Error field scalings and sideband effects - an update

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GENERAL ATOMICS

UKAEA Fusion Working with Europe

ITER

Outline

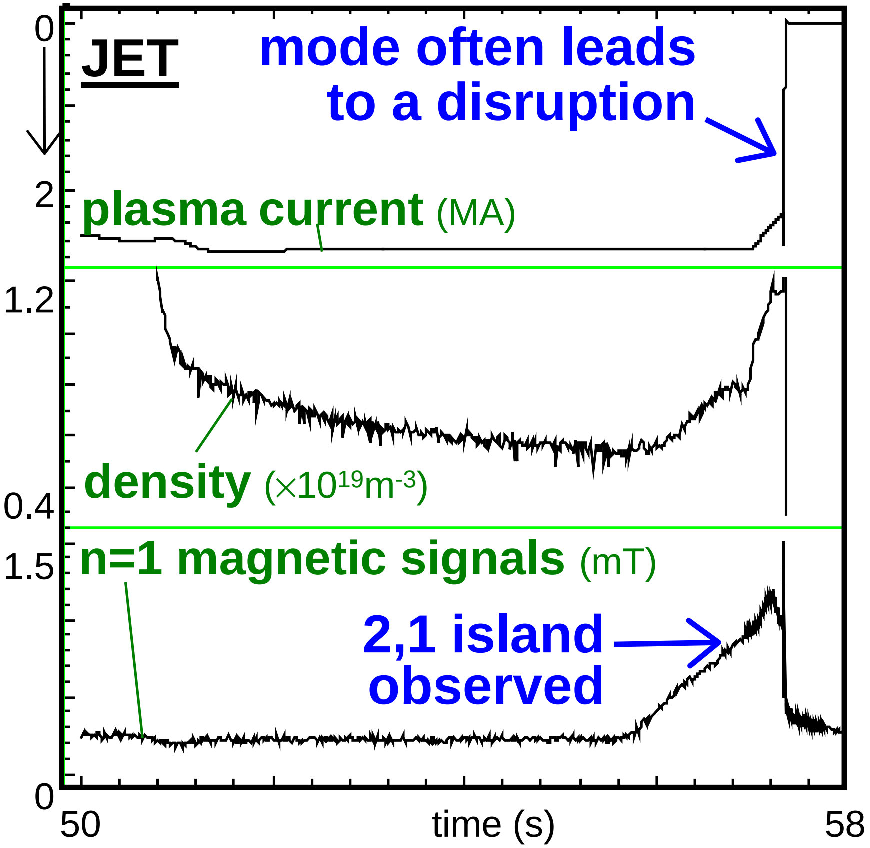
- Review and update error field studies
  - motivation - the error field problem
  - sideband effects → update from DIII-D
  - cross machine scalings → how do they do against C-Mod?
  - Underlying theory → cf new JET studies of rotation dependence
  - heating and mode avoidance → increased sensitivity at high β
  - ITER
  - → plus interesting observation of EF role in disruptions
- Updates to conclusions

Error field modes a problem for ITER

- Error fields naturally arise from asymmetries in coil design and position
  - overcomes plasma inertia and viscosity to drive mode growth
  - usually on q=2 surface

- Modes limit low density ***Ohmic*** operation:
  - *required for H-mode access for **ITER** or **other next step device***

- Issues:
  - *level of sensitivity for ITER?*
  - *which harmonics trigger modes?*
  - *what is likely ITER error?*
  - *how do we measure error fields and prevent modes?*



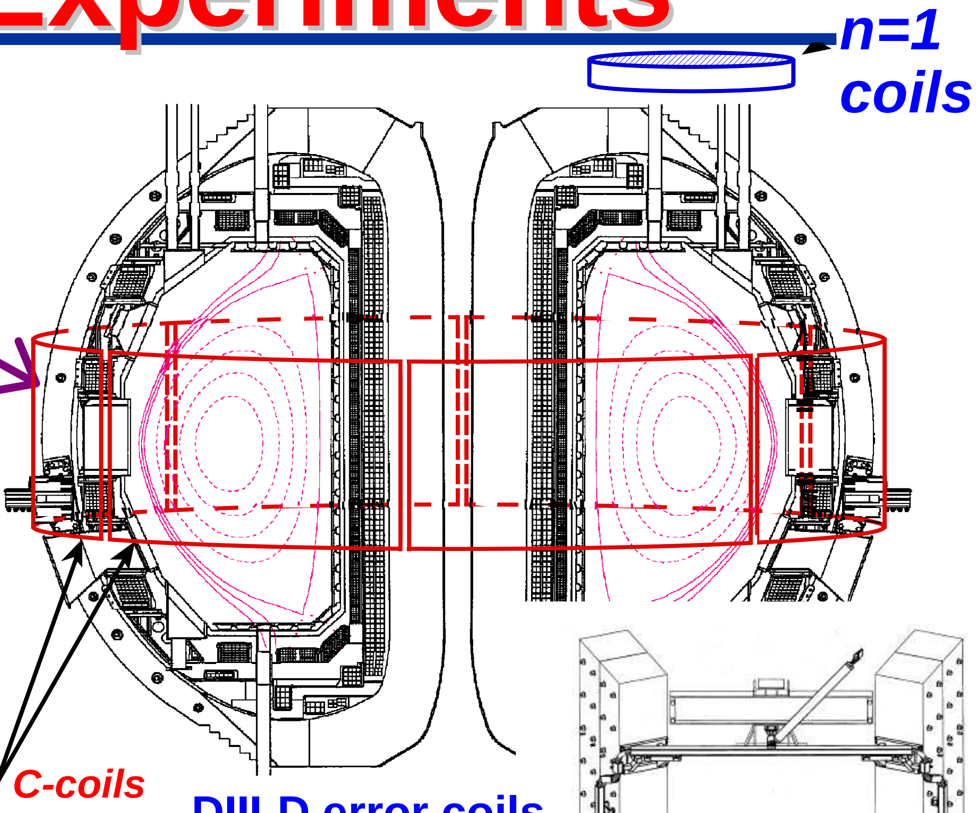
Error Field Experiments

Error fields simulated by using dedicated asymmetric coils:

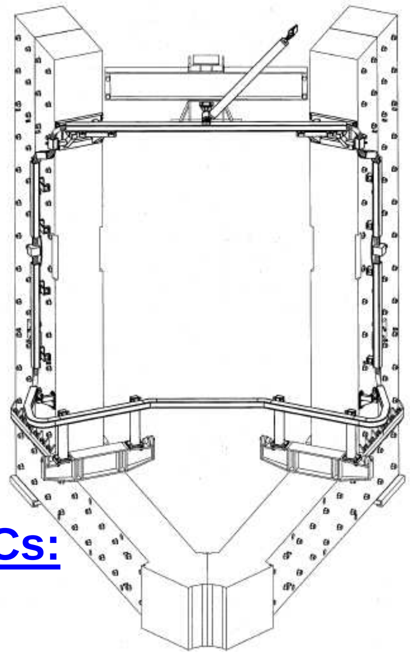
- DIII-D had ‘C’ coils (now also ‘I’)
- COMPASS-D has 8/10 bars in each quadrant *- ideal for sideband studies*
- JET has lower saddles + EFCCs *- vital point for ITER scaling*

Current in these ramped until mode formed:

- changing coil/bar combinations changes harmonic mix
- scan various parameters (TF, q, density)
- in Ohmic L-mode

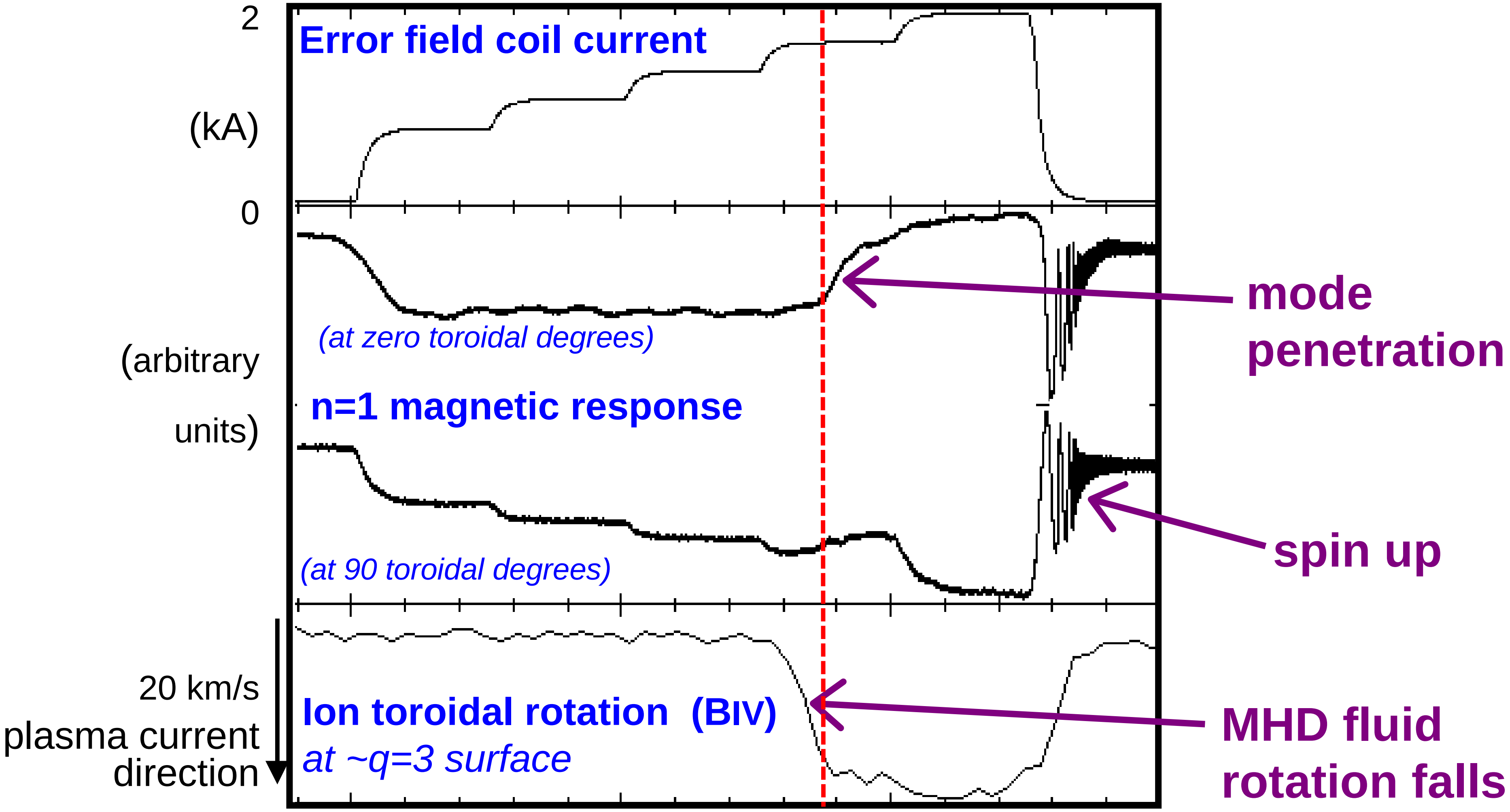


DIII-D error coils



JET EFCCs:

