Disruption Loads in SPARC

V. Riccardo and the SPARC Team

Second Technical Meeting on Plasma Disruptions and their Mitigation

Contents

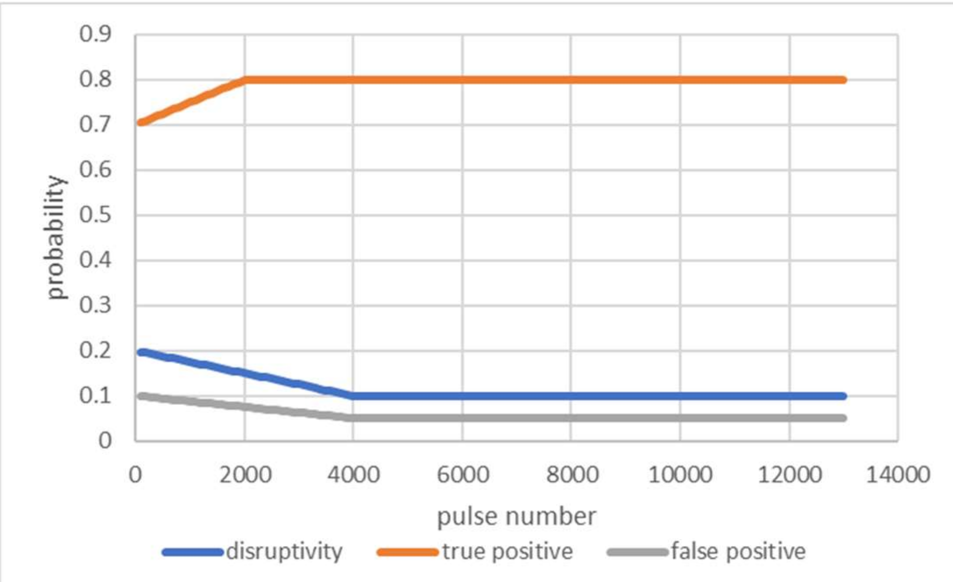
SPARC – Key disruption parameters

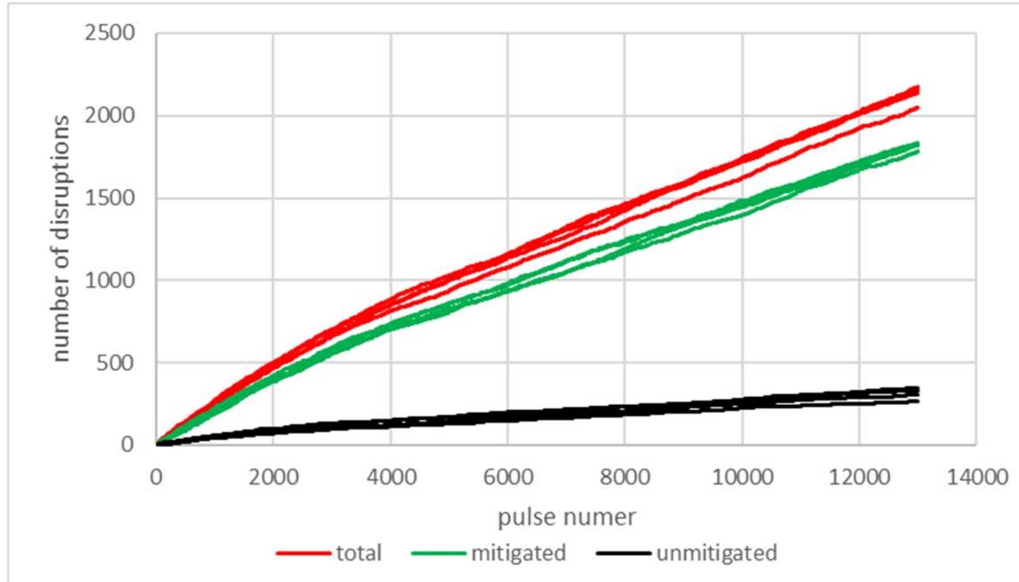
Major Radius	1.85 m
Minor Radius	0.57 m
Toroidal field at Major Radius	12.2 T
Plasma Current	8.7 MA
Nominal q_{95}	3.4
Plasma Thermal Energy	27 MJ
Magnetic Energy inside Vessel	70 MJ

Design number of disruptions

SPARC in designed for 10,000 DD and 3,000 DT pulses.
Disruption probabilities are based on exiting tokamaks and ITER assumptions.

P. C. de Vries, et al., Fusion Science and Technology, 69:2, 471-484



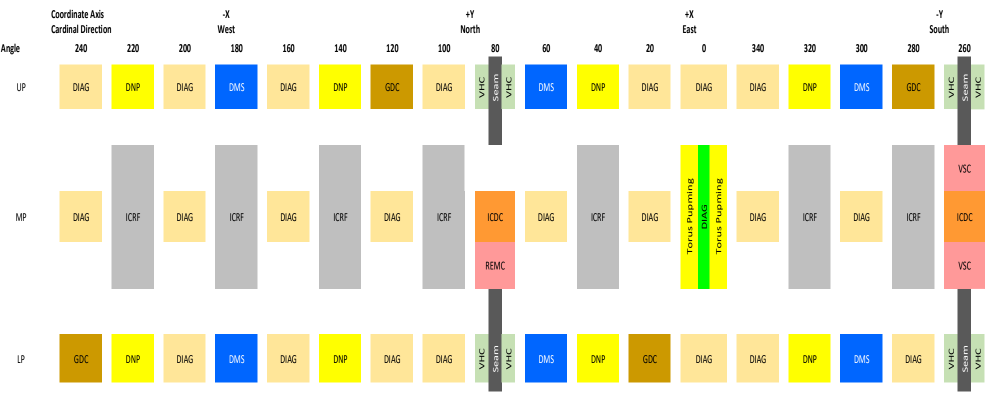


Design number of disruptions: 1800 mitigated and 300 unmitigated, all at full current.
SPARC life consumption will be counted to actual plasma current and disruption outcome.

Disruption mitigation

Thermal loads: massive gas injections

3 upper off midplane ports
3 lower off midplane ports

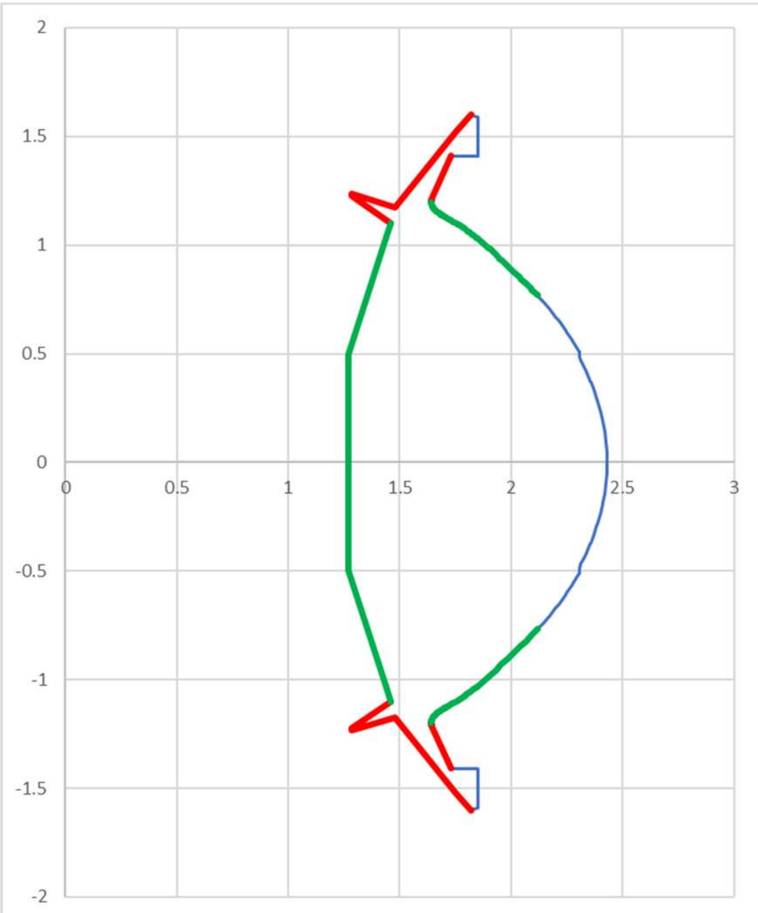


Able to handle variable mixtures of hydrogen isotopes (not T) and noble gases

Runaway electrons: Runaway mitigation coil

REMC

Thermal loads



- Divertor optimized for normal operation
- Main chamber shadowing includes off normal configurations
- Plasma facing components are not actively cooled, removing the risk of coolant leaks
- Expected to degrade gently due to disruption loads and mostly away from the power handling regions of the divertor

Challenges:

- **X-point thermal quench…**

  limit stored energy until disruption mitigation is established

- **Halo convective power…**

  expected to be away from strike point regions

- Runaway electrons…

  expected to be away from strike point regions

Electromagnetic loads

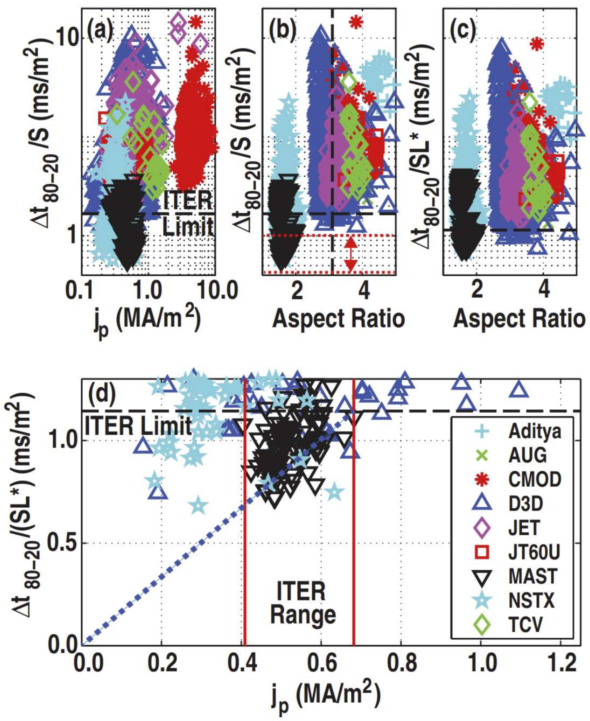
Unmitigated disruption:
- Vertical displacement
- Halo current
- Asymmetries
- Current quench

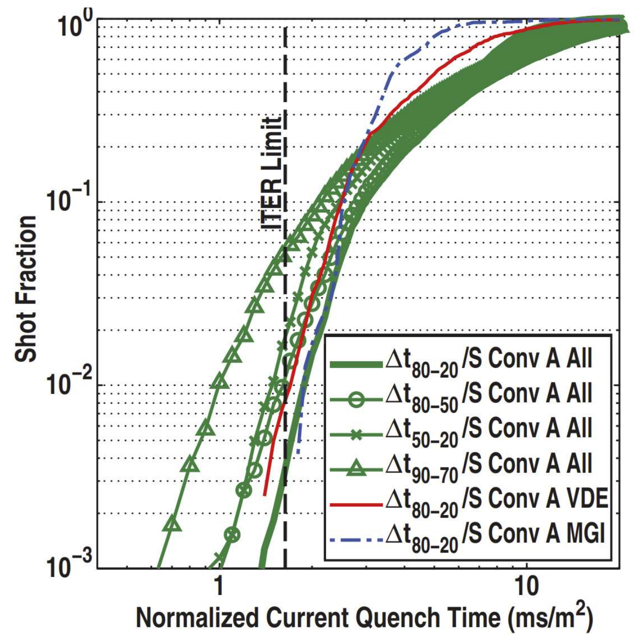
Mitigated disruption:
- REMC loads
- Current quench

Risk for double counting loads

Current Quench:
- Shortest = largest loads for in-vessel components
- Longest = largest loads for vacuum vessel

