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*(The CRONOS Project Team)*

## Outline

- The CRONOS suite of codes: overview
- Code validation
- Application to ITER scenarios
- Planned evolutions
- Conclusions



# Overview of CRONOS

## ■ Integrated modelling of:

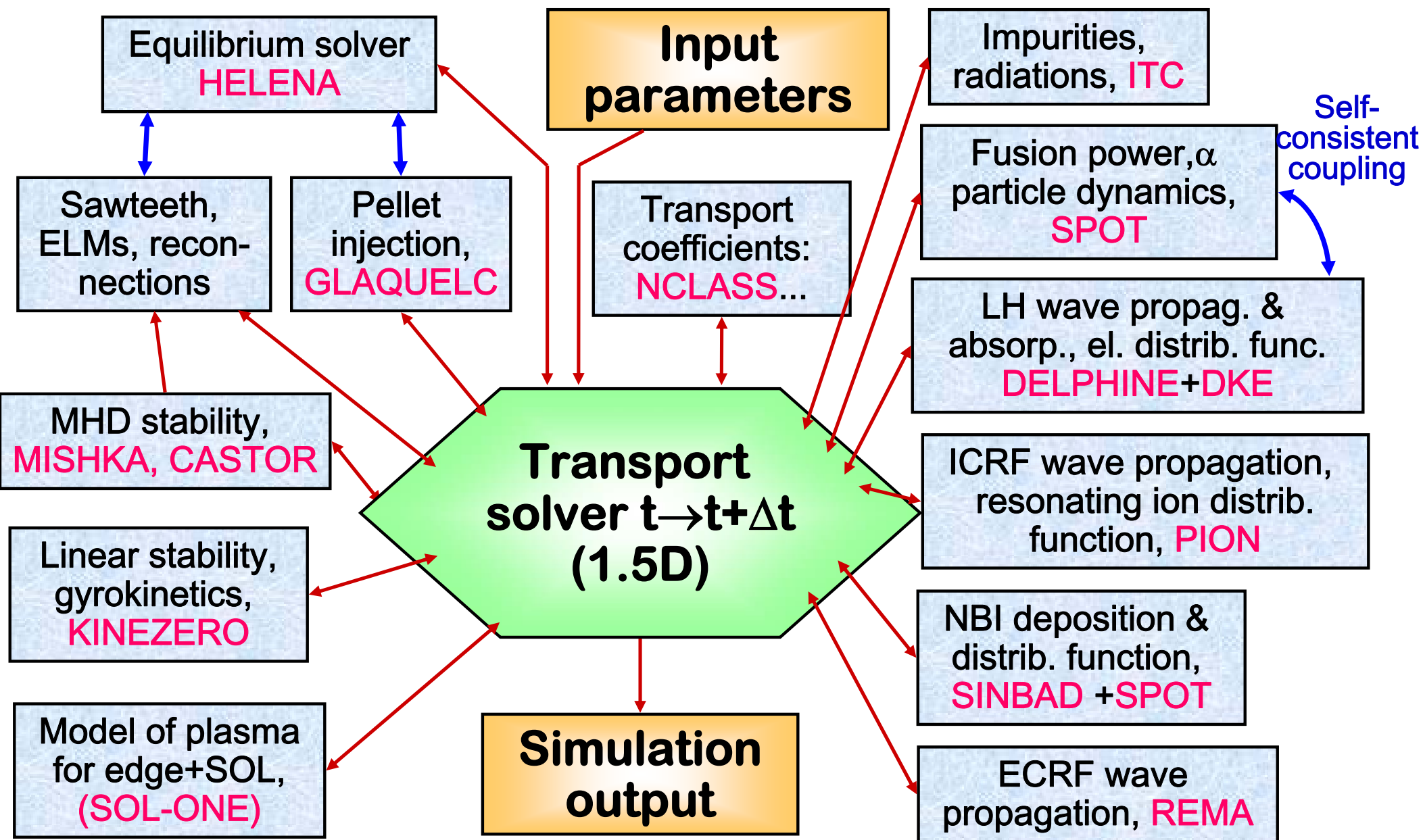
- Heat, particles, rotation ⇒ transport diffusion equations (heat, matter), source codes
- Current profiles ⇒ current diffusion equation
- Plasma equilibrium ⇒ 2D magnetic equilibrium code

## ■ Predictive or interpretative modelling:

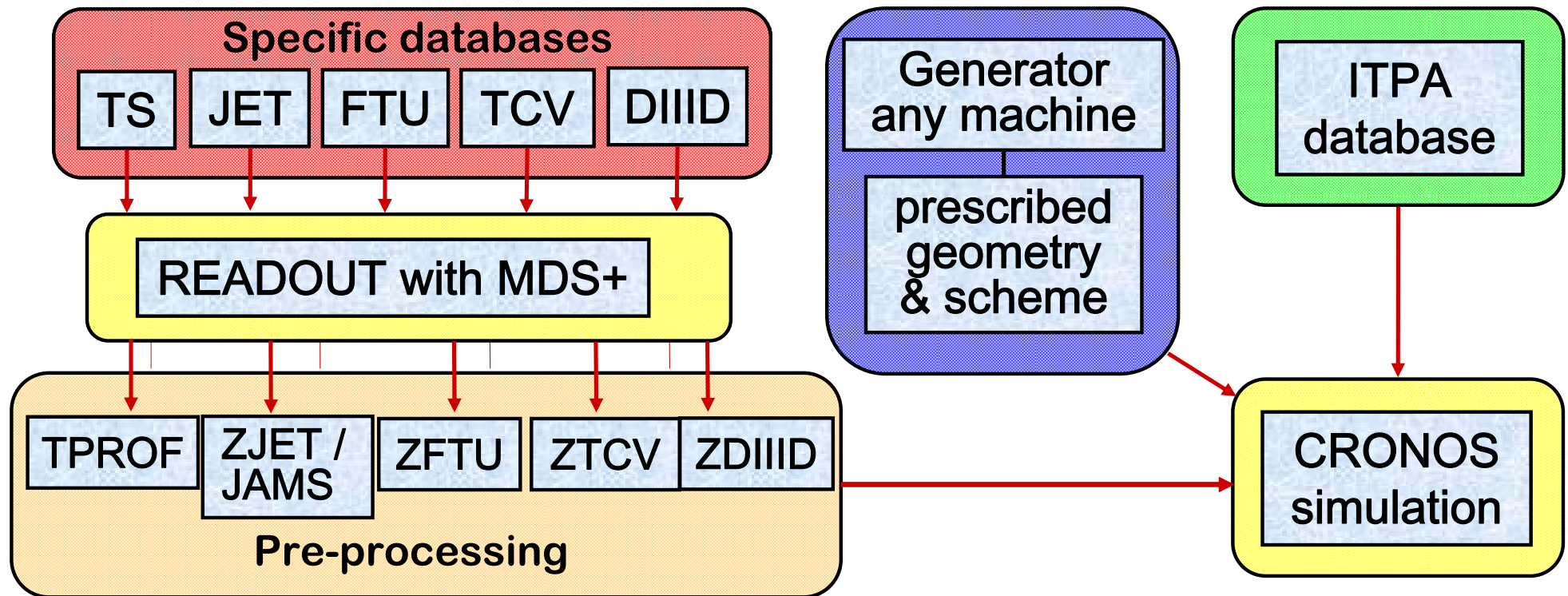
- Interpretative:
  - resolution of current diffusion only
  - measured electron & ion densities & temperatures
- Predictive:
  - transport modelling
  - initial profiles from model or experiments

Ref. [Basiuk et al., Nuclear Fusion **43** (2003) 822]

## ■ Built-in feedback controls



## User-friendly graphic interface (MATLAB):



- ➔ Experimental data converted into standard data structure readable by CRONOS.
- ➔ First step towards a basic interface of EU Task Force Modelling.

# METIS: a 0-D assistant for the preparation of CRONOS runs

- 0.5 D tool with profile effects, fast calculation (~ 1 min)
- Basic 0D parameters + scaling laws (CD efficiencies, energy confinement, profile peaking factors, radiated power)
- **O.D.E. integration for time evolution**
- $P_{\text{fusion}}$  : D,T profiles deduced from 0D time-dependent confinement, then integration using realistic cross-sections
- **NBI & ICRH**: analytical Fokker-Planck solution
- Bootstrap 0D scaling Laws
- **Pseudo 0-D current diffusion ( $I_i, I_p$ )**.  $I_i$  : estimated from position of CD sources. Then O.D.E. integration  $\rightarrow V_{\text{loop}}$ , pulse length.
- $Z_{\text{eff}}$  evolves depending on He ash transport (for a reactor).
- **At every time slice, convergence loop for solving non-linearities of the system ( $P_{\text{fusion}}$  especially)**

Ref. [Artaud et al., EPS 2005]

## HELENA

*G. Huysmans, CEA/Cadarache*

- 2-D fixed-boundary equilibrium code (including separatrix)
- finite elements Grad-Shafranov solver

