DE LA RECHERCHE À L'INDUSTRIE

Modelling of fusion plasma scenarios

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Outline

- the concept of plasma scenario
- the fusion plasma simulator
- main ingredients and approximations
- hierarchy of integrated modelling codes
- examples of ITER scenario simulations

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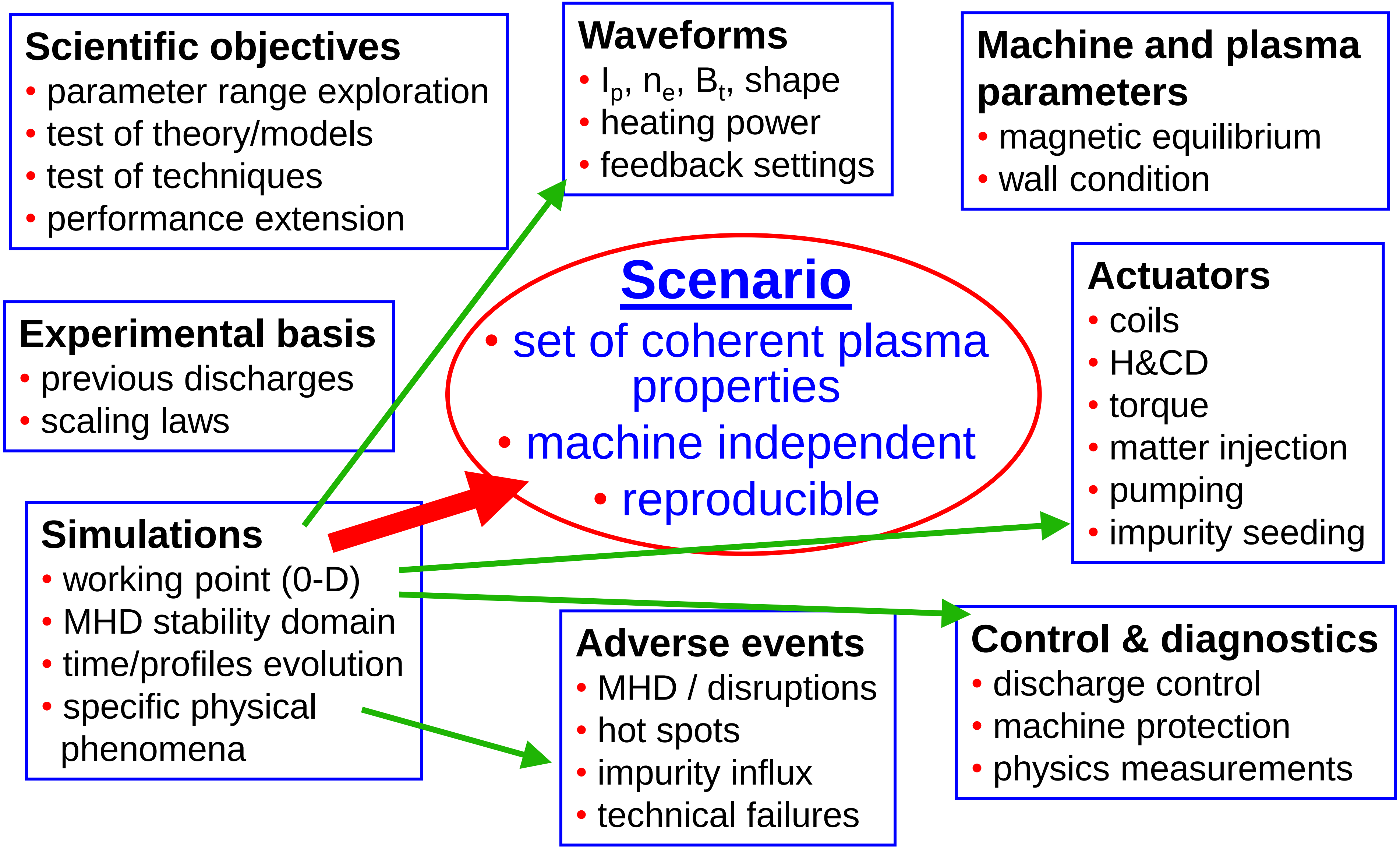
THE CONCEPT OF PLASMA SCENARIO

Plasma scenarios and the role of simulations



Scientific objectives

- parameter range exploration
- test of theory/models
- test of techniques
- performance extension

Waveforms

- I_p, n_e, B_t, shape
- heating power
- feedback settings

Machine and plasma parameters

- magnetic equilibrium
- wall condition

Experimental basis

- previous discharges
- scaling laws

Scenario

- set of coherent plasma properties
- machine independent
- reproducible

Actuators

- coils
- H&CD
- torque
- matter injection
- pumping
- impurity seeding

Simulations

- working point (0-D)
- MHD stability domain
- time/profiles evolution
- specific physical phenomena

Adverse events

- MHD / disruptions
- hot spots
- impurity influx
- technical failures

Control & diagnostics

- discharge control
- machine protection
- physics measurements

ITER and DEMO scenario design: physics challenges

- **Experimental scenarios exist, but are they extrapolable to ITER/DEMO ?**
  - different **dimensionless** parameter range (ρ^*, ν^*, β)
  - different properties of **sources** (e.g., rotation, fast particles)
  - different **control** requirements
  - different level of **self-organization**

- **Scenario design by integrated tokamak modelling:**
  - a more and more **indispensable tool**, that starts to be efficient
  - neither first-principle nor empirical **transport models** fully reliable
  - **pedestal** is critical: progress on both models and database
  - **edge:** time consuming codes, coupling with core difficult
  - experimental **validation** of code modules
  - interplay with **MHD**: probably the most formidable challenge

ITER and DEMO scenario design: computational challenges

- **Challenges related to intrinsic computational complexity:**
  - first-principle **turbulence** codes
  - plasma **edge** codes
  - 3-D non-linear **MHD** codes
  - some **actuator** codes (NBI, ICRH)

- **Challenges related to code integration:**
  - global **reliability** decreases with number of modules
  - software architecture / use on massively **parallel** computers
  - inclusion of **transients** and **controls**
  - inclusion of all the **transport channels** extremely complex (electrons, ions, current, particles, momentum, impurities)

→ **coordinated EU effort on Integrated Tokamak Modelling**

THE FUSION PLASMA SIMULATOR

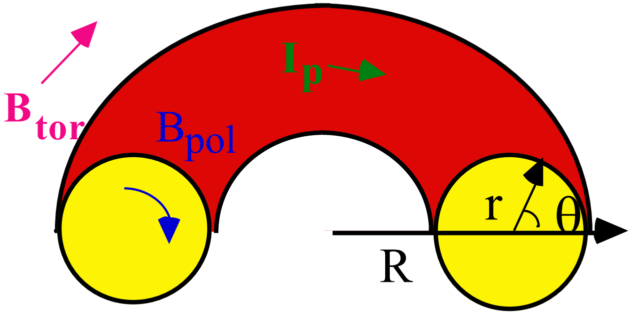
Why a fusion plasma simulator ?

