Thermal Load Specifications from ITER

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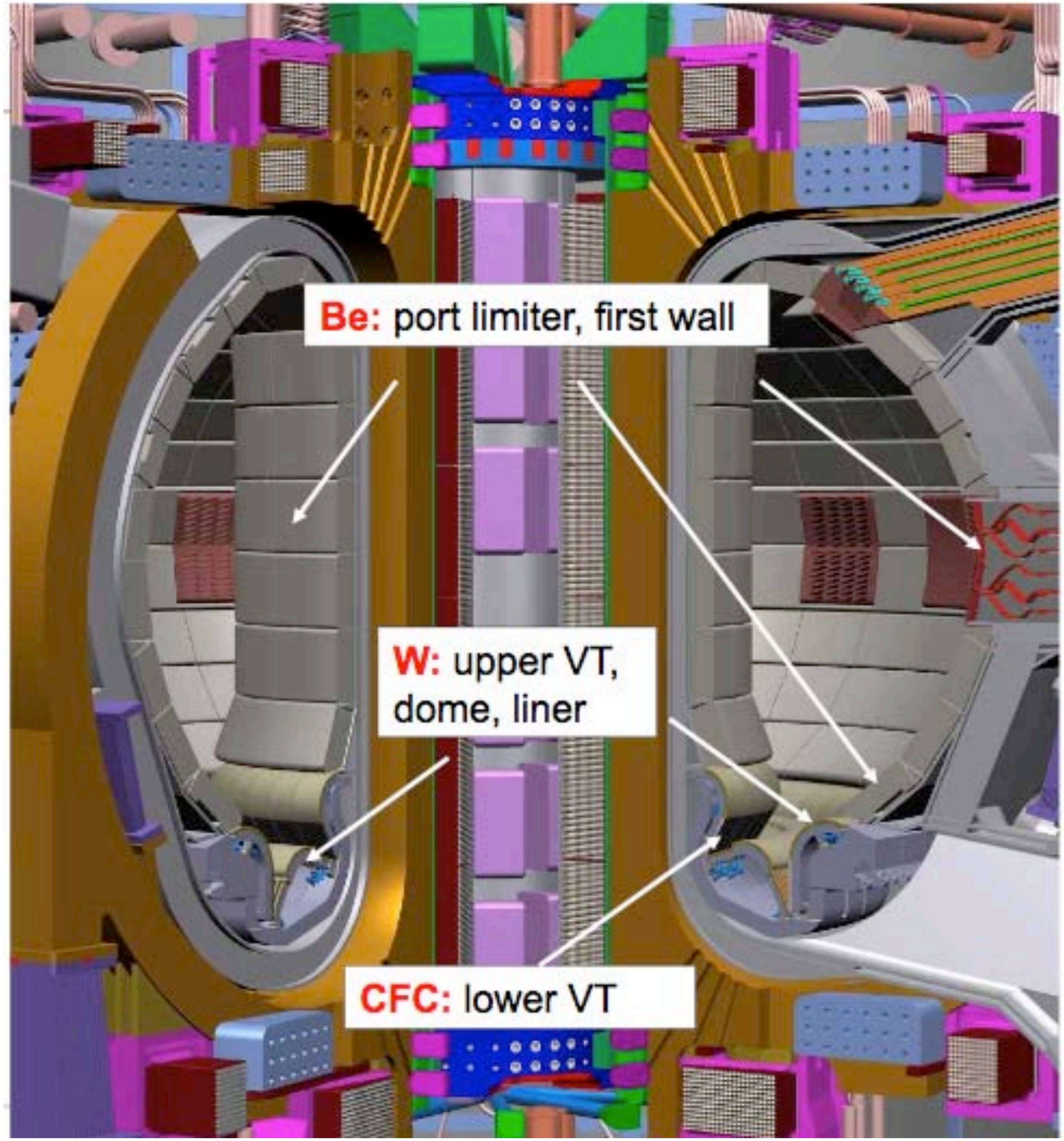
ARIES Project Meeting, May 19, 2010
UCSD