Minimum current quench duration



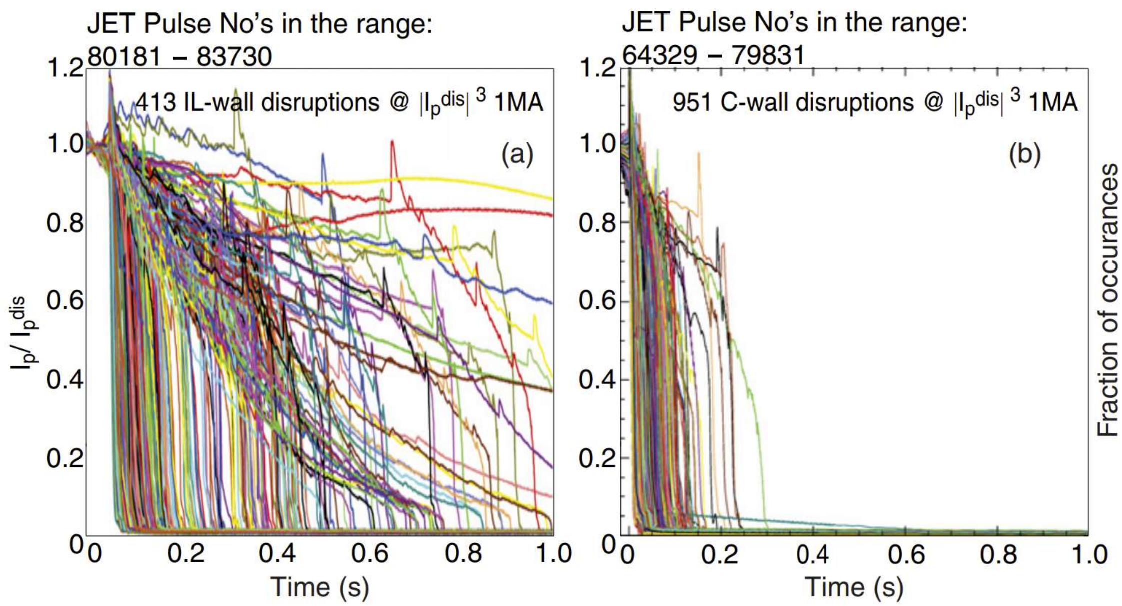


N.W. Eidietis *et al* 2015 *Nucl. Fusion* **55** 063030

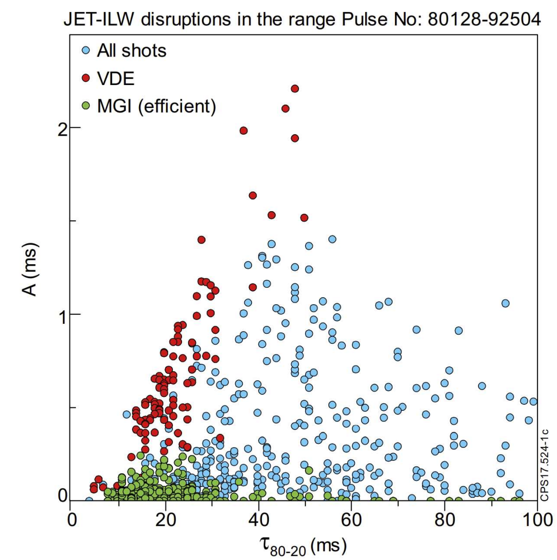
From the ITPA Disruption Database (IDDB), the minimum current quench duration is clearly set, and has a robust probability distribution.
The maximum duration of the current quench might be less well documented.

The minimum current quench duration for in-vessel design in SPARC is 3.2 ms, corresponding to 1.78 ms/m².

Maximum current quench duration



S.N. Gerasimov *et al* 2014 *Nucl. Fusion* **54** 073009

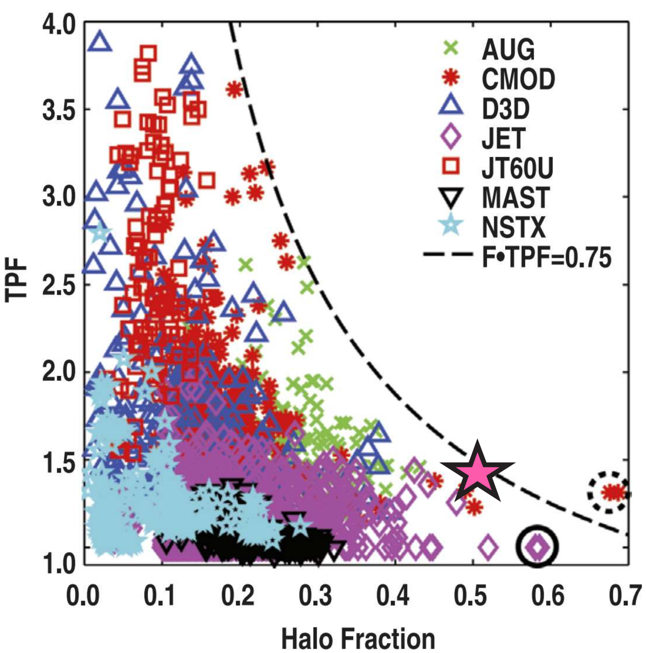


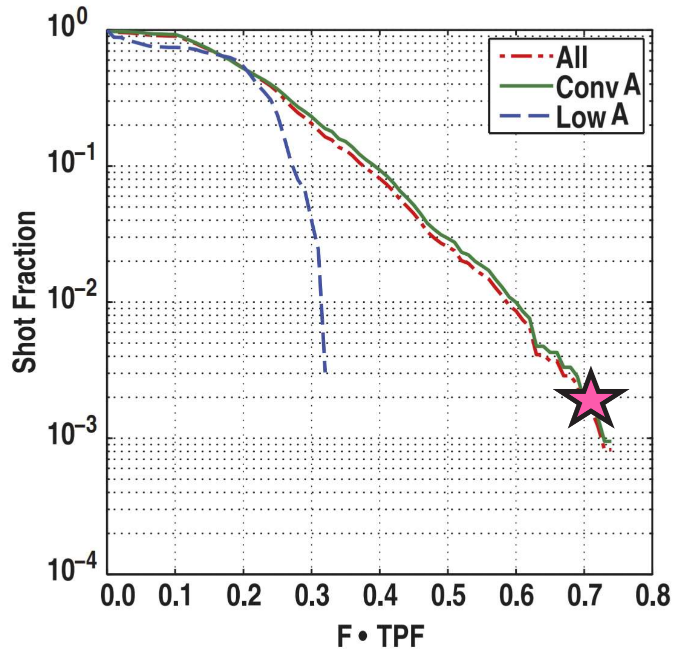
S.N. Gerasimov *et al* 2020 *Nucl. Fusion* **60** 066028

The IDDB does not contain ITER-like Wall (ILW) disruptions from JET. ILW disruptions extend to ~100ms (25ms/m^2), but VDEs remain under 50ms for the 80-20% duration, or normalized full current quench duration of 21ms/m^2.

The maximum current quench duration used for vessel design in SPARC is 40 ms.

Halo current fraction and toroidal peaking factor





From the ITPA Disruption Database (IDDB), the design point for SPARC is set at fraction times toroidal peaking factor (f*TPF) equal to 0.7.

Symmetric events:

f=0.5 and TPF=1

Asymmetric events:

f=0.5 and TPF=1.4

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Halo current density at wall

The halo current width is expected to be 8 cm to 20 cm.
8 cm = highest current density; 20 cm = more areas wetted

SPARC still lacks free boundary transient analysis.

Hypothetical disruption:

Step 1:

- Vertical displacement to $q_{cyl}=2$
- Halo current up to f*TPF=0.35

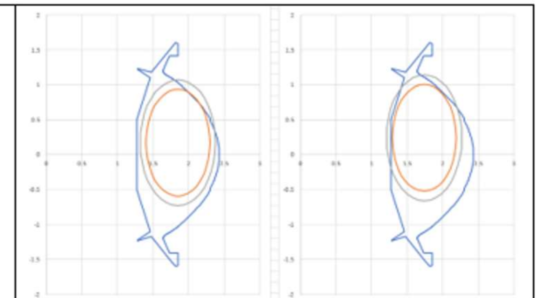
Step 2:

- Vertical displacement to $q_{cyl}=1$ at full plasma current
- Halo current up to f*TPF=0.7

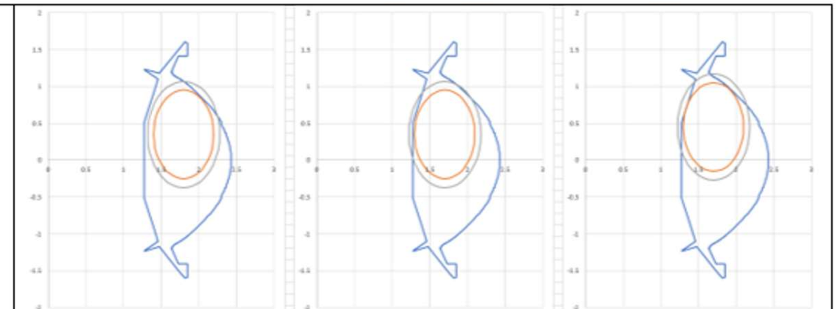
Step 3:

- Keep current density in core+halo as at $q_{cyl}=1$
- Shrink to enter the divertor

Step 3 might not be representative as the interaction with the divertor current… residual X-point?



8cm Step 1		
Outer	410 kA/m^2	470 kA/m^2
Inner	(outer wall) 540 kA/m^2	720 kA/m^2



8cm Step 2			
Outer	900 kA/m^2	(inner wall) 1380 kA/m^2	1020 kA/m^2
Inner	(outer wall) 1300 kA/m^2	1240 kA/m^2	1150 kA/m^2

8cm Step 3			
f	0.244	0.244	0.244
TPF	2.86	2.86	2.86
Ip	4.2 MA	4.2 MA	4.2 MA
Outer	(wall) 850 kA/m^2	(wall) 930 kA/m^2	(inner divertor) 1350 kA/m^2
Inner	(outer divertor) 1150 kA/m^2	(wall) 1350 kA/m^2	(wall) 1400 kA/m^2

Vessel vertical loads – rough envelope

$$F_v^{max} = \frac{F_{p,c}^{max}}{1-\tau'^{-1}_{cq}}\left[\exp\left(\frac{1}{\tau'_{cq}-1}\ln\frac{1+\tau'_{VDE}}{\tau'_{cq}+\tau'_{VDE}}\right) - \frac{1+\tau'_{VDE}/\tau'_{cq}}{1+\tau'_{VDE}}\exp\left(\frac{\tau'_{cq}}{\tau'_{cq}-1}\ln\frac{1+\tau'_{VDE}}{\tau'_{cq}+\tau'_{VDE}}\right)\right]$$

S Miyamoto 2011 *Plasma Phys. Control. Fusion* **53** 082001

where $\tau'_{VDE} = \tau_{VDE}/\tau_{L/R}$ and $\tau'_{CQ} = \tau_{CQ}/\tau_{L/R}$, which can be further simplified as

$$F_v^{max} = F_{p,c}^{max}\left(\frac{1+\tau'_{VDE}}{\tau'_{CQ}+\tau'_{VDE}}\right)^{\frac{1}{\tau'_{CQ}-1}}$$

For 40 ms CQ, ~100 ms VDE, L/R time ~100ms: F_v^{max} **<60%** of $F_{p,c}^{max}$

F_v^{max} is the total force on the vessel, including eddy, halo, local loads, etc as seen past the screening of the wall.

This is important when combining different sources of loads on the vessel to avoid double counting.

Vessel vertical loads – critical inputs

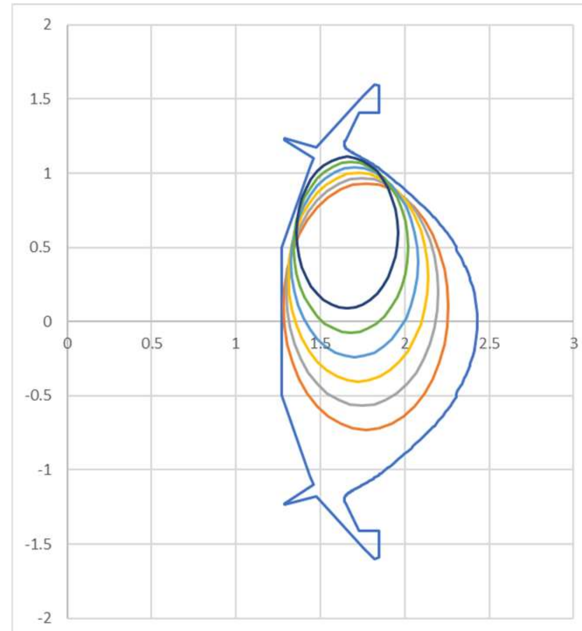
SPARC lacks validated free boundary transient analysis… specifying the worst-case for engineering loads.

