Core Plasma Particle Transport Benchmark Activities in International Tokamak Physics Activity (ITPA) Integrated Operation Scenario (IOS) Group

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(Deputy Chair)

on behalf of ITPA IOS TG

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Acknowledgement: C.E. Kessel, Dong-Hyun Na, A. Fukuyama, J. Garcia,
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Outline

- **Goal of modelling activities in ITPA IOS TG**
- **Motivation of particle transport benchmarking**
- **Overview of particle transport benchmarking activity**
  - Benchmarking guideline
  - Participating 1.5-D transport codes and modellers
- **First results of particle transport benchmarking**
- **Discussion**
- **Next-step work**

Goal of modelling activities in IOS

- **Establish reliable integrated operation scenarios in ITER**
  - Address ITER urgent issues related with IOS
  - Simulate and optimise ITER operation scenarios
  - Model and simulate integrated control for ITER

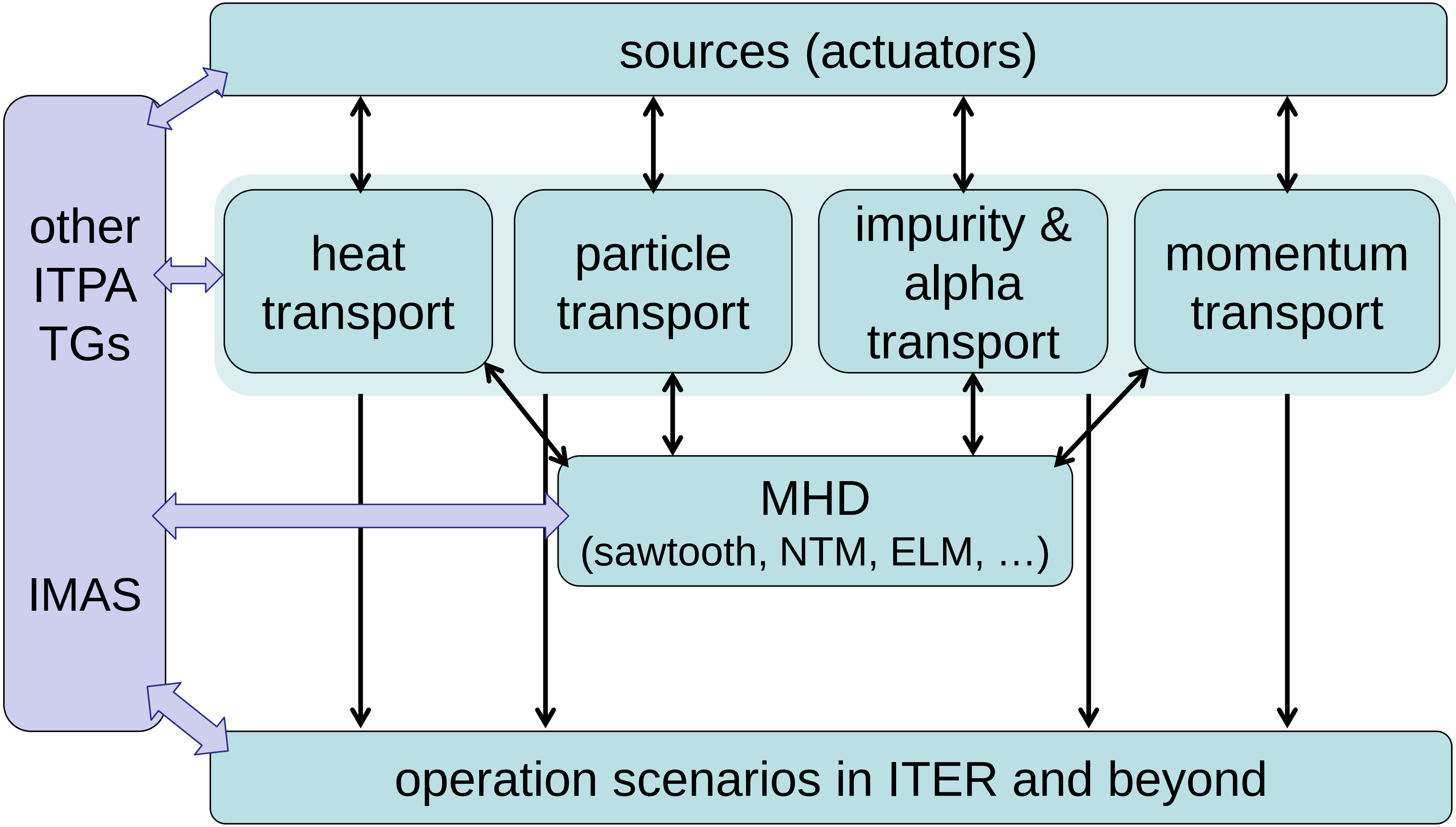
- **Improve predictive capability of integrated modelling**
  - Benchmark and verify existing models, modules, and codes
  - Integrate models, modules, and codes for better prediction

Short-term *partially collaborative* activities

- **Establish reliable integrated operation scenarios in ITER**
    - Address ITER urgent issues related with IOS
      - Development of H, He scenarios
      - Ramp-down and plasma termination modelling
      - W transport modelling
    - Simulate and optimise ITER operation scenarios
    - Develop integrated control schemes for ITER
      - Burn control simulation
      - Integrated control simulation with actuator sharing

- **Improve predictive capability of integrated modelling**
    - Benchmark and verify existing models, modules, and codes
      - Bootstrap current model benchmarking
    - Integrate models, modules, and codes for better prediction
      - Pedestal modelling
      - Core-edge-SOL integrated modelling

Long-term *fully collaborative* activities



sources (actuators)

other ITPA TGs

IMAS

heat transport

particle transport

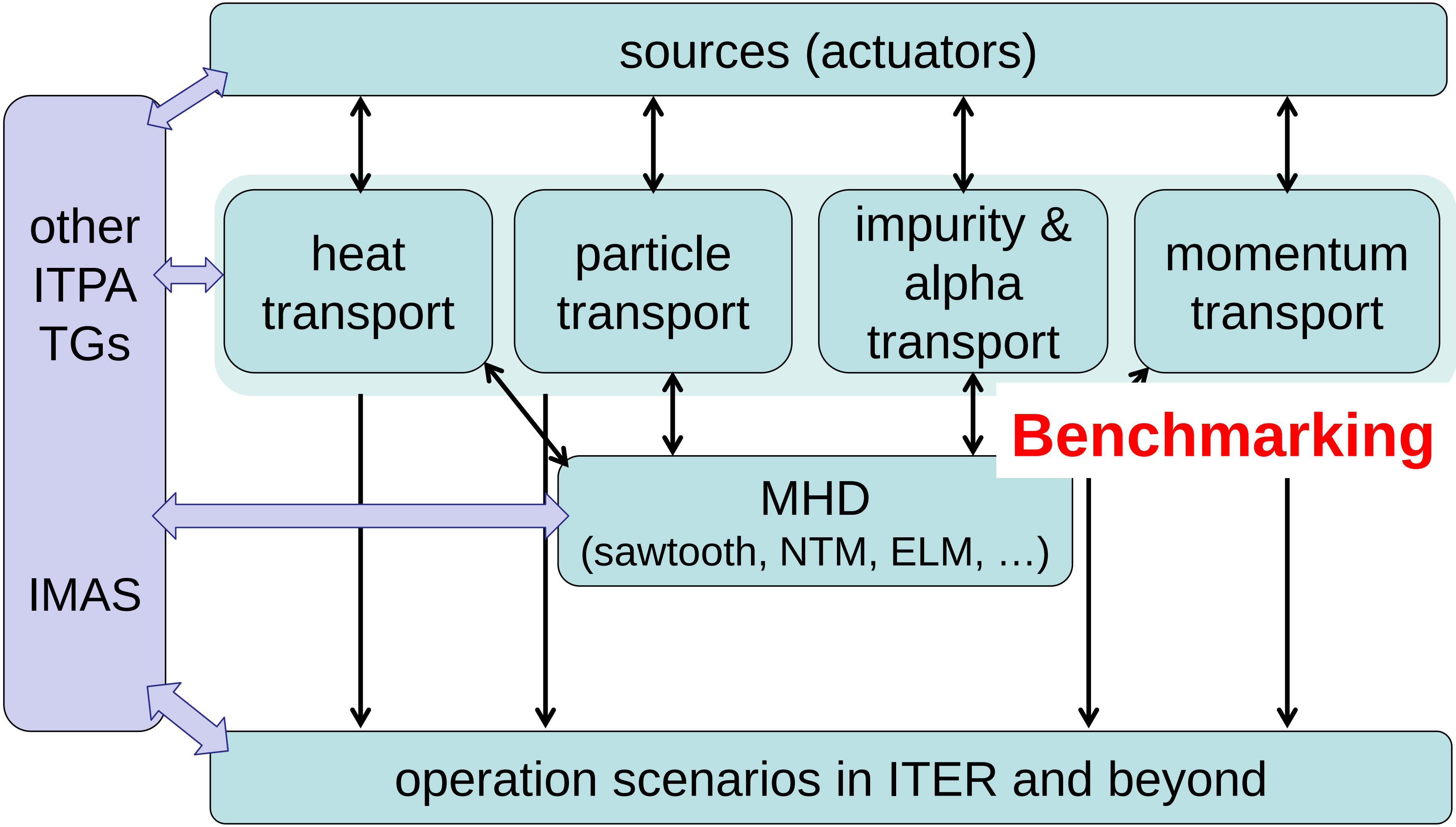
impurity & alpha transport

momentum transport

MHD
(sawtooth, NTM, ELM, …)

operation scenarios in ITER and beyond

Long-term *fully collaborative* activities



sources (actuators)

