Development of the Fenix Tokamak Flight Simulator

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EUROfusion

Flight simulator plays a key role in EU DEMO strategy

In order to arrive at a credible DEMO design, progress in both physics and technology is needed

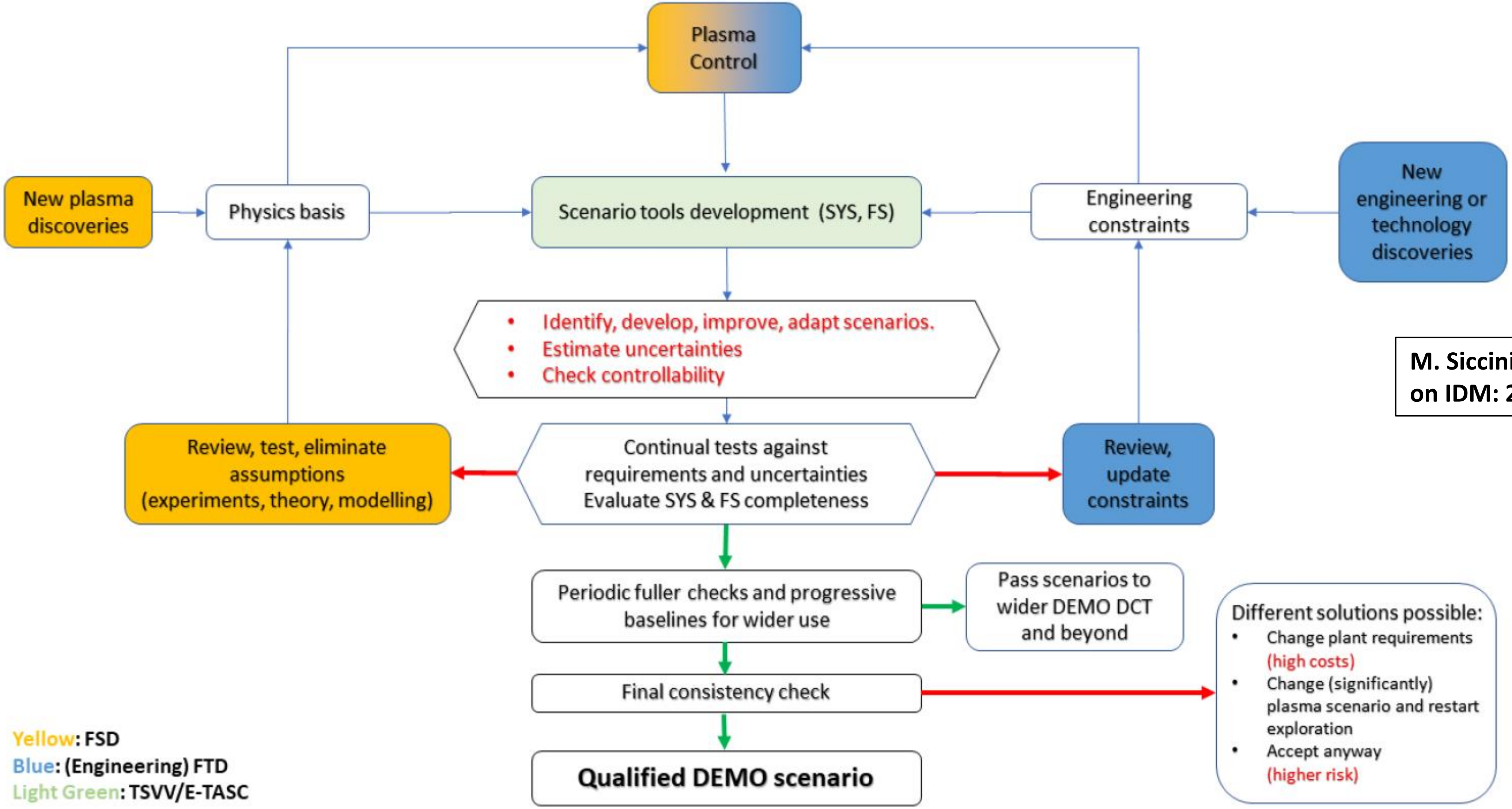
The present EUROfusion strategy for the DEMO plasma scenario is based around two tools:

- a *systems code* containing 0-D stationary models for all physics and technology elements
- a *flight simulator* linking a spatio-temporal plasma description to realistic sensors and actuators

While being used for scoping and design, these tools will be updated constantly according to progress in understanding made in theory and experiments in both physics and technology to be representative of state-of-the-art HiFi simulations (full ASTRA or JINTRAC)

Ultimate goal: flight smulator = ‚numerical tokamak‘ embedded in virtual control system

Designing a ‘qualified’ plasma scenario for DEMO



Plasma Control

New plasma discoveries

Physics basis

Scenario tools development (SYS, FS)

Engineering constraints

New engineering or technology discoveries

- Identify, develop, improve, adapt scenarios.
- Estimate uncertainties
- Check controllability

Review, test, eliminate assumptions (experiments, theory, modelling)

Continual tests against requirements and uncertainties Evaluate SYS & FS completeness

