EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

Error Field Amplification Experiments on JET

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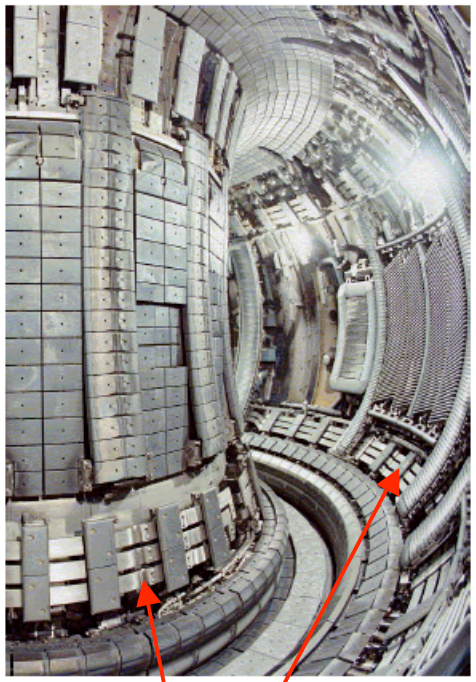
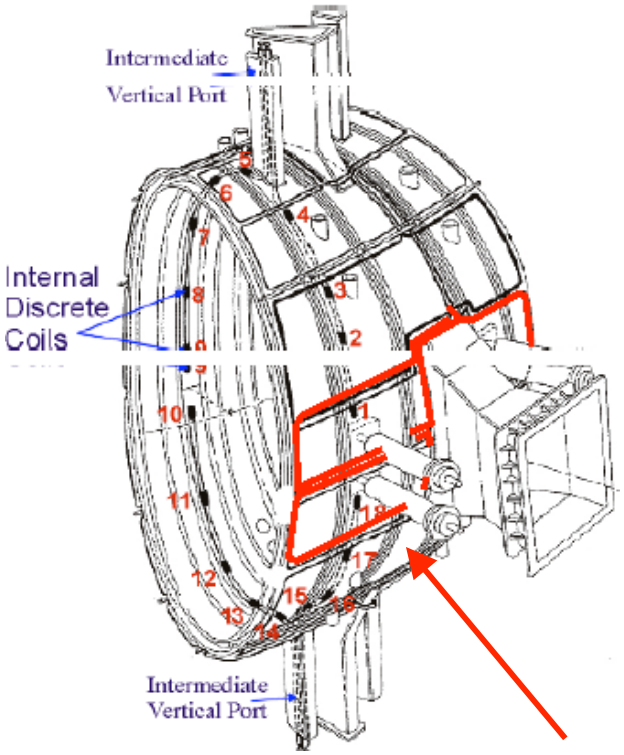
ACKNOWLEDGEMENT

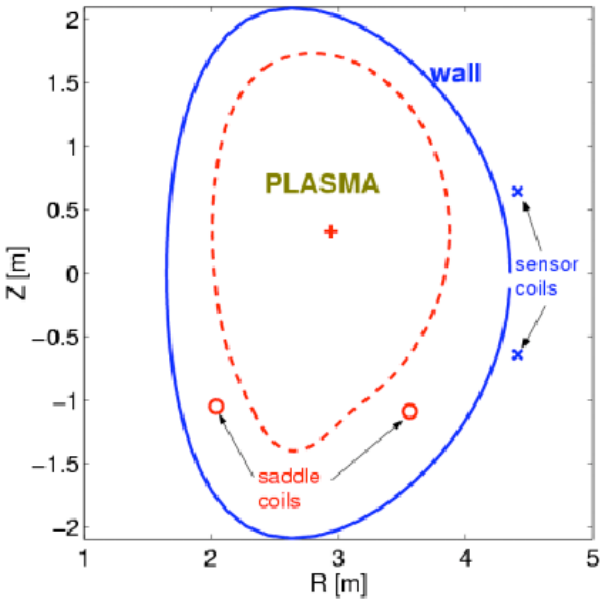
This work has been conducted under the European Fusion Development Agreement.

UKAEA Fusion Working in Europe

Internal “saddle coils” and measuring coils on JET







“saddle coils”

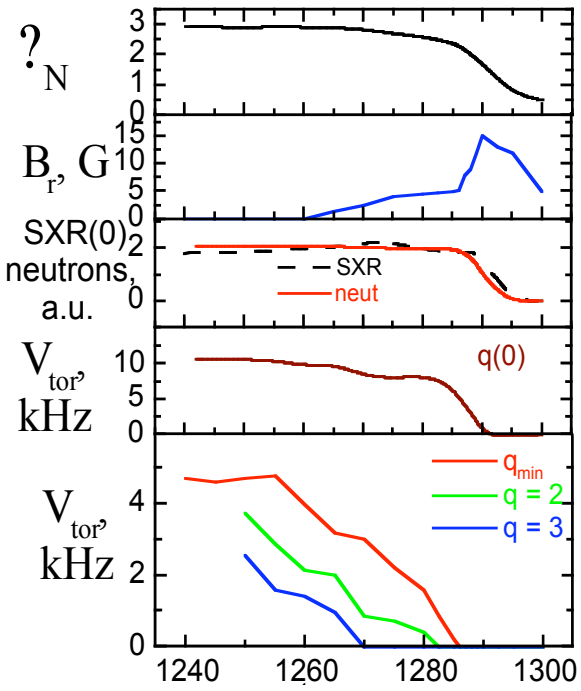
measuring loops

- Internal saddle coils were at the bottom, while measuring coils are at midplane
- New external midplane saddle coils are now operational

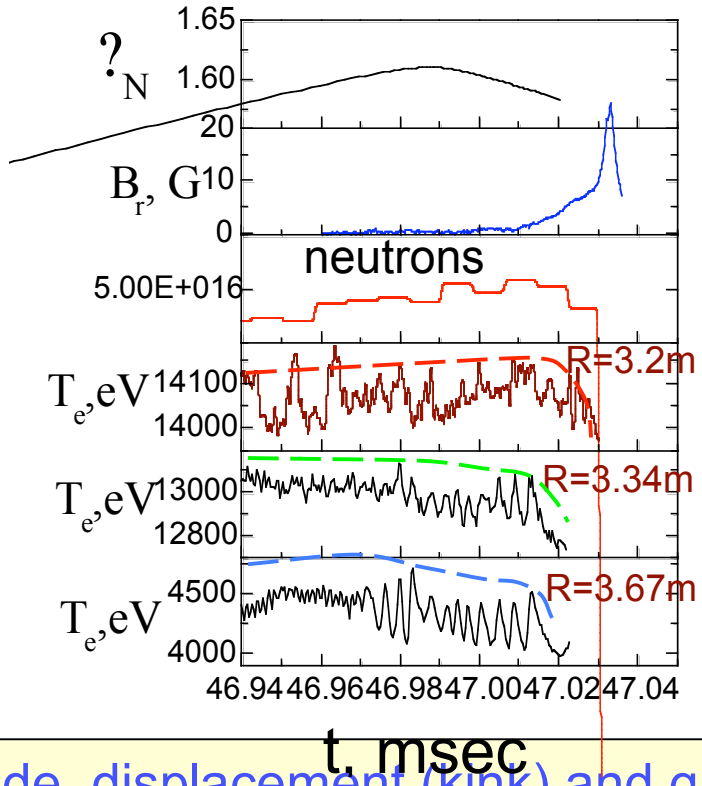
Analysis of old (~1996) Optimised Shear shots shows an RWM like mode

compare with DIII-D RWM:

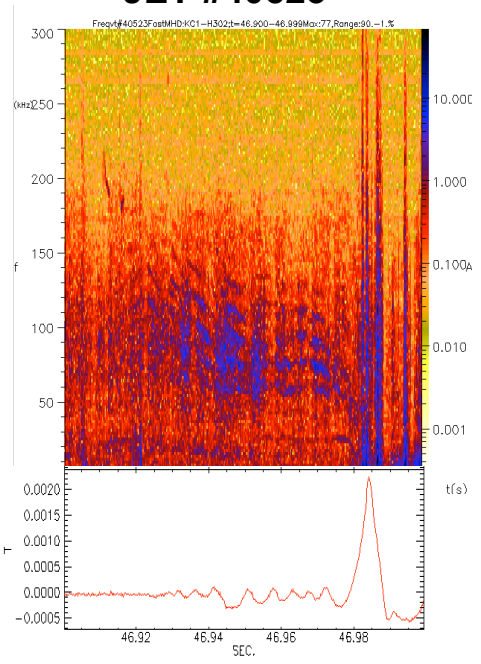
DIII-D #99503



JET #40183



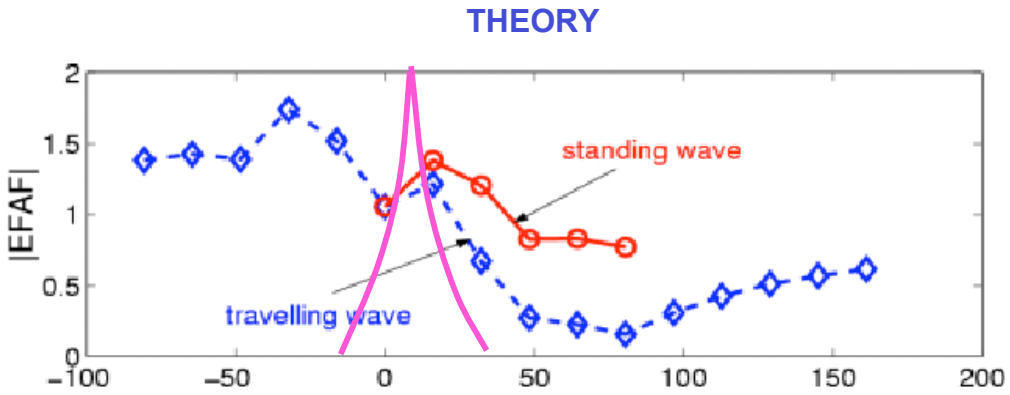
JET #40523



- similar in mode amplitude, displacement (kink) and growth scenario
- sudden increase in mode growth when rotation inside *q=2* surface vanishes

- Application of a “resonant” error field may cause resonant field amplification (RFA), if we are close to no-wall limit

