Max-Planck-Institut
für Plasmaphysik

Kinetic control of a tokamak burning plasma away from disruptive events

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Motivation

- **In DEMO (DEMOnstration fusion power plant) allowed disruptions per year is below 1**
- **Need to develop a scenario**
  - Provides the required electrical output
  - With margins inside operational and physics limits
- **Need to control scenario in case of**
  - Standard plasma development (plasma current ramp-up/down, L-H-L transition, etc.)
  - An unexpected event (e.g. impurity, loss of an actuator)
  - Anomaly of plasma parameters is detected (P_{rad}, li, n_e)
- **In case of an event - control system has to either recover the nominal plasma parameter or shutdown the plasma in a safe way**

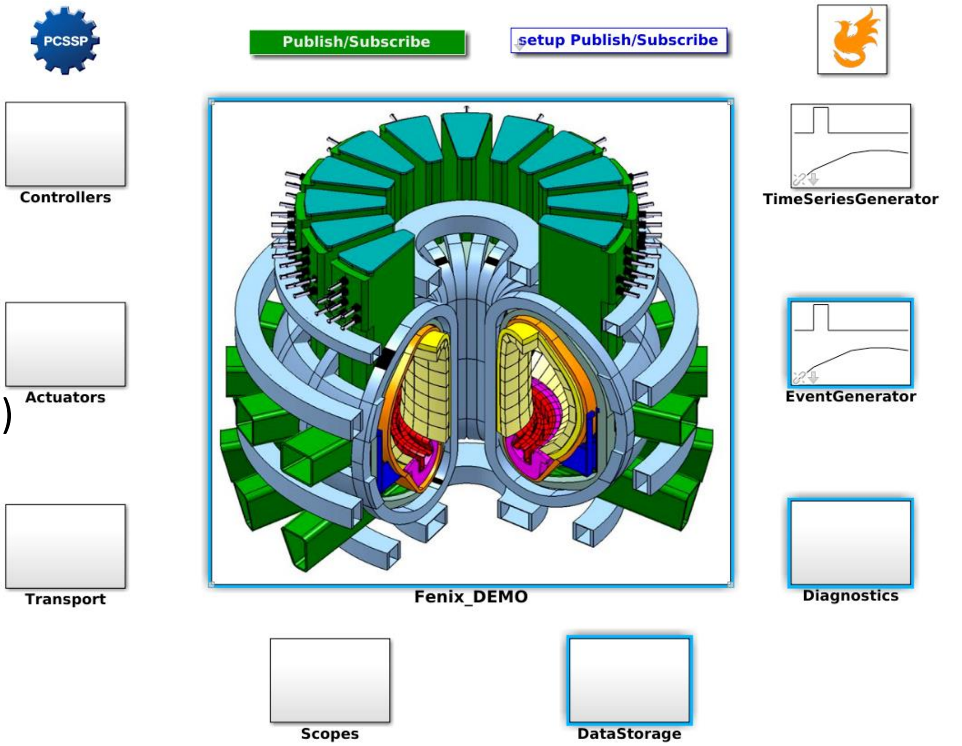
- **For dimensioning the control system and designing the plasma scenario**
  - Work must be carried out in simulations
  - So hardware, physics and knowledge limits can be clearly assessed and taken into account

Outline

- Fenix – tokamak flight simulator for physics and control studies and preparation and validation of tokamak plasma experiment
- Events that can lead to a disruption
- Results of the simulations
- Conclusions and outlook

Fenix

- **A tokamak flight-simulator** [1,2,3]
  - Plasma model - ASTRA (1-D transport) [4]
  - SPIDER (2-D coil current and equilibrium solver) [5]
  - models
    - Edge
    - Sawtooth
    - L-H
    - pedestal
    - SOL/divertor particle balance and exhaust model [6]
  - control system model (MATLAB/Simulink)
    - actuators and diagnostics
- **Simulates**
  - ASDEX Upgrade entire discharge with magnetic and kinetic control
  - DEMO kinetic control (fusion power, separatrix power, density, divertor heat loads)
  - DEMO flattop phase



