3D Effects on Disruptions and their Mitigation

T C Hender

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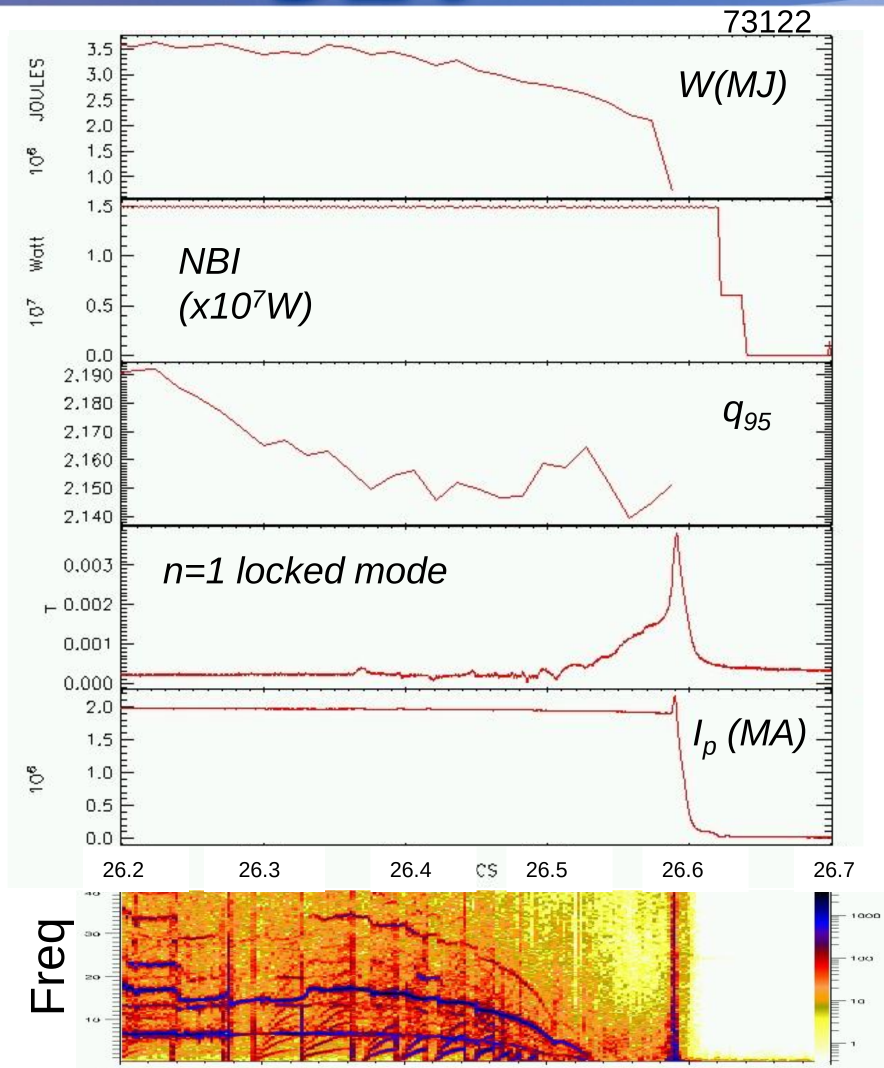
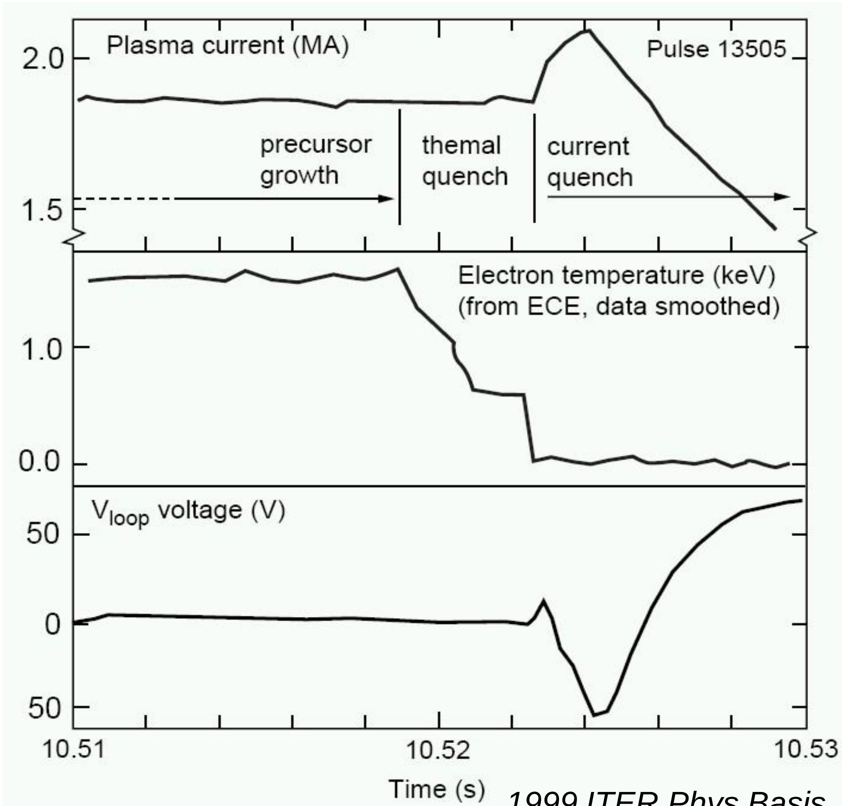
and JET EFDA contributors

Disruptions and their consequences are 3D



- *Pre-disruption energy loss, 3-D precursors*



1999 ITER Phys Basis, Nucl Fus

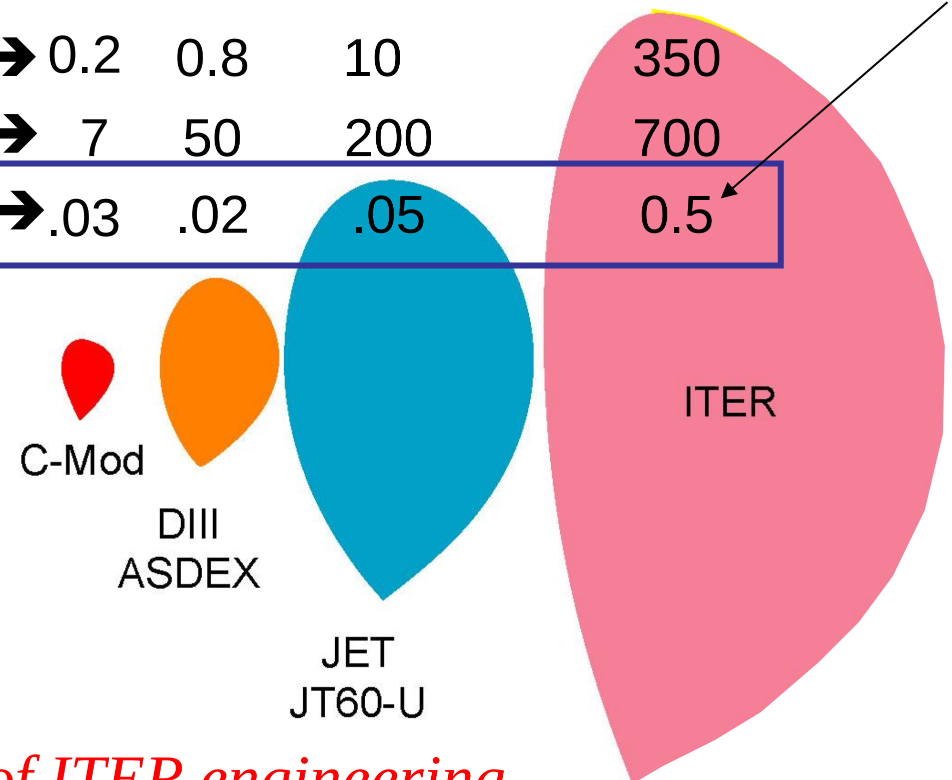
- *Thermal quench and current quench*
- *Consequences heat + EM loads, VDE, halos (which can be non-axisymmetric, i.e. 3-D)*

Disruptions get more severe in bigger tokamaks

In general local heat loads higher, due to conductive losses

Plasma Energy W (MJ) →	0.2	0.8	10	350
Surface Area A_{plas} (m^2) →	7	50	200	700
W/A_{plas} (MJ/m^2) →	.03	.02	.05	0.5

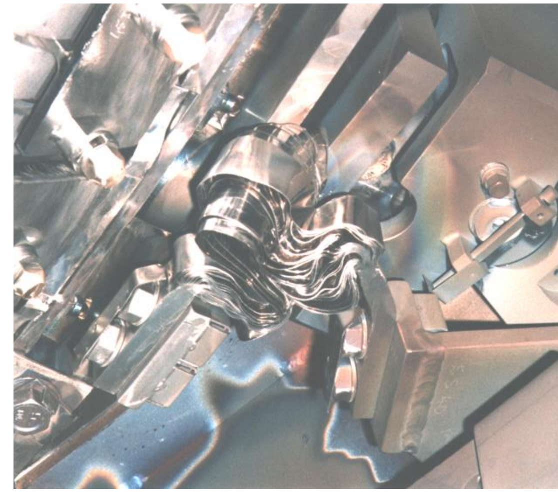
Perfect disruption mitigation

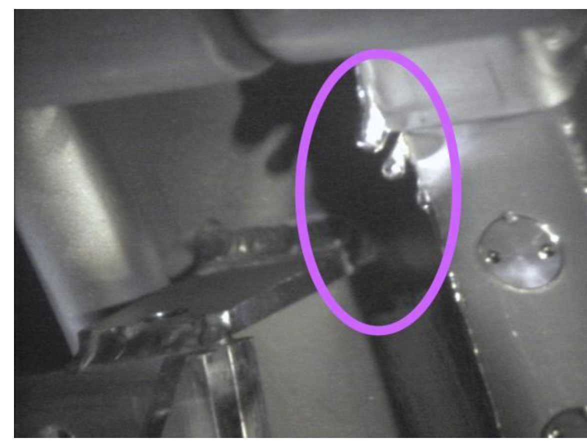


Disruptions main driver of ITER engineering

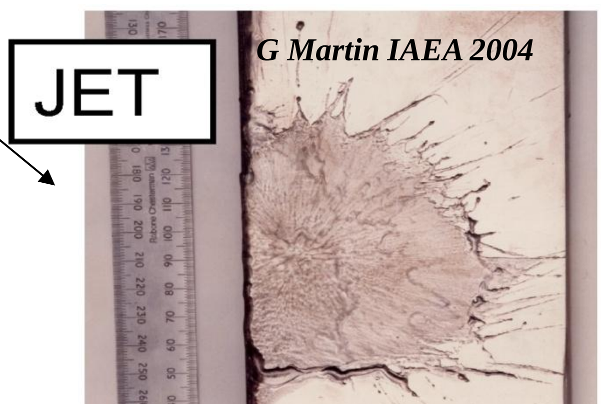
Disruption consequences

- Key issues to be resolved for disruptions:-
  - Forces (VDE symmetric load ~10,000 Tonnes, asymmetric ~5,000 Tonnes in ITER)
  - Heat Loads
  - Runaways (~10MA at 10-20MeV in ITER)





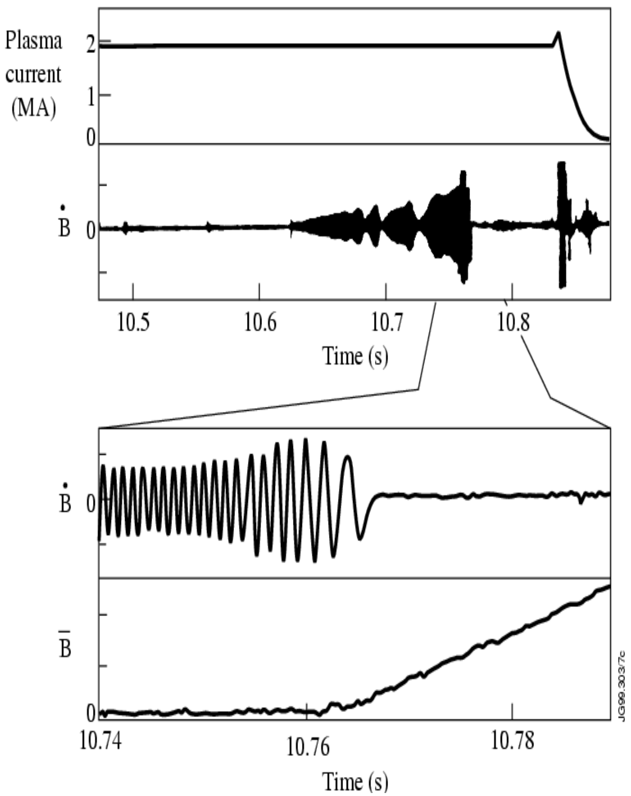
Examples from JET

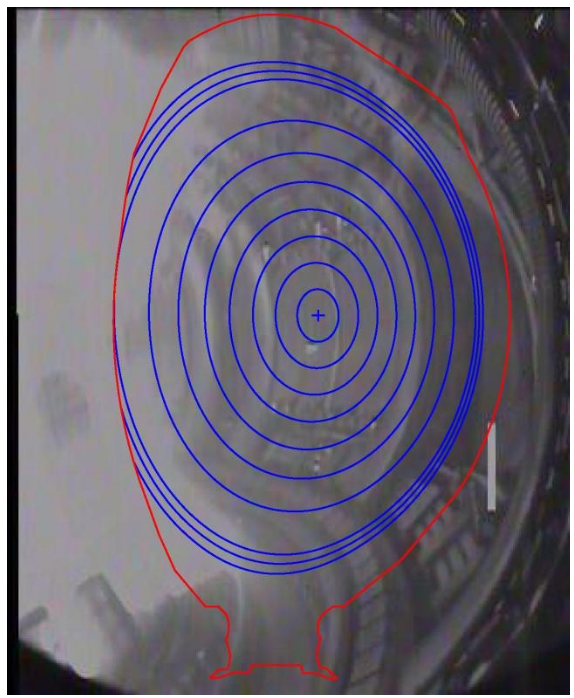


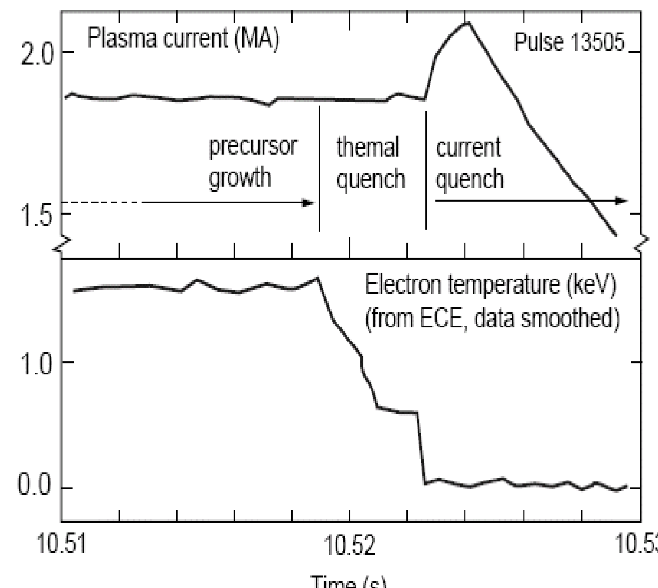
3-D mechanisms causing disruptions

Classical disruption picture

Limit approached → 3D Instability → Energy Loss → Plasma moves and hits wall → Impurities enter plasma → Plasma cools and highly resistive → I_p lost

