

Disruption avoidance strategies for DEMO

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Disruption avoidance strategies for DEMO

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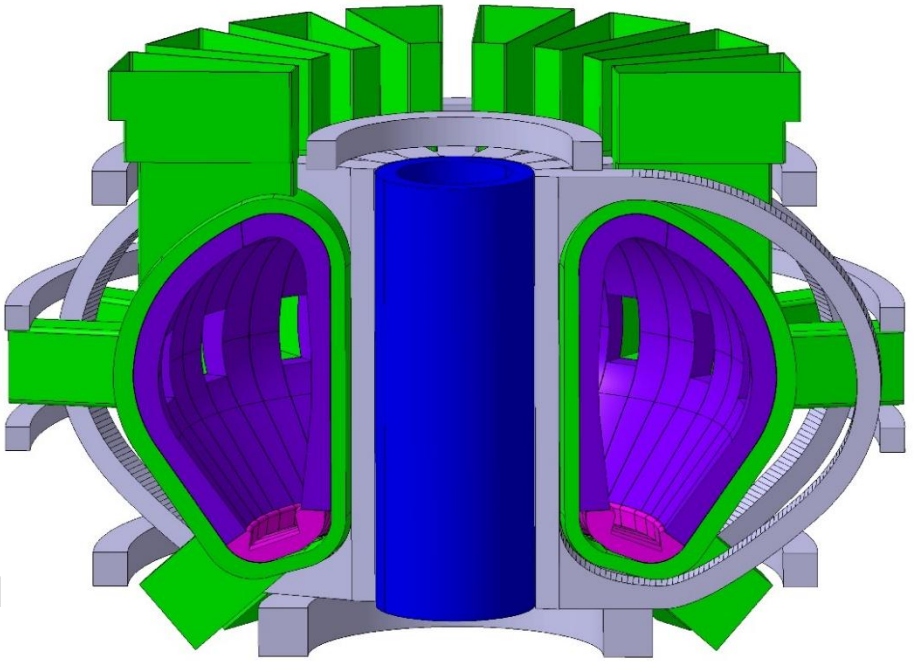
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Main input assumptions for the development of the DEMO D&C system

- Pulsed DEMO tokamak as baseline
- Machine size ~ 1.5 times of ITER
- Conservative plasma scenario with
  - predominantly ohmic current drive
  - confinement quality H_{H98y2} ~ 1
  - high core radiation fraction but P_{heat}-$P_{rad,core}$ > P_{LH}
  - high plasma density with fully detached divertor plasma operation (lower single null divertor)
  - no ELMs or very small ELMs (factor 100!)
- Vertical maintenance concept for blanket
  - only limited access for diagnostics from the top side
- Large equatorial ports
  - main access for diagnostics



Main DEMO parameters:

- R_0, a ~ 9 m, 2.9 m
- P_{therm} ~ 2 GW
- $P_{el,net}$ ~ 300…500 MW
- t_{pulse} > 2 h
- W_{kin} ~ 1.3 GJ
- V_{plasma} ~ 2500 m^3
- A_{wall} ~ 2000 m^2

First wall heat loads due to disruptions on DEMO (W_{kin} = 1.3 GJ)

See also F. Maviglia et al., IAEA technical meeting 20-23 July 2020, and EFDA_D_2P985Q

Heat impact factor:

$$\eta = W_{th}/\left(A_{eff}\sqrt{t}\right)$$

Critical heat impact factor (melting):

$$\eta_{melt} = (T_{melt} - T_{op})\sqrt{\pi\lambda\rho c/4}$$

where:

T_{melt}	=	melt temperature	
T_{op}	=	operational temperature	
λ	=	heat conductivity	(W/mK)
ρ	=	mass density	(kg/m^3)
c	=	heat capacity	(J/kgK)

Material data for tungsten:

λ	=	170	W/mK
ρ	=	19300	kg/m^3
c	=	138	J/kgK

Critical limits for tungsten:

$\eta_{melt} = 50$ MJ/(m^{2}s$^{0.5}$)

$\eta_{crack} = 5$ MJ/(m^{2}s$^{0.5}$)

