Some requirements and possibilities for the control of power and particle exhaust in ITER

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with thanks to:
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Control issues that will need to be addressed for power and particle exhaust

Power dissipation in the edge and divertor plasmas

- Control of radiation fraction and divertor detachment

Divertor target and main wall surface temperature

- “Steady-state”, general surveillance + transients

Particle throughput

- Enrichment factors, pumping

Disruptions

- Mitigation, avoidance

Materials

- Erosion and redeposition, tritium inventory

Baseline ITER divertor and edge plasma operating scenario

Partially detached divertor during inter-ELM periods - detached near strike points, attached further out. Even with an intrinsic radiator (Carbon), scenario requires impurity seeding	
Total power to be exhausted (divertor+edge)	~150 MW
Fractional radiated power, f_{rad}	~0.75
Nominal separatrix density, $n_{e,sep}$	~3 x 10^{19} m^{-3}
Nominal peak divertor plate heat load (peak, transient)*	10 (20) MWm^{-2}
Core He concentration	<0.06
Helium enrichment ($c_{Hediv}/c_{He,core}$)	~0.2
Core Z_{eff} limit	~1.7
Divertor target lifetime (full power, t = 400 - 500 s)	3000 cycles
Tritium in-vessel inventory	350 g

*with nominal target inclination

Power dissipation in the edge and divertor - constraints and sensors

Constraints for ITER

- Maintain peak, inter-ELM, power load below 10 MWm^{-2}
- Exhaust ~75 - 100 MW of power
- Avoid strong X-point MARFE formation
- Avoid core impurity accumulation and effect on C_{He}

Possible sensors to be used for feedback

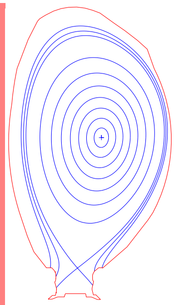
- Total radiated (bolometric) power or LOS combinations
- X-point radiation
- Seed gas emission lines
- Divertor T_e (thermocurrents)
- Surface temperature
- Divertor neutral pressure
- Langmuir probes

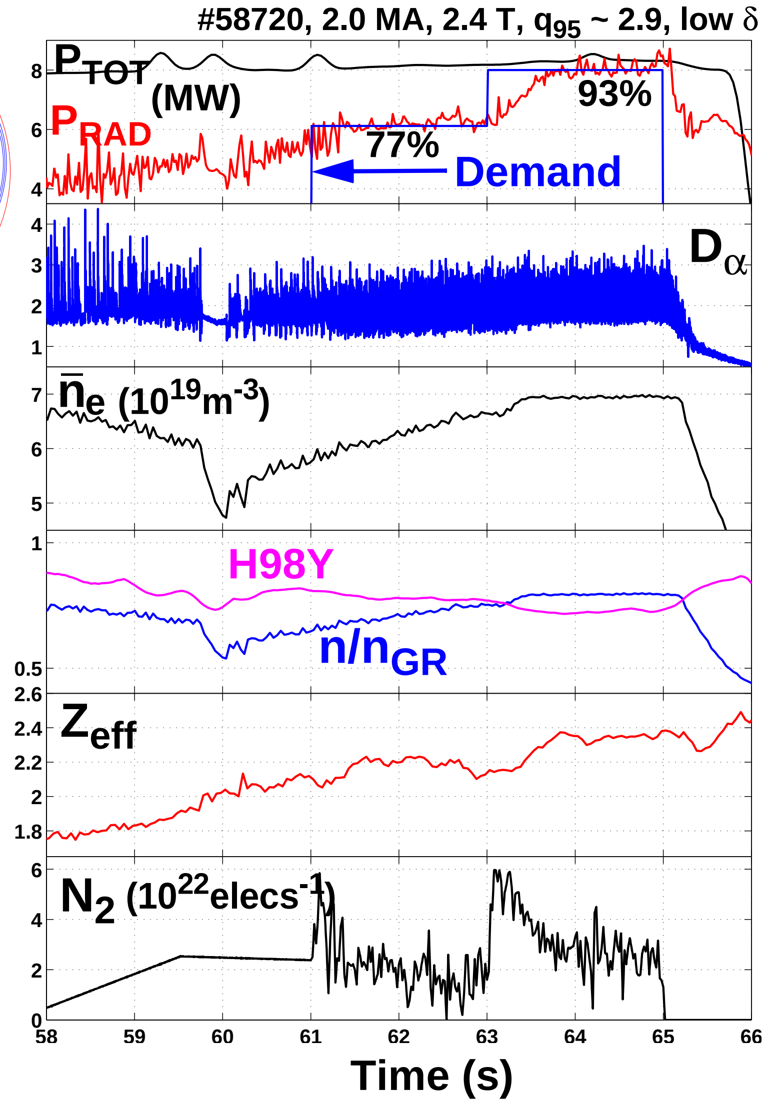
Example: JET - CDH mode with N_2 seeding and feedback on radiation fraction

Feedback on f_{rad} (= P_{rad}/P_{in})

High radiation fractions possible with Nitrogen - radiation mostly confined to the divertor region - but problematic for ITER (non-recycling + chemistry if C present)

CDH marginal as an ITER scenario but demonstrates how basic feedback will work.





