



Heat Loading in ARIES Power Plants: Steady State, Transient and Off-Normal

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Heat Loading in Power Plants and ITER

Heat Loading prescriptions have traditionally been poorly described from existing fusion experiments, and have contained large errors....

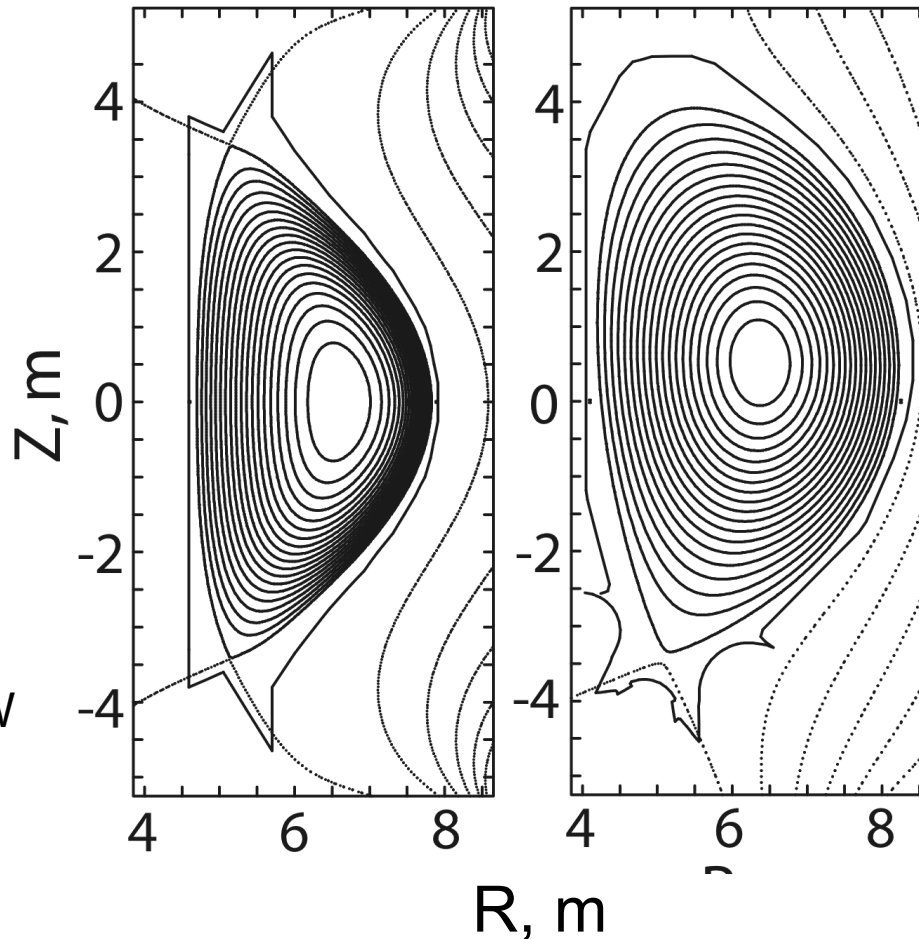
1999 power scrape-off width was proportional to $P_{\text{SOL}}^{0.44}$, then in 2002 it is reported to be proportional to $P_{\text{SOL}}^{-0.4}$ beware, most recent indicates $P_{\text{SOL}}^{0.23}$

Recently, ITER has required a significantly better description in order to design the plasma facing components (PFCs)

As part of the expanded treatment of the PFCs and the plasma edge, ARIES is examining the implications of these heating design criteria for the power plant regime

