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Integrated Tokamak Modelling: current status and future direction for ITER operation

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ITER INTERNATIONAL SCHOOL 2014

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I. Voitsekhovitch

OUTLINE

INTEGRATED MODELLING IN FUSION & ITER

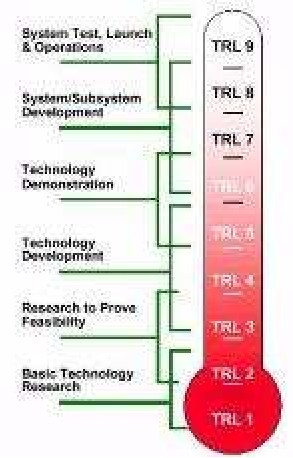
PLASMA OPERATIONAL SCENARIO:

- I) DEFINITION
- II) PHYSICS & COMPUTATIONAL CHALLENGES
- III) MODELLING OF ITER SCENARIOS

RECENT DEVELOPMENT OF INTEGRATED MODELLING PLATFORM & SUITE OF CODES

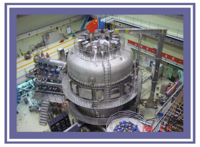
CONCLUSION AND PROSPECTS

TOWARDS A FUSION TOKAMAK REACTOR

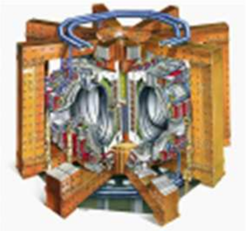


A scientific and technical challenge

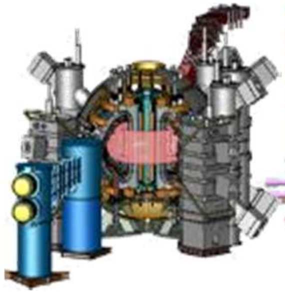
Tore Supra EAST



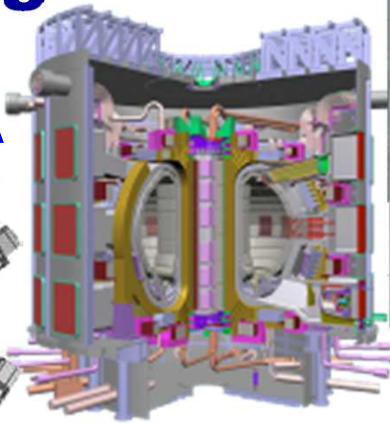
JET



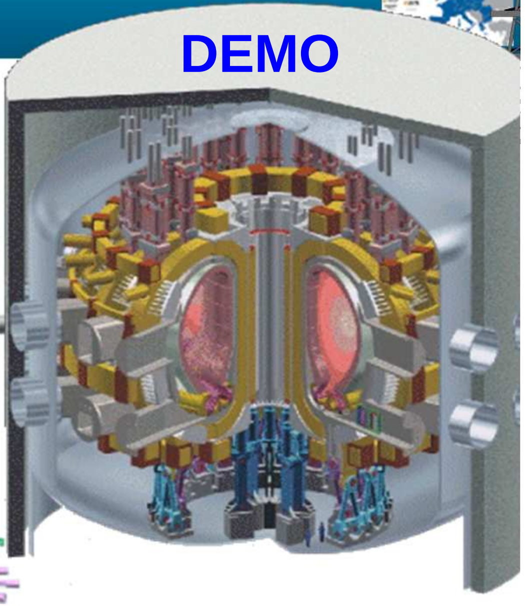
JT60-SA



ITER



DEMO



P_{fusion}/P_{add}	DD	Q ~ 0.7	DD	Q ~ 10	Q ~ 30
duration	~400s	2s	~100s	400-3600s	Continuous
self-heating	0%	10%	0%	70%	80 to 90%
bootstrap	20%	20%	>60%	10-50%	50-80%

WITH ITER , FUSION ENTERS IN THE NUCLEAR ERA

IMPORTANCE OF MODELLING IN NUCLEAR ERA

Bringing Fusion to its “Reactor Era” requires an innovative programme of “discharge mastering”, combining:

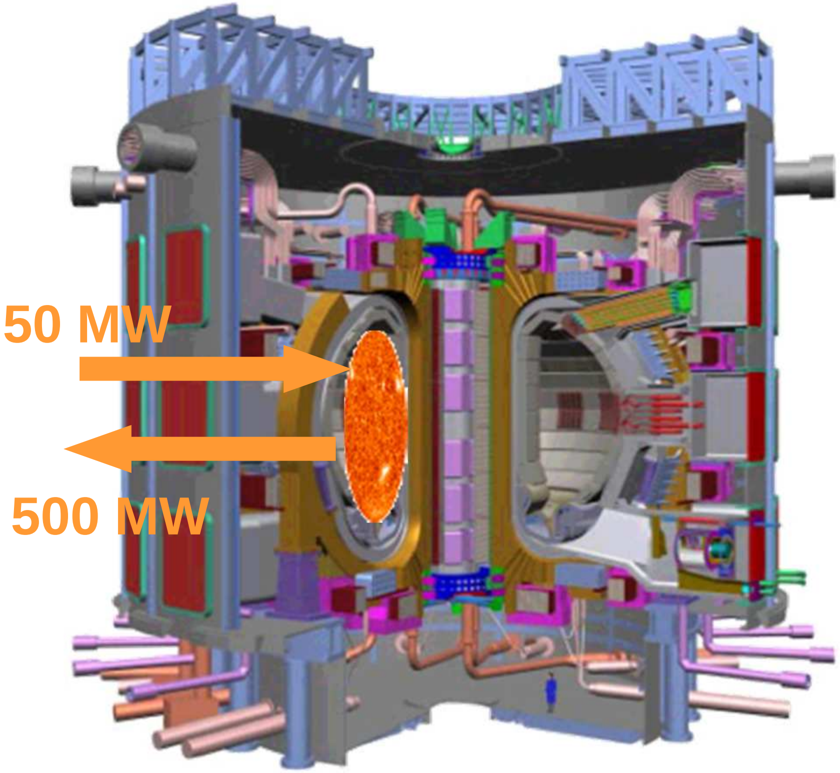
- Nuclear device with safety issue
- Design, safety case and preparation of operation with systematic modelling
- Limited experimental time for empirical approach
- Real time control of the magnetic/kinetic configuration (non-linear and time effects)
- Real time control of components integrity
- High-level algorithms and control schemes
- a consistent set of simulation tools:
    - first principles (“PFlops”)
    - integrated modelling (“CPU hours”)
    - fast simulators (“~ 10 ms”)

[Becoulet & Hoang PPCF 2008 and Joffrin et al PPCF 2003]

ITER PHYSICS AND TECHNOLOGY GOALS

Physics Goals:

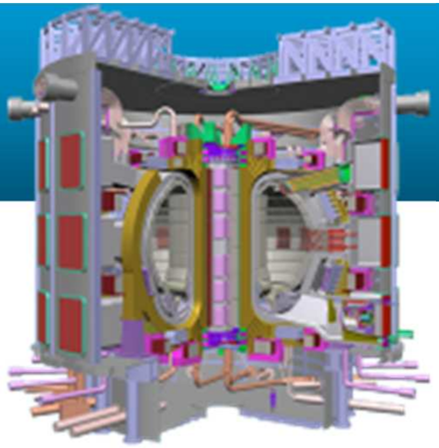
- ITER is designed to produce a plasma dominated by α-particle heating
- produce a significant fusion power amplification factor (Q ≥ 10) in long-pulse operation
- aim to achieve steady-state operation of a tokamak (Q = 5)
- retain the possibility of exploring 'controlled ignition' (Q ≥ 30)

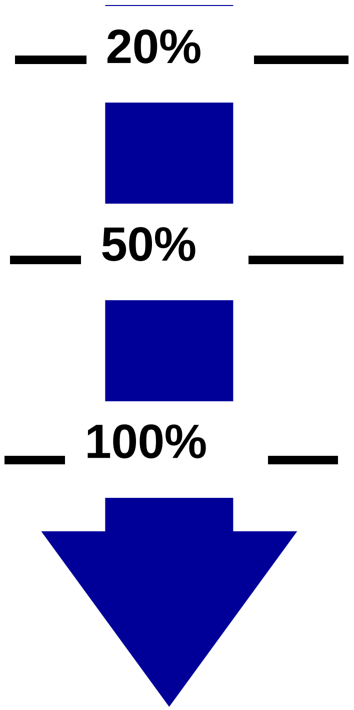


Technology Goals:

- demonstrate integrated operation of technologies for a fusion power plant
- test components required for a fusion power plant
- test concepts for a tritium breeding blanket

ITER OPERATIONAL SCENARIOS



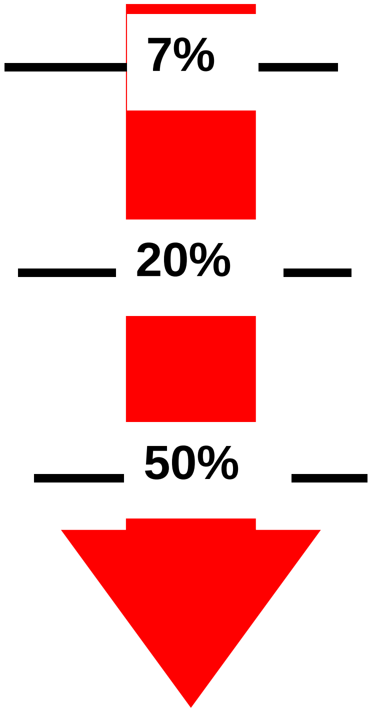


$I_{non\text{-}inductive}/I_p$

20%

50%

100%



$I_{bootstrap}/I_p$

7%

20%

50%

Inductive

Q ≥ 10 Ip~15MA 400s

Hybrid

Q ~5-10 Ip~12MA 1000s

Non-inductive

Q~5 Ip~9MA 3000s

Active research activity

Integration of physics & technology

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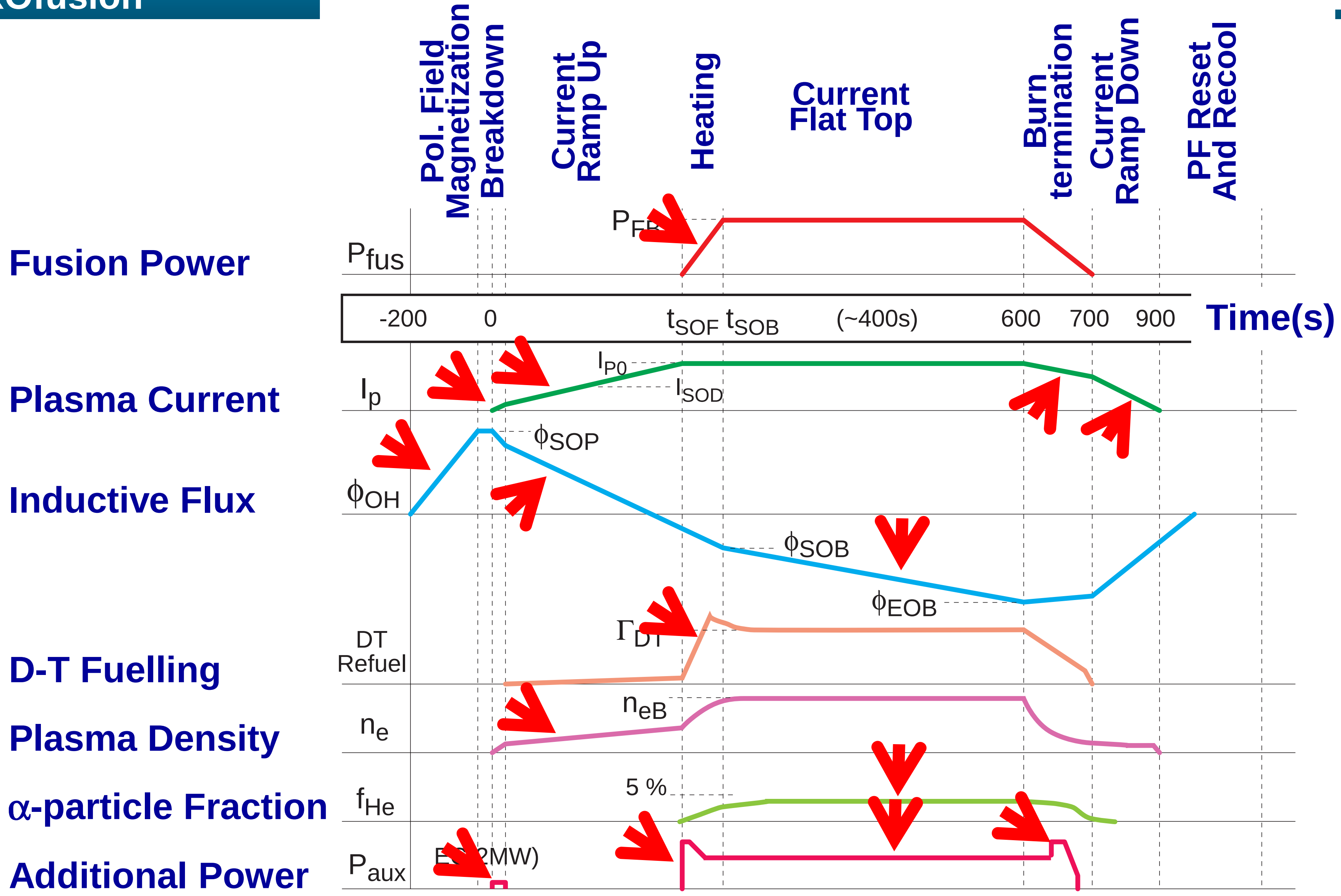
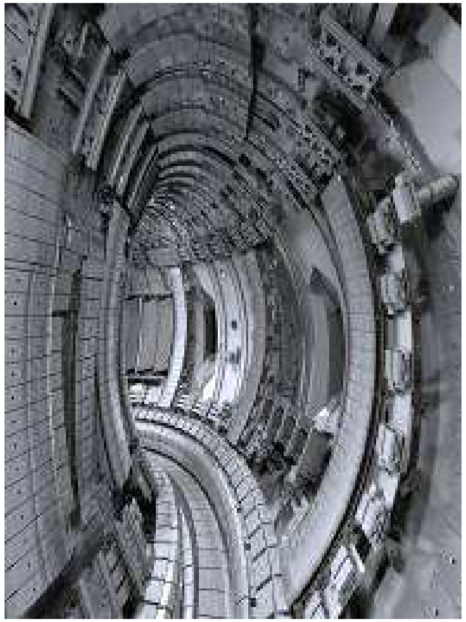
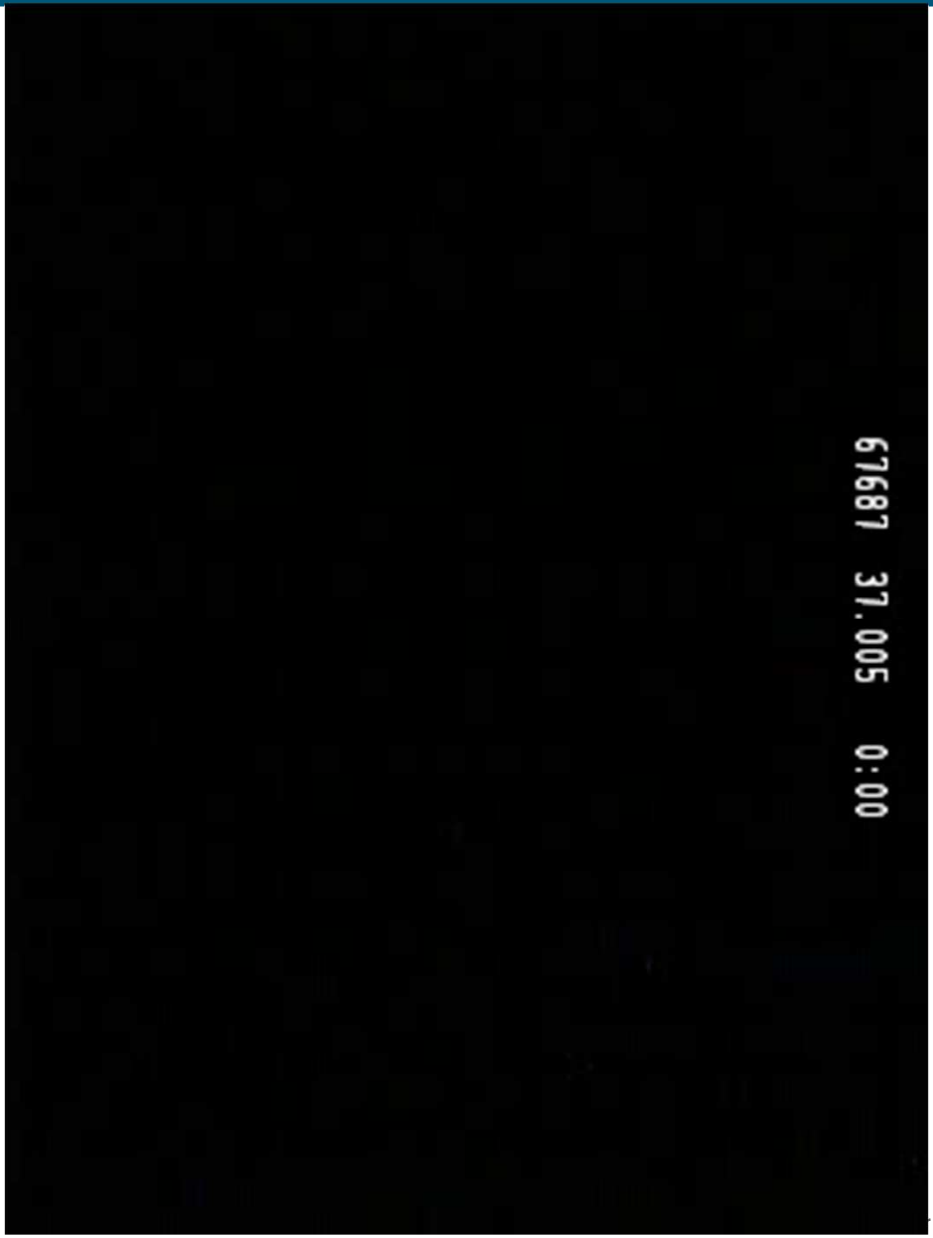
VARIOUS PHASES IN THE PLASMA SCENARIO



EXAMPLE OF SCENARIO: JET PLASMA

JET #67687





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MODELLING OF ITER SCENARIO : 15MA H-MODE