## MISHKA and CASTOR

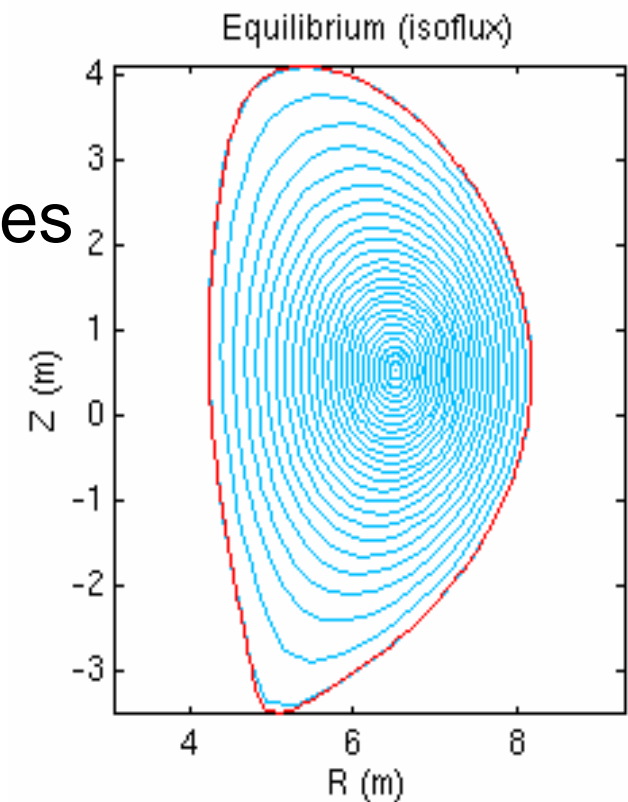
- linear ideal and resistive MHD stability codes (post-processing)

## Reconnection models

- Porcelli's model for sawteeth reconnection

## KINEZERO

- linear gyrokinetic microstability analysis (ITG, ETG, TEM)



*C. Bourdelle, CEA/Cadarache*

## **PION (Ion Cyclotron Heating)**

- simplified (1-D) Fokker-Planck code for fast ion tail
- IC wave absorption computed analytically

*L.G. Eriksson, CEA/Cadarache*

## **SINBAD (Neutral Beam Injection)**

- Fokker-Planck code with simplified beam model
- output: heat, particle, current and rotation sources due to NBI

## **DELPHINE / LUKE (Lower Hybrid Current Drive)**

- 3-D ray-tracing coupled to 2D / 3D Fokker-Planck
- output: power deposition, driven current and fast electron profiles

*Y. Peysson, CEA/Cadarache*

## **REMA (Electron Cyclotron Heating & Current Drive)**

- 3-D ray-tracing with analytical CD efficiency
- output: power deposition and driven current profiles

*G. Giruzzi, CEA/Cadarache*

## **JONASSLICE (gas puff, recycling)**

- cold neutral hydrogen from gas puff and wall recycling
- slab geometry
- output: heat, particle and rotation sources

*B. Pégourié, CEA/Cadarache*

## **GLAQUELC (Pellet ablation)**

- includes drift effects
- output: particle source from pellet injection

## **ITC (impurity transport solver)**

- radiation computation (line radiation + brehmsstrahlung)
- coupled to NCLASS for the neo-classical transport coefficients
- atomic physics data from ADAS database

*P. Thomas, CEA/Cadarache*

## NCLASS (neoclassical transport coefficients)

- multi-species, thermal, axisymmetric plasma, isotropic pressure
- output: resistivity, bootstrap, viscosity, heat diffusivity, etc.

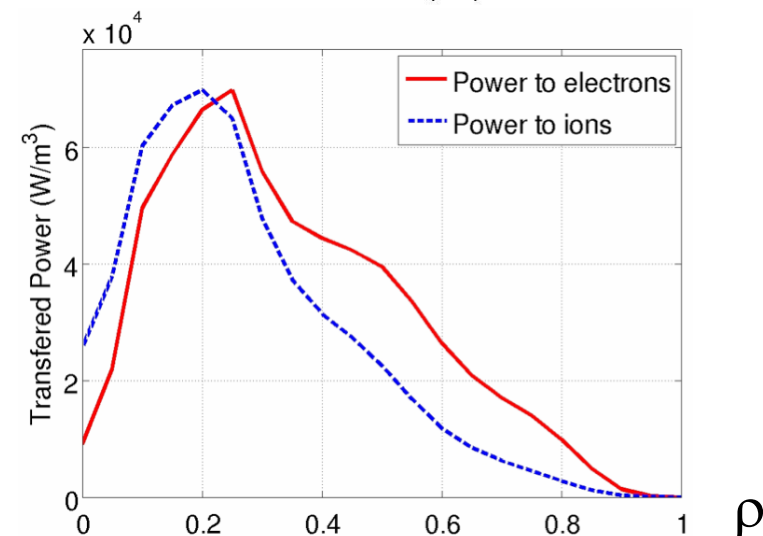
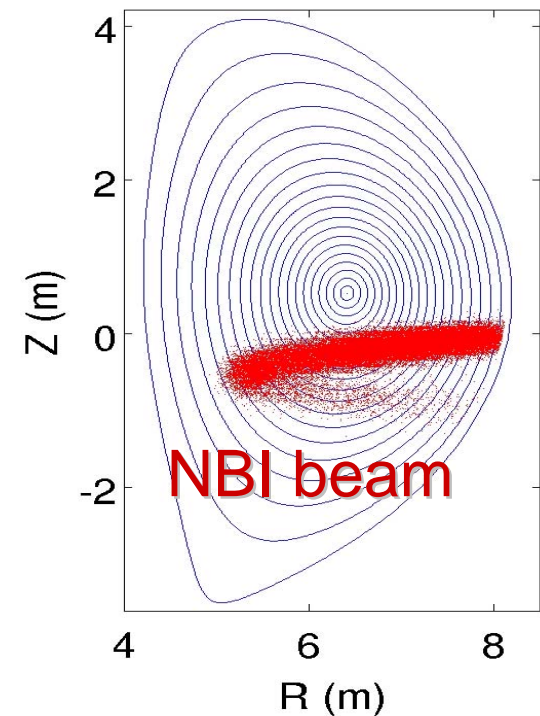
*W. Houlberg, Oak Ridge, USA*

## Anomalous transport models

- **empirical models:**
  - *kiauto*: reproduces a prescribed 0-D scaling law
  - *Bohm/gyro-Bohm* (optimised for various machines, with rotation effects)
- **first-principle based models:**
  - *GLF23* (combines linear gyrokinetic growth rates of ITG/TEM modes with results of the 3D non-linear gyro-fluid code GLF)
  - *Weiland* (fluid turbulence)
  - *Horton* (ETG+TEM, critical gradient)

- Orbit following Monte Carlo code, follows guiding centre orbits using **Boozer coordinates**.
- **Collisions:**  
Simulated by periodically applying Monte Carlo operators along the orbit, inducing spatial transport.
- **Finite orbit width effects:**  
    ➔ **Anisotropy, current drive, losses**
- **New operators for interaction RF waves ↔ fast ions**  
(L.-G. Eriksson & M. Schneider, Physics of Plasmas 2005)
- **Computing time reduction:**
  - Acceleration of collisions
  - Weighting scheme for low energy particles, ...
  - parallelisation
- **Input / output with CRONOS**