other ITPA TGs

IMAS

heat transport

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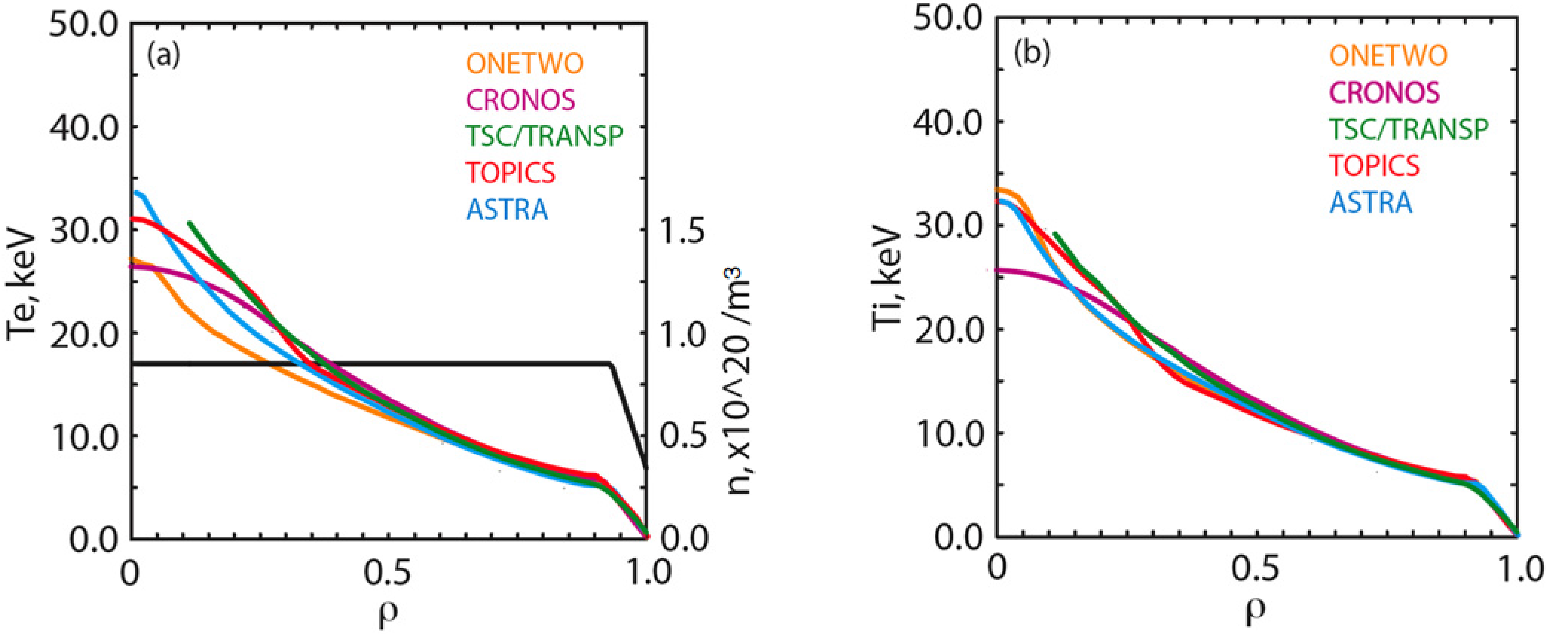
momentum transport

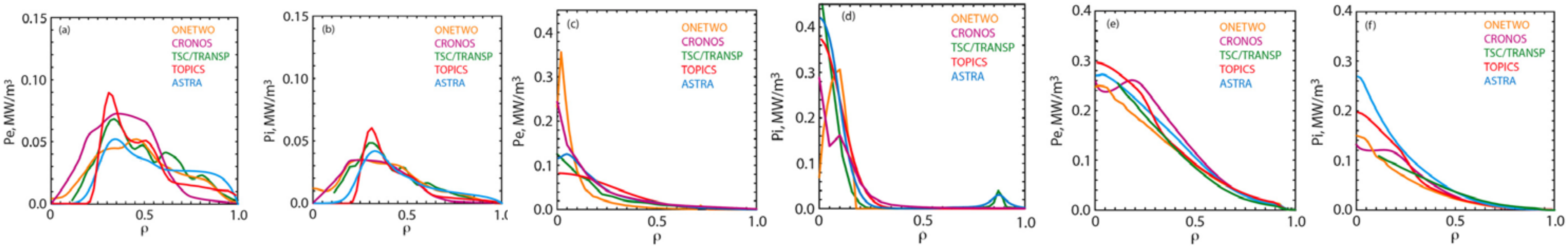
MHD
(sawtooth, NTM, ELM, …)

