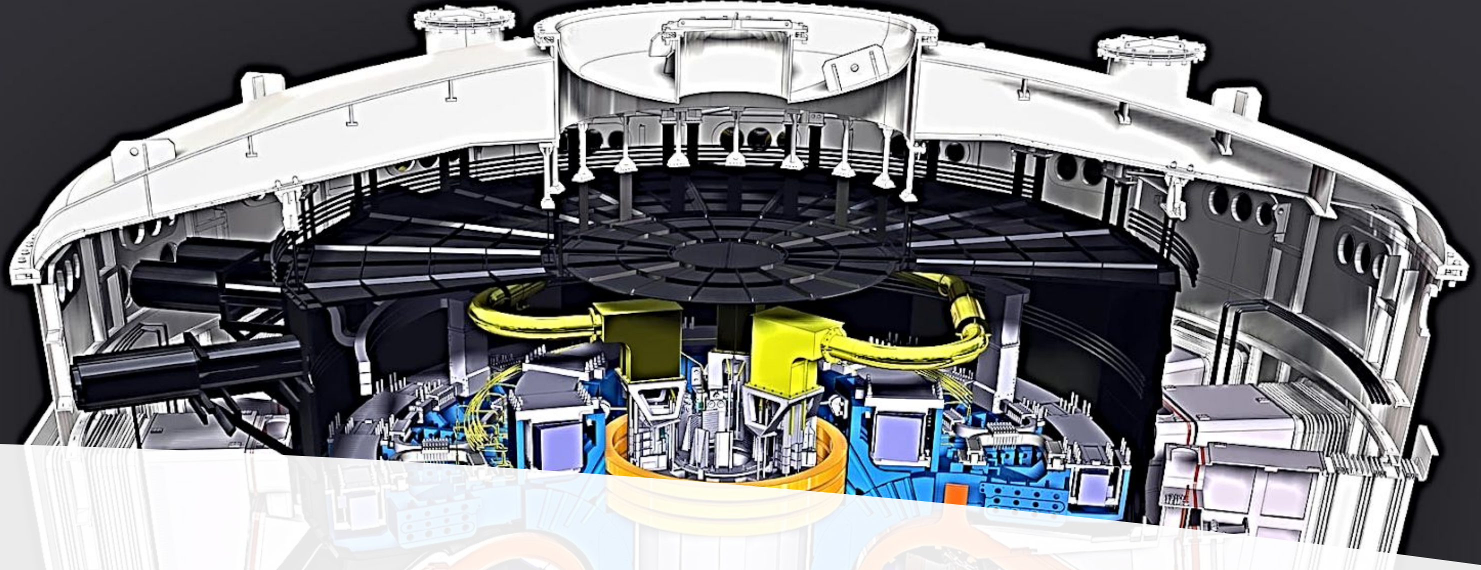


Modelling of the Thermal Quench during hot Vertical Displacement Events in AUG, JET and ITER

F.J. Artola[1], N. Schwarz[2], S. Gerasimov[3], A. Loarte[1] and the JOREK team[4]

[1]ITER Organization, Route de Vinon sur Verdon, 13067 St Paul Lez Durance Cedex, France
[2]Max Planck Institute for Plasmaphysics, Boltzmannstr. 2, 85748 Garching, Germany
[3]UKAEA, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK
[4]please refer to [M Hoelzl et al, Nuclear Fusion 61, 065001 (2021)]

china eu india japan korea russia usa

The thermal quench induced by a hot VDE

- Exponential vertical motion
  (given by the vessel's L/R time)
- "Intact" core flux surfaces
  (weak MHD activity)

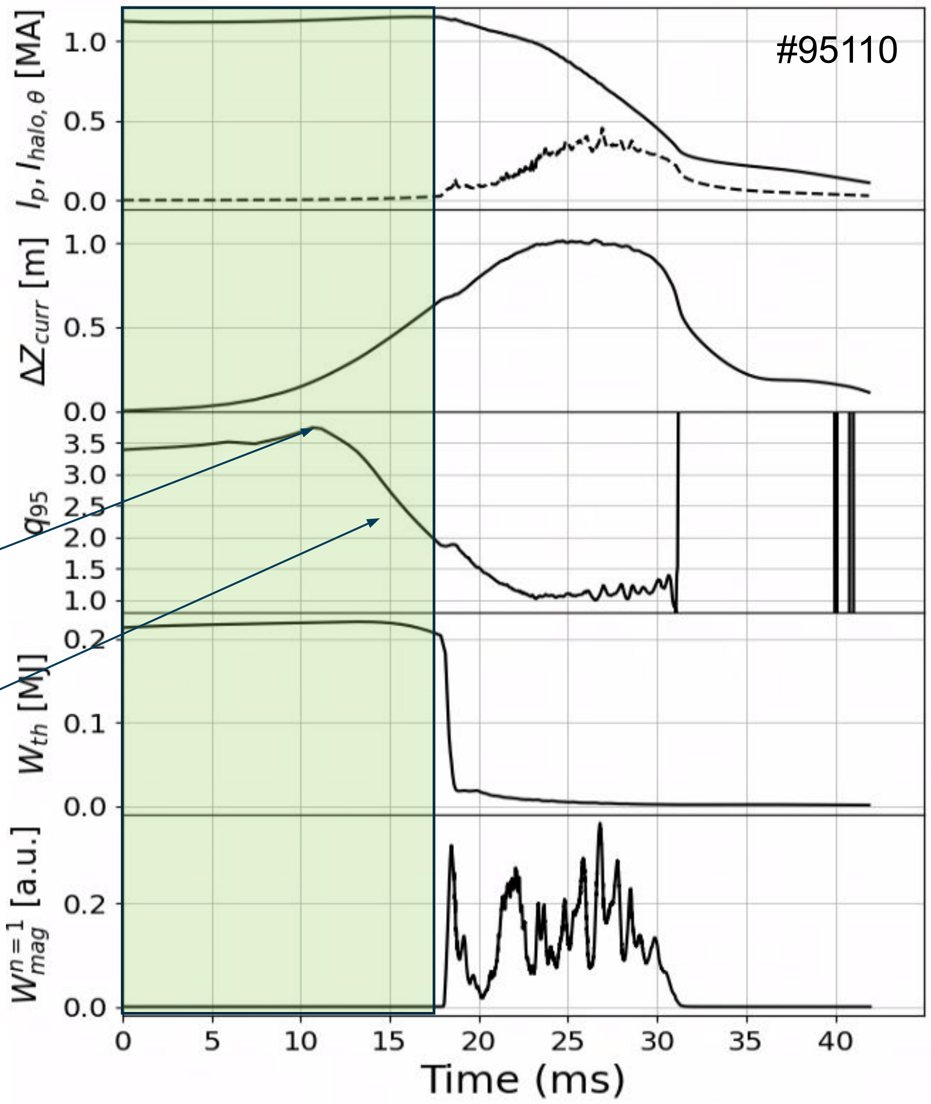
  $W_{th} \approx const$ → Low η → $I_p \approx const$

- Wall contact (from X-point to limiter configuration)

  → Core cross-section shrinks

  → **Drop of $q_{95} \propto a^2 I_{p,\text{core}}^{-1}$**

JOREK simulation of a JET VDE

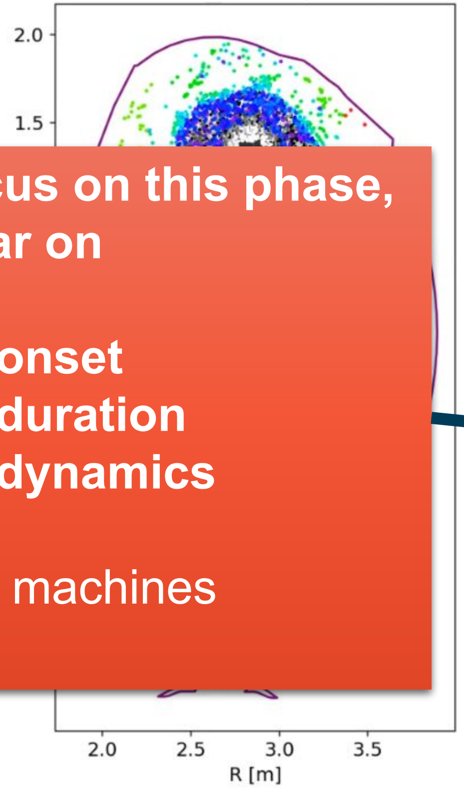


The thermal quench induced by a hot VDE

Growth of kink modes when $q_{95} \lesssim q_{th}$

- ➢ Break-up of magnetic su
- ➢ Parallel loss open field li
  - ➢ Thermal loss

Poincare plot during the TQ

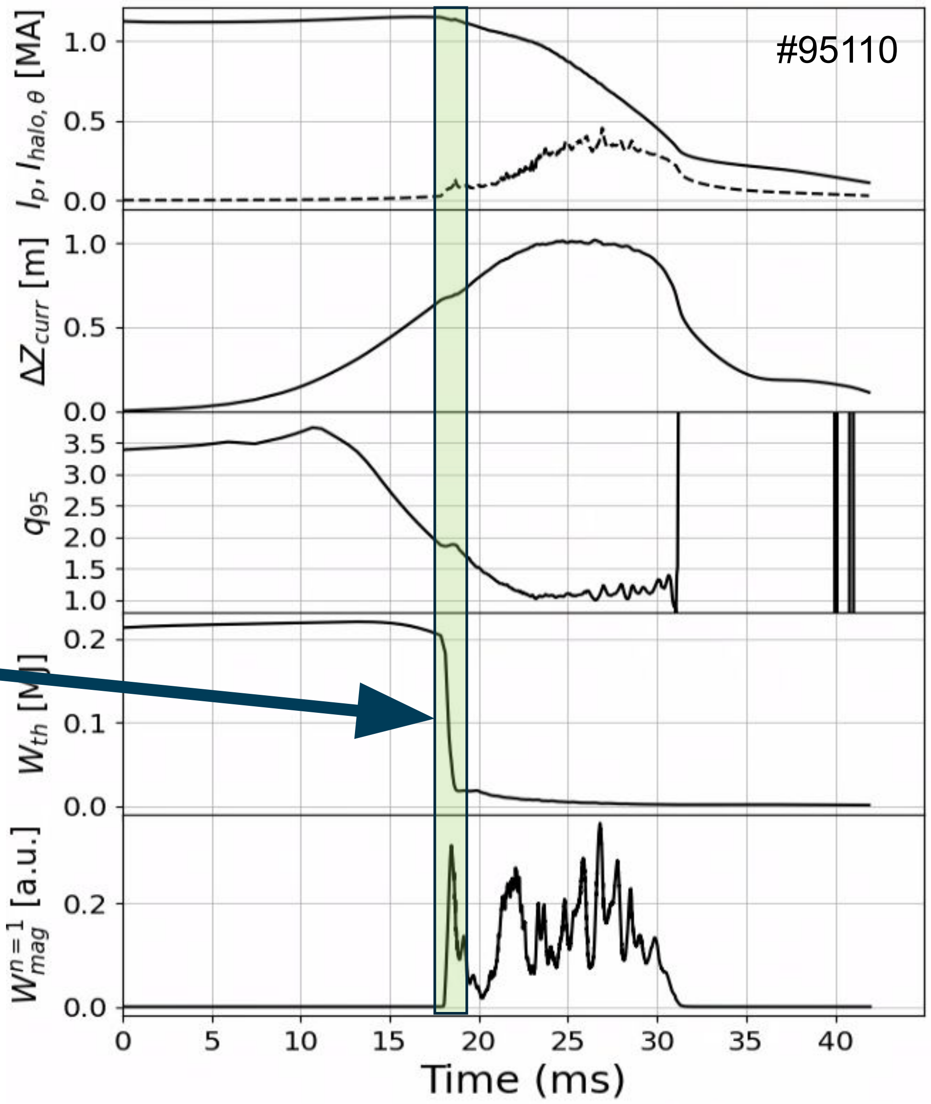


We will focus on this phase, in particular on

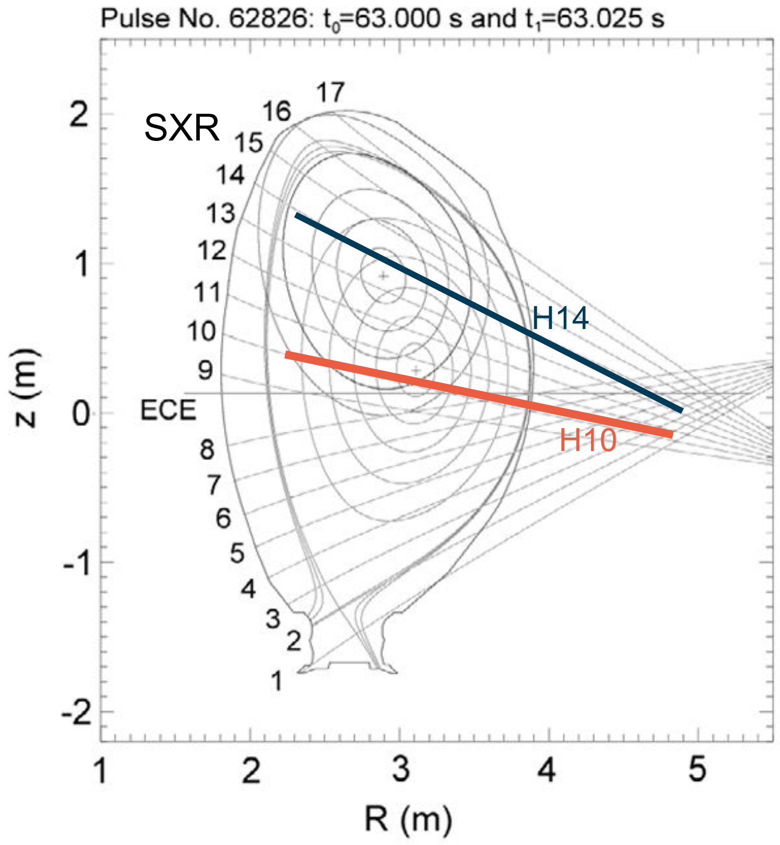
- **The TQ onset**
- **The TQ duration**
- **The TQ dynamics**