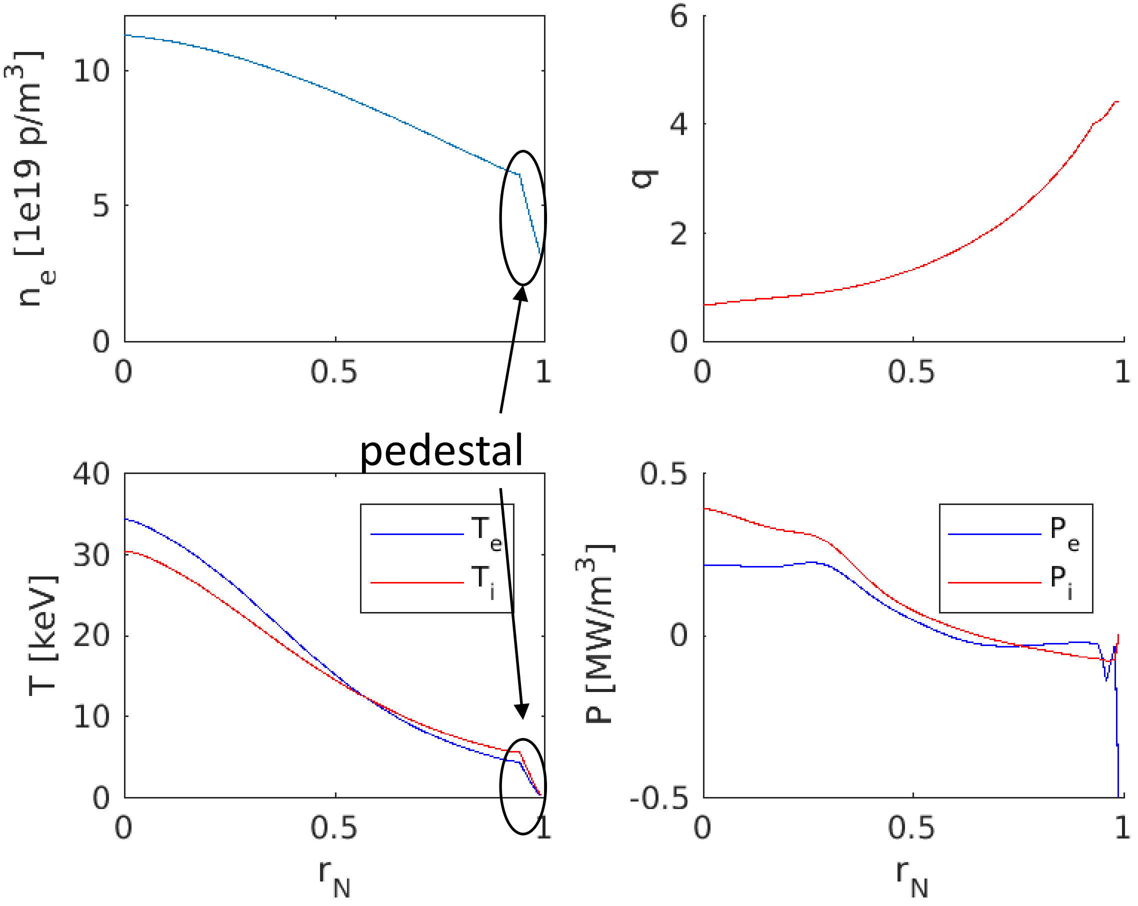
- **ITER Plasma Control System Simulation Platform (PCSSP) compliant**

DEMO overview

- **EU DEMO 2019 standard ELMy H-mode [7]**

R	8.94 [m]
a	2.883 [m]
B_t	5.744 [T]
κ	1.73
δ	0.341
I_p	18.21 [MA]
V	2500 [m^3]
T_{i0}	30 - 40 [keV]
n_{e0}	1e20 [m^{-3}]
P_{fus}	2 [GW]
P_{el}	500 [MW]
P_{LH}	130 [MW]

Plasma profiles



Diagnostics coverage: ITER vs. DEMO [8]

Control quantity	Operational limits	DEMO Diagnostics	ITER Diagnostics	Actuators + interactions
Plasma (edge) density	density limit	Reflectometry IR polarimetry/interferometry Plasma radiation	interferometer/polarimeter	pellet injection (fuel) gas injection pumping system
Plasma radiation, impurity mixture, Z_{eff}	radiation limit LH threshold	Spectroscopy+radiation meas. U_{loop}	bolometry: radiated power, Ha, vis. spectroscopy, VUV, X-ray (core + divertor), CXRS, BES	impurity gas injection auxiliary heating
Fusion power	wall loads (FW and div.) LH threshold	Neutron diagnostics FW/blanket and div. power (for calibration only)	diamagnetic loop: plasma energy, neutron flux monitors and cameras, neutron spectrometer: fuel ratio, neutral particle analyzer: fuel ratio, D/T influx: Ha, vis. spectroscopy	pellet injection (fuel) impurity gas injection auxiliary heating
Divertor detachment and heat flux control	divertor wall loads LH threshold	Spectroscopy+radiation meas. Thermography Divertor thermo-currents Reflectometry, ECE	IR thermography, VIS/IR imaging, pressure gauges, residual gas analysers, Langmuir probes	gas injection (impurities + fuel) pellet injection (fuel) PF coils, pumps
ELMs	Target overheat		Ha, vis. spectroscopy	ELM pellet inj, ITER: ELM ctr. coils
Gas pressure in main chamber			pressure gauges	gas injection, pumps
Te, ne profiles			Thomson scattering, ECE, reflectometry	EC
Ti profile			X-ray	
Current profile			MSE, polarimetry	EC, NBI
Plasma rotation			X-ray, CXRS	NBI

Legend:

- Usable/foreseen for DEMO
- Big issues/not feasible in DEMO
- Applicable with restrictions (e.g. resolution, sacrificial)

