Introduction to Disruptions

Slides from Michael Lehnen – ITER Science and Technology Meeting 3rd February 2014

Presented (with minor adaptations) by Eric Nardon, CEA Cadarache at the 9th ITER International School, 20th-24th March 2017

Outline

- ❑ **What is a disruption?**
- ❑ **What causes disruptions?**
- ❑ **Why worry about disruptions?**
- ❑ **How to deal with disruptions?**

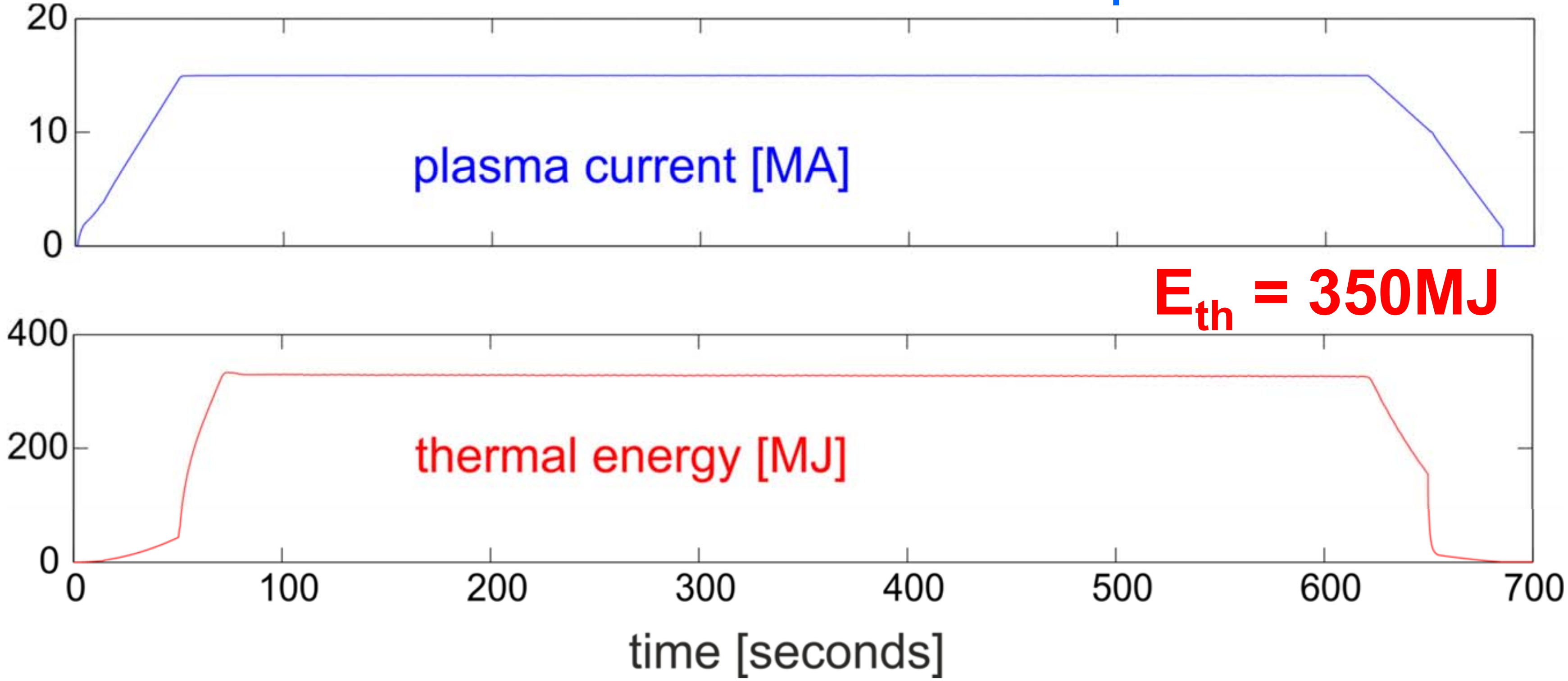
Disruptions in a nutshell – not at all a complete picture, simplifications everywhere

What is a disruption?

Fast accidental loss of plasma thermal and magnetic energy

What is a disruption?

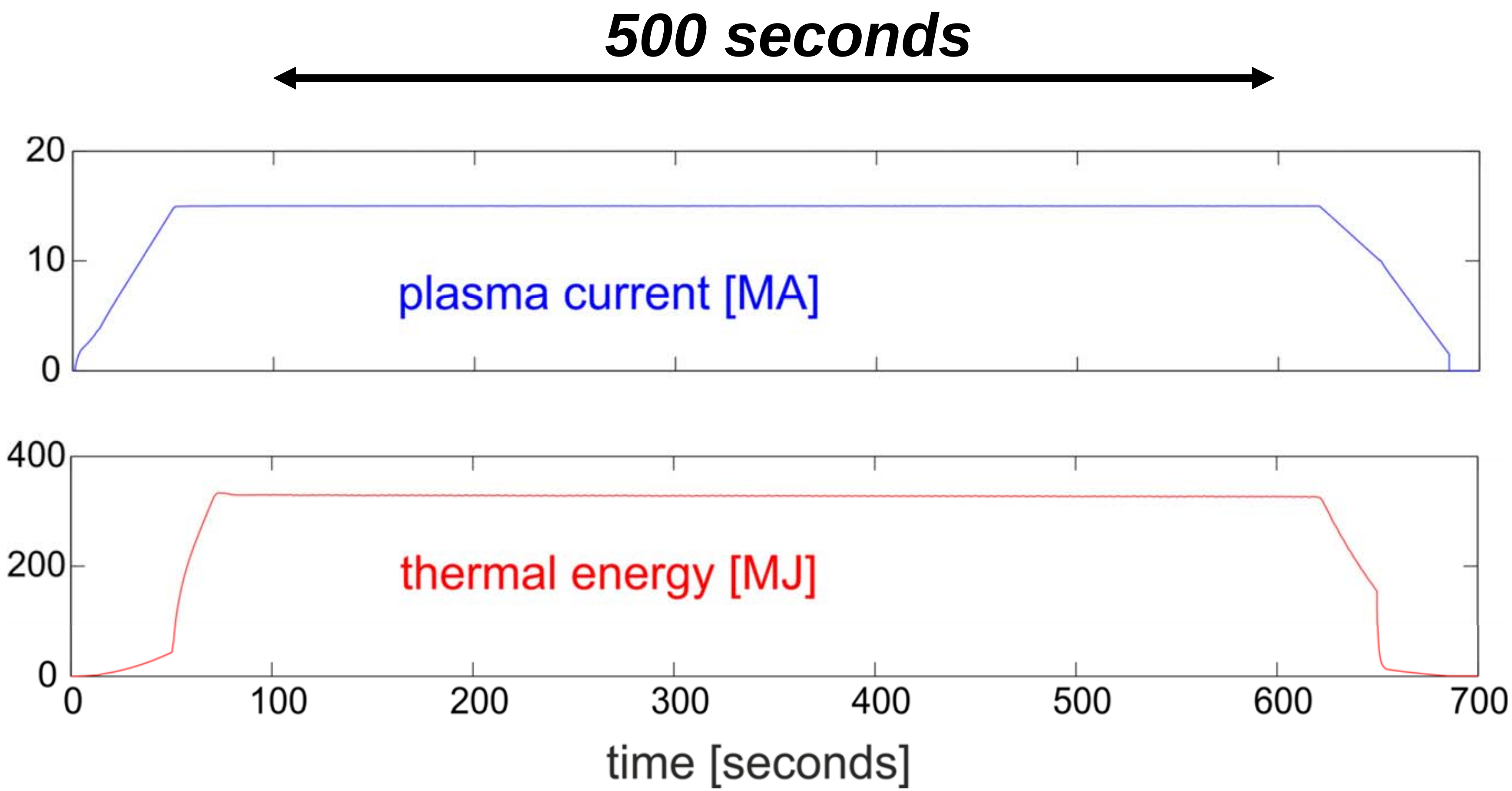
I_{plasma} = 15MA



E_{th} = 350MJ

DINA simulation

What is a disruption?



DINA simulation

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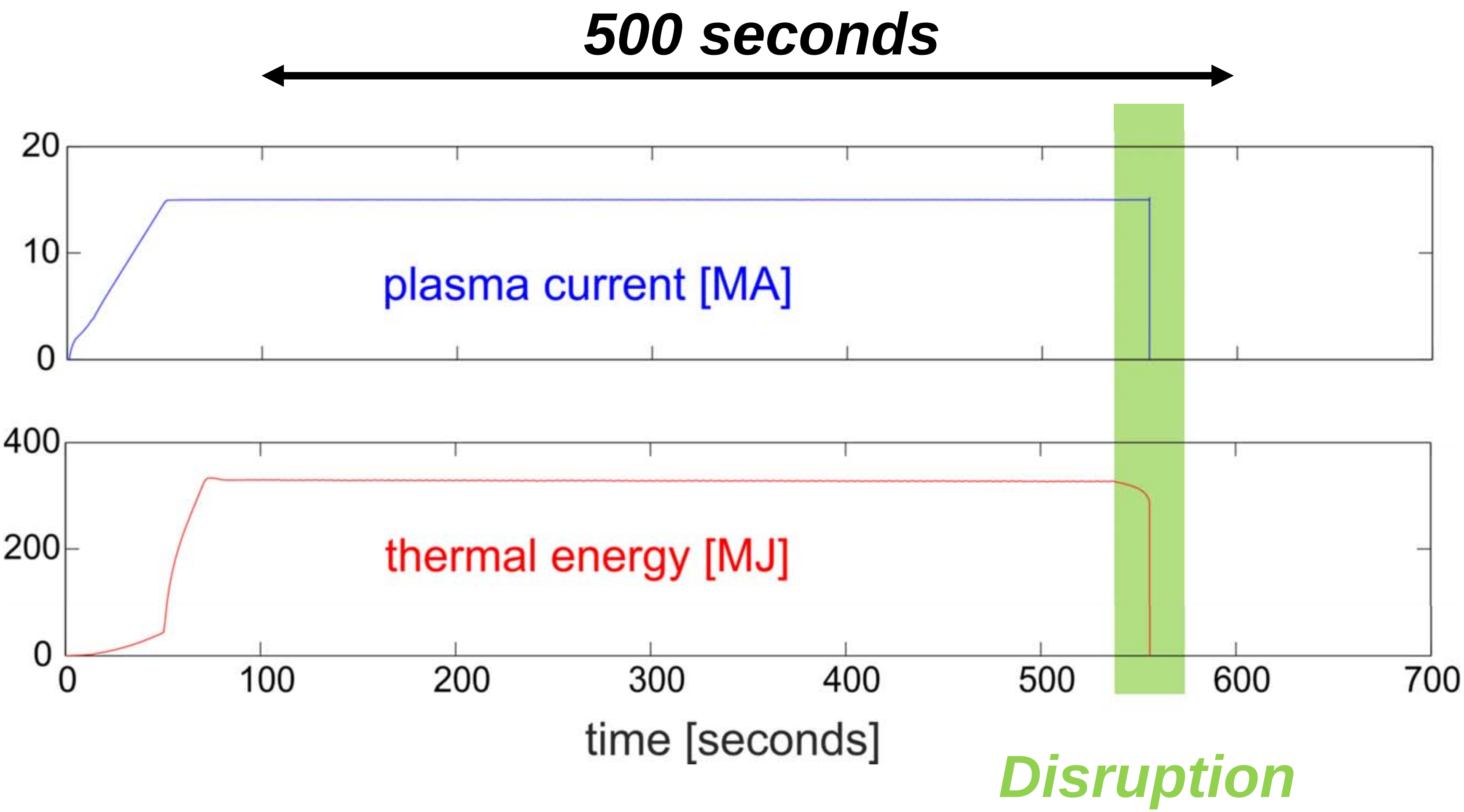
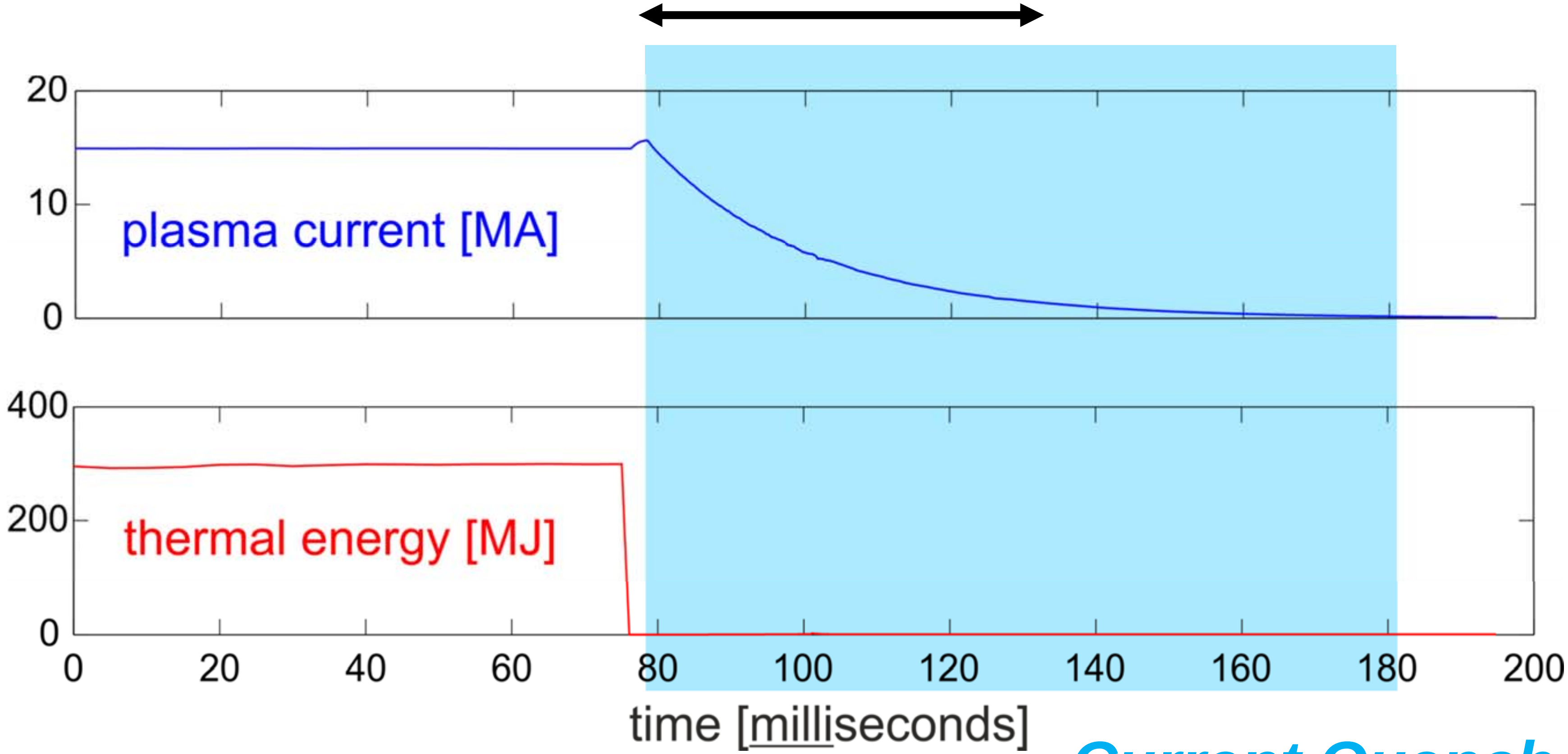


What is a disruption?

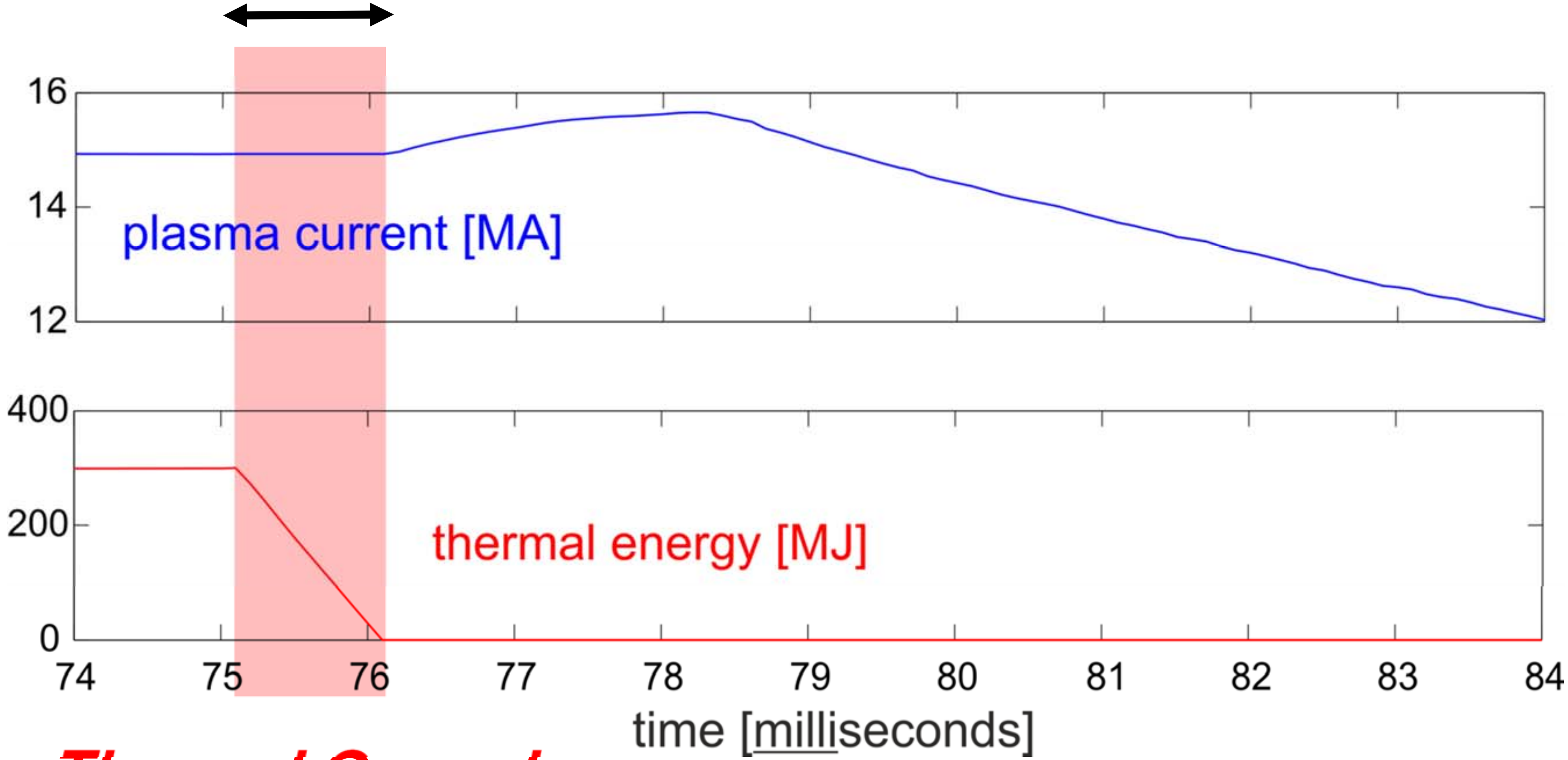
50 milliseconds = 500s / 10000



Current Quench

What is a disruption?

1 millisecond = 500s / 500000

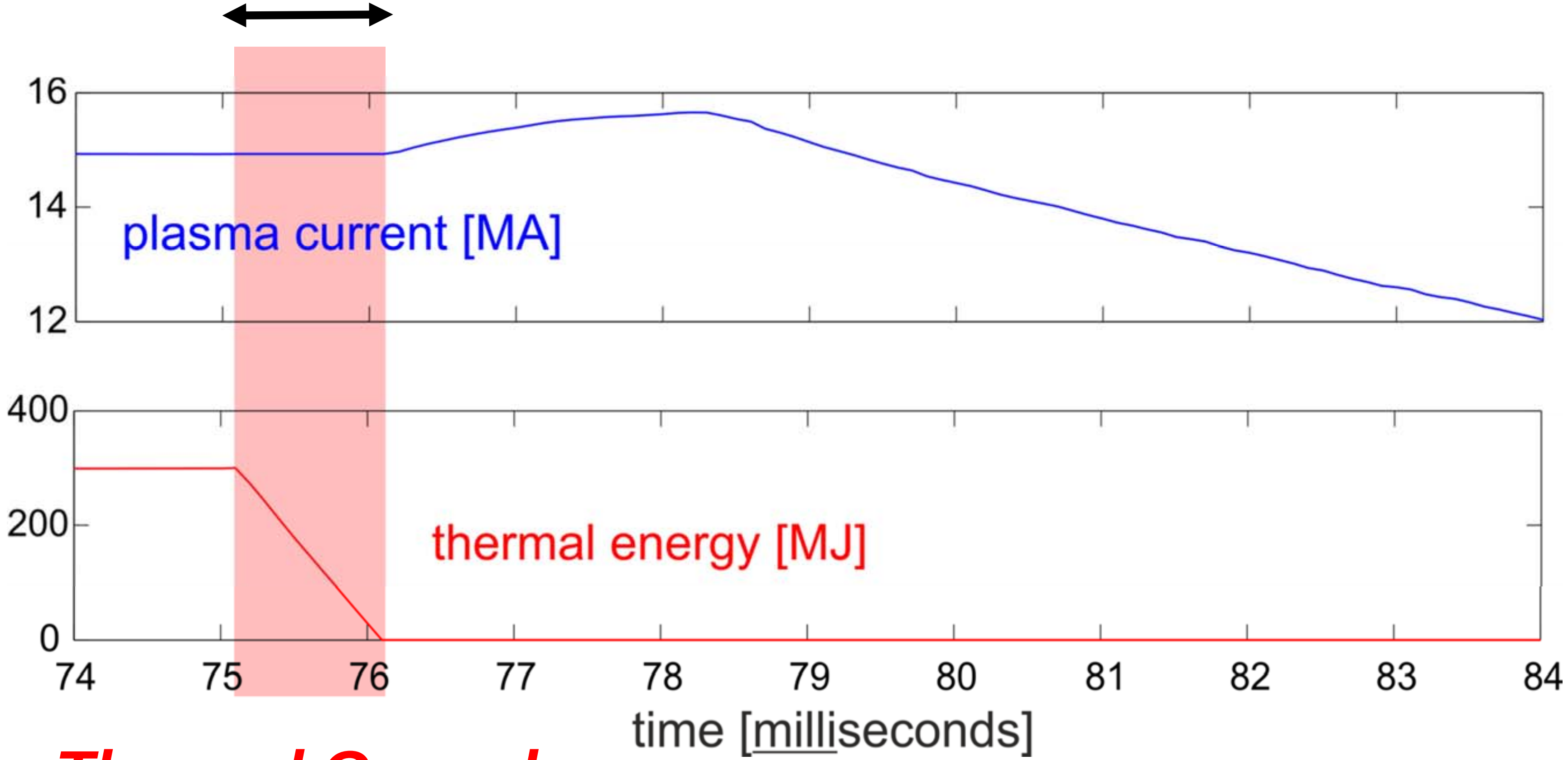


Thermal Quench

What is a disruption?

