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FÜR PLASMAPHYSIK

ASDEX Upgrade

Mechanism for the reduction of the global vertical force in mitigated disruptions

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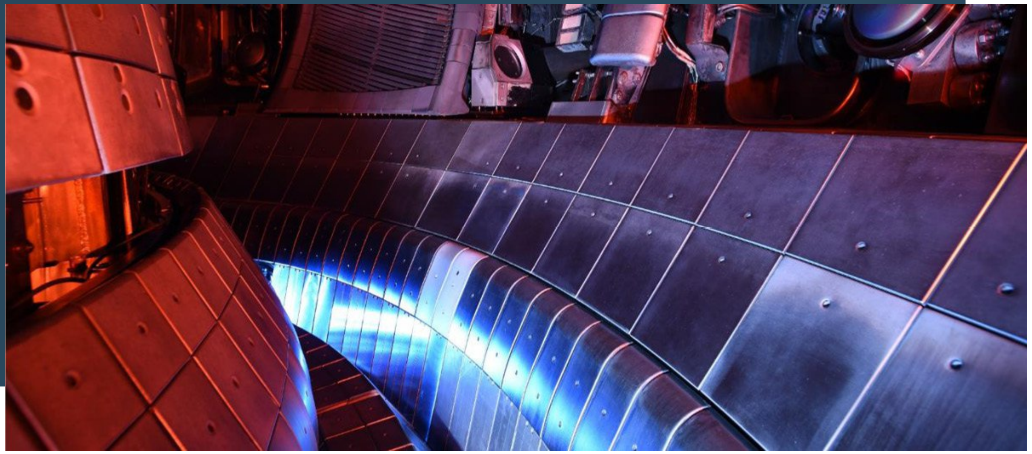

EUROfusion

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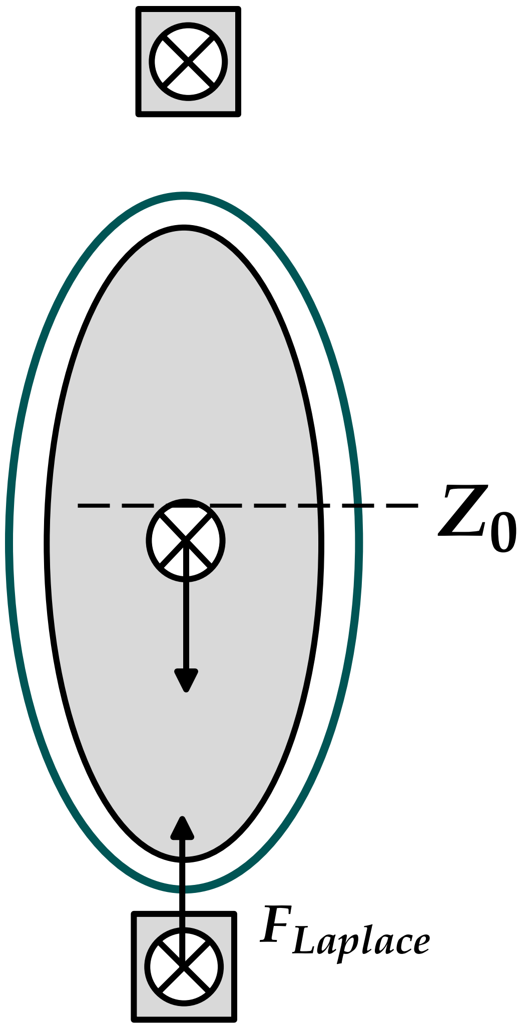
Vertical Stability in tokamaks



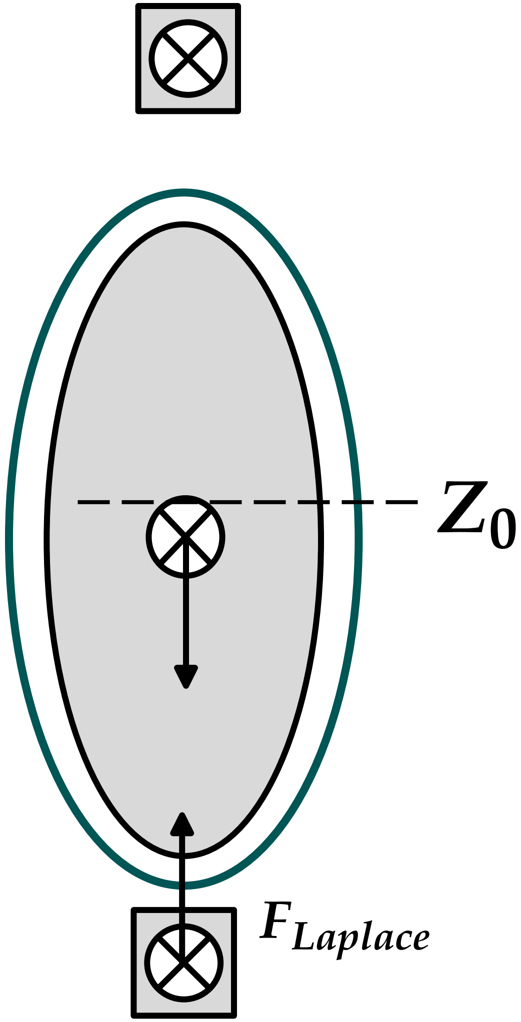
- **Vertical force due to field curvature**

$$dF_z \propto I_p \frac{dB_r}{dz} dz$$

- **Resistive wall stabilizes motion to τ_{wall}**

$$dF_{z,stab} \propto I_p^2 \left(\frac{dM_{cp}}{dz}\right)^2 dz$$

Vertical Stability in tokamaks



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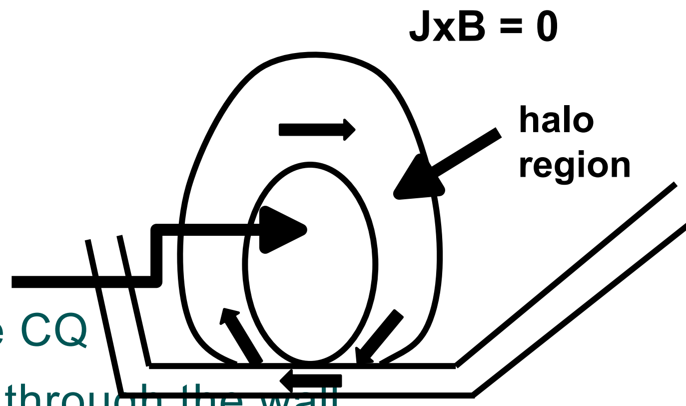
à I_p^2 vs I_p dependence

à Fast vertical movement during CQ



- Currents in the SOL are induced in the CQ

☾ These “Halo currents” close poloidally through the wall

Wall forces

- Forces on the structures appear due to **eddy currents** and **halo currents**

Vertical force on the vacuum vessel:

$$F = F_{p,c} + F_{vv,c}$$

c=PF coils, vv=vacuum vessel, p=plasma

$$F_{pc} \propto I_p \Delta z \approx \Delta M_{IZ}$$

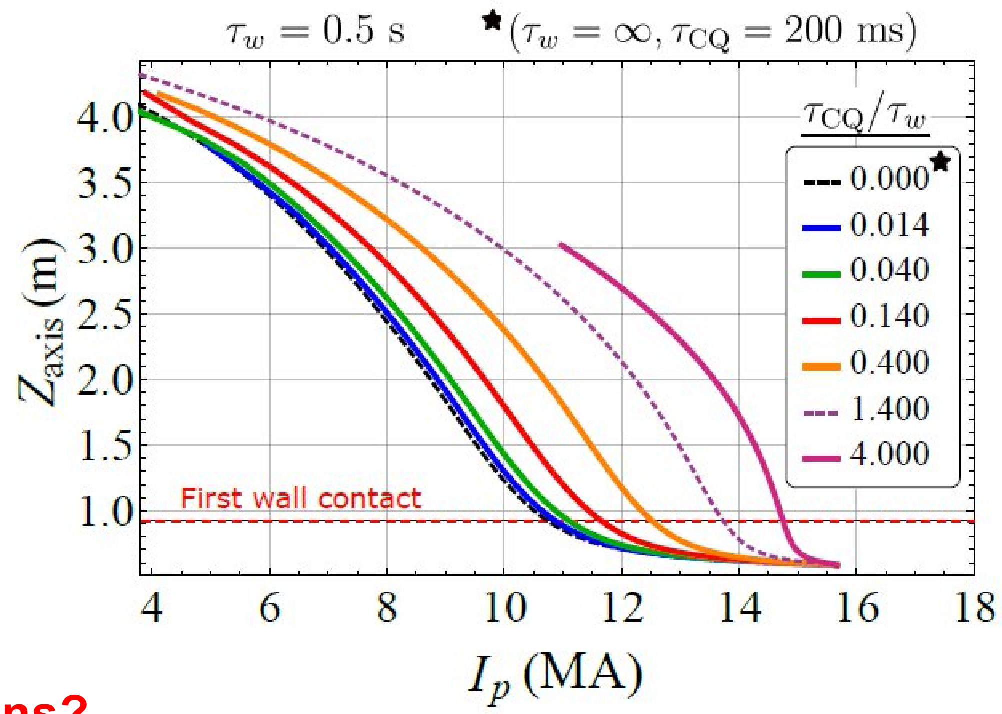
[S Miyamoto 2011 *PPCF* **53** 082001]

- The global force is related to the change in **vertical current moment** ΔM_{IZ}

$$M_{IZ} = \int j_\phi Z \, dS$$

Plasma current threshold for fast CQ

- Fast CQ: $\tau_{CQ} \ll \tau_w$
  - $Z_{axis} = f(I_p)$ [1]
- At critical I_p, stability threshold crossed [2,3]
- $I_p < I_{p,th}$
  - wall cannot stabilize any more
  - Wall contact at same Ip
- This theory does **not consider halo currents**



[F.J. Artola, PhD thesis 2019]

Why is it possible to mitigate forces in disruptions?