Review, update constraints

Periodic fuller checks and progressive baselines for wider use

Pass scenarios to wider DEMO DCT and beyond

Final consistency check

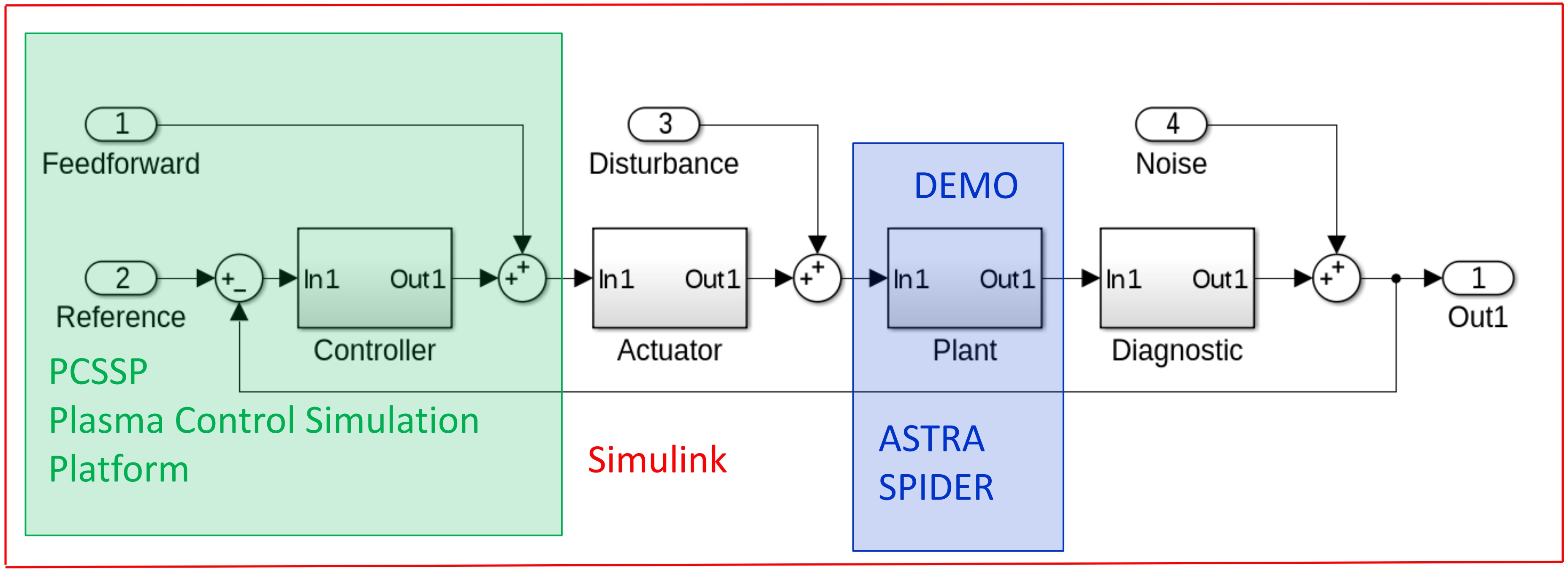
Qualified DEMO scenario

Different solutions possible:
- Change plant requirements (high costs)
- Change (significantly) plasma scenario and restart exploration
- Accept anyway (higher risk)

M. Siccinio et al., on IDM: 2PAVUS

Yellow: FSD
Blue: (Engineering) FTD
Light Green: TSVV/E-TASC

The Fenix framework



F. Janky, at SOFT 2020

- **Fenix – a tokamak flight simulator**
  - Validate discharge programs during development and before execution
  - Support design of new monitoring and control strategies – save experiment time
  - Co-simulation of ASTRA/SPIDER (with DEMO-specific reduced models) and PCSSP/Simulink (PCS, actuators, diagnostics)
  - Benefits from collaboration on Plasma Control System Simulation Platform (PCSSP)
  - Concept for multiple devices (currently AUG and DEMO)

Main Use Cases on ASDEX Upgrade / DEMO

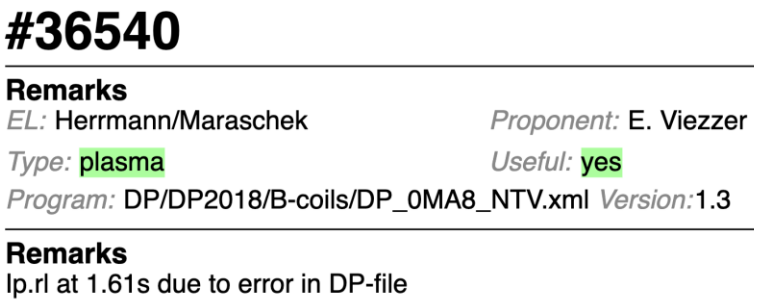
- **Before discharge (so far, only ASDEX Upgrade)**
  - Prepare and test experimental scenarios
  - Check if the discharge program (DP) meets experimental goals
  - Check if all the parameters and reference waveforms are consistent with the experimental program
  - Fast simulation with simplified models
- **For development, testing and validation**
  - Design and develop the control system
    - Simplified control oriented models
    - Optionally simulate with detailed physical models
  - Benchmark physical models against experiments (ASDEX Upgrade -> DEMO)
  - Guide design of sensors and actuators (DEMO)
  - Verify controllability of operational scheme (DEMO)