Tokamak simulation: free-boundary equilibrium (DINA-CH) & transport evolution (CRONOS)

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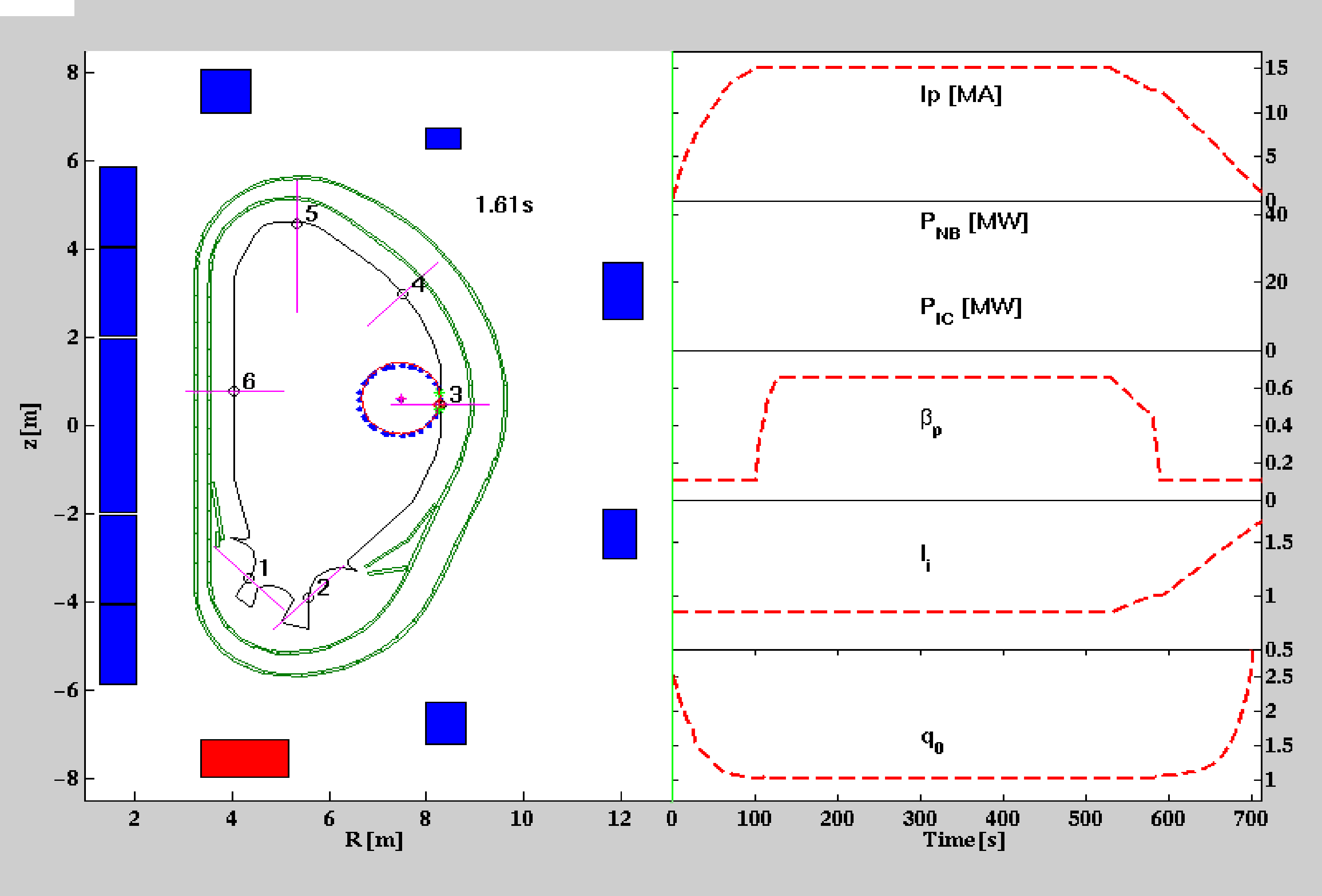
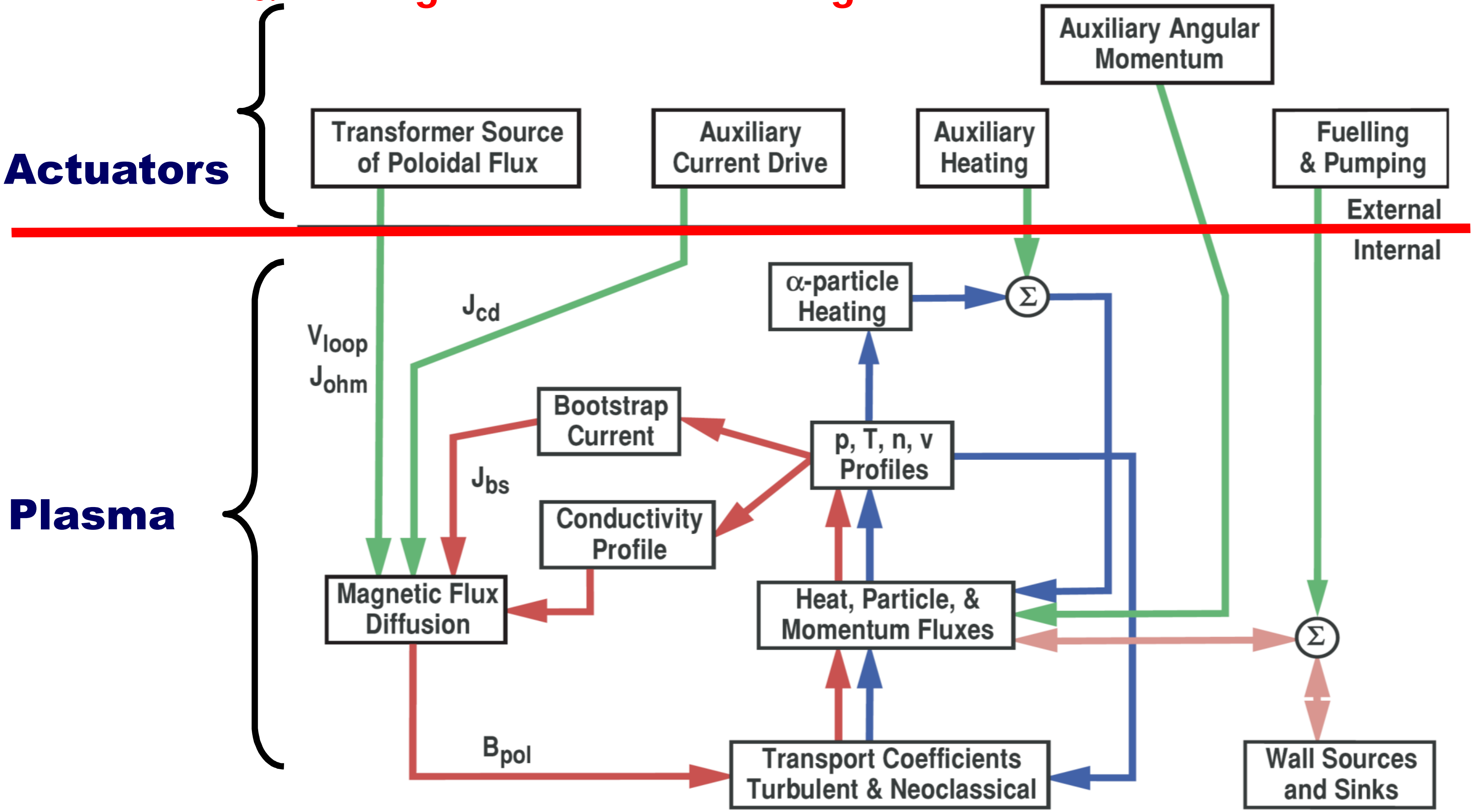
S.H. Kim *et al*, *PPCF* 2009



NUMERICAL TOKAMAK: ALL COUPLINGS, ALL NON-LINEARITIES

Different time scale: fast (blue) & Slow (red)

α-heating dominant in burning reactor



[Politzer et al NF 05]

INTEGRATED MODELLING (IM): SET OF CODES COUPLED TOGETHER TO MODEL ‘PLASMA + TOKAMAK’

IM covers different physical regions & time scale:

- Core and edge regions to the separatrix
- The scrape off layer (SOL) region and its connection with the divertor
- The effects of external circuits and systems in controlling the plasma
- Interaction with the plasma facing components (PFCs)

IM encompasses different levels of sophistication:

- **First principles models** (e.g. microscale) to explore details of the physics
- **Reduced models** (e.g. macroscale) for efficient computations; fidelity to first principles models, instead of being expressed empirically
- **Empirical models** (scaling laws from large data base)

Integrated modelling covers:

- Interpretative & predictive capabilities
- The **full discharge from initiation to termination** and **inter-discharge effects** e.g. conditioning and tritium retention

Magnetic Fusion Experiments mix:

- **sophisticated physics:** multi-physics, multi-scale time and space, often highly non-linear behaviors & couplings
- **complex devices:** coils, H&CD systems, Fuelling & Pumping, Cooling, diagnostics, …
- **complex control algorithms:** performance & safety

Performance means mastering all aspects together

In preparation to ITER, several initiatives were taken along these lines:

- more **dedicated experiments** to validate simulation modules and models
- more **systematic real-time controls** on experiments
- a dedicated **modeling architecture for Integrated Tokamak Modelling**

MODELLING APPLICATIONS FOR ITER

During ITER design:

- Design is based on a combination of theoretical understanding + experimental observations where theory/modelling is incomplete

During ITER construction:

- Focus on enhancing the physics understanding through development of theoretical and computational models and validating them against experimental observations
- Apply new understanding to planning the ITER experimental programme

During ITER operation:

- **Predictive** modelling of **each plasma** from **beginning to end**, including analysis of **control requirements**
- **Interpretative analysis** of each plasma to evaluate/validate models

W. Houlberg, S. Pinches, D. Campbell

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IM SUPPORT OF THE ITER FACILITY: EXPERIMENTAL PLANNING

Scenario studies for all ITER phases:

- H, He, D and D-T Phases full discharge
- All scenarios from inductive to non-inductive

Campaign planning:

- Experimental proposals are to be systematically supported by modelling

Session planning:

- More detailed modelling assessment over the expected parameter range

Pulse development:

- Simulation from initiation to termination, including system limitations
- Pulses expected to be composed of segments (e.g. start-up, several sequential flat-top, shutdown)

W. Houlberg et al

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IM SUPPORT OF THE ITER FACILITY: REAL-TIME CONTROL

Control strategies & Feedback models :

- Evaluate plasma response times, sensitivity of plasma parameters to actuators, impact of events
- Evaluate control models, gains and response times using idealized sensors

Input to control algorithms:

- Effectiveness of sensors and actuators, response times, secondary responses
- Estimated ranges for tunable parameters in various control algorithms (PID, SIMO, MIMO …) under a range of conditions

Testing control algorithms:

- Simulate plasma behavior using control algorithms
- Synthetic diagnostics linked to actuators

IM SUPPORT OF THE ITER FACILITY : ANALYSIS

Real-time analysis:

- Display of physics parameters using fast conversion of diagnostic signals
- Simultaneous display of modelled results in control rooms

Post-processing:

- More rigorous conversion of diagnostic signals emphasizing consistency in analysis, uncertainties (error bars), …
- Systematic inter-shot and overnight processing validated tools

Model validation and improvement:

- More detailed, more extensive modelling & long-term analyses

Forecasting:

- Live prediction from present state (similar to weather forecasting)

W. Houlberg et al

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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 flux surface averaged ne, ni, Te, Ti, j, V, impurities

Sources

- heat, injected matter, current, momentum, impurities, wall (neutrals, sputtering and recycling)

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)

ITER SCENARIO DESIGN: PHYSICS CHALLENGES

Experimental scenarios exist, but are they extrapolable to ITER ?

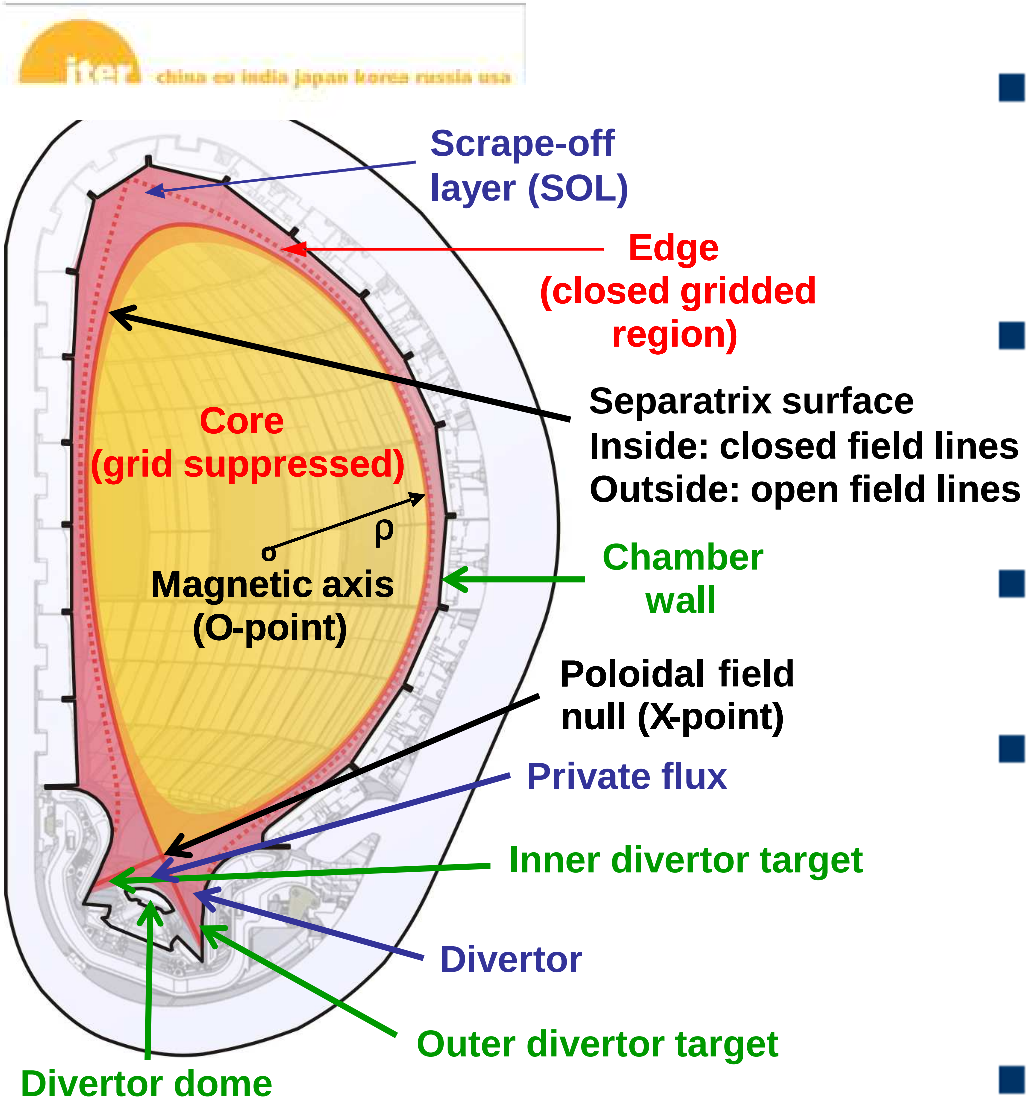
- different **dimensionless parameter** range
- different properties of **sources** (e.g., rotation, fast particles) & large fraction of alpha heating
- different **control** requirements
- different level of **self-organization**

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
- **pedesta**l is critical: progress on both models and database
- experimental **validation** of code modules
- **interplay with MHD**
- **core- edge coupling**: routine inclusion of W transport and radiation in ITER core integrated modelling

G. Giruzzi, PPCF 2011

ITER SCENARIO DESIGN: PHYSICS CHALLENGES



S. Pinches et al

- **Coupling of all spatial plasma domains** (core, edge, scrape-off layer & divertor)
- Dynamic coupling of individual physics models relevant to each domain
- Interaction between **plasma and PFCs**
- Coupling of plasma with external circuits, H&CD, fuelling, pumping and other systems to confine and control plasma
- **Synthetic diagnostics**

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ITER SCENARIO DESIGN: CORE AND EDGE INTEGRATION

Modelling of core fusion performance

- **control of kinetic & magnetic energy (confinement & stability) including impurities**

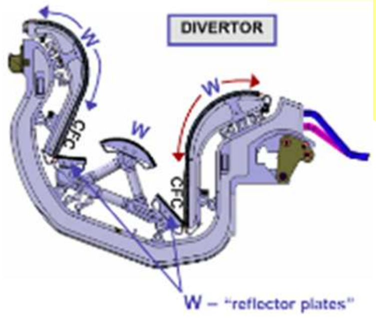
Core conditions

simultaneously with

Modelling power & particle exhaust

- Control transient & stationary power loads
- Control of fast particle losses
- Control of particle exhaust & recycling according to fuelling requirements, capacity of Tritium extraction plant & necessary Helium removal

boundary conditions core plasma



ITER SCENARIO DESIGN: COMPUTATIONAL CHALLENGES

Challenges related to intrinsic computational complexity:

- wide variety of physics models
- integration of **physics and technology**: antennas, machine description
- first-principle turbulence codes, edge codes, 3-D non-linear MHD codes
- inclusion of transients and controls in free-boundary simulations
- inclusion of all the transport channels extremely complex
- include description of actuators, controls, diagnostics
- compromise between **accuracy and approximations**

Challenges related to code integration:

- **integration** of tens of codes, global reliability with number of modules ?
- codes of different nature, language, generation, speed
- complexity of software architecture / use on massively parallel computers
- speed and memory optimization: imperative to bridge gap between **speed and accuracy**
- users: many physicists, with different backgrounds