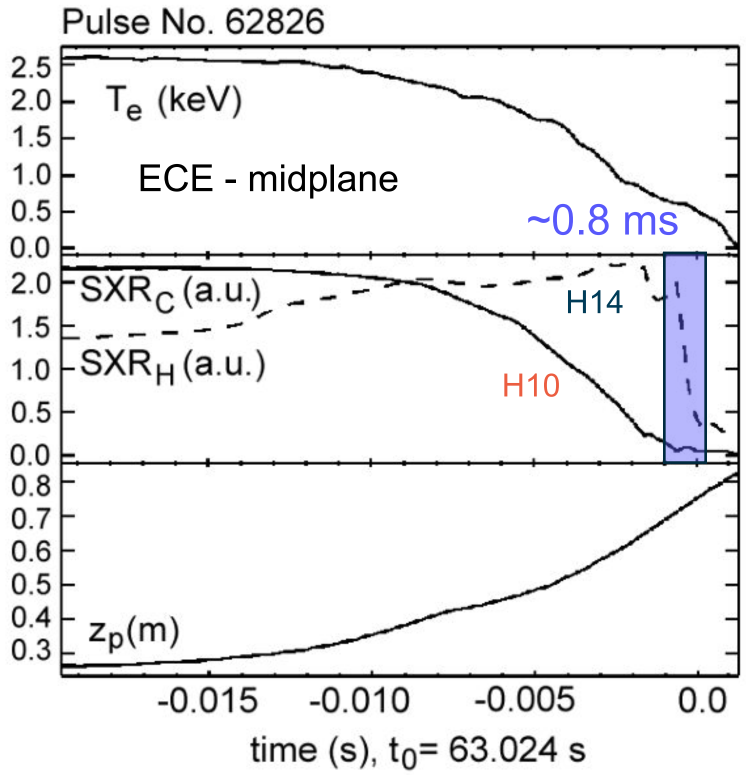
for different machines

JOREK simulation of a JET VDE



Measuring the TQ in JET

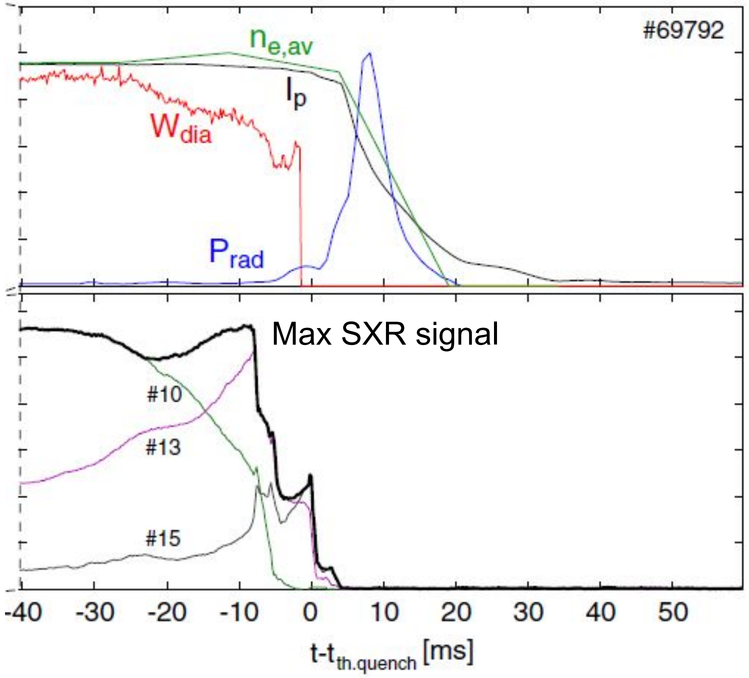




V. Riccardo et al 2005
Nucl. Fusion 45 1427

Measuring the TQ in JET

G. Arnoux *et al* 2009
Nucl. Fusion **49** 085038

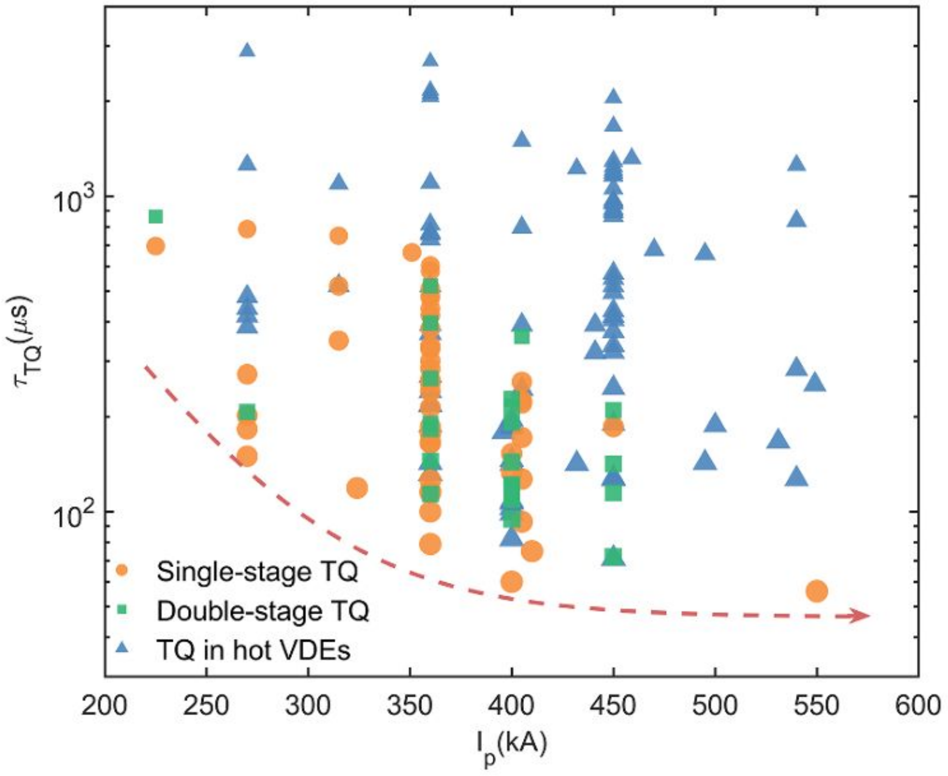


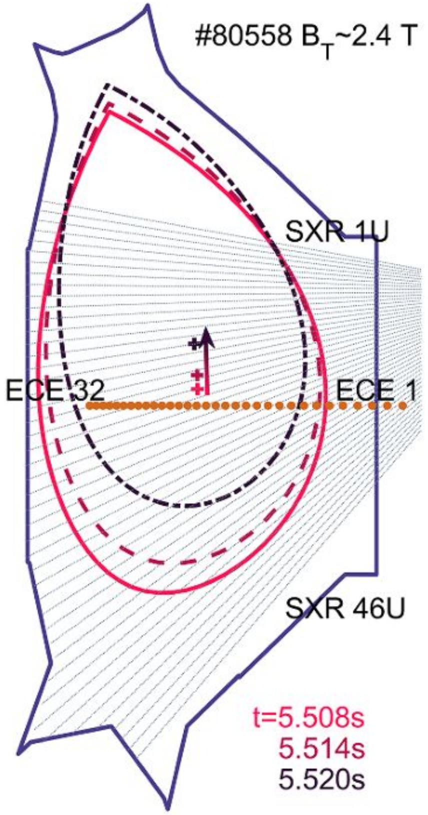
	$W_{dia,max}$ (MJ)	I_p (MA)	Δt_{IR} (ms)	$\tau_{TQ,IR}$ (ms)	$\tau_{TQ,SXR}$ (ms)	ΔT_{pk} (°C)	ΔT_{max} (°C)
69792 (VDE)	2.5	1.5	1.82	2.0 ± 1.0	1.6	347	763
72925 (VDE)	2.8	1.5	0.71	1.0 ± 0.3	1.0	327	1433
73124 (VDE)	5.0	2.2	0.71	3.7 ± 0.8	0.8	392	1002

Measuring the TQ in EAST

W Xia et al, 2023
PPCF 65 085011

- Large scatter in TQ duration for hot VDEs [0.1-3] ms

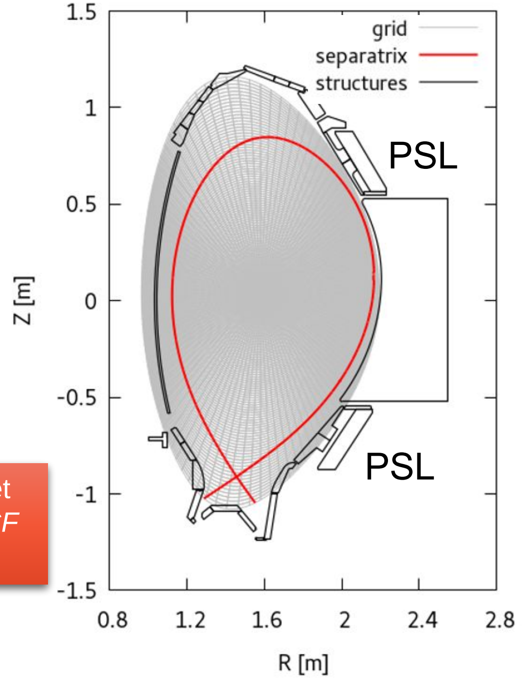




The simulated cases in JOREK

AUG (#39655)

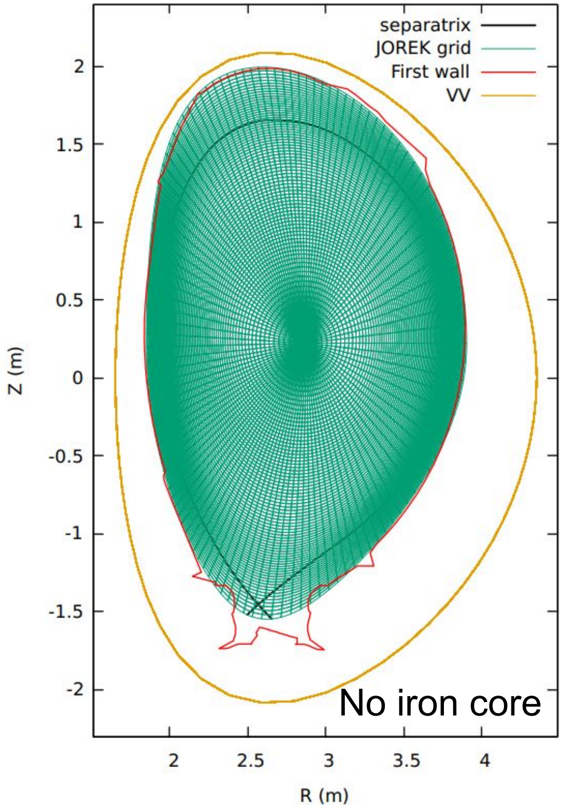
Ohmic – 0.8MA / 2T - $q_{95} = 4$



N Schwarz et al 2023 *PPCF* 65 054003

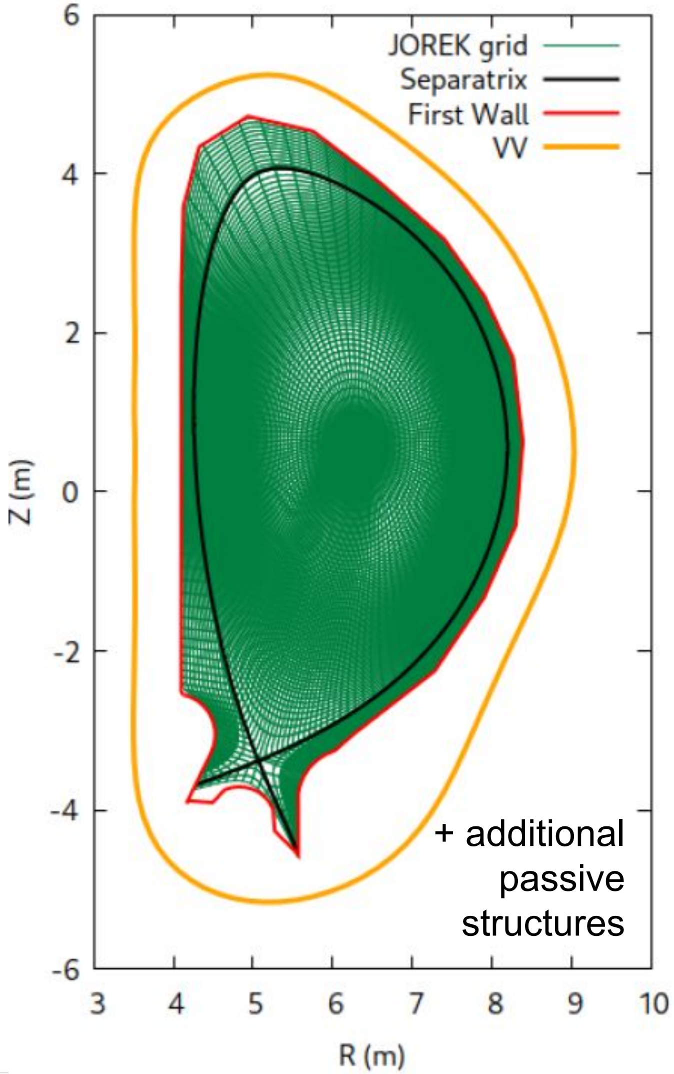
JET (#95110)

Ohmic – 1.1MA / 1.2T - $q_{95} = 3.4$



ITER (H26)

L-mode – 15MA / 5.3T - $q_{95} = 3$



JOREK setup

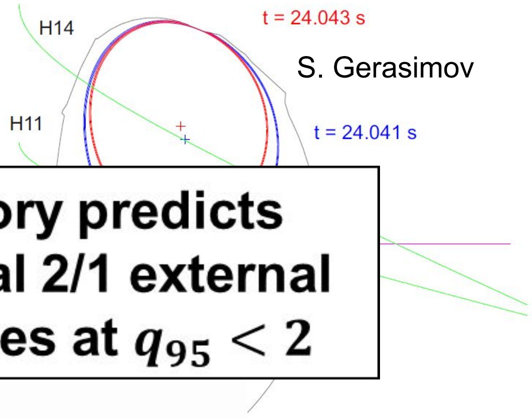
Reduced MHD - single temperature model [F.J. Artola *et al* 2022 *NF* **62** 056023]

+ Spitzer's η & Spitzer-Haerm $\chi_{\parallel}$

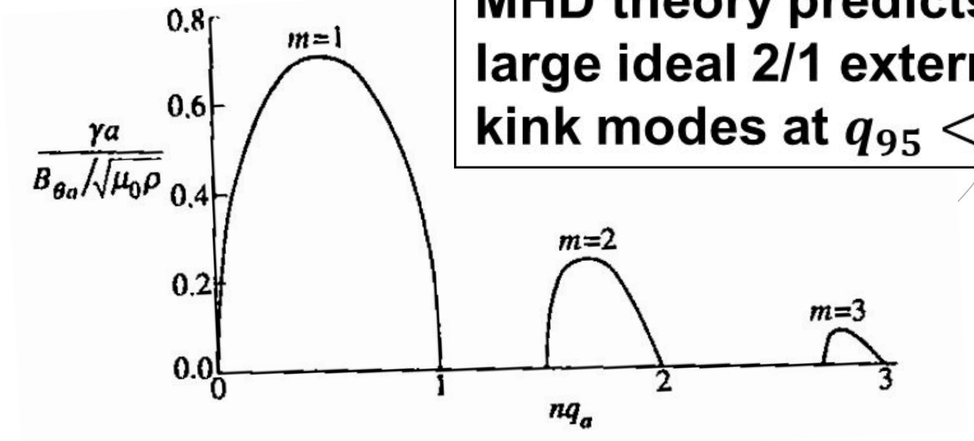
Parameters	**AUG** (N. Schwarz)	**JET** (J. Artola)	**ITER** (J. Artola)
VDE direction	Downwards	Upwards	Upwards
Parallel flows	**No**	Yes	Yes
Toroidal harmonics	0-4	0-5	0-5
	2.5	2	2
	2.5	2	2
	0.9, 0	2, 400	2, 300
Diamagnetic flows	**Yes**	No	No
	30	30	30

JET case: exp. features

In JET, the TQ is triggered at $q_{95} < 1.5$!!