+EM forces

+runaway electrons

Major (non-mitigated) disruption

- About 50% of the thermal energy (1.3 GJ) is released within the quench time t_{TQ} = 1…4 ms
- Most of the energy is deposited in the divertor
- Peak heat loads → $\eta > 130$ MJ/(m^{2}s$^{0.5}$)
- Large area melting of divertor surface with typically several hundred µm depth
- The heat load capability of the divertor can be affected after a single major disruption

Mitigated disruption

- About 60% of the thermal energy (1.3 GJ) is released within the quench time t_{TQ} = 1…3 ms
- Most of the energy is deposited at the first wall with a typical peaking factor 3
- Peak heat loads → $\eta > 30$ MJ/(m^{2}s$^{0.5}$)
- Near to melting in highly loaded areas, otherwise crack formation
- Several mitigated disruptions may be tolerable if the startup limiters (OML) are not damaged

JÜLICH FORSCHUNGSZENTRUM GHENT UNIVERSITY

Strategies towards disruption avoidance on DEMO

1) Define the plasma scenario and machine design with sufficient margins against any operational limits
   - See DEMO control requirements
2) Ensure redundancy and reliability of diagnostics and actuators for plasma control
   - See overview table
3) All elements of the plasma control system (measurements, actuators, controllers) have to be fast and strong enough to cope with any disturbances acting on the plasma
   - Plasma dynamics being analysed via control simulations
   - Requirements to be defined accordingly
   - Model-based and multivariable control for accurate and robust control
   - Exception handling for adequate and fast decision taking
   - Actuator management to make best use of the resources
4) Make DEMO resilient against those disruptions that cannot be avoided…
   - Protection limiters

… and of course provide disruption mitigation schemes (not addressed here)

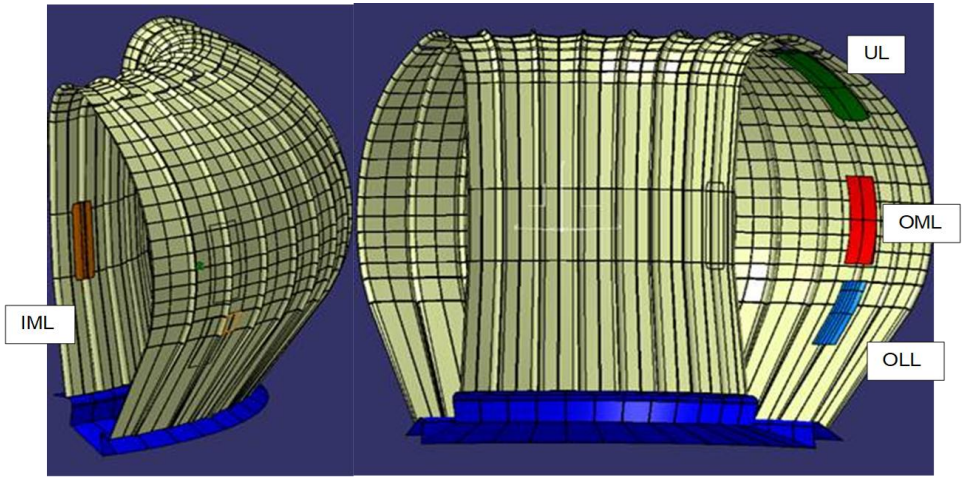
4) DEMO protection limiter concept

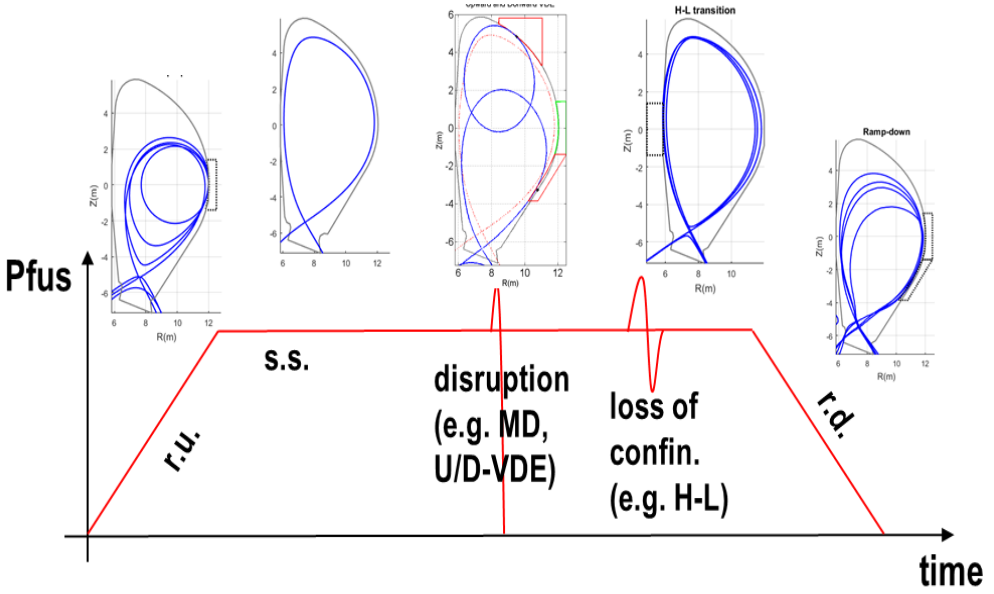
M. Siccinio, F. Maviglia et al., PSI 2021