- **Optimization of the operation**
- **Reactor safety issues**
- **Design next-step fusion reactors**
- **Development and validation of physics models**

- **extremely difficult and unpractical with a monolithic code (complex Physics/Technology coupling)**
- **Generations of modular simulators :**
  - **Various levels of approximation available for each element**
  - **Computing resources increase in time**
    ⇒ more and more accurate computations

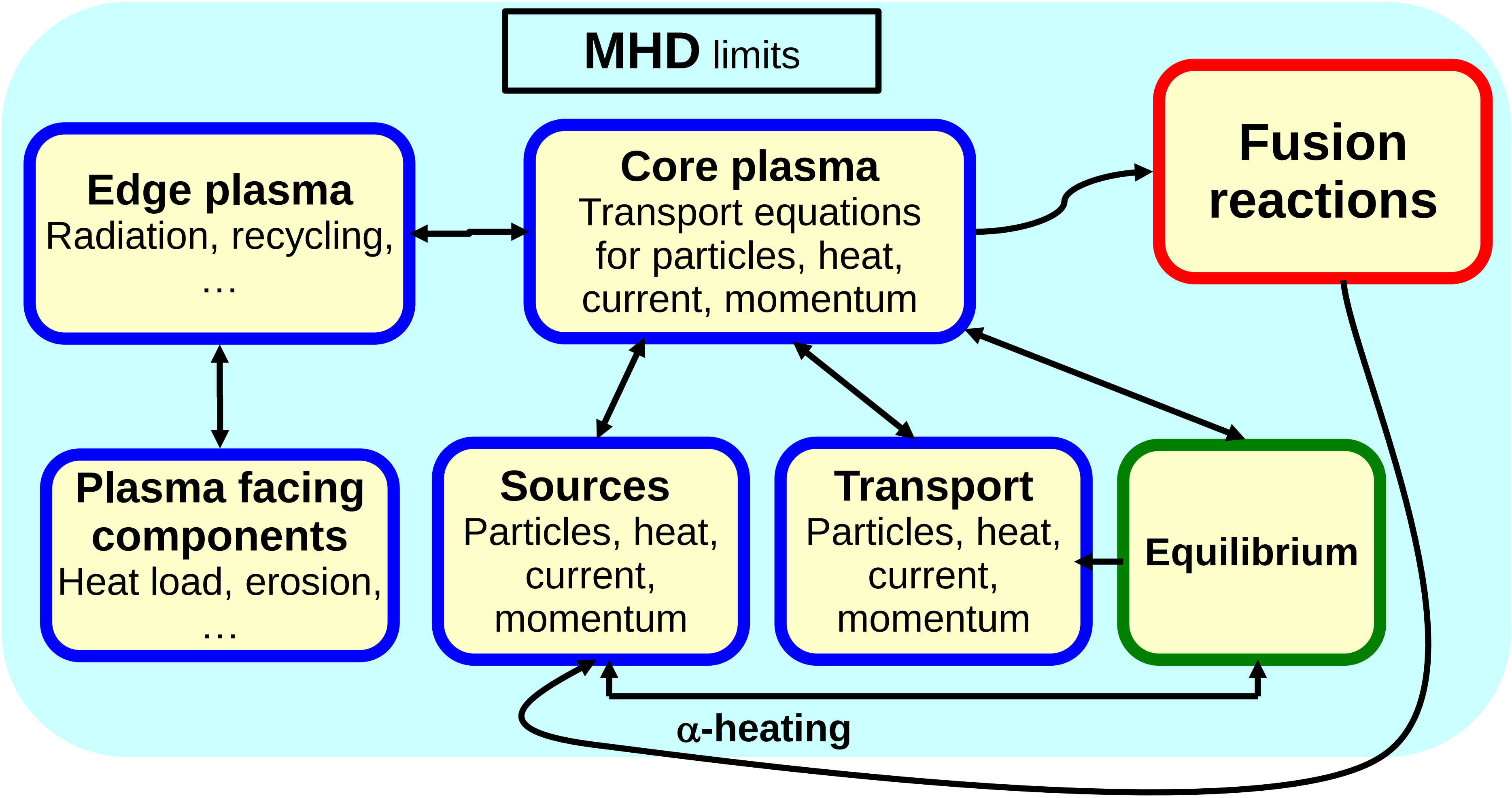
Basic ingredients of a fusion plasma simulator

- **Geometry: magnetic equilibrium**
  - at least 2-D (plasma shaping, separatrix) – 3D for stellarators
  - self-consistent with current and pressure evolution
- **Fluid equations (1-D)**
  - time evolution of n_e, n_i,T_e,T_i, j, V, impurities



- **Sources**
  - heat, injected matter, current, momentum, wall
- **Losses**
  - diffusion/convection of heat and particles
  - pumping / neutralisation
  - radiation (bremsstrahlung, synchrotron, line radiation)
  - viscosity
- **Link to machine data bases** (for application to experiments and validation of the models)

Numerical tokamak:
all couplings, all non-linearities



MHD limits

Edge plasma
Radiation, recycling, …

Core plasma
Transport equations for particles, heat, current, momentum

Fusion reactions

Plasma facing components
Heat load, erosion, …

Sources
Particles, heat, current, momentum

Transport
Particles, heat, current, momentum

Equilibrium

α-heating

Main challenges for the development of a fusion plasma simulator

- **Physics**
  - wide variety of **physics models** – all the fusion plasma physics
  - **integration** of physics and technology (example: antennas)
  - to remain as close as possible to the reality of **experiments**
  - include description of **actuators**, **controls**, **diagnostics**
  - compromise between accuracy and **approximations**

- **Computational**
  - integration of **tens of codes (modules)**
  - codes of different nature, **language**, generation, speed
  - complexity of **software achitecture / platform** conception
  - speed and memory **optimisation**
  - module **reliability**
  - **users**: many physicists, with different backgrounds

VARIOUS LEVELS OF SIMULATORS: EXAMPLES

Hierarchy of scenario modelling tools

seconds — minutes — hours — days — weeks

CPU time

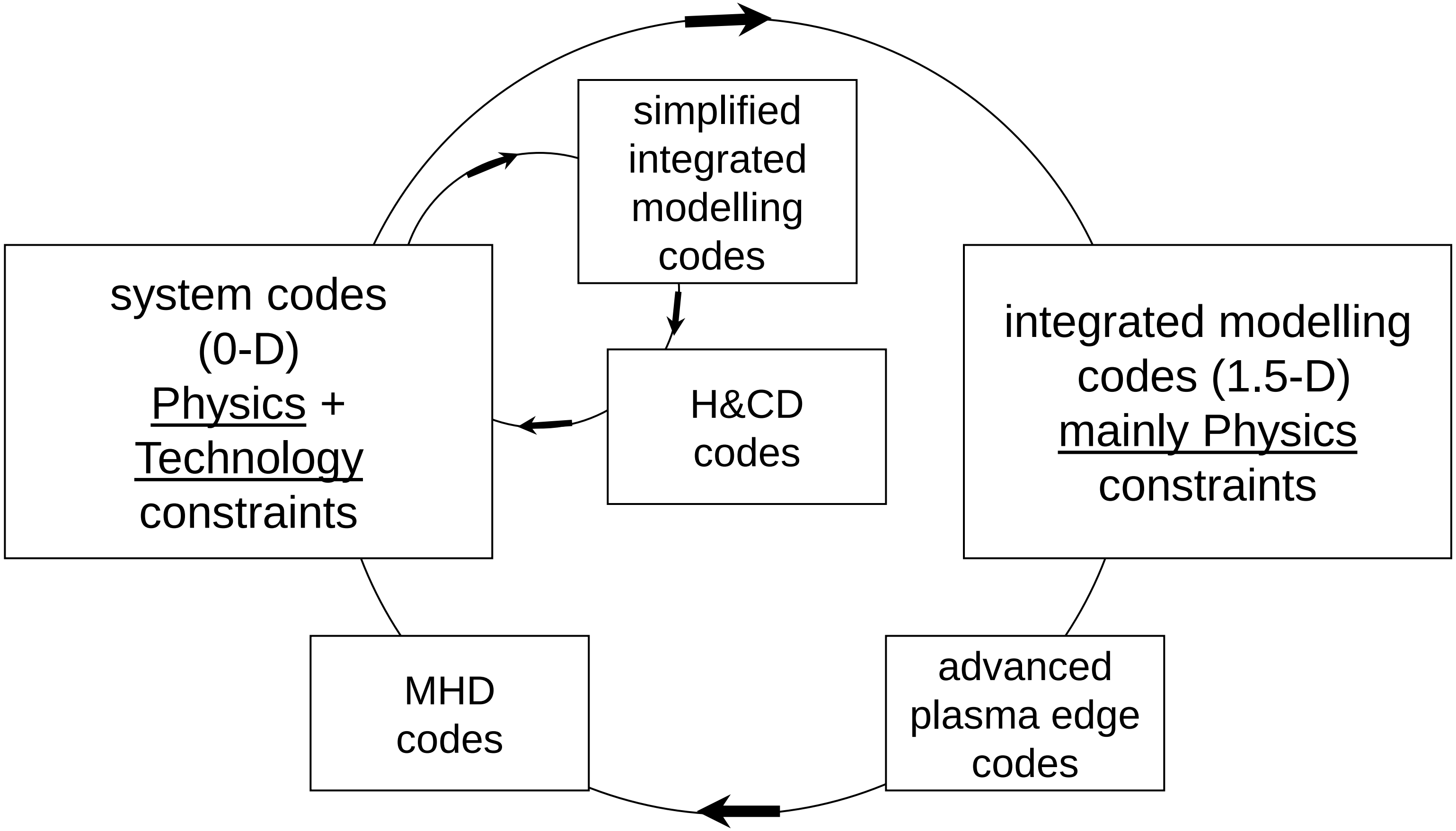
code outputs	working point average quantities	profile peakings time evolution simplified equilibrium	detailed profiles at a given time 2-D equilibrium	detailed profiles time evolution 2-D equilibrium	detailed profiles time evolution 2-D equilibrium 1st principle description of actuators & transport	detailed profiles time evolution 2-D equilibrium coil currents
code type	0-D	0.5-D	1.5-D snapshots mode	1.5-D simplified coefficients	1.5-D fixed boundary equilibrium	1.5-D free boundary equilibrium