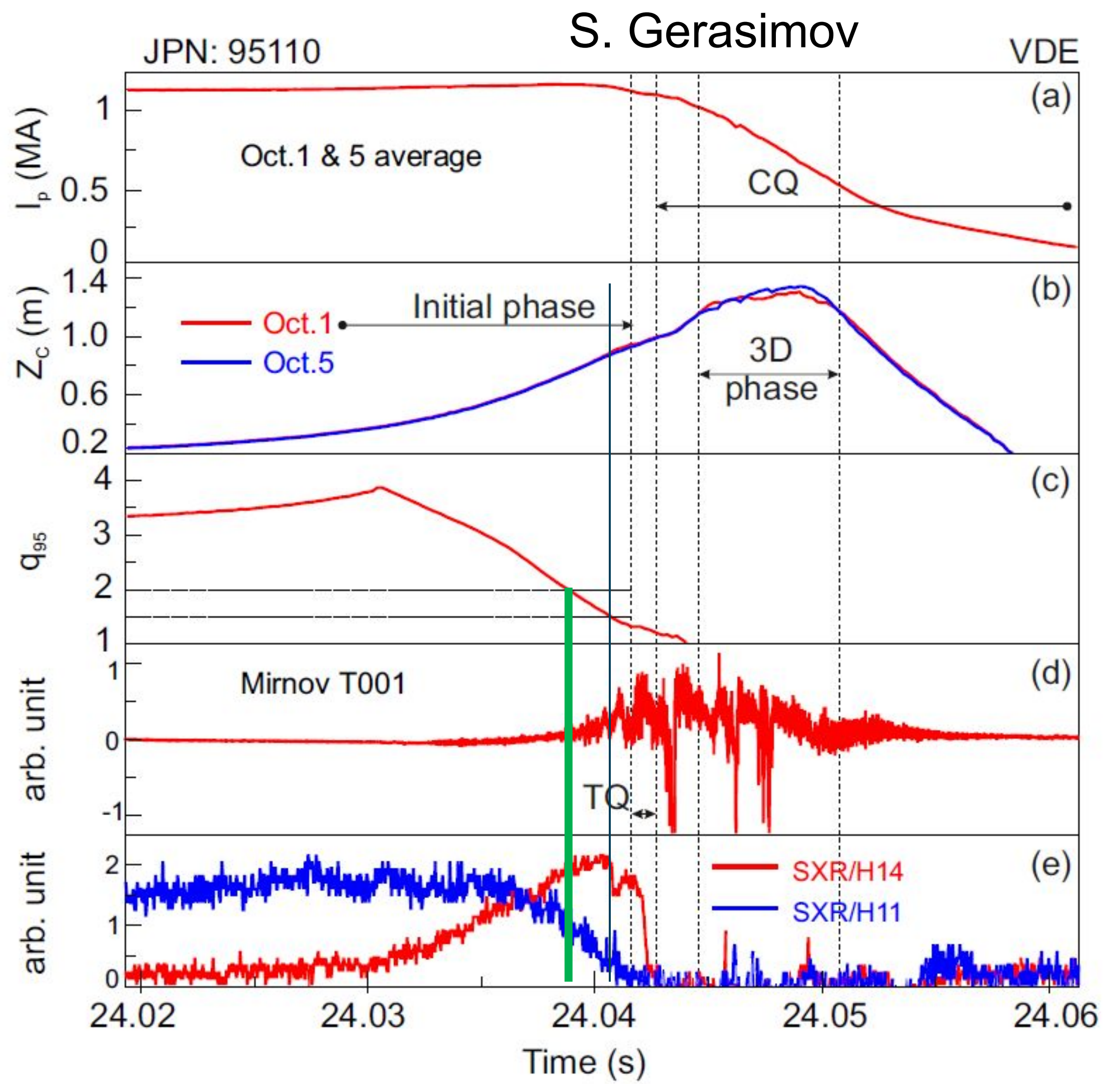


MHD theory predicts large ideal 2/1 external kink modes at $q_{95} < 2$



Shafranov, V.D, Soviet Physics Technical Physics **15** 175 (1970)

Figure from "Tokamaks", Wesson

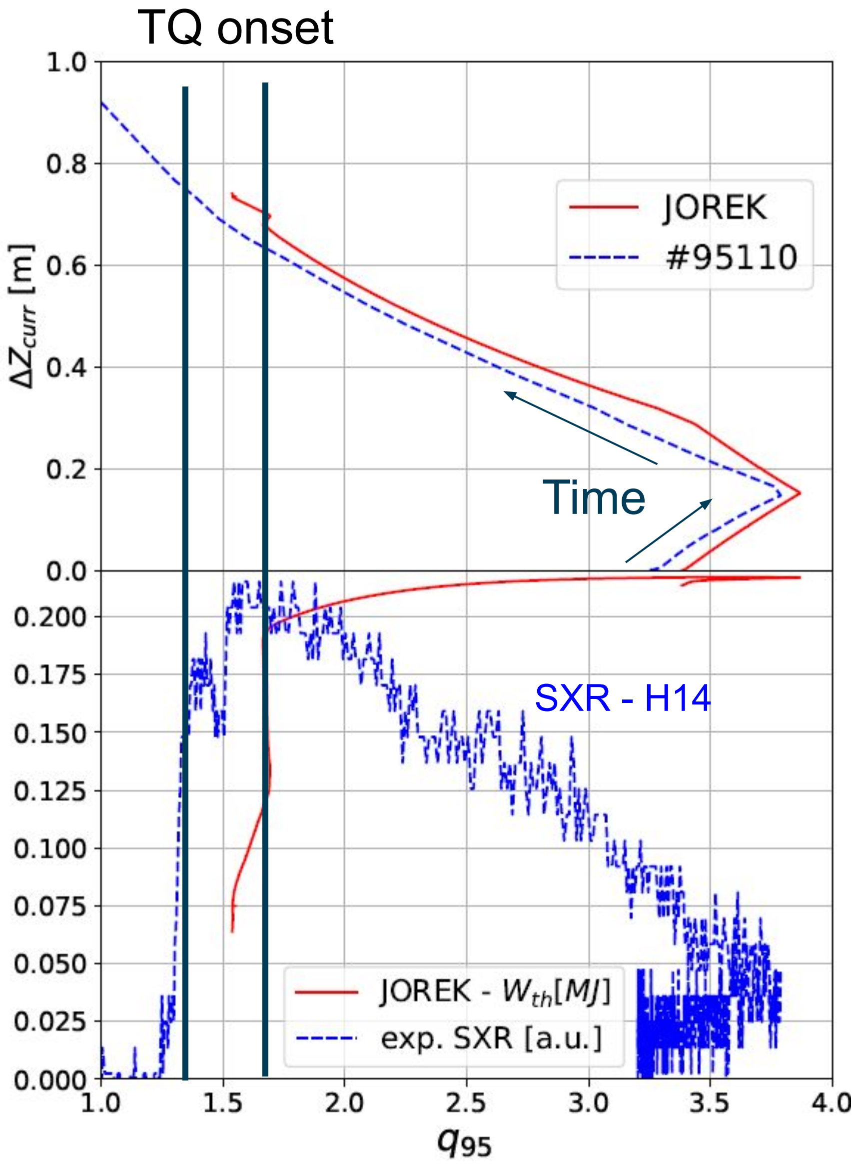


Comparison with JET

- ❑ Experimental reconstruction of current centroid (Z_{curr}) and (q_{95}) are consistent with JOREK simulations

- ❑ Experiment: $q_{95}@\mathrm{TQ}_{\mathrm{onset}} \approx 1.4$

- ❑ JOREK: $q_{95}@\mathrm{TQ}_{\mathrm{onset}} \approx 1.7$



Comparison with JET

TQ duration

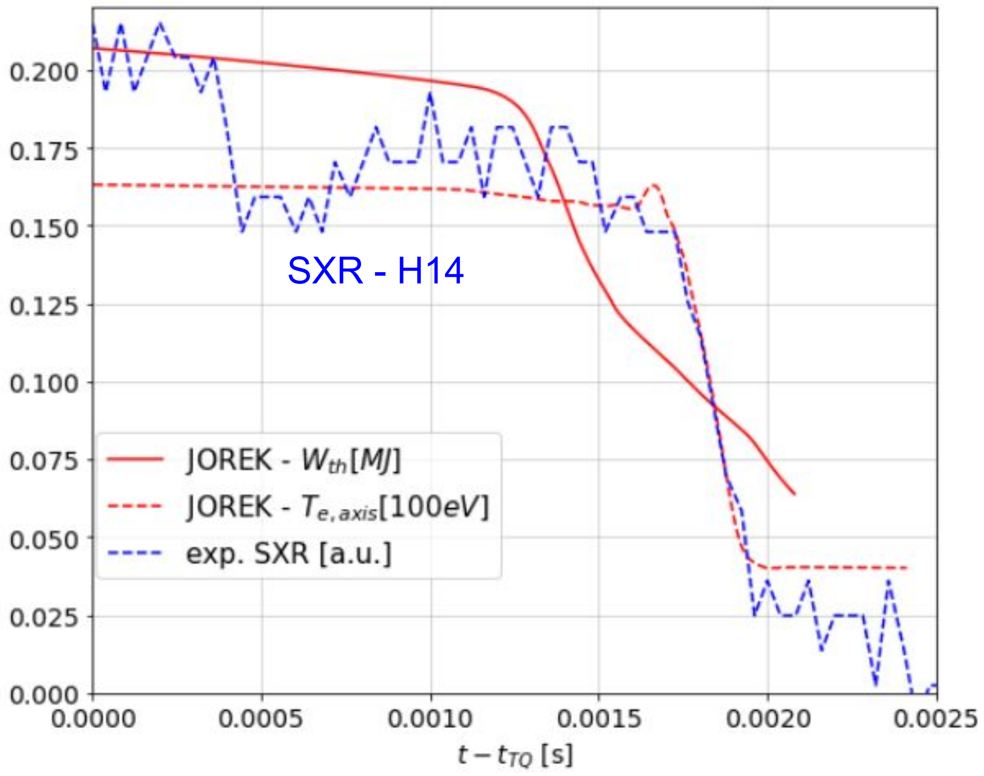
- Experiment: $\tau_{\mathrm{SXR}}^{30-90\%} \approx 0.32$ ms

- JOREK:

  - $\tau_{\mathrm{T}_{e,\mathrm{axis}}}^{30-90\%} \approx 0.28$ ms

  - $\tau_{\mathrm{W_{th}}}^{30-90\%} \approx 1.31$ ms

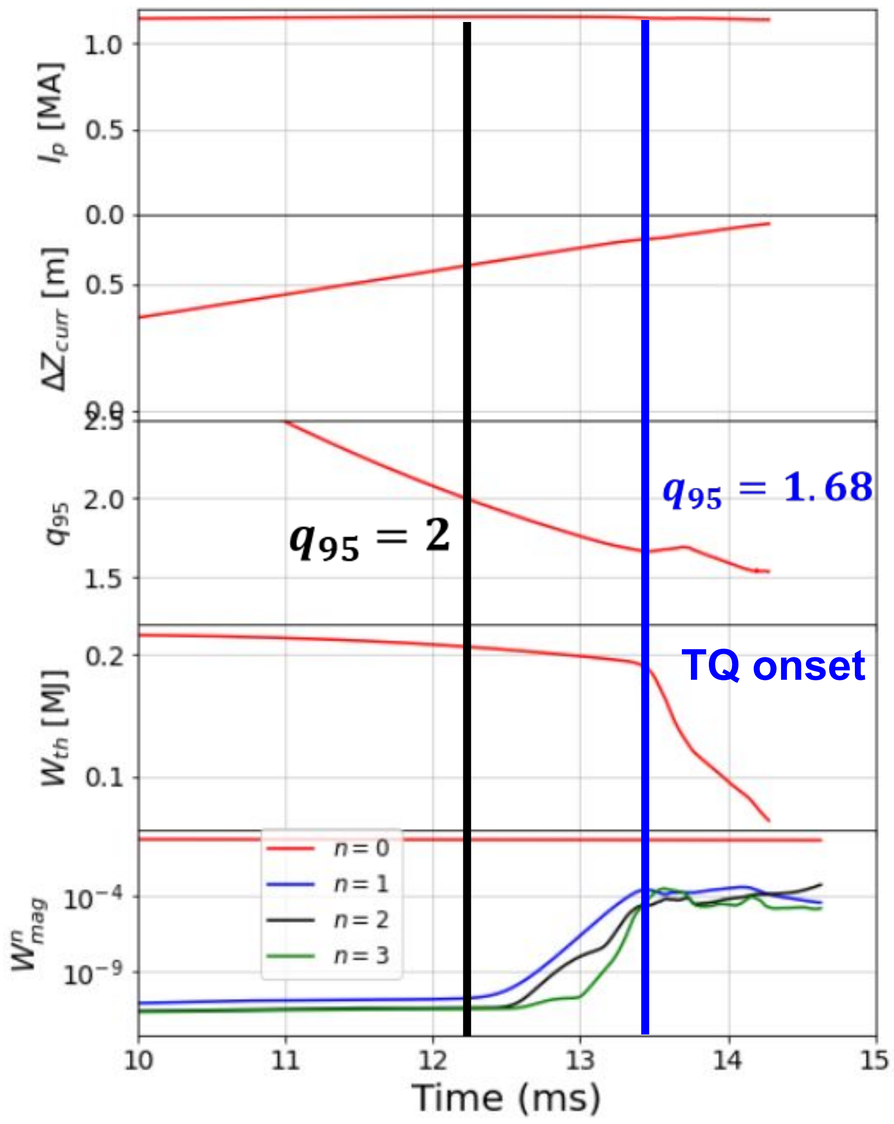
Global energy decays much slower than central temperature?