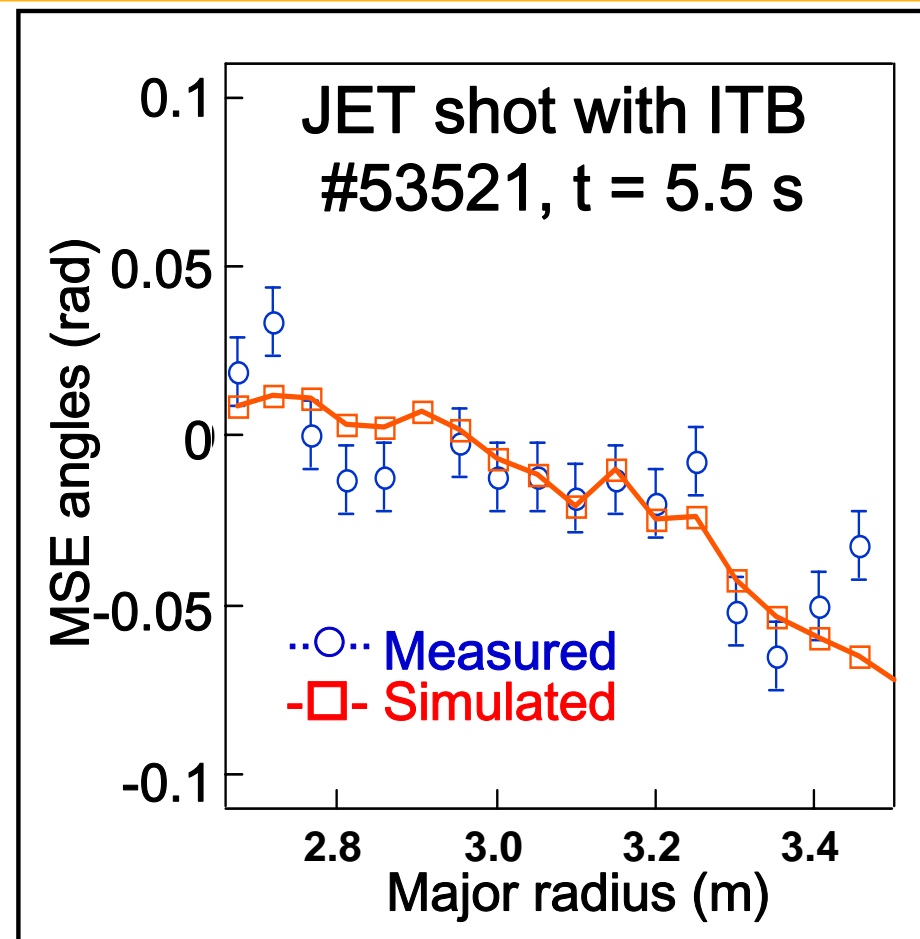
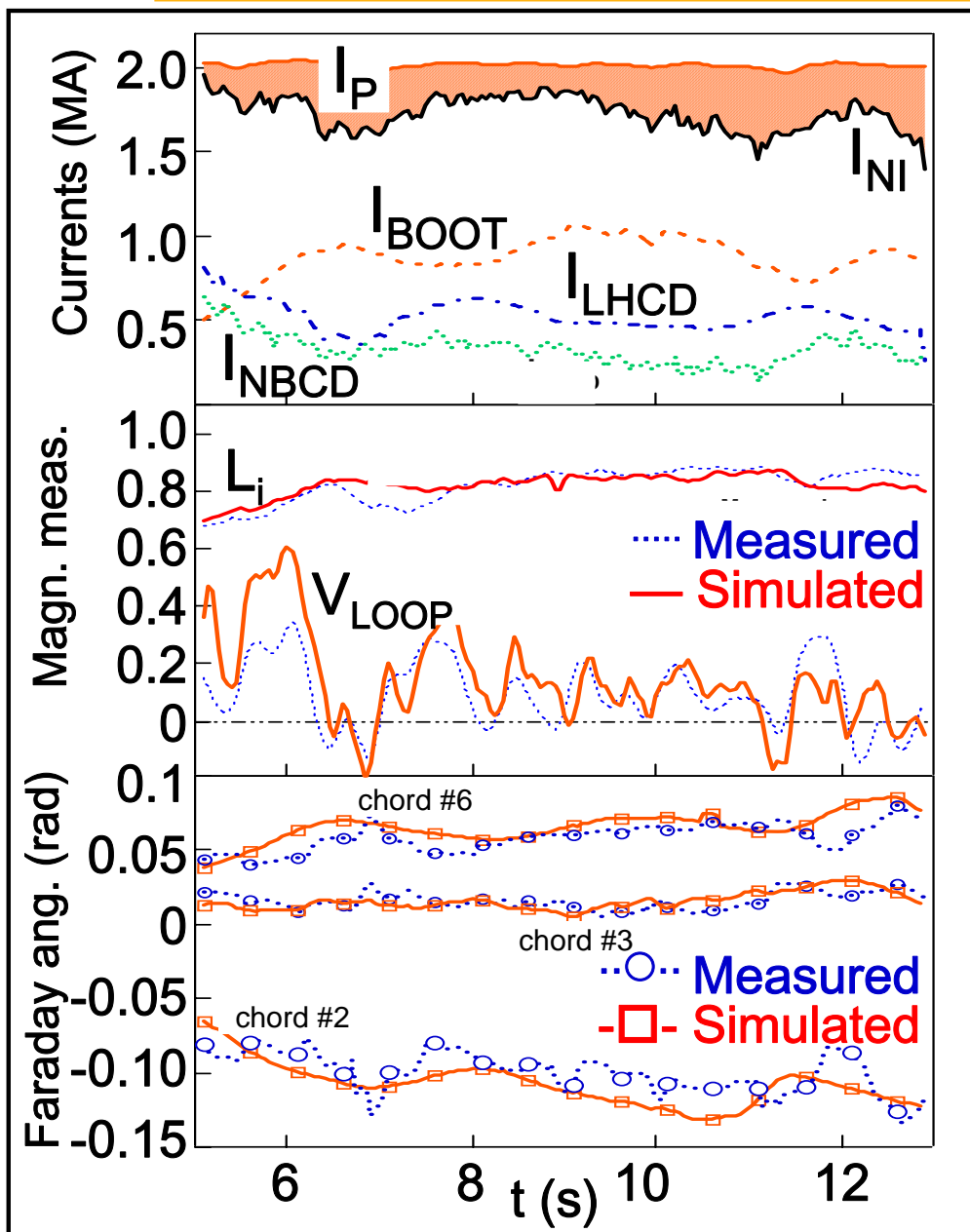
- SINBAD provides SPOT with the initial characteristics of NBI fast ions
- SPOT reconstructs the NBI fast ion source by generating MonteCarlo particles according to this fast ion distribution function.
- SPOT follows the guiding centre of the NBI fast ions inside the plasma and provides:
  - ⇒ density  $n_{\text{NBI}}$ , current  $j_{\text{NBI}}$ , transferred power  $P_{e,i}$ , fast ion losses



# Code validation



# An example of CRONOS interpretative simulation (JET)

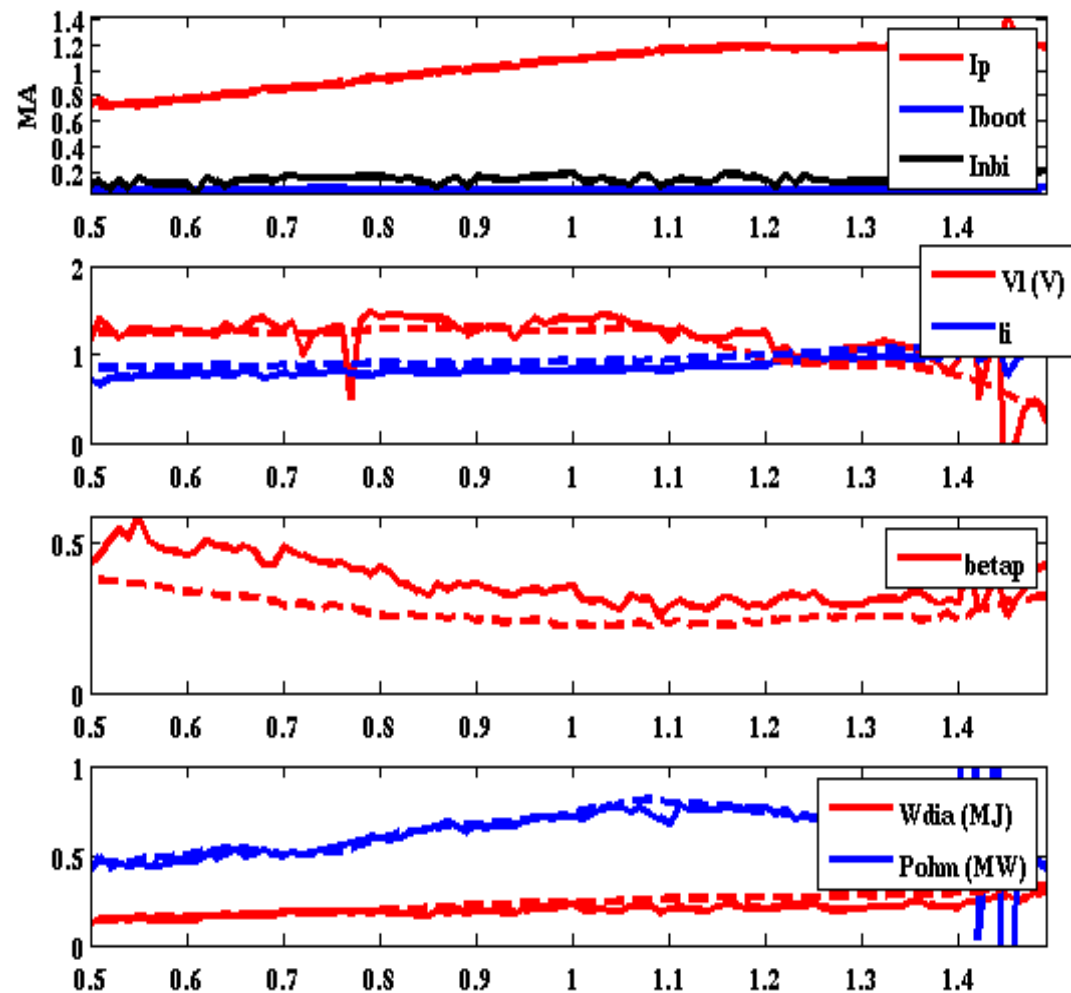


X. Litaudon *et al.*, Nucl. Fusion 44 (2002)

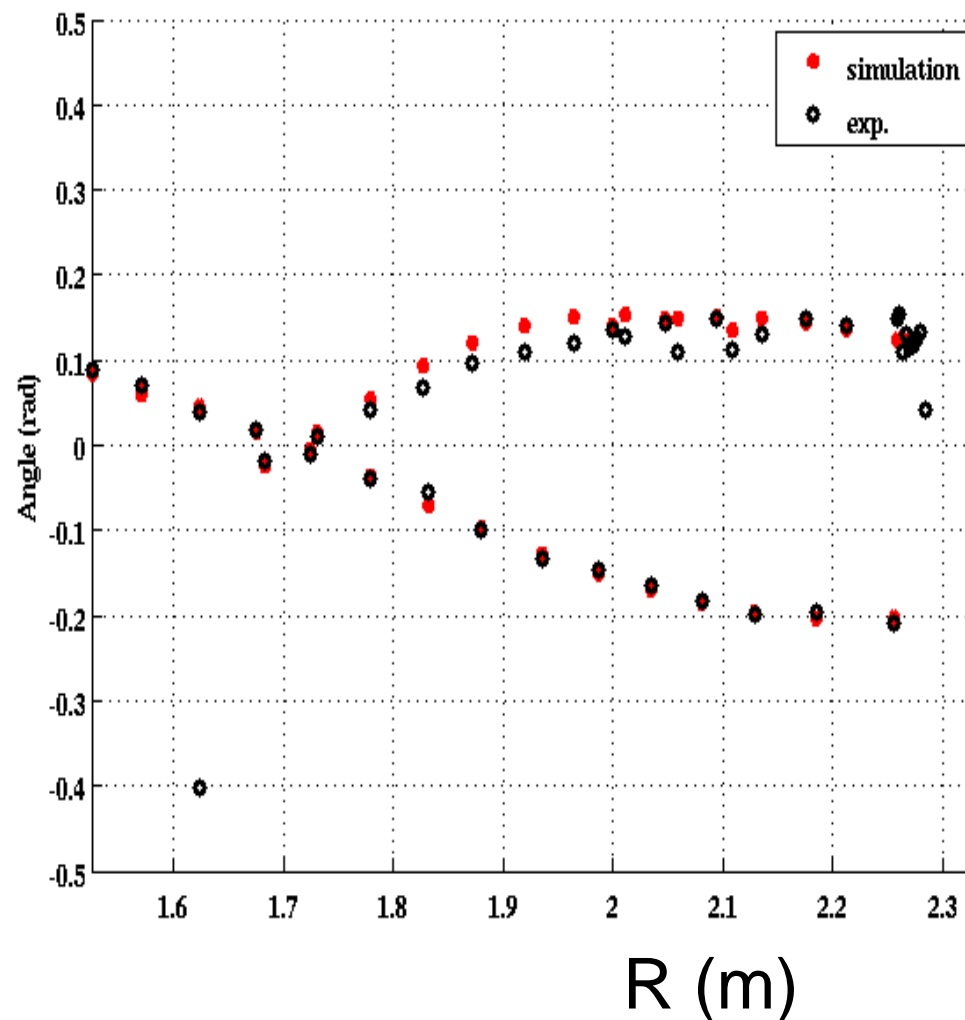
➔ CRONOS is able to reproduce diagnostic signals.