1.5-D → 1-D profiles (n_e, T_e, T_i, j, …)
1.5-D → 2-D magnetic equilibrium

fixed boundary: plasma boundary is given, B field computed in the plasma

free boundary: B field computed in and outside the plasma from coils currents

Strategy for scenario analysis



simplified integrated modelling codes

system codes (0-D)
Physics + Technology constraints

H&CD codes

integrated modelling codes (1.5-D)
mainly Physics constraints

MHD codes

advanced plasma edge codes

reactor concept optimized by iterations

0-D scenario modelling tools /1

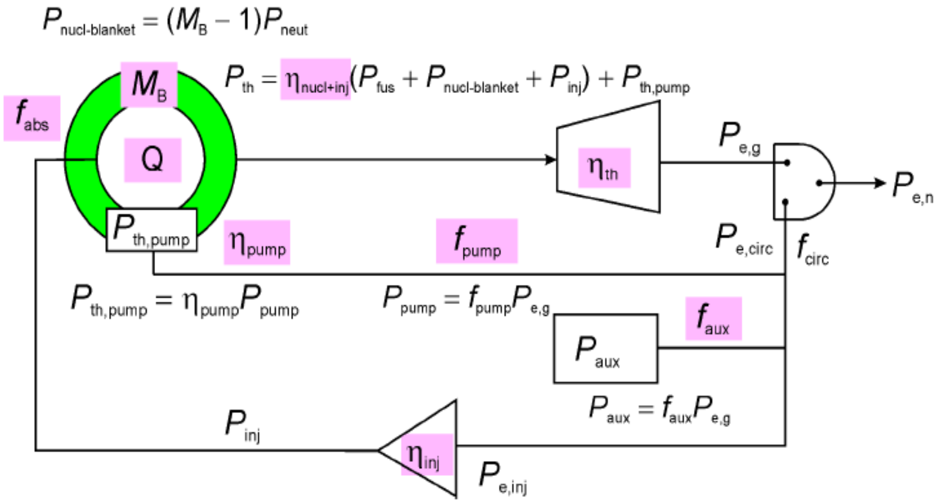
- computation of a "working point" for space-averaged plasma and machine parameters, with no time evolution
- solution of 0-D **core thermal equilibrium equation**

$$P_\alpha + P_{OH} + P_{add} = P_{brem} + P_{syn} + P_{line} + P_{cond}$$

heating /losses	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$
	alpha	ohmic	add. heating	brems-strahlung	synchrotron radiation	atom. line radiation	convection /diffusion

- physics constraints on He confinement, heat transport, plasma shape, CD efficiency, density limit, MHD, etc.

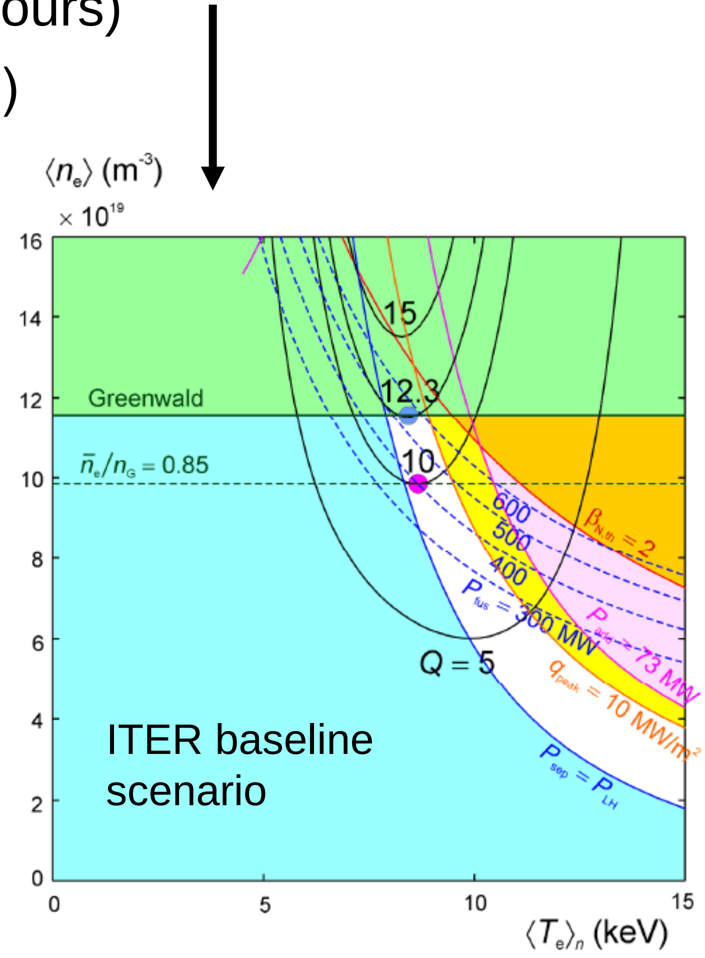
- technology constraints on divertor load, blanket properties, pumping, superconducting magnetic field, neutronics, conversion to electric energy, mechanics, etc.



0-D scenario modelling tools /2

- output: PopCon plots (plasma operation contours)
- example: **HELIOS** code (many other codes…)

  (J. Johner, Fusion Sci. Techn. ***59*** *(2011) 308)*



- possible automatic search of an optimum working point
- input: parameter boundaries and constraints
- example: **PROCESS** code

(D. Ward, Pl. Phys. Contr. Fus. ***52*** *(2010) 124033)*

- optimisation may include cost !
- these are also called "**system codes**"
- analogous codes exist in USA, Japan, etc.

1.5-D scenario modelling codes

- **1.5-D codes**: 1-D in space (minor radius coordinate) + 2-D equilibrium
- **output**: full time evolution of equilibria, radial profiles of fluid quantities (density, temperature, current density, plasma momentum) and global quantities (powers, currents, plasma energy, etc.)