Be: port limiter, first wall
W: upper VT, dome, liner
CFC: lower VT

Total Powers to In-vessel components

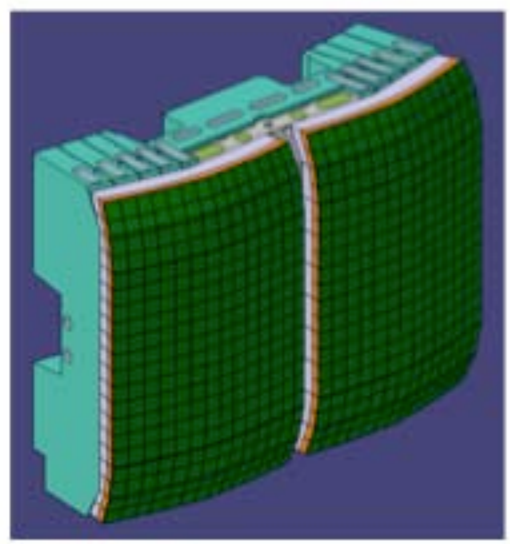
Parameters	Unit	H/D	DT[1] Inductive (P_{fusion}=500 MW)	TBA[1,3] (P_{fusion}=700 MW)	Hybrid[1] (P_{fusion}=400 MW)	Non-inductive[1] (P_{fusion}=356 MW)	Section
Total heat from plasma to in-vessel components	MW	77[2]	847[2]	1194[2]	693[2]	625[2]	3.1
of which:							
Nuclear Heating Power		-	660[2]	924[2]	528[2]	470[2]	
Alpha heating Power		-	110[2]	154[2]	88[2]	78[2]	
Additional Heating Input		77[2]	77[2]	116[2]	77[2]	77[2]	

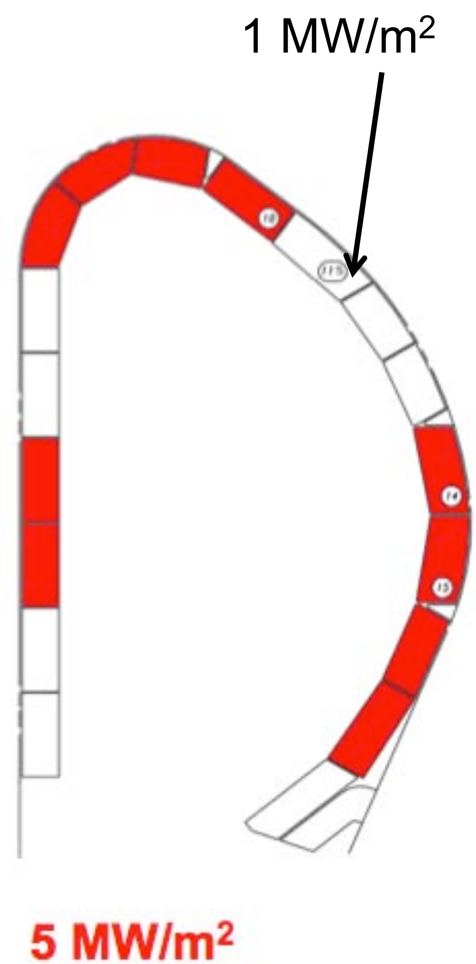
ITER has P_{fusion} ~ 300-700 MW

ARIES has P_{fusion} ~ 1700-2700 MW

ITER plasma power ~ 120-200 MW

ARIES plasma power 450-750 MW





Various divertor powers

Maximum power to the scrape-off layer (P_{SOL}= P_{alpha}+P_{aux}-$P_{core,radiation}$)

115-140 MW ARIES 211-284 MW

Maximum radiated power fraction (fraction of P_{SOL}) for partially detached (attached) divertor operation