- Plasma response is expected to peak at $f_{coil} \sim 0.8\, f_{RWM} = 0.8/(2\pi\tau_{wall})$ (Liu, MARS simulations) or at $1/5\, f_{RWM}$ (DIII-D)



if $\tau_{RWM} \sim \tau_{wall} \sim 6$ ms (f_{RWM}=25Hz), maximum response is expected at $f_{coil} \sim$ 20Hz (Liu) or 5Hz (DIII-D)

First, we need to know τ_{wall}

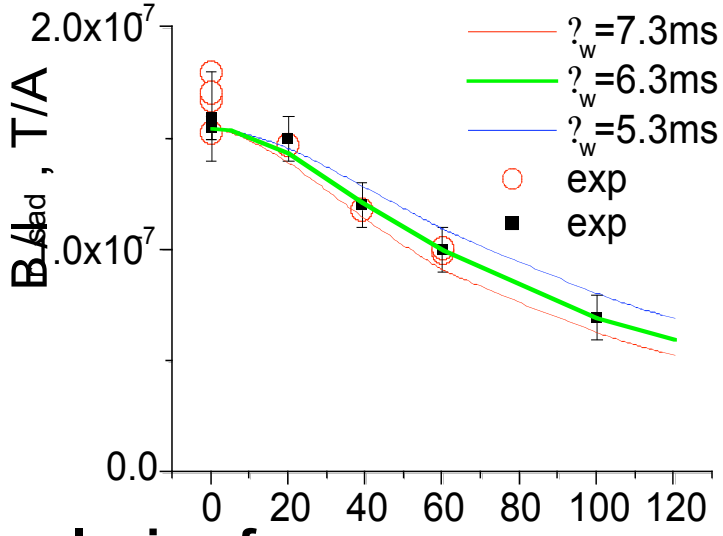
τ_{wall} was measured in no-plasma shots

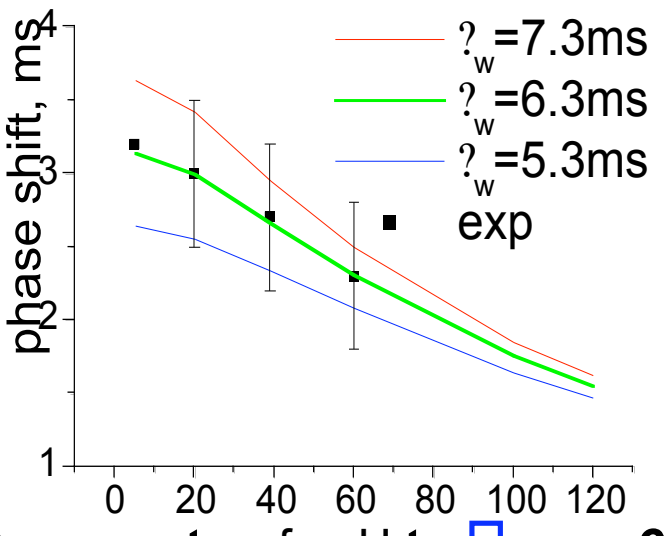
- Vacuum field reduction due to image currents in the wall depends on τ_{wall}:

$$B_r = B_{r0} / (1+(2\pi \times f)^2 \times \tau_{wall}^2/m^2)^{1/2}$$

- Phase shift: $\varphi_{shift} = \arctan(2\pi \times f \times \tau_{wall} / m) / (2\pi \times f)$

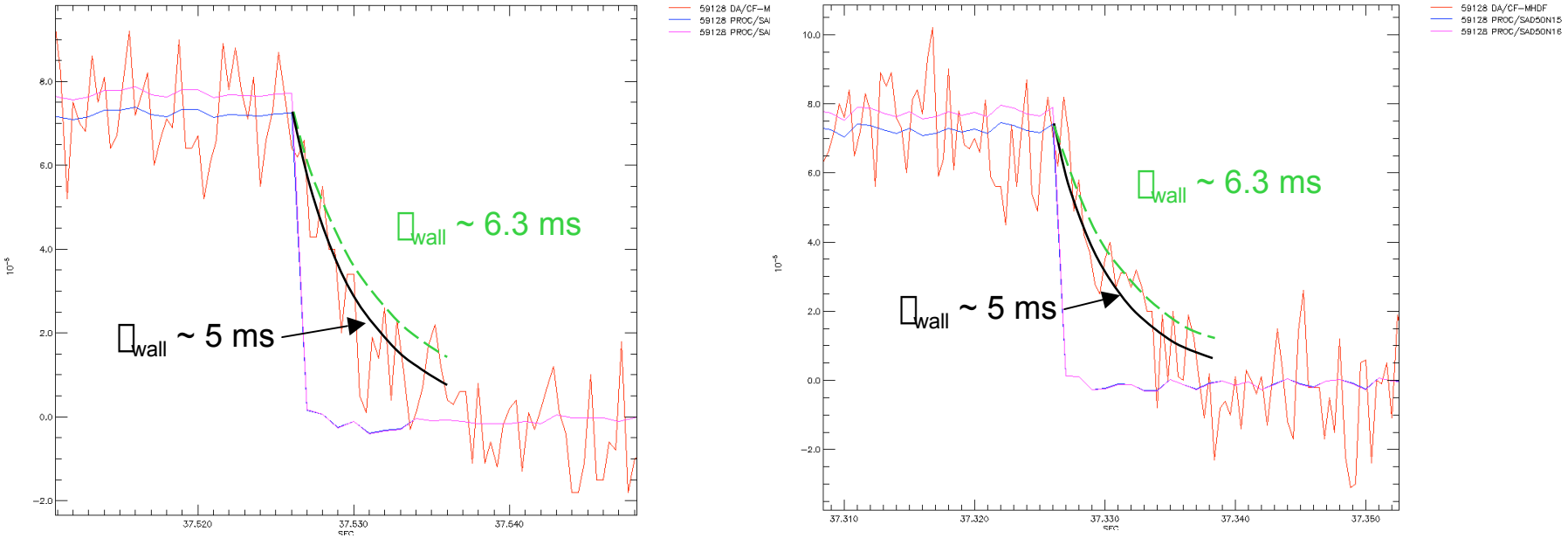
- Amplitude and phase shift were measured experimentally and calculated with τ_{wall} = 7.3, **6.3** and 5.3 ms and m = 2





Analysis of vacuum response to AC current suggests τ_{wall} ~ 6ms

τ_{wall} was measured in no-plasma shots



Decay of vacuum response to square blip indicates similar τ_{wall}

Experiment set-up:

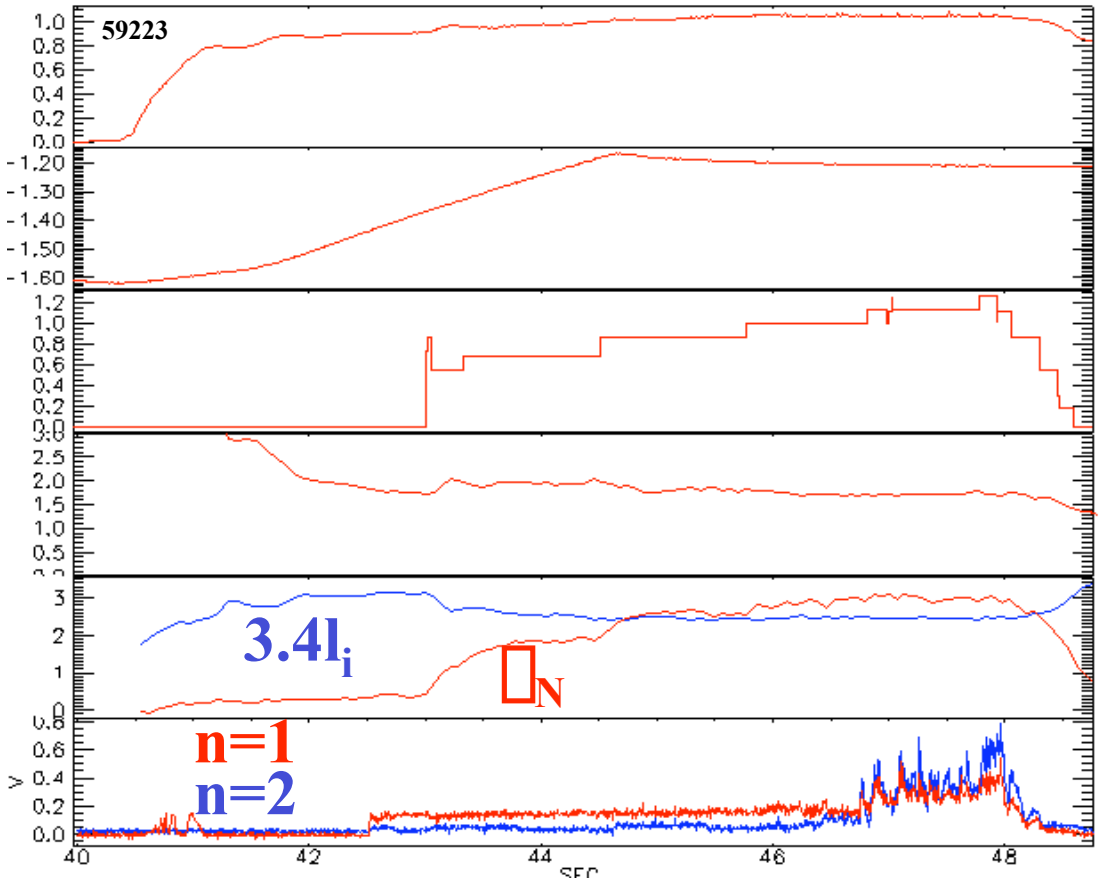
$I_p \sim 1MA$

$B_t \sim 1.2T$

max $P_{NBI} \sim 14MW$

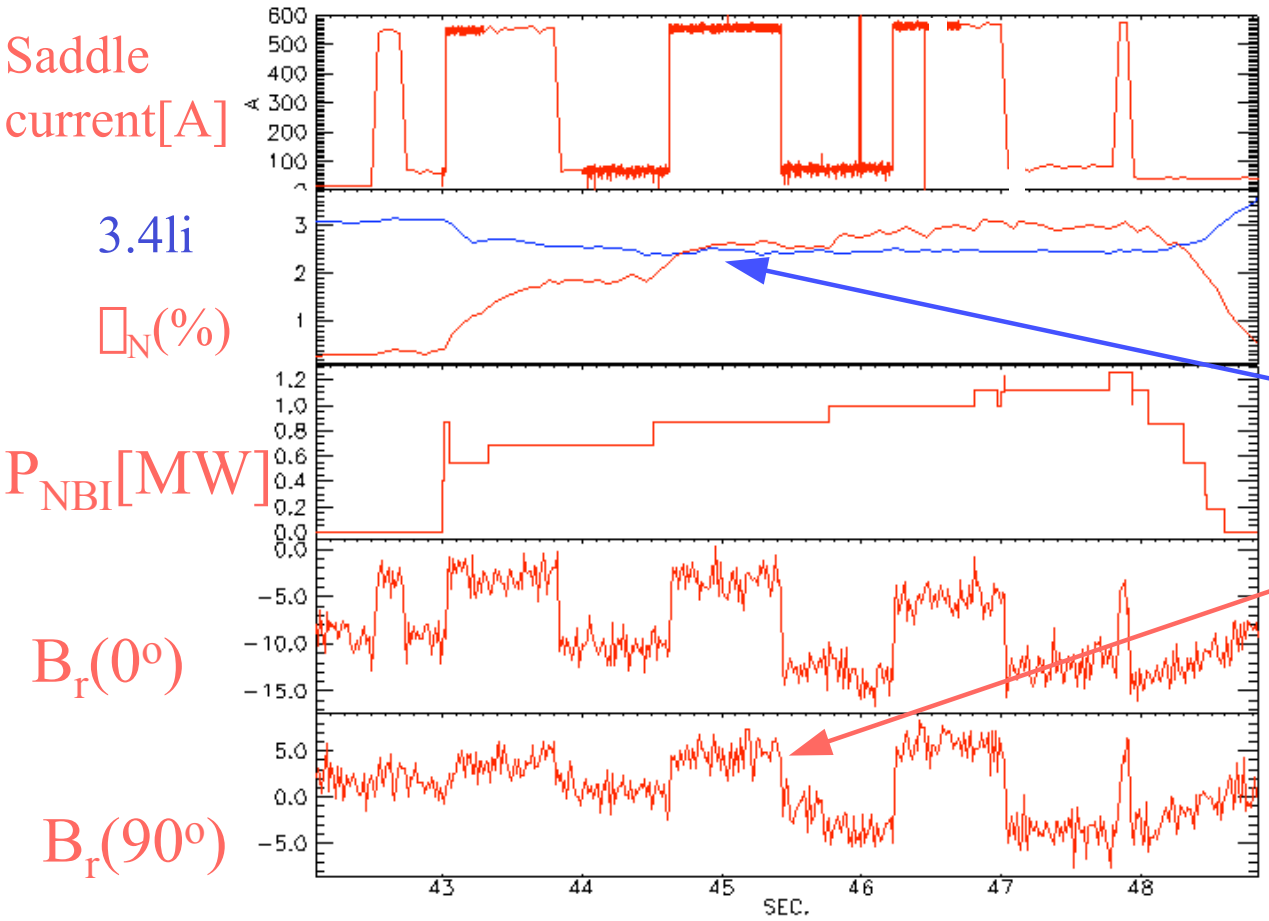
q_0 between 1 and 2

max $\beta_N \sim 3.2$,
MARS no-wall
limit ~ $3.4 l_i$



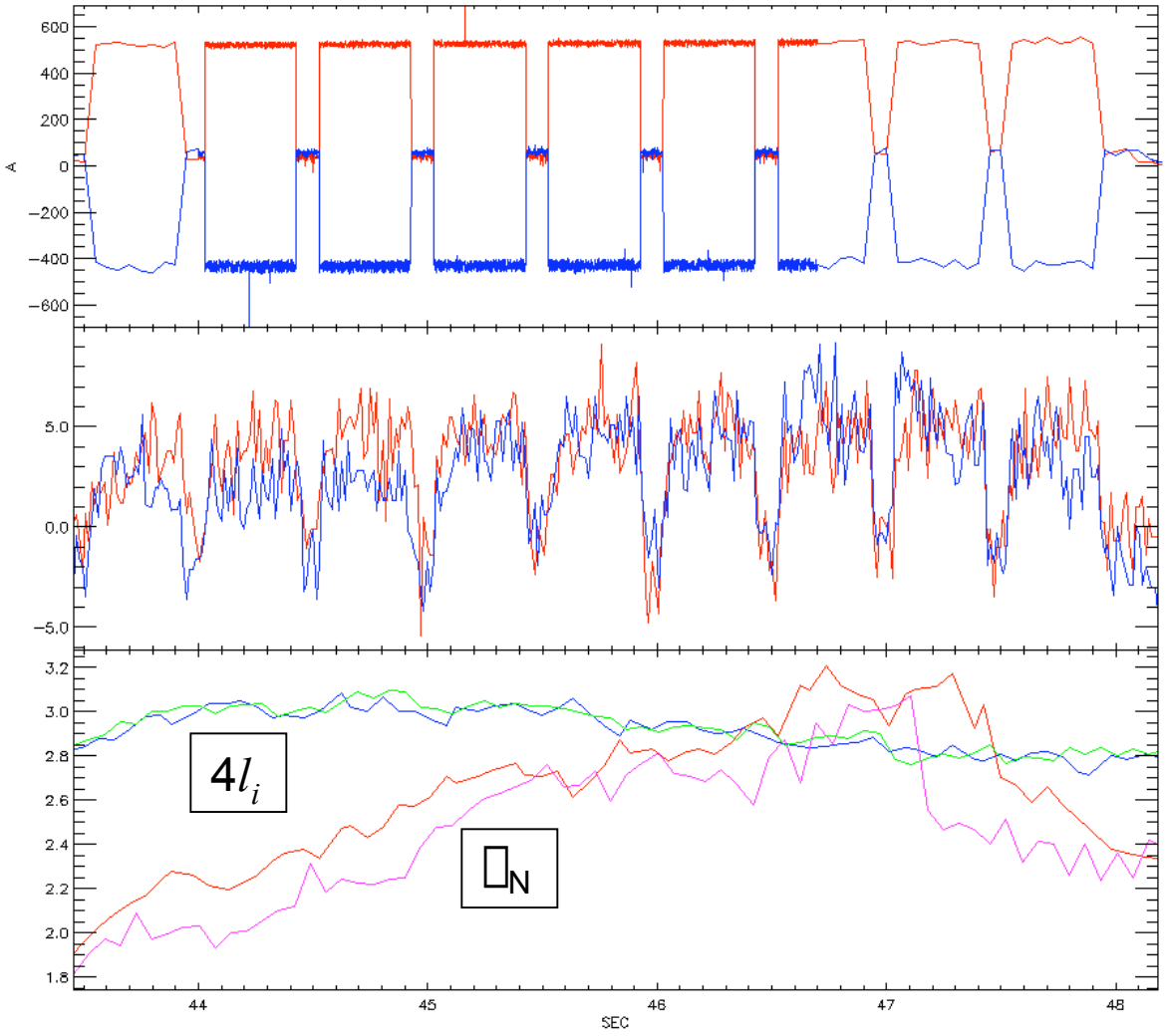
- Many shots have (2,1) NTM limit to β_N - we believe this occurs very near ideal wall β-limit ($\beta\beta$type seed)
- NB: due to low field B_t=1T and high NBI $\beta/\beta_{alfven} \sim 4\%$

Saddle current "blips" are amplified by plasma as □ rises:



*As □N approaches ideal limit, plasma response signal Br(90°), which sees **no** vacuum (or low □N) pick-up, clearly rises*

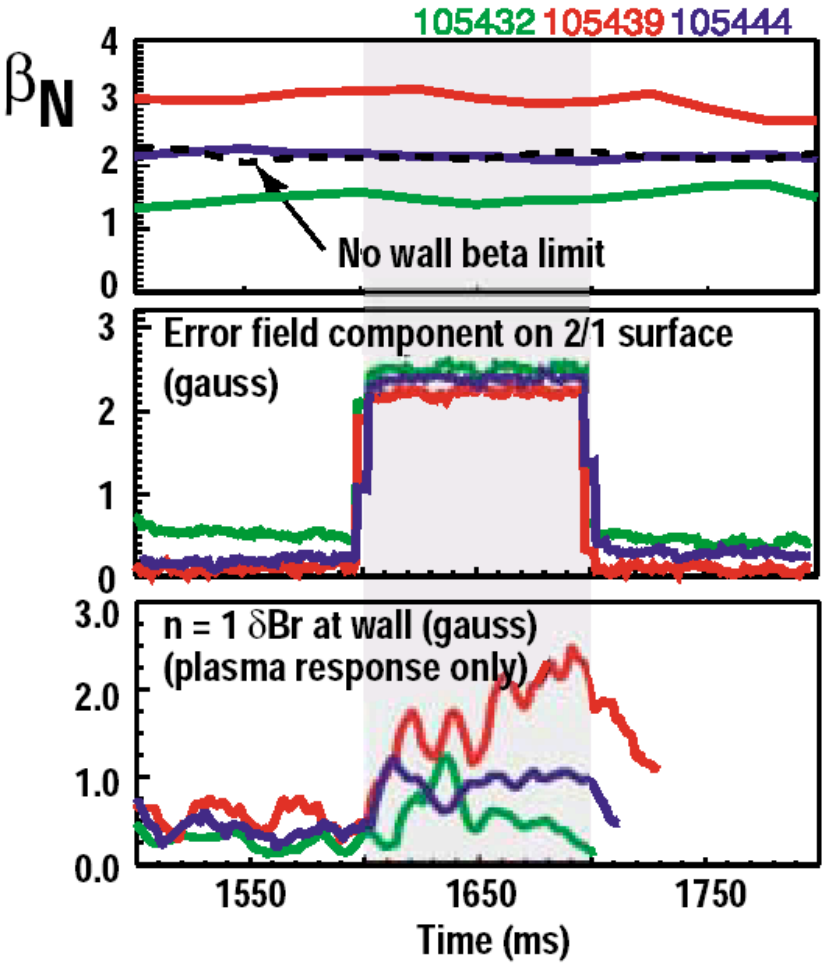
Positive/negative saddle coil current comparison allows to eliminate a natural error field effect (appears to be small)



