RWM Feedback Control Experiments on HBT-EP

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and

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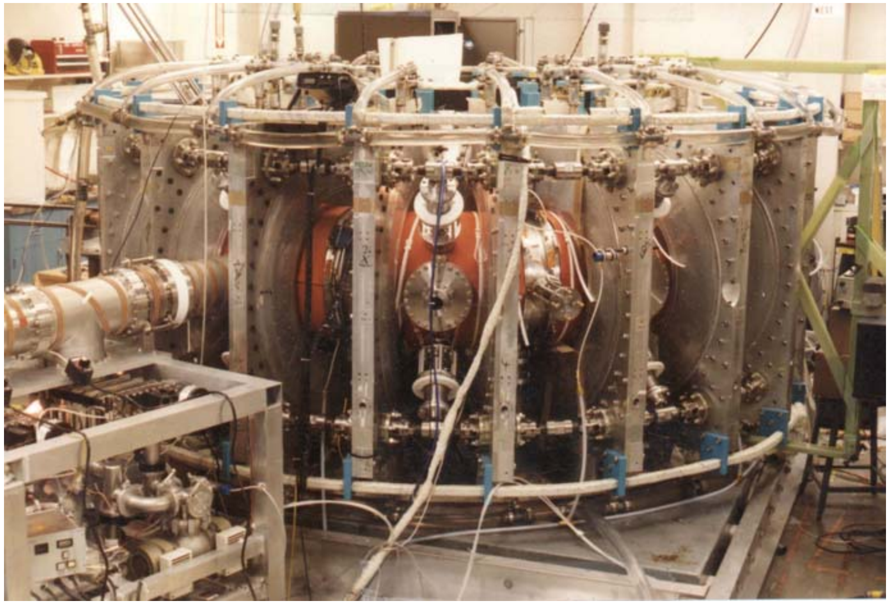
HBT-EP Tokamak Properties

Nominal Performance Parameters



Major Radius:	$R = 0.92$ m
Minor Radius:	$a = 0.15$ m
Toroidal Field:	$B_\varphi = 0.35$ T
Plasma Current:	$I_p <= 20$ kA
Pulse Length:	$\tau \sim 10$ ms
Temperature:	$<T_e> = 50 - 100$ eV
Density:	$<n_e> \sim 10^{19}$ m^{-3}

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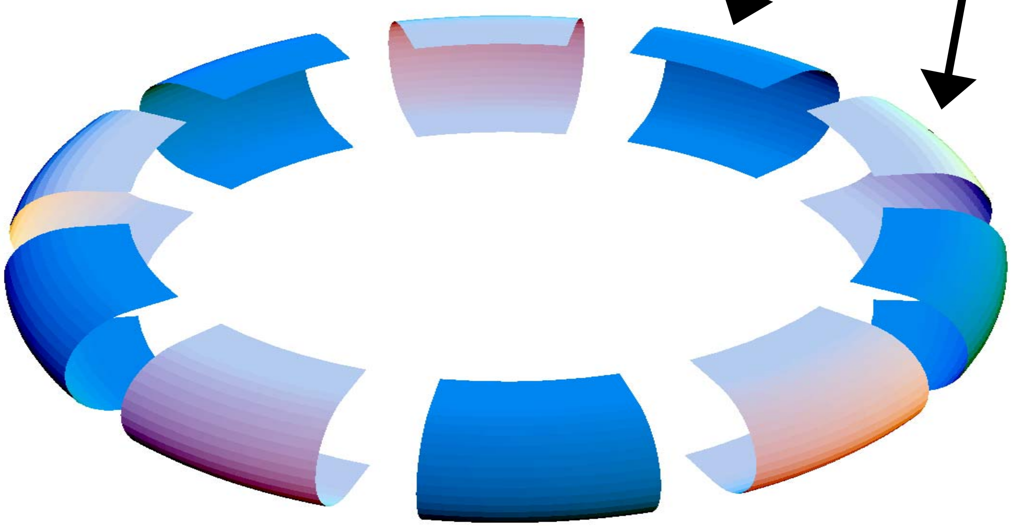
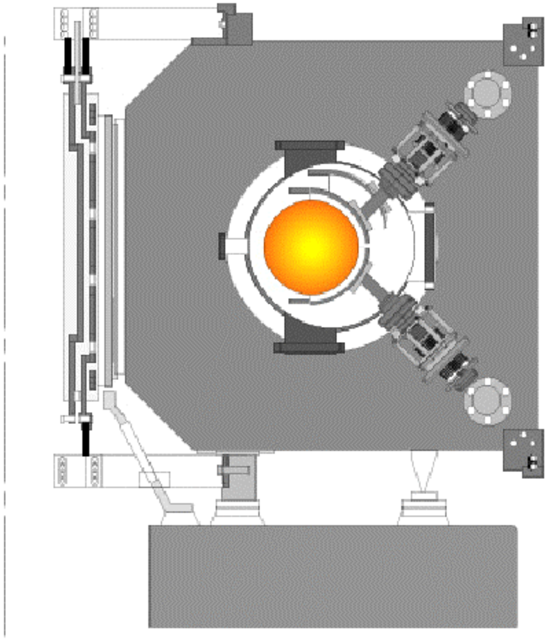
Adjustable Conducting Shells

- 20 Independently adjustable sections
- 1.07 < *b/a* < 1.52
- Poloidally and toroidally segmented
- Shells cover 78% of outboard plasma surface
- Plasma radius fixed by independent limiters

10 nickel plated aluminum shells
Thickness: $\delta = 2$ cm
Wall time: $\tau_w = 65$ ms

10 stainless steel shells
Thickness: $\delta = 2$ mm
Wall time: $\tau_w = 400\ \mu s$