Transients

Limiters are high flux (i.e. operable up to ~10 MW/m^2), toroidally and poloidally discontinuous structures which prevent plasma/wall contact during planned and unplanned transients.

- **Upper limiter (UL):**
  - U-VDE
- **Inner Midplane limiter (IML):**
  - loss of confinement (plasma shrinks)
- **Outer Midplane limiter (OML):**
  - Ramp up
- **Outer Lower limiter (OWL):**
  - D-VDE

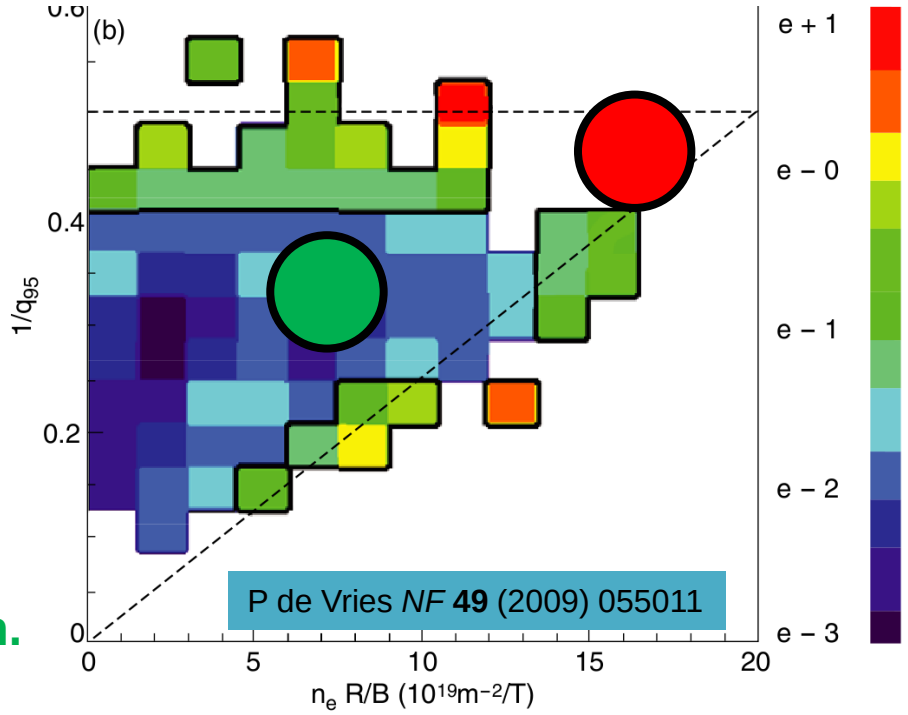




1) Control margins and baseline definition

- According to the confinement scaling, the highest fusion power is expected when operating as near as possible to the operational limits (marginally stable solution against infinitesimally small disturbance)
- However, experiments and control simulations show that the plasma reacts with major parameter changes on any small disturbance.
- Reliable operation requires keeping sufficient distance from operational limits (→ control margins)

A proper compromise has to be found between high fusion power and enhanced stability of operation.



Initial physics requirements for DEMO control (1)

(proposed by W. Biel and M. Siccinio)

1) Equilibrium control during flat-top phase:

a) The plasma current I_p should be controlled within +/- 0.5 MA, such that the edge safety factor during flat-top operation always remains in the interval q_{95} = 3.5 +/- 0.1 (presumably no problem here)

b) The horizontal and vertical position of the current centroid should be controlled such that an initial displacement of 15 cm can always be recovered, where the minimum distance between separatrix and first wall and limiters in all poloidal locations always remains larger than 8 cm, in order to minimize the wall loads.