Benchmarking

operation scenarios in ITER and beyond

Heat transport benchmarking

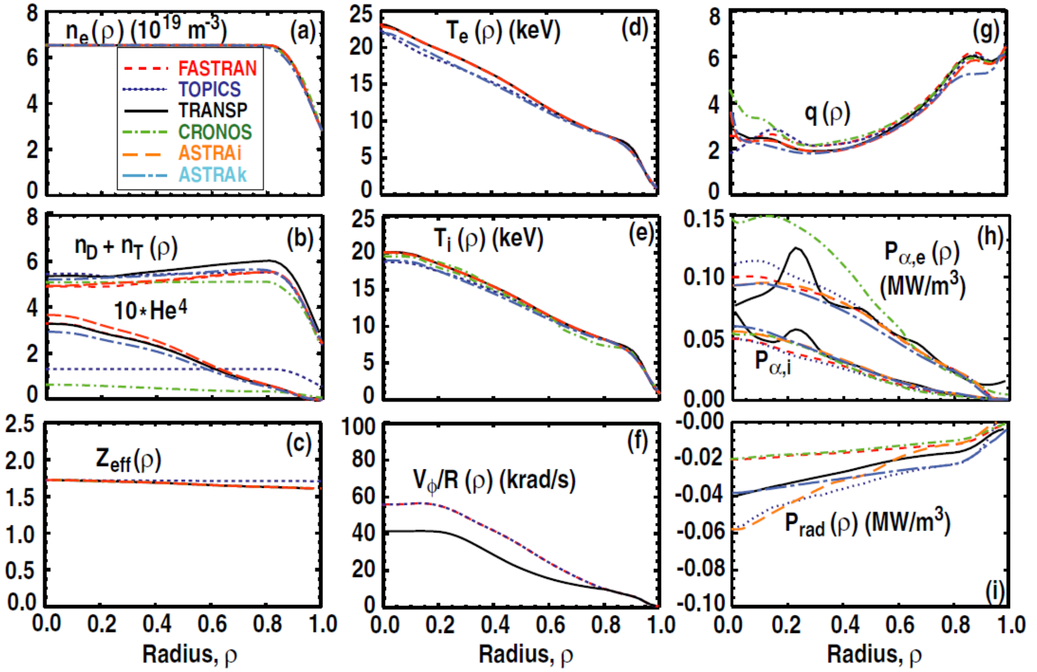


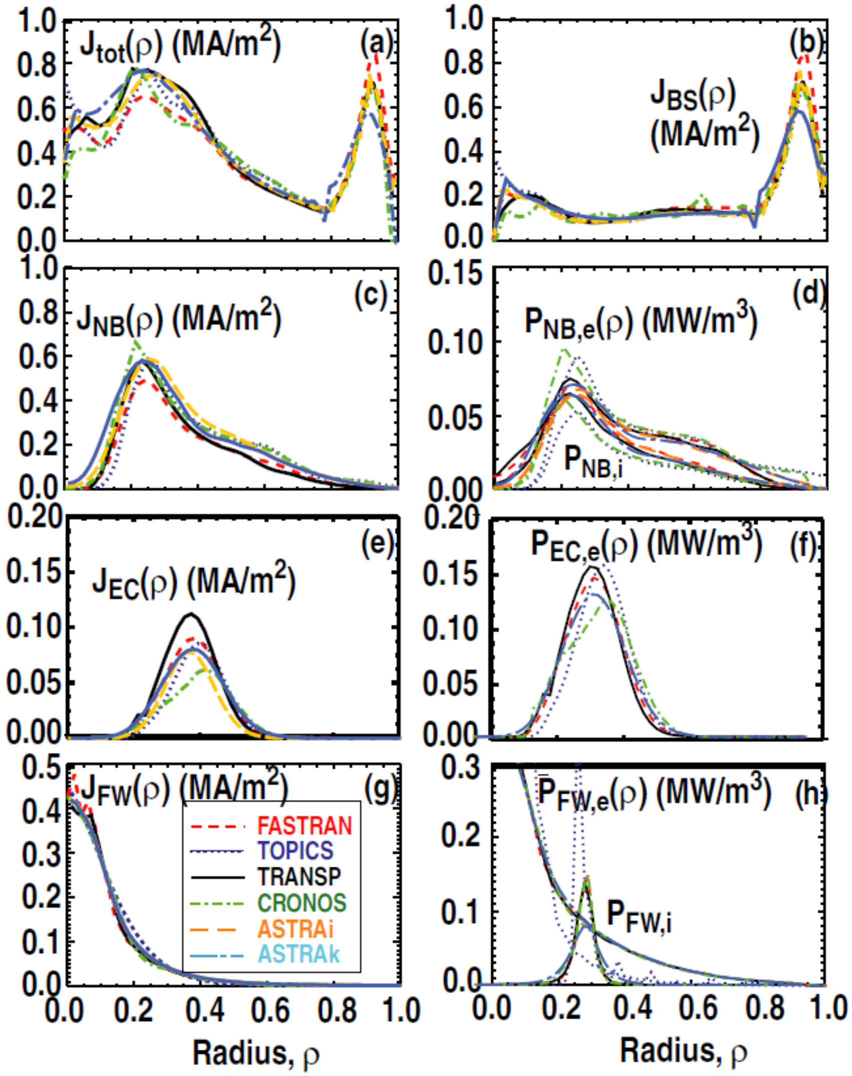


*C.E. Kessel et al, NF **47** 1274 (2007)*

Heat transport benchmarking

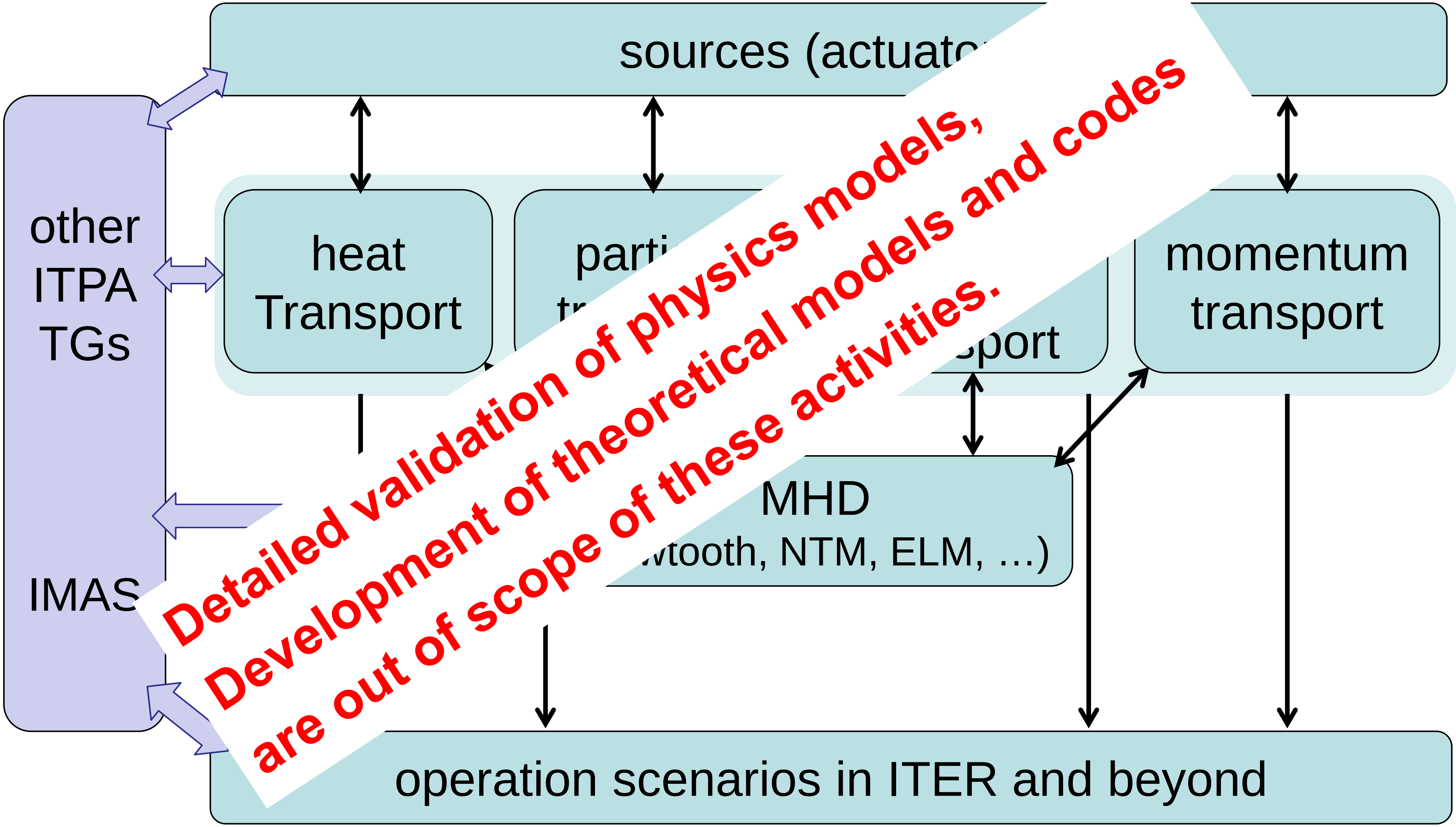
ITPA *Integrated Operation Scenarios*





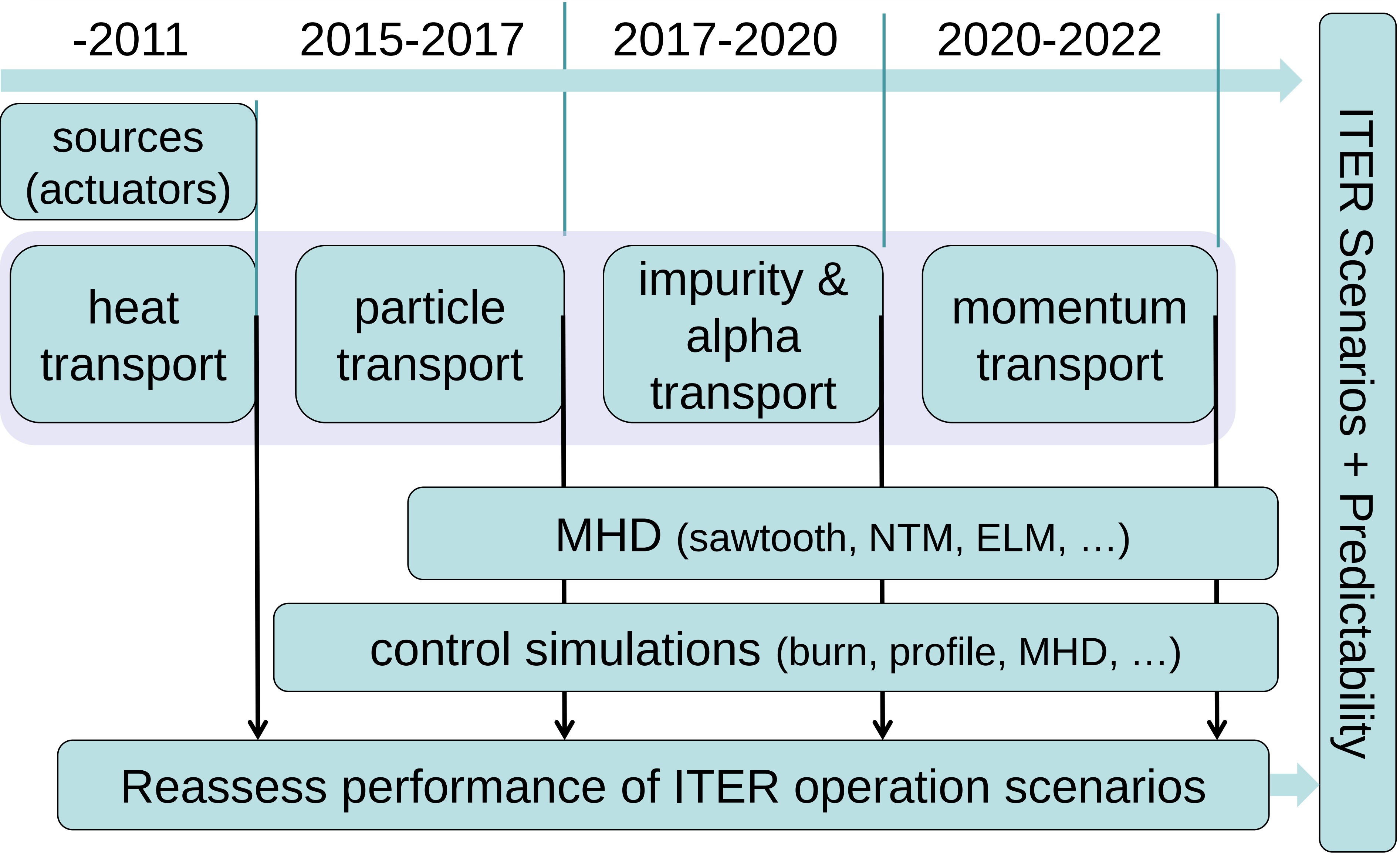
M. Murakami et al, NF ***51*** *103006 (2011)*

Long-term *fully collaborative* activities



Detailed validation of physics models,
Development of theoretical models and codes
are out of scope of these activities.

Plan for benchmarking activities



-2011

2015-2017

2017-2020

2020-2022

sources (actuators)

heat transport

particle transport

impurity & alpha transport

momentum transport

MHD (sawtooth, NTM, ELM, …)

control simulations (burn, profile, MHD, …)

Reassess performance of ITER operation scenarios

ITER Scenarios + Predictability

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Importance of particle transport in ITER prediction

- How is the density established in L-mode and does affect the L-H transition, and ultimately controlled in flattop H-mode?
- What is the density and density profile evolution at the L-H transition which has significant implications for entering and staying in H-mode?
- How to set credible burn control strategies for the H-mode in the flattop phase which depends sensitively on the particle balance of the mixed D-T fuels, He and impurities?
- How is the density and density profile evolution during the I_p ramp-down phase and the H-L transition phase?
- How much is the particle screening effect, charge exchange, recycling, and penetration of He and fuel into the core plasma which are central to understanding the dilution and tritium burnup?
- How much is the core fueling by pellet injection?
- How is the SOL/divertor plasma and its interactions with plasma facing components which sets the boundary conditions for the core transport?
- …

Particle transport modelling in ITER prediction

- Ultimate goal: modelling of integrated control of
  - Core density (burn control for DT)
  - Mode of operation (L, H)
  - ELM pacing
  - Divertor detachment
  - Impurity accumulation

- Responsibility of ITPA TGs:
  - Core transport models (T&C)
  - Pedestal models (PED)
  - Core boundary conditions (SOL/DIV)
  - Core transport solvers + integrated modelling (IOS)

- Core transport solvers:
  - Electron/ion transport simulation
  - Core fueling by pellets (permanent/instant models)
  - Sink with ELMs (permanent/instant models)
  - Core impurity transport (including control by ELM pacing)
  - Impact of boundary conditions (from SOL/DIV transport and control)
  - Efficiency of core fueling by gas puffing (penetration through the SOL)

Status of particle transport modelling

- Particle transport in the core plasma is often not treated regardless of its importance in integrated scenario simulations.
    - uncertainties of measurements to determine the separatrix density and the fuel sources (3-Dimentional) to validate transport models
    - complexity of multi-species impurity transport
    - complicated relationship with the SOL, divertor, and plasma facing materials

Particle transport benchmarking

- Goal
  - Verify agreement among various integrated modelling codes by approximating closely the expected scenario on ITER
  - Predict ITER plasmas more accurately based on knowledge accumulated from the benchmarking
  - Address the critical issues of ITER

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Steps in benchmarking

STEP 1: Benchmarking of particle transport solvers with prescribed transport coefficients and sources at one time point in the current flattop
Purpose: to ensure agreement and understand differences among particle transport solvers

STEP 2: Benchmarking of particle sources & sinks with prescribed transport coefficients at one time point in the current flattop
Purpose: to compare source & sink models

STEP 3: Sensitivity scans of transport coefficients at one time point in the current flattop
Purpose: to evaluate the impact of particle transport to fusion performance

STEP 4: Benchmarking of time-evolution in whole discharge with prescribed transport coefficients and sources in time
Purpose: to evaluate the impact of particle transport to scenario evolution

STEP 5: Application of physics-based transport models
Purpose: to predict particle transport in ITER

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Purpose: to predict particle transport in ITER

Integrating with heat transport!

