Validation of the Fenix ASDEX Upgrade flight simulator

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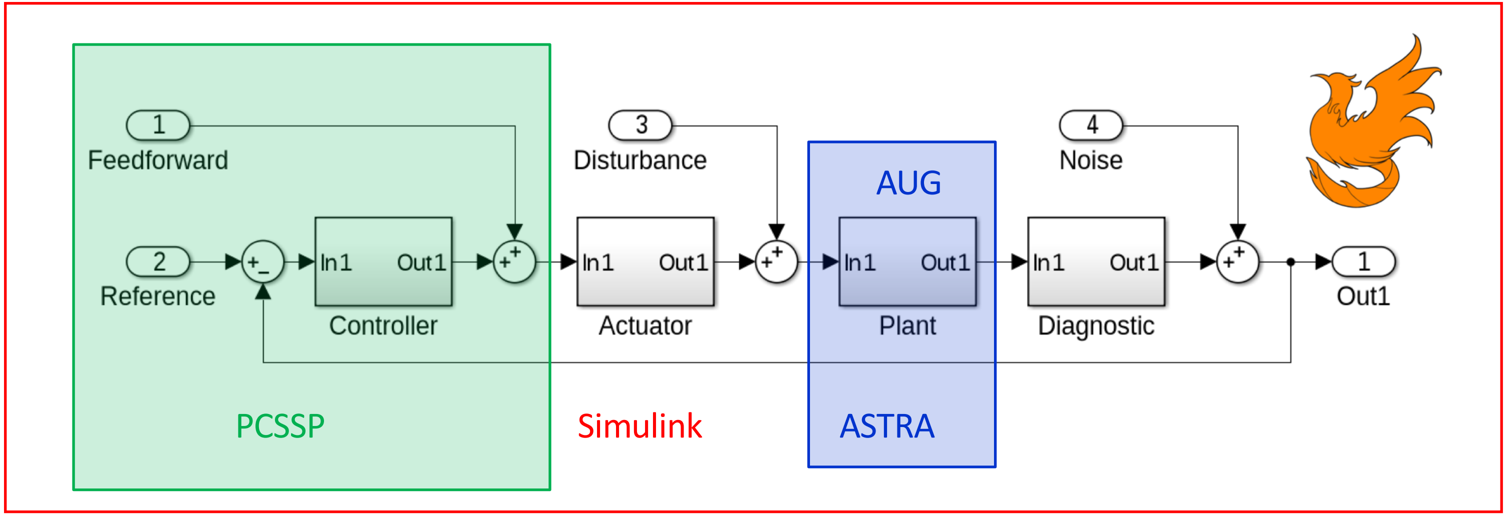
Motivation

- **Increase of confidence before the discharge**
  - Prepare and test experimental scenarios
  - Check whether the Pulse Schedule (PS) meets the experimental goals and for errors
  - Check whether all the parameters and reference waveforms are consistent with the experimental program
  - Fast simulation with simplified models

- **Faster and more robust development, testing and validation**
  - Design and develop the control system
    - Simplified control oriented physics models
    - Optionally simulate with detailed physics models
  - *Benchmark physical models against experiments*

