: current ramp up

NBI assisted Ipl ramp up at JET: accurate prediction at low NBI power, but GLF23 builds an ITB at high power. Even larger Ti over-prediction with 10 MW [Voitsekhovitch et al PPCF 2010]

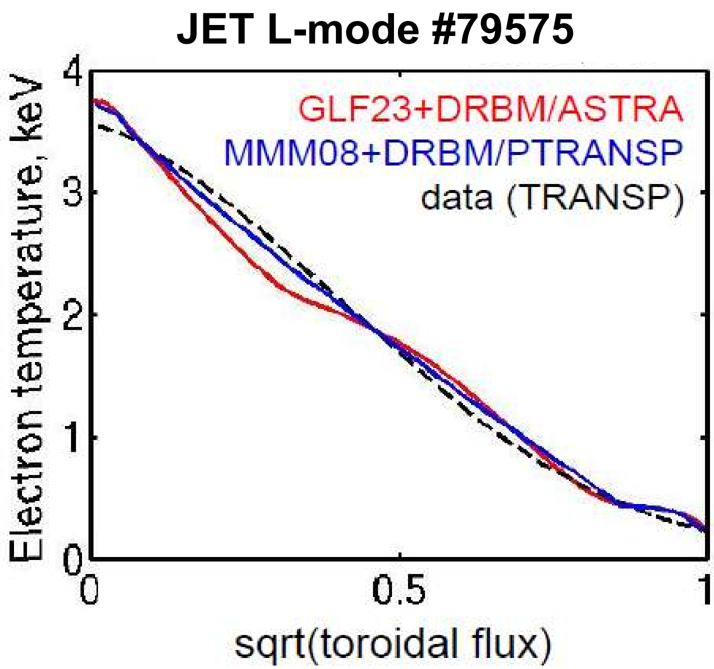


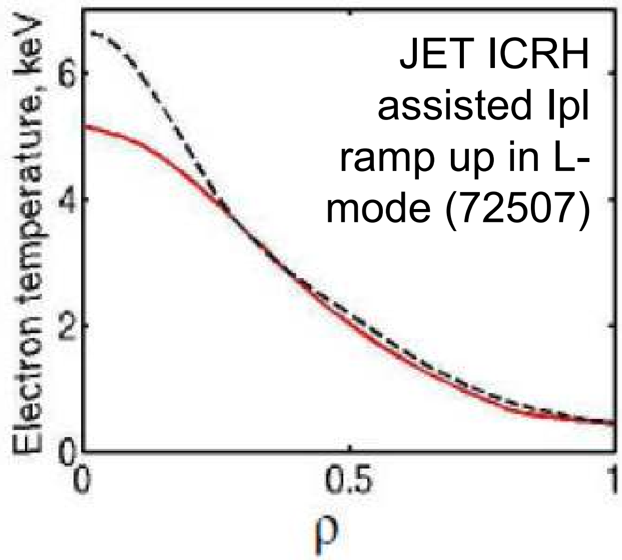
OH Ipl ramp up at AUG: satisfactory GLF23 prediction later during the Ipl ramp, while the discrepancy at lower currents [Fable et al, NF 2011]

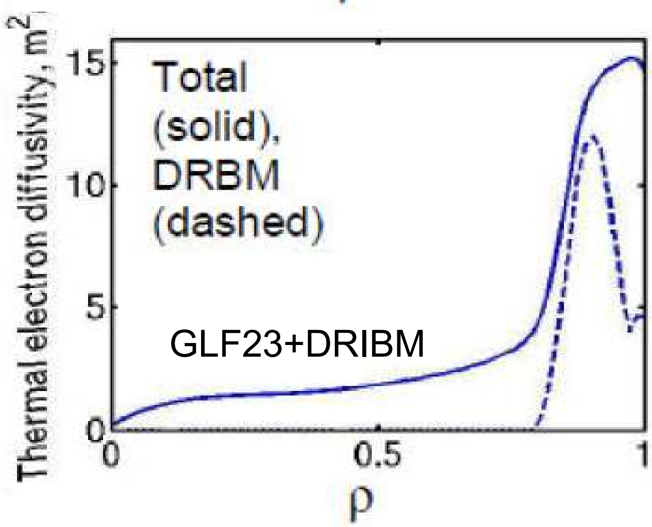


Validation of theory-based transport models: L-mode

Theory-based core transport models (GLF23, MMM07) in combination with DRIBM model for edge transport







More L-mode examples for DIII-D, JET and TFTR are in Rafiq et al IAEA 2012

Validation of core theory-based transport models: H-mode

Tardini et al Nucl. Fusion 2002

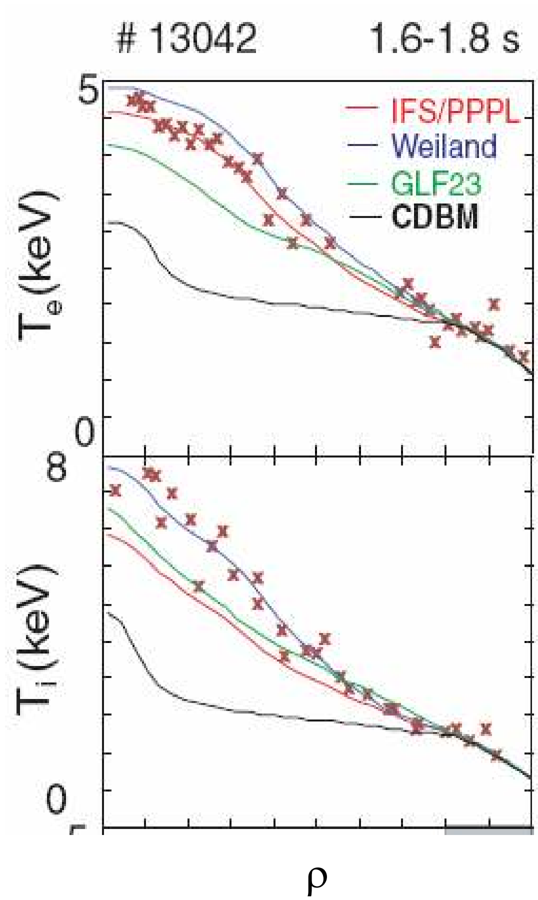
- AUG: scan in n_e ((3.85-6.2)e19 m^{-3}), I_{pl} (0.4-1.2MA), P_{NBI} (2.5-12.5MW)

- T_i profiles are stiff (similar $L_{Ti,cr}= -(T_i/\nabla T_i)_{cr}$ ~4 in all shots) while T_e change shape at low n_e

- *$\partial\chi_i/\partial(R/L_{Ti})$:* 20m^2/s for IFS-PPPL, 2.5 m^2/s for Weiland model