J. Rapp, R. Felton

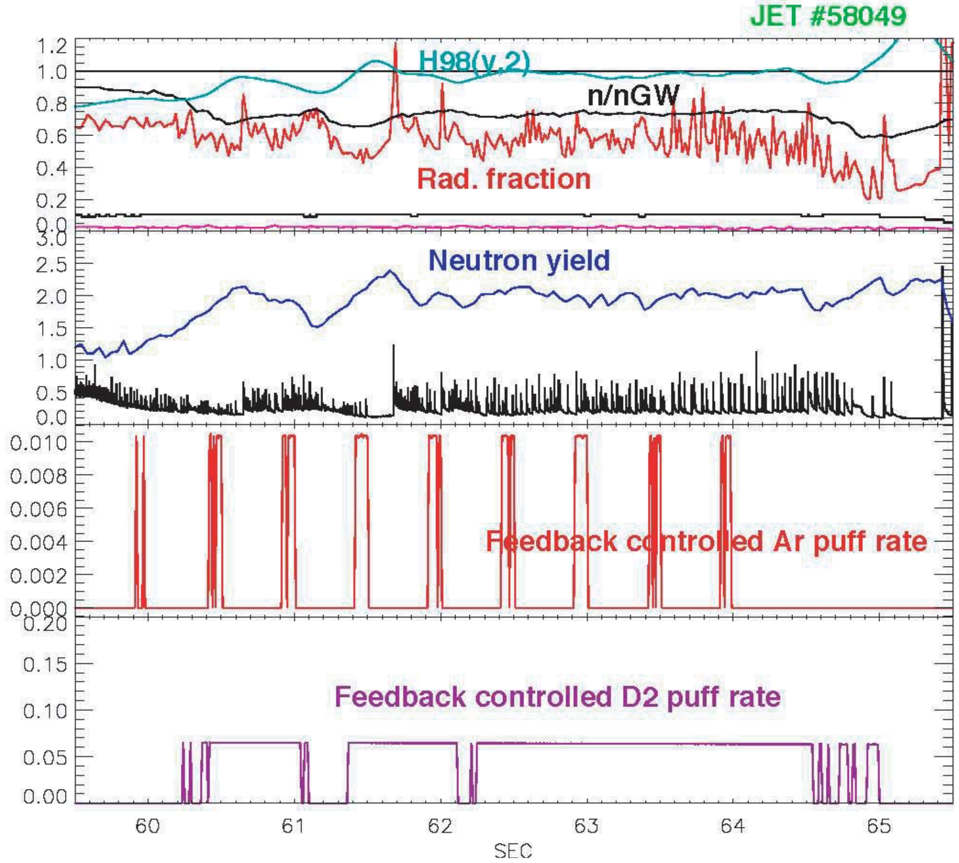
Example: JET - Low δ, Type I ELMing H-mode with feedback on radiation fraction and deuterium fuelling

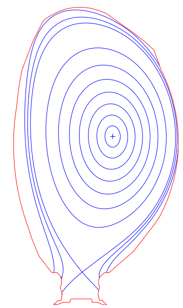
Noble gases (Ar, Ne, Kr, Xe) also used on JET - more main chamber radiation, lower f_{rad} than for N - radiating mantle

Crude feedback (on-off) of D2 puff for density (H98(y,2)) and Ar puff for f_{rad}

Reasonably steady conditions - big improvement on previous control of f_{rad} only + Ar blips

Simultaneous feedback control of H98(y,2) and Prad/Ptot



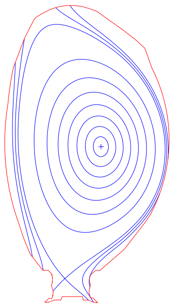


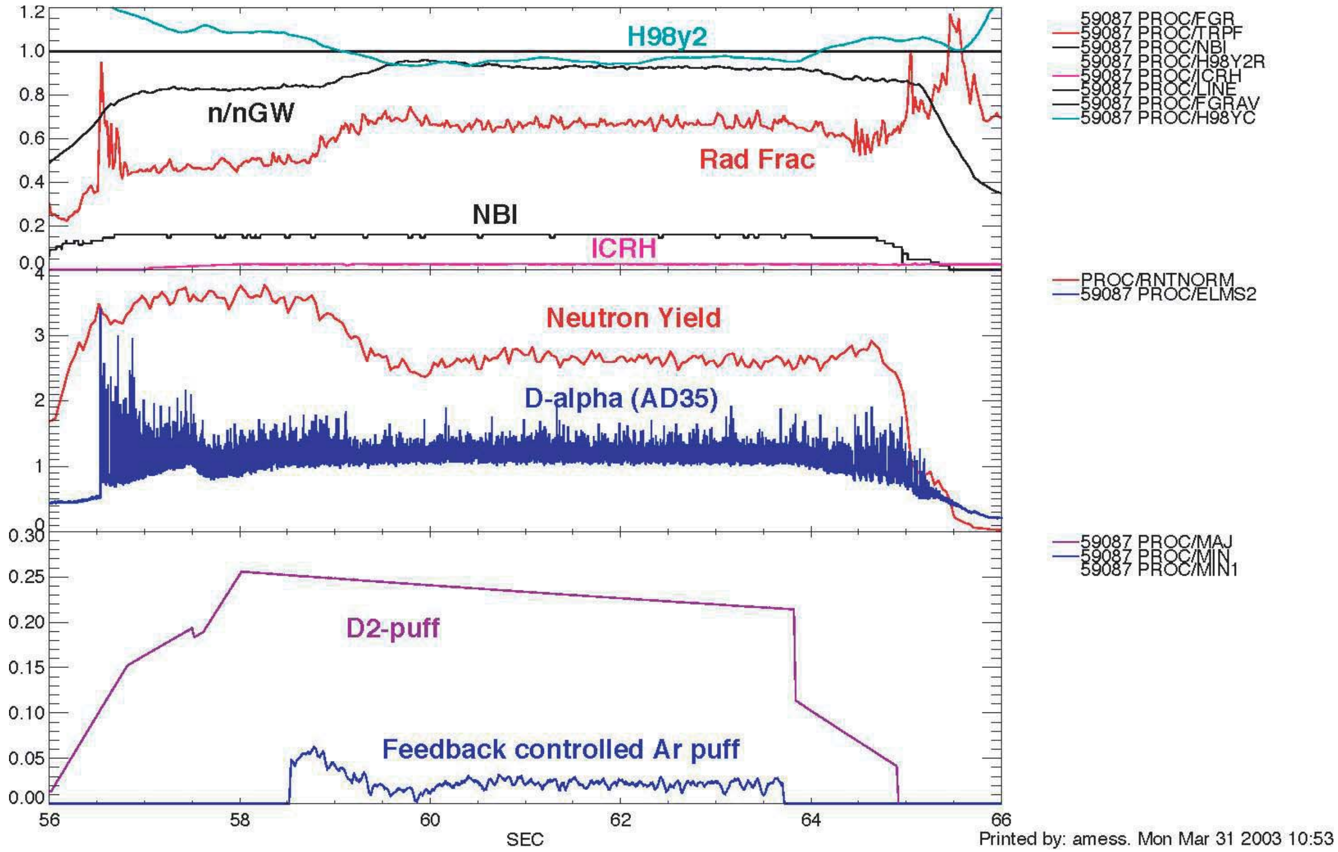
#58049, 2.0 MA, 2.4 T, q_{95} ~ 3.7, low δ (δ_u~0.24, δ_l~0.27)

