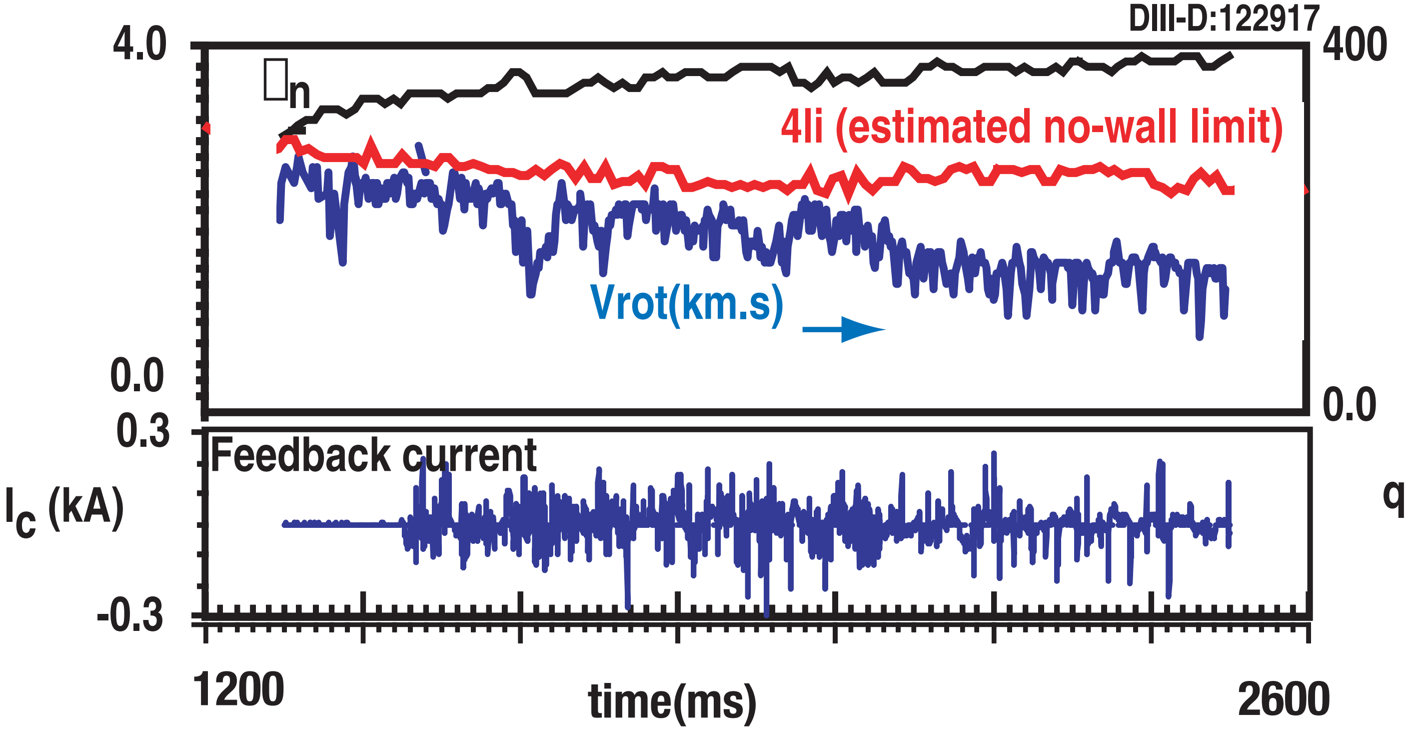
Present understanding of RWM physics
and
possible approaches for RWM control in burning plasmas

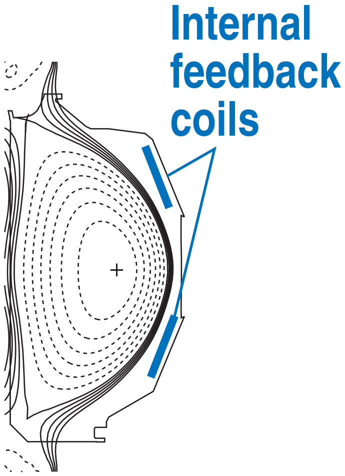
Workshop (W60) on “Burning Plasma Physics and Simulation”
4-5 July 2005, University Campus, Tarragona, Spain
Under the Auspices of the IEA Large Tokamak Implementing Agreement

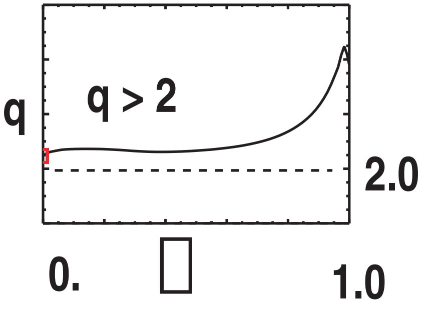
Goal of RWM Control in Burning Plasmas

- Sustainment of AT plasmas well above no-wall limit -

- Achievement of high β_n AT plasmas was assisted by combined stabilization of plasma rotation and magnetic feedback



