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

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Heat Loading in Power Plants and ITER

Heat loading prescriptions traditionally have been poorly described from existing fusion experiments, and have contained large uncertainties….

- in 1999 the power scrape-off width was proportional to $P_{SOL}^{0.44}$
- in 2002 it was reported to be proportional to $P_{SOL}^{-0.4}$….
- the most recent prescription indicates $P_{SOL}^{0.23}$

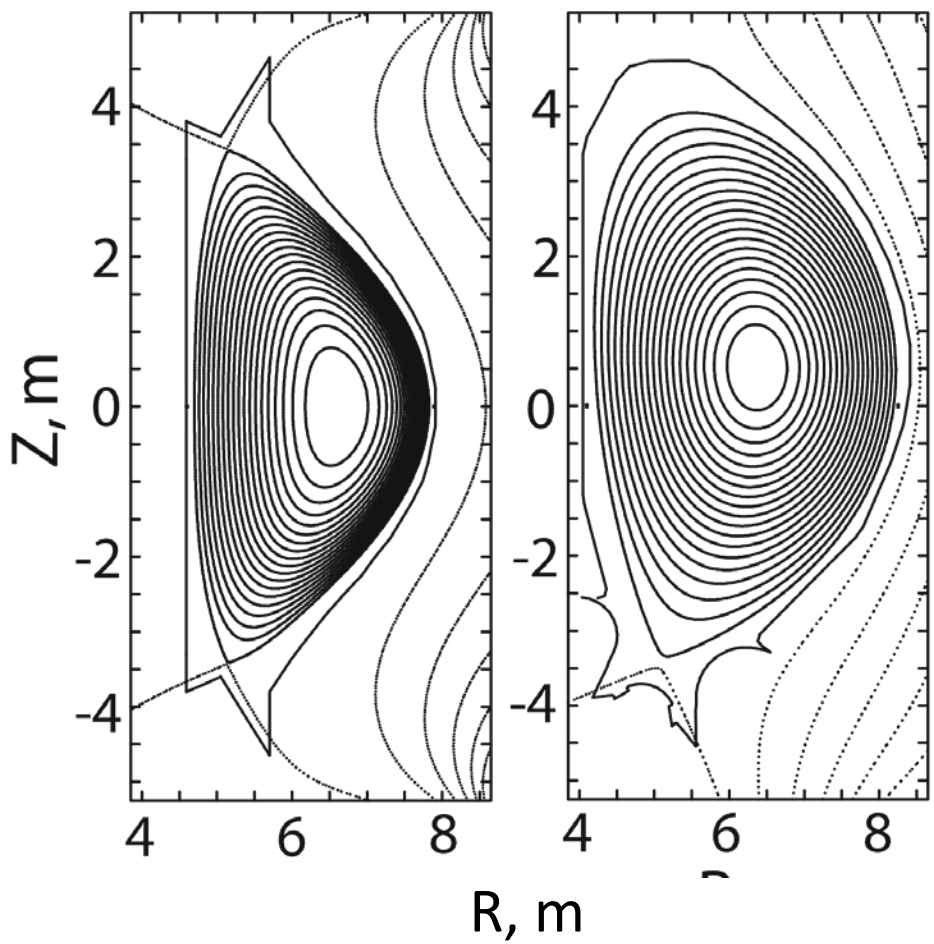
Recently, ITER has required a significantly better description in order to design its plasma facing components (PFCs).