## MSE angles vs R

shot #119562 comparison with EFIT01 data (--)

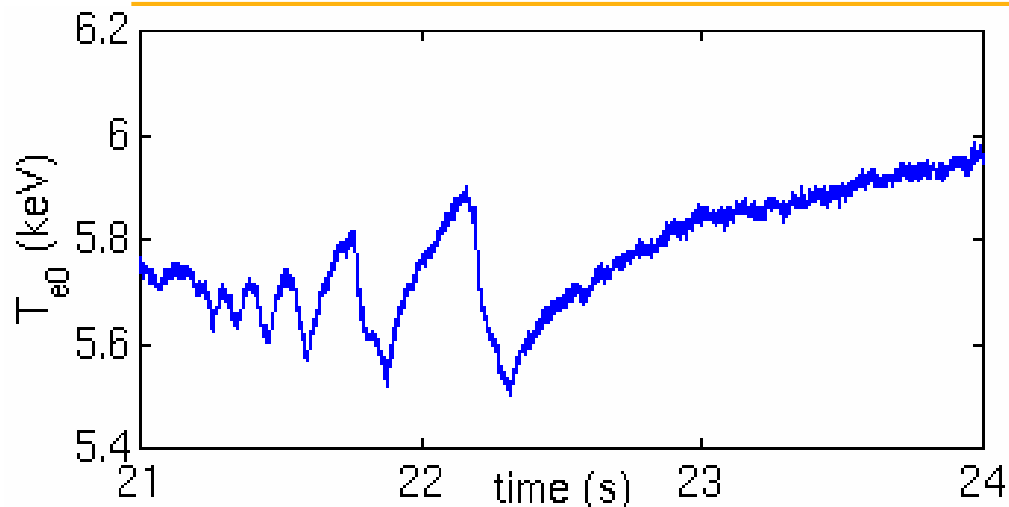


choc DIII-D #119562,  $t = 0.5:0.01:1.5$ , nbrho = 101



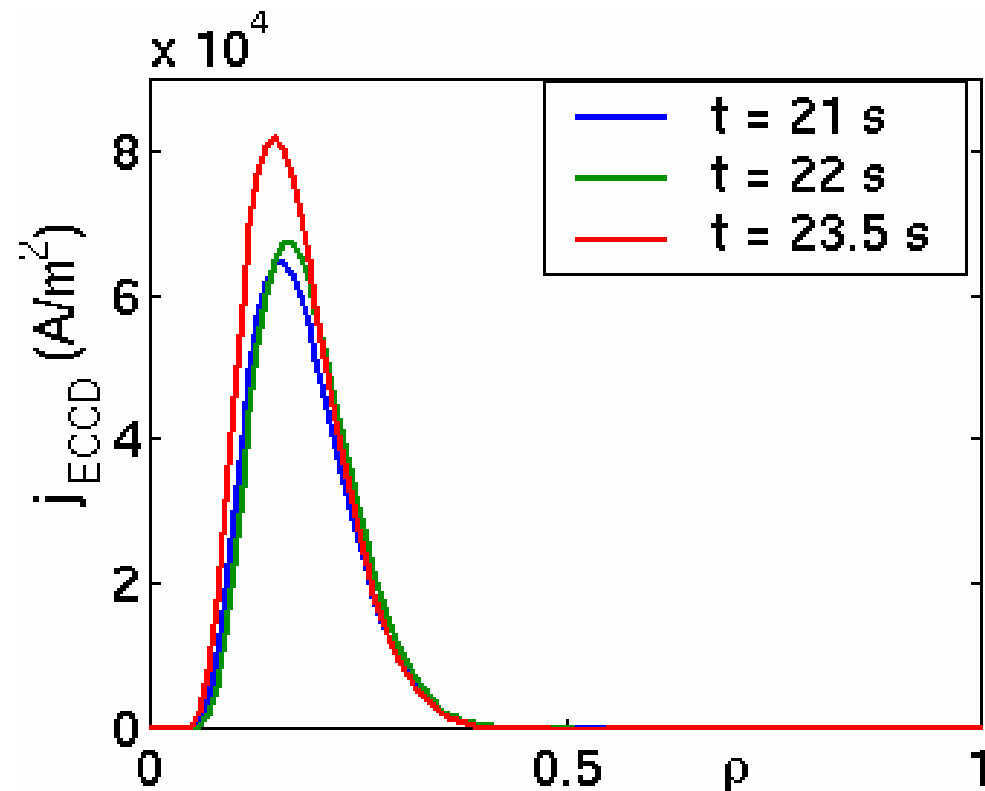
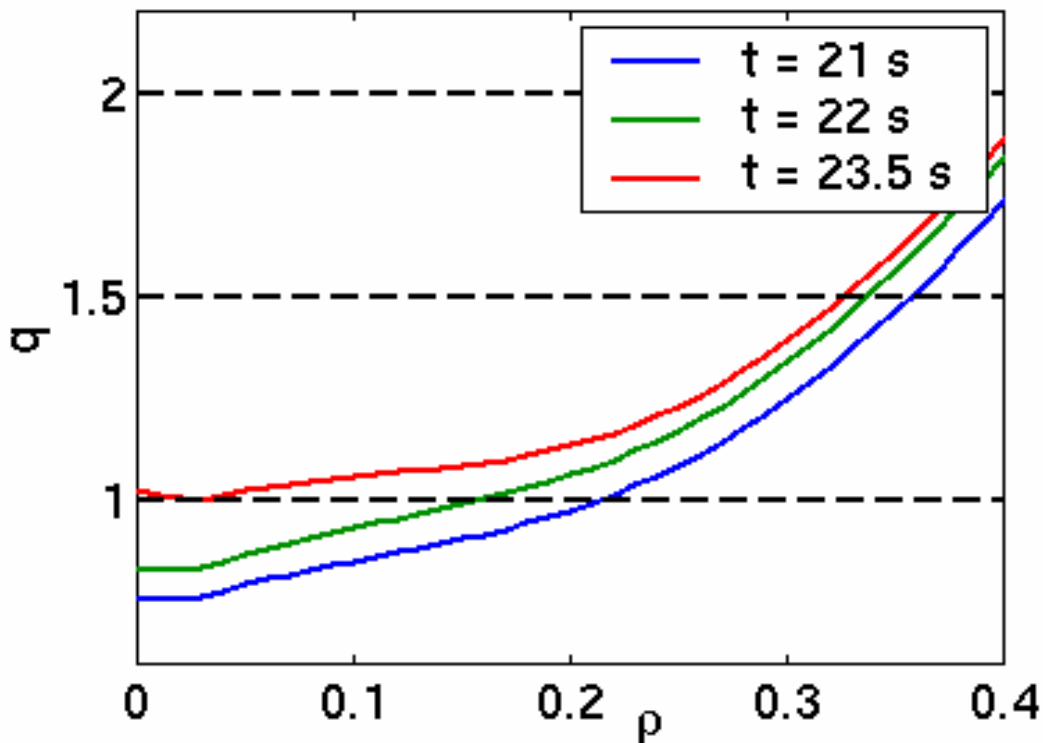


