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A Multi-Timescale approach for Fusion Power Plants Systems Codes focused on models for Fuel and Power Cycles

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Abstract

Systems Codes (SCs) are fundamental tools in Fusion research that allow for parameter space exploration and technology integration evaluation through parametric studies that may identify relevant systemic dependencies in Fusion Power Plants (FPPs). However, current state-of-the-art SCs model each plant system operating within its own inherent timescale and neglect the dynamic interdependence between them at a power plant level. To fill out this gap, a novel Multi-Timescale approach for SCs has been applied to an EU-DEMO model built in MIRA, a multi-fidelity SC developed at the Karlsruhe Institute of Technology.

Preliminary assessment identifies three timescales in which most FPP systems are categorized: (a) the Operation of a FPP (a collection of pulses), (b) a single reactor Pulse and (c) the characteristic time in which Plasma dynamics evolve. To couple these timescales, a set of mathematical models that depict essential phenomena at a systems-level and allow inter-coupling (i.e. SC modules) have been developed for systems identified as main contributors of each timescale.

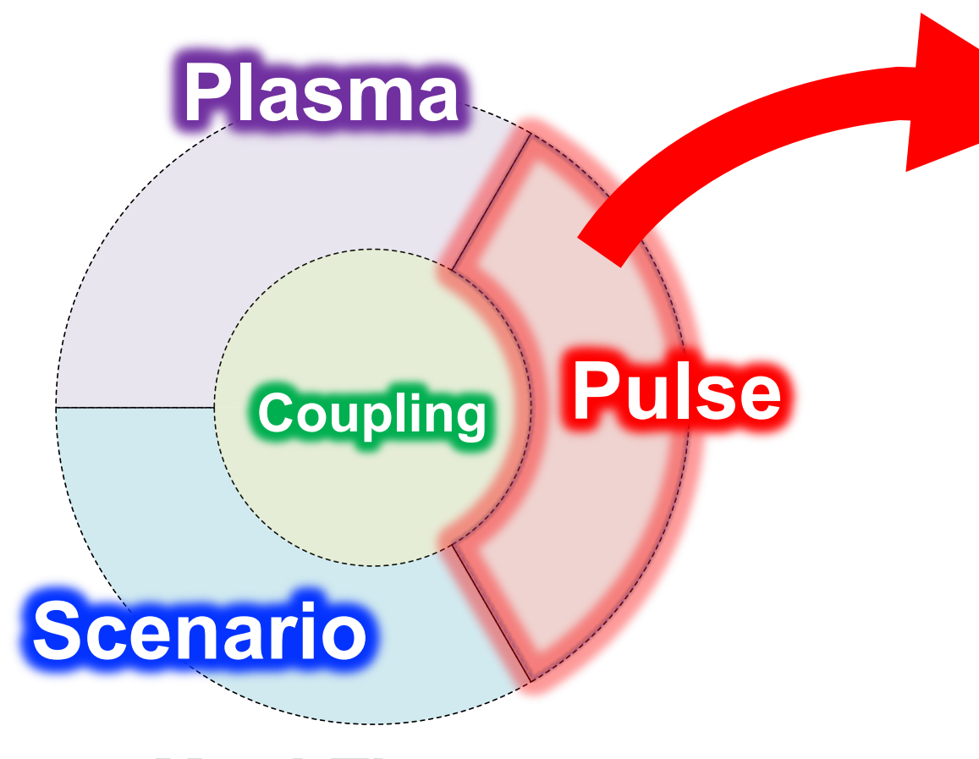
To represent (a), a multi-species Fuel Cycle (FC) module is implemented with a physics-generic 0D mass balance that computes fuel accumulation rates using a residence-times (τ) model, with τ-parameters derived from the characterization of selected technologies. To represent (b), a Power Cycle (PC) module is implemented with a physics-specific 0D mass/power balance that computes the net power production by the Balance-of-Plant systems using thermodynamic models. To represent (c), SOL plasma dynamics are estimated with scaling laws and an optimized surrogate of the code TOKES, to assess heat and particle distributions along the reactor chamber wall. Results from (c) are used to calculate transient outgassing fluxes during dwell-time with the double-diffusion code TESSIM, which consistently couples all timescales through the reactor pump-down time and its impact on the dynamics of both (a) and (b).