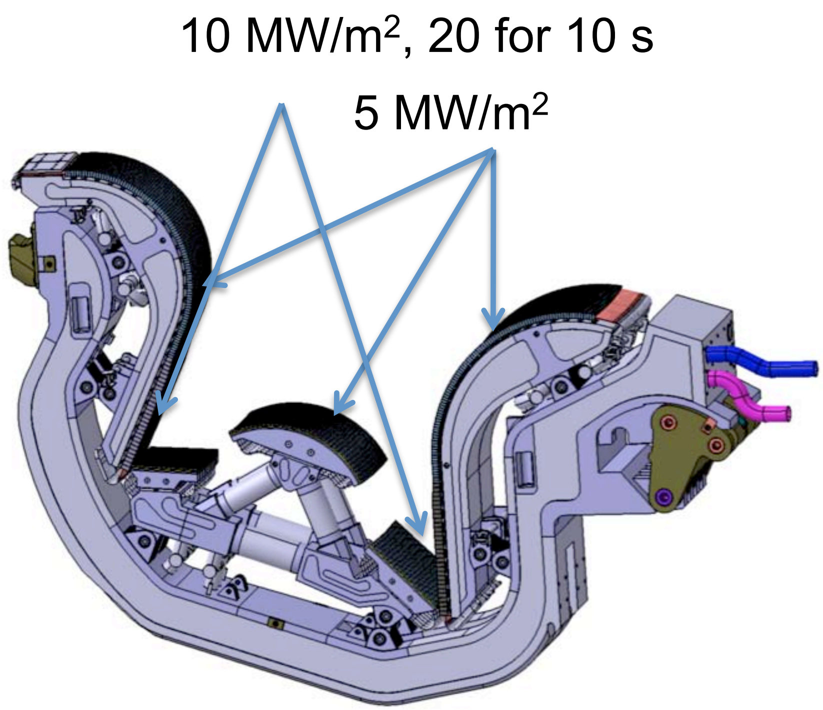
70% (20%) ARIES (detached) 75-90%

Maximum of duration of any uncontrolled attached divertor phase

0.5 s

Maximum nuclear (total) power to the divertor

45-90 MW (165-205 MW)
ARIES 155-200 MW (350-500 MW)



Various divertor powers, cont'd

Maximum power flux at outboard divertor in detached (attached) operation

10 MW/m^2 (42 MW/m^2)

Power flux e-folding length mapped to outboard midplane

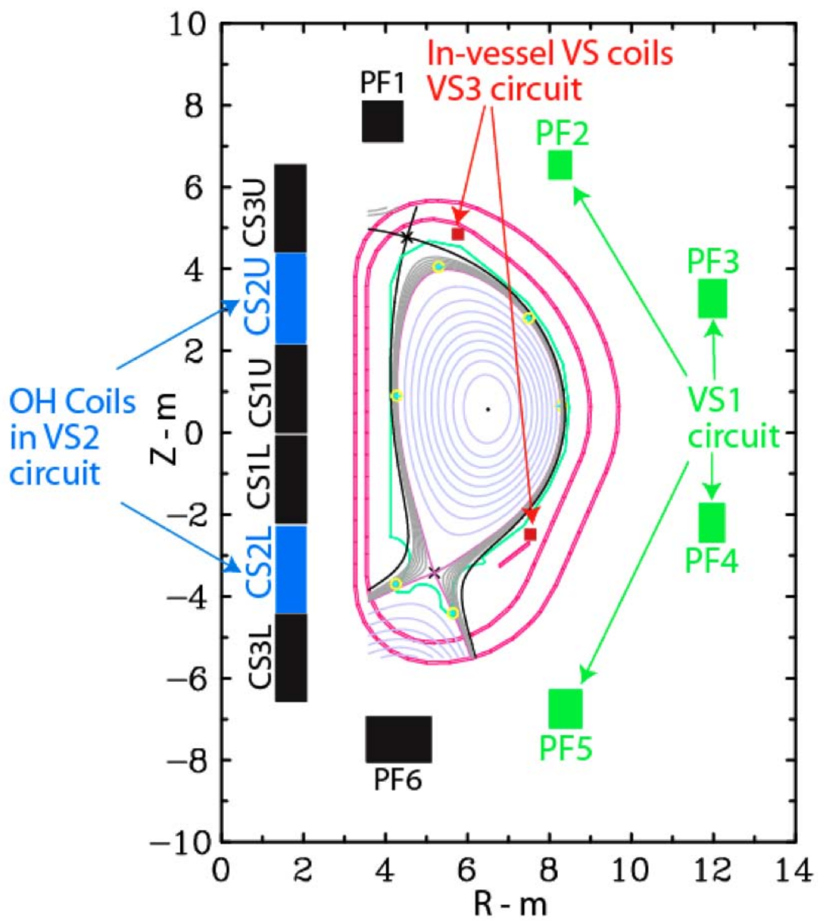
0.5 cm

Maximum static fraction of thermal power to outboard (inboard) divertor

2/3 (1/2) ITER is SN ARIES has double null, 80% outboard and 20% inboard and then can assume 65% in each outboard

Maximum fraction of time-averaged ELM power to outboard (inboard) divertor

½ (2/3) for ITER SN DN for ARIES??