- Accurate predictions with ITG-based models: Weiland, IFS-PPPL

- CDBM model failed to predict linear relations between core and edge T_i



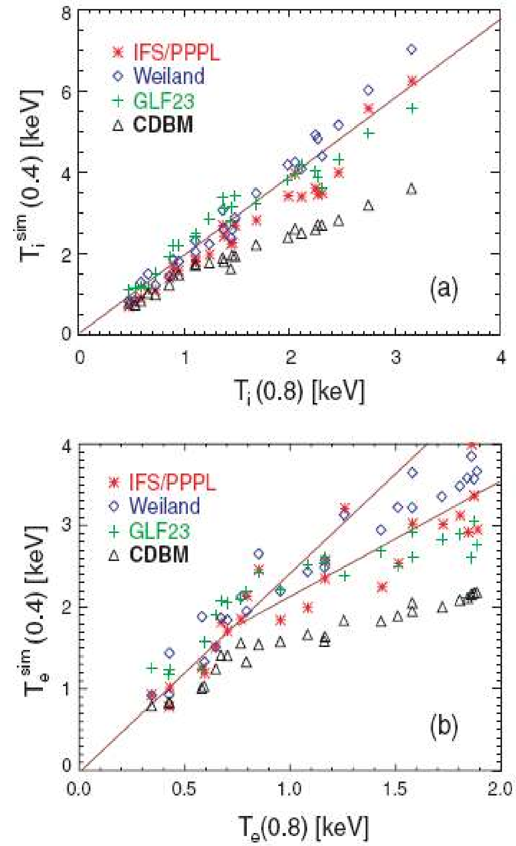
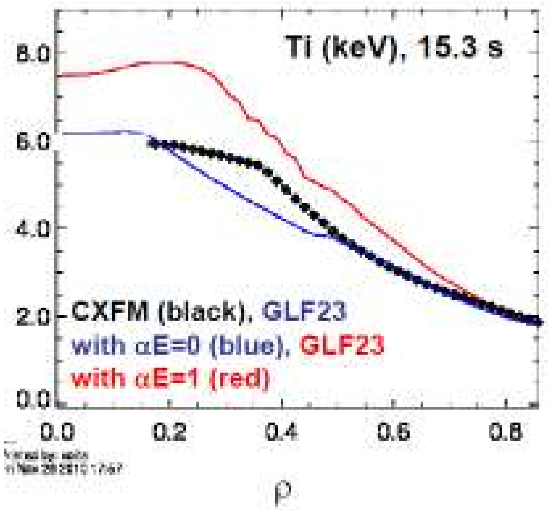


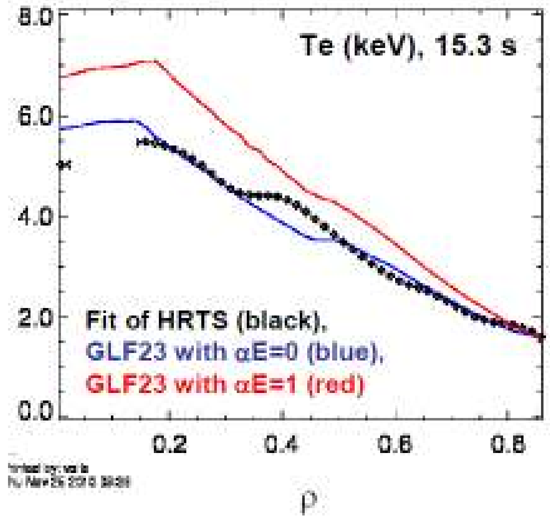
Figure 5. Simulated core to edge temperatures; blue diamonds correspond to the Weiland model, red stars to IFS/PPPL, green crosses to GLF23 and black triangles to CDBM: (a) T_i, (b) T_e. In (a) the line reproduces the experimental points, being the same as that in Fig. 1(a). In (b) the lines reproduce the experimental points at low and high $T_e(0.8)$, as in Fig. 1(b).

Similar study of stiffness at JT60-U and validation of MMM and RLW models: *Mikkelsen et al NF 2003*

Validation of core theory-based transport models: impact of stiffness on plasma performance in H-mode

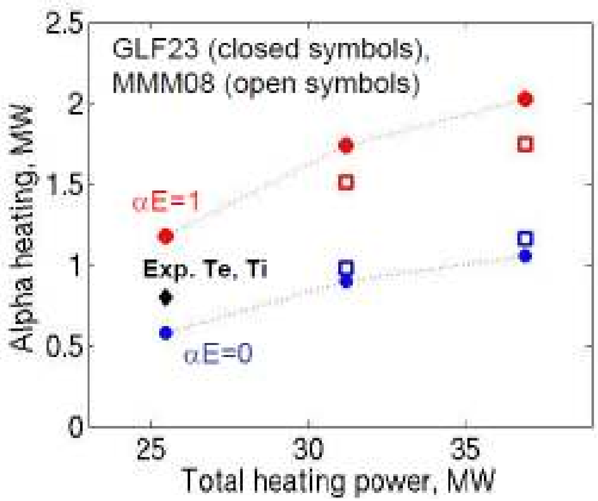
Voitsekhovitch et al, ISM Working Session, November 2010

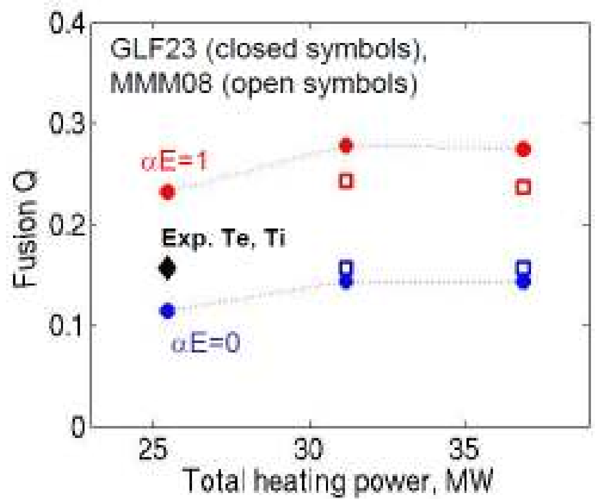




JET H-mode (79698):

- 3.6 T / 4.5 MA
- DD / C wall
- 23 MW of NBI, 2.5 MW of ICRH
- projection to DT (same density and rotation velocity)