Keywords: DEMO, Fuel Cycle, Systems-Codes, Nuclear Fusion Technology

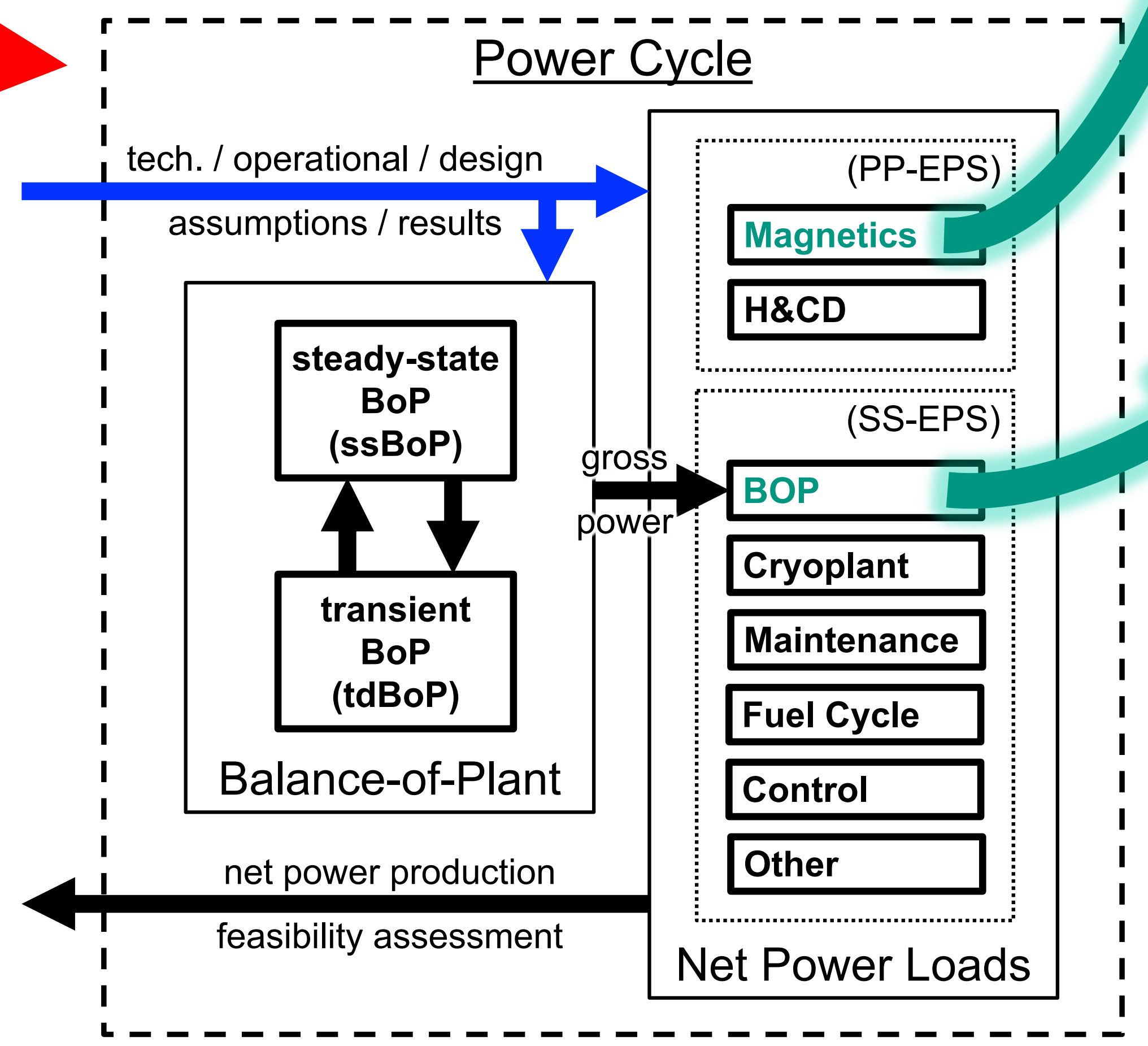
Objectives

- ❑ **Challenge** – current major systems-codes only estimate net power production with steady-state 0D power balances, which do not account for the impact of transients on the energy directed to the Power Conversion System nor to many plant design parameters [1,2].
- ❑ **Goal** – develop a time-dependent, thermodynamically-consistent and flexible simulation tool to be used by systems-code like MIRA and BLUEMIRA to characterize the net power production during a fusion power plant pulse and assess technology feasibility.
- ❑ **Strategy** – develop a Power Cycle (PC) module with two sub-modules:
  - Balance-of-Plant (BOP), to compute gross power production;
  - Net Power Loads (NET), to compute net power production.
- ❑ **Methodology** – develop simplified (quick) models and compare performance to commercial codes used to design the HCBP PC (indirect ESS, EU-DEMO 2017):
  - (full pulse) transient description of Coil Power Supply: PowerFactory;
  - (flat-top & dwell phases) steady-state description of BOP: EBSILON [3];
  - (flat-2-dwell – dwell-2-flat phases) transient description of BOP: APROS [4].