Error field mode penetration on COMPASS-D



Sidebands have strong effect

Scan 3,1 field for 2,1 penetration:

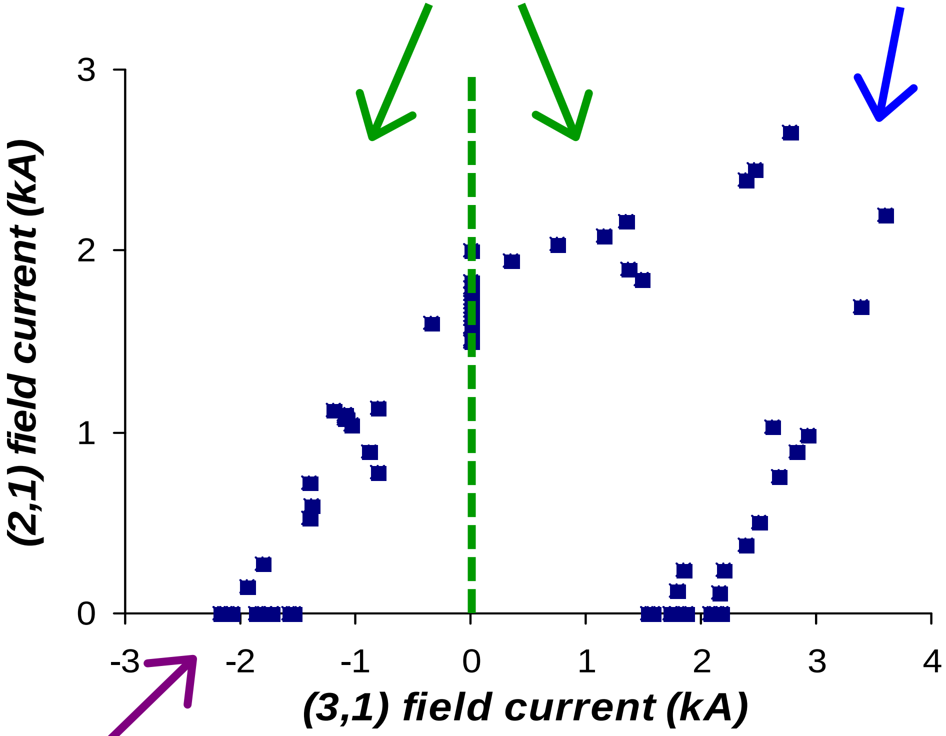
- 3,1 field penetrates at similar levels to 2,1
- mode always forms on q=2
- two coupling mechanisms
- (1,1) harmonics also play a role

Model must include these effects . . .

COMPASS-D: Ohmic L-mode

asymmetry indicates toroidal coupling

closure indicates viscous coupling



coupling is strong:

- effect of 3,1 is comparable to 2,1

Good fit obtained for DIII-D DND plasmas

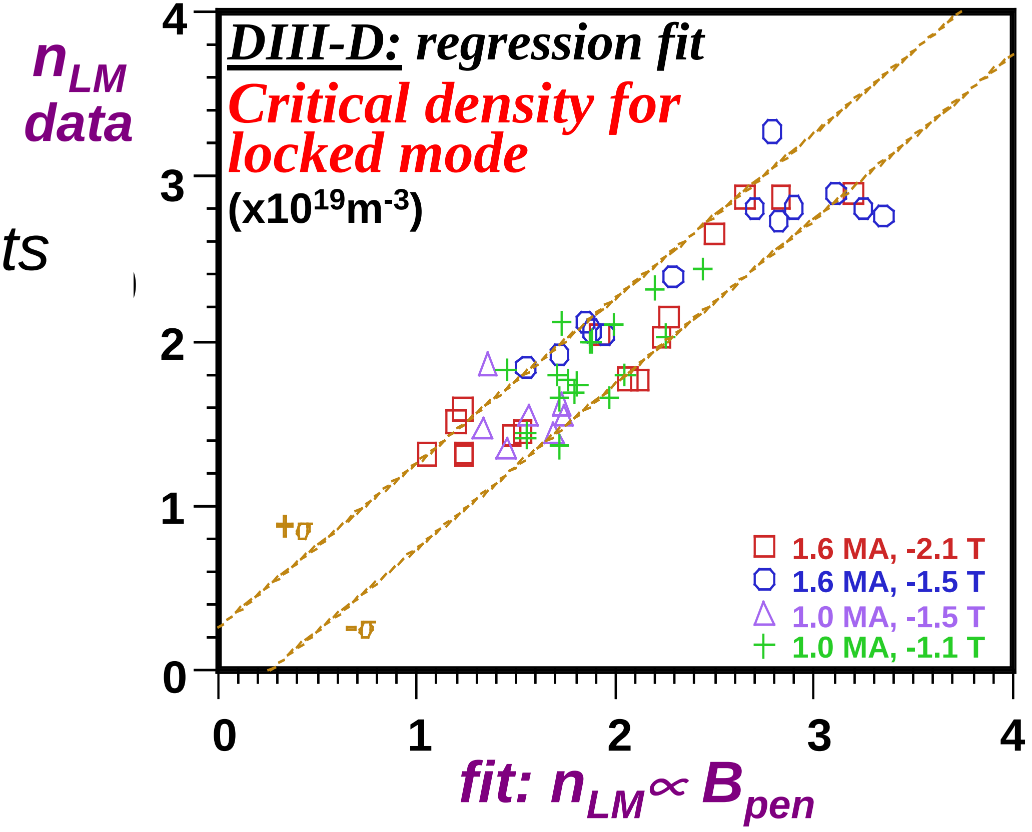
Fit for critical torque on DIII-D in DND gave:

$$T \propto B_{pen}^{2} \propto \underbrace{|B_{2,1} - 0.05B_{3,1} + 0.25B_{1,1}|^{2}}_{\textit{Toroidal coupling}} + \underbrace{0.28|B_{1,1}|^{2} + 0.51|B_{3,1}|^{2}}_{\textit{Viscous drag}}$$

equivalent threshold of pure 2,1 field

- *Equivalent sideband effects are seen in COMPASS-D SND plasmas*

⇒**Separate sideband correction desirable in any next step device**



DIII-D I coils can test sideband fits

- COMPASS-D SND sideband weights differ from DIII-D DND:

C-D: $T_{tot}(q=2) \propto B^2_{pen} = 0.13|B_{1,1}|^2 + 1.69|B_{3,1}|^2$ much more 3/1

$$+|(0.21+0.02\mathrm{i})B_{1,1} + B_{2,1} + (0.85-0.17\mathrm{i})B_{3,1}|^2$$

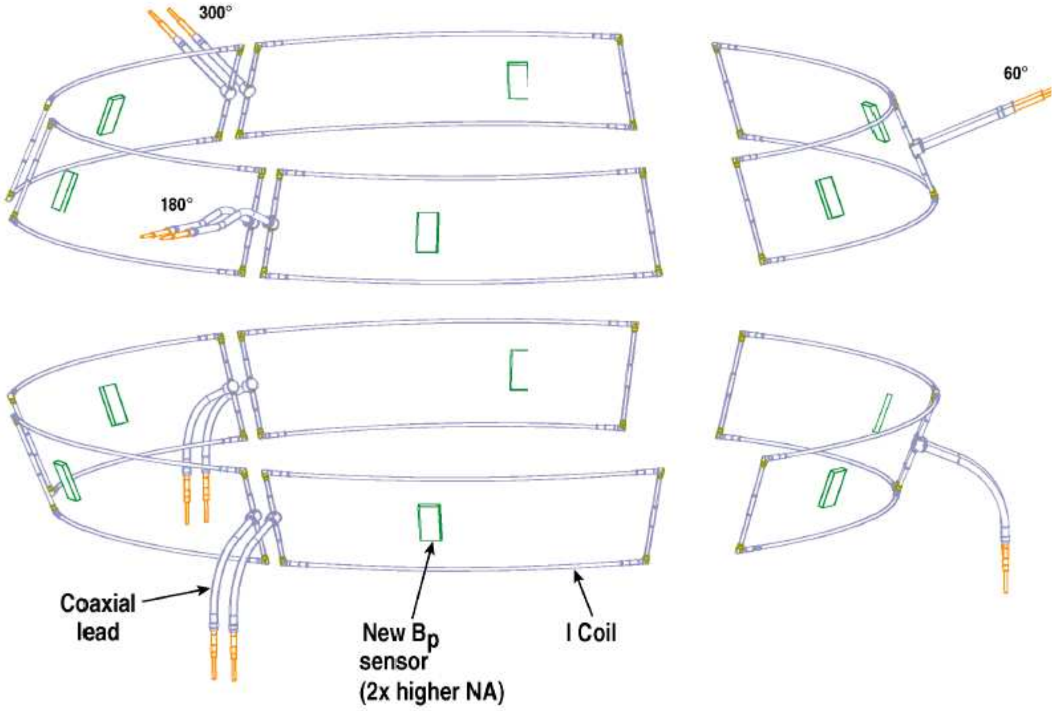
DIII-D: $\mathbf{T \propto B_{pen}^2 \propto |B_{2,1} - 0.05B_{3,1} + 0.25B_{1,1}|^2 + 0.28|B_{1,1}|^2 + 0.51|B_{3,1}|^2}$