iter

JET simulations

- Equilibrium evolves significantly during the linear growth phase



The initialization problem

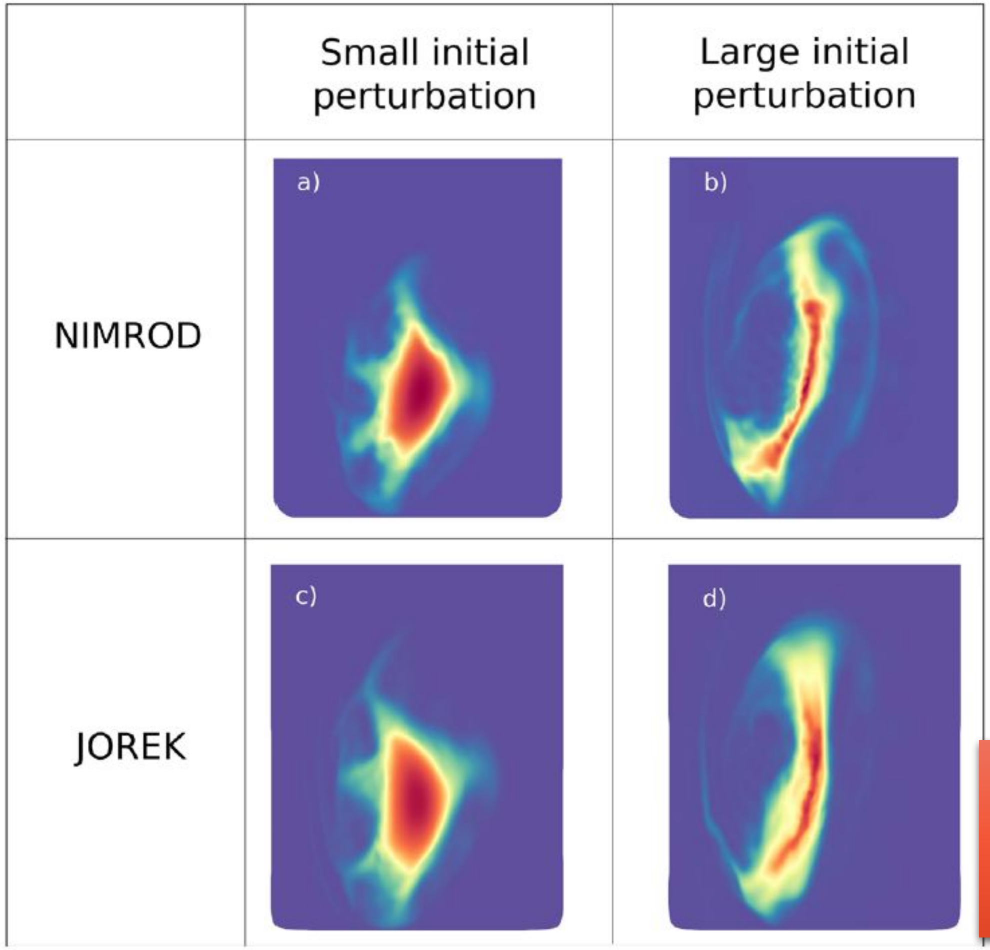
VDE induced TQ in NSTX

- MHD codes initialize $n \neq 0$ modes with an **arbitrary perturbation**

- **If**

  Time to reach saturation ~ Timescale for equilibrium evolution

  → **Initial perturbation changes TQ dynamics**

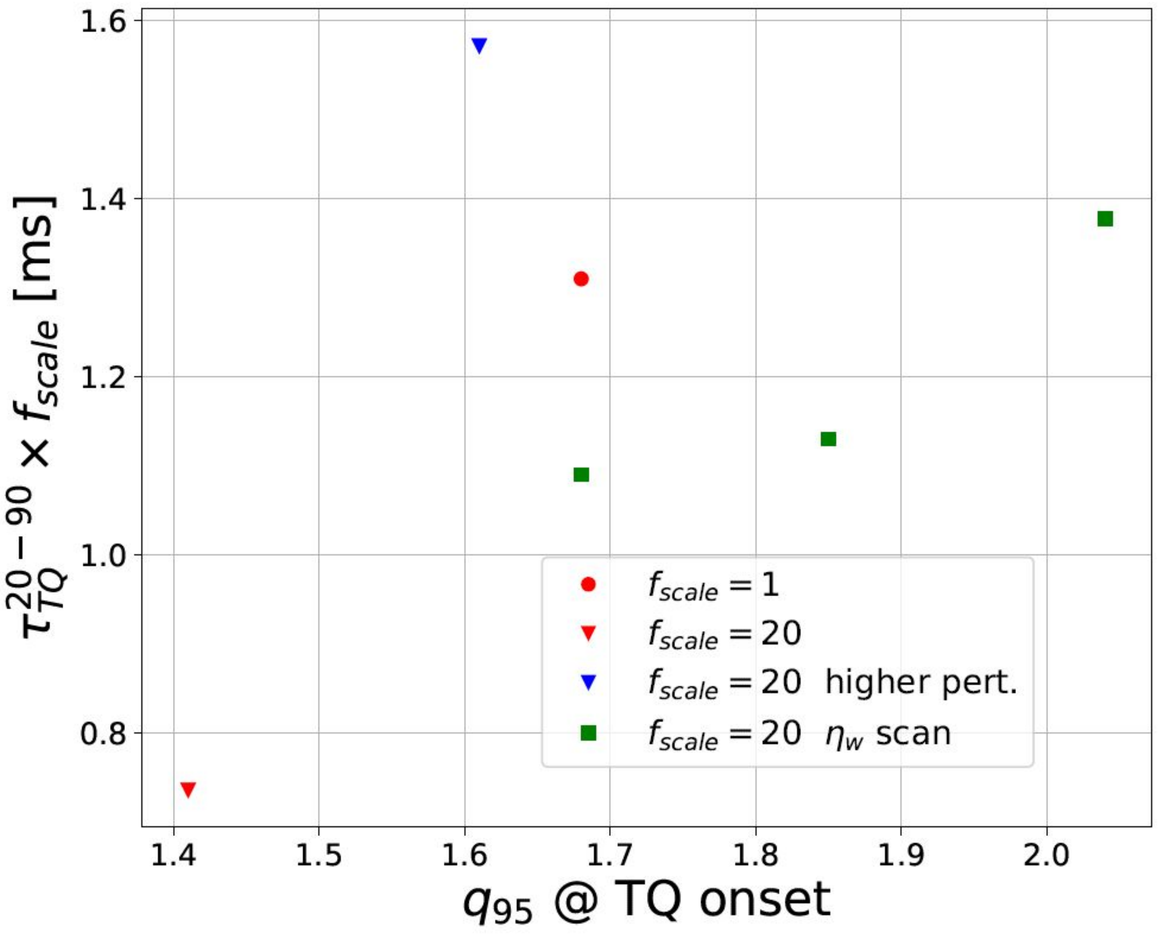


Artola, F.J., C. Sovinec, S. Jardin et al, Phys. Plasmas **28**, 052511 (2021)

How does τ_{TQ} depend on q_{95}?

- Changing q_{95} by
  - Modifying amplitude of initial $n \neq 0$ perturbation
  - Scaling wall resistivity (η_w) (to slow down VDE)
- Tendency of faster TQ with lower q_{95}
- See next slides for f_{scale}

JET simulations



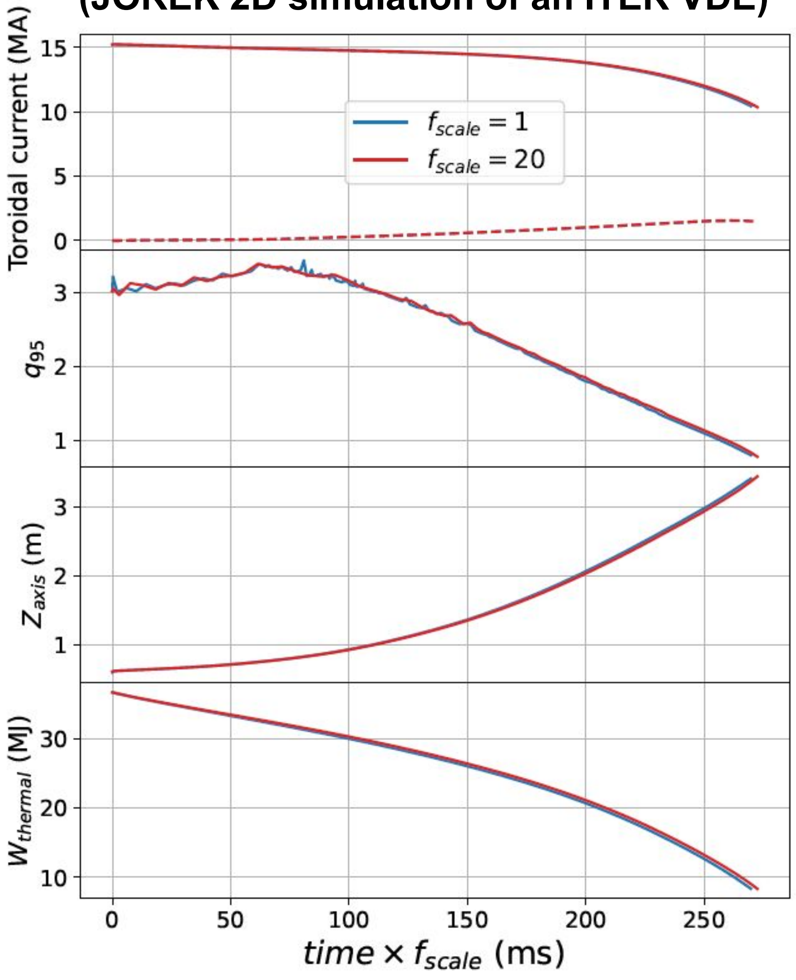
Re-scaling technique

- Time step typically constrained by Alfvén time ($\sim 1\mu s$)
- **VDE time scales can be rather long** (~500 ms in ITER)
- **Re-scaling technique to approach τ_{VDE} to τ_{Alfven}**
  - By ignoring inertia (and viscosity)
    MHD equations are invariant under the transformation

$$t \to \tilde{t}\, f_{\text{scale}}$$
$$\mathbf{v} \to \tilde{\mathbf{v}}\, / f_{\text{scale}}$$
$$D \to \tilde{D}\, / f_{\text{scale}}$$
$$\chi \to \tilde{\chi} / f_{scale}$$
$$\eta \to \tilde{\eta} / f_{scale}$$
$$\eta_w \to \tilde{\eta}_w\, / f_{\text{scale}}$$

$$\tau_{\text{VDE}} = \tau_{VDE}^{\text{real}} / f_{\text{scale}}$$

Keep identical dynamics for 2D VDEs (JOREK 2D simulation of an ITER VDE)

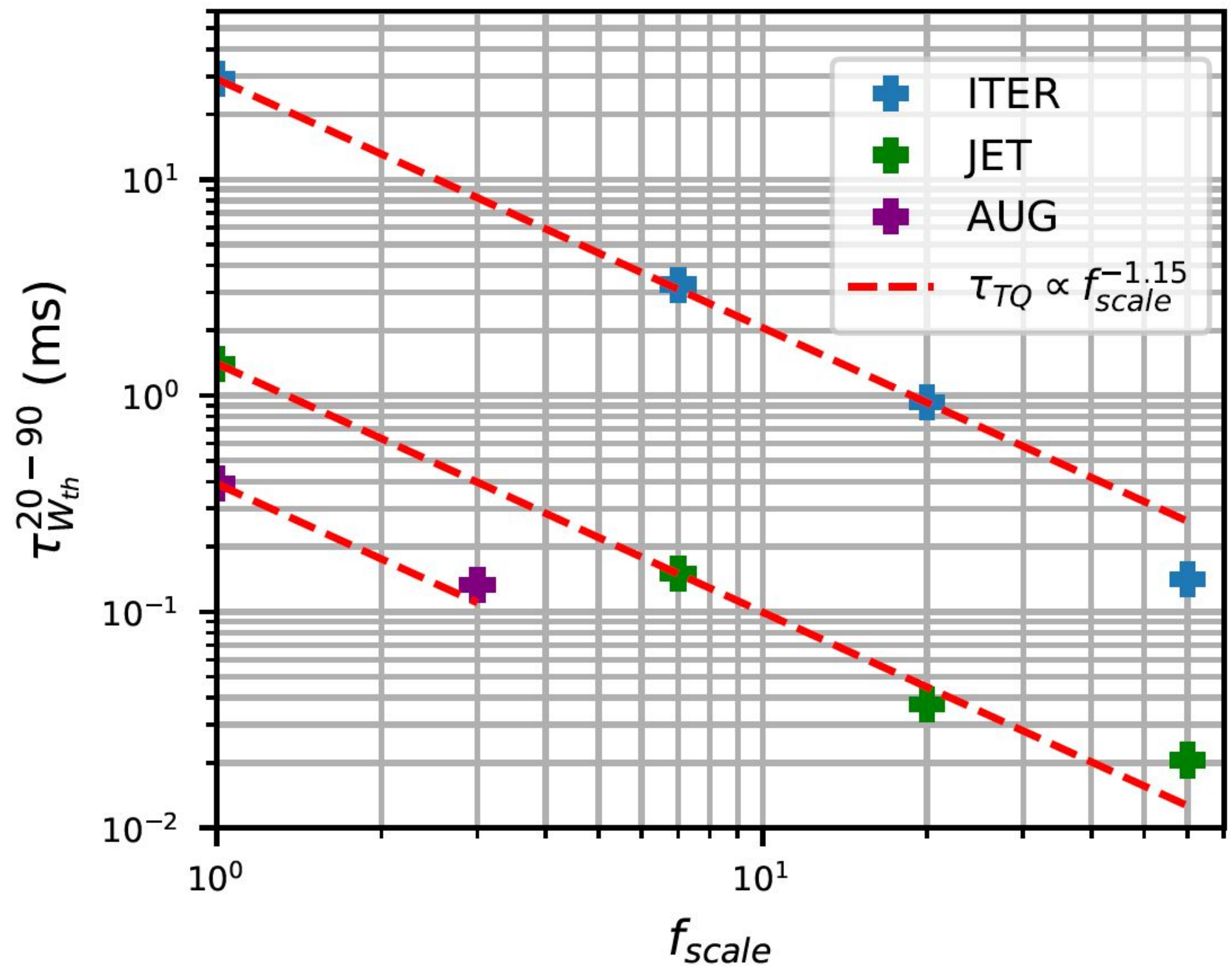


- Useful to study the TQ duration at reduced cost?