J. Ongena

Example: JET - High δ, Type III ELMing H-mode with feedback on radiation fraction

#59087, 2.0 MA, 2.7 T, q_{95} ~ 4.5, high δ (δ_u~0.46, δ_l~0.36)





Now continuous Ar fuelling to control f_{rad} - not yet with simultaneous D2 feedback - more experiments to account for synergy of D and Ar puffs H98(y,2) ~ 0.95, n/n_{GW} ~ 0.90, f_{rad} ~ 0.6m, constant neutron yield, C_{Ar} ~ 0.1%

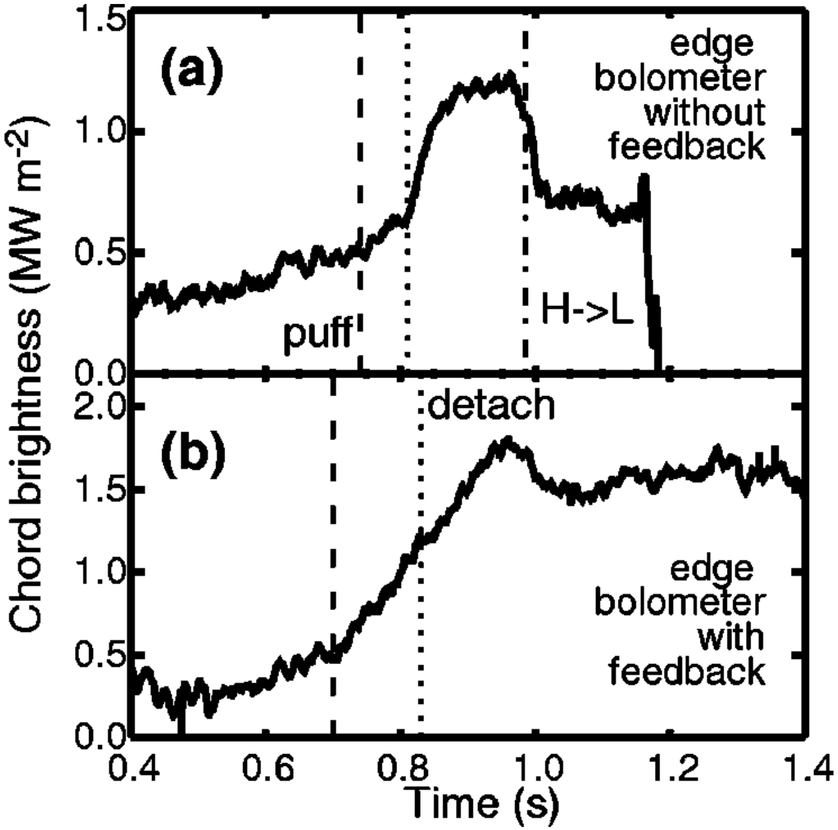
Example: C-Mod - EDA H-mode with N_2 seeding

Use fast piezo electric valve in divertor floor tiles to puff N2 - 2 ms response time and low conductance to divertor

Feedback on injection rate to achieve edge radiation and maintain H-mode

Use (tangential) edge bolometer chord for feedback

EDA avoids core impurity accumulation so that N_2 can be used as detachment actuator



J. A. Goetz et al., Phys Plasmas 6 (1999) 1899

Example: AUG - Type I ELMing H-mode with Ar seeding and feedback

Feedback on:

Divertor neutral density, $n_{0,div}$

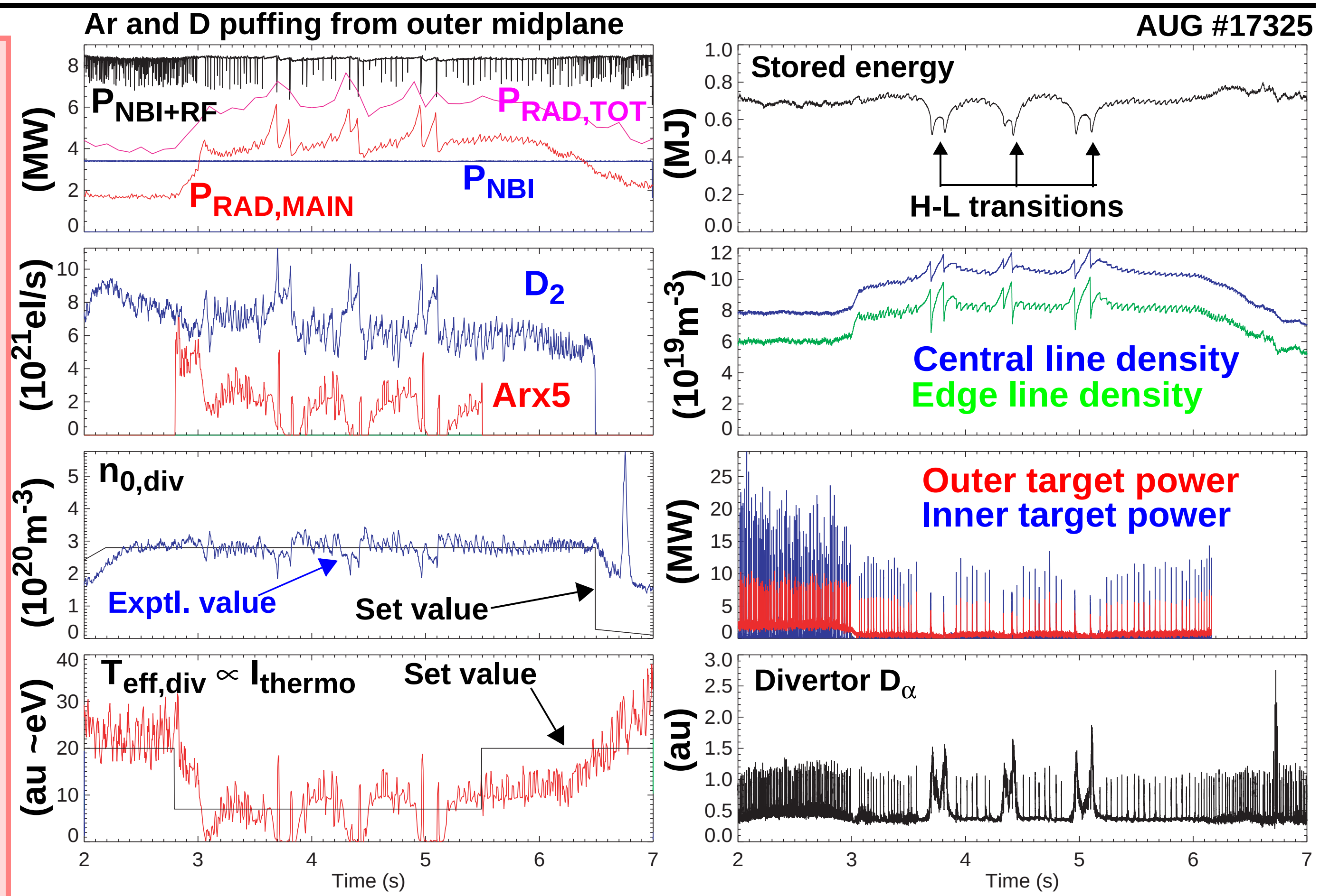
Tile thermo-currents

to control:

D_2 puff rate (hence n_{sep} and pumping)

and

Ar puffing rate (hence divertor power deposition and f_{rad})



Existence of thermocurrents associated with good confinement on AUG

Use Ar to retrieve thermocurrents when ELM delays lead to increased P_{rad} and hence H-L transitions

Simultaneously reduced divertor power flux

A. Kallenbach, IPP

AUG - Integrated scenario compatible with all Tungsten first wall (carbon free)

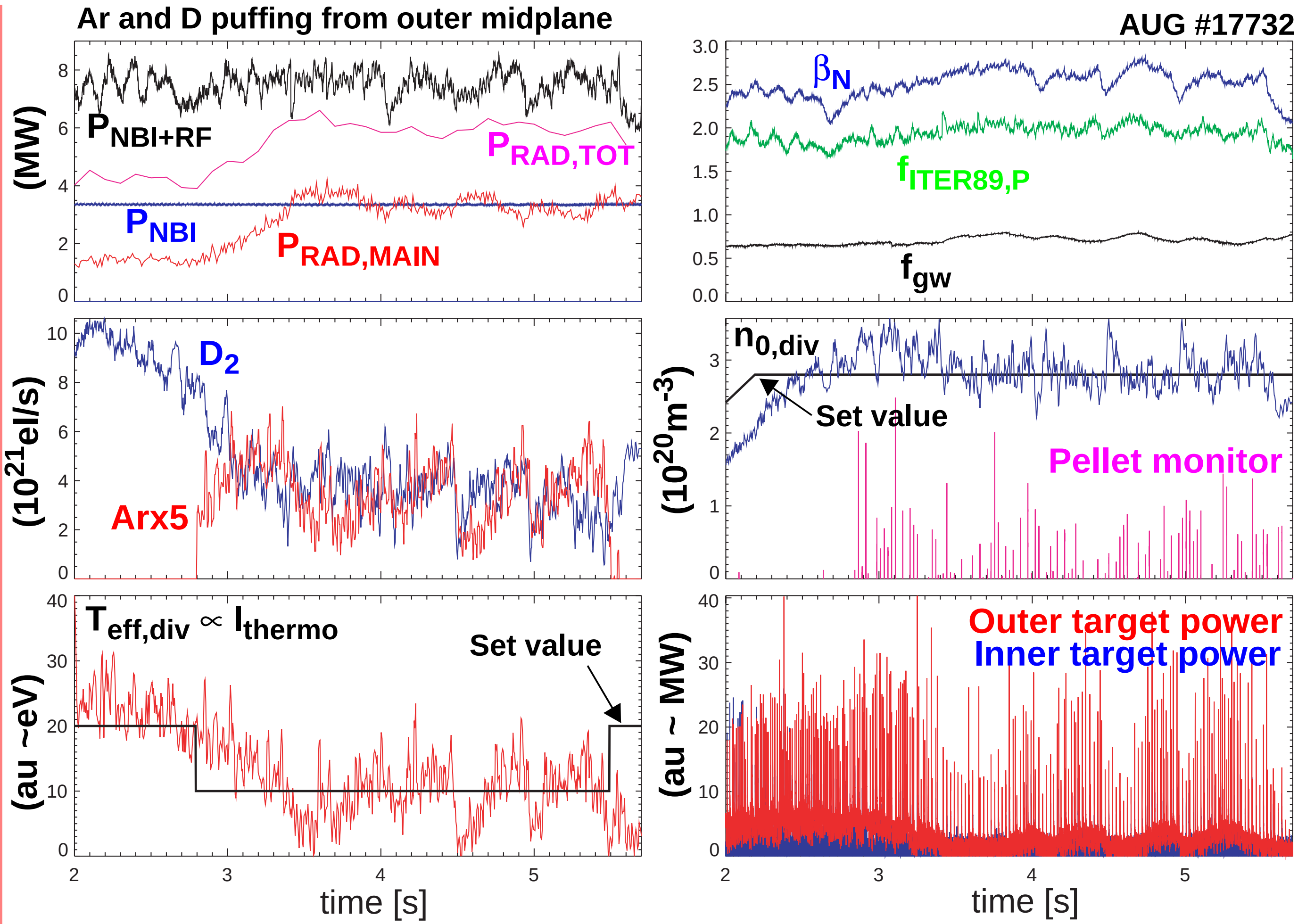
Feedback on:

Divertor neutral density, and tile thermo-currents

Now add HFS 40 Hz pellet launch for ELM triggering

No central rdiation peaking

Core tungsten concentration remains low



A. Kallenbach, IPP

Divertor and first wall surface temperature

Not generally an issue in todays devices

- **Diagnostic coverage usually very poor - we don't know in general anyway when and where abnormal power loads occur**
- **Divertor plates the worst affected areas (ELMs). Power deposition very localised in space and occurs on fast timescales - diagnostic access difficult**

On ITER

- **First wall designed for average surface heat flux = 0.25 MWm^{-2} (3000 cycles, t = 400 - 500s), 20 MWm^{-2} transient for 10 s on 300 cycles**
- **Will need global monitoring of surface temperatures to the largest extent possible - very difficult in the divertor**
- **Control will have to use a combination of signals (IR, thermocouples, cooling water temperature) possibly with support from algorithms based on magnetics (eg. wall gaps - WALLS at JET).**

Example: JET - Wall Load Limitation System (WALLS)

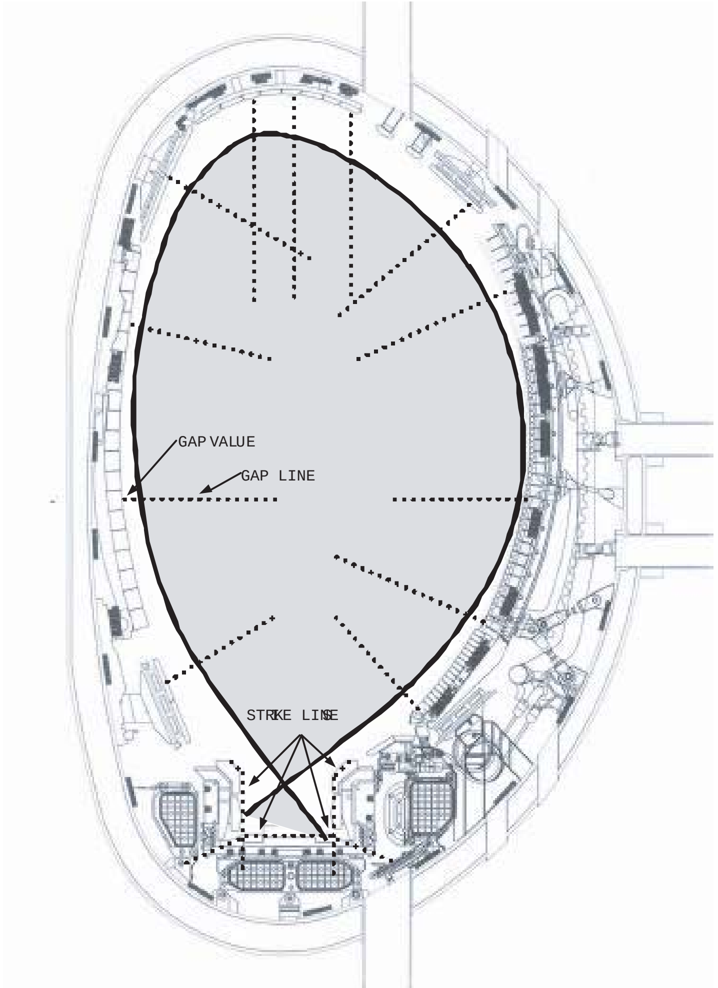
Plasma boundary location specified as positions along set of poloidal lines + 4 curves for divertor

Real time check of plasma-wall clearance along chosen lines and calculation of accumulated energy due to additional heating

Each gap rated with maximum energy handling capacity

Once the maximum is exceeded pulse is terminated by soft stop

Situation more complicated for the divertor but an algorithm has been implemented for the MarkIISRP