[1] [Kiramov, PoP **24** 10 100702, 2017]
[2] [Gruber, PPCF **35** B191-B204, 1993]
[3] [Boozer, PoP **26** 114501 2019]

The role of toroidal halo currents

Experiments in JET and AUG

Simulations with the MHD code JOREK

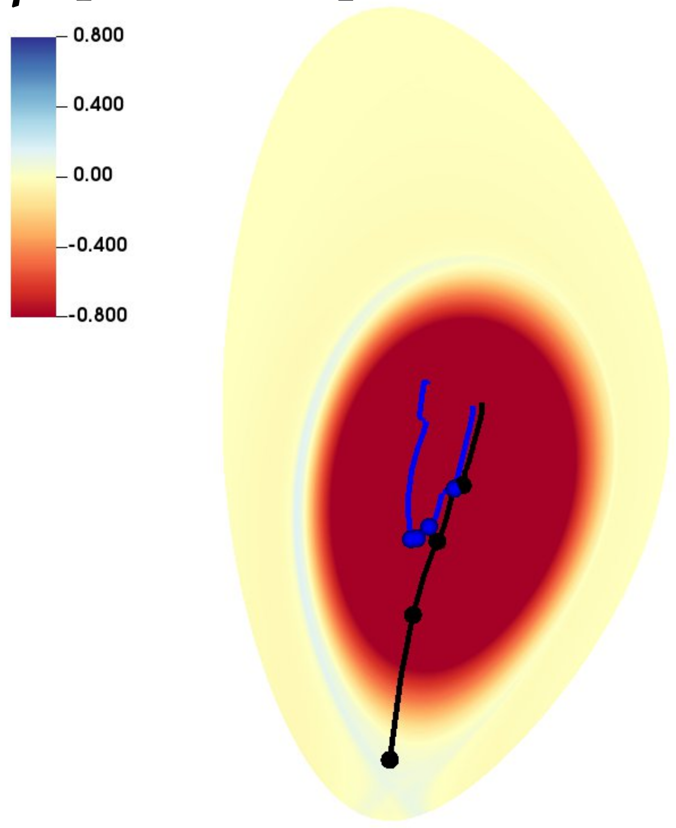
First results for ITER

Theory

Toroidal halo currents

- Radiation leads to a temperature around 10eV in the core and SOL
  - $T_{core} \approx T_{halo}$
  - **Large toroidal halo currents induced in SOL**

$j_\phi \ [MA/m2]$ Pre - TQ



Current centroid

Magnetic axis

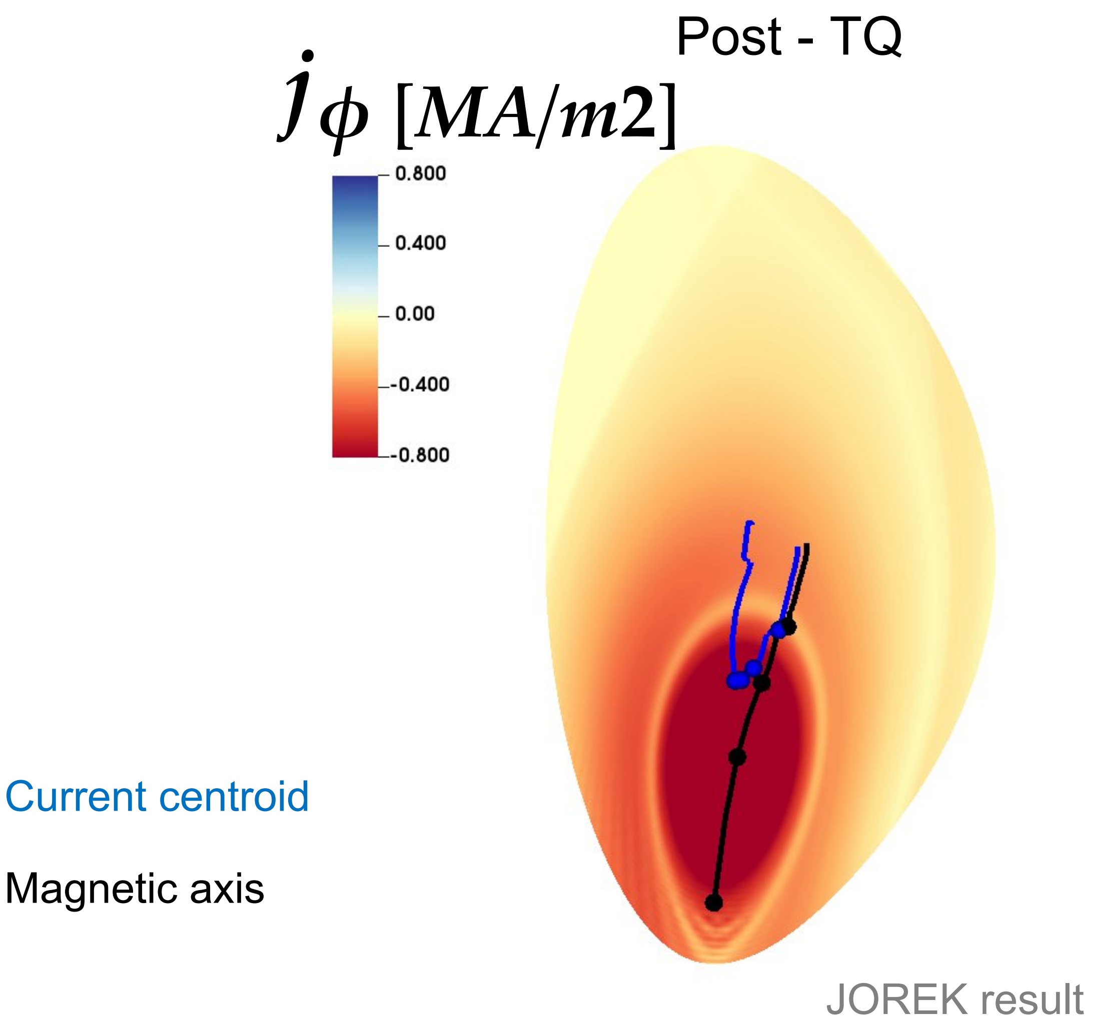
JOREK result

Toroidal halo currents

- Radiation leads to a temperature around 10eV in the core and SOL
  - $T_{core} \approx T_{halo}$
  - **Large toroidal halo currents induced in SOL**

- Most of the current is carried by the halos
  - **Current centroid stationary**
  - **Core moves vertically**

- $q_{95} \uparrow$ due to I_p decay
- As $q_{95} \gg 1$, the poloidal halo currents are reduced
  - Less asymmetries



Toroidal halo currents

- Radiation leads to a temperature around 10eV in the core and SOL
  - $T_{core} \approx T_{halo}$
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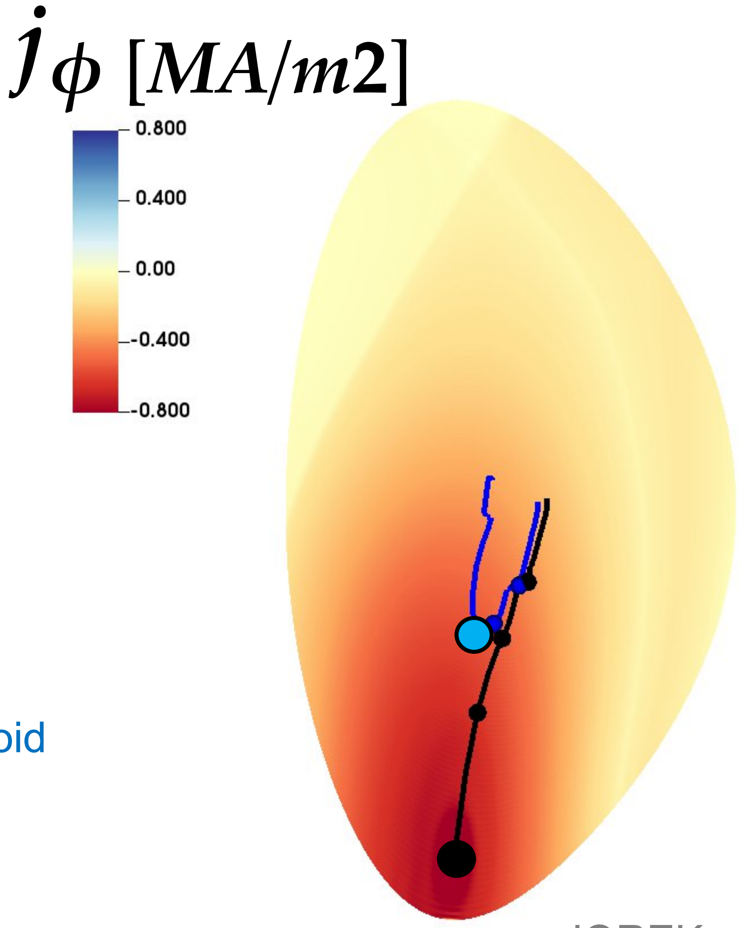
- Most of the current is carried by the halos
  - **Current centroid stationary**
  - **Core moves vertically**