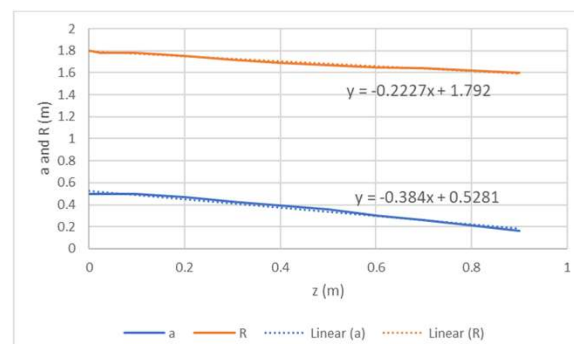
Cylindrical q at the start of the current quench:

- Alcator C-Mode reference

VDE duration:

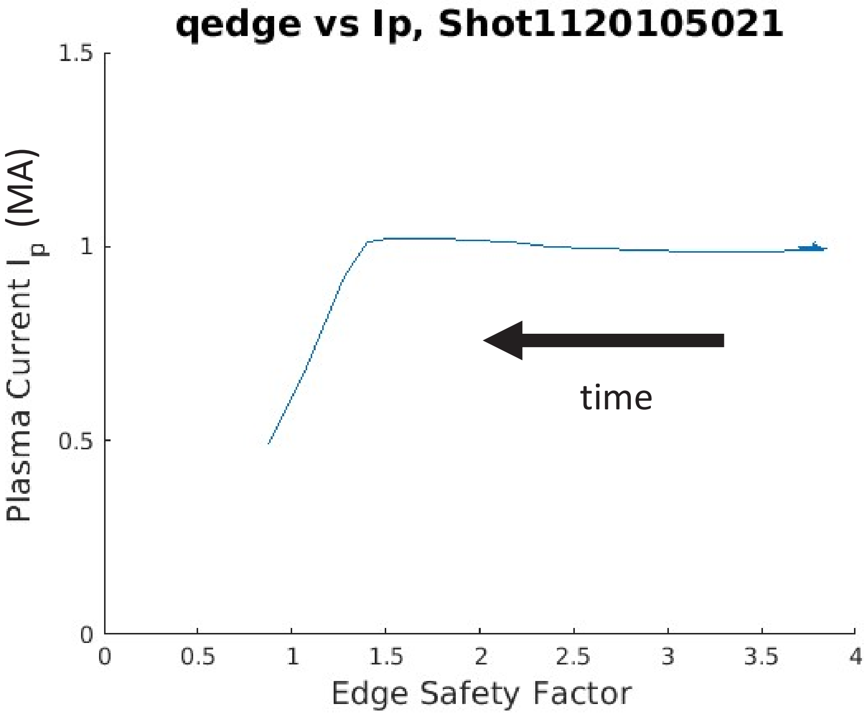
- Reverse engineering of simulations
    - Vertical position set as exponential… free parameter, determined to have ~force free~ plasma
    - Radial position and minor radius as a function of the vertical position to fit in the plasma facing contour
    - Set plasma to keep the largest cross section during displacement, so reaching the critical cylindrical q the furthest from the midplane



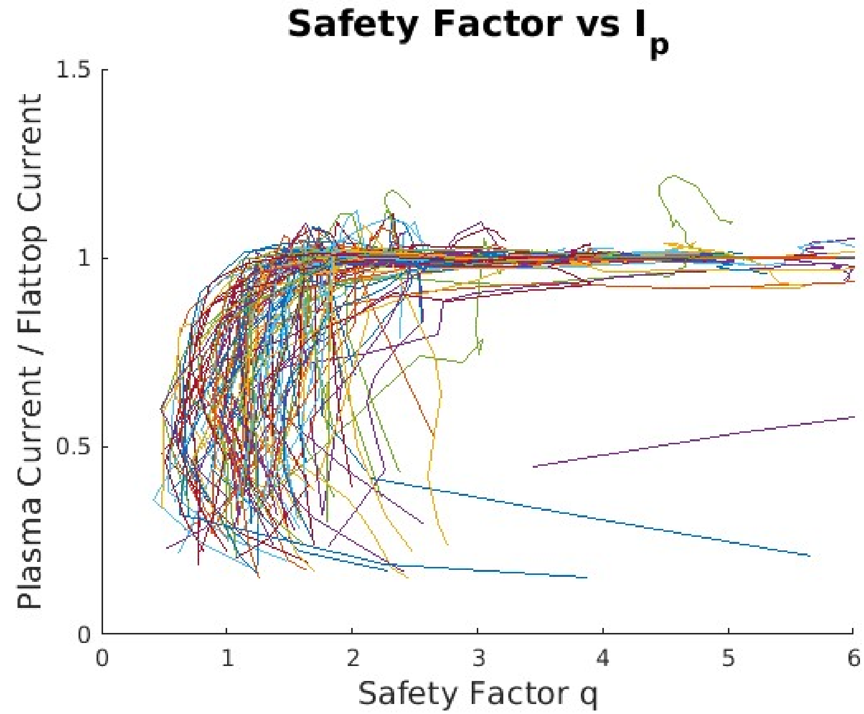


Minimum q_{cyl} at current quench (1/2)

SPARC



1 shot

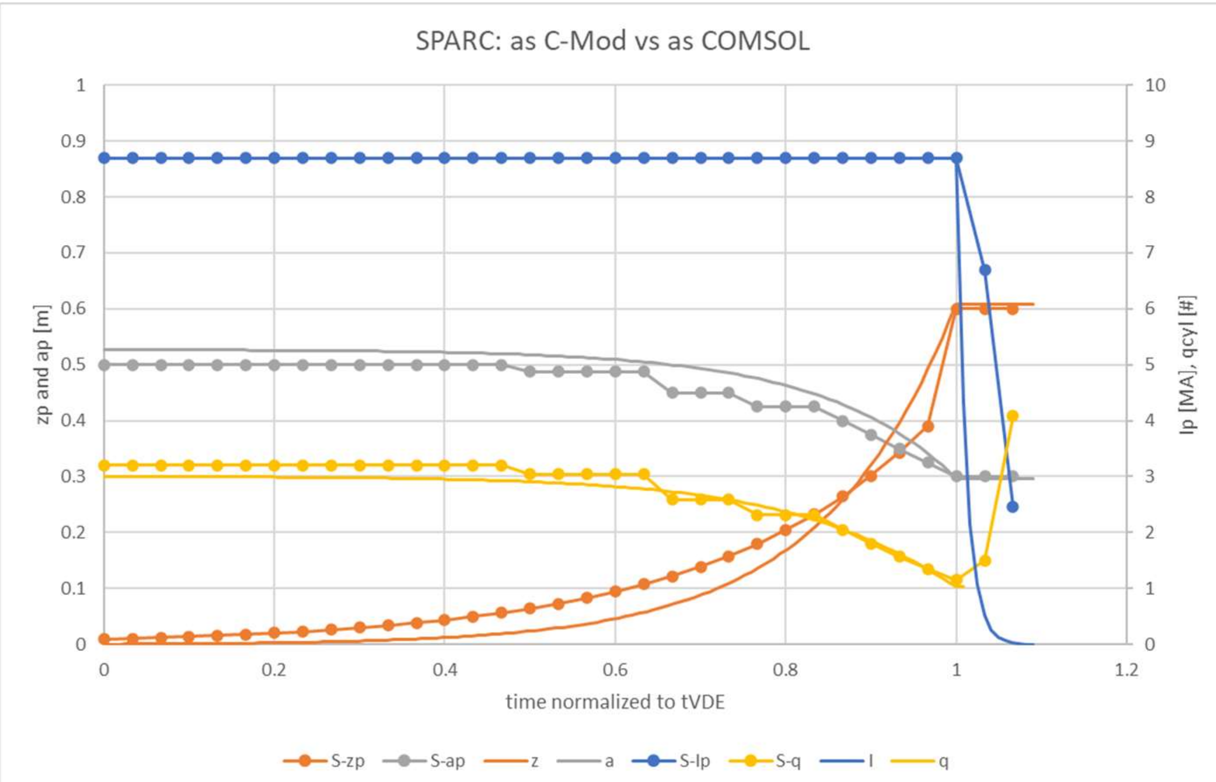


127 shots

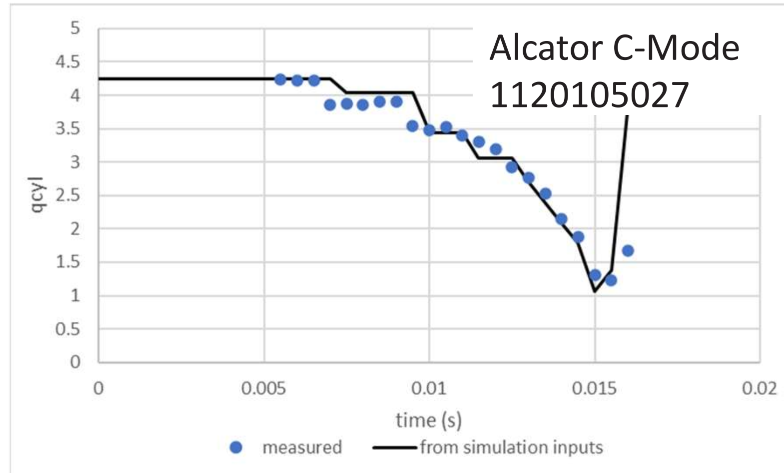
Alcator C-Mod (courtesy of Robert Granetz and Ben Stein-Lubrano)

Minimum q_{cyl} at current quench (2/2)

SPARC



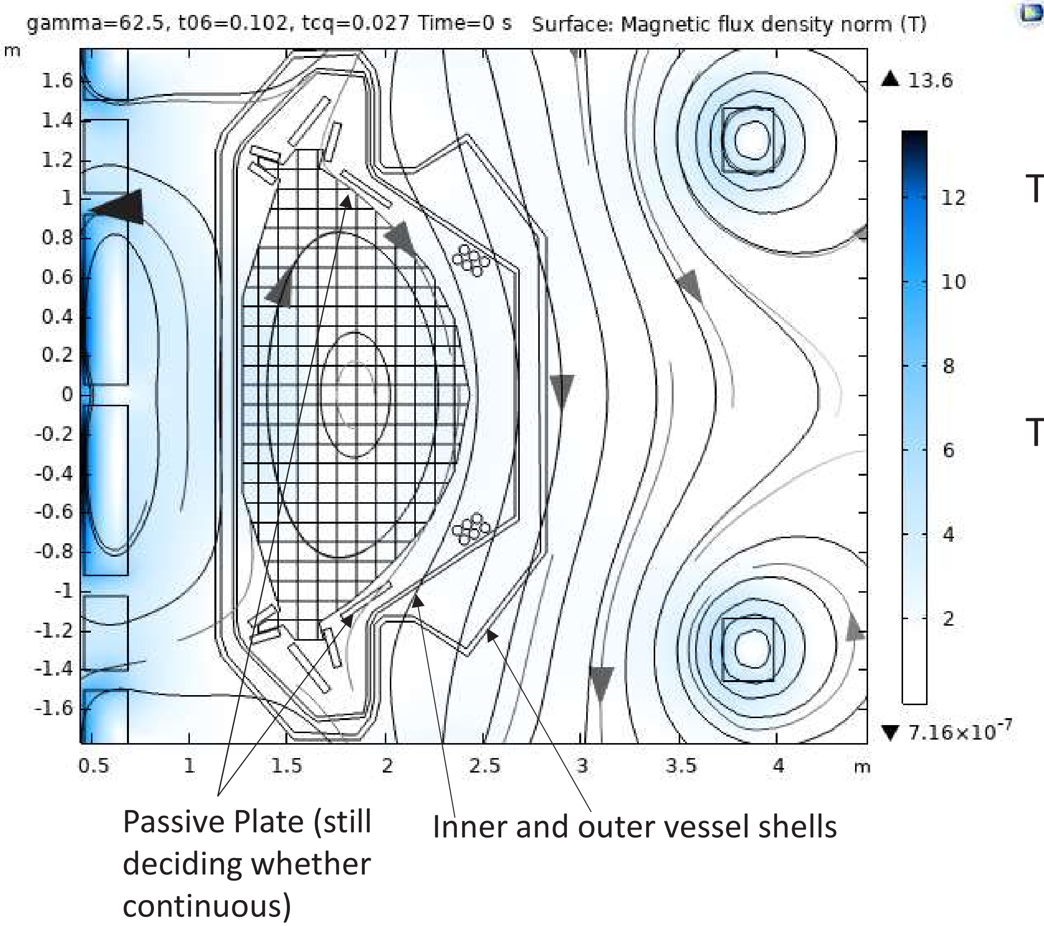
S-## Alcator C-Mod example scaled to SPARC compared with typical SPARC simulation



Start current quench when q_{cyl}=1

In SPARC q_{cyl} for the reference discharge is reached 0.6 m away from the midplane.