Elements of the kinetic control

- **Fusion power, P_{fus} → target controlled via core ECRH/*ICRH*/NBI heating**
  - 2 GW
  - *diagnostic* – neutron diagnostic
  - central heating also taking care of W control during ramp-up
- **Electron density, n_e → target via pellets (pedestal top Greenwald fraction) & gas puffing (deuterium tritium) reinjected mixture to the midplane**
  - $n_e^{pedtop}(GW) < 1$
  - *diagnostic* – infrared polarimetry, reflectometry, interferometry
- **Separatrix power, P_{sep} and instability control → via Xe puffing and edge ECRH**
  - $P_{sep} > 1.2\ P_{LH}$
  - *diagnostic* – spectroscopy, radiation measurement, loop voltage
- **Divertor temperature (or power), t_{div} or P_{div} → divertor Ar (Kr) puffing**
  - Fully detached ($T_{div} < 5$ eV)
  - *diagnostic* – divertor thermo-currents, spectroscopy

- **NTM control → ECCD at the q=2 or q=3/2 location**
  - Pre-emptive stabilisation or actively controlled (up to 50 MW of ECRH necessary)
  - *diagnostic* – ECE, magnetics?

Causes for disruptions in DEMO

- **During different phases of the discharge:**
  - ramp-up: breakdown, variation of internal inductance, *li*, (avoid vertical displacement event - VDE), L-H transition
  - flat-top: burn control, detachment, keep the plasma inside limits
  - ramp-down: li control (avoid VDE), H-L transition
- **During the flat top phase:**
  - Sawteeth: core events, not dramatic per se, but can trigger NTMs
  - Impurity accumulation: not dramatic in a low-collisionality hot plasma
  - NTMs: need to be controlled or pre-emptively avoided
  - Pedestal events: ELMs (ELM-free scenario or very small), radiation anomalies
  - Density limit: keep density below limits at pedestal top AND separatrix
  - Loss of detachment: avoid divertor damage

- **Technical issues**
  - Failure of actuators: need redundancy as much as possible
  - Failure of diagnostics: strategy to detect it and stop plasma safely

DEMO scenario can be prone to problems

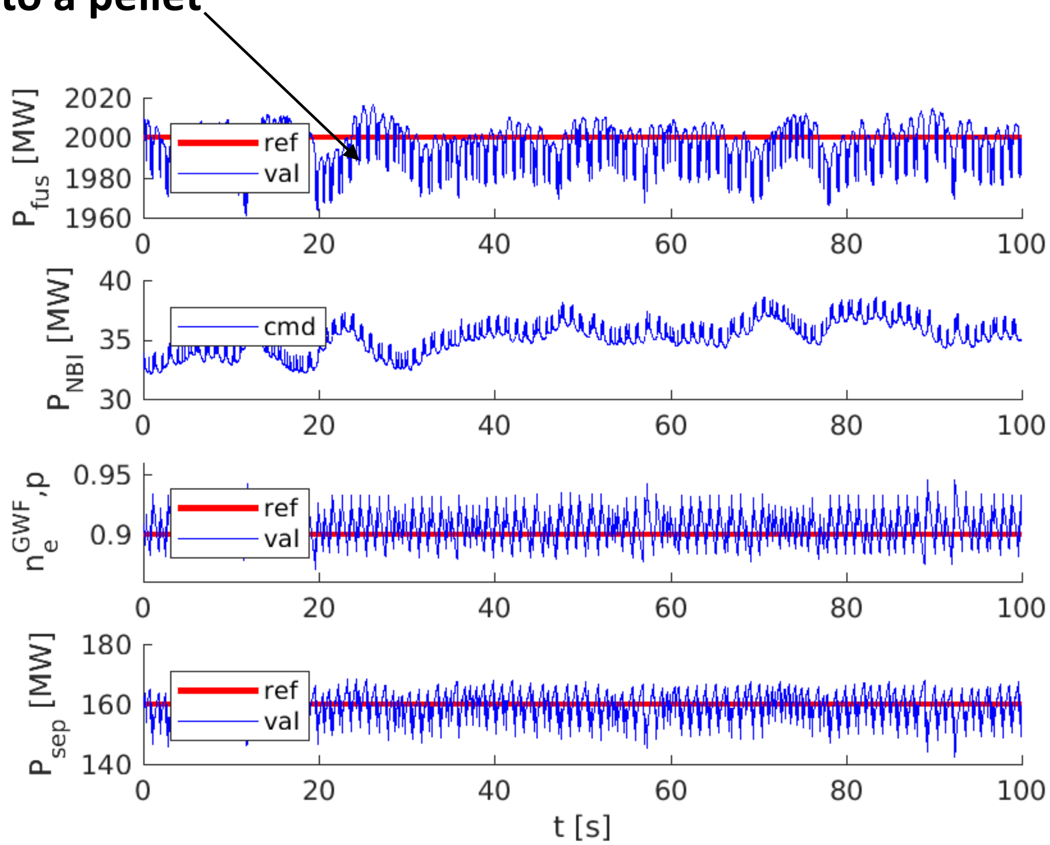
- **Close to the Greenwald limit at the edge → need to understand Greenwald limit physics [9]**
- **Radiative instability (impurity event, detachment control) due to SOL cooling**
  - Edge sensitive due to presence of Xe and Ar
  - Operation close to H-L transition
  - Do we have enough heating power to prevent it [10]?
  - Do we have enough time to detect such an event and react on it?
- **Detachment**
  - T_{div} control → too late to protect divertor once attached as gas puff reaction can take seconds
  - Ar feedback pulses could cause density to go over limit → use feed-forward strategy with feedback on a general performance quantity and feedback on an event
  - Spectroscopic recombination → quantifying ”detachment quality” - ongoing investigation of its feasibility
- **Large sawtooth radius prone to NTM triggering → pre-emptive strategy**
  - Detection and location
  - Speed of mirror
  - ECRH power availability