G. Giruzzi, PPCF 2011

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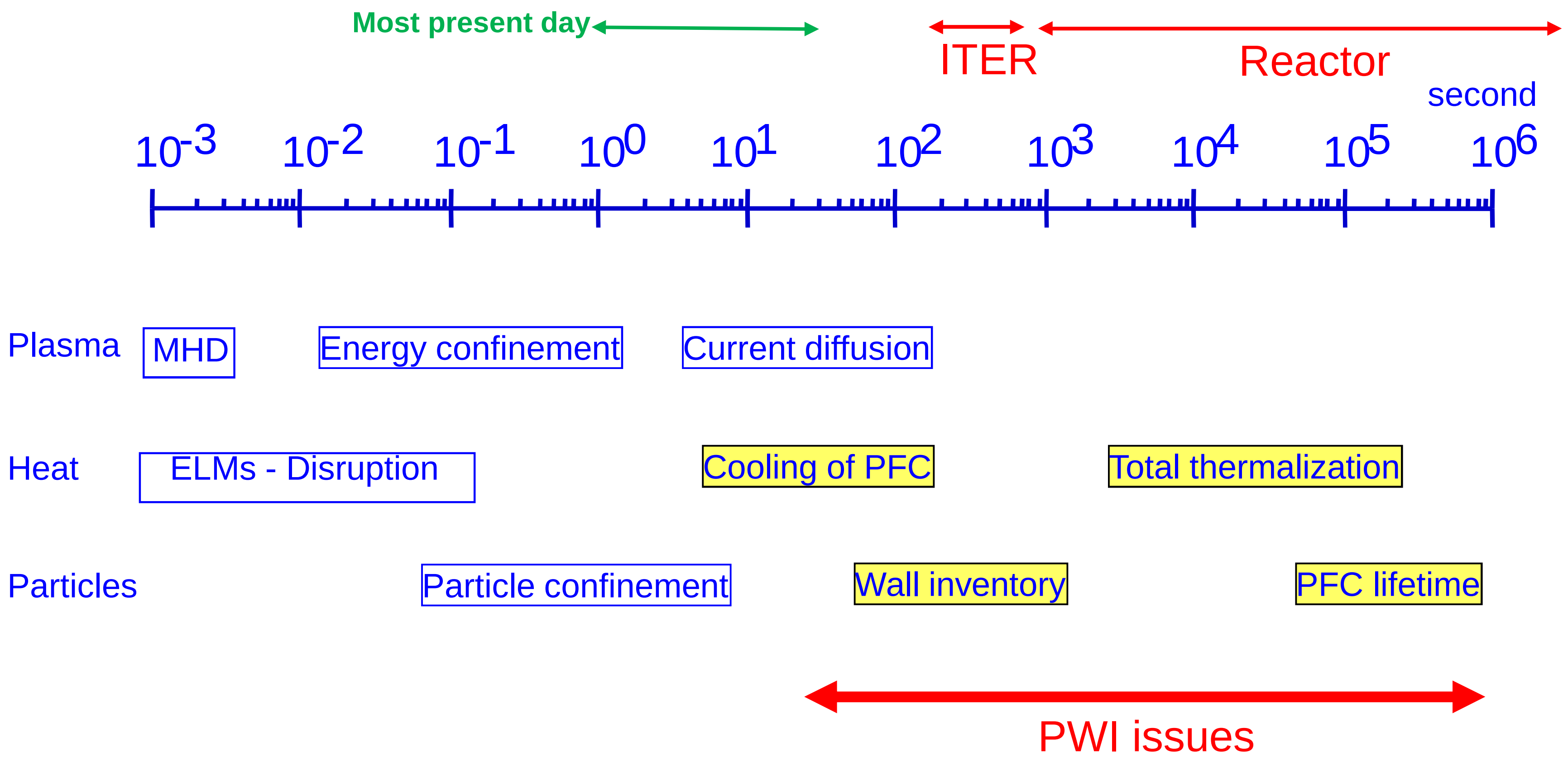
MAIN CHALLENGES : WIDE RANGE OF TIME AND RADIAL SCALES



Most present day

ITER

Reactor

second

10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}

Plasma: MHD, Energy confinement, Current diffusion

Heat: ELMs - Disruption, Cooling of PFC, Total thermalization

Particles: Particle confinement, Wall inventory, PFC lifetime

PWI issues

HIERARCHY OF INTEGRATED MODELLING CODES AND MODELS

0-D codes:

- solution of 0-D core thermal equilibrium equation
- fast, give a working point, used in optimisation loops for machine design

0.5-D codes:

- 0-D tool + profile effects, fast calculation (~ 1 min)
- compute time evolution with simplified profiles and actuators
- profile peaking time evolution with simplified equilibrium

1.5-D codes:

- 1.5-D: 1-D flux surface average profiles and 2-D magnetic equilibrium
- full space-time solution, with 2-D equilibria (free or fixed boundary) and detailed description of the actuators (H&CD, sources), diagnostics
  - ➢ fixed boundary: plasma boundary given, B field computed in the plasma
  - ➢ free boundary: B field computed in and outside the plasma from coils currents

0-D SCENARIO MODELLING TOOLS

- 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	$\uparrow$
P_α	alpha
P_{OH}	ohmic
P_{add}	add. heating
P_{brem}	brems-strahlung
P_{syn}	synchrotron radiation
P_{line}	atom. Line radiation
P_{cond}	convection /diffusion

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

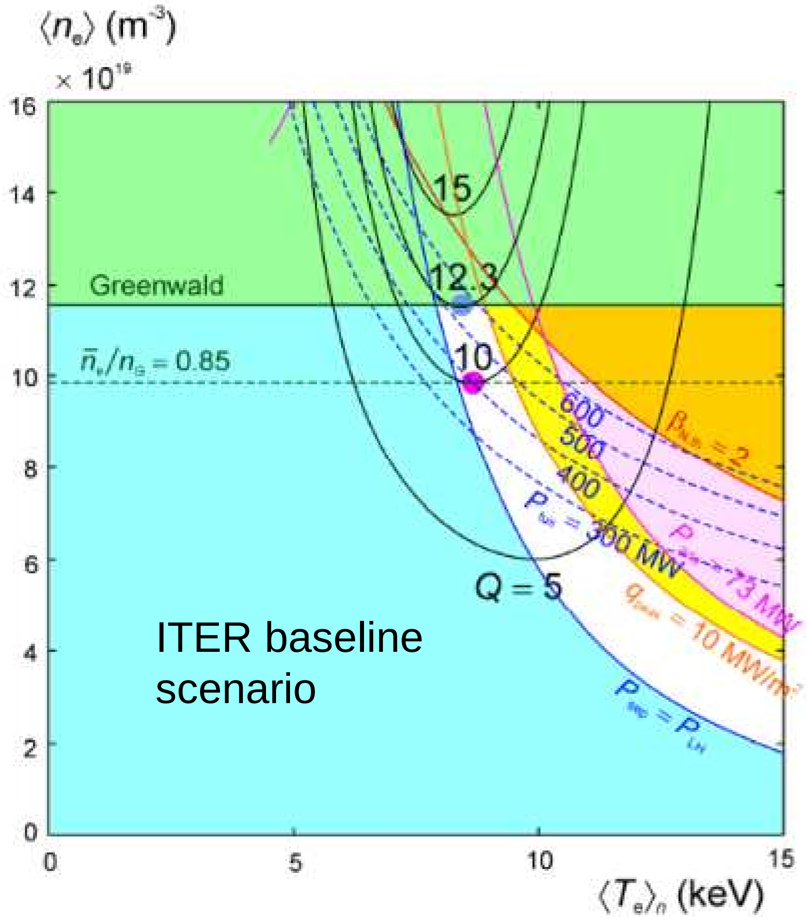
- **Technology constraints** on divertor heat load, blanket properties, pumping, superconducting magnetic field, neutronics, conversion to electric energy, mechanics, etc.

G. Giruzzi, Master on Fusion Energy

0-D SCENARIO MODELLING TOOLS

- output: PopCon plots (**P**lasma **op**eration **Con**tours)
- example: HELIOS code (J. Johner, Fusion Sci. Techn. 59 (2011) 308)

- System codes for machine design :
  - ➢ possible automatic search of an optimum working point
  - ➢ optimisation may include cost !
  - ➢ example: PROCESS code [Ward, Pl. Phys. Contr. Fus. 52, 2010 124033] or SYCOMORE (Imbeaux FEC 2014)
  - ➢ analogous codes exist in USA, Japan, etc.



ITER baseline scenario

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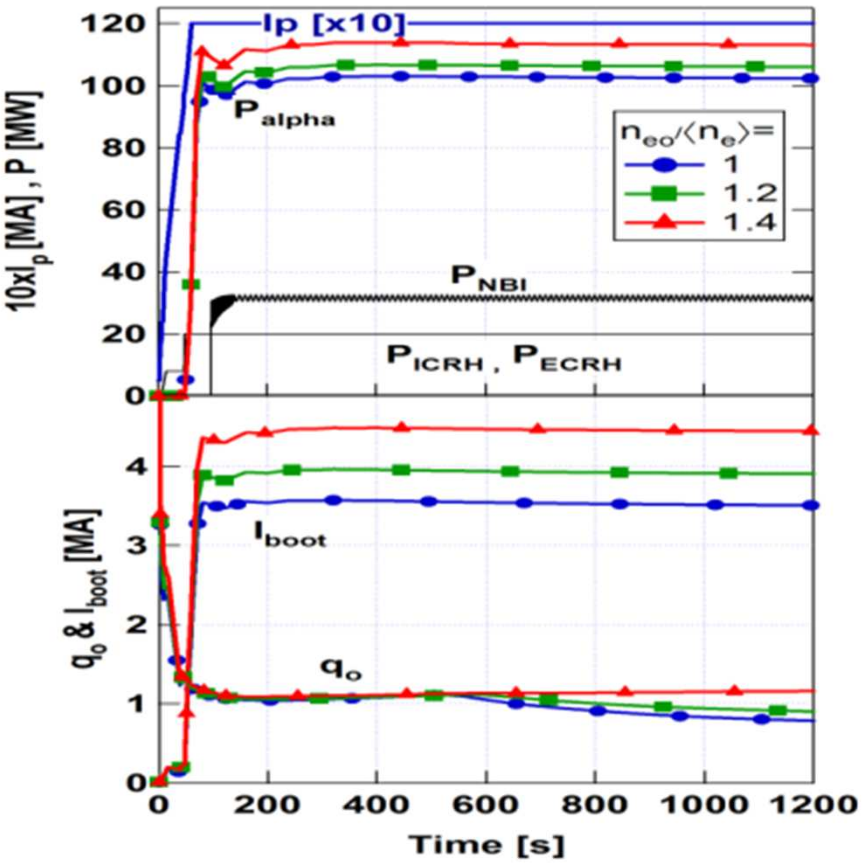
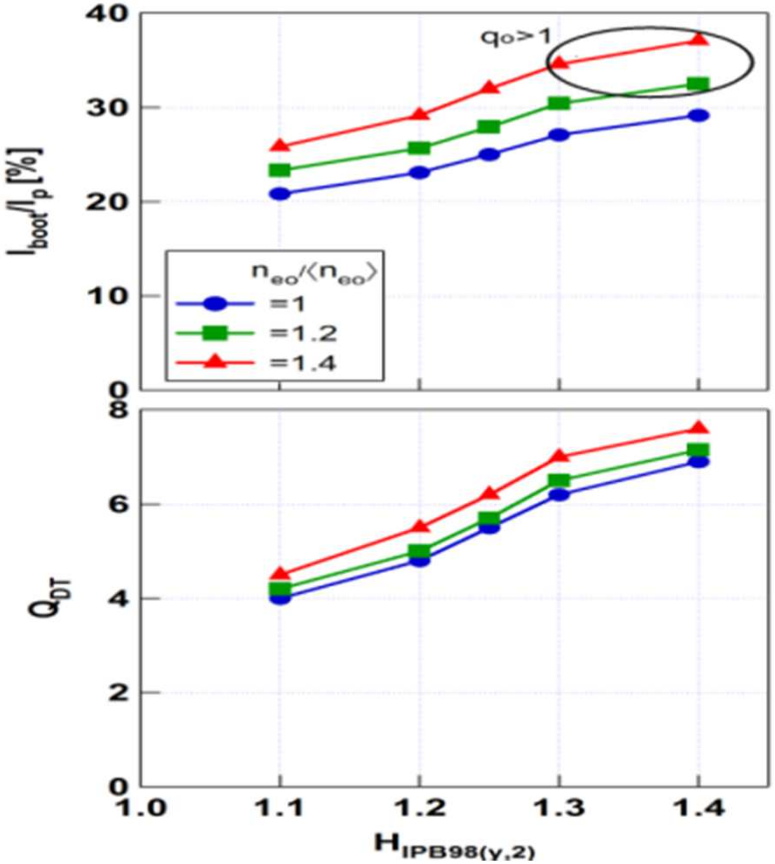
ITER HYBRID OPERATIONAL DOMAIN FROM SIMPLIFIED 0-5D MODELING

- ITER hybrid scenario : $q_0>1$ for 1000s and Q_{DT}, $Q_{DT}>5$
- Narrow operating domain: it requires high confinement and peaked density profile to reach a critical value of bootsrap current fraction





X. Litaudon et al., Nucl. Fusion 44 (2013)

1.5-D INTEGRATED MODELLING TOOLS

Integrated modelling of:

- Heat, particles, rotation: transport diffusion equations (1D) + source codes
- Current profiles: current diffusion equation (1D)
- Plasma equilibrium: magnetic equilibrium code (2D)

Interpretative or Predictive modelling:

- Interpretative: to check data consistency and to calculate effective transport coefficients
  - ➢ measured electron & ion densities & temperatures
  - ➢ resolution of current diffusion & synthetic diagnostic simulations
- Predictive: to validate transport and models against experimental data + prepare new scenarios
  - ➢ transport modelling
  - ➢ initial profiles from model or experiments

Built-in feedback controls

1.5-D INTEGRATED MODELLING TOOLS

Time dependent simulation integrating various modules to describe the complexity of whole operation

Large variety of codes with different strength and weakness depending on the physics problem to be solved :

- **ASTRA :** G. V. Pereverzev, G. Corrigan CPC 179 (2008) p.579
- **CORSICA :** J. A. Crotinger, et al. LLNL Report UCRL-ID-126284 (1997)
- **CRONOS**: J.F. Artaud et al., Nuclear Fusion 50 (2010) 043001
- **European Transport Simulator ETS :** Coster D. et al 2010 IEEE Trans. Plasma Sci. 38 2085
- **Integrated Plasma Simulator, IPS:** cswim.org/ips/
- **JETTO:** Cennacchi G. and Taroni A. 1988 JET-IR(88) 03 and **JINTRAC:** M. Romanelli et al Plasma and Fusion Research Volume 9, 3403023 (2014)
- **ONETWO :** Murakami et al PoP 2003
- **PTRANSP :** Budny R.V., Nuclear Fusion 49, (2009), 085008.
- **TASK:** Fukuyama et al. 2004, Proc. of 20th IAEA Fusion Energy Conf. CD/TH/P2-3
- **TOPICS-IBS:** Shirai H et al PPCF 42 (200) 1193
- **Tokamak Simulation Code (TSC):** Jardin S.C. et al 1986J. Comput. Phys. 66 481
- Etc. …

THE CRONOS SUITE OF CODES

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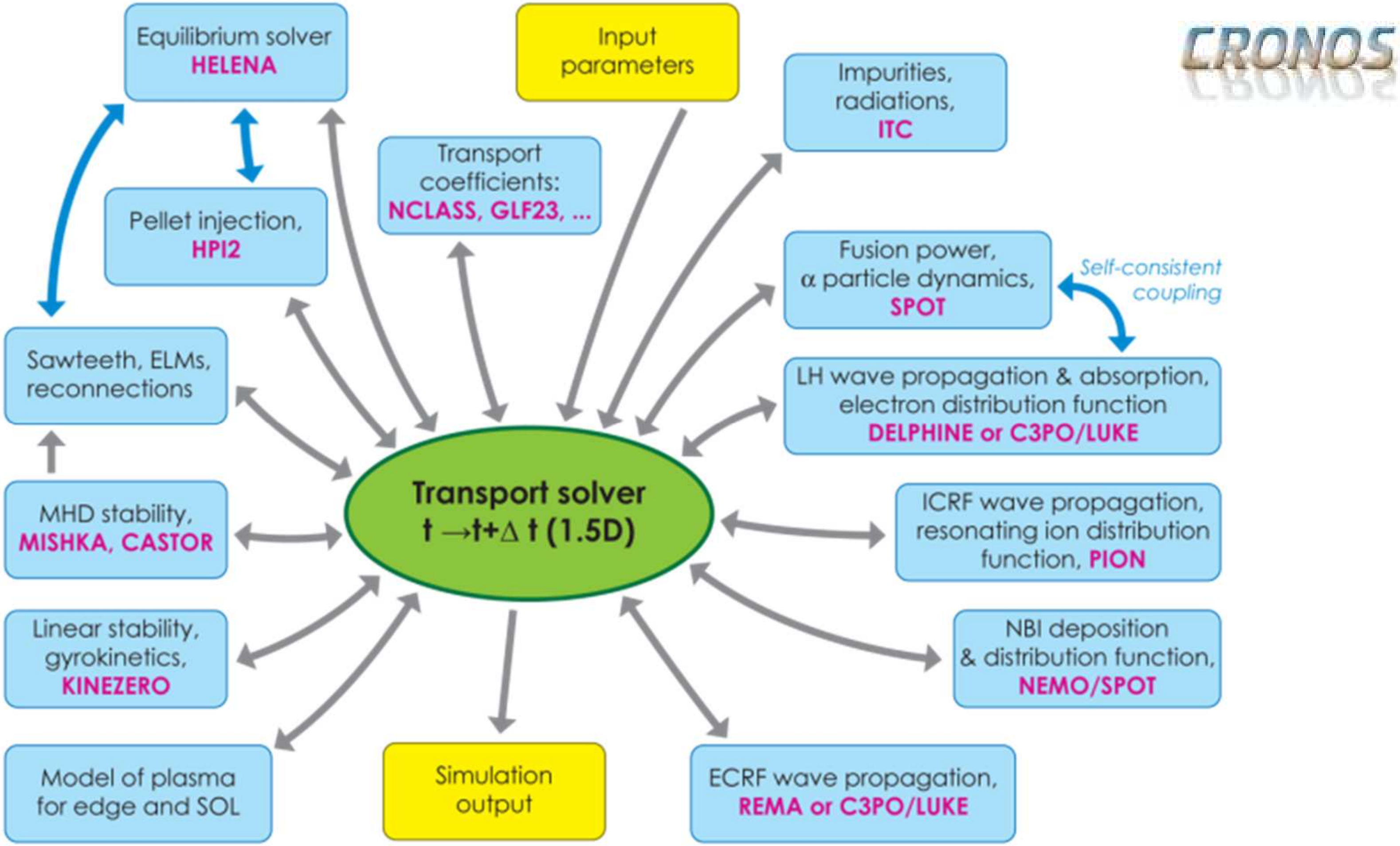
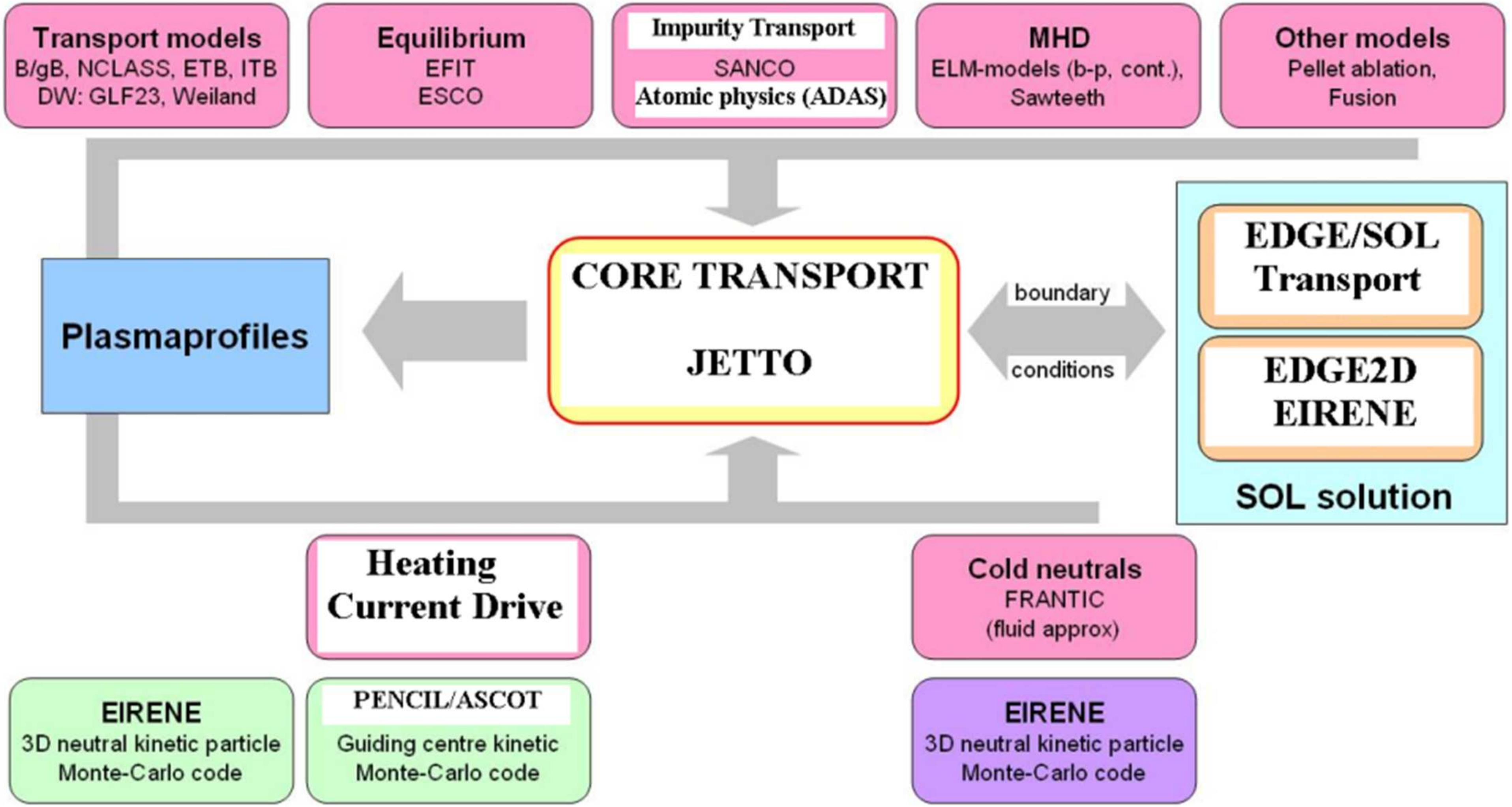