$$F_z \propto I_p \Delta Z_{curr}$$

- As the current centroid is stationary, the **vertical force is reduced**

Post - TQ



Current centroid

Magnetic axis

JOREK result

Experiments

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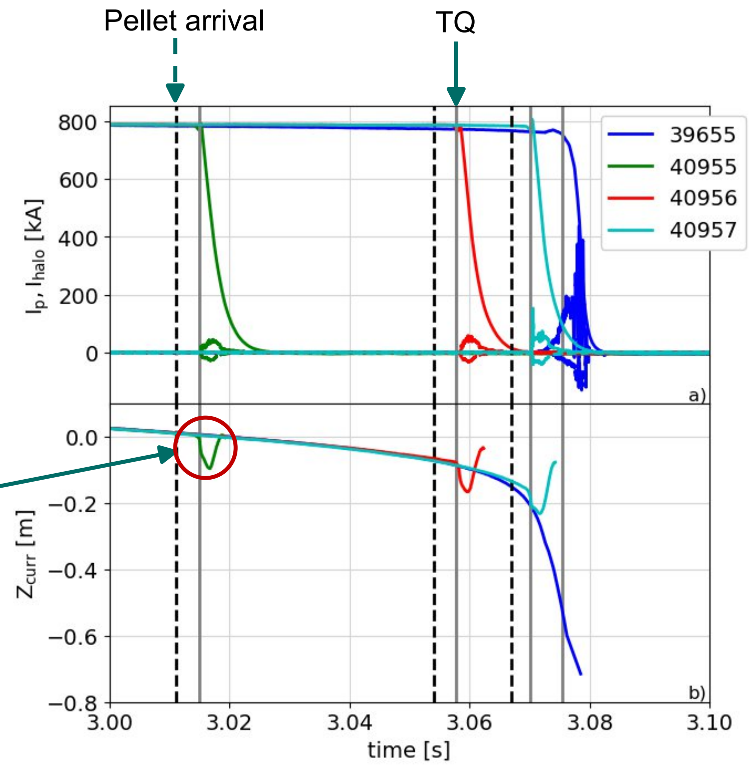
- Equilibrium: 800kA, Ohmic L-mode
- VDE triggered by forced displacement by position controller
- 1 hot VDE
- SPI mitigation at 3 different displacements
- Z_{curr} stationary

  (not fully reliable during disruption)



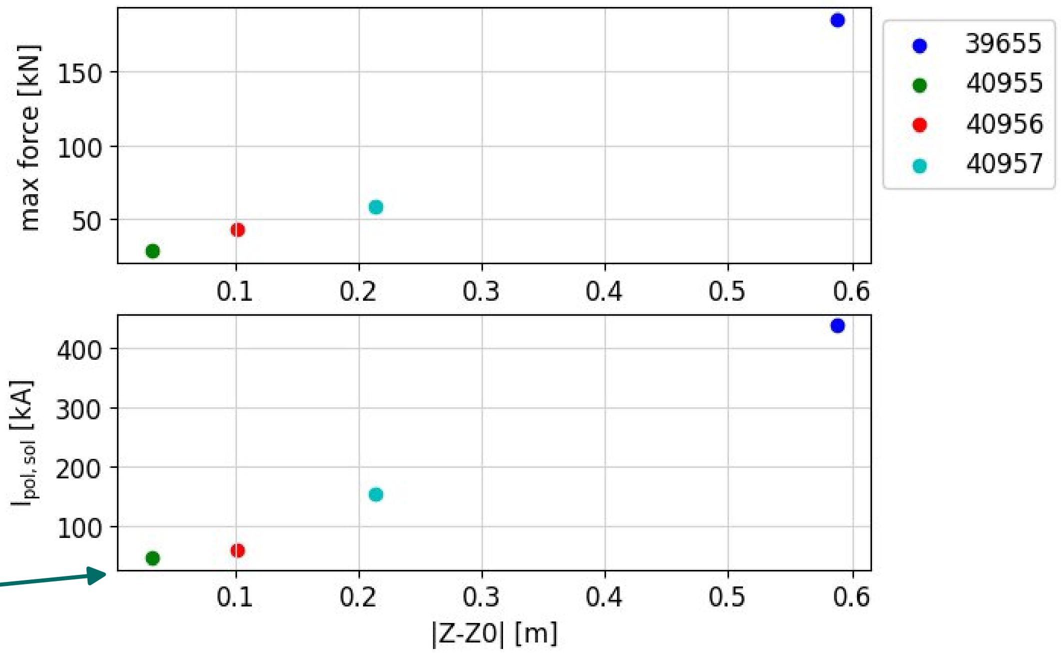
ASDEX Upgrade

- Z_{curr} stationary

- Reduction in poloidal halo currents

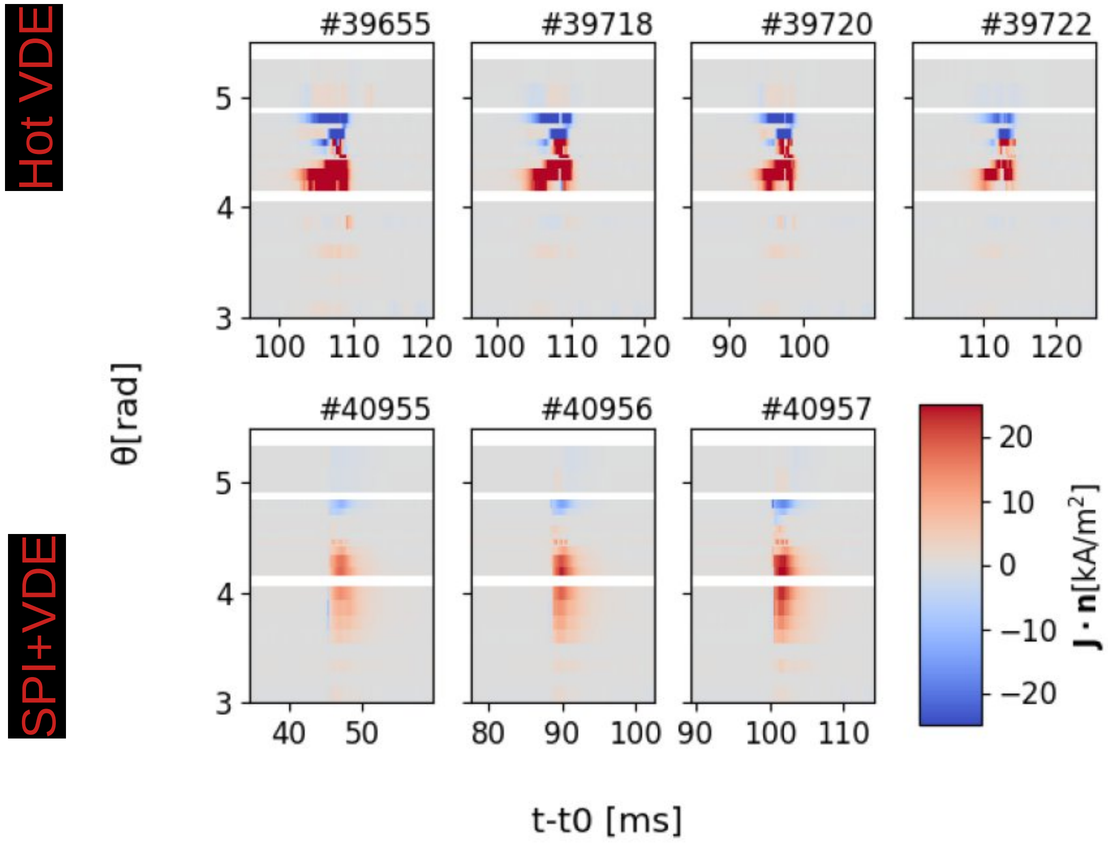
Reduction of the $I_{h,pol}$ possible as $q_{95} \gg 1$, while $I_{h,tor}$ is still big

- Reduction in vertical forces with $|Z-Z_0|$



at TQ onset

Halo current width



Hot VDE:

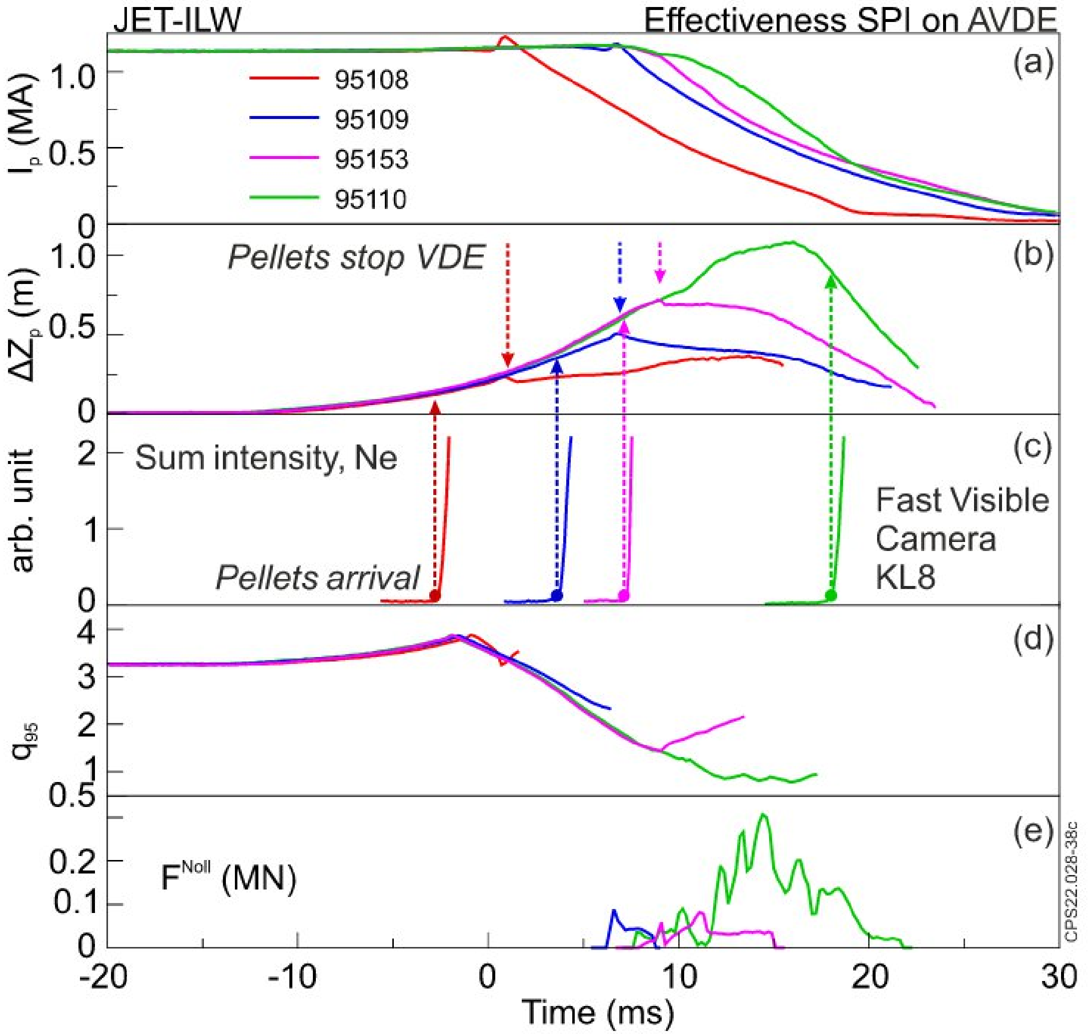
- halo current mainly in divertor
- Large current density