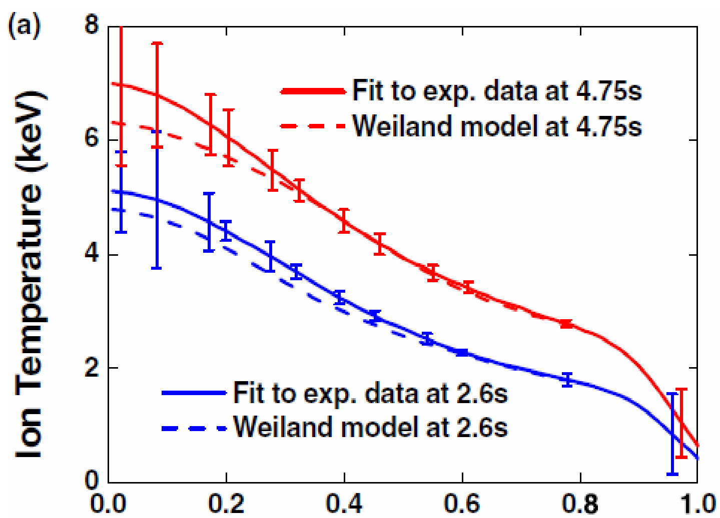


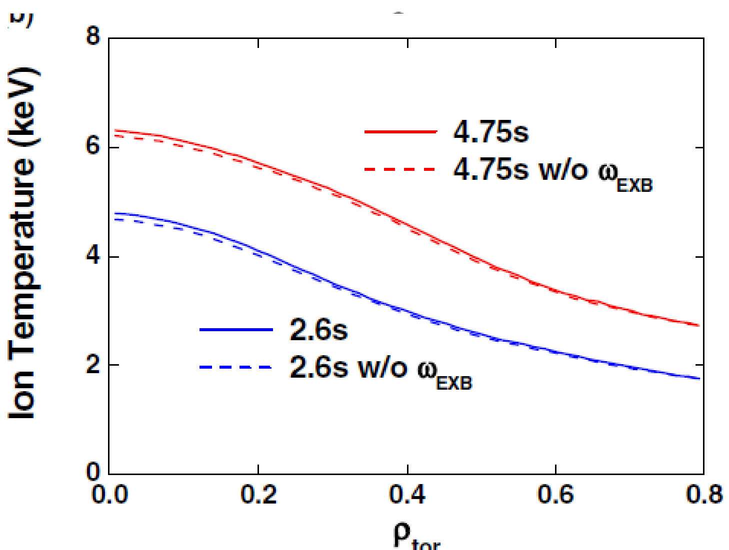
Prediction for DT plasma:

- Increase of NBI power up to 35 MW is envisaged
- increase of χs with power → little/no effect on temperature and Q

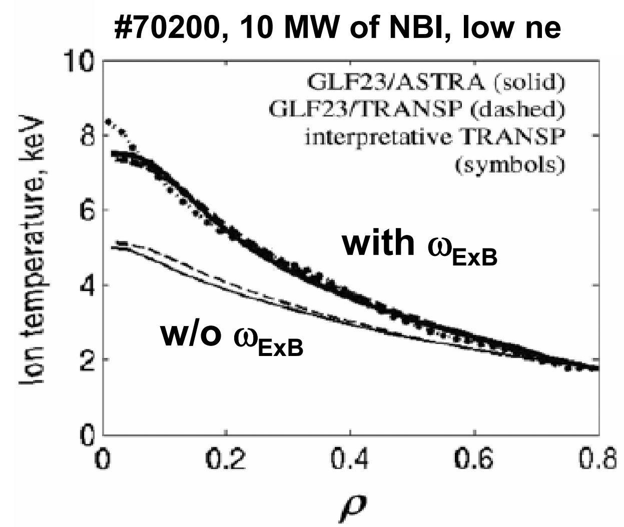
Validation of core theory-based transport models: improved H-mode (AUG) / high β_N (JET)

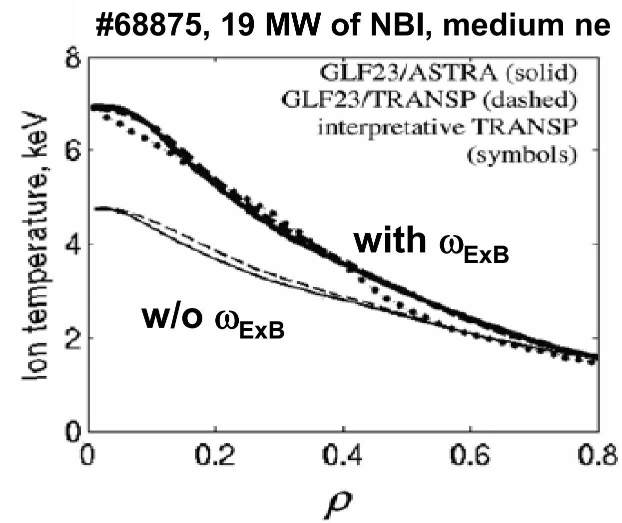
AUG: weak *ExB* shear effect on core confinement, but improved pedestal [Na et al, NF 2006]





JET: *ExB* shear stabilisation is important for core confinement [Voitsekhovitch et al, NF 2009]





Validation of core transport models: Internal Transport Barrier

ITB with monotonic *q* in AUG18695: GLF23 (solid), Weiland model (dashed). Measurements are shown by symbols [*Tardini et al NF 2007*]