Power Cycle (PC) Module Architecture

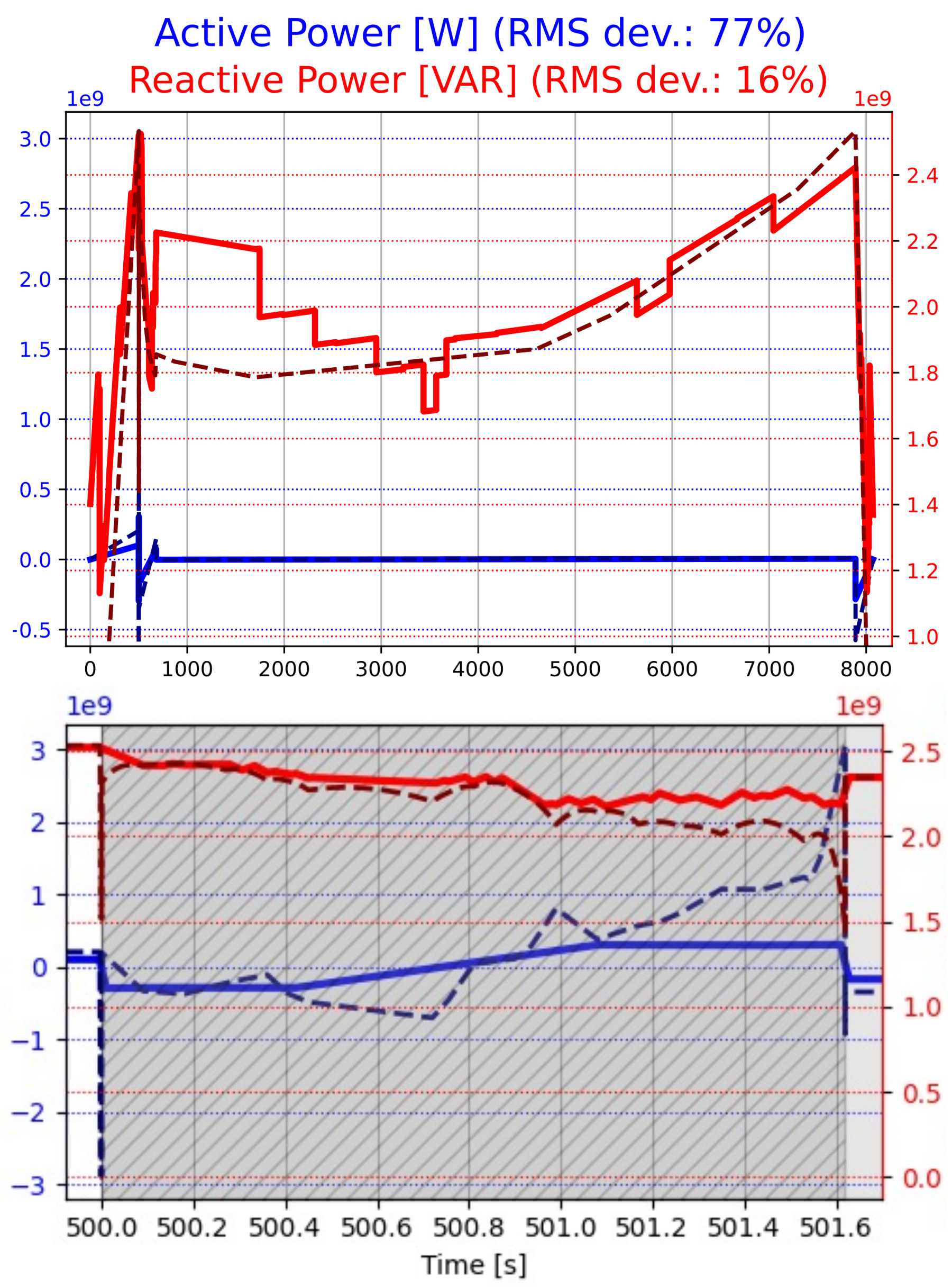


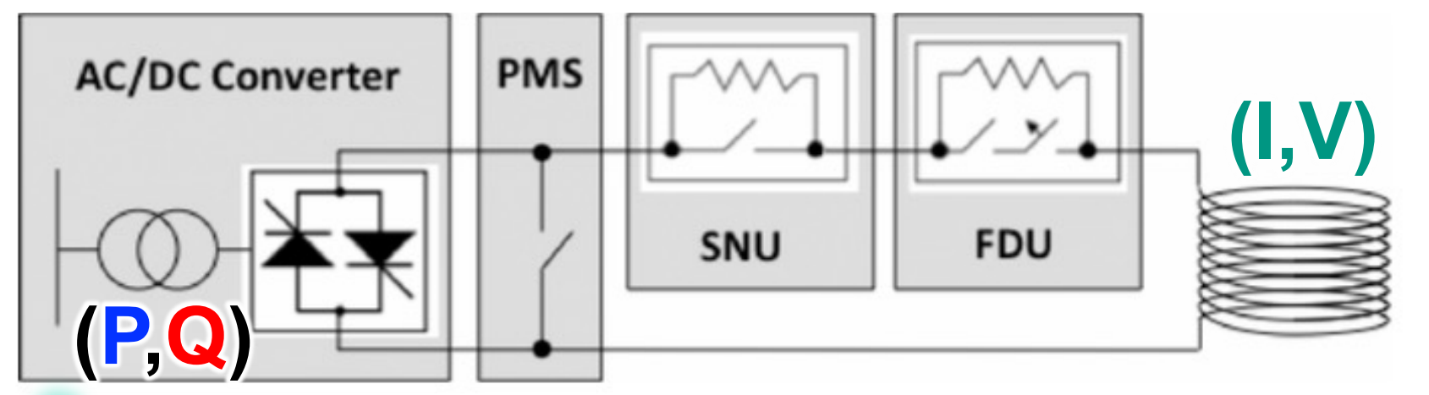
Multi-Timescale Systems-Code Strategy



- ❑ Phenomena in the pulse timescale are represented by the Power Cycle.
- ❑ Model main effects of each system, *e.g.*:
  - BOP thermodynamics
  - MAG power electronics
  - …