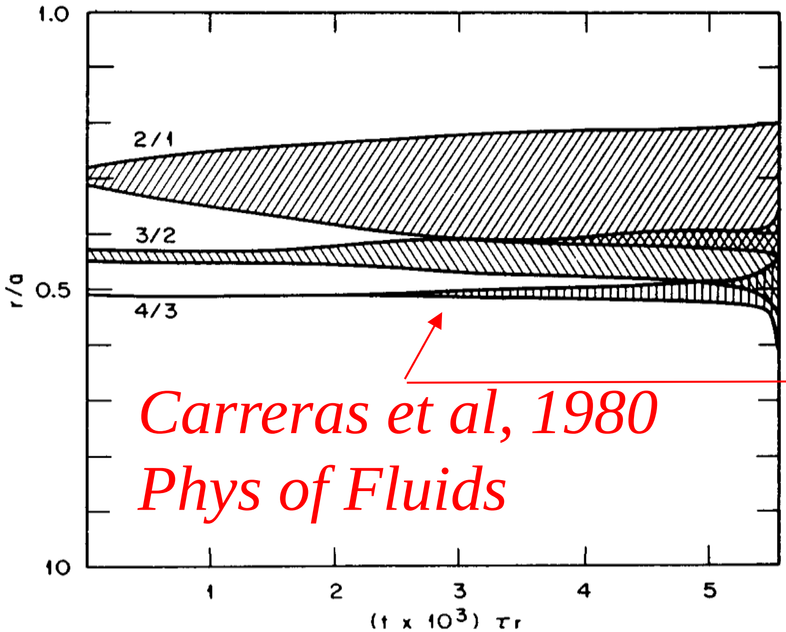




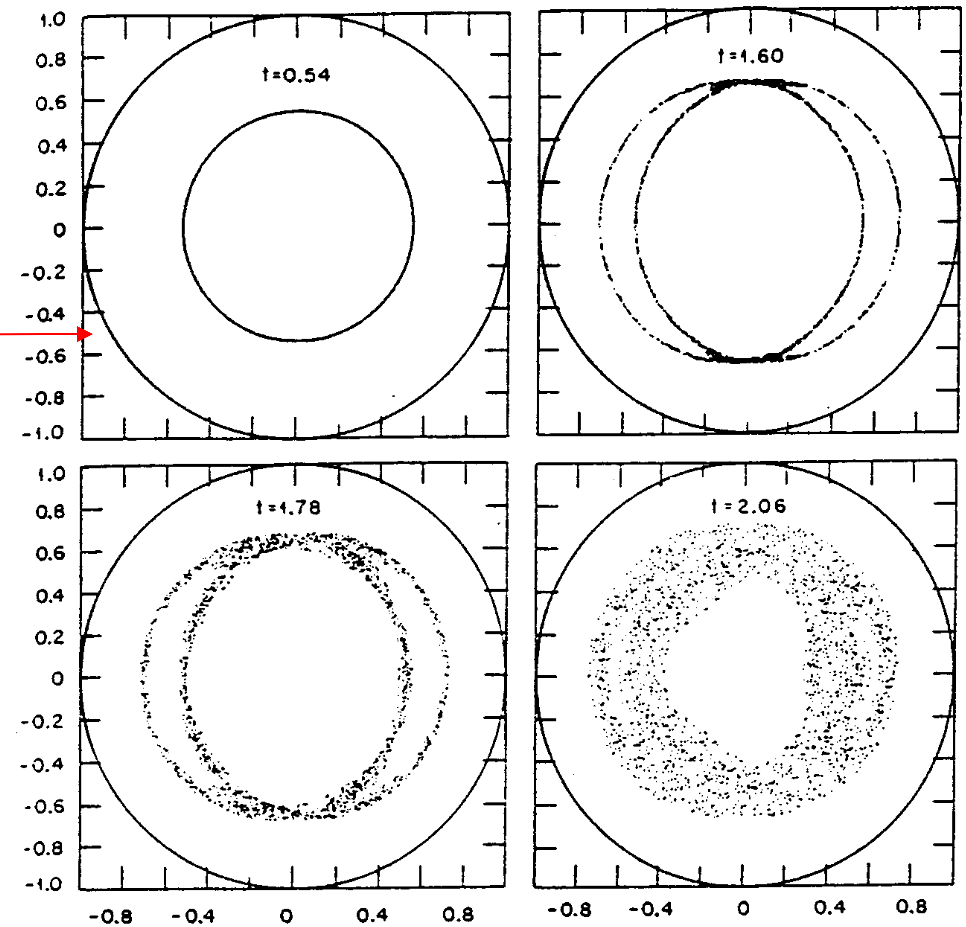


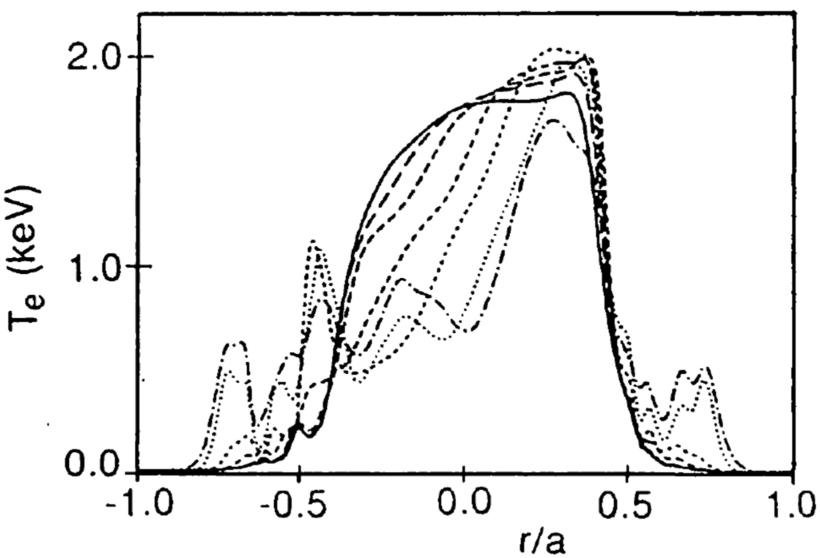
Wesson et al Nucl Fus 1989

Classical picture - energy loss is stochastic



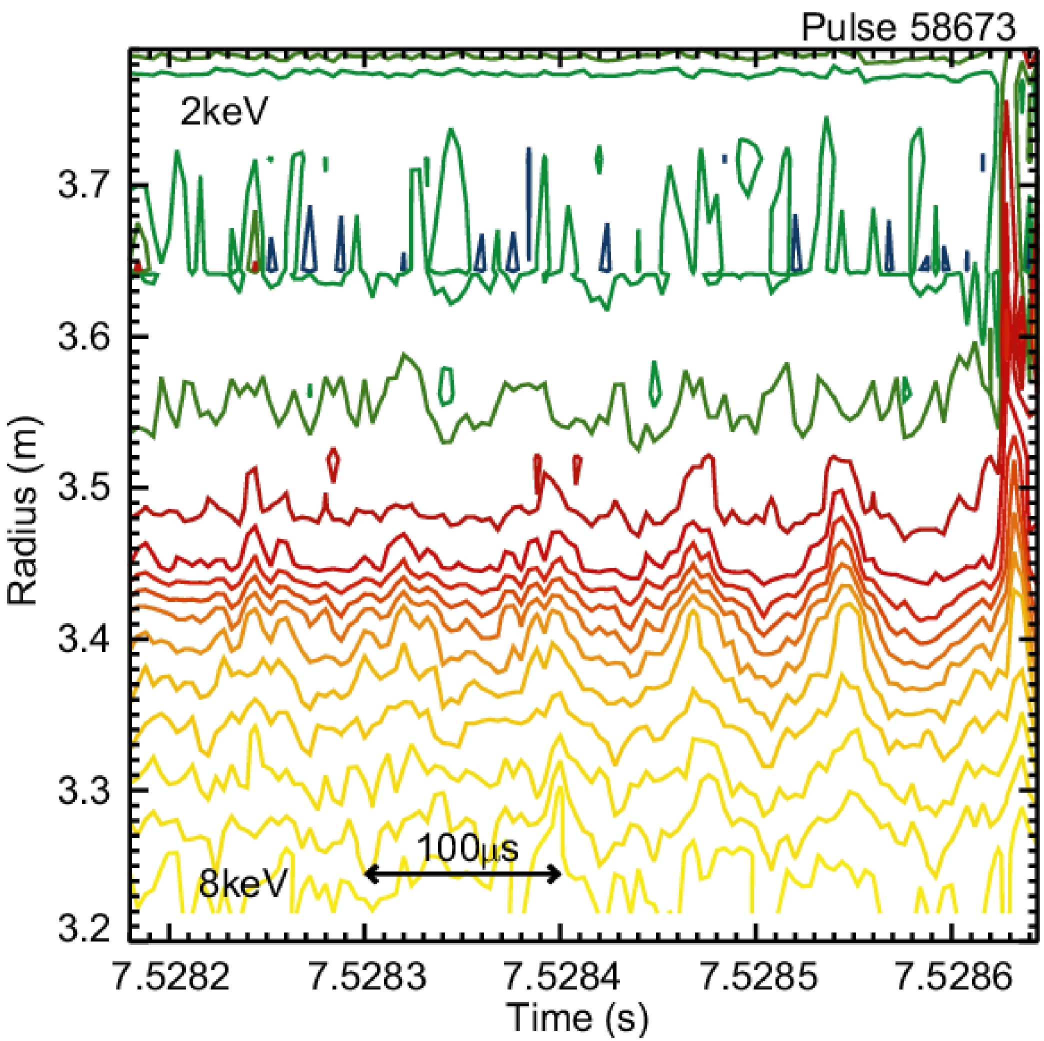
Carreras et al, 1980
Phys of Fluids

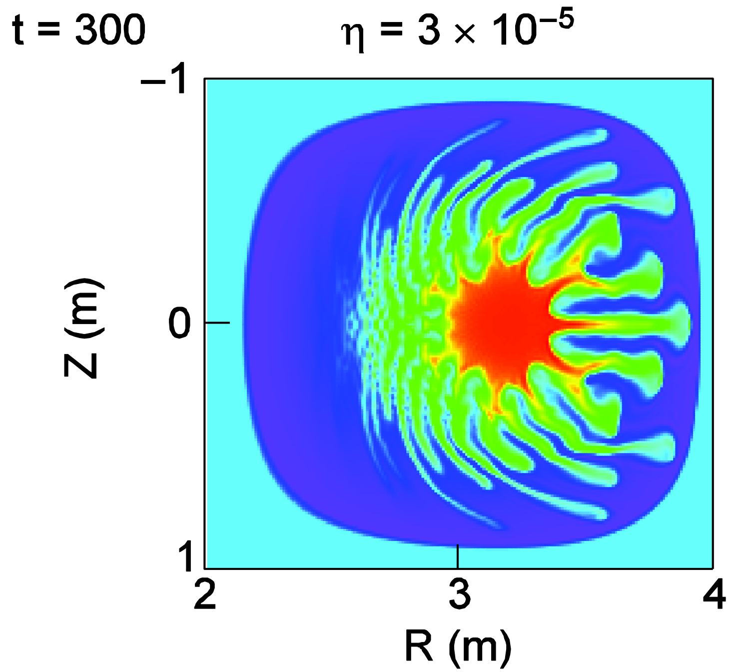




MHD simulation
Bondeson et al, NF 1991

Explosive instability picture





Kleva et al, Phys Plas 2001

Ballooning mixing

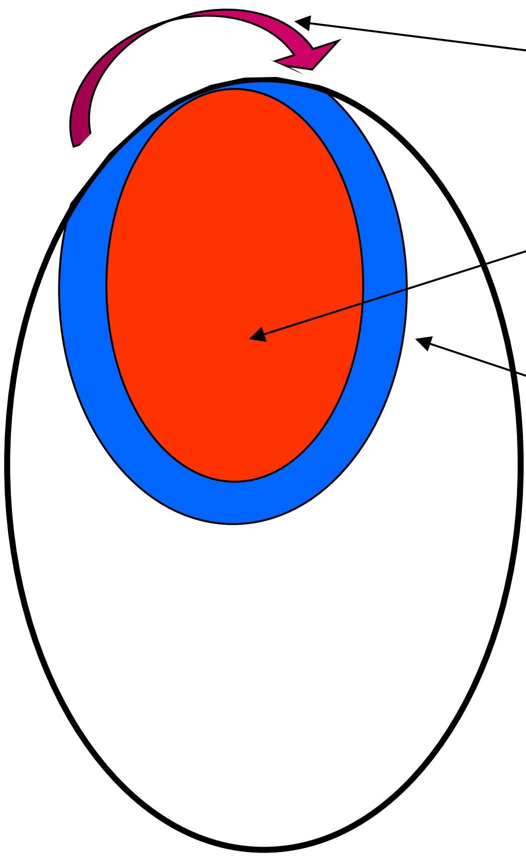
J Paley, S Cowley et al JET preprint *EFDA–JET–CP(04)02/16*