Simulation framework



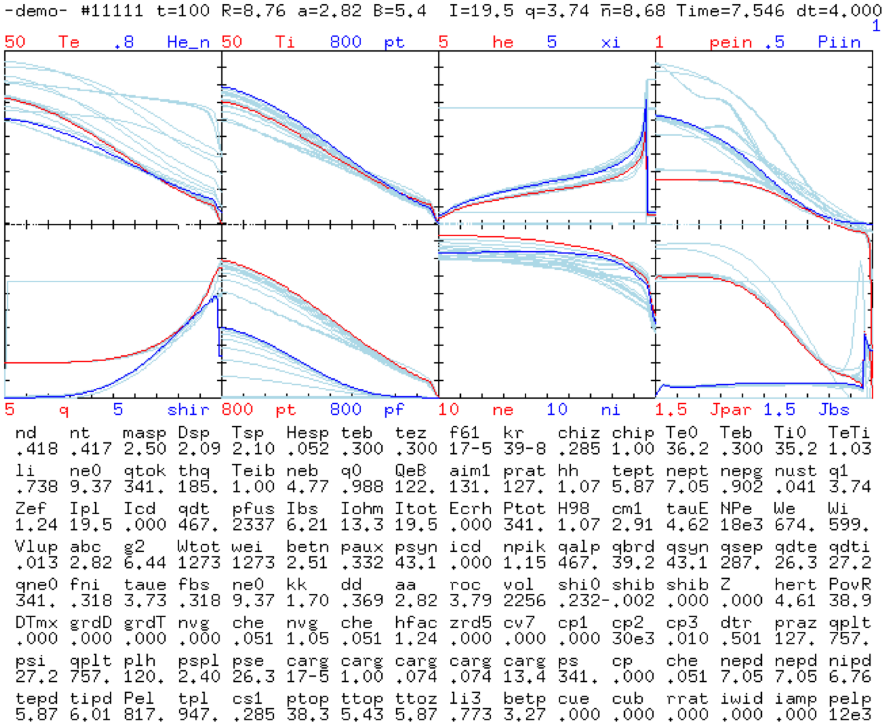
Plasma Control System Simulation Platform - (PCSSP)

- Framework developed within Simulink for ITER tokamak with control system based on AUG control system architecture
- Waveforms for the references and for pre-programmed trajectories
- Events generators
- Easily adaptable for different machines (currently ITER, DEMO, AUG as Fenix)

Tools

ASTRA [1]

- 1-D transport code with 2-D MHD equilibrium solver (SPIDER)[2]
- Serves as a plasma model



[1] G. V. Pereverzev and Yu. P. Zushmanov, IPP 5/98 **2002**

[1] E. Fable, et al., **2013**, Plasma Phys. Control. Fusion, 55 124028

[2] A. A. Ivanov and S. Yu Medvedev, EPS 2005]

Physics: core

- Core transport model: semi-empirical model fitted to the present experiment (ASDEX Upgrade - AUG)

  [M. Erba *et al* 1998 *Nucl. Fusion* **38** 1013]

$$\chi \propto q^2 \frac{T_e^{1.5}}{B_t^2\, a^2} \frac{a}{L_p} + \chi_{neo}; \qquad L_p = \left| \frac{\partial p}{p\, \partial r} \right|^{-1}$$

- L-H/H-L model with no hysteresis based on $P_{sep,i} > P_{LH} / 2$

  [*Martin Y.R. et al., 2008 J. Phys.: Conf. Ser.* ***123*** *012033]*

$$P_{LH} = 1.53\ B_t^{0.78}\ R^{1.75}\ (a/R)^{0.57}\ (n20)^{0.66}$$

- Sawtooth model - complete reconnection if magnetic shear $s > s_{crit}$
- Pedestal model – ion neoclassical transport for $T_{i,e}$, $n_{i,e}$; pedestal top pressure saturates according to EPED scaling $\sim \beta_N^{0.43}$

  [E. Fable et al., FED, 2018] (e.g. QH-mode)

- NBI heating model RABBIT

  [M . Weiland, NF 2018]

- NTM model based on the Rutherford equation

Physics: edge

- SOL/div 0-D particle balance model for main fuel and impurity seeding

$$\frac{dN_j^{sol}}{dt} = \Gamma_j^{plasma} - \Gamma_j^{wall} + \Gamma_j^{\text{mid-plane puff}} - D_j(N_j^{sol} \cdot \epsilon_j - N_j^{div})$$
$$\frac{dN_j^{div}}{dt} = \Gamma_j^{\text{divpuff}} - \Gamma_j^{pump} + D_j(N_j^{sol} \cdot \epsilon_j - N_j^{div})$$