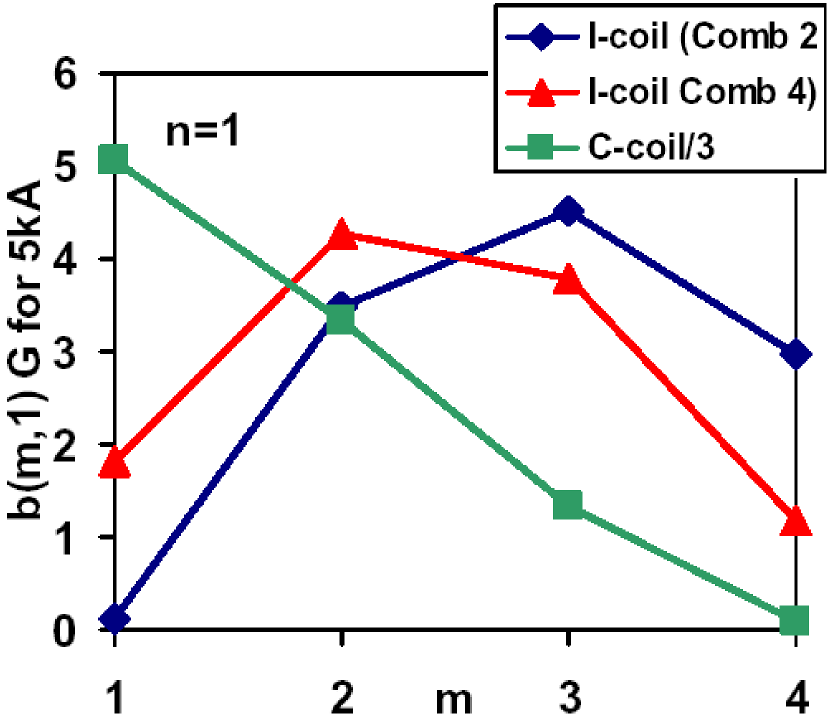
- *Note also discrepancies between COMPASS-D scalings and JET/DIII-D*
  - *different physics regime?*

- New I coils provide opportunity to test the fits in ‘ITER’ conditions and SND

DIII-D I coils can test sideband fits

- I coils very flexible wiring with more sidebands possible:





New I coils sideband fits

- New I coil SND results cf old DIII-D DND C coil results:

with complex mode-coupling coefficients:

$$B_{pen}^2 = 0.0\, B_{11\_q1}^2 + \left|(-.55 - 0.1i)\, B_{11} + B_{21} + (-.68 - .32i)\, B_{31}\right|^2 + 0.1 B_{31\_q3}^2$$

more 1/1

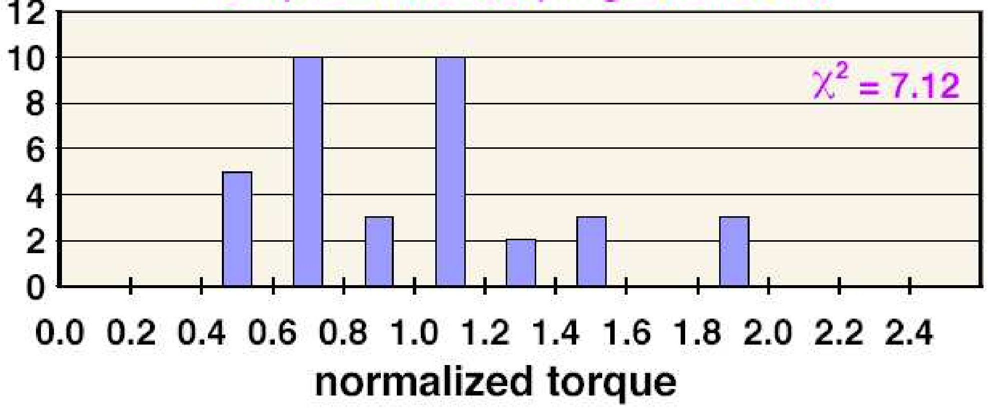
less viscous coupling

force real mode-coupling coefficients:

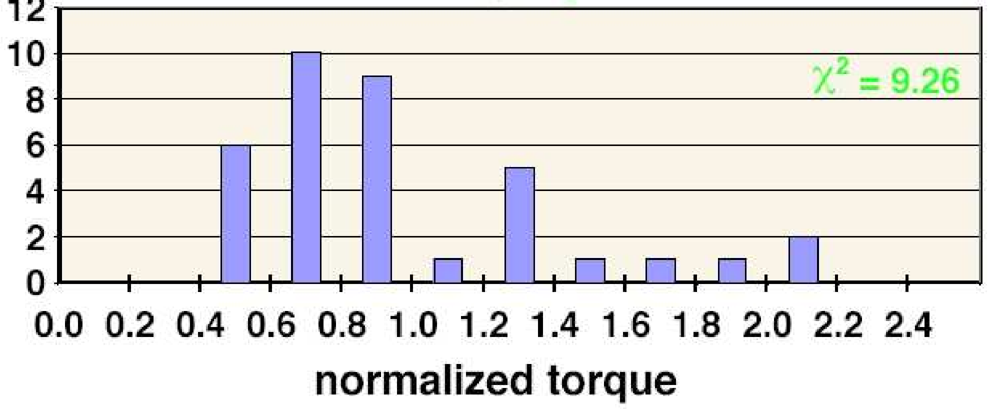
$$B_{pen}^2 = 0.0\, B_{11\_q1}^2 + \left| -.60\, B_{11} + B_{21} - .74\, B_{31}\right|^2 + 0.1 B_{31\_q3}^2$$

- Considerable differences between old and new and C-D
  - but profiles changed (Ohmic H mode)
  - calculated intrinsic error has changed:

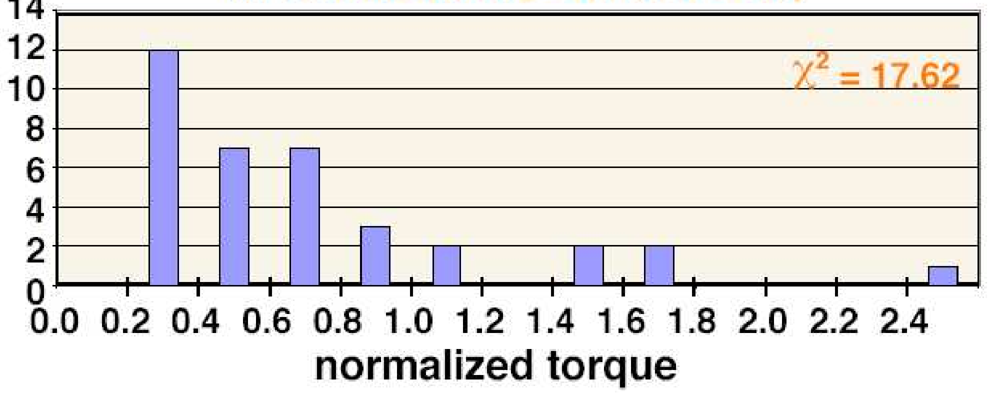
	m=1	m=2	m=3	m=4
new	.086 @ 209°	.811 @ 126°	.326 @ 333°	1.01 @ 74°
old	2.03 @ 75°	2.31 @ 73°	1.60 @ 323°	0.85 @ 28°



complex mode-coupling coefficients



real mode-coupling coefficients



no mode coupling - 2/1 mode only

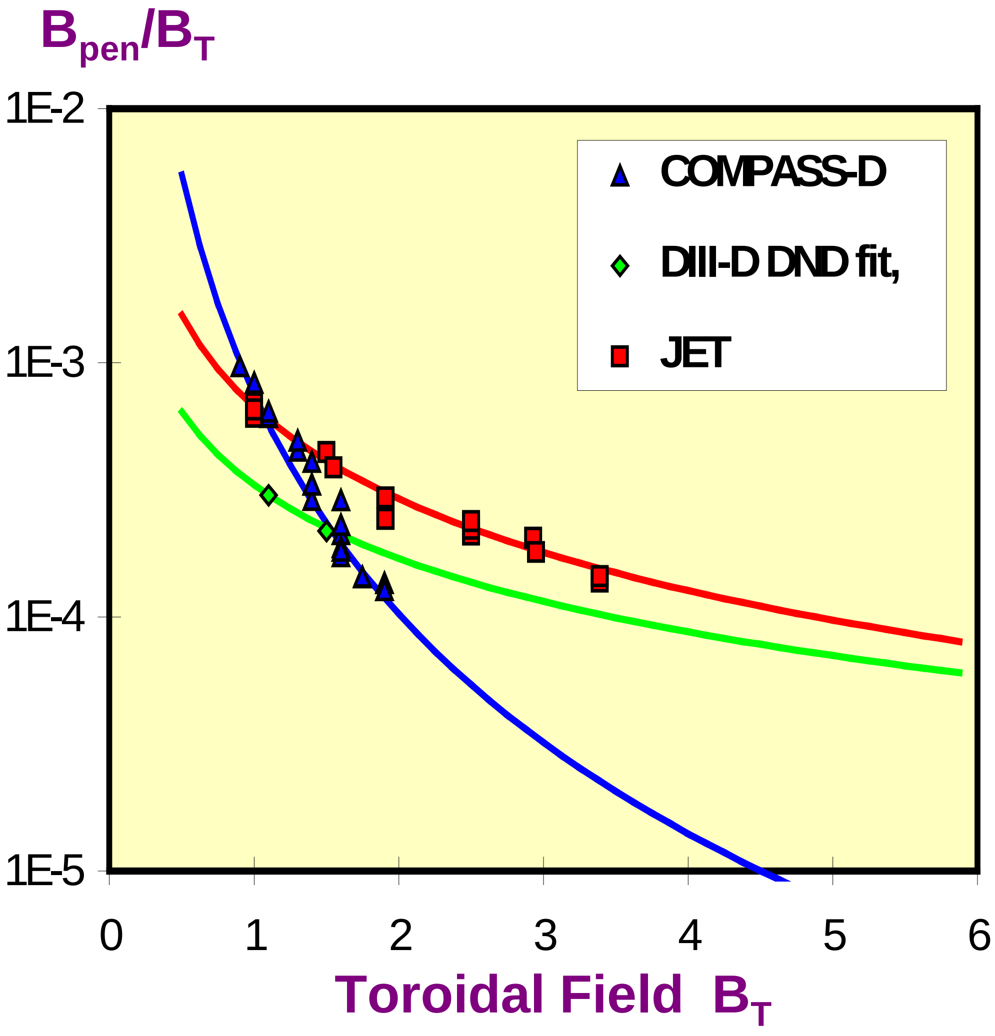
Fits show sidebands are important

Compare fits using sidebands with results only including 2/1 harmonics

Summary on sideband effects

- New DIII-D I coil results confirm sidebands are important
  - but fits differ from C-coil and COMPASS-D results
  - ...and give different intrinsic error measurements
    - *...although agree on phase*
- Further analysis ongoing to resolve discrepancies
  - is it result of more data or different shapes, etc.
  - compare each fit from COMPASS-D & DIII-D against other machine's data
  - more data required?
- More JET experiments in January 2004 will help by using new EFCC coils set (hopefully with saddles simultaneously)