3-D consequences of disruptions:-

- Halo currents and EM forces
- Heat Loads
- Runaway electrons

Forces

- Forces from halo and eddy currents are the main design constraint on the vessel and in-vessel components in ITER
  - Symmetric loads on the vessel reach ~10,800 tonnes
  - Asymmetric sideways loads ~5,000 tonnes

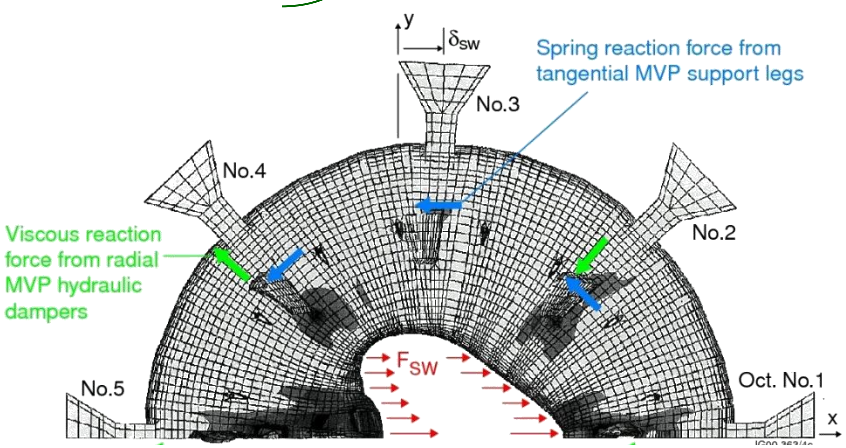


Halo current flowing in vessel etc, (normally dominantly *poloidal flow* for symmetric currents)

Core plasma:- shrinking and I_p decreasing

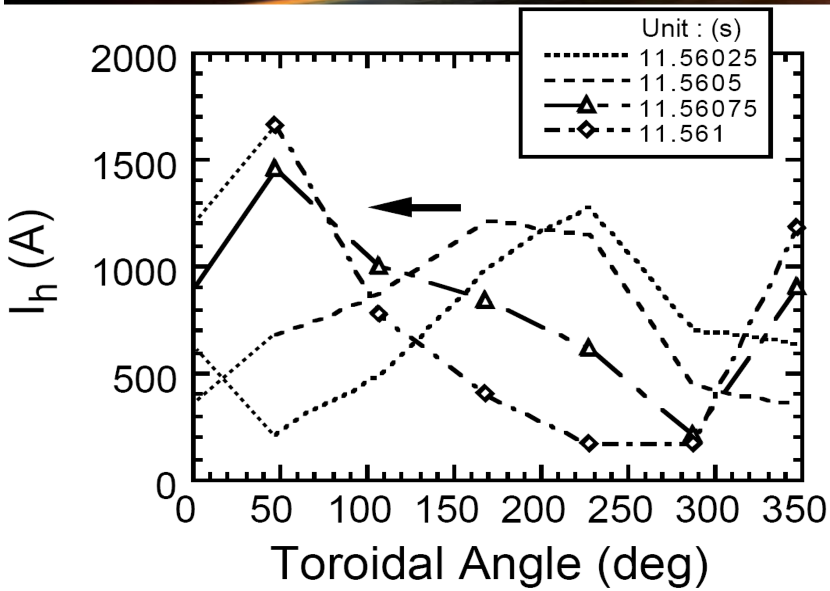
Halo region

Toroidal halo current flows in I_p direction and poloidal current in direction to increase B_t

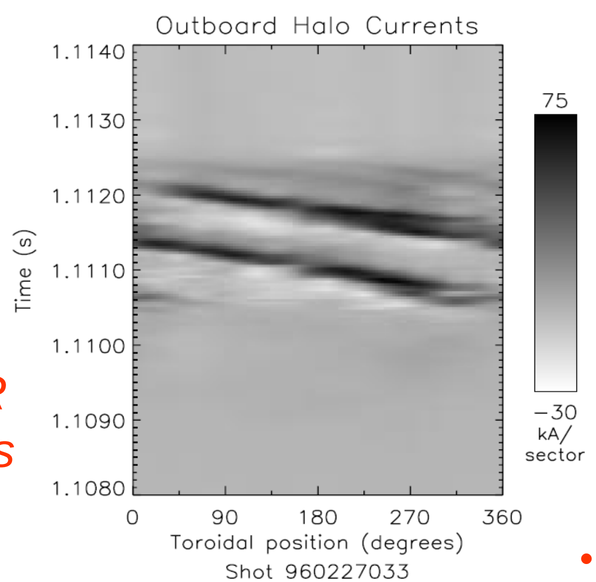


- For JET peak sideways force ~400Tonnes

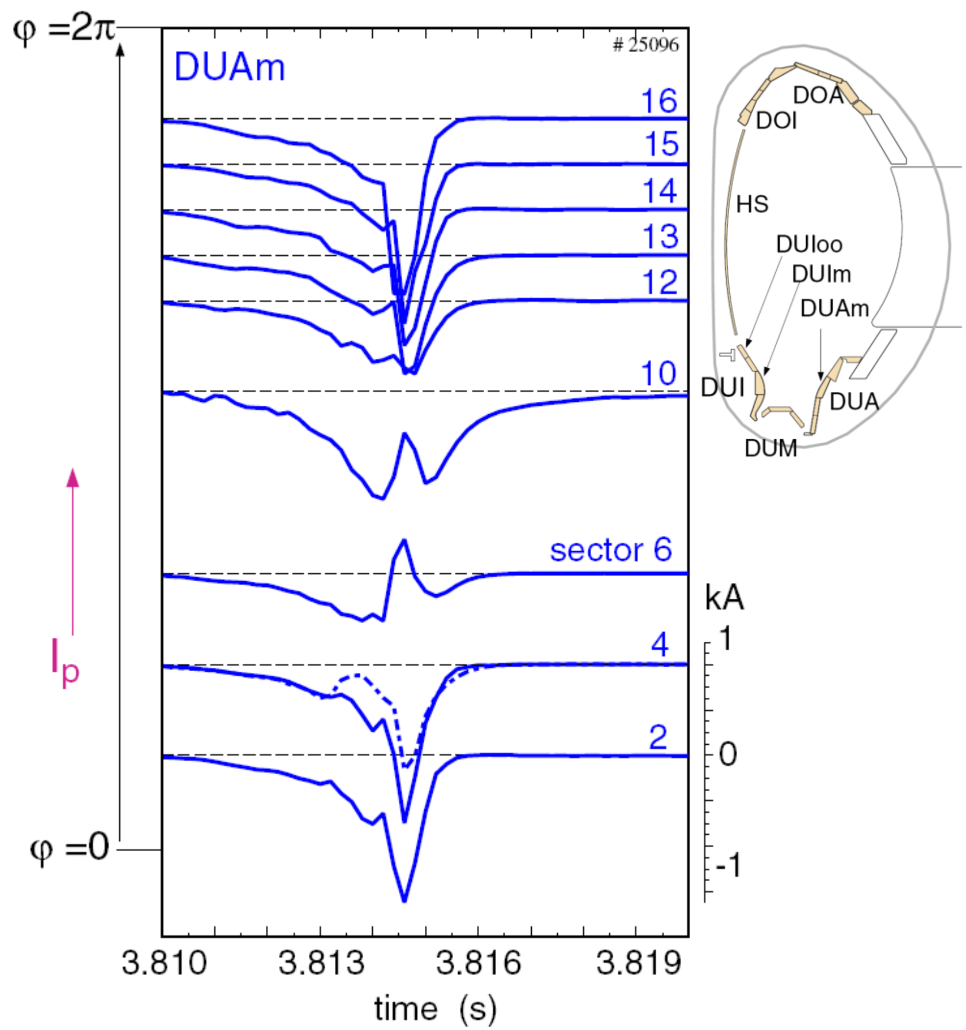
Halo Currents can be toroidally asymmetric



JT-60U NF 1999, Neyanti et al



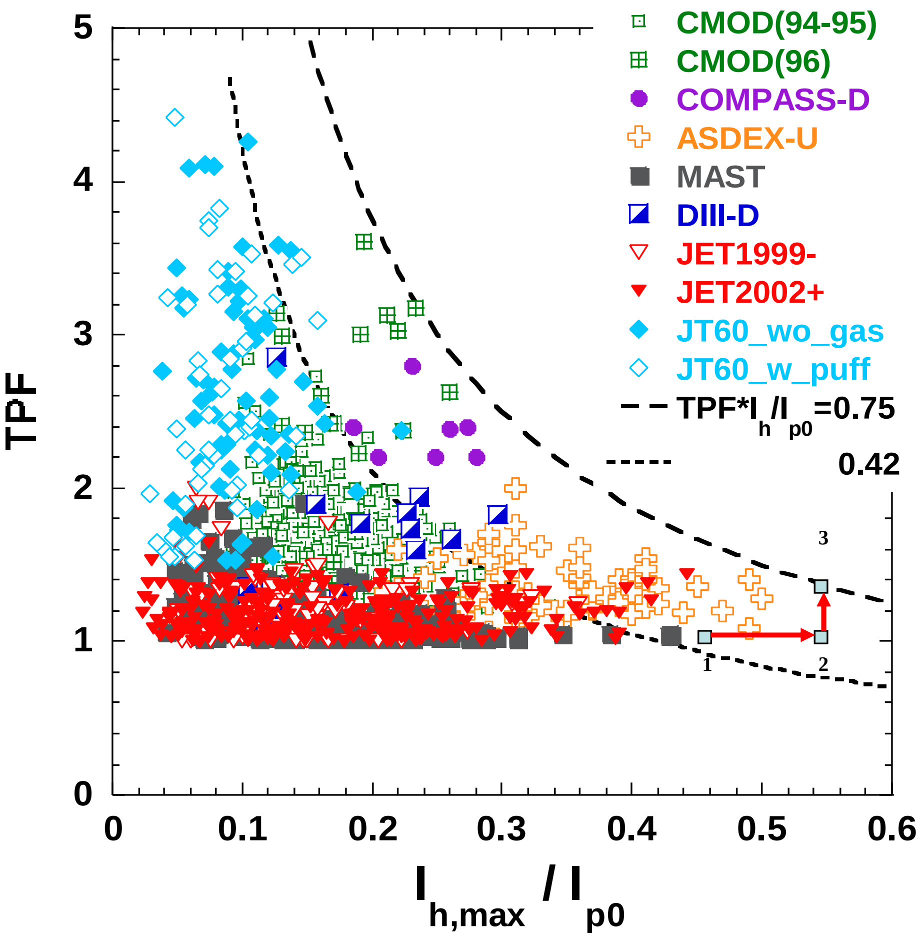
C-MOD
1999 ITER
Phys Basis



AUG NF 2011, Pautasso et al

- In JET 41% of disruptions have significant asymmetry

Halo Current Asymmetries



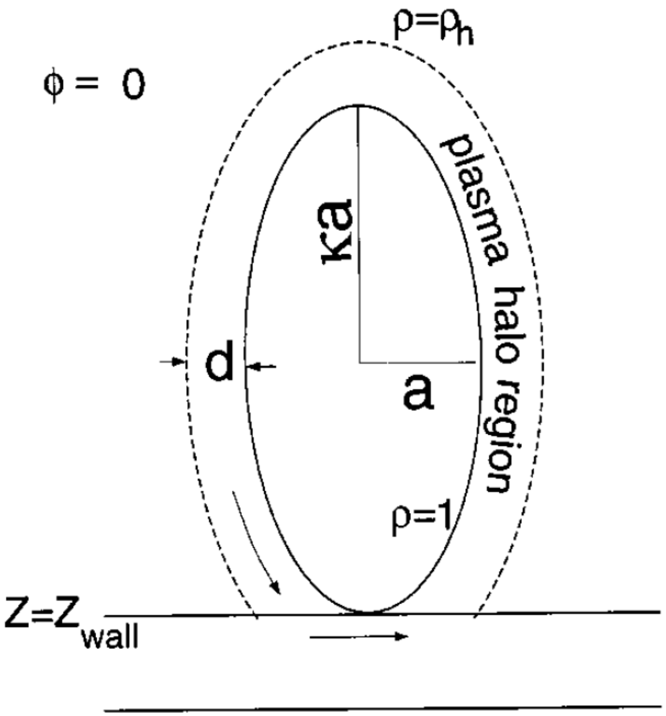
- Empirically data bounded by *TPF*I_{halo}(average)/I_p*
- ⇒ A limit on maximum halo current flowing to vessel?
- But in a given machine evidence is weaker