Enrichment factor ϵ_j – N 20, Ar 20, W 6;

– D_j – SOL/div time scale = 0.01 [s^{-1}]

- SOL/div analytical exhaust model "c" fit to 1-D model [*] – in practice

$$T_{div} \propto \frac{P_{sep} B_t}{q\ A\ R} \cdot \arctan\left(c \cdot y^{16}\right); \quad y = \frac{P_{sep} B_t}{q\ A\ R\ N_e^{sep} N_{Ar}^{div}}$$

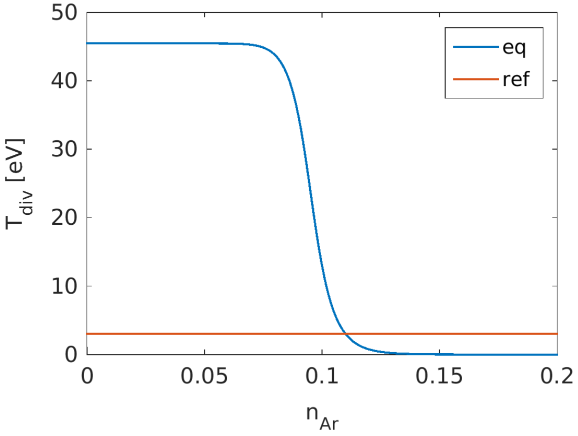
– W flux model:

$$\Gamma_W \propto \sqrt{max(0, T_{div} - 5)} \sum_j n_j^{div} m_j\ (1 - f_r); \quad f_r = 0.95$$

f_r – redeposition factor; *j* - species

[*] M. Siccinio, et al., **2016**, Plasma Phys. Control. Fusion, 58, 125011

Physics: edge



for main fuel and impurity seeding

$$ma - \Gamma_j^{wall} + \Gamma_j^{\text{mid-plane puff}} - D_j(N_j^{sol} \cdot \epsilon_j - N_j^{div})$$

$$\text{uff} - \Gamma_j^{pump} + D_j(N_j^{sol} \cdot \epsilon_j - N_j^{div})$$

W 6;

s^{-1}]

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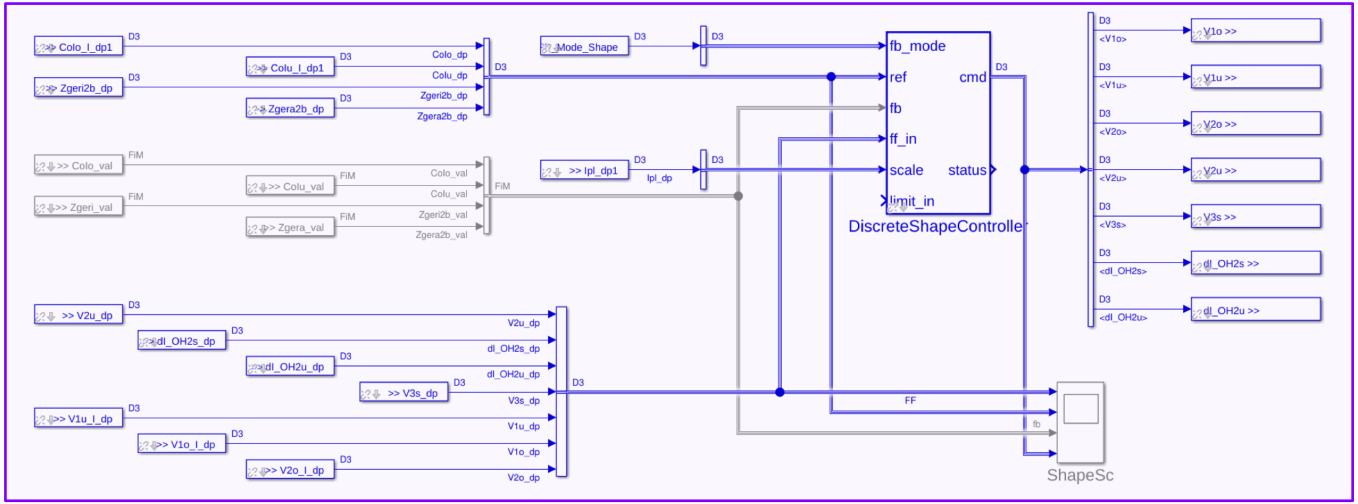
Diagnostics