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

- Steady state
- Transient (e.g., ELM's)
- Off-normal (e.g., disruptions)

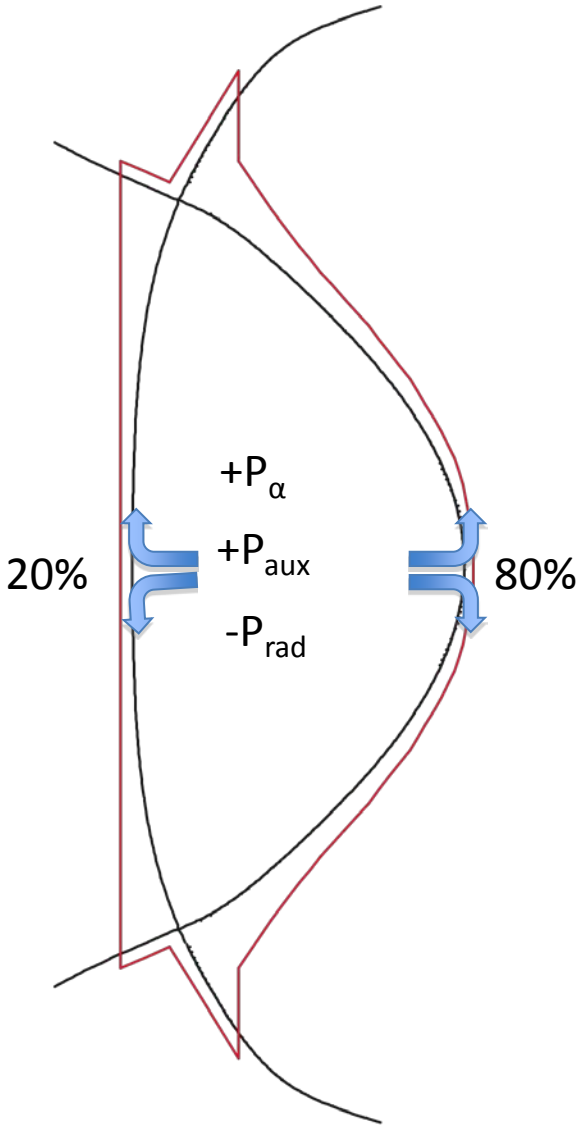
Although ARIES-ACT1 and ITER have a similar R, they have quite different plasmas

I_p = 10.9 MA
R = 6.25 m
a = 1.56 m
V = 558 m^3
A_{surf} = 586 m^2
B_T = 6 T
κ_x = 2.2
δ_x = 0.7
β_N = 5.75
n/n_{Gr} = 1.0
H_{98} = 1.65
P_{fusion} = 1800 MW
P_{aux} = 45 MW
P_{SOL} = 290 MW



I_p = 15.0 MA
R = 6.20 m
a = 2.0 m
V = 837 m^3
A_{surf} = 678 m^2
B_T = 5.3 T
κ_x = 1.80
δ_x = 0.44
β_N = 1.75
n/n_{Gr} = 0.85
H_{98} = 1.0
P_{fusion} = 500 MW
P_{aux} = 45 MW
P_{SOL} = 100 MW