FW powers

Maximum power to FW from radiation and plasma 115-140 MW

Maximum total static plasma power to the outboard (inboard) first wall

15 MW (5 MW) particle loads are up to 7.5×10^{23} /s (2.5×10^{23} /s)

Peak radiated and charge-exchange heat flux to FW during stationary conditions (during stationary MARFE, transient MARFE), radiation peaking factor is 2x

0.5 MW/m^2 (0.25 CX & 0.25 radiation)
Strong CX peaking on outboard 3-4x, radiation is 2x

MARFE's (stationary core, X-pt), radiate all core input power, or all P_{SOL} power

MARFE (stationary 0.6 MW/m^2, transient 0.8 MW/m^2), poloidal peaking 3x

Alpha particle loss peak loads at outboard midplane

0.1-0.3 MW/m^2

Maximum neutral beam shinethru

4 MW/m^2

Static Plasma Heat Loads

- Up to 20% excursion in fusion power for no more than 10 s
- Up to 75% of (P_{alpha}+P_{aux}) can go to the FW or to the divertor
- ITER H-mode diverted operation, power scrape off width ~ 0.5 cm
- The $q_{div,peak}$ < 10 MW/m^2 and He ash removal can only be achieved with highly radiating semi-detached operation

ELMs

- ELM power flux has similar power decay length as between ELMs and high degree of toroidal symmetry
  - Toroidal asymmetries are seen away from separatrix, with 1/10 the power flow
  - Inboard/outboard split for SN plasmas ranges from 1-2……DN need to find this ratio for ARIES

- Time scale for rise of ELM power deposition on divertor target is 250-500 micro-seconds ($2\pi R q_{95}/c_{s,ped}$)

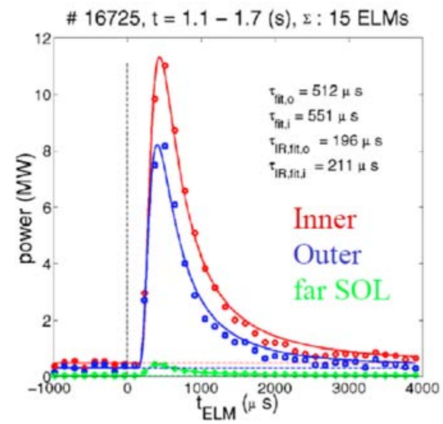
- Energy per unit area = $f_{in/out} \Delta W_{ELM} / A_{wetted,div}$
  - f_{in} = 2/3 for ITER SN
  - f_{out} = ½ for ITER SN
  - ΔW_{ELM} ~ 20 MJ in ITER

- Power loss per ELM is ~20-40% of input power to plasma

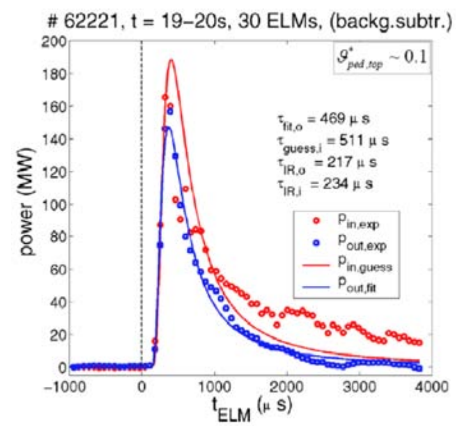
- $P_{ELM} = f_{ELM} \times \Delta W_{ELM} = 0.2\text{-}0.4 \times P_{SOL}$ (f_{ELM} ~ 1-2 Hz)