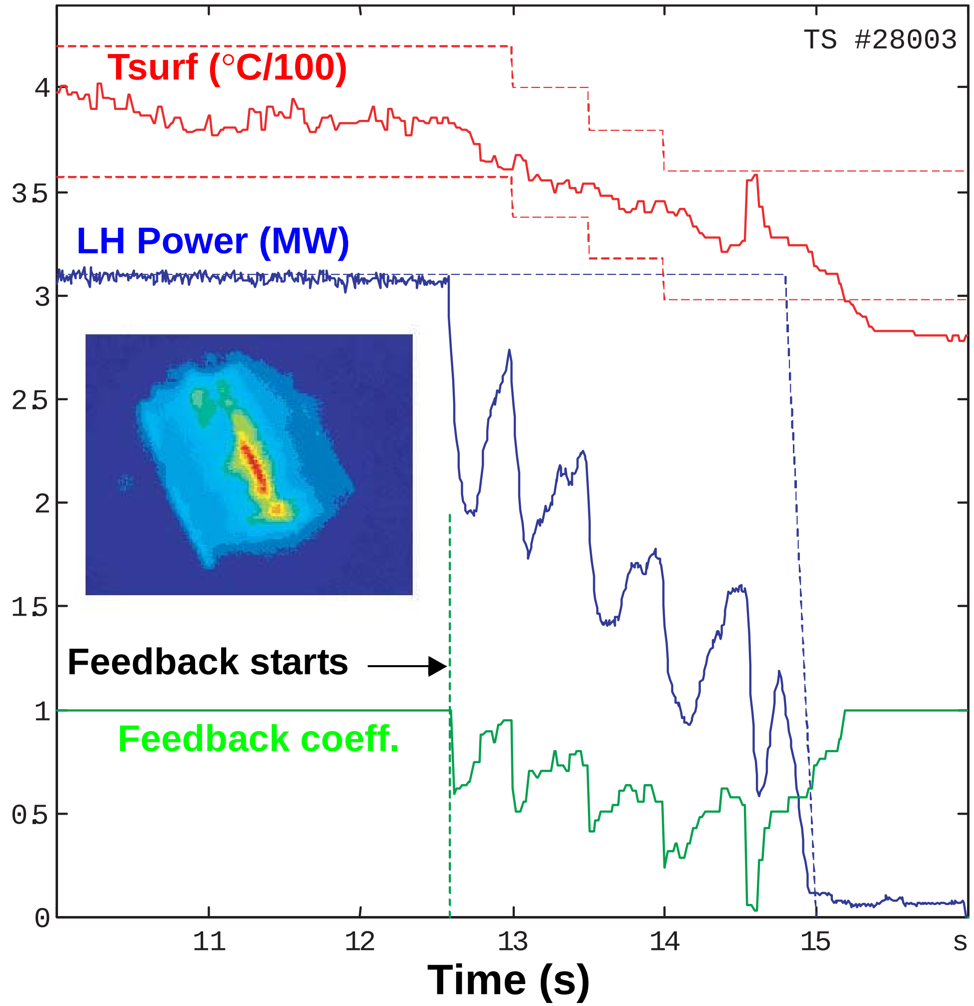
A. Canadese et al., SOFT 2002

Example: Tore Supra - feedback on Infra-Red surface temperature for control of LH power

Demonstration: constrain T_{surf} on main outboard limiter to remain within certain range

Modulate pre-programmed LH power waveform with feedback coefficient.

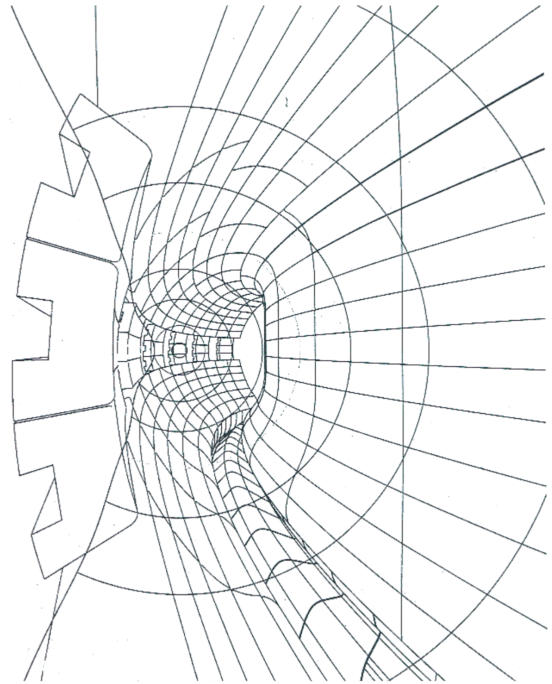
Similar technique might be applied on a machine like ITER, but diagnostic probably insufficiently robust and actuator much more complex



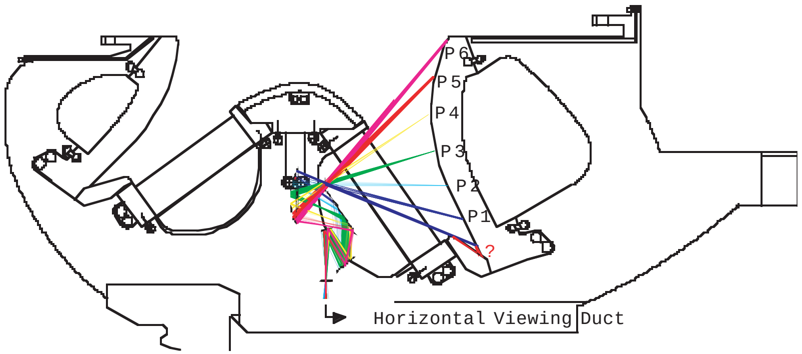
G. Martin et al., IAEA Sorrento 2000

Infra Red measurements planned in ITER in the divertor and main chamber. Also wide-angle view in JET.