Calculation of Steady State Heat Load in Divertor



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

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

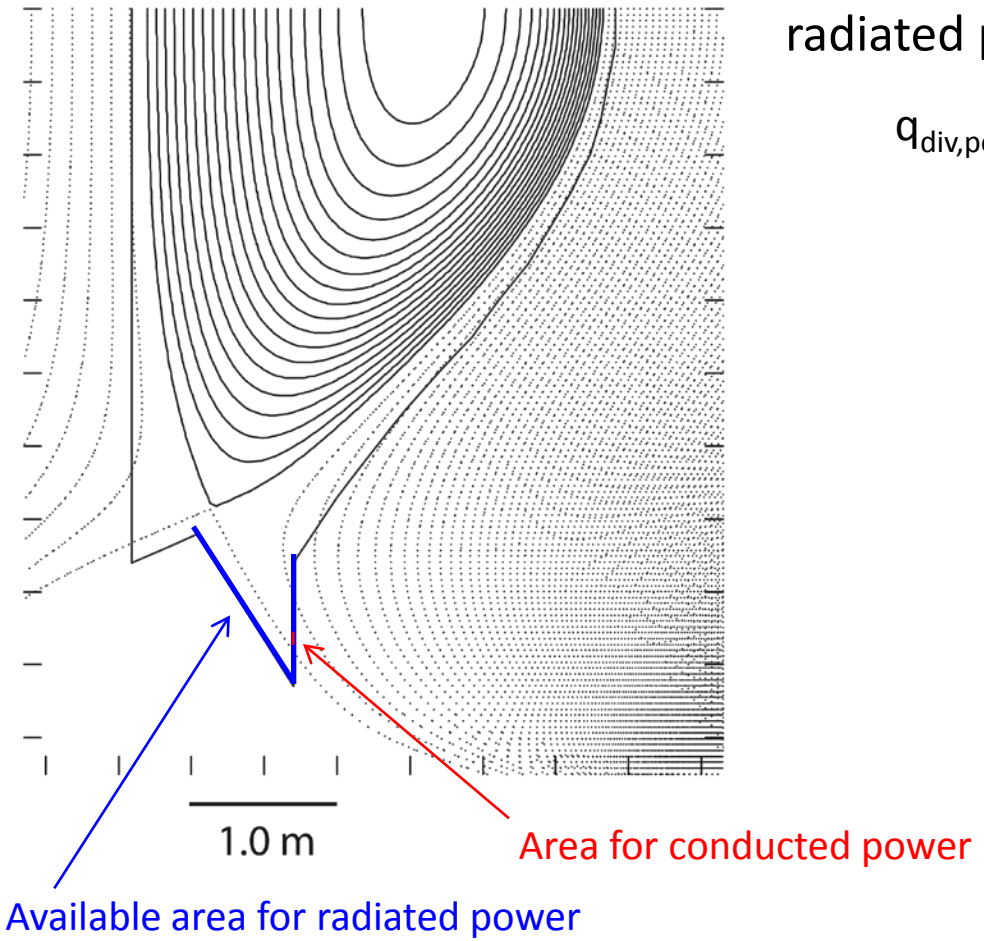
$$\boldsymbol{\lambda_q \sim 7.5\text{x}10^{-2}\, q_{95}^{0.75}\, n_L^{0.15} / (P_{SOL}^{0.4}\, B_T)}$$

λ_q ~ 4 mm for ARIES-ACT1 at the OB midplane

The width expands with the magnetic flux as it travels to the divertor (x10)