- **Diagnostics computed by ASTRA and SPIDER**
  - Magnetics
    - Plasma current, equilibrium, coil currents
  - Electron density profile, line averaged density according to interferometric Line of Sights (LOS)
  - Electron temperature profile
  - Radiated power (core)
  - W_{MHD} (diamagnetic measurement) – volume integrals of $n_{e,i}$ and $T_{e,i}$ profiles
  - Divertor temperature
  - β – poloidal, li - (internal inductance)

Tools

Simulink

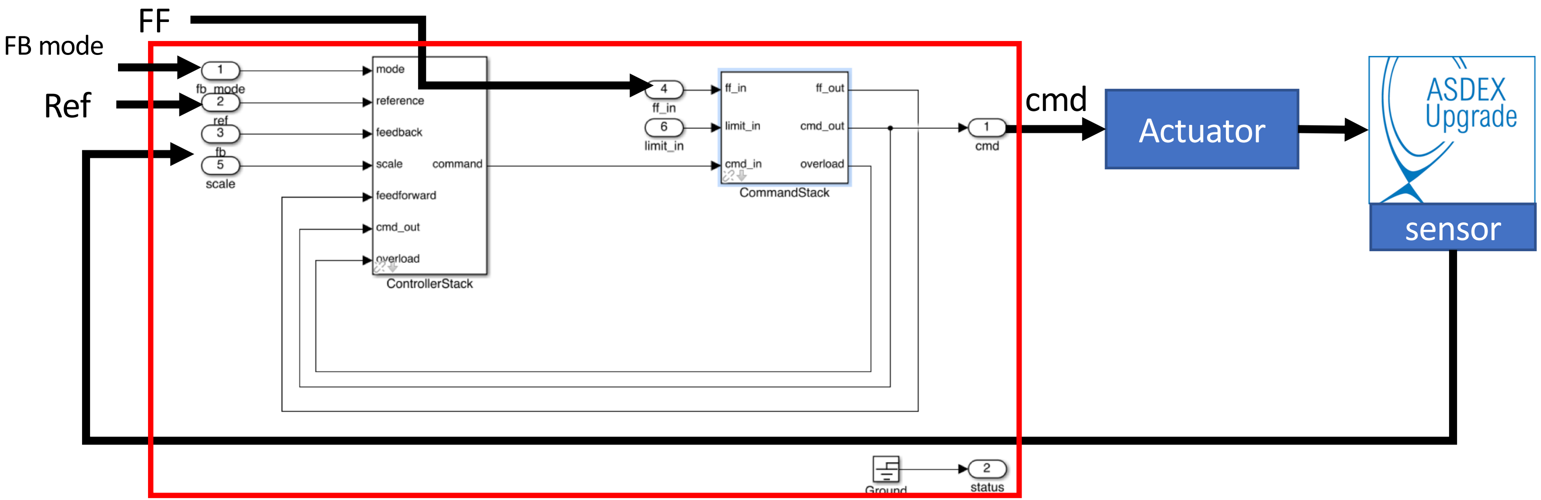
- Commercial tool for simulation purposes
- Provides environment to simulate different physics and control oriented tasks with a graphical user interface
- Simulates the control system, diagnostics and actuators



Control architecture: DCS Controller

The controller is composed of two main components:

- ControllerStack: selection of different control modes
  - Feedforward in all the control modes
- CommandStack: configures different commands and their limits