Status (ASDEX Upgrade)

- **Physics: reduced model**
  - Core&pedestal (see later), 0-D divertor physics model by M. Siccinio, detachment and impurity transport models still missing
  - Optional: equilibrium iteration, transport models, NBI power deposition
- **Actuators: first order models**
  - Coil power supplies, gas system, pellet injector, NBI, ECRH
  - No ICRH, no Bcoils
- **Diagnostics: ideal models**
  - Direct use of physics quantities, no reconstruction
- **Control System Model**
  - *Model*, not a software *copy* of DCS (better inspection, easier prototyping, exploit simulator language)
  - DP parsing, Segment Scheduler, Reference Generator
  - Plasma Current-, Position-, Shape-, Fueling and Central Heating Control
  - Not yet: Radiation Control, Actuator Management, MHD control, Disruption Avoidance
  - In progress: validation of machine, operation and range limits for coils and Zsquad, I^2t limits coil force limits, required generator energy

Status (ASDEX Upgrade)

- **Can simulate an entire discharge in ≈ 3 minutes**
  - Including pre-magnetization, breakdown, ramp-up, shaping and flattop phases
  - L-, H- and I-mode



#36540

Remarks

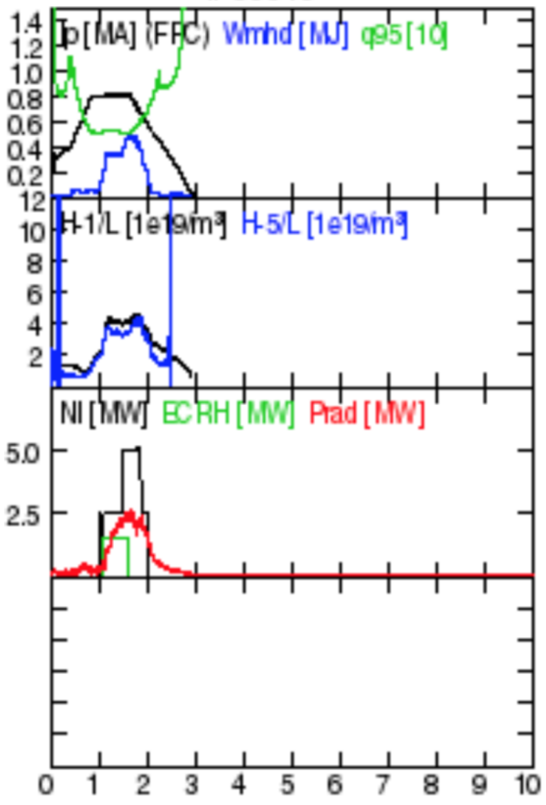
EL: Herrmann/Maraschek *Proponent:* E. Viezzer

Type: plasma *Useful:* yes

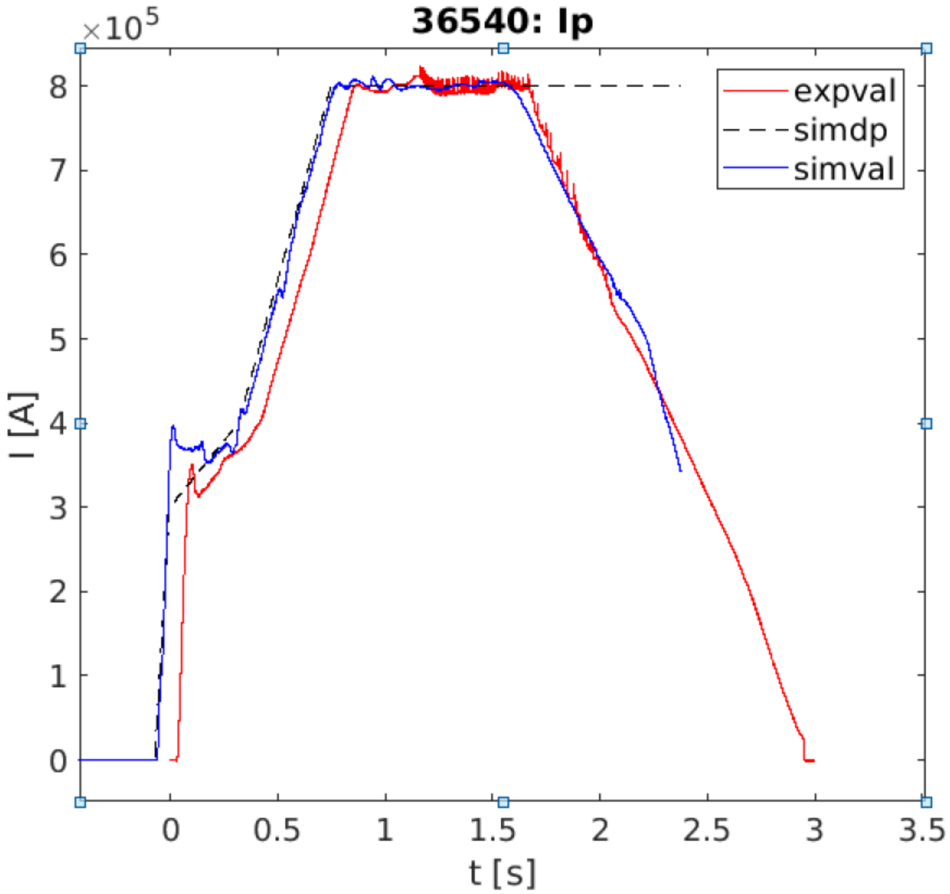
Program: DP/DP2018/B-coils/DP_0MA8_NTV.xml *Version:*1.3