Code name	**Lab/country**	**Strong points**
ASTRA	IPP / Germany	Many users, flexibility, open structure, reliability
JINTRAC	JET / EU - UK	Validation on JET data, coupling with edge, impurities, pellets
CRONOS	CEA / France	Modularity, H&CD modules, built-in controls, interface
ETS	EU	Integration in a platform of EU codes
TSC / TRANSP	Princeton / USA	Free-boundary capability, H&CD modules, validation on experiments
TOPICS	JAEA / Japan	H&CD modules, validation on Japanese experiments

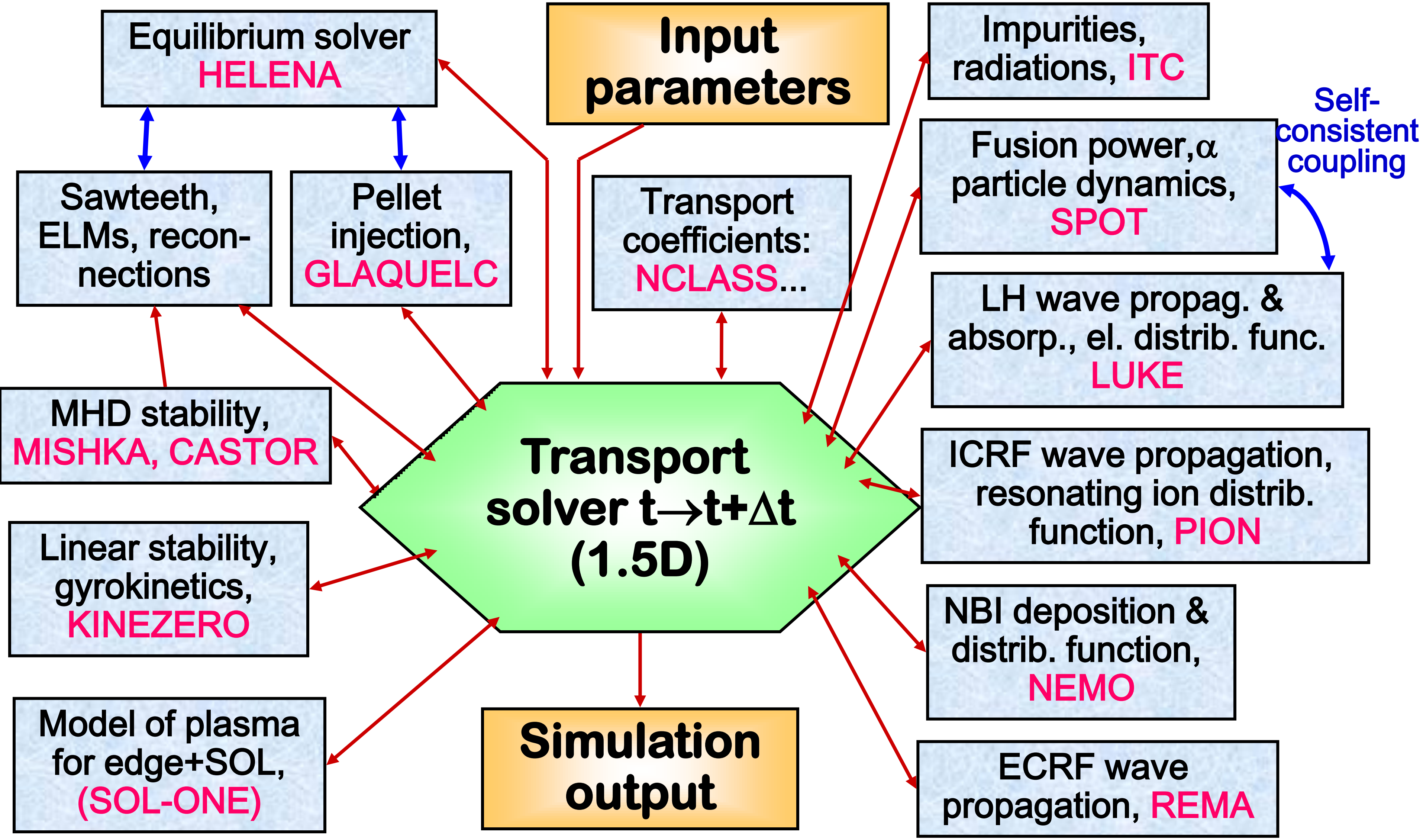
1.5-D scenario modelling tools. An example: the CRONOS suite of codes

- **Integrated modelling of:**
  - Heat, particles, rotation ⇒ transport diffusion equations **(1D)** (heat, matter), source codes
  - Current profiles ⇒ current diffusion equation **(1D)**
  - Plasma equilibrium ⇒ magnetic equilibrium code **(2D)**
- **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. [J.F. Artaud et al., Nuclear Fusion **50** (2010) 043001]

- **Built-in feedback controls**
- ~900 000 lines Fortan 77, ~75 000 lines Fortran 90/95, ~100 000 lines C, ~12 000 lines C++, ~550 000 lines Matlab

The CRONOS platform



Equilibrium solver
HELENA

Input parameters

Impurities, radiations, ITC

Self-consistent coupling

Fusion power,α particle dynamics, SPOT

Sawteeth, ELMs, reconnections

Pellet injection, GLAQUELC

Transport coefficients: NCLASS...

LH wave propag. & absorp., el. distrib. func. LUKE

MHD stability, MISHKA, CASTOR

Transport solver $t \rightarrow t+\Delta t$ (1.5D)

ICRF wave propagation, resonating ion distrib. function, PION

Linear stability, gyrokinetics, KINEZERO

NBI deposition & distrib. function, NEMO

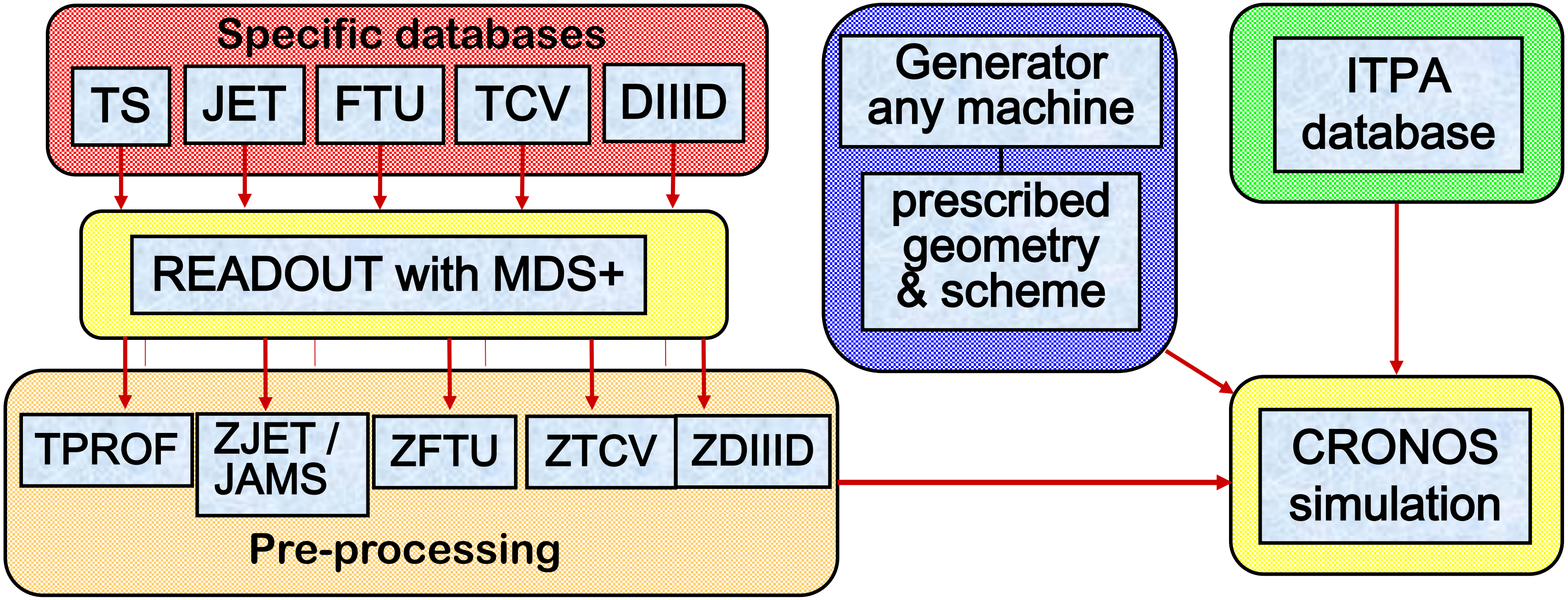
Model of plasma for edge+SOL, (SOL-ONE)