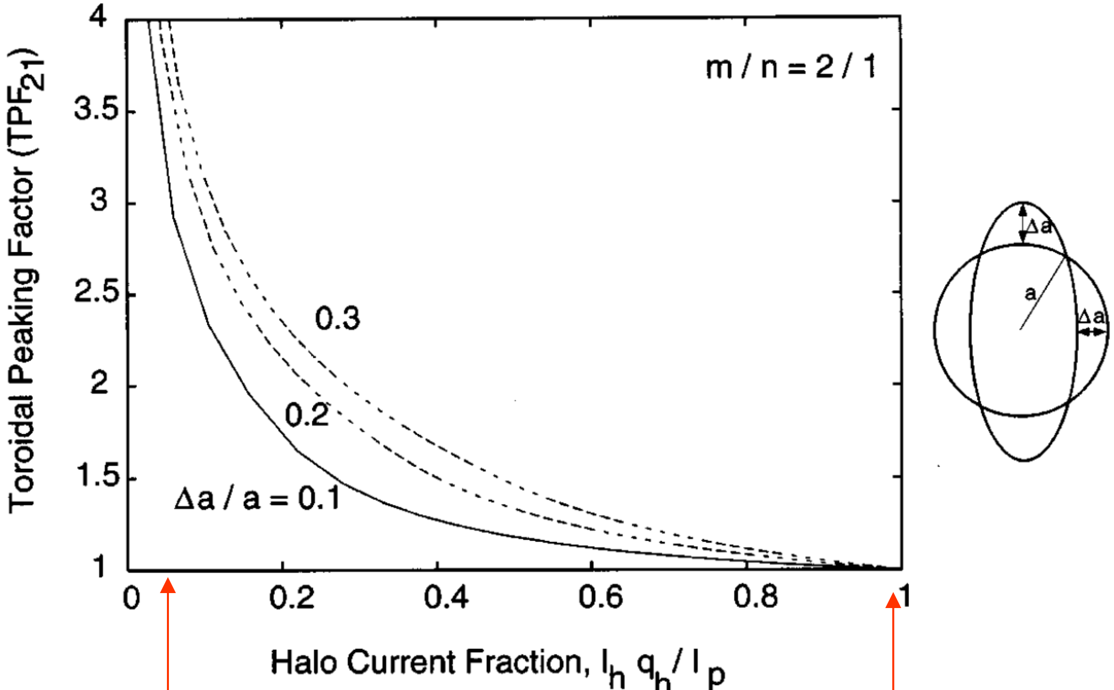
$$TPF = \left| \frac{I_{halo}(\max)}{I_{halo}(average)} \right|$$

Maximum in space and time

Halo Current Asymmetries - theory

At q_a=2 m=2,n=1 kink distortion:-





NB Helically rotating elliptic distortion

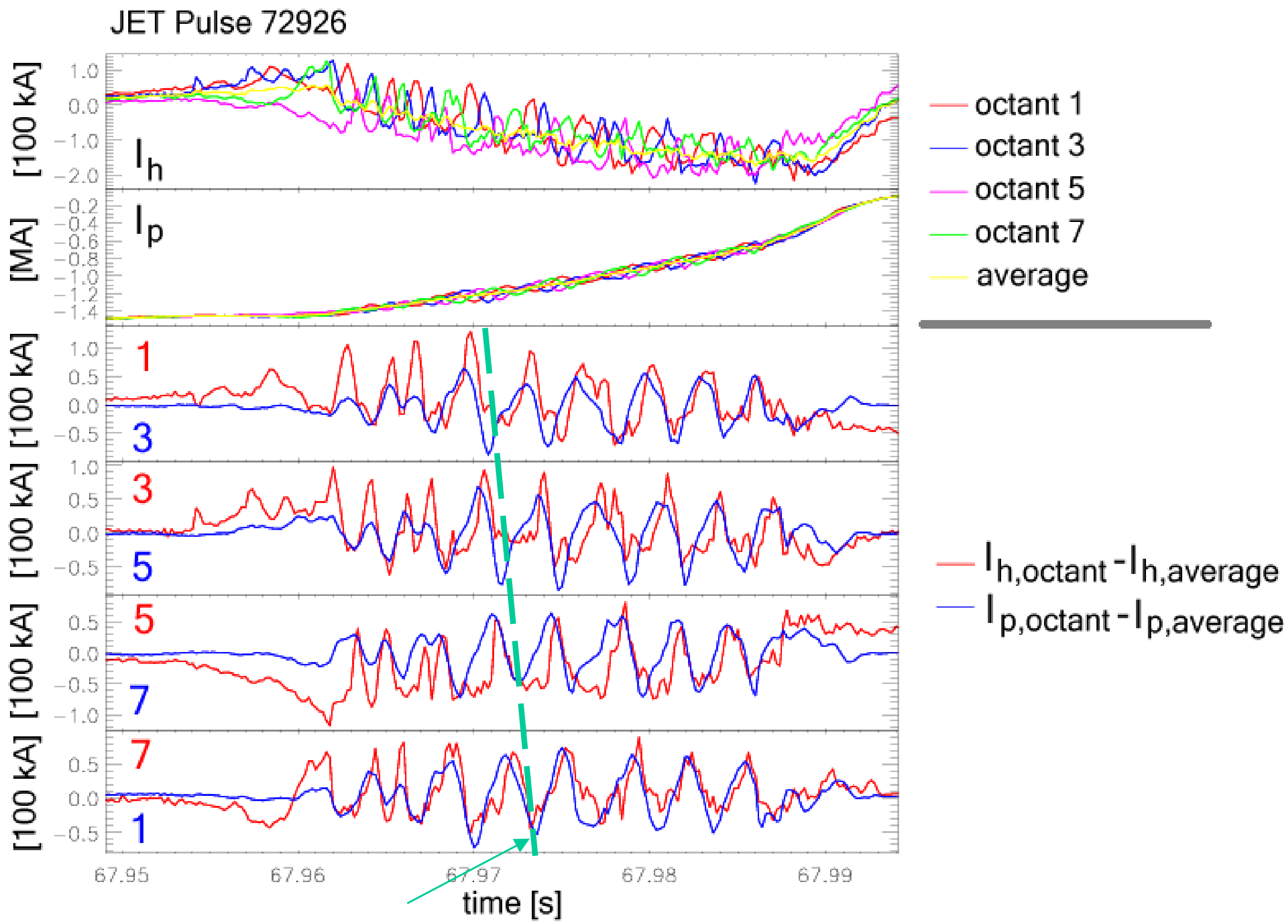
Ellipse just touches at ϕ=0 and 180°
$\Rightarrow I_{halo}(av)=0$

d>>a all current in halo

Pomphrey et al, Nucl Fus 1998

- Similar result at q=1, with m=n=1 kink

Halo currents can rotate



n=1 structure rotating counter to I_p

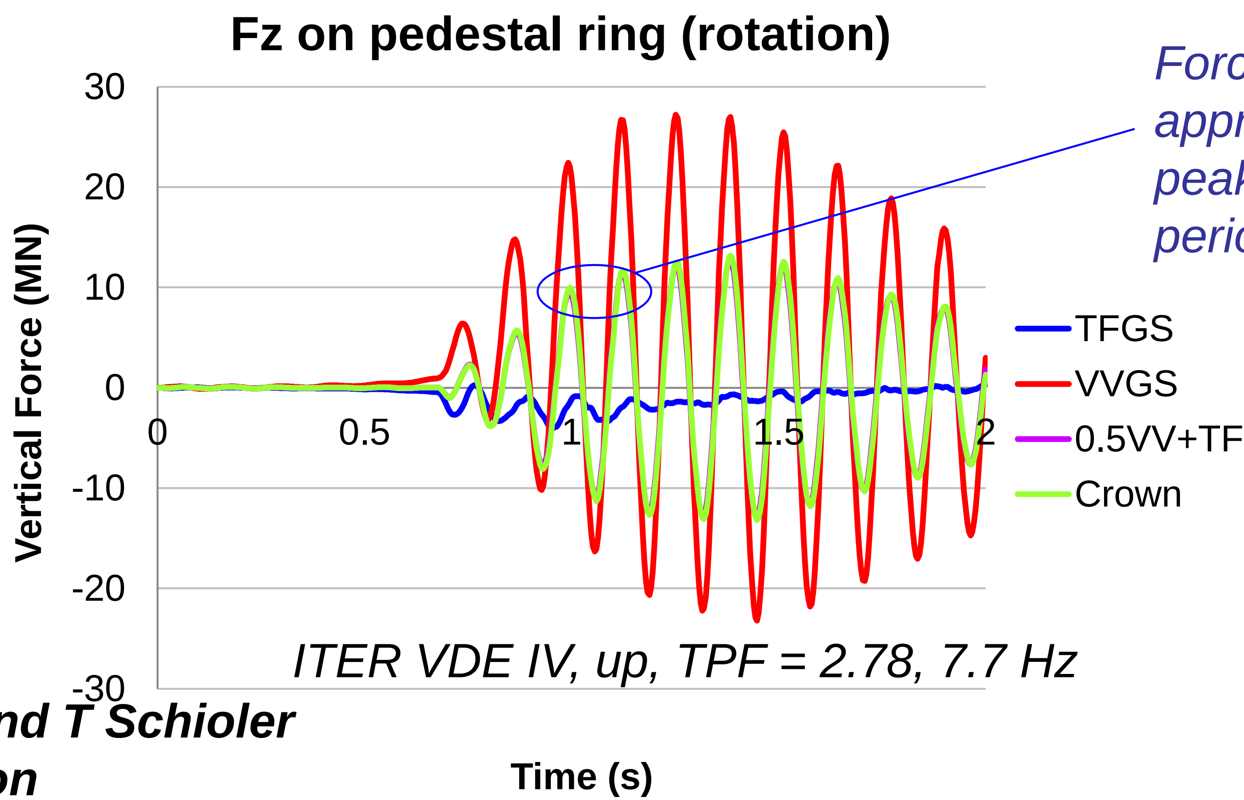
- Poloidal halo currents phase leads ΔI_p by ~90°

Halo current rotation important

- **Vacuum vessel and coil systems have low frequency resonances**
- **Possibility of dynamic amplification**

Mode	F (Hz)	Mass fraction
U – xy	2.77	0.95
U – z	8.61	0.77
Rot - xy	8.41	0.80
Rot - z	4.50	0.88

Natural frequencies of the 360° VV

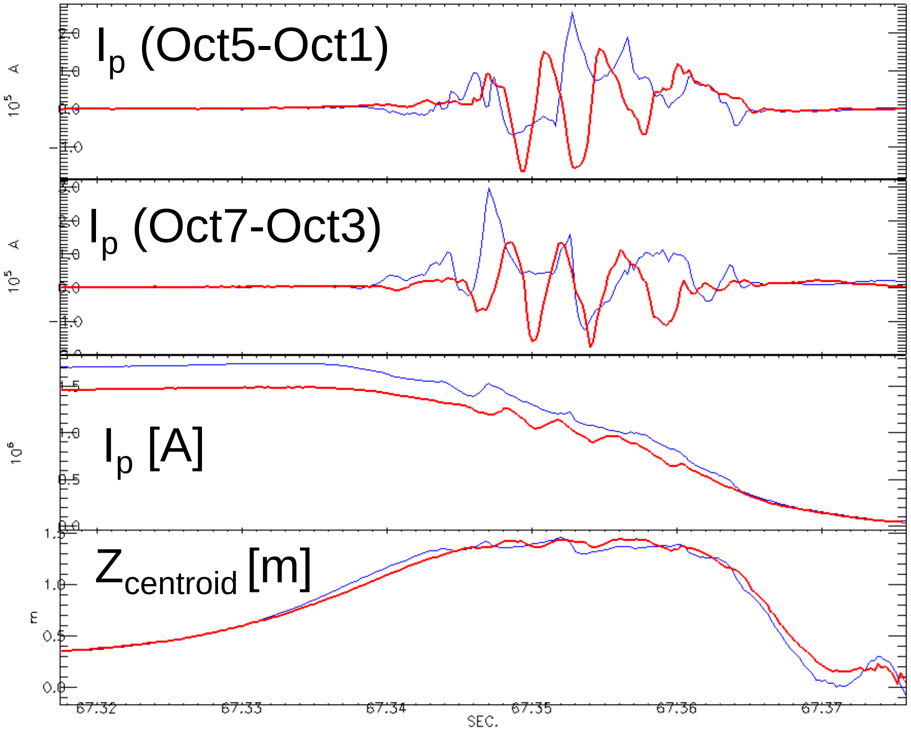


Forces approach peak in 2 to 3 periods

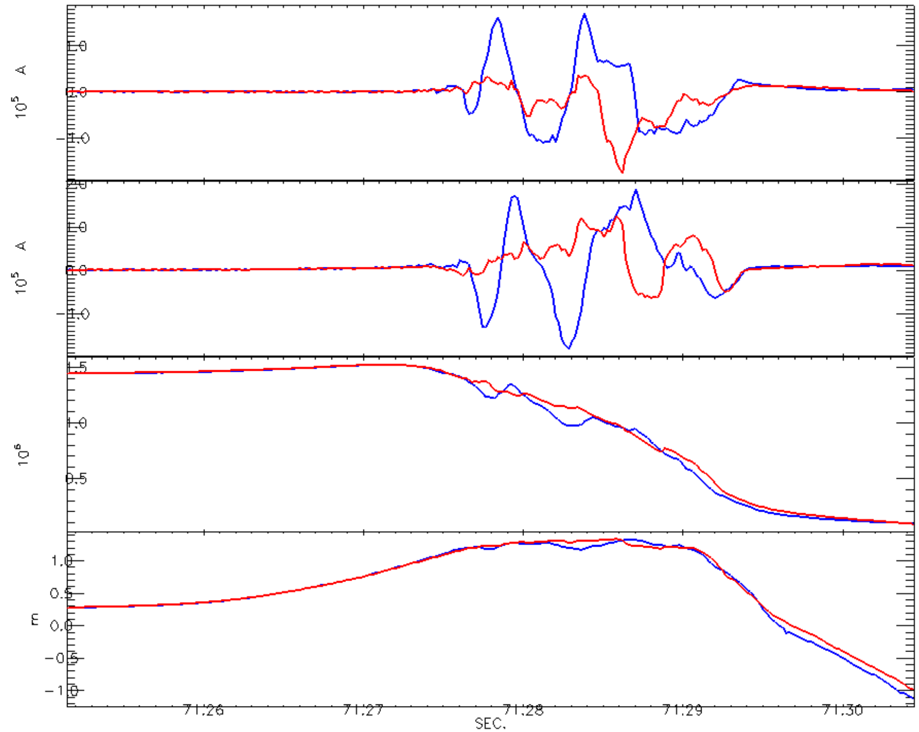
G. Sannazzaro and T Schioler
ITER Organisation