- Initial DEMO equilibrium control simulations with external PF coils did not meet this requirement.
- We will employ more "advanced" control, but we might need also:
  - stronger (faster) external PF coils (this might marginally work), and/or
  - additional in vessel control coils (simulations show that this would work), and/or
  - larger clearance between plasma and wall, and/or
  - reduction of plasma shaping, and/or
  - a combination of all these



c) The plasma shaping has to be controlled such that both the elongation and the triangularity remain within +/- 0.03 of their absolute target values, respectively.

- This new requirement might require a change of the baseline:
  - Stable control needed also at the upper limit of elongation → reduction of κ needed ?

Initial physics requirements for DEMO control (2)

(proposed by W. Biel and M. Siccinio)

2) Kinetic control during flat-top phase:

a) The electron density at the separatrix should be controlled at a level of 0.45 n_{GW} (Greenwald limit) with a margin of +/- 0.05 n_{GW} (presumably no problem)

b) The fusion power should be controlled to keep the variations of fusion power always below +/- 20 percent over not more than 20 seconds. (??)

c) The power loss P_{sep} across the separatrix should be controlled to maintain a value of 1.2 times the confinement mode threshold (e.g. P_{LH}), where deviations of up to additional 50 MW within up to 20 seconds represent the tolerable limit. → Compatibility to divertor protection needs to be shown.

d) The divertor plasma should be controlled to keep strongly detached plasma conditions, i.e. a high density plasma with a plasma temperature in front of the target of less than 2 eV. It is assumed that under these conditions both the heat flux density and the erosion rate at the divertor targets are tolerable. Any loss of detachment (T > 3 eV) has to be recognized by the control system within less than 0.2 seconds.

→ dynamic divertor plasma modelling needed for validation.

a) The plasma pressure should be controlled such that the normalized plasma beta will not exceed 90% of the ideal beta limit (presumably no problem here)

Initial physics requirements for DEMO control (3)

(proposed by W. Biel and M. Siccinio)

3) Control of unforeseen events:

a) In case of island formation in the plasma, an island width of w = 6 cm should be clearly detectable by the control system within less than 0.1 seconds.
   - Looks good for fast rotating islands (> 100 Hz); for slow islands to be investigated

b) The control system should be able to recognize any unplanned increase of plasma radiation greater than $dP_{rad}/dt > 0.1\ W_{kin}/\tau_E^2$ ("impurity events") within less than 0.2 seconds.
   - Caveat: too large impurity events can be easily recognized but there might no counter-measures available



c) The DEMO plasma should be ELM-free, or the ELMs should be smaller than 1 percent of the "natural ELMs" (the latter would deposit a typical energy onto the divertor targets of $E_{ELM,nat} \sim 10\ MJ/m^2$) – ref. M. Siccinio
   - Caveat: reliable control of ELM size by a factor > 100 with not more than a few ELMs per fpy has never been shown → consequently, alternatives to H mode are now being considered

(ELM free plasma scenarios see sessions 1+2)