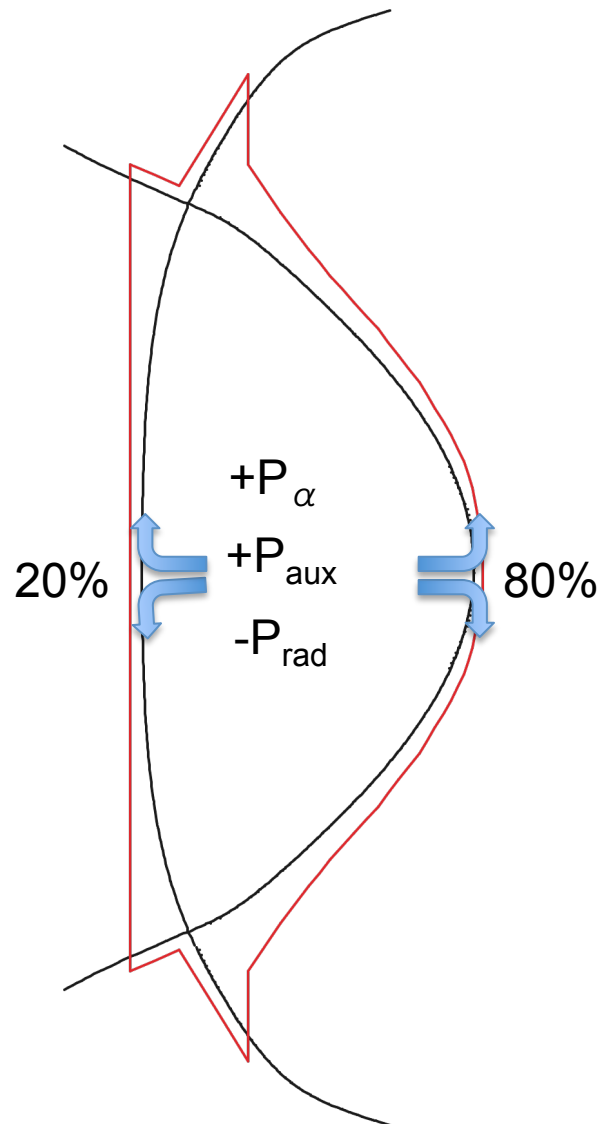
Although the ARIES-ACT1 and ITER have a similar R, they are quite different

$I_p = 10.9 \text{ MA}$
 $R = 6.25 \text{ m}$
 $a = 1.56 \text{ m}$
 $V = 558 \text{ m}^3$
 $A_{\text{surf}} = 586 \text{ m}^2$
 $B_T = 6 \text{ T}$
 $\kappa_x = 2.2$
 $\delta_x = 0.7$
 $\beta_N = 5.75$
 $n/n_{\text{Gr}} = 1.0$
 $H_{98} = 1.65$
 $P_{\text{fusion}} = 1800 \text{ MW}$
 $P_{\text{aux}} = 45 \text{ MW}$
 $P_{\text{SOL}} = 290 \text{ MW}$
 $W_{\text{th}} = 690 \text{ MJ}$
 $W_{\text{mag}}^{\text{int}} = 140 \text{ MJ}$



$I_p = 15.0 \text{ MA}$
 $R = 6.20 \text{ m}$
 $a = 2.0 \text{ m}$
 $V = 837 \text{ m}^3$
 $A_{\text{surf}} = 678 \text{ m}^2$
 $B_T = 5.3 \text{ T}$
 $\kappa_x = 1.80$
 $\delta_x = 0.44$
 $\beta_N = 1.75$
 $n/n_{\text{Gr}} = 0.85$
 $H_{98} = 1.0$
 $P_{\text{fusion}} = 500 \text{ MW}$
 $P_{\text{aux}} = 45 \text{ MW}$
 $P_{\text{SOL}} = 100 \text{ MW}$
 $W_{\text{th}} = 350 \text{ MJ}$
 $W_{\text{mag}}^{\text{int}} = 350 \text{ MJ}$

Steady State Heat Loading



$$P_{\text{SOL}} = P_{\alpha} + P_{\text{aux}} - P_{\text{rad}}$$

The SOL power flows to the divertor within a very narrow layer called the power scrape-off width

