EFDA
EUROPEAN FUSION DEVELOPMENT AGREEMENT
Task Force
INTEGRATED TOKAMAK MODELLING

21st International Conference on Numerical Simulation of Plasmas 2009
2009-10-06

The European Transport Solver

Presented by: D. Coster
ETS Team, IMP3, TF-ITM teams

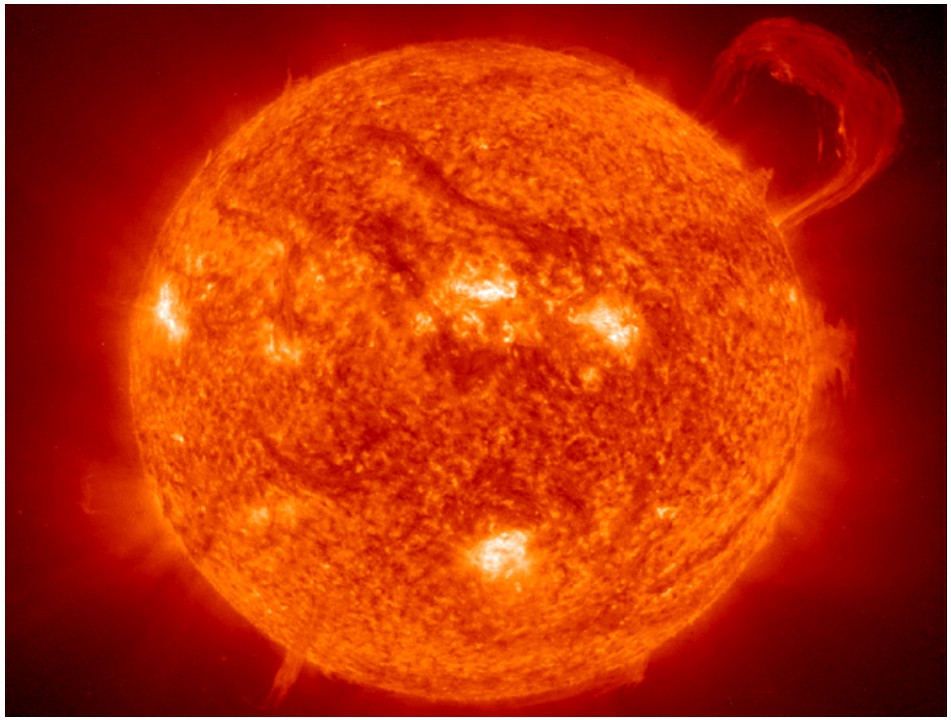
IMP3 leader: D. Coster,
IMP3 deputies: G. Pereverzev, V. Basiuk

TF Leader : P. Strand,
Deputies: L-G. Eriksson, R. Coelho, G. Falchetto

EFDA CSU Contact Person: D. Kalupin

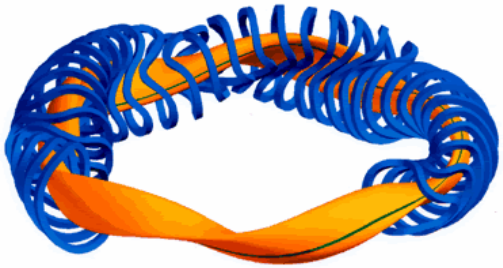
Fusion

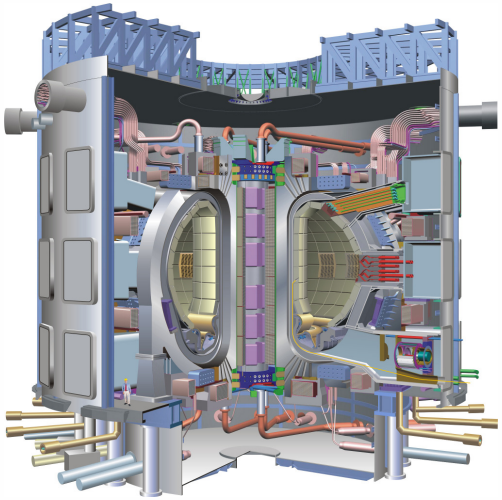
- Energy source for the sun and other stars
- Provides a potential source of base load energy production
- Been working on this for more than 50 years
- Has turned out to be a very difficult problem



Fusion

- Two main lines of research
  - Inertial confinement
    - Implosion of small pellets
    - NIF at LLNL
  - Magnetic confinement
    - Two main lines of research at the moment
      - Stellarator – W7X
        - » Currently under construction in Greifswald in Germany
      - Tokamak – ITER
        - » To be constructed in Cadarache in France





ITER

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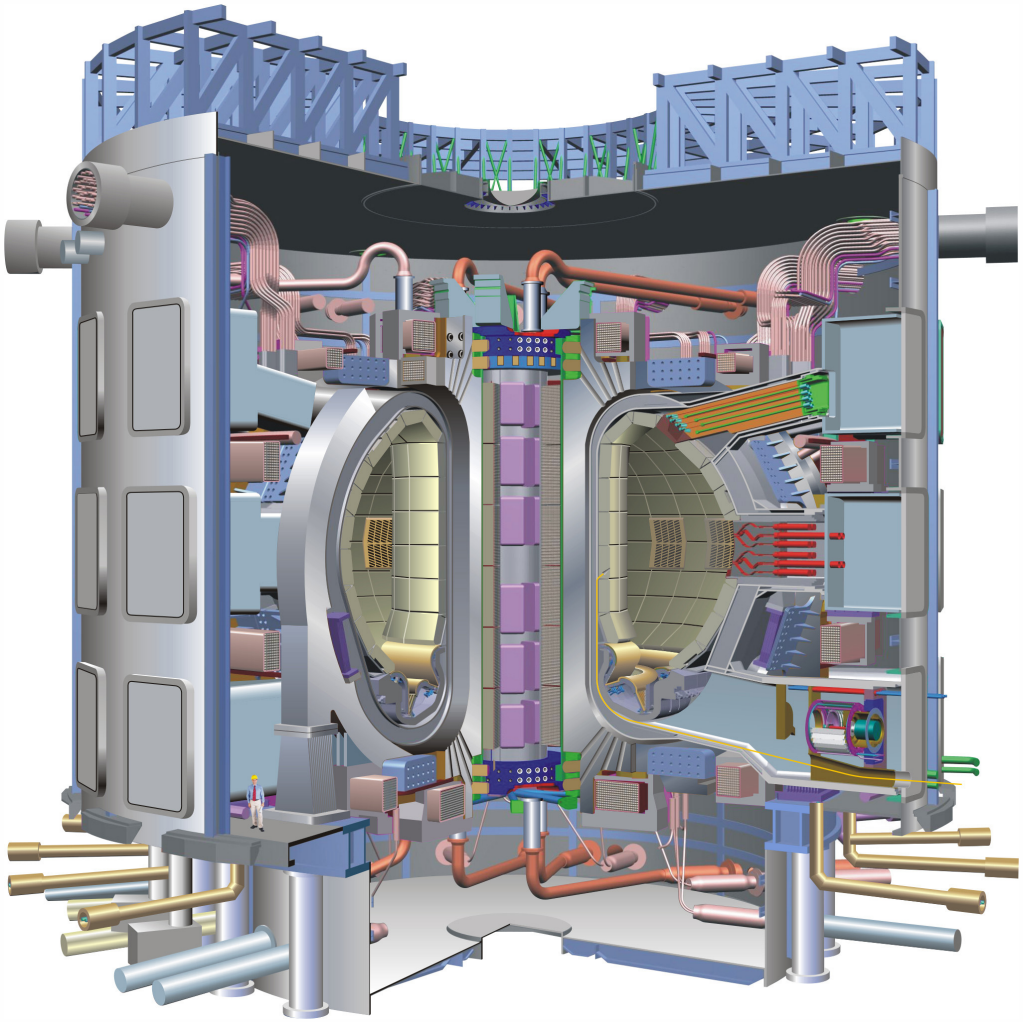

Involves 7 partners representing more than 50% world population
Costs > 10 G$
Under construction in Cadarache, France
Key element on the path to fusion energy production

ITER

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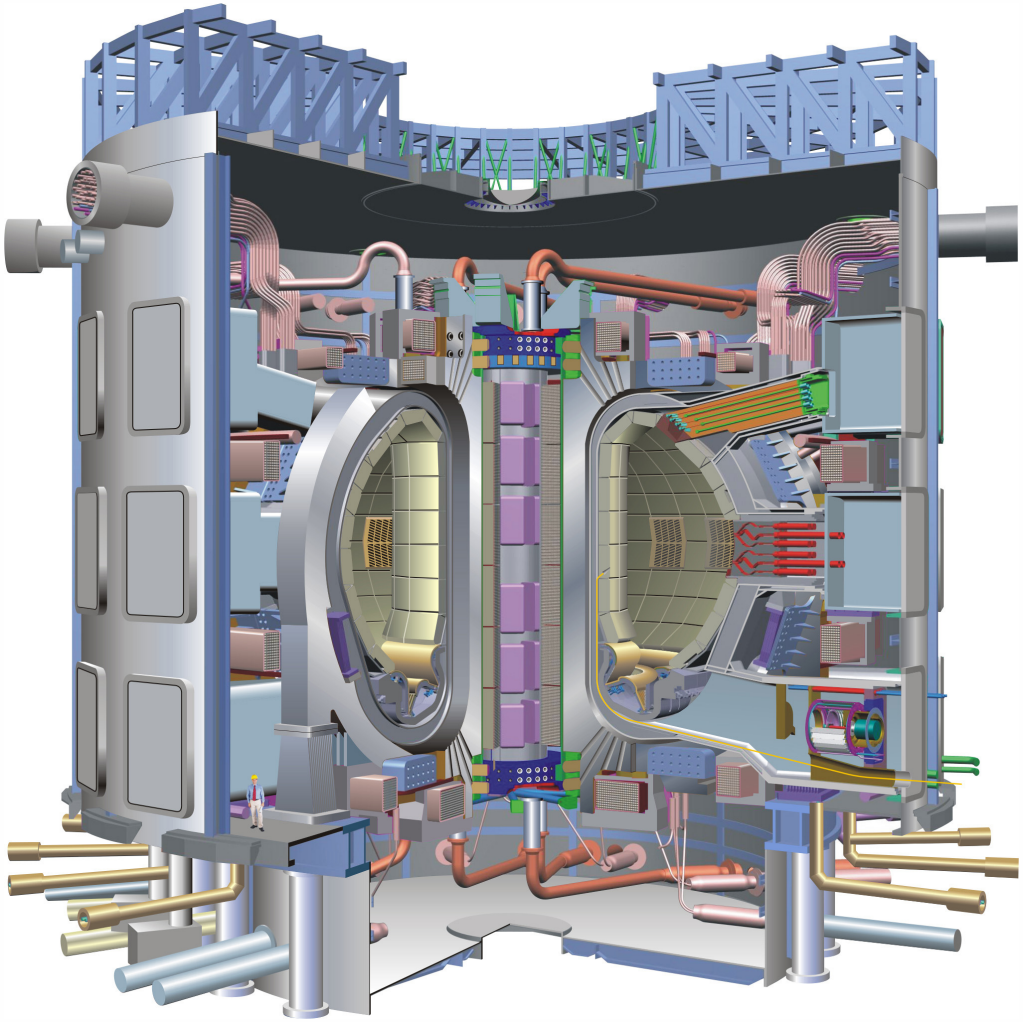
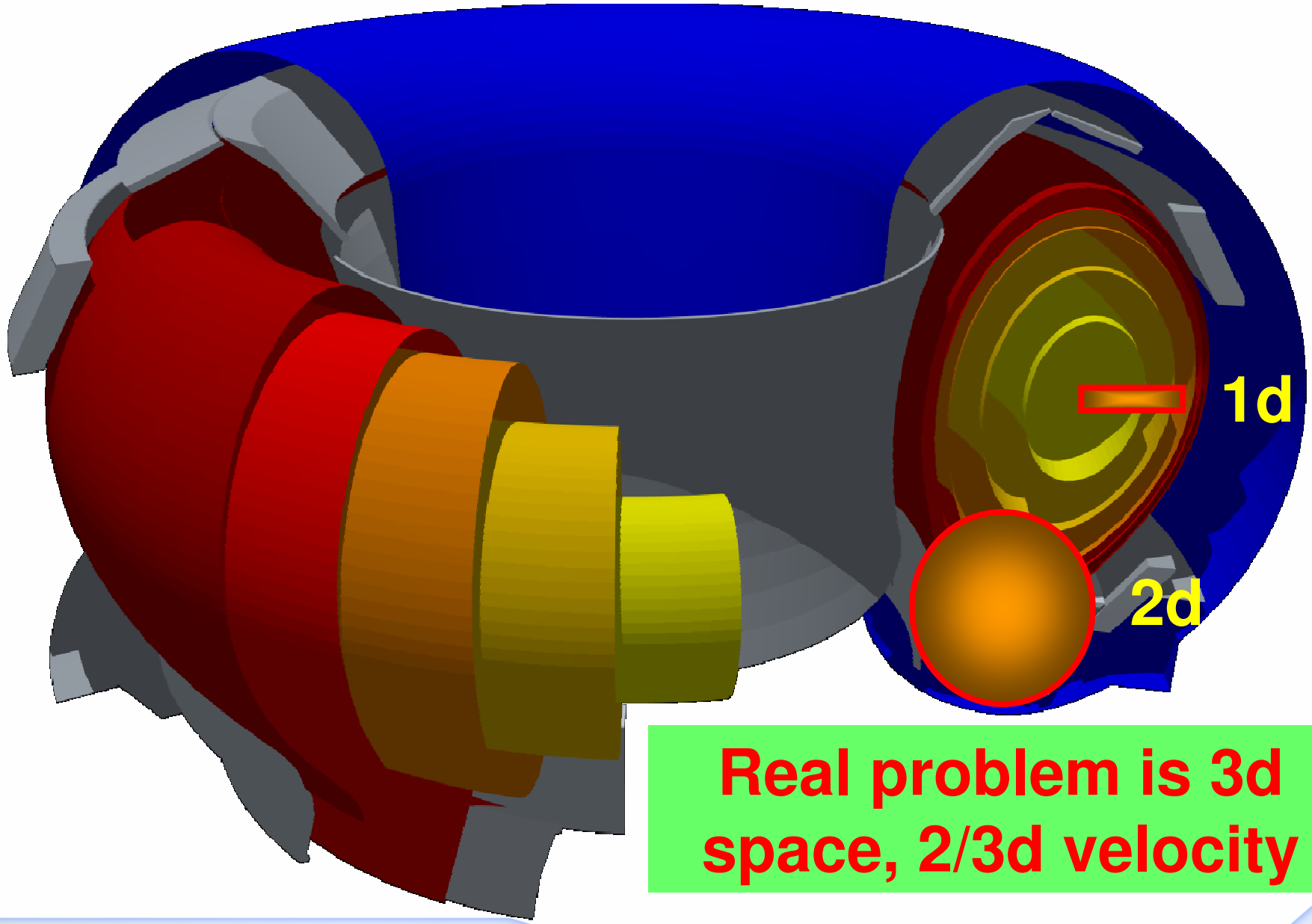


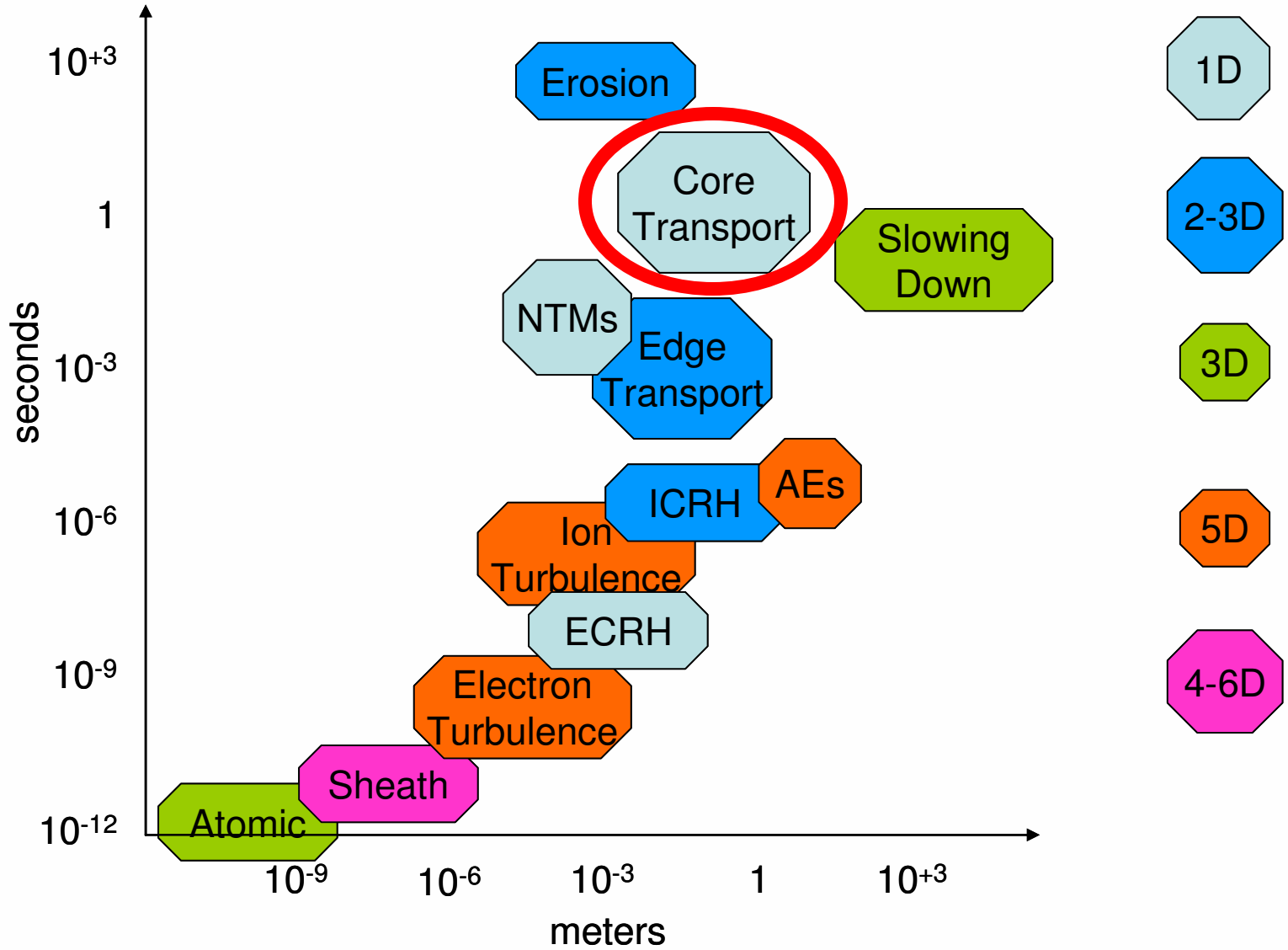
		Units
Plasma Major Radius	6.2	m
Plasma Minor Radius	2.0	m
Plasma Volume	840	m3
Plasma Current	15.0	MA
Toroidal Field on Axis	5.3	T
Fusion Power	500	MW
Burn Flat Top	>400	s
Power Amplification	>10	

Simulations



Real problem is 3d space, 2/3d velocity

Models describing the plasma vary in complexity



Outline

- What is the European Transport Solver (ETS)?
- Why should anybody be interested in the development of the ETS
- Who is doing the work?
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What is the ETS?