Toroidal field scalings



- JET shows weak TF scaling
- DIII-D's points support this
- Clear difference in gradient with COMPASS-D
  - may be due to different rotation behaviour *(- ion losses?)*
- ***Highlights uncertainty in scaling***
  - ***intrinsic problem of using global scaling for local behaviour***

Comparison of scalings

- Scale multimode threshold, using power law form:
  - $B_{pen} / B_T \propto n^{\alpha_n} R^{\alpha_R} B^{\alpha_B} q^{\alpha_q}$

  – deduce $\alpha_R = 2\alpha_n + 1.25\alpha_B$ from dimensional considerations, in line with approach for confinement scaling

  (Connor and Taylor NF 17 1047)

Exp scans:	α_n	α_B	α_q
JET	0.94	-1.2	0.05
DIII-D	0.99	-0.96	0.83
COMPASS-D	~1	-2.9	1.6

- density scaling consistent across machines
- q scalings expected to differ due to different mode spectra

Extrapolates to moderate ITER sensitivity

- *Use data from JET to minimise extrapolation:*

  ⇒ Gives $\alpha_R = 0.4 \pm 0.2$

  ⇒ Predicts ITER threshold of B_{pen}/B_T ~ **$1.25\text{x}10^{-4}$**

  at ITER reference density of $2 \times 10^{19} m^{-3}$ and $q_{95} = 3.3$

  (using COMPASS-D SND sideband formula)

  - Comparable with DIII-D DND extrapolations **($\sim 2\text{x}10^{-4}$)**

- COMPASS-D shows uncertainties in scaling - changes in regime can cause different rotation behaviour and TF scaling

  ⇒ *Important to examine rotation and β effects*

  – additional heating studies on **JET**, **COMPASS-D** and **DIII-D** . . .

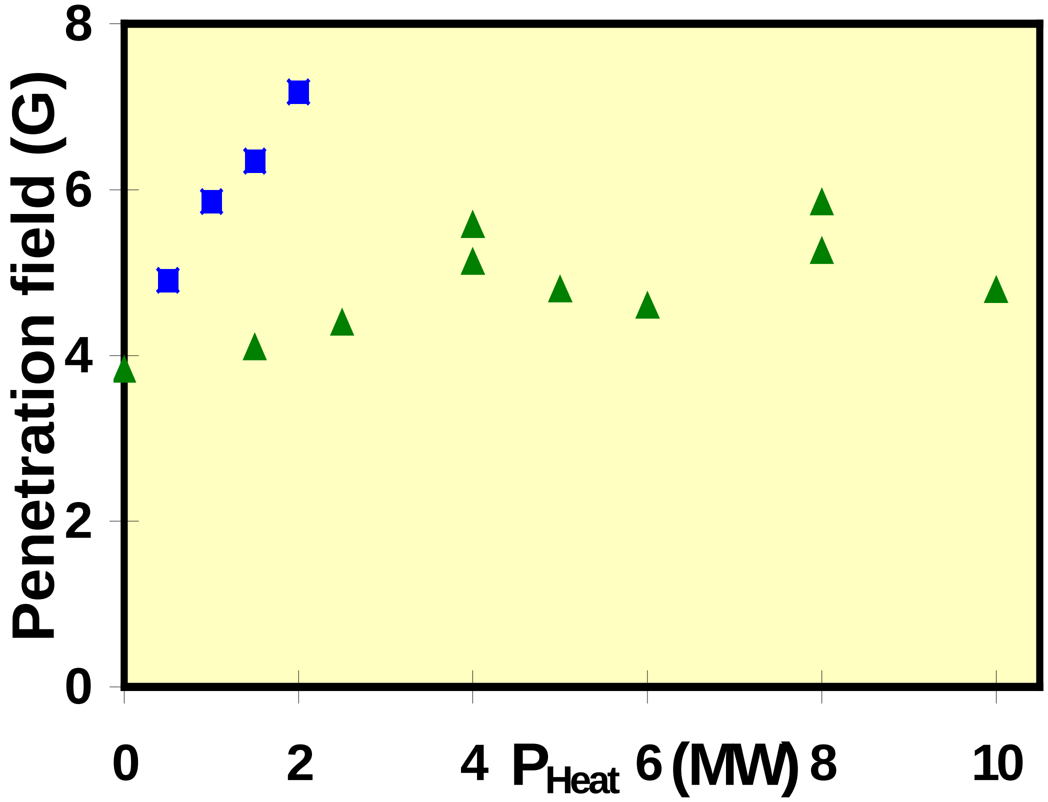
Extrapolation to CMOD

- Take TF & density dependence fits and scale to CMOD parameters: **B_T=4T n_e=5e19m^{-3}**

Step	**JET fit**	**DIII-D fit**
Fit formula	$B_{pen}=5.23B^{-0.2}(n_e/1.6e19)$	$B_{pen}=(n_e/0.6e19)(q/3.3)^{0.79}(B/2.1)^{0.01}$
B_{pen} at CMOD TF and n_e	12.5 Gauss for R=2.9m	8.4 Gauss for R=1.67m
Size scale exponent	0.4	0.76
B_{pen}CMOD	6.9 Gauss	4.2 Gauss

- Combined 1/1, 2/1 and 3/1 field using fits from C-D or DIII-D
  - on JET 2/1 is about ~70% of B_{pen}
  - on DIII-D 2/1 is about ~80% of B_{pen}
- ➨These are in right ball park for CMOD 2/1 thresholds
  - uncertainties: α_R, sideband form, CMOD spectrum, shape, q_{95}
- JET-CMOD identity experiments desirable - and planned!

Heating: NBI rotation is key effect



NBI and RF to separate ω and β dependence:

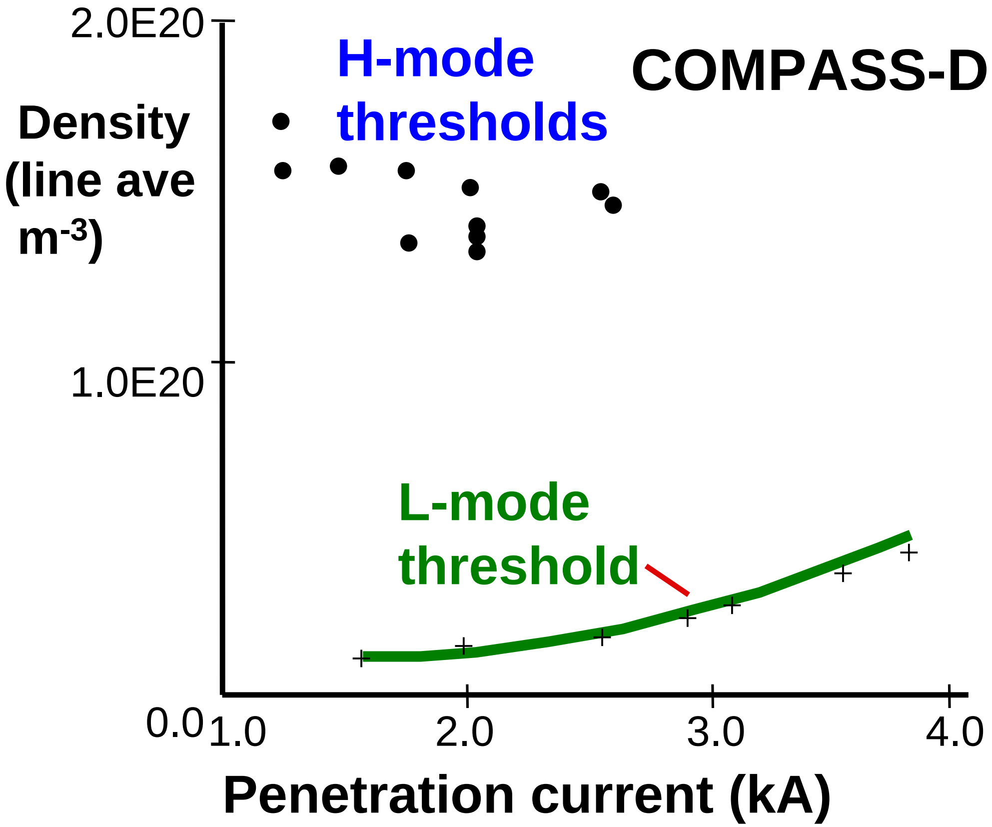
- modest rise in β has weak effect
- H-mode transition has little effect
- rotation from NBI raises threshold

⇒NBI rotation possible technique for avoidance on ITER

Role of rotation

- Modes form when resonant surface is braked by resonant response to EF to half it’s natural frequency
  - tiny static island induced by EF
  - viscous forces try to keep bulk plasma rotating slipping about island
    - *this opposes island growth*
  - torque exerted through island and viscosity by EF brakes plasma
  - if rotation slows enough, island can grow, increasing torque and bifurcating to a locked mode state
  - threshold scales as $B_{pen} \sim B_T \, \omega_0 \, \tau_A \, (\tau_{rec} / \tau_v)^{1/2}$
    - ω_0 *often taken to be electron diamagnetic rotation*
- Expect cancelling natural q=2 rotation should lower thresholds
  - *didn’t see in normal B operation on JET so look in reverse B...*