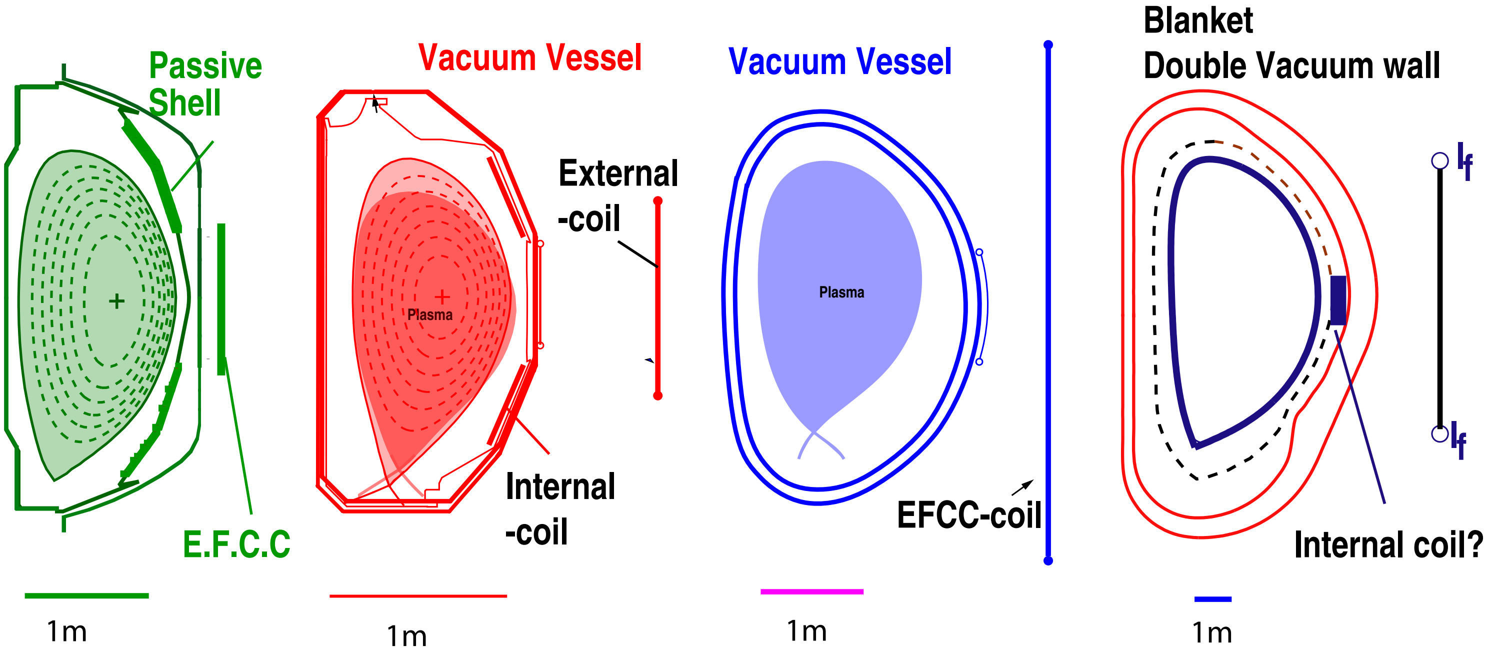




OUTLINE

- RWM physics understanding has been significantly advanced by collaborative efforts (DIII-D, JET, NSTX,........)
  - High betan AT plasma has been achieved
  - Experimental results and theoretical predictions are in qualitative agreement
  - Analysis using numerical codes (e.g., MARS, VALEN, ...) has advanced the understanding of RWM physics
  - Plasma rotation is marginal for RWM stabilization in ITER: present prediction
- Advantages of Internal coils (DIIID experiments)
  - Low current required for dynamic error field correction
  - Fast time-response compared with external coils
  - Achievement of high betan
- ITER
  - Internal control coils are attractive
- Open issues

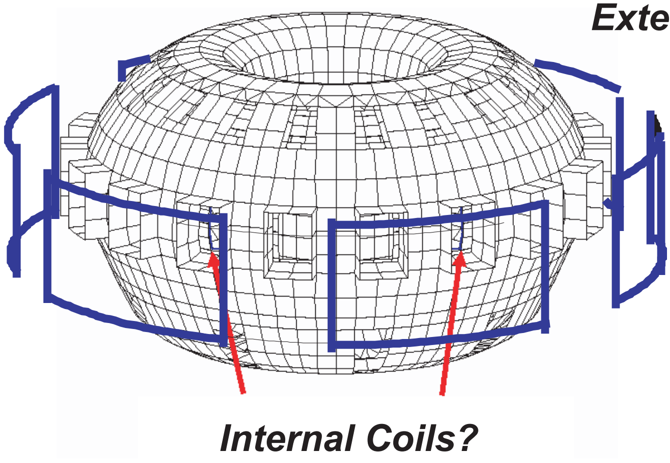
Non-axisymmetric Coils on Various Devices