Vertical growth rate (1/2)



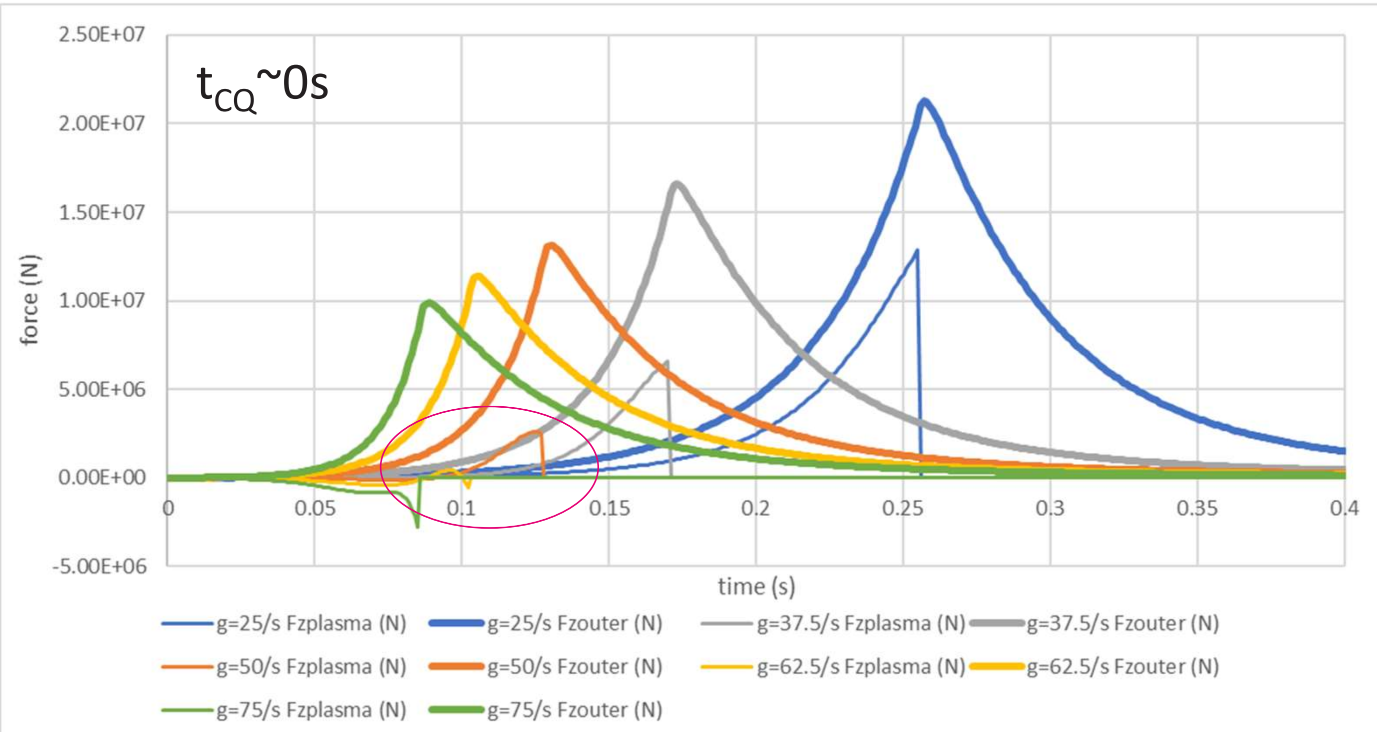
The vertical force seen by the vessel supports is

$$\frac{1}{\mu_0}\oint_{oute\quad wall}\left((\boldsymbol{B}\cdot\boldsymbol{n})B_z-\frac{B^2}{2}n_z\right)dS$$

The plasma is force free, the “force” on the plasma is

$$\frac{1}{\mu_0}\oint_{inne\quad wall}\left((\boldsymbol{B}\cdot\boldsymbol{n})B_z-\frac{B^2}{2}n_z\right)dS\ -F_{in-vessel\ conductors}$$

Vertical growth rate (1/2)

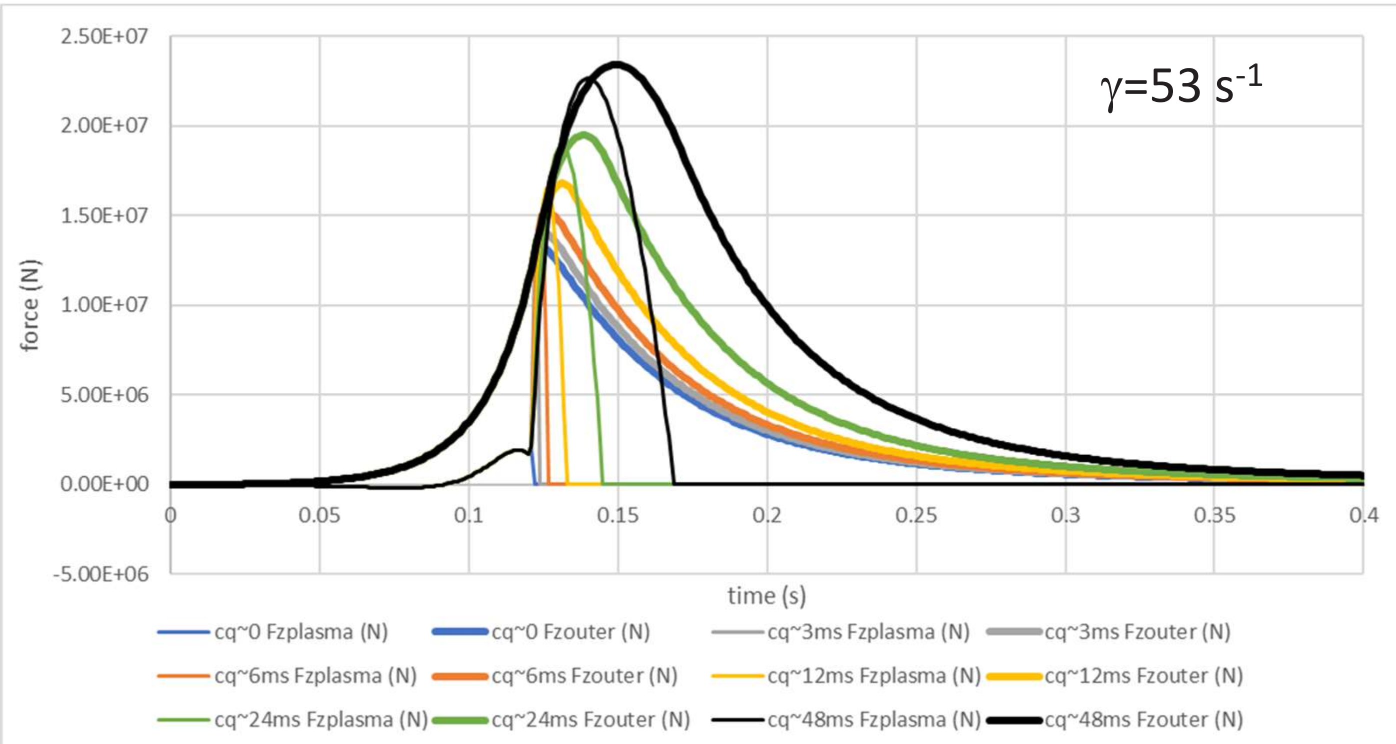


The SPARC vertical growth rate is between 50 and 62.5 s^{-1}… this is where the "plasma" force remains close to zero during the displacement.

The VV net vertical forces increases as the VDE gets longer, BUT slow events are inconsistent with a force free plasma.

Best fit growth rate ~53 s^{-1}.

Longer current quench = larger net vertical load

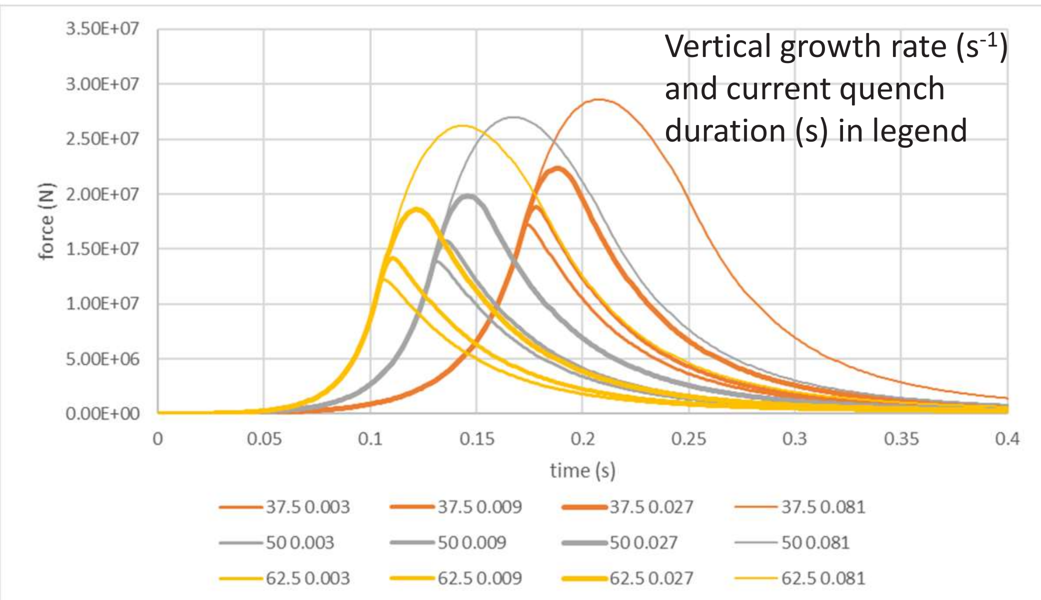


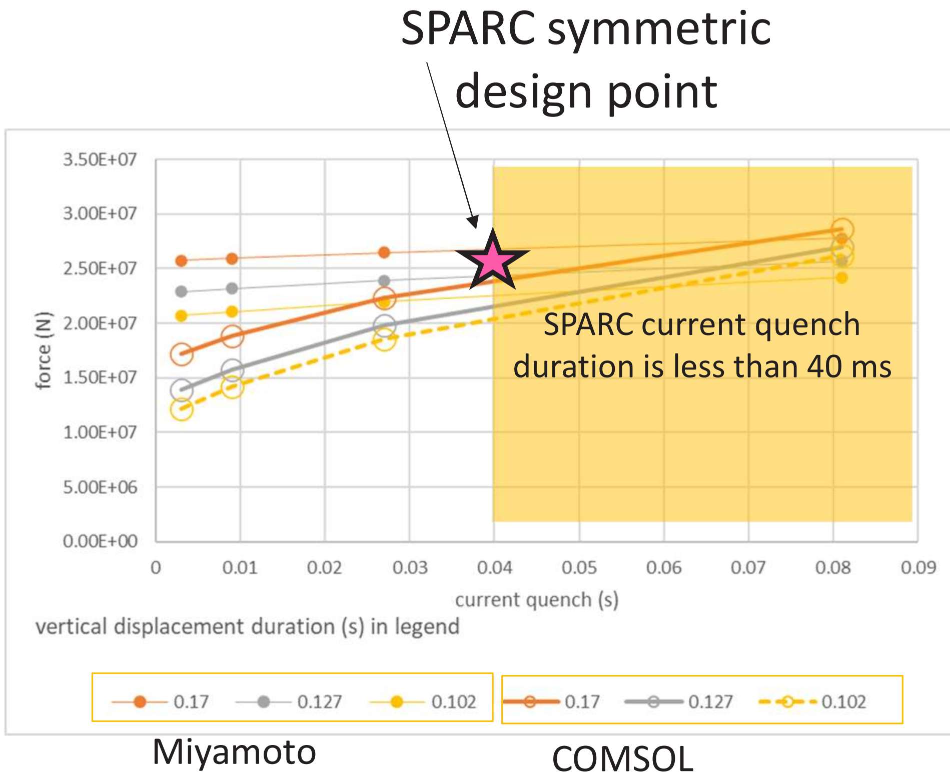
The SPARC longest current quench is <40 ms.