Guideline for Benchmarking

- Solving n_e and T_e, T_i
- ITER baseline scenario at the plasma current flattop phase
  - $I_p = 15.0$ MA, $B_T = 5.3$ T at R = 6.2 m
- Basic assumptions
  - $n_Z = f_z n_e$, quasi-neutrality
  - Set Helium density profile as

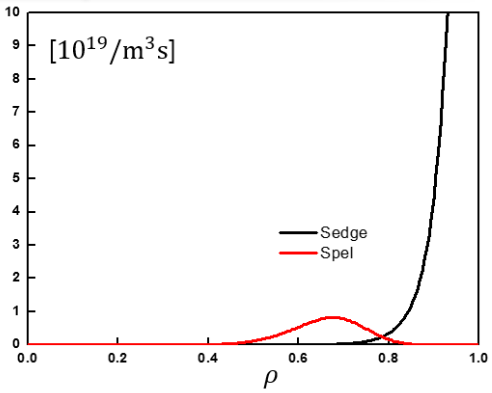
    $n_{He}(\Phi) = n_0\,[1 - (\Phi/\Phi_{edge})^2]^2$ Φ: toroidal magnetic flux

    $n_0 = 0.95\mathrm{x}10^{19}$ /m^3
  - Ignore NB fueling and current drive
  - Zero toroidal rotation
  - No sawtooth

- Plasma equilibrium: using a TSC result or approximate geometric values

R_0 (m)	a (m)	κ	δ	Z_{mag} (m)	Volume (m^3)
6.20	1.99	1.85	0.45	0.50	819.4

Guideline for Benchmarking



- Transport model setup
  - Edge particle source

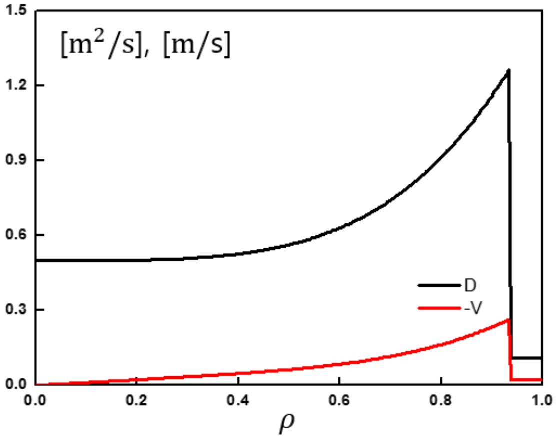
    $S(\Phi) = S_0 \exp\{15\ (\Phi - \Phi_{edge})/\Phi_{edge}\}$

    $S_0 = 7.5\text{x}10^{20}$ atom/m^3
  - Core particle source by pellet fueling (continuous)

    $S(\Phi) = C{*}d^2{*}(\Phi/\Phi_{edge})^{6.5}{*}[1-(\Phi/\Phi_{edge})]^{8.5}/\{d^2+[(\Phi/\Phi_{edge})-0.5]^2\}$

    $C = 0.25\text{x}10^{24}$, $d = 0.225$

    Pellets injected every 50 ms, so continuous source is ~ 50x smaller



  - Particle transport

    $D(\Phi) = D_0 + D_1(\Phi/\Phi_{edge})^2$ for $\Phi < \Phi_{ped}$

    $D(\Phi) = D_2$ for $\Phi \geq \Phi_{ped}$

    $R_0{*}v/D = V_0{*}(\Phi/\Phi_{edge})^{1/2}$

    $D_0 = 0.5$ m^2/s, $D_1 = 1.0$ m^2/s, $D_2 = 0.11$ m^2/s

    $V_0 = 1.385$ (positive is inward pinch)

Guideline for Benchmarking

- Transport model setup
  - Impurity specification

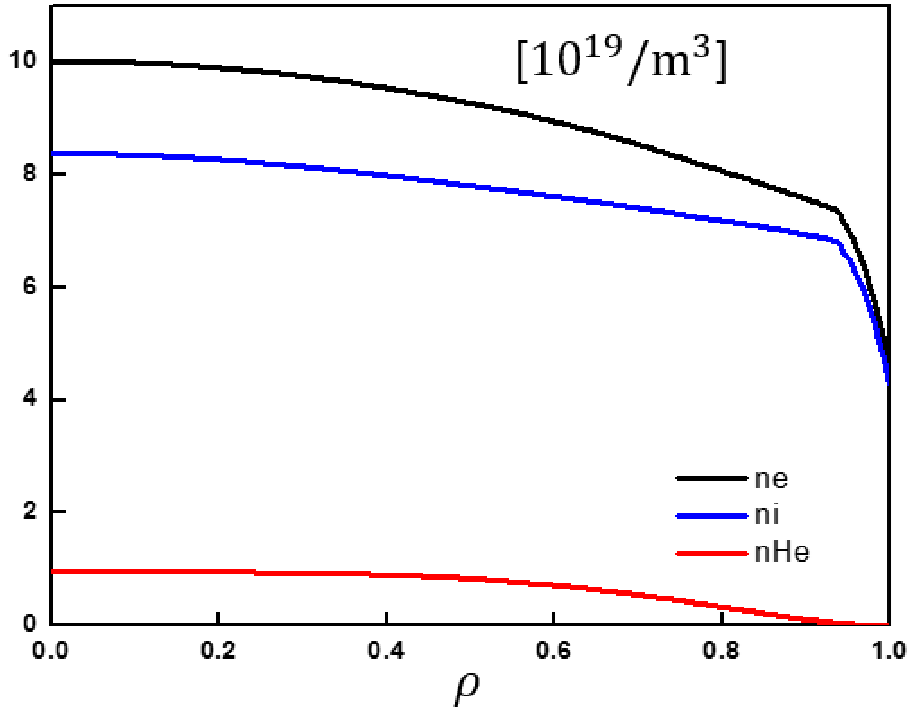
    Be: $n_{Be}/n_e = 0.02$, profile same as electrons

    Ar: $n_{Ar}/n_e = 0.0005$, profile same as electrons

    W: $n_W/n_e = 0.0$

  - Boundary condition

    $n_e(a) = 4.6 \times 10^{19}$ /m^3



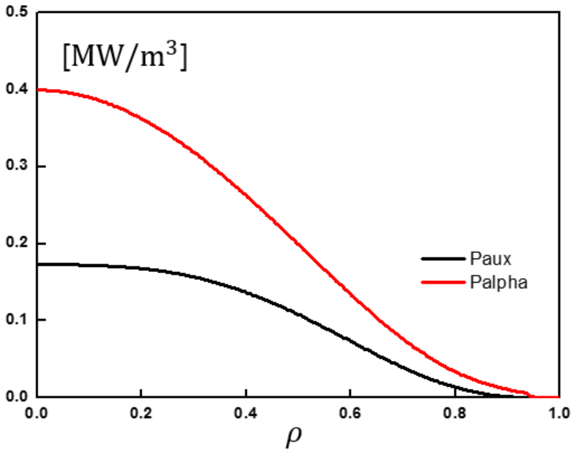
Guideline for Benchmarking

- Transport model setup
  - Heat source

    $P(\Phi) = P_0[1 - (\Phi/\Phi_{edge})^{1.5}]^{3.5}$

    Normalise P_0 to match $P_{total} = 53.0$ MW

    $P_{elec}/P_{total} = 0.7$, $P_{ion}/P_{total} = 0.3$



  - Heat transport

    $\chi_{e,i}(\Phi) = \chi_0$ for $\Phi < \Phi_{ped}$

    $\chi_{e,i}(\Phi) = \chi_{ped} \exp\{2.5\,[(\Phi - \Phi_{ped}) / (\Phi_{edge} - \Phi_{ped})]^2\}$ for $\Phi \geq \Phi_{ped}$

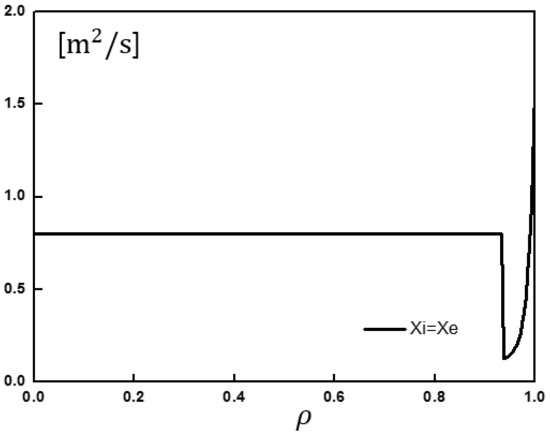
    $\chi_0 = 0.802$ m²/s

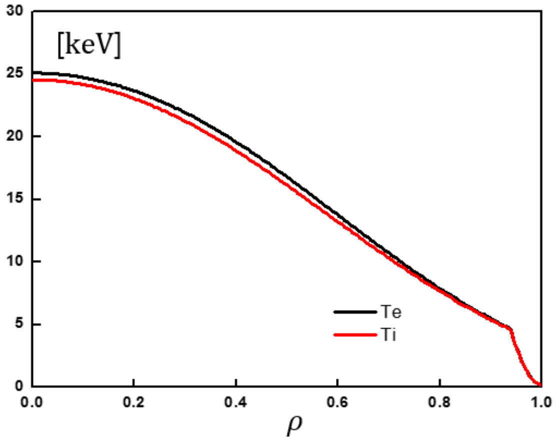
    $\chi_{ped} = 0.13$ m²/s

    $\Phi_{ped}/\Phi_{edge} = 0.88$

  - Boundary condition

    $T_e(a) = T_i(a) = 150$ eV





Main plasma parameters (reference)

β_N	2.0	n_e/n_{GW}	0.74
τ_E	3.0 (including radiation)	$n_e(0)$	$1.0\text{x}10^{20}$ /m^3
H_{98}	1.1 (including radiation)	$<n_e>$	$0.85\text{x}10^{20}$ /m^3
W_{th}	403 MJ	$\overline{n}_e$	$0.9\text{x}10^{20}$ /m^3
$T_i(0)$	24.6 keV	$n_e(0)/<n_e>$	1.18
$T_e(0)$	25.1 keV		
$T_{i,ped}$	4.6 keV		
$T_{e,ped}$	4.7 keV	$<Z_{eff}>$	1.51
P_α	106 MW	$<n_{He}>/<n_e>$	0.062
P_{line}	5.1 MW	$<n_{DT}>/<n_e>$	0.786
P_{cycl}	6.0 MW		
P_{brem}	17.1 MW		
P_{net}	135 MW		