SPI + VDE:

- Broad halo current
- Magnitude reduced

JET

- Experiments on the mitigation of asymmetric VDEs (AVDE)
- Upward VDE mitigated by SPI at different displacements
- **Current centroid constant after injection** (from magnetic measurements)
- q95 increases after injection
  - ☾ Sideways force decreases due to missing 1/1 kink



[Gerasimov, EPS 2020, P1.1031]

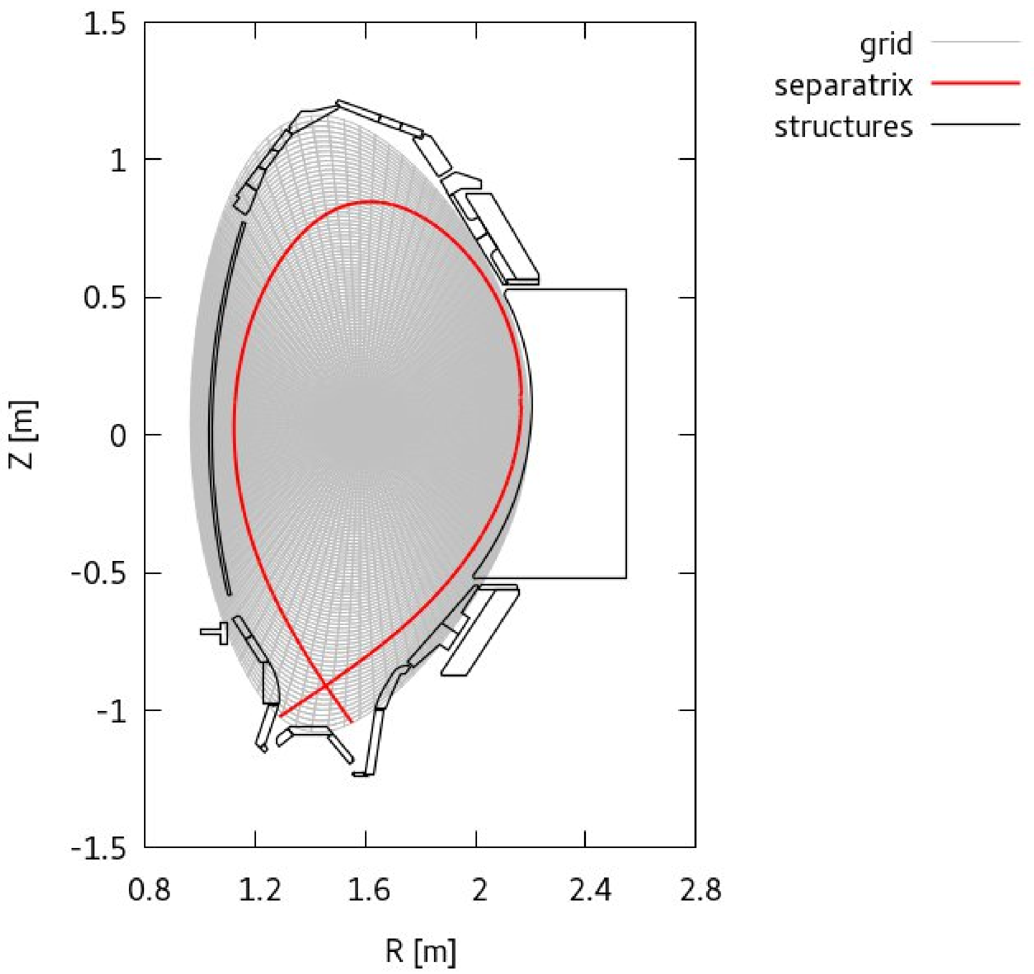
SIMULATIONS

JOREK - setup

Simulations based on work of
Di Hu and Tim Driessen

- **2D simulations** (3D possible, but expensive)
- Here: simplified Neon SPI injection
  - uniform impurity density
  - **tune n_{NE} to reach initial CQ rate of experiment**
- **Halo current width and magnitude depends on the SOL temperature**

AUG setup



[Hoelzl et al 2021 Nucl. Fusion 61 065001]
[Merkel, arXiv:1508.04911]
[Hölzl et al 2012 J. Phys.: Conf. Ser. 401 012010]
[D . Hu et al 2018 Nucl. Fusion 58 126025]

Simulation steps

1. Initial movement
2. Artificial thermal quench by large perpendicular conduction
3. Flattening of the current with hyperresistivity
4. Injection of impurities by uniform source
5. Plasma current decay

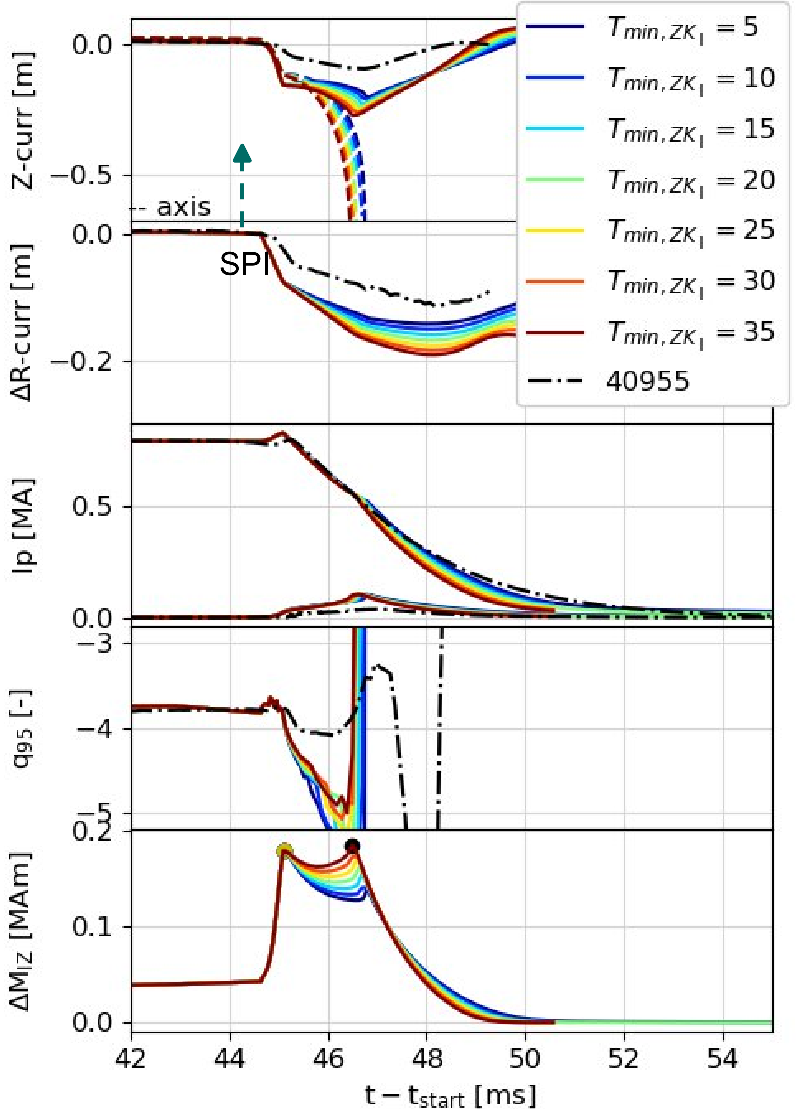
AUG simulations

- Sheath physics not taken into account
- Scan in SOL temperature
- T_{SOL} varied by imposing a minimum value on the parallel thermal conduction