Magnetics (MAG) Model & Validation



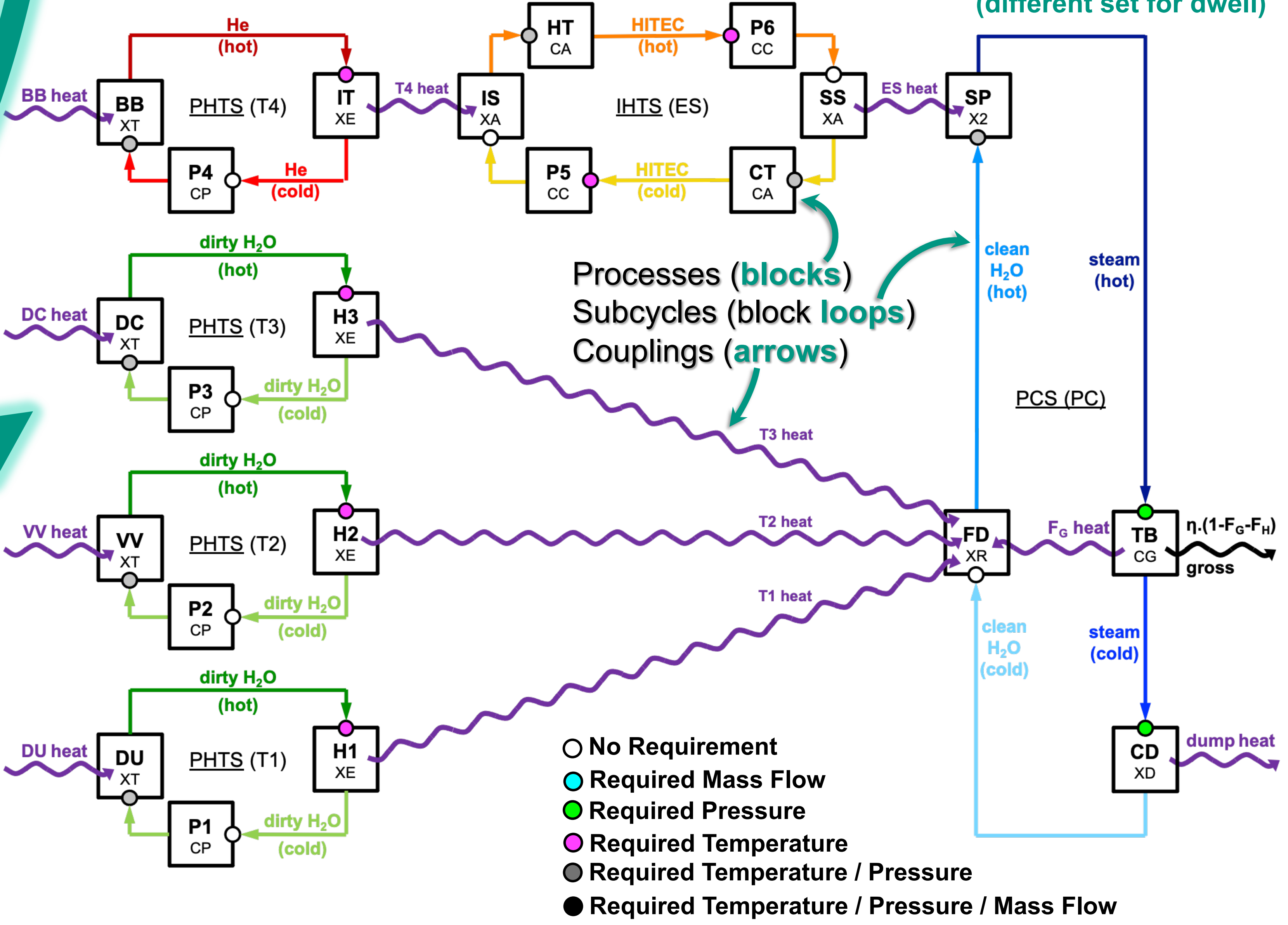


- ❑ Estimate **active (P) and reactive (Q)** power loads required by the Coil Power Supply System (thyristors).
- ❑ Inputs: currents (I) and voltages (V) from **magnetic equilibrium** model.
- ❑ Model:

$$N_b = ceil\left({}^{max(V)}/_{V_b}\right)$$
$$R_V = V_b \cdot N_b$$
$$\varphi_p = \cos^{-1}\left({}^{V}/_{R_V}\right)$$
$$P = \left(R_V \cdot I \ \cdot \cos(\varphi_p)\right) \cdot \prod_i (1 + L_i)$$
$$Q = \left|R_V \cdot I \ \cdot \sin(\varphi_p)\right|$$