The VV net vertical forces increases as the current quench gets longer.

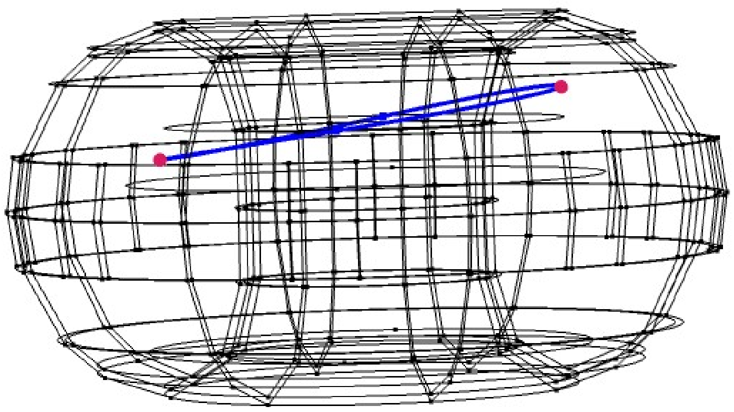
Vessel vertical load – design point

The design point for the vessel net force, 26MN, is equivalent to a ~200 ms vertical displacement, about double the duration of a force-free plasma displacement (102 ms).

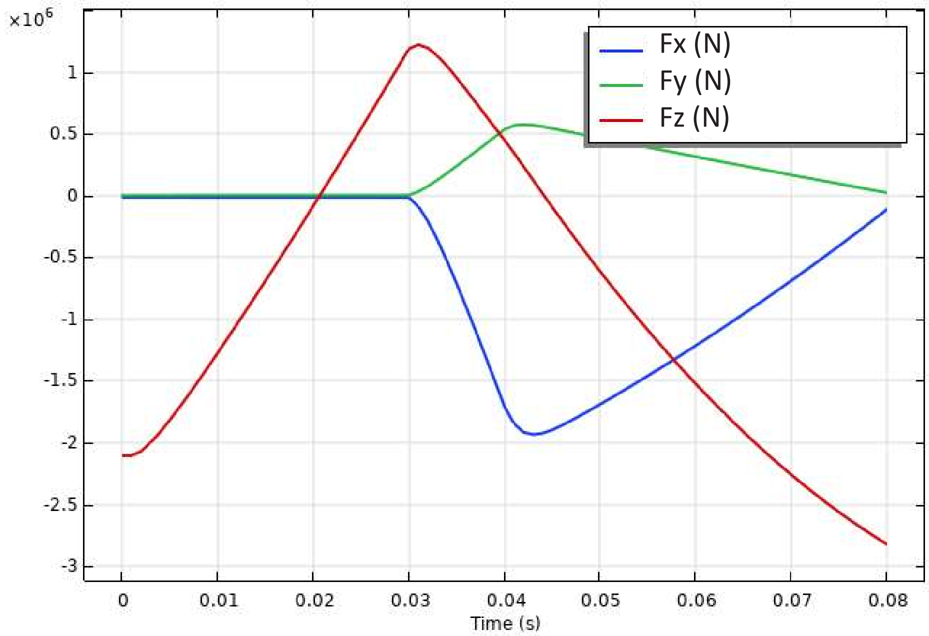




Asymmetric loads – matching JET 38070 (1/2)



JET model: saddle loop positions to set the vessel profile, vessel toroidal resistance to set the vessel equivalent thickness

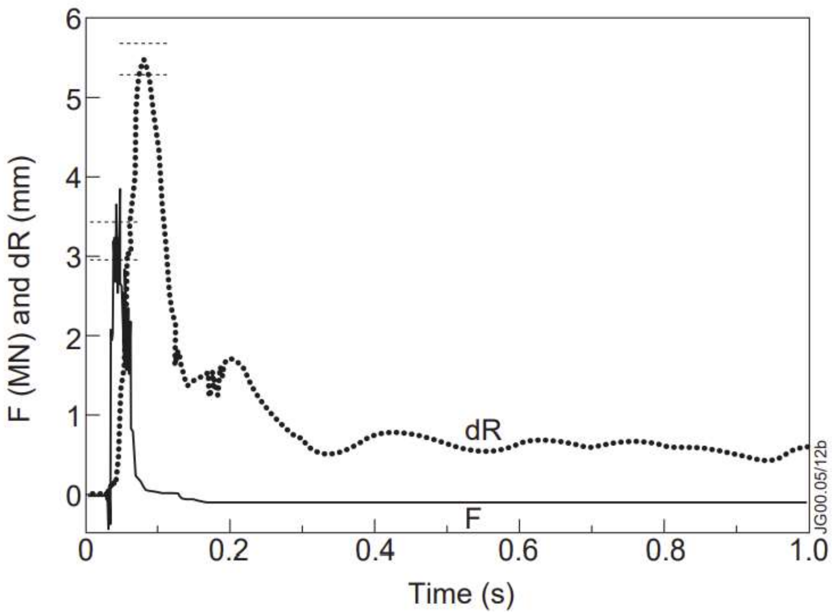


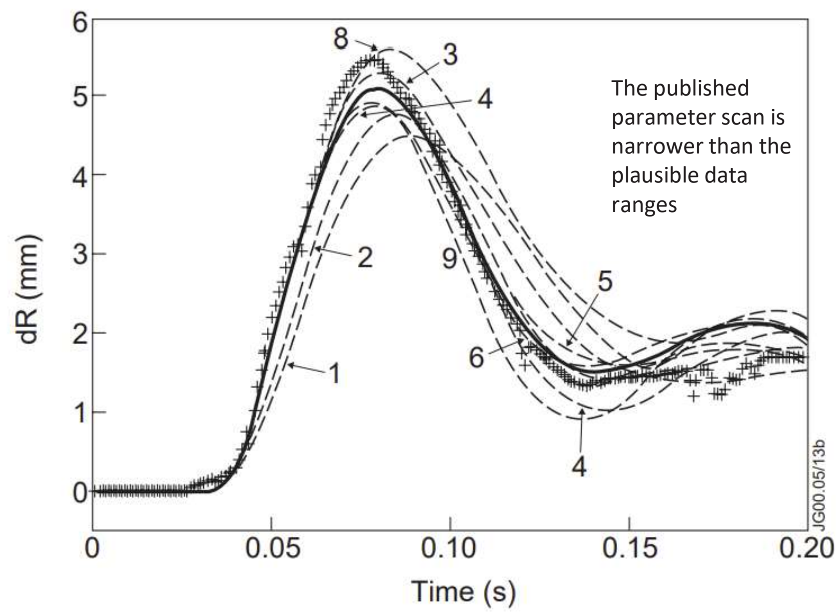
Kink (m=1/n=1) to match saddle loop data →

Vertical displacement at kink ~ 2/3 minor radius
Plasma major radius at kink ~ unchanged
Kink amplitude 40-45% minor radius
Kink current 40% initial plasma current

Asymmetric loads – matching JET 38070 (2/2)

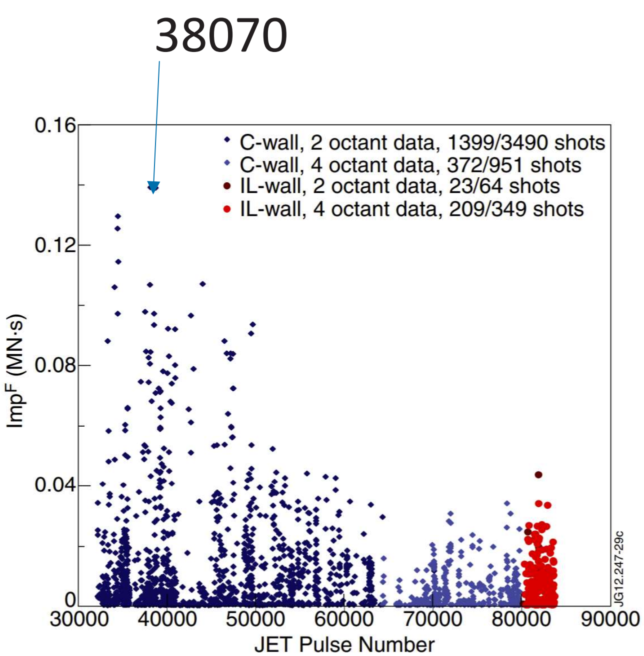
The best match is ~2MN, **but** the sideways force of 38070 is quoted in literature as 3.5MN.
The peak reaches briefly 3.5MN, the smooth version is <3MN.
The impulse on the VV matches sideways displacement within a broad margin: it could be 25% off either way.

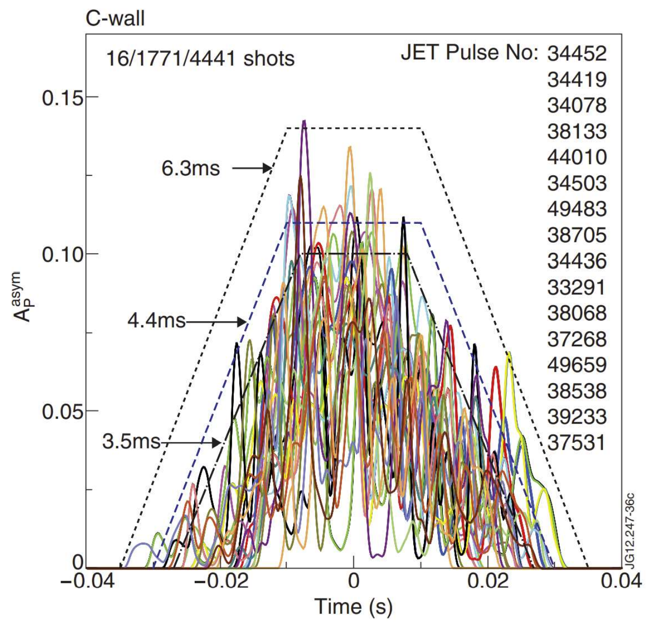


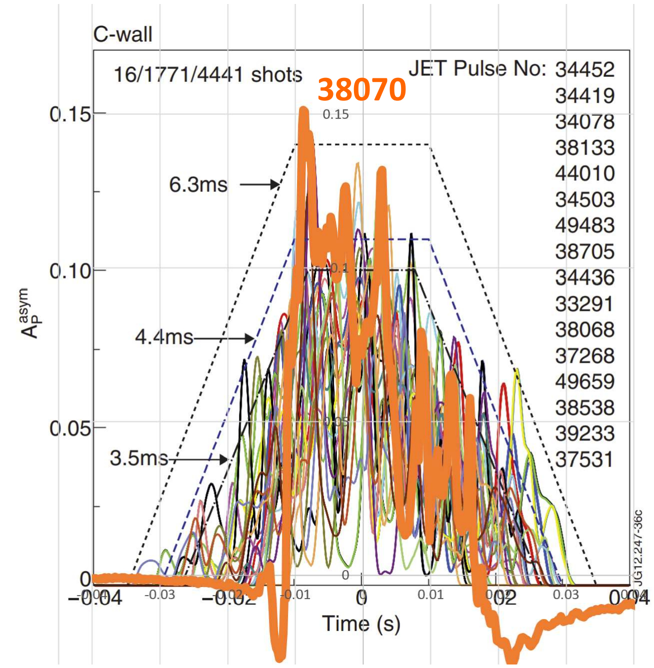


V Riccardo, S Walker, P Noll, 2000 *Fusion Engineering and Design* **47**, 389-402