	NSTX	DIII-D	JET	ITER
non-axisym-metric coils	External(6)	External (6) internal (6x2)	External (4)	External (9) Internal coil (7)?
R/a	1.27	3.1	3.0	3.4
R(m)	1.10	1.69	2.85	6.35

Non-axisymetric Coils on Various Devices

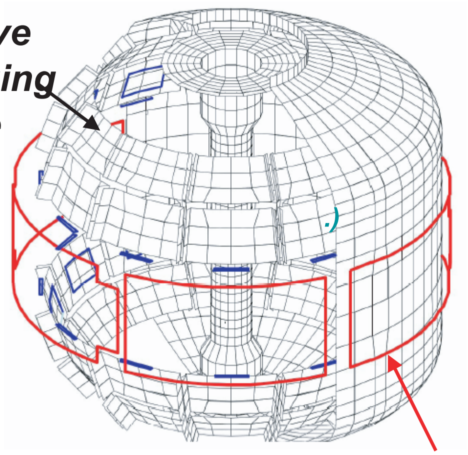
ITER



External Coils

Internal Coils?

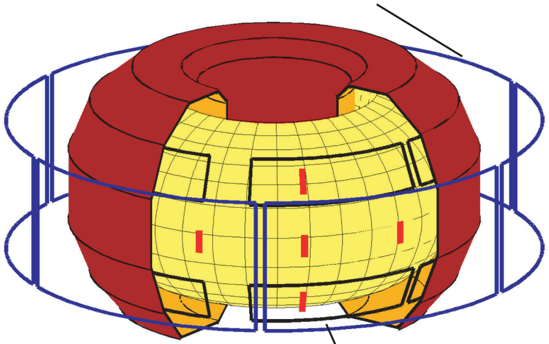
NSTX



Passive stabilizing plate

Active feedback coil

DIII-D



External Coils (C-coils)

Internal Coils (I-coils)

Excellent Progress of Experiments and RWM Theory Has Led to Quantitative Understanding of RWM Physics

- 1996 - concept of rotational stabilization and feedback

$$\underbrace{(\gamma + in\Omega)^2 - \delta W_p}_{\text{Ideal Stability}} + \underbrace{\frac{\delta W_{pw}\gamma\tau_w}{\gamma\tau_w + 1}}_{\text{Resistive Wall}} + \underbrace{(\gamma + in\Omega)\, D}_{\text{Plasma Dissipation}} = 0$$

- 1998 Use of non-axisymmetric coils
- 2001 Discovery of Dynamic Error Field Correction (DEFC)
- 2002 Confirming Resonant error Field Amplification (RFA)
- 2003 - Joint Experiments with DIII-D, JET, NSTX

- MARS
- VALEN
- Analytical models
- ....

Dissipation stabilizing force

$$j\mathrm{Im}(\Delta W_C + \Delta W_T) = -\frac{1}{2}\int \vec{F}_{\text{diss}} \cdot \vec{\xi}_\perp^{\,*}\, d^3x$$

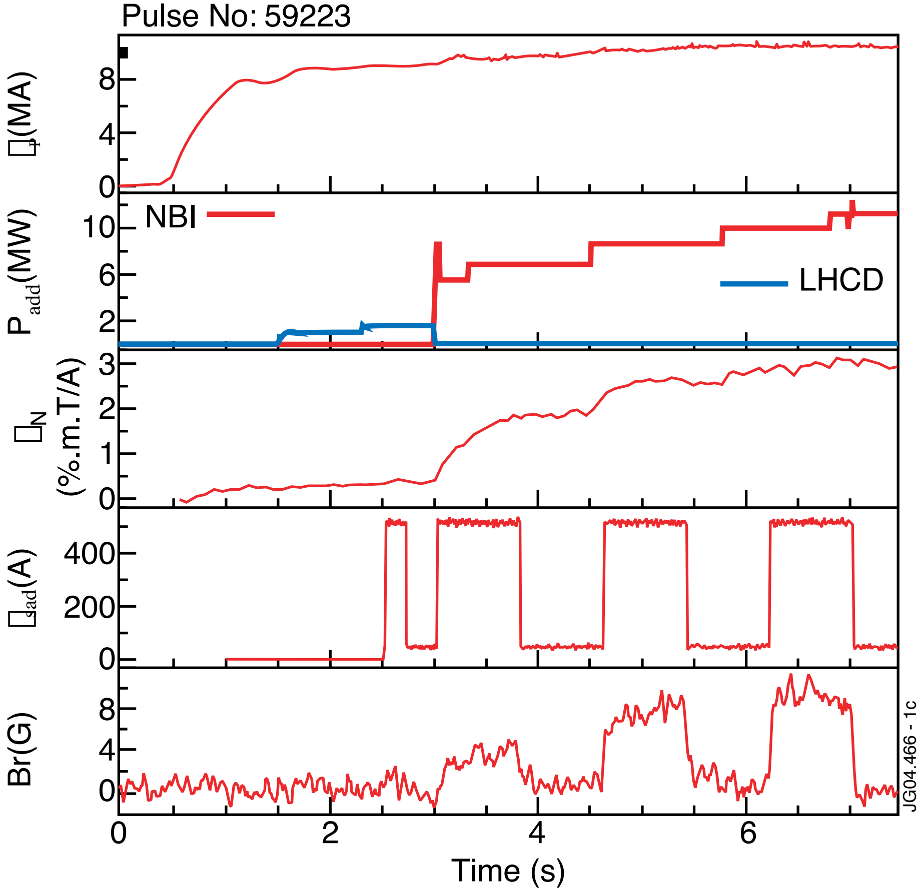
$$\Delta W_T = \frac{1}{2}\sum_{m'}\int d^3x \int_{\text{trapped}} d\Gamma \left(-\frac{\partial f}{\partial E}\right)\frac{\omega}{\omega + m'\omega_b}\left| < \exp(j\chi_{m'})H > \right|^2$$