Simulation output

ECRF wave propagation, REMA

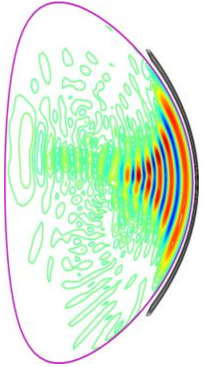
CRONOS and databases

User-friendly graphic interface (MATLAB):



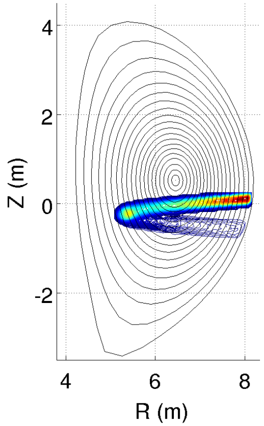
⇨ Experimental data converted into standard data structure readable by CRONOS.

Heat Source modules



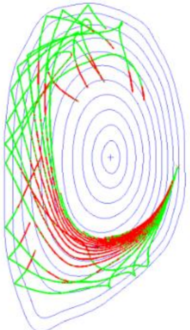
PION (Ion Cyclotron Heating)

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



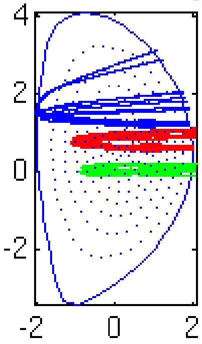
NEMO/SPOT (Neutral Beam Injection)

- orbit following MonteCarlo code
- <u>output</u>: heat, particle, current and rotation sources



LUKE (Lower Hybrid Current Drive)

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



REMA (Electron Cyclotron Heating & Current Drive)

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

Transport coefficients (neoclassical and anomalous)

NCLASS (neoclassical transport coefficients)

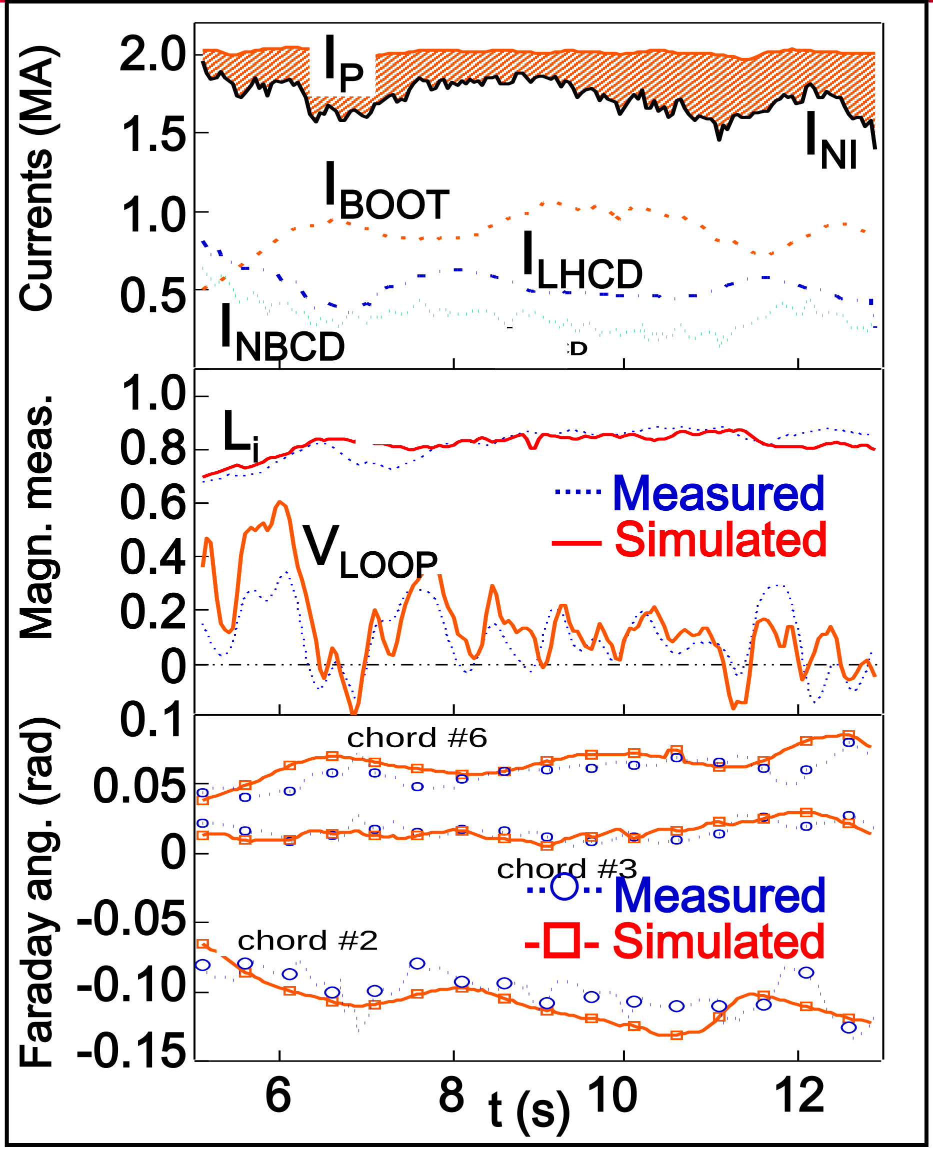
- multi-species, thermal, axisymmetric plasma, isotropic pressure
- output: resistivity, bootstrap, viscosity, heat diffusivity, etc.

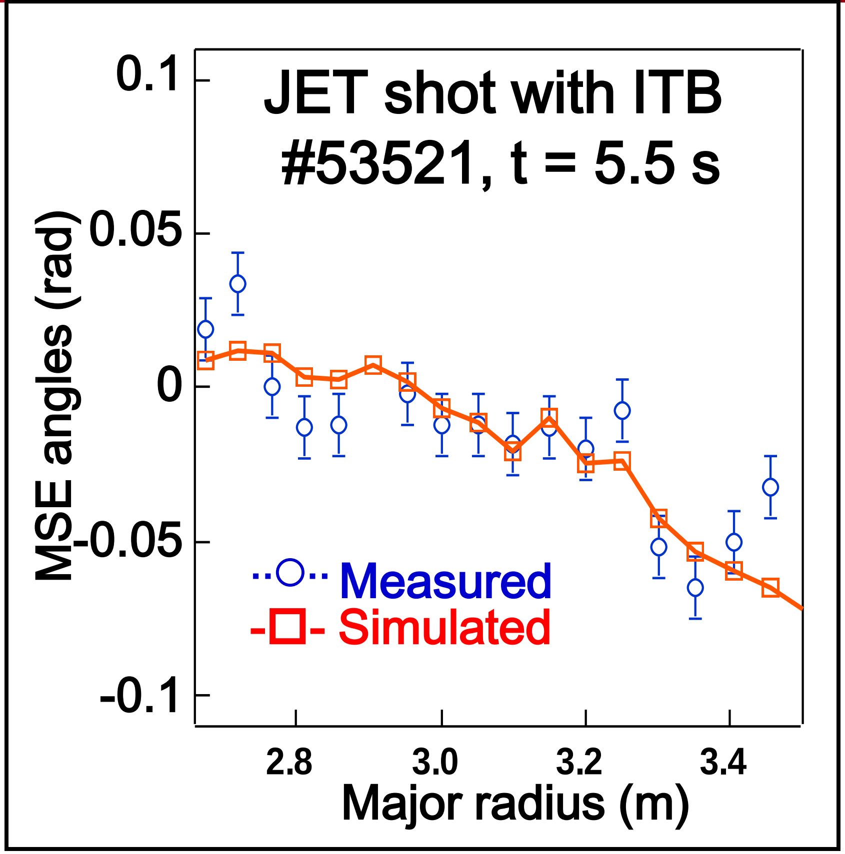
Anomalous transport models (turbulence physics)