2) Redundancy in the DEMO D&C concept

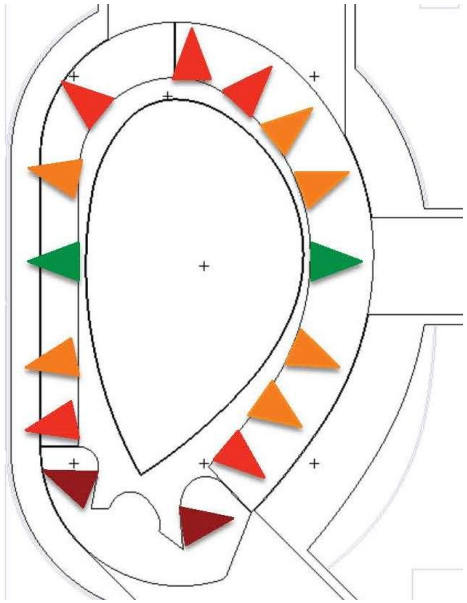
	Control quantity	Operational limits	Diagnostics	Actuators + interactions
equilibr. control	Plasma current	safety factor limit (q_{95})	Magnetic diagnostics Faraday sensors	CS+PF coils Heating+current drive (HCD)
	Plasma position and shape, incl. vertical stability	Wall loads (FW and div.) Max. Δz / VDE disruption	Magnetic diagnostics Reflectometry, ECE Neutron/gamma diagnostics IR polarimetry/interferometry Radiation power profile	PF+CS coils HCD
kinetic control	Plasma edge density	Density limit Divertor detachment access	Reflectometry IR polarimetry/interferometry Spectroscopy (pellet injection)	Pellet injection (fuel) Gas injection
	Fusion power	wall loads (FW and div.) LH threshold	Neutron diagnostics FW/blanket and div. power (for calibration only)	HCD Pellet injection (DT ratio) Impurity gas injection PF+CS coils (shaping)
	Power flow across separatrix	Radiation limit LH threshold, divertor loads	Spectroscopy+radiation meas. U_{loop}	Impurity gas injection HCD
	Divertor detachment and heat flux control	Divertor wall loads LH threshold	Spectroscopy+radiation meas. Thermography Divertor thermo-currents	Gas injection (impurities + fuel) Pellet injection (fuel) PF coils
instabilities/events	Mode control	various (→ disruptions)	Reflectometry, ECE IR polarimetry/interferometry Magnetic diagnostics Neutron/gamma diagnostics Radiation power measurements U_{loop}	HCD CS+PF coils
	Unforeseen events (e.g. impurity ingress)	various (→ disruptions)	All	all
	Disruption mitigation		all	Matter injection

Risk mitigation via redundancy: Reflectrometry for equilibrium control

Diagn. methods:	➢ reflectometry ➢ ECE
Control tasks to be covered:	➢ n_e profile in gradient region ➢ T_e profile ➢ plasma position and shape ➢ plasma instabilities (up to kHz frequencies)
Implementation:	➢ > 100 antennae distributed toroidally and poloidally (LFS, HFS, upper, x-point) ➢ integration of antennae + waveguides in slim poloidal diagnostic cassettes ➢ routing of waveguides to upper port (attached to „blanket bananas“) ➢ Microwave feedthroughs or ceramic windows near upper port

In case of 2 full poloidal sectors (< 25 cm each) the effect on TBR would be ΔTBR < 0.01

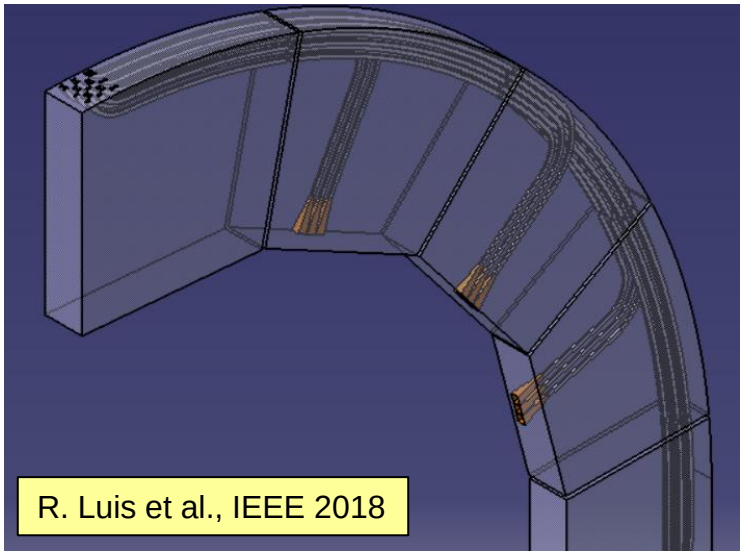
A. Silva,
A. Malaquias,
C. Sozzi,
G. de Masi, et al.