Error fields penetrated easily when rotation stopped in COMPASS-D Ohmic H-mode



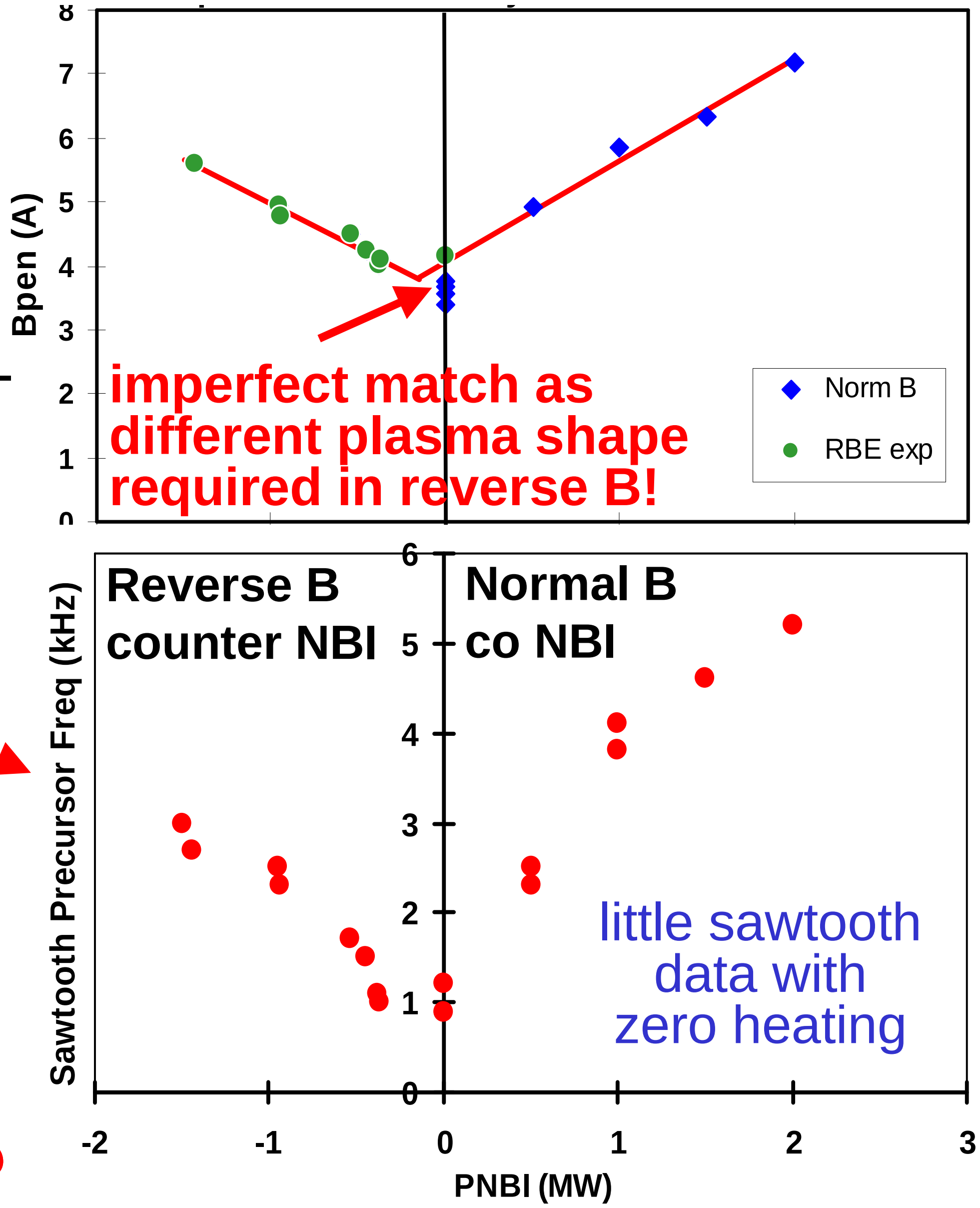
Ohmic ELM-free H-mode

- Error-field penetrates at 10x density for L-mode penetration
- MHD fluid slows leading to a very low penetration threshold
  - Confirms key role of rotation

- Leaves open question of what will happen to rotation in ITER H-mode?

JET rotation scan

- Threshold does not plunge towards 0 at any power!
- Possible minima for counter injection power:
  - 0→0.5MW: strong rise with co-, no rise with counter
  - natural plasma rotation in ion (co-) direction
    - get less core rotation for given P_{NBI} in reverse B
    - also observed with charge exchange measurements
    - Ohmic modes spin up in ion direction
  - all consistent with counter NBI opposing a naturally co-dir'n ω



imperfect match as different plasma shape required in reverse B!

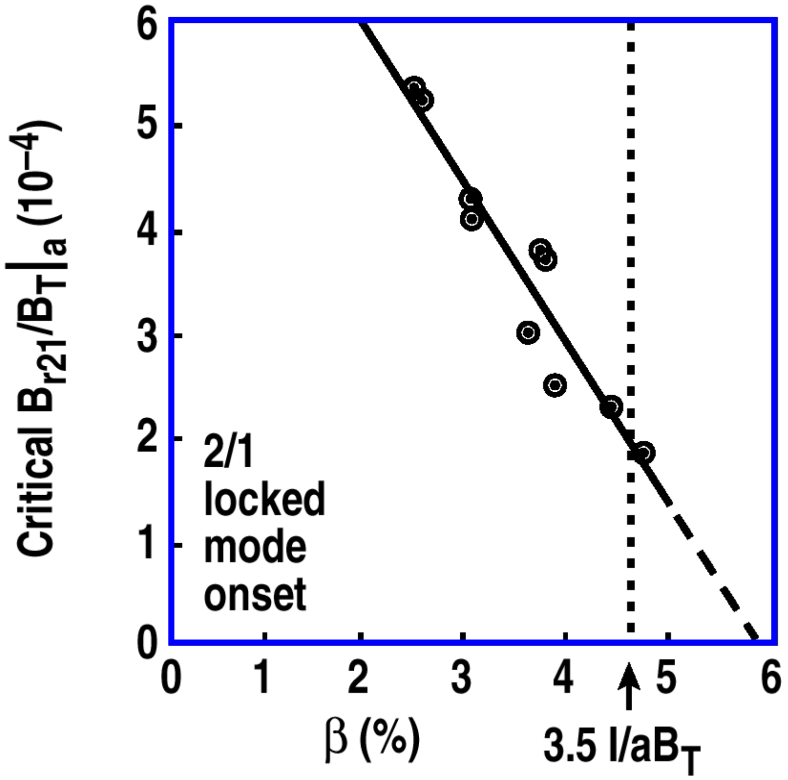
Reverse B counter NBI

Normal B co NBI

little sawtooth data with zero heating

What about at high β?

- Old result from DIII-D shows thresholds fall as ideal limit approached
    - generally locked modes
    - error field amplification effect?
- *What about proximity to NTM?*



1992 La Haye experiments

Error field thresholds fall at high β

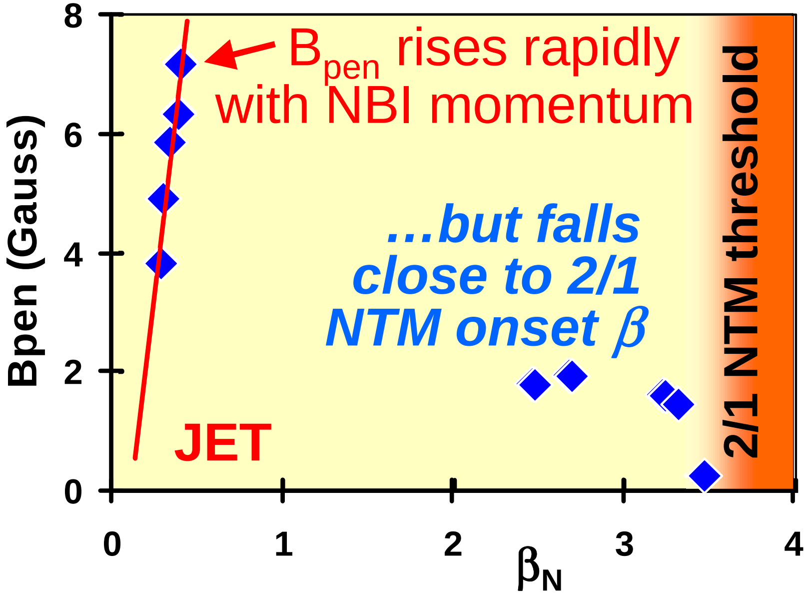
- Error field thresholds fall close to the 2/1 NTM onset β on JET