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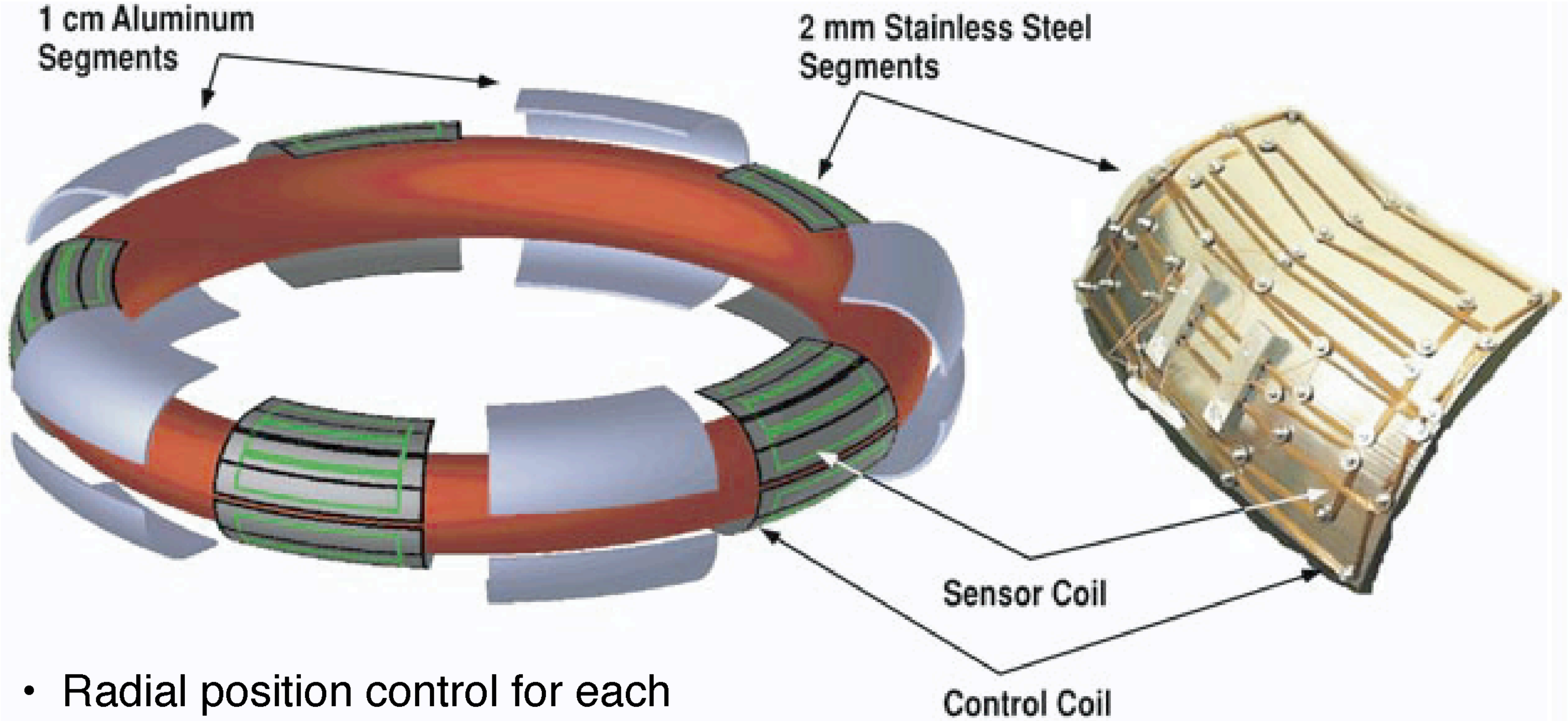
HBT-EP RWM Control Experiments: Smart Shell Feedback



- Radial position control for each Aluminium and Stainless Steel passive plate segment

- Ideal beta limit and effective wall time constant (and hence mode stability) controllable through passive plate radial position

- Three control and sensor coils per SS passive plate as shown

- Thirty independent control/sensor pairs for radial flux cancelation

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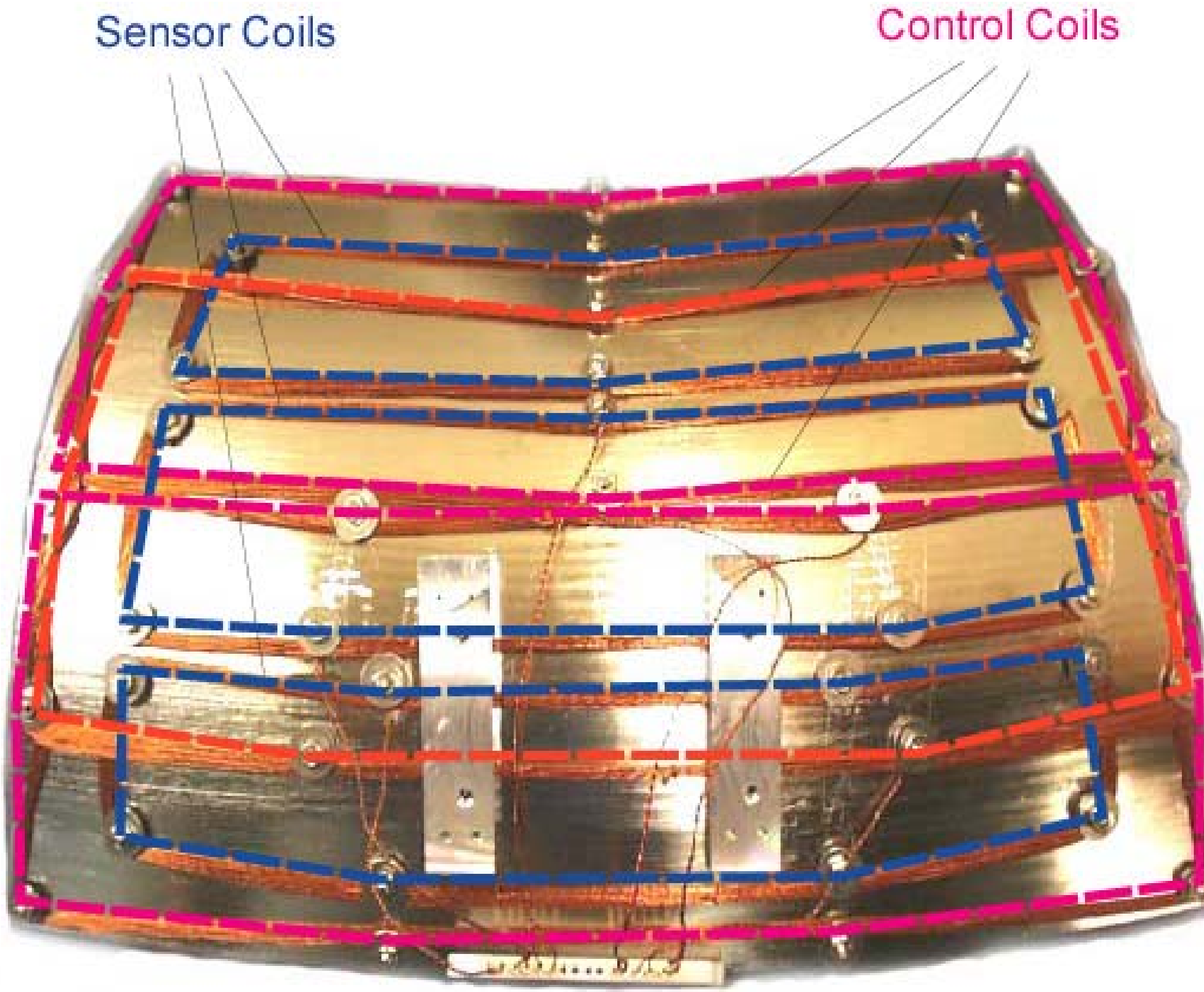
Stainless Steel Shell Coils