Predicted gap accuracy:
green: high (few cm)
red: low (~ 10 cm)

G. Marchiori et al., IEEE 2018

Integration study of MW antennae



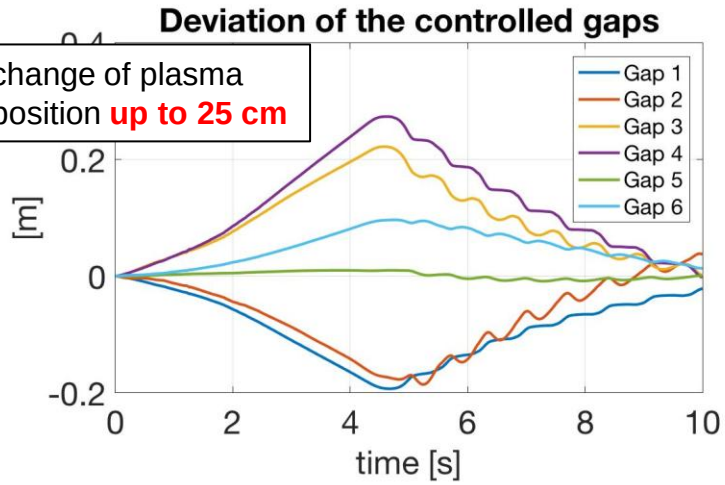
R. Luis et al., IEEE 2018

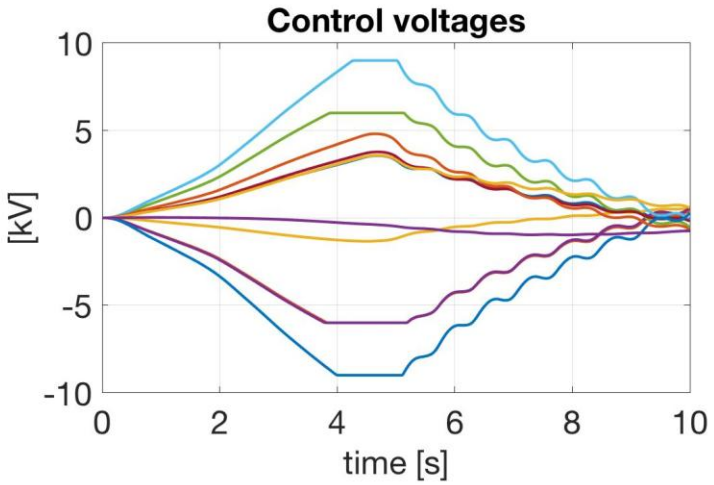
3) „Strong control?“: Simulation of equilibrium control using ex- vessel PF coils in a loss of confinement event

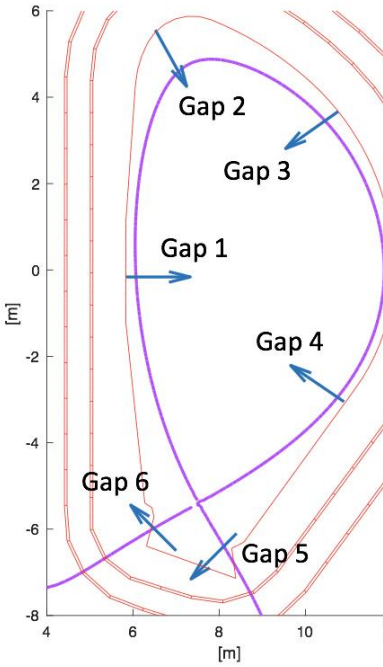
M. Ariola et al. P 3.045, SOFT 2018

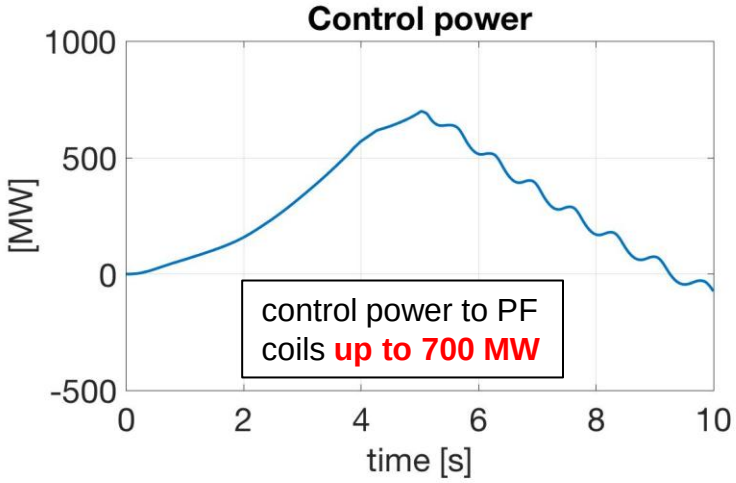
(time traces of β_{pol} and ℓ_i from E. Fable were used as input)