What can Fenix address

- **Models of physics, actuators, diagnostics and control**
  - Physics – different models (e.g. L-H, pedestal, transport etc.)
  - Actuators – delays, necessary power, limits
  - Diagnostics – noise, delays
  - Control – different control strategies
- **Scenario**
  - Different scenarios avoiding physics and machine limits
  - Controllability of scenario
- **Event handling in case of an event**
  - Keep plasma running and bring plasma back to the nominal parameters
  - Safely terminate down

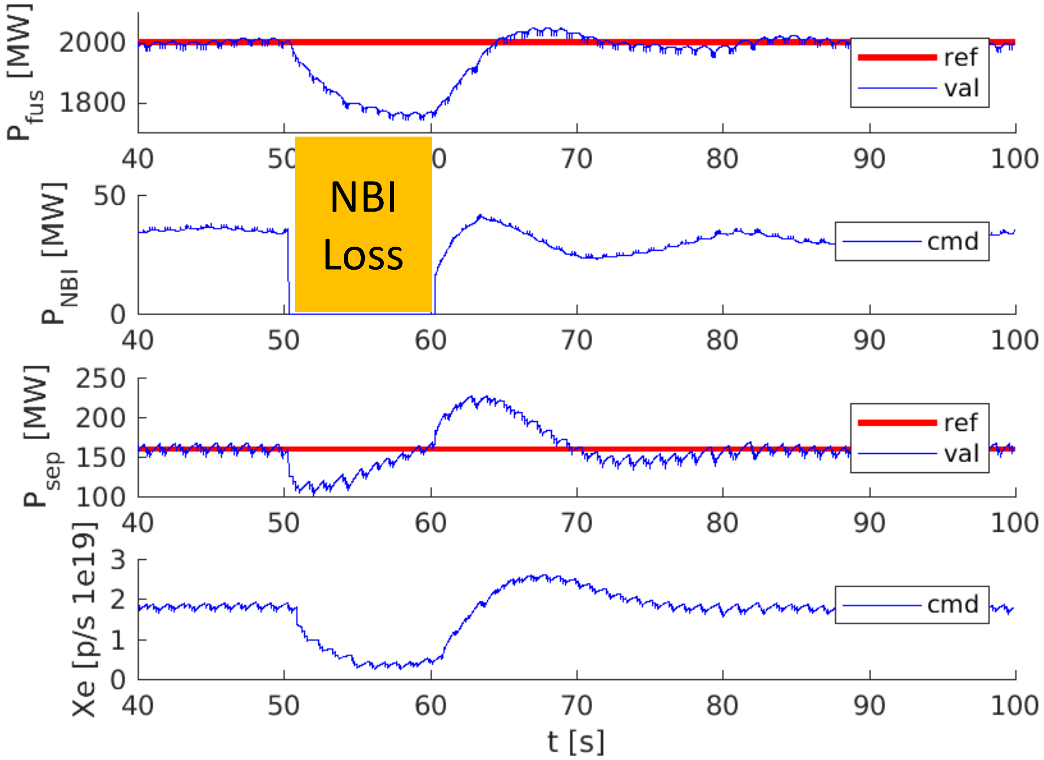
Reference control case

- **Fusion power controlled with NBI (via ion heating) ~ 30 MW**
- **Pedestal top density controlled with pellets**
- **Separatrix power controlled from above with midplane xenon puff**
- **Each small spike corresponds to a pellet**
- **Realistic pellet success 90 %**
  - Based on AUG pellet system
- **P_{fus} oscillations < 50 MW**
  - No problem for the blanket
  - No problem for electric production as energy is stored in water heat capacity
  - Small oscillations do not cause large separatrix power fluctuations