HBT-EP RWM Feedback Gain

Proportional Gain (Volt/Weber) and Derivitive Gain (Volt/Volt)

$$V_C = -G_P\Phi_S - G_D\dot{\Phi}_S = -(G_P + i\omega G_D)\Phi_S$$

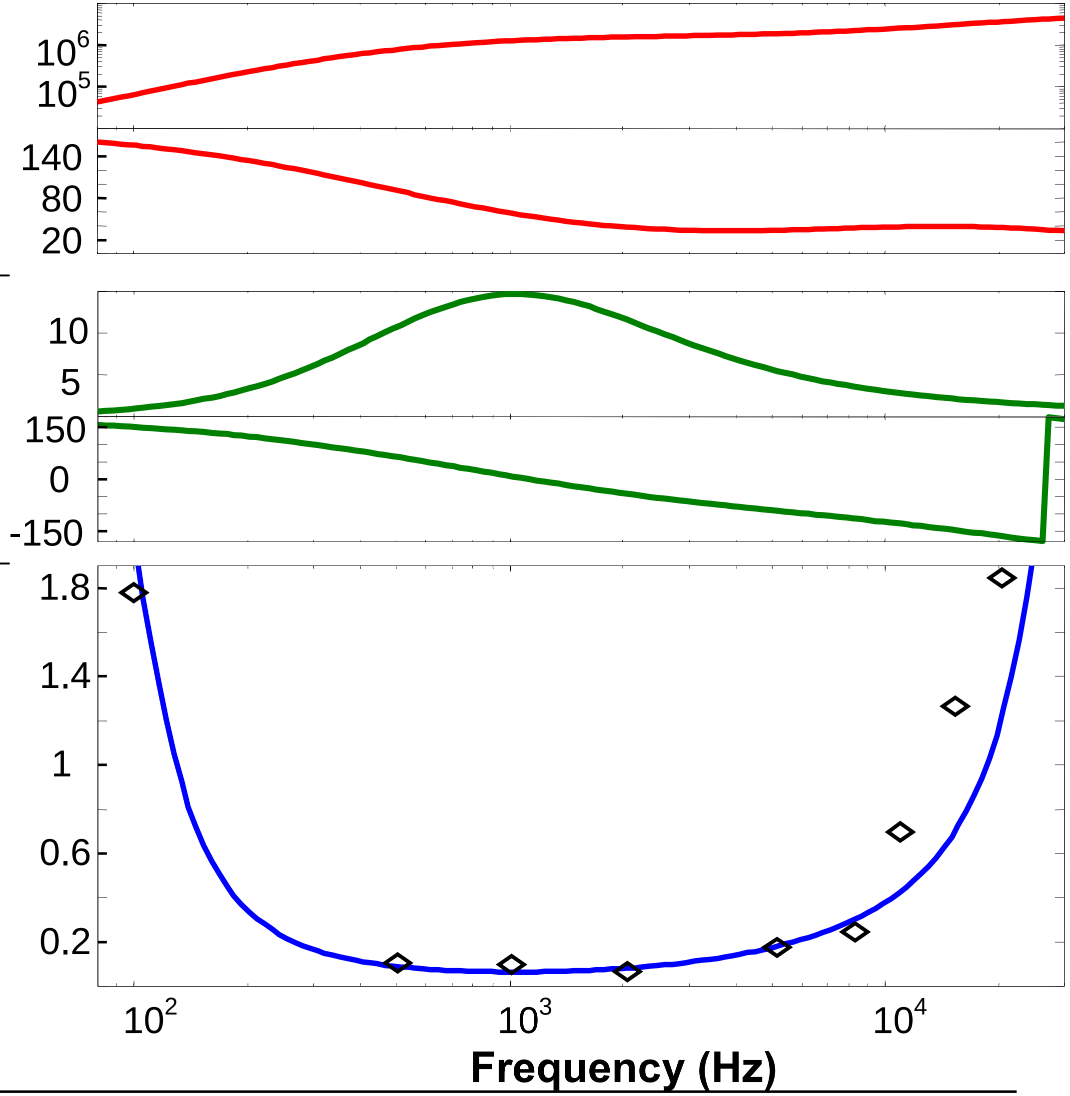
Flux Gain (Weber/Weber)