Comparing the AUG, JET and ITER TQ

The TQ duration

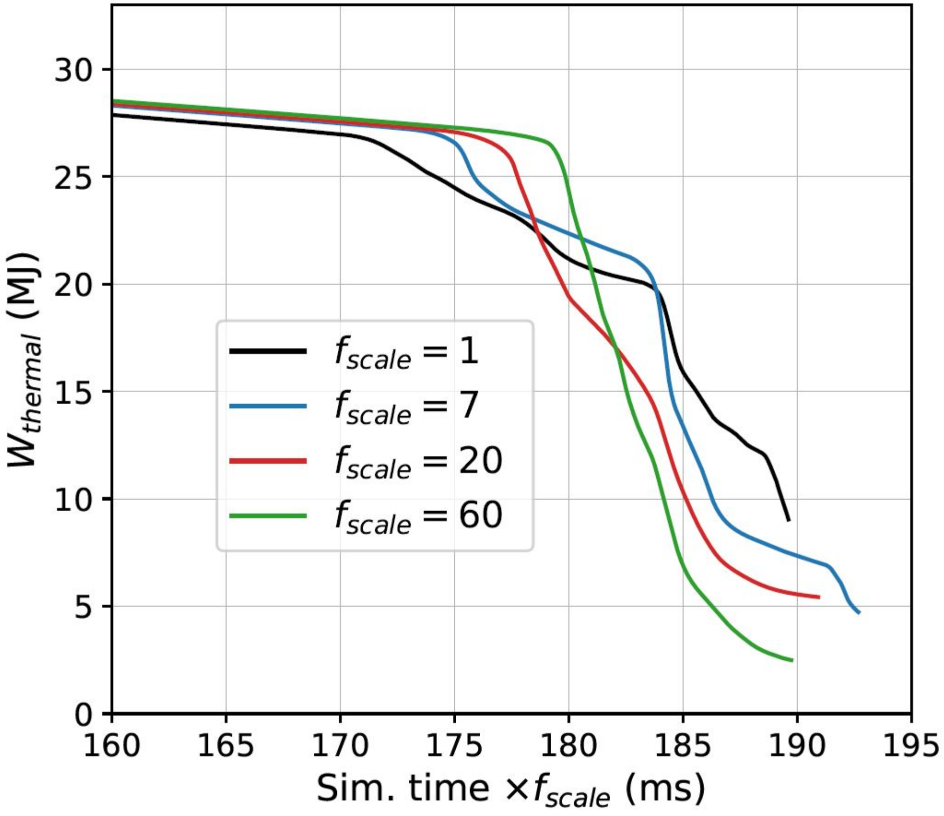
- ❑ Important difference with machine size
- ❑ Duration in ITER is an order of magnitude larger than in JET!
- ❑ Re-scaling technique performs well for duration envelope at $f_{scale} \leq 20$



Dynamics differ with scaling technique

- Single step TQ at high f_{scale}
- Two step TQ at realistic values
- Difficulties to define τ_{TQ}

ITER case

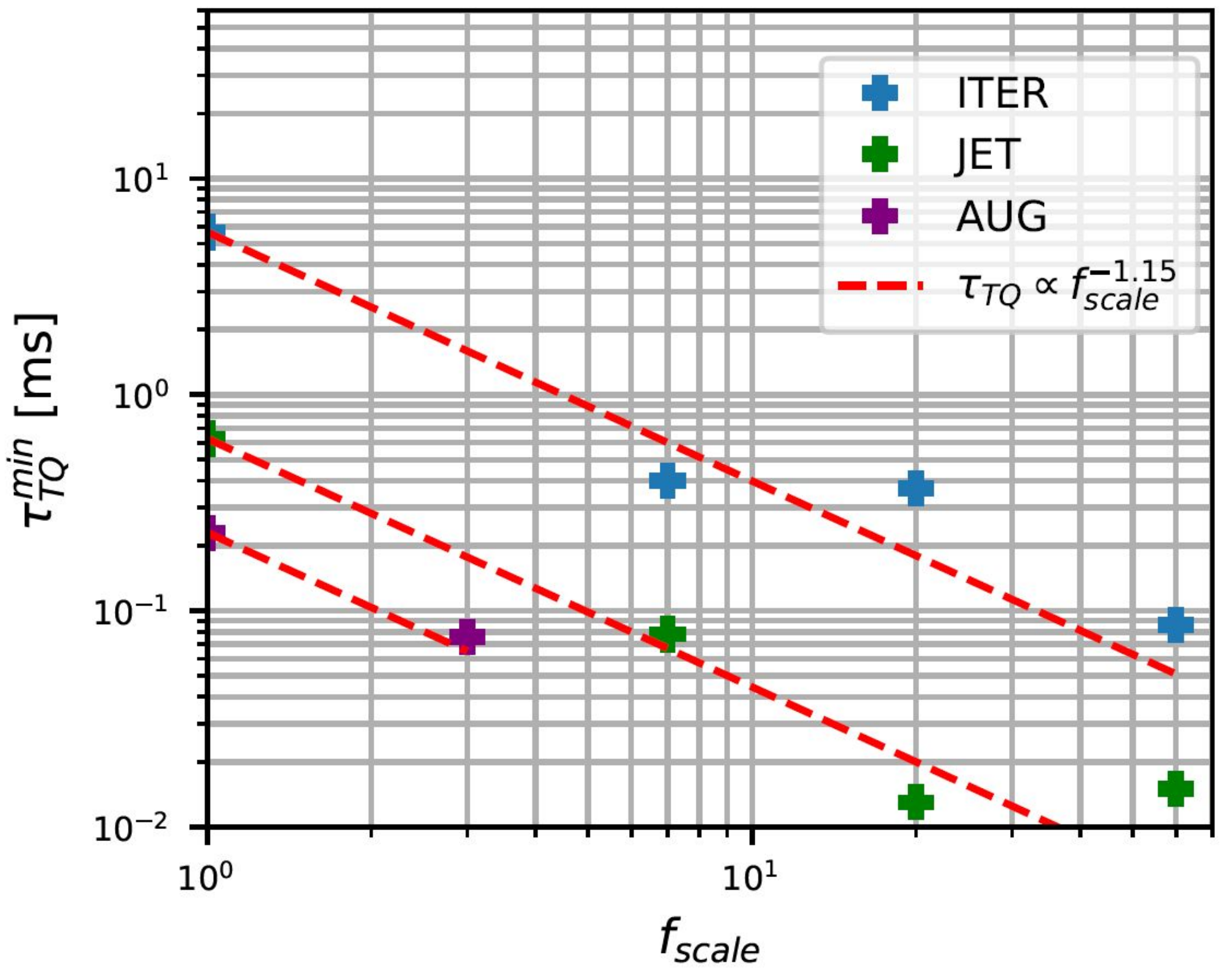


Minimum TQ duration

- Defined as

$$\tau_{TQ}^{\min} = \frac{w_{th}\left(t_{TQ}^{\text{onset}}\right)}{\left|\frac{dW_{th}}{dt}\right|_{\max}}$$

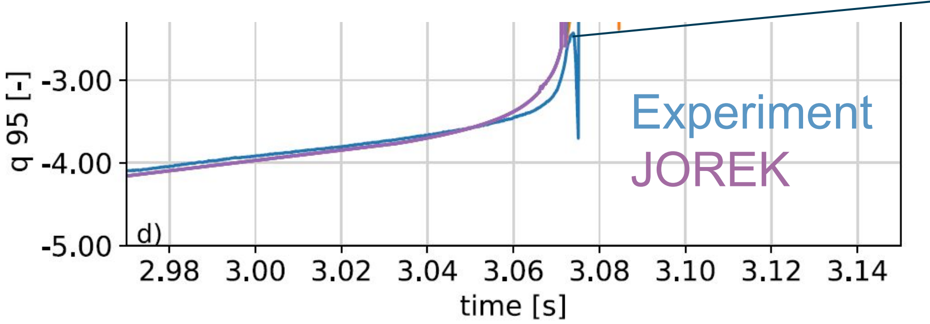
- Optimistic predictions for ITER, $\tau_{TQ} > 5$ ms



The TQ is triggered at different q_{95} for the studied cases

$$f_{scale} = 1$$

Parameters	AUG	JET	ITER
	4	3.4	3
	2.8	2.1	2.0
	2.6 (consistent with experiments)	1.7 (experiments show 1.4)	1.97



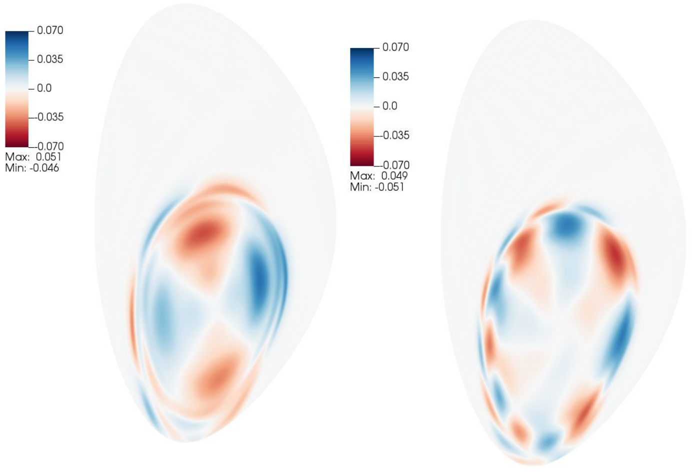
Equilibrium reconstruction fails at expected TQ time

N Schwarz et al 2023
PPCF 65 054003

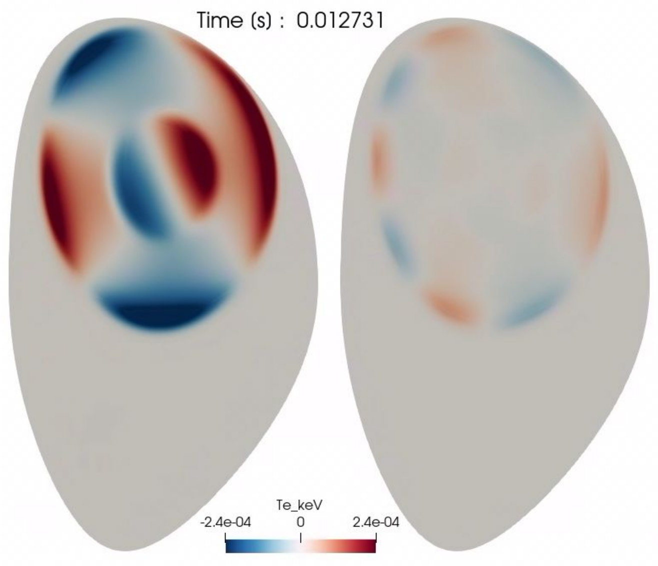
Nature of the modes depends on q_{95}

Parameters	AUG	JET	ITER
	2.8	2.1	2.0
	2.6 (consistent with experiments)	1.7 (experiments show 1.4)	1.97