Energy confinement time in H-mode

1 millisecond = 3s / 3000



Thermal Quench

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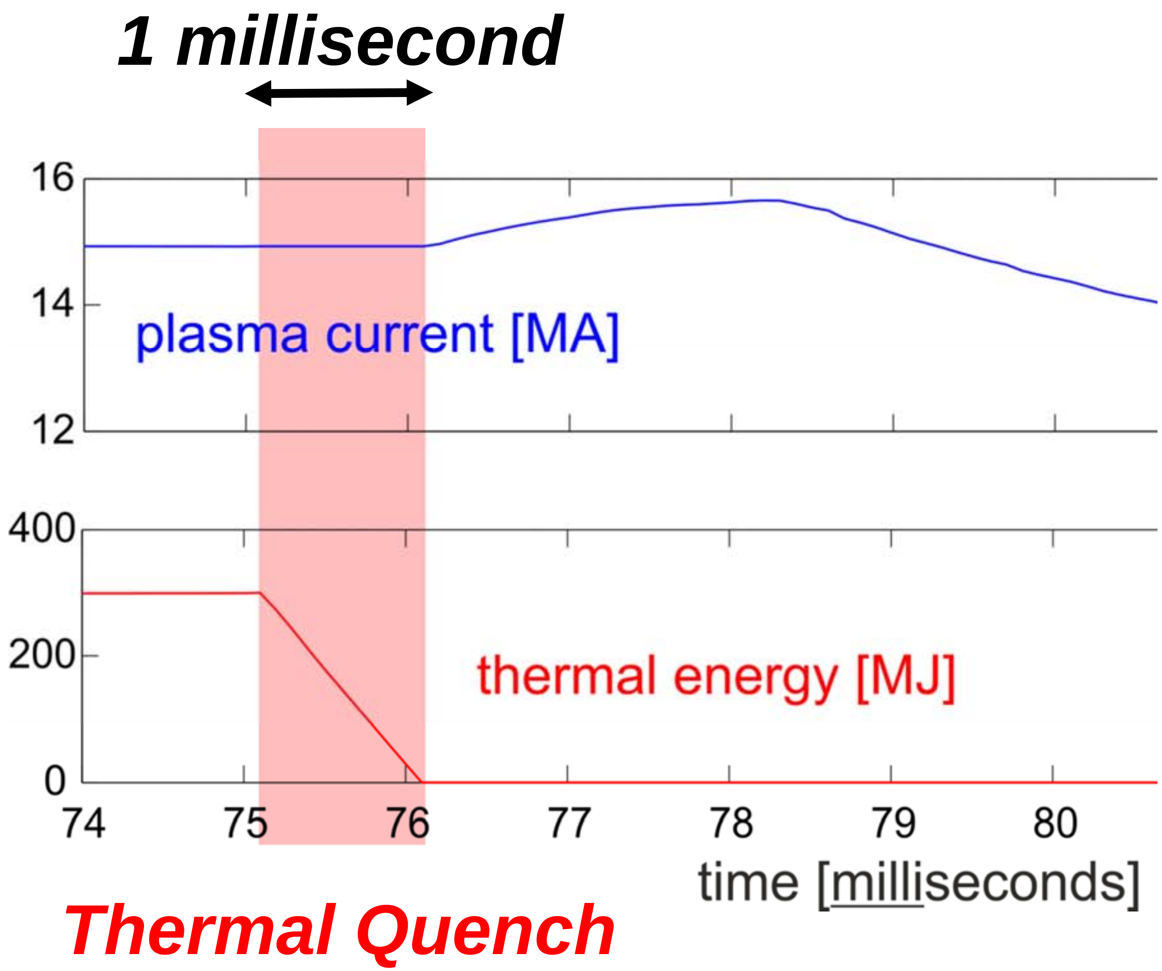
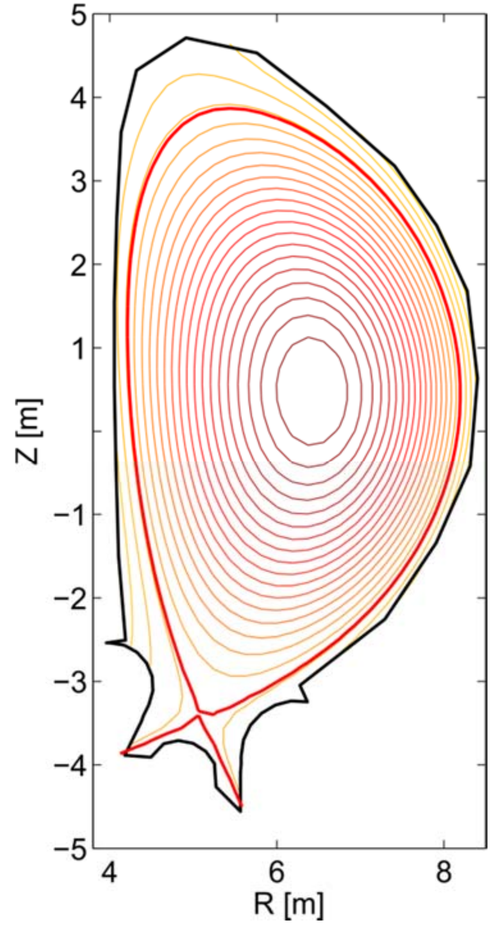


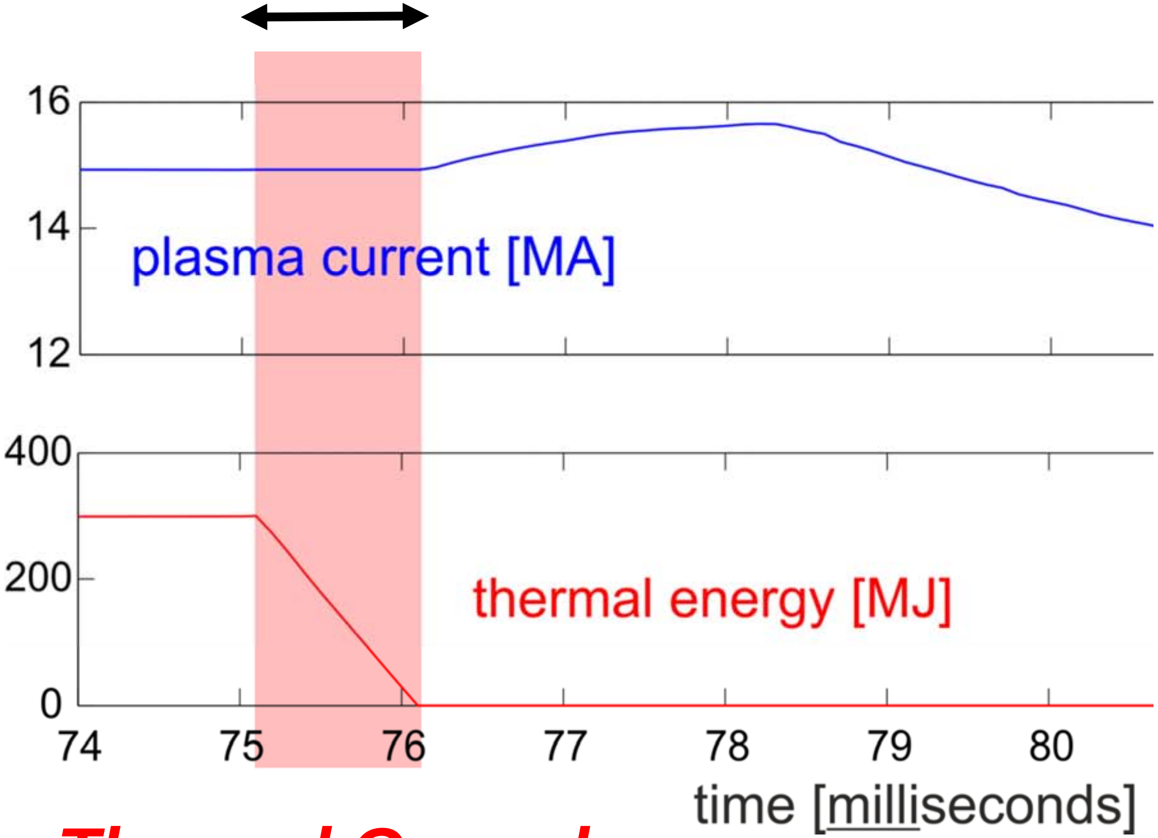


What is a disruption?

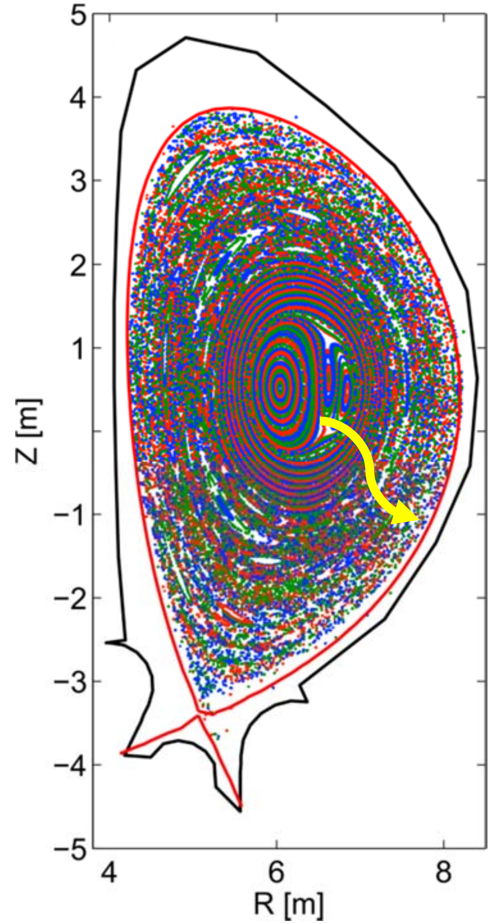
chaotic field lines

core-edge short-circuited

1 millisecond

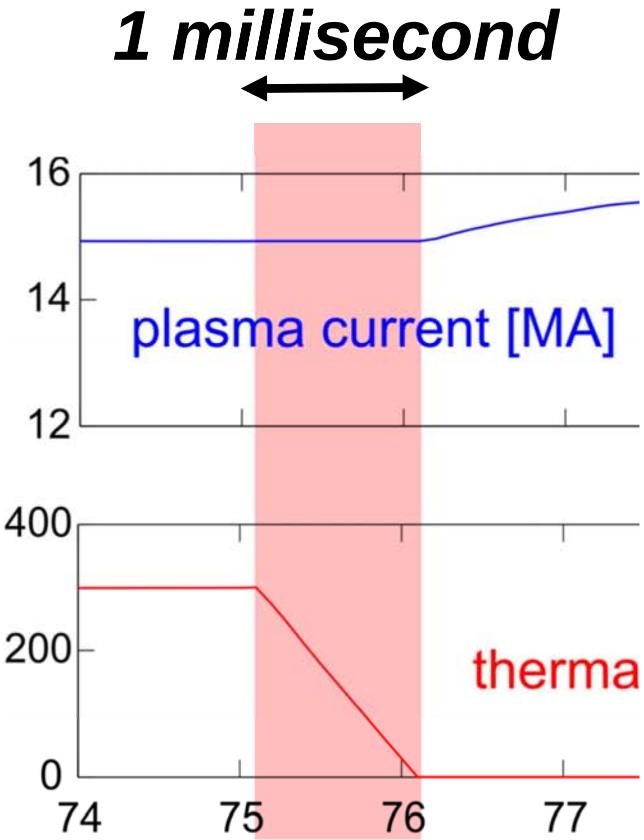


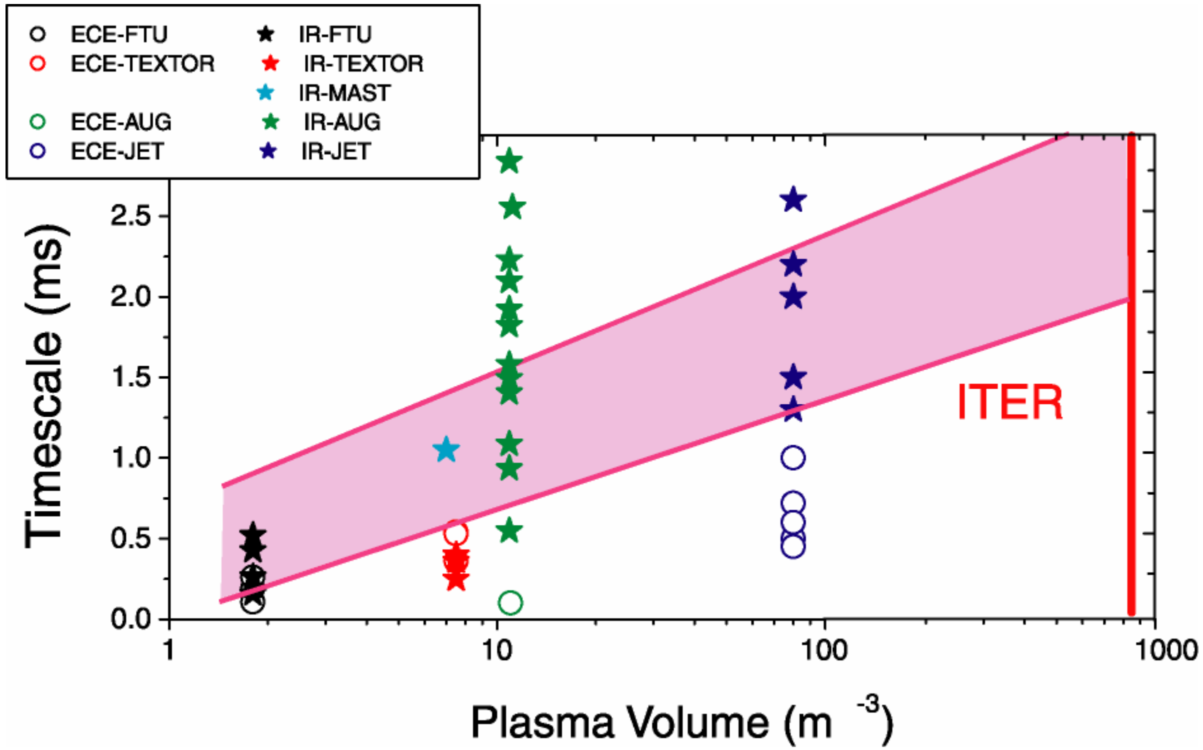
Thermal Quench



MHD 3D simulation NIMROD, V. Izzo et al., US-DA TA

What is a disruption?

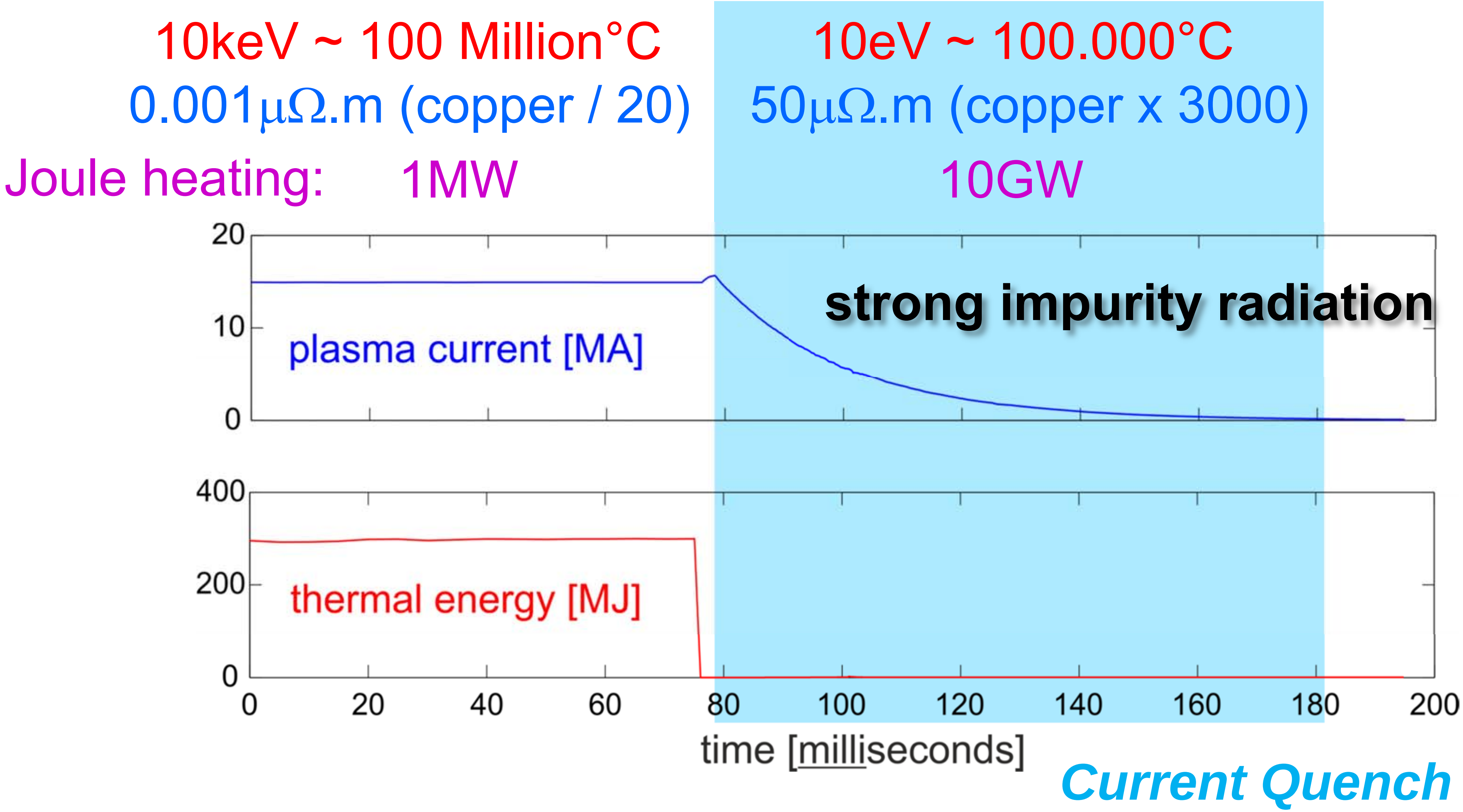




Thermal Quench

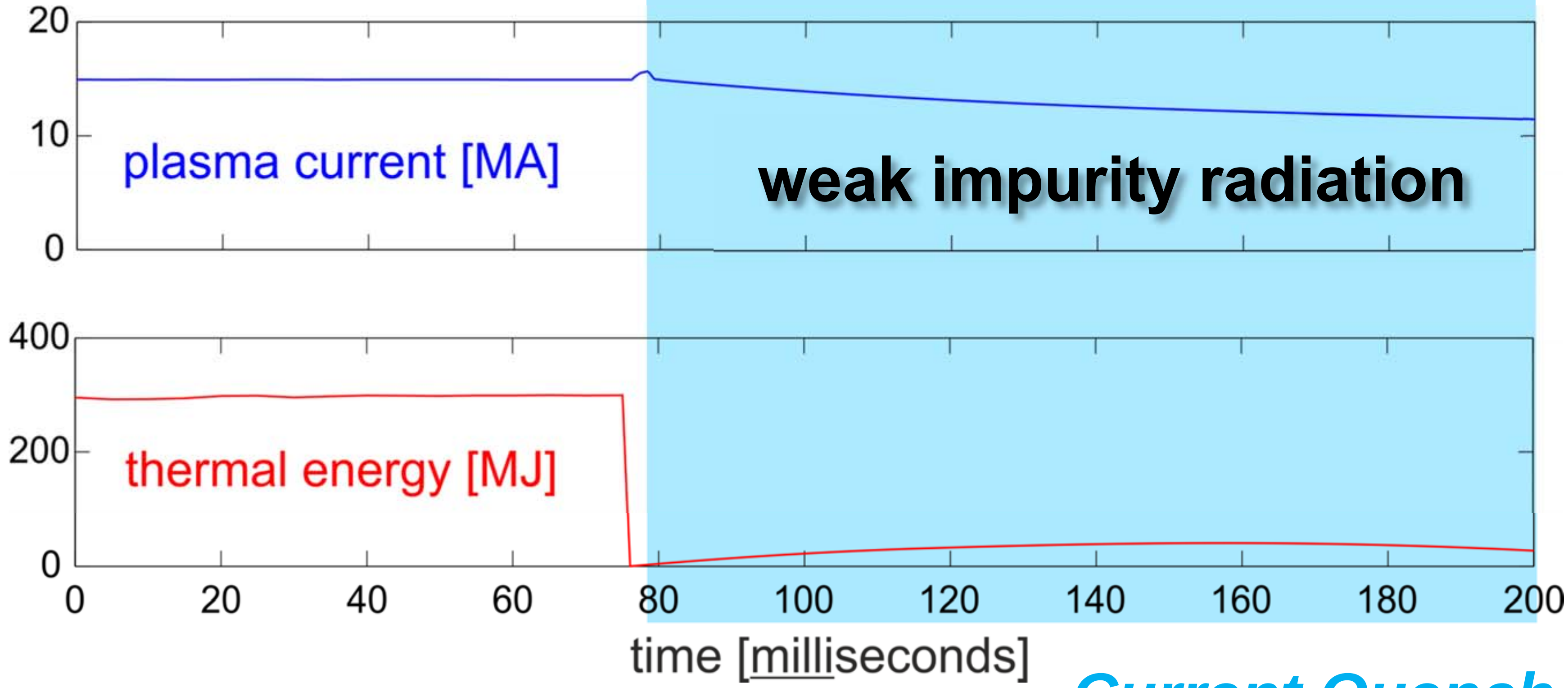
A. Loarte, Heat and Nuclear Load Specifications, ITER_D_2LULDH v2.4