No obvious pattern for why some shots have substantial halo rotation

71790, 71791



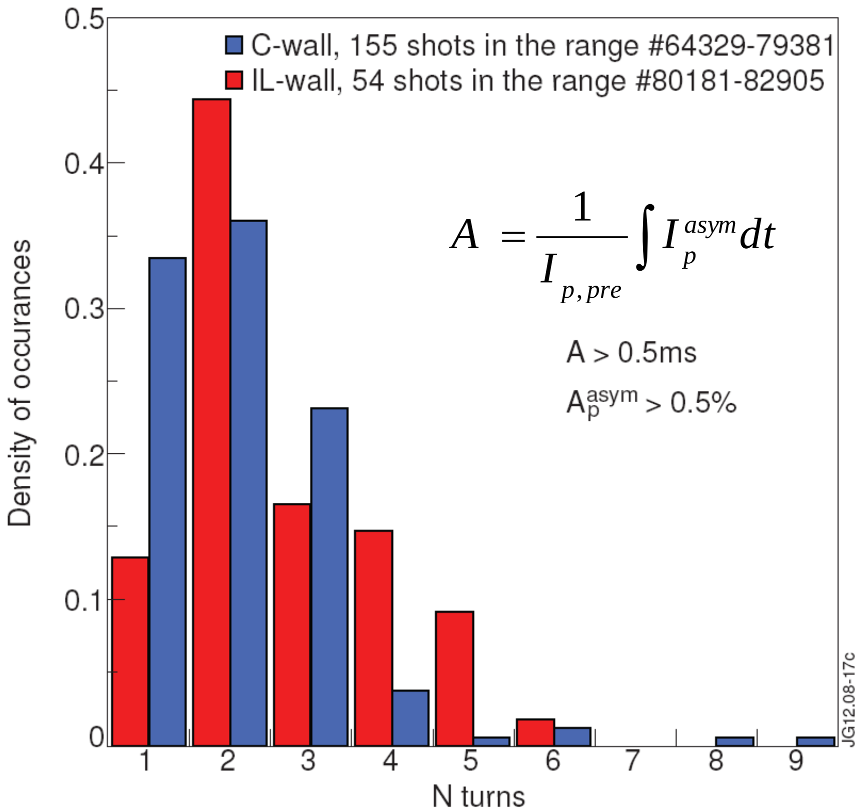
70238, 70237

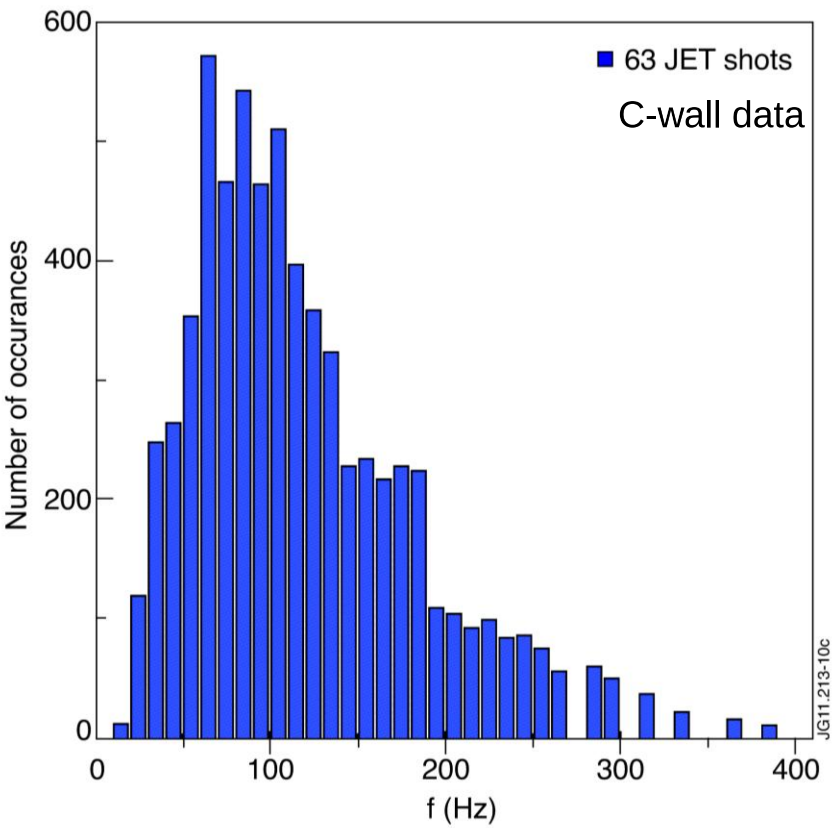


Neighbouring similar shots have very different halo rotation

Typically rotation of 2 turns and f~100Hz

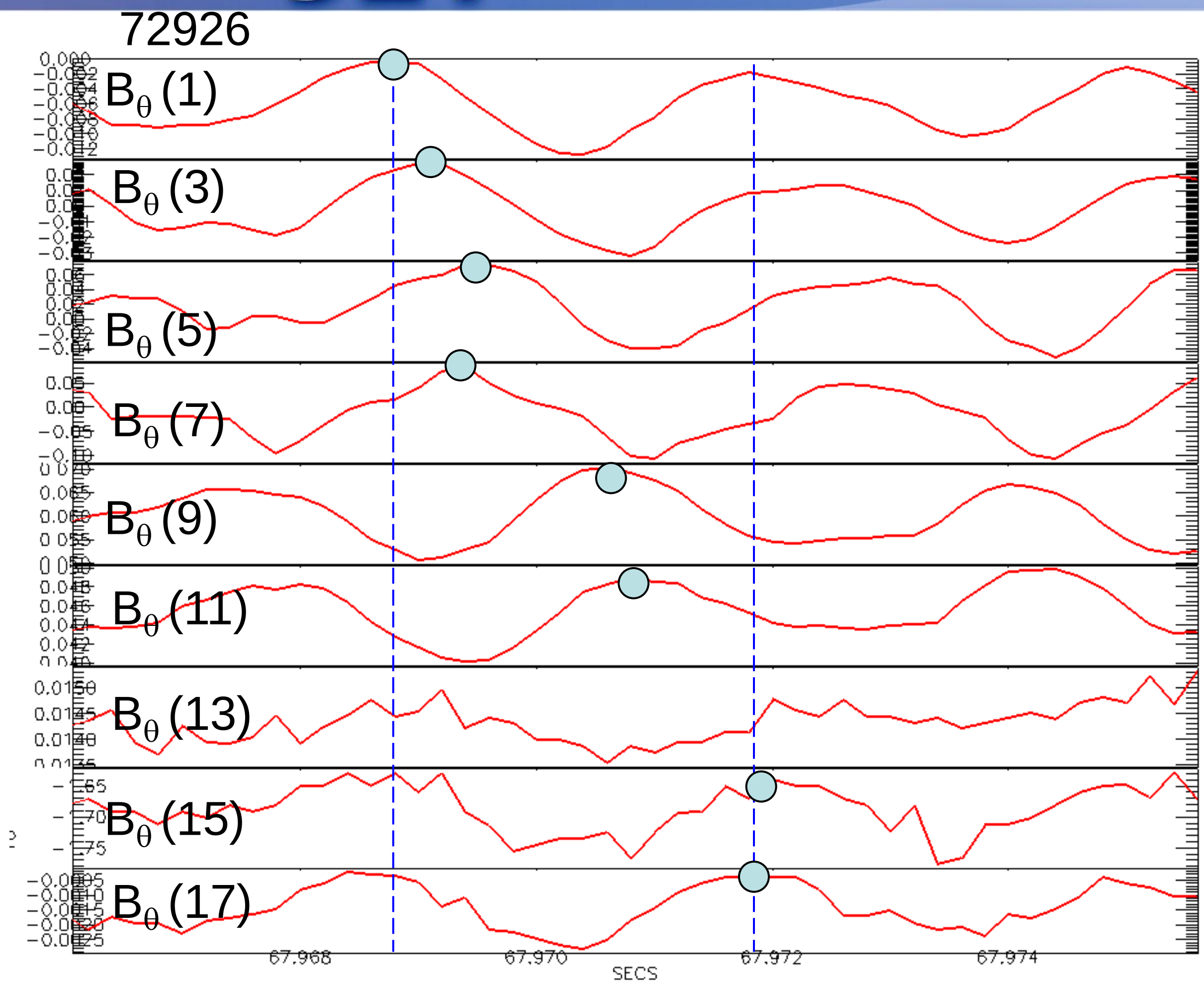
- But long tails to multi-turns and ~400Hz

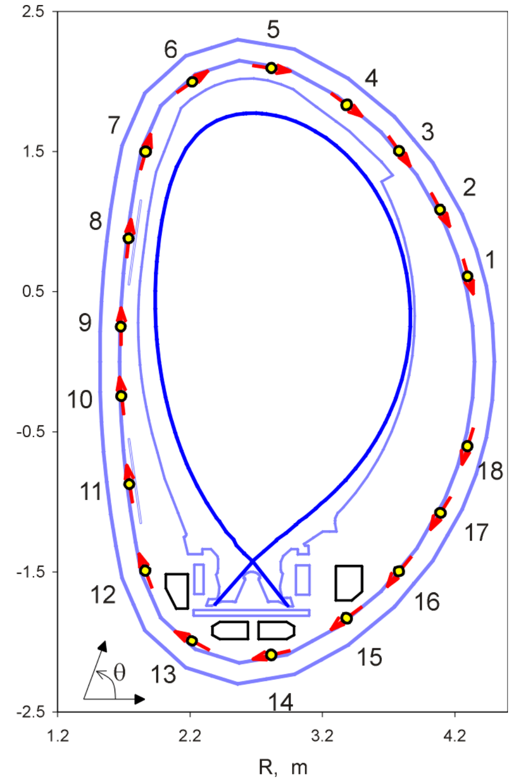




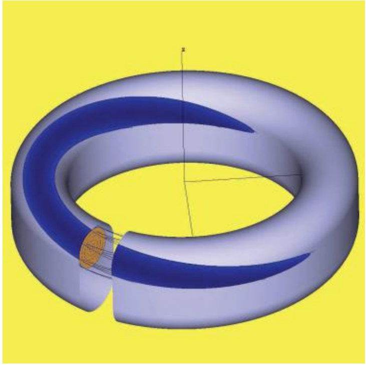
S Gerasimov, 2012 EPS

Halo Asymmetry is m=1 dominantly

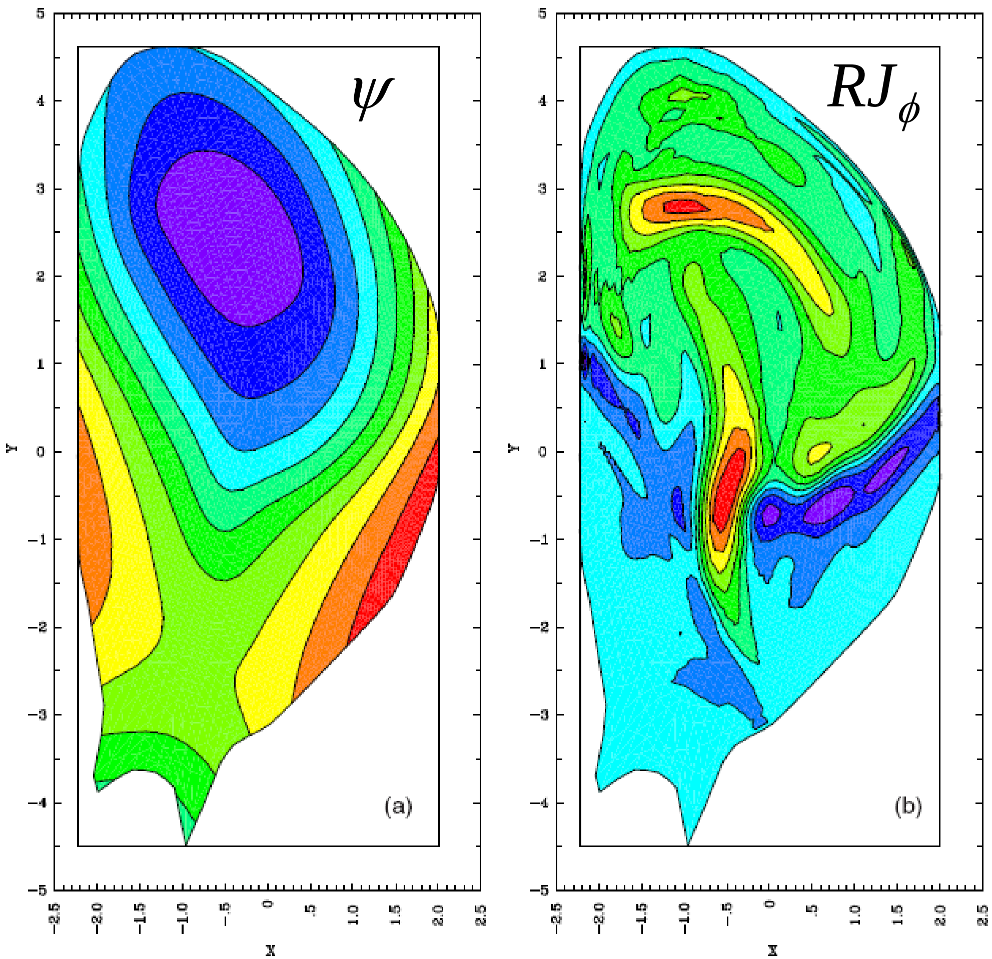




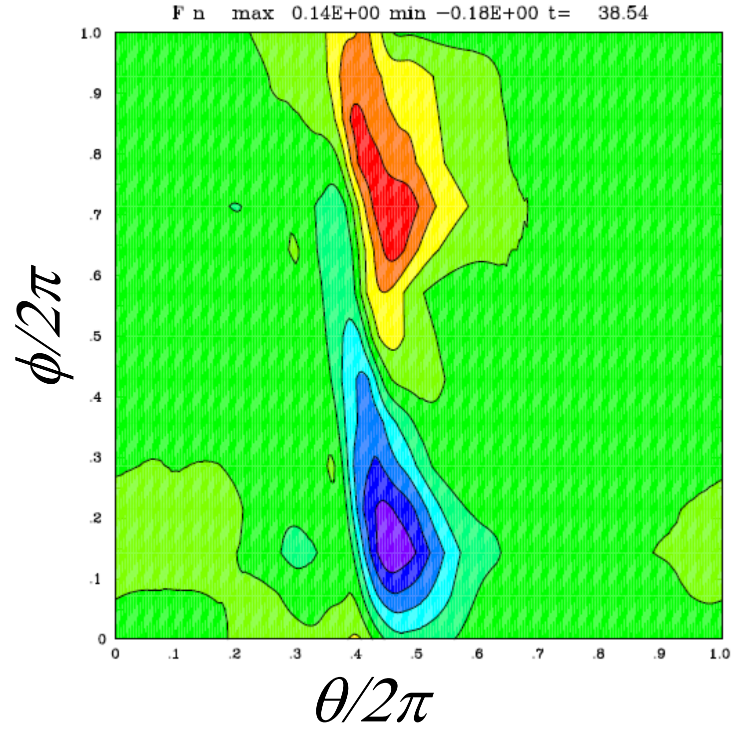
Consistent with *m*=*n*=1 kink mode (Zakharov et al)