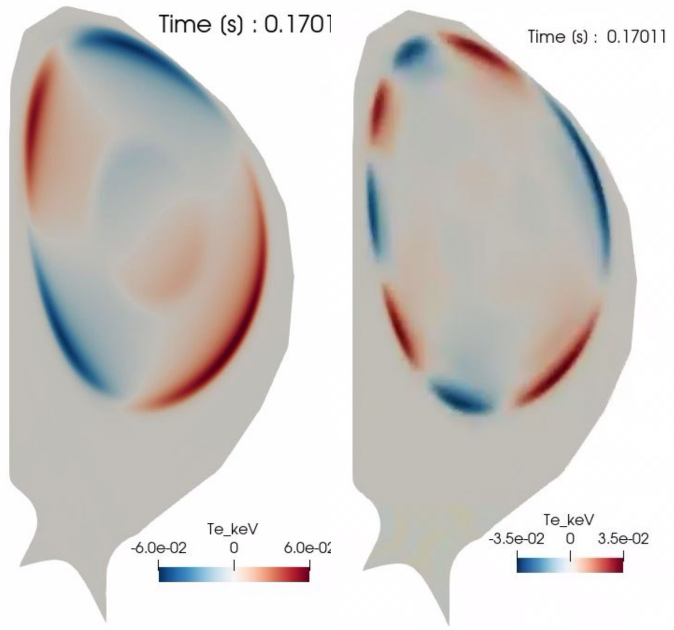
Internal 2/1 mode
+ external 3/1 & 5/2



External 2/1 and 4/2 modes + internal 1/1



External 2/1 and 4/2 modes + internal 1/1

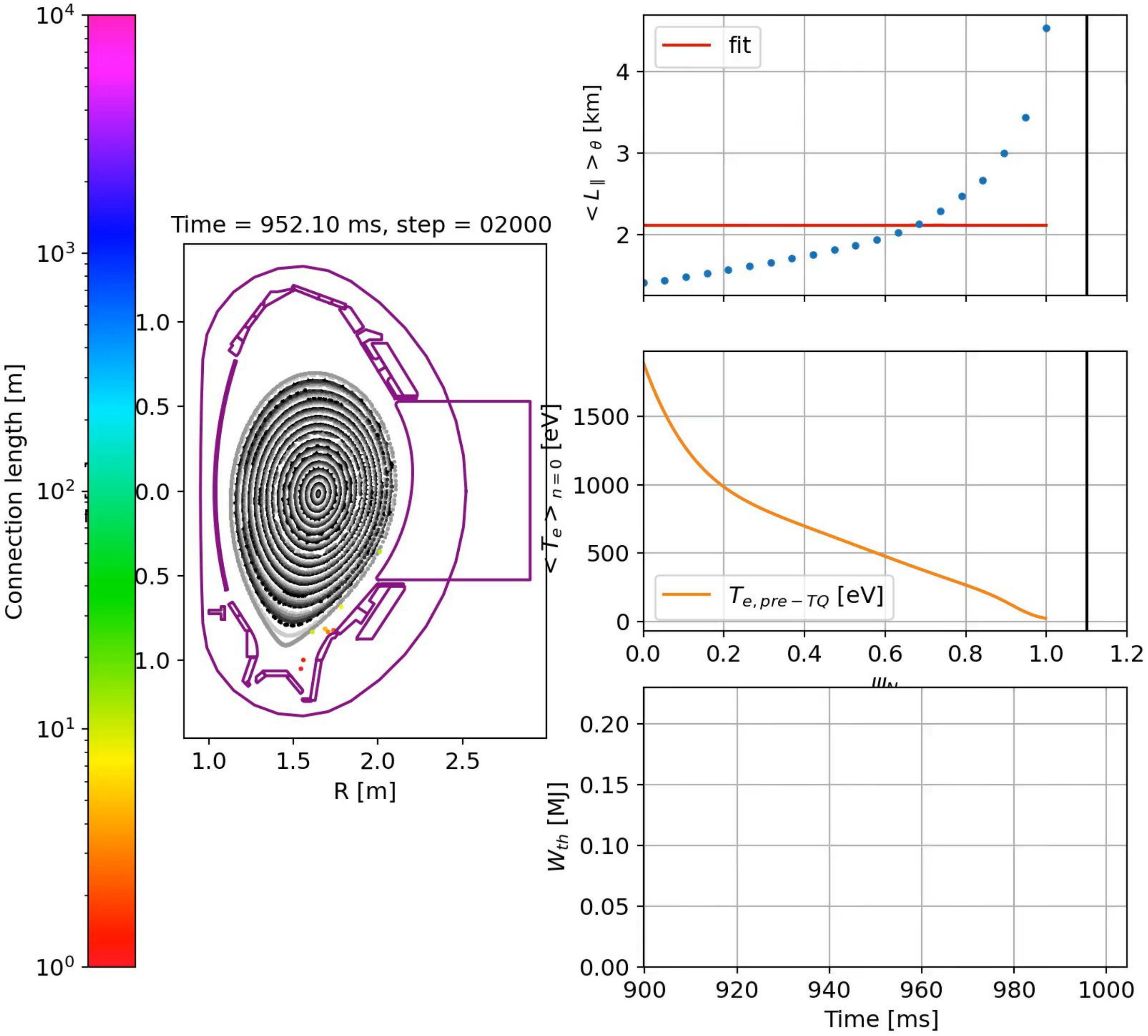


The AUG TQ

Poincare plots

1. Initial W_{th} loss → Stochastic regions with short $L_{\|}$ localized at plasma edge

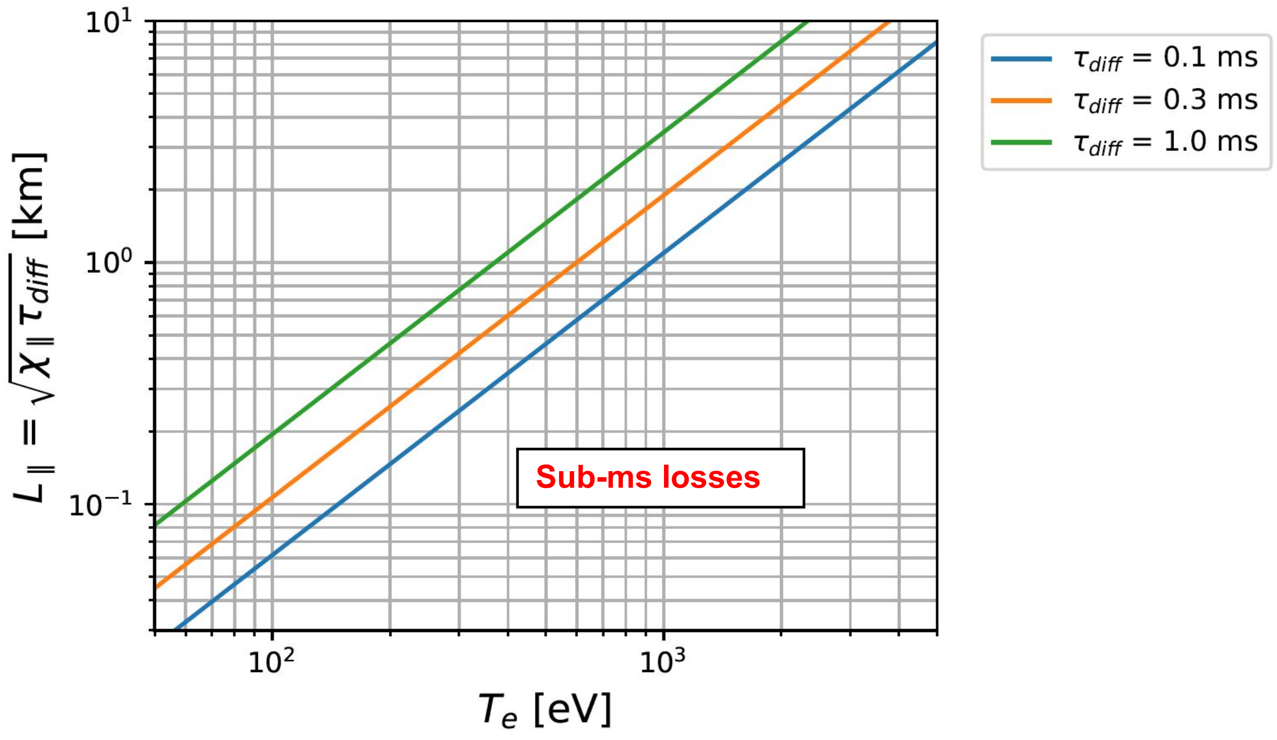
2. Quick stochastization of the full cross section and short connection length (100-1000 m)