- **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 / TGLF (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)
  - CDBM (current diffusive ballooning mode)

CRONOS validation by interpretative simulation of JET experiments





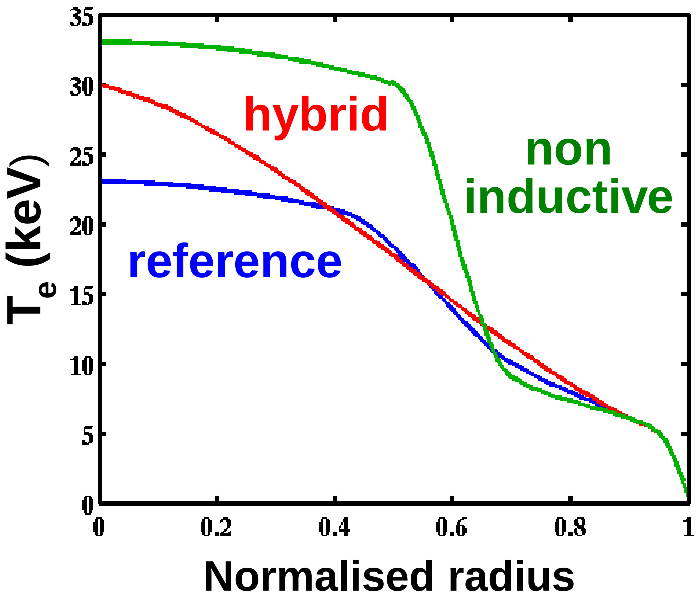
*X. Litaudon et al., Nucl. Fusion **44** (2002)*

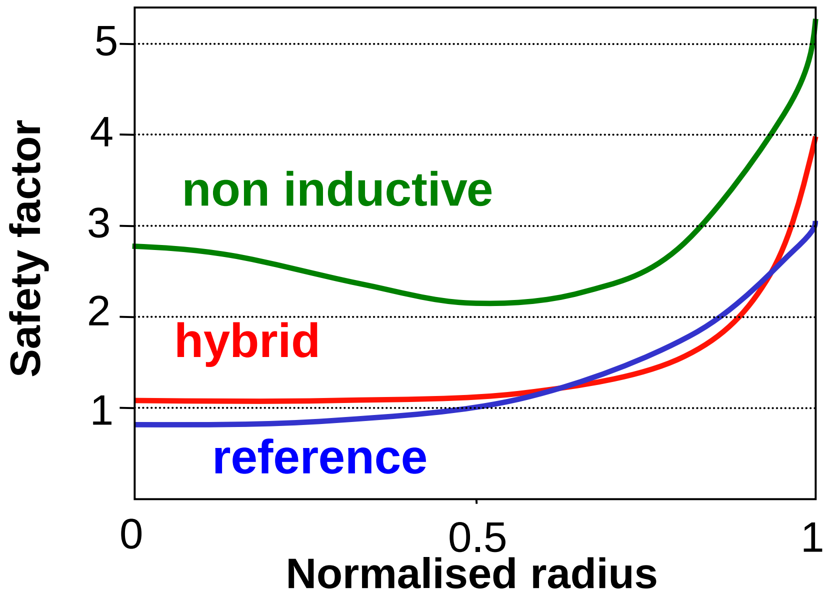
CRONOS is able to reproduce diagnostic signals.

ITER scenarios

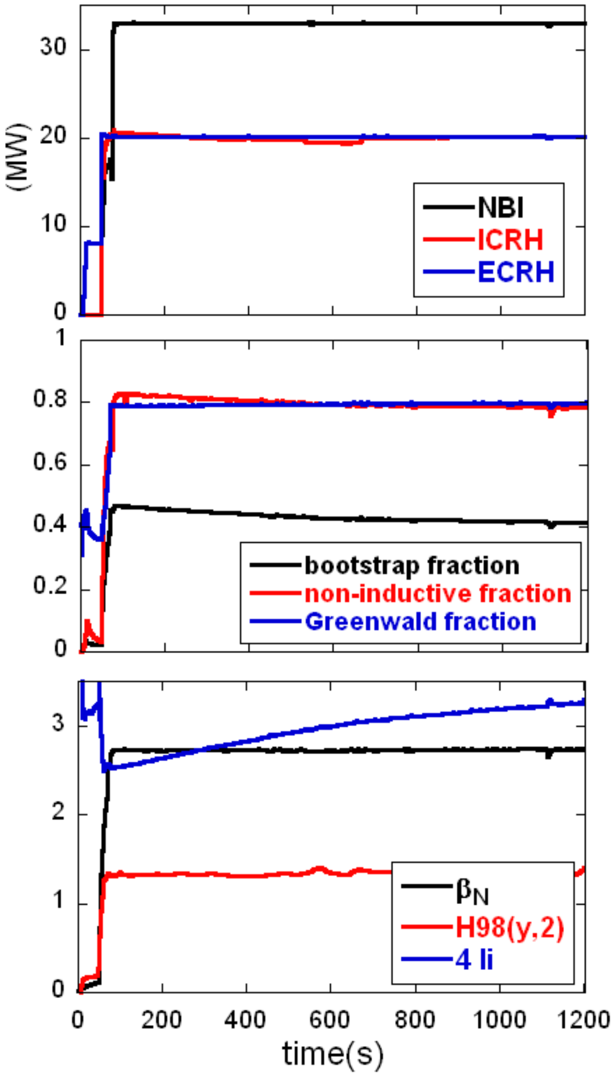
Scenario	Ip (MA)	Duration (s)	Q	Non inductive current
Reference	**15**	**~ 400**	**10**	**< 30 %**
Hybrid	**11 to 13**	**> 1000**	**5 to 10**	**~ 50 %**
Non inductive	**9**	**Steady state**	**~ 5**	**100 %**