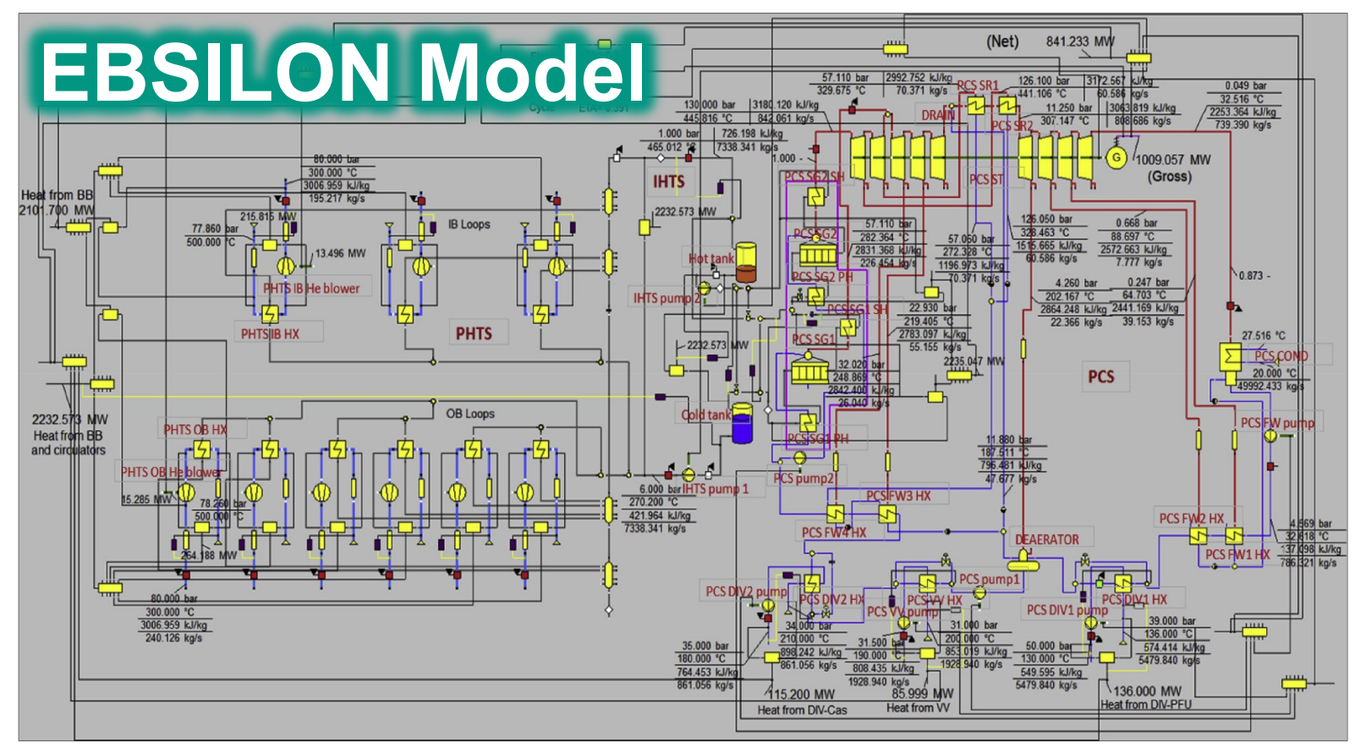
- ❑ **Technology** params.: thyristor bridge voltage (V_b), loss factors (L_i) *e.g.* transformer and busbars, …
- ❑ Comparison against dedicated code show high **deviation** (dev):
  - outside range [start of breakdown; end of flat-top], due to neglected circulating current mode (*e.g.* $Q(0) = 0$) ⟹ dev is only calculated in range;
  - when expected value ~0, (*e.g.* $dev(P) \gg dev(Q)$) ⟹ dev must be assessed piecewise.
- ❑ Model neglects Control Engineering strategies/electronics, but estimates are obtained **quicker** (~s) than with dedicated code (~day).