$$\Phi_C = -\alpha\Phi_S$$

$$\alpha = \frac{M'_{SC}(G_P + i\omega G_D)}{Z'_C}$$

Feedback Reduction

$$\frac{\Phi_S}{\Phi_{Ext}} = \left|\frac{1}{(1+\alpha)}\right|$$



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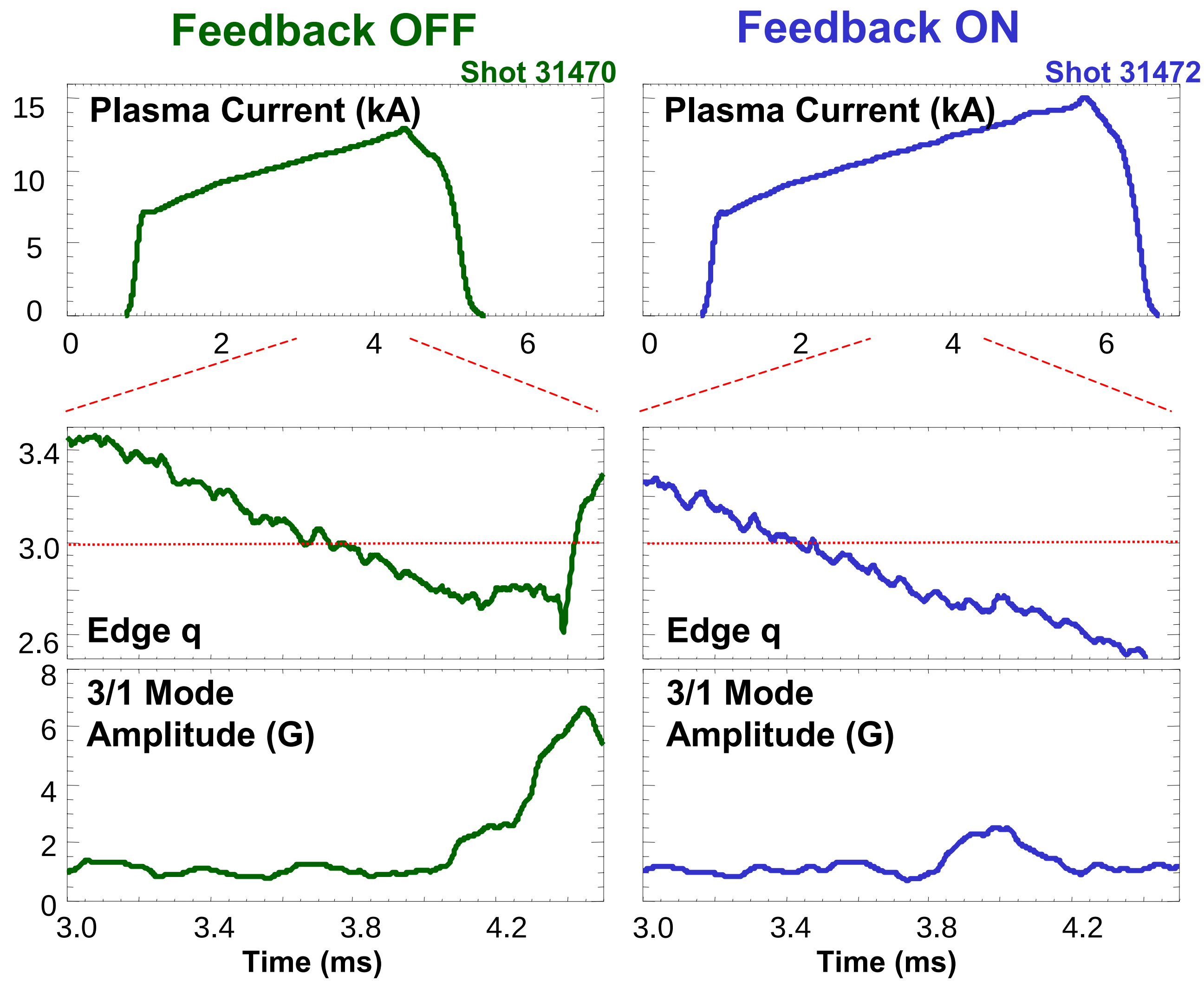
Active feedback suppresses current driven RWM disruption

- The external m/n = 3/1 RWM grows as the edge q drops below 3.
- When feedback is applied the amplitude of the RWM remains at the noise level.
- Without feedback, the RWM leads to disruption of the discharge.



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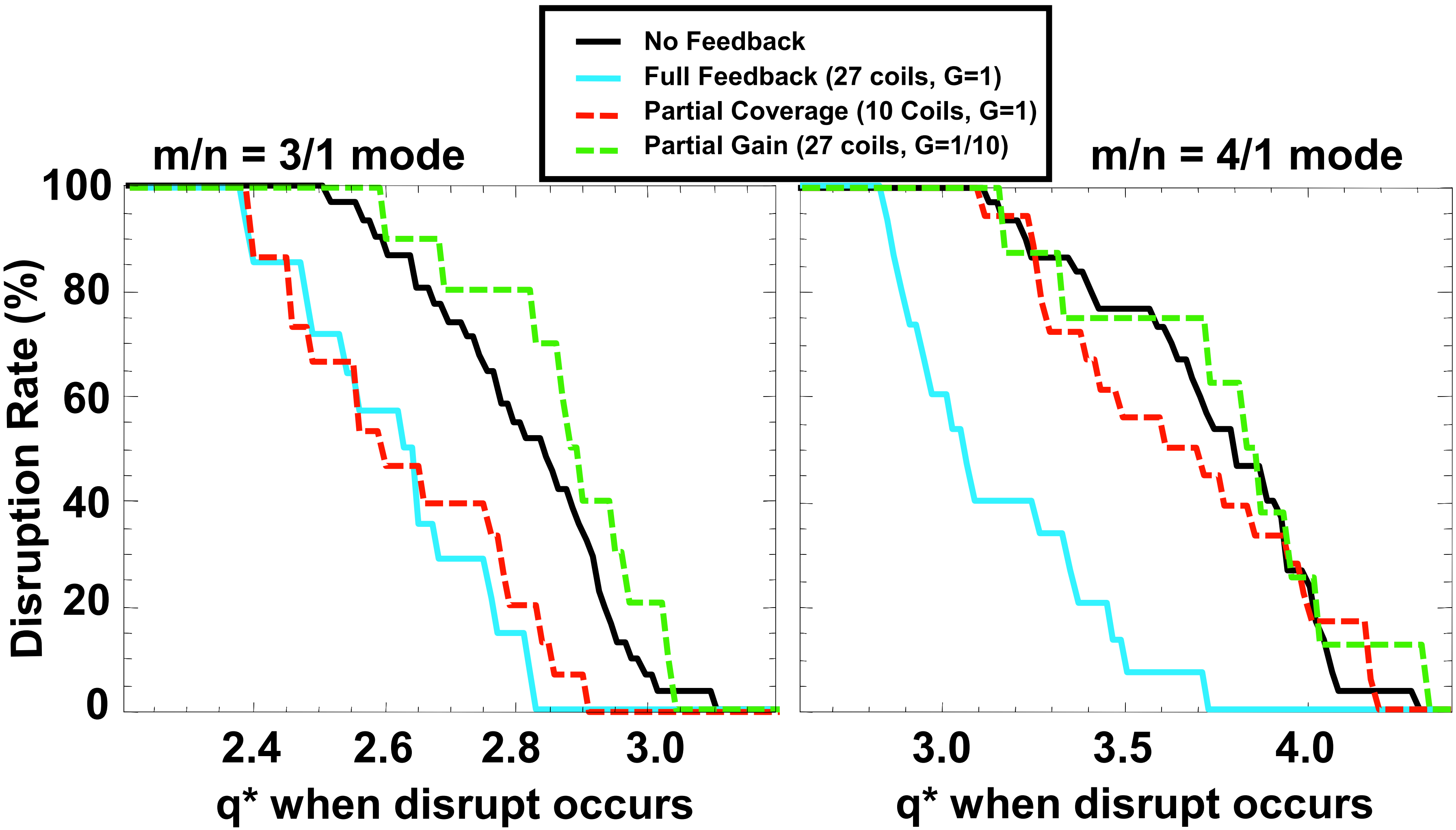
Disruption Rates for Resistive Wall Mode Feedback