- The ETS is a new 1D core simulation framework
- The name is also used to refer to the core solver component
- Designed to solve the standard set of equations describing the evolution of the core plasma
- Existing codes: ASTRA, CRONOS, JETTO, TRANSP, …

ETS: Transport Equations

$$\sigma_{\parallel}\left(\frac{\partial}{\partial t}-\frac{\rho\dot{B}_0}{2B_0}\cdot\frac{\partial}{\partial\rho}\right)\Psi=\frac{F^2}{\mu_0 B_0\rho}\frac{\partial}{\partial\rho}\left[\frac{V'}{4\pi^2}\left\langle\left|\frac{\nabla\rho}{R}\right|^2\right\rangle\frac{1}{F}\frac{\partial\Psi}{\partial\rho}\right]-\frac{V'}{2\pi\rho}\left(j_{\mathrm{ni,exp}}+j_{\mathrm{ni,imp}}\cdot\Psi\right)$$

$$\left(\frac{\partial}{\partial t}-\frac{\dot{B}_0}{2B_0}\cdot\frac{\partial}{\partial\rho}\rho\right)\left(V'n_i\right)+\frac{\partial}{\partial\rho}\Gamma_i=V'\ \left(S_{i,\mathrm{exp}}-S_{i,\mathrm{imp}}\cdot n_i\right)$$

$$\frac{3}{2}\left(\frac{\partial}{\partial t}-\frac{\dot{B}_0}{2B_0}\cdot\frac{\partial}{\partial\rho}\rho\right)\left(n_iT_iV'^{\frac{5}{3}}\right)+V'^{\frac{2}{3}}\frac{\partial}{\partial\rho}\left(q_i+T_i\ \gamma_i\right)=V'^{\frac{5}{3}}\left[Q_{i,\mathrm{exp}}-Q_{i,\mathrm{imp}}\cdot T_i+Q_{\mathrm{ei}}+Q_{\mathrm{zi}}+Q_{\gamma i}\right]$$

$$\frac{3}{2}\left(\frac{\partial}{\partial t}-\frac{\dot{B}_0}{2B_0}\cdot\frac{\partial}{\partial\rho}\rho\right)\left(n_eT_eV'^{\frac{5}{3}}\right)+V'^{\frac{2}{3}}\frac{\partial}{\partial\rho}\left(q_e+T_e\gamma_e\right)=V'^{\frac{5}{3}}\left[Q_{e,\mathrm{exp}}-Q_{e,\mathrm{imp}}\cdot T_e+Q_{\mathrm{ie}}-Q_{\gamma i}\right]$$

$$\left(\frac{\partial}{\partial t}-\frac{\dot{B}_0}{2B_0}\cdot\frac{\partial}{\partial\rho}\rho\right)\left(V'\ \langle R\rangle\, m_in_iu_{i,\varphi}\right)+\frac{\partial}{\partial\rho}\Phi_i=V'\ \left(U_{i,\varphi,\mathrm{exp}}-U_{i,\varphi,\mathrm{imp}}\cdot u_{i,\varphi}+U_{\mathrm{zi},\varphi}\right)$$

ETS: Transport Equations

All of the equations are cast into a standard form

$$\frac{a(\rho)\cdot Y(\rho,t)-b(\rho)\cdot Y(\rho,t-1)}{h}+\frac{1}{c(\rho)}\frac{\partial}{\partial\rho}\left(-d(\rho)\cdot\frac{\partial Y(\rho,t)}{\partial\rho}+e(\rho)\cdot Y(\rho,t)\right)=f(\rho)-g(\rho)\cdot Y(\rho,t)$$

With boundary conditions

$$v(\rho_{\text{bnd}})\cdot\left.\frac{\partial Y(\rho,t)}{\partial\rho}\right|_{\text{bnd}}+u(\rho_{\text{bnd}})\cdot Y(\rho_{\text{bnd}},t)=w(\rho_{\text{bnd}})$$

The generalized solvers get ρ, $a(\rho)$, $b(\rho)$, $c(\rho)$, $d(\rho)$, $e(\rho)$, $f(\rho)$, $g(\rho)$, h, $Y(\rho,t-1)$, $u(1:2)$, $v(1:2)$, $w(1:2)$

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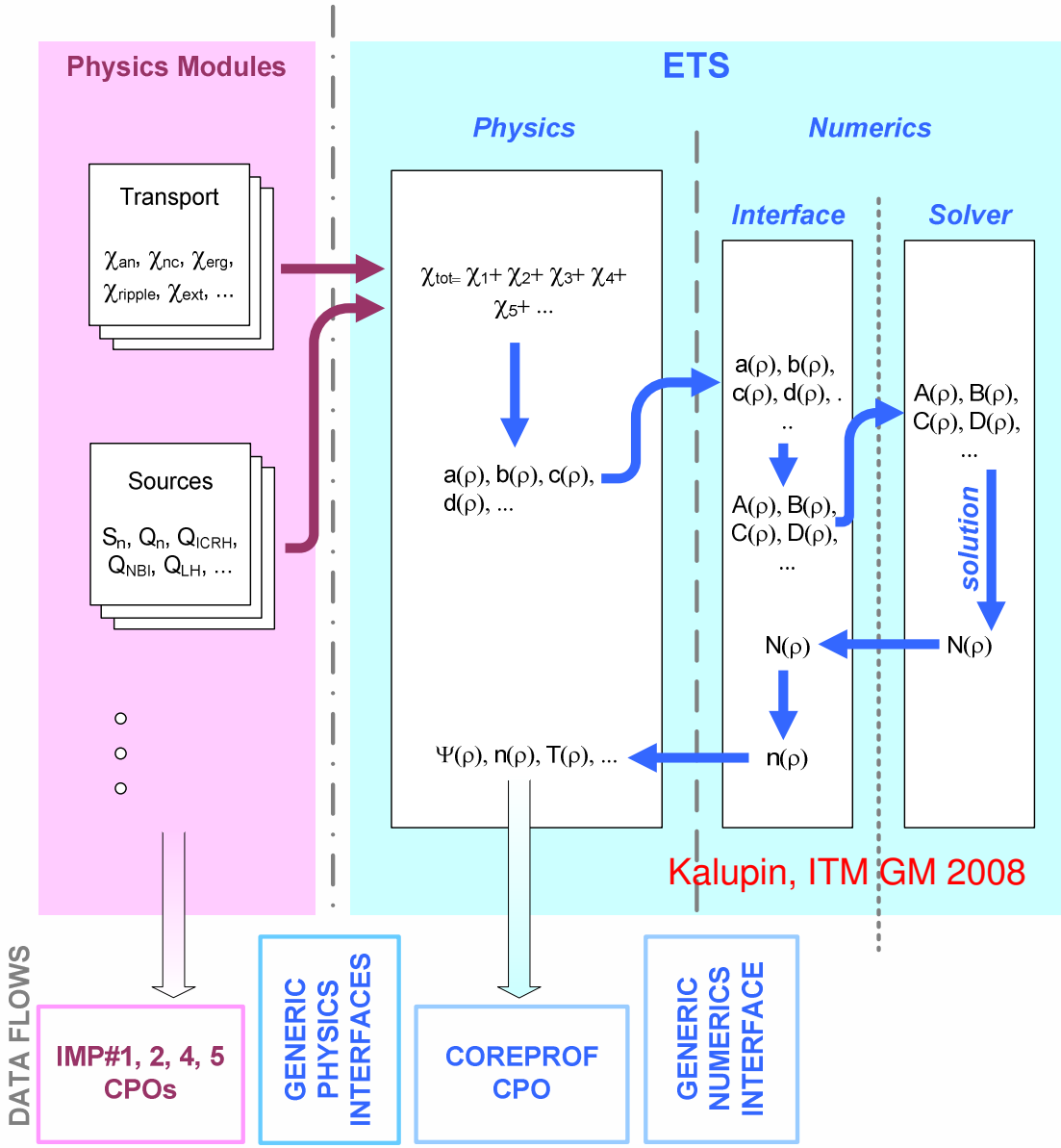
Why should it be of interest?

- The ETS workflows are designed to be completely modular allowing the exchange of any component by any other of the same class
- Internally the ETS solver is also modular separating the physics part and the numerical part

Schematic ETS view



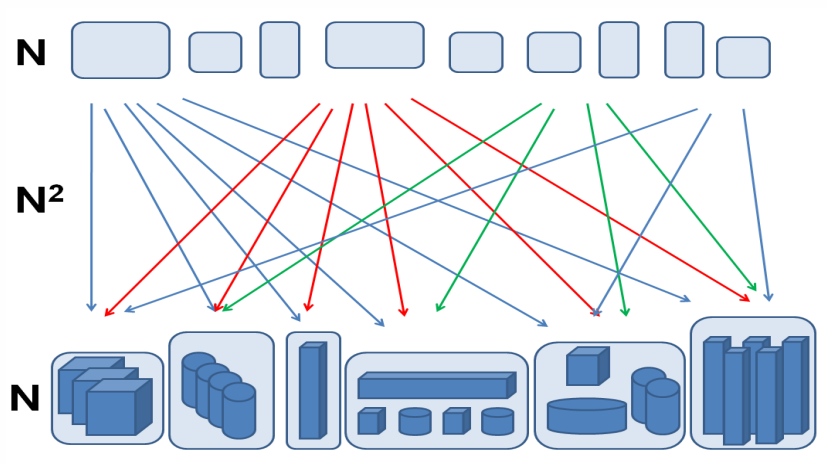
- ☺ communication to physics modules through generic interfaces
- ☺ Multi-language capability (fortran, c, c++, java, matlab)
- ☺ centralized physics part
- ☺ Separated numerics part
  - ☺ several options for numerical solver

Modular workflows

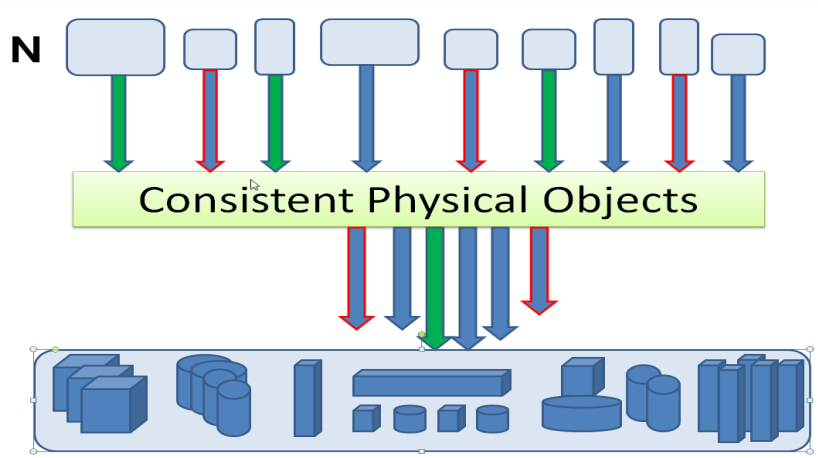
- The ITM has invested many man years of effort in defining the data to be transferred between different classes of codes → Consistent Physical Objects (CPOs)
- These are defined in XML and then language specific data structure descriptions are automatically generated
- At the code level deal with derived data types
- Using Kepler as the workflow engine

Coupling codes and applications

N modules integrated in N different applications



N modules coupled into a dynamic application framework

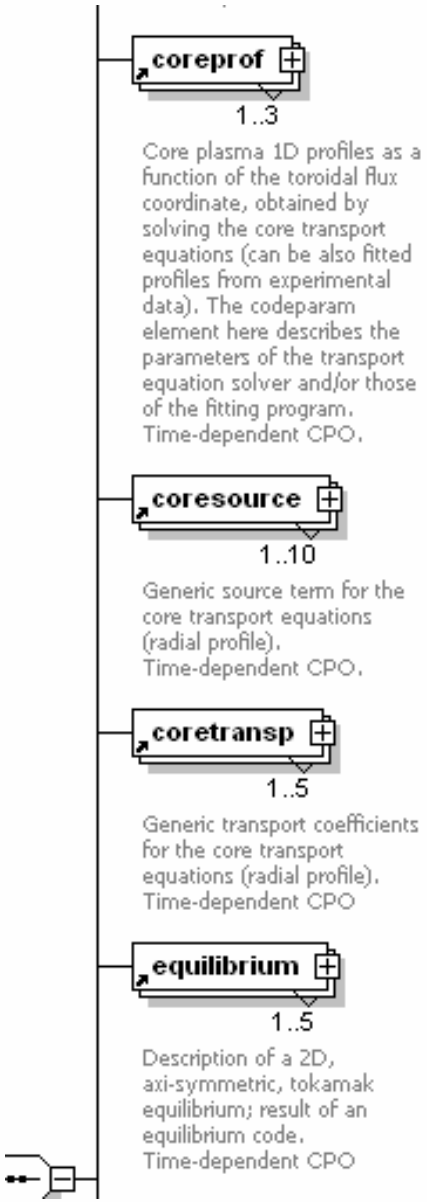


The data model – or ontology - is the key to providing a consistent framework!

Strand, ITM General Meeting 2009
Bastardised from David De Roure

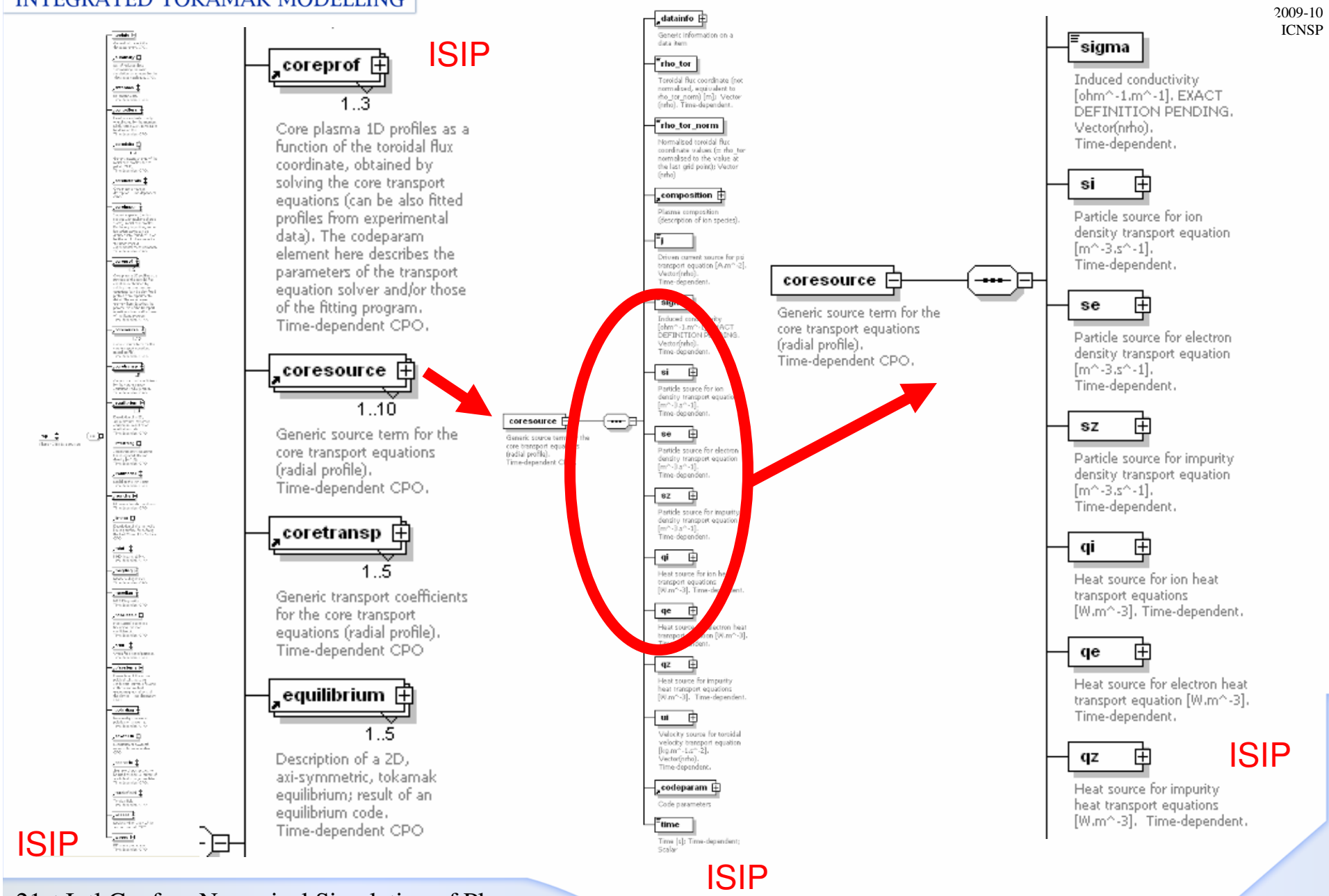
Example CPOs

- Equilibrium code
  - → equilibrium CPO
  - ← equilibrium CPO
- ETS solver
  - → equilibrium CPOs
  - → coreprof CPOs (1d plasma state)
  - → coresource CPO (1d sources)
  - → coretransp CPO (1d transport coefficients)
  - …
  - ← coreprof CPO