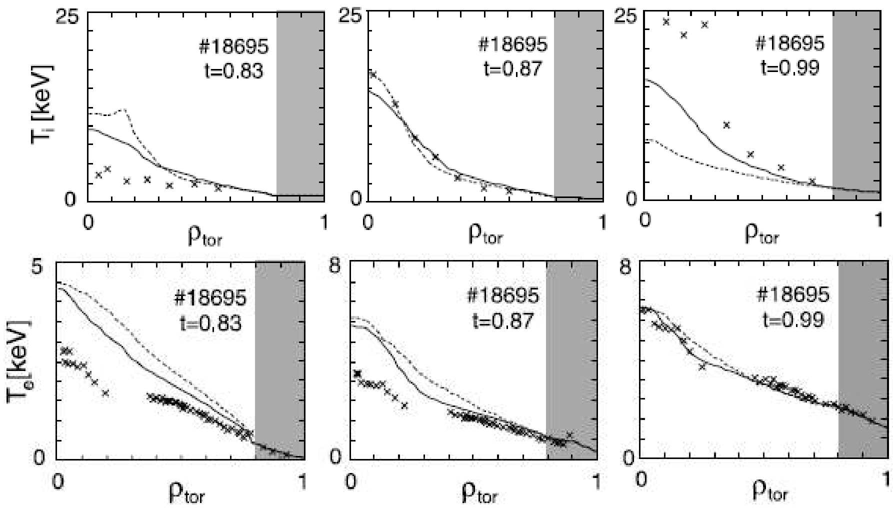
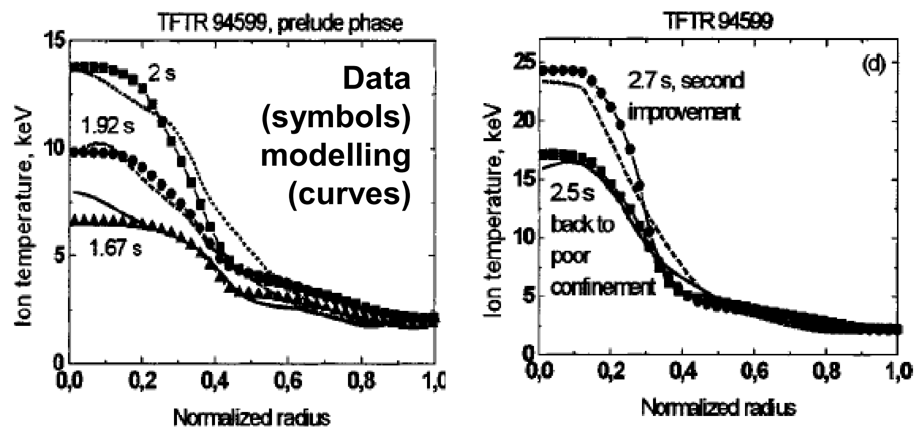
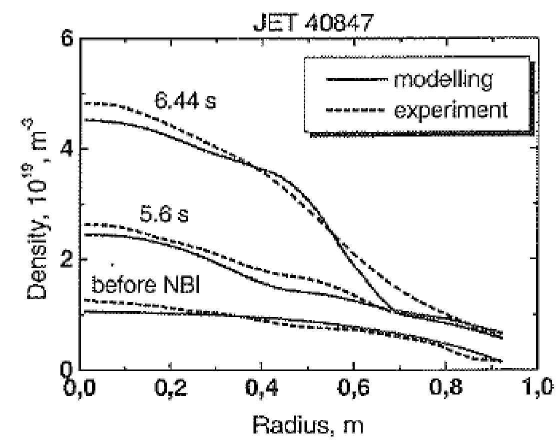


Figure 9. ASTRA T_e simulations of discharge # 18695. Time points and line code as in figure 8.

ITB with semi-empirical ExB and magnetic shear stabilisation model for TFTR, DIII-D and JET *[Voitsekhovitch et al, Phys. Plasmas 1999; Czech J. Phys. 1999]*





More on ITB modelling: Kinsey et al, Phys. Plasmas 2005 (GLF23), Tala et al, NF 2006 (Bohm-gyroBohm)

- simulations of ITB dynamics is not always successful

- estimation / measurements of ExB shear?

- anomalous poloidal rotation [K Crombe et al PRL 2005]?

- more complicated physics of turbulence stabilisation?

Non-linear ExB shear quench rule in JET hybrids?

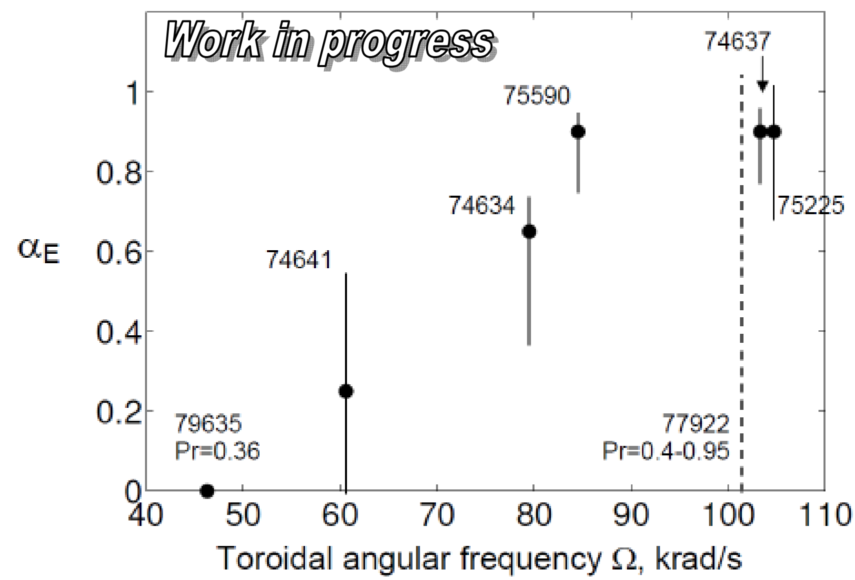
- *ExB* shear quench rule in GLF23: $\gamma_{net}=\gamma_{max} - \alpha_E\gamma_{ExB}$ ($0.5 < \alpha_E < 1.5$) [Waltz et al, PoP 1997]

- α_E determined in gyrofluid & gyrokinetic turbulence simulations (large α_E range depending on physics assumptions and plasma conditions)

- here α_E is adjusted in self-consistent modelling of Te, Ti, ni and Vtor for each of 7 JET hybrid shots performed under different conditions

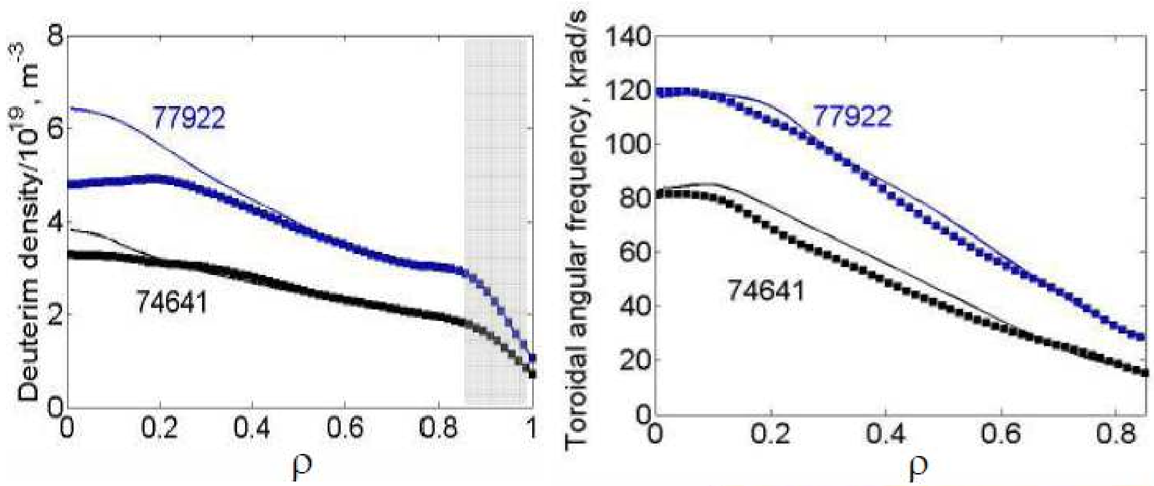
- $\chi_\varphi = \Pr\chi_i$, Pr=0.3 for shots with strong *ExB* shear stabilisation, otherwise larger Pr uncertainty

Self-consistent Te, Ti, ni and Vtor modelling: αE uncertainty is determined by 15% deviation from data



- non-linear ExB shear quench rule (α_E increases with rotation)?