- ~900 000 lines Fortan 77, ~75 000 lines Fortran 90/95, ~100 000 lines C, ~12 000 lines C++, ~550 000 lines Matlab

JINTRAC (JET INTEGRATED TRANSPORT CODES) IS A SUITE OF 25 MODULES



Transport models
B/gB, NCLASS, ETB, ITB
DW: GLF23, Weiland

Equilibrium
EFIT
ESCO

Impurity Transport
SANCO
Atomic physics (ADAS)

MHD
ELM-models (b-p, cont.),
Sawteeth

Other models
Pellet ablation,
Fusion

Plasmaprofiles

CORE TRANSPORT

JETTO

boundary
conditions

EDGE/SOL Transport

EDGE2D EIRENE

SOL solution

Heating Current Drive

Cold neutrals
FRANTIC
(fluid approx)

EIRENE
3D neutral kinetic particle
Monte-Carlo code

PENCIL/ASCOT
Guiding centre kinetic
Monte-Carlo code

EIRENE
3D neutral kinetic particle
Monte-Carlo code

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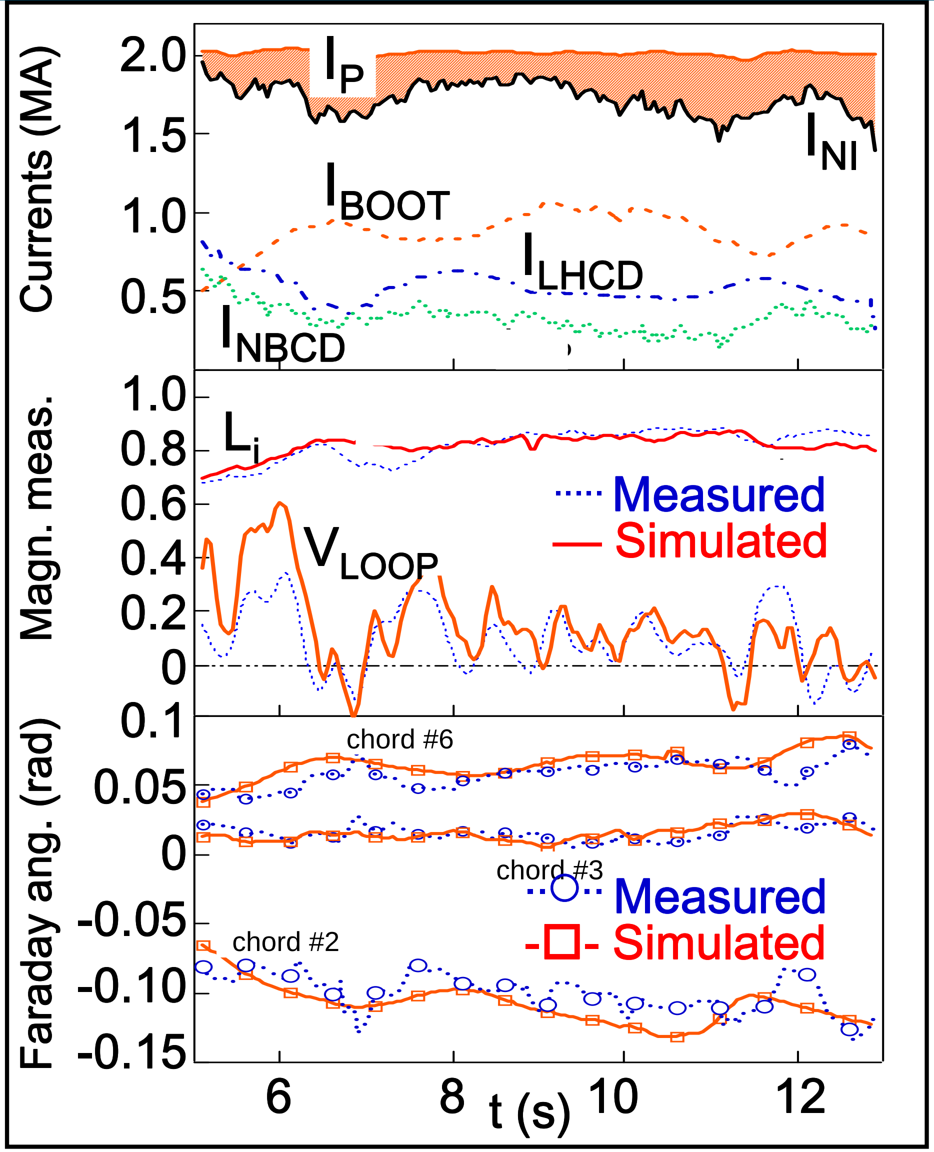
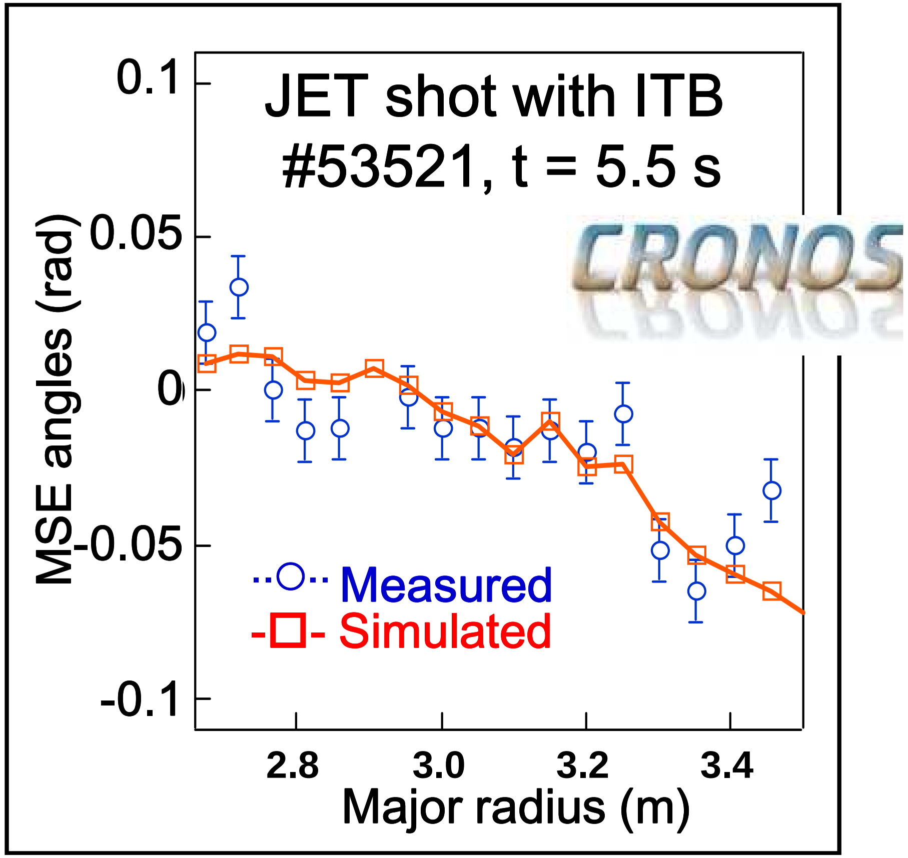
VALIDATION BY INTERPRETATIVE SIMULATION OF JET EXPERIMENTS

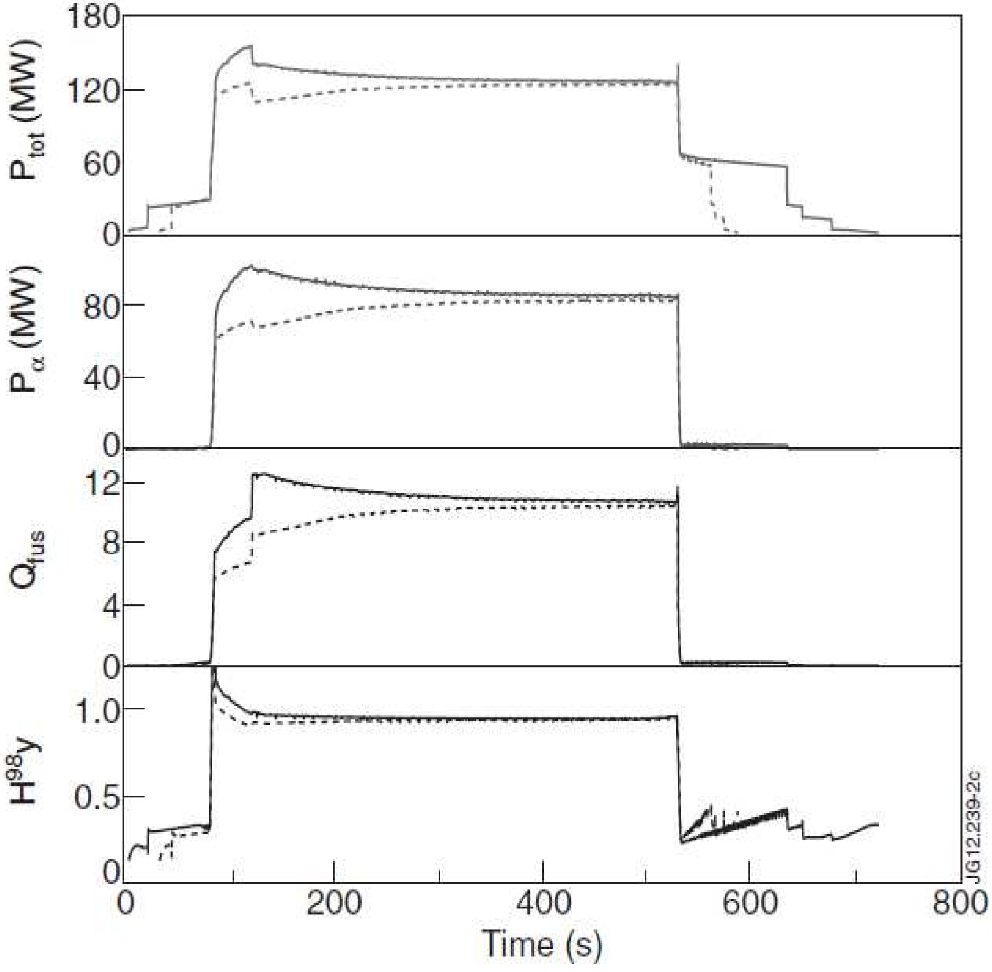


X. Litaudon et al., Nucl. Fusion 44 (2002)

Synthetic diagnostic



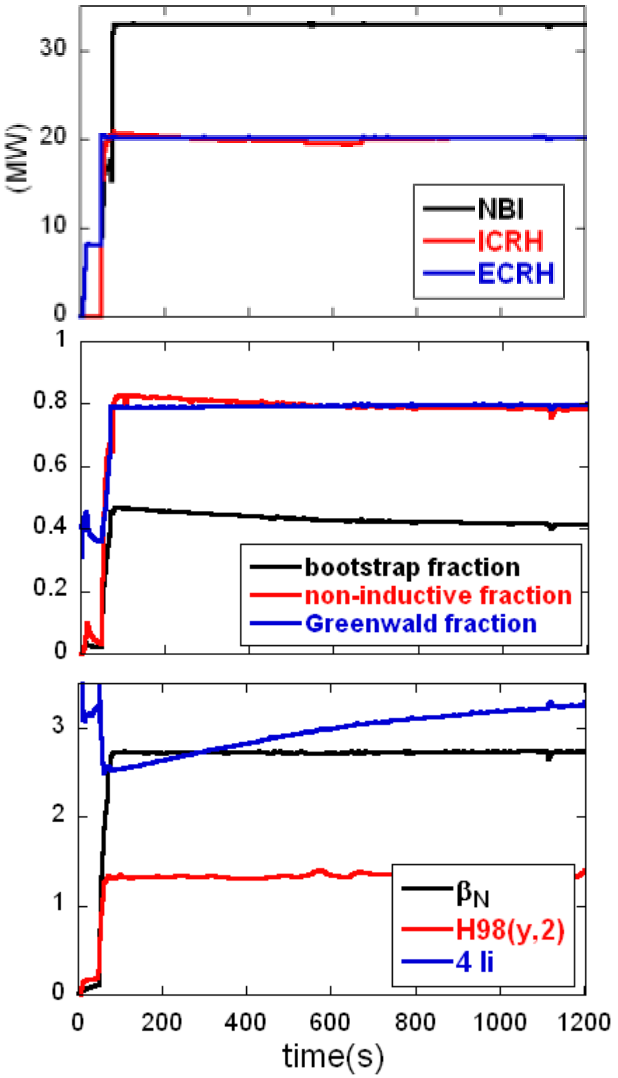
ITER BASELINE SCENARIO: Q ~ 10 FOR 400S

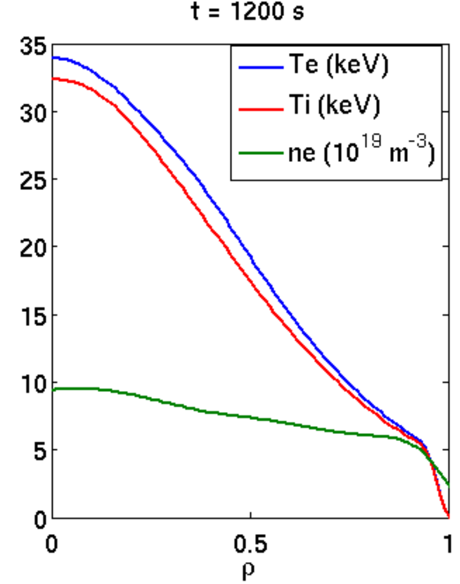


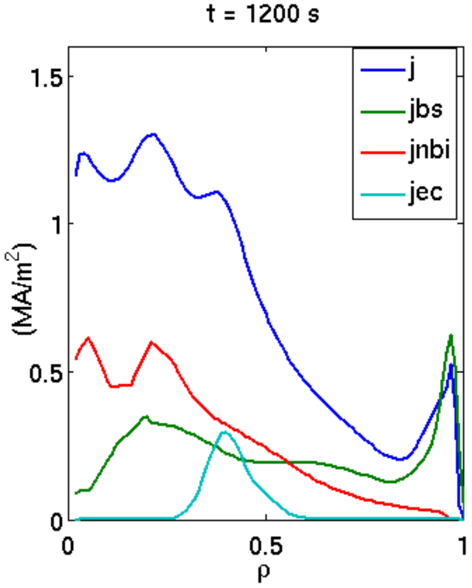
- Simulation of 15MA/5.3T inductive burn DT Scenario, Q=10 and its variants in H, D and He using the JINTRAC suite 1.5D core/2D SOL and the free boundary equilibrium evolution code CREATE-NL
- Position Control System compatible
    - with 80s Ip ramp-up,
    - 450s flat-top,
    - 170s Ip ramp-down
- Sensitivity for the ramp-up rate (dashed lines)
- Q~10 predicted but sensitive to pedestal assumption