Current quench duration is determined by electron temperature, itself determined by impurity radiation



Current quench duration is determined by electron temperature, itself determined by impurity radiation

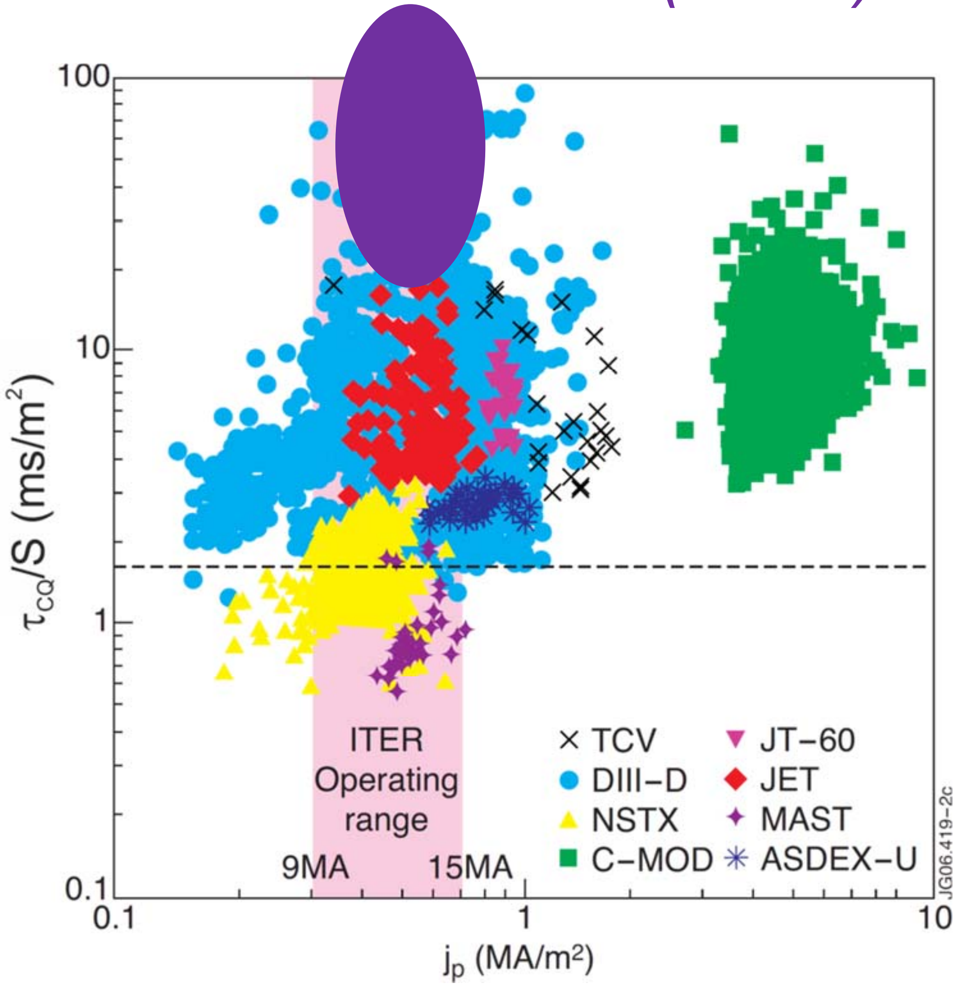
	10keV ~ 100 Million°C	1keV ~ 10 Million°C
	0.001μΩ.m (copper / 20)	0.05μΩ.m (copper x 3)
Joule heating:	1MW	10MW

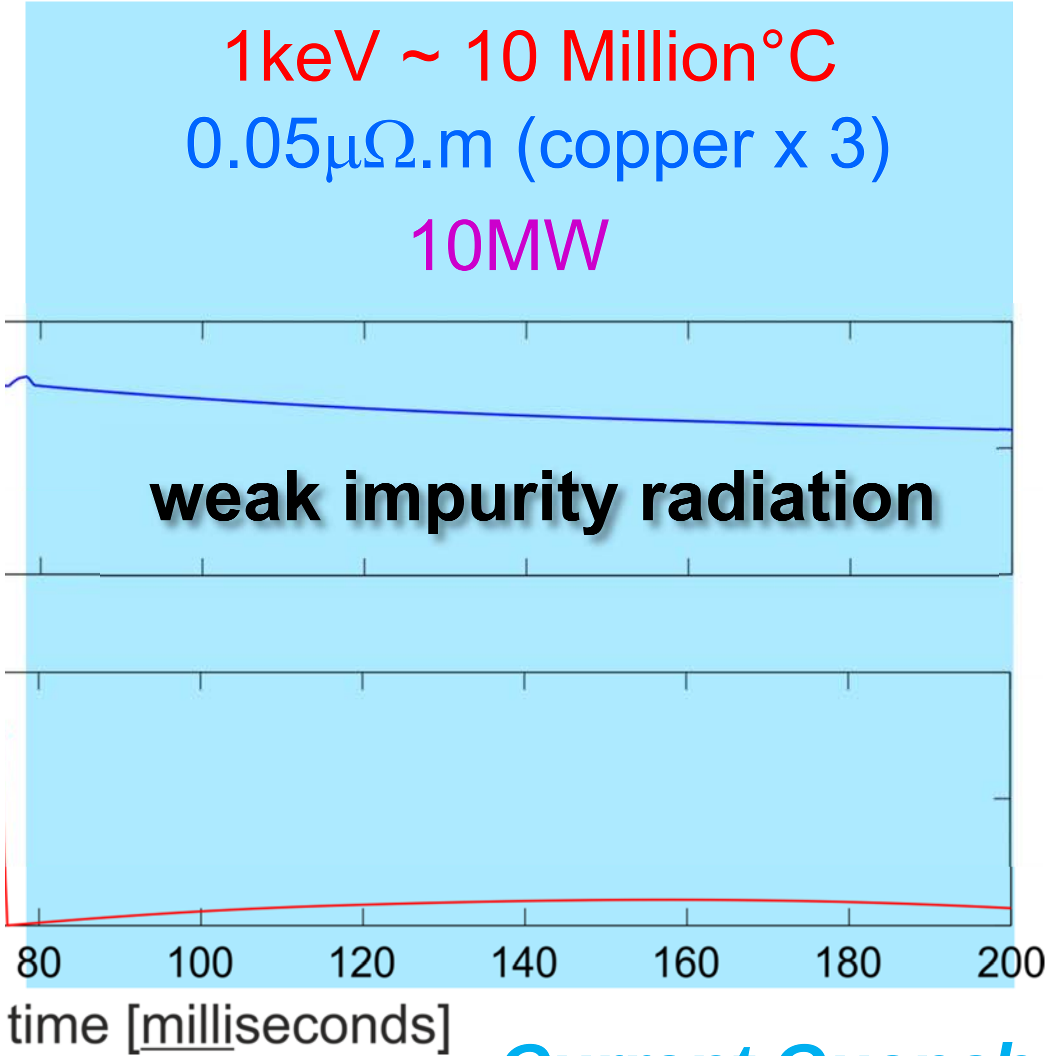


Current Quench

Current quench duration is determined by electron temperature, itself determined by impurity radiation

JET ITER-like wall (Be/W)

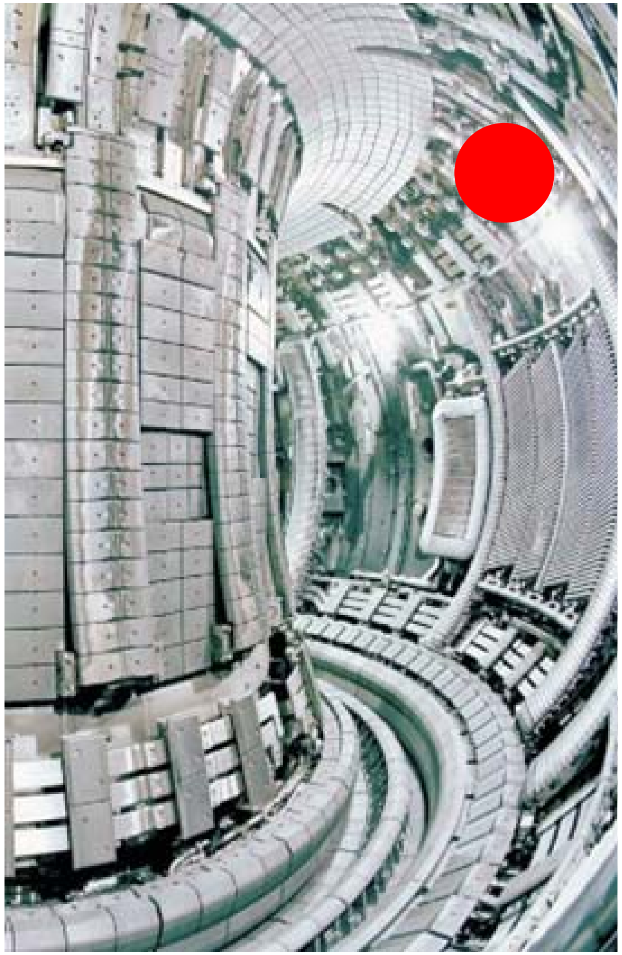




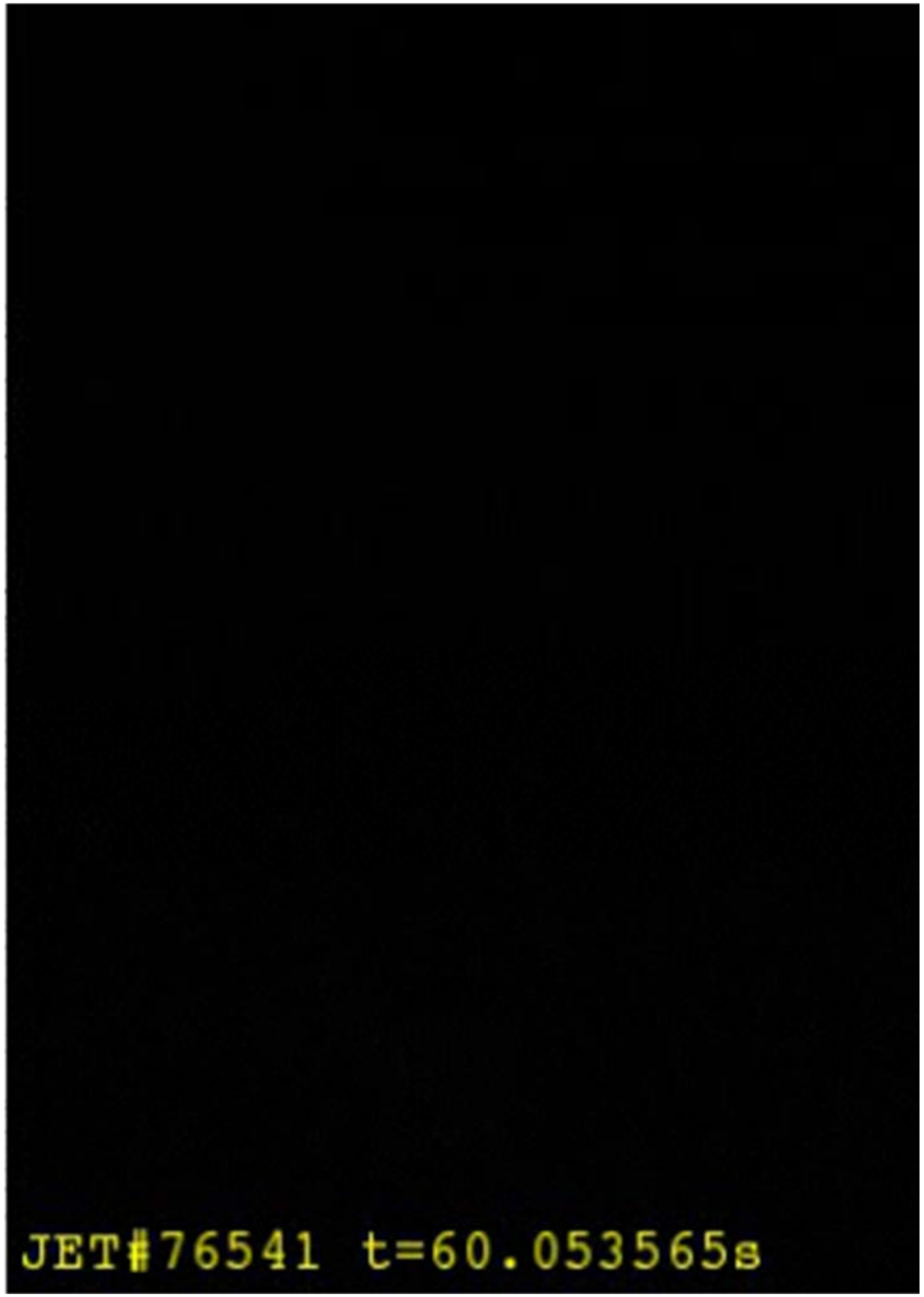
Current Quench

What is a disruption?

JET



movie: 0.04 seconds



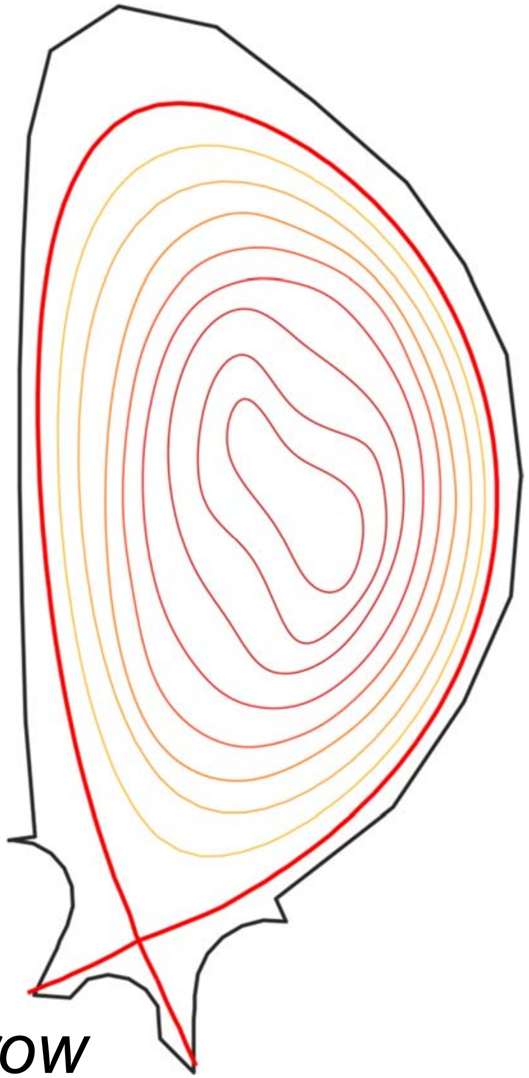
What causes disruptions?

MagnetoHydroDynamic (MHD) instabilities

kink mode

ideal MHD

microseconds

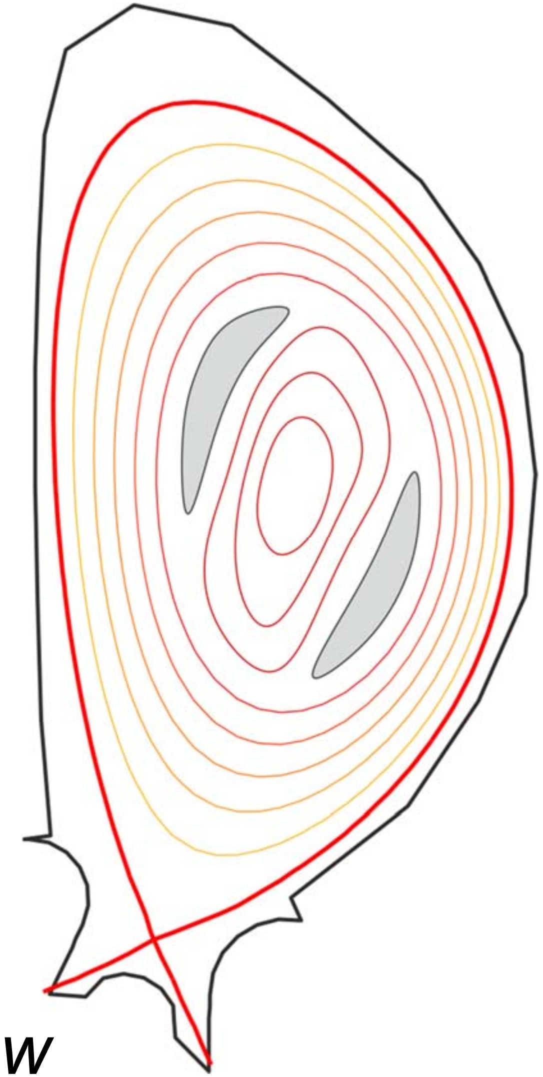


→ P. Beyer's lecture tomorrow

tearing mode

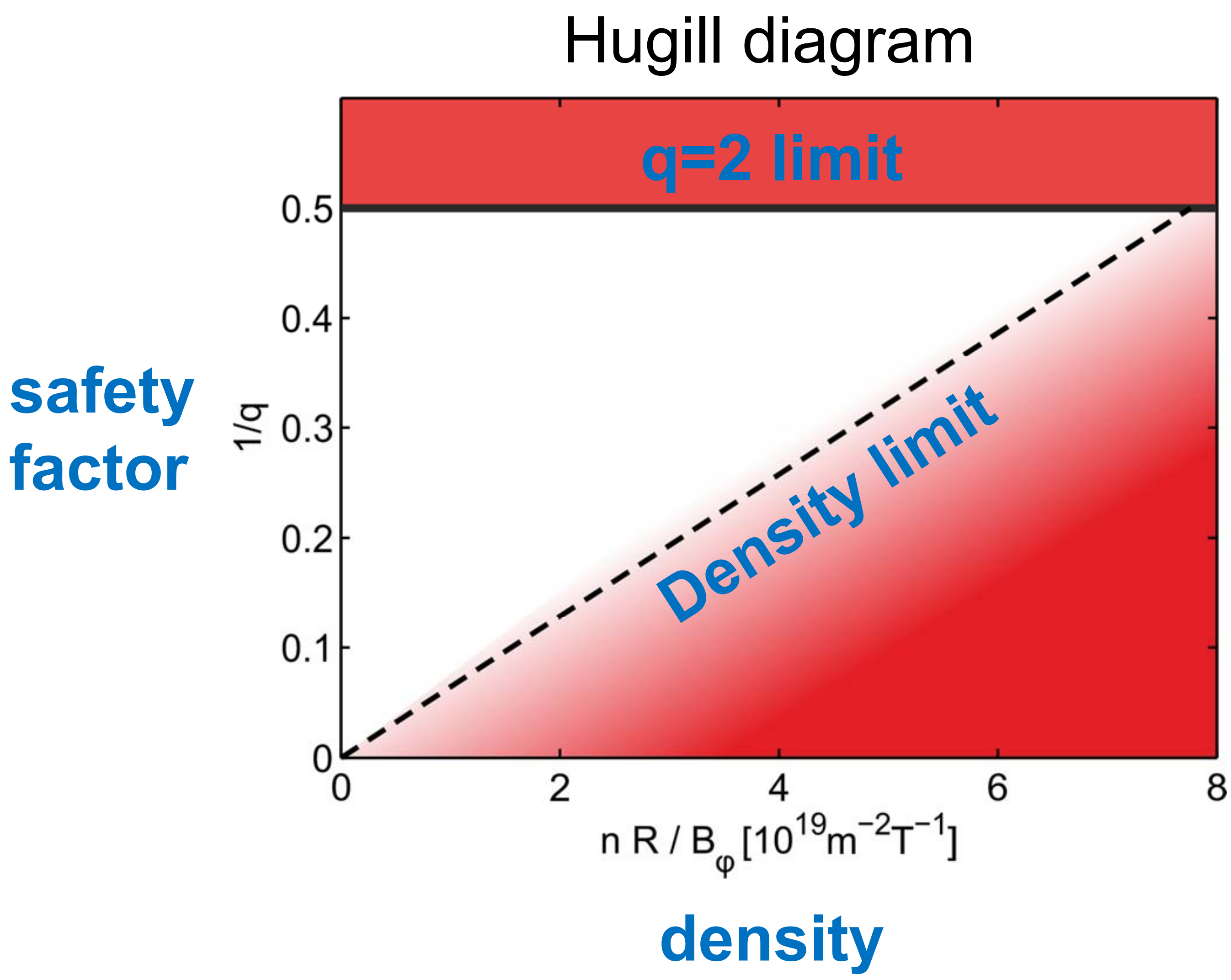
resistive MHD

milliseconds
-
seconds



→ O. Agullo's lecture tomorrow

What causes disruptions?