Connection length and parallel transport

- ❑ A connection length ~ 1 km leads to sub-ms losses at $T_e > 400$ eV

- ❑ T_e stops fast decay at ~200 eV for AUG $L_{\parallel}$



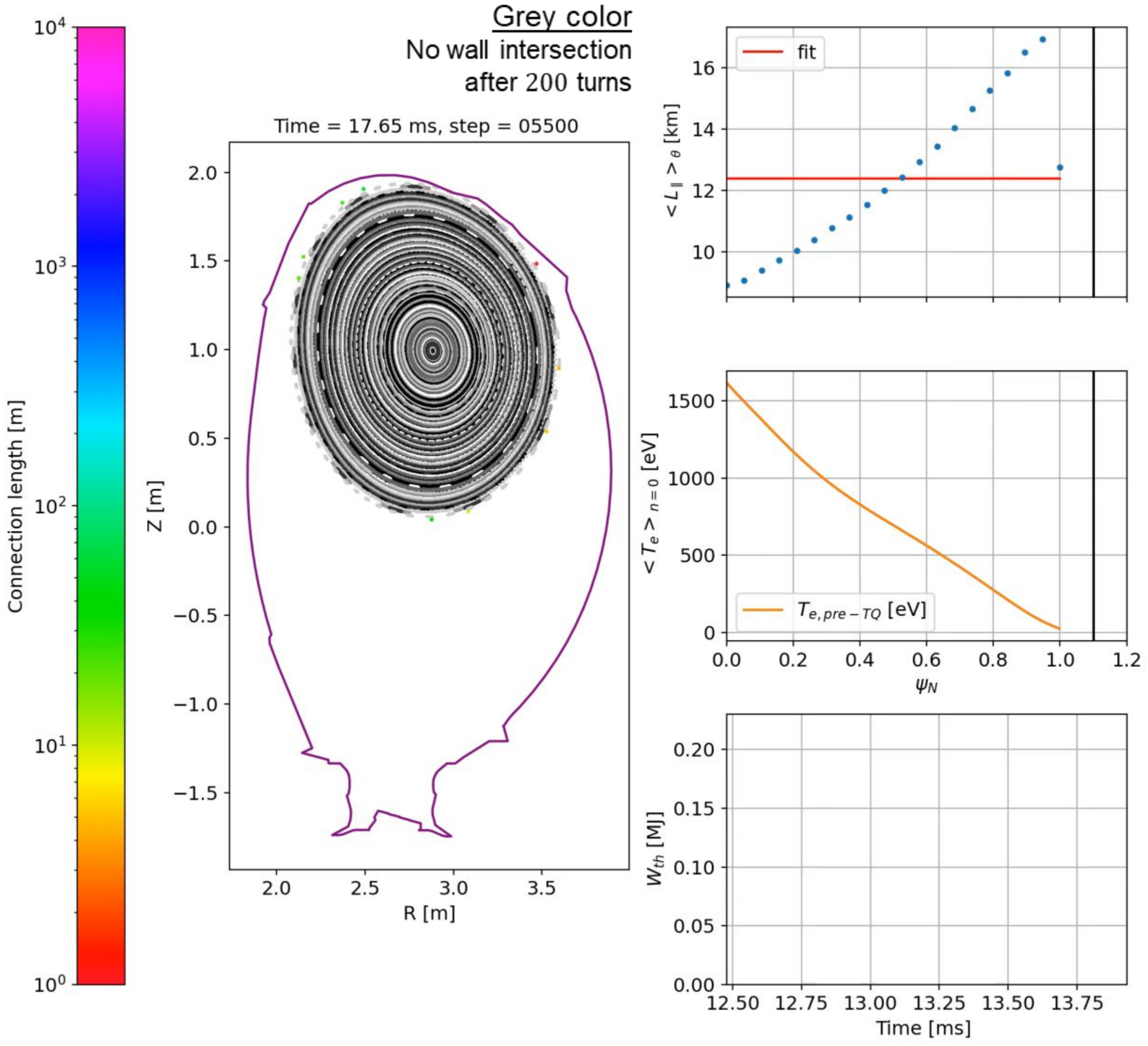
The JET TQ

Poincare plots

1. Initial W_{th} loss → Stochastic regions with low $L_{\|}$ localized at plasma edge

2. Penetration of stochastic front up to q=1 surface

3. Internal 1/1 kink mode reconnection and final energy loss



The ITER TQ

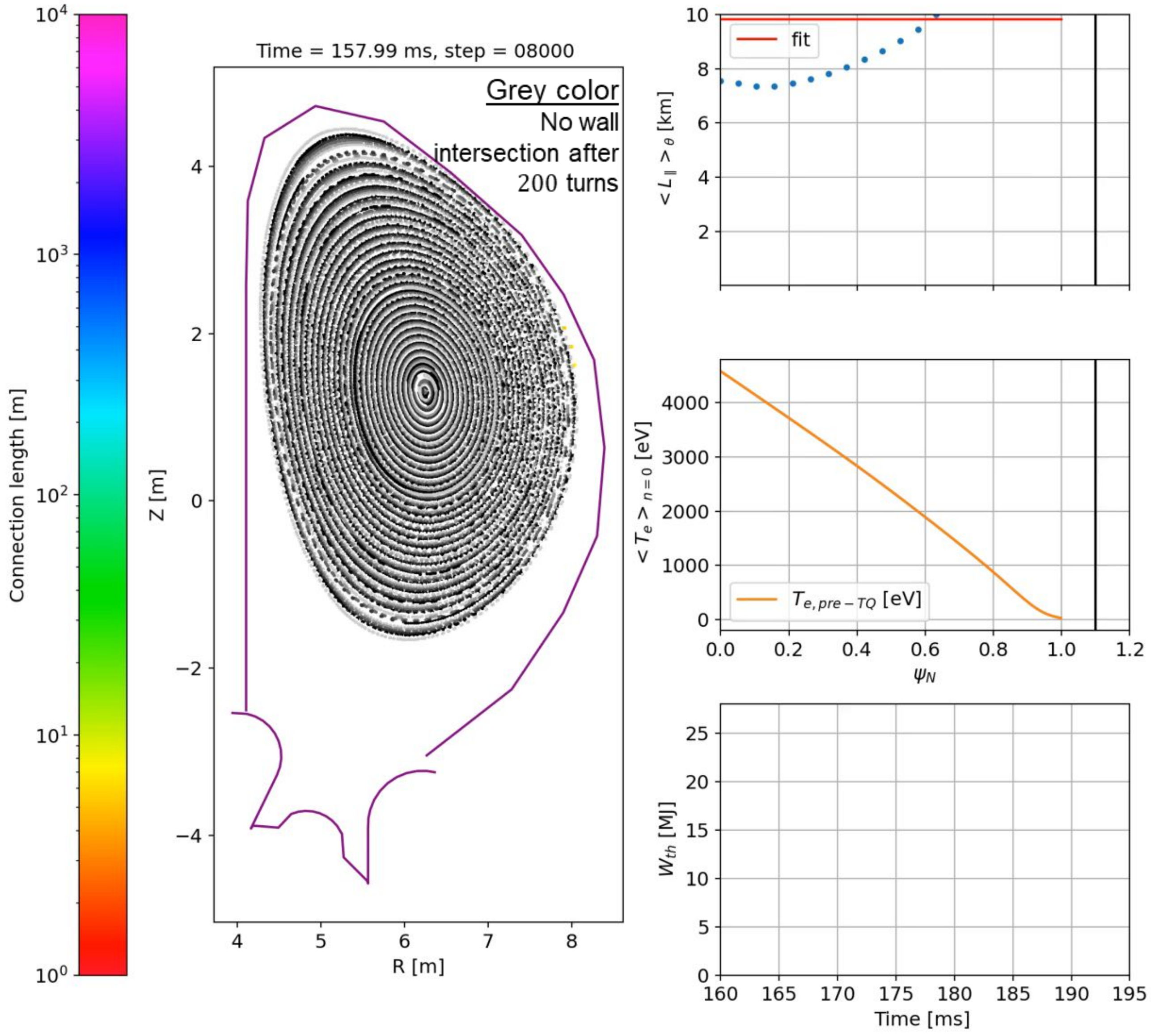
Poincare plots

1. Initial W_{th} loss → Stochastic regions with low $L_{\parallel}$ localized at plasma edge

2. Field line mixing at mid-radius transports energy towards the edge, (but $L_{\parallel} > 10$ km)

3. W_{th} loss acceleration → 1/1 kink flattens T_e profile and transports energy to the edge

4. Stochastic region spreads + convective loss

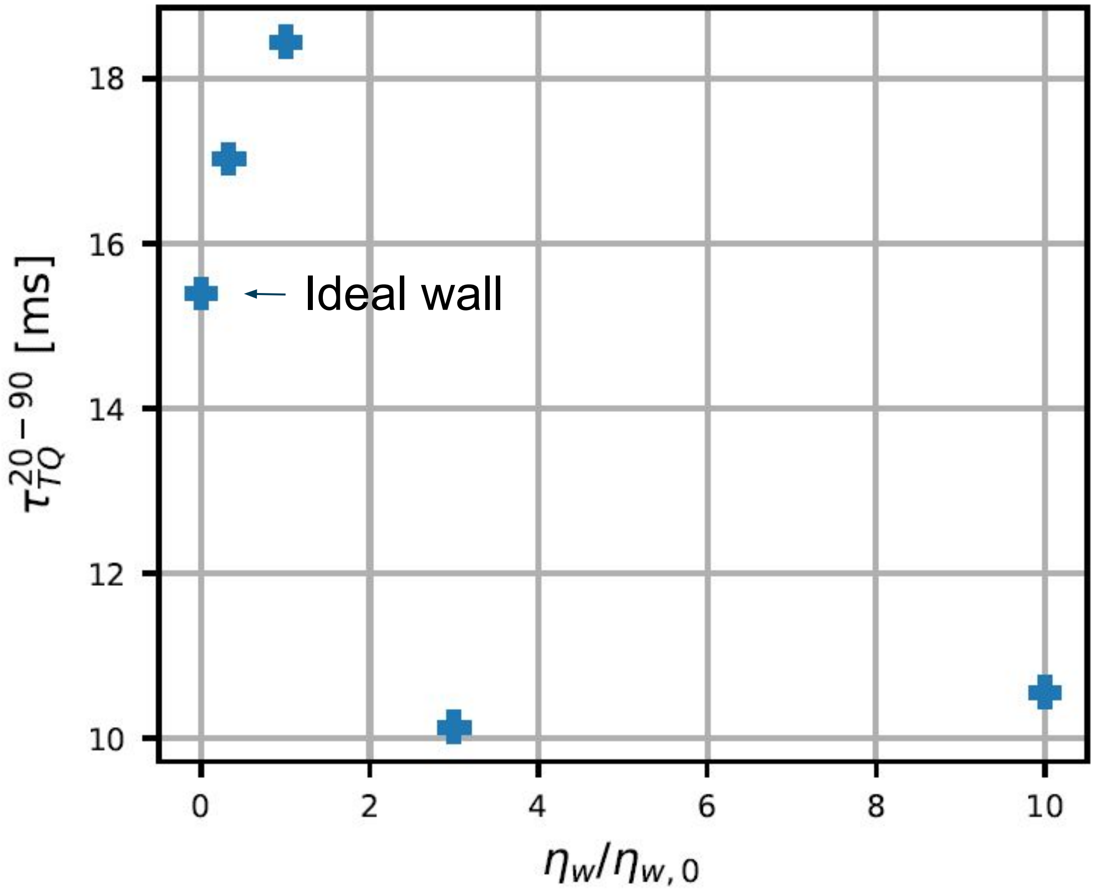


Scans for ITER and JET

Influence of wall resistivity

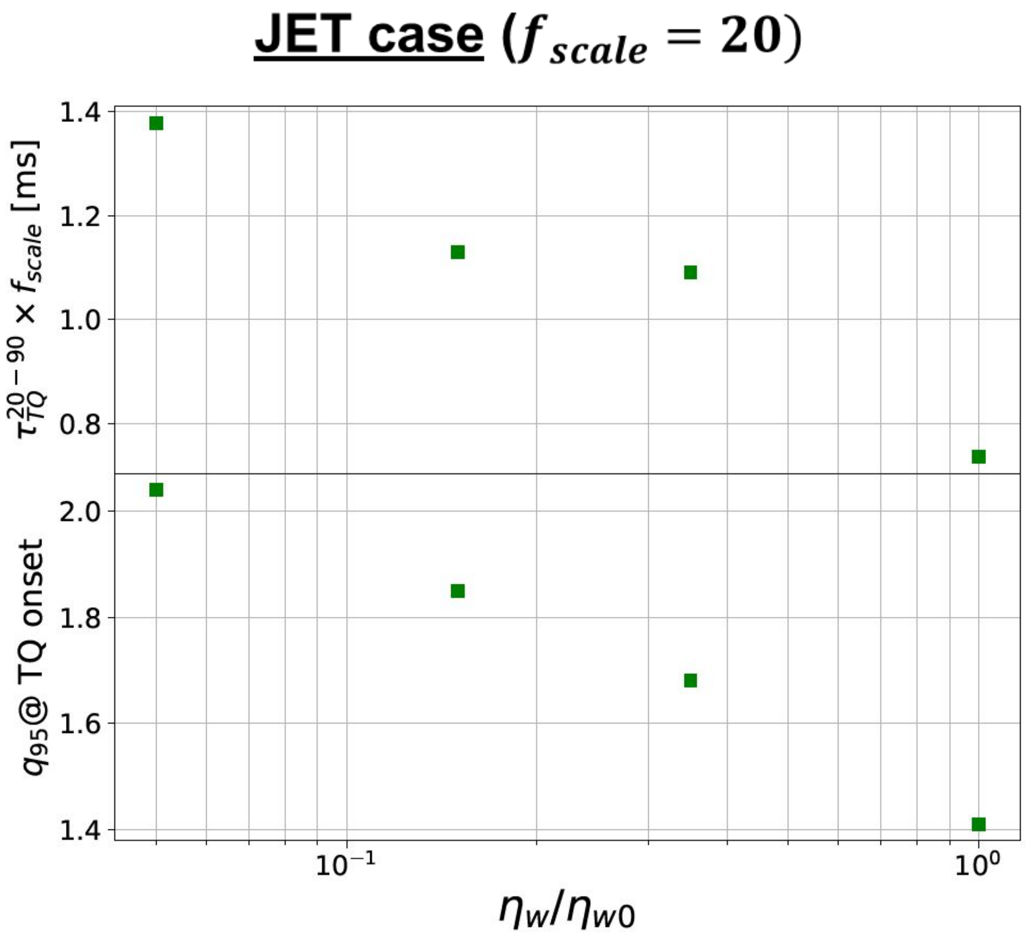
- **Changing wall resistivity at TQ onset**
  - Weak dependence (< 2 factor difference for variations of a factor 30)

ITER case ($f_{scale} = 20$)



Influence of wall resistivity

- ❑ **Changing wall resistivity at TQ onset**
  - ➢ Weak dependence (< 2 factor difference for variations of a factor 30)
  - ➢ In JET the wall time affects q_{95} @ TQ onset
  - ➢ **VDE-TQ is not driven by RWM**



Influence of plasma size

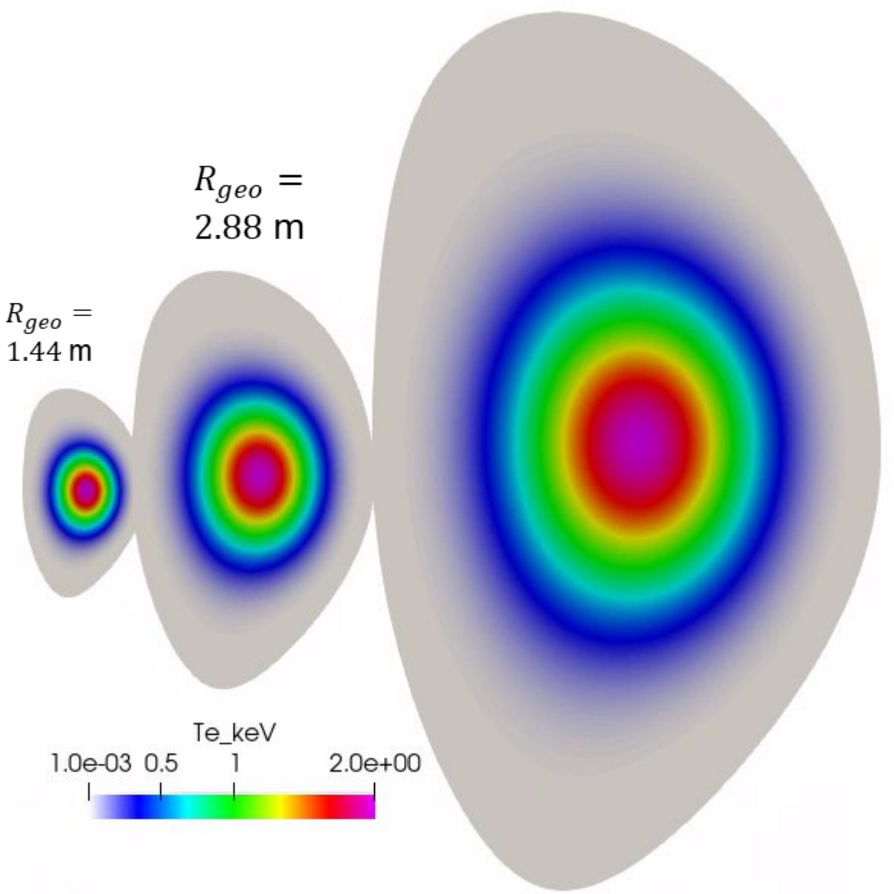
Re-scaling the JET equilibrium size

- **Identical magnetic equilibrium**
  $(\beta, q, \kappa, \epsilon)$

- **Identical local quantities**
  $(T, J_\phi, \eta, \eta_w, \chi_{\perp/\parallel}, D_{\perp/\parallel}, \nu_{\perp/\parallel}, \mathrm{v}_{\mathrm{Alfvén}})$

  except n, p and B_ϕ

- **Some global quantities must change**
  $(\mathrm{a}, \mathrm{R}, I_p, W_{th})$



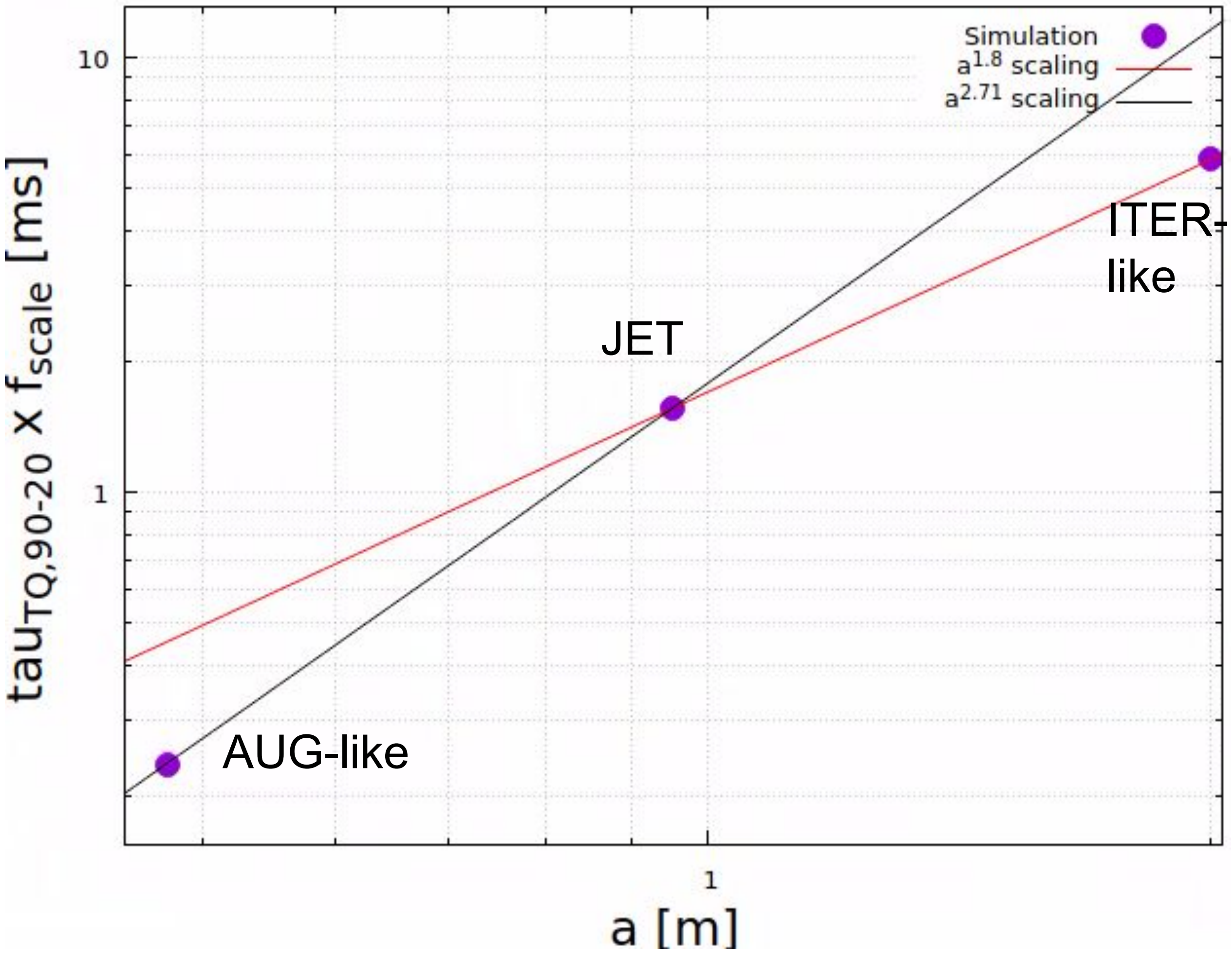
Influence of plasma size

Re-scaling the JET equilibrium size

The TQ duration strongly depends on the plasma size ($\tau_{TQ} \propto a^{1.8-2.7}$)

From this analysis, a factor of ~4 difference is expected between ITER and JET

$$f_{scale} = 20$$

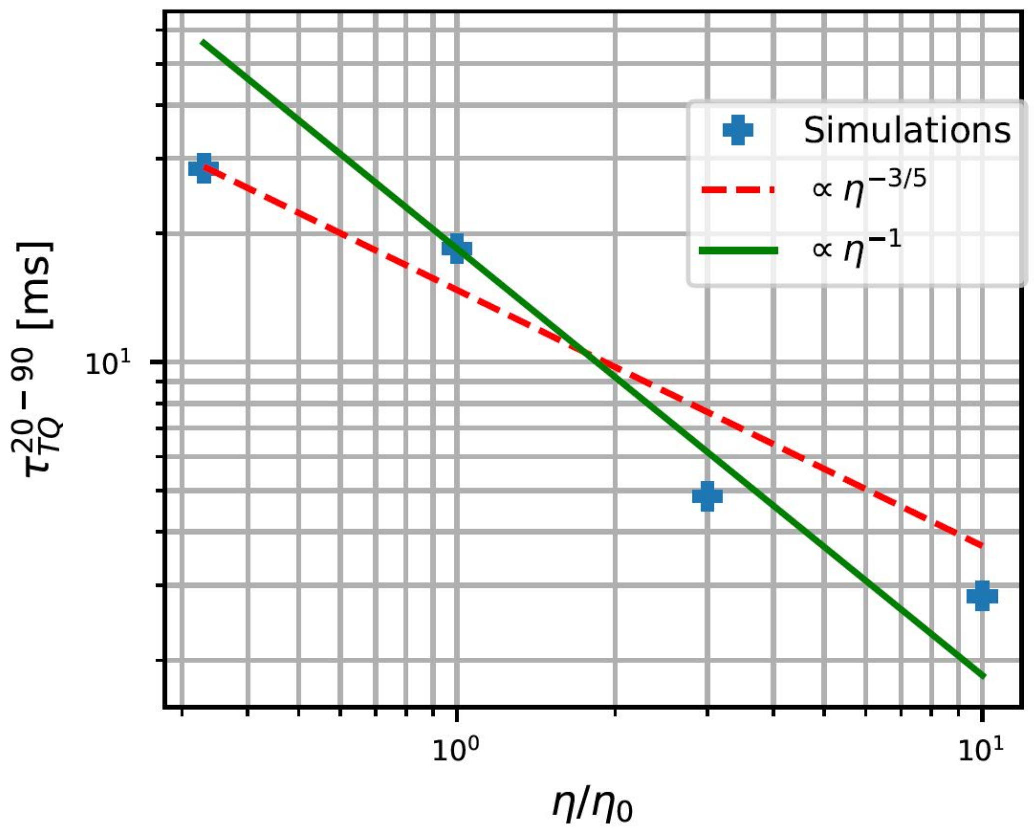


Influence of plasma resistivity

❑ **Changing η at mode growth**

- ➢ ITER scans show a strong dependence on η

ITER case $(f_{scale} = 20)$



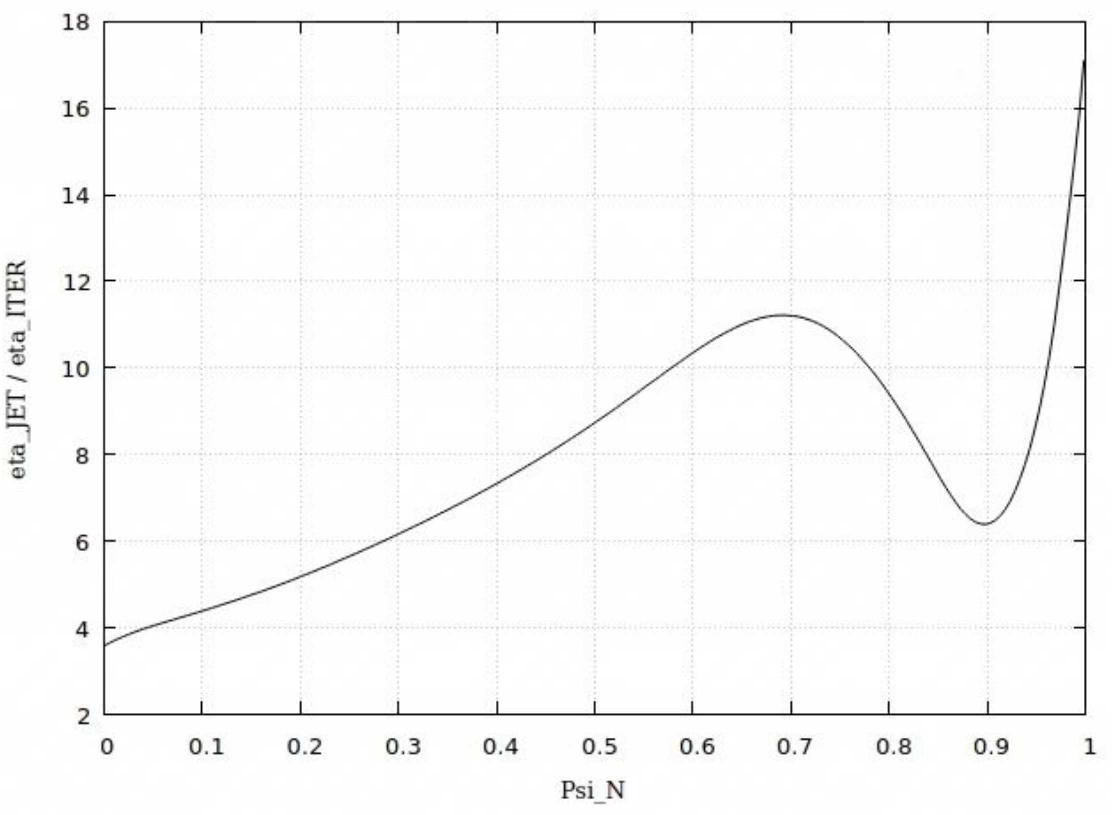
Influence of plasma resistivity

JET's lower temperature profile
→ larger η than ITER

From η difference alone & assuming a $\eta^{-3/5}$ scaling, we would expect

$$\tau_{TQ}^{\text{ITER}} > 3\,\tau_{TQ}^{JET}$$

η profiles before TQ onset



Can the size and η effect explain the difference between ITER and JET?