- Requirement is to keep energy flux < 0.5 MJ/m^2

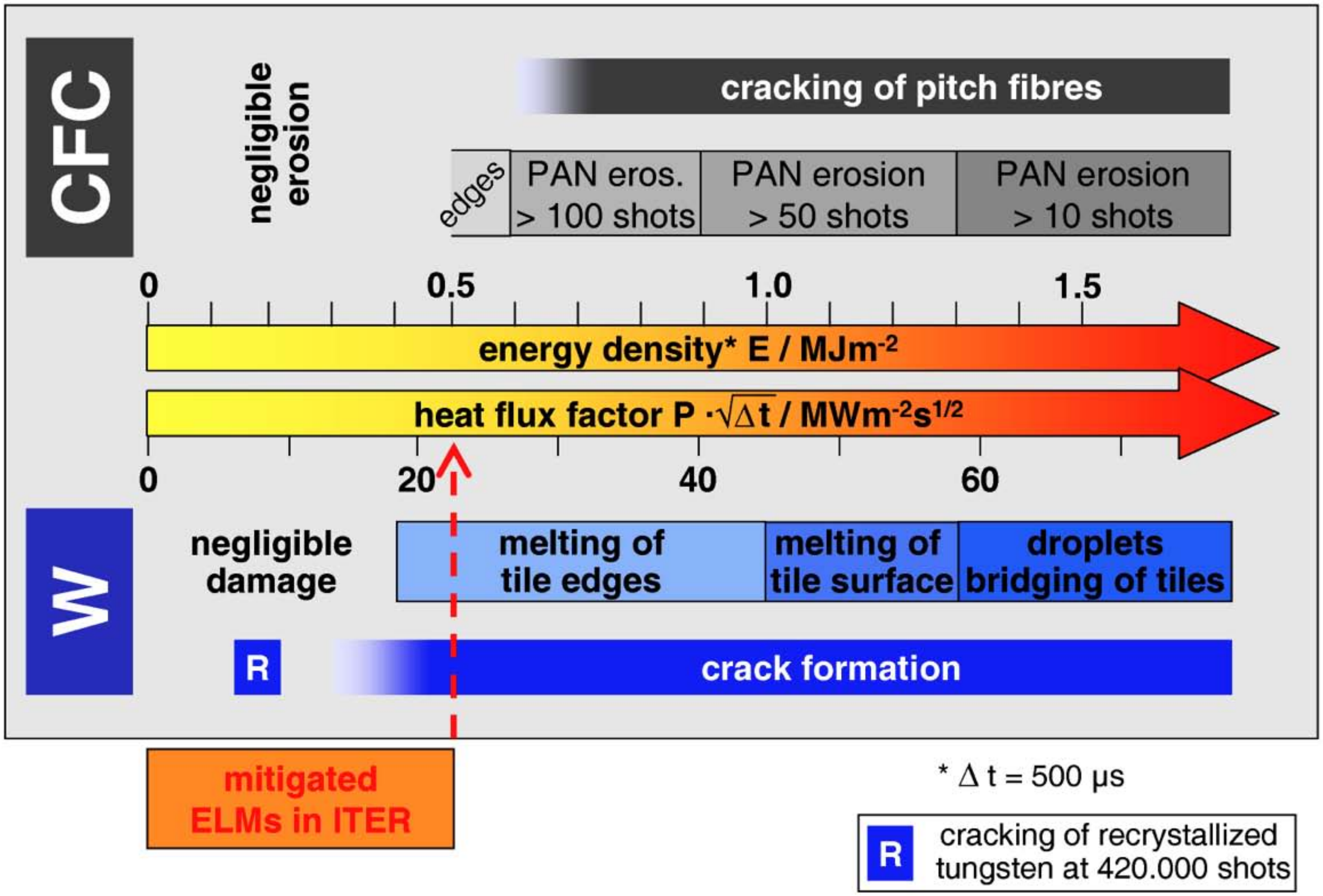
ASDEX-U



JET



Time →


CFC
negligible erosion
cracking of pitch fibres
edges
PAN eros. > 100 shots
PAN erosion > 50 shots
PAN erosion > 10 shots
0
0.5
1.0
1.5
energy density* E / MJm-2
heat flux factor P ·√Δt / MWm-2s1/2
0
20
40
60
W
negligible damage
melting of tile edges
melting of tile surface
droplets bridging of tiles
R
crack formation
mitigated ELMs in ITER
* Δ t = 500 μs
R
cracking of recrystallized tungsten at 420.000 shots