V. Parail et al., Nucl. Fusion 44 (2002)

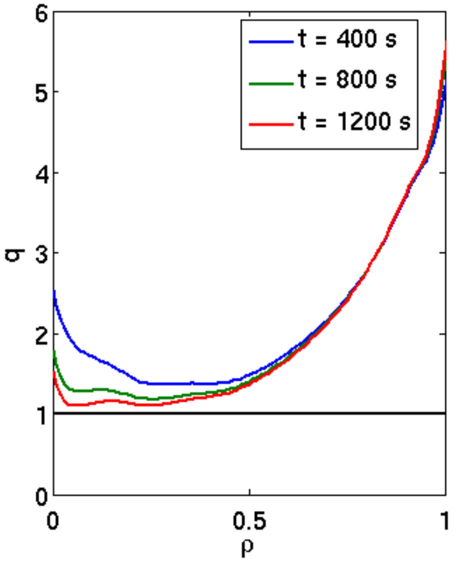
ITER HYBRID SCENARIO: Q ~ 8 FOR 1200 S, IDEAL MHD STABLE







CRONOS simulation

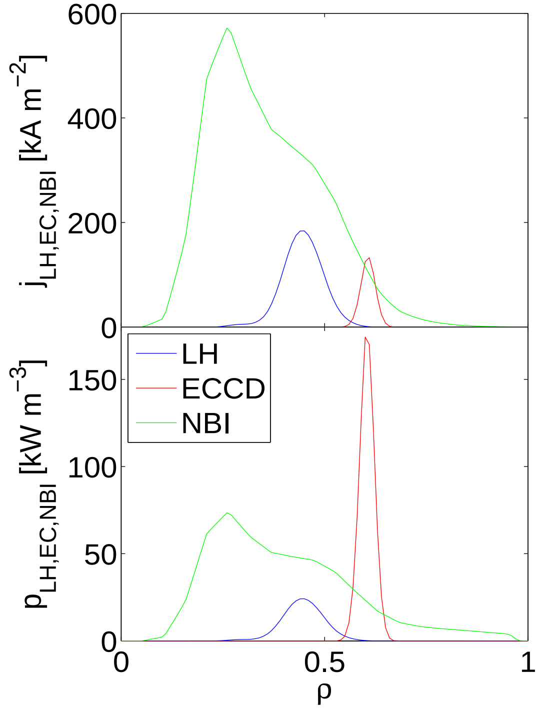


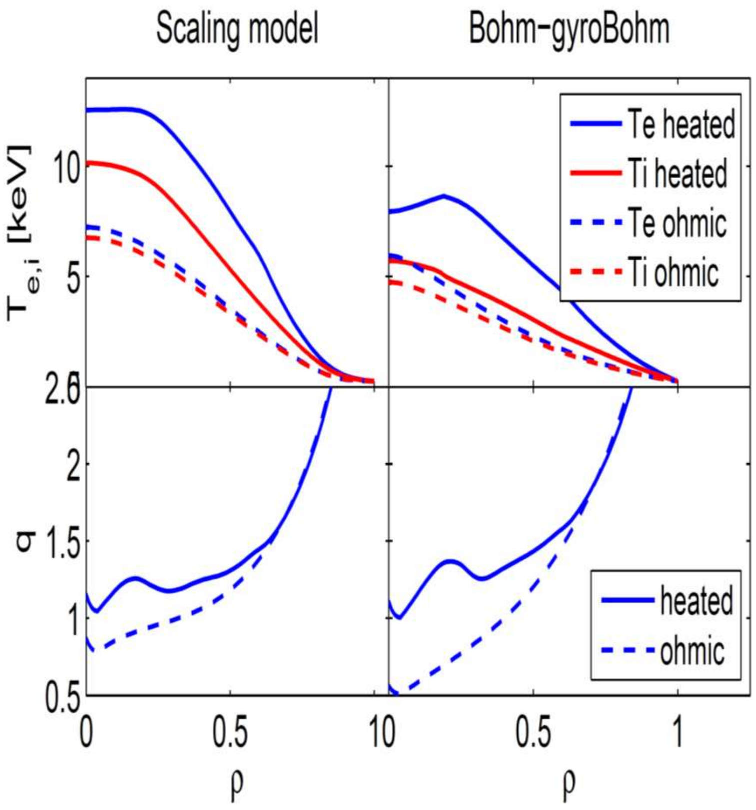
<u>Fixed density</u> ($n_{e0}/<n_e>\sim1.4$)
<u>Fixed T pedestal</u> (~ 5 keV)
<u>Fixed H-factor</u> (~ 1.3)
I_p = 12 MA P_{add} ~ 73 MW
Bootstrap fraction ~ 40%
Non-inductive fraction ~ 80%
Fusion gain Q ~ 8
Fusion Power (MW) ~ 585

Giruzzi G. et al., PPCF 2011
Besseghir K et al PPCF 2013

CURRENT PROFILE OPTIMIZATION DURING CURRENT RAMP-UP PHASE

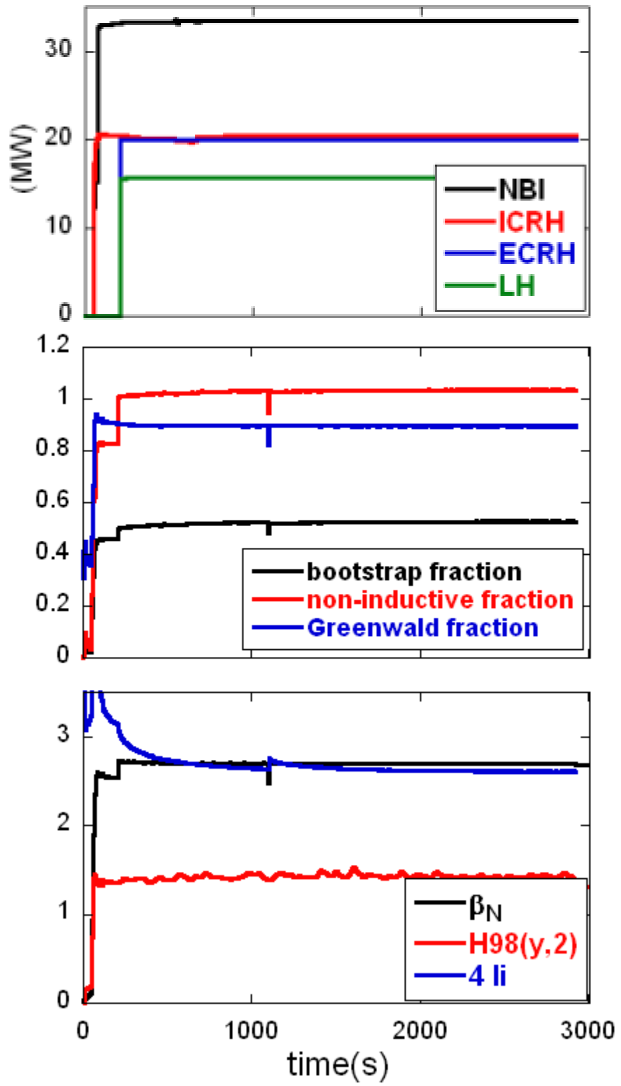
- Access condition to the class of hybrid-like q-profiles ?
- Optimisation of the current ramp-up phase: plasma current waveform, heating & current drive waveform, L to H transition
- the heating systems available at ITER allow to reach a hybrid q-profile at the end of the current ramp-up.

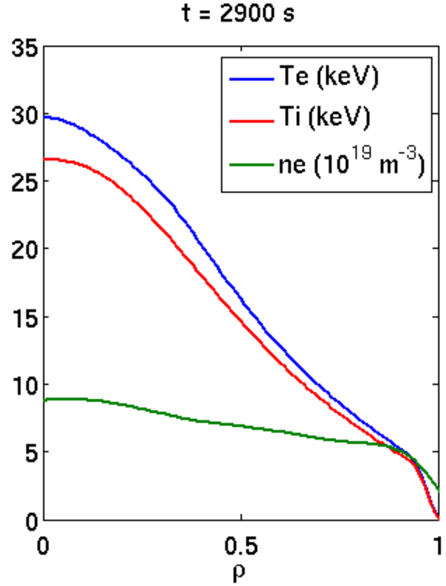


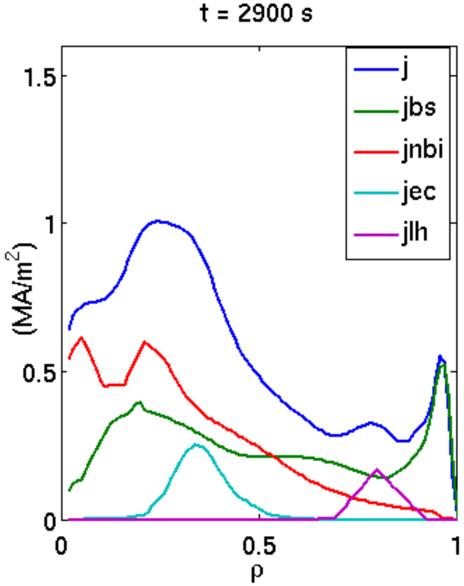


Hogeweij G. et al, Nucl. Fusion 2013

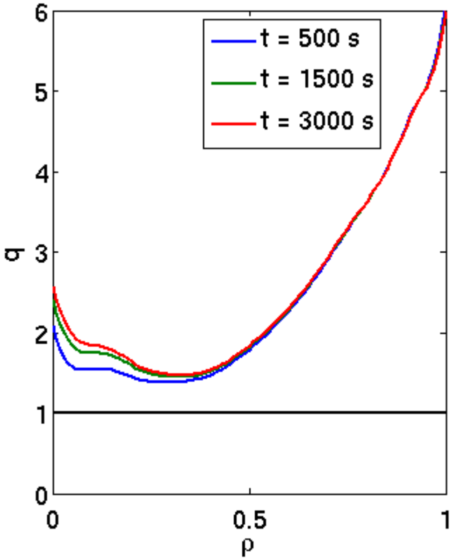
ITER STEADY-STATE SCENARIO: Q ~ 5 FOR 3000 S, IDEAL MHD STABLE







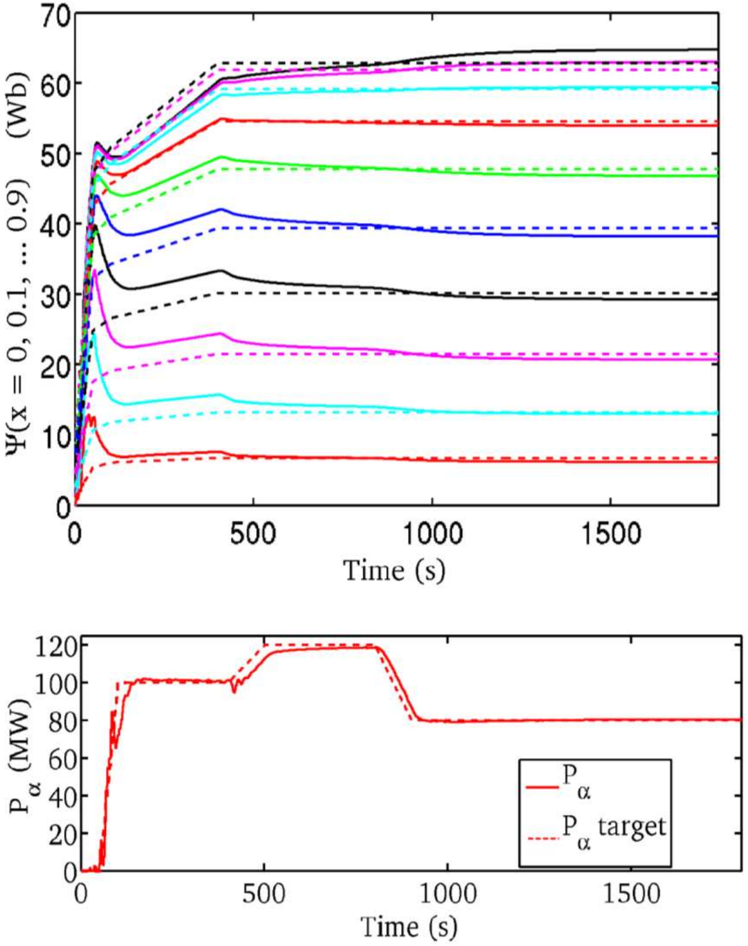
CRONOS
simulation



Fixed density (n$_{e0}$/<n$_e$>~1.4)
Fixed T pedestal (~ 4 keV)
Fixed H-factor (~ 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

Giruzzi G. et al., PPCF 2011
Besseghir K et al PPCF 2013

MODEL-BASED MAGNETIC AND KINETIC REAL TIME CONTROL FOR ITER STEADY-STATE SCENARIO



Moreau D. et al. Nuclear Fusion 2013, Liu F. et al., in Proc. 39th EPS Conference 2012

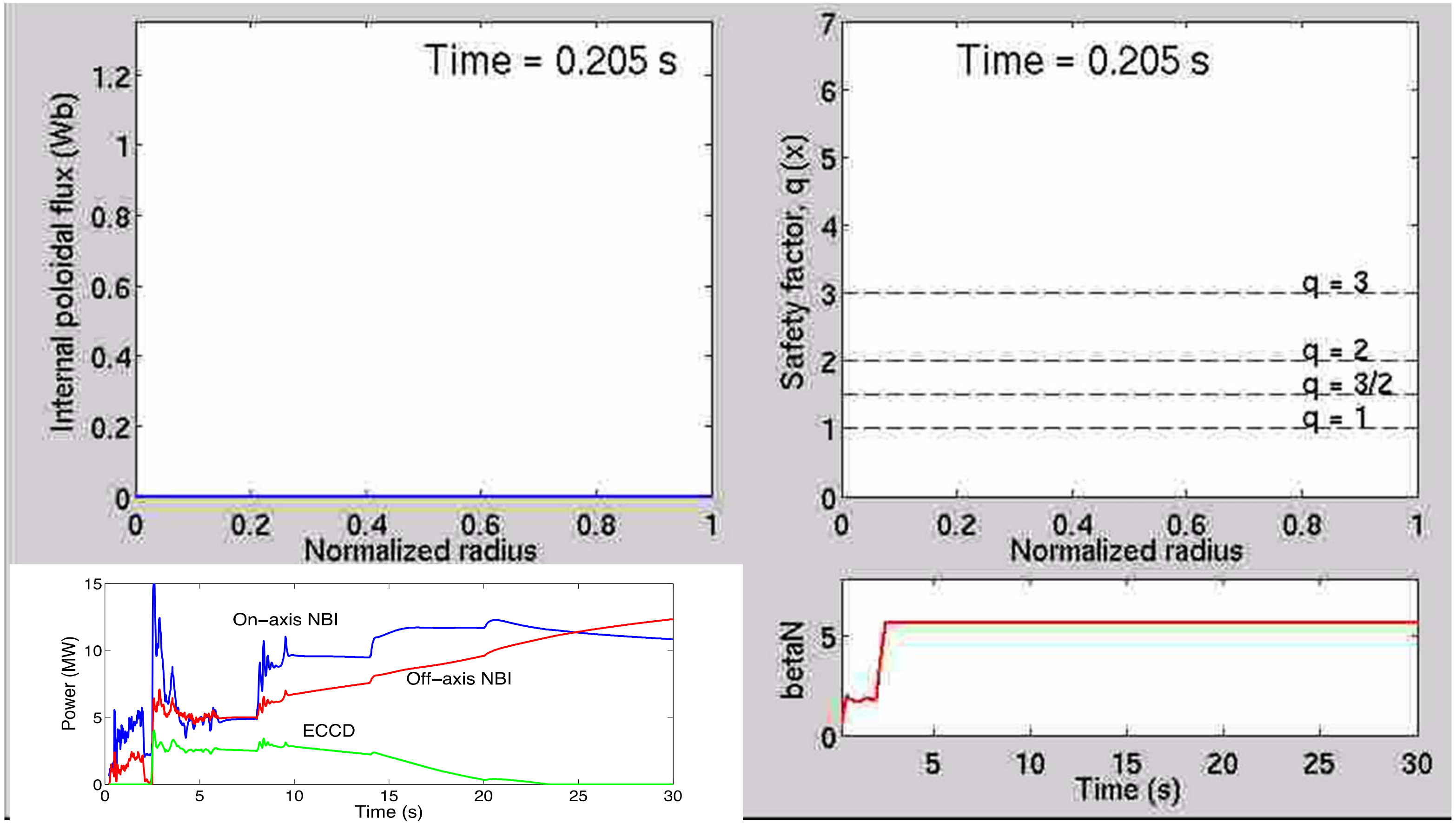
- An integrated model-based plasma control strategy for the control of the poloidal flux profile and Pα
- The control actuators are NBI, ECRH, ICRH , LHCD and surface loop voltage.
- A two-time-scale model identified from open-loop simulations.
- Closed-loop control simulations : current profile control can be combined with burn control

EUROfusion

CONTROL ROBUSTNESS (ITER STEADY-STATE SCENARIO): Loss of confinement, density increase, Zeff increase

Vsurf = 0 @ t > 2.5 s

30% H factor drop @ t > 8 s **25% density increase @ t > 14 s** **25% Zeff increase @ t > 20 s**



Moreau D. et al. 21st EFPW, 9-11 December 2013, Ringsted, Denmark & FEC ST Petersburg 2014

OUTLINE

INTEGRATED MODELLING IN FUSION & ITER

PLASMA OPERATIONAL SCENARIO:

- I) DEFINITION
- II) PHYSICS & COMPUTATIONAL CHALLENGES
- III) MODELLING OF ITER SCENARIOS

RECENT DEVELOPMENT OF INTEGRATED MODELLING PLATFORM & SUITE OF CODES

CONCLUSION AND PROSPECTS

EU INTEGRATED TOKAMAK MODELLING APPROACH

Development of a standardized platform & an integrated modelling suite

- **Generic approach**, i.e. not specific to transport simulator problem, to a chain of coupled codes, to a machine etc
- **Modular**, **flexible**, code, language and machine independent
- A new data and communication ‘ontology’* for **standardizing the data exchange** between different codes, through a **generic data structure** incorporating both **simulated and experimental data**
    - ➢ modules describing the same physics is easily interchanged
    - ➢ eases code coupling & rigorous code verification / benchmark
    - ➢ enhanced quality / reproducibility
- **Multi-machine capability**: modules within a workflow run on local cluster or HPC or GRID

*Ontology is the structural framework for organizing information used in systems/software engineering, artificial intelligence etc (~ grammar for data)