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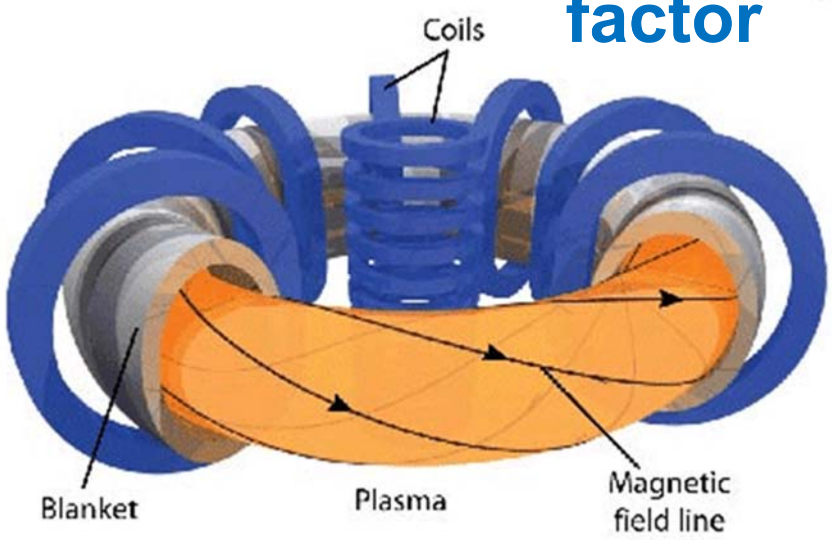
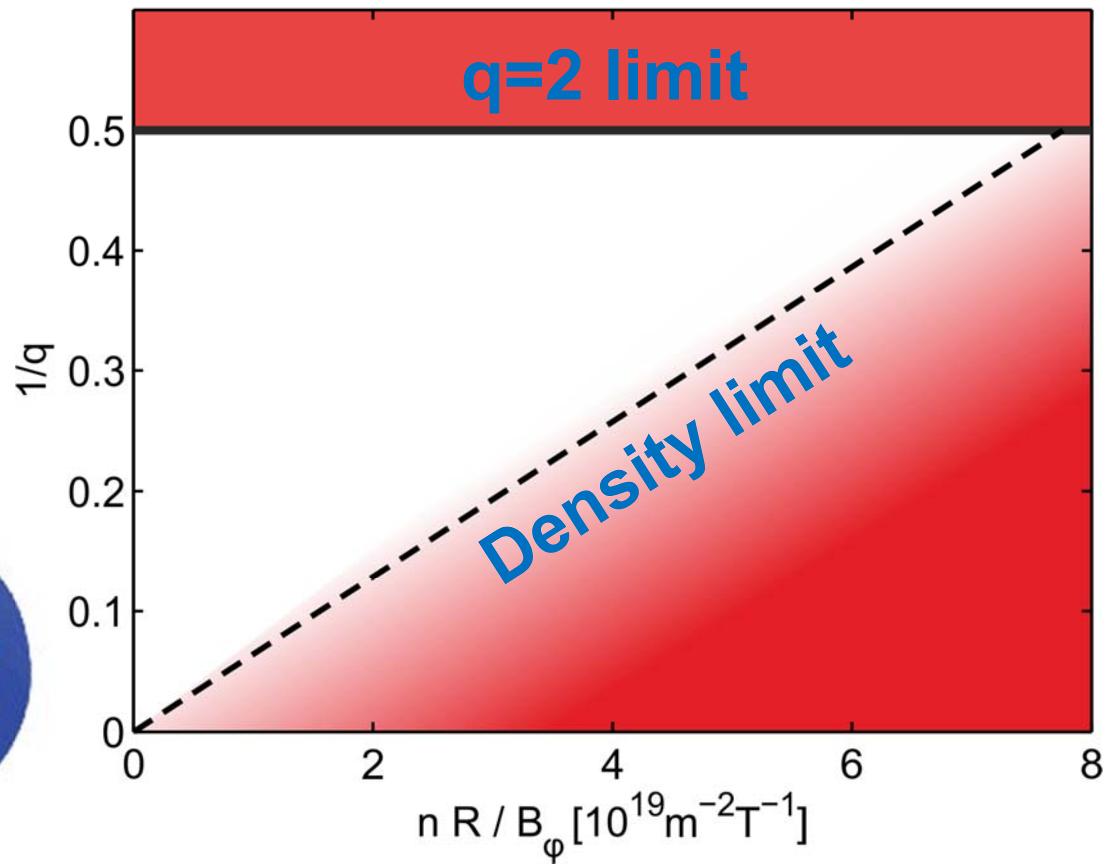


safety factor

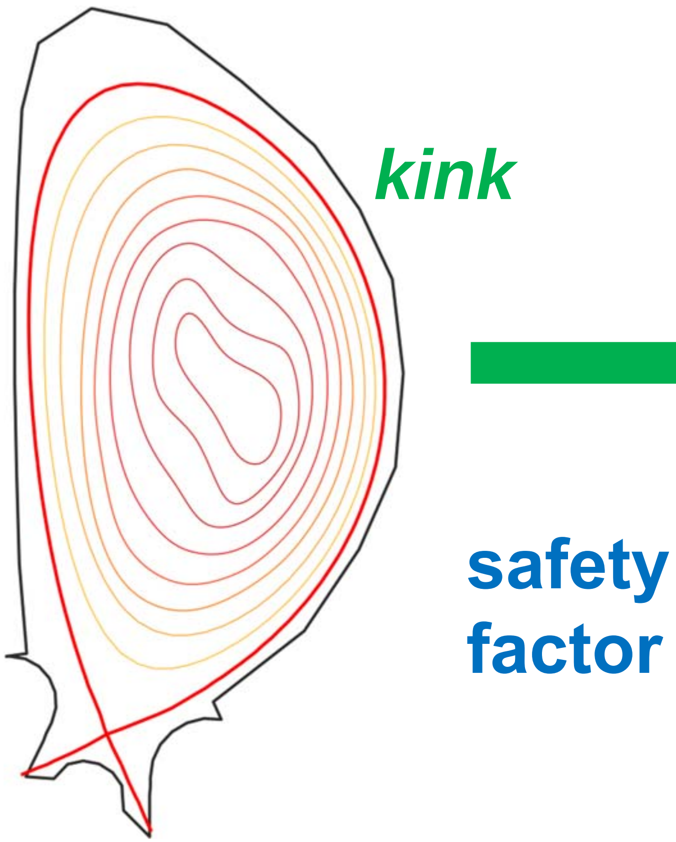
Hugill diagram



density

q = toroidal turns / poloidal turns

What causes disruptions?



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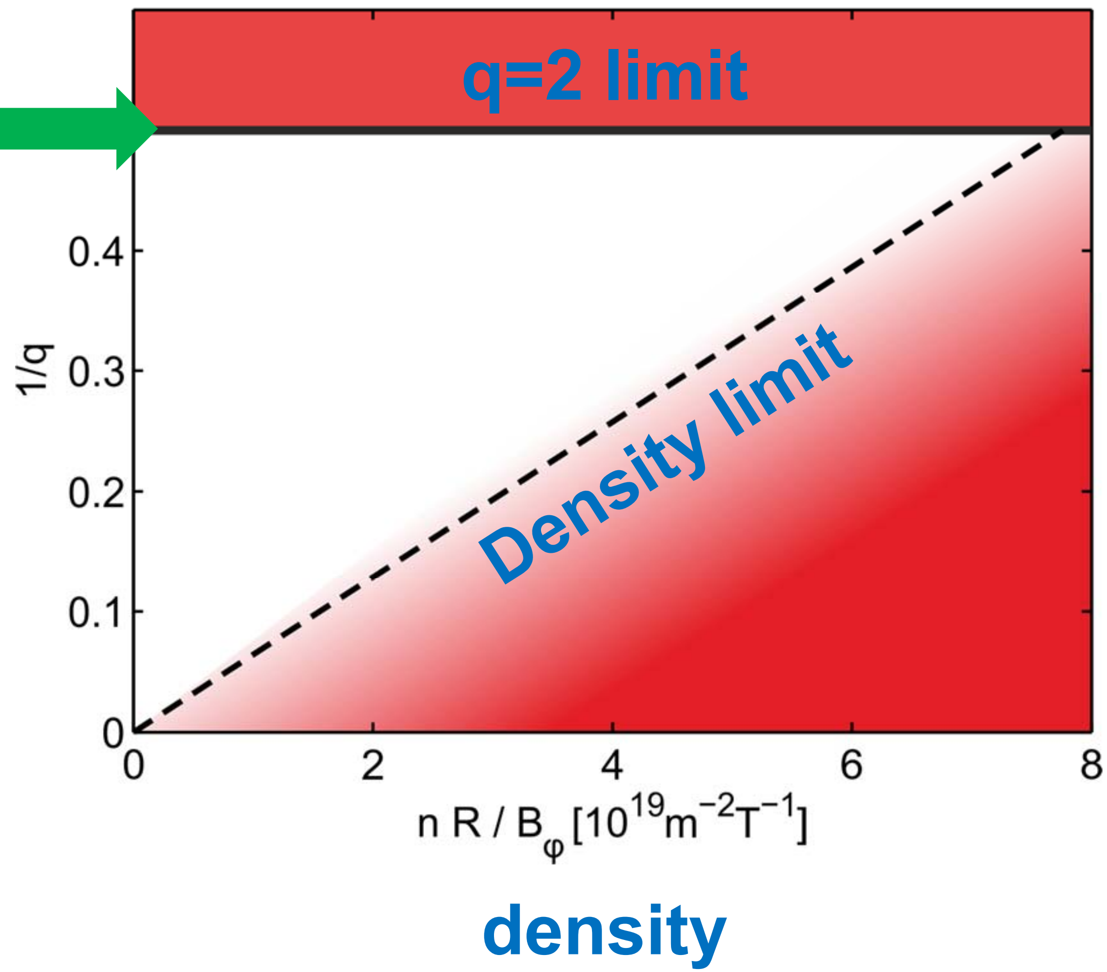

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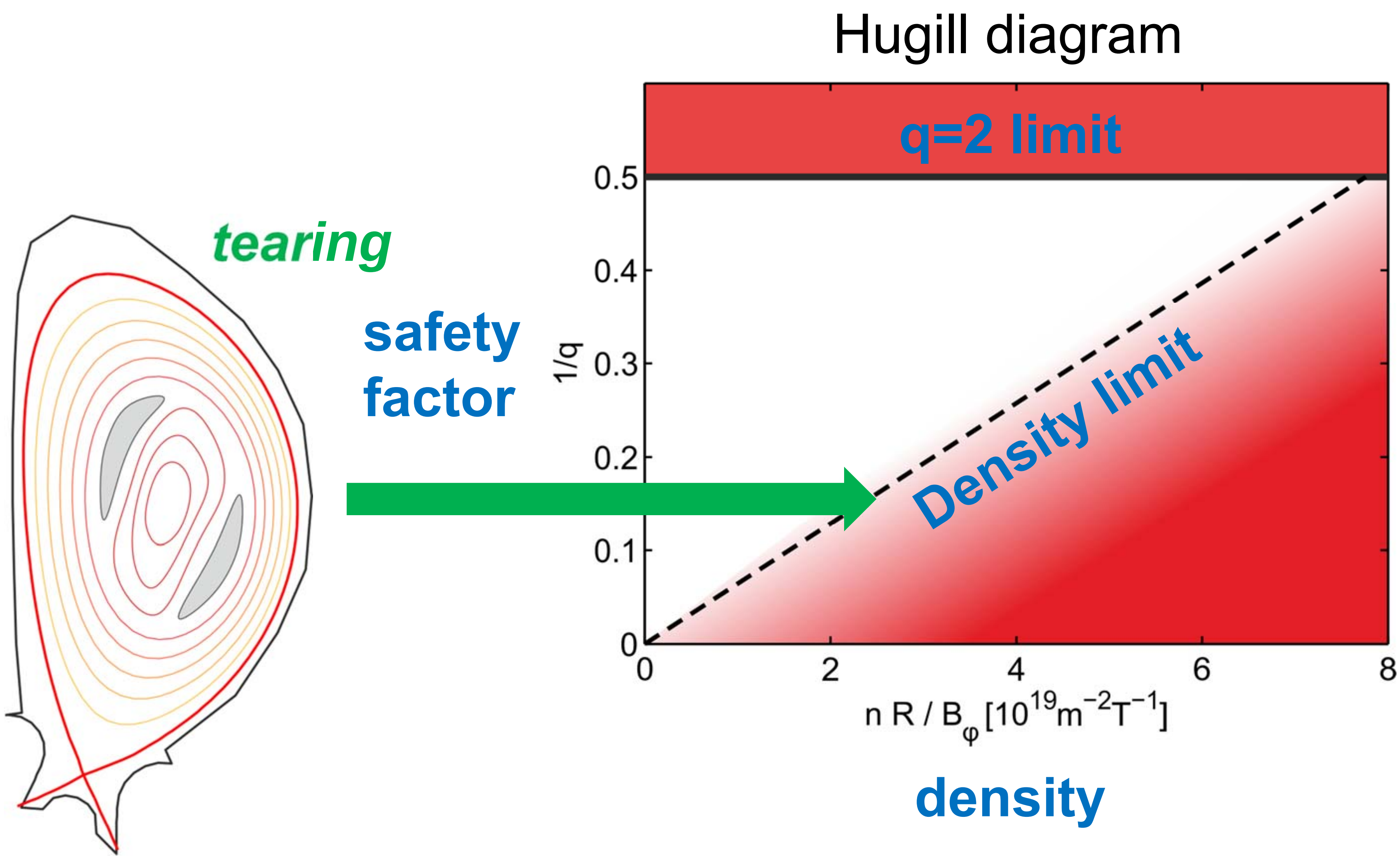
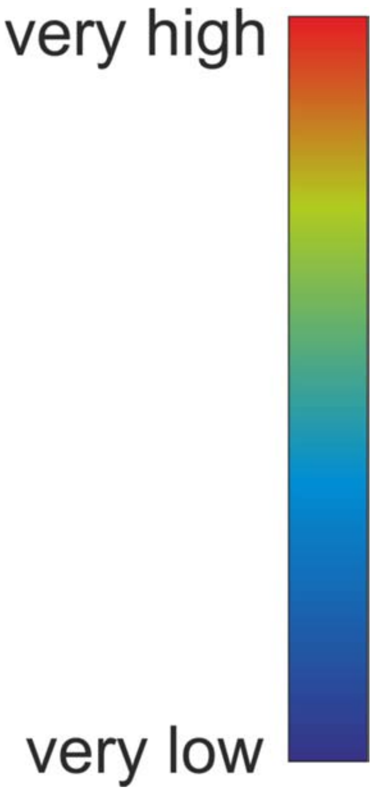


What causes disruptions?

JET statistics:
probability to disrupt



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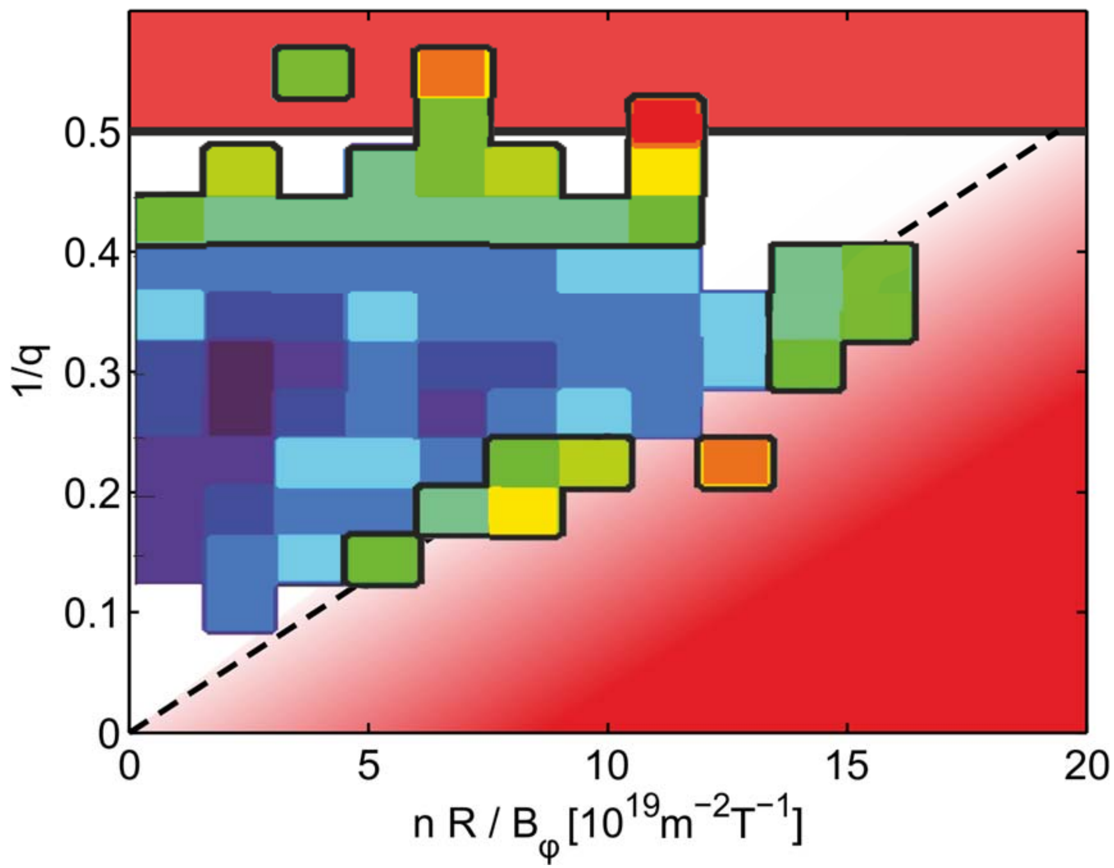


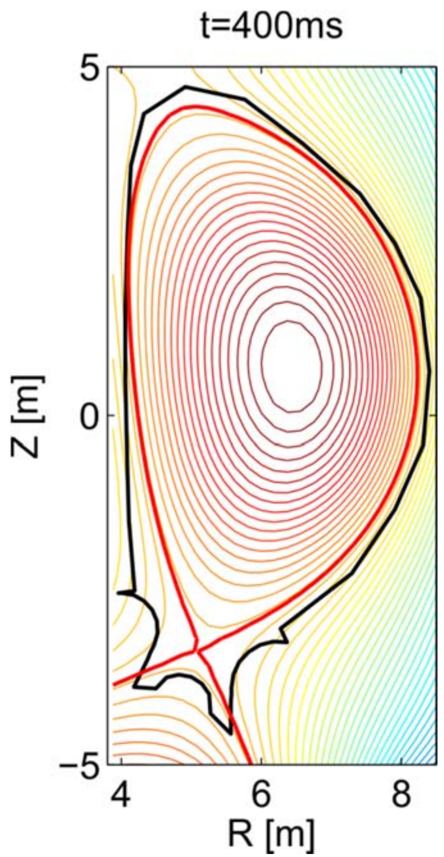
density

P. de Vries, Nuclear Fusion 2009

Vertical Displacement Event – VDE

Elongated plasmas are vertically unstable and need careful position control

ITER can control vertical excursion < 16 cm (in-vessel coils)



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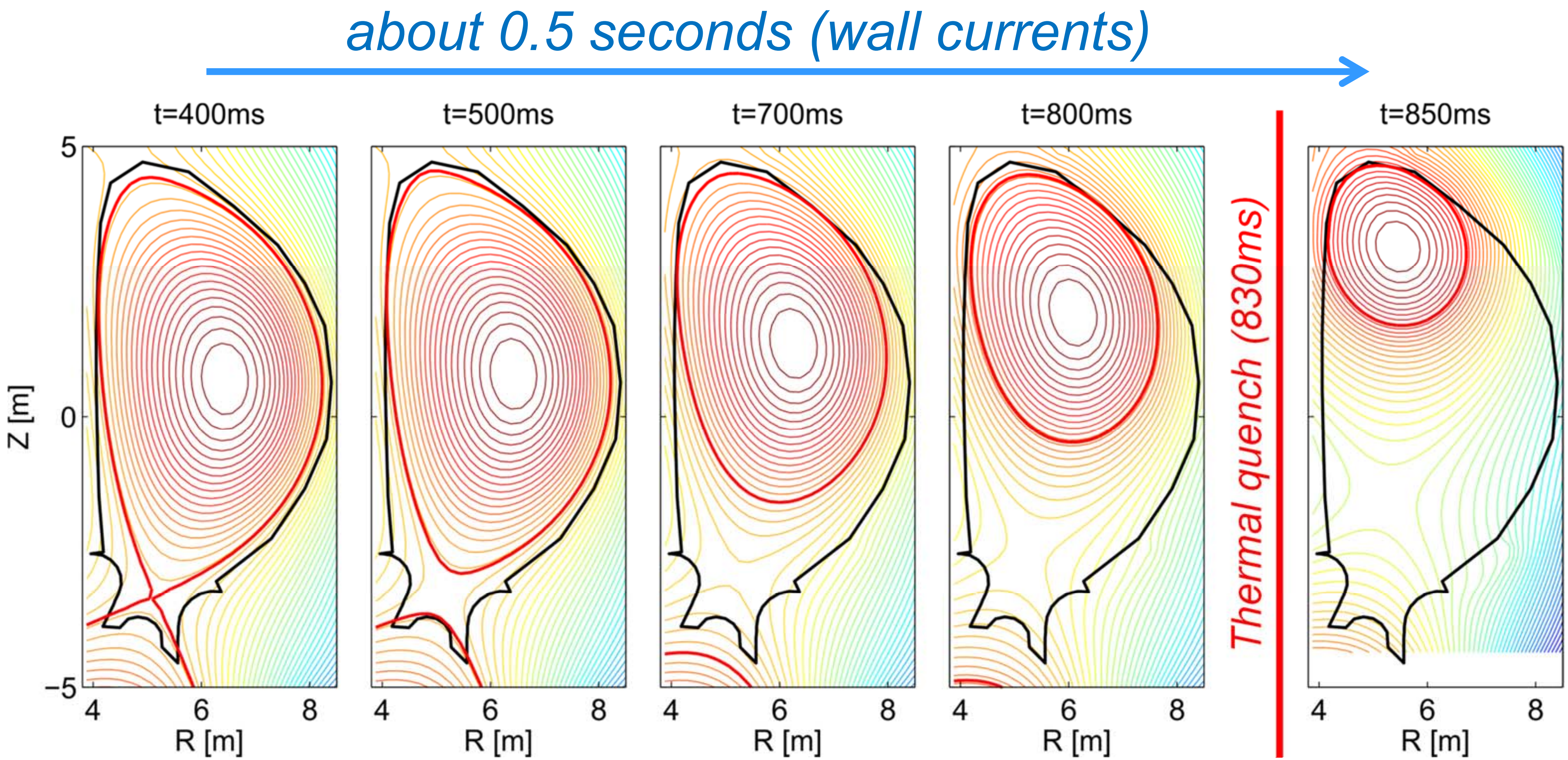


What causes disruptions?