change of plasma position **up to 25 cm**

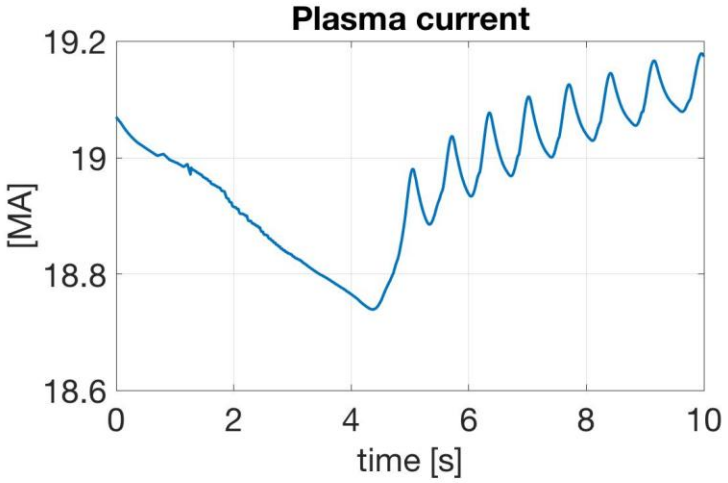








control power to PF coils **up to 700 MW**



→ **This control action is too weak; the plasma distance to first wall becomes too small**
The required electrical power is nevertheless high

Electrical power requirements for DEMO control

I. Core plasma kinetic control simulation shows strong variation of fusion power (→ tendency to accept some variation, see requirem. 2b)
   - strong auxiliary heating is the only „fast“ actuator for kinetic control
   - requires hundreds of MW electrical power, which would reduce $P_{net,el}$

II. Loss of confinement events lead to inboard movement of plasma
   - Current equilibrium control simulations show electrical power demands of > 700 MW without achieving reliable control
   - The power requirements follow from Shafranov equation (necessary change of vertical field Bz in a large volume) – would be much lower with in vessel control coils
   - Control action may include auxiliary heating in addition (would increase power needs)

III. Vertical control for strongly shaped plasmas
   - Current simulations show additional > 100 MW power requirement for ex vessel PF coils, less with in vessel coils
   - Electrical power requirement can be reduced by reducing plasma shaping, on the expense of less fusion power

→ provision of sufficient electrical power (~ 1 GW_{el}) is a mandatory element of reliable control → electrical storage system needed