Balance-of-Plant (BOP) Model



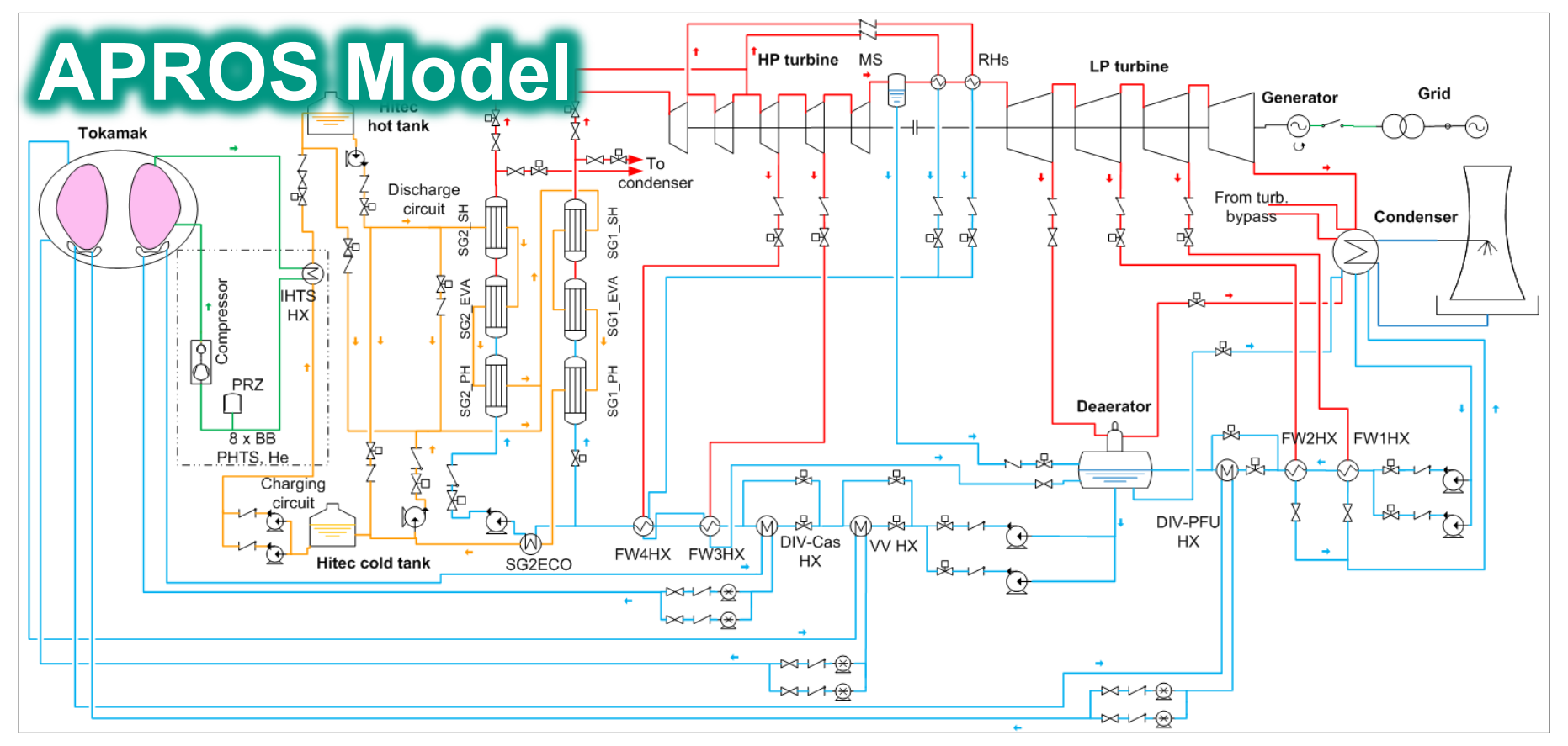
Balance-of-Plant (BOP) Validation

ssBOP x EBSILON



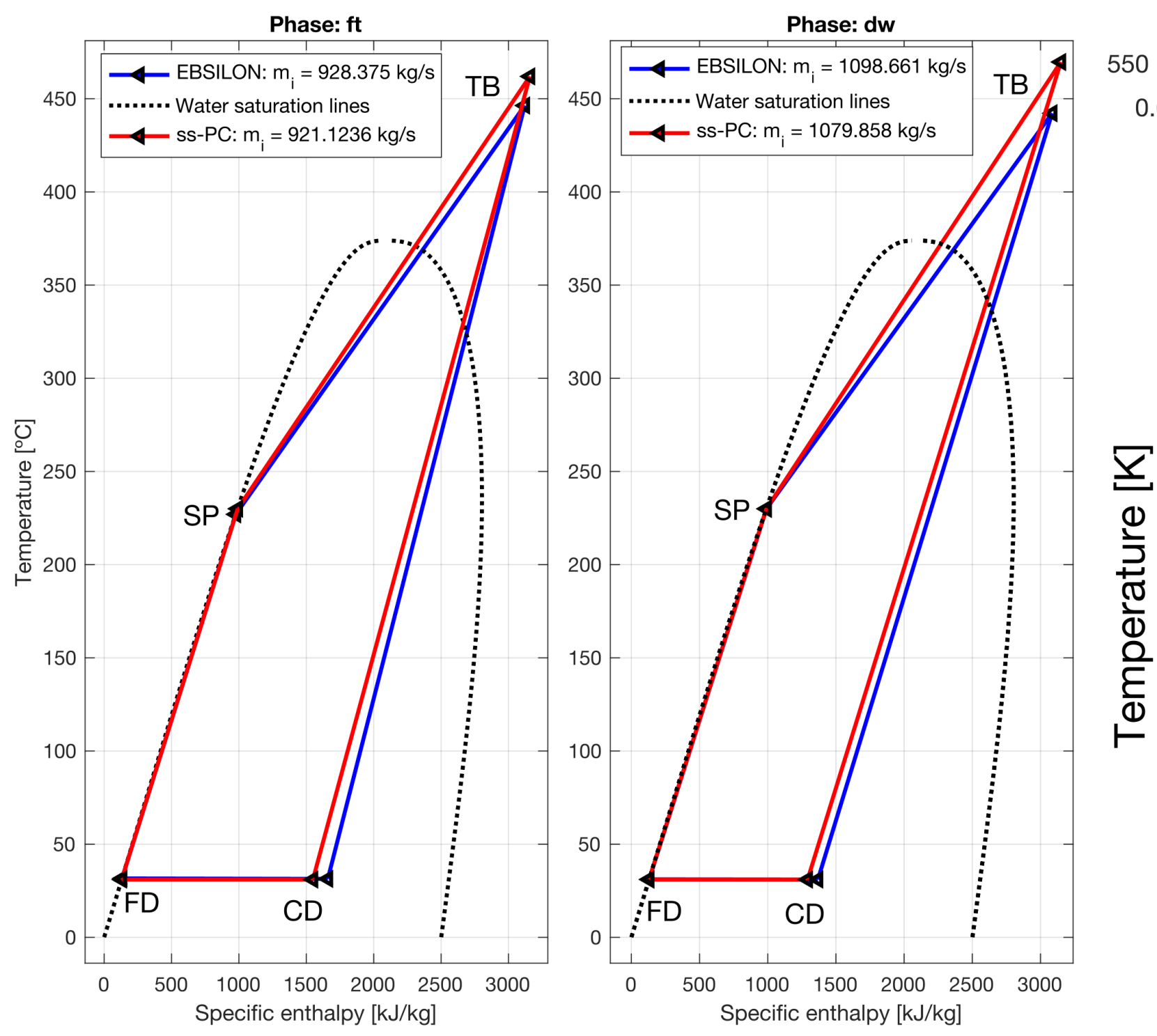
Courtesy of E. Bubelis [3].