38070 is a worst-case asymmetric load for JET







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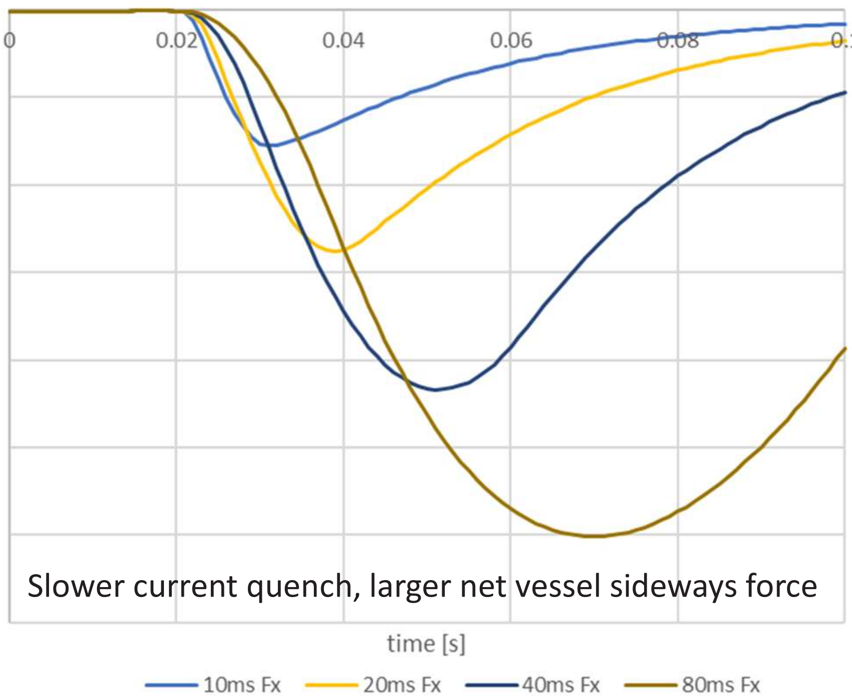
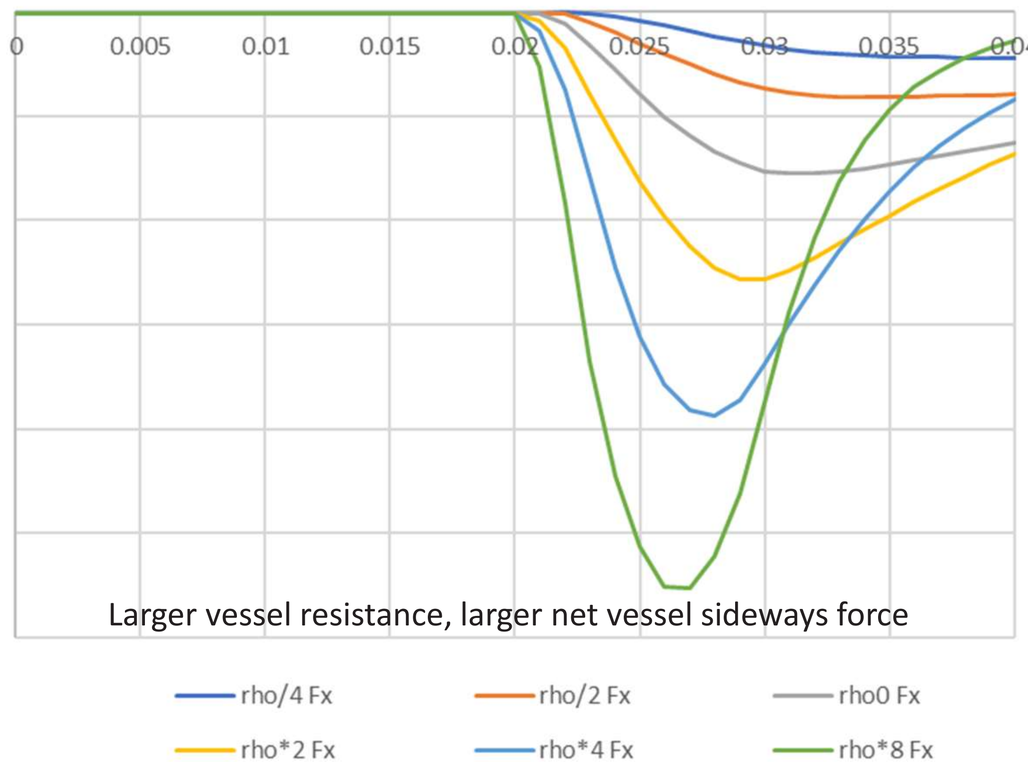
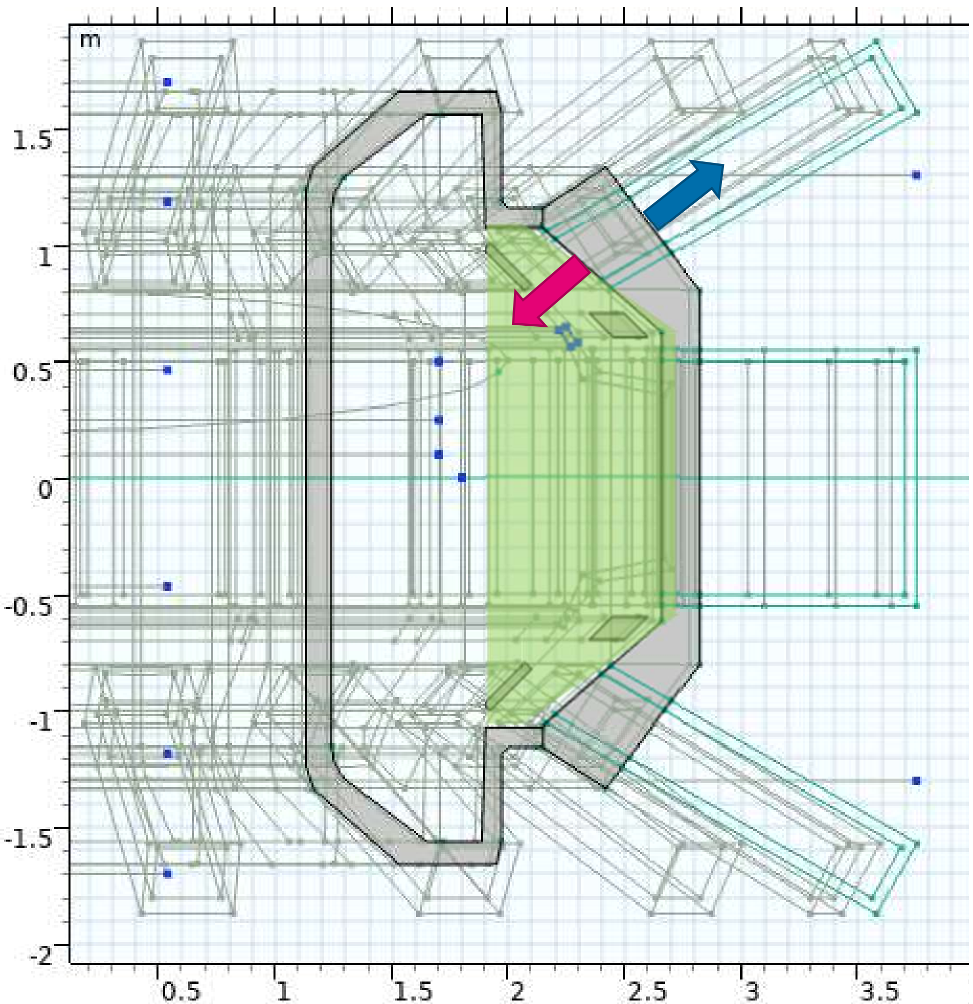
Longer event OR higher resistance = larger sideways force





Deliberately no axis labels

Sideways force on SPARC



The model has no plasma.
The plasma is represented by variable current filaments (axisymmetric or kinked)

Force produced by any current inside the surface
This is the net force on the VV

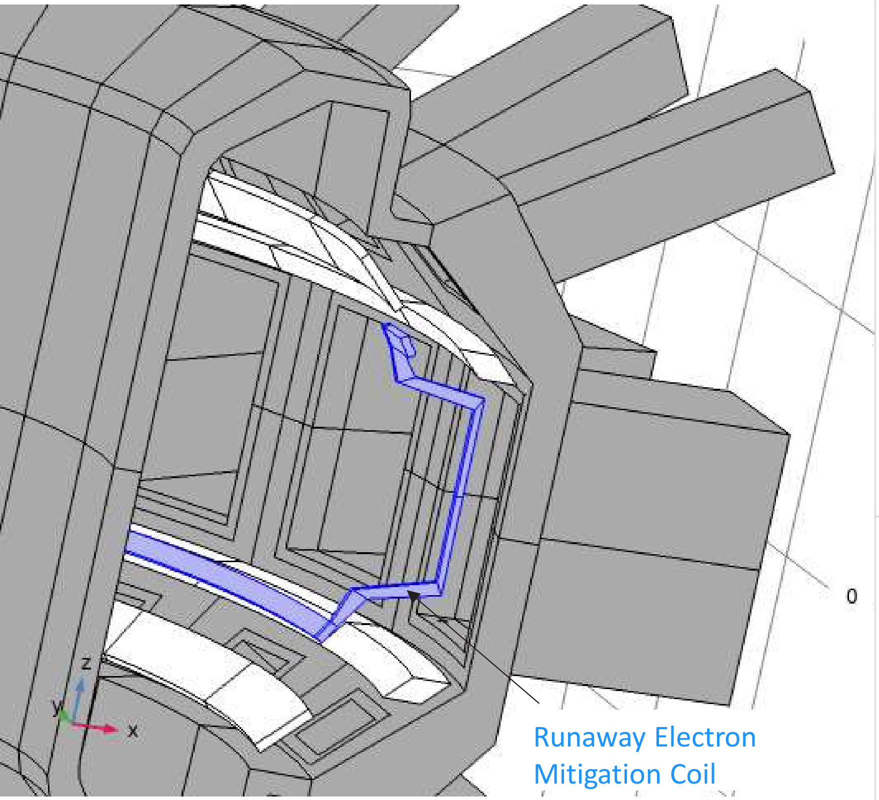
Force produced by any current inside the surface

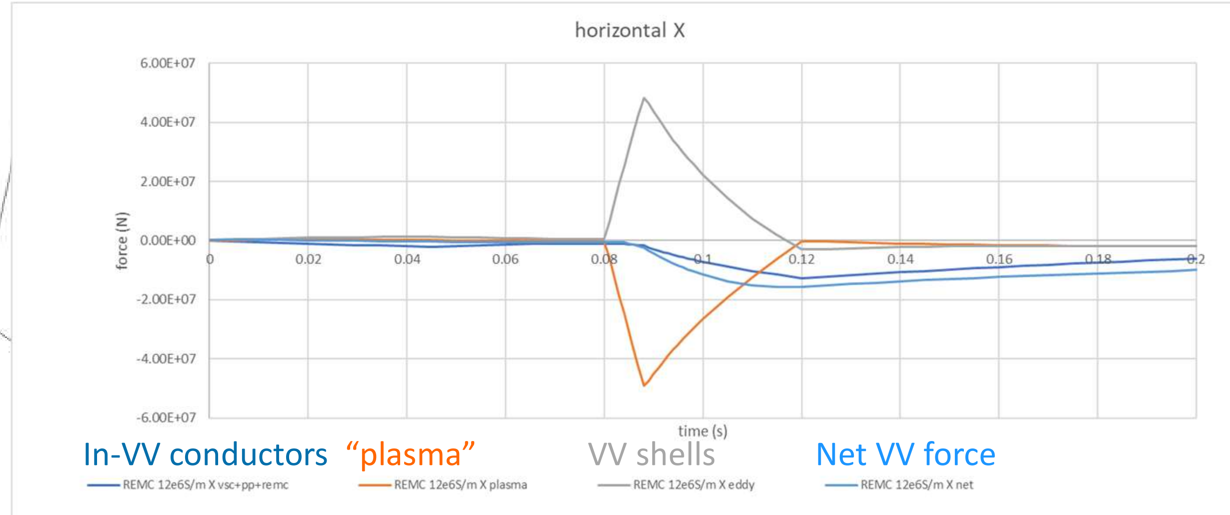
Force on in-vessel conductors

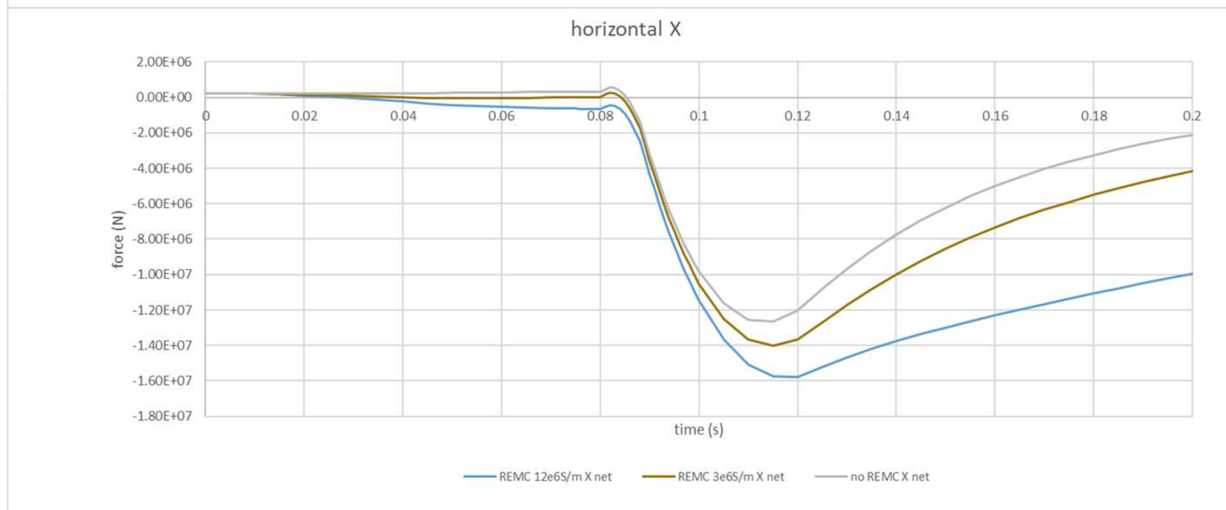
The force on the plasma is obtained by removing the conductors force ( ) from the inner wall force (-)