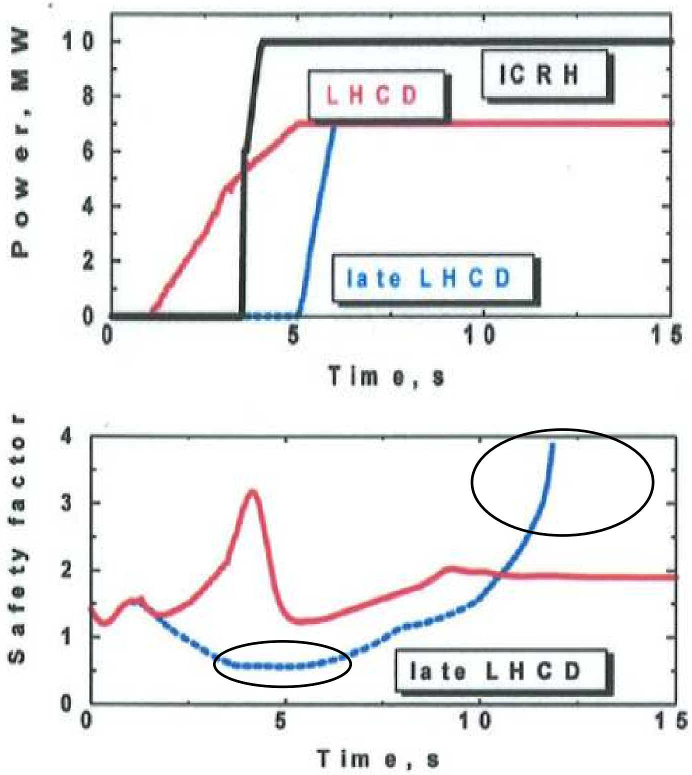
- or other hidden effects? turbulence stabilisation by fast ion pressure?



Development of advanced scenario with RF heating and current drive (Tore Supra)

- *fully non-inductive operation*
- *improved confinement (flat or reversed q-profile)*
- *validated transport models (strong coupling between transport, q, pressure, heating and current drive)*

I Voitsekhovitch, D Moreau NF 2001



- start after breakdown

- LHCD at low density to form slightly reversed q at low n_e,

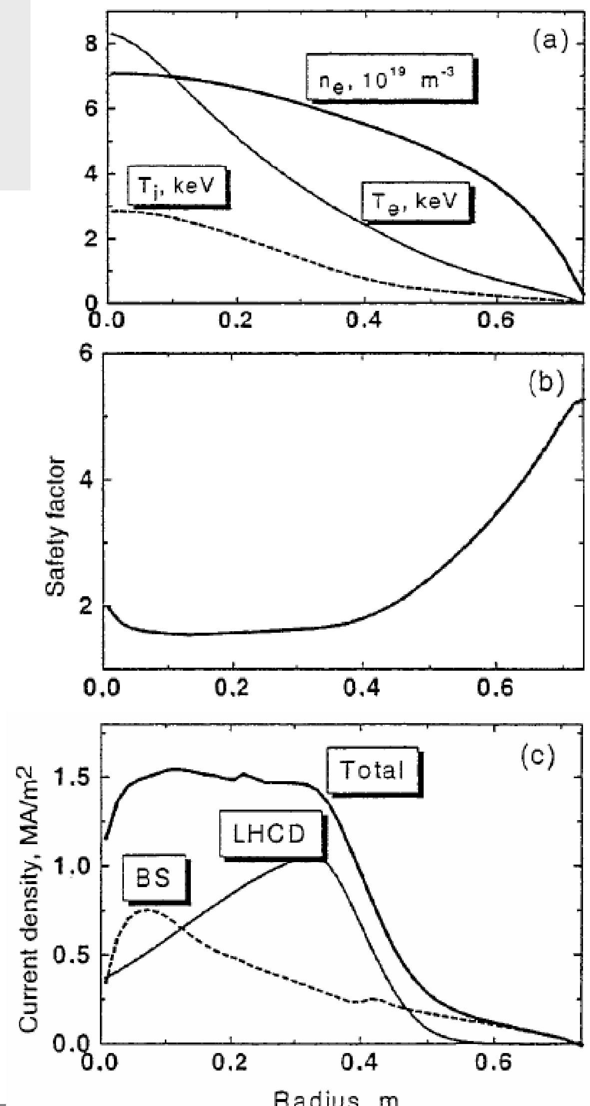
- increase density and heating: LHCD efficiency reduces, but BS current replaces LHCD

- LHCD timing is important: q0 below 1 with late LHCD

- steady-sate: I_{BS}/I_{tot}=0.4, I_{LH}/I_{tot} = 0.6

- scenario optimised manually, plasma control is desirable

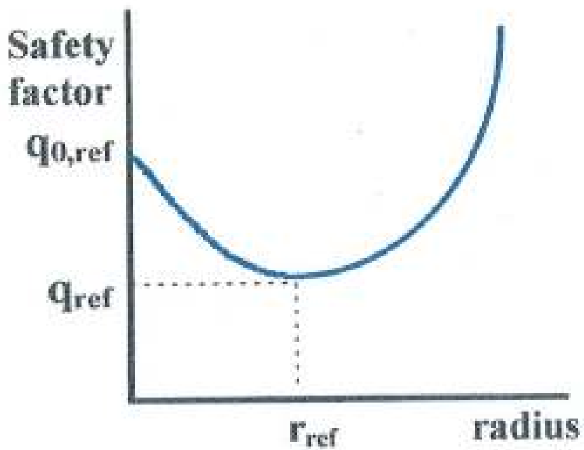
Profiles at steady state



Plasma control algorithms

Two point current profile control

[*Moreau et al Nucl. Fusion 1999*]

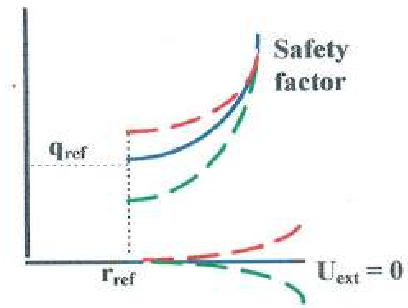


Actuators:

- Loop voltage

- LHCD and FWEH power

(1) Control of *q* at reference radius r_{ref} using loop voltage

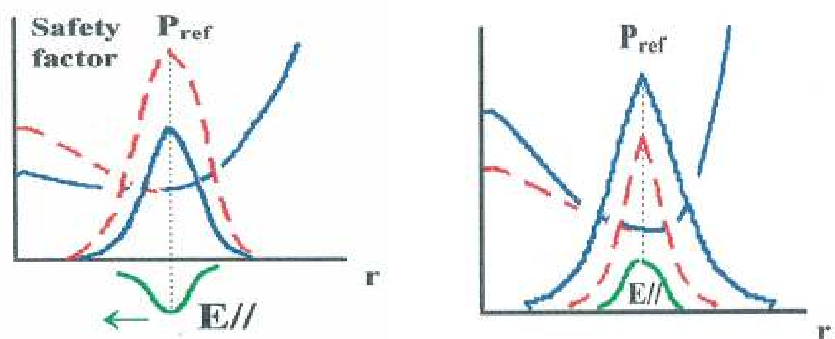


if $q(r_{ref}) > q_{ref}$ then $U_{ext} > 0$

if $q(r_{ref}) < q_{ref}$ then $U_{ext} < 0$

$$U_{ext}(t) = C_U\left(\frac{1}{q_{ref}} - \frac{1}{q\left(r_{ref},t\right)}\right)$$

(2) Replacement of OH current with a NI current at reference radius, i.e. ($E_{//}(r_{ref}) = 0$) and control of q_0



$$\delta P\left(r_{ref},t\right) = C_{ref}\left[E_{//}\left(r_{ref},t\right) - C_1\left(1/q_{0ref} - 1/q(0,t)\right)\right]$$

(3) Control of central $E_{//}$

$$\delta P_{central} = C_0 E_{//}\left(r = 0, t\right)$$

(4) Control of LH deposition via LH spectrum

(5) Burn control for ITER via density

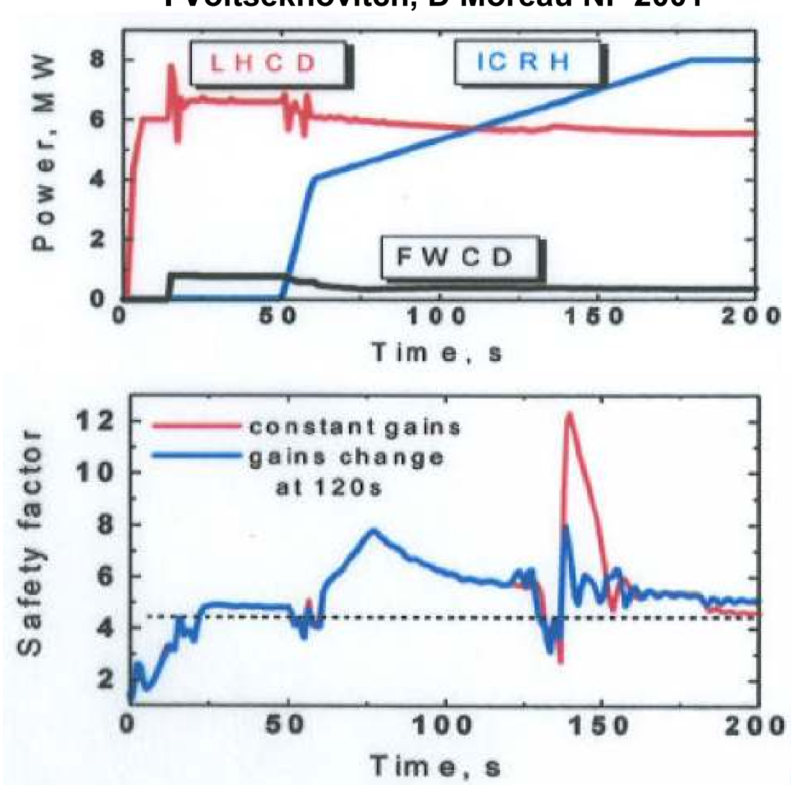
Advanced scenario with current profile control (Tore Supra)

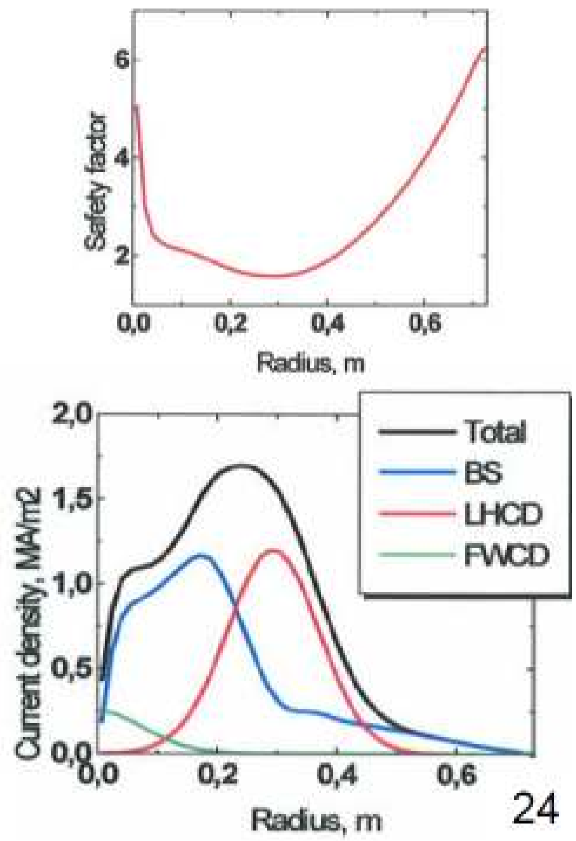
- feedback control starts at 15 s, q_{0ref} = 4.5, $q(r_{ref}$=0.5) = 1.7

- stationary reversed shear configuration and ITB achieved

- same reference q values are achieved with different transport models, but different power is needed