Control models

- **Implemented**
  - Plasma position control (R,z)
  - Plasma current control (I_{pl})
  - Plasma shape control (strike points positions)
  - Electron density control
    - Gas valve: line average density
    - pellets: line average density
  - β_{pol} : in both H or L mode scenarios

- **In development**
  - Neoclassical tearing mode (NTM) control
  - Radiation control – divertor, separatrix power
  - Error field control – "need for a reduced 2-D model"
  - ECRH control (power and mirror position)
    - (O. Kudlacek P.558, B. Sieglin O. 518)
  - NBI control
  - ICRH control (power and frequencies)

Actuators models

- **Implemented**
  - Power supplies model for PF coils
  - Pellet launcher
  - Gas puffing (one valve)

- **In the plan**
  - Realistic valves model with delays, gas types and gas channels
  - NBI model – currently uses only NBI1 (scales 1-8 source)
  - ECRH model (power, mirror, X/O mode)
  - ICRH model (currently not in DCS)
  - Actuator management - (O. Kudlacek P.558, B. Sieglin O.518)

Configuration

- **Implemented**
  - Reading the Pulse Schedule
  - Segments changing
    - Pre plasma phase, ramp-up and flattop, ramp-down

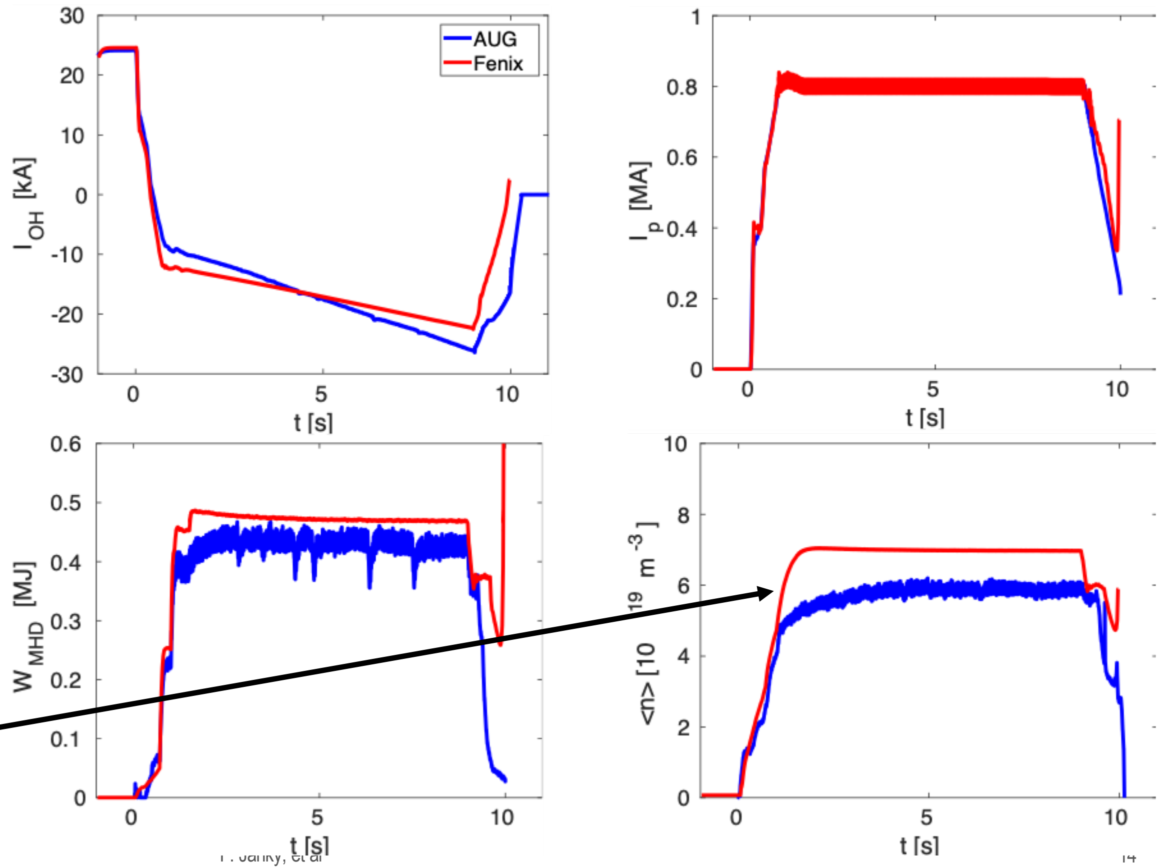
- **In the plan**
  - Automatic configuration of controllers
  - Automatic configuration command limits
  - ECRH mode, priority list
  - Gas type – gas valve connection configuration
  - Exception handling