Becoulet et al CPC 177 (2007) 55–59
Strand P.I. et al 2010 Fusion Eng. Des. 85 383–7
Falchetto et al Nucl. Fusion 54 (2014) 043018

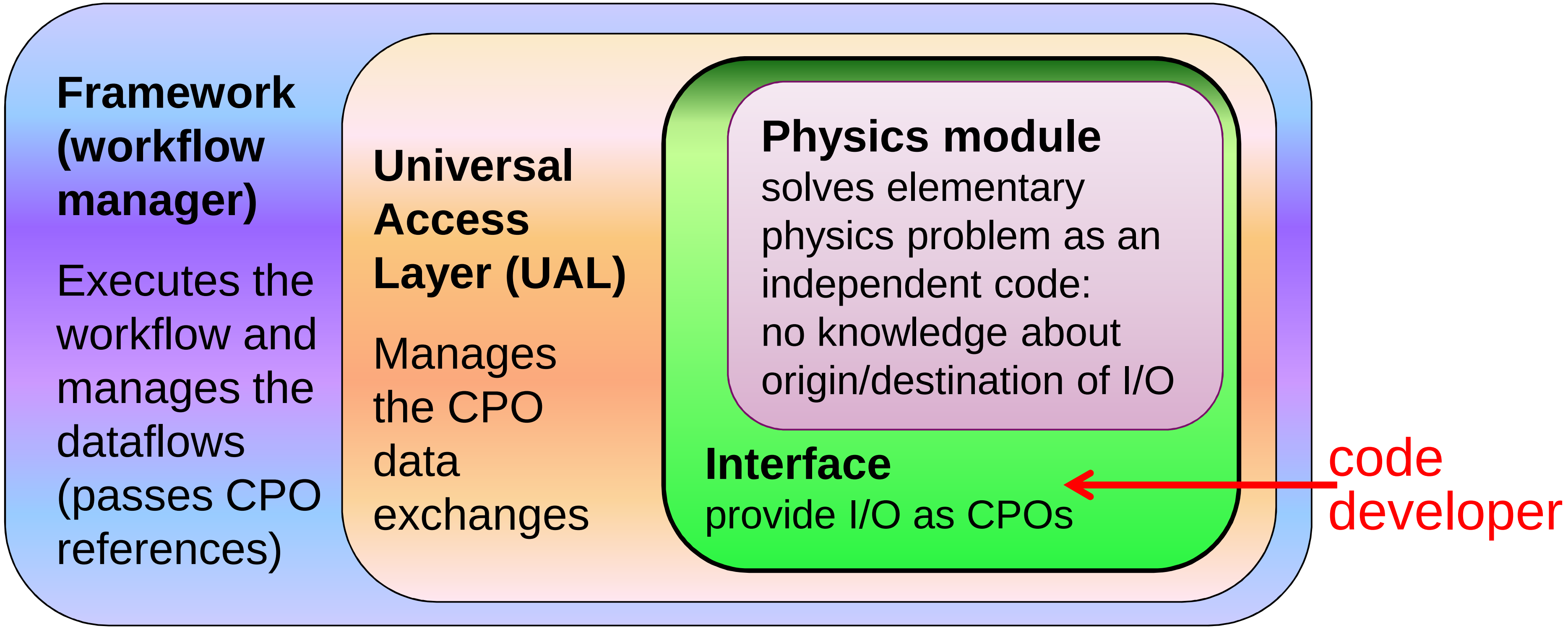
EU INTEGRATED TOKAMAK MODELLING APPROACH

EFDA Task Force
EUROPEAN FUSION DEVELOPMENT AGREEMENT
INTEGRATED TOKAMAK MODELLING

- the integrated simulation "workflow" solves an elementary problem (e.g. equilibrium reconstruction, wave propagation, synthetic diagnostic, …)
  - ➢ modularity, flexibility
- the data transfer between components uses exclusively standardized interfaces (I/O) : Consistent Physical Objects (CPOs) [F. Imbeaux et al, Comp. Phys. Comm. 2010]
  - ➢ consistent data-blocks defined from the elementary physics/technology problem solved (equilibrium, PF coils …)
  - ➢ generic data structure for machine and simulation data
  - ➢ independent of programming language
- the data management is hidden to the user, data exchanges are dealt by a Universal Access Layer (UAL)
- a graphical workflow manager allows to easily build integrated simulations reflecting transparently the physics

Falchetto et al Nucl. Fusion 54 (2014) 043018

EU INTEGRATED TOKAMAK MODELLING APPROACH: GENERIC APPLICATION STRUCTURE



Framework (workflow manager)

Executes the workflow and manages the dataflows (passes CPO references)

Universal Access Layer (UAL)

Manages the CPO data exchanges

Physics module
solves elementary physics problem as an independent code:
no knowledge about origin/destination of I/O

Interface
provide I/O as CPOs

code developer

A dedicated tool automatically converts a module into a Kepler actor :

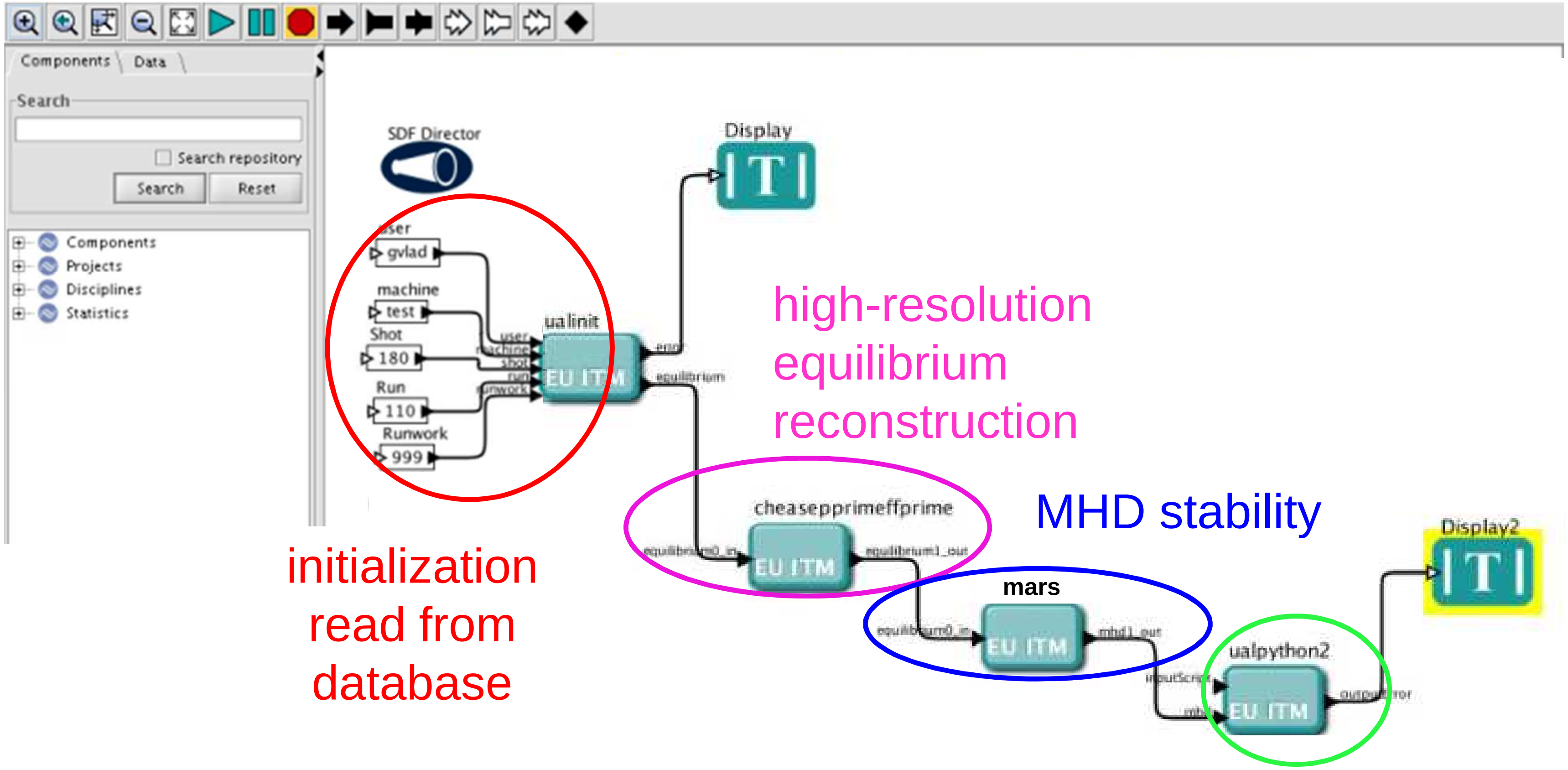
CPO_in

CPO_out

https://kepler-project.org/

Falchetto et al Nucl. Fusion 54 (2014) 043018

Kepler workflow: graphical version of a code flowchart



high-resolution equilibrium reconstruction

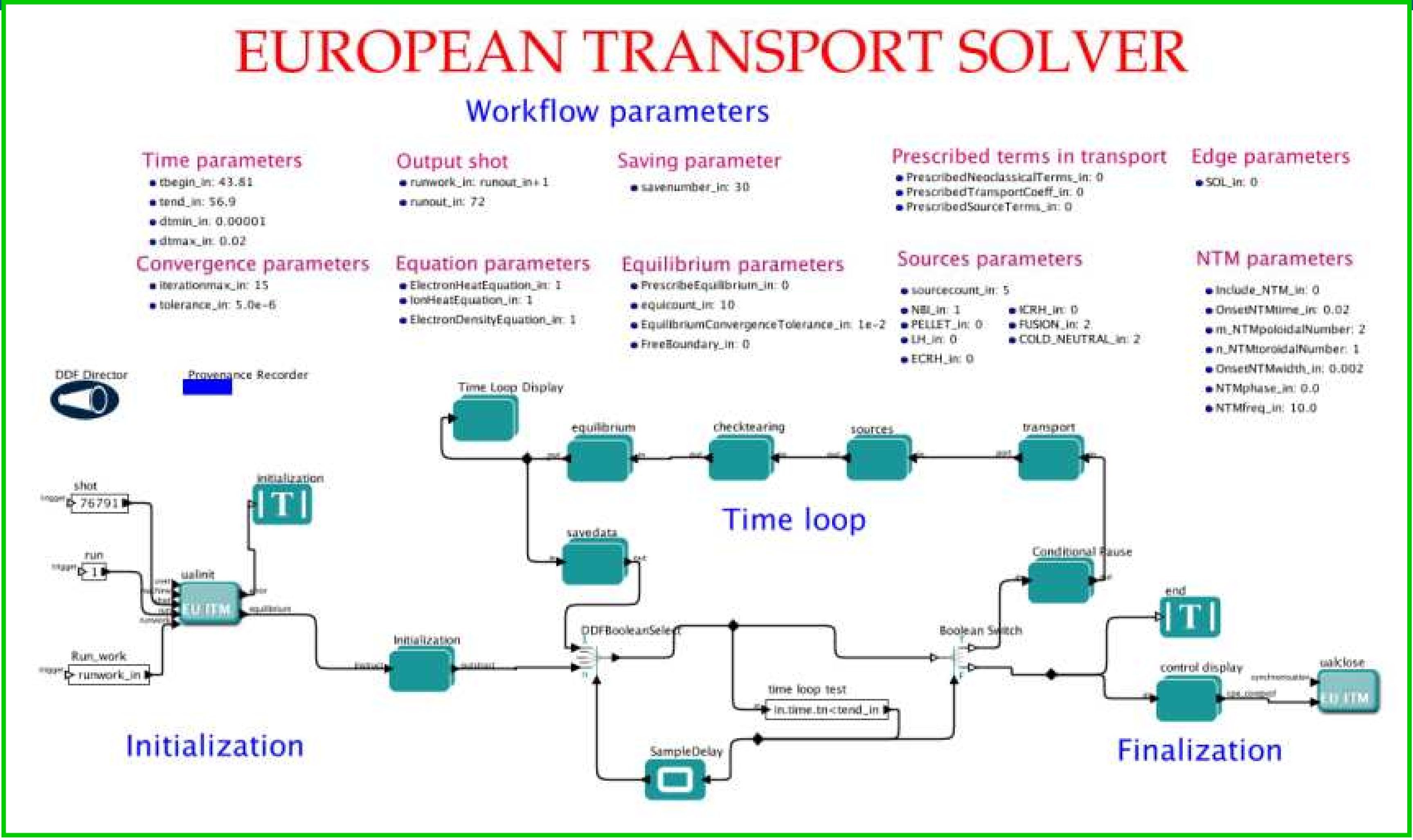
MHD stability

initialization read from database

visualization actor

Falchetto et al Nucl. Fusion 54 (2014) 043018

EUROPEAN TRANSPORT SOLVER , ETS



EUROPEAN TRANSPORT SOLVER

Workflow parameters

Time parameters
- tbegin_in: 43.81
- tend_in: 56.9
- dtmin_in: 0.00001
- dtmax_in: 0.02

Output shot
- runwork_in: runout_in+1
- runout_in: 72

Saving parameter
- savenumber_in: 30

Prescribed terms in transport
- PrescribedNeoclassicalTerms_in: 0
- PrescribedTransportCoeff_in: 0
- PrescribedSourceTerms_in: 0

Edge parameters
- SOL_in: 0

Convergence parameters
- iterationmax_in: 15
- tolerance_in: 5.0e-6

Equation parameters
- ElectronHeatEquation_in: 1
- IonHeatEquation_in: 1
- ElectronDensityEquation_in: 1

Equilibrium parameters
- PrescribeEquilibrium_in: 0
- equicount_in: 10
- EquilibriumConvergenceTolerance_in: 1e-2
- FreeBoundary_in: 0

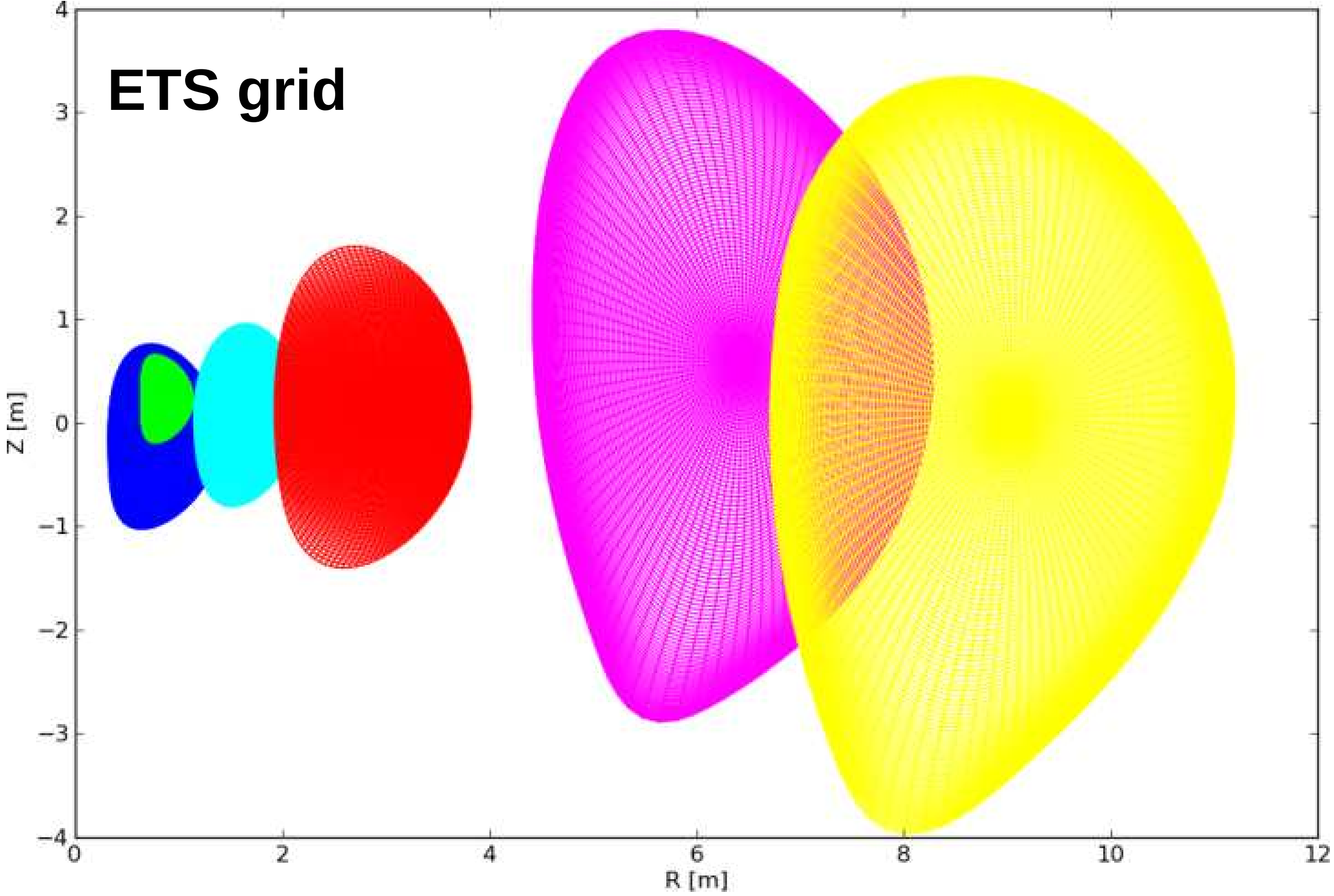
Sources parameters
- sourcecount_in: 5
- NBI_in: 1
- PELLET_in: 0
- LH_in: 0
- ECRH_in: 0
- ICRH_in: 0
- FUSION_in: 2
- COLD_NEUTRAL_in: 2

NTM parameters
- Include_NTM_in: 0
- OnsetNTMtime_in: 0.02
- m_NTMpoloidalNumber: 2
- n_NTMtoroidalNumber: 1
- OnsetNTMwidth_in: 0.002
- NTMphase_in: 0.0
- NTMfreq_in: 10.0

- ~1000 Kepler actors
- ~5000 data for the data structure

EUROPEAN TRANSPORT SOLVER FOR VARIOUS TOKAMAKS GEOMETRY

Core workflows running under Kepler for MAST, TCV, AUG, JET, ITER, DEMO



Kalupin D. et al

ALTERNATIVE APPROACH : IPS , INTEGRATED PLASMA SIMULATOR

IPS, Integrated Plasma Simulator:

- A flexible, extensible computational framework capable of coupling state-of-the-art models for energy and particle sources, transport, and stability for tokamak core plasma

IPS Design Approach

- permit massively parallel physics modules to interoperate with flexibly and efficiently
  - ➢ Framework/component architecture – *written in Python*
  - ➢ Components implemented using existing whole codes (usually in Fortran) wrapped in standard component interface (written in Python)
  - ➢ File-based communication
  - ➢ Plasma State: official transfer mechanism for time-evolving data that must be transferred between components

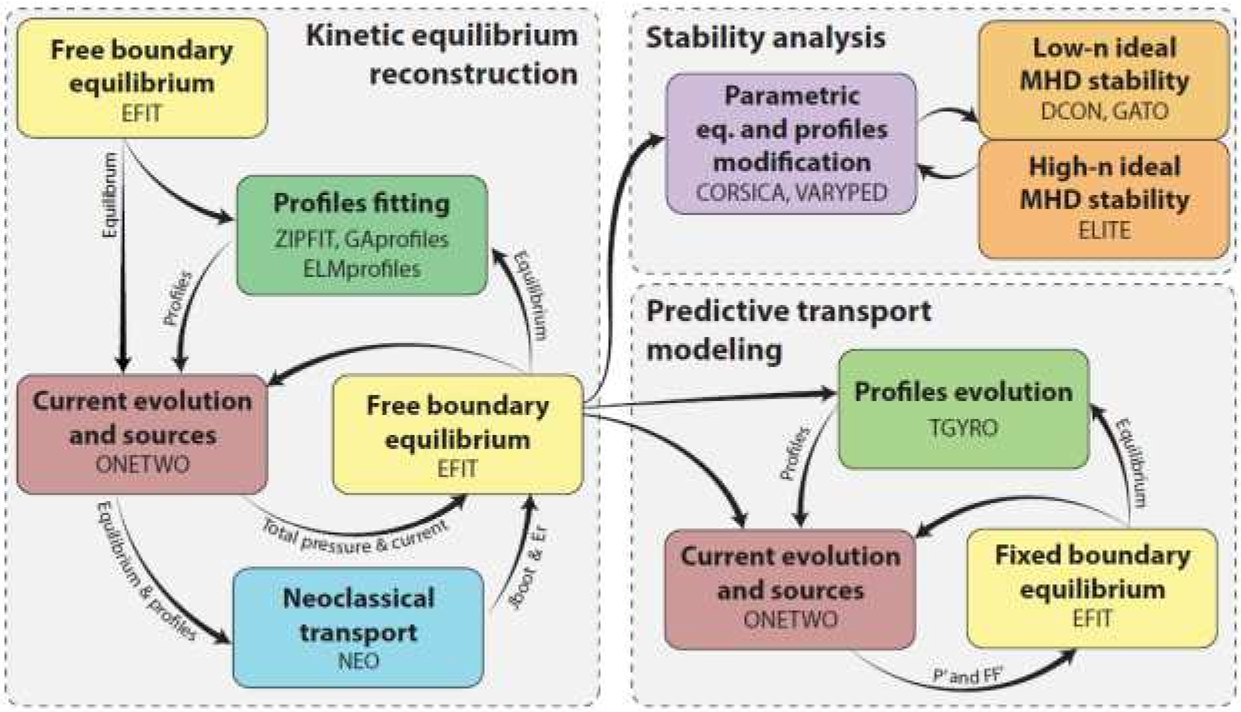
D. B. Batchelor et al

ALTERNATIVE APPROACH : OMFIT FRAMEWORK

OMFIT : One Modeling Framework for Integrated Tasks:

- A comprehensive framework designed to facilitate experimental data analysis and enable integrated simulations
- Collect data from different sources into a single, self-descriptive, hierarchical data structure

Routinely used for DIII-D equilibrium, stability and transport analyses



Kinetic equilibrium reconstruction

Free boundary equilibrium
EFIT

Profiles fitting
ZIPFIT, GAprofiles
ELMprofiles

Current evolution and sources
ONETWO

Free boundary equilibrium
EFIT

Neoclassical transport
NEO

Stability analysis

Parametric eq. and profiles modification
CORSICA, VARYPED

Low-n ideal MHD stability
DCON, GATO

High-n ideal MHD stability
ELITE

Predictive transport modeling

Profiles evolution
TGYRO

Current evolution and sources
ONETWO

Fixed boundary equilibrium
EFIT

DIII-D NATIONAL FUSION FACILITY

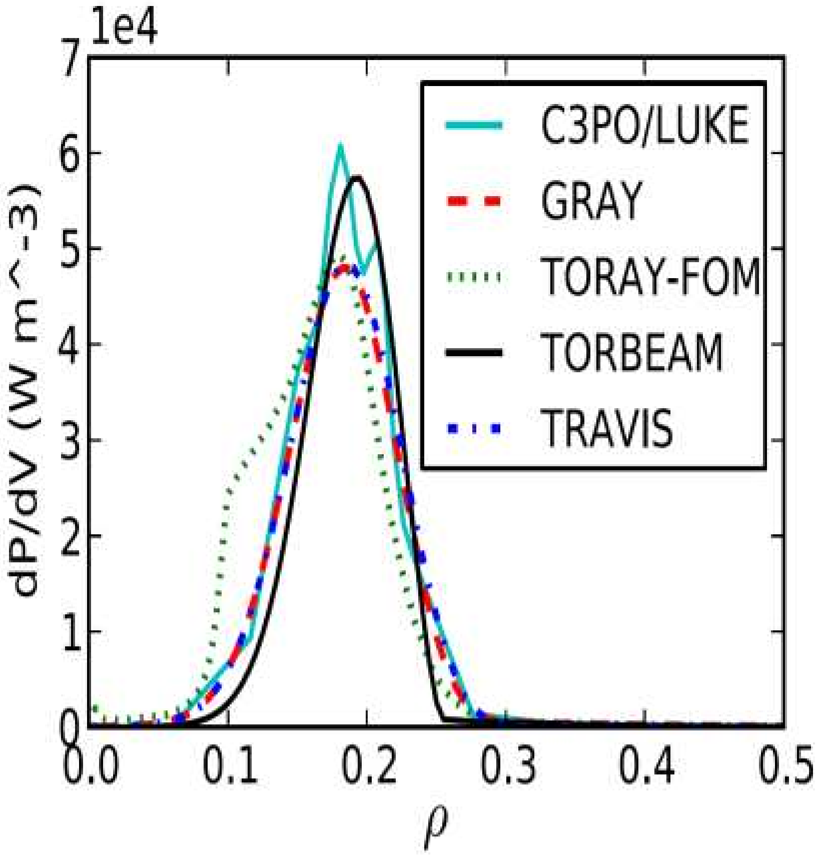
GENERAL ATOMICS

Oak Ridge Institute for Science and Education

O. Meneghini et

VERIFICATION USING EU FRAMEWORK

Benchmarking of electron cyclotron heating and current drive codes on an ITER inductive scenario



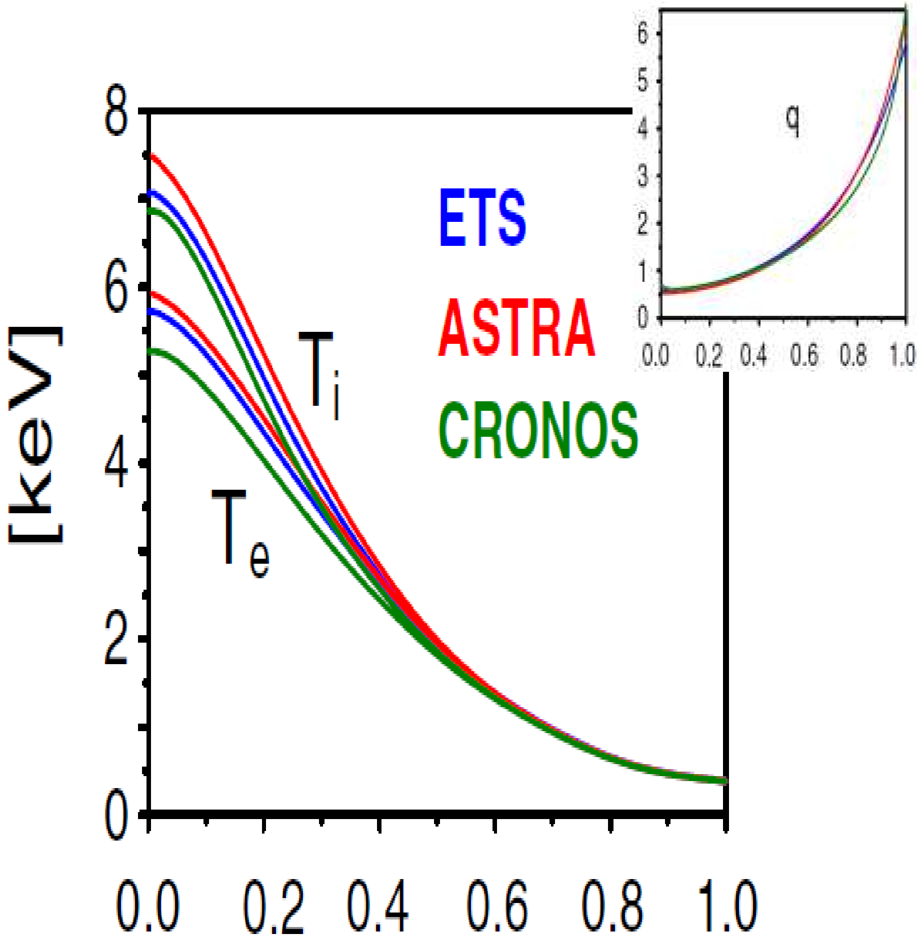
Equatorial launcher with poloidal & toroidal launching angles 0° and 25°

- **Benchmark 5 EU EC beam/ray-tracing codes** performed within the EU framework for 3 different launching conditions
- **Simplifies verification**: the 5 codes run in the same workflow
- **Good agreement found**, differences in total current < 15%, and with peak values of power density dP/dV and driven current density matching within 10%, and the position of the profiles matching within δρ ~ 0.02

Figini L. et al 2012 et al EC-17

ETS VERIFICATION

Benchmarking of the ETS against ASTRA and CRONOS performed using the parameters of JET hybrid discharge



Kalupin D. et al 2011 38th EPS Conf.

- Self-consistent evolution of electron and ion temperatures, current diffusion and equilibrium
- fixed electron density profile, Gaussian heating and current drive profiles
- Spitzer resistivity, Bohm–gyro-Bohm transport model
- Satisfactory agreement. Differences attributed to different equilibrium solvers
- Laying the foundation for ETS usage for predictive and interpretative runs on present devices and ITER.

FULL JET DISCHARGE SIMULATION WITH ETS

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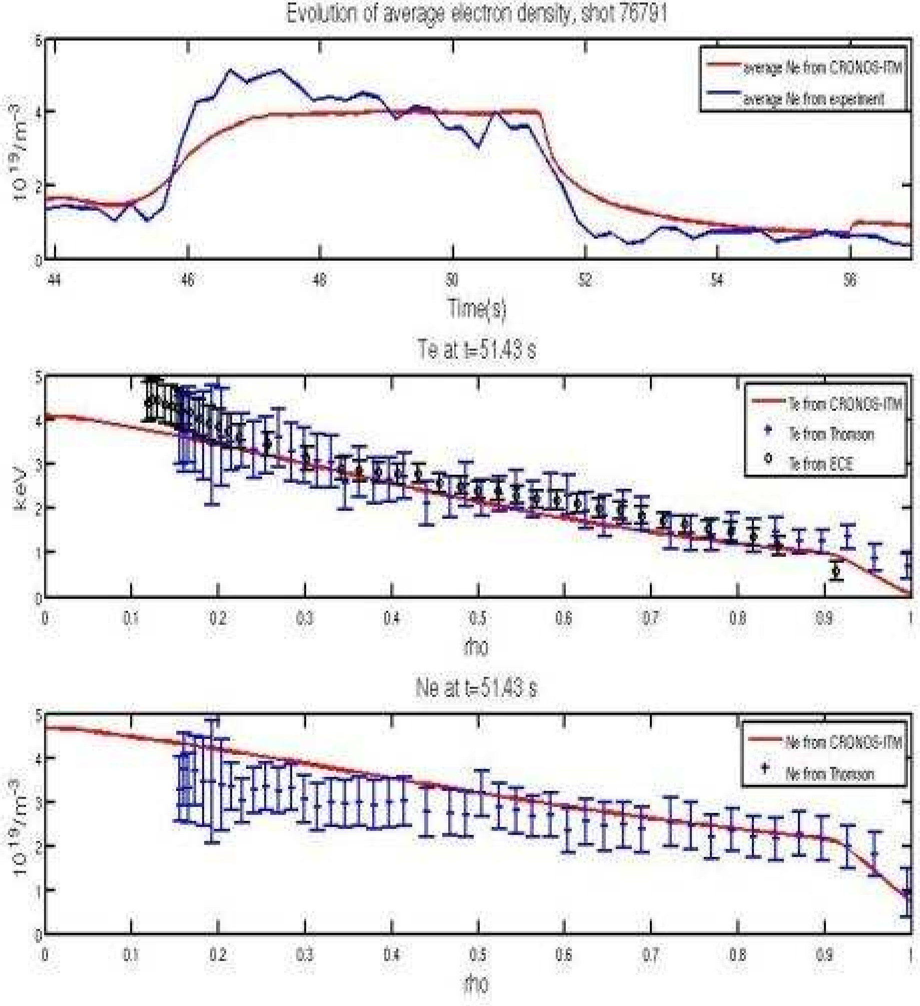
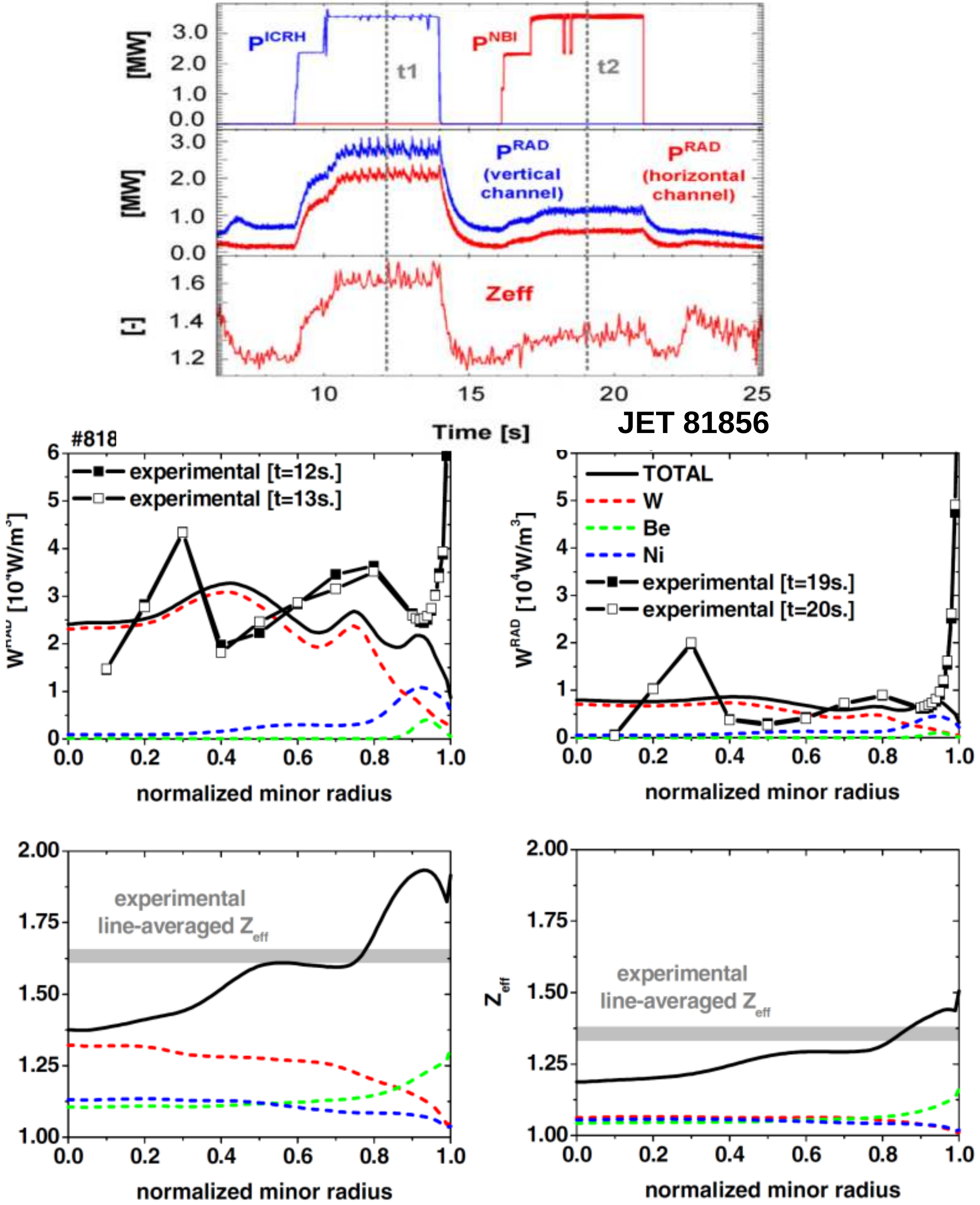


- **Simulation covering the full plasma discharge duration (13s).**
- **Solves coupled transport equations of magnetic flux, temperature and density simultaneously**
- **Good agreement between experimental data and simulation**