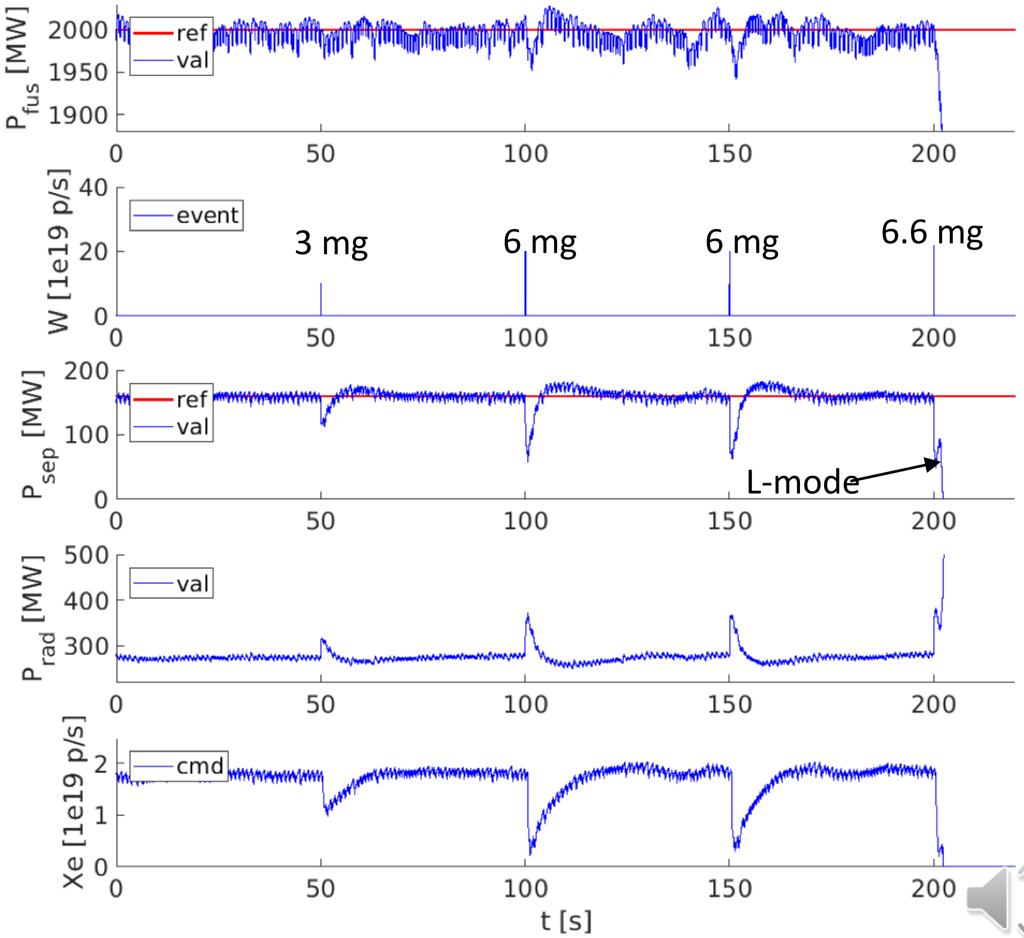
Loss of core heating system

- **NBI heating loss for 10 s**
- **Fusion and separatrix power drops**
- **Separatrix power drop is compensated by decreasing xenon puff**
- **After 10 s NBI beam is switched on and plasma recovers**
- **How long the NBI drop can be?**
  - Further detailed studies must be carried out
  - Depends on core radiation
  - Depends on enrichment factors of core and edge impurities
  - Depends on L-H model



Unexpected radiation from W influx

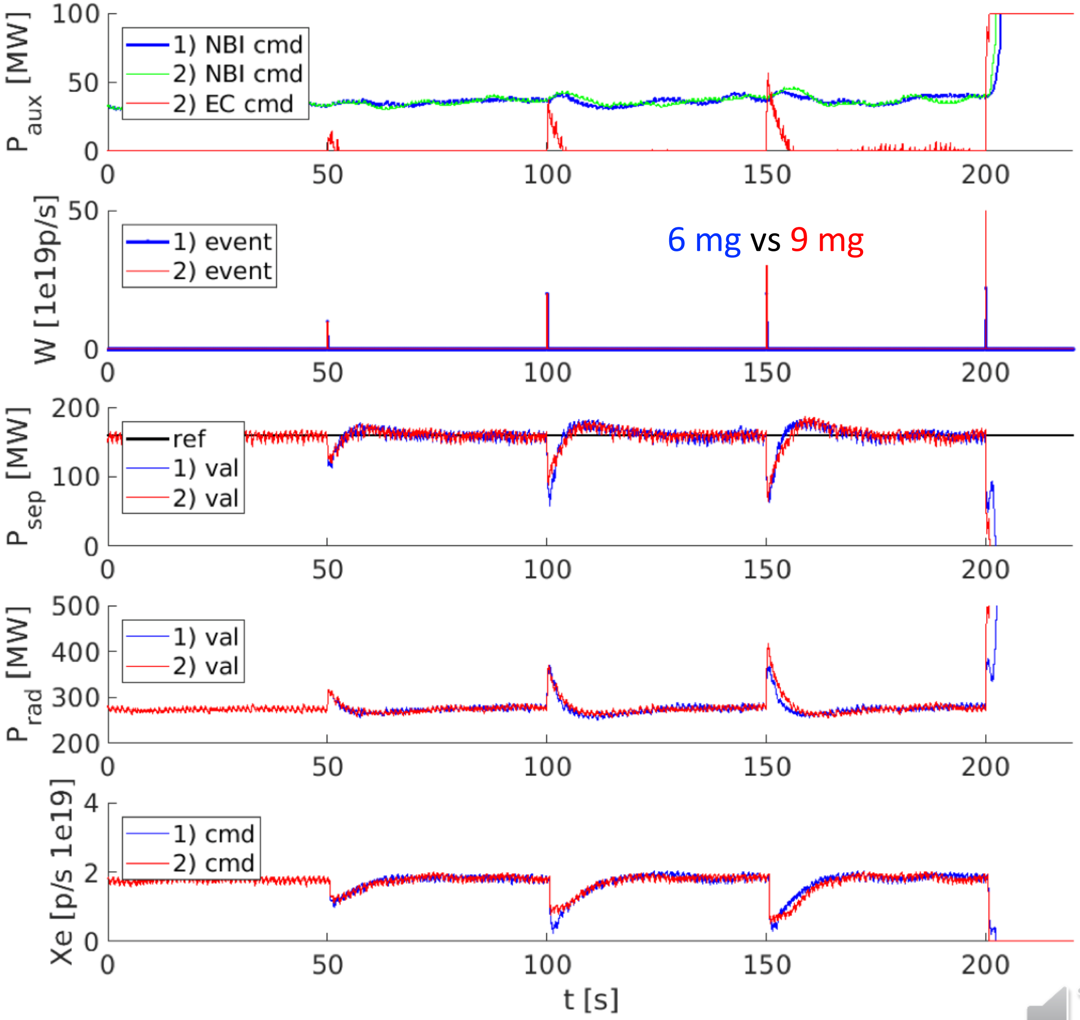
- **Tungsten influx for from 1e19 to 2.2e19 particles/seconds (3 mg, 6 mg, 6 mg, 6.6 mg)**
- **E.g. Tungsten flake falling from the upper tiles or erosion from divertor**
- **Separatrix power controlled by Xe puff from "top" Psep (ref) = 160 MW**
- **Heuristic finding 6.6 mg**
  - W puff at the separatrix (model)
  - No rocketing effect
- **Technical and control aspects to avoid disruptions**
  - Pipes length
  - Diagnostic latencies
  - Control of pumping speed and pumping impurities is not possible
  - Stop injecting xenon is slow