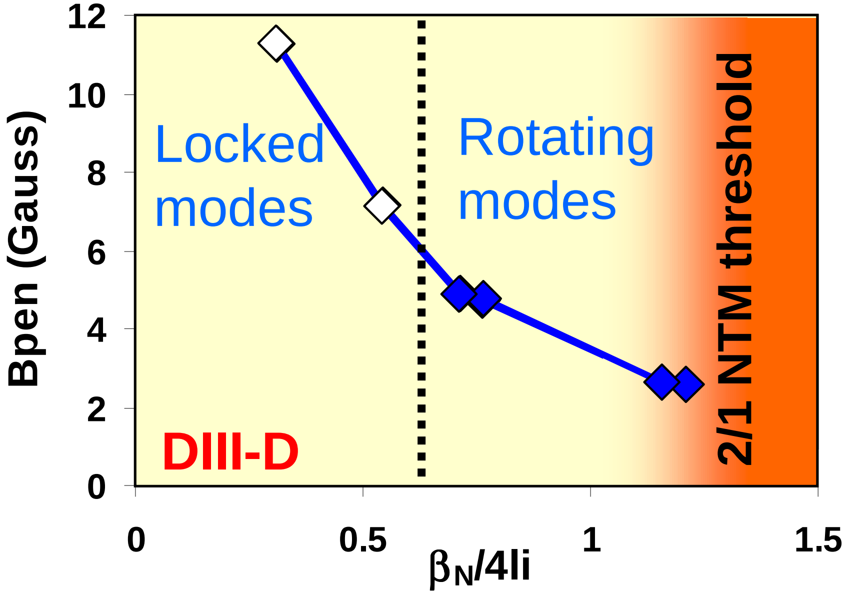
  ⇒ increased error field sensitivity

- Also observed on D3D…

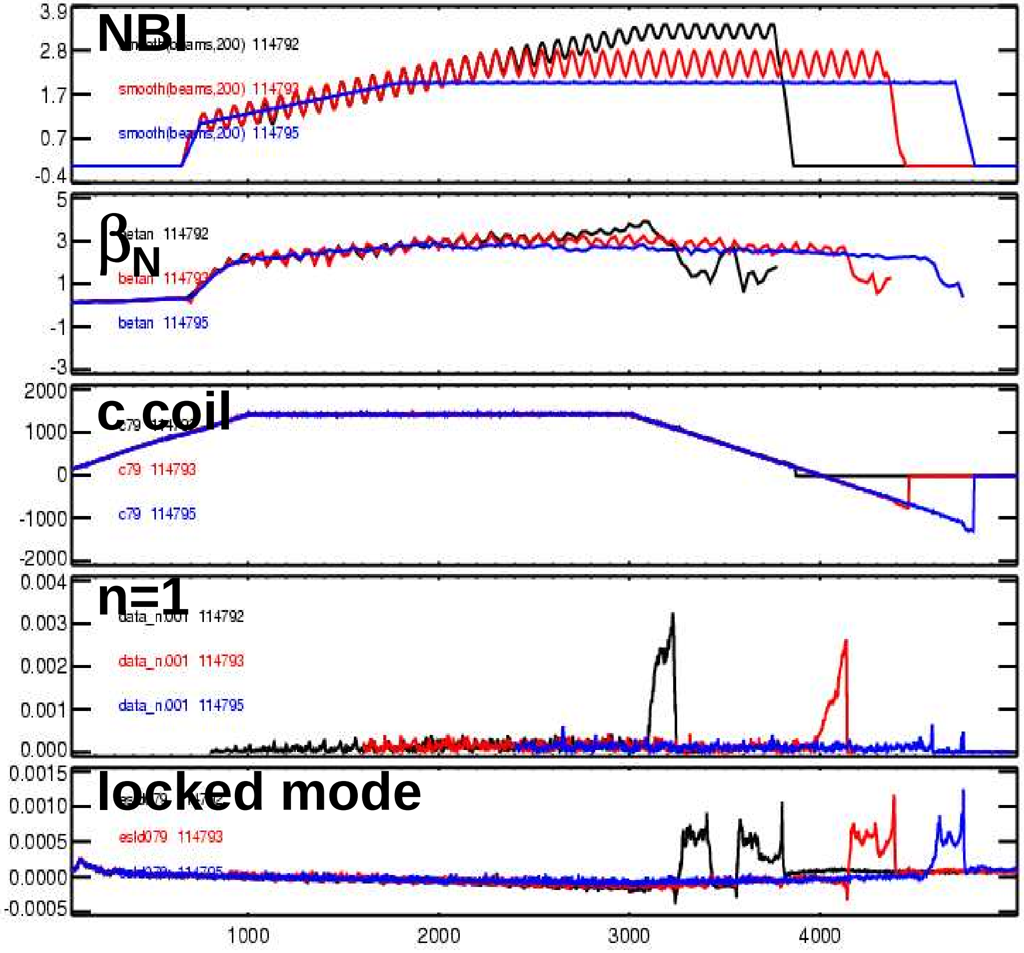
  – here modes formed rotating at intermediate β_N

  ⇒ EF is directly assisting NTM onset mechanism





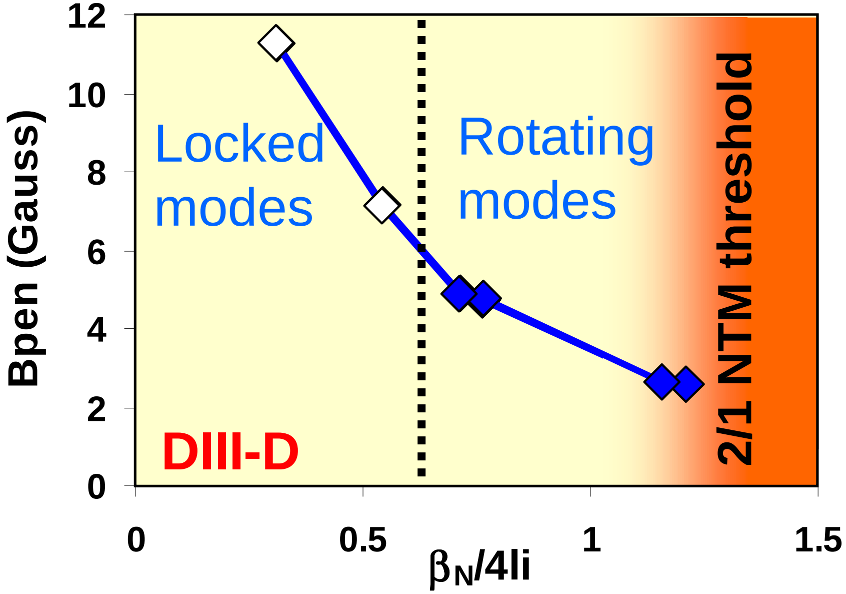
DIII-D: error field - NTM interplay



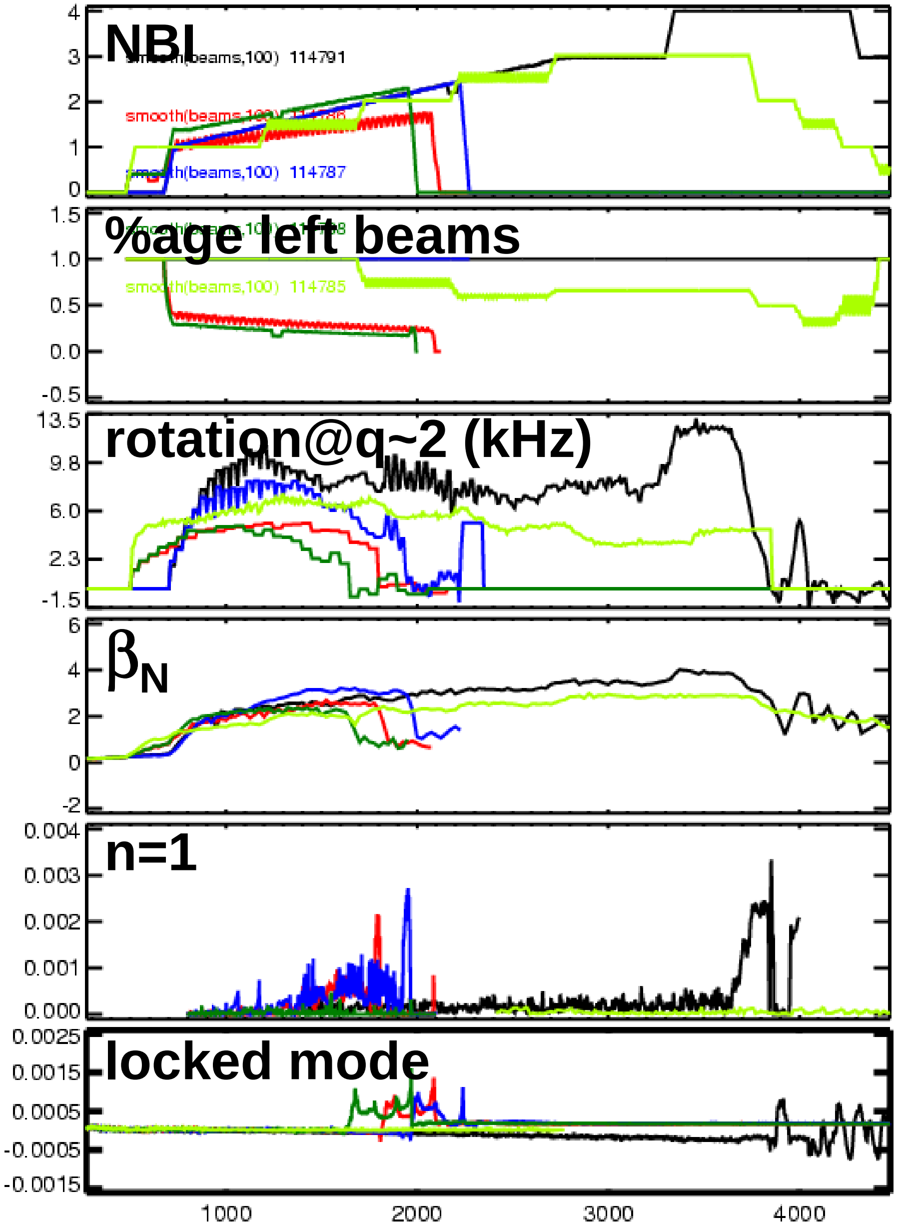
- Fix at subcritical β
  - – apply EF ramp

⇒EFs assist NTM onset

- – at medium β modes born rotating - NTMs
- – low β: standard locked modes



NTMs at lower β with pre-existing errors



- Pre-existing error field in coloured cases **(not black)**
- Leads to error field modes during beam ramp up
  - plasma slows first
  - goes rapidly to locked mode
- Using ‘left’ beams helps avoid modes

Why no mode for light green?

Original conclusions

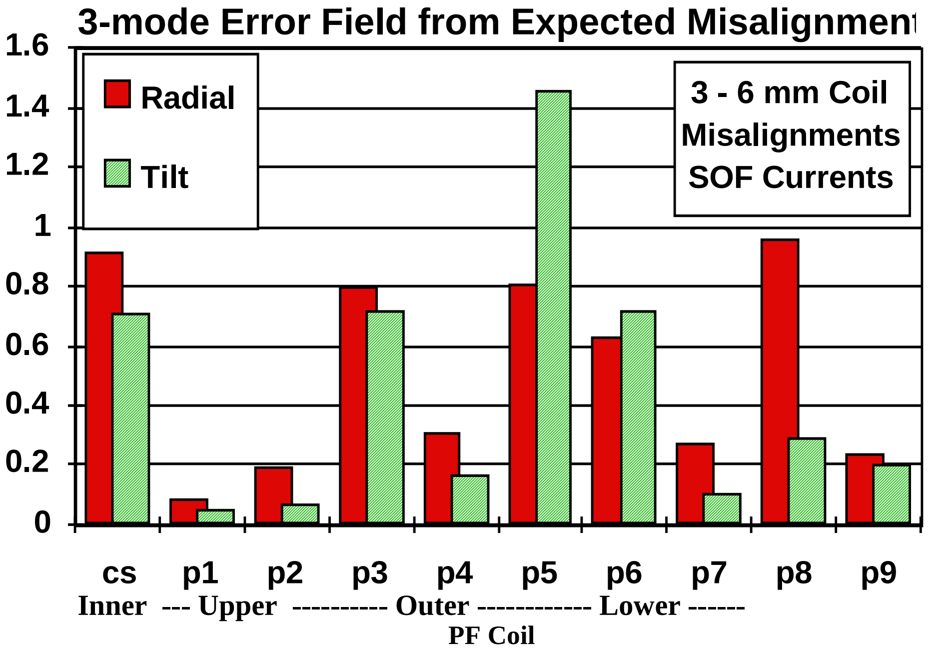
- Error fields limit low density operation in tokamaks
  - likely to be a problem for H-mode access on ITER or other next step devices
- (1,1) (2,1) and (3,1) harmonics all contribute to mode formation
- Predicted ITER sensitivity comparable to likely intrinsic error ($B_{3mode} \approx 1.10^{-4}$)
  - some level of correction important