$$\lambda_q \sim 7.5e-2 q_{95}^{0.75} n_L^{0.15} / (P_{\text{SOL}}^{0.4} B_T)$$

~ 4 mm for ARIES-ACT1 at the OB midplane

The width expands with the magnetic flux as it travels to the divertor

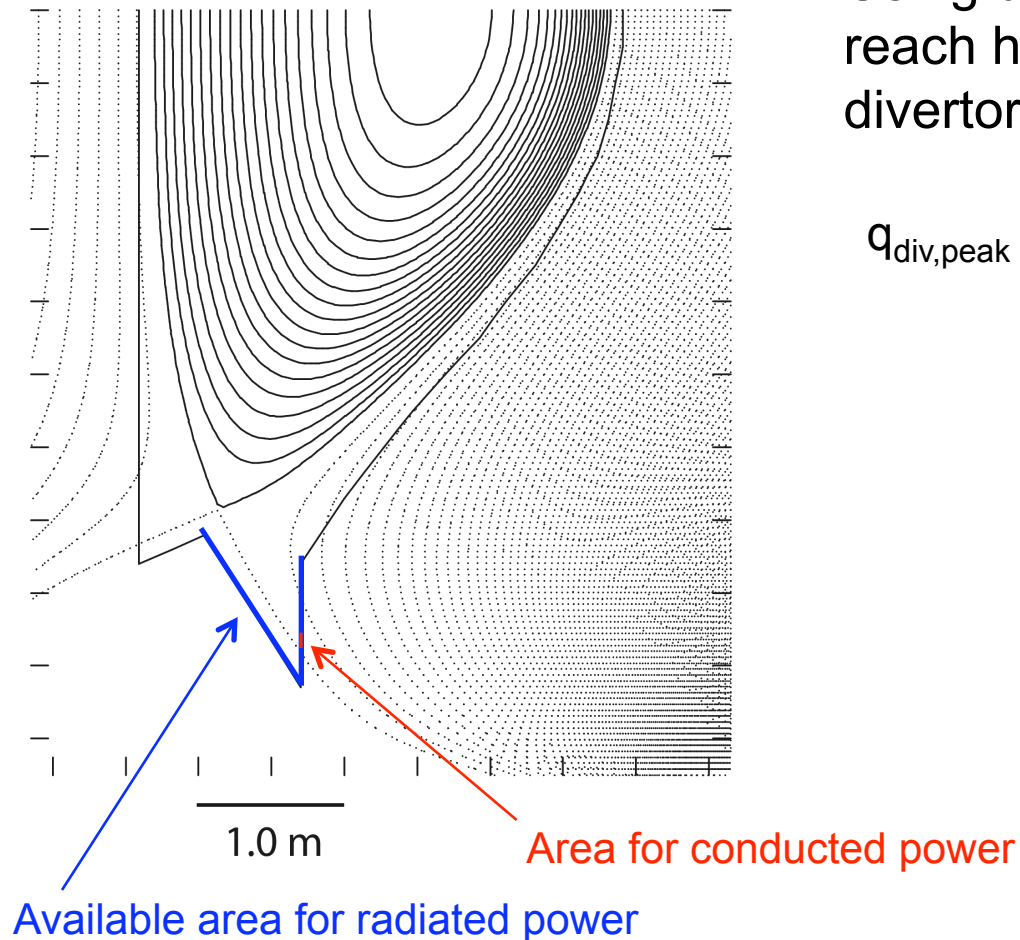
The final area which the power impinges on is ~ 1.38 m² OB and 1.17 m² IB

Steady State Loading, cont'd

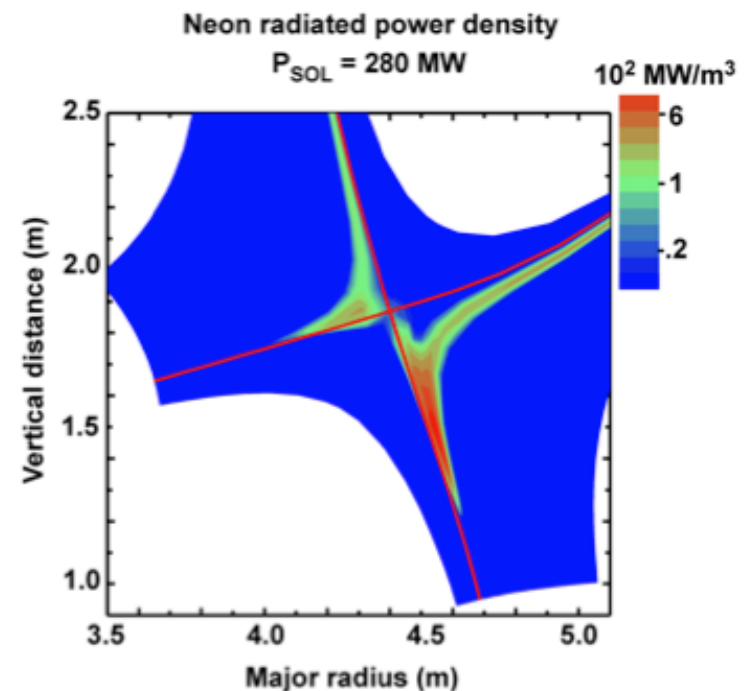
Using detached divertor solution to reach high radiated powers in the divertor slot of 90%