ASTRA v.6

Participants of the activity

1.5-D transport Code	Modeller
ASTRA (v.6 + α)	Dong-Hyun Na (Seoul National University) Yong-Su Na (Seoul National University)
ASTRA (v.6x + v.7)	A. Polevoi (ITER IO)
CRONOS	J. Garcia (CEA)
FASTRAN	J.M. Park (ORNL) Kyungjin Kim (Seoul National University)
JINTRAC (JETTO)	F. Koechl (CCFE)
TASK/TR	A. Wisitsorasak (King Mongkut's University of Technology Thonburi, Thailand) A. Fukuyama (Kyoto University)
TOPICS	N. Hayashi (JAEA)
TRANSP	X. Yuan (PPPL) Yong-Su Na (Seoul National University)

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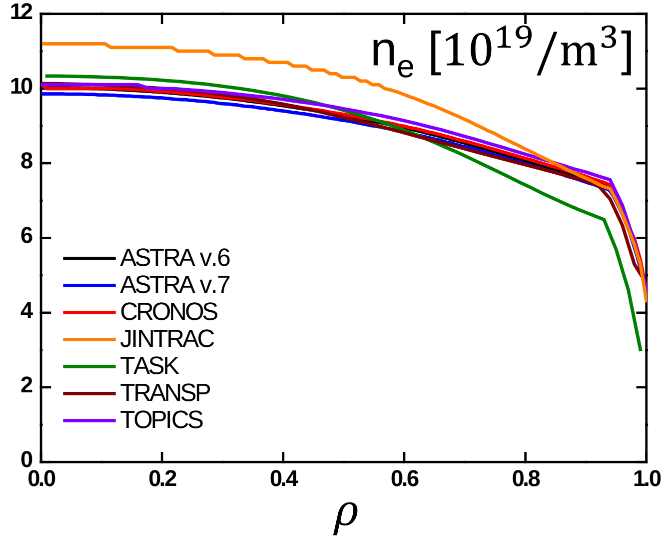
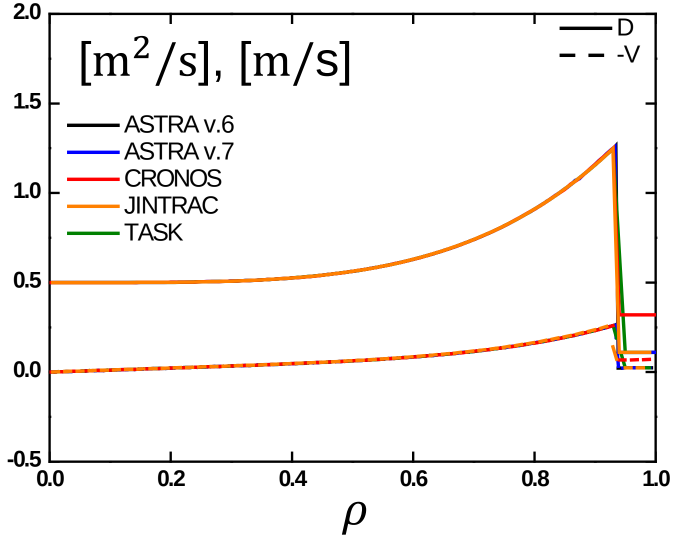
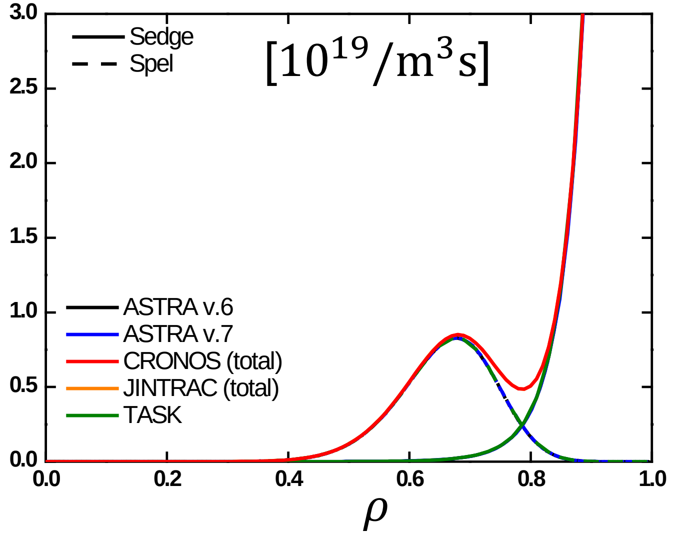
Particle transport







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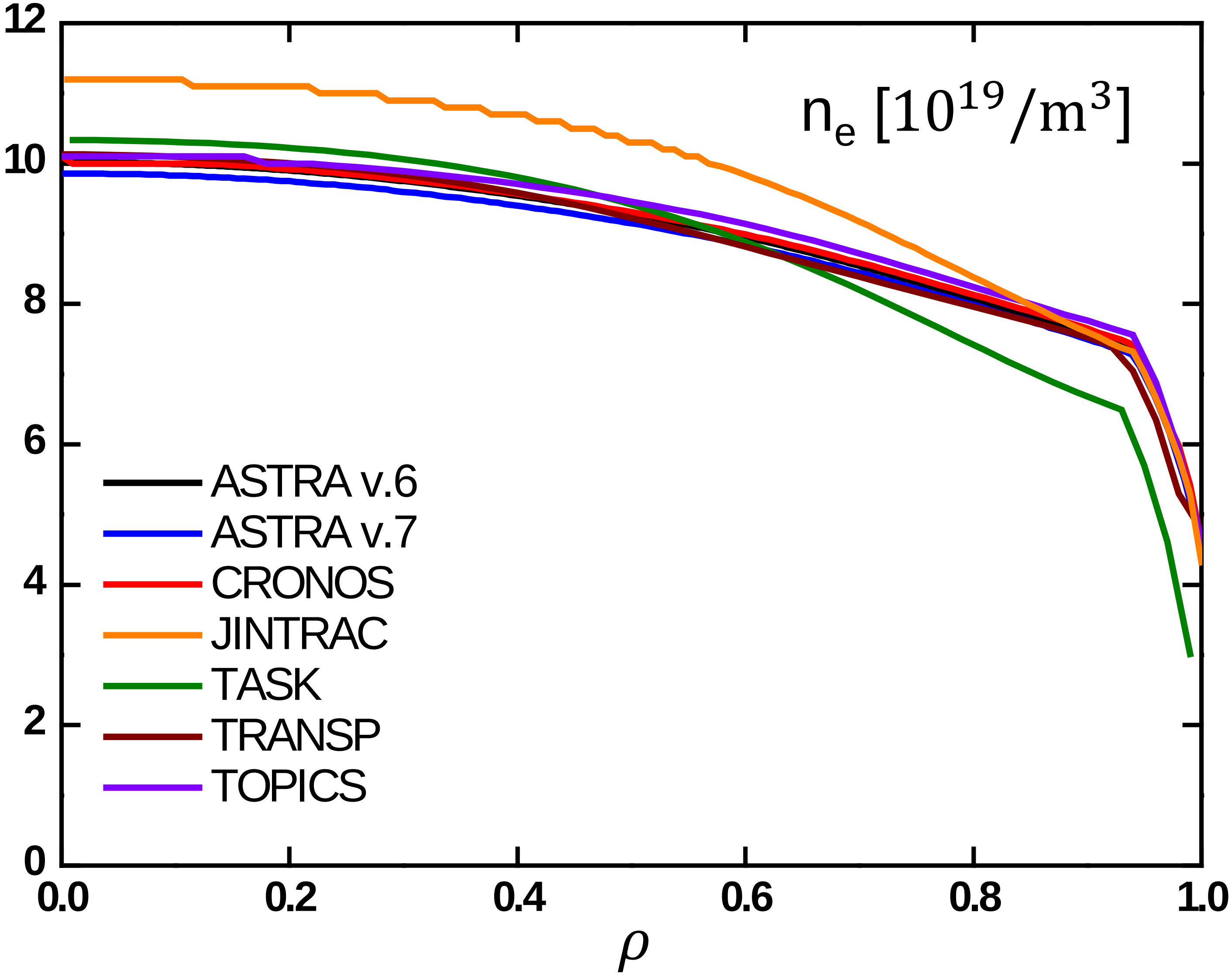

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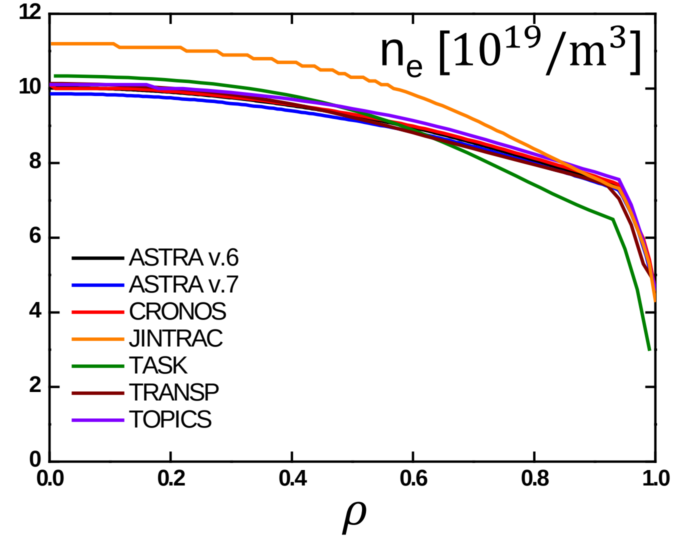