Remarks

Ip.rl at 1.61s due to error in DP-file

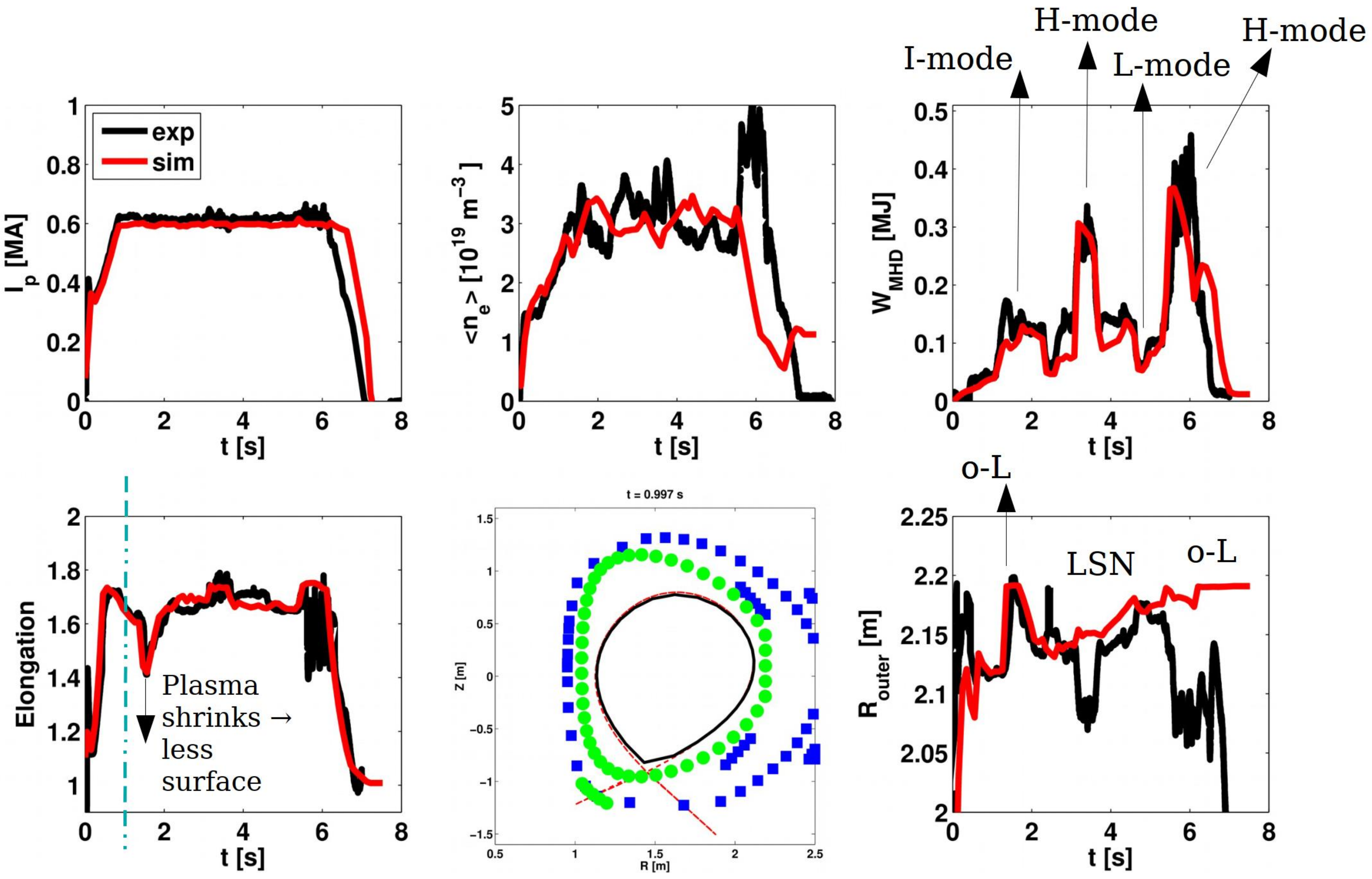


Fenix simulated discharge



- **Already good agrement**

Status (ASDEX Upgrade)



- **Already good agreement, even for non-standard shapes**

Status (DEMO): physics models

Predictability/Availability of reduced models

~ 100%

~ 70%

~ 30%

~ 10%

- Globally:

* quasi-stationary MHD equilibrium model (Grad-Shafranov equation)

* Breakdown model

- Locally:

* Core transport models for T_e, T_i, n_e, n_Z, $j_{||}$

* Edge/pedestal models, L-I-H H-I-L transition models

* SOL transport model for exhaust (heat flux) and for particle balance (fueling)

Status (DEMO): physics models

- PF currents are evolved before plasma is formed. The loop voltage in the main chamber is evaluated as:

$$V_{loop} = \frac{d}{dt} \Psi_{coils \rightarrow (R0, Z0)}$$

- Switch on plasma current evolution when a specific loop voltage in the chamber is obtained. Typically $V_{loop,crit} \sim 10\ V$, to be replaced with *f(Pressure,geom)*

- Then: $$L_p \frac{dI_p}{dt} + R_p I_p = V_{loop} \qquad (1)$$

! no prediction of burn-through or botched breakdowns possible

- L_p and R_p fitted to reproduce several discharges “on average”

- I_p initial condition is 1 A (small arbitrary number)

- Equation (1) is solved up to a user-defined current (i.e. 100 kA).
After this value, the full transport-equilibrium problem is solved, using an initial circular limited plasma as guess.