$$q_{\text{div,peak}} \text{ (MW/m}^2\text{)} = P_{\text{SOL}} f_{\text{IB/OB}} f_{\text{vert}} \times$$

$$\left[(1-f_{\text{div,rad}})/A_{\text{div,cond}} + f_{\text{div,rad}}/A_{\text{div,rad}} \right]$$

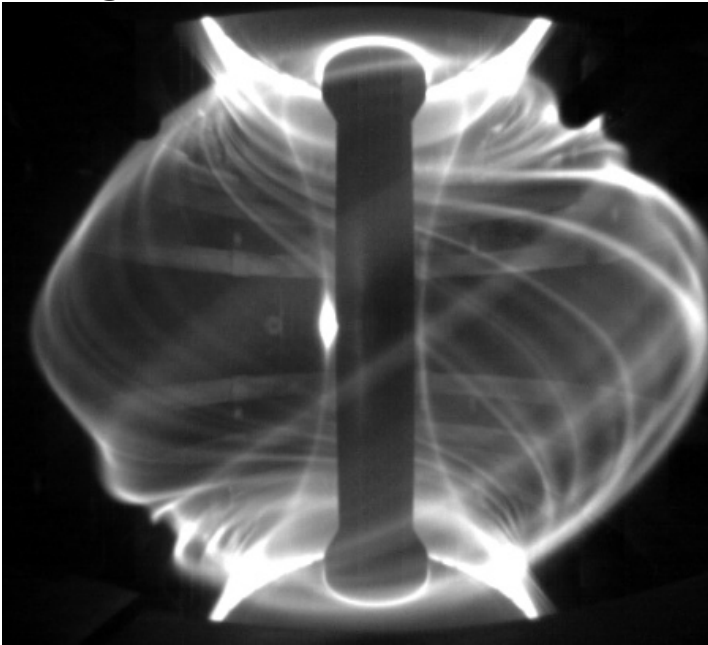


UEDGE analysis, LLNL



Transient Heat Loading

MAST



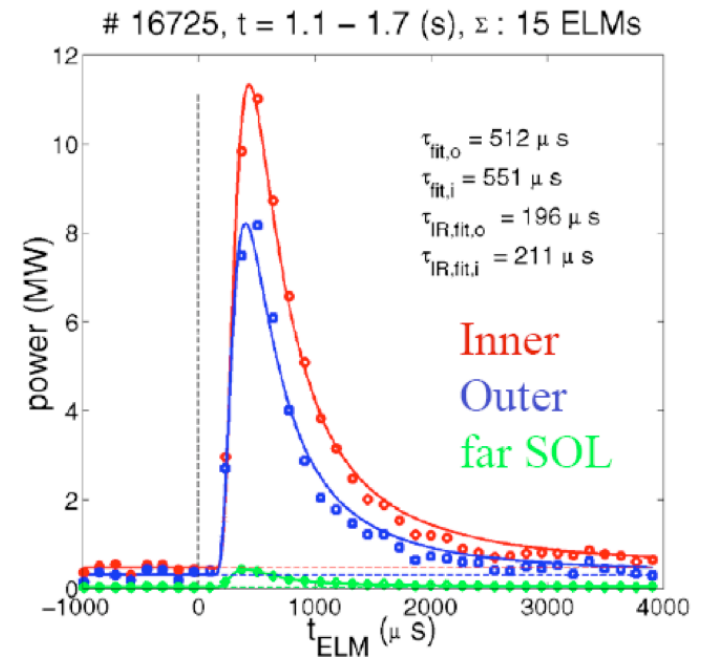
The timescale for ELMs to deliver power to the divertor or the first wall is a few $\times \tau_{||}$ ($= 220$ microseconds)