Controlled tungsten radiation event with ECRH

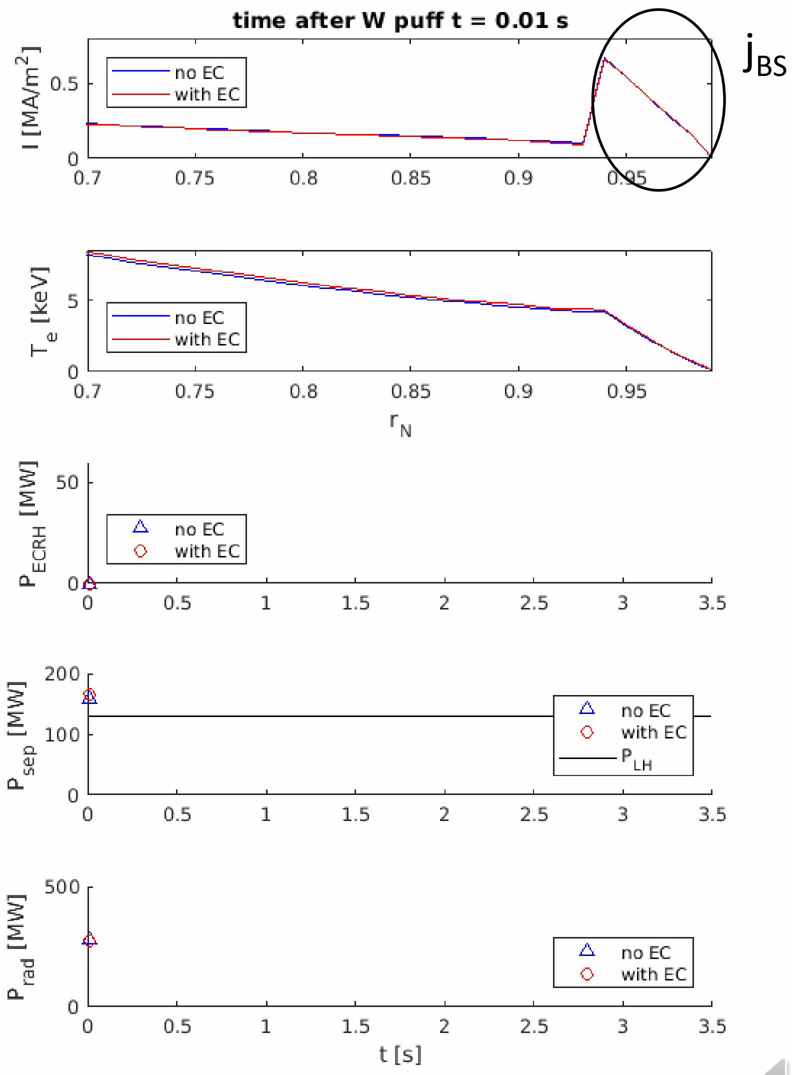
- **Tungsten influx for from 1e19 to 50e19 particles/seconds (3 mg to 6.6 mg, 3 mg to 15 mg)**

- **1) Psep controlled only from "top"**
  - *Xe puff, P_{sep} target = 160 MW*
  - Max 6 mg of tungsten
- **2) Psep control as 1) plus**
  - *Xe puff, P_{sep} target = 160 MW*
  - Max ECRH power = 100 MW
  - ECRH @ r_N 0.8 (close NTM location)
  - P_{sep} target = 140 [MW]
  - Max 9 mg of tungsten
  - Surviving ~ 50 % bigger tungsten influx