- ❑ Low safety factor
- ❑ High density (or radiation)
- ❑ High plasma pressure
- ❑ Pressure and current profiles
- ❑ UFOs
- ❑ Loss of plasma position control (VDE)

Operating close to the limits to drive performance increases the risk of disruptions

But the plasma can also come close to these limits during ramp-up, scenario exit and ramp-down

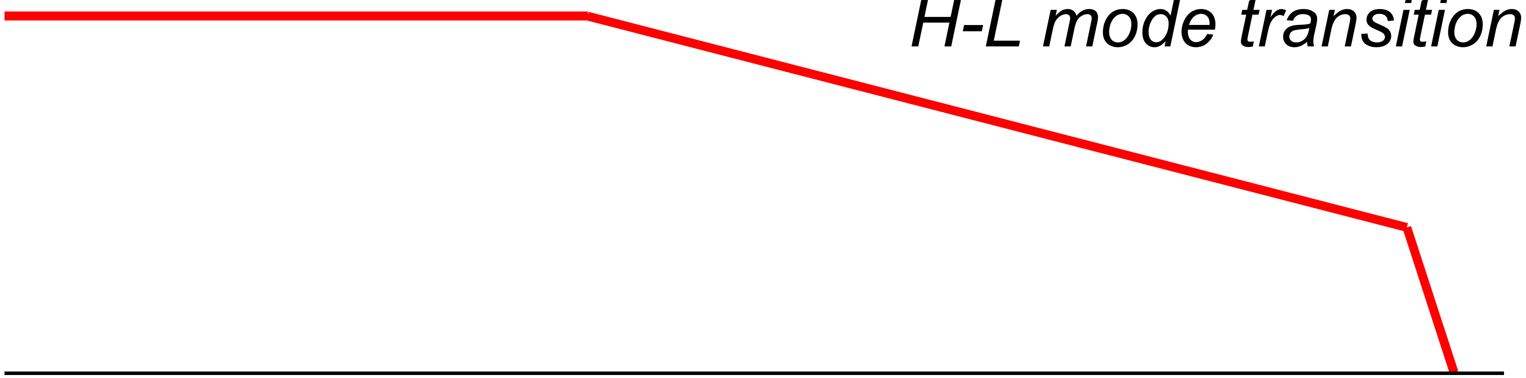
Why worry about disruptions?

- Heat loads
- Electro-magnetic loads
- Runaway electrons

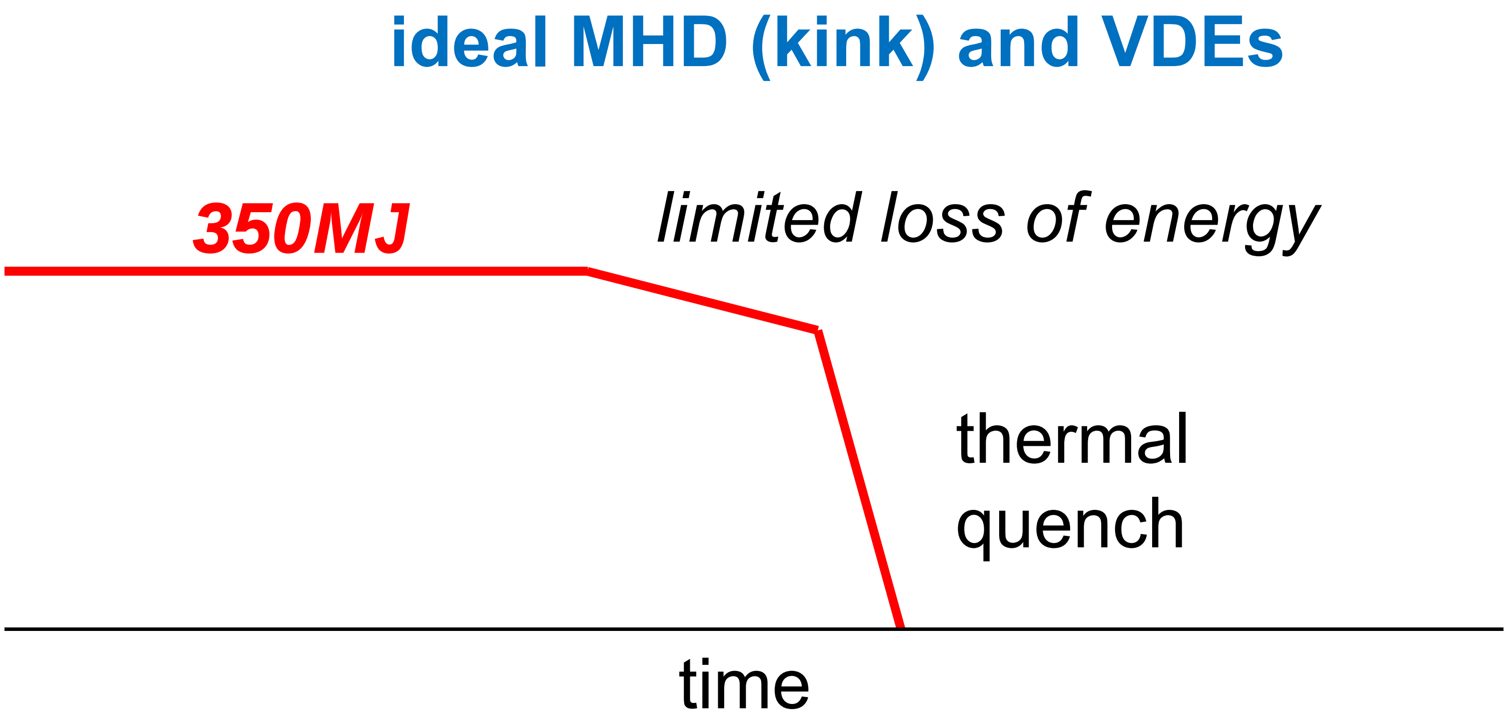
Why worry about disruptions?

Heat loads

resistive time scales (tearing mode)

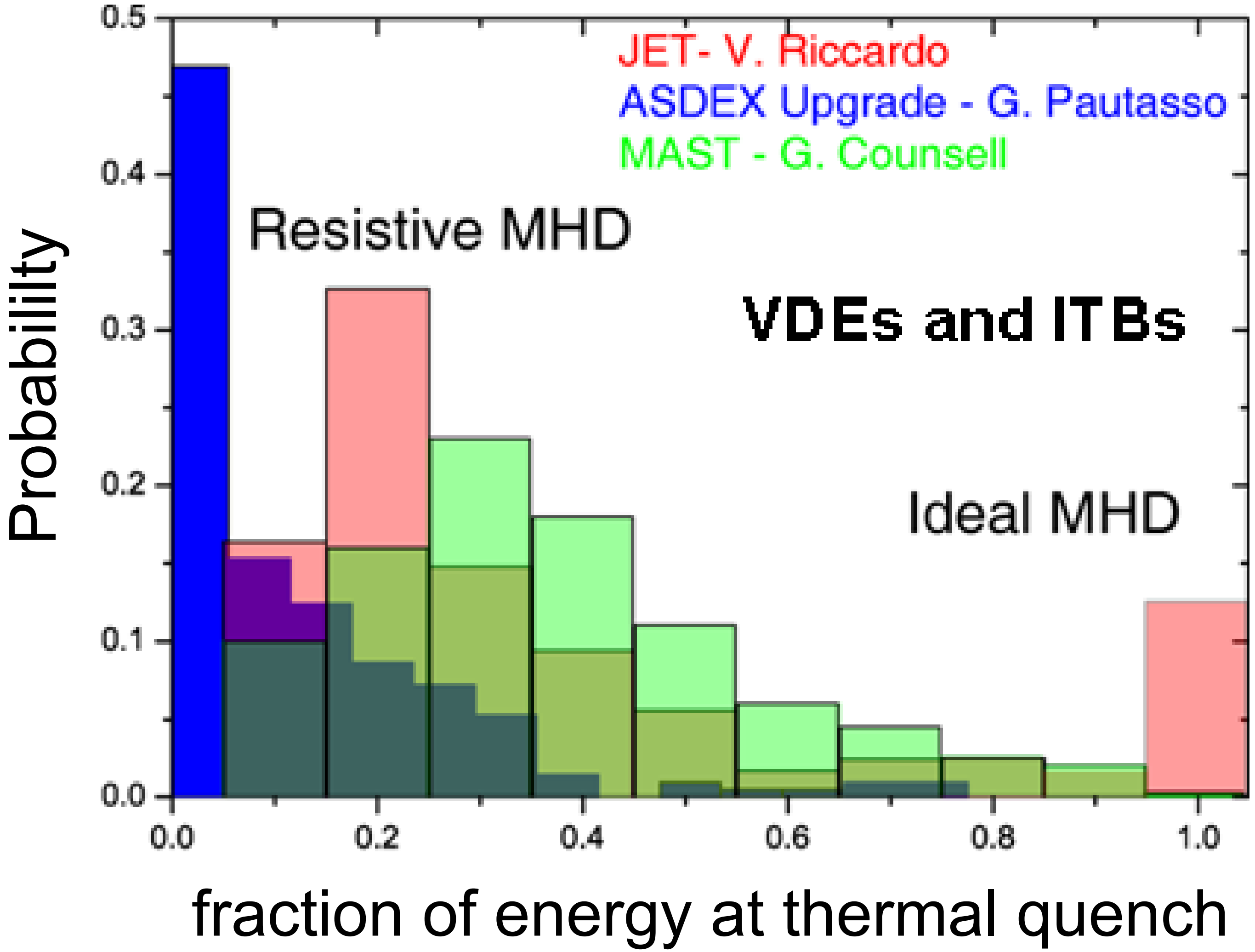


Heat loads


ideal MHD (kink) and VDEs
350MJ
limited loss of energy
thermal
quench
time

Why worry about disruptions?

Heat loads



A. Loarte, Heat and Nuclear Load Specifications, ITER_D_2LULDH v2.4

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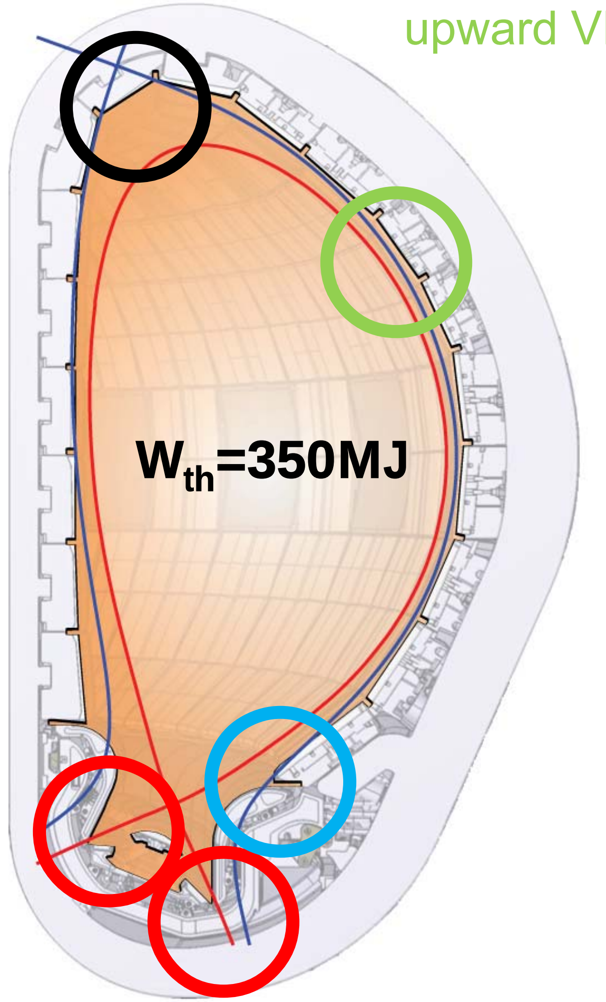


Why worry about disruptions?

Surface temperature increase during fast events:

$$\Delta T \sim \frac{energy}{\sqrt{time} \times area}$$

$energy \approx 280\ \mathrm{MJ}\ (80\%)$

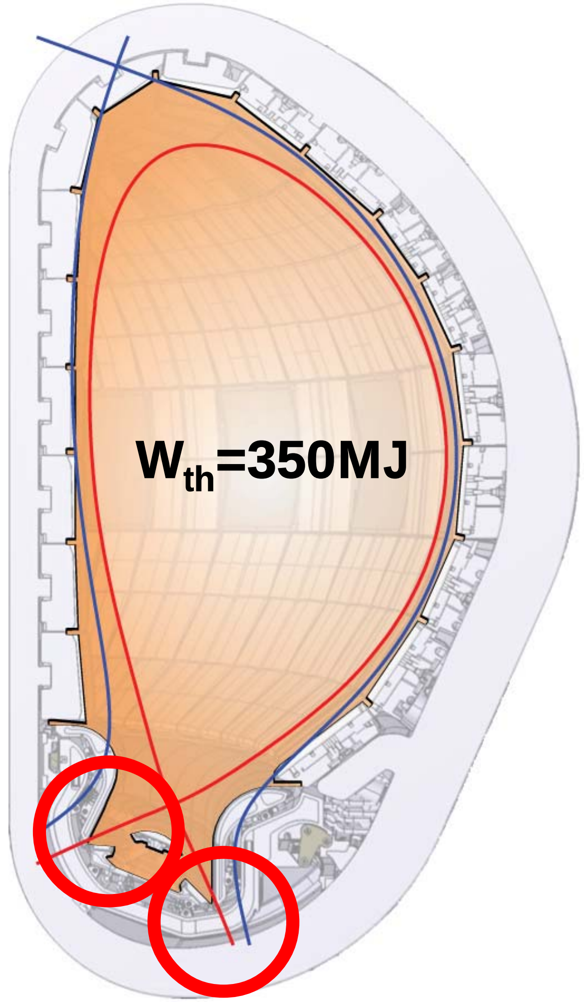
$time \approx 1\ \mathrm{ms}$

R. Pitts, 13 Jan 2014:

$area\ (divertor) \approx 1 - 5\mathrm{m}^2$

experiments show area broadening:

$area\ (divertor) \approx 7 - 35\mathrm{m}^2$



W divertor targets during TQ of MD

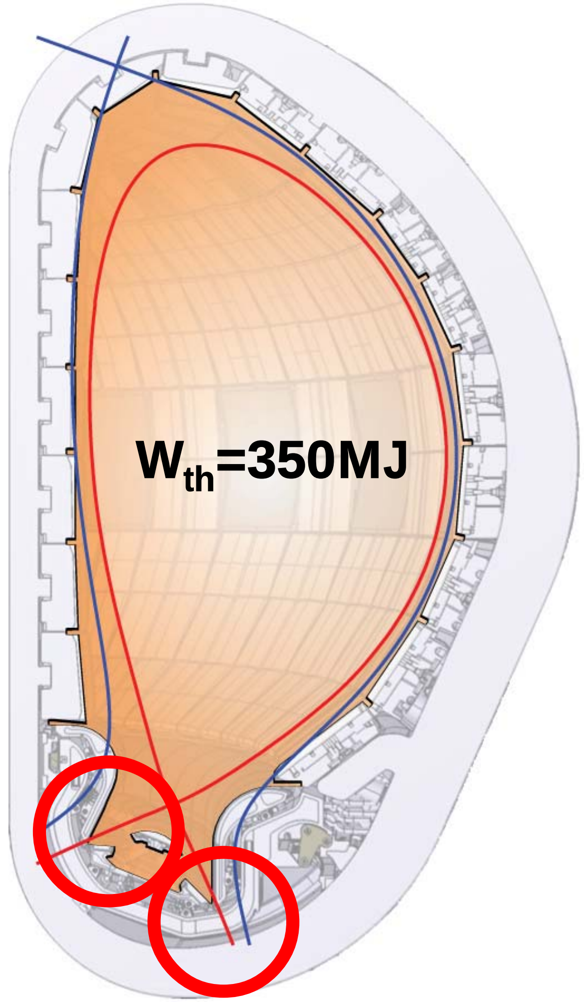
Why worry about disruptions?

Surface temperature increase during fast events:

$$\Delta T \sim 250 - 1250 \frac{\mathrm{MJ}}{\mathrm{m}^2\sqrt{\mathrm{s}}}$$

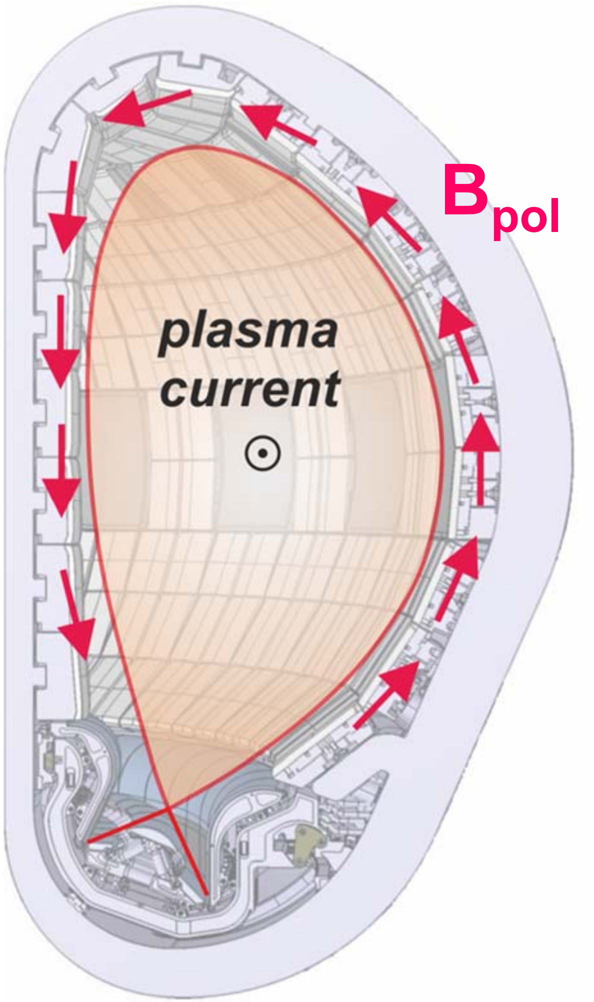
Melting limit for tungsten:

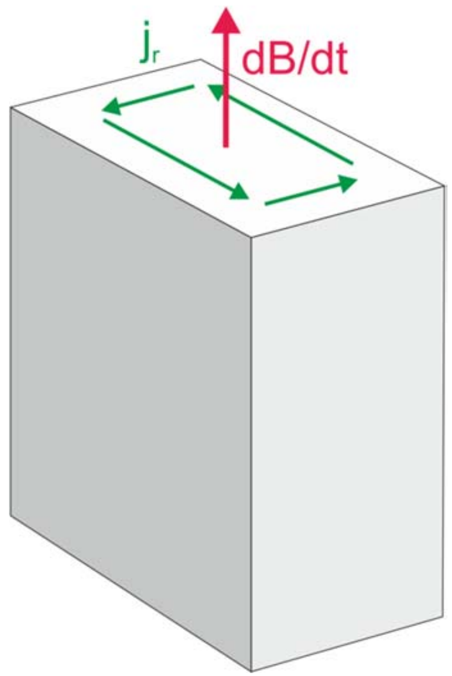
$$\Delta T \approx 2700^{\circ}\mathrm{C} \sim 50 \frac{\mathrm{MJ}}{\mathrm{m}^2\sqrt{\mathrm{s}}}$$



W divertor targets during TQ of MD

Electro-magnetic loads: eddy currents

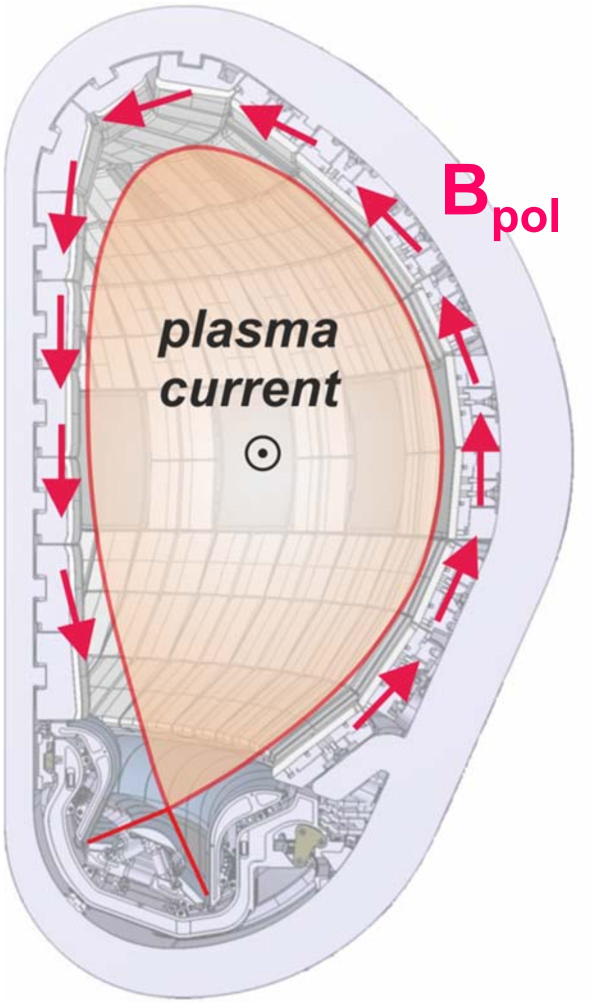


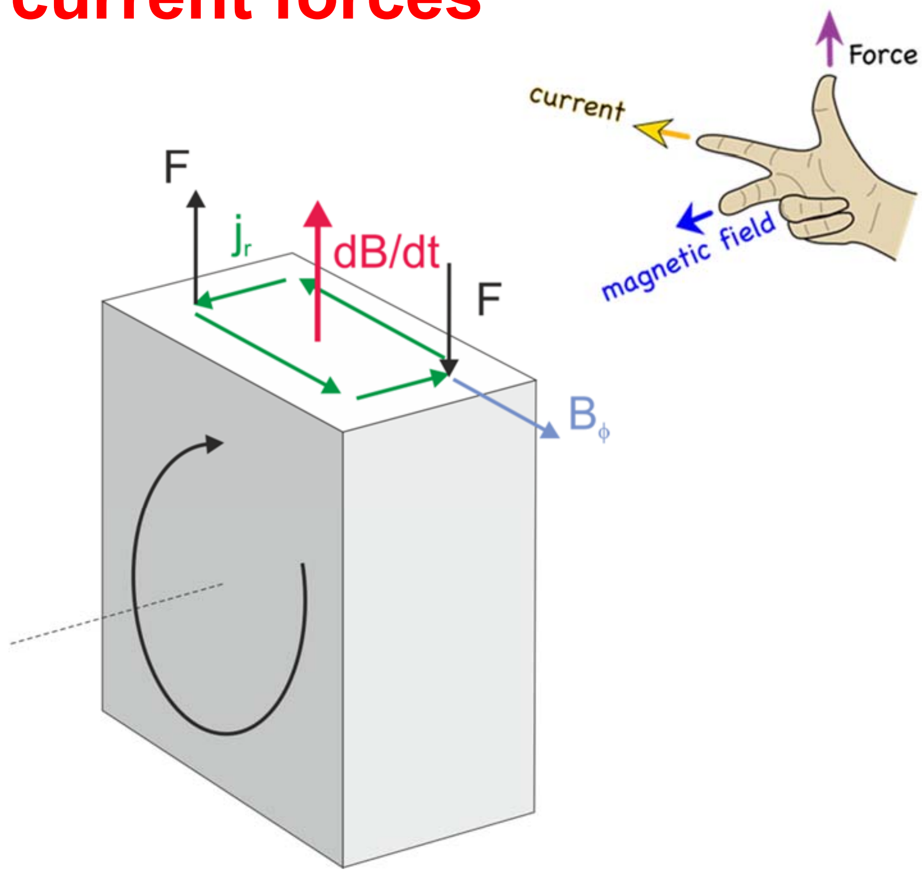


Why worry about disruptions?