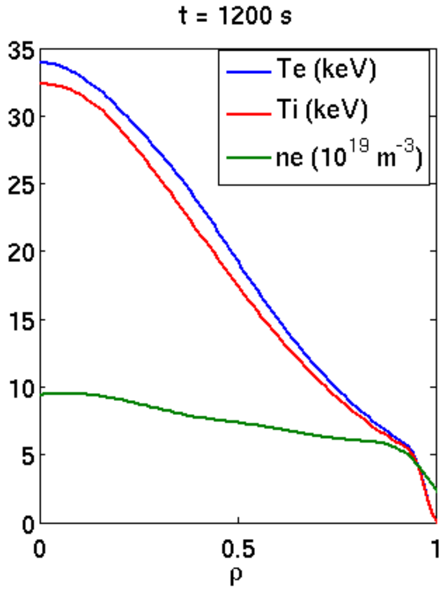
$$Q = \frac{P_{fus}}{P_h}$$

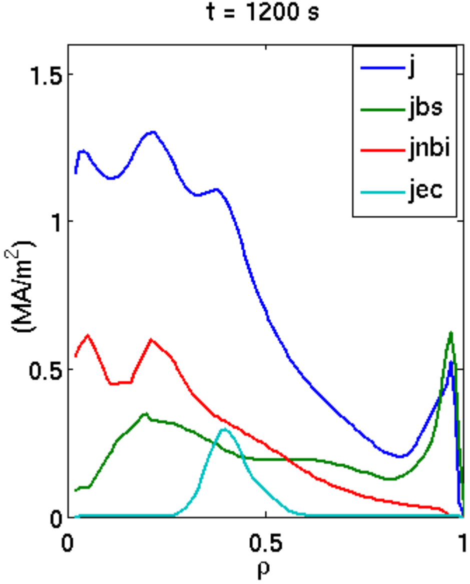


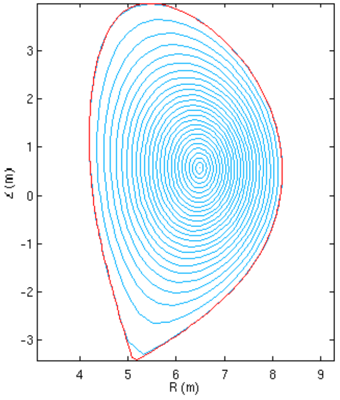


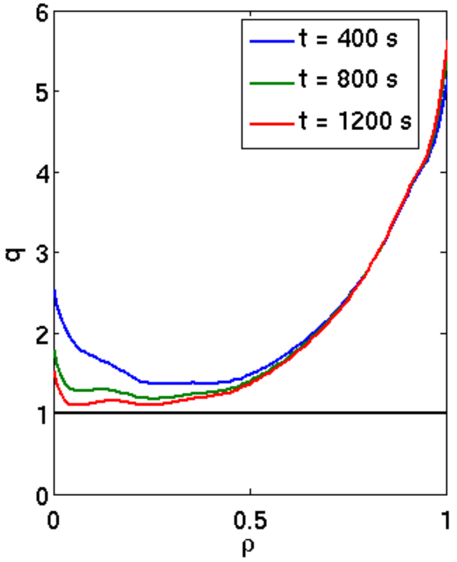
ITER hybrid scenario
(Q ~ 8 for 1200 s, ideal MHD stable)





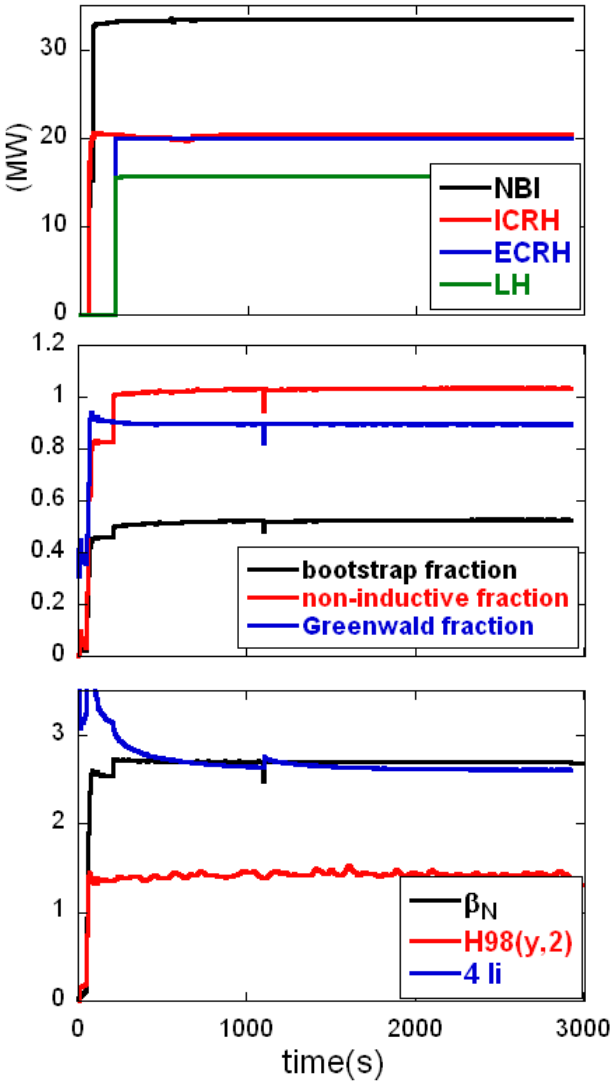


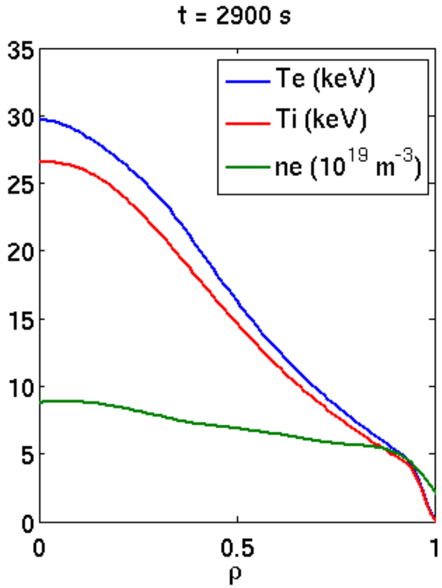


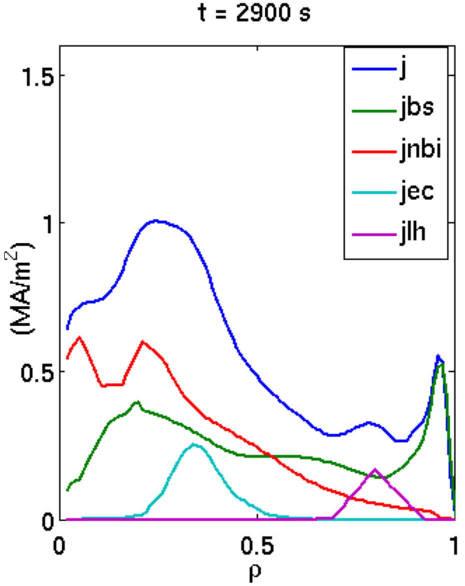


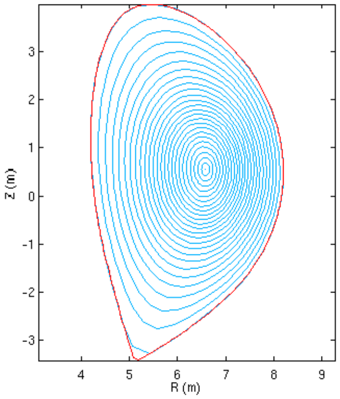
<u>Fixed density</u> $(n_{e0}/\langle n_e\rangle \sim 1.4)$
<u>Fixed T pedestal</u> (~ 5 keV)
<u>Fixed H-factor</u> (~ 1.3)
I_p = 12 MA P_{add} ~ 73 MW
Bootstrap fraction ~ 40%
Non-inductive fraction ~ 80%
Fusion gain Q ~ 8
Fusion Power (MW) ~ 585

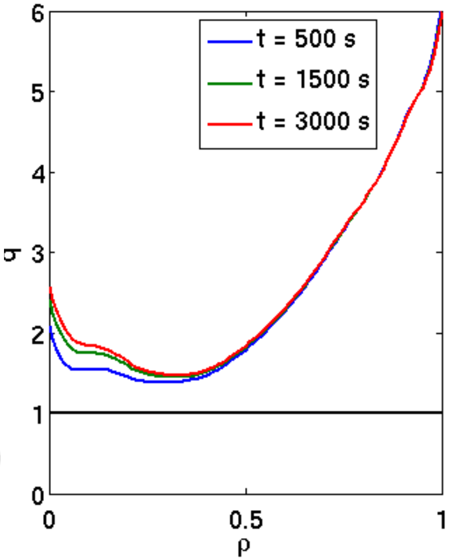
ITER steady-state scenario
(Q ~ 5 for 3000 s, ideal MHD stable)











<u>Fixed density</u> ($n_{e0}/<n_e>\sim1.4$)

<u>Fixed T pedestal</u> (~ 4 keV)

<u>Fixed H-factor</u> (~ 1.4)

I_p = 10 MA P_{add} ~ 90 MW

Bootstrap fraction	~ 53%
Non-inductive fraction	~ 100%
Fusion gain Q	~ 5
Fusion Power (MW)	~ 425