ISIP

Hierarchical structure: coresource



Coresource → qi

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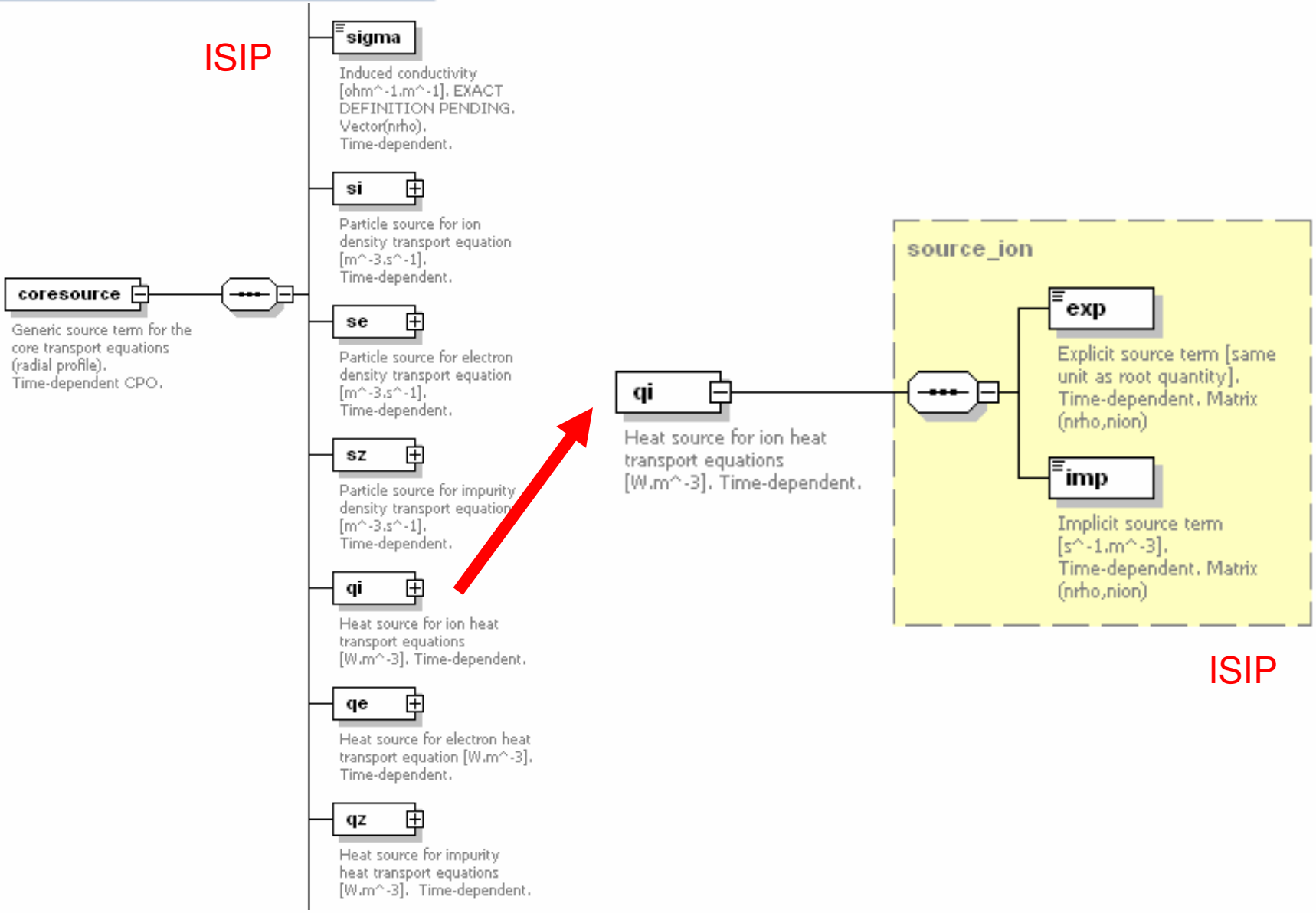

Coreprof

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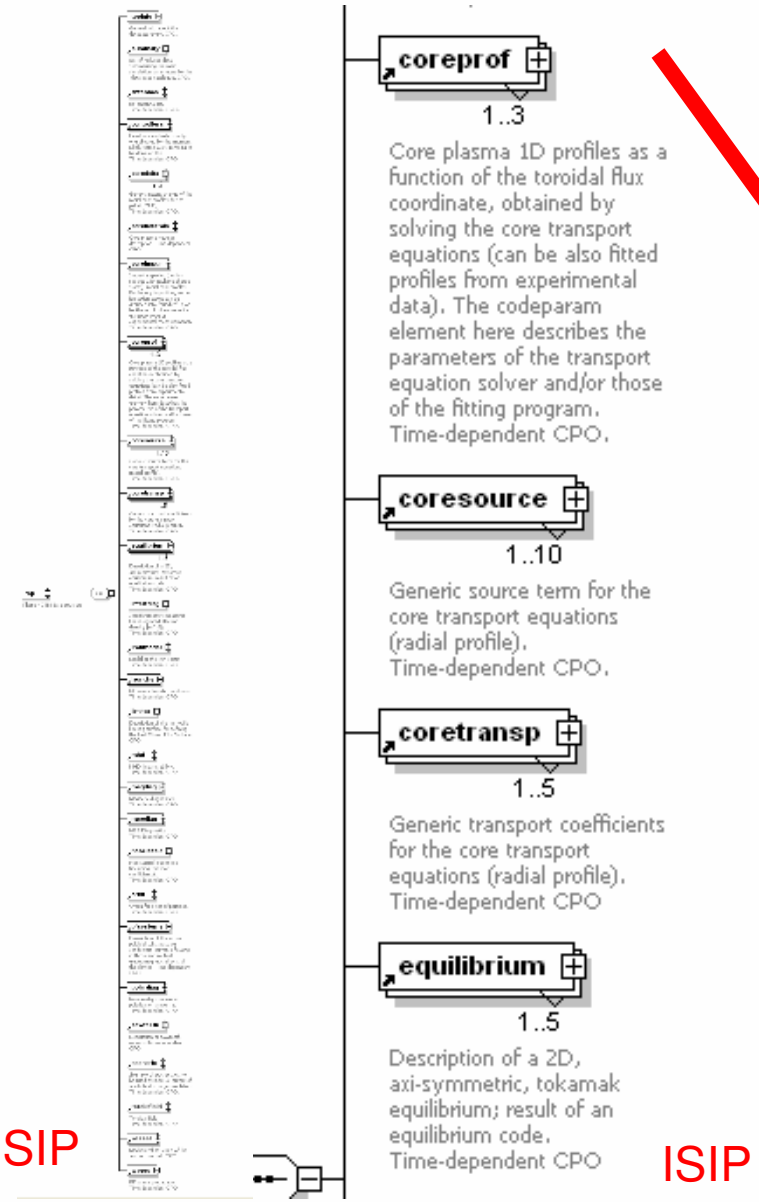

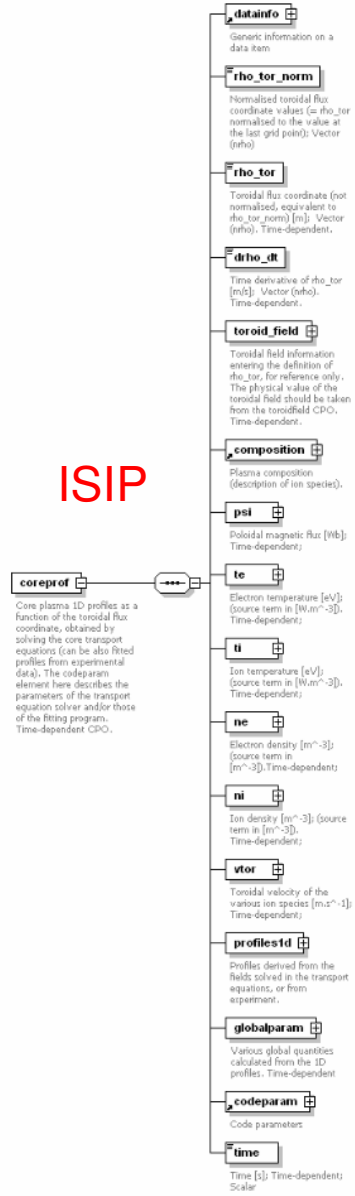

Coreprof

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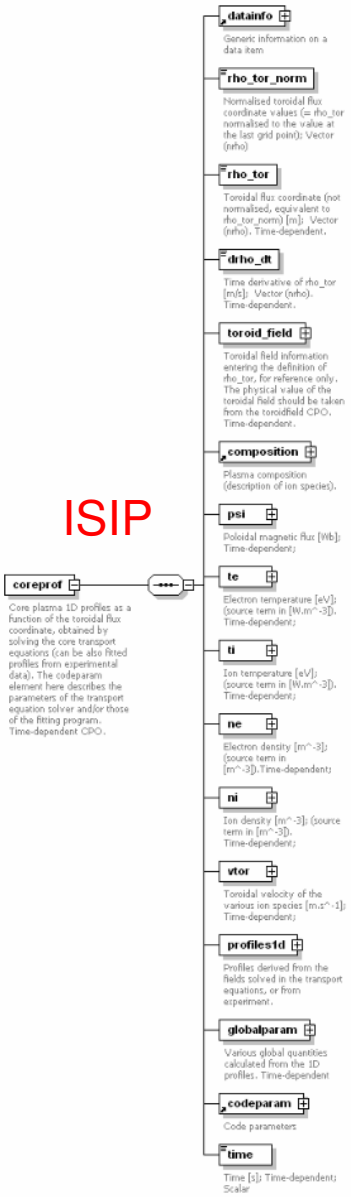

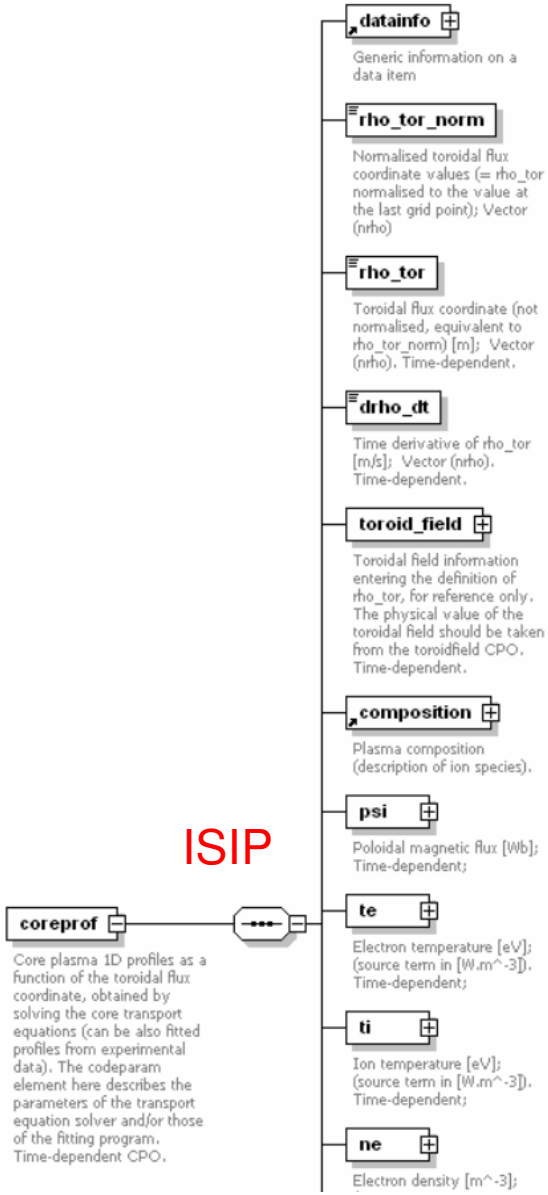

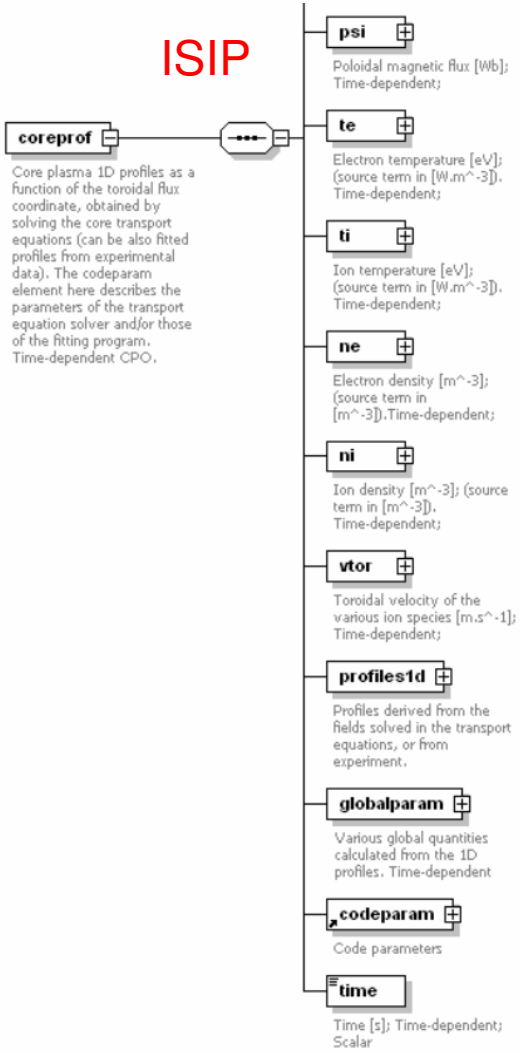

Coreprof

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ICNSP

ISIP

coreprof

Core plasma 1D profiles as a function of the toroidal flux coordinate, obtained by solving the core transport equations (can be also fitted profiles from experimental data). The codeparam element here describes the parameters of the transport equation solver and/or those of the fitting program. Time-dependent CPO.