Status (DEMO): physics models

- Turbulence theory for magnetized plasmas → gyroBohm scaling:

$$\chi_{gB} \sim \frac{T^{3/2}\sqrt{M}}{B^2 R} \rightarrow \text{non-linear dependence on temperature} \rightarrow \text{stiffness}$$

- Turbulence phyiscs: $\chi = \chi_{gB} * f(geom, T_e/T_i, R/L_X,$ *e.m. & fast ions effects, flows, impurities, …)* → existence of a threshold

- Fit coefficients to get H ~ 0.5 in L-mode

- Density peaking ↔ energy transport & source
- For impurities: turbulent diffusion, neoclassical pinch, small turbulent pinch (better model in progress)

- MHD: sawtooth and NTM models (but no saturated kink mode)

- $P_{rad} \sim L_Z(T_e)$ → non-linear reaction of temperature to radiation

! fast ion physics still missing

- Foreseen: use of TGLF-NN [G. M. Staebler et al., PoP 2007], QualiKiZ-NN [K. L. van de Plassche et al., PoP 2020], and theory-based regressions (PhD thesis)

Status (DEMO): physics models

- L-mode → 5 m²/s fixed, to be improved...

- L-H transition:
  - * Compare ion heat flux at pedestal top entry with this scaling:

$$Q_{i,ped} = 0.0011\,\bar{n}^{1.07}\,B_T^{0.76}\,Surf \qquad [MW]$$

[M. Schmidtmayr et al., NF 2018]

  - * When this value is overcome, diffusion coefficients in the pedestal are set to neoclassical only + anomalous “ELM-average” part

- Pedestal pressure: limited to this value

$$P_{ped,crit} = 0.33\,R^{-0.38}\,e^{5\delta}\,I_p^{1.25}\,k^{0.62}\,\beta_N^{0.43} \qquad [keV\;10^{19}\,m^{-3}]$$

(adapted from S. K. Kim et al., NF 2018)

! no prediction of diverse ELM-regimes or ELM-free regimes & pedestal width

Status (DEMO): physics models

- 0D exhaust model from M. Siccinio et al., PPCF 2016
  - * Similar to the model by A. Kallenbach et al., NF 2013

- Inputs: P_{sep}, geometry, n_{sep}, n_{divr}, impurities
  Outputs: q_{div}, T_{div}, T_{sep}

- $P_{rad} \sim L_Z(T_e) \rightarrow$ non-linear reaction of temperature to radiation

- Parametrized as:

$$q_{||,plate} \simeq q_{||,midp}\, atan(x^{16}) \quad ; \quad x = C \frac{q_{||,midp}}{n_{e,sep}\, n_{ions,divr}}$$

$$T_{plate} \propto q_{||,plate} \quad ; \quad T_{e,sep} \propto T_{plate}$$

* where $n_{ions,divr}$ is the main radiator densiy and C depends on the element

→ similar to “Reinke scaling”

$$f_Z = 0.014 \frac{B_T^{0.88} f_{LH}^{1.14} q_\star^{0.32} R^{1.33} \varepsilon^{0.59}}{f_{SEP}^2 f_{GW}^{1.18} (1+\kappa^2)^{0.64} \hat{l}^{0.86} m_L(Z, n_e\tau)}. \quad (10)$$

[M. Reinke et al., NF 2017]

! no neutral physics, include empirical elements. no prediction of T_i/T_e. no prediction of detachment dynamics or position of radiation front

Status (DEMO): physics models

* 0D balance equations for 2 regions: SOL and divertor

$$\frac{dN_{j,sol}}{dt}=\Gamma_{j,plasma}+\alpha_j\Gamma_{j,midp}+D_j\left(N_{j,divr}/\varepsilon_j-N_{j,sol}\right)+D_{j,w}\left(-1+\alpha_j\left(1-R_j\right)\right)N_{j,sol}$$

$$\frac{dN_{j,divr}}{dt}=\Gamma_{j,divr}-\Gamma_{j,pump}-D_j\left(N_{j,divr}-N_{j,sol}\varepsilon_j\right)$$

* neutrals in the plasma: $n_{0,j}\sim\left(1-\alpha_j\right)\left(\Gamma_{j,midp}+\left(1-R_j\right)D_{j,w}N_{j,sol}\right)$