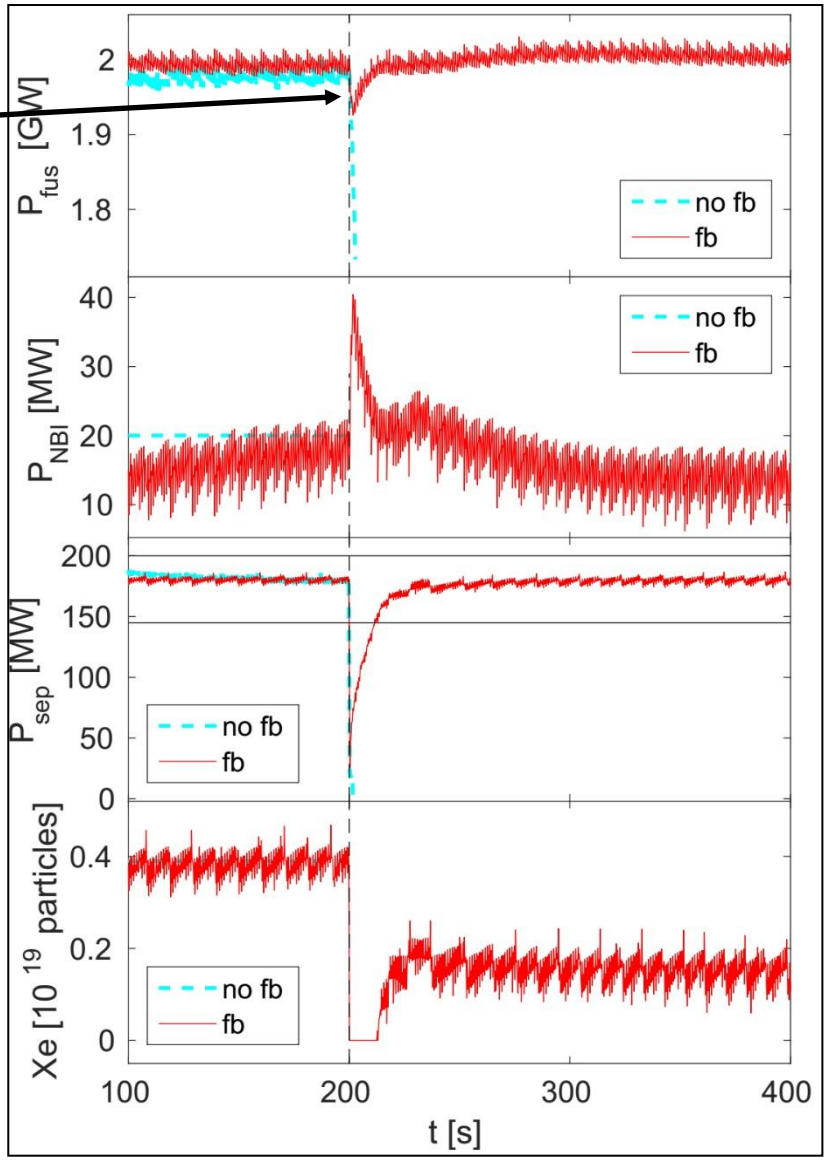


Tungsten flake (simulation)

- 3 mg of a tungsten penetrating into the plasma
  - FF vs. FB
  - FB on P_{fus} (P_{NBI}), P_{sep} (Xe)
  - „Old“ electric field shear LH model with high hysteresis
    - No HL transition occurred
  - „**New**” P_{sep}/P_{LH} model without hysteresis
    - **radiation collapse**

- Realistic physics models are extremely important to answer DEMO questions

- NB: 3mg W in plasma is != W falling from the wall (no model for that)



Conclusions: Root causes of disruptions, avoidance strategies and impact on DEMO design

1) Plasma equilibrium, kinetic and MHD control against „normal disturbancies“
   - → Margins in the plasma scenario (keep distance from operational limits)
     - → reducing the fusion power
   - → Margins in the machine design (e.g. limited elongation and shaping)
     - → reducing the fusion power
   - → Design of diagnostic&control system towards accuracy and performance
     - → high effort and cost
2) Failure or control components or control system
   - → achieve high reliability standards and install redundancy (number of channels and methods)
     - → high effort and cost
3) Human error
   - → should be very unlikely in the final DEMO operation (only one plasma scenario)
   - → but cannot be excluded during DEMO commissioning
4) Unforeseen events, e.g. impurity events, leakage, SC magnet quench
   - → above a certain size or speed of the event, the control system can only reduce but not avoid machine damage (mitigation)
     - → try to avoid unforeseen events by design (robust components, low wall loads, low amount of accumulated dust)

→ The probability of causes #1 - #3 can be in principle reduced by expensive choices in machine and control design; for #4 this is less obvious.

→ DEMO should have a certain degree of resilience against disruptions

Additional control requirements for alternative plasma scenarios, and impact on disruptivity

- **QH mode:** results in additional requirements for diagnostics and actuators
  - requires control of plasma rotation (NBI as actuator)
  - requires measurement of core plasma rotation (high resolution x-ray spectroscopy under at least 20 degree angle against poloidal plane for W or Xe) → 20 km/s should be measurable
  - requires also measurement of edge rotation gradient (high resolution imaging x-ray spectroscopy under at least 20 degree angle against poloidal plane for Ar) → 15 km/s should be measurable



- **I mode:** probably no additional diagnostic and actuator functionality needed but more stringent requirements
  - plasma operation under reversed B field → H mode threshold increases
  - I mode threshold is lower than H mode threshold → keep P_{sep} between P_{LI} and P_{LH} : $P_{LI} < P_{sep} < P_{LH}$



- **„Flexi DEMO / advanced scenario“:** probably requires q profile control
  - beam aided spectroscopy could be applied in plasma edge region (limited by beam penetration?)
  - for core plasma, consider IR polarimetry (additional requirements)
  - A lot of NBI or ECRH power needed



- **Negative triangularity (L mode)**
  - Less stringent P_{sep} control needed
  - Sightline geometry of some diagnostics to be adapted