The final area which the power impinges on is ~ 1.38 m^2 OB and 1.17 m^2 IB

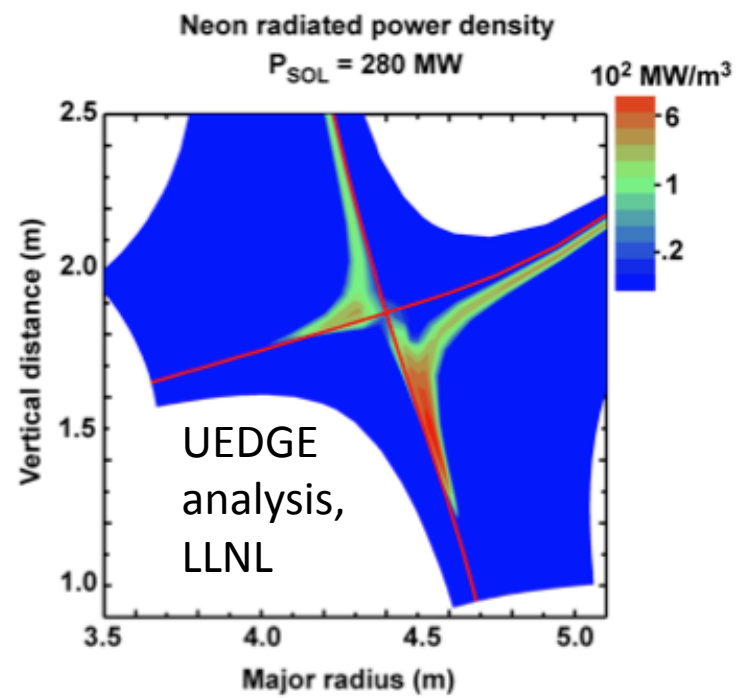
Steady State Loading, cont'd



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

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

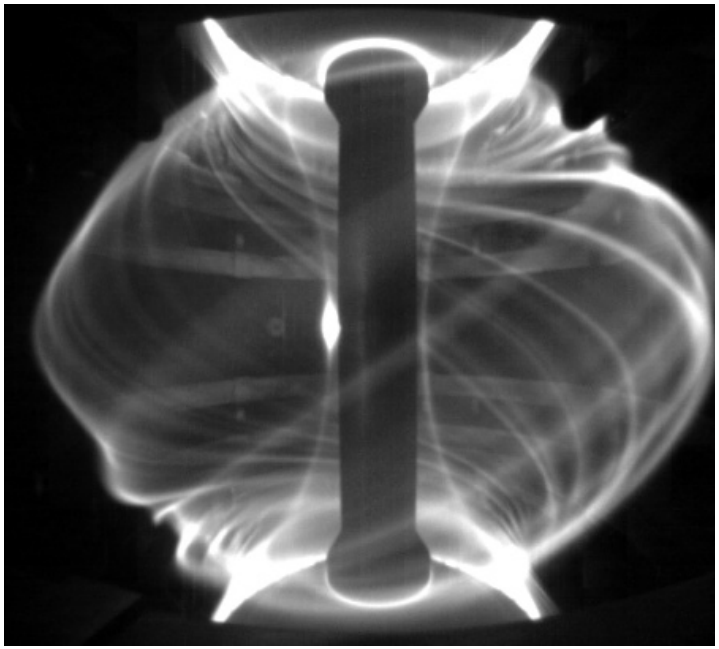
$$[\ (1-f_{div,rad})/A_{div,cond} + f_{div,rad}/A_{div,rad}\ ]$$



Typical values range from 10 to 15 MW/m^2

Transient Heat Loading

MAST



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)

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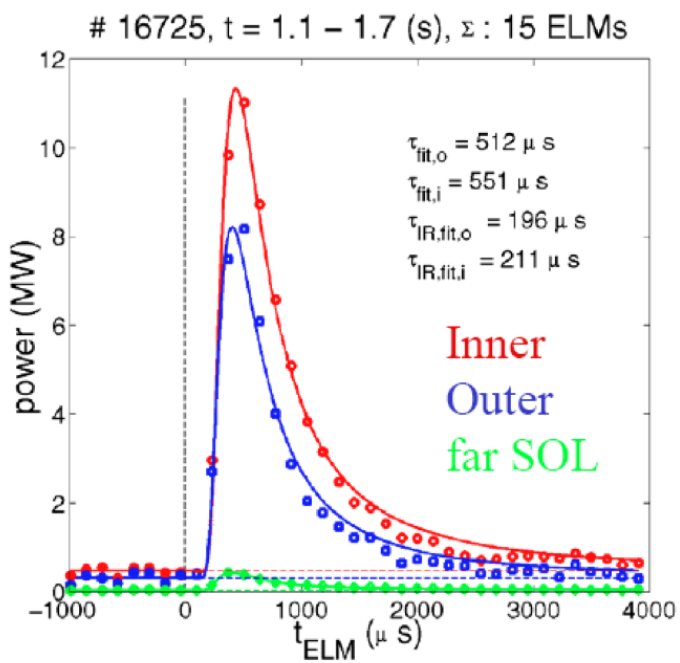

The timescale for ELMs to deliver power to the divertor or the first wall is a few x $\tau_{||}$ (= 220 μs), where $\tau_{||} = 2\pi R q_{95}/c_{s,ped}$

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

ELM Heat Loading to the Divertor

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

$\Delta W_{ELM} / W_{ped} = 0.15\text{-}0.2$ for large ELMs giving 19-24 MJ per ELM

$\Delta W_{ELM} / W_{ped} = 0.05\text{-}0.12$ for smaller ELMs giving 4.9-5.9 MJ per ELM