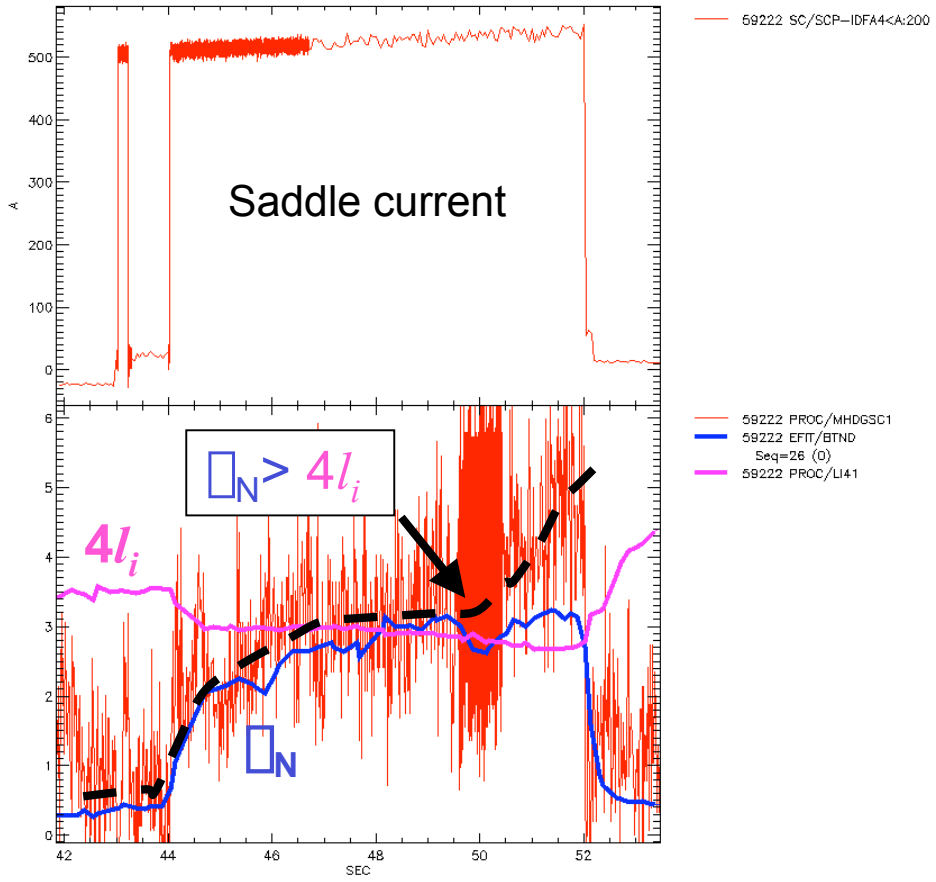
Saddle current

$B_r(90^o)$ - plasma response

This is what we expected to see:

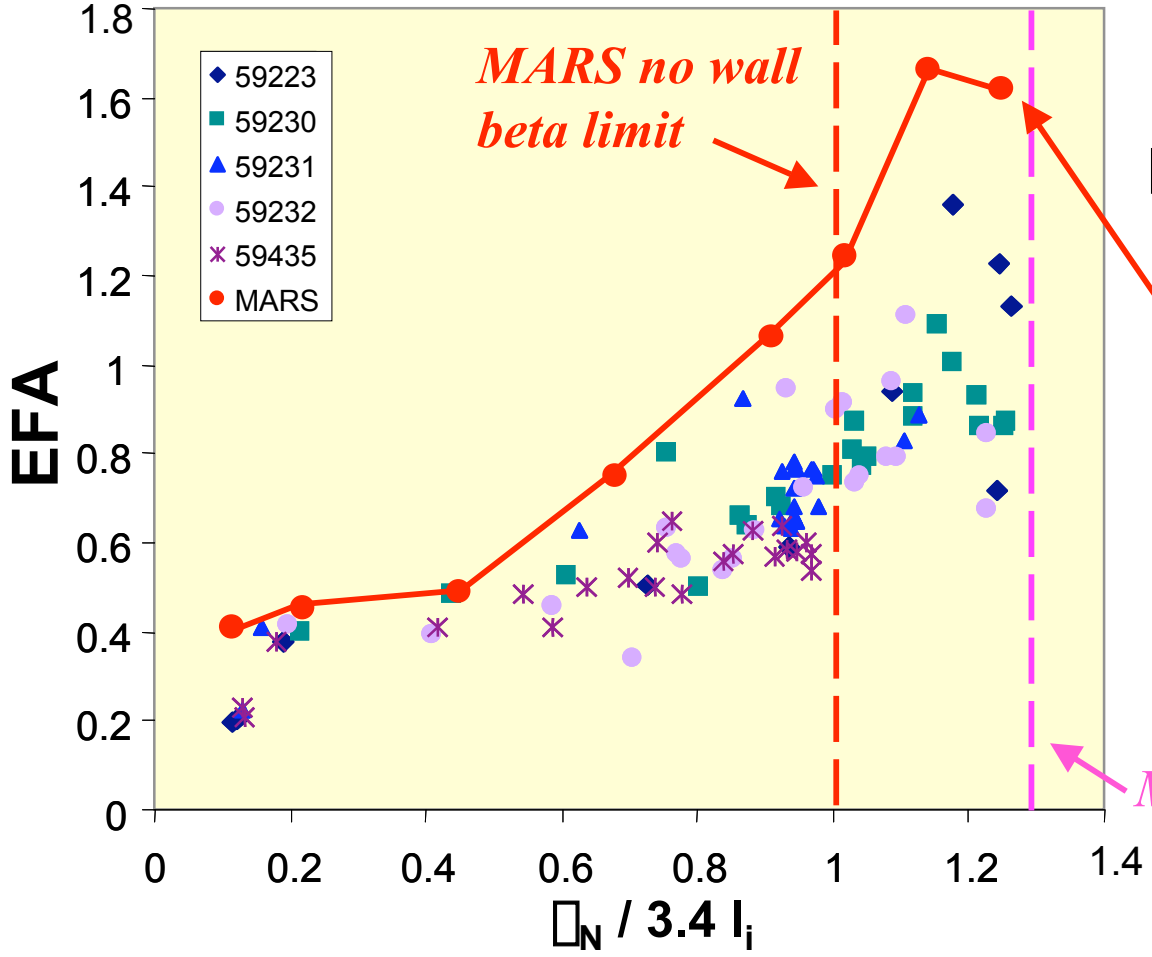


This is what we see: faster growth close to limit



B_r at the wall (plasma response only, 90⁰), a.u.

Experimental results and comparison with theory: “blips”

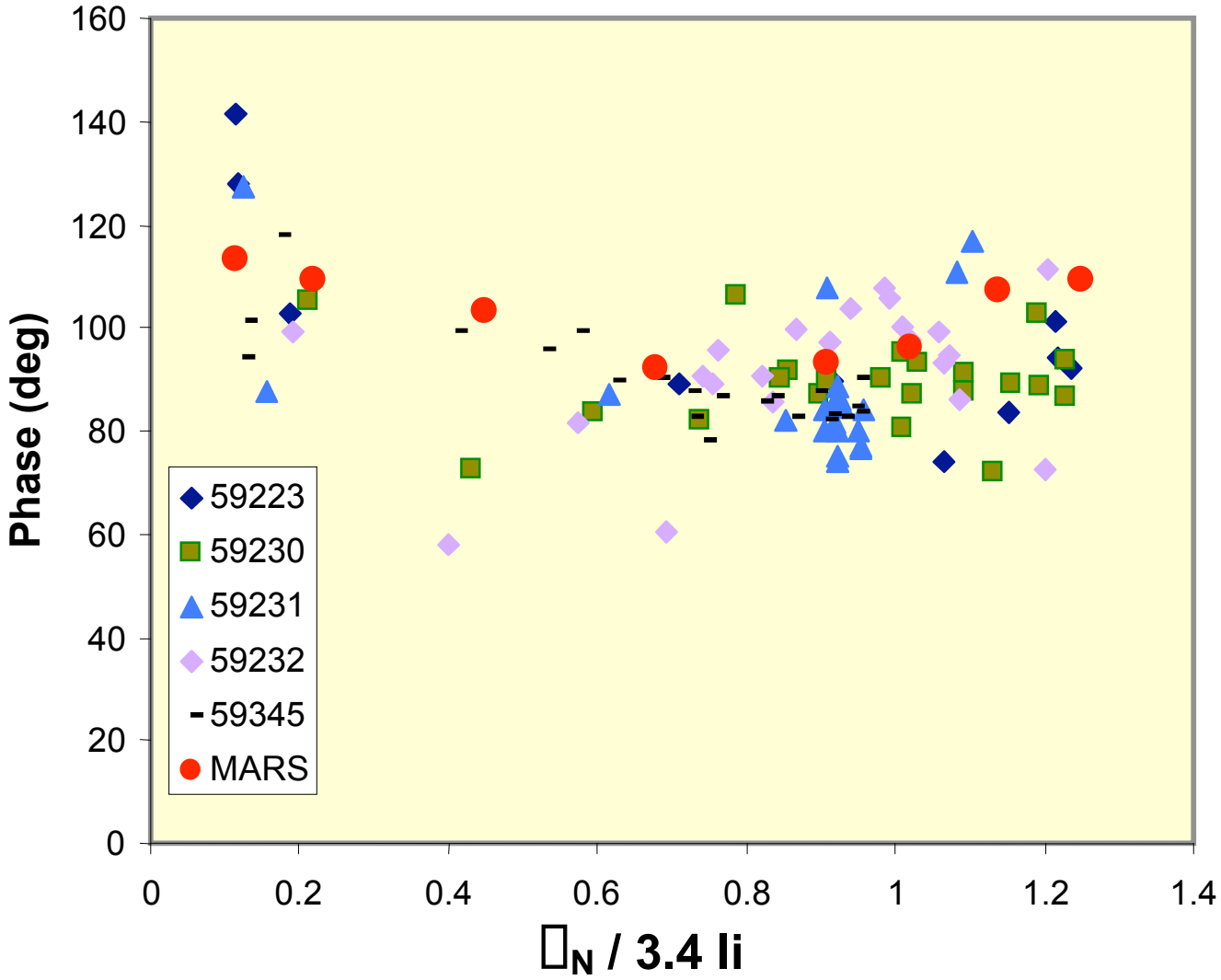


$$EFA = \frac{|\text{Flux-Vac Flux}|}{|\text{Vac Flux}|}$$

MARS code results including kinetic damping model - no free parameters.