Current density and T_e profile tungsten case analysis

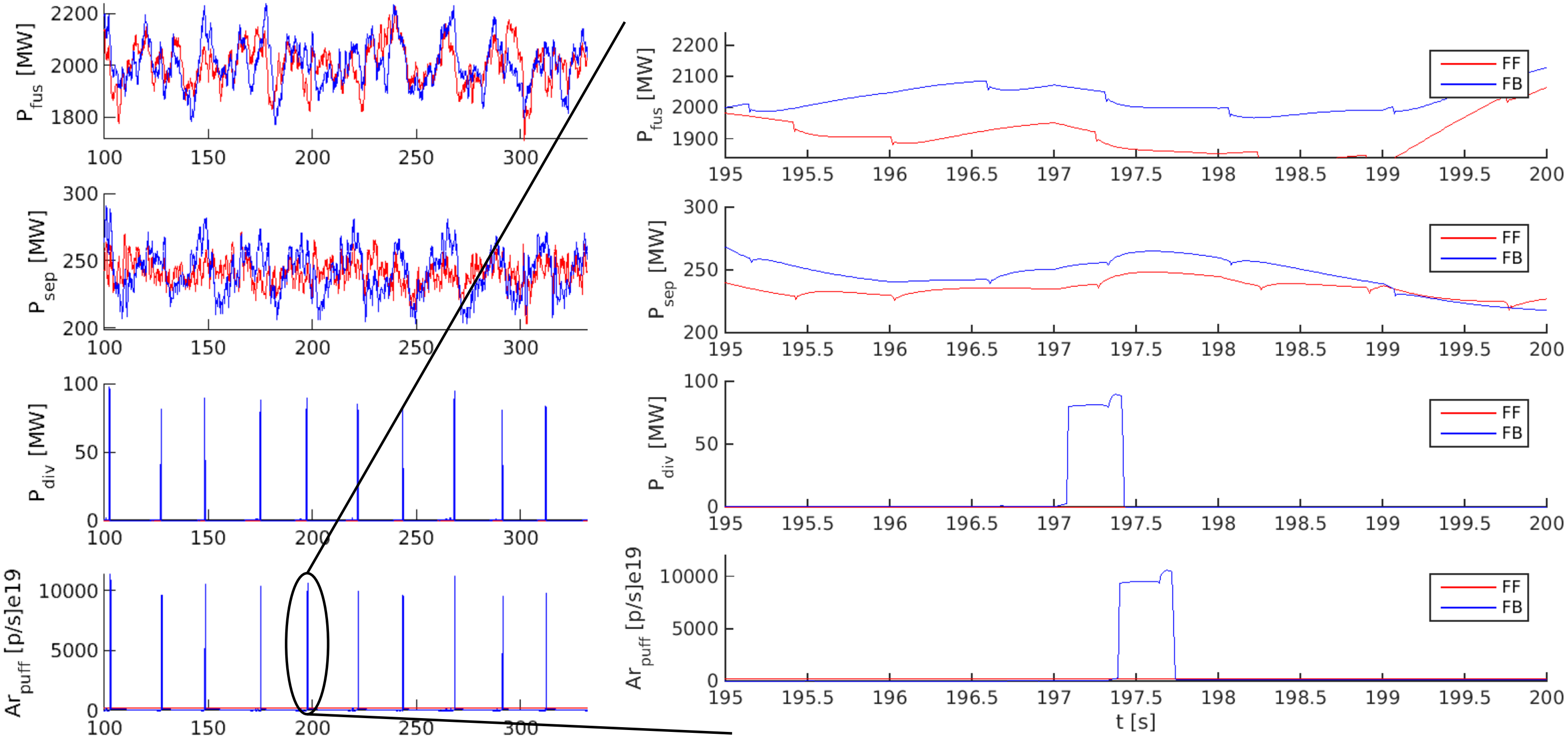
- **Comparison of two cases with and without ECRH control**
  - 6.6 mg vs 9 mg of tungsten
  - 0 MW ECRH vs 50 MW of ECRH at $r_N = 0.8$ if $P_{sep} < 140$ MW
  - P_{sep} controlled with xenon puff if $P_{sep} > 160$ MW in both cases
  - $P_{LH} = 130$ MW
  - $P_{sep} = P_\alpha + P_{aux} - P_{rad} - dW/dt$
    - ○ In foreseen P_{sep} diagnostic there is missing plasma thermal stored energy derivative term
    - ○ It is advantage for control



Current density analysis

- **As long as the plasma stays in H-mode**
  - Edge perturbations do not cause substantial deformations to the current and temperature profiles
  - Thus recovering the plasma without leading to a disruption
- **If the plasma suddenly drops into L-mode due to the edge cooling**
  - Radiated power strongly increases,
  - The current profile forms a strong gradient which could lead to the appearance of a disruptive MHD mode
- **Final message: the kinetic control has to be designed such as to**
  - Maintain the plasma into H-mode at all times during flattop
  - Similarly, the wall has to be designed to avoid spurious material entering into the plasma
  - If an anomaly is detected, plasma must be safely driven into L-mode before disruption, in case the anomaly is predicted to not be controllable in H-mode