- **psi** — Poloidal magnetic flux [Wb]; Time-dependent;
- **te** — Electron temperature [eV]; (source term in [W.m^-3]). Time-dependent;
- **ti** — Ion temperature [eV]; (source term in [W.m^-3]). Time-dependent;
- **ne** — Electron density [m^-3]; (source term in [m^-3]).Time-dependent;
- **ni** — Ion density [m^-3]; (source term in [m^-3]). Time-dependent;
- **vtor** — Toroidal velocity of the various ion species [m.s^-1]; Time-dependent;
- **profiles1d** — Profiles derived from the fields solved in the transport equations, or from experiment.
- **globalparam** — Various global quantities calculated from the 1D profiles. Time-dependent
- **codeparam** — Code parameters
- **time** — Time [s]; Time-dependent; Scalar

ISIP

te

Electron temperature [eV]; (source term in [W.m^-3]). Time-dependent;

corefield

- **value** — Signal value; Time-dependent; Vector (nrho)
- **source** — Source of the profile (any comment describing the origin of the profile : code, path to diagnostic signals, massaging, ...); String
- **flag** — Flag describing how the profile has been processed : 0-not calculated 1-interpretative; 2-calculated by the transport solver; 3-calculated by a separate code : in that case only, description of the code provided in codeparam at the same level; 4-used value from the previous time step; Time-dependent; Scalar
- **boundary** — Boundary condition for the transport equation. Time-dependent.
- **source_term** — Total source term for the transport equation. Time-dependent.
- **transp_coef** — Total transport coefficients. Time-dependent
- **flux** — Fluxes of the quantity, two definitions. Time-dependent.
- **time_deriv** — Integral of the time derivative term of the transport equation. Time-dependent. Vector (nrho)
- **codeparam** — Code parameters

ISIP

- **value** — Signal value; Time-dependent; Vector (nrho)
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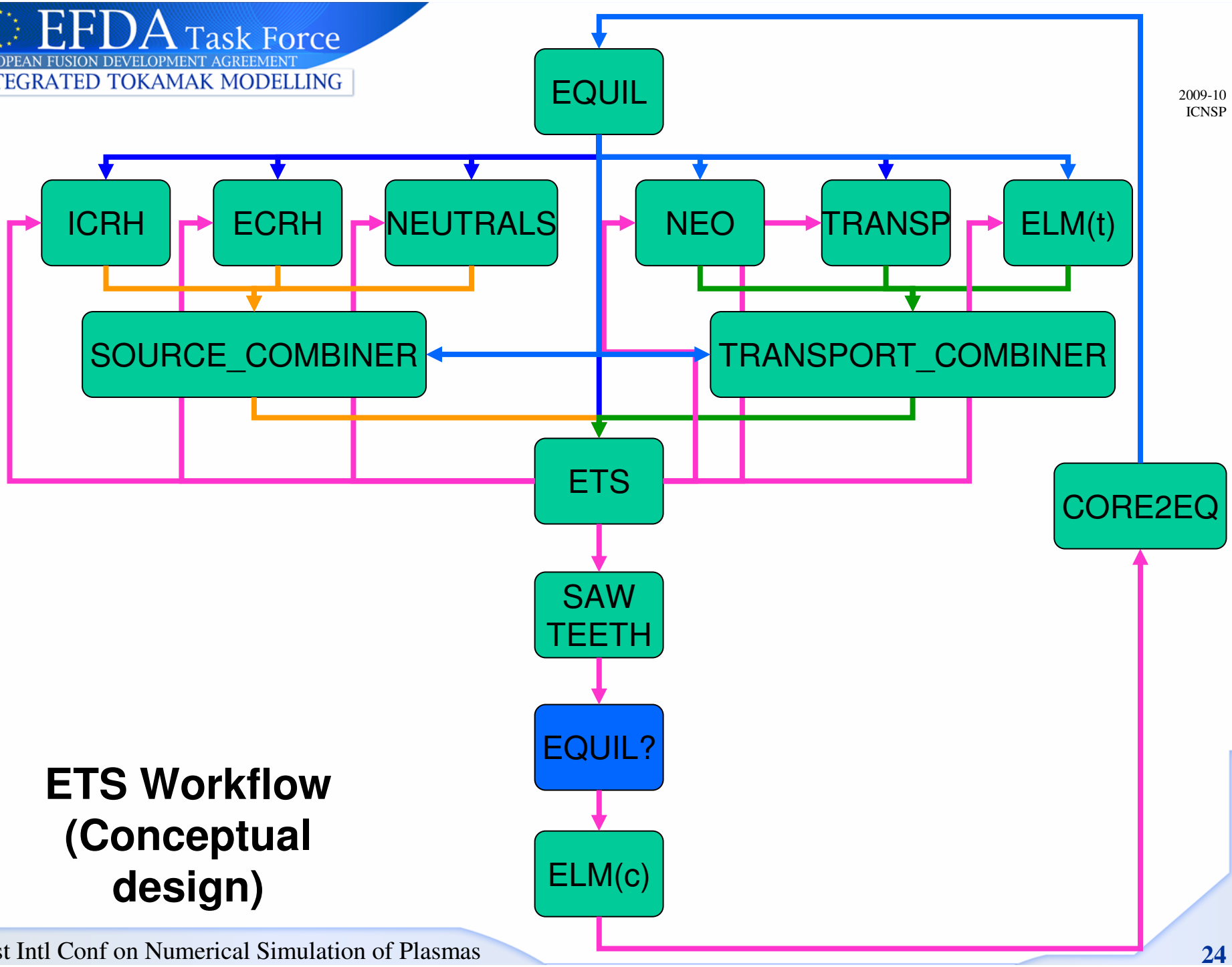
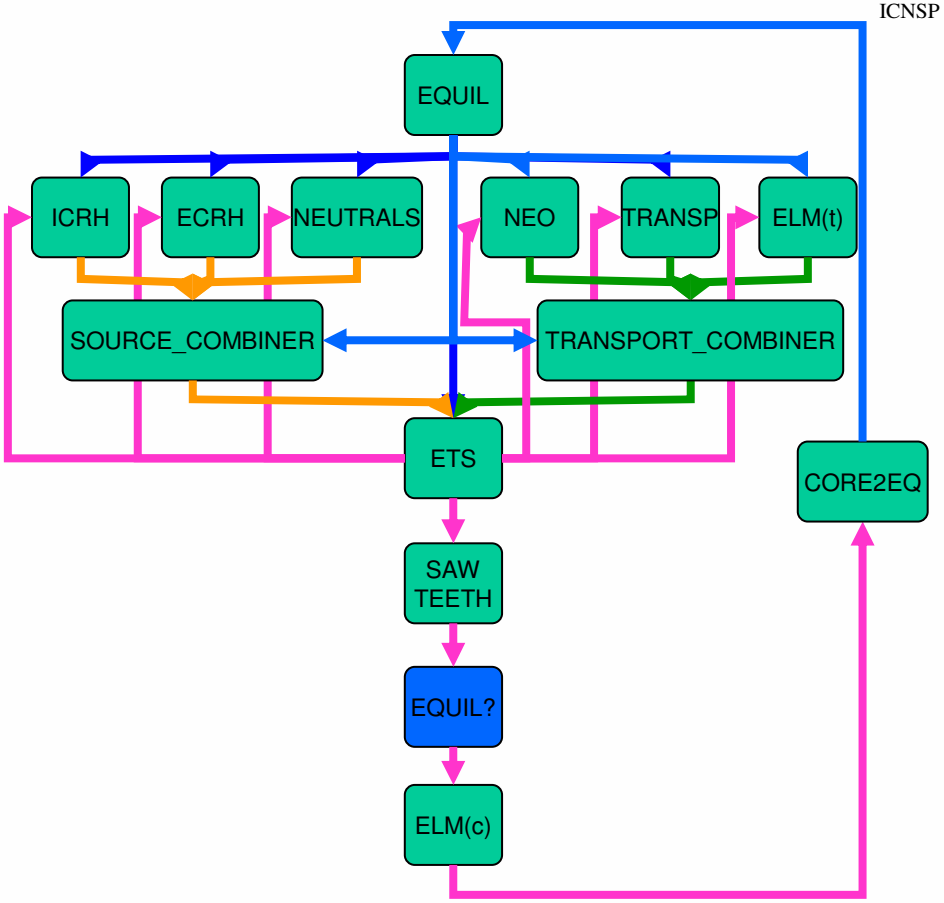
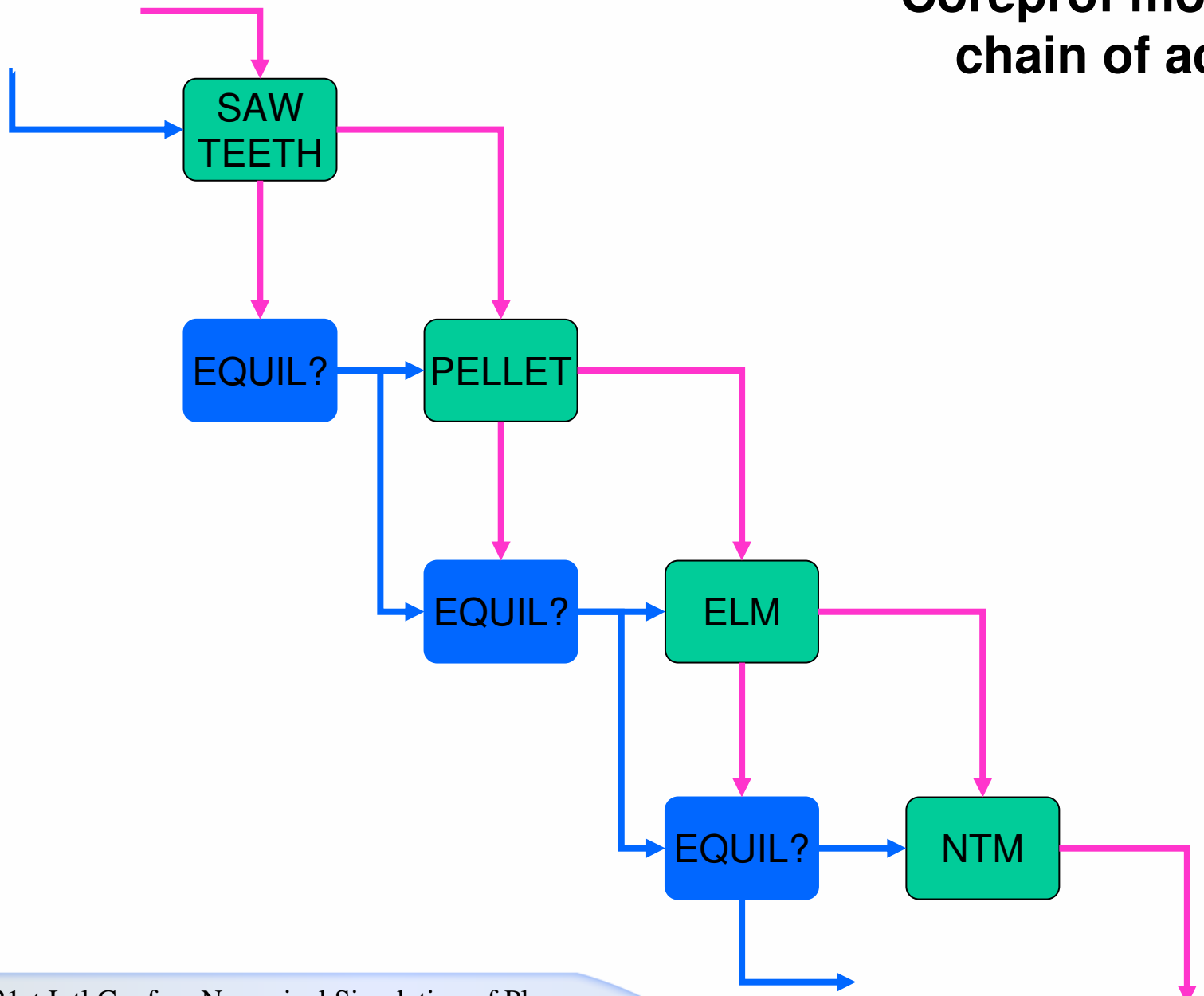


ETS Workflow (Conceptual design)

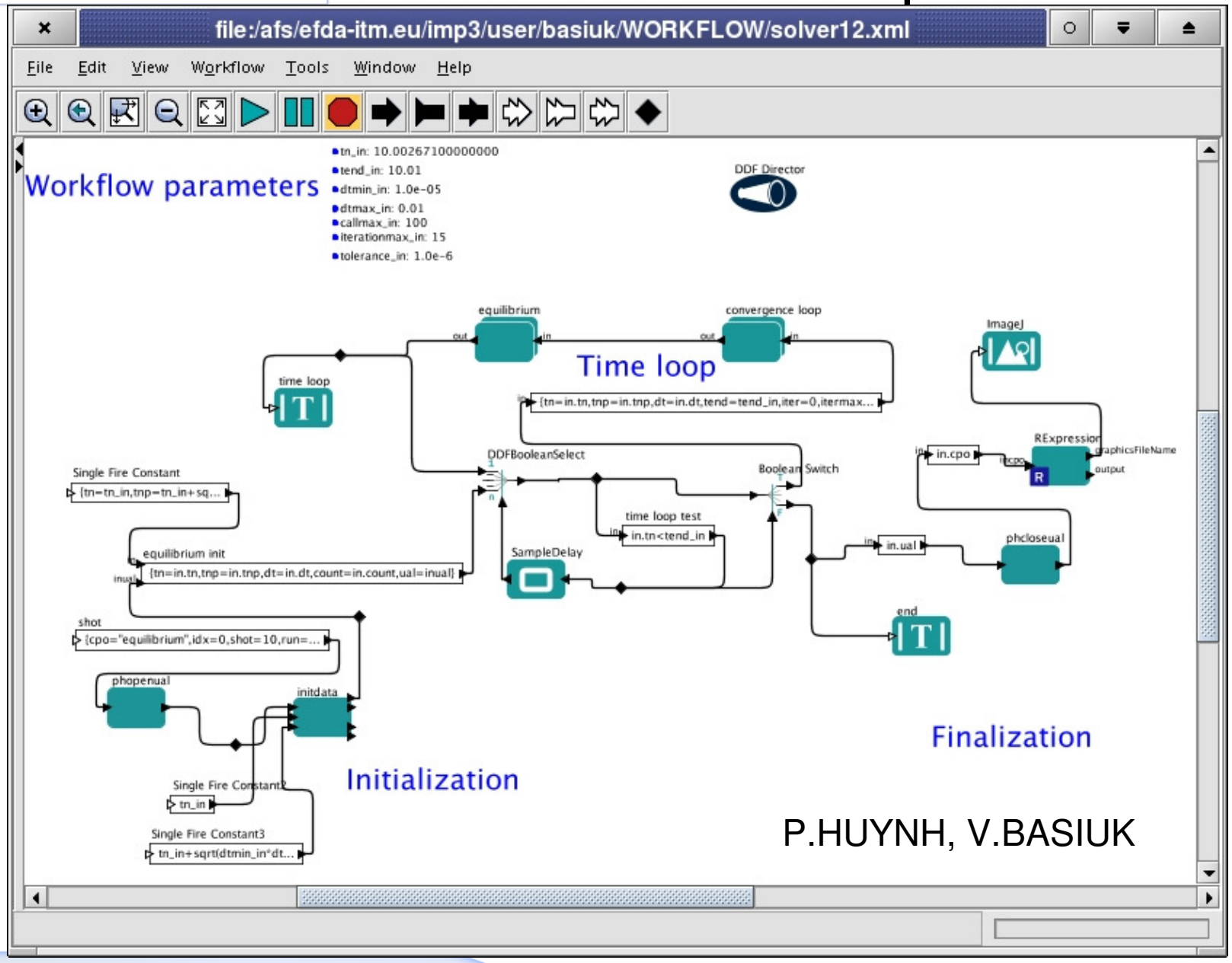
- **Modularity/flexibility**
  - **Choice of modules**
    - **Drop in any compatible equilibrium code**
  - **Choice of where modules run**
    - **HPC/GRID/LOCAL**
  - **Easy to change individual components**
- **Free boundary version available within same structure**
- **Edge core integration implemented as a change of BC to the ETS**



Coreprof modifying chain of actors



KEPLER Transport Workflow



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EFDA

European Fusion Development Agreement

All EU Laboratories / Institutions working on Fusion are parties to EFDA

Defined under EURATOM under "Contract of Associations"

EURATOM : KEY ACTION FUSION Associated Laboratories, parties to EFDA

Euratom - Belgian State
(Brussels) - (Mol)

Euratom - CEA
TORE SUPRA (Cadarache)

Euratom - CIEMAT
TJ-II (Madrid)

Euratom - Conf. Suisse
TCV - SULTAN
(Lausanne) - (Villigen)

Euratom - DCU
(Dublin) - (Cork)

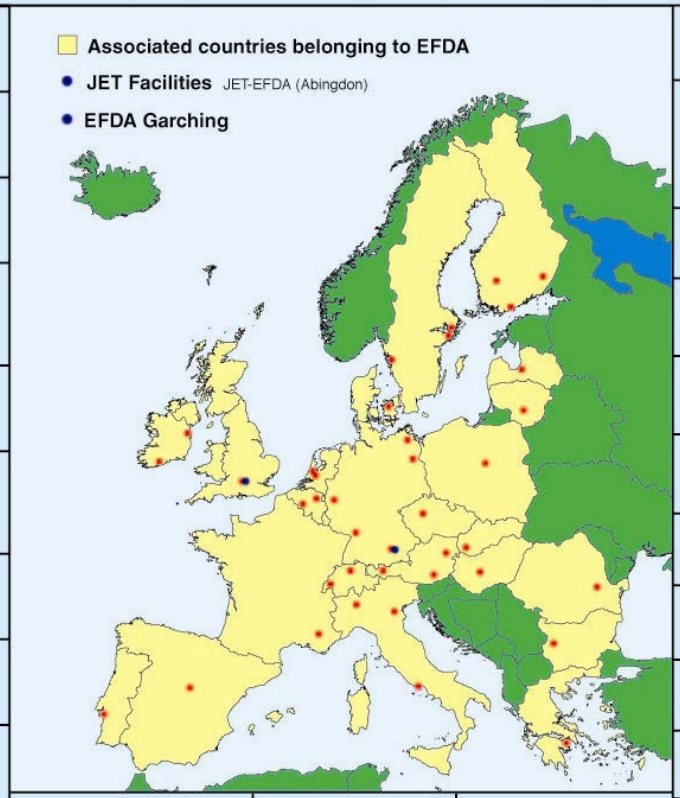
Euratom - ENEA
FTU - RFX
(Frascati) - (Milan) - (Padua)

Euratom - FOM
(Petten) - (Nieuwegein)

Euratom - FZJ
TEXTOR (Julich)

Euratom - FZK
TOSKA (Karlsruhe)

Euratom - Greece
(Athens) - (Heraklion) - (Ioannina)



Euratom - INRNE
(Sofia)

Euratom - LEI
(Kaunas)

Euratom - CU
TOSKA (Bratislava)

Euratom - HAS
(Budapest)

Euratom - IPP
Asdex Upgrade - Wendelstein 7-AS
Wendelstein 7-X
(Garching) - (Greifswald) - (Berlin)

Euratom - IPP.CR
CASTOR (Prague)

Euratom - IST
ISTTOK (Lisbon)

Euratom - Latvia
(Riga)

Euratom - MEC
(Bucharest)

Euratom - ÖAW
(Vienna) - (Graz) - (Innsbruck)

Euratom - RISØ
(Roskilde)

Euratom - TEKES
(Helsinki) - (Tampere) - (Lappeenranta)

Euratom - UKAEA
MAST - JET (Culham)

Euratom - VR
EXTRAP T2R (Stockholm) - (Lund)
(Gothenburg) - (Studsvik) - (Uppsala)

JG03.241-6c

EUFORIA FP7-INFRASTRUCTURES-2007-1, Grant 211804

Who is doing the work?