- EFA increases with β - no sharp threshold at no wall limit

- **Phase also agrees well MARS simulation**



Plasma response to AC saddle coil current with 6 different frequencies at = 0⁰ and = 90⁰:

40/20Hz

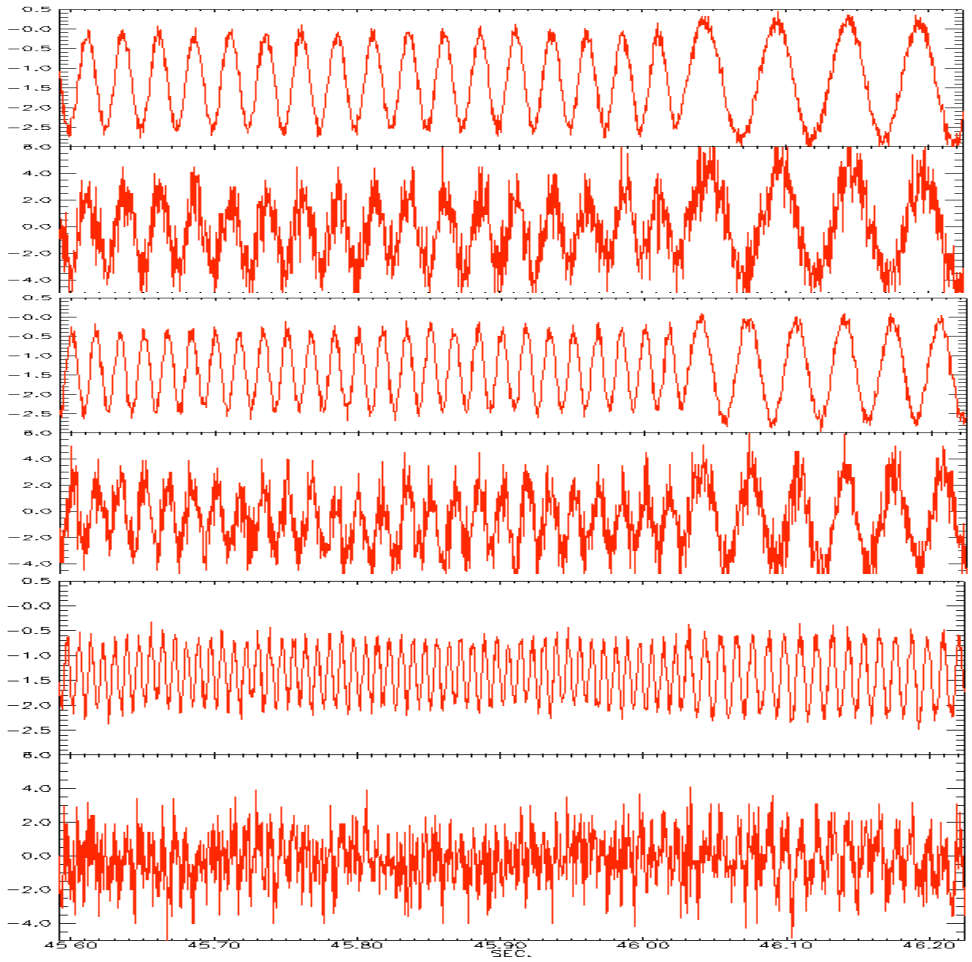
59440

60/30Hz

59436

120/90Hz

59441



$B_r(0^o)$

$B_r(90^o)$

$B_r(0^o)$

$B_r(90^o)$

$B_r(0^o)$

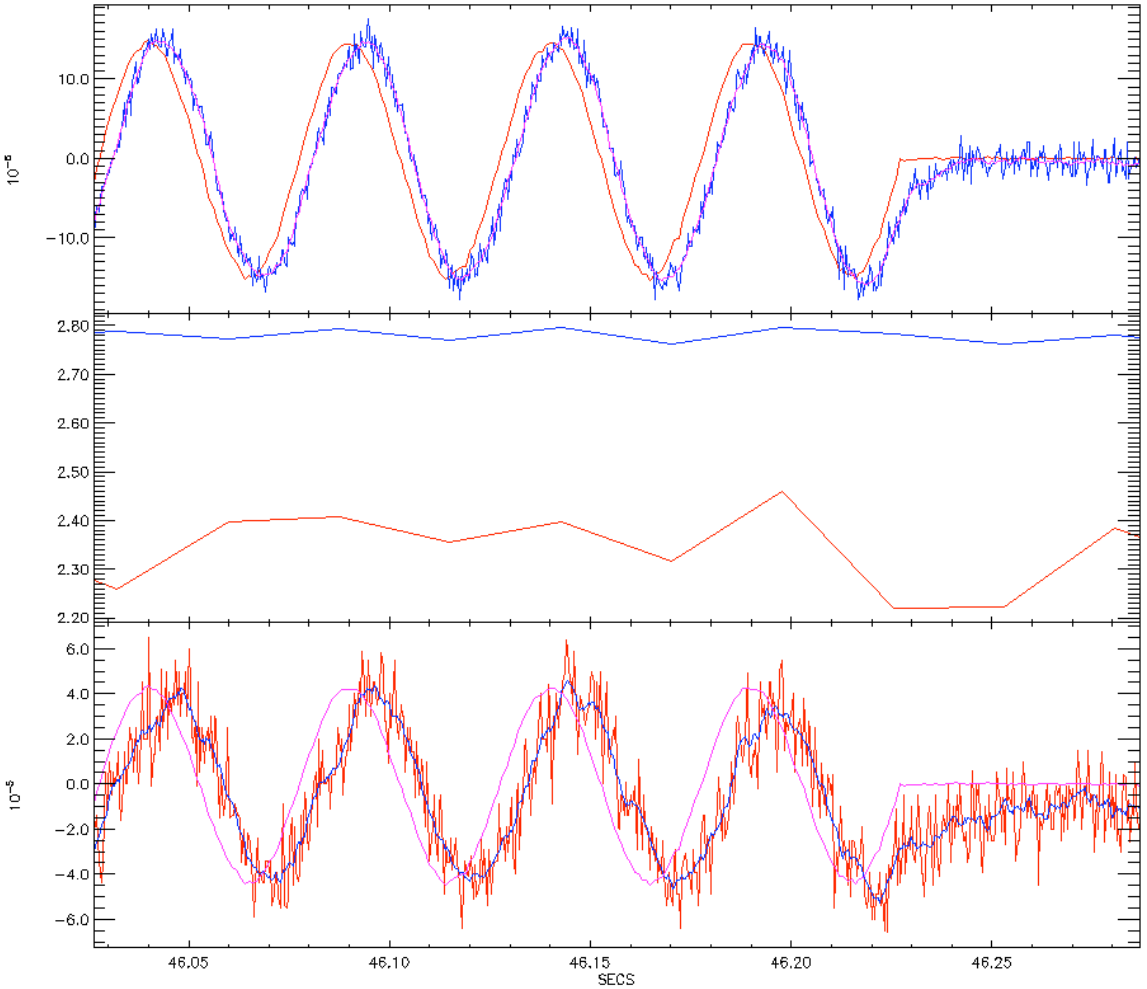
$B_r(90^o)$

$B_r(90^o)/B_r(0^o)$ does not vary much with freq

EFA doesn't vary much with freq

CALCULATION OF AMPLIFICATION AND PHASE SHIFT in AC runs