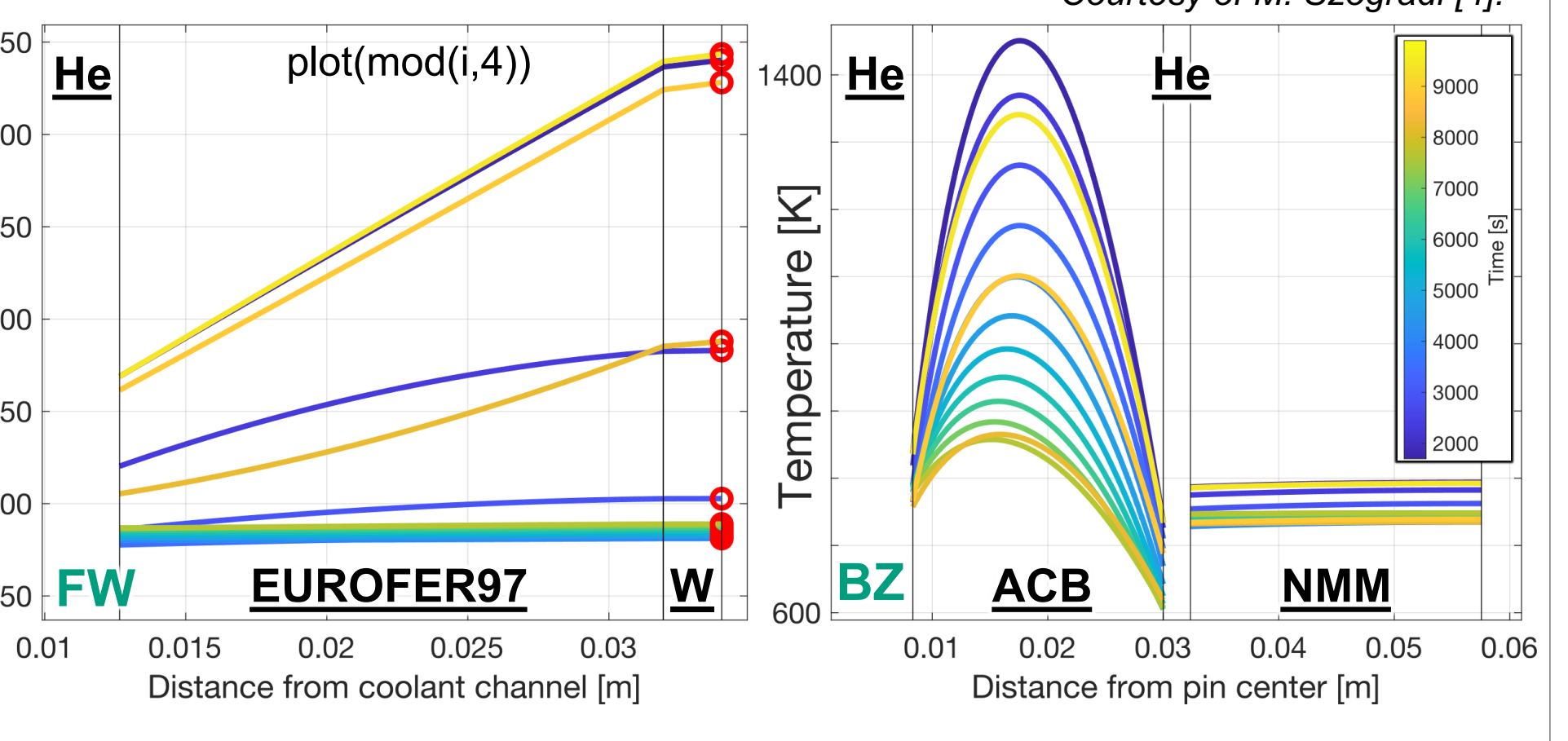
ttBOP x APROS

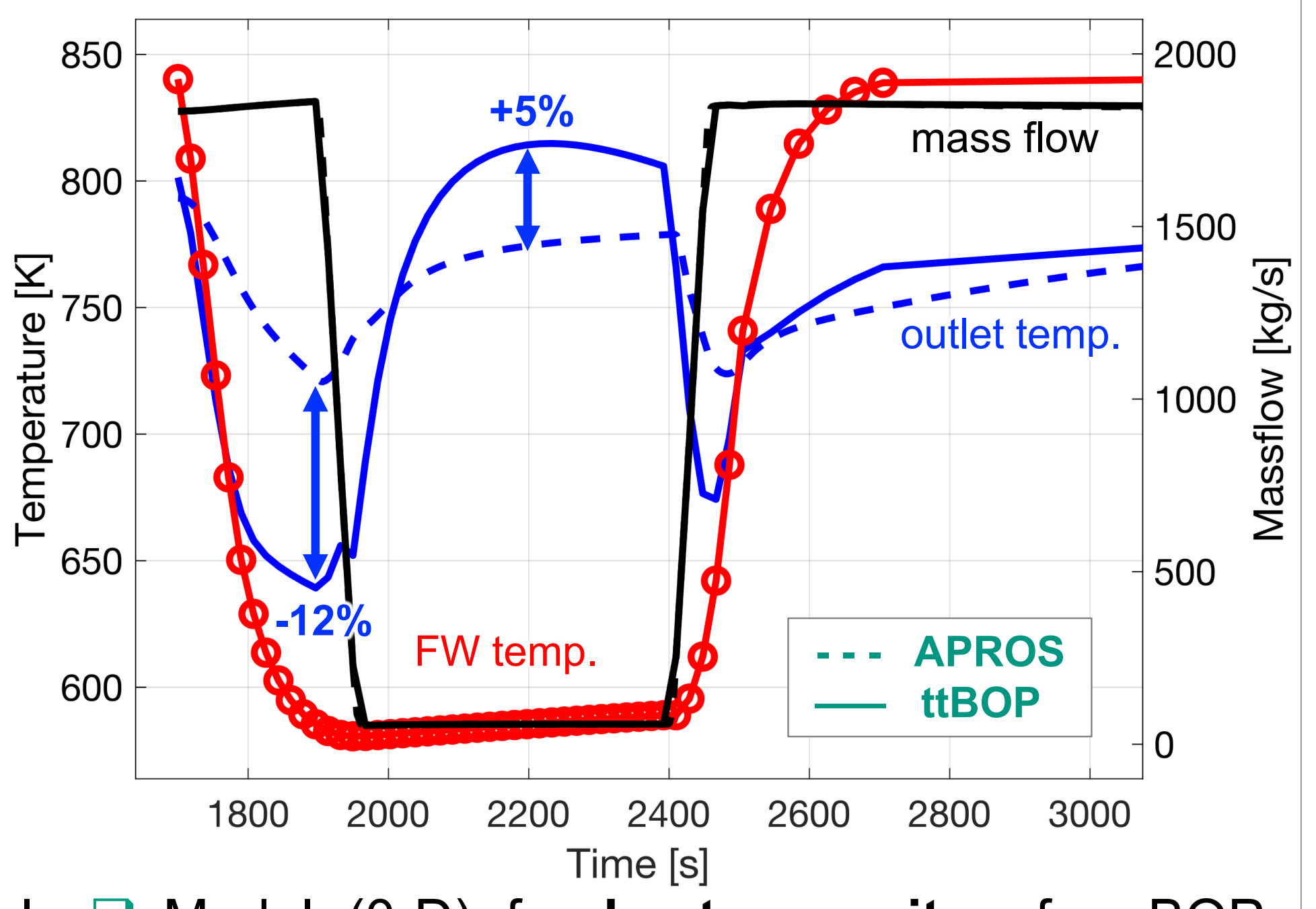


Courtesy of M. Szogradi [4].

Flat-Top Property	EBSILON	ssBOP	dev. (%)
HCPB He Flow [kg/s]	1841.774	1838.248	0.19
HCPB Pump Power Consumption [MW]	87.954	87.111	0.96
PCS Water Flow [kg/s]	928.375	921.124	0.78
Gross Electrical Power Production [MW]	892.511	871.721	2.33







- ❑ Identifies/models main thermodynamical processes in BOP with minimal set of design parameters for **characterization**:
  - coolant mass flows to remove heats;
  - pump powers for each Subcycle pressure drop, estimated with Darcy-like factors ($f_p \propto \dot{m}^{-2}$);
  - HITEC® mass flows dependent on the heat transfer to the PCS (direct & indirect);
  - Turbine model (Rankine) estimates steam flow fractions for regenerative and reheat processes.
- ❑ Resulting **state tables** are fully consistent in and between pulse phases, show low deviation and can produce simple thermodynamical cycle diagrams.

- ❑ Model (0-D) for **heat capacity** of a BOP process by iteratively computing, for each time step (i): heat distribution (surf., volume, material), thermo-hydraulics (Nusselt), and steady-state thermal profiles (T_i^{SS}).
- ❑ Approximates transient by **mixing profiles (temp. & flux)** using Green function for heat diffusion equation ($t^{-\frac{1}{2}} \cdot \exp\left(\frac{-x^2}{4\alpha t}\right)$) and the Fourier number for the time delta (Fo_i) to compute a time-reversal gauge (g_i):