Results #35706

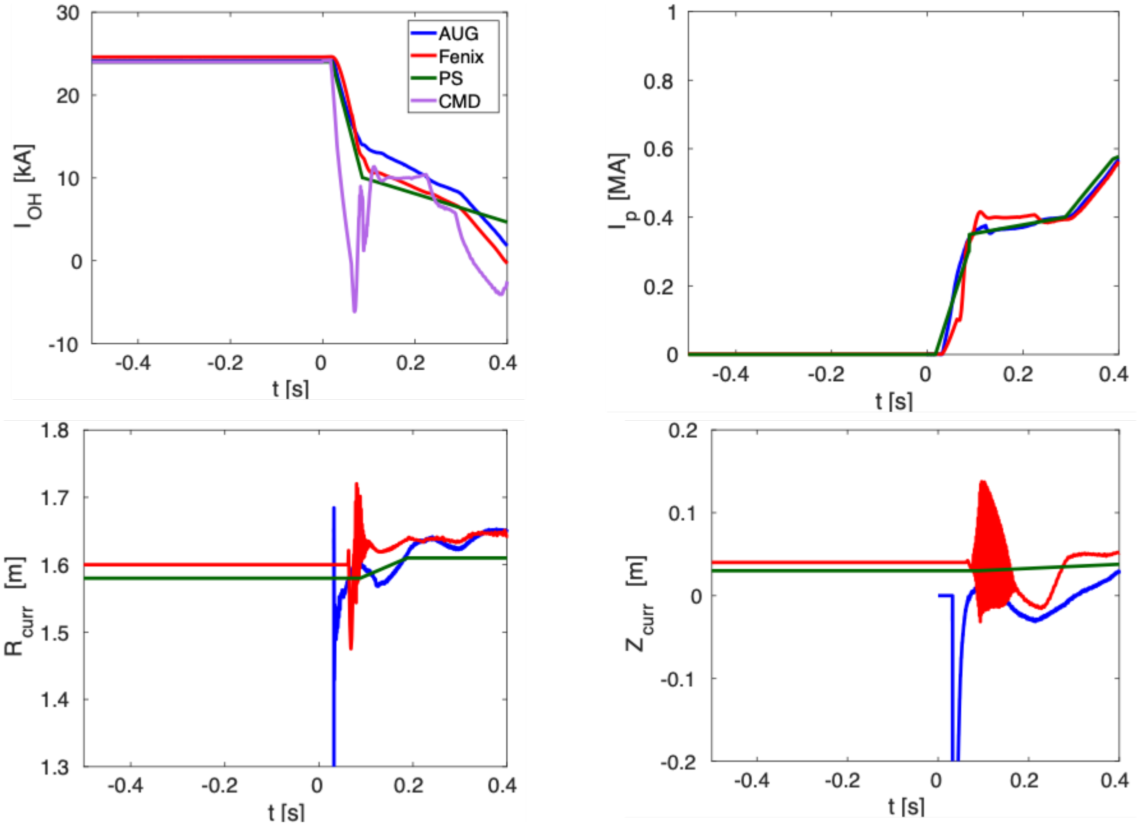
- The difference in OH current comes from the Z_{eff} assumption