Detachment control strategies



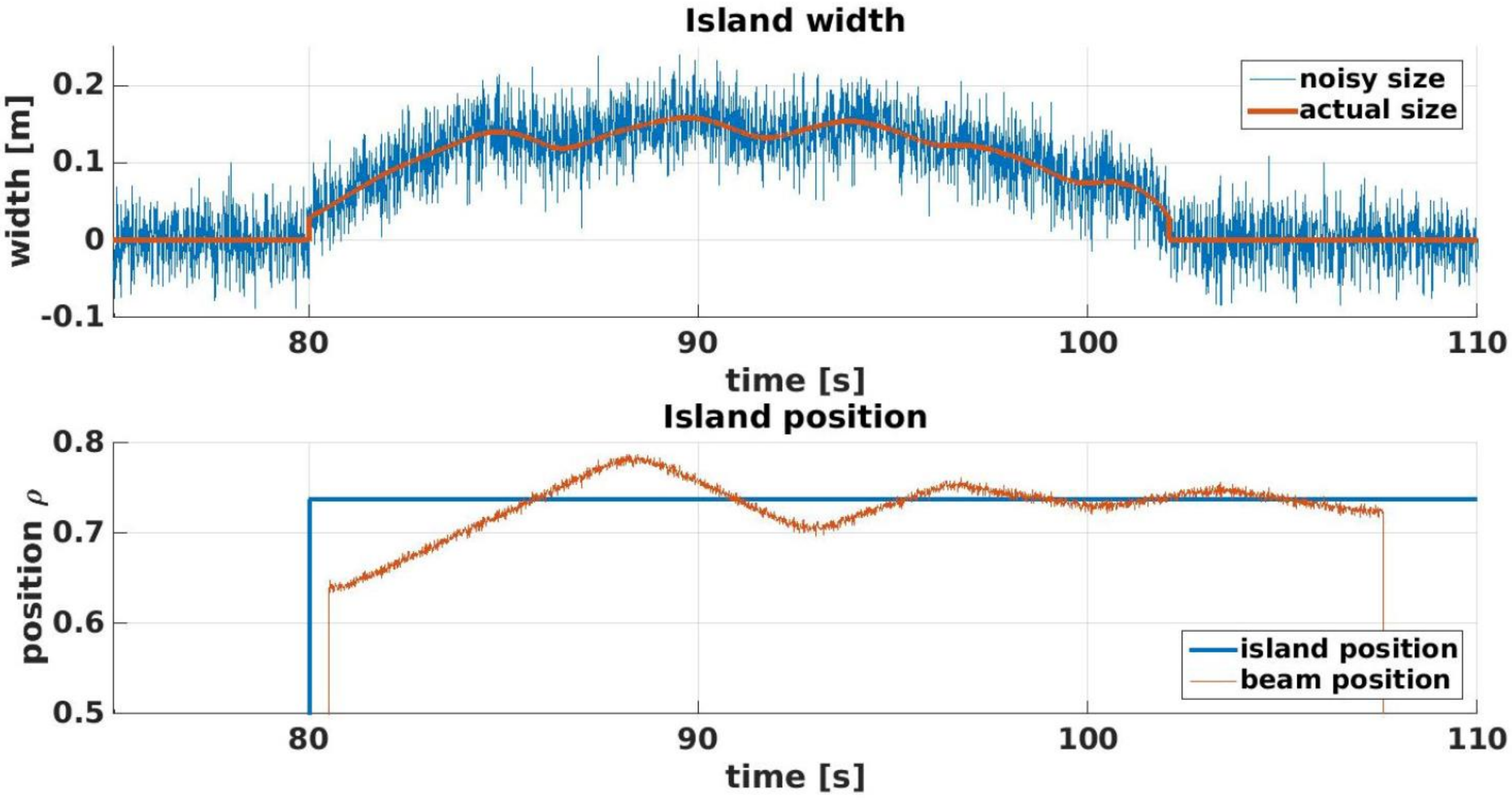
220e19 Ar p/s constant flow

Real values also depend on enrichment!

- Problem: high Ar puff can
  - create a MARFE and it can lead to radiation collapse
  - increase the separatrix density above the density limit and lead to disruption

NTM control [9]

- **Successful stabilisation of an NTM (2,1) mode using < 20 MW of ECRH**
- **Gaussian noise 0.0009 m^2, detection delays 50 ms, beam speed ∼ 5 cm/s**
  - No beam broadening



Conclusions and plans

Conclusions

- **Fenix adaptation for DEMO can address control problems related to**
  - Scenario physics limits
  - Operation (diagnostics, actuators) limits
  - Unwanted events
  - Simulations presented in this work show that we can quantify how much anomalous edge radiation can be tolerated giving the cap in available auxiliary power
  - We can also provide requirements on diagnostics (accuracy of P_{rad} measurement) and actuators (pellet, heating) to minimize plasma parameters excursions around nominal values
- **Both the scenario (engineering parameters) and the actuators/diagnostics requirements can be tailored accordingly**
- **Inclusion of density limit physics and tearing mode physics trigger will provide essential push in ability to predict the scenario control strategy**

Current development

- **Coupling to a CREATE-based controller to tackle DEMO kinetic and magnetic control**

Acknowledgments and references

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