The power arrives in a fast ramp over $2 \tau_{||}$ and a slower decay over $4 \tau_{||}$

Although there are slow transients associated with power plant operations on the thermal time constant of the PFCs

we will concentrate on fast transients, edge localized modes (ELMs)

ASDEX-U



Transient Heat Loading, ELMs

The amount of energy released by an ELM has been scaled to the energy in the plasma pedestal

$$\Delta W_{\text{ELM}} / W_{\text{ped}} = 0.15-0.2 \quad \text{for large ELMs}$$

giving 19-24 MJ per ELM

$$\Delta W_{\text{ELM}} / W_{\text{ped}} = 0.05-0.12 \quad \text{for smaller ELMs}$$

giving 4.9-5.9 MJ per ELM

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Experiments indicate that large ELMs have 50% of their energy going to the divertor, and 40% arrives in the rise phase

For our power plant we assume all to the outboard, and 65% to each divertor

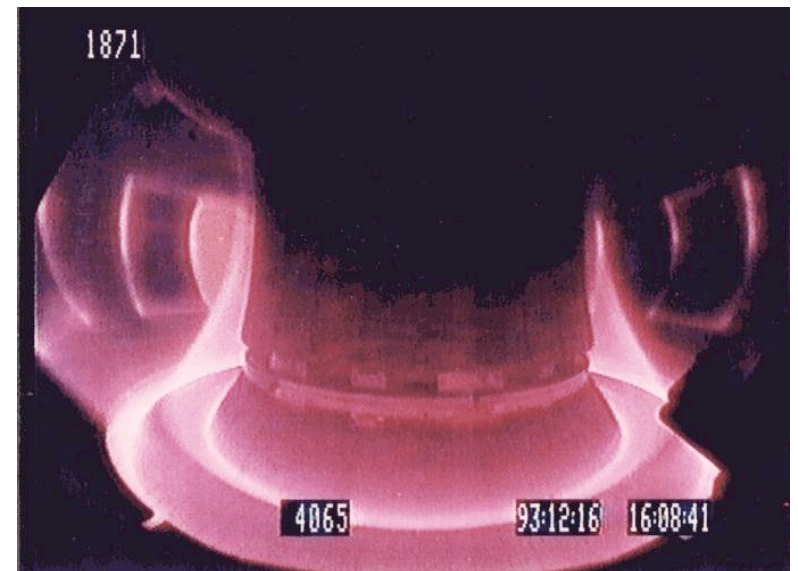
$$\Delta T = \frac{2}{3} C_{\text{material}} \Delta W_{\text{ELM,div}}^{\text{rise}} / A_{\text{ELM,div}} (2 \tau_{\parallel})^{1/2}$$

$$= 4360 \text{ }^{\circ}\text{K} \text{ (large ELM)} \rightarrow 1090 \text{ }^{\circ}\text{K} \text{ for}$$

expanded $A_{\text{ELM,div}}$

$$= 730 \text{ }^{\circ}\text{K} \text{ (small ELM)}$$

Tungsten operating temps between 800-1300 °C
 $T_{\text{melt}}(\text{tungsten}) \sim 3400 \text{ }^{\circ}\text{C}$



Transient Heat Loading, ELMs to the FW

Experiments indicate that the FW can receive 50% of the energy released in a large ELM, with 4x peaking

All the energy is released to the outboard

Treat all the energy over the full pulse

$$\Delta T = C_{\text{material}} \Delta W_{\text{ELM,FW}} / A_{\text{ELM,FW}} (6 \tau_{\parallel})^{1/2}$$