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Measurement of RWM Response in the case of Rapid Formation, "High Beta" Discharges

Typical Plasma Parameters

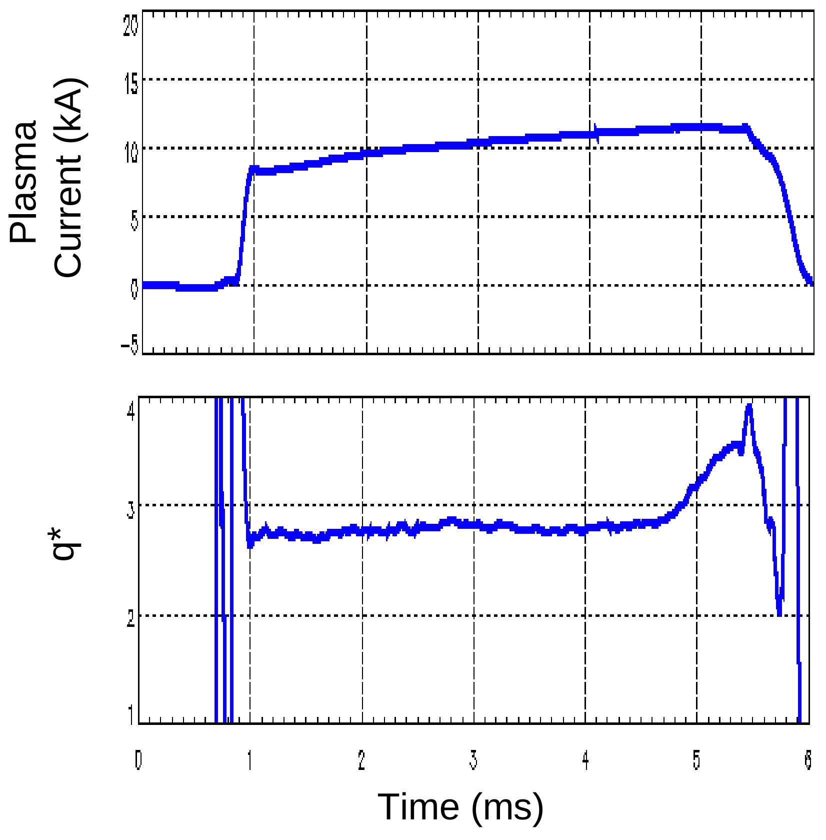
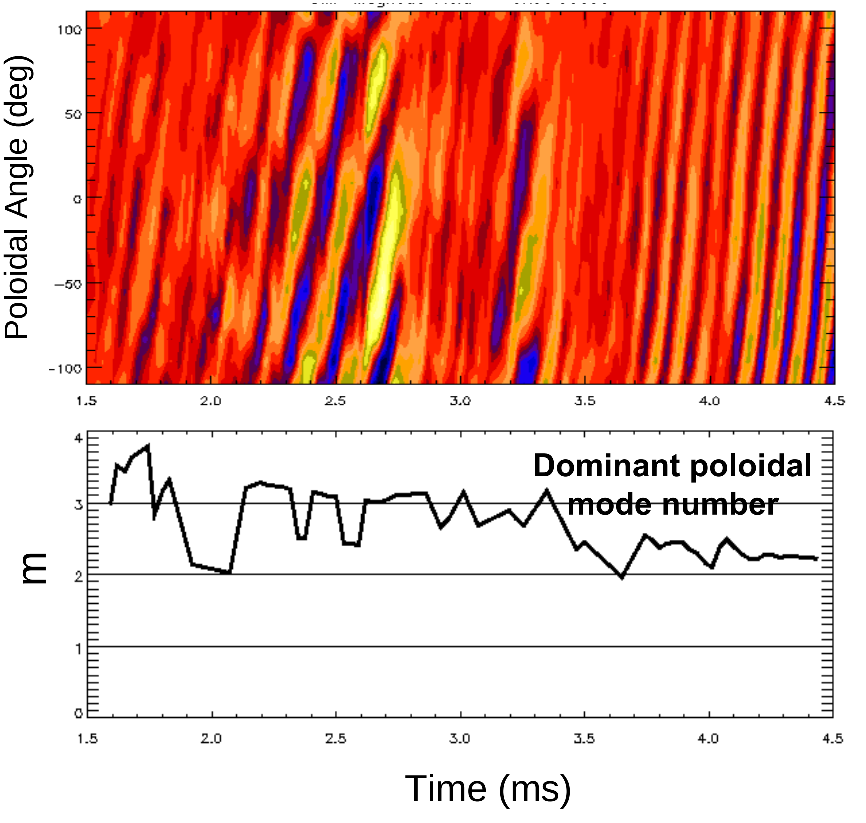
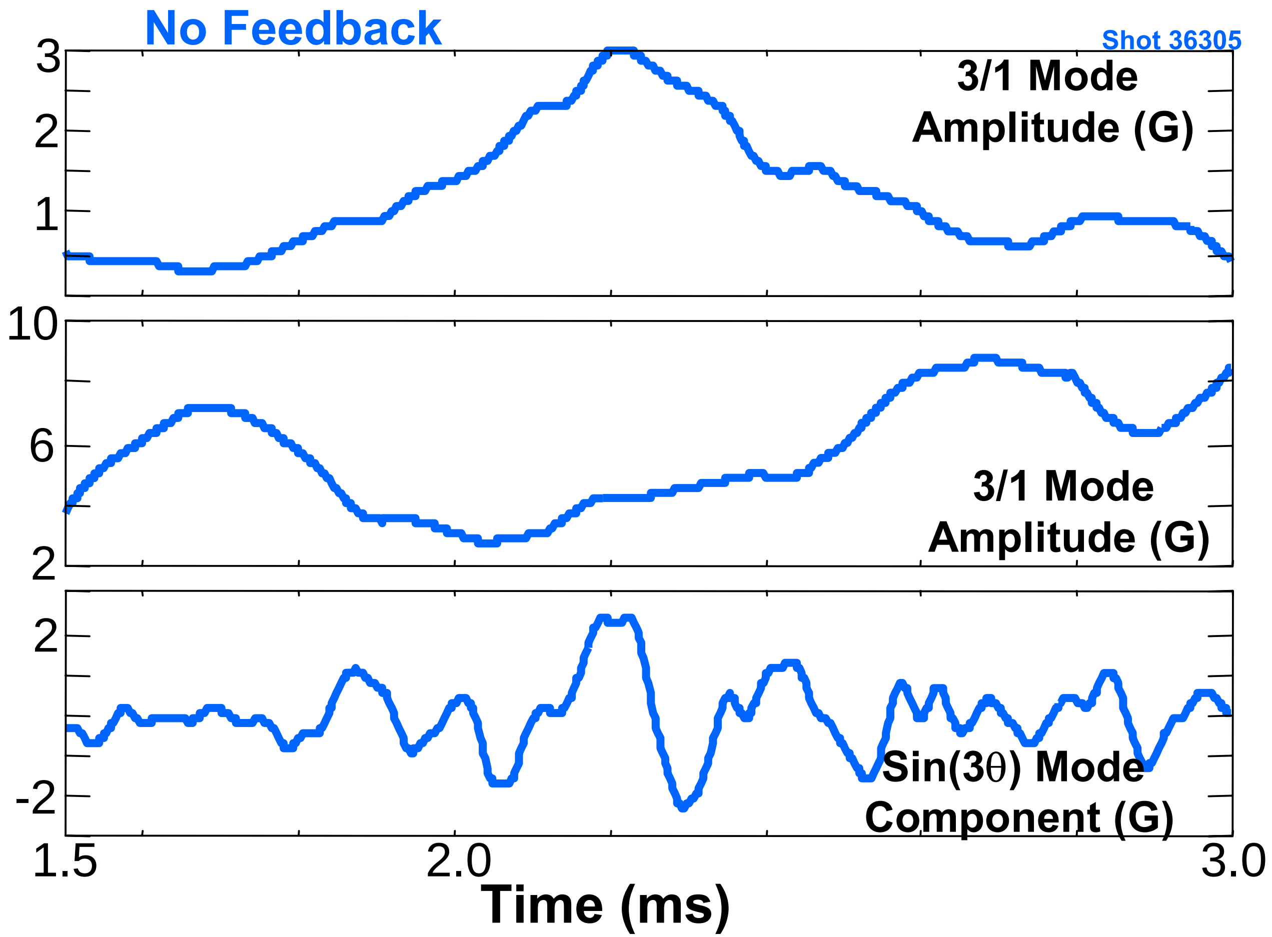