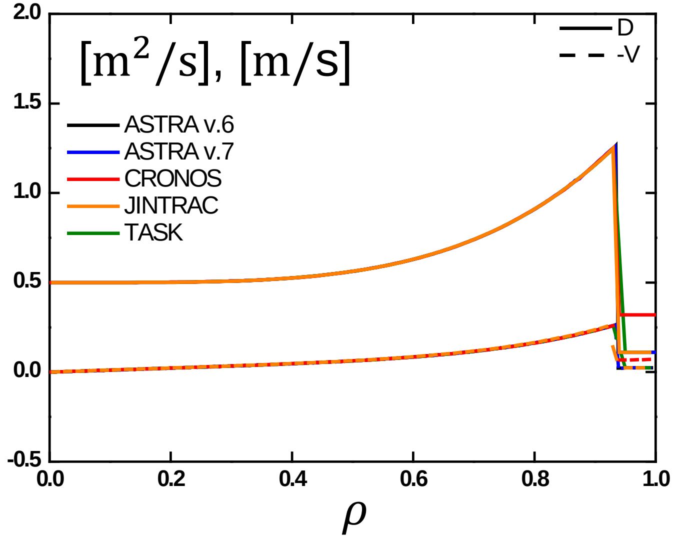

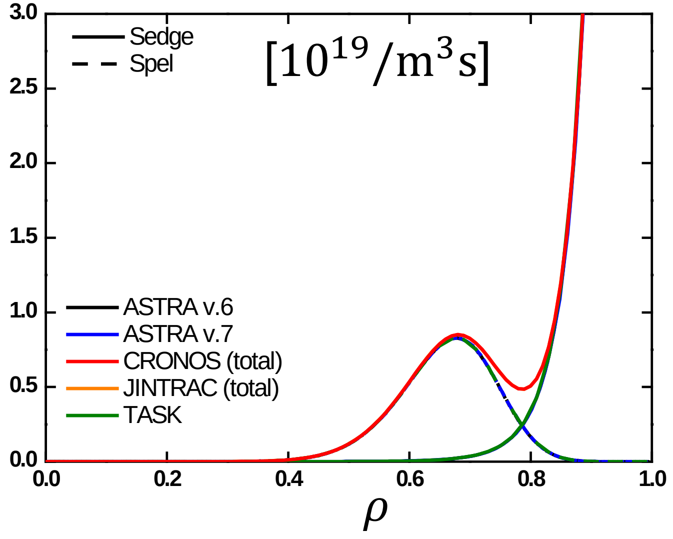

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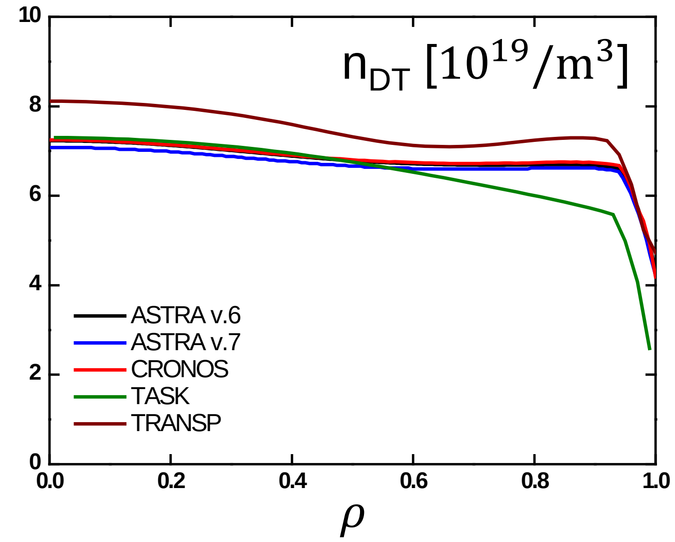

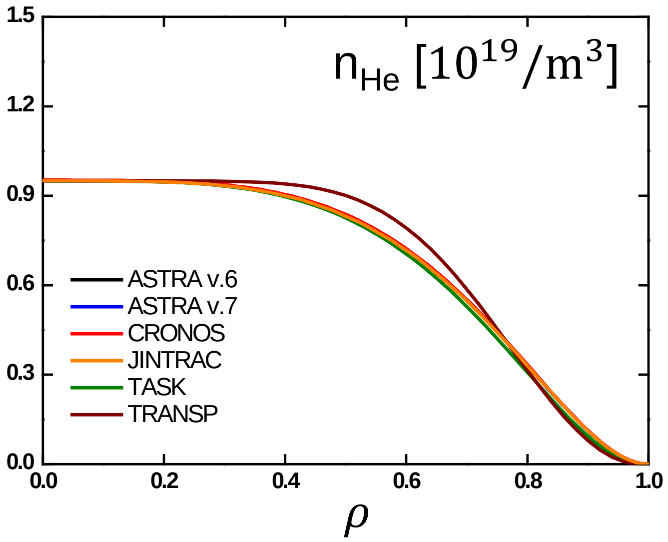

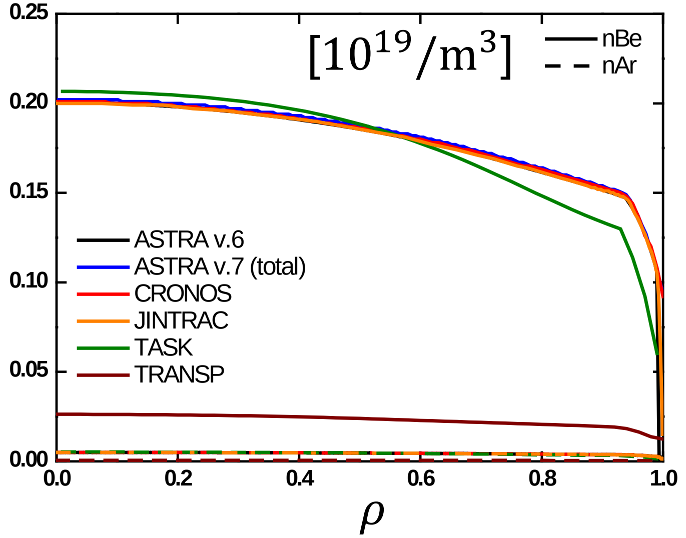

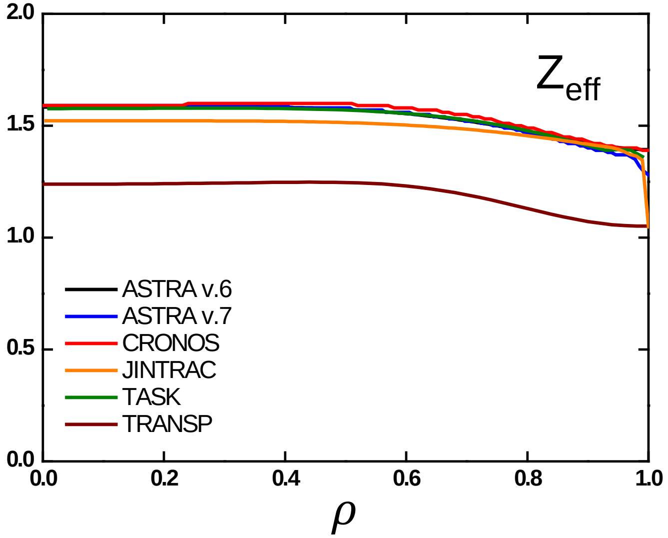

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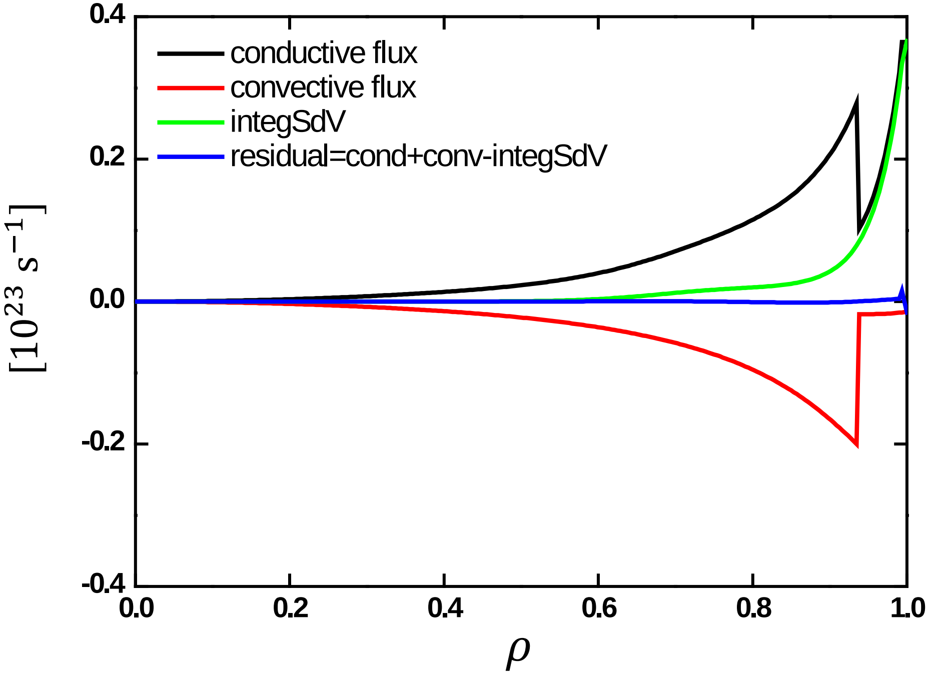
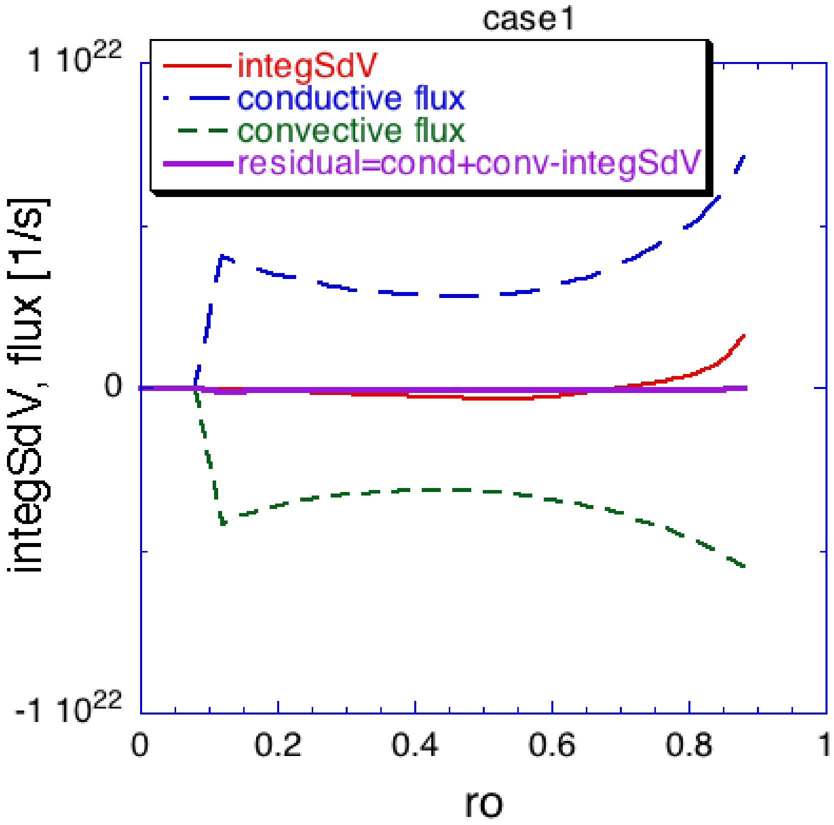
Possible reasons for disagreement

- Errors in the transport solver?
- Different equilibrium?
  - some using the prescribed one but the others solving the current diffusion equation
- Radial grid?
- Solving ion transport?
- Different definition of transport coefficients?
- Different treatment of impurities?
- …

Check particle flow balance





ASTRA v.6

TOPICS

Transport equations being solved

- ASTRA

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

$$\frac{\Gamma_e}{n_e}=-V'G_1\left(D_n\frac{1}{n_e}\frac{\partial n_e}{\partial\rho}+D_e\frac{1}{T_e}\frac{\partial T_e}{\partial\rho}+D_i\frac{1}{T_i}\frac{\partial T_i}{\partial\rho}+D_E\frac{E_\parallel}{B_p}\right)$$

$$G_1\equiv\langle(\nabla\rho)^2\rangle \qquad V'=\frac{\partial V}{\partial\rho}$$

The Ware pinch term $\frac{E_\parallel}{B_p}$ is replaced by -1 to adapt arbitrary pinch model in ASTRA.