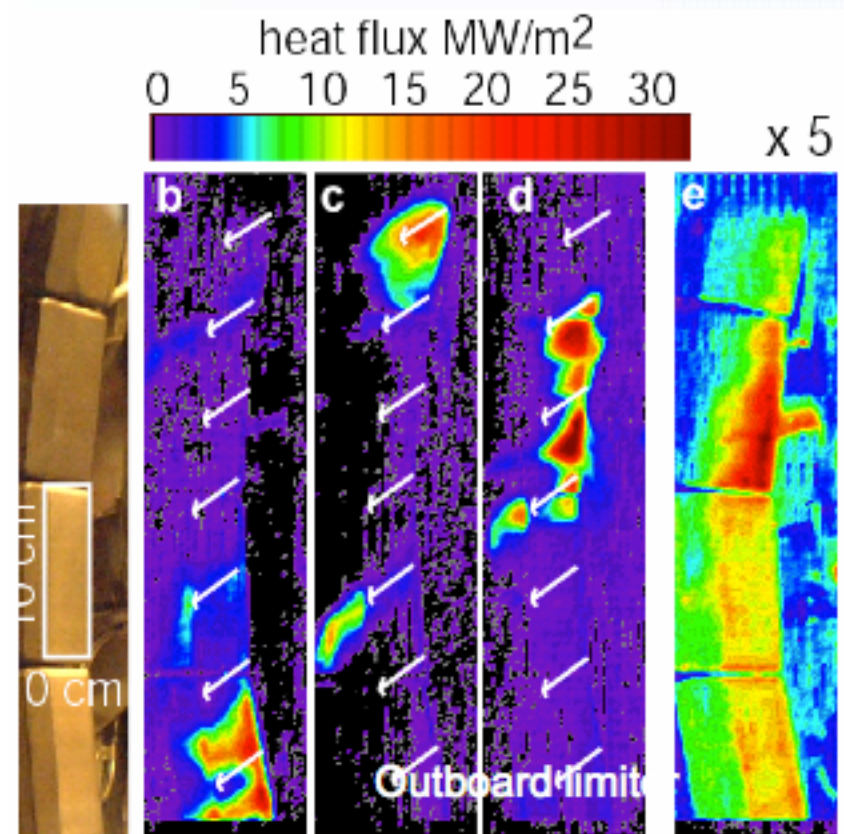
$$= 203 \text{ }^{\circ}\text{K for tungsten}$$

$$= 278 \text{ }^{\circ}\text{K for ferritic steel (or SiC)}$$

SiC has similar C_{material} to Fe-steel,
while it operates at 1000 °C,

$$T_{\text{melt}}(\text{SiC}) = \sim 2500 \text{ }^{\circ}\text{C}$$

Fe steel has operating temperatures in
the range of 500-650 °C, $T_{\text{melt}}(\text{Fe-steel}) \sim 1500 \text{ }^{\circ}\text{C}$



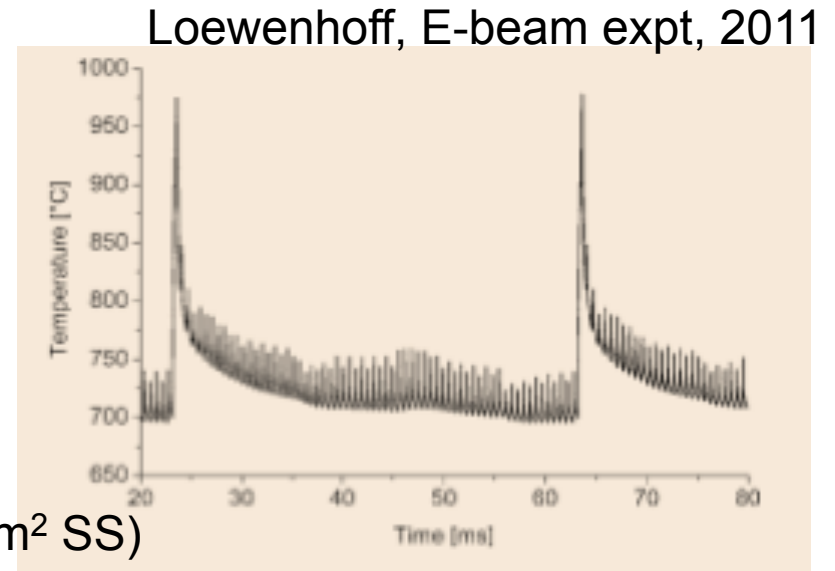
ASDEX-U, Eich, 2003

Transient Heat Loading, Cycling from ELMs

For a power plant, the ELM frequency ranges from 3-20 /s

This means we will have > 100 million ELMs in one year

From E-beam expts with cycles up to 10^6 at 200 °C (1.5 MW/m²) and 700 °C (10 MW/m² SS)