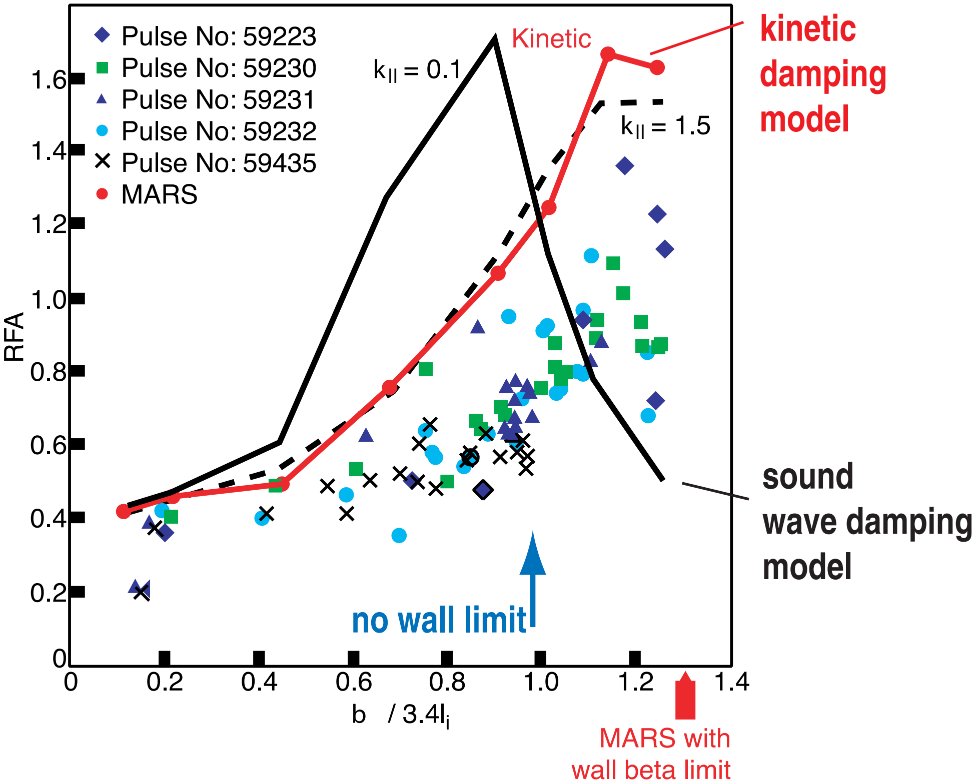
$$\Delta W_C = \frac{1}{2}\sum_{m'}\int d^3x \int_{\text{circ}} d\Gamma \left(-\frac{\partial f}{\partial E}\right)\frac{\omega}{\omega - (nq - m')\omega_t}\left| < \exp(j\chi_{m'})H > \right|^2$$

Kinetic damping model

RFA Has Been Observed at $\beta_n \geq \beta_{n.no\text{-}wall}$ in JET

- RFA is common feature in the toroidal device
- MARS code provides qualitative agreement