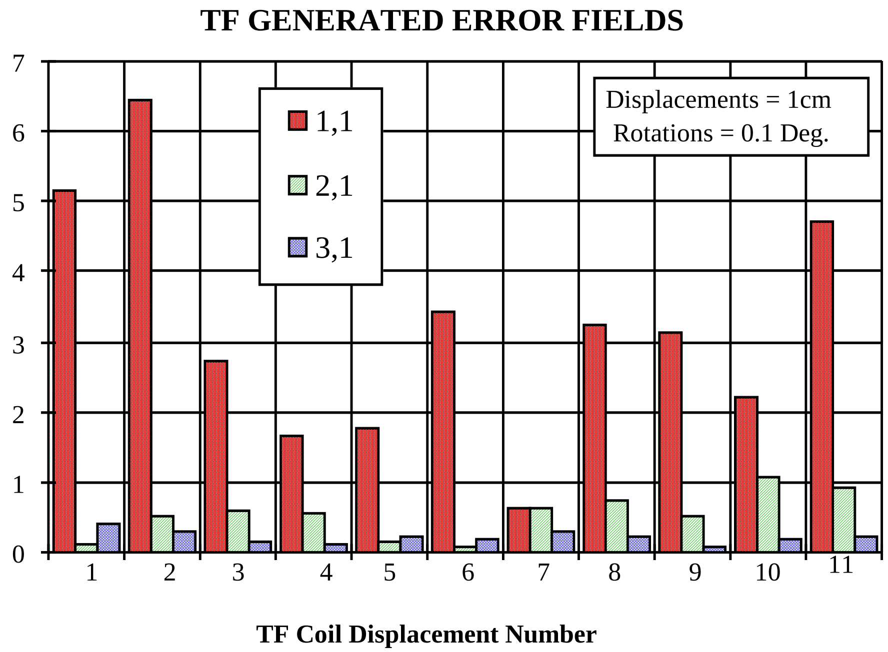
    → *3 harmonic design was a prudent approach*
- Neutral beams may also assist mode avoidance

Likely ITER error field $B_{3mode}\approx1.10^{-4}$

Design studies have identified key sources of error on ITER:

- calculate 3-mode error according to: $B_{3mode}=(0.2B_{1,1}{}^2+B_{2,1}{}^2+0.8B_{3,1}{}^2)^{1/2}$
- combine to give probability distribution: $P(B_{m,n})=\int f(B_{m,n})\,dB_{m,n}$





- *plus additional sources from test blanket and NBI shields*

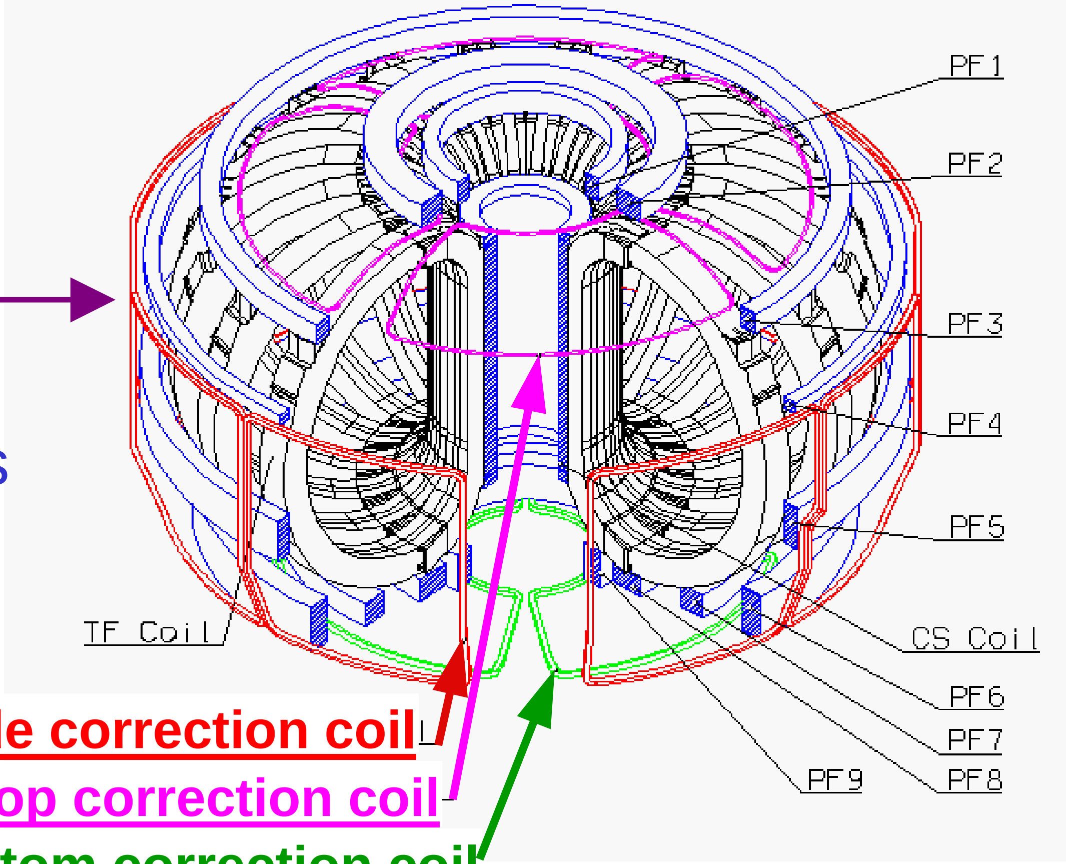
ITER Correction System

ITER intrinsic error comparable to predicted tolerance

- sideband harmonics also play a role

⇒ 3-harmonic correction designed as prudent approach

- capable of reducing errors of $\delta B/BT \sim 12\text{x}10^{-5}$ down to $2\text{x}10^{-5}$

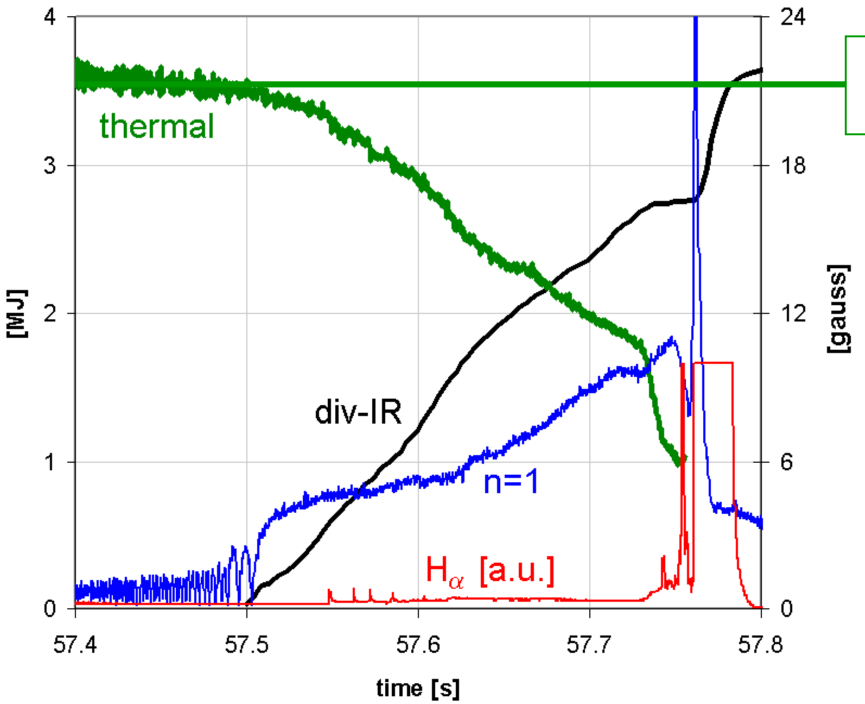


Side correction coil

Top correction coil

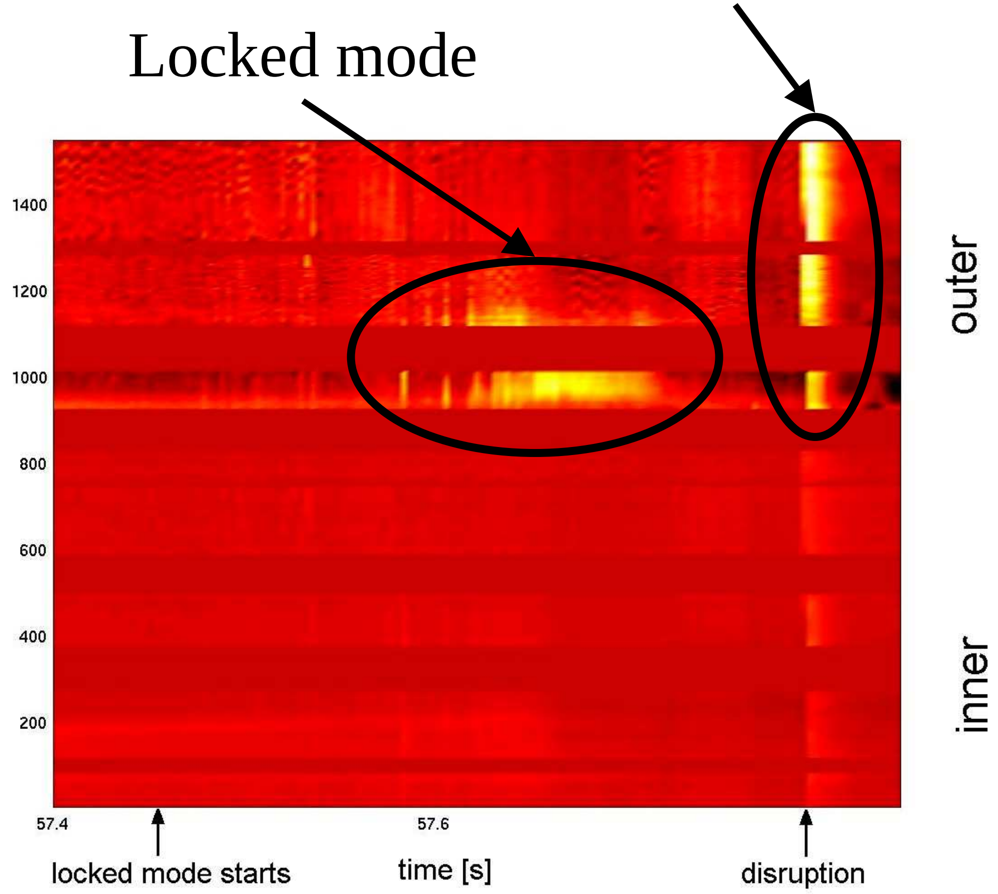
Bottom correction coil

Disruption heat loads - divertor



All E_{th} to divertor

disruption



Large area of plasma-target interaction

Updated conclusions

- **ITER still looks conservatively designed for H-mode access**
  - scaling does well for CMOD *- further ‘identity’ tests a high priority*

- Some uncertainties in sideband physics
  - discrepancies with old/new DIII-D and COMPASS-D scalings
  - but sidebands clearly still important

- But increased sensitivity close to NTM thresholds
  - can lead to locked modes with less error field
  - + rotating NTMs more easily triggered if high error field

- Rotation appears to play a role
  - though not as strong as in theory (could not get $B_{pen} \rightarrow 0$)
  - natural rotation possibly in ion diamagnetic direction on JET

- Locked modes during disruptions spread heat loading and send all the energy to divertor

- Reserve slides...