VV Current Asymmetries – 3D MHD



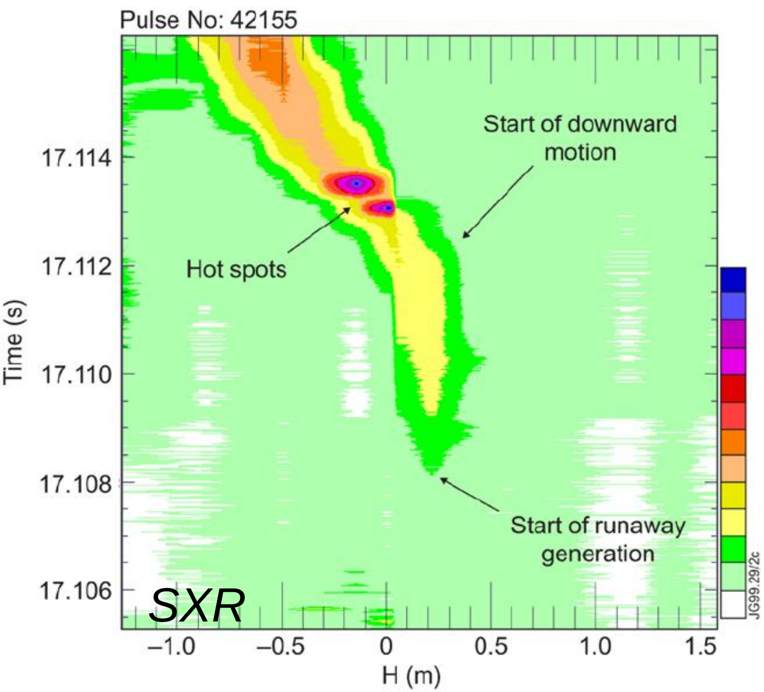
Asymmetric force normal to wall

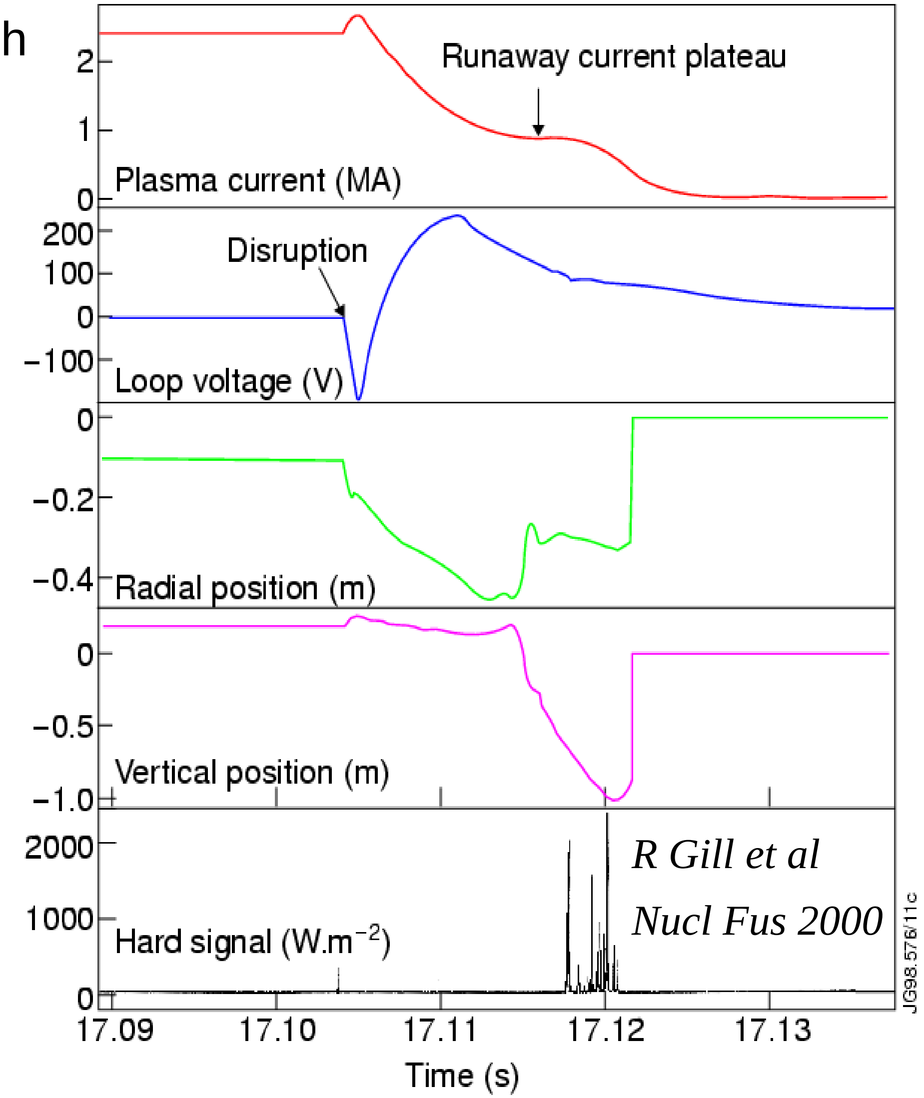


Strauss and Paccagnella, PoP 2010

Runaway electrons

- Runaway electrons are generated, which
  - are accelerated to ~ MeV range.
  - carry much of the original current.
  - usually hit the wall => hard X-rays.
  - can cause serious damage.
  - occasionally remain in the cool plasma (~ 10 eV) for several s.

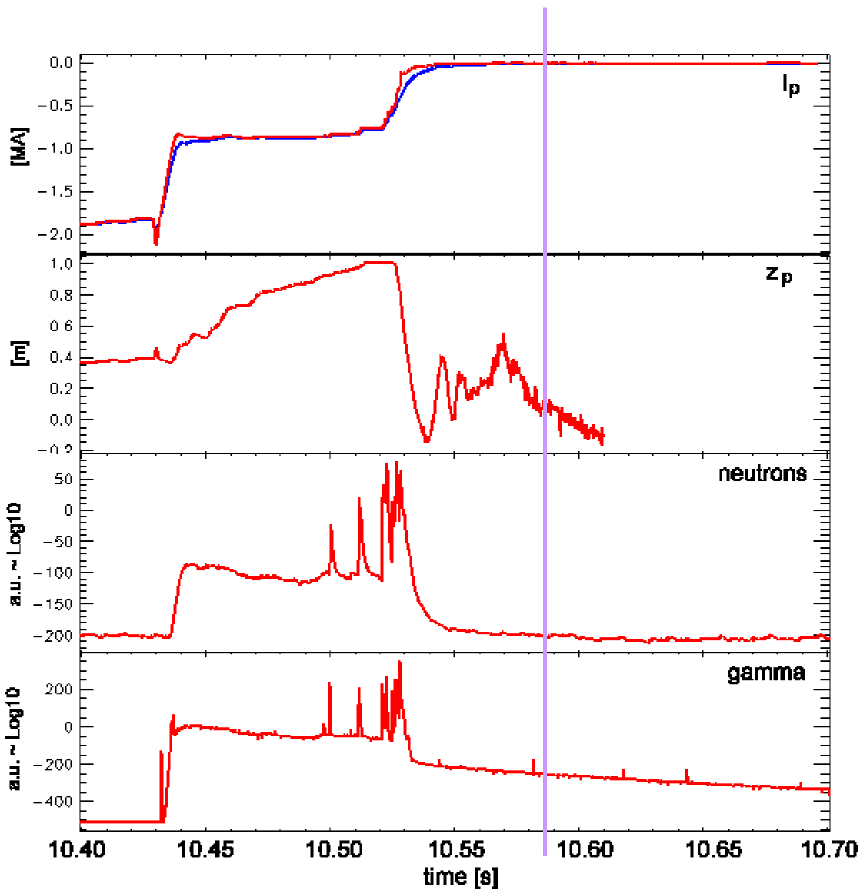




R D Gill et al, Nucl. Fusion (2000)