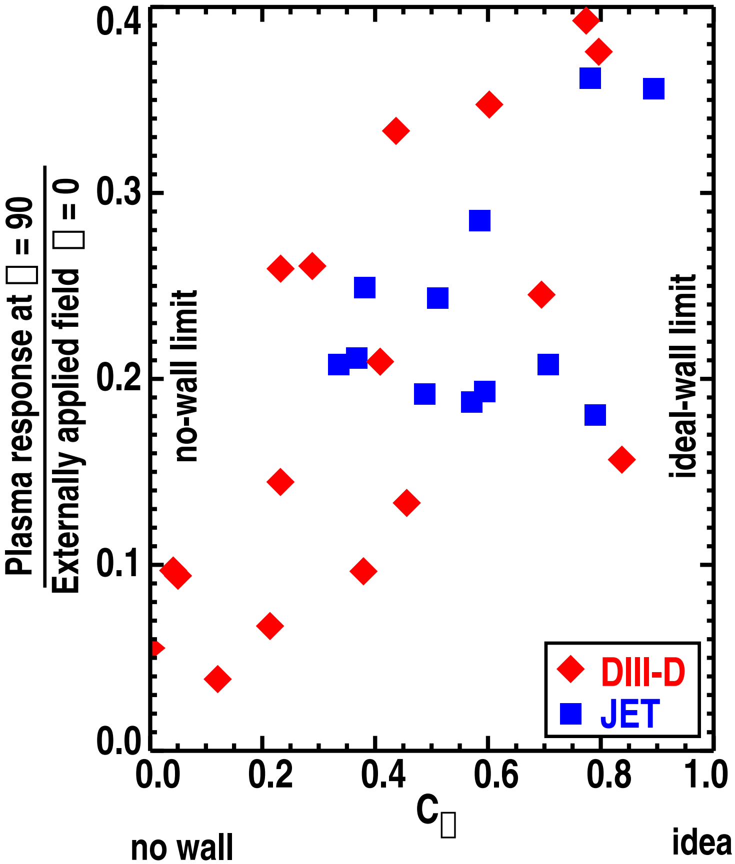


JET RFA with internal coils

ref: T. Hender et al., [IAEA 2004]

- Mode rigidity is the fundamental assumption of understanding in the rotational stabilization.
  -> Internal mode structure measurement should verify the hypothesis.
    - MSE techinque is now available [R. Jayakumar RSI 75(2004)2995]

RFA Observations in JET, DIII-D and NSTX Have Provided Consistent Dependence of RFA Magnitude on $\Box_n$



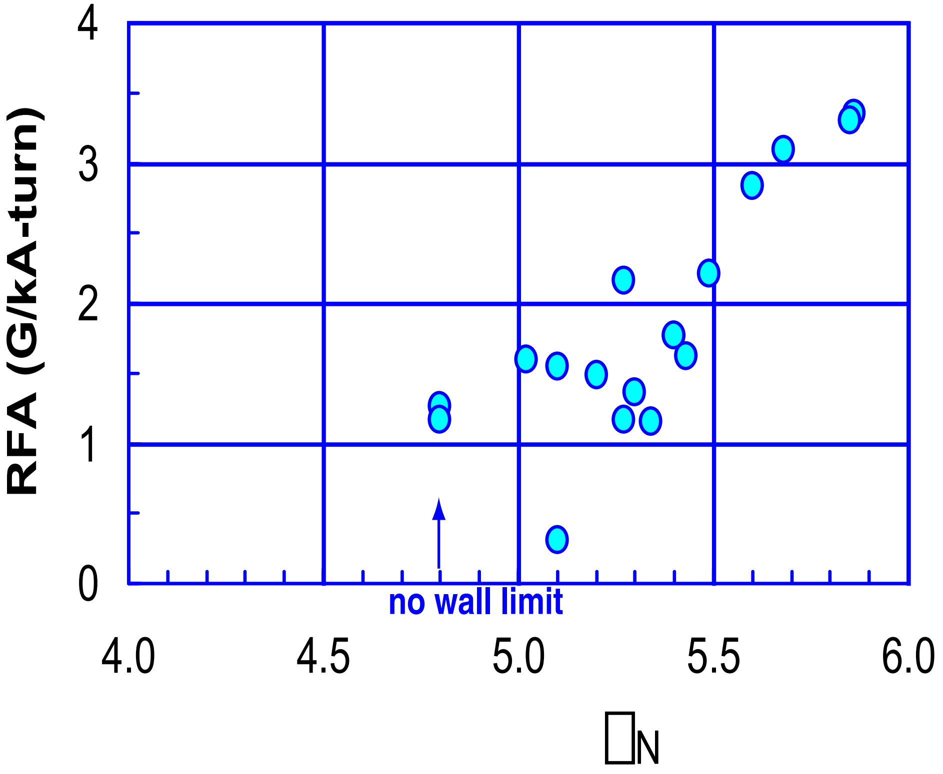
no wall limit

ideal wall limit

JET / DIII-D

with External coils

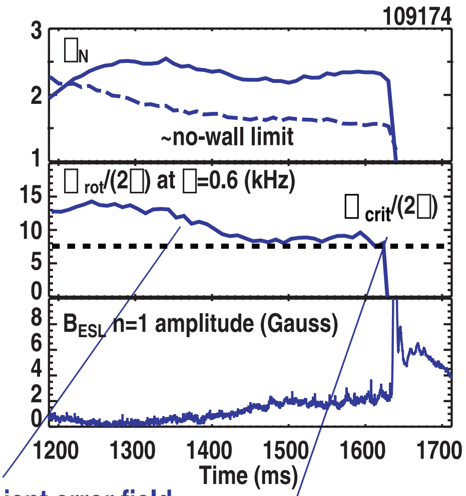
H. Reimerdes EPS[2005]