#59440, 20Hz, $\beta_N/3.5 x l_i = 0.85$



blue: $B_r(0^o)$ +0.000134

red : I_{sad}*1.5e^{-7}

phase shift ~ +3.5 ± 0.5 ms

red : betaN

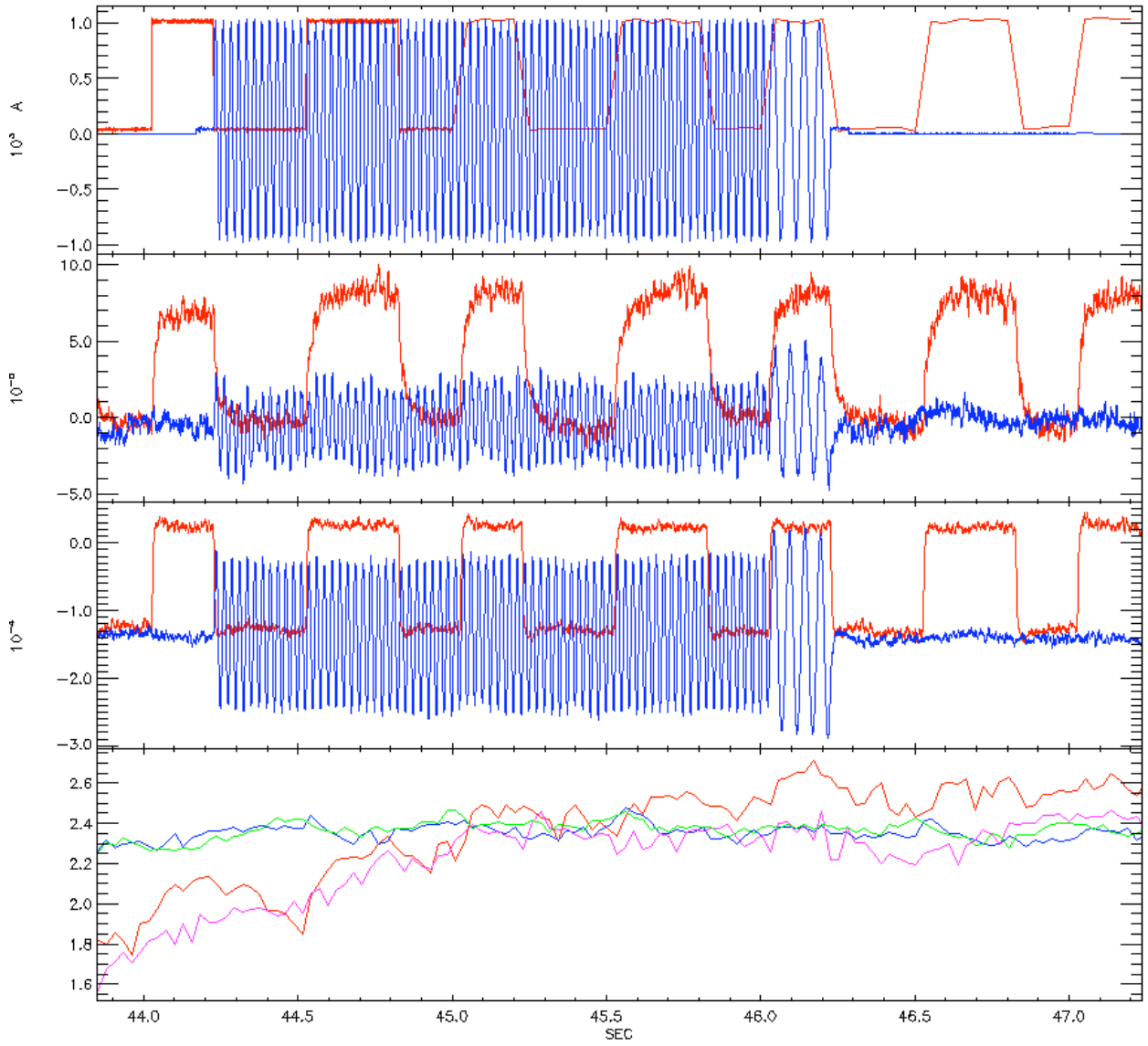
blue: 3.5 x l_i

red : $B_r(90^o)$ - 5e^{-6}

pink : I_{sad}*4.4e^{-8}

phase shift ~ +5.5 ± 1ms

EXPERIMENT: square or AC saddle current at no-wall limit



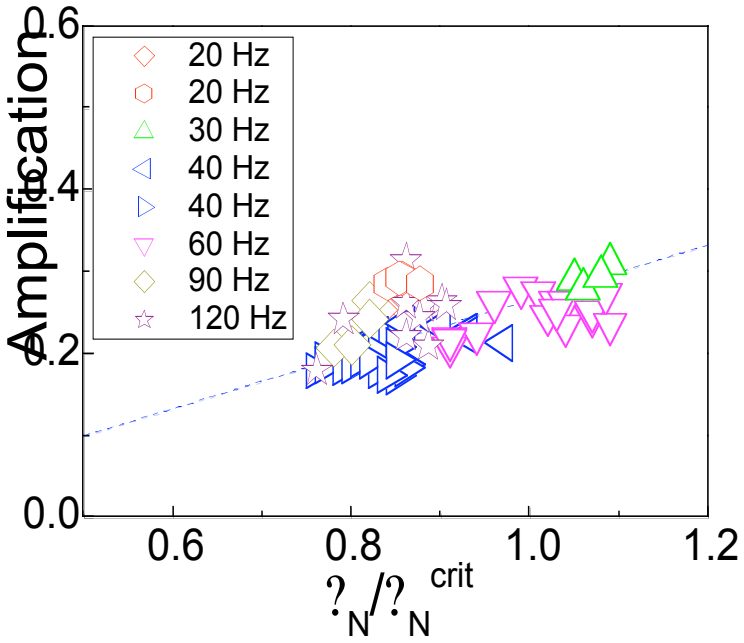
Saddle current

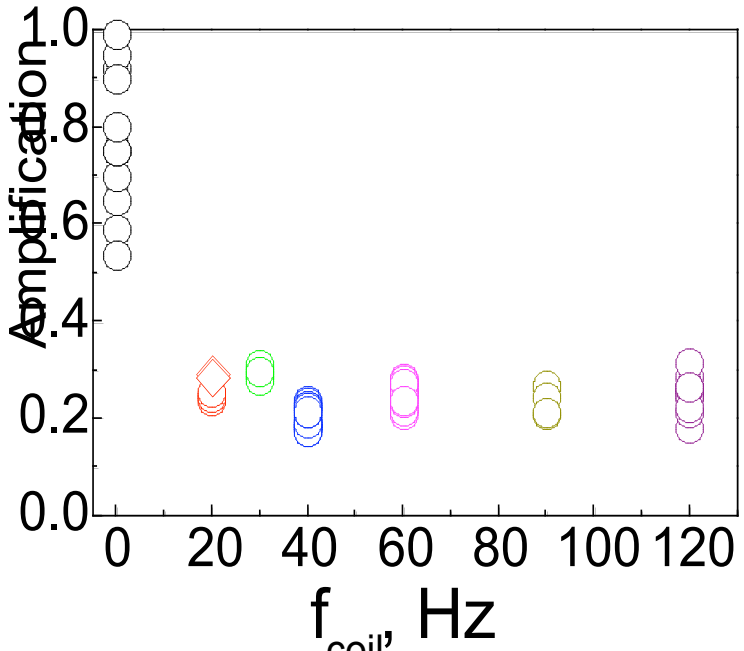
$B_r(90^o)$ - plasma response

$B_r(0^o)$

$\beta_N, 3l_i$

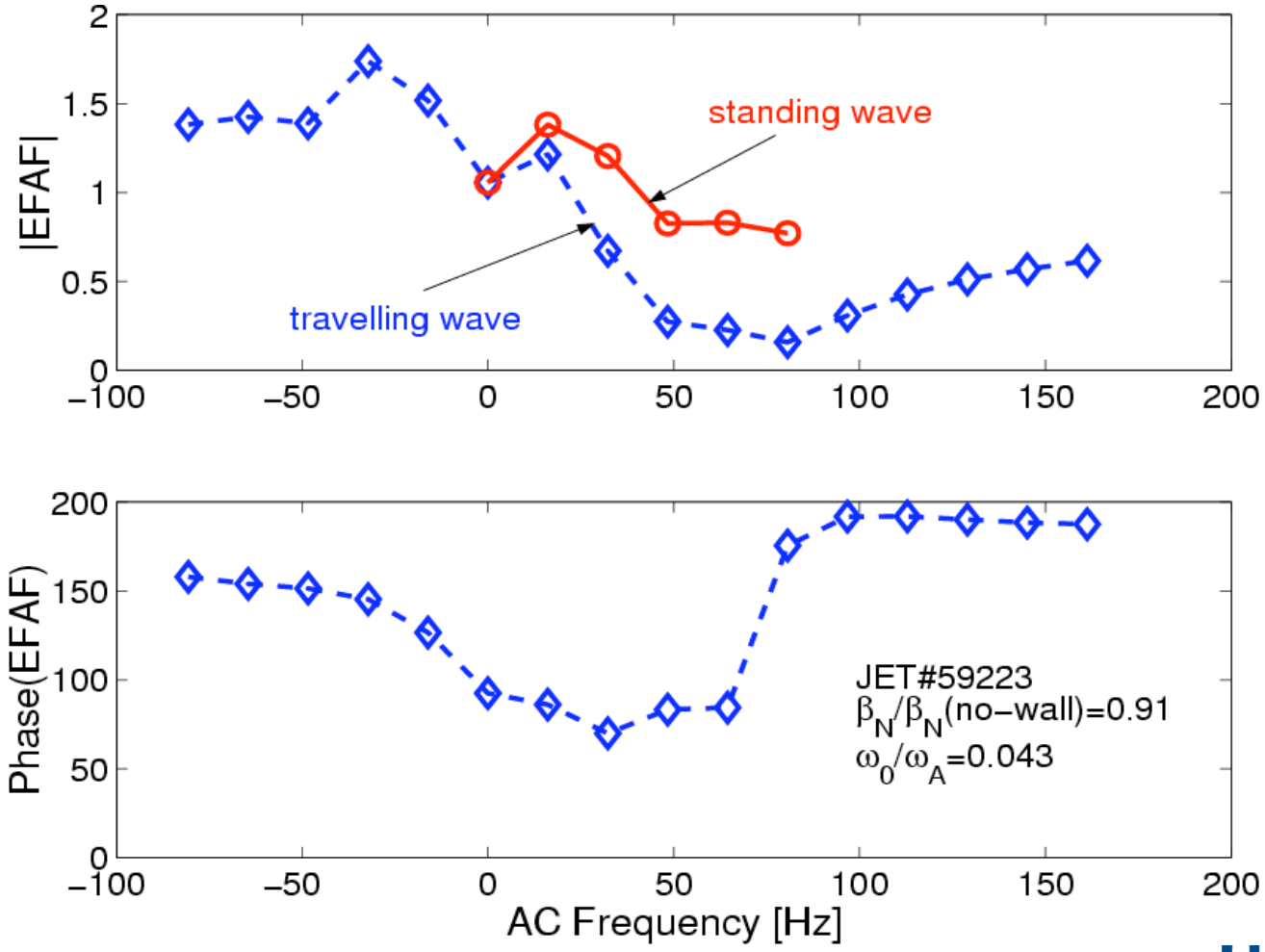
Experimental results and comparison with theory: AC