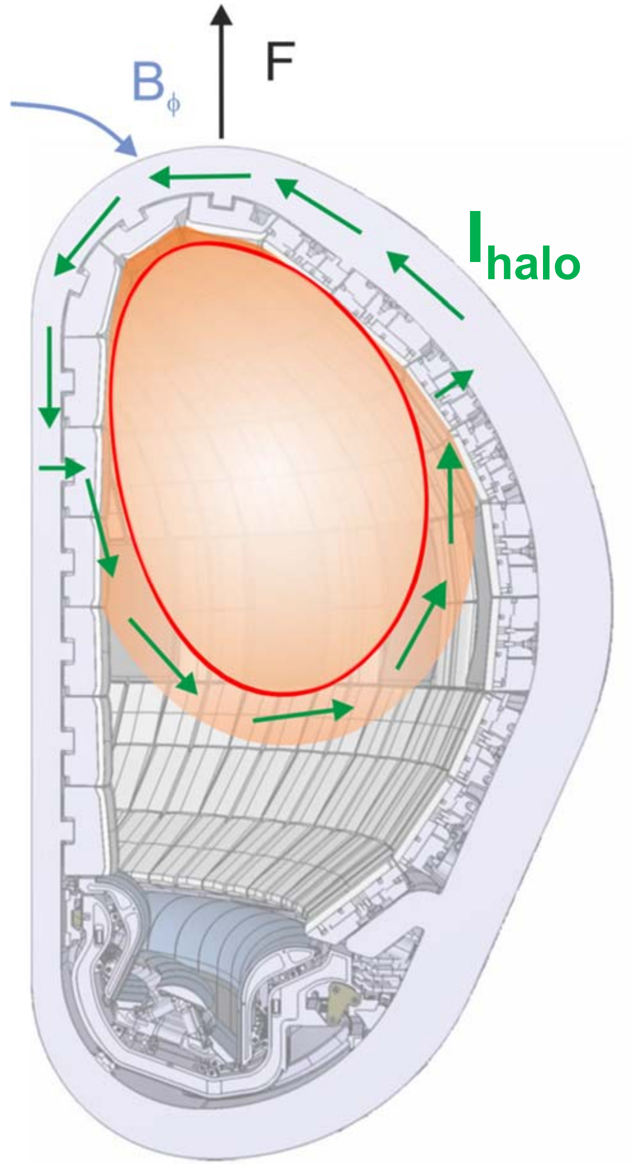
Electro-magnetic loads: eddy currents

fast current decay ➡ high eddy current forces





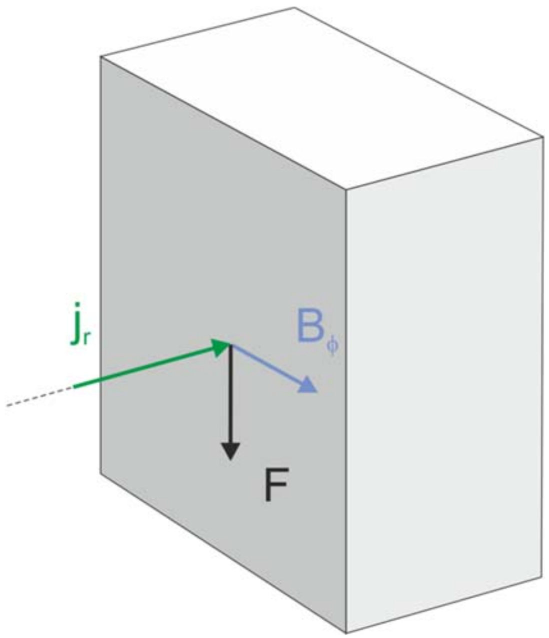
Electro-magnetic loads: halo currents



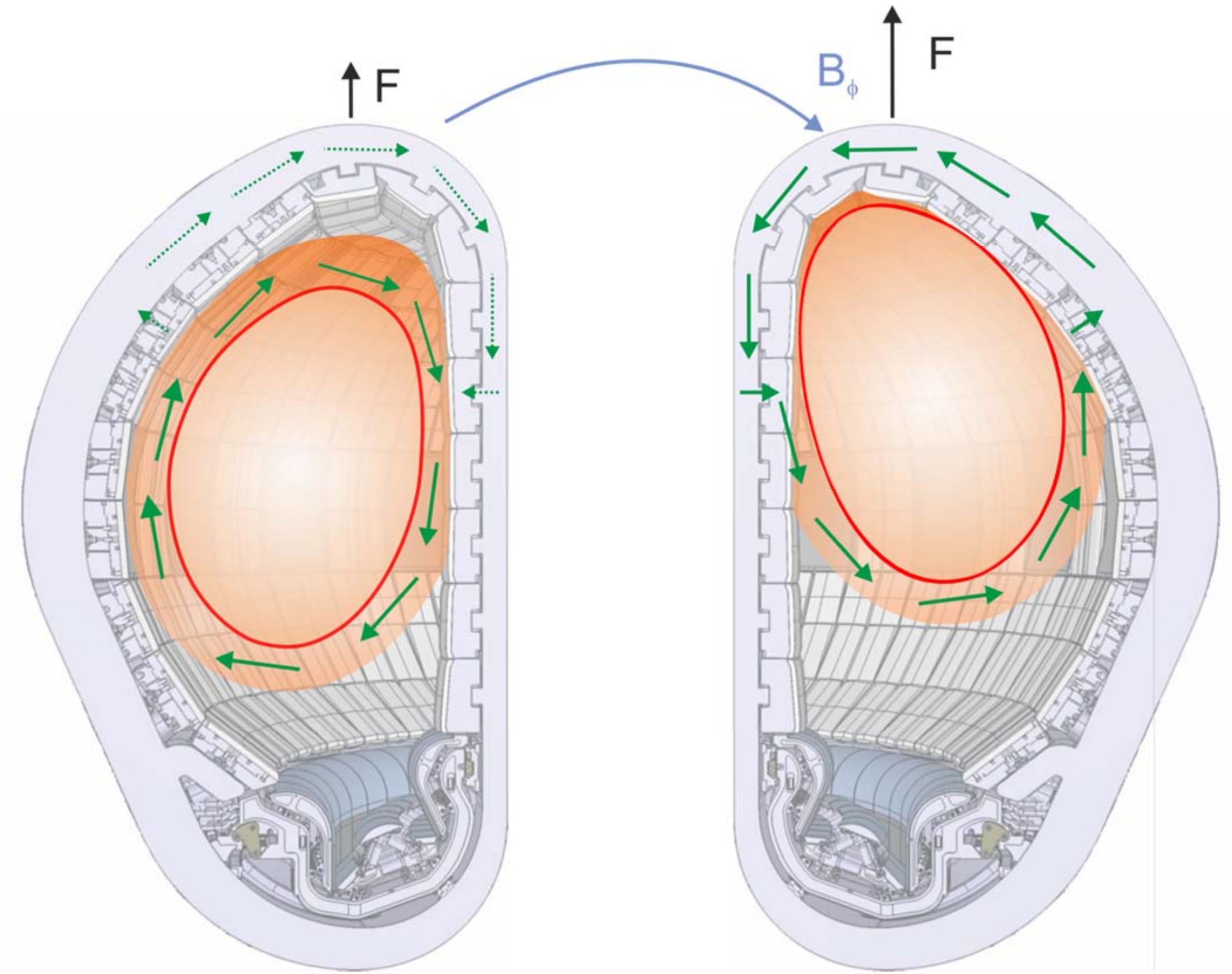
slow current decay

⬇

high halo current forces



Electro-magnetic loads: halo current asymmetries

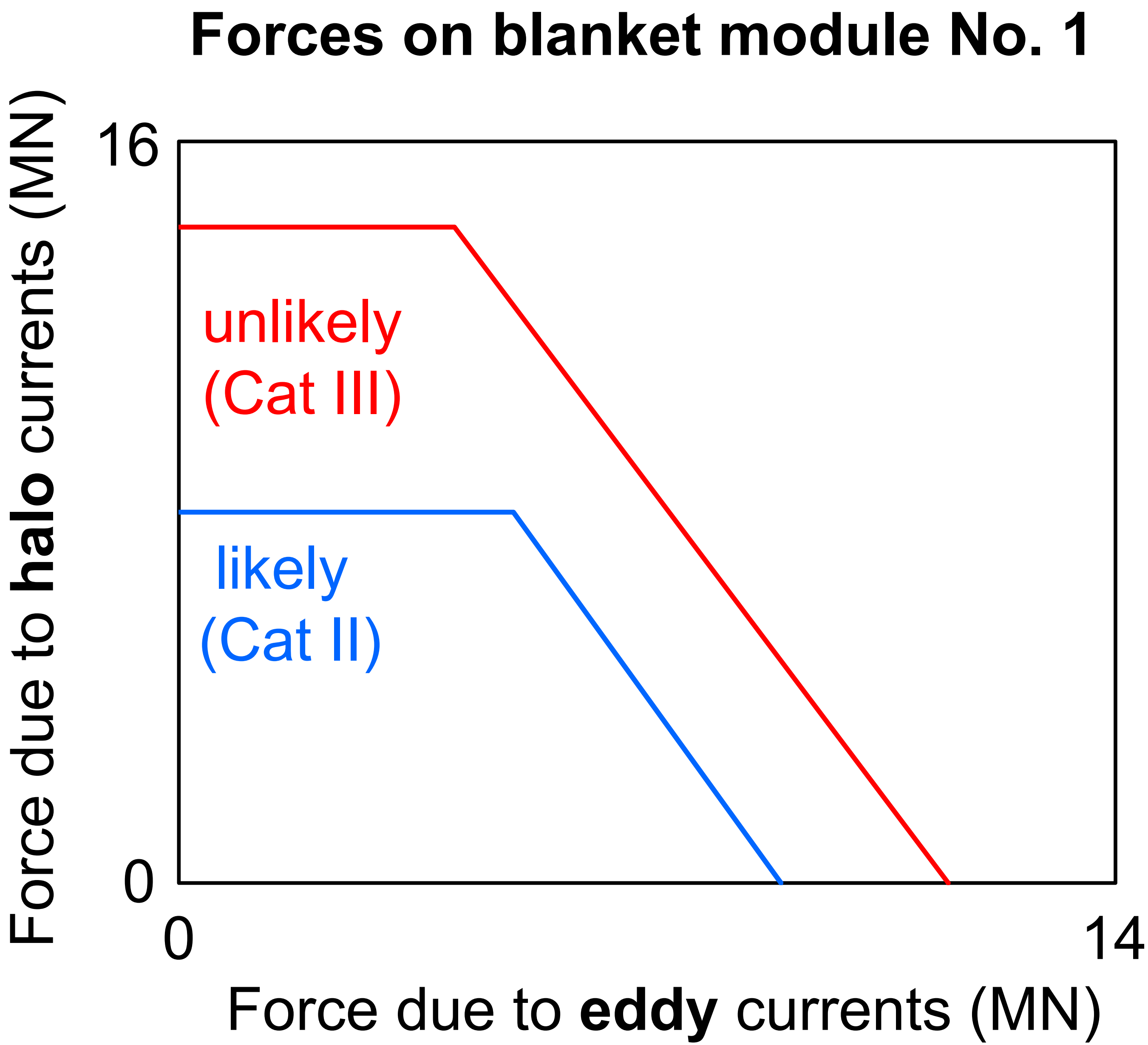


Tilting moment

Sideways forces
(not shown)

S. Gerasimov, EPS 2010

Why worry about disruptions?



10 MN ≙ 1000 tons

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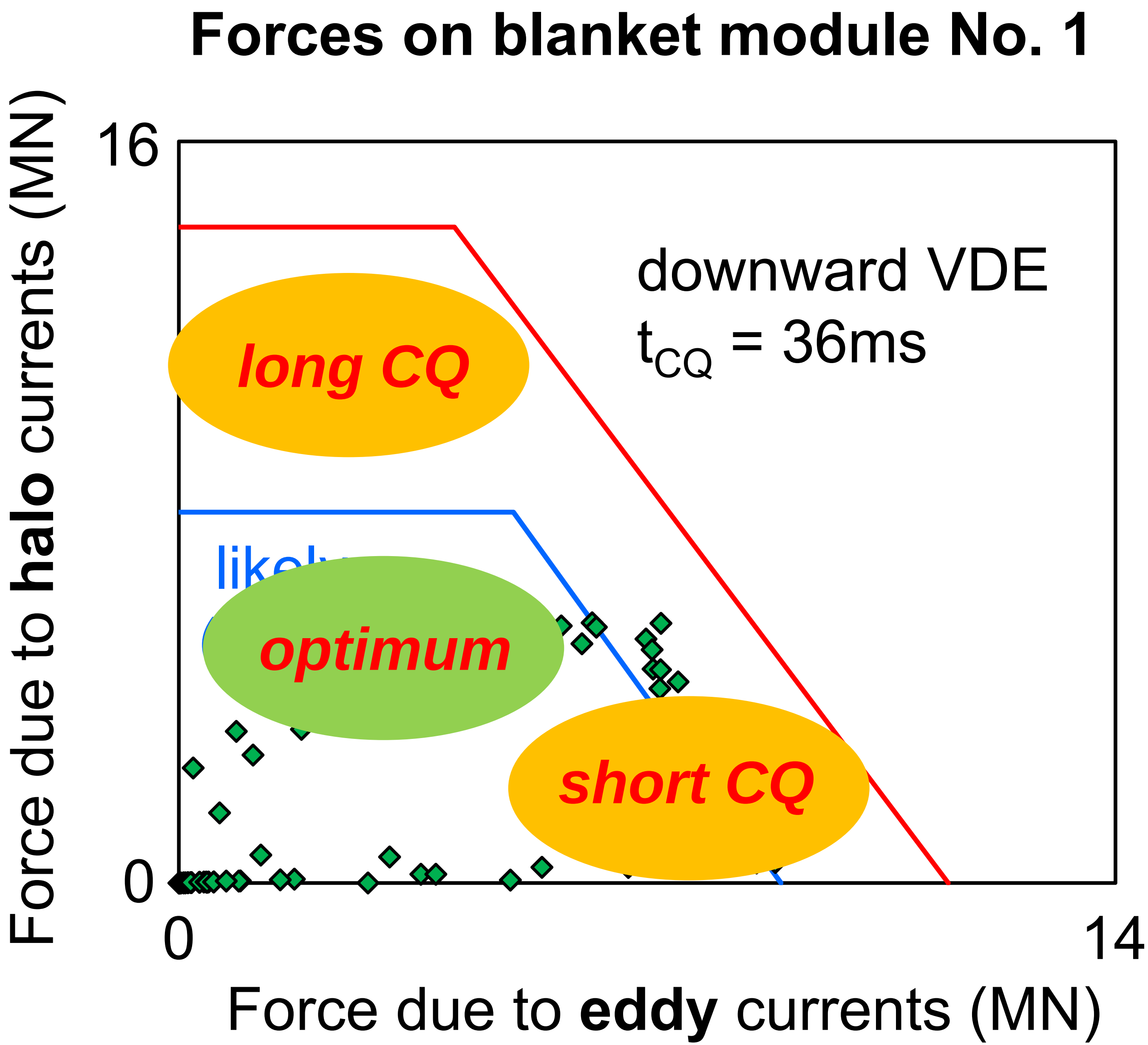


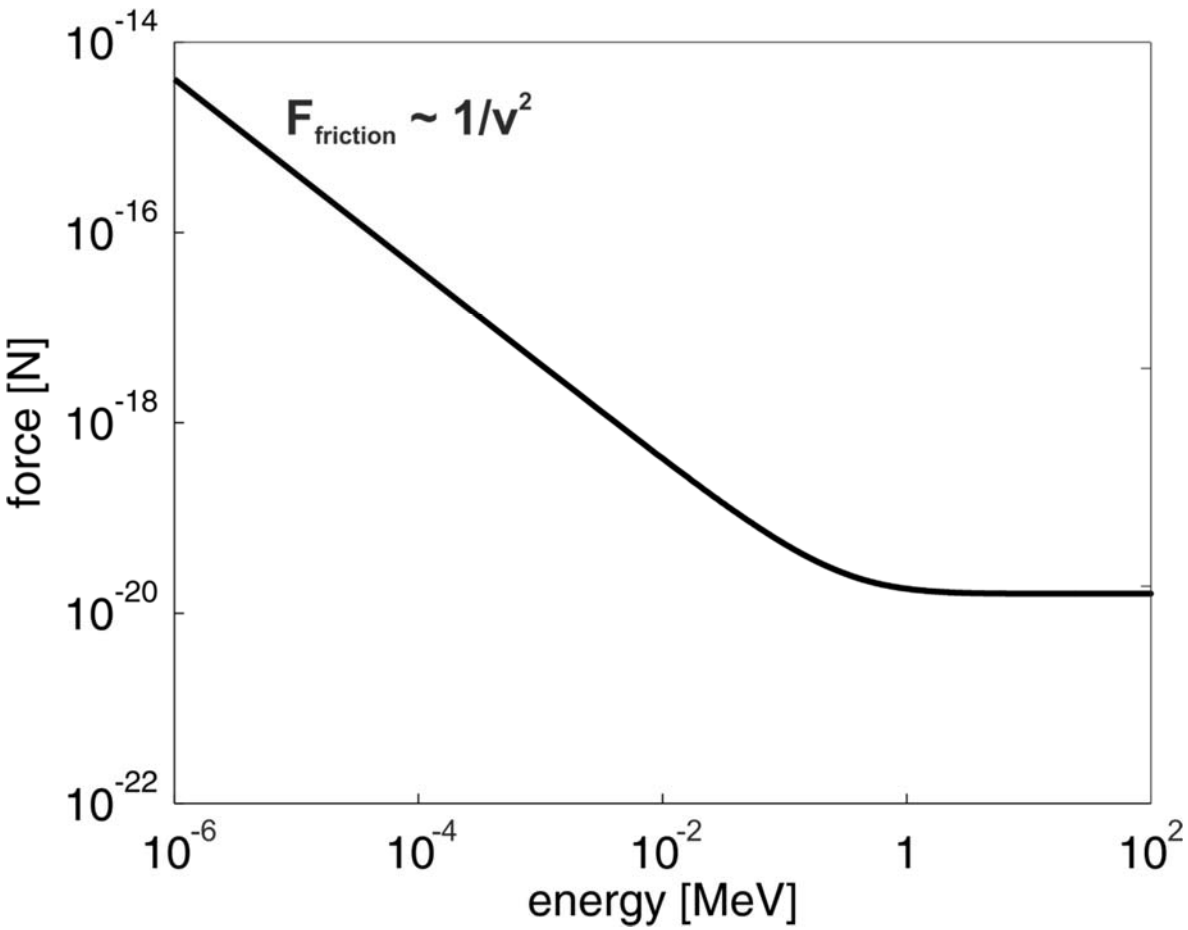
10 MN ≙ 1000 tons

Why worry about disruptions?

The design of Safety Important Class (SIC) components – like the vacuum vessel – has to ensure their safety function for all foreseeable electro-magnetic loads during disruptions.