NSTX

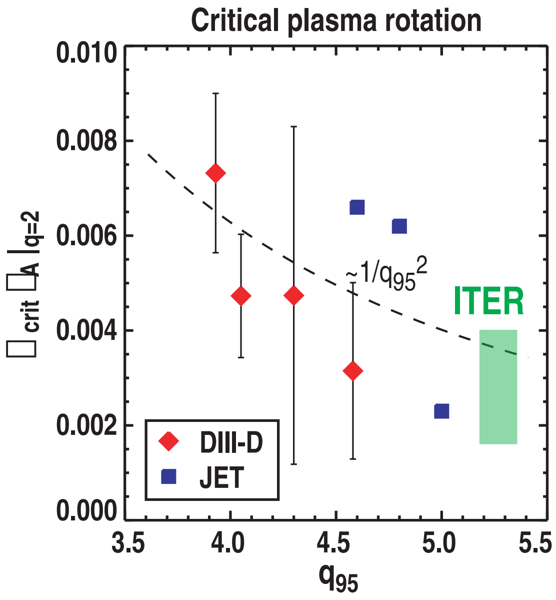
S. Sabbagh IAEA(2004)

Results from DIII-D/JET Indicates that the Rotation in ITER will be Marginal for RWM Stability

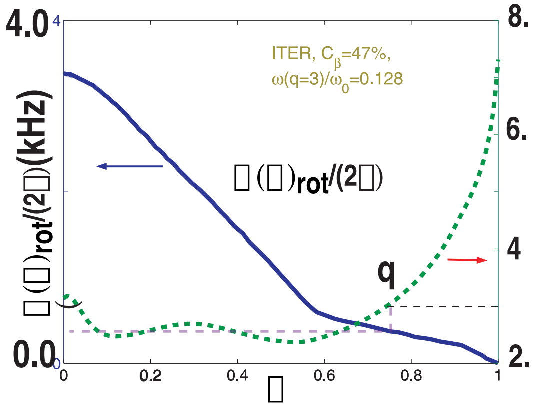


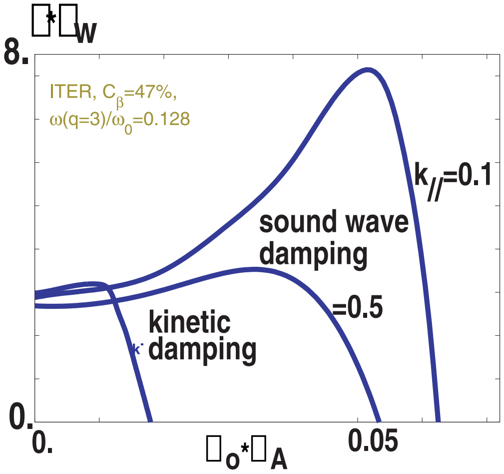
Insufficient error field correction causes slow-down

Onset of RWM marks critical rotation



	DIIID Exp.	ITER prediction	ITER predicted by MARS (kinetic)	ITER expected rotation
R(m)	1.69	6.35		
q_{min}	1.5	2.4		
□A(□s)	0.40	0.75		
□crit*□A	0.004 (q=2)	0.004	0.002 (q=3)	
□crit/(2□)	1.6 (q=2)	1.0	0.45 kHz	
□expected /(2□)				0.5 kHz