# Appearance/suppression of MHD relaxations reproduced in Tore Supra



**Tore Supra** LHCD+ECCD shots

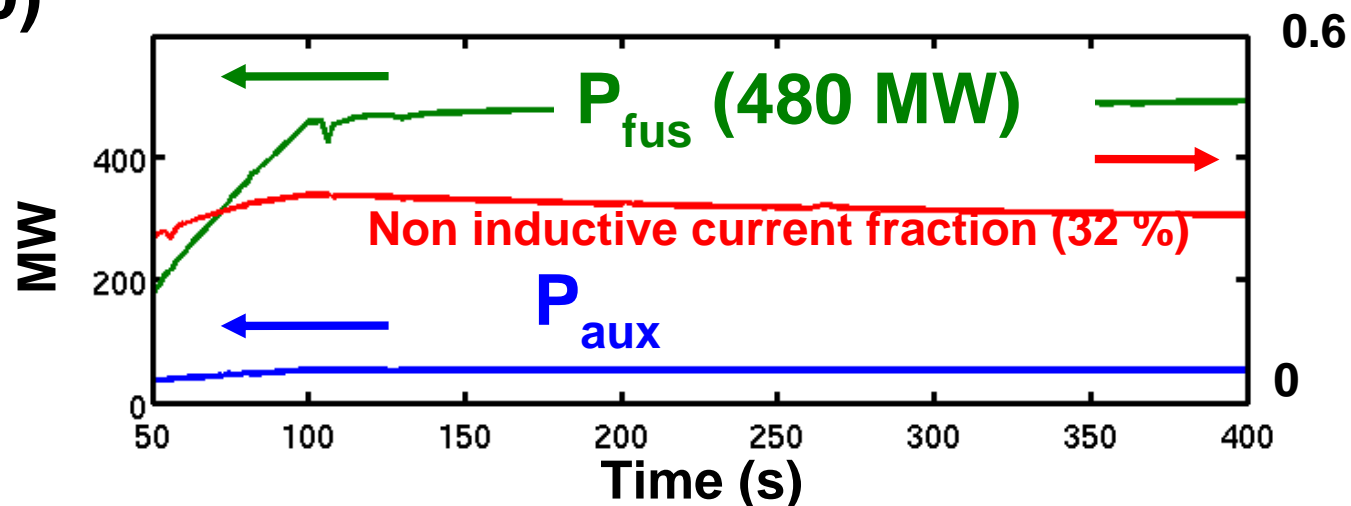
**Validation of:**  
REMA+CRONOS (ECCD and current diffusion)



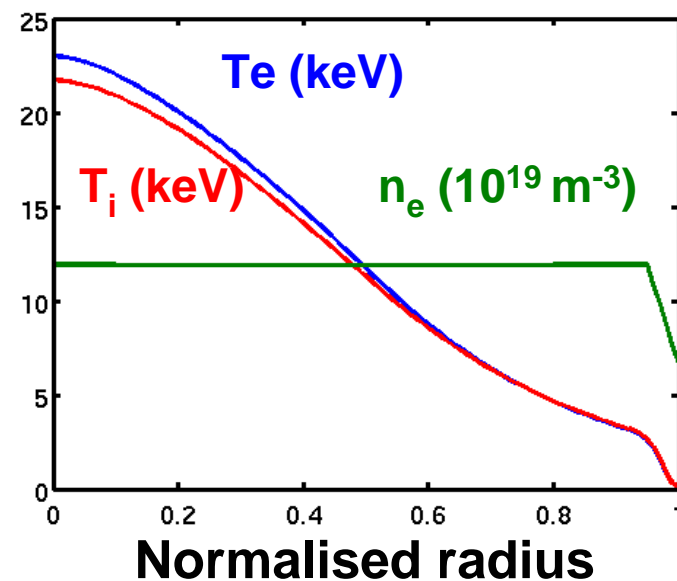
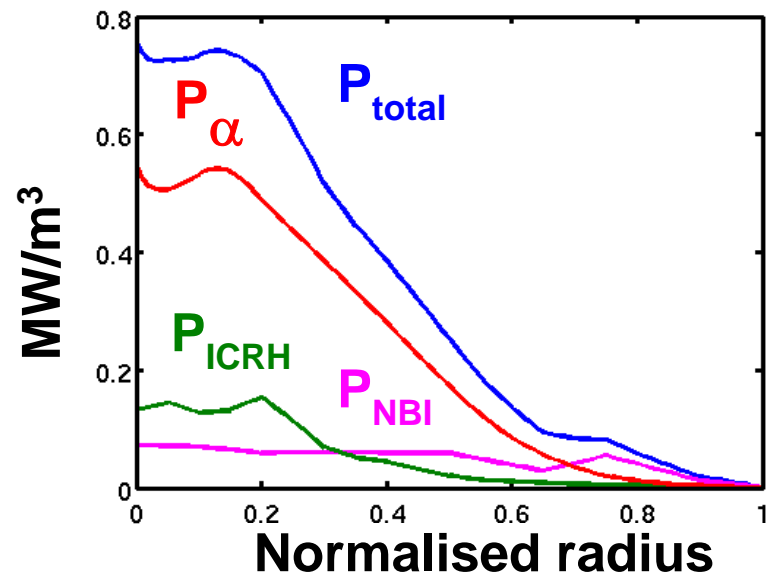
# Application to ITER scenarios

Designed reference scenario well confirmed by integrated simulation ( $Q \sim 10$ )

$P_{aux} = 20 \text{ MW ICRH} + 30 \text{ MW NBI}$

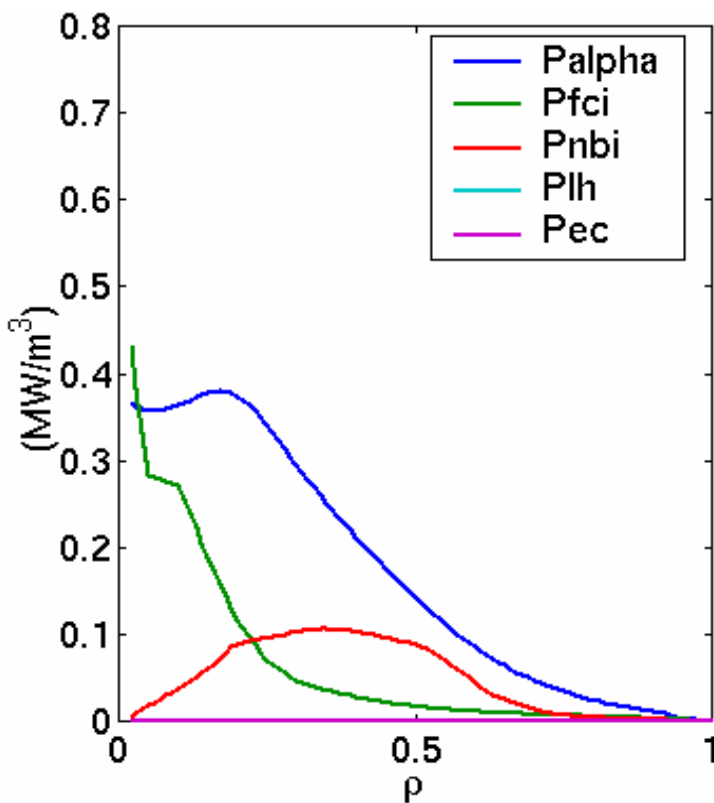
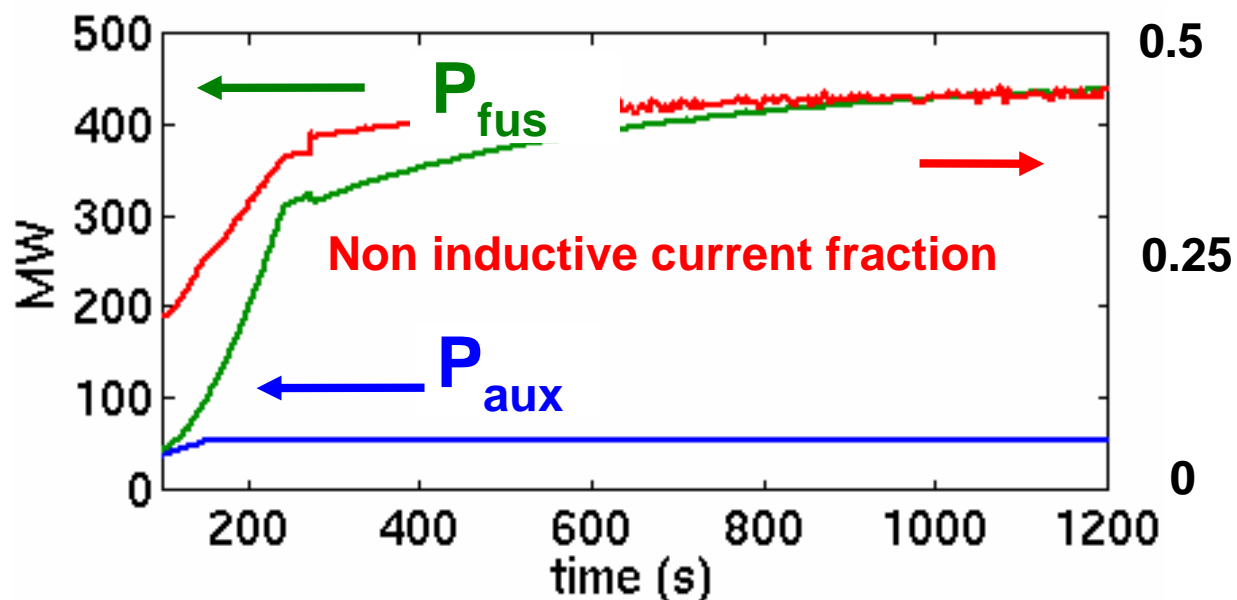