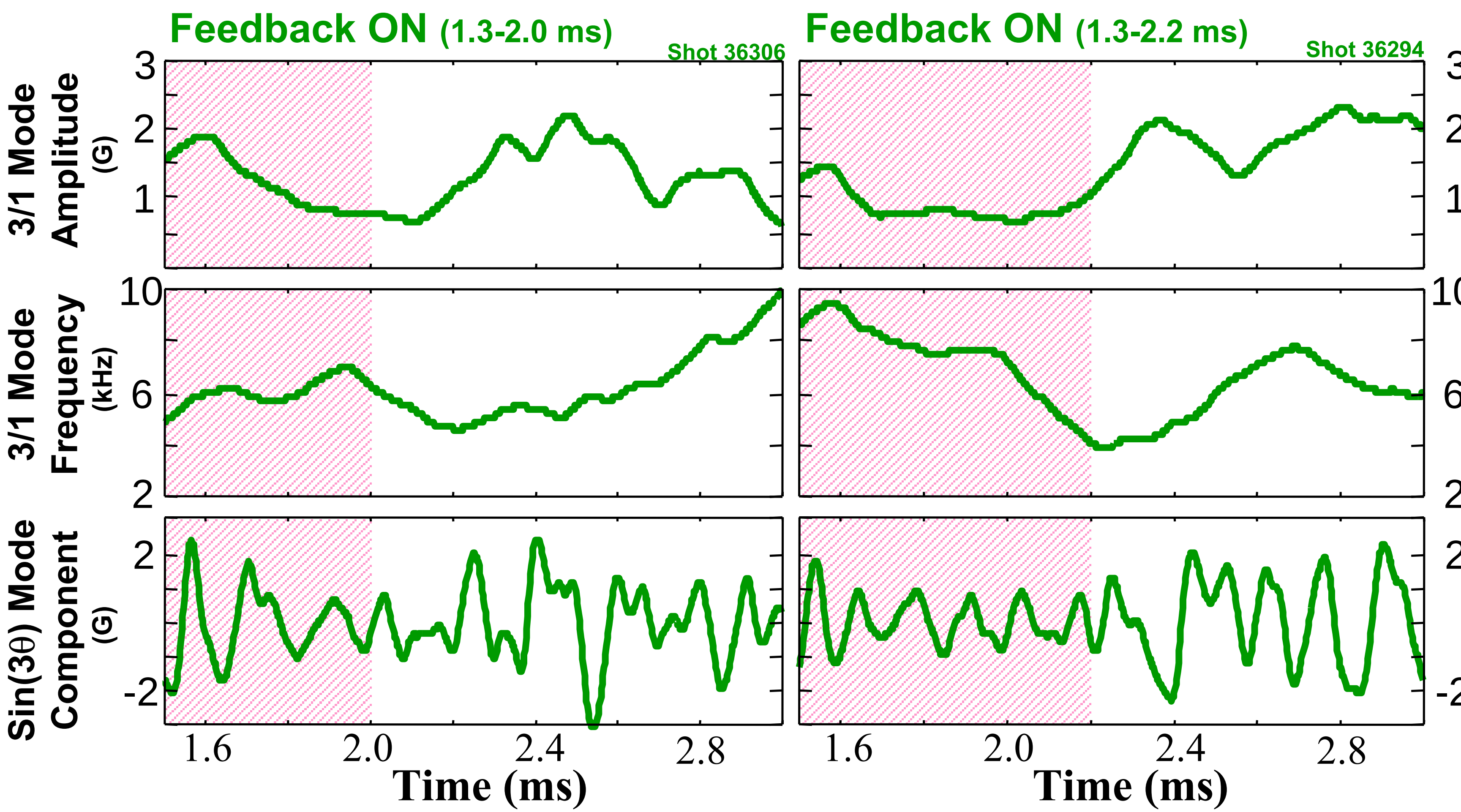
Image of the poloidal field fluctuation measured with Shell Mounted Probes during natural shot (no feedback, no external error field, thick shells retracted)