The difference between the outer shell and the inner shell gives the force from the eddy current in the VV

Sideways force due to plasma asymmetries

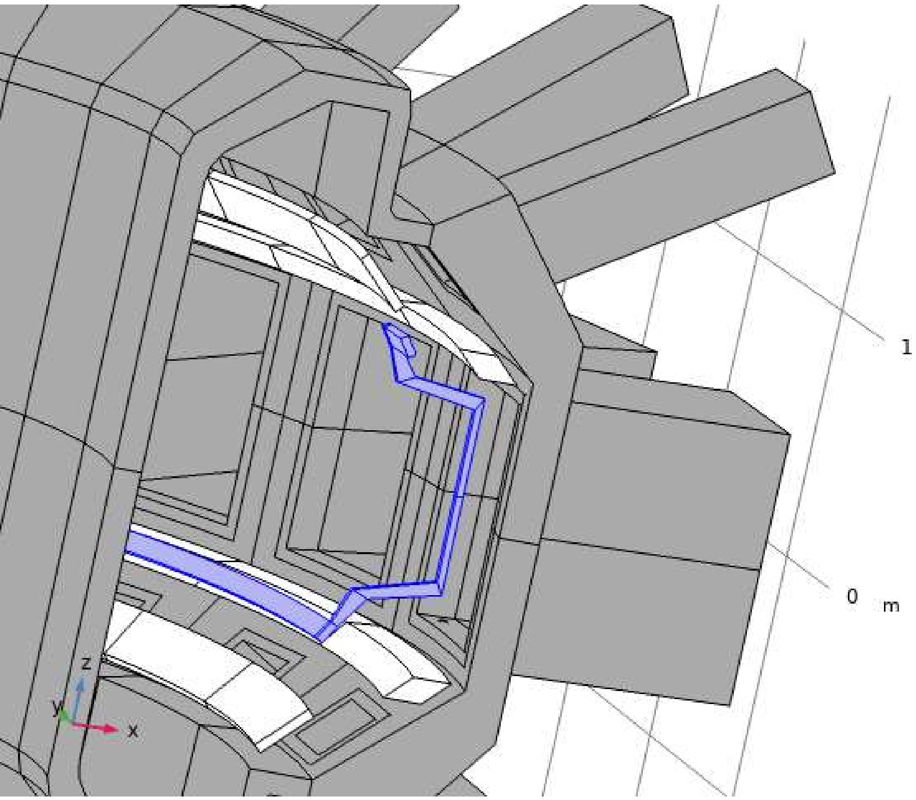


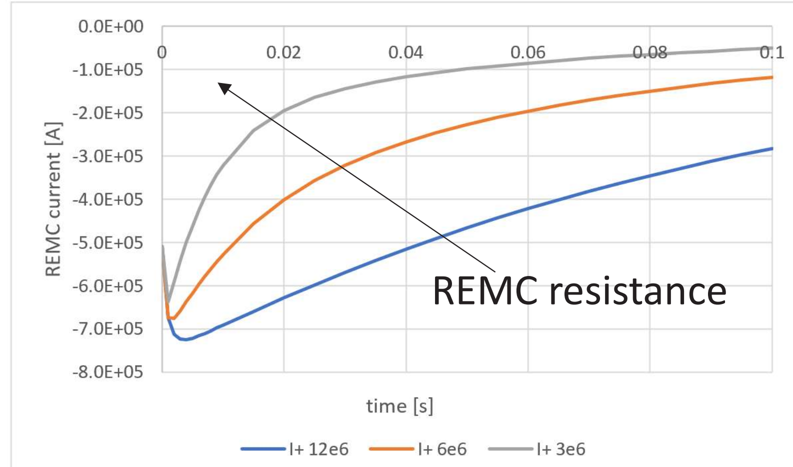


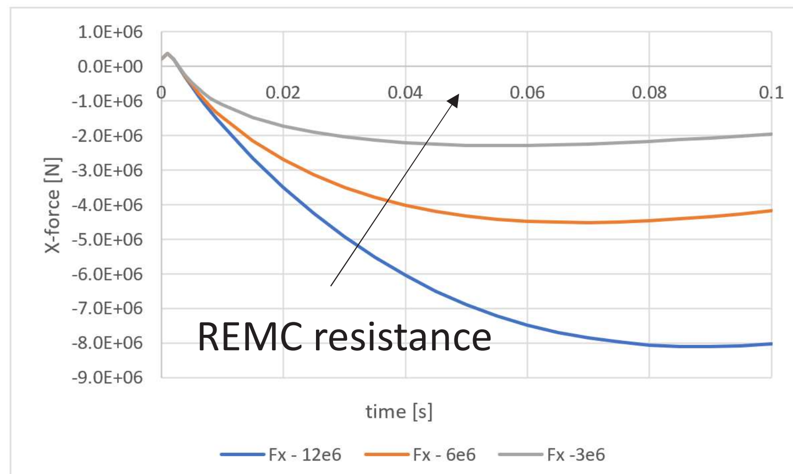


Without REMC: 12 MN
With low resistance REMC: 16 MN

Sideways force due to REMC alone

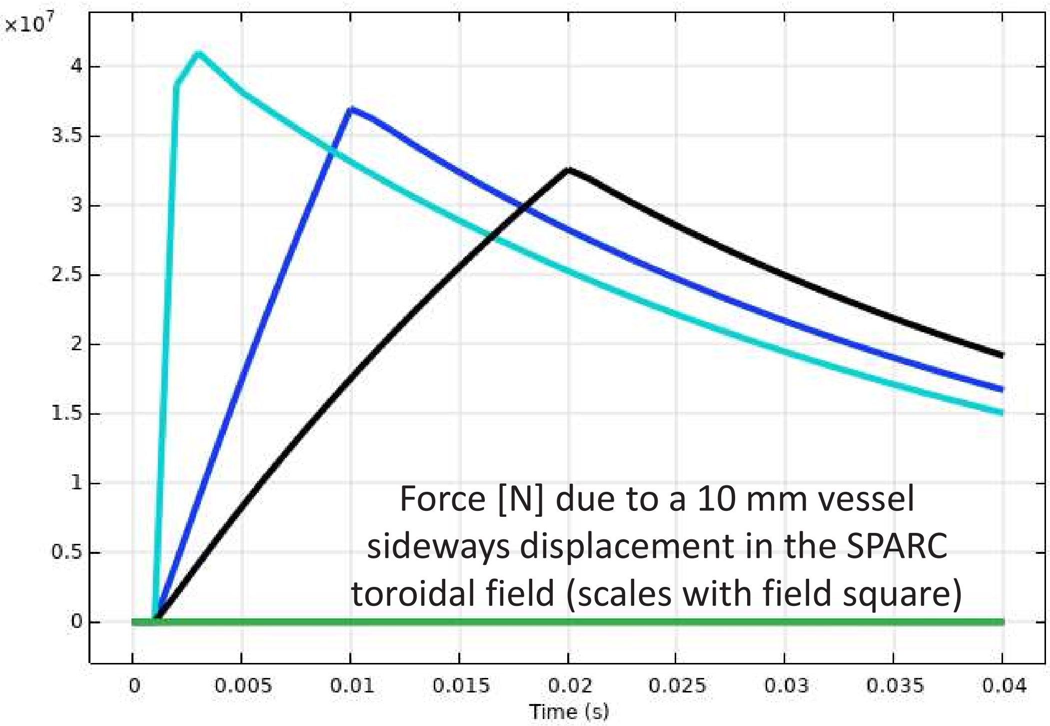


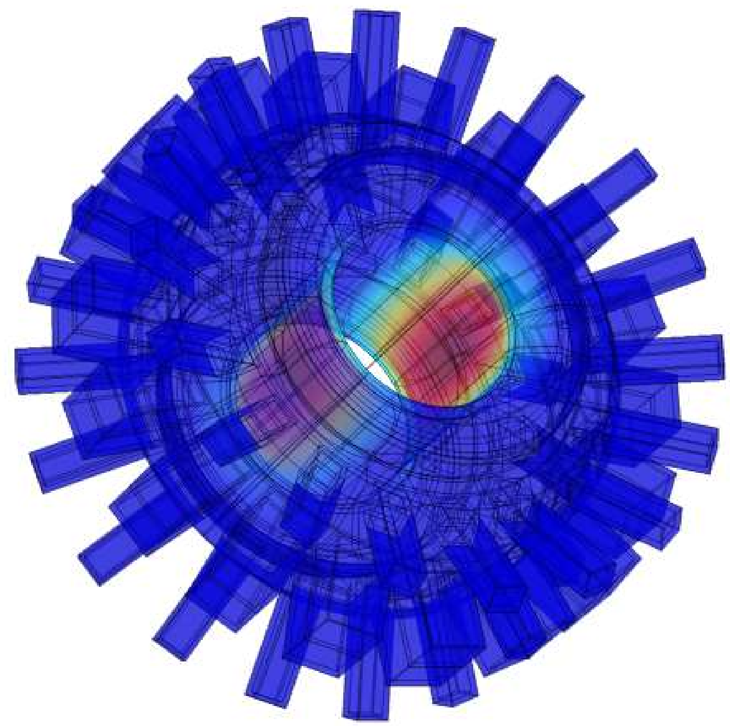




Even without plasma asymmetries, REMC gives a net sideways force, which depends on its resistance, up to 9 MN.