*Using empirical transport model according to 0-D scaling law (kiauto)*

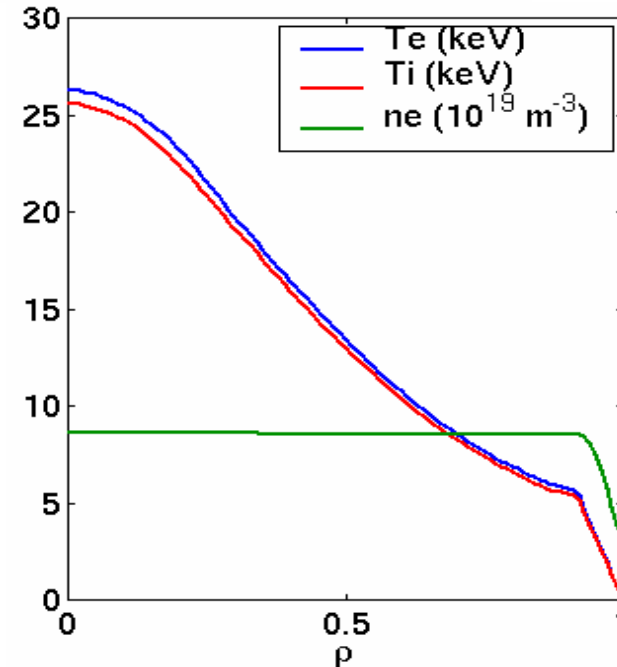


**$Q \approx 8$  can be achieved**

**$P_{aux} = 20$  MW ICRH  
+ 30 MW NBI**

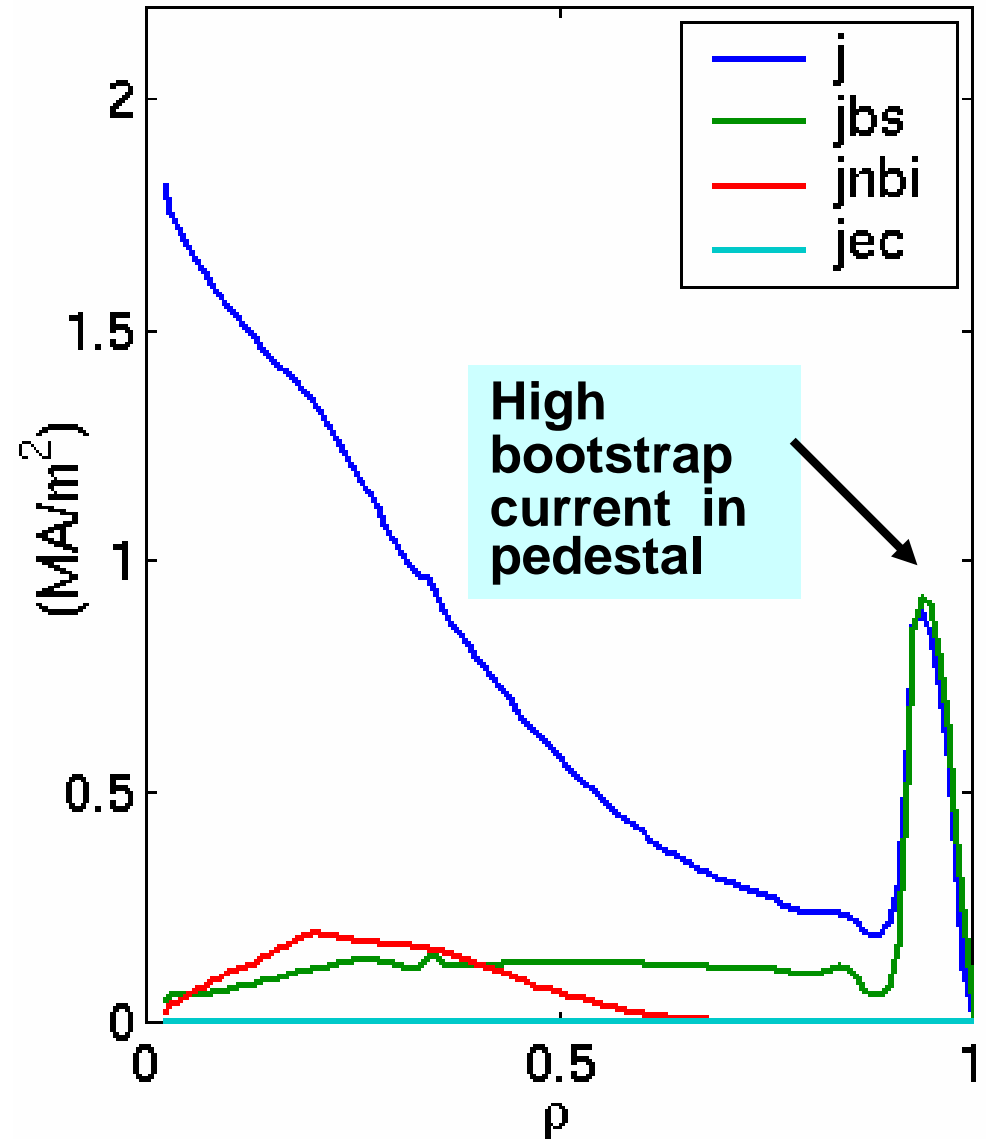


*Using transport model GLF23 based on first principle*

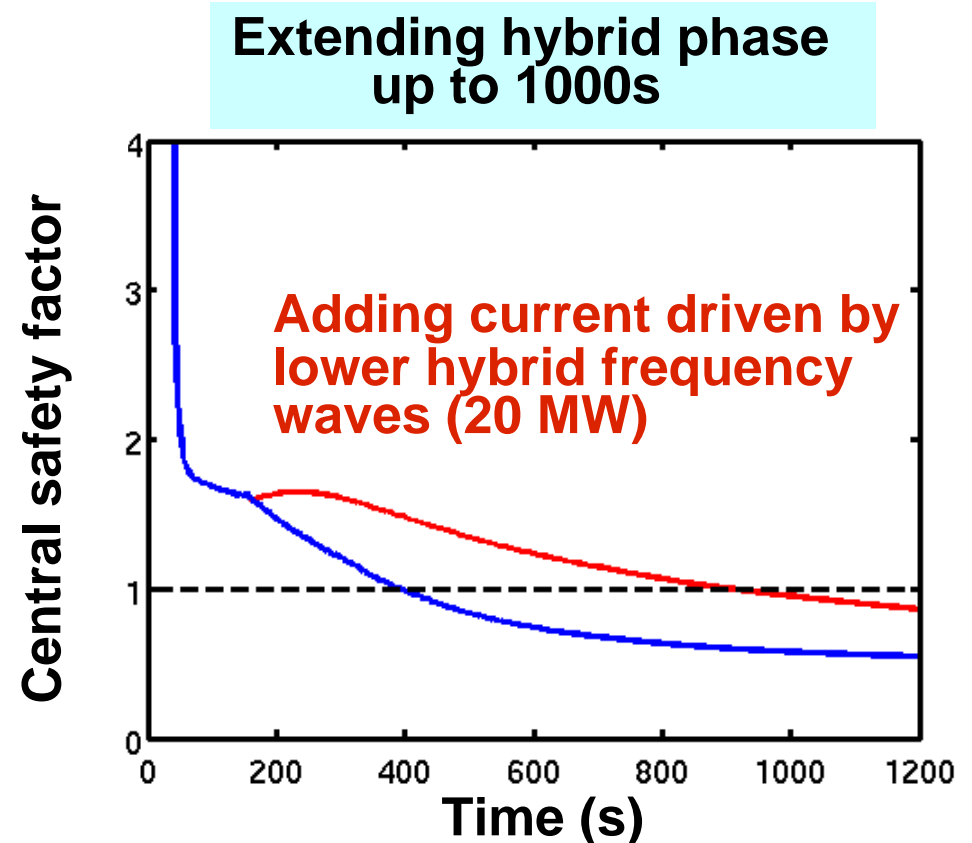
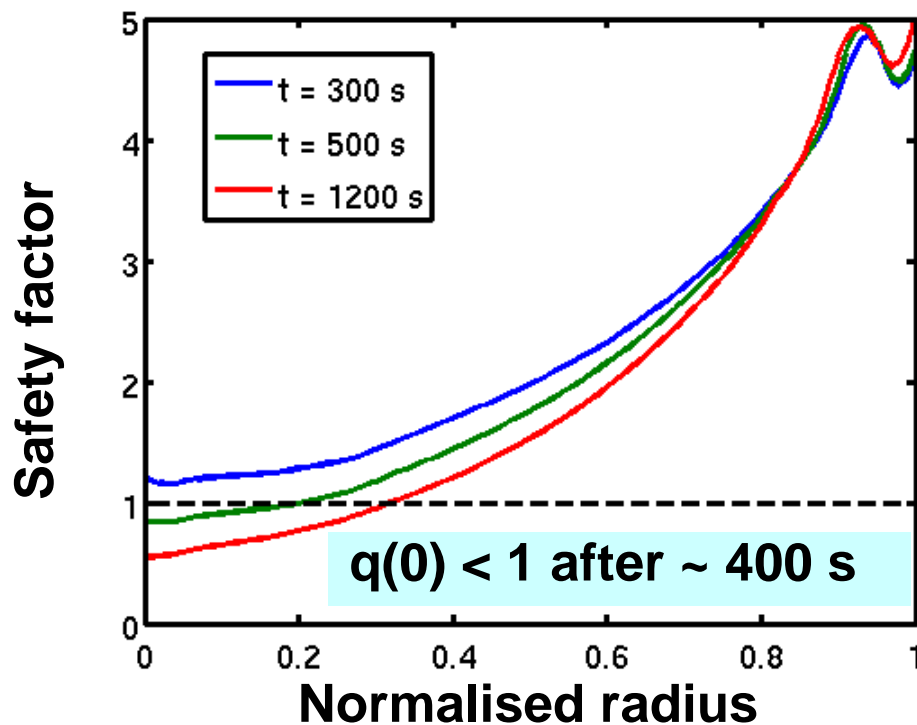


About half of the plasma current is non-inductively driven:

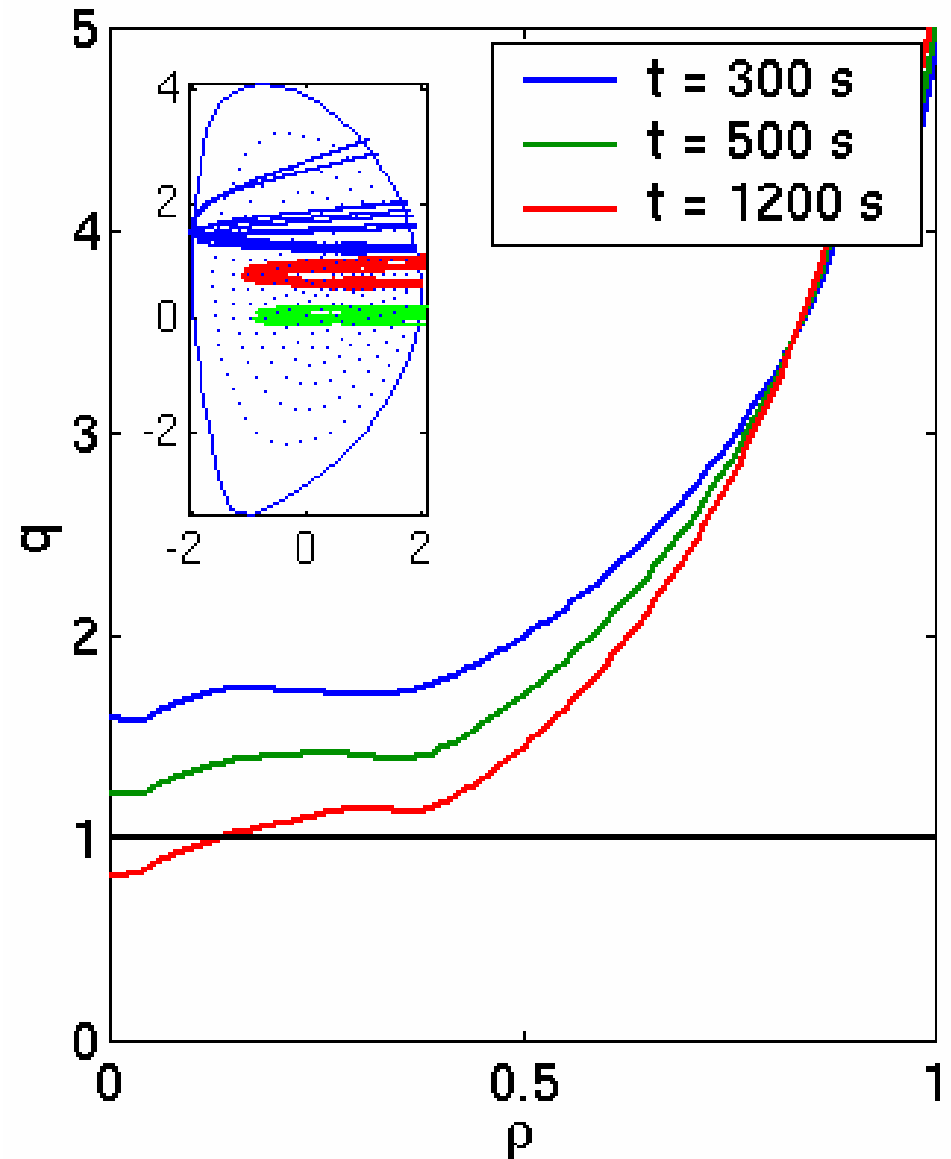
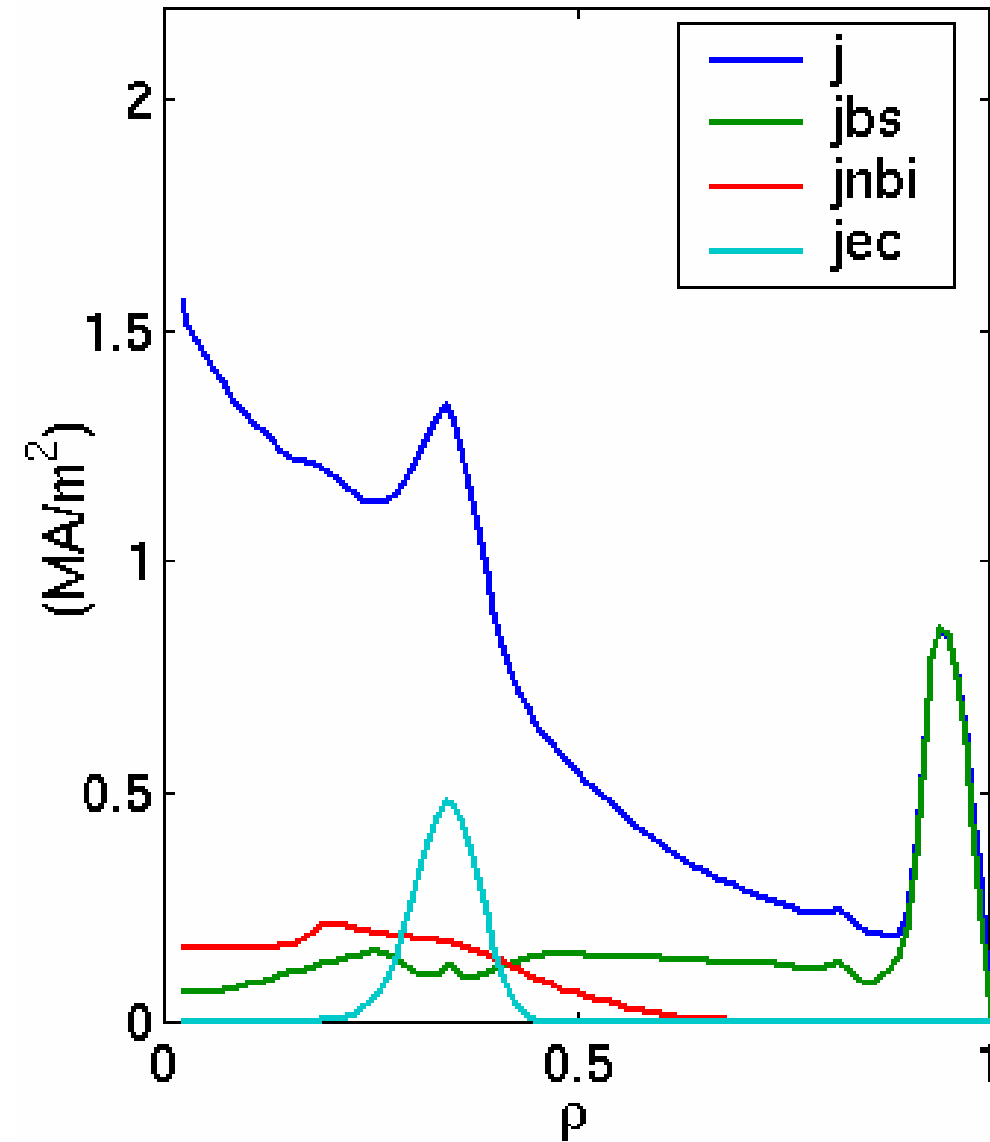
- **10% by Neutral Beam injection**
- **40% self-generated by pressure gradient (bootstrap current), located mainly in the pedestal**



- Hybrid regime disappears after 400s ( $q$  below 1)
- **Optimise resistive current diffusion**
- **Need to increase external non-inductive current drive to maintain safety factor above 1**