$$g_i = {Fo_i}^{-1/2} \cdot e^{\left(1-{Fo_i}^{-1}\right)}$$
$$T_i(x) = T_{i-1} \cdot (1 - g_i) + T_i^{SS} \cdot g_i$$

- ❑ Model for BB heat capacity overestimates **outlet temperature** drop (-12%) and rise ($+5\%$); but are quickly obtained (~2min) and cumulative deviation is limited (-1.5%).

Conclusions & Outlook

https://bwsyncandshare.kit.edu/s/r7oDXP85GPxb3jH (Suppl.)

- ❑ Models developed for systems codes show **satisfactory performance**:
  - **MAG:** good computational cost and acceptable deviation (given model goal);
  - **ssBOP:** negligible deviation against EBSILON implies favourable modelling approach;
  - **ttBOP:** instantaneous deviation against APROS implies approach might not be able to assess process design feasibility (*e.g.* operational temperature ranges for materials), but does not hinder the goal of net power studies (low cumulative deviation ⟹ negligible impact to BOP) or *e.g.* L-H transition studies.
- ❑ **Future work**:
  1. **MAG:** implement routines to emulate control strategies (*e.g.* circulating current mode);
  2. **ttBOP:** overestimation perhaps due to stiffness ⟹ test other solvers;
  3. **PC:** couple BB heat capacity to ssBOP model to estimate transient net power;
  4. **MIRA:** couple BB heat capacity to FW hydrogen diffusion model to estimate outgassing.

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