- EFDA Task Force on Integrated Tokamak Modelling

ITM-TF charge

- *Co-ordinate the development of a coherent set of validated simulation tools for ITER exploitation*
- *Benchmark these tools on existing tokamak experiments*
- *Provide a comprehensive simulation package for ITER and DEMO plasmas.*
- *Coordinate the European Software developments with the aim to increase quality and reduce parallel efforts. (Streamline the code base)*

ITM-TF Remit

- *Development of the necessary standardized software tools for*
  - *interfacing code modules and*
  - *accessing experimental data.*

Medium term activities

- *Support the development of ITER-relevant scenarios in current experiments.*

ITM Structure

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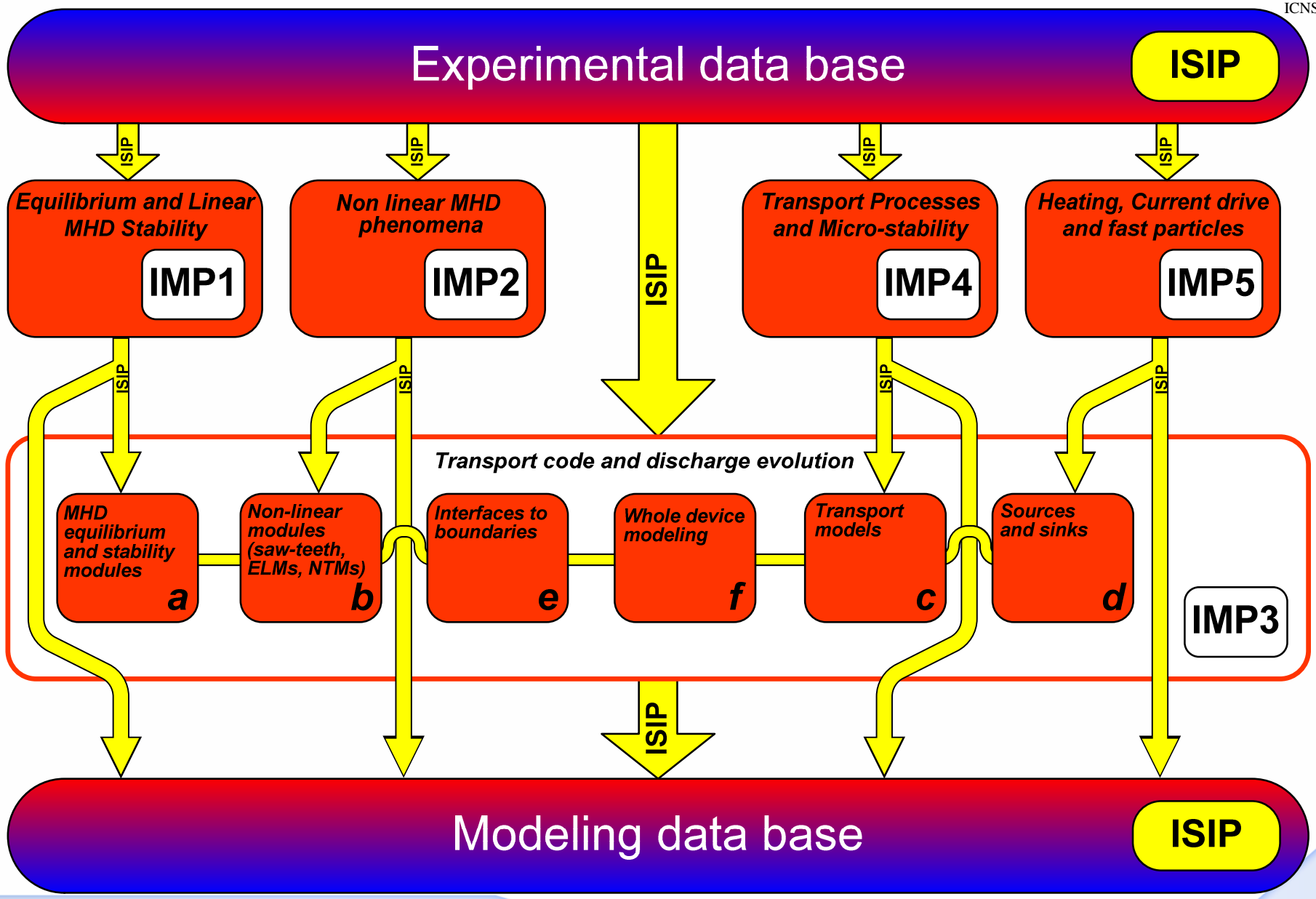
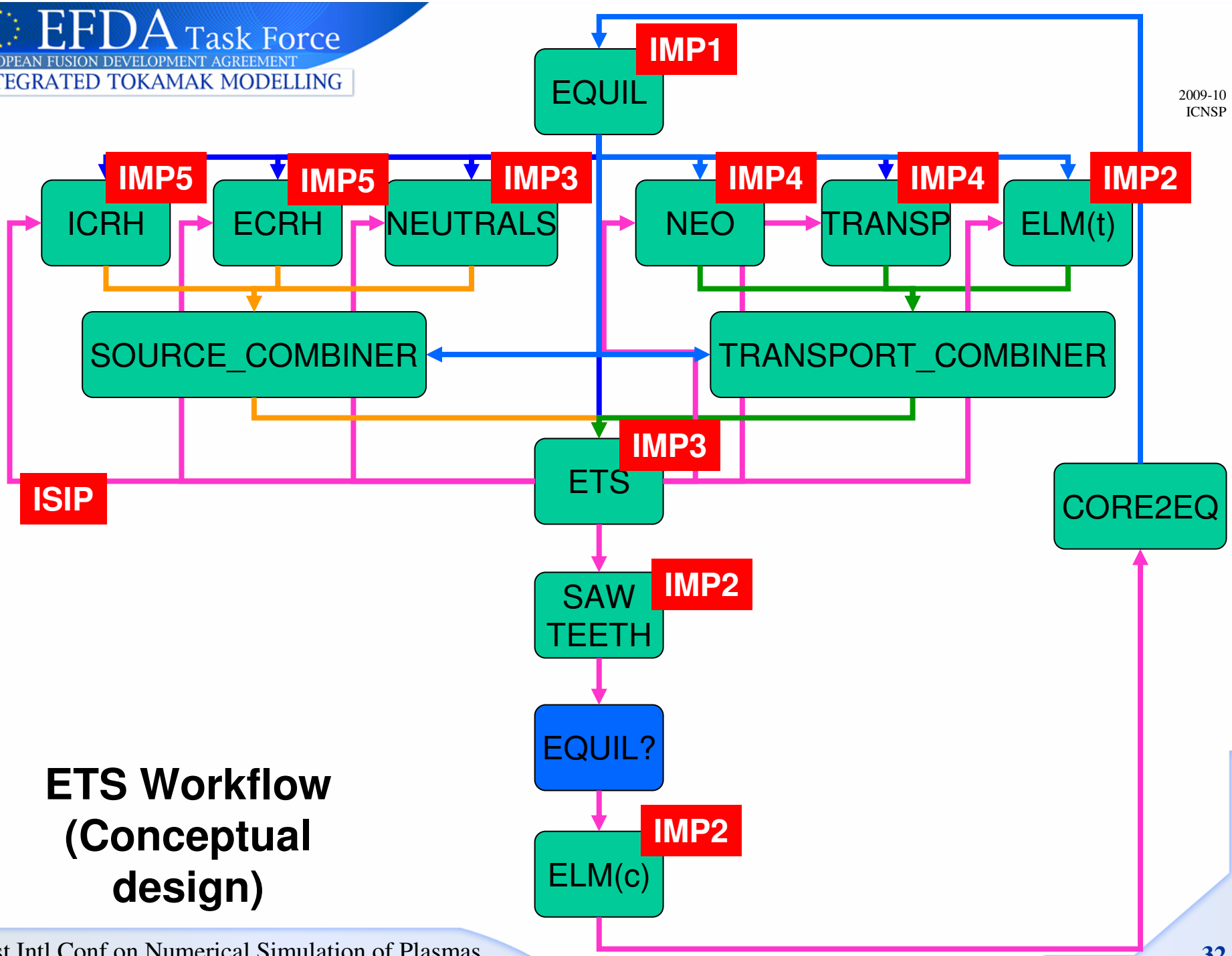
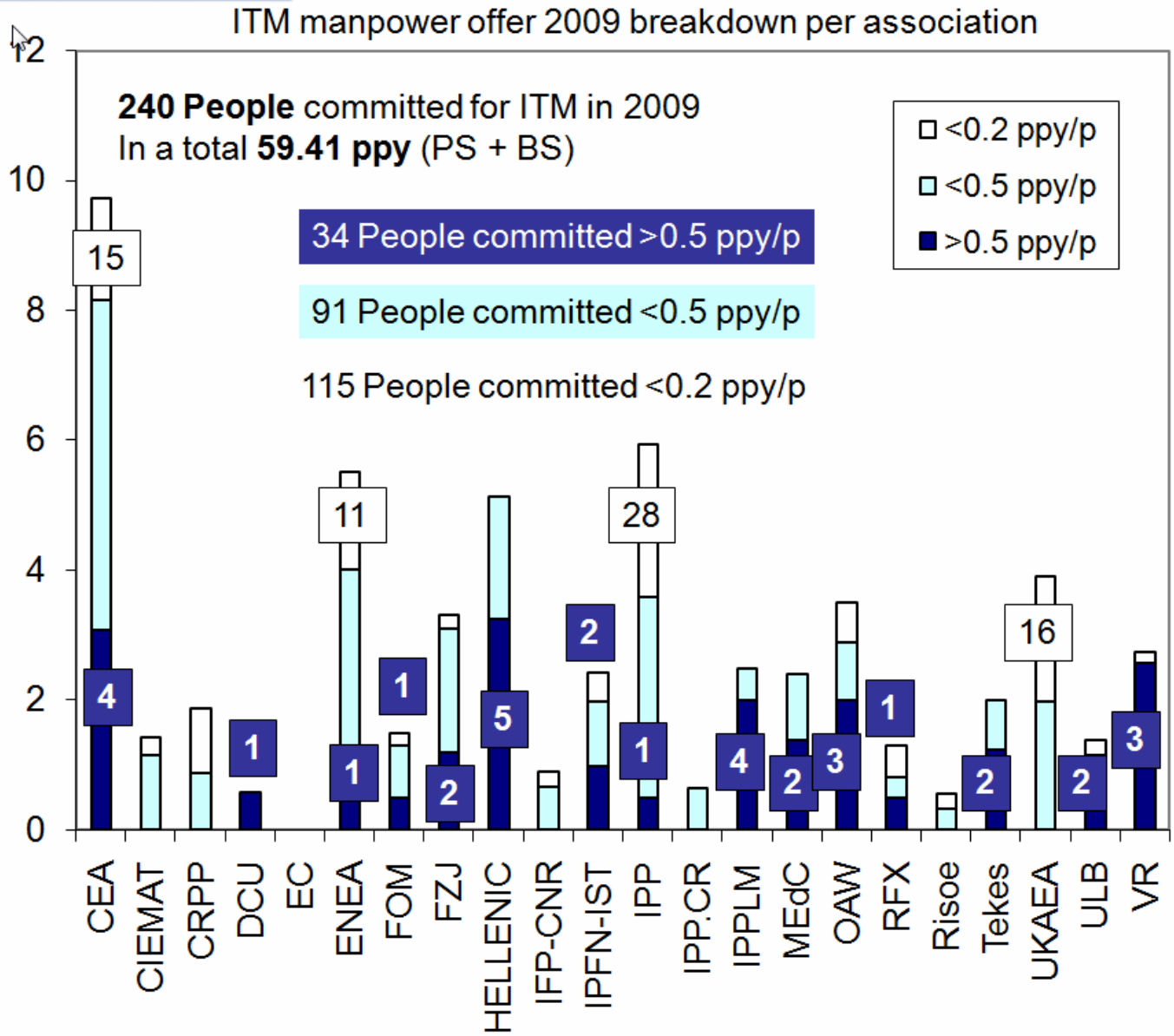




ETS Workflow (Conceptual design)

Resources in the ITM



EUFORIA

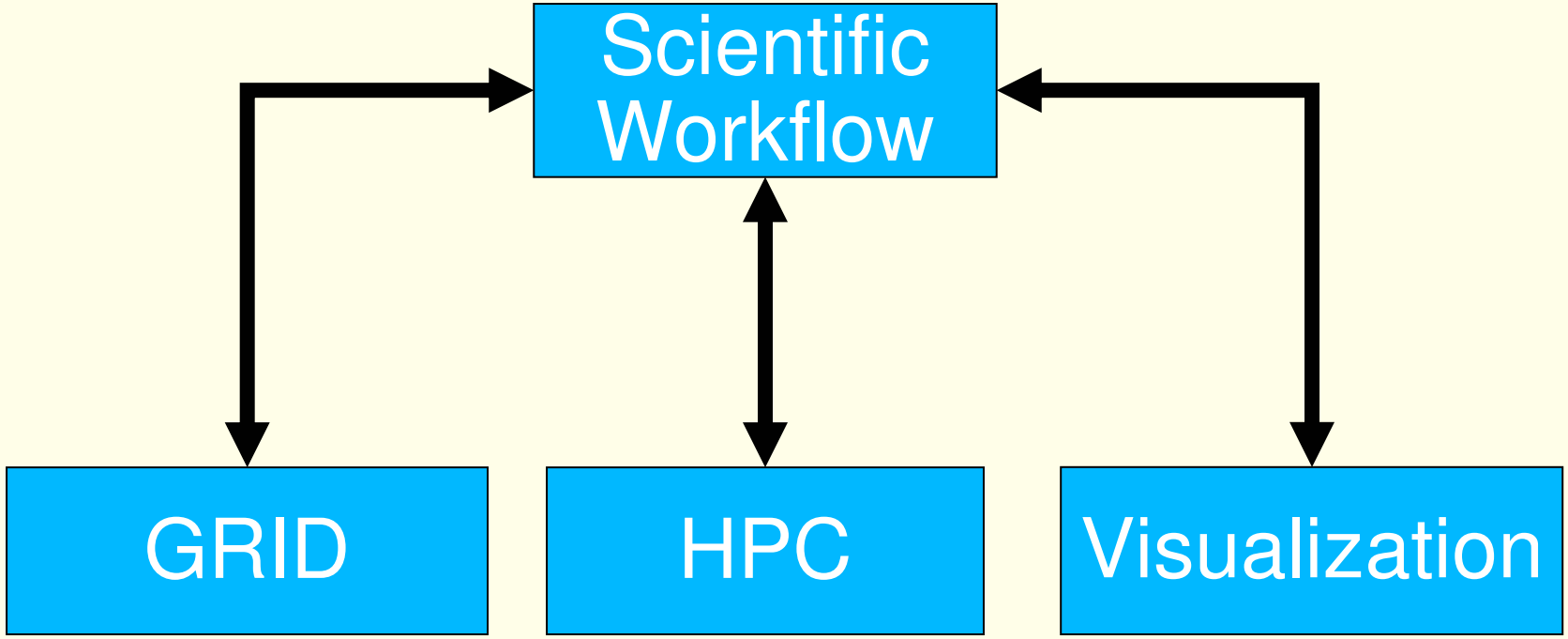
14 member Institutes
3.65M€ over 36 months

522pms covering

- Management
- Training
- Dissemination
- Grid and HPC infra-structure & support
- Code adaptation & optimization
-Workflows
-Visualization

EUFORIA FP7-INFRASTRUCTURES-2007-1, Grant 211804

Developing a new paradigm for fusion computing



EUFORIA FP7-INFRASTRUCTURES-2007-1, Grant 211804

Batch, GRID and HPC

	Batch	GRID	HPC
Current usage within the fusion community	Extensive • JET (339 cpus) • Most associations (IPP-TOK 400 cpus) • Gateway (128 cpus)	• Only at CIEMAT • Starting to see some usage at Juelich • Plans for usage at IPP	• Extensive use of national facilities • Extra-national usage via DEISA
Main issue preventing more usage	• Lack of more local cpus	• Lack of knowledge • Difficulties getting certificates	• Difficult for Associations without strong national facilities
Currently being addressed by		EUFORIA • has provided training • also developing facilities to launch jobs from the Gateway	EUFORIA • has provided training • has worked on codes HPC-FF starting August 1st • HLST
Longer term		?	IFERC computer (2012)

EUFORIA FP7-INFRASTRUCTURES-2007-1, Grant 211804

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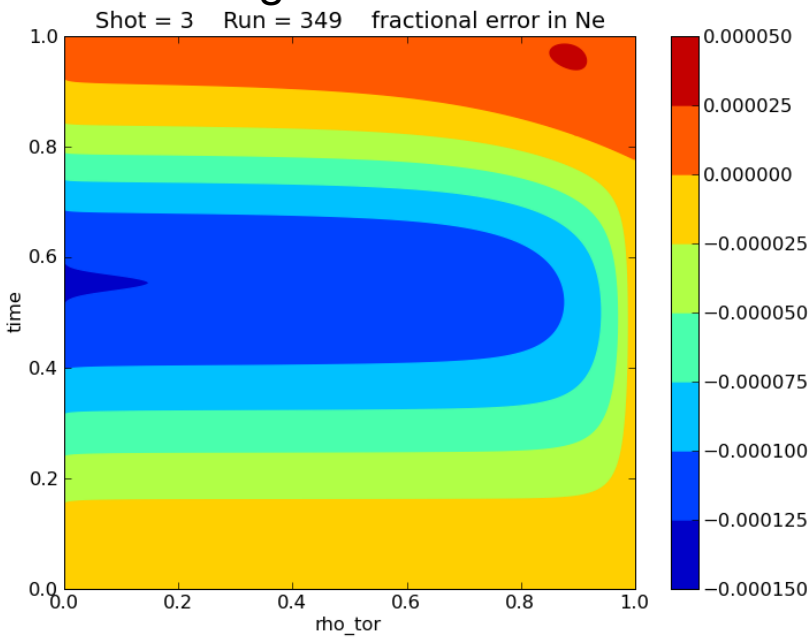
What is the status of the ETS?