No significant difference was seen between 200 °C and 700 °C tests

For both temperatures, a damage threshold exists between 0.14-0.27 GW/m² with deterioration above a few $\times 10^5$ cycles

At 700 °C a heat flux of 0.14 GW/m² up to 10^6 cycles showed no deterioration.....that is only a $\Delta T \sim 200\text{-}250$ °C

There are also plasma gun expts, that are consistent at lower cycles

Off-Normal Heat Loading

The disruptions expected for a power plant are Vertical Displacement Events (VDEs) and Midplane Disruptions (MDs)

Disruptions proceed through a

Thermal Quench (loss of plasma's stored energy = 345-690 MJ)
1.5-2.75 ms

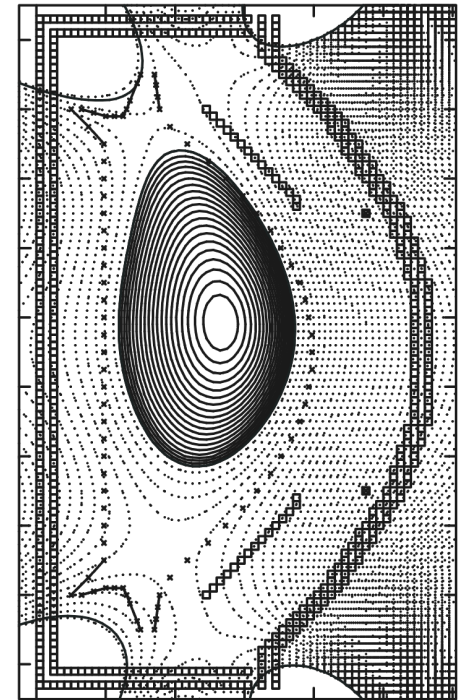
Current Quench (loss of plasma's magnetic energy = 280 MJ,
induction of eddy currents in structures) 25 ms

Possible (probable) Runaway Electrons

Experiments indicate that during a TQ about 10-50% of the energy goes to the divertor and 90-50% goes to the first wall

The energy deposition in time is similar to an ELM, with a rise phase and a decay phase

The deposition footprint in the divertor expands by 10x during the TQ, while the FW has a deposition peaking factor of 2x



1059.990s

Off-Normal Heat Loading, Disruptions

For the TQ of the MD we find

$\Delta T = 2250\text{-}11260\text{ }^{\circ}\text{K}$ (**melting**) in the divertor for tungsten

$\Delta T = 1210\text{-}2170\text{ }^{\circ}\text{K}$ on the FW for tungsten

$\Delta T = 1660\text{-}2980\text{ }^{\circ}\text{K}$ on the FW for Fe steel (or SiC)

The VDE releases $\sim \frac{1}{2}$ of its stored energy before the TQ over about 1-2 s, however this would raise the PFC temperatures prior to the TQ

For the CQ 40-80% of the magnetic energy is radiated to the FW, 10-30% induces eddy currents in structures, and 0-30% is conducted/convected to the FW

$\Delta T = 340\text{-}355\text{ }^{\circ}\text{K}$ on the FW for tungsten (outboard)

$\Delta T = 89\text{-}177\text{ }^{\circ}\text{K}$ on the FW for tungsten (inboard)

$\Delta T = 470\text{-}490\text{ }^{\circ}\text{K}$ on the FW for Fe steel (outboard) (or SiC)

$\Delta T = 122\text{-}243\text{ }^{\circ}\text{K}$ on the FW for Fe steel (inboard) (or SiC)