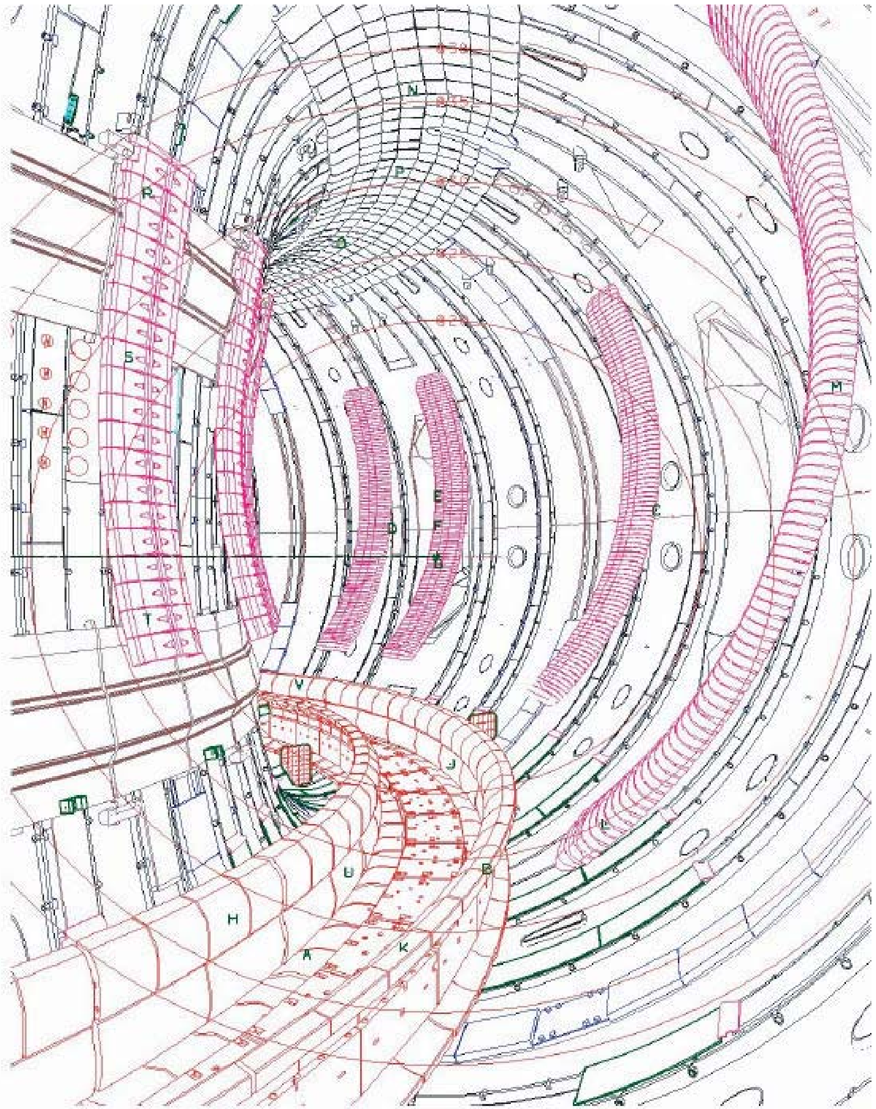
ITER



Multiple vertical and equatorial views



Divertor viewing at single toroidal location



JET - planned, 2005

Particle exhaust (I)

ITER ref. scenario expects $\tau_{He}^*/\tau_E \sim 5$ for $c_{He} < 0.06$

Control issues for He pumping when divertor conditions change not generally addressed in current machines - only in a nuclear machine can this be properly implemented

- **ITER Fuel throughput (gas puffing, pellet injection) max: $\Gamma_{DT} = 200\ Pam^3s^{-1}$ limited by capacity of tritium processing facilities and problem of tritium inventory**
- **He enrichment depends on divertor compression, itself dependent on state of detachment**
- **Detachment very sensitive to $n_{e,sep}$, itself important for performance**
- **c_{He} also very sensitive to Z_{eff} - τ_{He}^*/τ_E, must decrease if Z_{eff} rises to maintain dilution for given performance - Z_{eff} rise dependent on seed impurity injection for radiative exhaust at plasma edge**
- **Effect of ELMs on He enrichment poorly understood**

Particle exhaust (II)

Control laws not established - important processes inter-linked. But number of actuators and sensors quite limited

- **Actuators: DT fuel mix, fuelling rate and location, impurity seed injection rate, perhaps local edge heating to affect ELM freq.?**
- **Sensors: main chamber and divertor spectroscopy, fast neutral pressure gauges (perhaps), sub-divertor partial pressures of D,T,He (relatively slow timescale), total radiation, divertor IR, Langmuir probes (but lifetime?).**
- **Still a few unknowns:**
  - **How much T back from the walls if D-rich DT mix?**
  - **Importance of intrinsic vs. extrinsic particle sources**
  - **Situation very unclear for He exhaust in ITB scenarios - deposit He inside barrier - accumulation**
  - **Strike point movements - eg. during large ELMs - big jumps seen at JET - effect on enrichment?**

Disruption mitigation (I)

High energy content disruptions threaten plasma facing components in 3 ways:

- **Divertor plate melting - restricts ITER target material choice (C)**
- **Reduce poloidal halo currents - reduce stresses on VV and in-vessel components**
- **Increase background density to avoid loss of runaway electrons which will otherwise cause severe damage to the first wall**

Now being actively addressed within the community

- **ITPA collaboration (SOL & Divertor + MHD)**
- **EU Task Force on PWI - disruption working group**
- **Experiments on mitigation techniques already performed on most major tokamaks (fast noble gas injection, killer pellets)**
- **Control methods, mostly neural networks, sometimes tried (AUG, JET)**

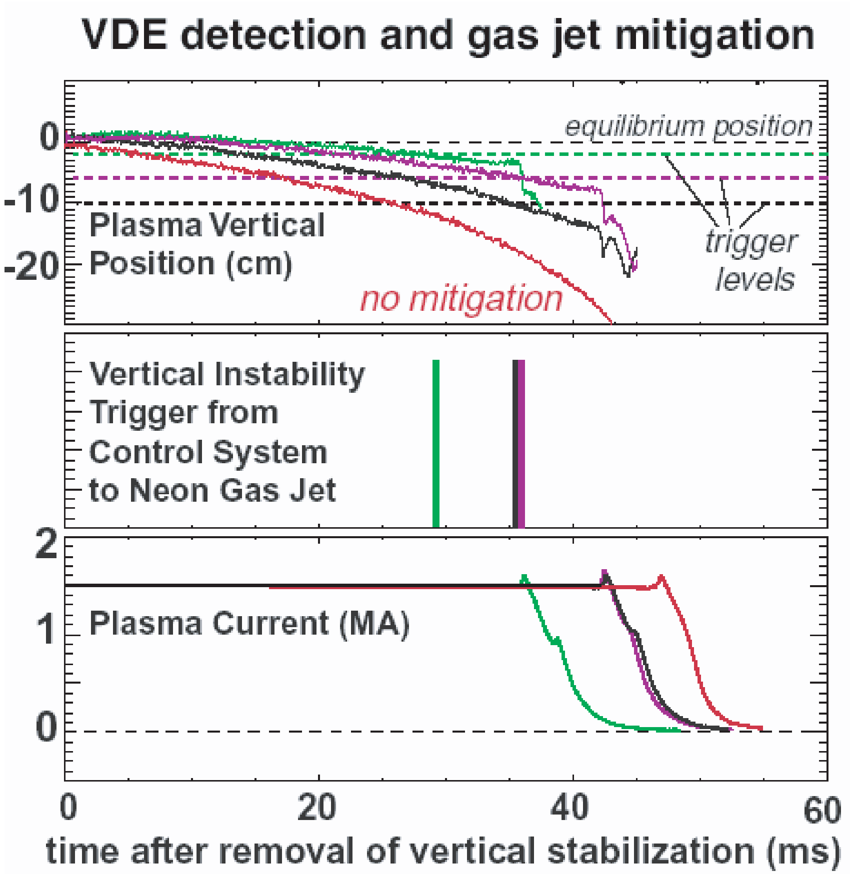
Disruption mitigation (II)

Cannot afford to train a neural-net detection system on ITER disruptions themselves