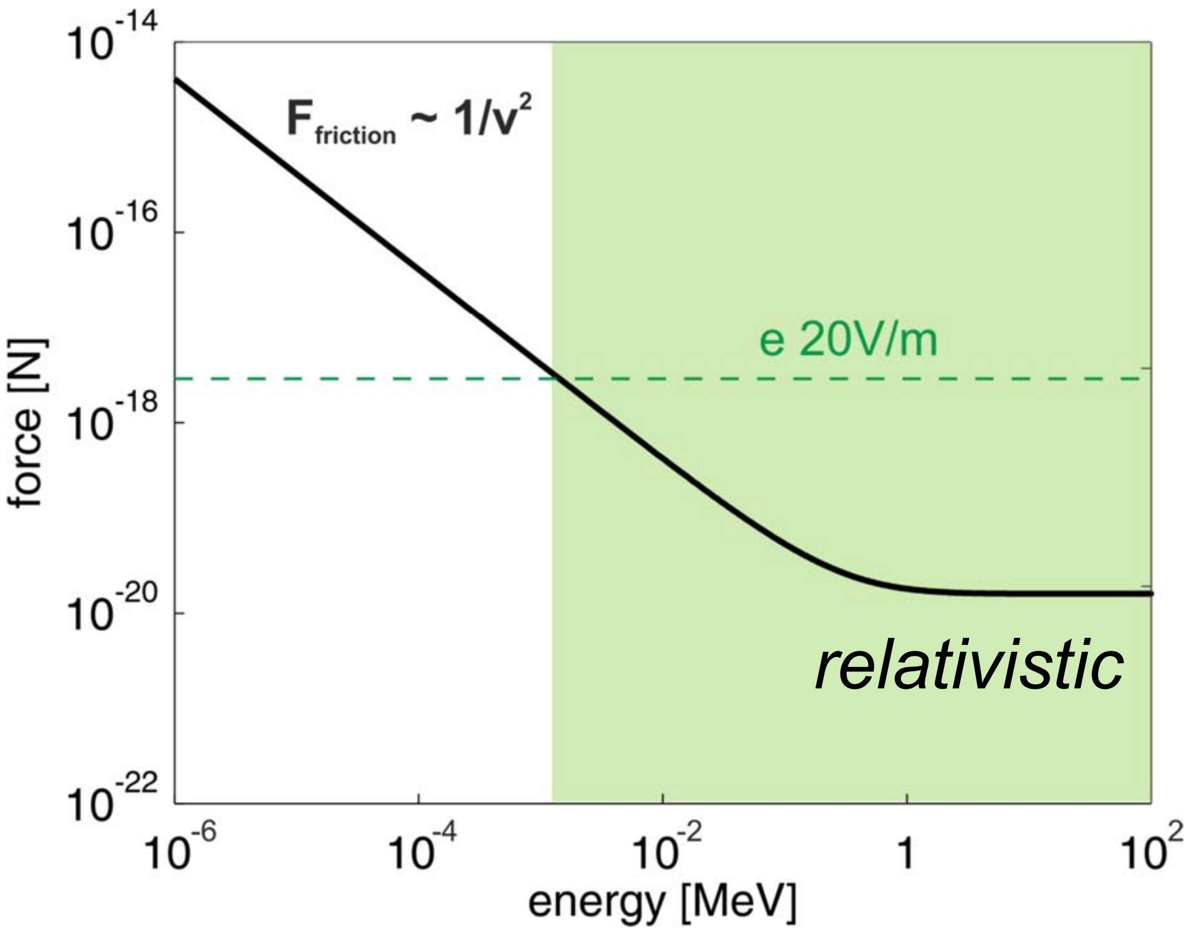
These loads will be monitored during the progressive increase of plasma current to ensure safe operation.

Runaway electrons generated during the current quench



Runaway electrons generated during the current quench

Electric field 20V/m ≈ Resistance 50μΩ x Current 15 MA / L 40 m



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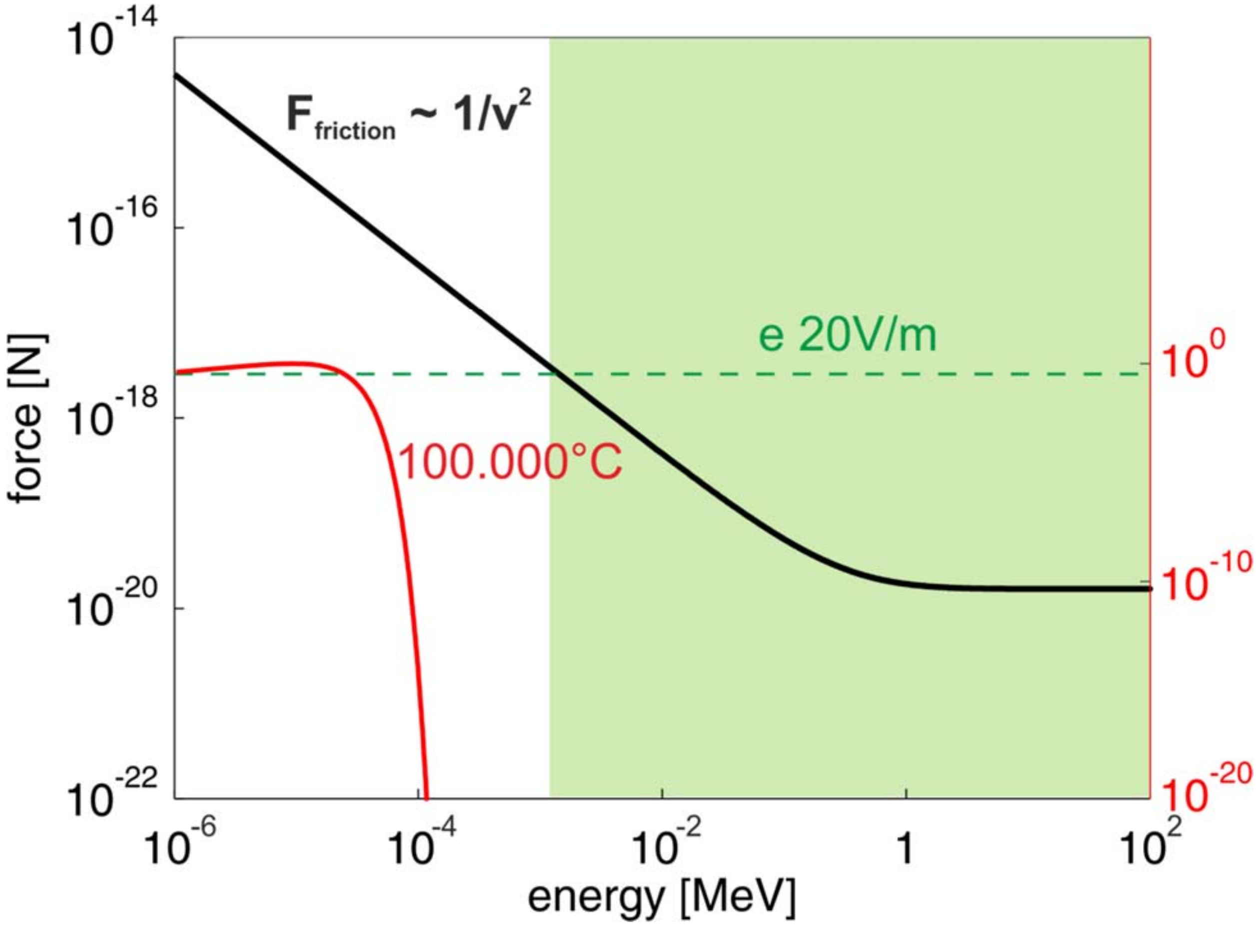
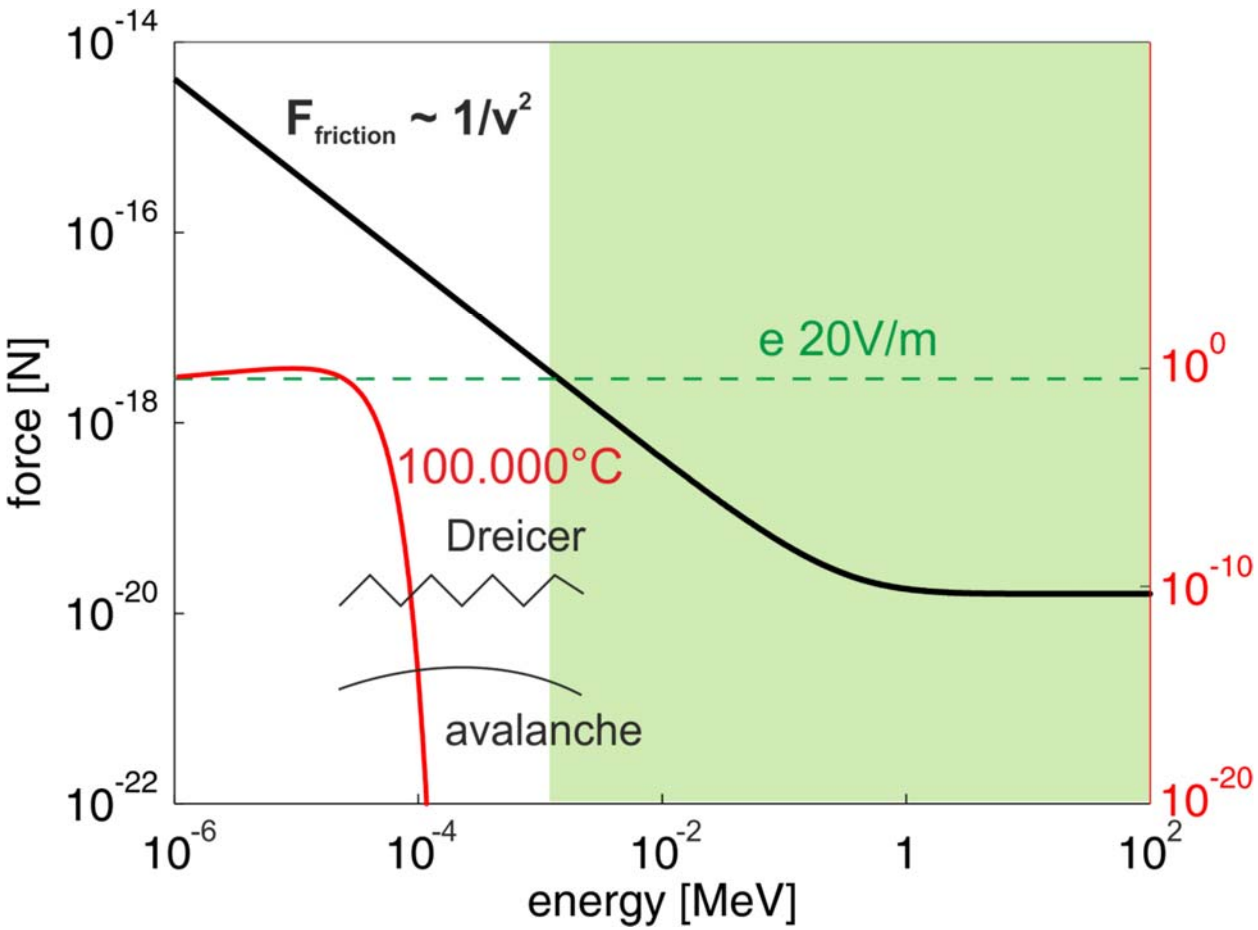


Runaway electrons generated during the current quench

Electric field $20V/m \approx$ Resistance $50\mu\Omega$ x Current $15\ MA$ / L $40\ m$



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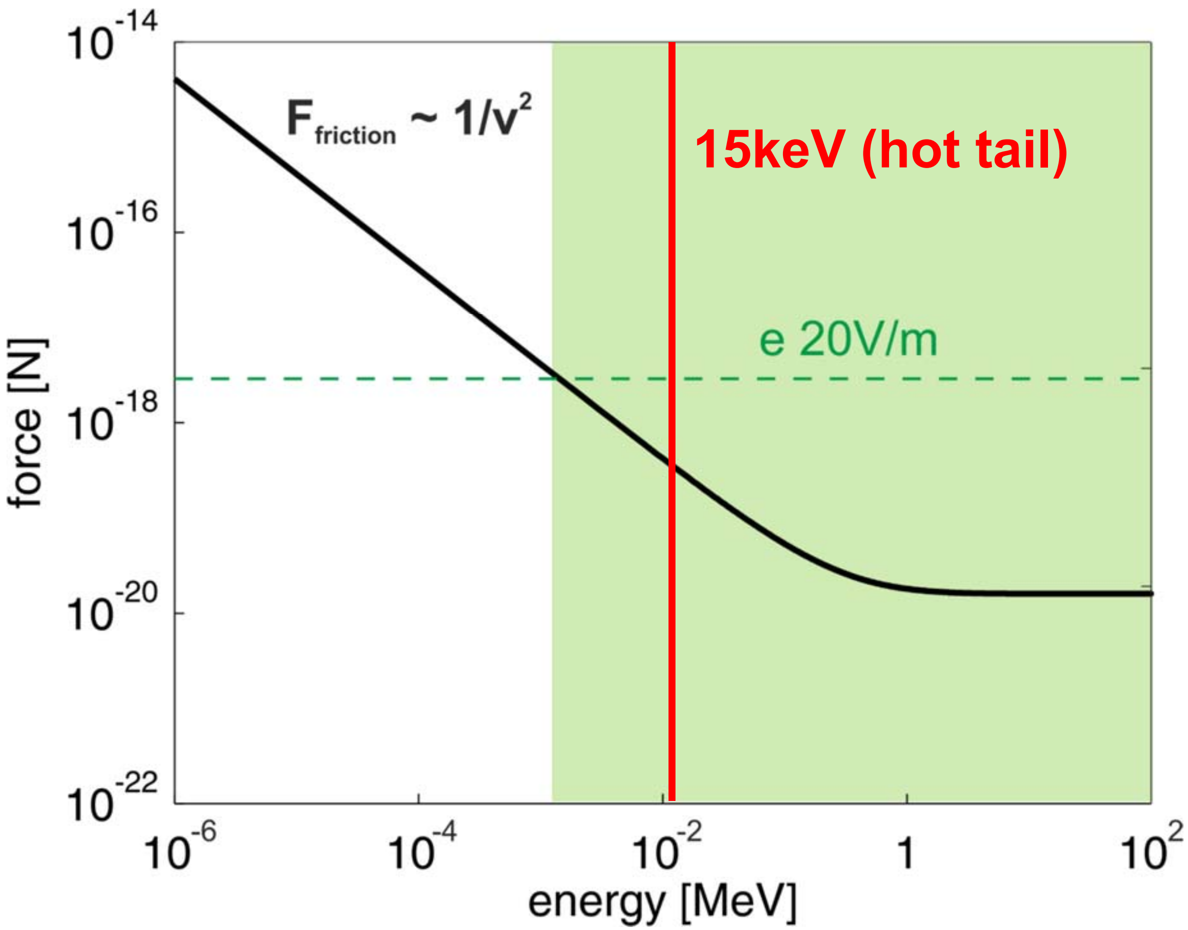
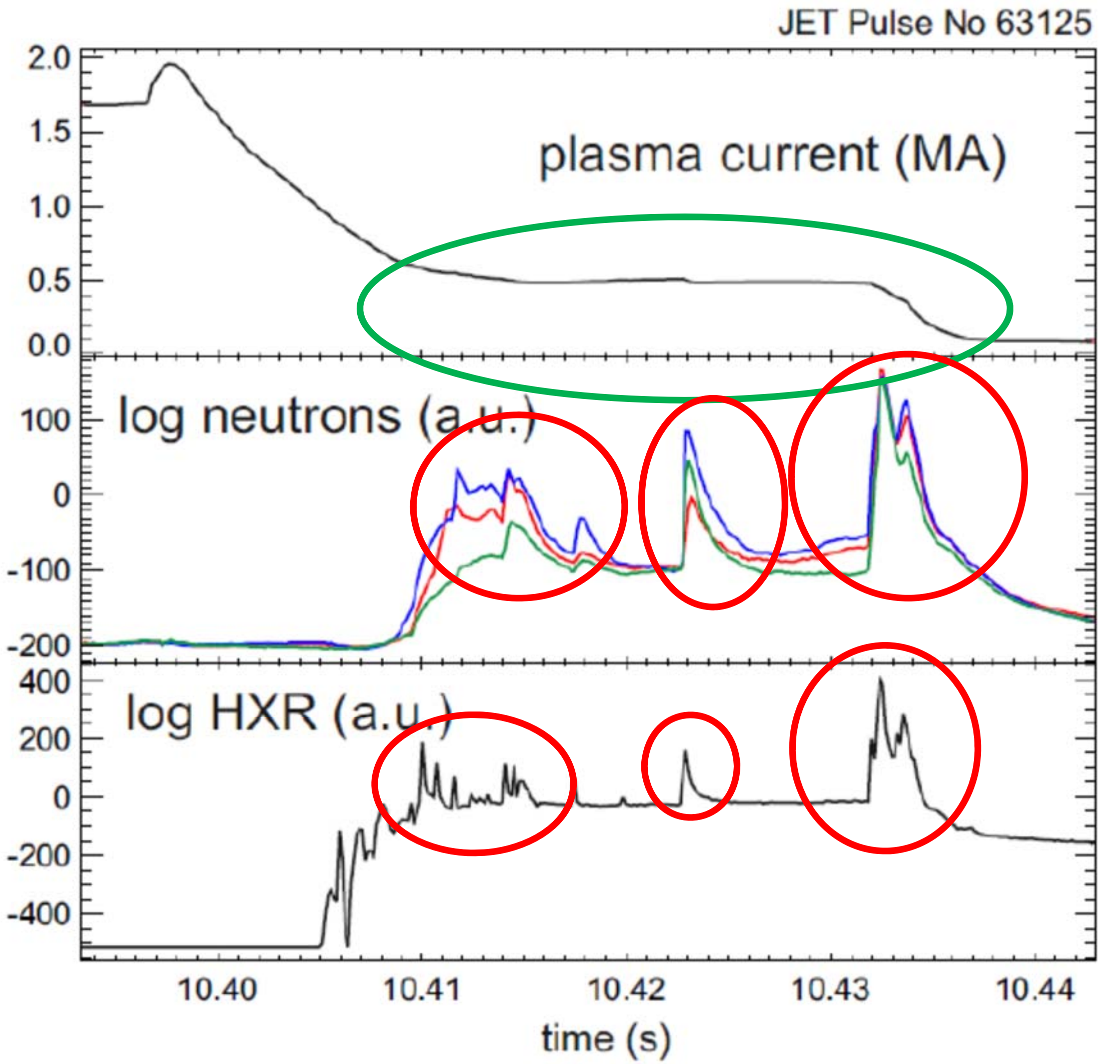


Why worry about disruptions?

JET – runaway generation during a disruption



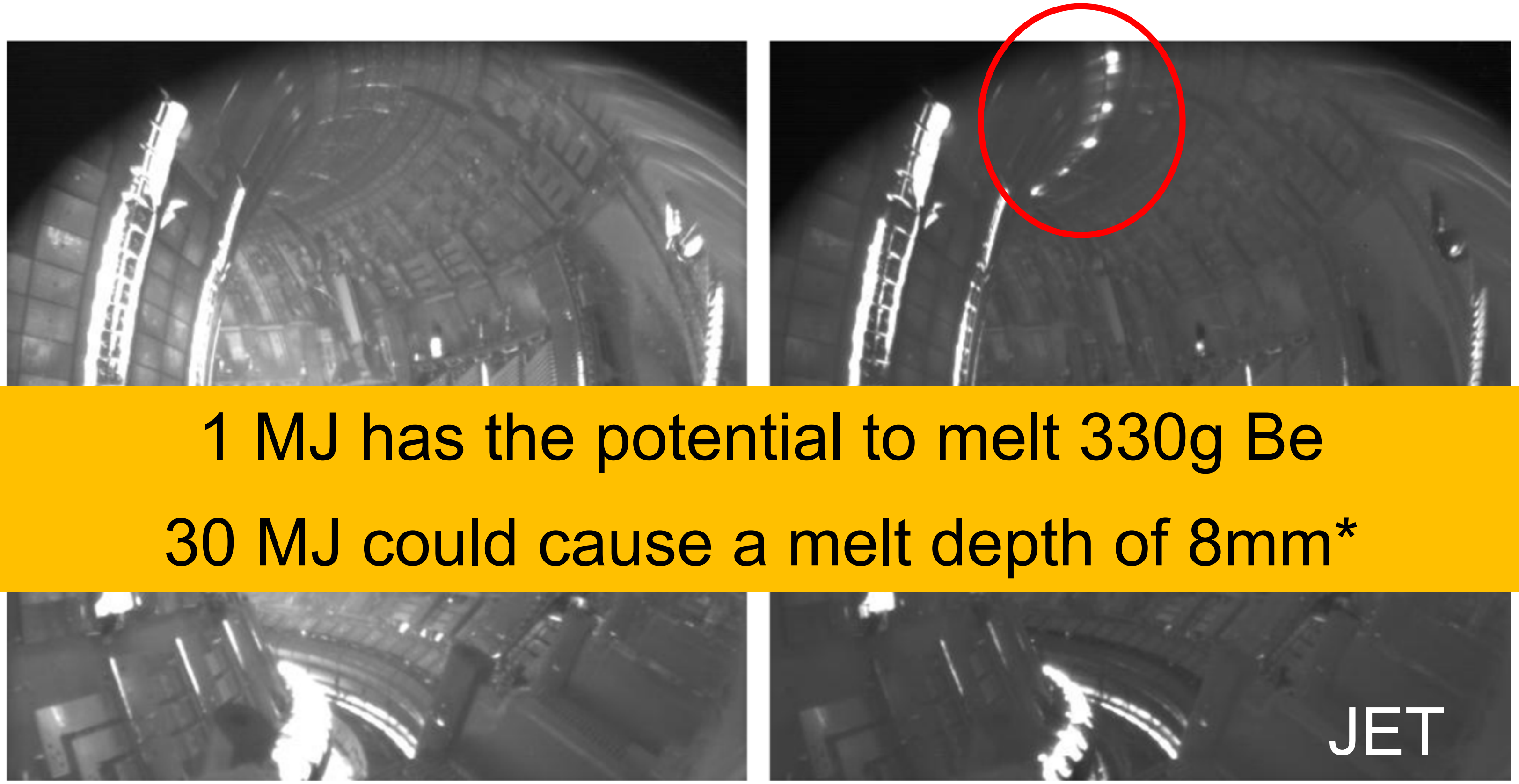
runaway plateau

fast loss events driven by instabilities

Why worry about disruptions?