I Voitsekhovitch, D Moreau NF 2001





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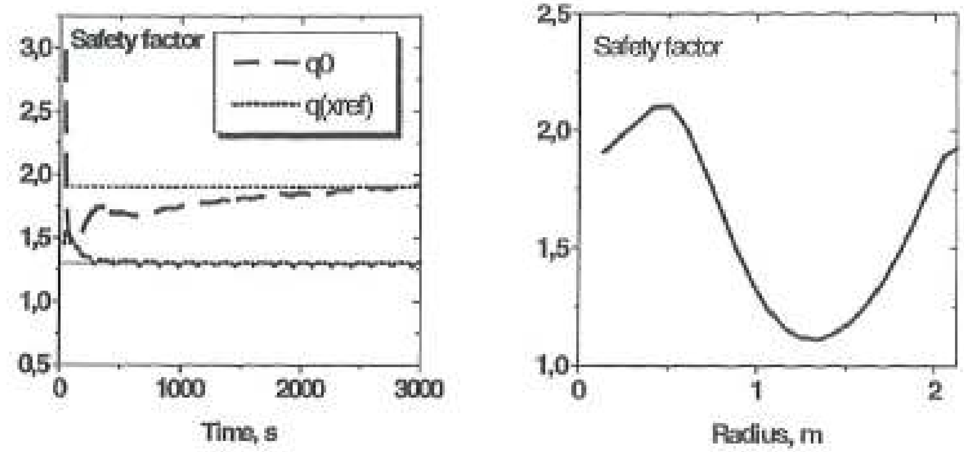
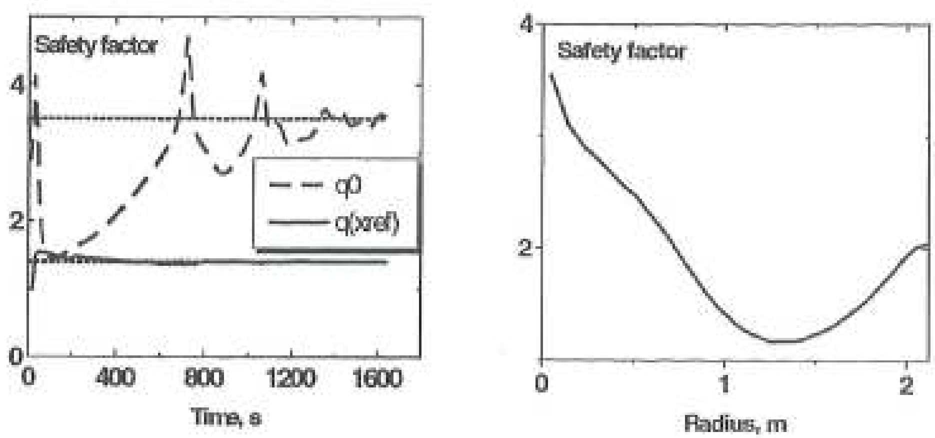
Advanced scenario with current profile control (ITER)

q-profile control at low β phase

$q_{0,ref}$ = 1.9, q_{ref} = 1.3, ρ_{ref} = 0.45



$q_{0,ref}$ = 3.5, q_{ref} = 1.4, ρ_{ref} = 0.45



Control algorithms allow to achieve the prescribed q values, but:

- Long relaxation time and large transient deviations from reference: gains adjustment for smooth and relatively fast evolution?

- q profile is not controlled apart from two reference points (MHD stable?)

Further developments for control of kinetic and magnetic profiles:

D. Moreau et al, Nucl. Fusion **51** (2011) 063009

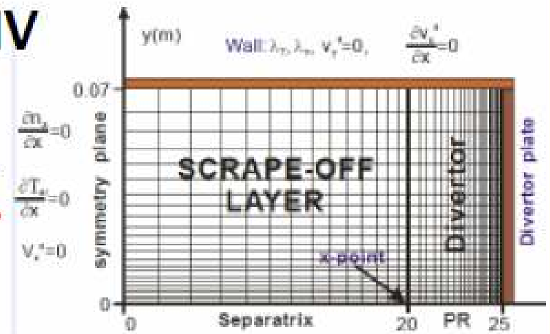
Beyond core modelling: core-SOL-divertor simulations including impurity

Core / pedestal: impurity and main species, *but simplified sources and transport (H98(y,2)), no equilibrium*

COREDIV

Fluxes →

← Boundary values



$\Gamma_i, P_{rad}, P_{ion}, P_{Brem},$

$P_\alpha, Z_{eff}, P_j^{rad,k}, n_j^k$

$\Gamma^k_{j,'divertor'}, Q_{'divertor'}$

Helium, impurity

$R, a, B_T, \varepsilon, \kappa, I_p$

$H_{98}, P^e_{aux}, P^i_{aux}$

$\langle n_e \rangle, n_{sep},$

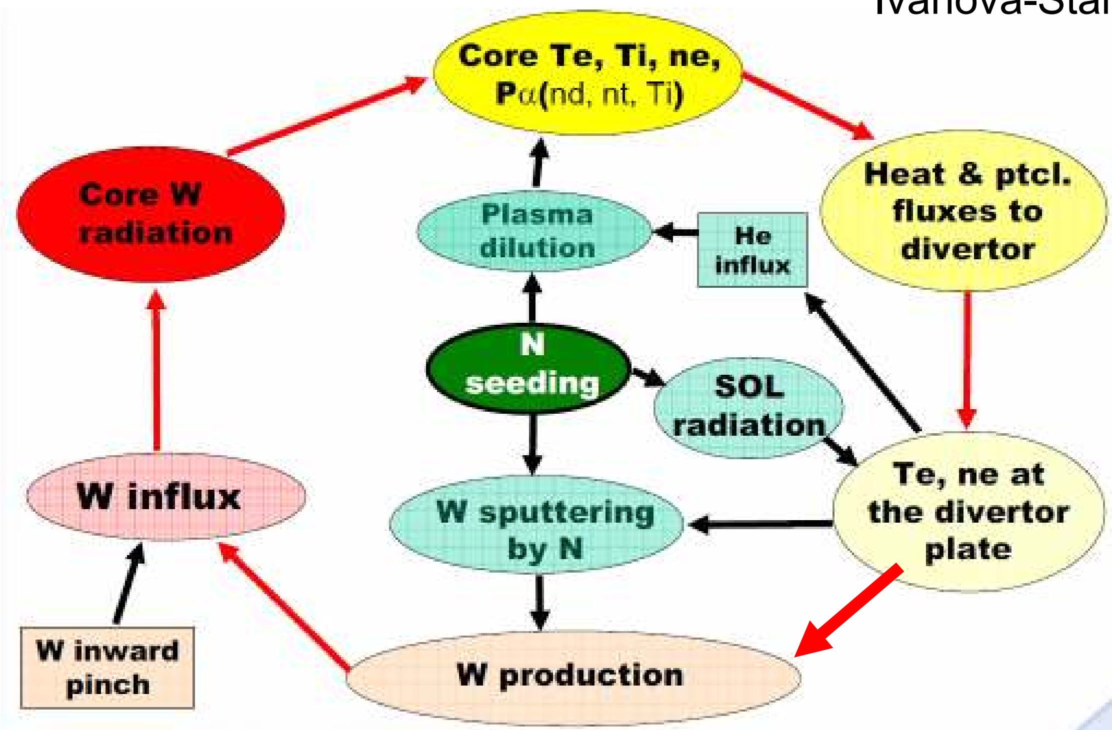
$T_{e(i),sep}, T_{e(i),ped}, \rho_{ped}$