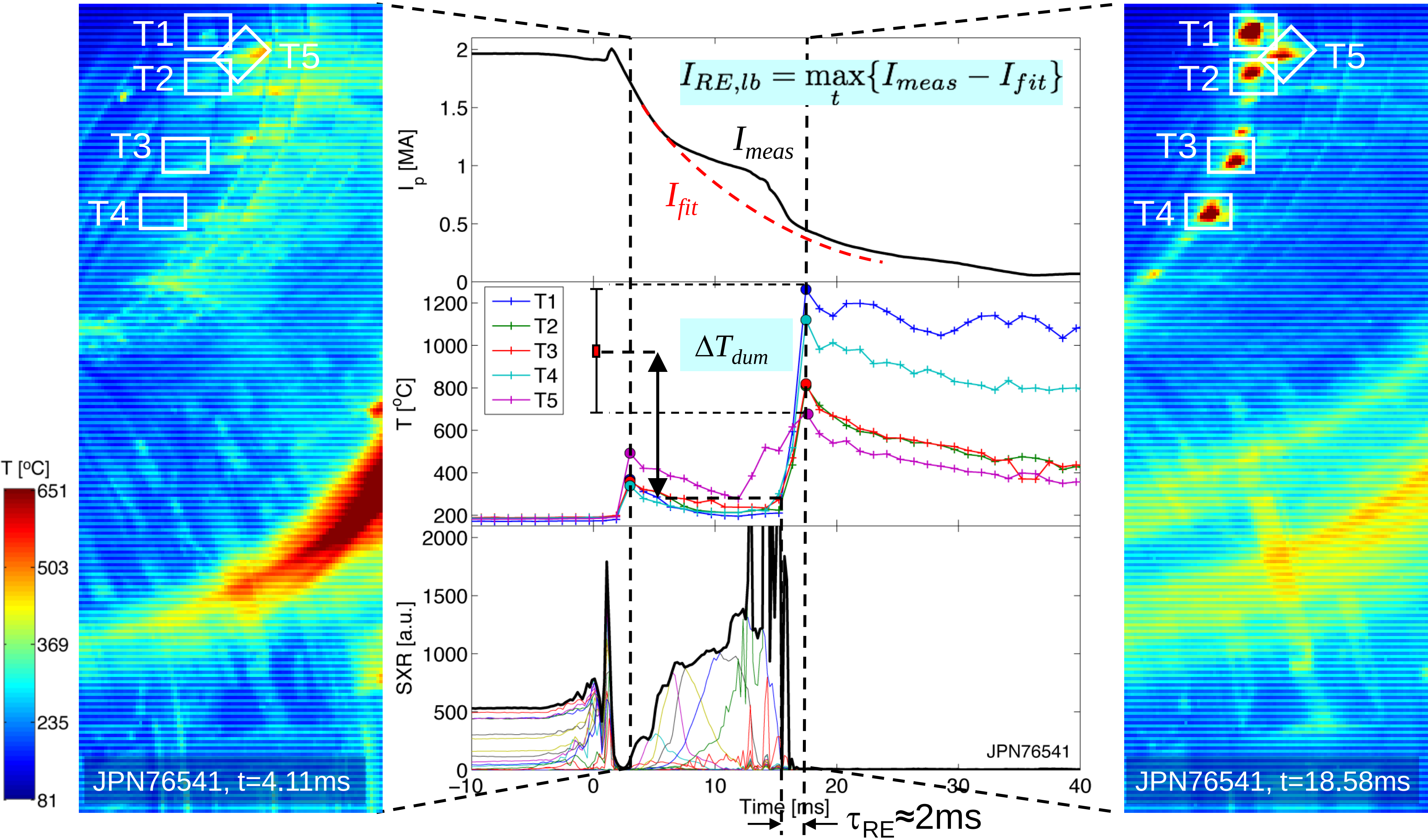
RE event in JET

No REs left

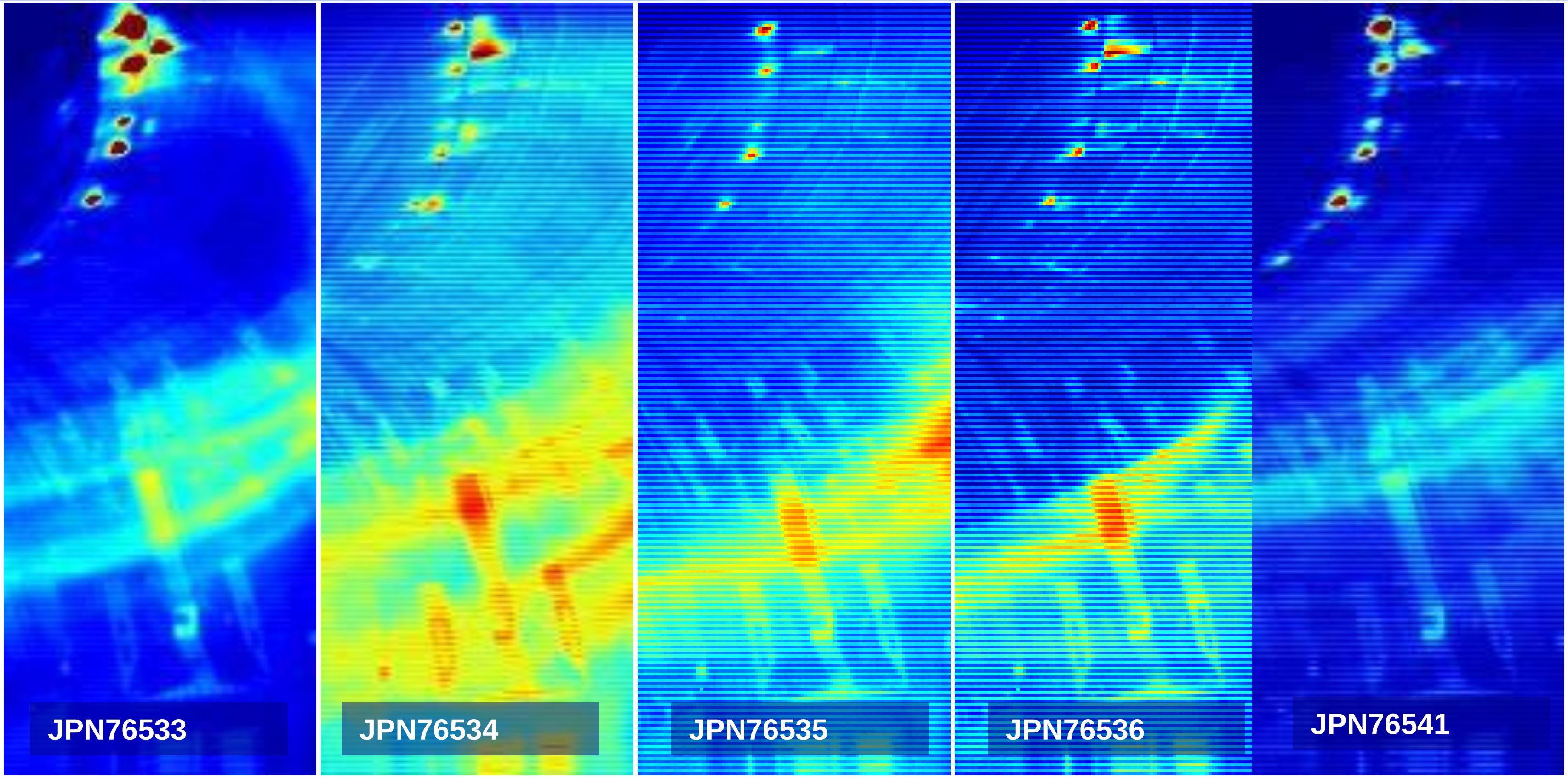


Note the tokamak continued to operate normally after this event

Runaway Electron Heat Loads



Runaway Electron energy is localised



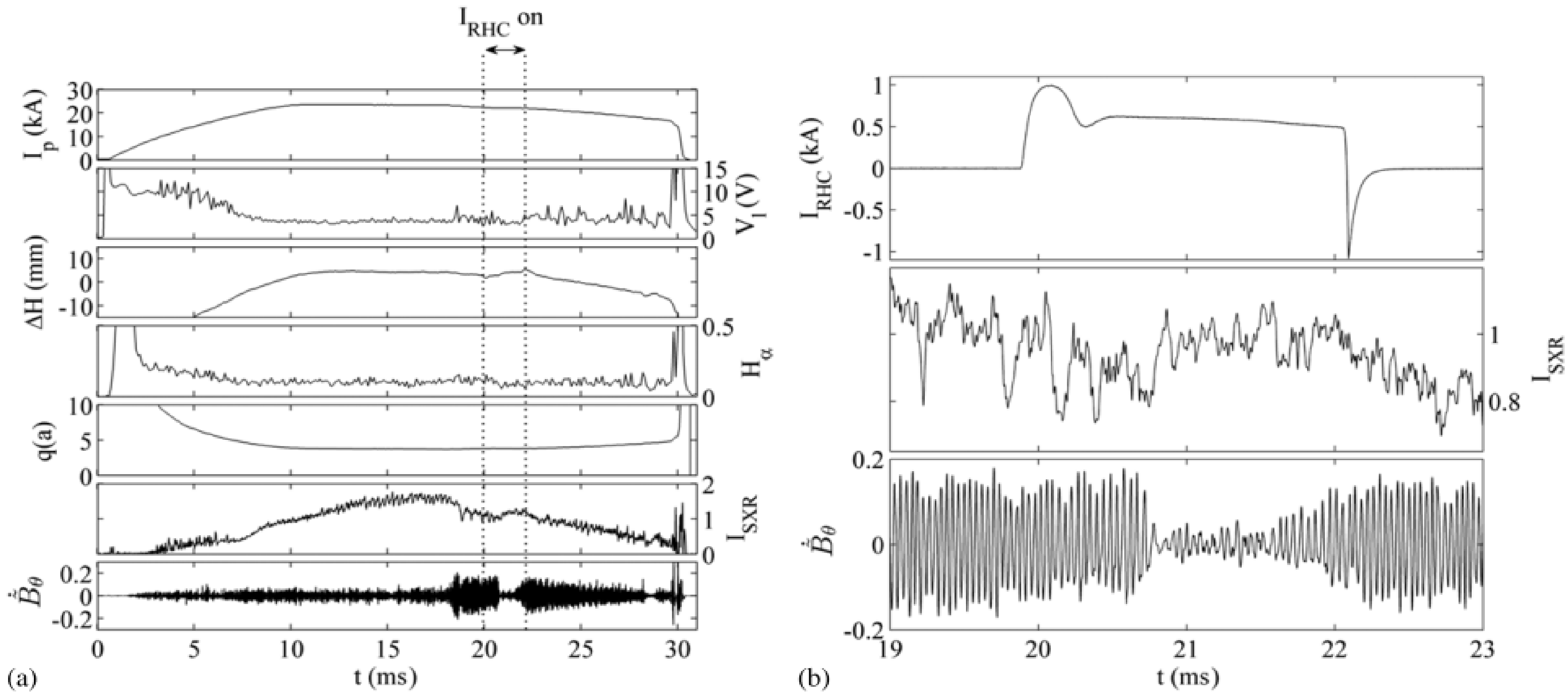
I_{RE}=502 kA | I_{RE}=425 kA | I_{RE}=285 kA | I_{RE}=360 kA | I_{RE}=502 kA

- The poloidal extent less than two tiles (area <1.3 m^2) of which only a fraction is wetted (installation inaccuracy)
- 0.5 MJ in 2 ms give $\Delta T \sim 800^oC$ ➔ wetted area is ~0.3-0.5m^2

Disruption Control and Mitigation

m=2, n=1 control by applied helical fields

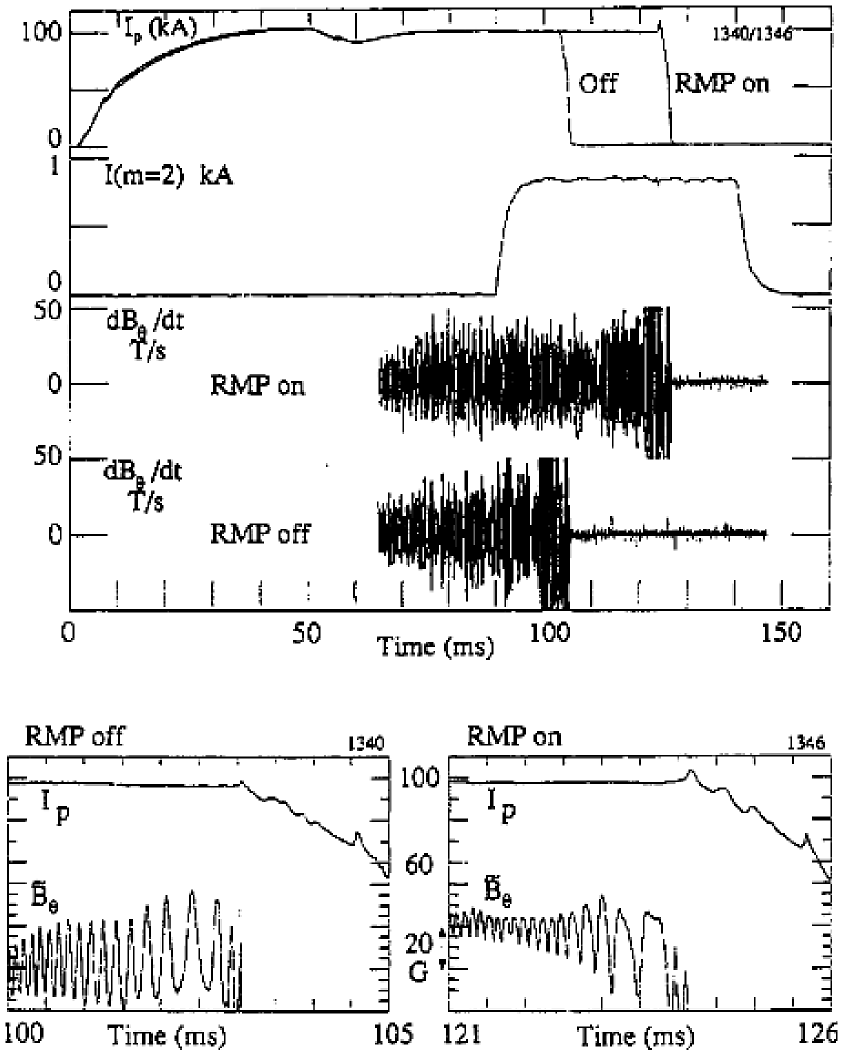
- Known for a long time that applying static helical field can control rotating instabilities (e.g. 1980's on DITE and 1990's COMPASS-C)



STOR-M tokamak Elgriw et al NF 2011

$$\frac{d}{dt}\left(\frac{W}{a}\right) \propto \Delta_0'(W)a - 1210.4\,\mathcal{I}\,\frac{(\Delta f \tau_H)^2}{(ns)^2 (W/r_s)^2}$$

Can extend disruption boundaries

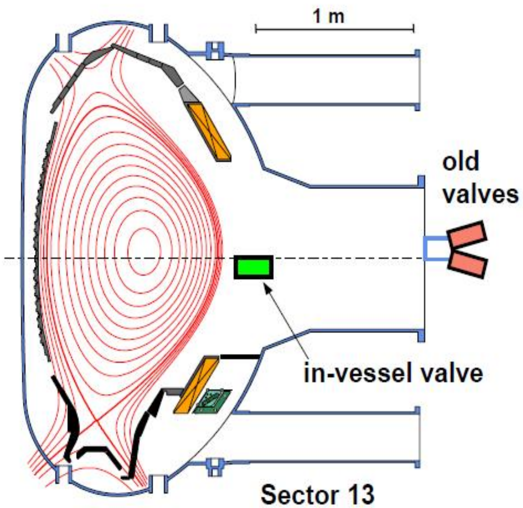


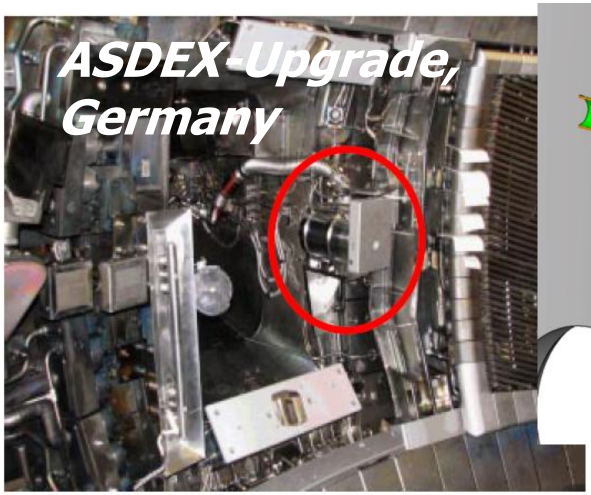
- Also experiments using rotating helical fields as means of direct disruption control (e.g. on DITE)

COMPASS-C Hender NF 1992

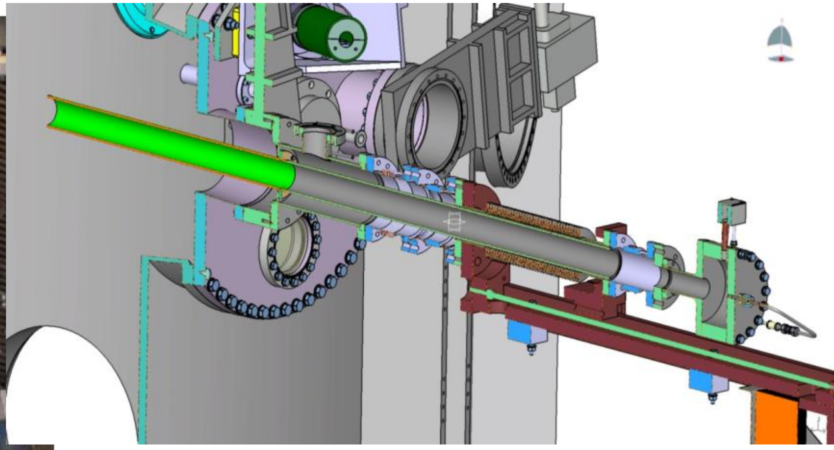
Disruption Avoidance & Mitigation

- Most popular mitigation method is massive gas injection (using noble gas)