RWM Growth in Rapid Formation, "High Beta" Discharges



Stabilized RWM Grows when Feedback Switched Off



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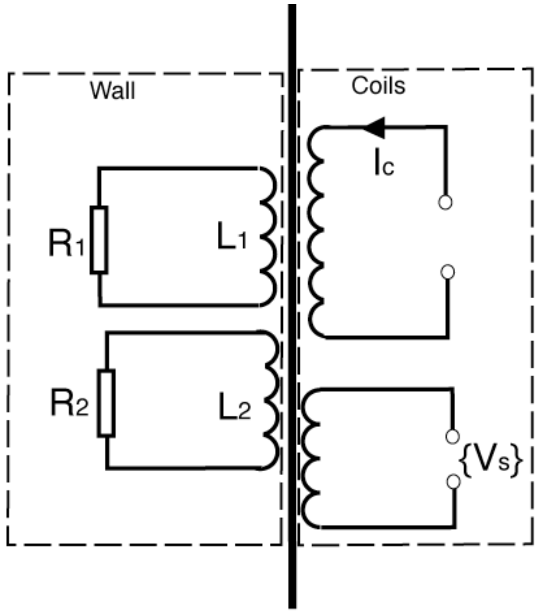
Conclusions

- Active feedback control of the resistive wall mode (RWM) has been achieved and RWM induced disruptions have been suppressed with an in-vessel array of 30 sensor-loop and control-coil pairs each of which is connected through an independent feedback circuit in a "smart shell" configuration, capable of suppressing up to 95% of the mode radial flux through the resistive wall.
- This system effectively stabilized the RWM in HBT-EP when applied to a series of current-ramp experiments (dI/dt~2 MA/s) that produce disruptive RWM activity at the q* ~ 4 and q* ~ 3 transitions.

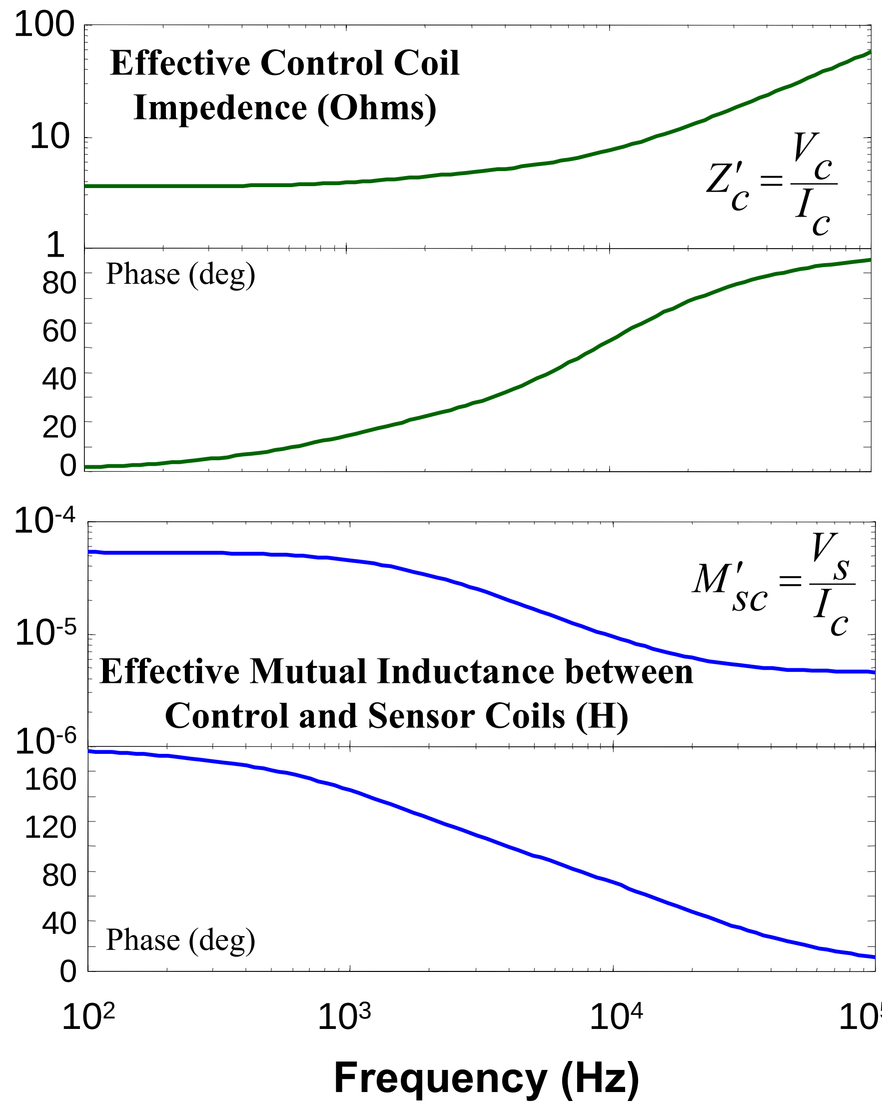
  3/1 modes
  - The disruption rate for discharges which reach a given value of q* was reduced by 40% when full feedback was applied
  - Feedback with a partial coverage using only 10 midplane coils was equally effective at suppressing disruptions.
  - Reducing the feedback gain by a factor of 10 was observed to have no effect on the disruption rate.