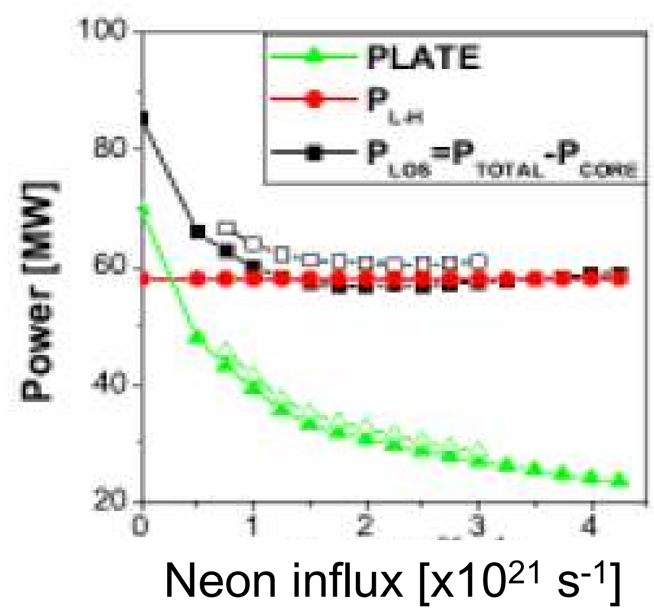
JETTO (ASTRA, CRONOS): ***sophisticated equilibrium, transport, H&CD modules, current diffusion, but no impurities/SOL/divertor***

- **COREDIV:**
  - *impurity simulations (ionization, CX, recombination, transport)*
  - *self-consistent particle source from divertor (sputtering cross-sections)*
  - *parallel losses in SOL*
  - *core and SOL radiation*
- **Core transport codes:**
  - *fixed/free boundary equilibrium*
  - *H&CD: NBI (NUBEAM. FP), ICRH (TORIC)*
  - *theory-based transport: GLF23, TGLF, MMM, NCLASS*
- **Compromise between physics complexity and simulation speed**

Neon seeding in ITER H-mode

Ivanova-Stanik et al, PET 2013





- Without impurity seeding, the radiation is 33% and $P_{sep} > P_{LH}$ (H-mode), but power to plate is too large (76 MW)

- Neon seeding reduces the power to plate, but W production & radiation increases (W self- and sputtering by D is replaced with sputtering by N) → power through separatrix is below L-H power threshold

- model for W diffusion and pinch?

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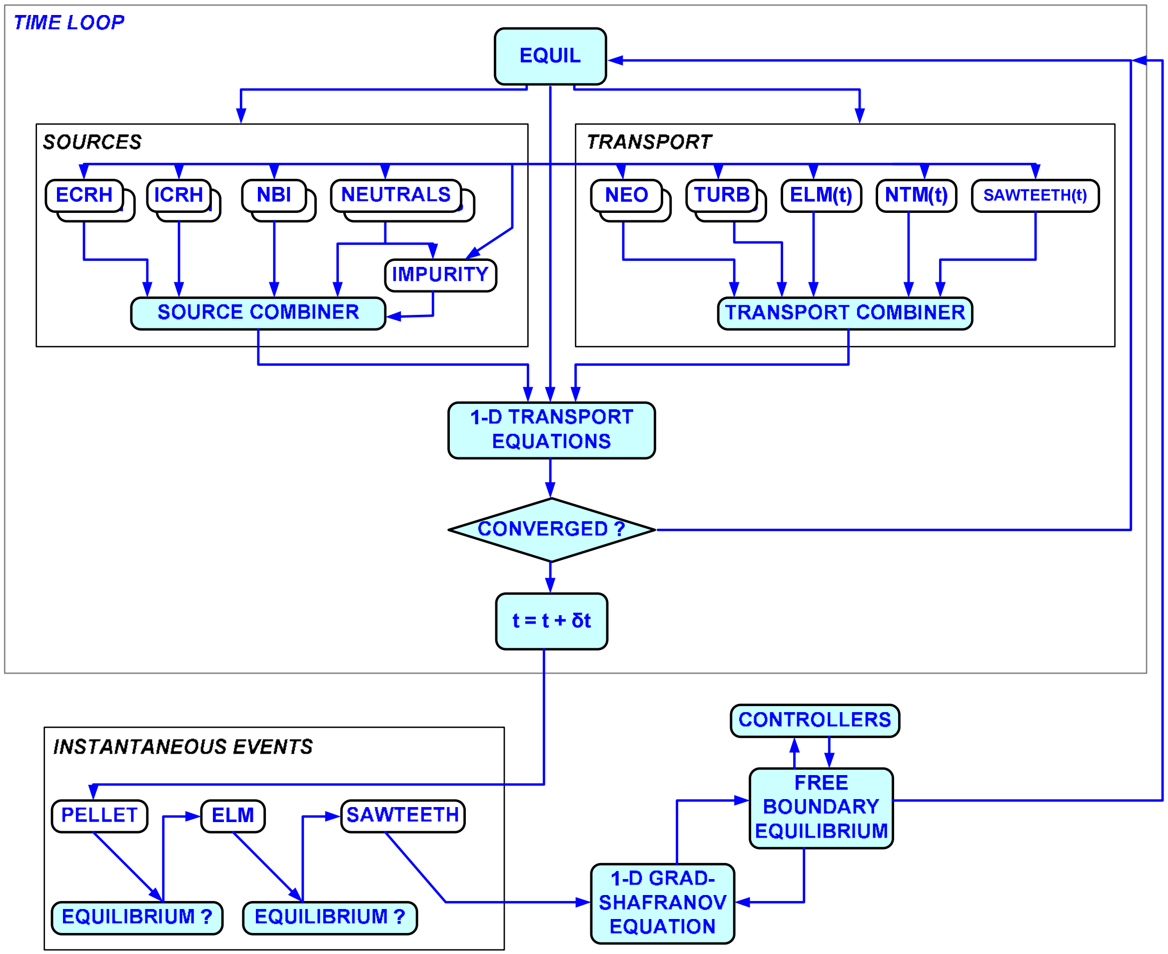
Summary, perspectives and open issues

- Broad application domain for transport codes (multi-physics, multi-machine) has been illustrated
- Good predictive capabilities of theory-based models achieved in a number of cases illustrate applicability of transport theories
- Still more work needs to be done (mechanisms of suppression of anomalous transport, impurity transport, …)
- Improvement of numerics for stiff transport
- Integrated modelling tools are needed (coupled transport, free boundary, MHD, core-SOL-divertor)

Future numerical tools

- **ASTRA as a prototype of European Transport Solver (ETS_A):**



European Transport Solver: a schema of the workflow [Kalupin et al IAEA 2012]

- **Next step: IMAS - planning, execution and analysis of ITER pulses**

Grigory Pereverzev developed and maintained a unique, flexible, user-friendly, multi-machine transport code used for a number of interesting and important physics studies - a very valuable contribution, highly appreciated by fusion transport community!