- Currently running outside of Kepler (as a fortran workflow)
  - Analytical test case
    - Method of Manufactured Solutions [R. Stankiewicz et al., "Verification of the European Transport Solver for Transport Barrier", poster on Tuesday]
  - Workflow
    - Equilibrium code
    - Transport coefficients from simple transport modules or from the database
    - Source coefficients from the database
    - ETS
- Simpler case running within Kepler

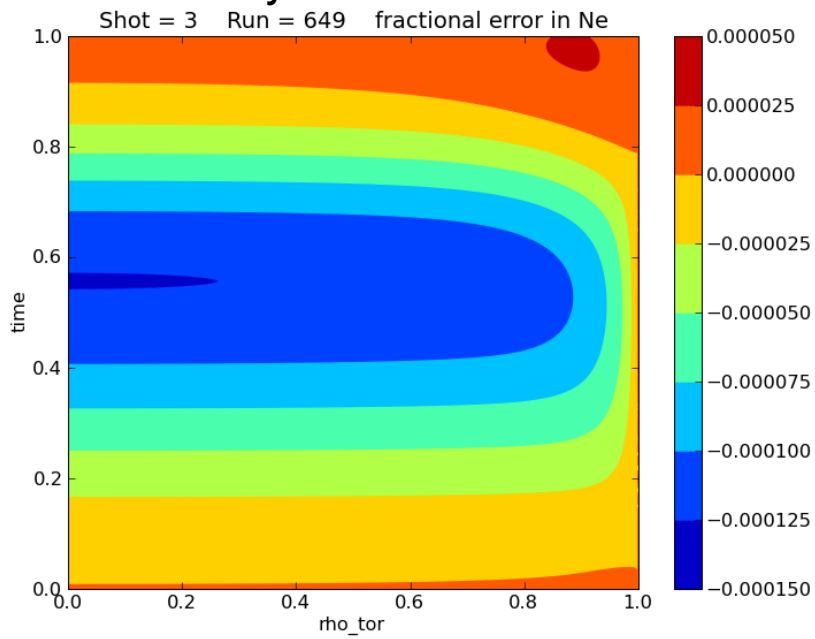
- Cases run
  - All equations
  - With multiple ion species
  - Cylindrical
  - Toroidal (circular & triangular)
- Verification
  - Against analytical results
    - Started
  - Against existing codes
    - Started against ASTRA
    - Others still to be added
- Validation
  - Still to be started

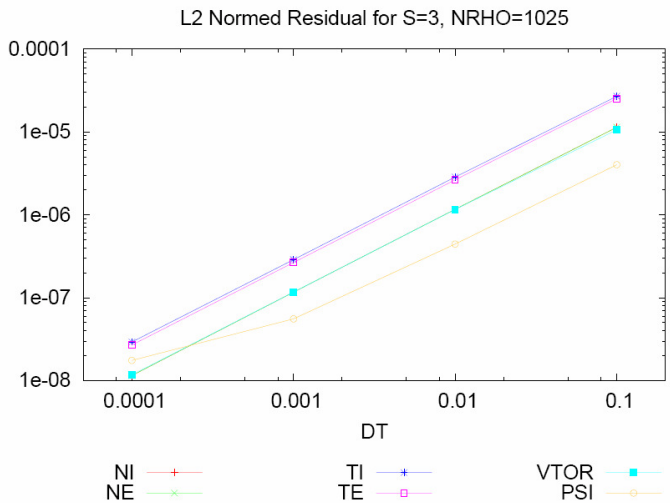
Solver scaling

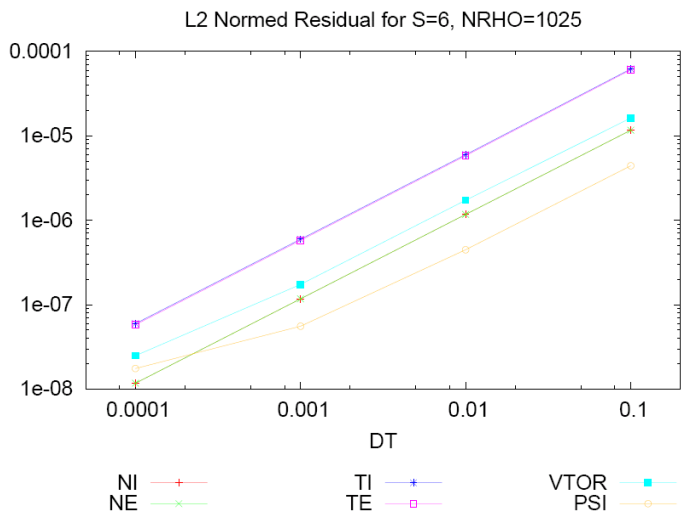
"Progonka" Solver



"Huysman's Solver

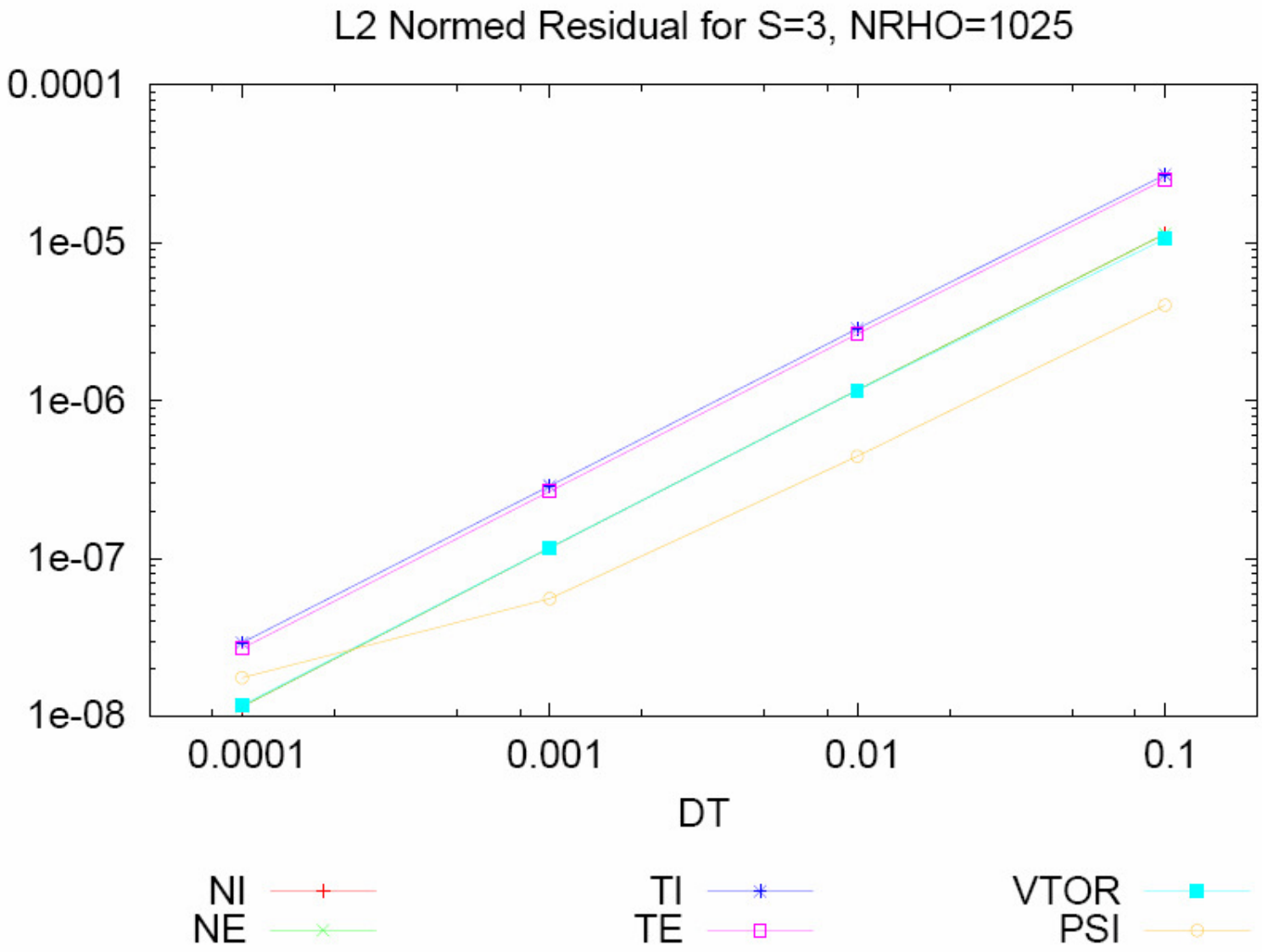






Solver scaling

"Progonka" Solver



eq_ets_test: analytics

Cylindrical Geometry

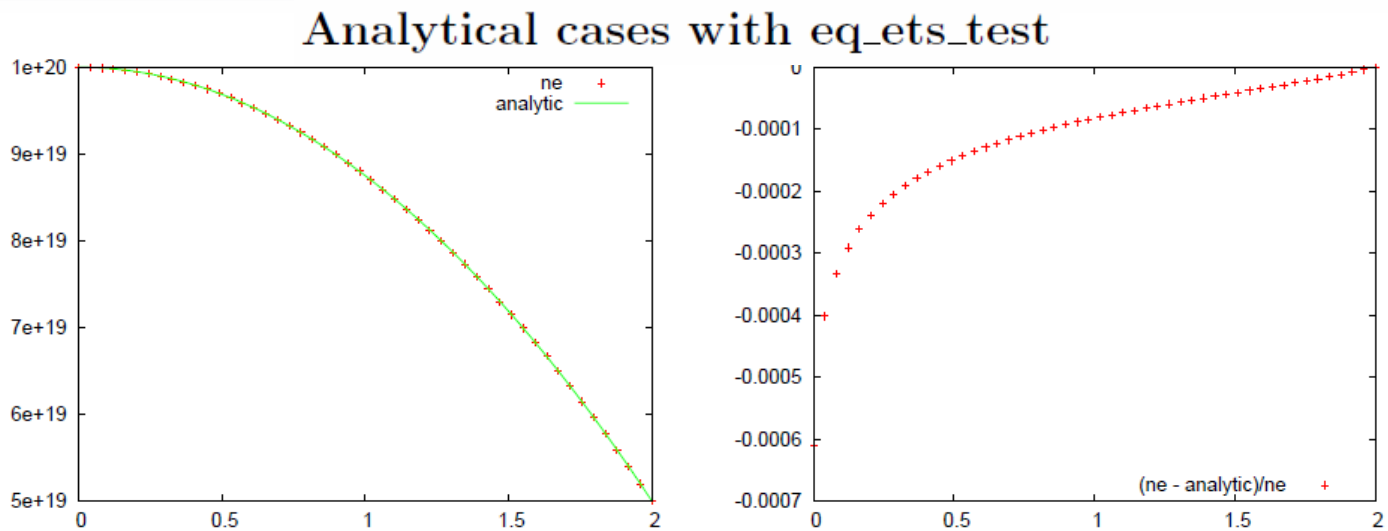


Figure 15: Cylindrical case, density profiles.

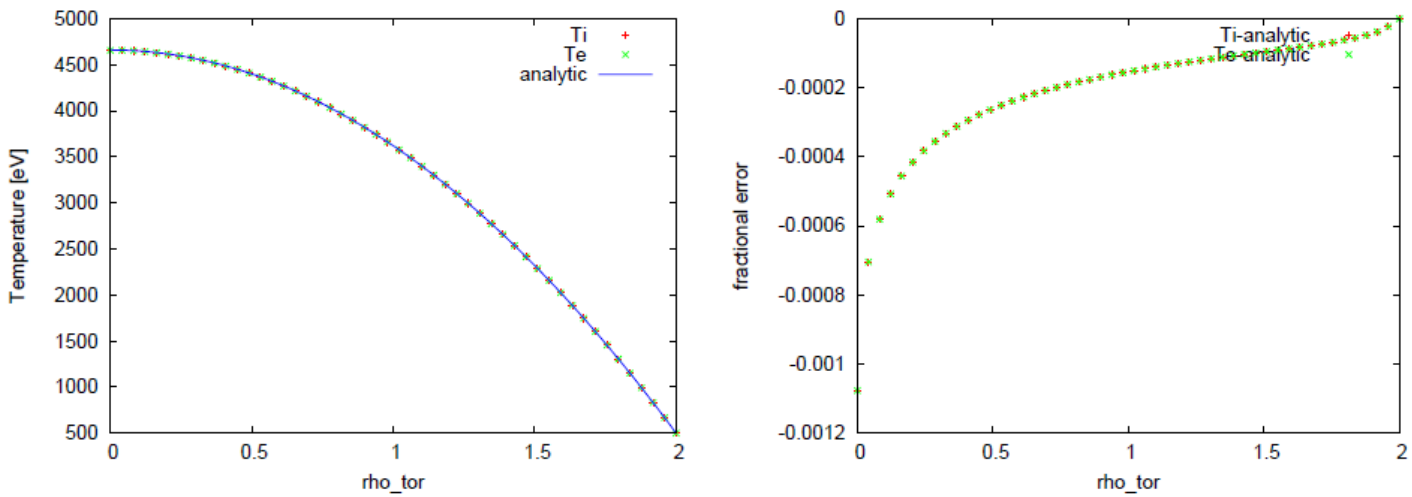


Figure 16: Cylindrical case, temperature profiles.

ETS-ASTRA comparison

Cylindrical Geometry

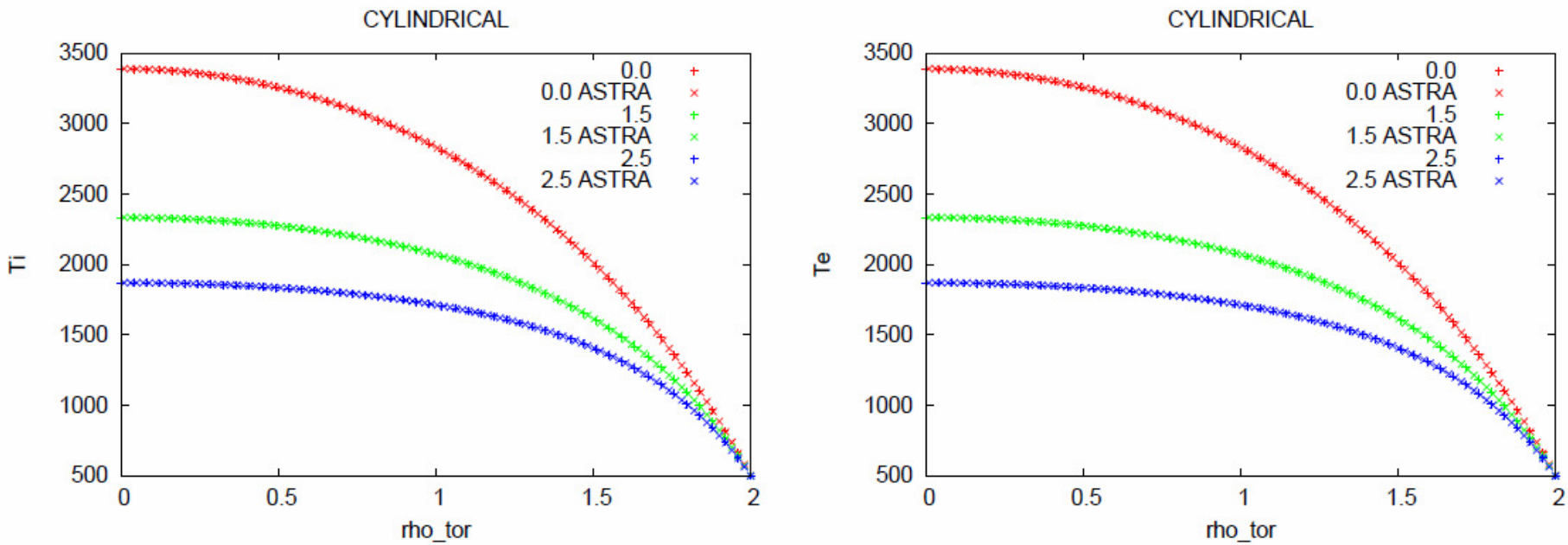


Figure 37: Comparison of temperatures for convective heat multipliers of 0.0, 1.5 and 2.5.