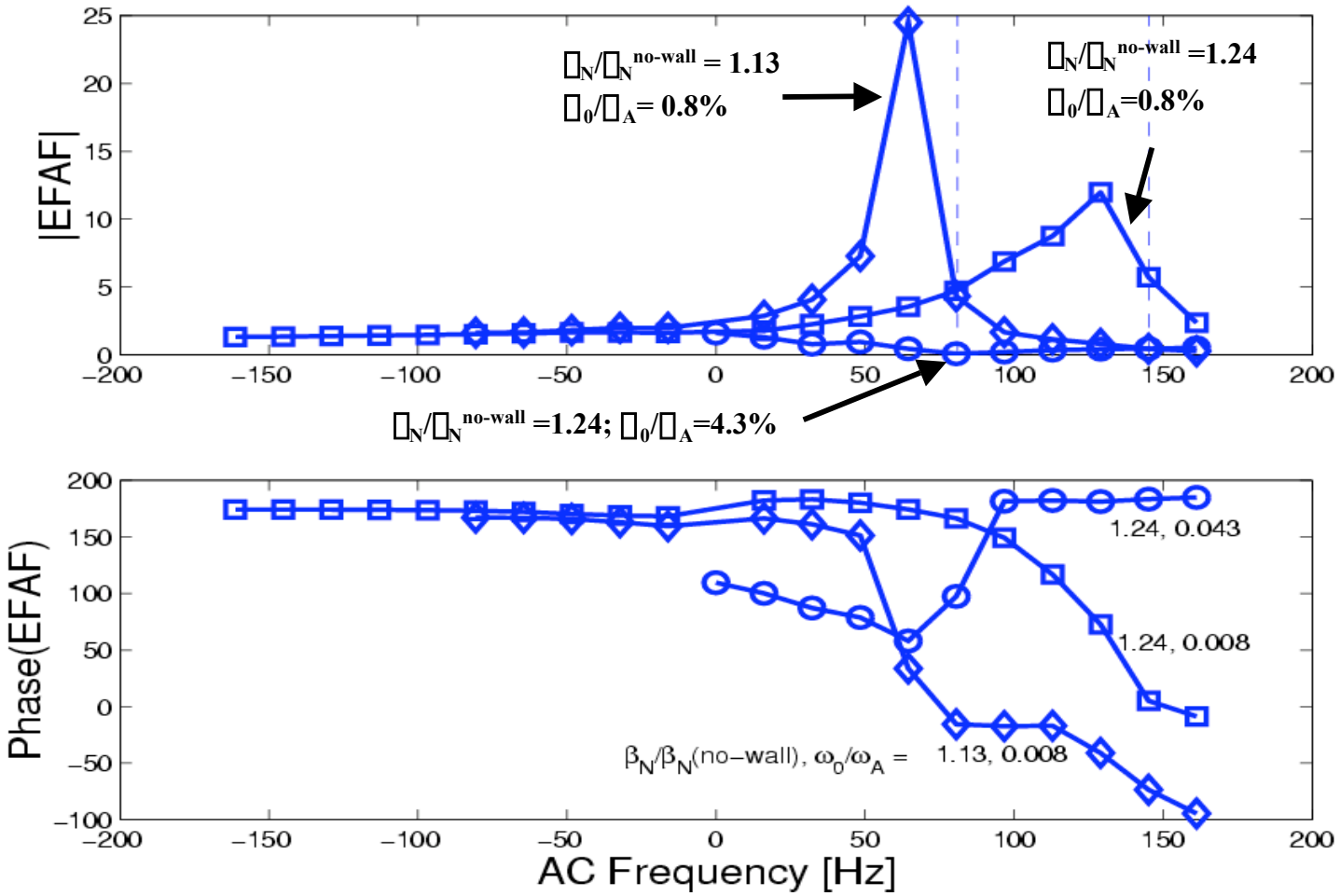


- **Much lower amplification was observed with AC saddle coil current compared to "blips"**
- **Amplification of AC current also increases with □**
- **No dependence of AC current amplification suggests EFA resonance at frequency below 20Hz. This agrees with MARS predictions:**

MARS shows similar EFA vs freq - lack of clear $\Omega \neq 0$ resonance due to strong RWM damping

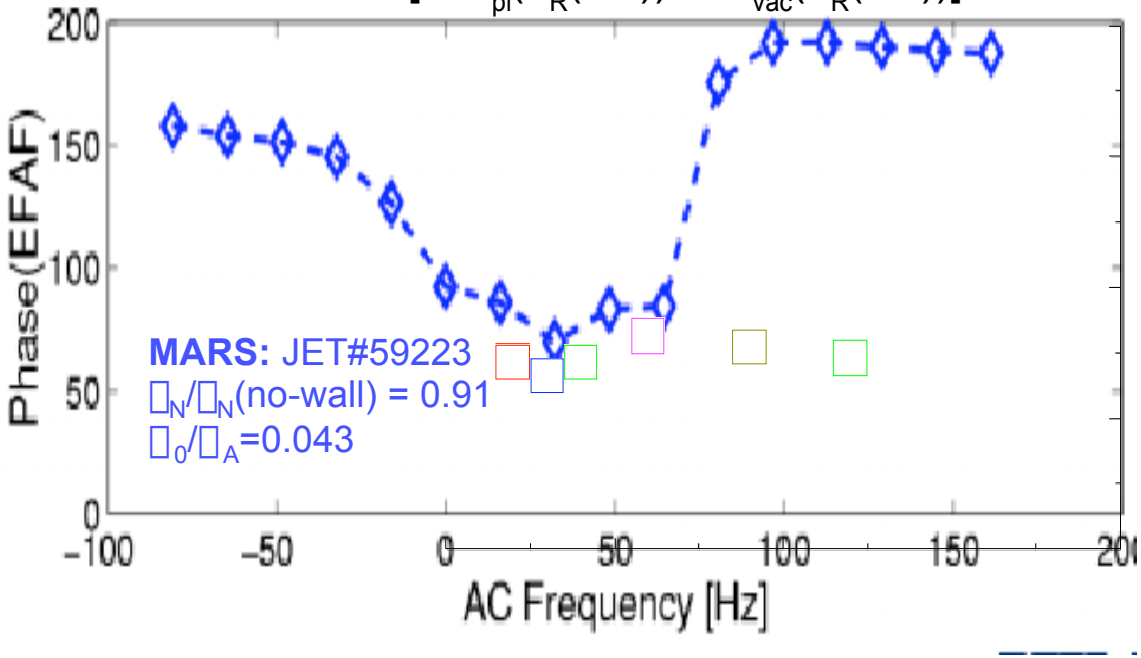


Reducing rotation rates gives clear frequency resonance



Experimental results and comparison with theory: phase shift in AC runs

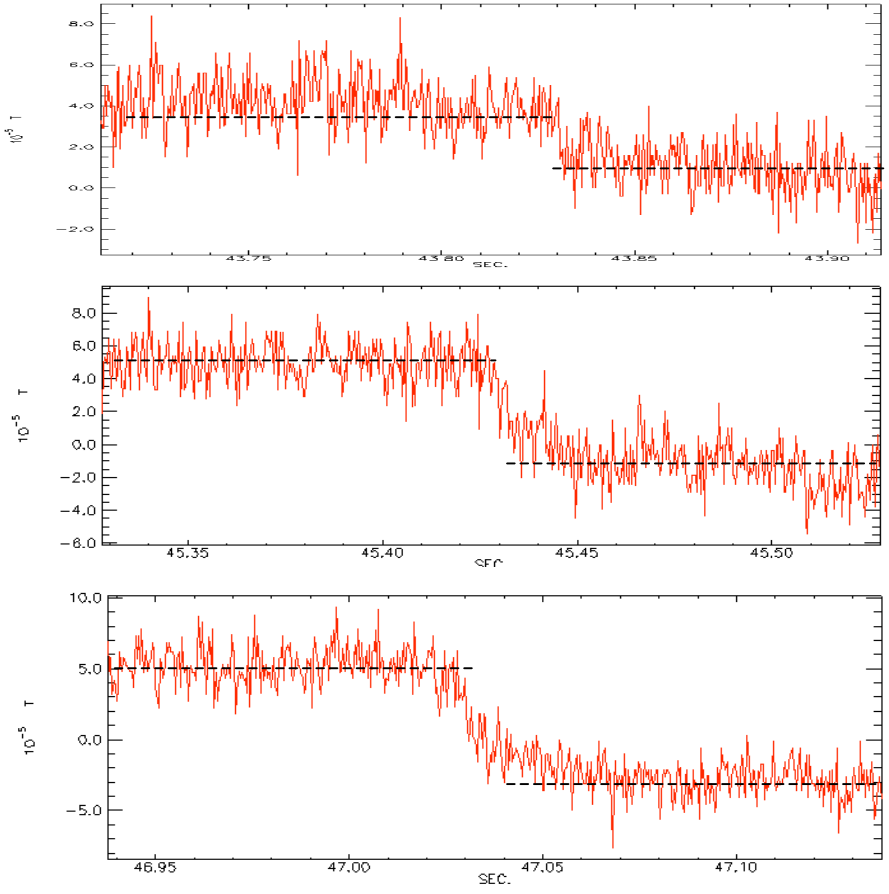
Experiment: plasma phase shift:
90^0-[$shift_{pl}(B_R(90^0))$-$shift_{vac}(B_R(90^0))$]



- **Phase shift** is in agreement with MARS predictions

Decay rate of "blips" at different □ was expected to reflect RWM growth dependence on □-value:

Br(90°) [0.1G]