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

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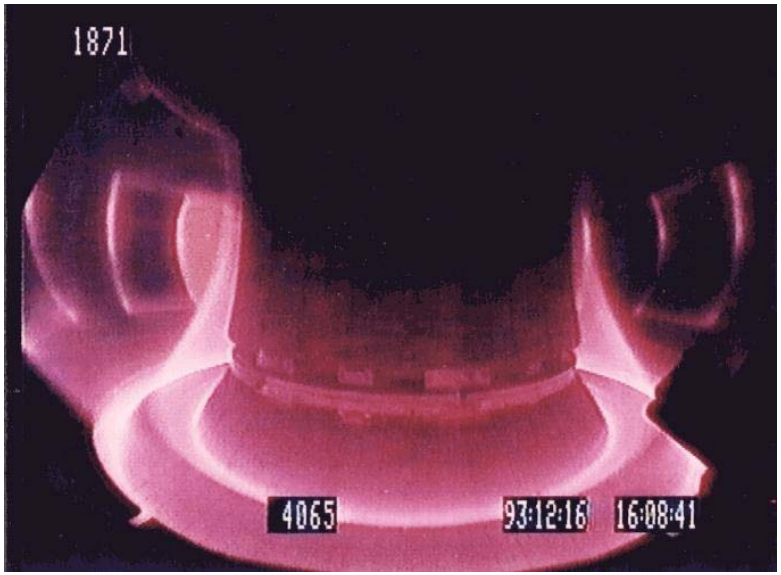


For our power plant we assume all to the outboard, and 65% to each divertor

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

= 4360 ^{o}K (large ELM)

→ 1090 ^{o}K for expanded $A_{ELM,div}$

= 730 ^{o}K (small ELM)

ELM Heat Loading to the First Wall

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

All of the energy is released to the outboard

Treat all the energy over the full pulse

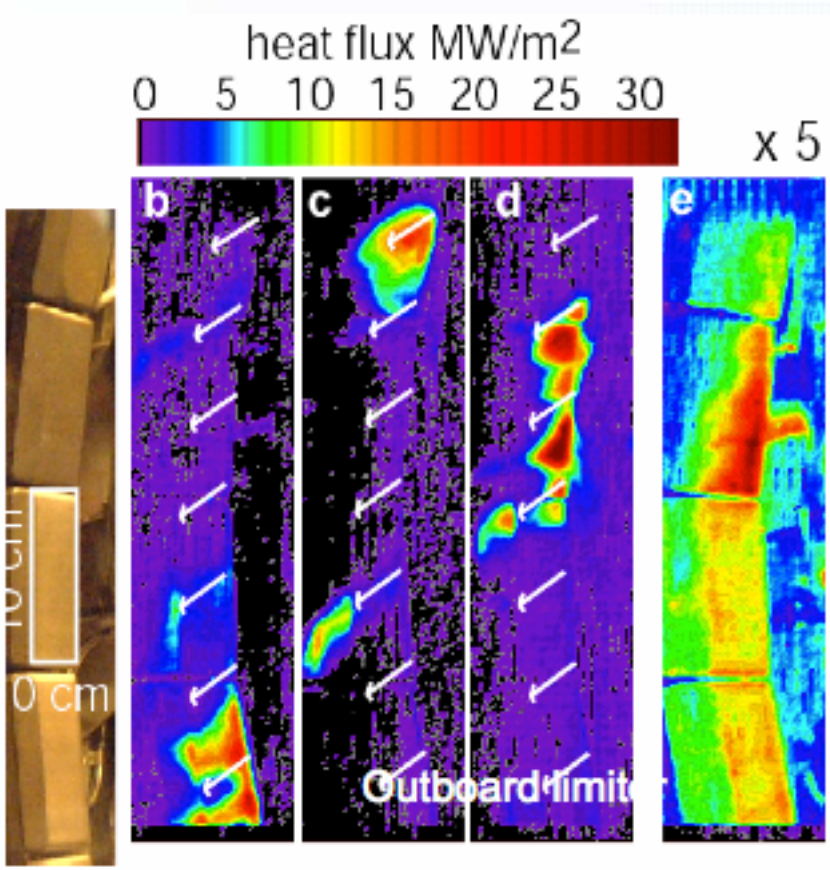
$\Delta T = C_{material}\, \Delta W_{ELM,FW} / A_{ELM,FW}\, (6\tau_{||})^{1/2}$