Curves from ETS and ASTRA on top of each other

ETS-ASTRA comparison

Toroidal Geometry

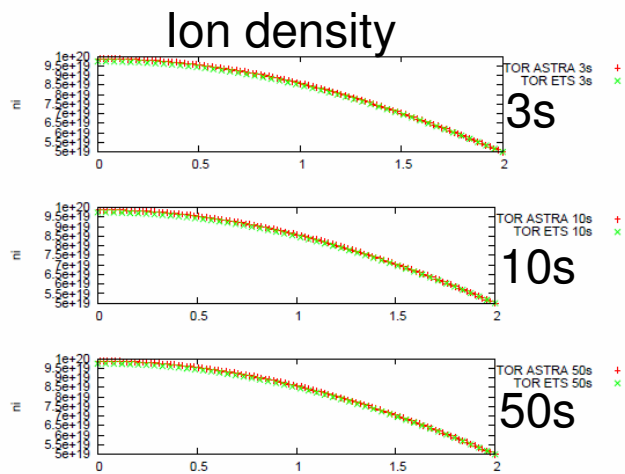


Figure 41: Comparison of ion densities at 3, 10 and 50s.

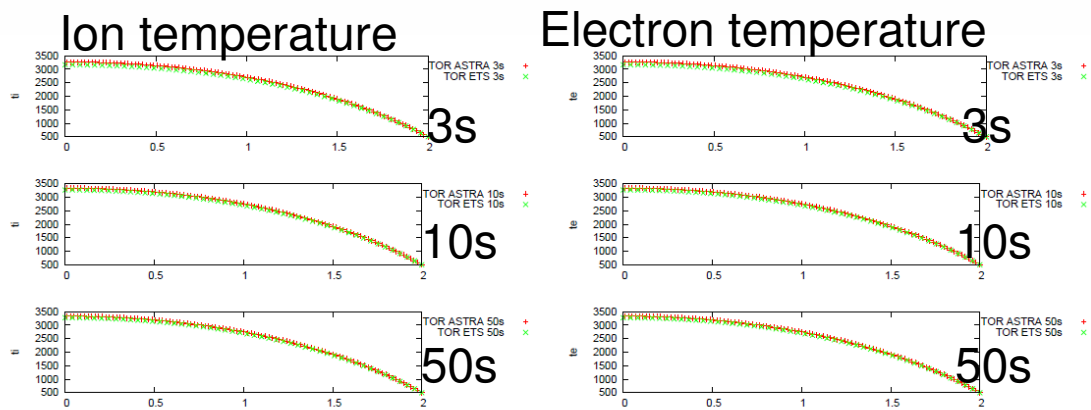


Figure 42: Comparison of ion and electron temperatures at 3, 10 and 50s.

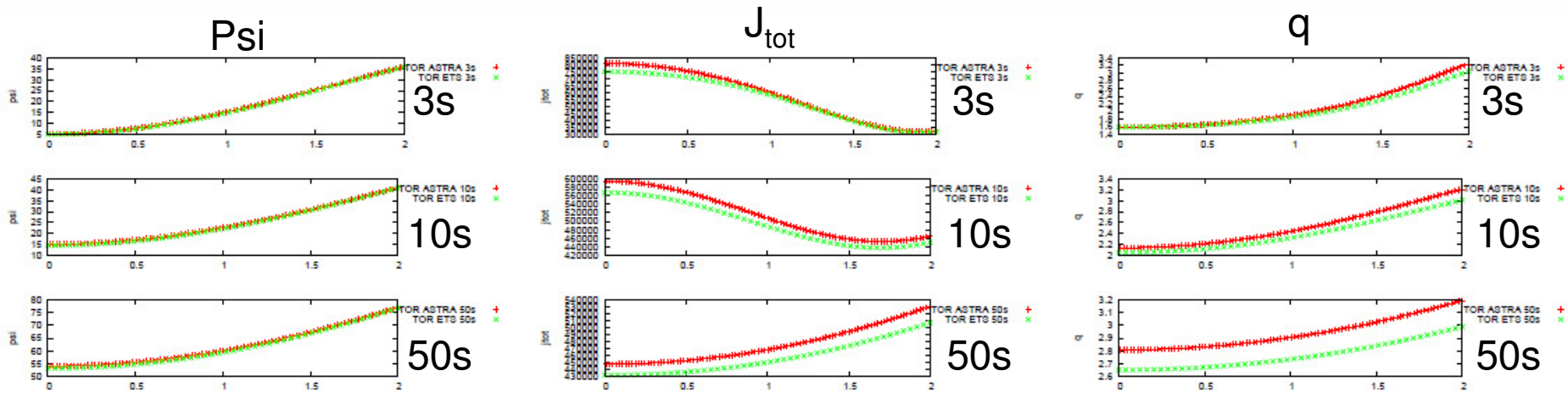


Figure 43: Comparison of ψ, total current and q at 3, 10 and 50s.

Development status

Coding →

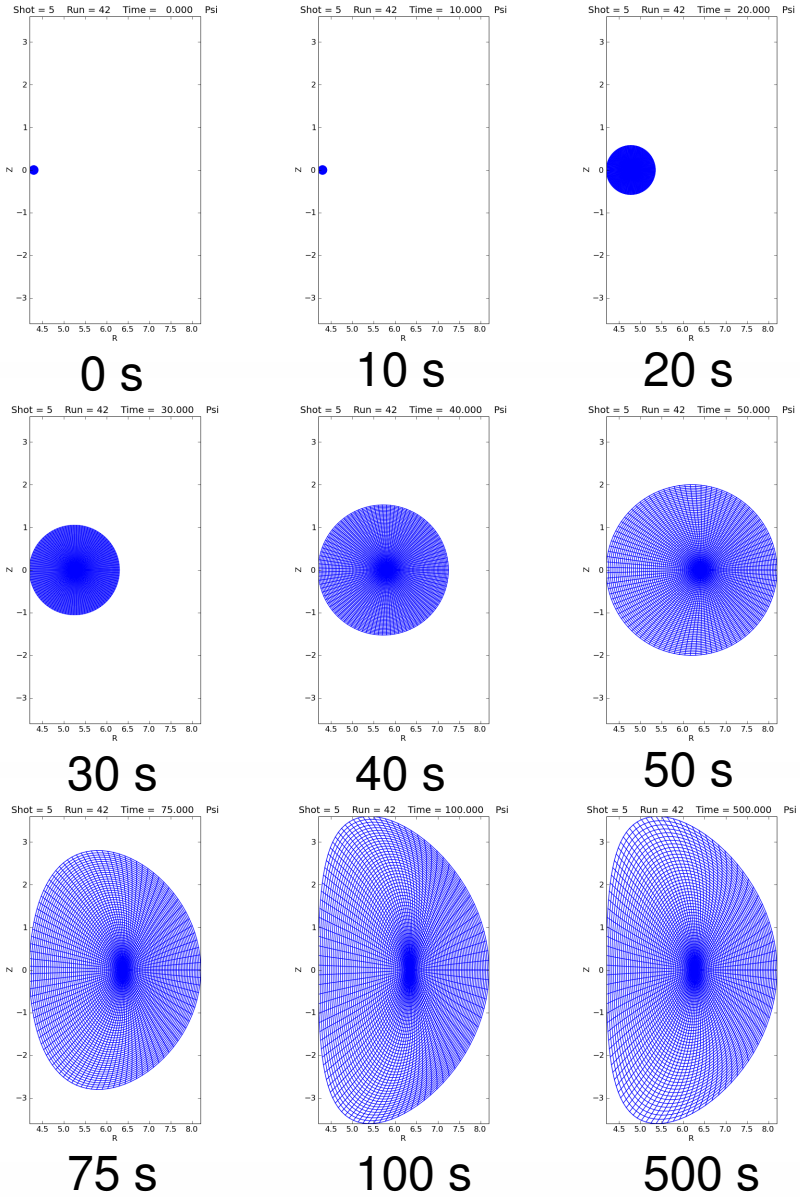
Checking the Coding →

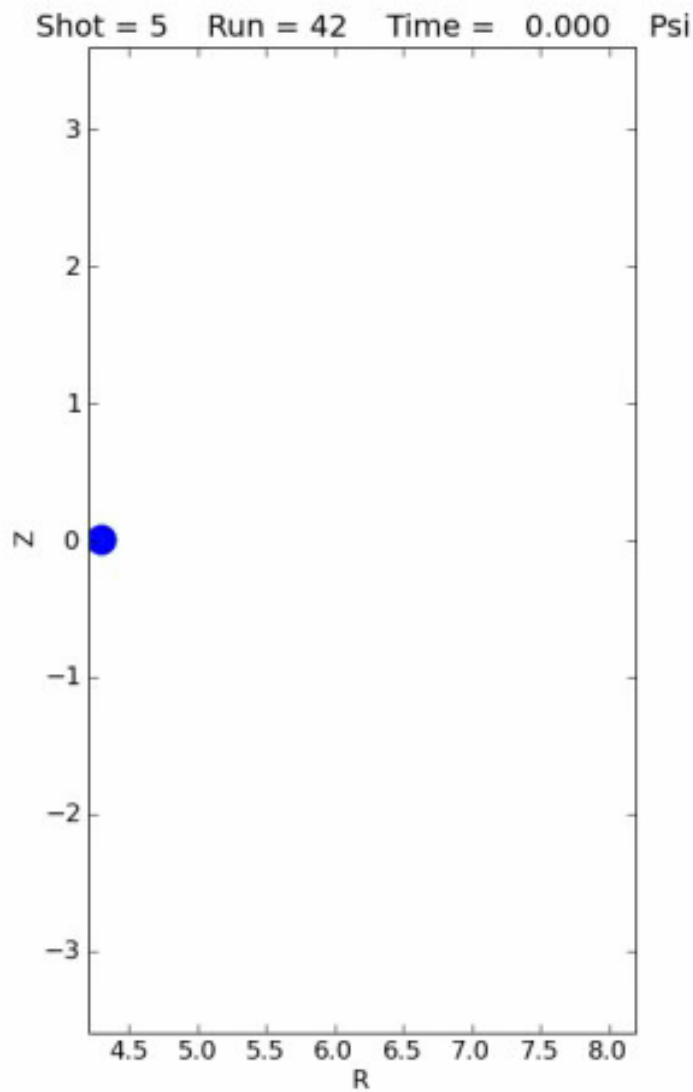
Verification and Benchmarking →

Validation ▶

This is an ongoing process --- every new piece of physics/code/… requires verification/benchmarking and validation