  4/1 modes
  - The disruption rate for discharges which reach a given value of q* was reduced by over 60% when full feedback was applied
  - A reduction in gain or coverage completely reduced the effectiveness of the feedback in disruption suppression.
- Active feedback control of RWM demonstrated during rapid formation, high beta discharges. When the feedback is switched off the mode amplitude grows and the mode frequency decreases.

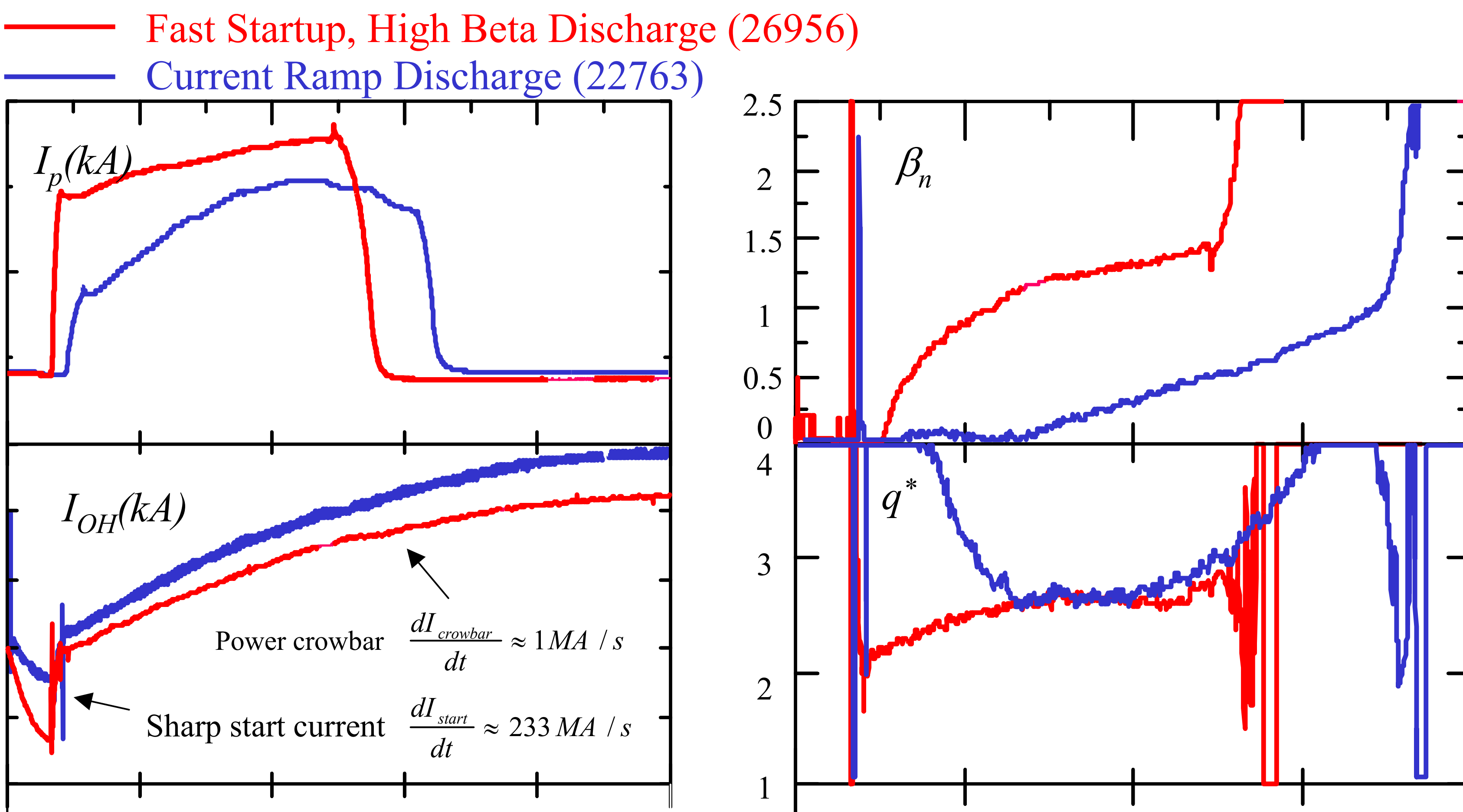
HBT-EP RWM Feedback Coil Characteristics



Resistive Wall	Feedback Coils
τ_{w1} = 77 μs	L_c=170 μH
f_{w1}=2.1 kHz	R_c=3.6 Ω
	τ_c= 47 μs
τ_{w2} = 12.7 μs	f_c=3.3 kHz
f_{w2}=12.6 kHz	M_{sc}=41 μH



External Kink and RWM Instabilities Observed During Two Types of Discharges on HBT-EP



HBT-EP group has experience with passive stabilization of external kinks during these types of discharges. (Ivers, et al, Phys Plasmas, 1996)

Valen Calculations for 3/1 Feedback with varying Gain and Coverage