D_E is defined as v in Guideline.

- CRONOS

$$\frac{\partial}{\partial t}\left(V'n_{\mathrm{e}}\right)+\frac{\partial}{\partial\rho}\left(V'\left\langle|\nabla\rho|^2\right\rangle\Gamma_{\mathrm{e}}\right)=V'S_{\mathrm{ne}},$$

$$\Gamma_{\mathrm{e}}=-D_{\mathrm{e}}\frac{\partial n_{\mathrm{e}}}{\partial\rho}-\frac{n_{\mathrm{e}}D_{\mathrm{e}}^{\mathrm{e}}}{T_{\mathrm{e}}}\frac{\partial T_{\mathrm{e}}}{\partial\rho}-\frac{n_{\mathrm{e}}D_{\mathrm{e}}^{\mathrm{i}}}{T_{\mathrm{i}}}\frac{\partial T_{\mathrm{i}}}{\partial\rho}$$

$$-n_{\mathrm{e}}D_{\mathrm{e}}^{E}\frac{E_\parallel}{\mu_0B_{\mathrm{p}}}-n_{\mathrm{e}}V_{\mathrm{e}}^{\Gamma}$$

- TRANSP (PTSOLVER)

$$\rho=\sqrt{\Phi/\Phi_{\lim}}$$

$$\frac{\partial}{\partial t}\left[V'n_e\right]+\frac{\partial}{\partial\rho}\left[V'\left\langle|\nabla\rho|^2\right\rangle\left(n_ev_e-D_e\nabla n_e\right)\right]-\xi\frac{\partial}{\partial\rho}\left[\rho V'n_e\right]=S_eV' \qquad \xi=\frac{1}{2\Phi_{\lim}}\frac{d\Phi_{\lim}}{dt}$$

Some codes solve ion transport

- TOPICS

$$\frac{\partial n}{\partial t}=\frac{1}{V'}\frac{\partial}{\partial \rho}V'\left(D\left\langle\left|\nabla\rho\right|^{2}\right\rangle\frac{\partial n}{\partial t}+V_{pinch}\left\langle\left|\nabla\rho\right|\right\rangle n\right)+S_{edge}+S_{pellet}+S_{fusion\ loss}$$

- JINTRAC

$$\frac{1}{V'}\frac{\partial}{\partial t}\left(n_i V'\right)+\frac{1}{V'}\frac{\partial}{\partial \rho}\left(V'\Gamma_i\right)=\left\langle S_i\right\rangle \quad \Gamma_i=-D_i\frac{\partial n_i}{\partial \rho}\left\langle\left(\nabla\rho\right)^{2}\right\rangle+\mathrm{v}_i n_i\left\langle\left|\nabla\rho\right|\right\rangle$$

Some codes solve ion transport

- TOPICS

$$\frac{\partial n}{\partial t}=\frac{1}{V'}\frac{\partial}{\partial\rho}V'\left(D\left\langle|\nabla\rho|^2\right\rangle\frac{\partial n}{\partial t}+V_{pinch}\left\langle|\nabla\rho|\right\rangle n\right)+S_{edge}+S_{pellet}+S_{fusion\ loss}$$

- JINTRAC

$$\frac{1}{V'}\frac{\partial}{\partial t}\left(n_i V'\right)+\frac{1}{V'}\frac{\partial}{\partial\rho}\left(V'\Gamma_i\right)=\left\langle S_i\right\rangle \quad \Gamma_i=-D_i\frac{\partial n_i}{\partial\rho}\left\langle(\nabla\rho)^2\right\rangle+\mathrm{v}_i n_i\left\langle|\nabla\rho|\right\rangle$$

- Simulation rerun with the following modified settings:

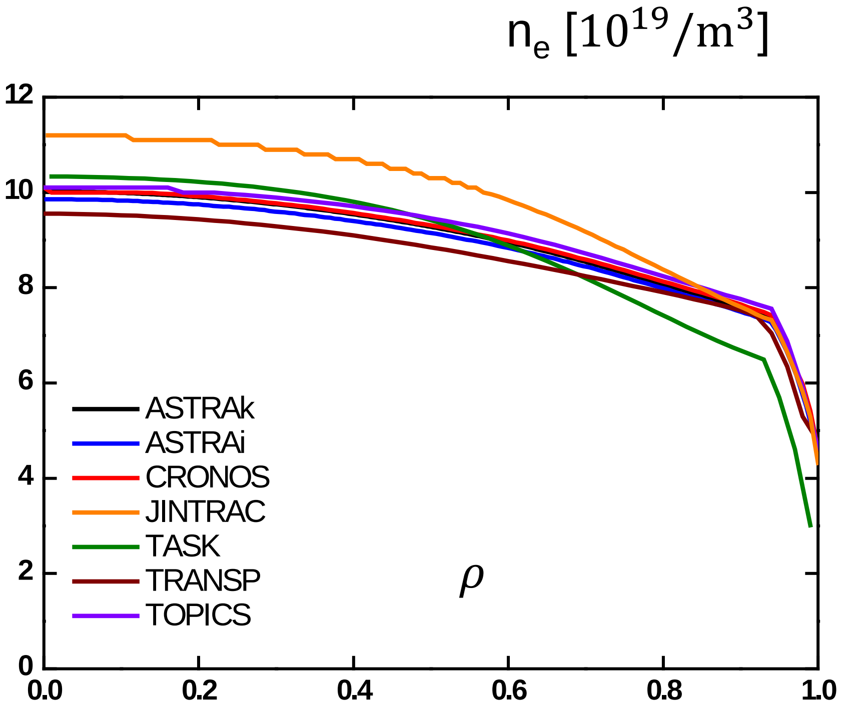
Additional pinch terms to accommodate for differences between solutions obtained with electron vs. ion particle transport equations in case of different impurity density profile shape:

$$\mathrm{v}_i=\mathrm{v}_{inp}+\mathrm{v}_{inp}\frac{n_e-n_i}{n_i}-\frac{D_{inp}}{n_i}\left(\frac{\partial n_e}{\partial\rho}-\frac{\partial n_i}{\partial\rho}\right)\frac{\left\langle(\nabla\rho)^2\right\rangle}{\left\langle|\nabla\rho|\right\rangle},\quad n_i=n_D+n_T$$

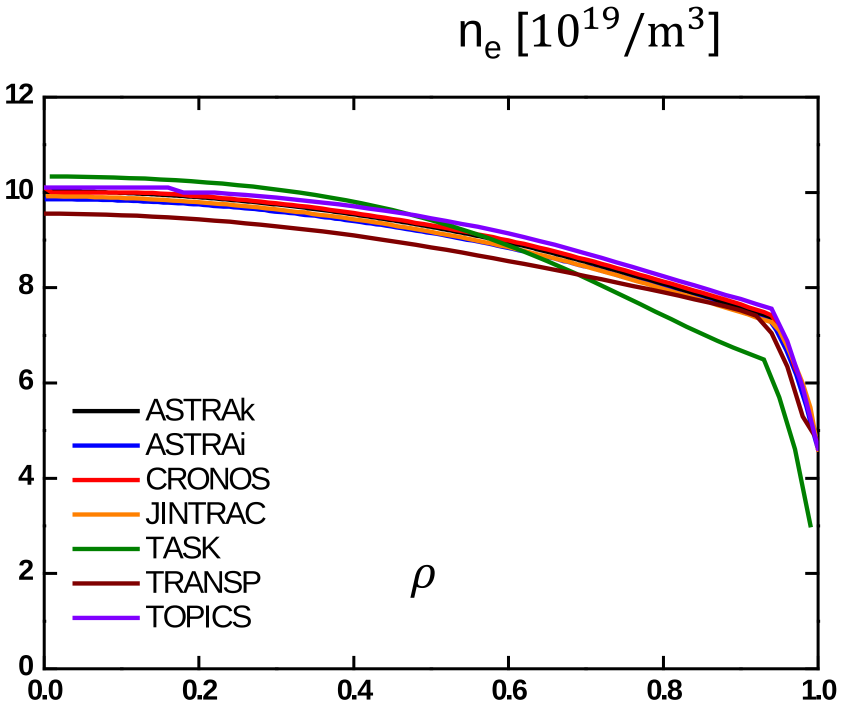
That way, the electron flux that would be obtained with an electron transport equation with fixed impurities can be calculated with the ion particle transport equations.

- The boundary condition of main ion densities at the separatrix has been adjusted in order to match $n_e(a) = 4.6\text{x}10^{19}\ /\text{m}^3$.