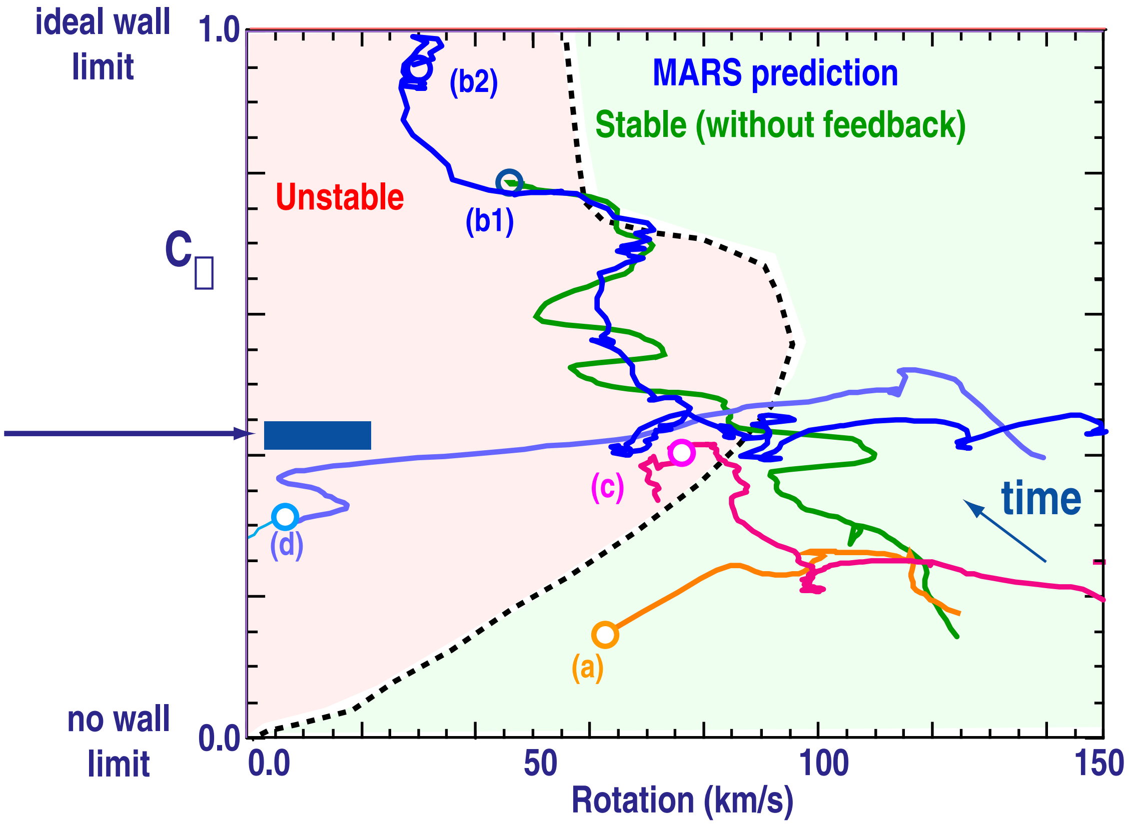
ITER prediction for scenario 4

[Y.Q.Liu IAEA 2004]

Combination of Rotational Stabilization and Feedback Has Increased Stable RWM Domain

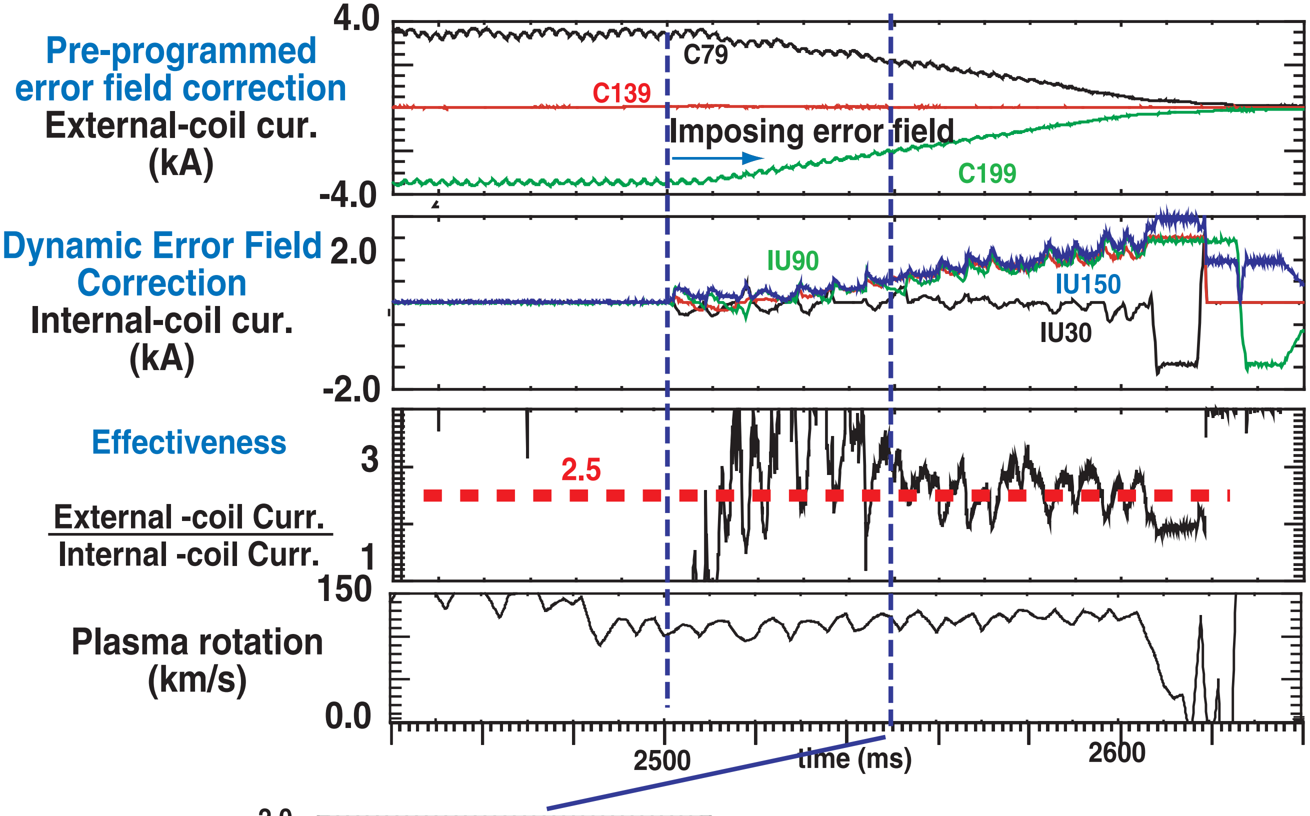
$$C_\beta = \frac{\beta - \beta^{no.wall}}{\beta^{ideal.wall} - \beta^{no.wall}}$$