Set of parallel algorithms will have to pre-designed based on known plasma theory and empirical results:

- Position control/VDE
- Radiation/density limits (detachment control - MARFE formation)
- Ideal MHD, q and β-limits
- NTM stability

Control must not produce to many false-positive mitigation events



Example of real-time VDE detection and mitigation with high pressure Ne gas jet on DIII-D

D. G. Whyte, Univ. Wisconsin

Erosion of divertor surfaces

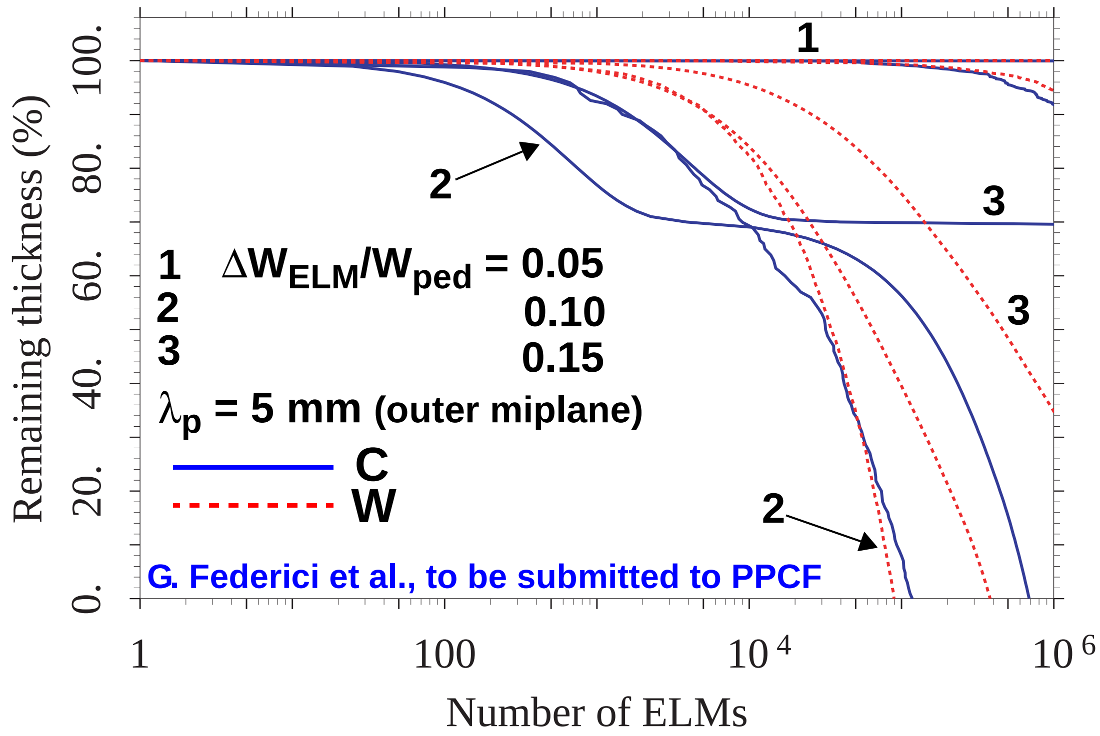
Undoubtedly one of the most outstanding problems

Is it really a control problem?

- **Degree of difficulty during tritium operation will depend on choice of wall material. If Carbon targets (steady state):**
  - **Peak net erosion rate ~ 6.5 nm/s***
  - **Tritium co-deposition rate ~0.5 - 2.5 g/pulse***
  - **No. of pulses prior to recovery of co-deposited Tritium: 200-900**
- **Situation considerably less clear if Type I ELMs must be tolerated**
- **If W targets, erosion problem less severe (but implies that we have solved the ELM problem).**
- **No experimentally tested erosion monitor available**
- **Post pulse net erosion monitoring probably ok, but if significant erosion occurs in a single pulse, this is of little use**

***Data from modelling by Jeff Brooks (Argonne NL/2000)**

ELM induced erosion of target surfaces



Assume pedestal energy ~ 105 MJ, 50% loss of melt layer per ELM for W target
Triangular waveform of target power deposition: ramp-up/down = 0.5 ms, inter-ELM power deposition of 5 MWm^{-2}
Basic picture is that ELMs must stay at around ΔW_{ELM} ~ 5 MJ for acceptable lifetime (> 10^6 ELMs or 3000 full power pulses)
Anything else means that erosion rates will be faster than baseline and we need to try and measure/control them

Erosion of divertor surfaces - control options

Current options very limited - development required

- **Erosion monitor under consideration for ITER**
  - Divertor: Speckle interferometry - possibility for real time (nm resolution)
  - Divertor: Optical radar - post pulse
  - Main vessel + divertor: LIDAR (IR laser radar) - only infrequent inspections possible - offline
- **Most obvious and simplest possibility would appear to be tile markers**
  - Implant materials inside a number of divertor target tiles and watch spectroscopically (eg with ITER divertor impurity monitor) for the first appearance of each species
  - Multiple implants at different depths are possible
  - But very coarse solution - does not constitute "control"
- **Development of erosion rate predictor algorithms - no direct measurement?**

Additional general remarks

There is still a lot more we can learn in current devices:

- Control of partial detachment
- Importance of gas puff location (divertor/main chamber) - linked to relative radiation distribution
- Relationship between D and seed impurity puffing
- Impact of different seed gases
  - Modelling indicates that type of noble gas used in ITER relatively unimportant
- More detailed characterisation of how acting on the edge plasma affects the core
  - Strong link between divertor and upstream plamsa densities
- Which are the best sensors?
  - What is the absolute minimum that we must provide for ITER?
  - Is what is currently envisaged sufficient?

Conclusion

- Issue of control of power and particle exhaust for ITER in a relatively immature state - core more advanced. In some areas (eg. erosion), little or no work yet done, encouraging in others
- Divertor power and particle control cannot always be dealt with in isolation from core control
- Much will depend on correct choice early on of required sensors (ie edge diagnostics)
- Little known about power and particle control in advanced scenarios
- It is timely to begin thinking about these issues now!