Runaway impact

- ❑ high velocity (speed of light): spatially very localised
- ❑ high electron energies: deep penetration
- ❑ total energies of up to 300 MJ in ITER cannot be excluded



1 MJ has the potential to melt 330g Be

30 MJ could cause a melt depth of 8mm*

*Based on simple geometrical considerations

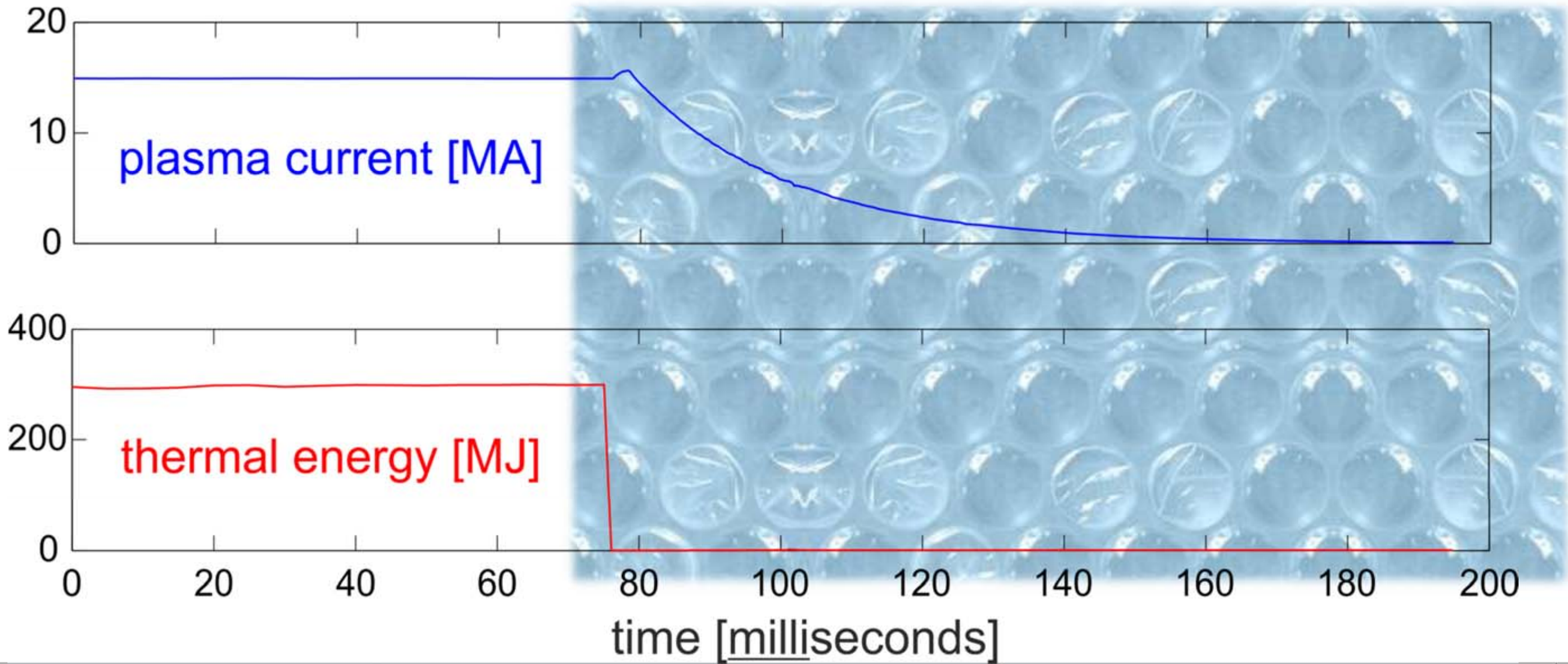
How to deal with disruptions?

Prediction | **Avoidance** | **Mitigation**

J. Vega's lecture on Friday

-MHD mode control: F. Volpe's lecture on Thursday

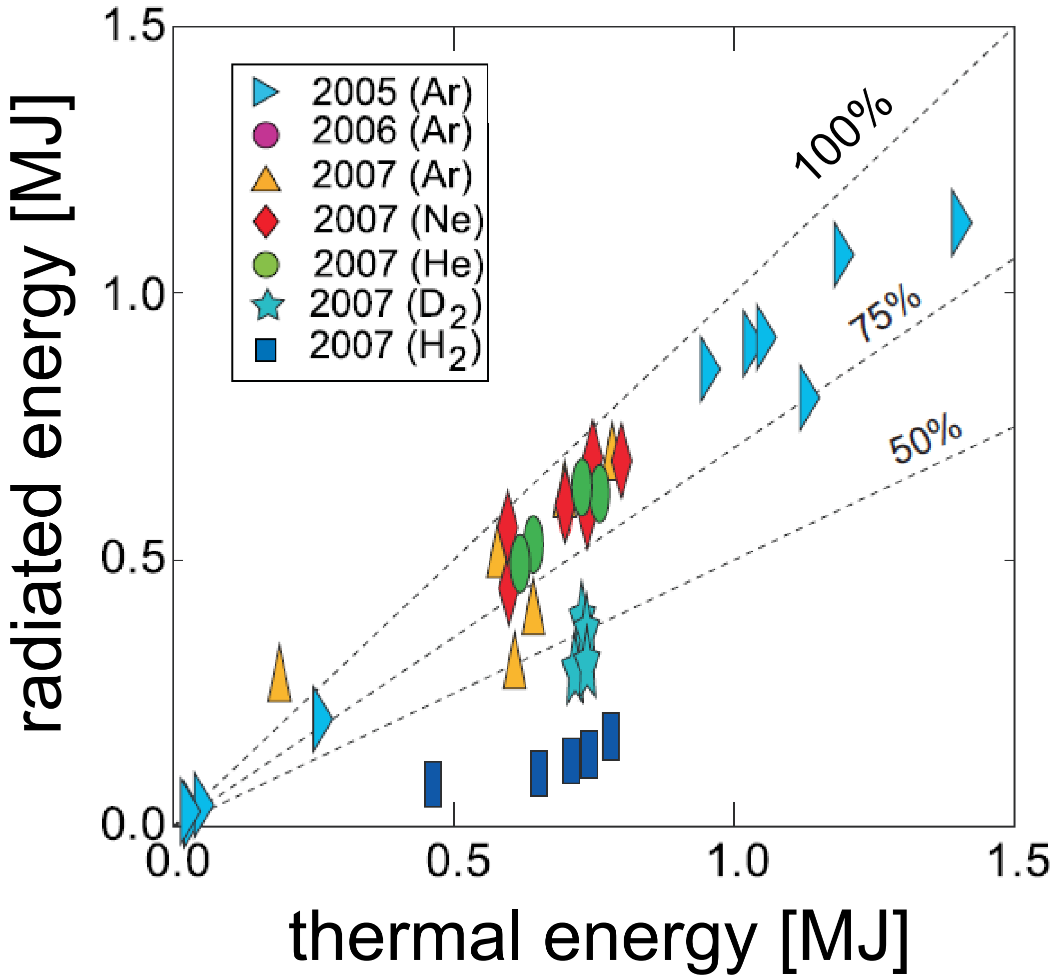
-Discharge management strategies (e.g. fast discharge termination)



How to deal with disruptions?

Thermal load mitigation

Massive injection of high Z impurities like neon or argon
Radiation distributes energy over larger area

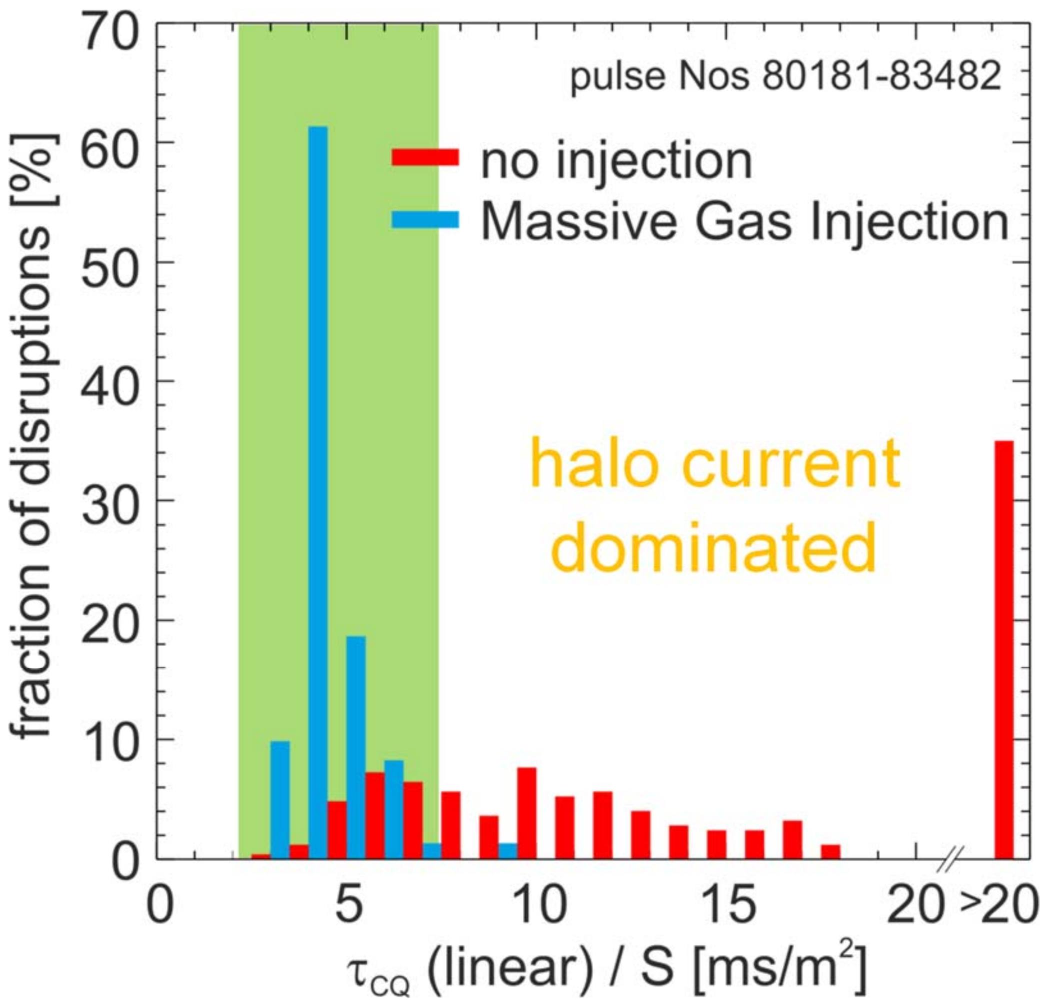


DIII-D
Massive Gas Injection

E. Hollmann
Nuclear Fusion 2008

Electro-magnetic load mitigation

Control of current decay rate / impurity radiation



Current quench times with the JET ITER-like wall

low halo current forces
and
low eddy current forces:

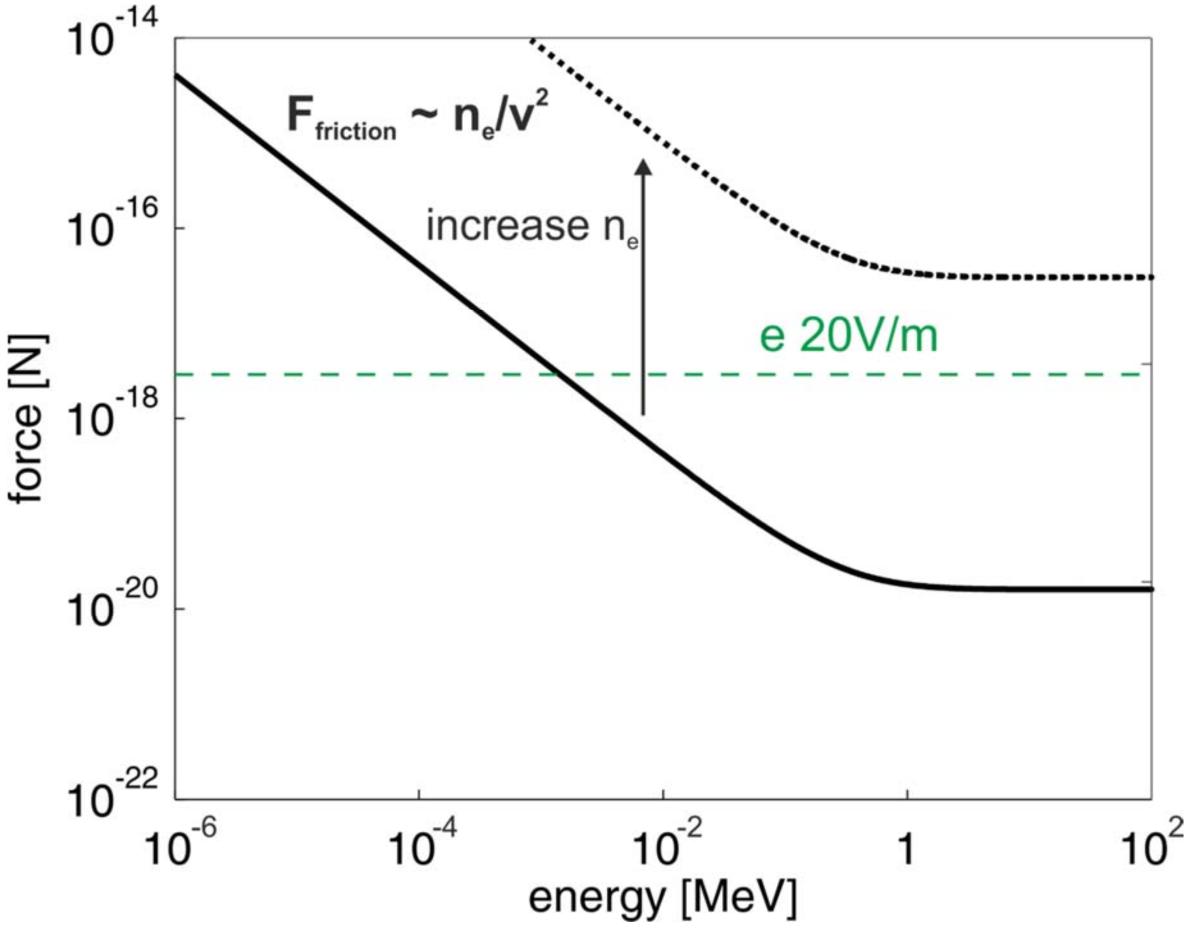
50 ms < t_{CQ} < 150 ms

M. Lehnen, Nuclear Fusion 2013

How to deal with disruptions?

Runaway electron mitigation

Increase electron density



current quench times

machine downtime (gas handling)

but

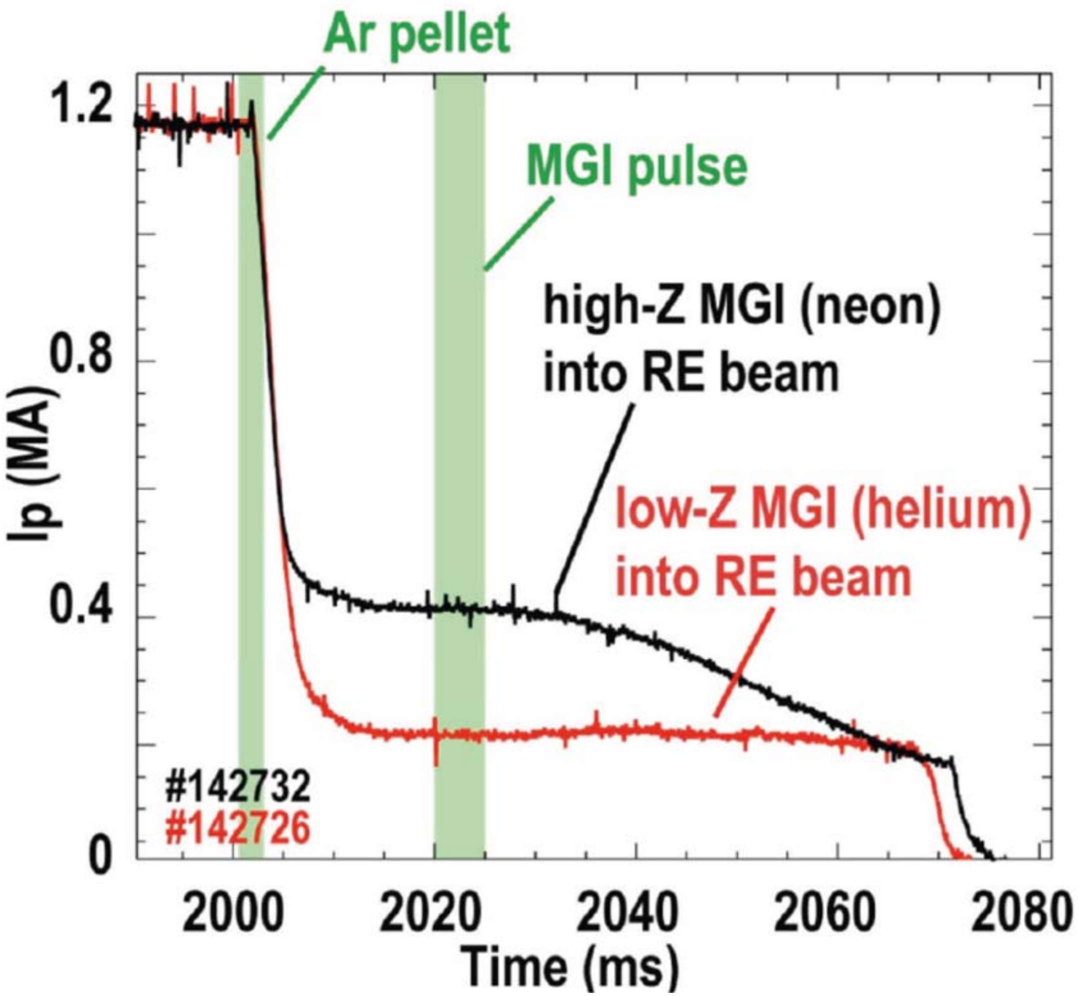
experiments suggest*:

n_c (exp) < n_c (theory)

** R. Granetz, APS 2013*

Runaway electron mitigation

Energy dissipation by scattering on high-Z nuclei*



DIII-D
injection of high-Z impurities leads to runaway current decay

E. Hollmann, Nuclear Fusion 2013

** K. Aleynikova, EPS 2013*

How to deal with disruptions?

The challenge of disruption mitigation is to ***<u>simultaneously</u> achieve all three goals:***

- ❑ Thermal load mitigation: 90% radiation
- ❑ Electro-magnetic load mitigation: $50\ ms < t_{CQ} < 150\ ms$
- ❑ Runaway electron mitigation: $I_{RE} << 1MA$

Summary / Conclusions

- ITER will face considerable disruption loads – reliable and efficient prediction, avoidance and mitigation is mandatory

- Disruption physics are a rich topic, in which many open questions still exist, due to:
  - ✓ Complexity: non-linear MHD, runaway electrons, …
  - ✓ Challenge of making measurements
  - ⇒ Lots of interesting work for young motivated physicists!

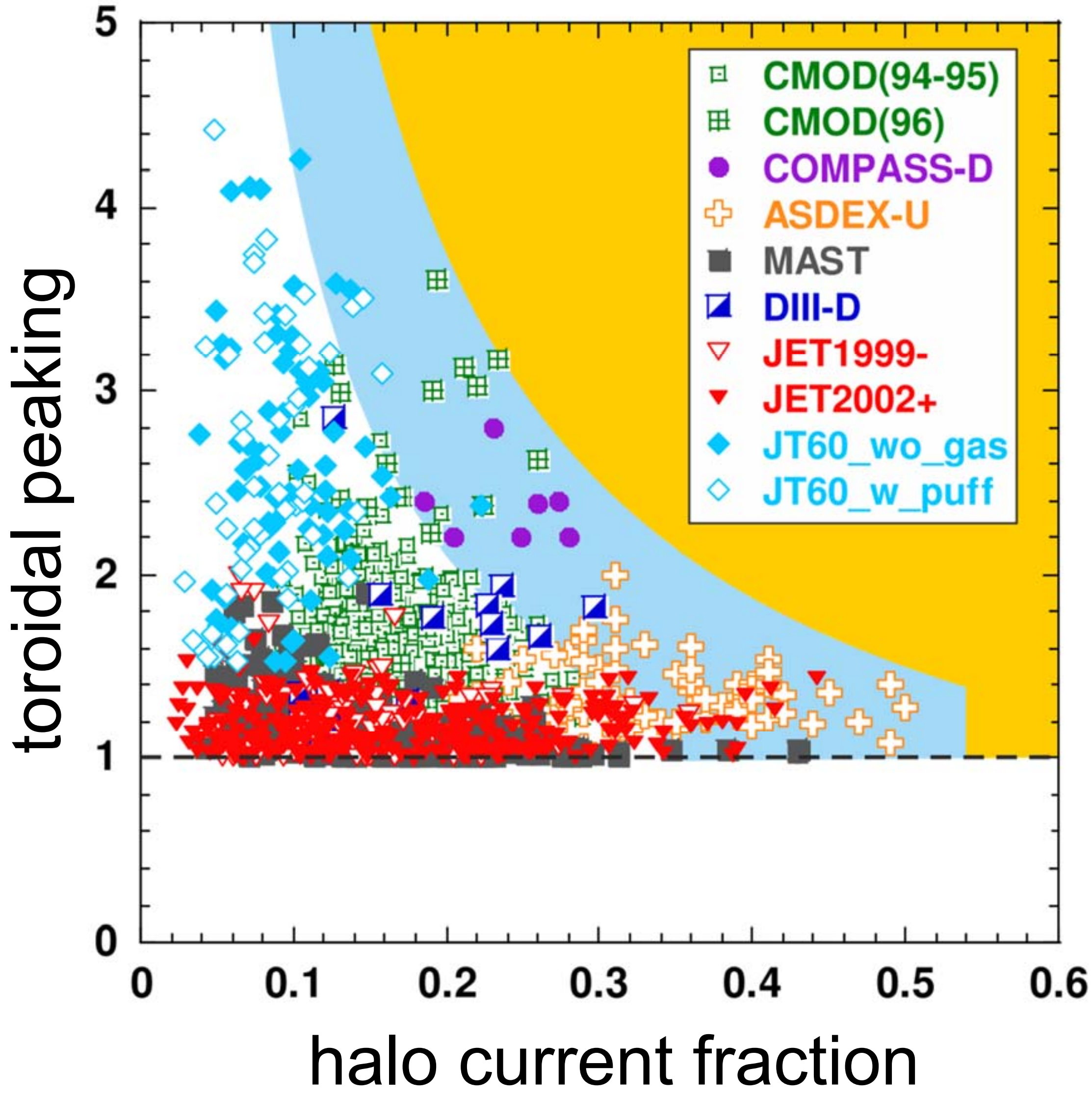
- Physics basis is continuously being improved

- Wherever possible, allow for enough <u>margin</u> in component design and enough <u>flexibility</u> of mitigation systems to ensure that ITER will be able to operate at nominal values

Extra slides

Why worry about disruptions?

Definition of load limits: halo current



extremely unlikely

unlikely