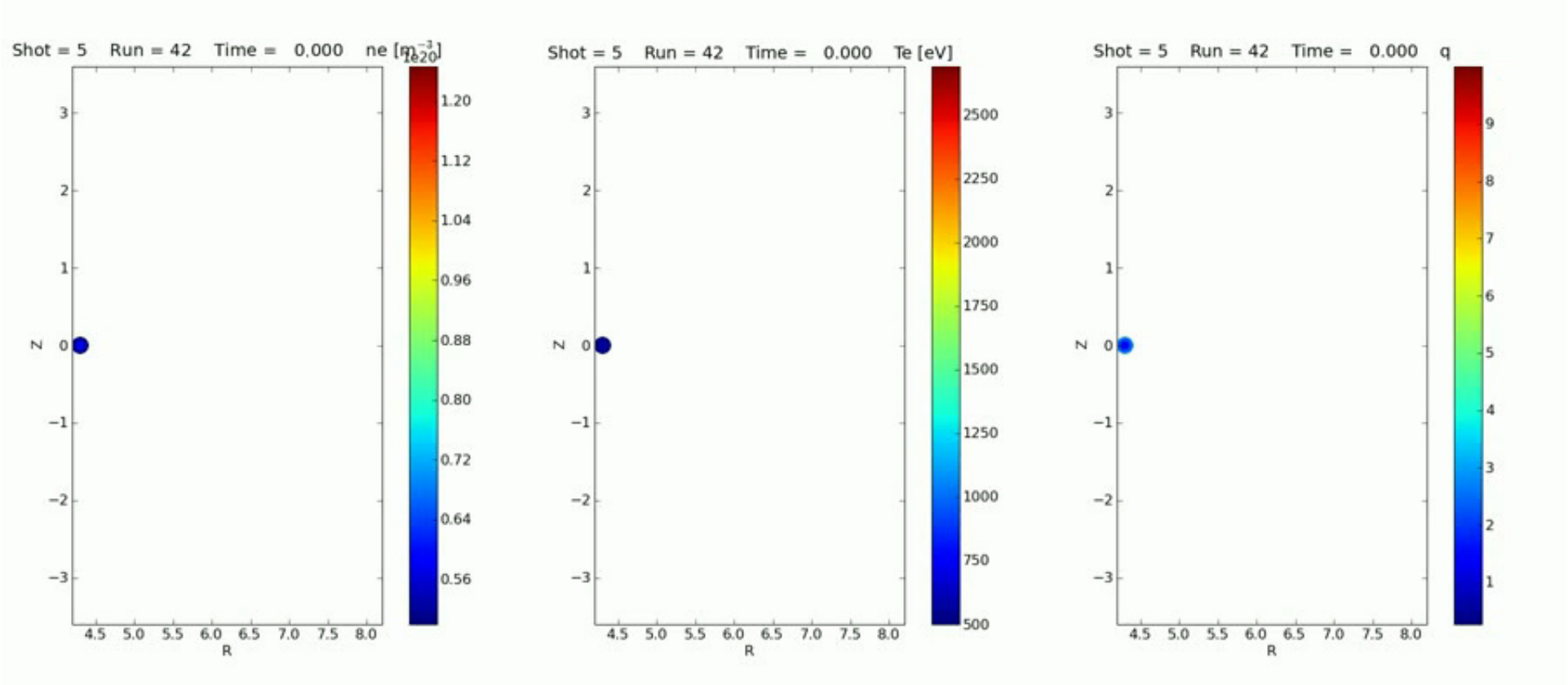
Experimental version of the ETS



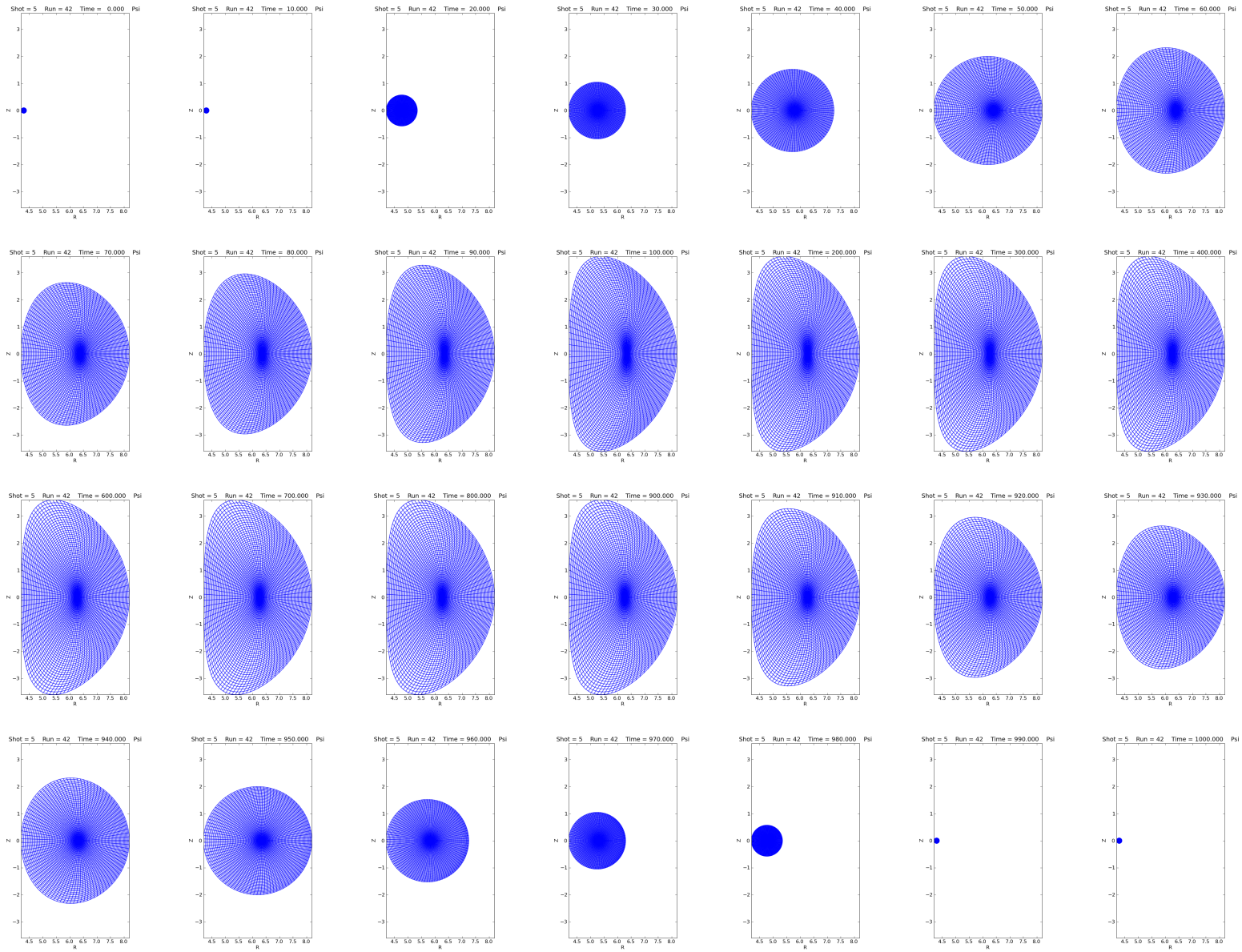


Experimental version of the ETS

n_e T_e q

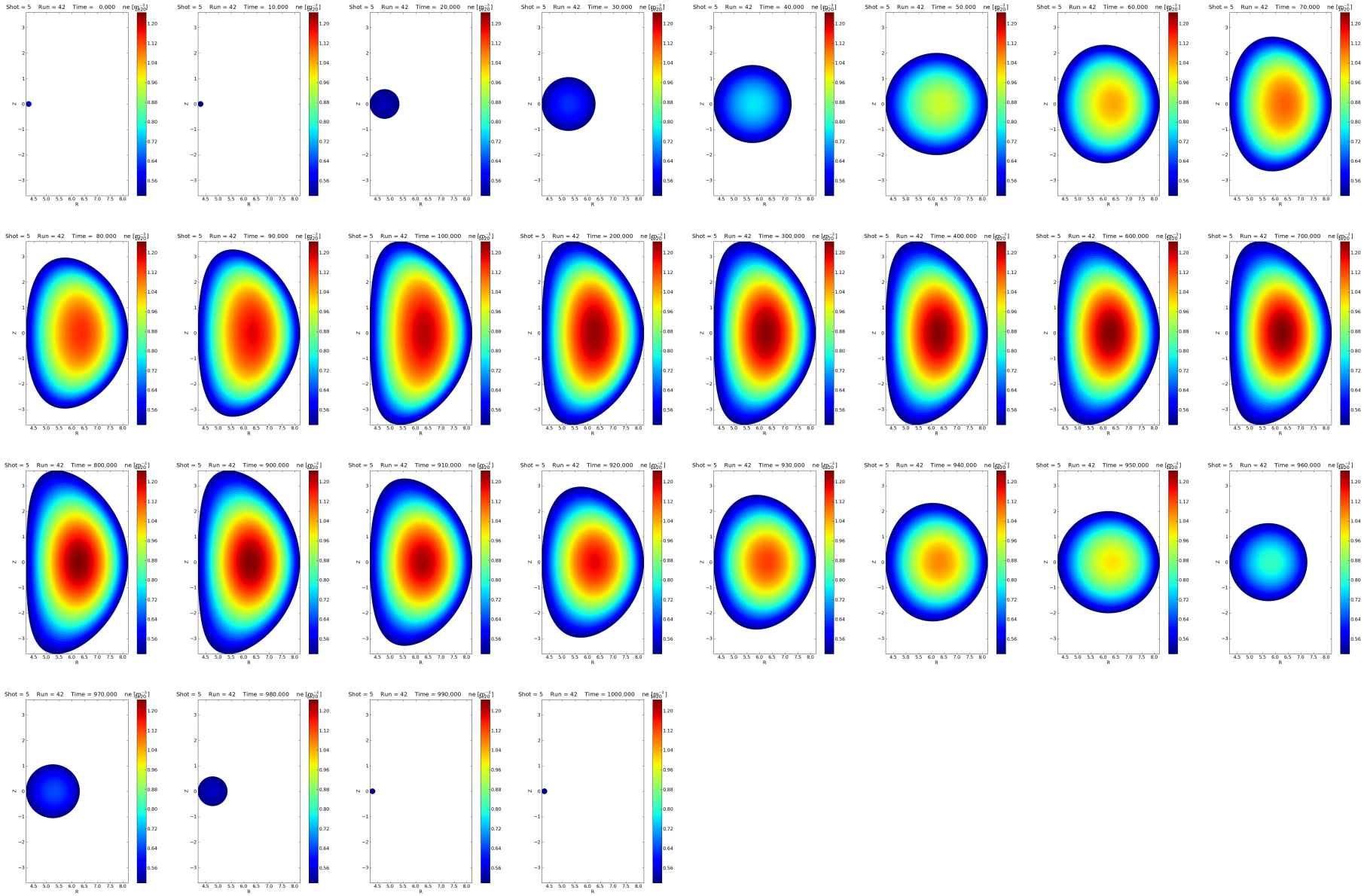


Evolution of the equilibrium



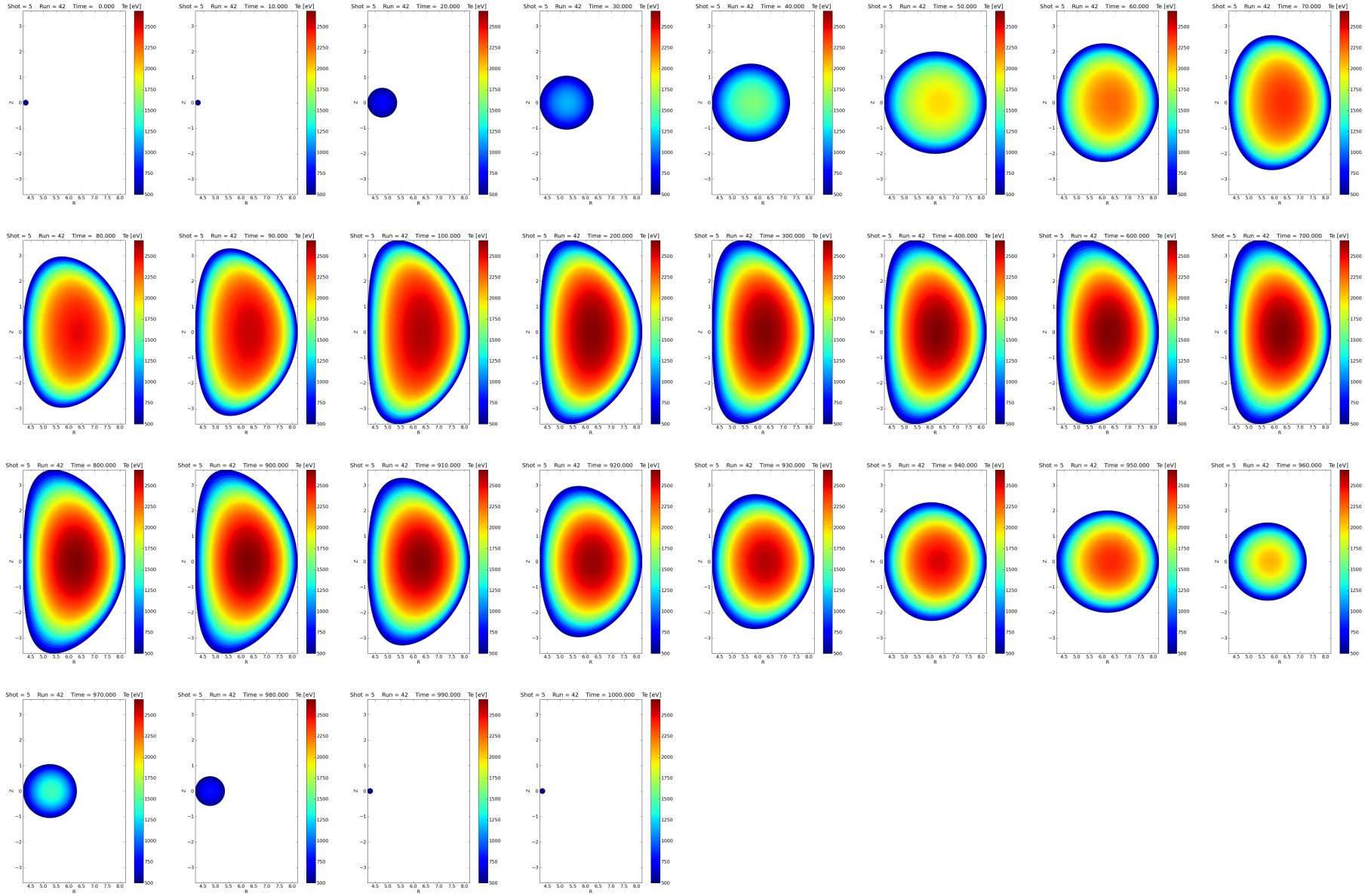
Evolution of n_e

2009-10
ICNSP



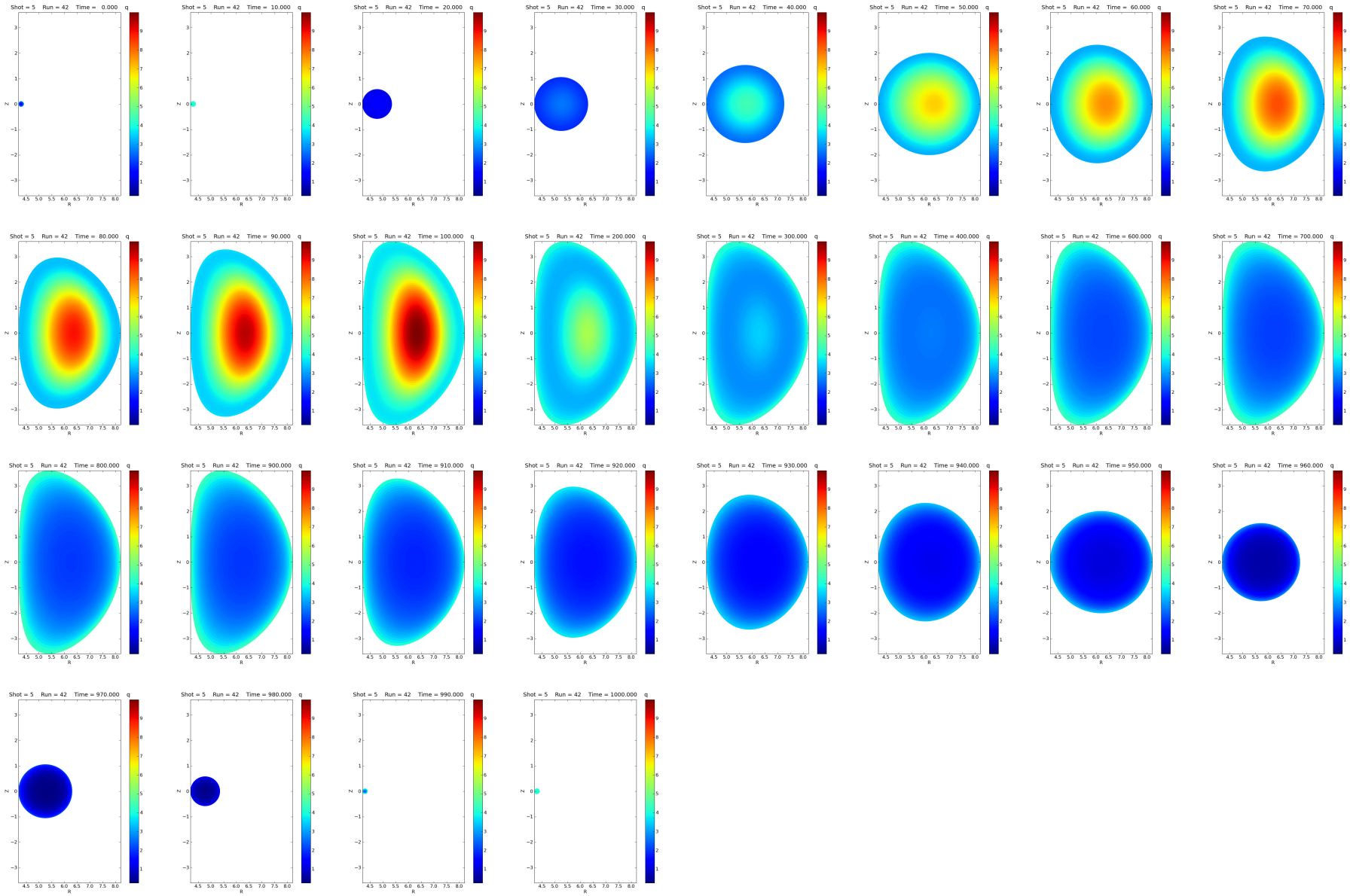
Evolution of T_e

2009-10
ICNSP



Evolution of q

2009-10
ICNSP



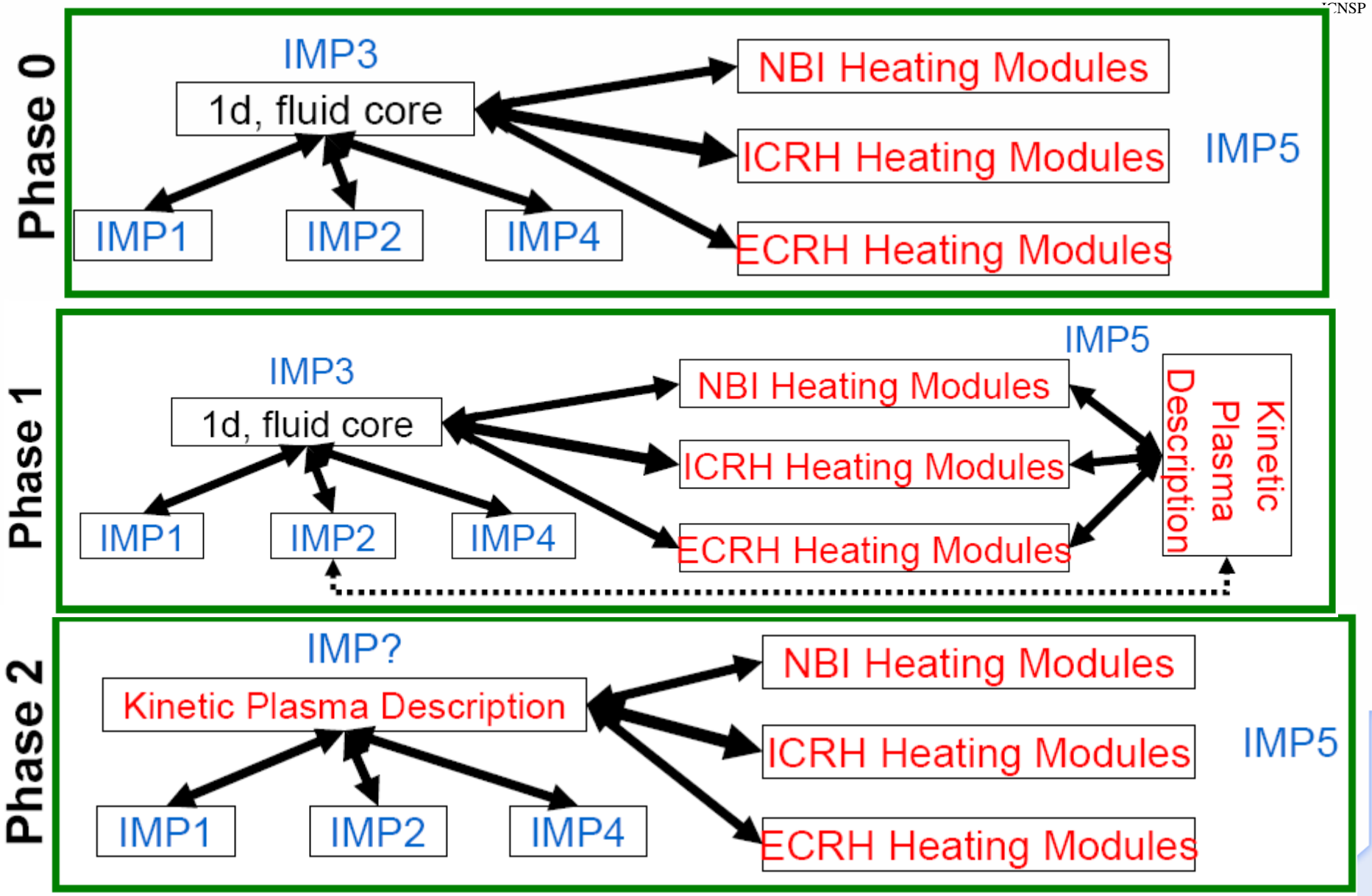
Outline

- What is the European Transport Solver (ETS)?
- Why should anybody be interested in the development of the ETS
- Who is doing the work?
- What is the current status of the ETS?
- What are the plans for the ETS?

Present Plans

- End of 2009
  - Present Fortran Workflows implemented in Kepler
    - With additional physics modules
      - Neutrals
      - Impurities [I.M. Ivanova-Stanik et al., “Verification and Benchmarking of the Impurity Transport Solver”, Poster Session on Tuesday]
      - Sawteeth
      - Transport coefficients
      - Heating and current drive sources
- 2010
  - Free boundary equilibrium code (& feedback loops)
  - Coupled to an edge code
- 201?: ETS successor with core kinetic profiles (????)

201?: ETS Successor?



Summary

- Shown the development of the European Transport Solver (ETS)
- The approach taken (fusion ontology, modular components) is applicable to a much wider range of problems, inside fusion as well as in other areas
- The results should be a very flexible framework for doing a wide range of simulations, of which the outlined core transport is just one example.

Code/module requirements/status

Phase I (initial porting)

(A) porting to the ITM Gateway (runs on ITM Gateway, compilers, libraries, etc.)

(B) completion of "grant of software license and rights to the ITM-TF" procedure

(C) creation of a project under GForge and code under subversion (on the ITM Gateway or mirrored there)

Phase II (preparation of stand-alone module)

(D) conversion into a module using CPOs

(E) conversion of code specific input to XML

(F) creation of standalone wrapper for testing ("test bed")

(G) provision of standard test cases

(H) standardized build procedure (make)

(I) standardized test procedure

Phase III (preparation of Kepler actor)

(J) creation of a Kepler actor

(K) creation of a Kepler test workflow

(L) benchmark of Kepler module against original version of code

(M) verification of Kepler module (code-code benchmarks)

Phase IV (documentation)

(N) code documentation (for developers and maintainers)

(O) user documentation (for users)

Phase V (release candidate cycle)

(P) validation by module author/responsible officer

(Q) release candidate for Kepler module (approved by Project Leader)

Phase VI (release cycle)

(R) validation by IMP

(S) release of Kepler module (approved by Task Force leader)

Acknowledgements

- Thanks go to
  - ETS Team (WP09-ITM-IMP3-T1 & WP09-ITM-IMP3-T2)
  - The members of IMP3
  - The members of ISIP
  - The members of IMP1, IMP2, IMP4 & IMP5
  - The members of the ITM
  - The members of EUFORIA
- This work is very much a team effort!

THANKS!