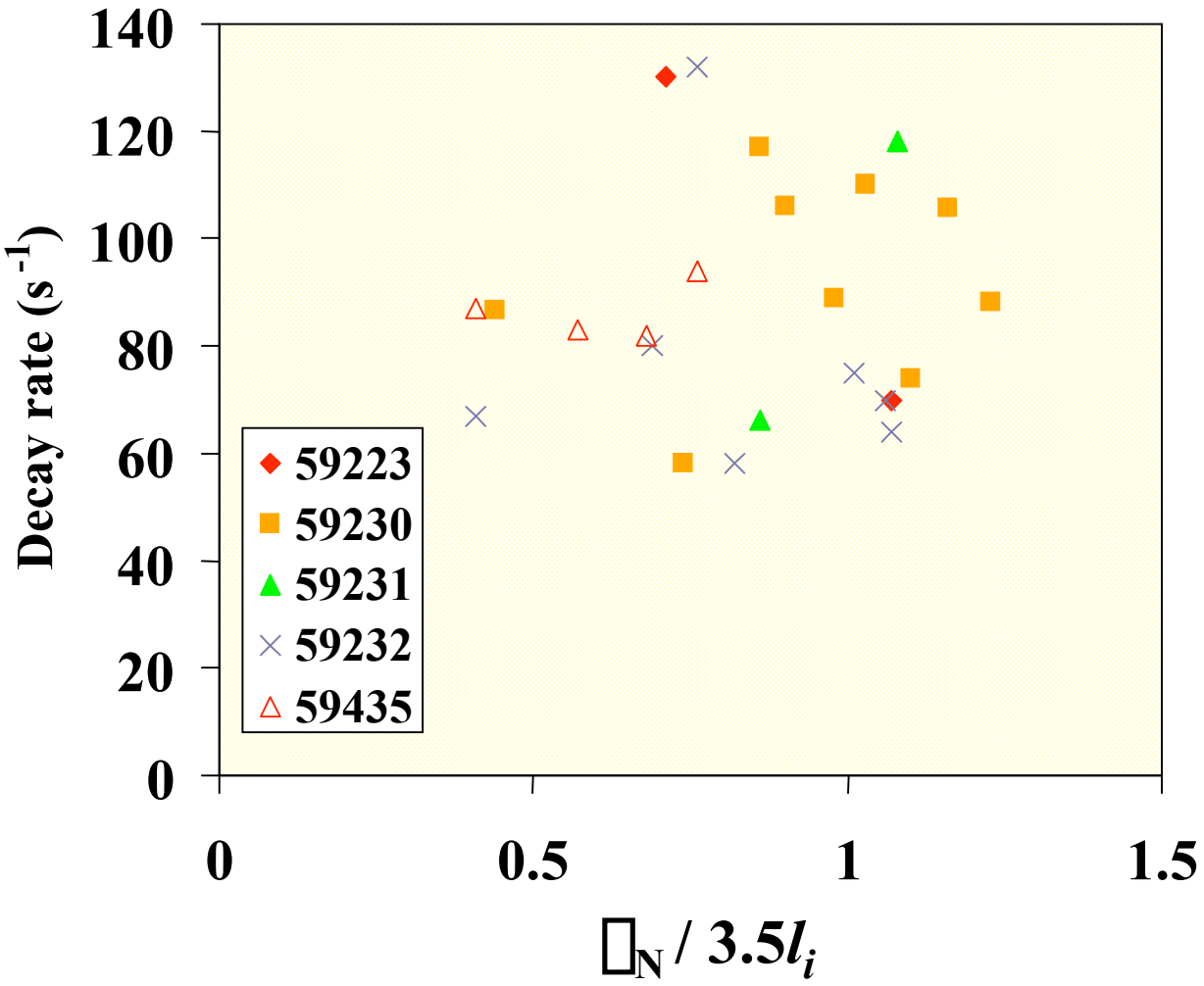
$\square_n/3.4l_i=0.74$

$\square_n/3.4l_i=1.10$

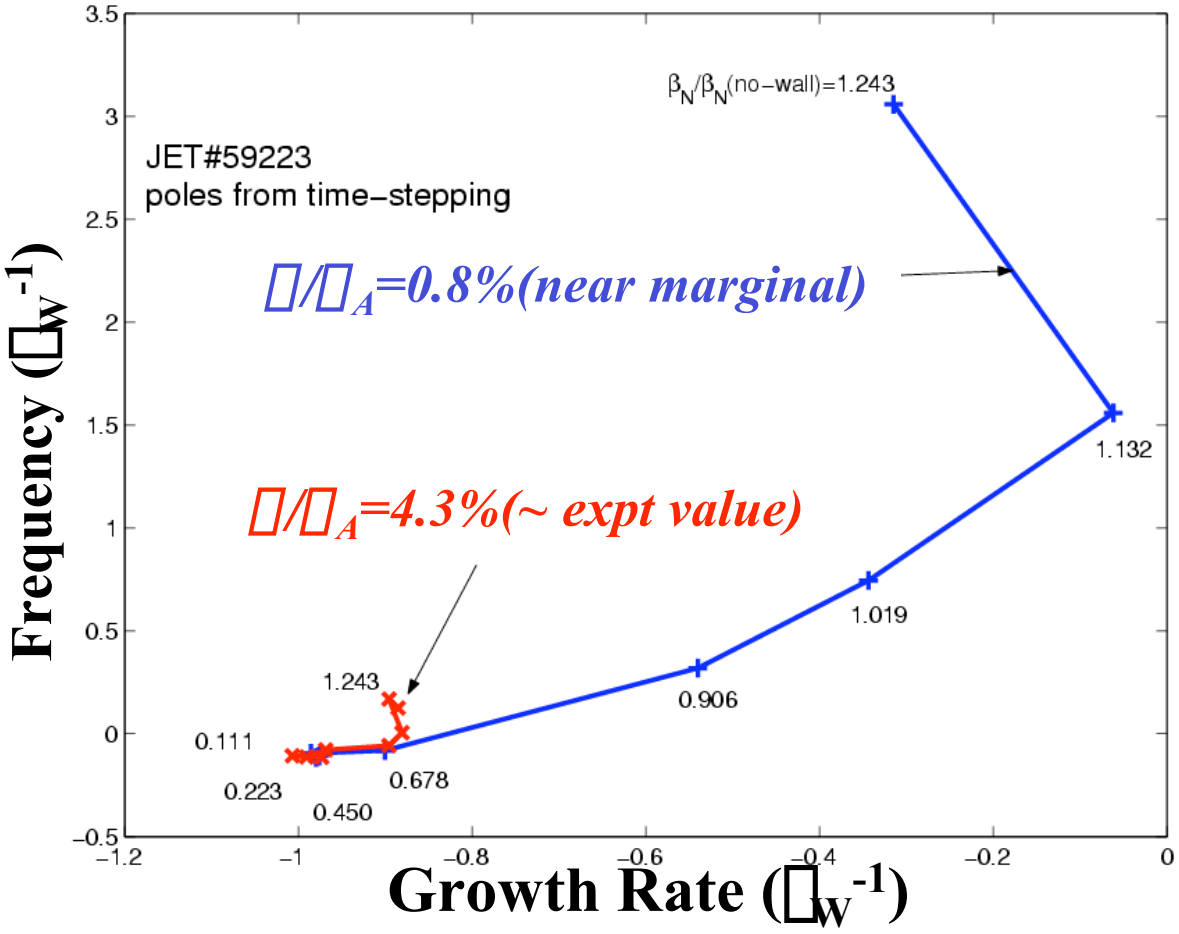
$\square_n/3.4l_i=1.26$

At first sight the decay rate story is clear...

But over all discharges there is no clear story….



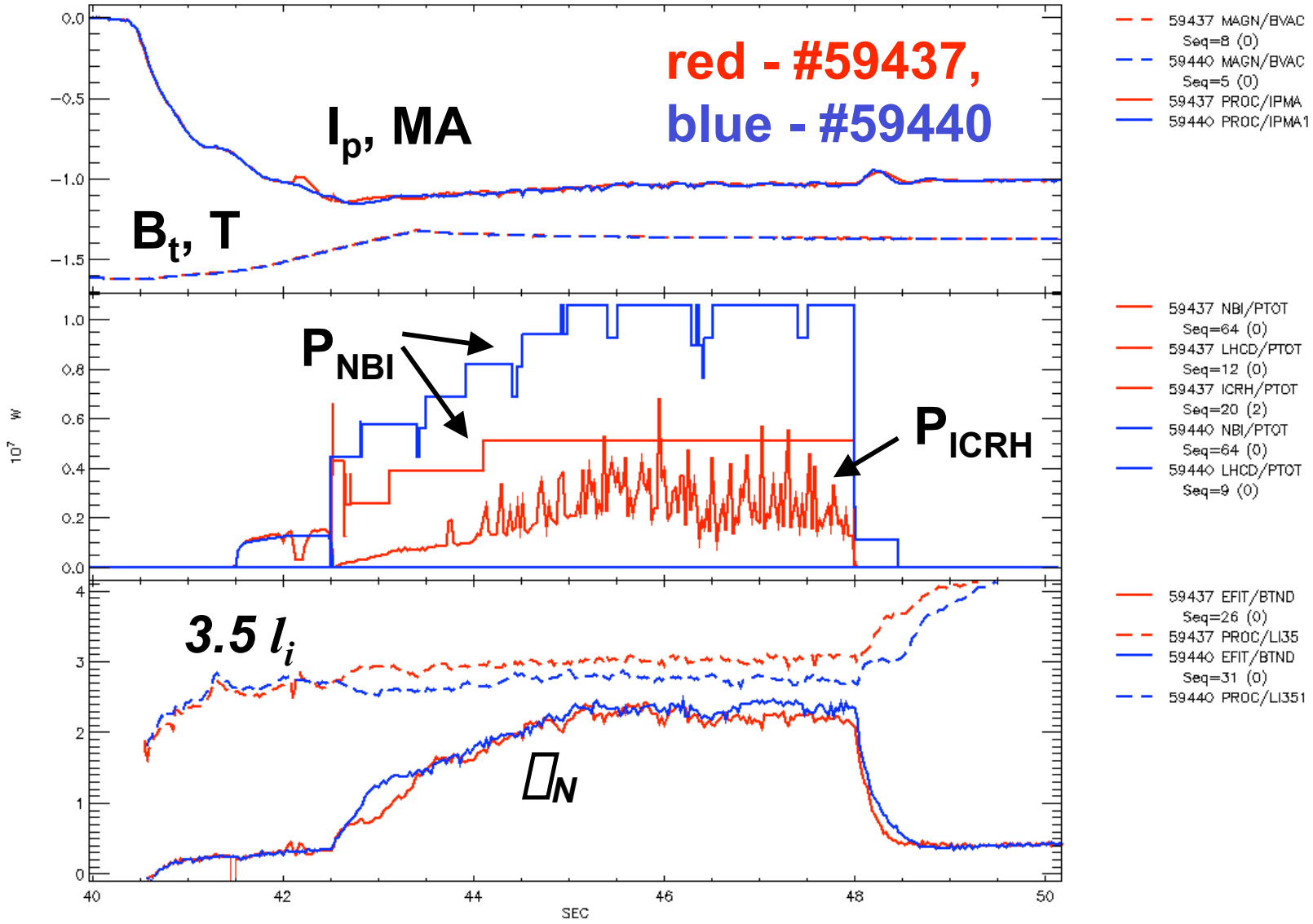
Due to strong rotation RWM strongly damped in JET experiments ($\gamma/\omega_A \sim 4\%$)



Least damped RWM eigenvalue

Future work

- JET expts with reduced $\omega_{plasma}/\omega_{Alfven}$
- Development of cross-machine models (e.g. by experimental benchmarking of MARS), allowing extrapolation to ITER



In #59437 half of P_{NBI} was replaced by ICRH to reduce toroidal rotation

SUMMARY

- First EFA experiments with DC and AC external error fields have been performed on JET
- Results dominated by strong RWM damping $\gamma_{plasma}/\gamma_{Alfven}$~4%
- DC Error Field Amplification in good agreement with MARS
- AC results show no finite frequency resonance and square wave decay little variation with ω - due to strong RWM damping