C-Mod W divertor tile



$$T_{\text{melt}}^{\text{W}} \sim 3400\text{ }^{\circ}\text{C}$$

Off-Normal Heat Loading, Runaway Electrons

Runaway Electrons (RE) can be generated by the large electric field created at the TQ, and their population rises during the current quench

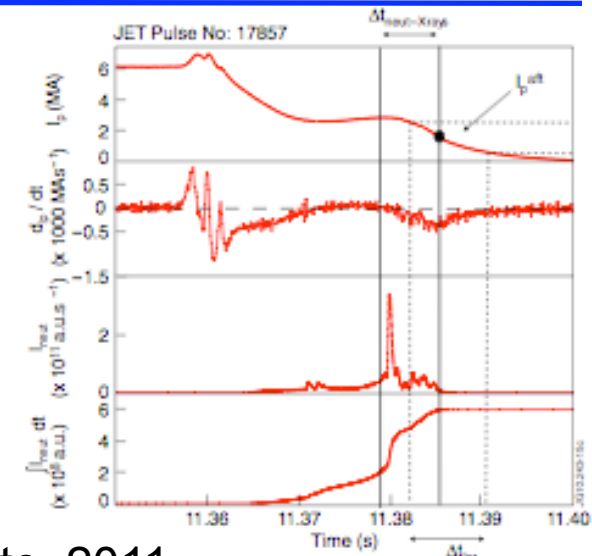
The electrons can obtain energies of 1-20 MeV

The power plant has a RE current of ~ 6.2 MA

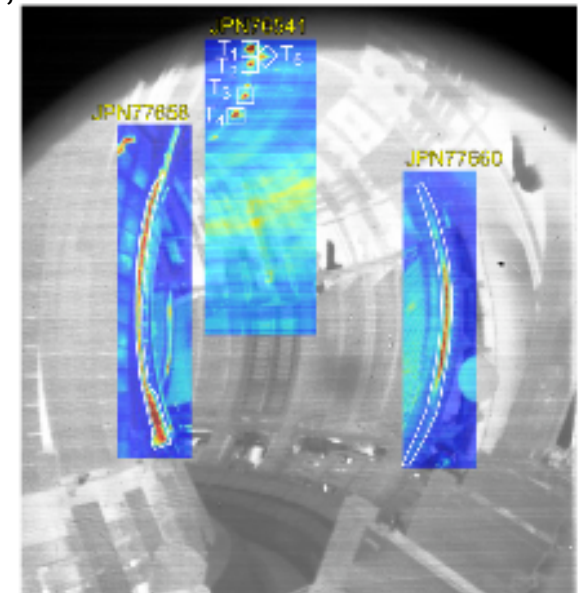
When the RE current terminates, the magnetic energy in the plasma is turned into
kinetic energy of REs
ohmic heating of the residual plasma
conducted/convected to the FW

The RE heat load would involve 28-84 MJ,
deposited on 0.3 - 0.6 m², over about < 1 ms
melting and penetration

Mitigation of REs requires large particle numbers
that would likely require some re-conditioning



Loarte, 2011



JET

Thermal Loading in ARIES Power Plants

Summary

We are beginning to assess the implications of the complex thermal loading environment in a tokamak, for power plant parameters

SS Heat Loading:

- Are designs with very high heat flux ($\geq 20 \text{ MW/m}^2$) capability useful?
- Need to examine vertical position control in the DN, and time varying loading
- Radiated power levels of ~90%, are these accessible and controllable?

Transient Heat Loading:

- Avoiding melting appears to be a necessary criteria in a power plant
- More recent (and accurate) measurements indicate large ELMs might be tolerable
- In a power plant the number of cycles are very large, can we understand a cracking regime well enough to project lifetimes, or do we need to avoid cracking?

Off-Normal Heat Loading:

- Avoiding melting of PFC appears very difficult, mitigation may help avoid the worst scenarios
- If a disruption occurs....does lead just to PFC damage, or can it lead to an accident?
- What is the number of disruptions economically allowed with PFC damage only

Neutron irradiation will likely alter the material and its material responses