Origin of dimensional scaling constraint

[Connor and Taylor (NF ***17*** *1047):]*

Take given basic equations for a regime (eg Collisional Vlasov at high β)

- there are only certain (typically 1-3) transformations on basic parameters that leave them invariant
- these must also leave quantities such as Q(basic params) invariant
- thus each transform places a constraint on Q's dependencies
- if power law form for Q get ***linear relations between coef's***

⇒ showed Bτ obeyed relation (B≡cyclotron freq ⇒Bτ dimensionless),

Generally true for all dimensionless quantities, *provided regime or physics does not change over scaling region.*

Relevant regime is Ohmic collisional high β *(this works for confinement scaling, so use here)* and dimensionless quantity is:

$B_{pen}/B_T \sim n^{\alpha_n} B^{\alpha_B} R^{\alpha_R}$ and constraint is $8\alpha_n + 5\alpha_B - 4\alpha_R = 0$

(Collisional high β encompasses collisionless and low beta regimes - most general approach.
Ohmic heating forces T(n,R,B) and so all regimes have same constraint.
This approach has been seen to work experimentally for confinement scalings.)

Mechanism for additional ion losses on C-D?

Toroidal rotation from neoclassical theory:

$$v_\phi = \frac{-T_i}{m_i \Omega_{i\theta}} \left(\frac{d \ln P_i}{dr} + \frac{e}{T_i} \frac{d\phi}{dr} + k \frac{d \ln T_i}{dr} \right)$$

(Hinton & Hazeltine, 1976)

simplifies to: $v_\phi \sim E_r / B_\theta \propto E_r / I_P$, *if radial electric field dominates*

(otherwise P and T terms dominate which may scale differently with TF, I_p)

Ion banana orbit: $width = \frac{2mv_{par}}{eB_\theta} \approx \frac{1.6\sqrt{2mE}}{eB_\theta}$ for trapped particles...

calculate for high energy tail ions (E~3xTemperature) on q=2:

C-D: 4.5cm JET: 3.4cm ITER: 3.1cm

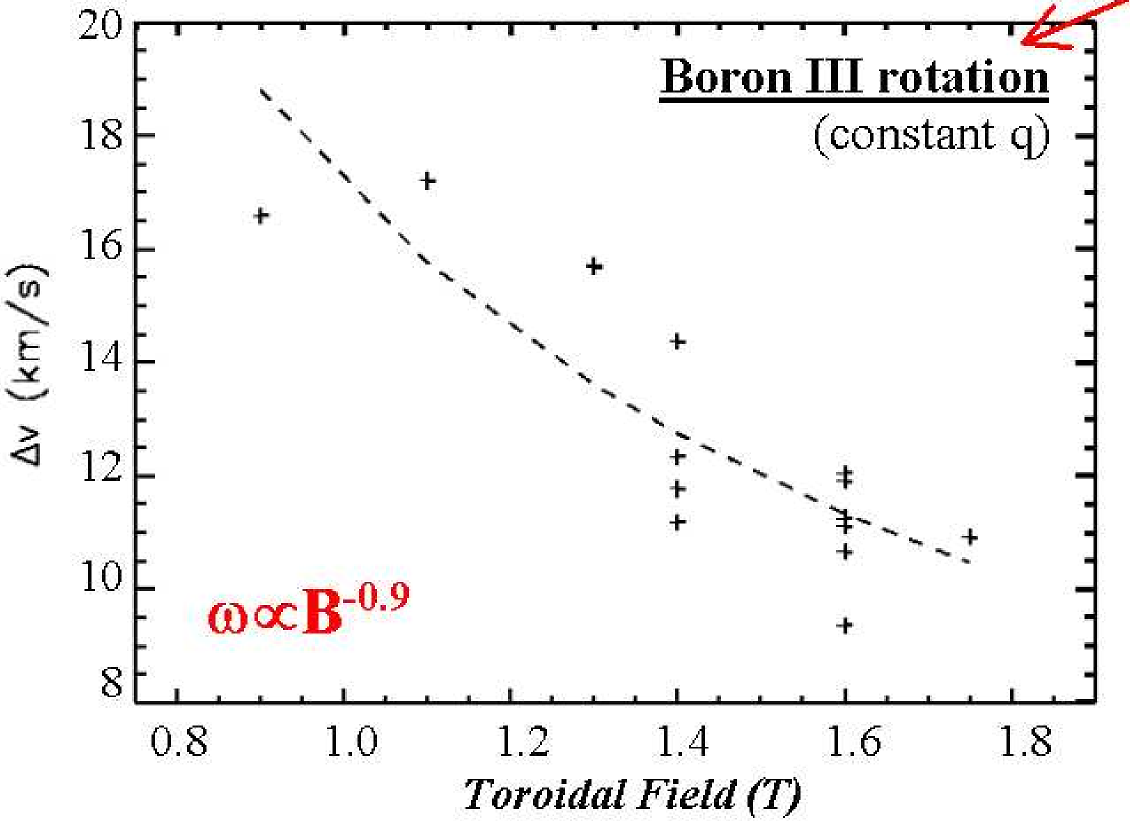
↗comparable with distance from q=2 to edge/vessel

⇒Ion loss may set up a strong electric field on C-D, not others

⇒Gives rise to increased flow, occurs most at low TF and I_p, possibly explaining strong scaling of flows and thresholds seen on COMPASS-D

COMPASS-D different scalings - rotation?

Different TF and q scaling may be due to changes in rotation behaviour on COMPASS-D:

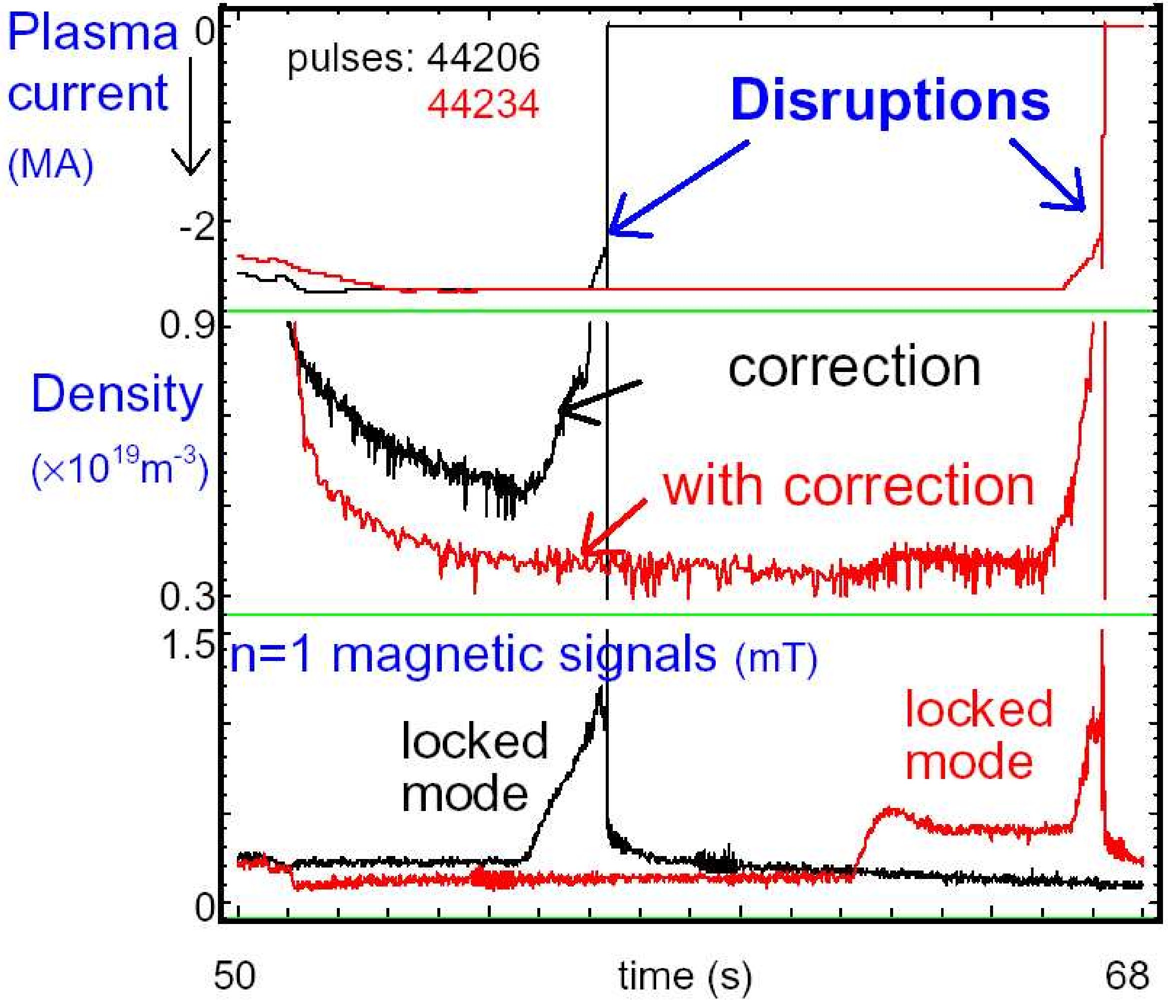


- C-D rotates much slower at higher TFs (**constant q**)
- DIII-D: C-VI shows $\omega \propto B^{+1.0}$ (**constant I_p**) cf B^0 for C-D

May be related to ion losses?

- JET ripple exps showed ion losses raised threshold (and rot'n) in Ohmic plasmas
- C-D ion banana orbits may take ions out of plasma, esp at low TF. . . (EXTRA SLIDE)

Intrinsic error correction accesses lower n_e



- 35% lower density achieved with correction on JET
- on DIII-D 50% lower achieved with C-coil
- non-perfect correction indicates significance of sideband effects
  - (also significantly reduced disruptions following locked modes on JET)

Benefits of error correction

- 84% of 25 uncorrected locked modes disrupted, cf 20% of 10 corrected
- In density ramp-down pulses correction accessed much lower density:
  - – 14 fringes (5.7x10^{19}m-3) no correction
  - – 9 fringes (3.7x10^{19}m-3) with correction
- *Routine correction may reduce disruptions and aid low density access*