ELMs, cont'd

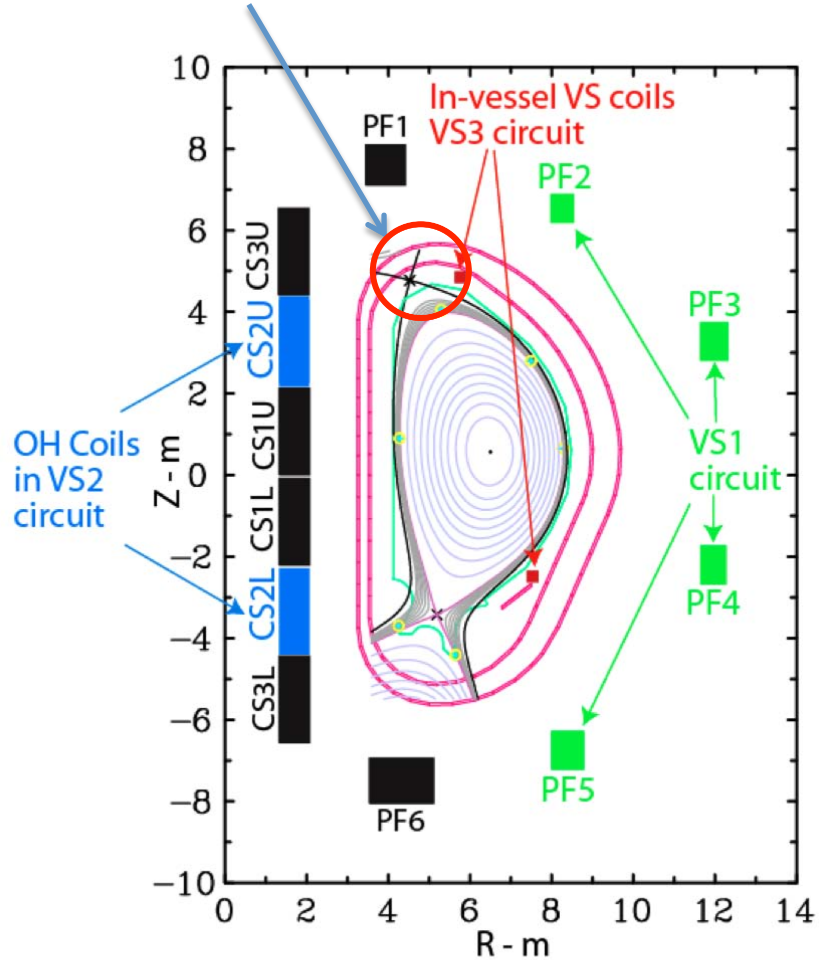
- Erosion of CFC and W in divertor sets 0.5 MJ/m^2 limit
  - Must reach 20 MJ → 0.6 MJ
  - Must reach 1-2 Hz → 33-67 Hz
  - NEED ELM control strategies

- For uncontrolled ELMs 5-20% of ELM energy released is deposited on plasma facing component (0.05-0.2 x ΔW_{ELM})

- Recall that an ELM is like a burst of particles and energy from the plasma edge into the scrape-off layer and it travels parallel to the field line very fast, but also perpendicular to the field lines toward the FW (1 km/s)

- These energy/power fluxes are often quoted as "parallel" values, which appear very high, but this value reflects perpendicular impact, while the actual magnetic field lines graze the FW at shallow angles, spreading the real energy/power flux out. $E_{||}^{upper\text{-}Xpt} \sim 0.1 x E_{||}^{lower\text{-}Xpt}$