$$\kappa_{\|,min} = \kappa_{\|}(T_{e,min}) \text{ if } T_e < T_{e,min}$$

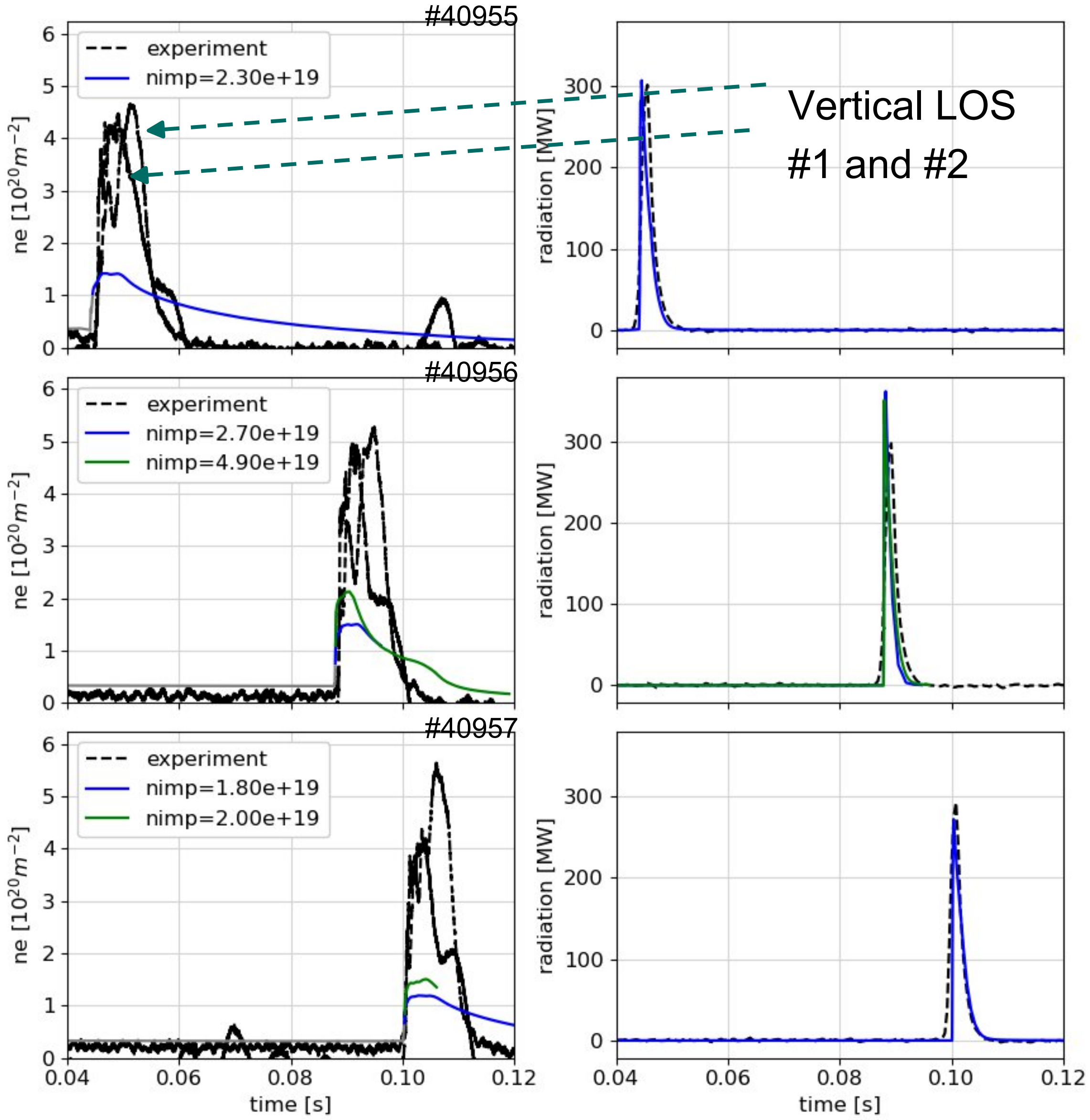
- Current centroid is stationary while magnetic axis moves
- Current quench time reproduced
- **q95 increases due to Ip decay**
- **Current moment reduced**

ASDEX Upgrade results



Radiation and electron density

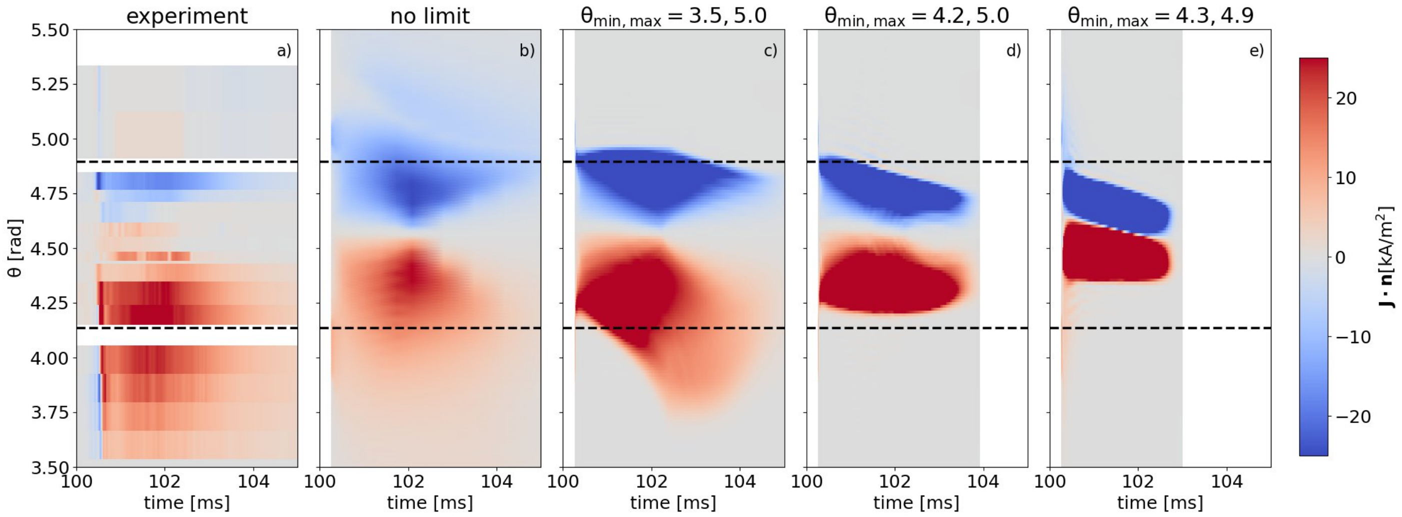
- Radiation peak from bolometer signals reproduced
- Electron density smaller than in the experiment