- W_{MHD} too large due to assumptions based on transport

- Electron density too high - has to be check

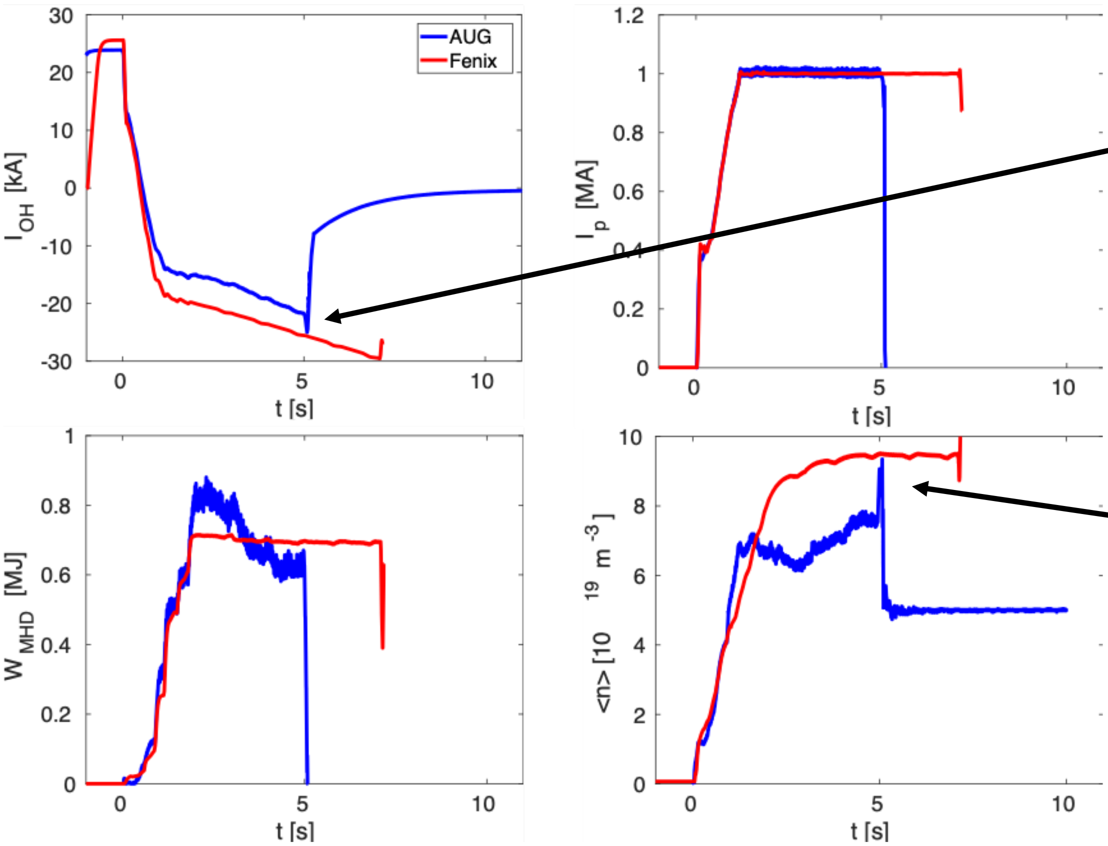


Results #35706



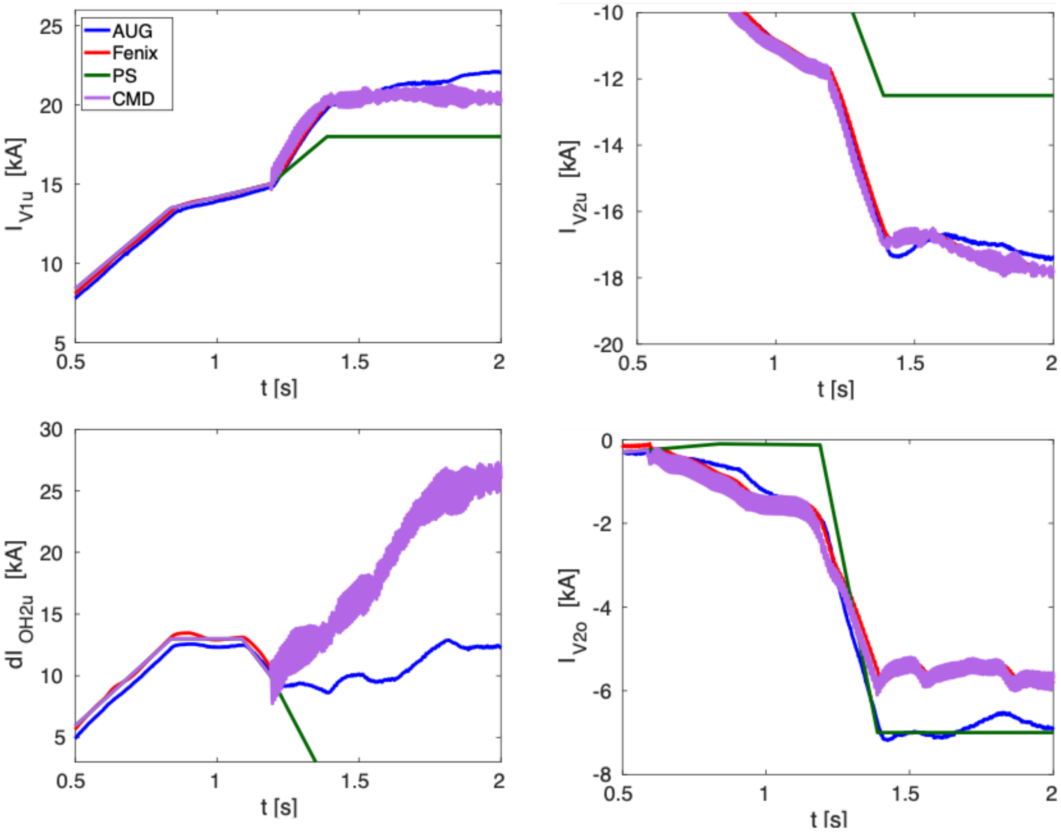
- R_{curr} and Z_{curr} oscillations at the beginning due to initialisation. It can be cured with some numerical work

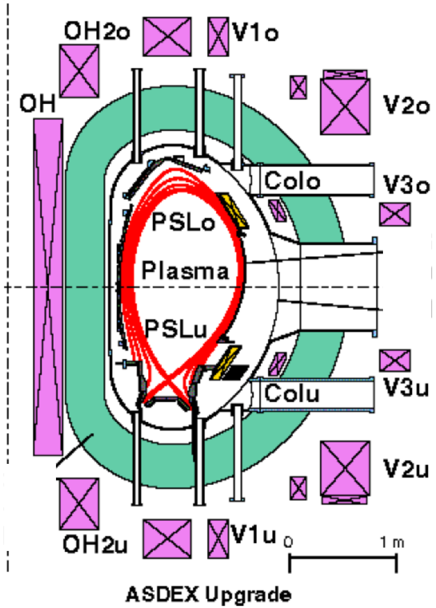
Results #33173



- Ohmic slope too large due to missing T_e barrier
- density too large

Results #33173





- dIOH2u strong deviation due to sensitivity of strike points position on X-point angle, which in turn depends on edge current

Conclusions and future work

Conclusions

- **We are simulating the entire discharge with realistic physics models and the actual Pulse Schedule!**
- **Smooth transition between segments and control modes**
- **Modularity of plasma model allows for fast development and validation**
- **The first results of Fenix implementation show**
  - 1 to 10 min per run depending on the models
- **Stores simulated data**
- **Automatic comparison with the discharge**

Future work

- **Current monitor**
- **Actuators: Gas puff system, heating systems, management**
- **Improve physic models**
- **User-friendly GUI**
- **Integration in the execution of the discharge**
- **Improve speed (without sacrificing realism)**