CD efficiency and bootstrap

For steady state

(V_{loop} = 0):

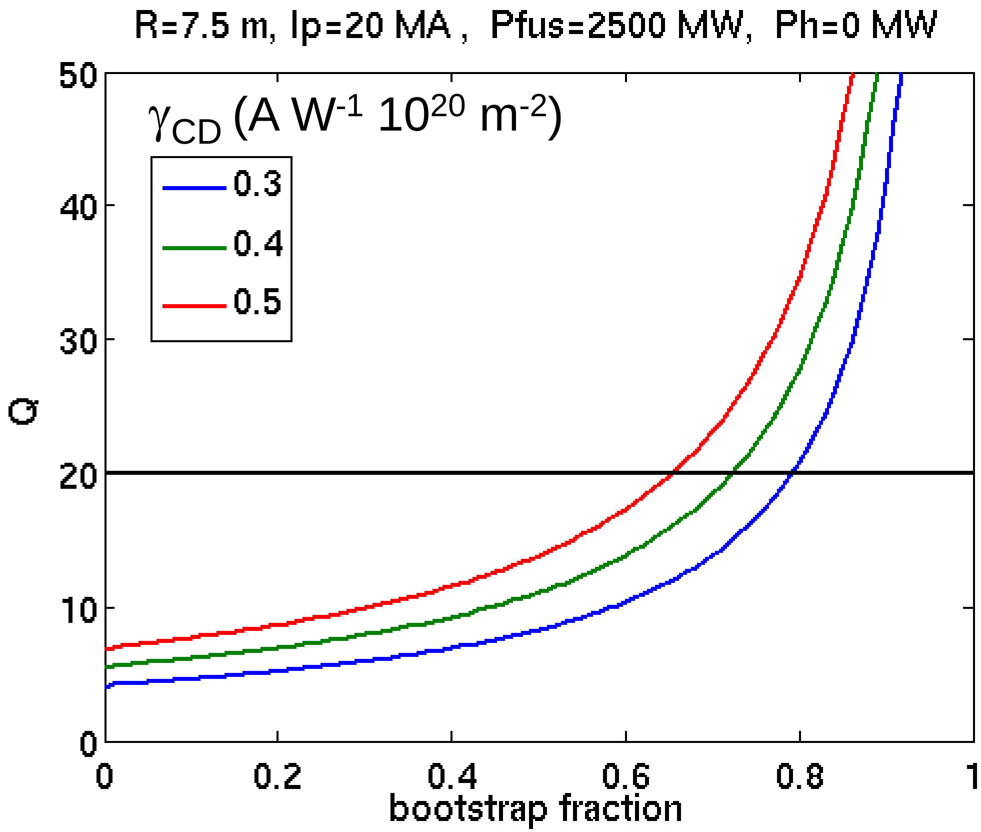
$$Q = \frac{P_{fus}}{P_h + \frac{\bar{n}_e R I_p}{\langle \gamma_{CD} \rangle}(1 - f_{bs})}$$

P_h: pure heating power

For realistic CD efficiencies,

large bootstrap fractions

are required



$$Q = \frac{P_{fus}}{P_h + P_{CD}} \qquad \gamma_{CD} = \frac{\bar{n}_e R I_{CD}}{P_{CD}} \qquad I_p = I_{CD} + I_{bs} \quad (if\ V_{loop} = 0)$$

METIS : a 0.5-D plasma simulator

- ✓ METIS is a Plasma Simulator with simplified assumptions
- ✓ METIS is fast : ~ 1 mn per simulation for 300 time slices
- ✓ Mixed 1D and 0D equations
  - Current diffusion 1.5D with equilibrium computed using moment equations
  - Source profiles deduced from simple models
  - Global energy content from 0D ODE (scaling, transients)
  - Temperature profiles : stationary 1D solution, χ scaled to W_{th}
  - All non-linearities solved (dependence of sources on profiles, fusion power, He ash transport, …)

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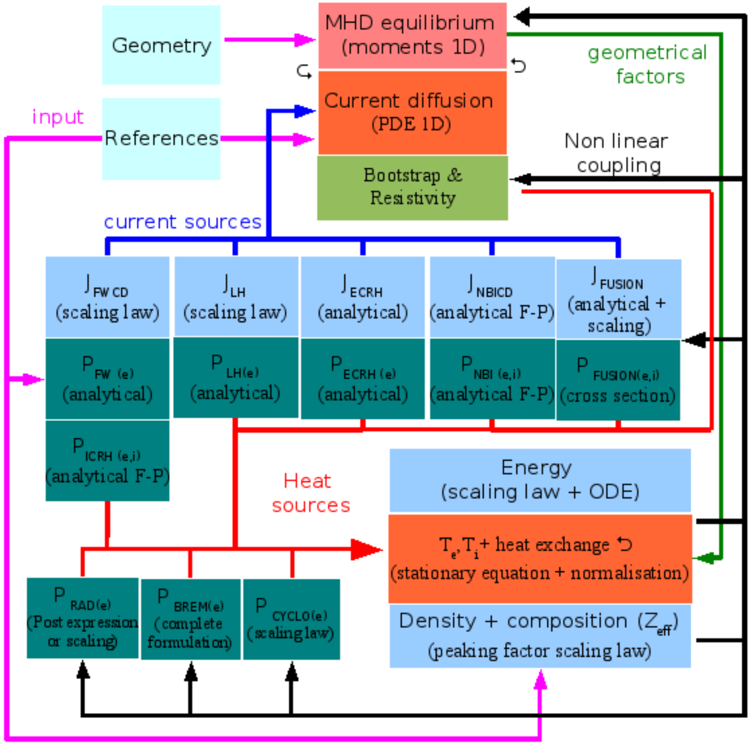
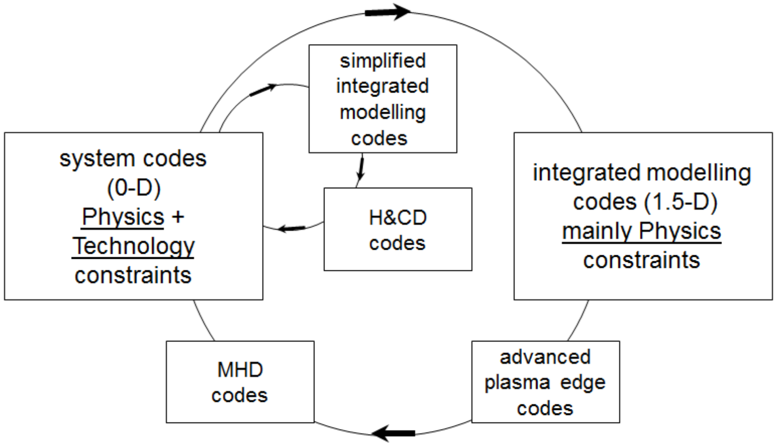


- ➢ METIS is included in the CRONOS suite of codes (preparation of CRONOS runs)
- ➢ Also available as a stand-alone code for Linux, Windows, Mac OSX

Summary: what you should not forget of this Lecture



simplified integrated modelling codes

system codes (0-D) Physics + Technology constraints

H&CD codes

integrated modelling codes (1.5-D) mainly Physics constraints

MHD codes

advanced plasma edge codes

- What's a plasma scenario ?
  - a set of coherent plasma properties
  - machine independent
  - reproducible
- Why a tokamak simulator ?
  - Optimization of the operation
  - Reactor safety issues (very first element)
  - Design of next-step fusion machines
  - Development and validation of physics models
- What is needed is a hierarchy of codes/models:
  - **0-D:** fast, give a working point, can be used in optimisation loops
  - **0.5-D:** compute time evolution with simplified profiles and actuators
  - **1.5-D:** full space-time solution, with 2-D equilibria (free or fixed boundary) and detailed description of the actuators (H&CD)

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