P. Huynh, V. Basiuk

IMPURITY TRANSPORT MODELLING WITH ETS: ITER LIKE WALL JET EXPERIMENTS



- Impurity transport simulated to match the radiative power profiles

Output ETS modelling

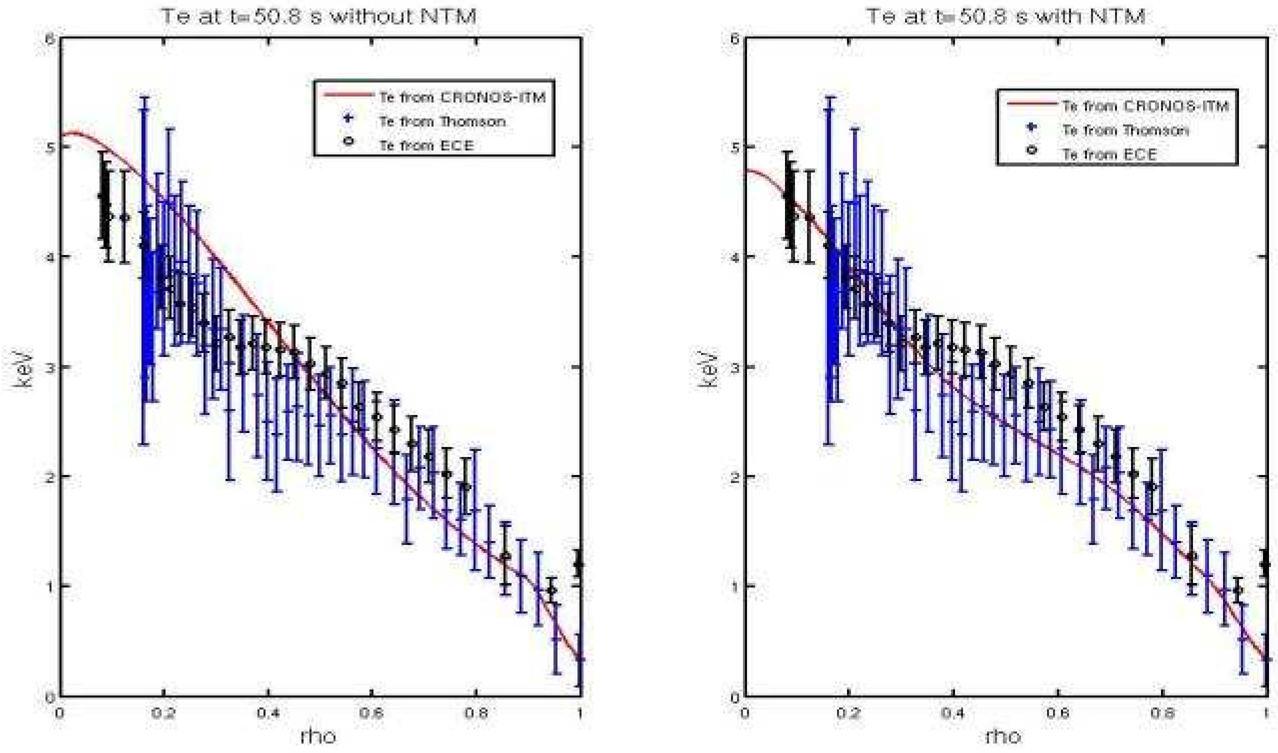
- Impurity profiles and transport coefficients
- radiation
  - Core ~ W
  - edge injected Ni
  - Be weak contributions

- impurity increase during ICRH phase analysed as an edge W-source increase instead of transport modification

Kalupin, Nucl. Fusion 53 (2013) 123007

NEOCLASSICAL TEARING MODE MODULE COUPLED TO ETS

- **Neoclassical Tearing Modes (NTMs) are magnetohydrodynamic modes which degrade locally the energy and particle confinement**
- **Flattening of Te by a 3/2 NTM was simulated on JET pulse 76791, in good agreement with experiment**

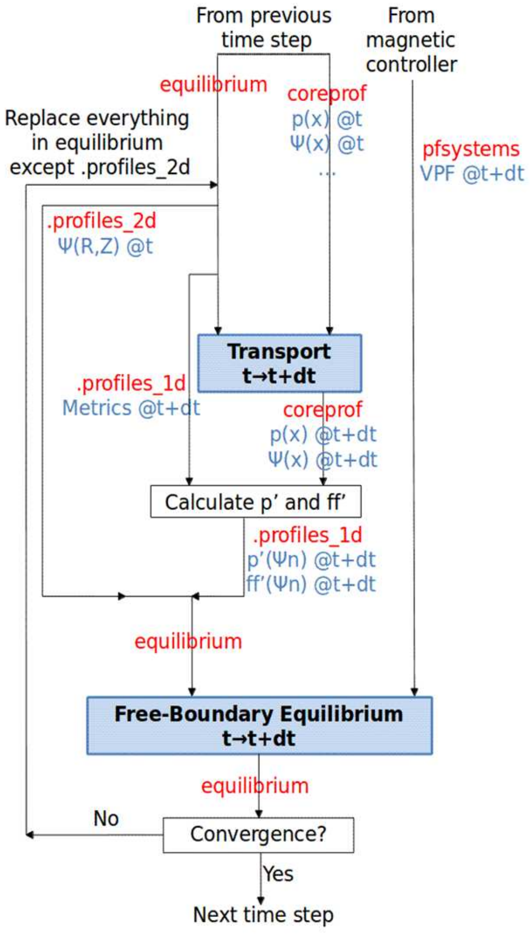


P.Huynh, V.Basiuk, S.Nowak, O.Sauter

EUROfusion

COUPLED EQUILIBRIUM-TRANSPORT SIMULATIONS ON ETS

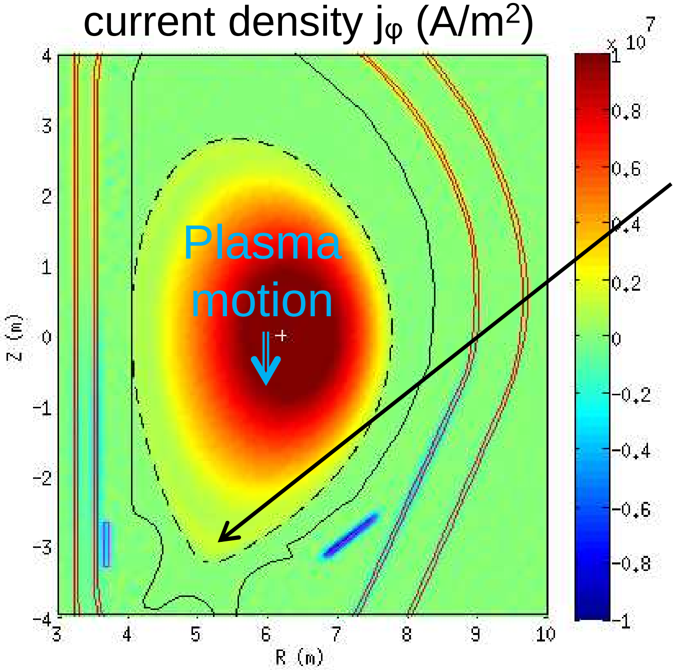
- Tokamak scenario preparation requires a consistent modeling of the poloidal field system, plasma force balance and plasma core transport
- coupling Free boundary equilibrium CEDRES++ (2D plasma force balance + PF system) with the European Transport Solver


From previous time step
From magnetic controller
equilibrium
coreprof
p(x) @t
Ψ(x) @t
...
Replace everything in equilibrium except .profiles_2d
pfsystems
VPF @t+dt
.profiles_2d
Ψ(R,Z) @t
Transport
t→t+dt
.profiles_1d
Metrics @t+dt
coreprof
p(x) @t+dt
Ψ(x) @t+dt
Calculate p' and ff'
.profiles_1d
p'(Ψn) @t+dt
ff'(Ψn) @t+dt
equilibrium
Free-Boundary Equilibrium
t→t+dt
equilibrium
No
Convergence?
Yes
Next time step

Proof of princple:

Simulation of a vertical displacement event in ITER

Cross-section of the toroidal current density j_φ (A/m^2)



Current sheet induced at the edge of the plasma due to the interplay between transport, force balance and PF system

CONCLUSION [1/3]

- With ITER, Fusion research enters in the ‘**Nuclear and Reactor Era**’.
- Bringing Fusion research to its “Reactor Era” requires an innovative programme of “discharge mastering”, where modelling plays a crucial role
    - **Limited experimental time for empirical approach**
    - **Design**, **safety** case and **preparation of operation** with systematic **modelling**
- Integrated Modelling: Set of codes coupled together to model the complex & coupled ‘plasma + tokamak’ system
- Integrated Modelling for ITER scenario
    - **Predictive** modelling of **each plasma** from **beginning to end**, including analysis of **control requirements**
    - **Interpretative analysis** of each plasma to evaluate/validate models
- ITER scenario design: **physics** and **computational** challenges

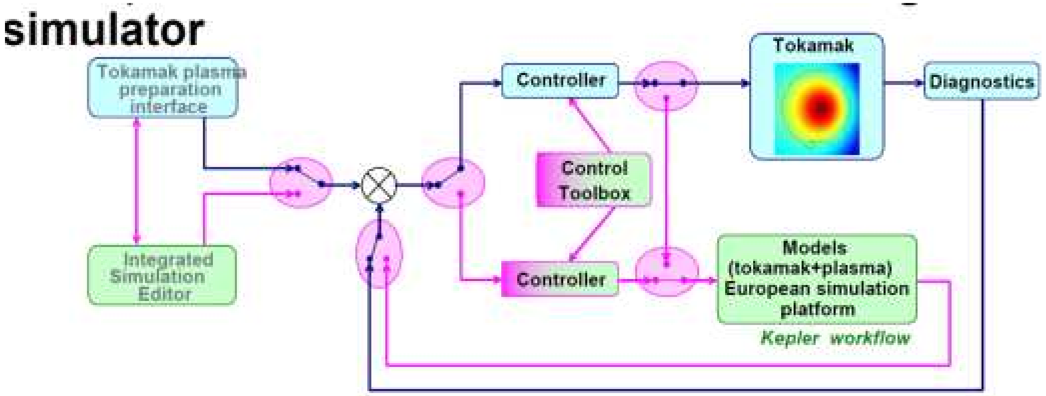
PROSPECTS [2/3]

- Finalisation of the ITER **modeling architecture & analysis suite for Integrated Tokamak Modelling**
- **Systematic validation and benchmark** on existing experiments with more accurate reproductions of present-day tokamak data**, e.g.**
  - **Core & edge integration** (full 2D coupling) **with metallic walls**
  - **Impurity source and transport**
  - **Disruption modelling**
  - **MHD & confinement , pedestal**
  - **Fast particles physics**
  - **…**
- Imperative to **bridge the gap between speed and accuracy** for routine integrated modelling
  - **computational challenge:** parallization and computing resources
  - **physics challenge:** reduced model

PROSPECTS [3/3]

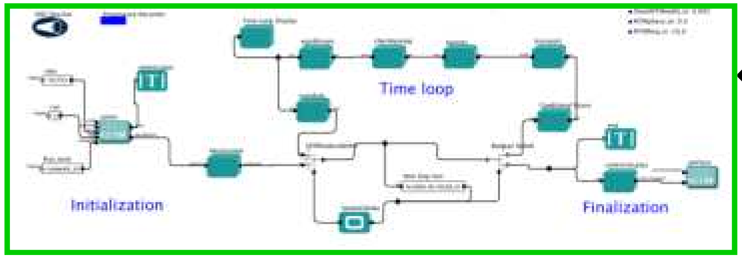
Integrated simulation that includes all the complexity of tokamak operation

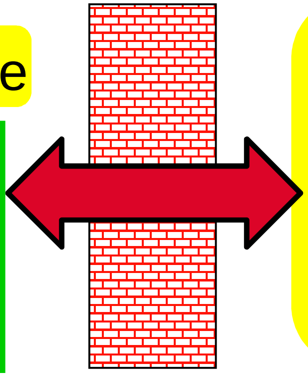
- Towards the **flight simulator** for ITER & fusion reactors



- Towards the **numerical tokamak**, the **ab-initio integrated modelling**
  - ➢ Integrate with first principle codes with multi-platform resources (cluster, grid, HPC)

Integrated modelling architecture





First principle modelling :
- Transport
- MHD
- Sources
- Fast particles …

SOME REFERENCES …

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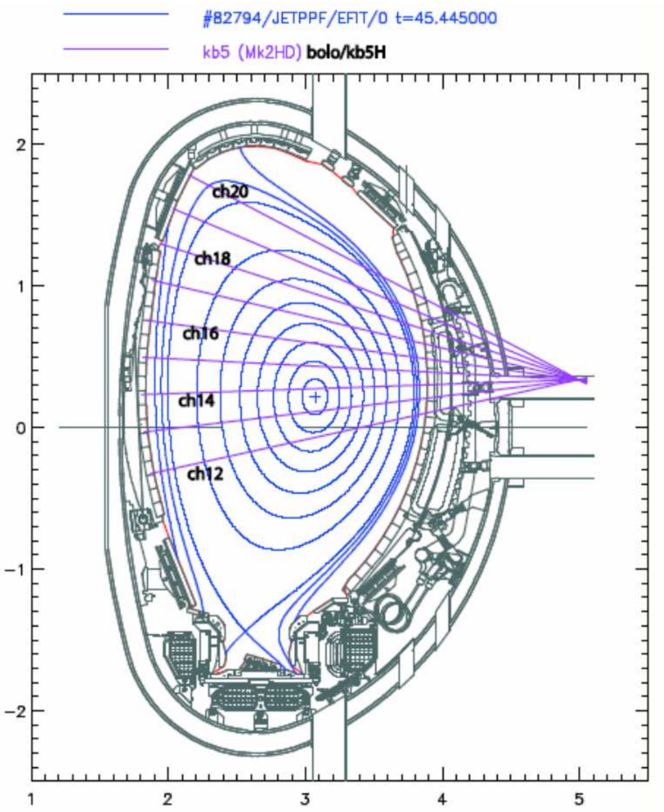
EXTRA-SLIDES

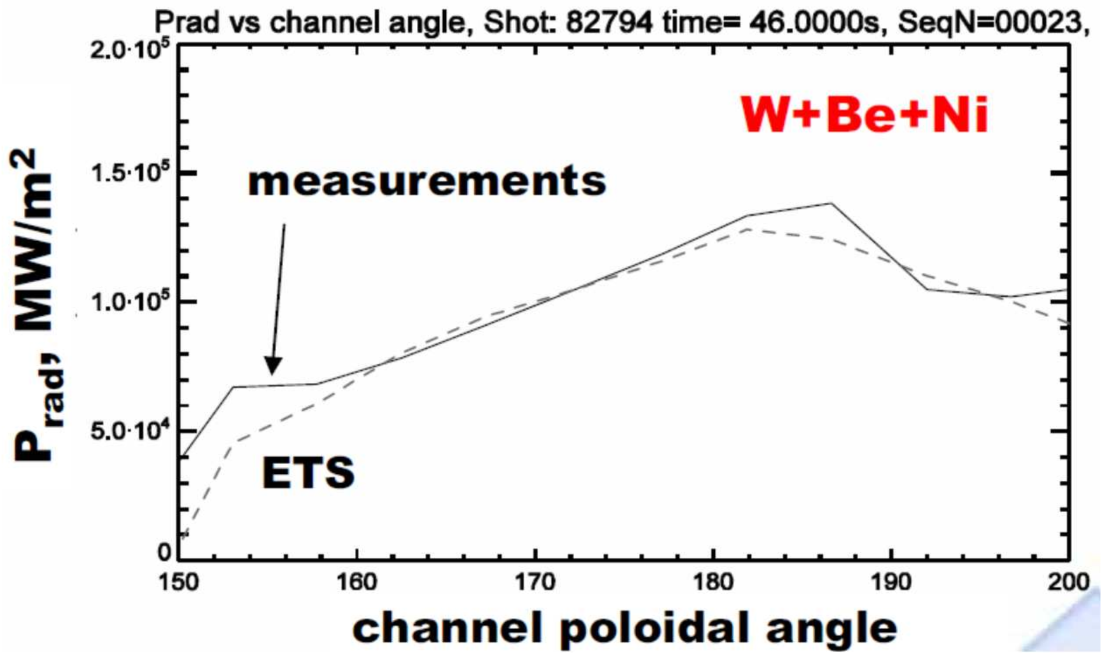
EUROfusion

IMPURITY TRANSPORT WITH ETS: ITER LIKE WALLS JET HYBRID SCENARIO

- Intrinsic Be and W, and injected Ni impurities simulated with ETS (all charge states, non-coronal equilibrium, empirical impurity transport):

Radiation measurement from different bolometer channels is reasonably well reproduced





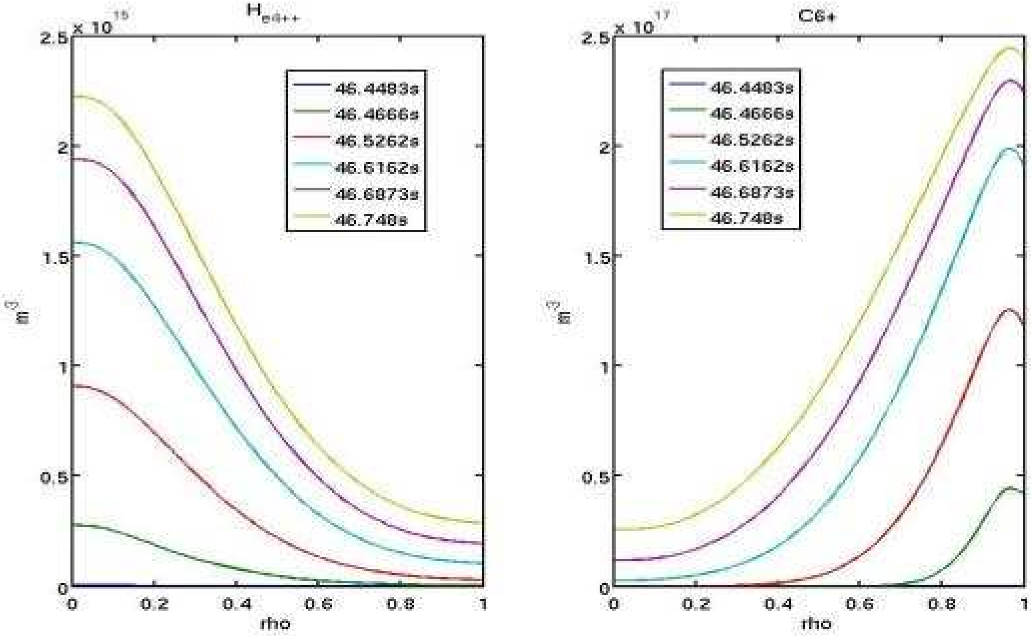
I. Ivanova-Stanik, Yu. Baranov

I. Voitsekhovitch and J. Garcia, ITM GM, Nov. 2013

EUROfusion

TRANSPORT OF IMPURITIES IMPLEMENTED IN ETS

Evolution of He^{2+} and C^{6+} radial density profiles showing the penetration from the edge to the core.



- **Transport of multiple impurities, including multiple charge states in ETS**
- **First verifications performed on test cases for light impurities on a JET-like geometry**
- **Perspectives: extend verification to heavy metallic impurities (Tungsten) and coupling to turbulent transport models**

P. Huynh, J.Li, J.F Artaud, V.Basiuk, R.Guirlet