= 203 ^{o}K for tungsten

= 278 ^{o}K for ferritic steel (or SiC)

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

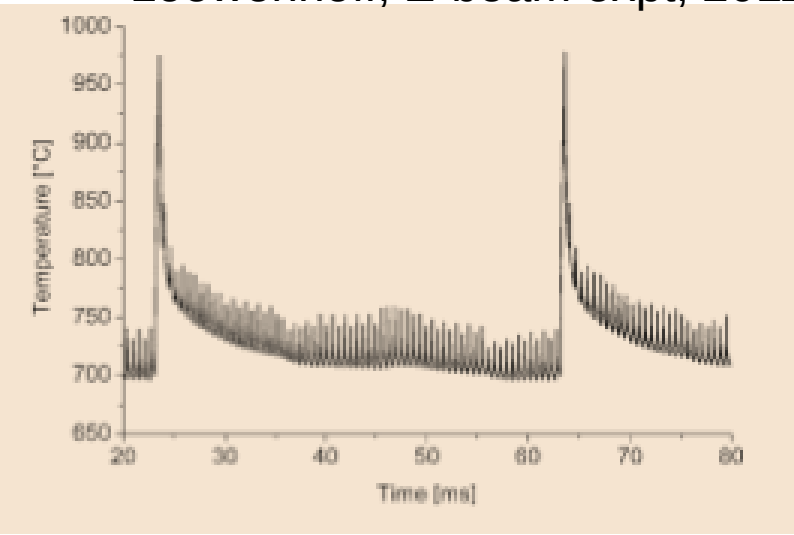
Fe steel has operating temperatures in the range of 500-650 ^{o}C



ASDEX-U, Eich, 2003

Cyclic Heat Loading from ELMs

Loewenhoff, E-beam expt, 2011



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

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

E-beam experiments have been performed with cycles up to 10^6 at 200 ^oC (1.5 MW/m^2) and 700 ^oC (10 MW/m^2 SS)

No significant difference was seen between 200 ^oC and 700 ^oC tests

For both temperatures, a damage threshold exists between 0.14-0.27 GW/m^2 with deterioration above a few x 10^5 cycles

At 700 ^oC a heat flux of 0.14 GW/m^2 up to 10^6 cycles showed no deterioration…..that is only a $\Delta T \sim 200$ ^oC

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

Off-Normal Heat Loading

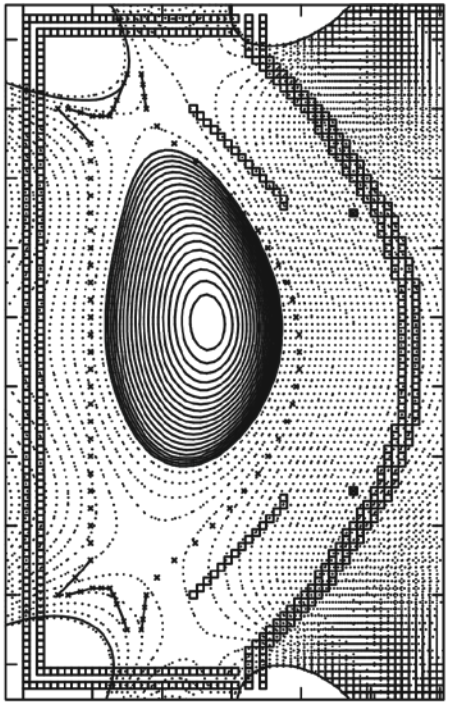
The disruptions expected for a power plant are Vertical Displacement Events (VDEs) and Midplane Disruptions (MDs)

Disruptions proceed through several stages:

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



1059.990s

Experiments indicate that during a thermal quench 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

Off-Normal Heat Loading from Disruptions

For the Thermal Quench of a Midplane Disruption we find

ΔT = 2250-11260 ^{o}K (melting) in the divertor for tungsten

ΔT = 1210-2170 ^{o}K on the FW for tungsten
ΔT = 1660-2980 ^{o}K on the FW for Fe steel (or SiC)

A VDE releases ~ ½ of its stored energy before the thermal quench over about 1-2 s, however this would raise the PFC temperatures prior to the thermal quench

C-Mod W divertor tile

T_{melt}^{W} ~ 3400 ^{o}C

For the Current Quench, 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.