Values of energy/power flux are determined at upper X-pt

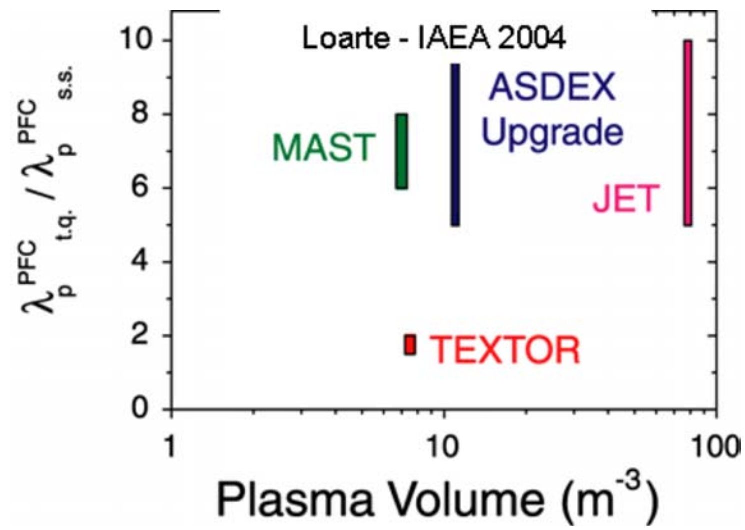


ELMs, cont'd

- Uncontrolled ELMs, 20% of ELM energy and power flux goes to FW, controlled ELMs it is 10% → outboard due to ballooning nature of burst

Disruption thermal loads

During thermal quench there is significant broadening of the thermal footprint, power e-folding



The rise time of power flux in the divertor is a few ms, similar profile in time as ELMs

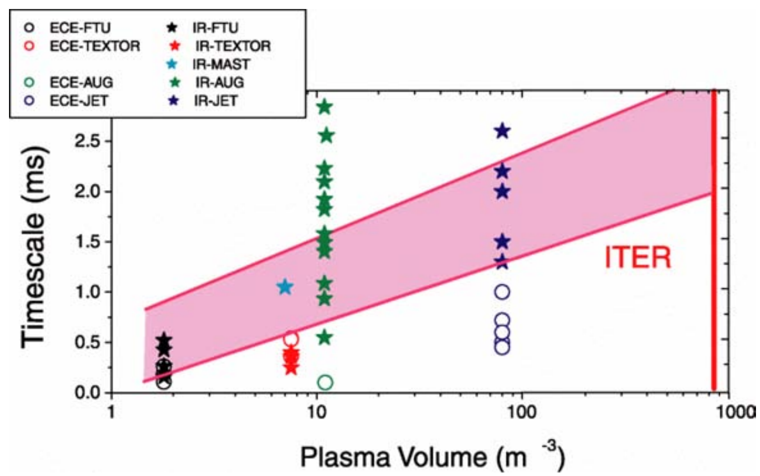
Disruption types:

Major Disruption,

Ideal MHD, Full thermal quench from high performance, Ip quench (non-inductive plasmas)

Resistive MHD, Prequench H→L-mode, thermal quench, Ip quench (inductive plasmas)

Vertical Displacement Events are similar to resistive, but have a different time sequence

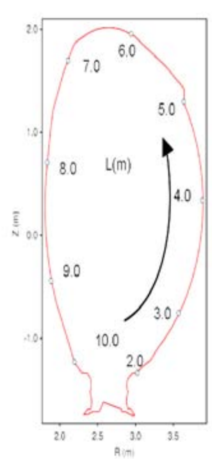


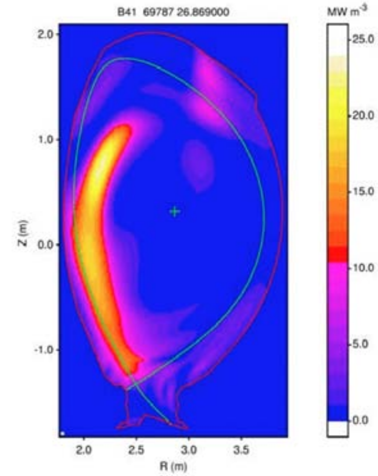
Disruptions, cont'd

- Fast thermal quenches lead to radial plasma motion inward, need to avoid wall contact

- VDE sequence
  – Loss of vertical position, drift of plasma vertically and also radially, plasma remains in high performance H-mode
  – First wall contact leads to H to L-mode transition
  – Edge safety factor reaching 1.5 initiates the thermal quench
  – Ip current quench then follows

- Most of the plasma poloidal magnetic energy is radiated away during the Ip current quench
  – Strong poloidal asymmetry, peaking up to 2x