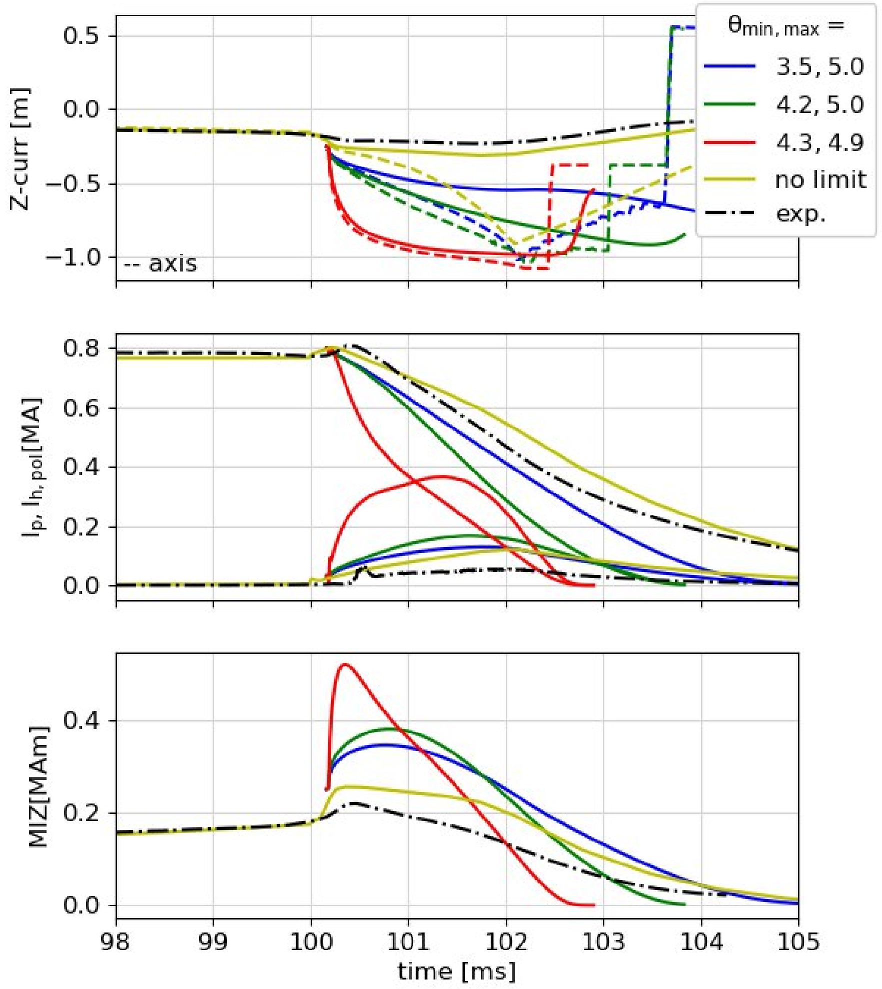


ASDEX Upgrade results

Scan in the halo current width

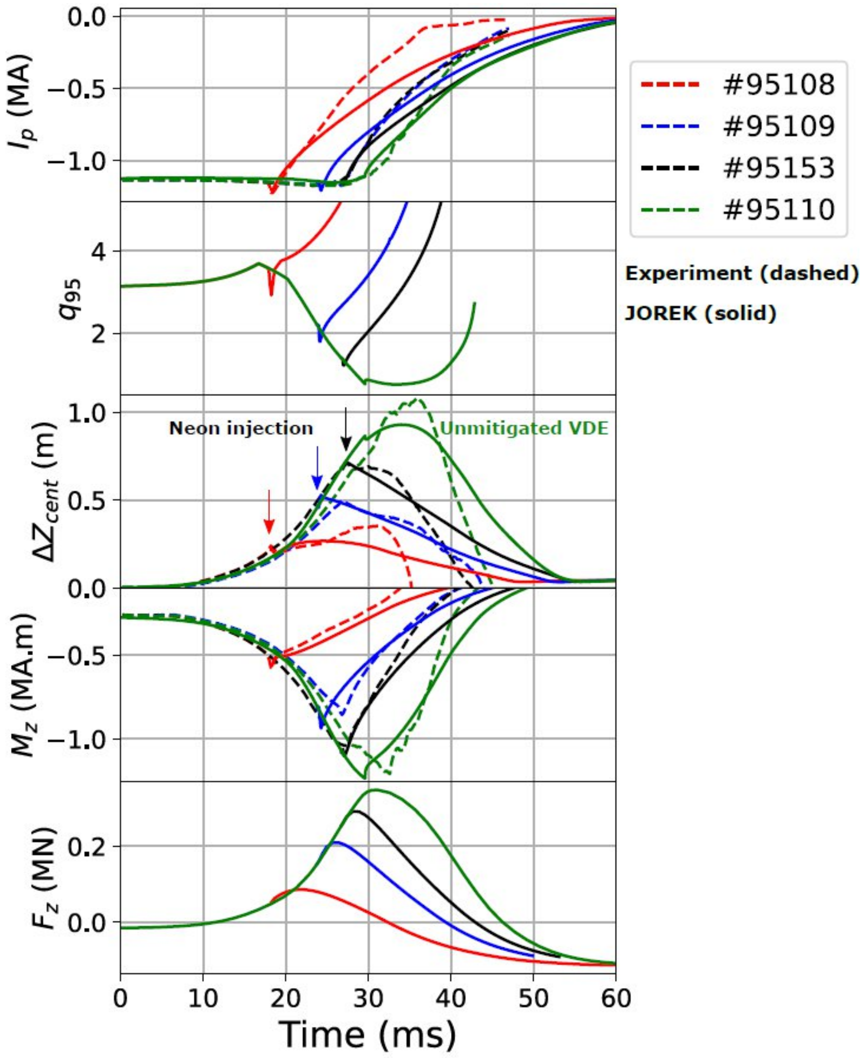
- Introduce space dependent η to vary the halo current width
- Smaller width leads to a coupling of z_{mag} and z_{curr}
- ☾ Force increases and q_{95} increases





Summary of all JET simulations

JET results by J. Artola



- Injections at different times during the hot VDE
- The peak Δz_{curr} and ΔM_Z are well reproduced from the experiment (and directly measured)

- q95 increases after injection due to Ip decay

à Reduces poloidal halo currents

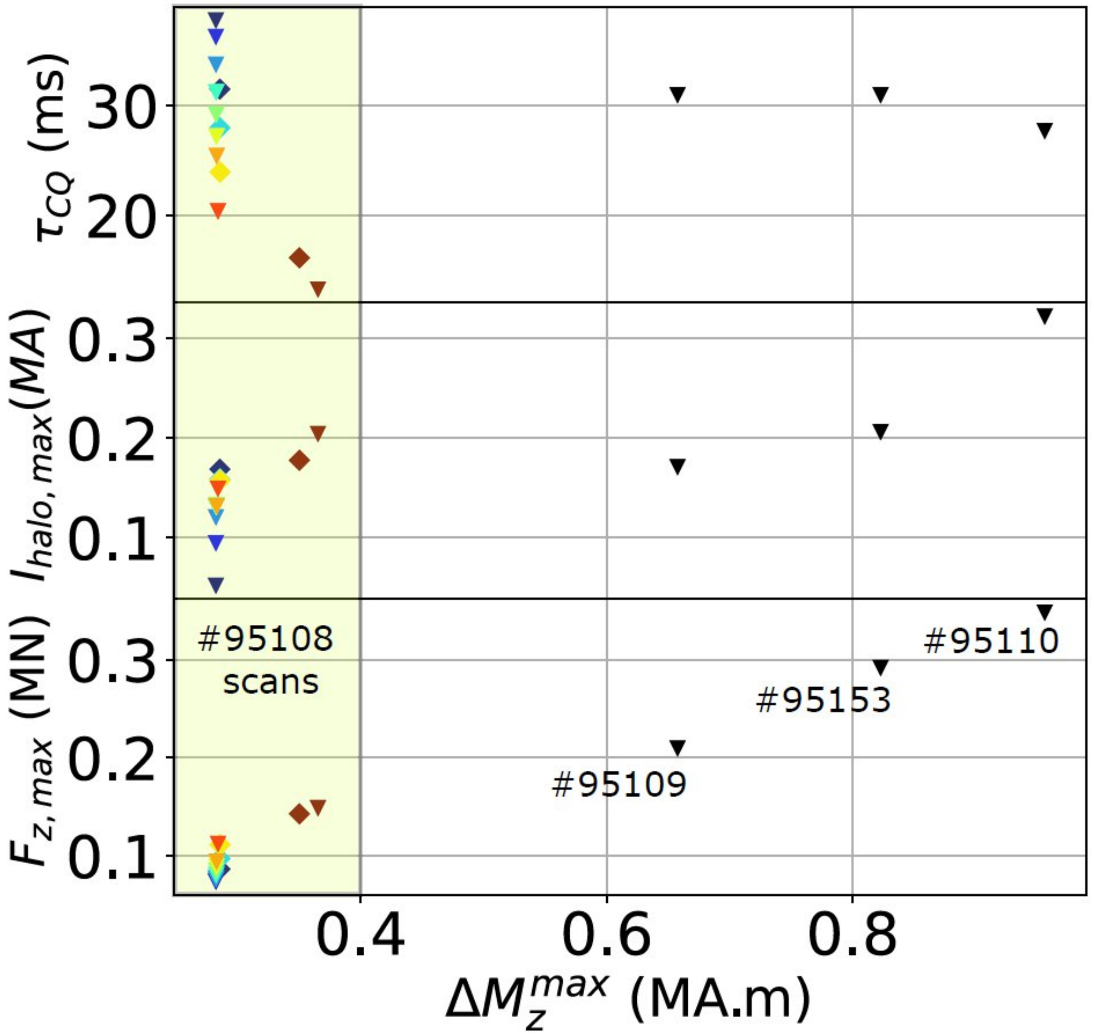
- ΔM_Z is reduced with earlier injection

☾ The force reduces with earlier injection

Summary of all JET simulations

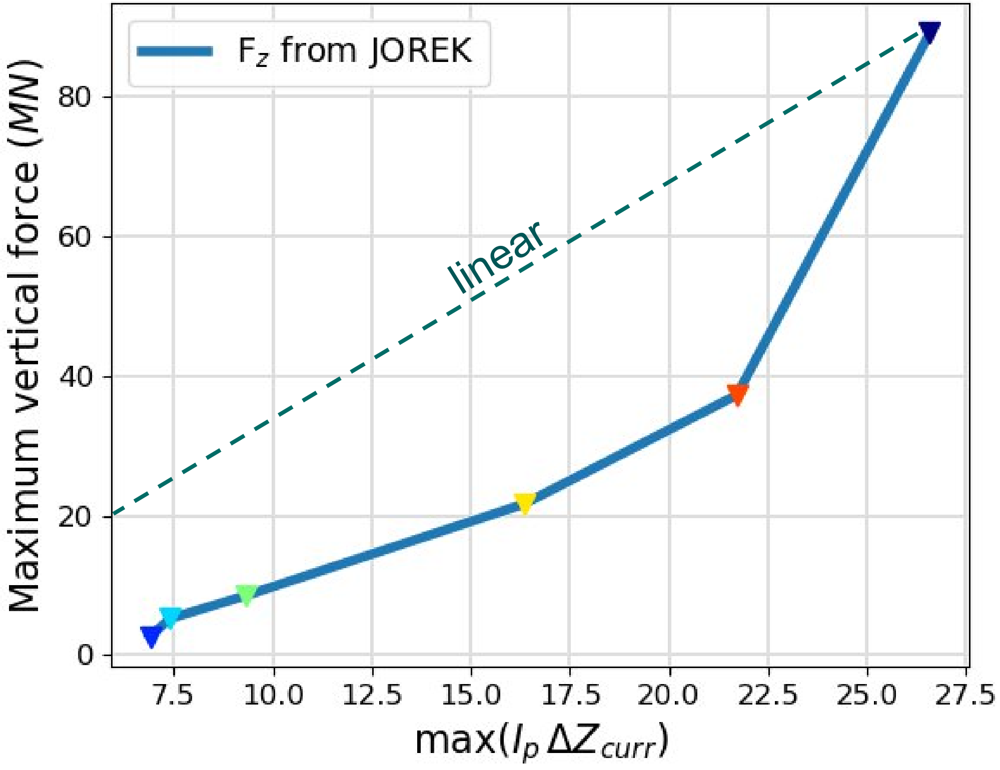
- The change of M_{IZ} is proportional to the maximum of the vertical force as predicted
- The force does **not** depend on the halo current magnitude or the current quench time