ΔT = 340-355 ^{o}K on the FW for tungsten (outboard)
ΔT = 89-177 ^{o}K on the FW for tungsten (inboard)

ΔT = 470-490 ^{o}K on the FW for Fe steel (outboard) (or SiC)
ΔT = 122-243 ^{o}K on the FW for Fe steel (inboard) (or SiC)

Off-Normal Heat Loading from Runaway Electrons

Runaway Electrons (RE) can be generated by the large electric field created at the Thermal Quench, and their population rises during the Current Quench

The electrons can obtain energies of 1-20 MeV

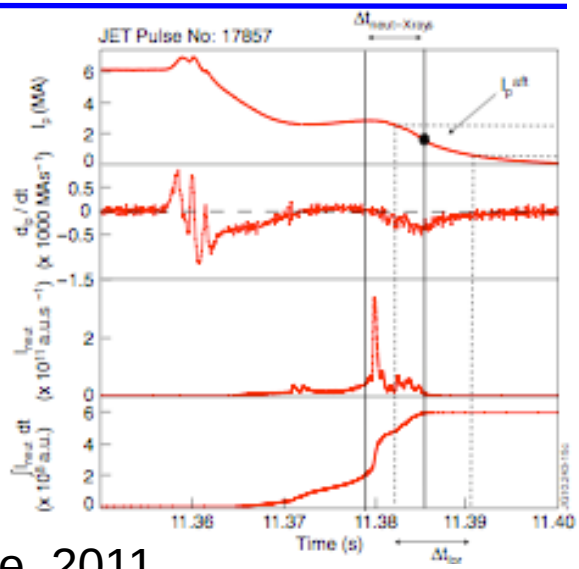
The power plant has a RE current of ~ 6.2 MA

When the RE current terminates, the magnetic energy in the plasma is turned into

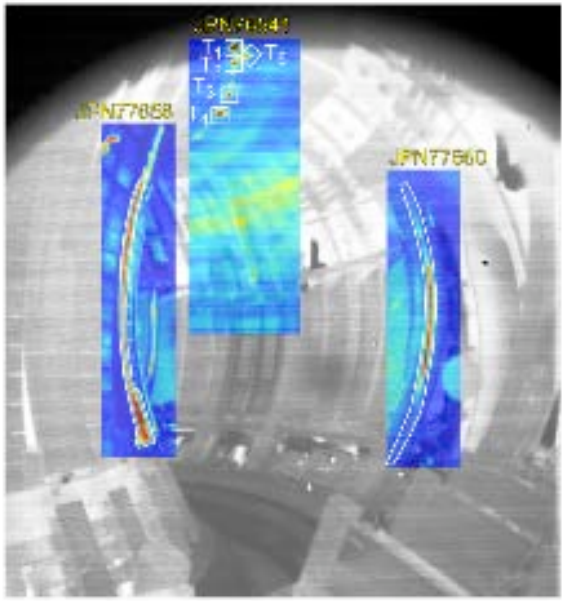
- kinetic energy of REs
- ohmic heating of the residual plasma
- conducted/convected to the FW

The RE heat load would involve 28-84 MJ, deposited on 0.3-0.6 m^2, over about < 1 ms
melting and penetration

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



Loarte, 2011



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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

Steady State Heat Loading:

Are designs with very high heat flux ($\geq$ 20 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 microcracking?

Off-Normal Heat Loading:

Avoiding melting of PFC appears very difficult, mitigation may help avoid the worst scenarios
If a disruption occurs….does it 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