Some codes solve ion transport



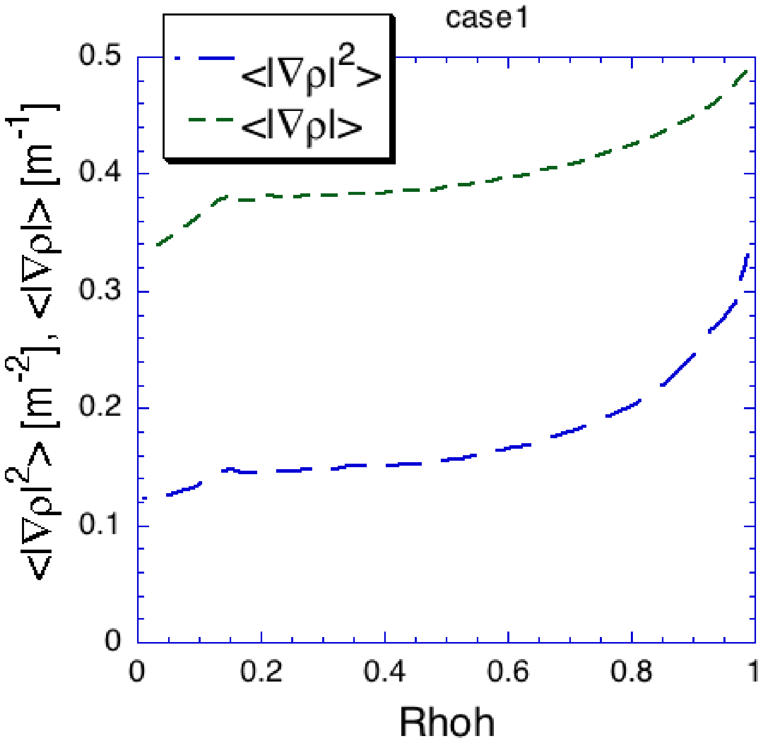
JINTRAC without correction



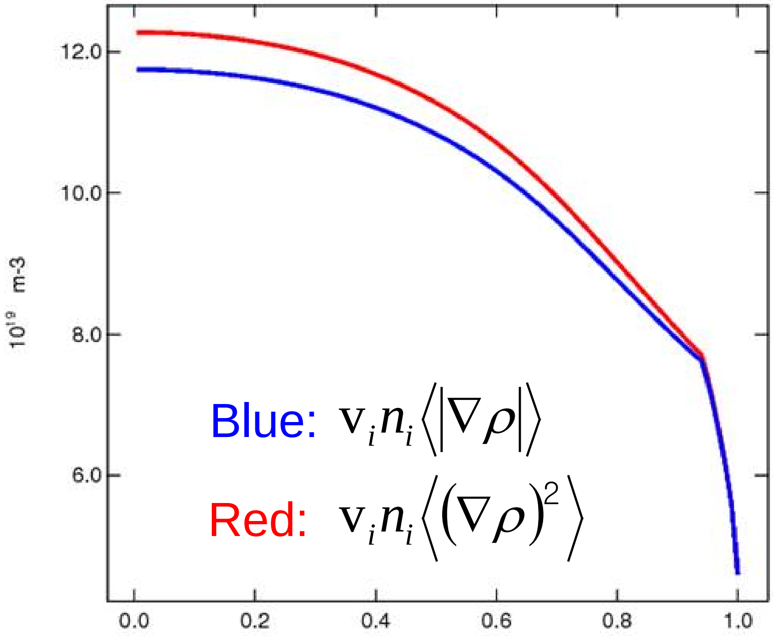
JINTRAC with correction

Effect of $\langle(\nabla\rho)^2\rangle$ .vs. $\langle|\nabla\rho|\rangle$ in pinch term

$$\Gamma_i = -D_i \frac{\partial n_i}{\partial \rho}\left\langle(\nabla\rho)^2\right\rangle + \mathrm{v}_i n_i \left\langle|\nabla\rho|\right\rangle$$



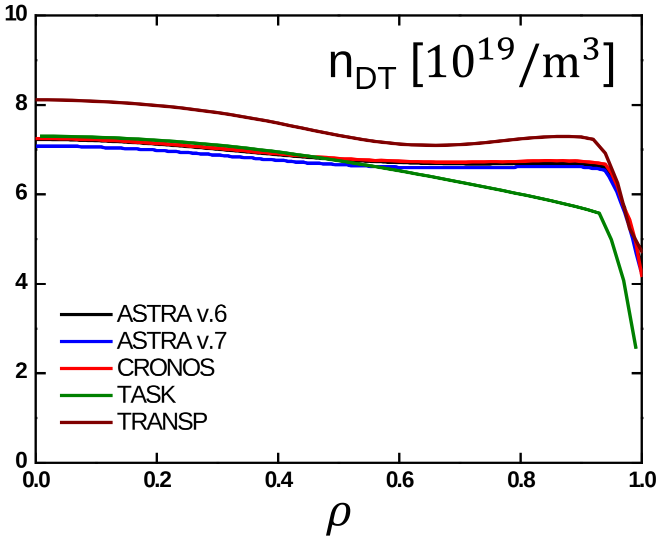
TOPICS

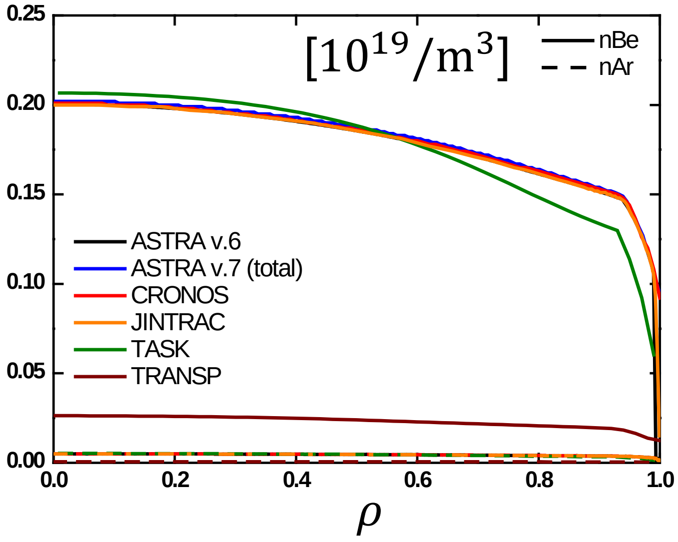


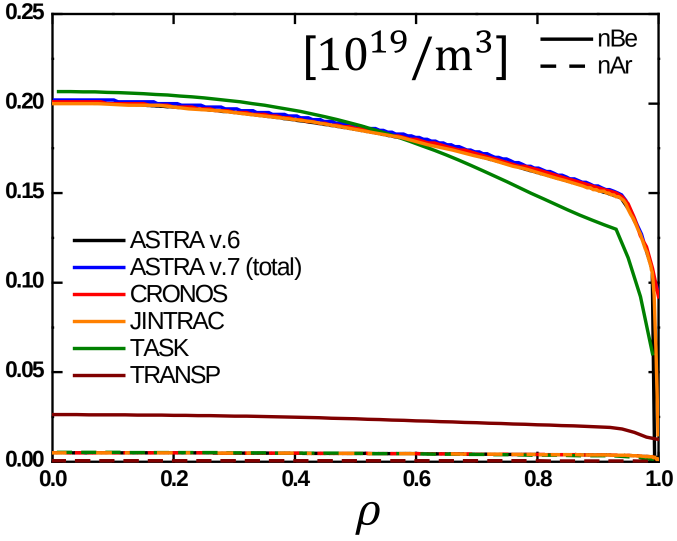
JINTRAC

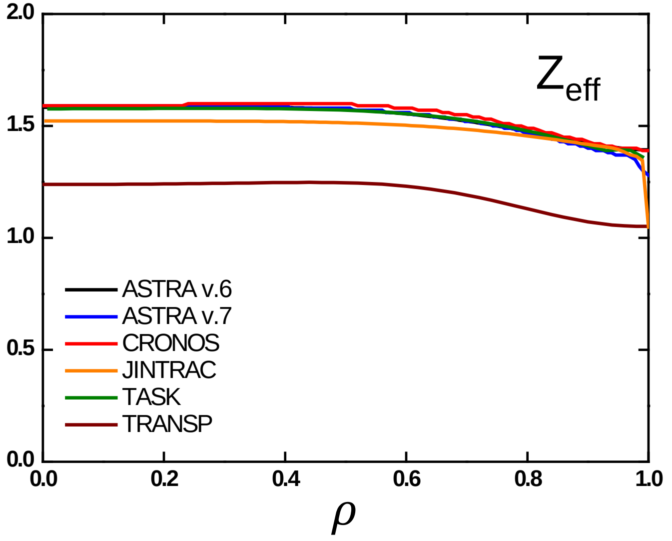
Treatment of impurities

- TRANSP solved impurity ionisation so that non-full striped impuritis (Be, Ar) are used.









Outline

- **Goal of modelling activities in ITPA IOS TG**
- **Motivation of particle transport benchmarking**
- **Overview of particle transport benchmarking activity**
  - Benchmarking guideline
  - Participating 1.5-D transport codes and modellers
- **First results of particle transport benchmarking**
- **Discussion**
- **Next-step work**

Steps in benchmarking

STEP 1: Benchmarking of particle transport solvers with prescribed transport coefficients and sources at one time point in the current flattop

Purpose: to ensure agreement among particle transport solvers

STEP 2: Benchmarking of particle sources & sinks with prescribed transport coefficients at one time point in the current flattop

Purpose: to compare source & sink models

STEP 3: Sensitivity scans of transport coefficients at one time point in the current flattop

Purpose: to evaluate the impact of particle transport to fusion performance

STEP 4: Benchmarking of time-evolution in whole discharge with prescribed transport coefficients and sources in time

Purpose: to evaluate the impact of particle transport to scenario evolution

STEP 5: Application of physics-based transport models

Purpose: to predict particle transport in ITER

STEP 2

STEP 2: Benchmarking of particle sources & sinks with prescribed transport coefficients at one time point in the current flattop

Purpose: to compare source & sink models

- Particle pinch verification
- Particle source verification
  - – Core source

    Pellet source: size, frequency, velocity (limits from hardware…)

    .vs

    Continuous core source: atoms/m^3/s and profile shape
  - – Edge source

    How large and how deep should edge source be in H-mode
- Edge density specification, what do we base this on?
- D and v magnitudes, target τ_p and τ_P^*, relate to τ_E
- $n_e(a)$, S_{edge}, S_{core}, D, v → solutions (uniqueness) $n_e(\Phi)$, …..
  - – Examine range from flat n_e to $n_{e0}/\overline{n}_e \leq 1.4\text{-}1.5$
- Probable usage of ITER Baseline discharges from various devices to identify particle transport terms and behaviors.

Summary

- **Goal of modelling activities in ITPA IOS TG**
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