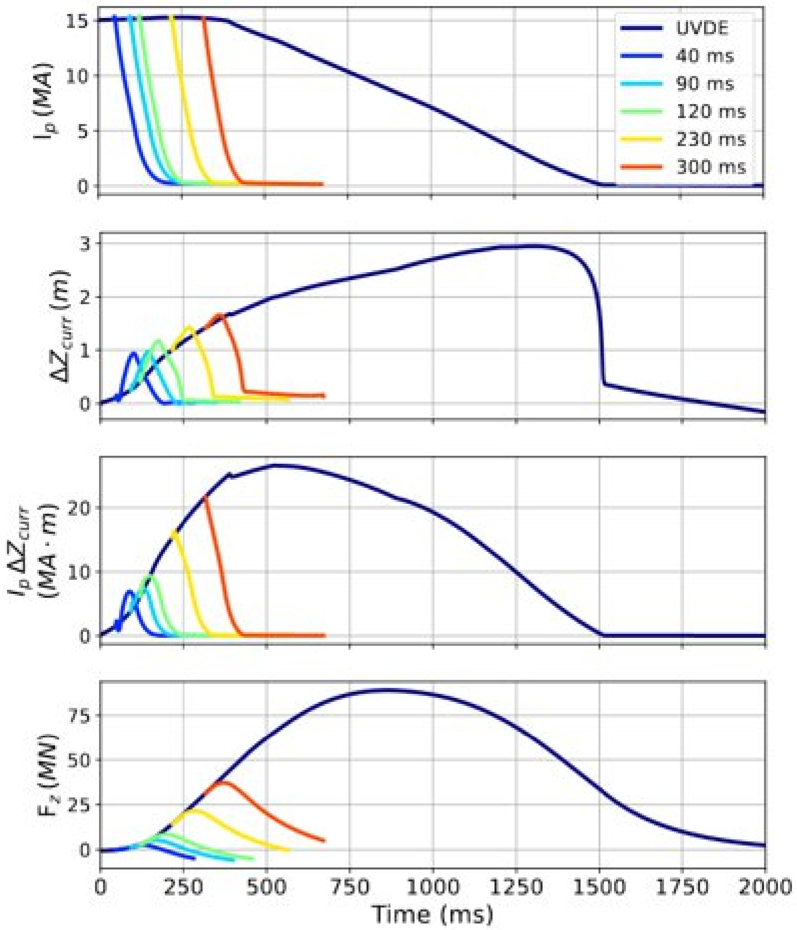
JET results by J. Artola



ITER prediction

Simulations by F. Vannini





max (F_z) **reduces more than** linear with $I_p \Delta Z_{curr}$

Is the theory wrong?

Wall damping

Back to the theory

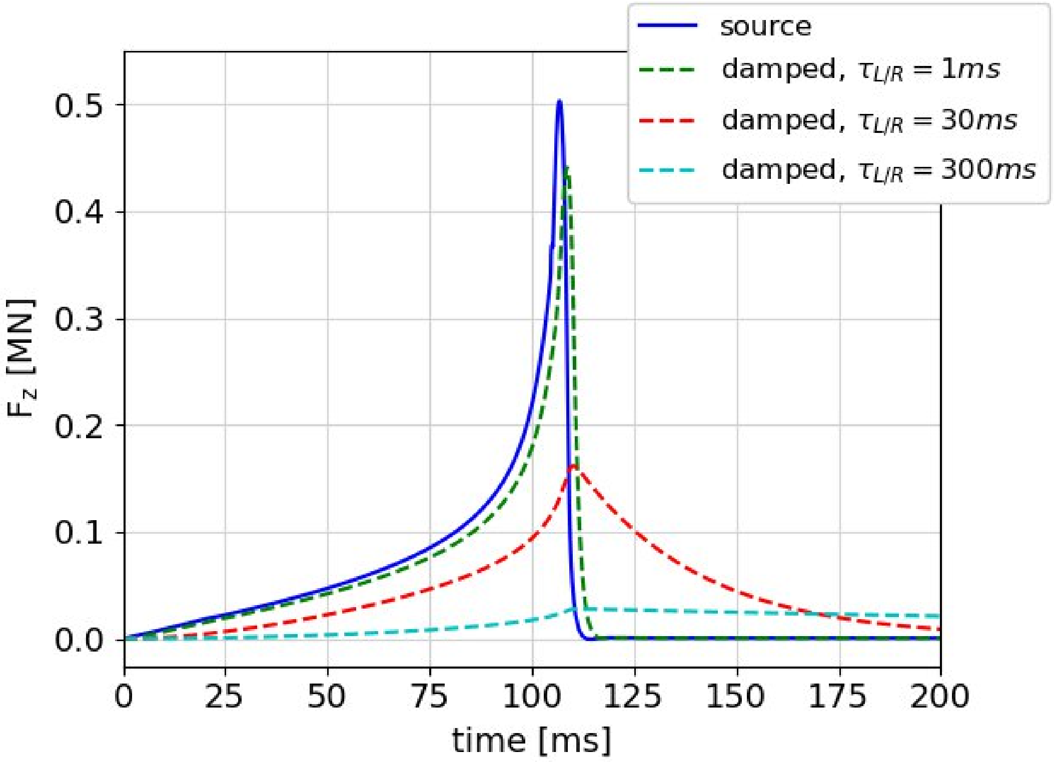
$F_{z,vv} = F_{p,c} + F_{vv,c}$

- $F_{vv,c}$ is a damping term describing the shielding by wall currents

It can be expressed by: [S Miyamoto 2011 *PPCF* **53** 082001]

$$F_{z,vv}(t) = \frac{1}{\tau_{L/R}} \int_{-\infty}^{t} \exp\left(-\frac{t-t'}{\tau_{L/R}}\right) F_{p,c}(t'-\tau_d)\, dt'$$

τ_d : delay to take into account multiple decay times
$\tau_{L/R}$: decay time of eddy currents
$F_{p,c}$: force on the plasma



Strong damping if $\tau_{L/R} \geq \tau_{disruption}$

In JET, AUG $\tau_{L/R} < \tau_{disruption}$

Wall damping: fitting ITER

$$\max(F_{z,vv}) = \max\left(\frac{\alpha}{\tau_{L/R}}\int_{-\infty}^{t} \exp\left(-\frac{t-t'}{\tau_{L/R}}\right)(I_p \Delta Z_{curr})(t'-\tau_d)\,dt'\right)$$

With

$F_{p,c} = \alpha I_p \Delta Z_{curr}$

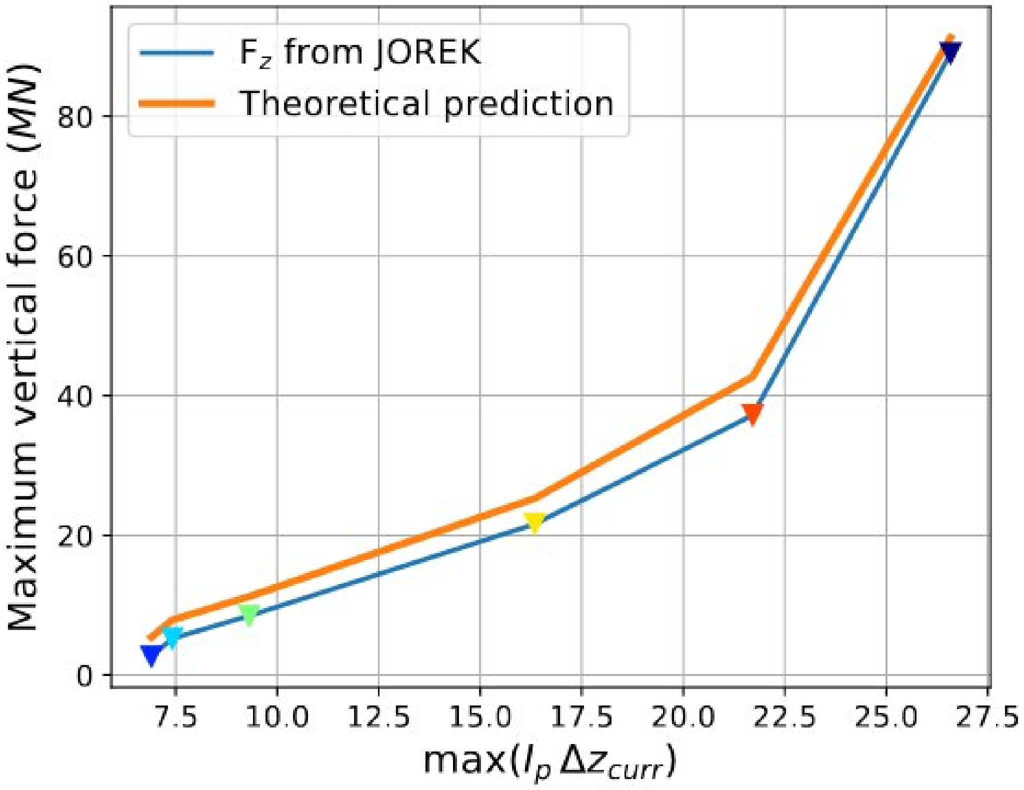
and $F_{z,vv}$ from the JOREK simulation,

we fit α

$$\alpha = \frac{F_{z,vv}(t)}{\frac{1}{\tau_{L/R}}\int_{-\infty}^{t} \exp\left(-\frac{t-t'}{\tau_{\frac{L}{R}}}\right)(I_p \Delta Z_{curr})(t'-\tau_d)dt'}$$

For ITER: τ_d= 50ms, $\tau_{L/R}$ =235ms

[S Miyamoto 2011 *PPCF* **53** 082001]



Conclusion

Conclusion

- The vertical moment is proportional to the global vertical force

$F_z \propto \Delta M_{IZ}$

- Large toroidal halo currents stop the movement of the current centroid
- **Theory explains reduction of the vertical forces in today's experiments**
- Sensitivity to SOL characteristics ☾ more physics needs to be included