Magnetic stiffness and damping

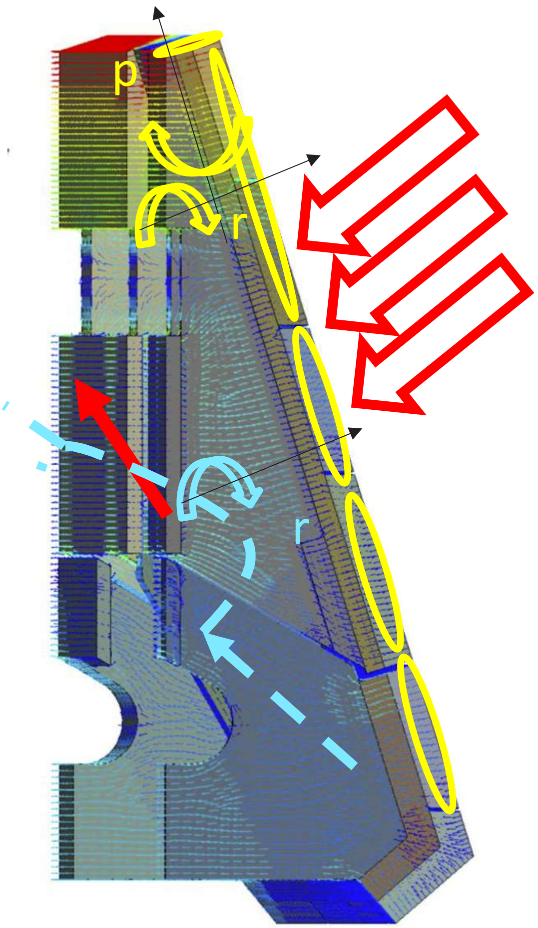




The reaction to the movement of a conductor in a magnetic field is proportional to B^2, for SPARC at 12 T:

- Magnetic stiffness 3.2GN/m
- Magnetic damping 225MN/(m/s) [half used for dynamic models to stay conservative]

Loading Plasma Facing Components



Halo current:

- Shear loads along the vessel shell, from current going to/from plasma facing surface and vessel shell
- If the current path in the component needs to revers from the direction in the plasma pulling loads as well

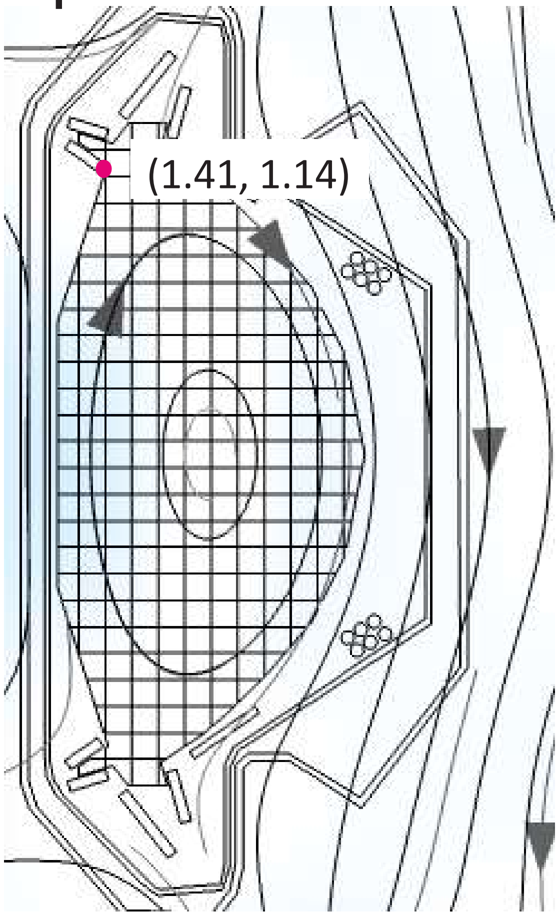
Floating eddy current:

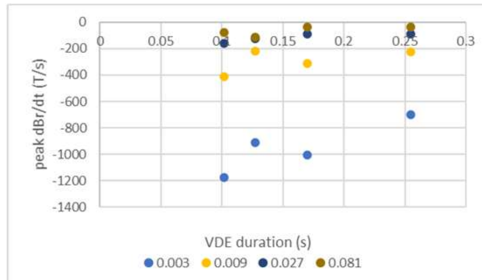
- Moments, largest around the radial and poloidal directions

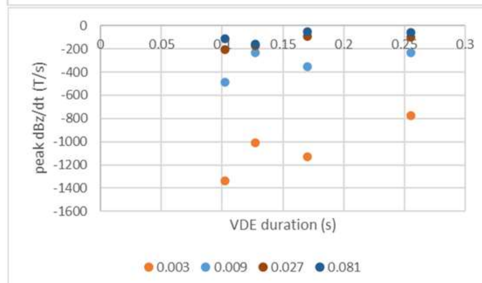
Eddy current shared with the vacuum vessel:

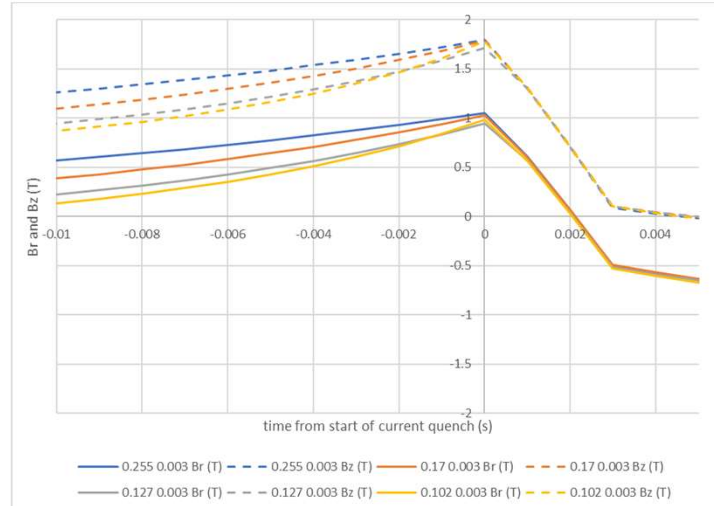
- Moments, largest around the radial direction

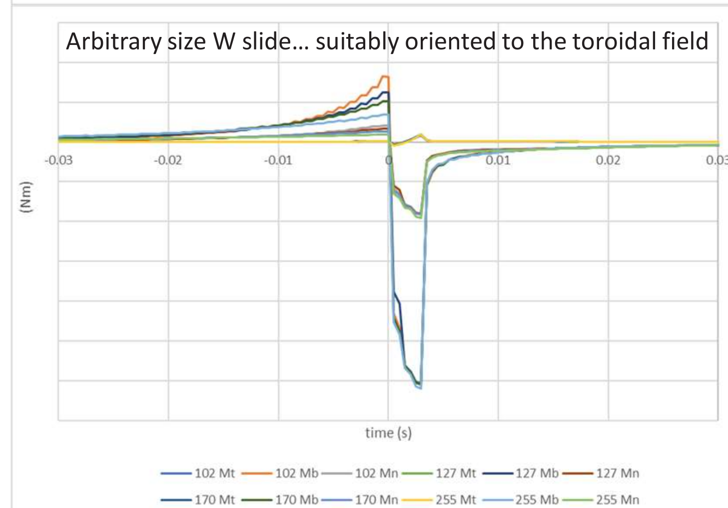
Slice eddy current loads inversely proportional to current quench duration





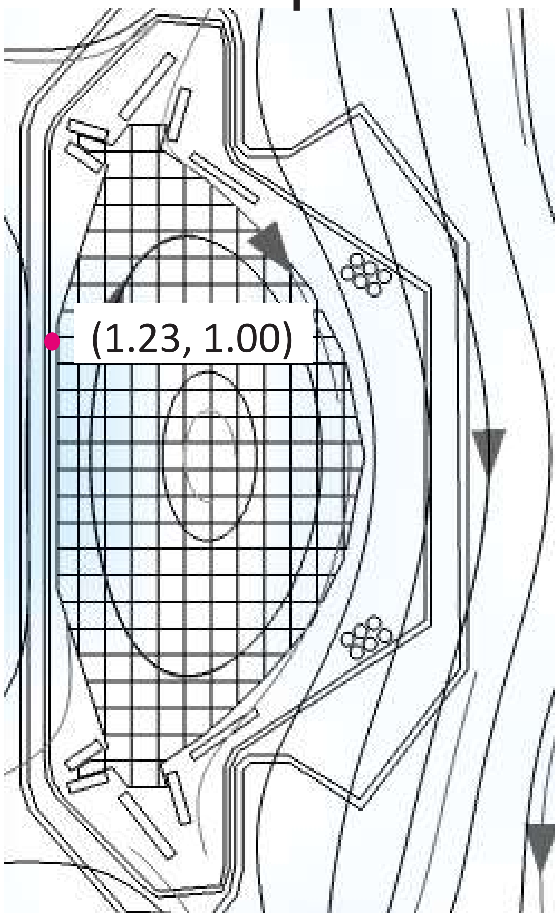


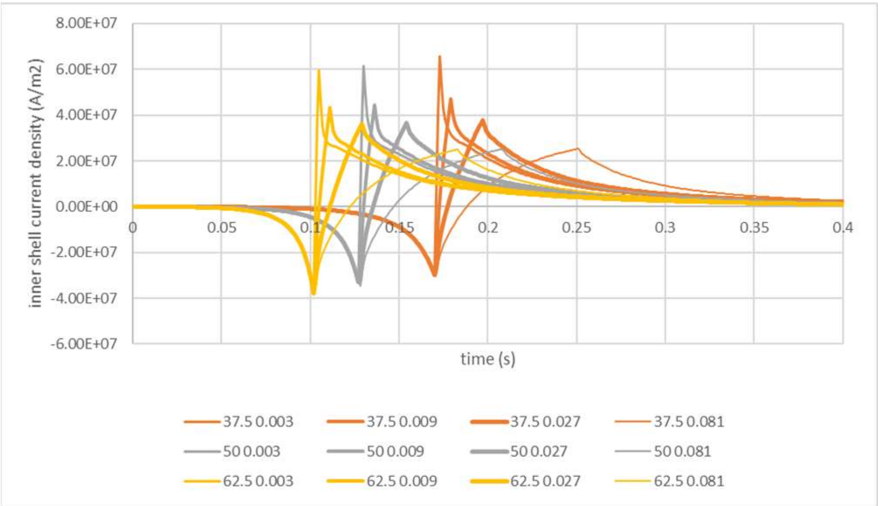




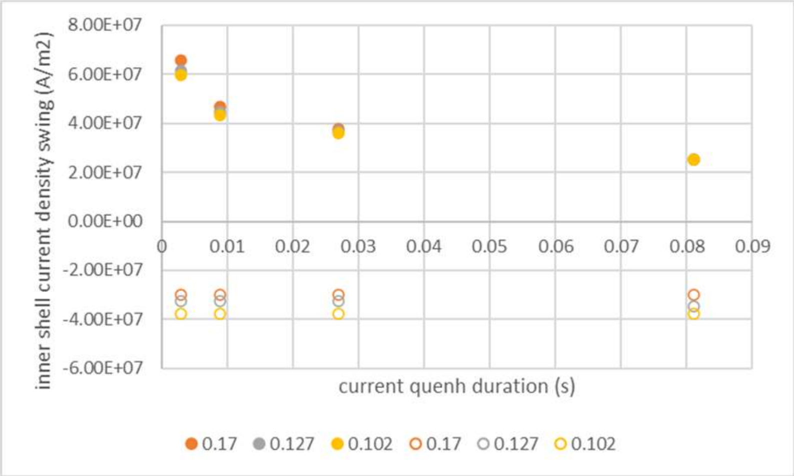
Different vertical displacement durations do not affect the peak moment on “floating” components

Shared eddy current loads inversely proportional to current quench duration





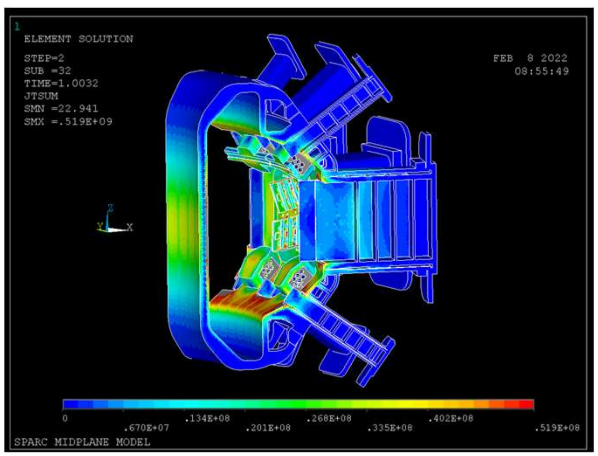
The maximum of the shared current correlates more with the current quench duration that the vertical displacement duration.



Summary load cases

In-vessel components

- Major and mitigated disruption
  - 3.2 ms current quench
- Vertical displacement events
  - 100 ms plasma displacement to q_{cyl}=1
  - 3.2 ms current quench
  - Halo current at f*TPF=0.7



Vacuum vessel

- Major and mitigated disruption (40 degree model)
  - 3.2 ms current quench
  - REMC sideways force
- Vertical displacement events (40 degree model)
  - 100 ms plasma displacement to q_{cyl}=1
  - 3.2 ms current quench
  - Supported system loads + halo to reach nominal max vertical force
- Asymmetric vertical displacement events (360 degree model)
  - Vertical force asymmetry factor 1.4
  - Sideways force of aligned plasma and REMC
  - Magnetic stiffness and damping