* $n_{j,sep}=N_{j,sol}/V_{sol}$; $n_{j,divr}=N_{j,divr}/V_{divr}$

* All Ns and Γs are in 10^{19} [p/s], Ds are in 1/s
* α_j : ionization fraction in the SOL
* R_j : recycling coefficient
* ε_j : enrichment coefficient ~ $n_{divr}^{0.67}$ → results in $n_{sep}\sim\Gamma_{divr}^{0.3}$

! no divertor asymmetries or 2D effects, no neutral dynamics, no PWI physics or machine conditioning

Status (DEMO): Control schemes

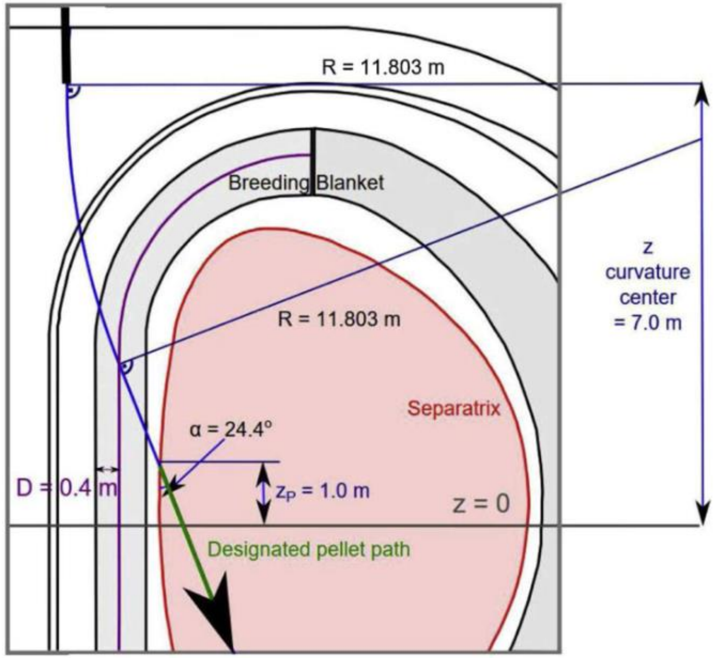
- **Currently use *ideal* diagnostics**
- ***Realistic* pellet actuators according to AUG technology**
  - Different pellet size, success rate and launch frequencies
- **Delays on every actuator based on realistic assumptions**
- **Transport coefficient χ with random noise 5%**
- **Controllers with FF and FB PI components**

- **Fusion power P_{fus}**
  - Target: 2 GW
  - Actuators: NBI, pellet D/T ratio, pellet frequency
  - Diagnostics: $P_{fus} = 5 \times P_{\alpha} \sim n_{neutron}$
- **Pedestal top electron density Greenwald fraction, n_e/n_{GW}**
  - Target: 0.8 – 0.95 (given by density limit – operational limit)
  - Actuators: pellet frequency
  - Diagnostics: *electron density at r/a = 0.94*

Status (DEMO): Control schemes

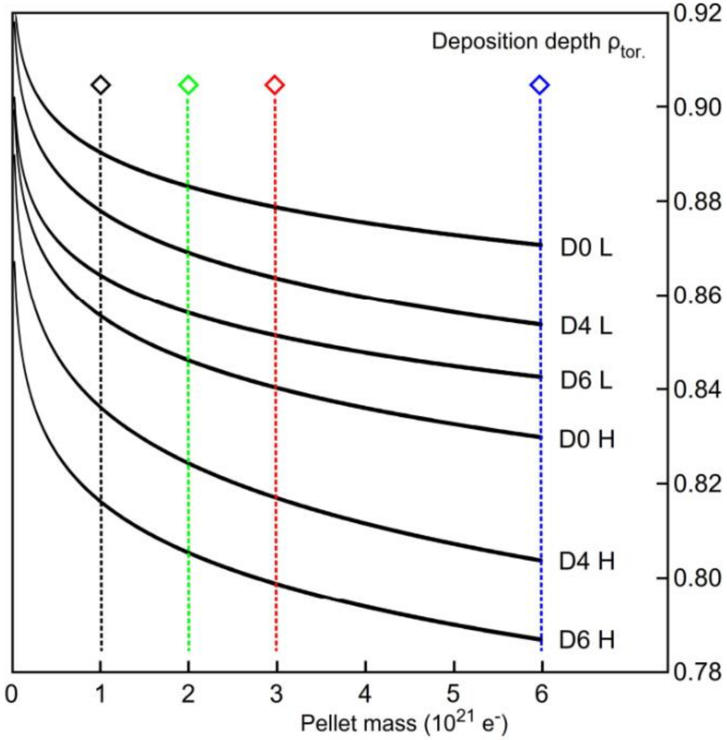
- **Divertor temperature**
  - Target: < 5 eV
  - Actuators: Ar or Kr gas puff to divertor
  - Diagnostics: *divertor temperature*
- **Separatrix power P_{sep}**
  - Target: P_{sep} > 170 : 200 MW (about 1.2 P_{LH})
  - Actuator: Xe gas puff to midplane
  - Diagnostics: $P_{sep} = P_{\alpha} + P_{NBI} + P_{ECRH} - P_{rad}$
- **NTM control**
  - Target: small or no island
  - Actuator: ECCD at rational surface
  - Diagnostics: *electron temperature profile*
- **Equilibrium control (under development)**
  - Target: desired magnetic equilibrium configuration
  - Actuator: PF coil system
  - Diagnostics: ???