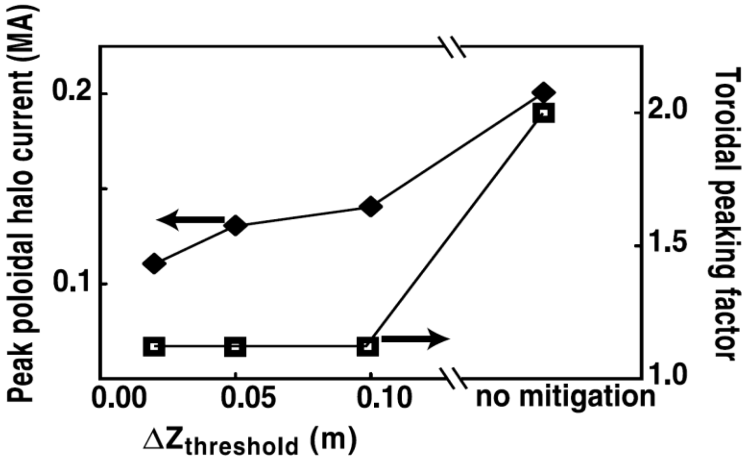


valve screened by a protecting tile



MAST

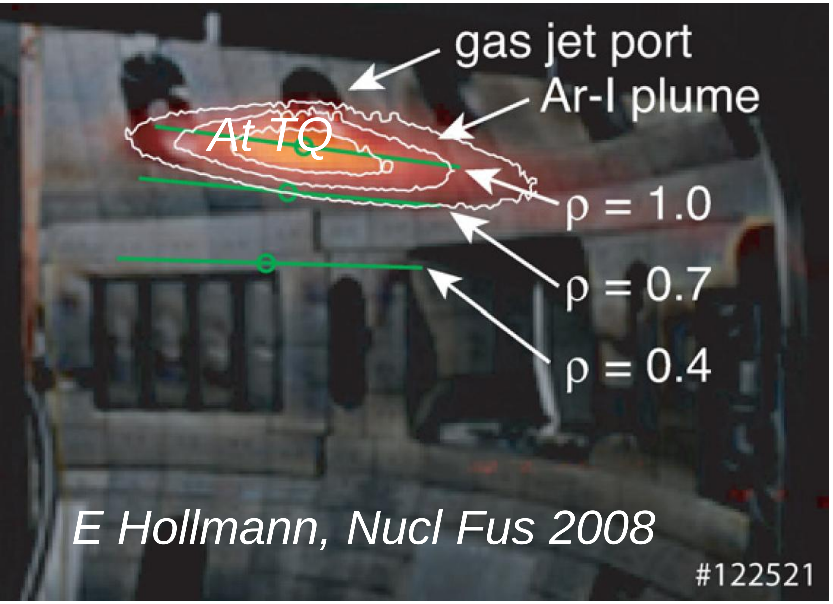
- Very effective at reducing disruption forces and heat loads but not proven on REs

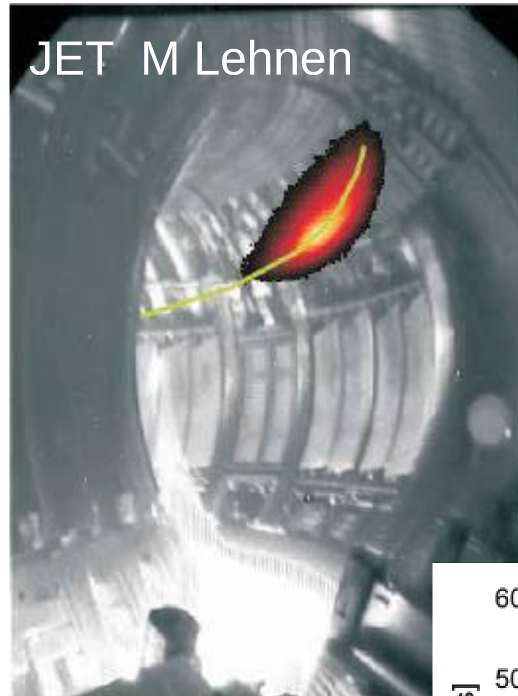


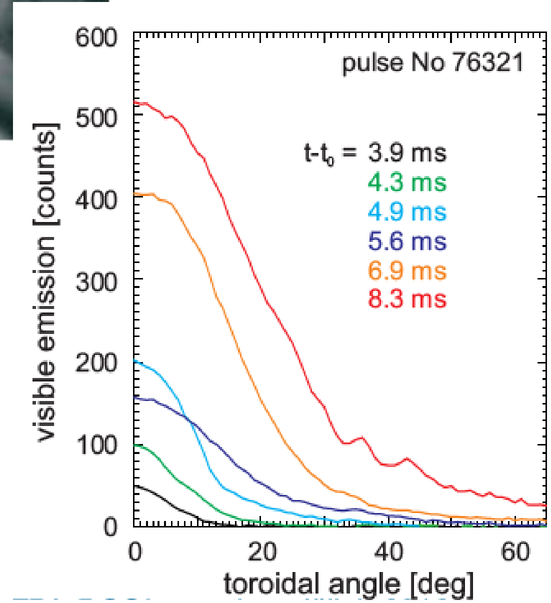
D Whyte et al Jrnl Nuc Mat 2003

Massive Gas Injection is localised (⇒3D)

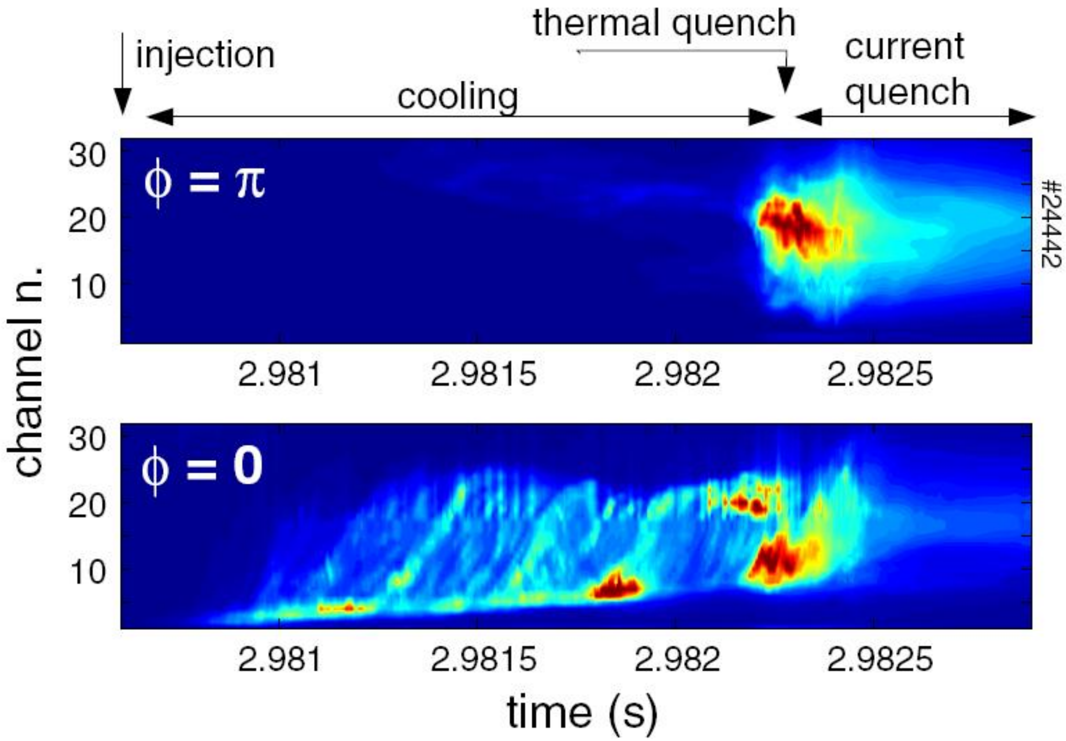
DIII-D

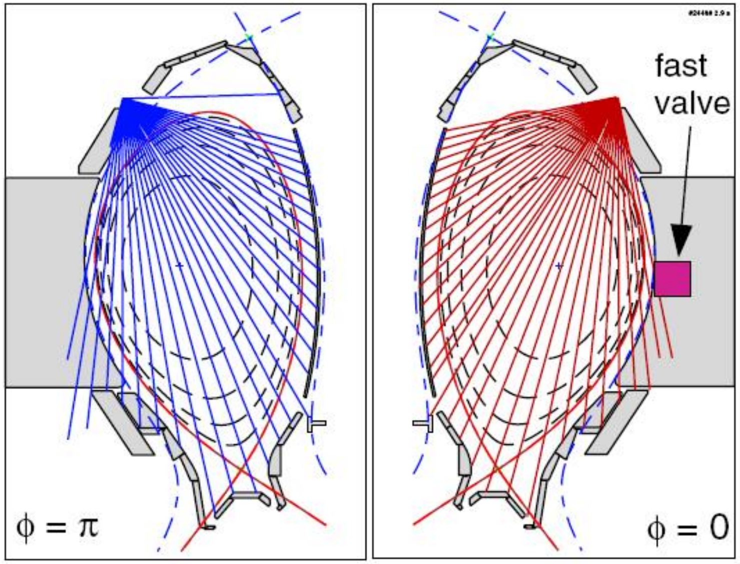






Massive Gas Injection is localised (⇒3D)

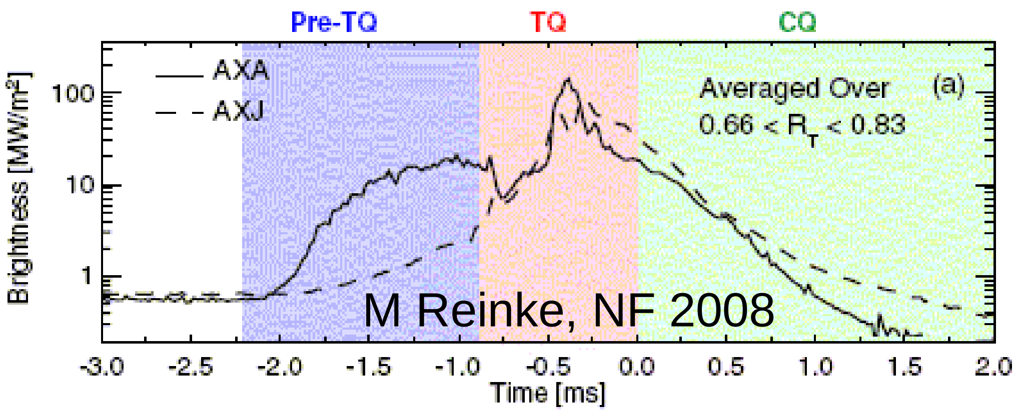


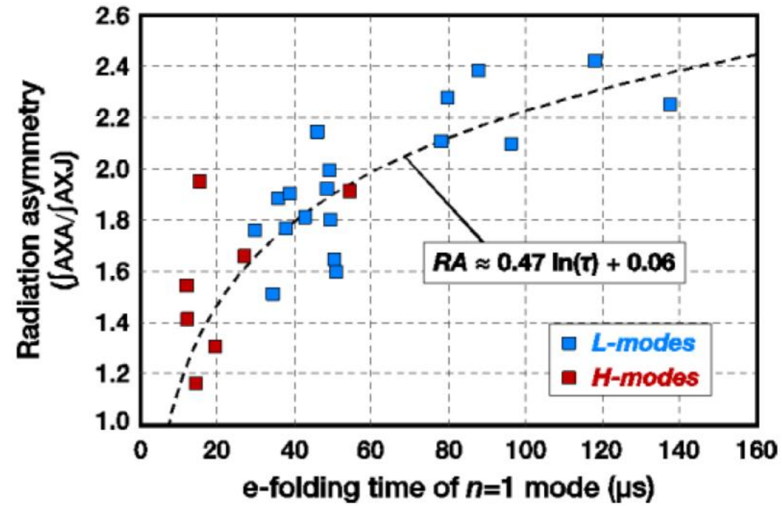


G Pautasso Nucl Fus 2011, $\phi=0^o$ *is MGI neon injection location*

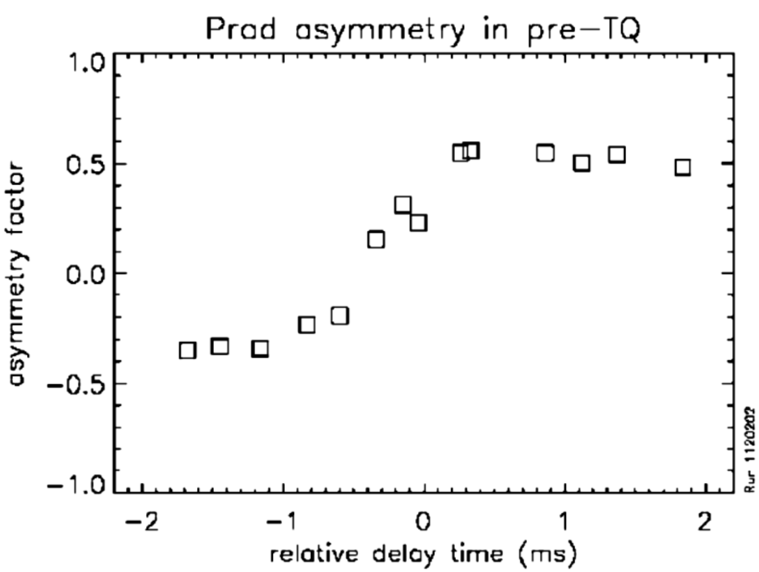
ALCATOR C-Mod two nearly opposite MGI's

1 gas jet results:-





2 gas jet results:-



- With 2 gas jets asymmetry can be controlled pre-thermal quench
- But MHD still affects asymmetry during thermal quench
- ITER plan with 3 equally spaced upper port toroidal locations and 1 equatorial port for MGI

Summary

- Disruptions are caused by helical instabilities and are ∴ intrinsically 3D
- More importantly consequences are 3D:-
  - Halo currents non-symmetric toroidal (leads to sideways forces on vacuum vessel, more difficult to handle)
  - Non-symmetric halo currents can rotate ⇒ can cause mechanical resonances
  - Runaway electron power loads can be non-symmetric due to asymmetries in surrounding structures
- Disruption control by applied helical fields demonstrated but not considered viable in general (risk of locked modes)
- Disruption mitigation by massive gas injection – local radiation loads a issue ⇒ multiple injection locations on ITER (needs careful timing)