If $\tau_{TQ} \propto a^2 \ \eta^{-3/5}$

$$\frac{\tau_{TQ}^{ITER}}{\tau_{TQ}^{JET}} \sim 12$$

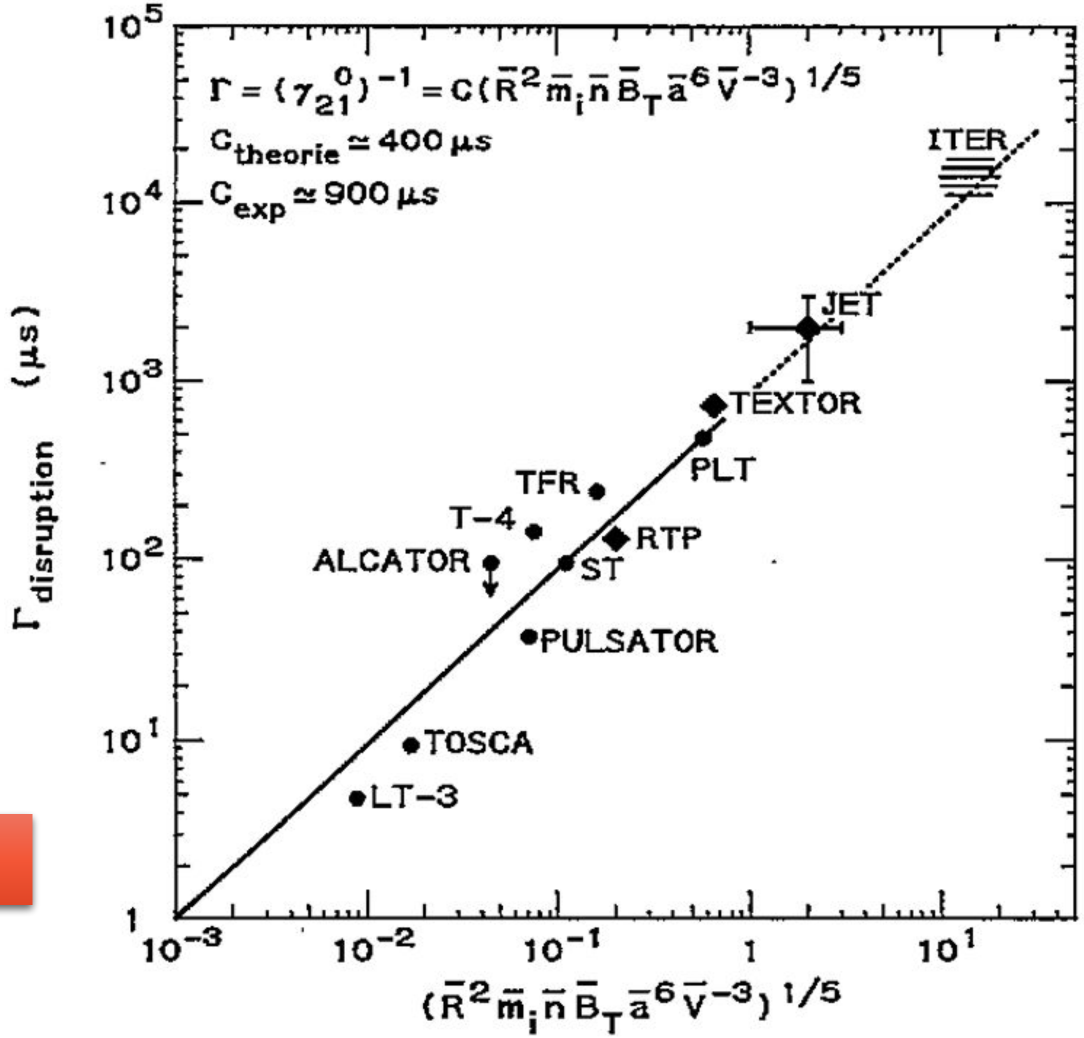
which could explain the order of magnitude difference

The tearing mode scaling

Time scale based on non-linear interaction of 2/1, 3/2, 1/1 islands

$$\tau_{2/1} = \left(\tau_R^3\, \tau_{A,\theta}^2\right)^{1/5}$$

Callen, J.D., Waddell, B.V., Carreras, PPCF (Proc. 7th Int. Conf. Innsbruck, 1978)



F C Schuller 1995 Plasma Phys. Control. Fusion 37 A135

The tearing mode scaling

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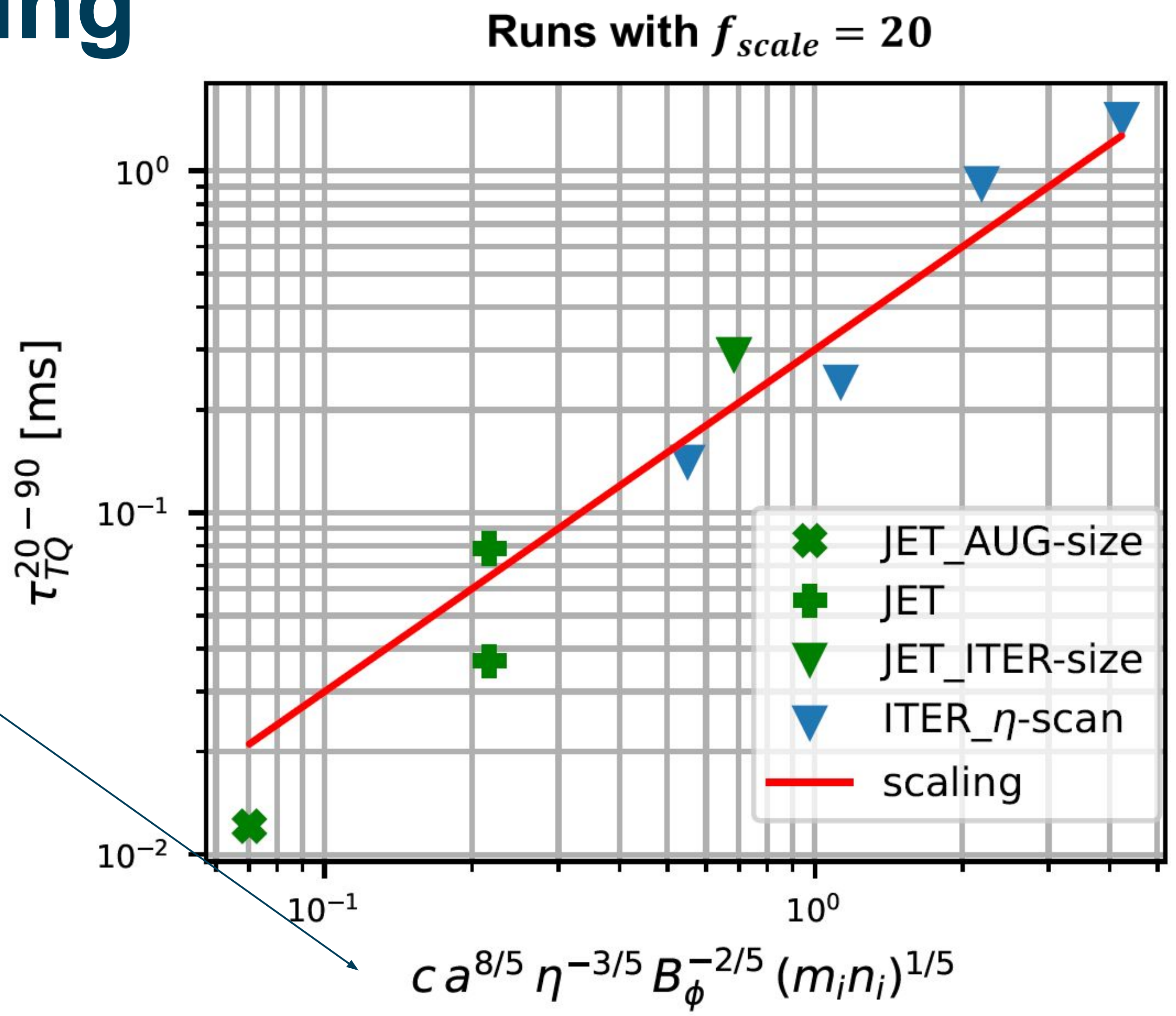
Callen, J.D., Waddell, B.V., Carreras, PPCF (Proc. 7th Int. Conf. Innsbruck, 1978)



The tearing mode scaling

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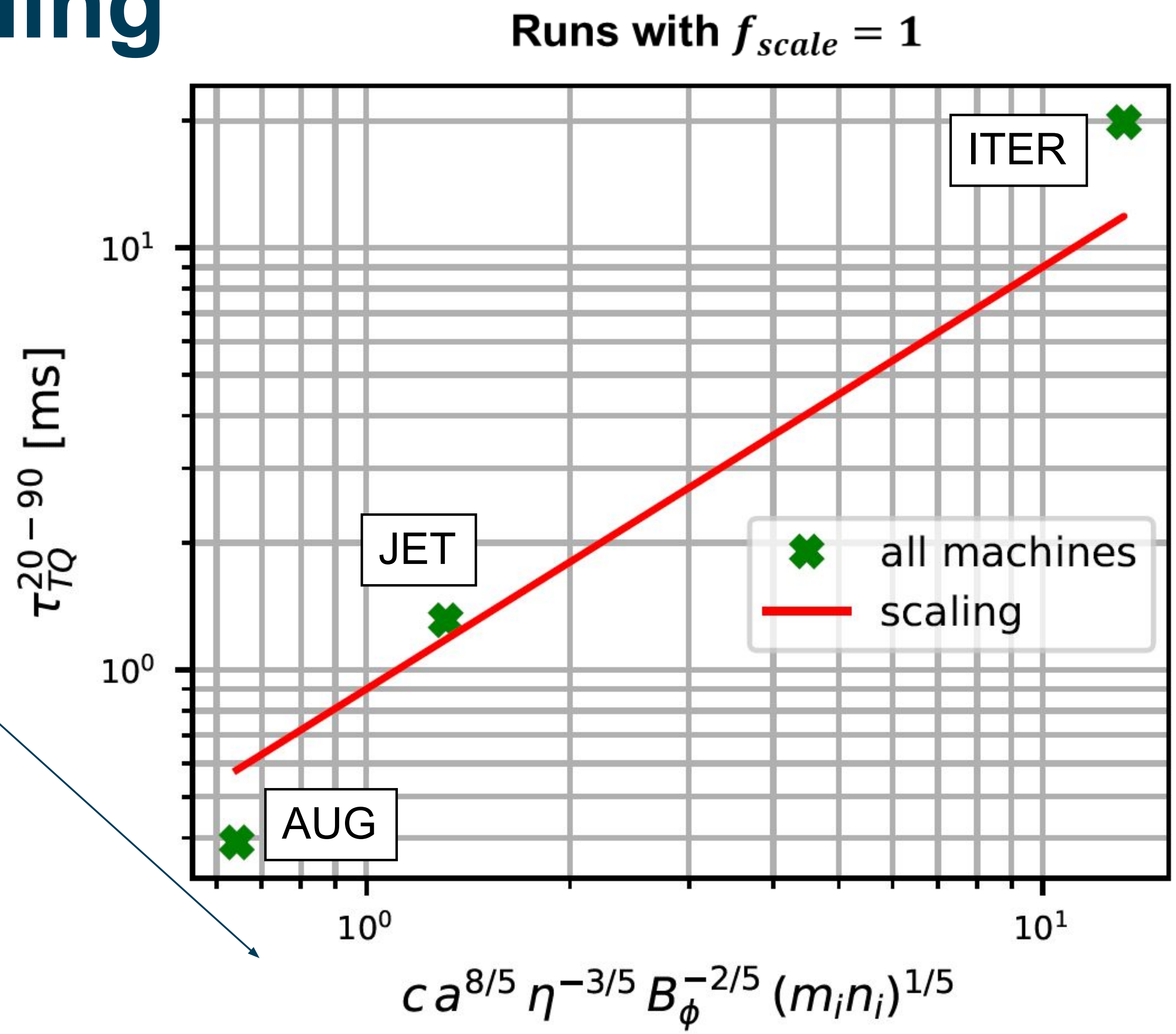

Conclusions

Conclusions

"JOREK simulations of the TQ during hot VDEs in AUG, JET and ITER"

❑ Differences on q_{95} at TQ onset

- AUG sim. consistent with experiments (internal modes)
- q_{95}~1.4 in JET experiments while in JOREK is ~1.7
  - Perturbation initialization problem
  - How the plasma retains W_{th} when $q_{95} \in [1.4, 2]$?
- ITER and JET show 2/1 & 4/2 external modes + influence of a 1/1 internal mode

❑ TQ duration

- Large experimental scatter
- Re-scaling technique useful for duration envelop, but dynamics are different
- Optimistic predictions to ITER ($\tau_{TQ} > 5$ ms)
- Very weak dependence on wall resistivity
- Machine size and resistivity dependencies could explain differences between ITER and JET
  - $L_{\parallel}$ is orders of magnitude larger in ITER than AUG