Status (DEMO): integrated actuator design



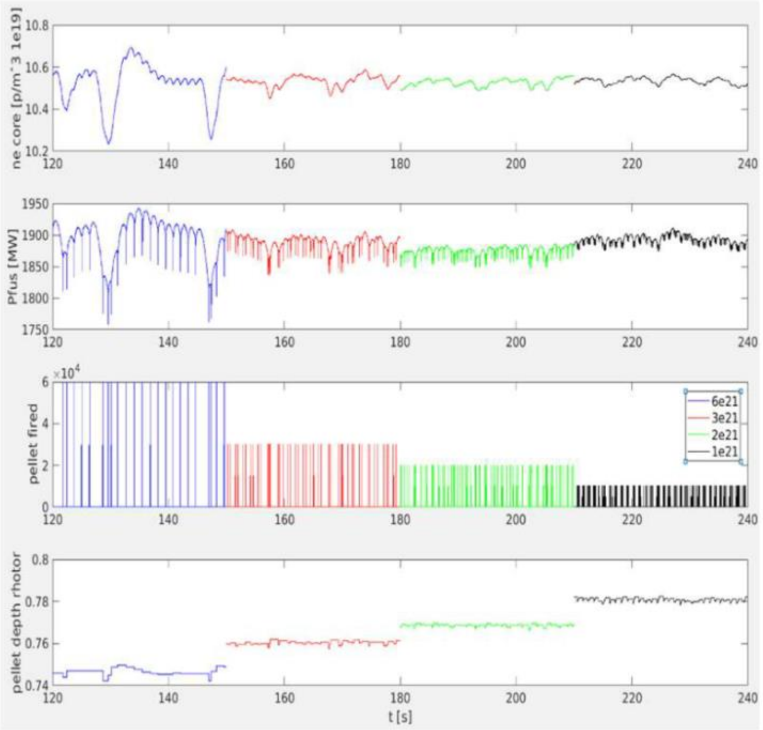
DEMO design integration

- minimise impact on breeding blanket
- maximise perpendicular pellet speed



Estimate source profile

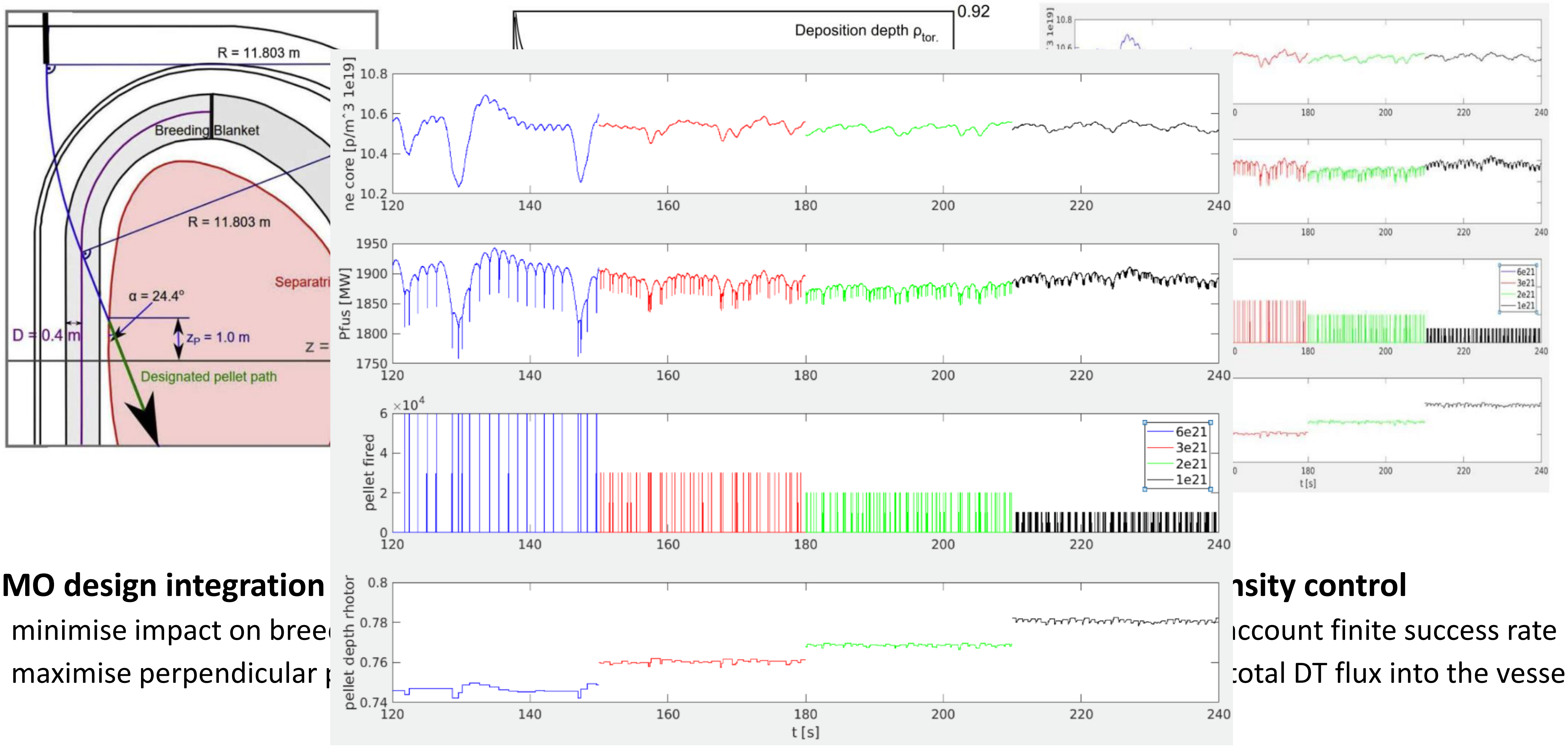
- depth and width of deposition
- HPI2 model parametrised for ASTRA