$t = 1200 \text{ s}$

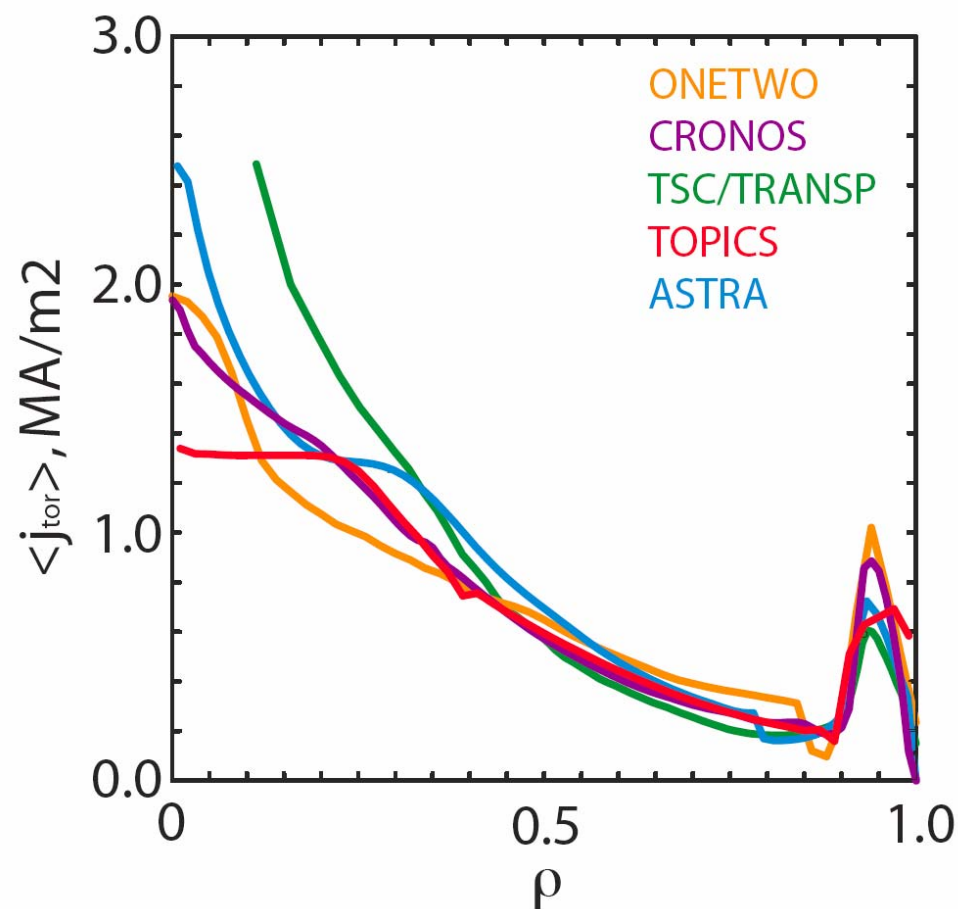
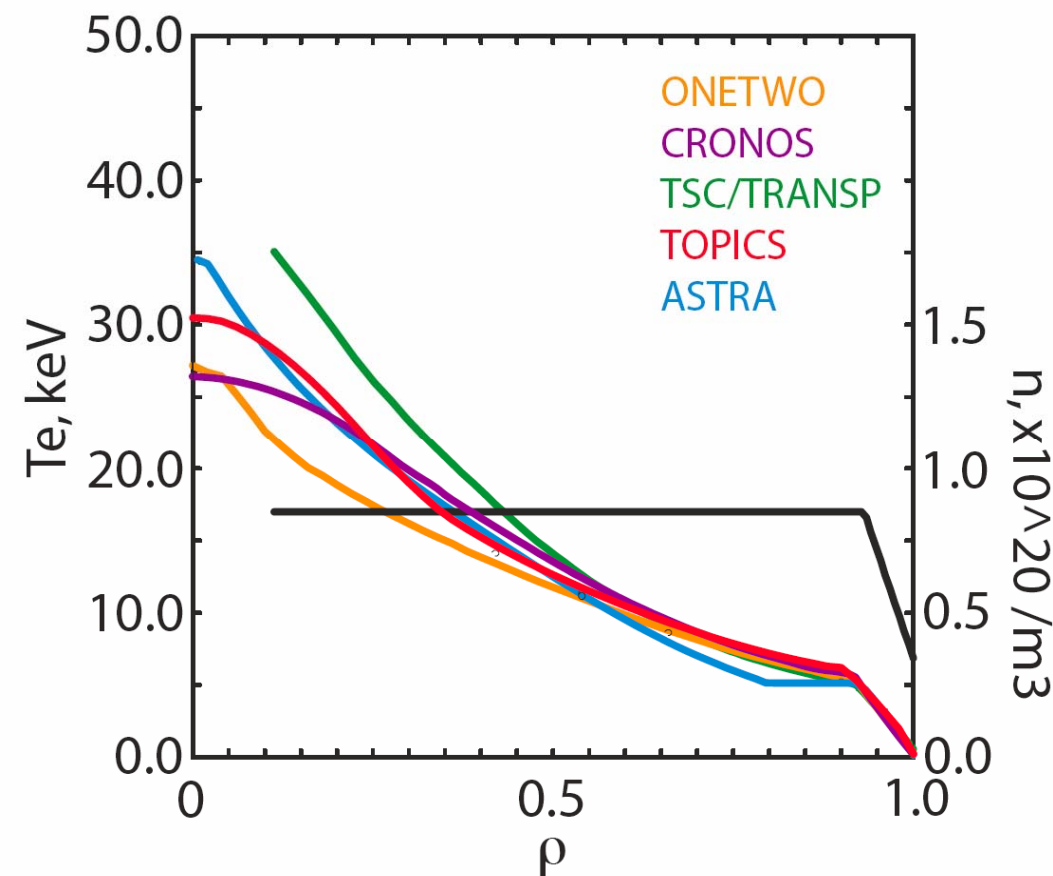


# ITPA-SSO Code Benchmark (hybrid regime)

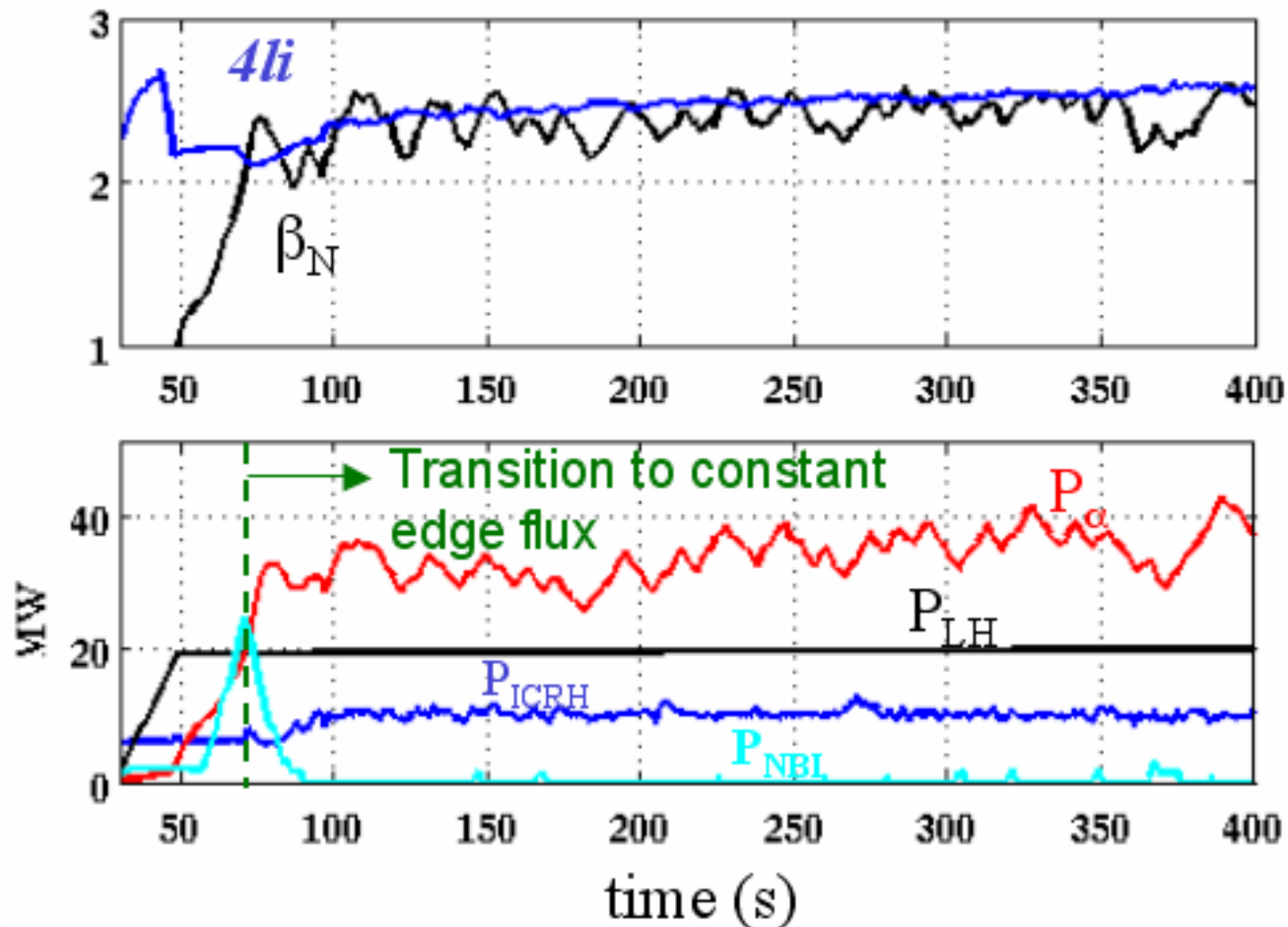
*C.E. Kessel, G. Giruzzi, et al., IAEA 2006*

$I_p = 12 \text{ MA}$   
 $\tau_p^*/\tau_E = 5.0$   
 $T_{ped} = 5.0 \text{ keV}$

$P_{NBI} = 33 \text{ MW (1 MeV, off-axis)}$   
 $P_{ICRF} = 20 \text{ MW (53 MHz)}$   
 transport model: GLF23



- **Multiple feedback control on the steady-state scenario (9 MA): aims at sustaining internal transport barrier without exceeding operational limits and obtaining the prescribed Q**



# Planned evolutions

## Short term

- Coupling to other equilibrium codes (in particular, free-boundary)
- **Coupling to DINA (to be completed) ← essential for ITER**
- Coupling to full-wave ICRH code EVE
- Integration of beam-tracing code for EC waves
- Add synthetic diagnostics

## Long term

- Particle and rotation sources and transport models
- New synchrotron loss module, with better treatment of wall reflections
- Integration of first-principle / empirical **pedestal** model
- Coupling to a **SOL** code
- Self-consistent MHD & turbulence modules
- Interface to RF antenna codes

- Improving the code reliability
- New equilibrium solver integrating current diffusion (robustness)
- Numerical optimisation of slower modules
- Parallelization of various modules
- Web site, users' forum, etc.
- Archive of simulations
- New core solver (2-D for easier core-edge coupling ?)
- New graphical I/O interface
- Expanding and improving users' guide (both text and on-line)

## Significant progress required :

- **Coupled transport with improved predictive models :**
  - **current**
  - **heat**
  - **rotation**
  - **particles**
  - **impurities**
- **Precise pedestal predictions**
- **Modelling  $\alpha$ -particle distribution self-consistently with  $\alpha$ -driven Alfvén modes**
- **Detailed simulations of the whole plasma (including SOL and divertor)**
- **Improved module for synchrotron radiation (important for reactor)**
- **Apply to optimise reactor design**

## Radiation profiles in DEMO

EXATEC prediction, code coupled with CRONOS