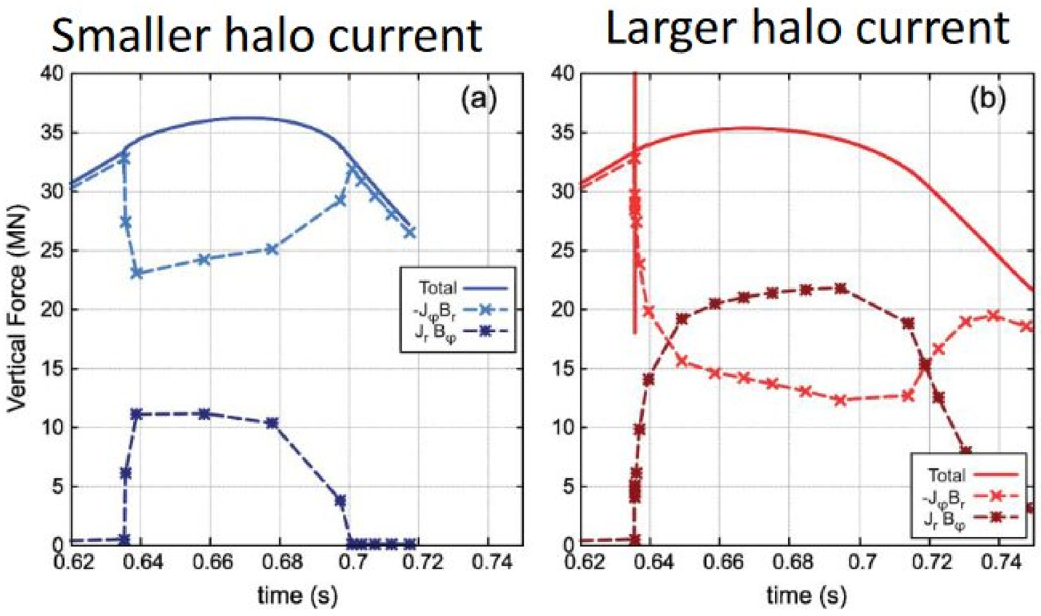
- **Limits of this theory**
  - Runaway Electrons (REs) not included in the model
  - If the plasma current is concentrated in REs:
    - Melting due to RE energy deposition
    - Moving RE beam leads to mechanical forces (but lower than in hot VDEs)

Backup

Halo currents do not determine the vertical force

M3D-C1 simulations of VDEs:

Clauser, et al, Nuclear Fusion, 2019

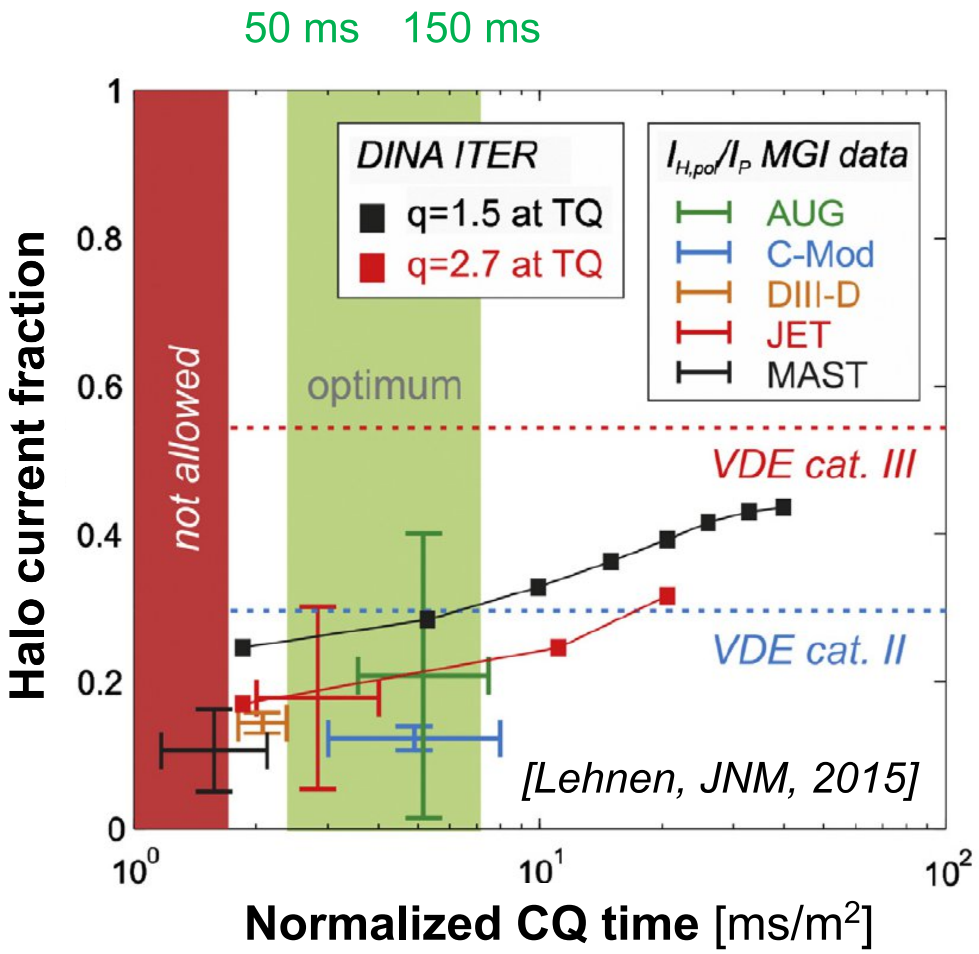


Wall force mitigation in ITER

Based on DINA simulations

- **Target CQ times 50-150 ms** to reduce **eddy** and **halo** currents
- CQ times controlled by Neon injection (SPI)
- Slow limit (150 ms) due to **halo currents** producing large
  - ➢ **Local forces** (BMs)
  - ➢ **Global forces** (full vessel)

What is the mechanism of the reduction?



Difference between hot and cold VDE

- **Vertical Displacement Event (VDE)**

  = not controllable vertical motion

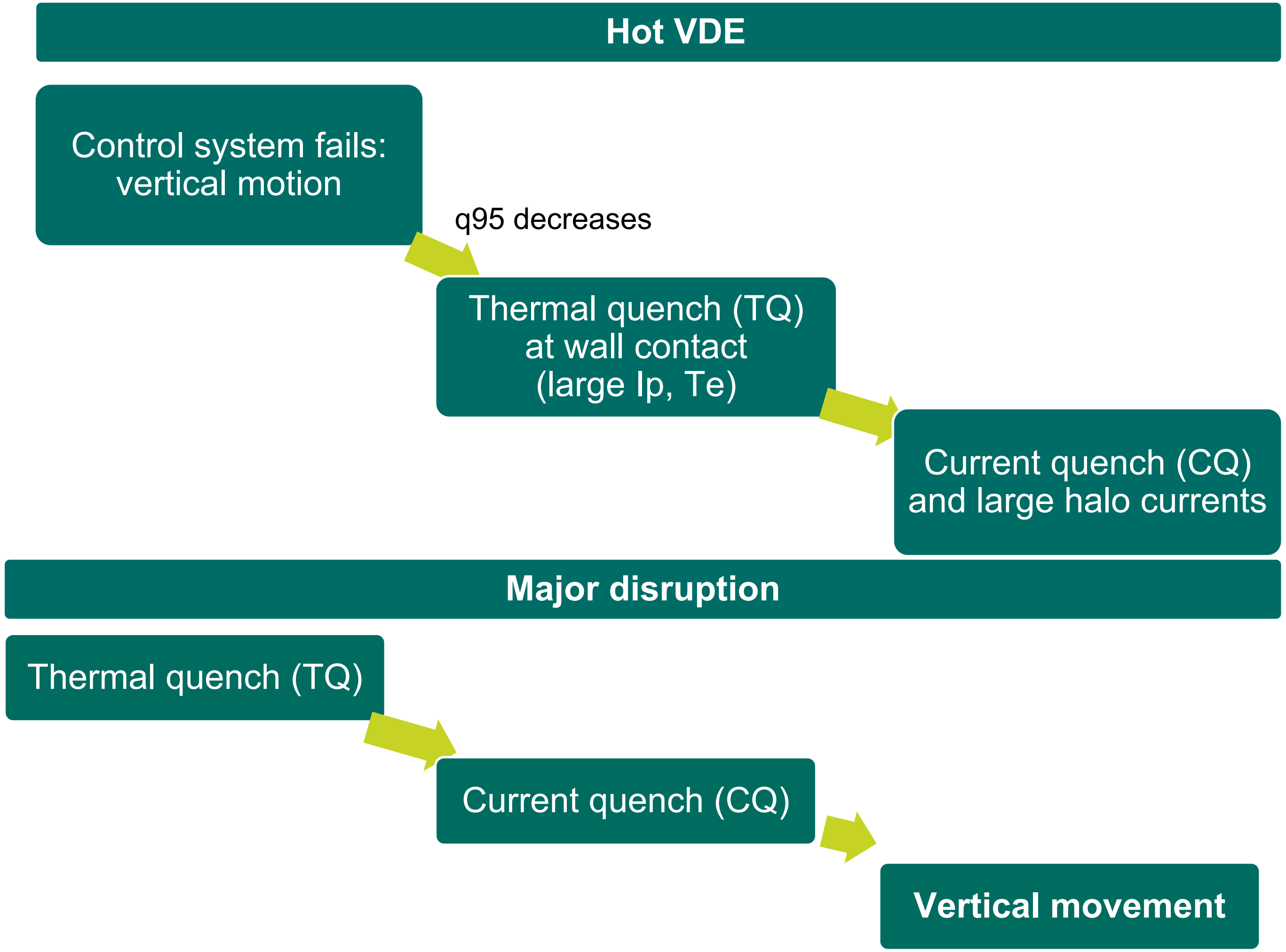
- **Hot VDEs:**
  - Large mechanical forces
  - Large heat loads

- **Major disruption**

$dF_z \propto I_p \frac{dB_r}{dz} dz \qquad dF_{z,stab} \propto I_p^2 \frac{dM_{cp}}{dz} dz$

- Ip vs Ip^2 dependence

☾ **Ip threshold below which wall cannot stabilize**



Results – heat flux scan

- T_{SOL} scan by varying the heat flux at the boundary

$$q_{||} = \gamma_{sheath} n_e \nabla_{||} T_e$$

- Boundary density not known

à Scan in boundary density to scan T_{SOL}

- Large heat flux recovers hot VDE behavior

JET result by J. Artola