Simulate density control

- take into account finite success rate
- minimise total DT flux into the vessel

Status (DEMO): integrated actuator design



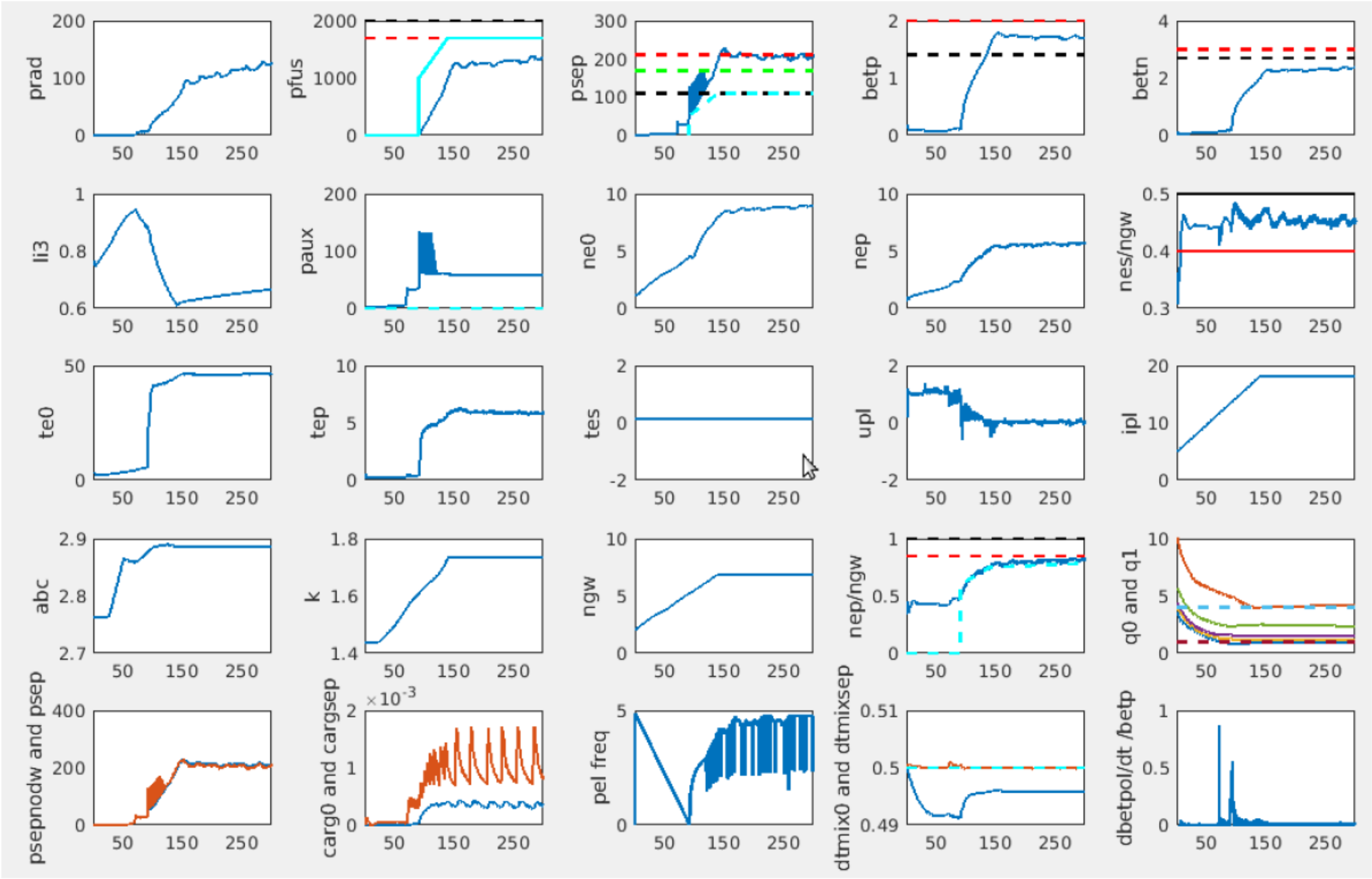
DEMO design integration

- minimise impact on bree
- maximise perpendicular

nsity control

- ccount finite success rate
- total DT flux into the vessel

Status (DEMO): full discharge simulation



Entire discharge can be simulated with ‘weak coupling’ magnetics/kinteics

- Closed loop will be achieved by ~ end of the year (CREATE eq. controller implemented in Fenix)