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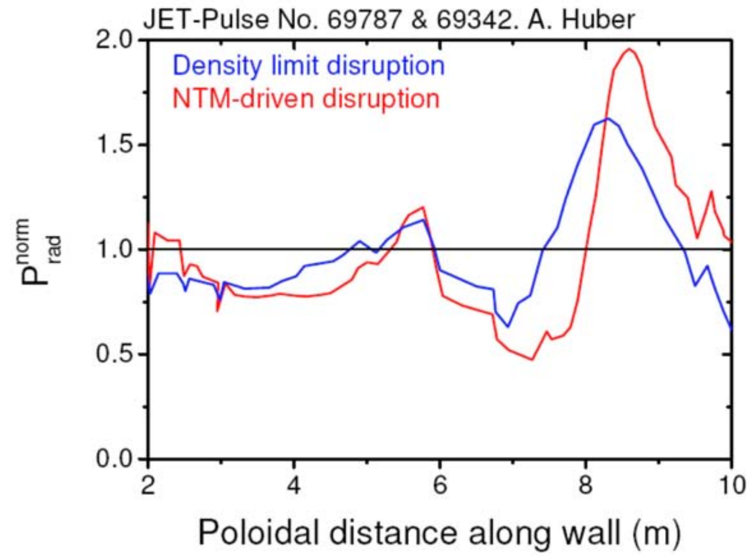

Disruption Specifications

Thermal quench: 1 ms beta drop, 2-3 ms current profile flattening

Current quench: linear over 36 ms, exponential with 16 ms time-constant

Edge safety factor: 3 for major disruption, 1.5-2 for VDE's

Current profile change: li changes by 0.15-0.20

Energy release in thermal quench: ½-1 x W_{peak}

Expansion of heat load footprint: 3-10x (over steady state width)

Toroidal and poloidal peaking: toroidal 2x, poloidal 2x

Time duration of heat deposition divertor/wall: 1.5-3 ms rise, up to 6 ms decay

Disruption scenarios:

- Major disruption
- VDE up
- VDE down
- VDE down with slow Ip quench (0.6-1.0 s)

Other disruption features

- Massive gas injection to mitigate a disruption, then assume entire plasma thermal energy is radiated
  - 350 MJ for 15 MA scenario
  - 325 MJ for Non-inductive scenario
  - Both lead to ~ 0.5 MJ/m^2 average load
  - Peaking factor taken as 3x
  - Duration of radiation load, 1 ms
  - Radiation load during Ip current quench is 500-600 MJ

- Runaway electrons can be induced during disruptions
  - Total energy deposition, 20 MJ, about 1.5 MJ/m^2 average on FW
  - Duration of deposition, 100 ms
  - Maximum energy density deposition, 25 MJ/m^2 for about 10 ms
  - Occurs every major disruption

Nuclear Loads

Ave neutron wall load, 500 MW plasma is 0.56 MW/m^2

Outboard peak is 0.77 MW/m^2

Inboard peak is 0.59 MW/m^2

Divertor entrance is 0.49 MW/m^2

Damage over lifetime in ITER, highest values throughout thickness

Be is 2.0 dpa

Copper is 5.5 dpa

Steel shielding block, 3.0 dpa

Significant effort to identify gap loads between blanket modules, behind and in-between divertor cassettes

Total fluence to end of DT operation is 0.3 MW-year/m^2

Fast fluence, maximum inboard at TF coil 3×10^{21} n/m^2 ($E_n > 0.1$ MeV)

Inboard TF coil insulator dose, 2.8 MGy

Maximum nuclear heating at inboard TF coil is 14 kW

Conclusions

- Will need to look for appropriate scaling relations where they exist
  - For example we are using a Fundamenski scaling for power scrape-off width that has scrape-off layer power, q, Bt, and density
- There are static, anticipated transients, and off-normal loading conditions
- Setting margins for nominal (static loads) with headroom to handle anticipated transients
- Can one of our power plant designs handle an ITER-like disruption prescription?
  - Does disruption mitigation really help, radiating all thermal and magnetic energy to the FW? Our first wall is metal, NOT beryllium
- Fast particle losses, ions or runaway electrons, we need to characterize these to know how to protect the FW