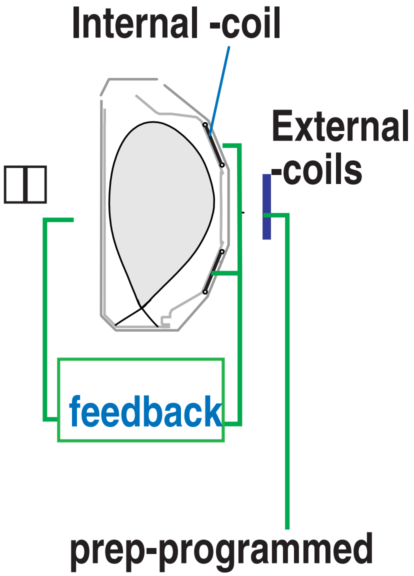
MARS /VALEN prediction
with measured
power supply time response
for zero rotation

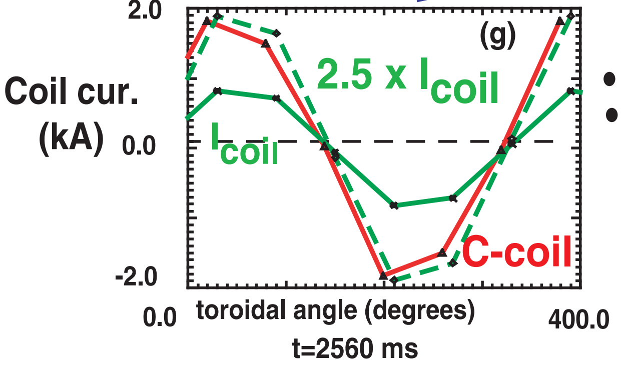


Internal Coils Need only □ 1/3 of External Coil Current for Dynamic Error Field Correction

- Error field imposed by External Coils was replaced by Internal Coils through feedback







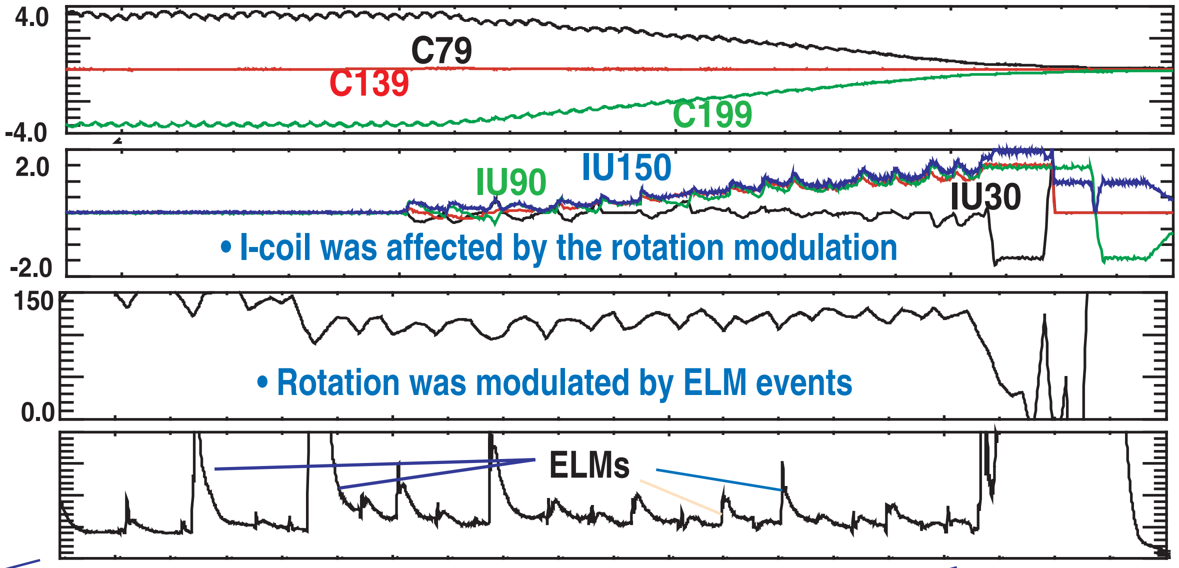
- Internal coils: $1/2*L*I^2$ □1% of External -coil
- Internal coils: L*I □3% of Exrternal-coil

	L	R
Internal coils	10 □H	4 m□
External coils	170 □H	10 m□

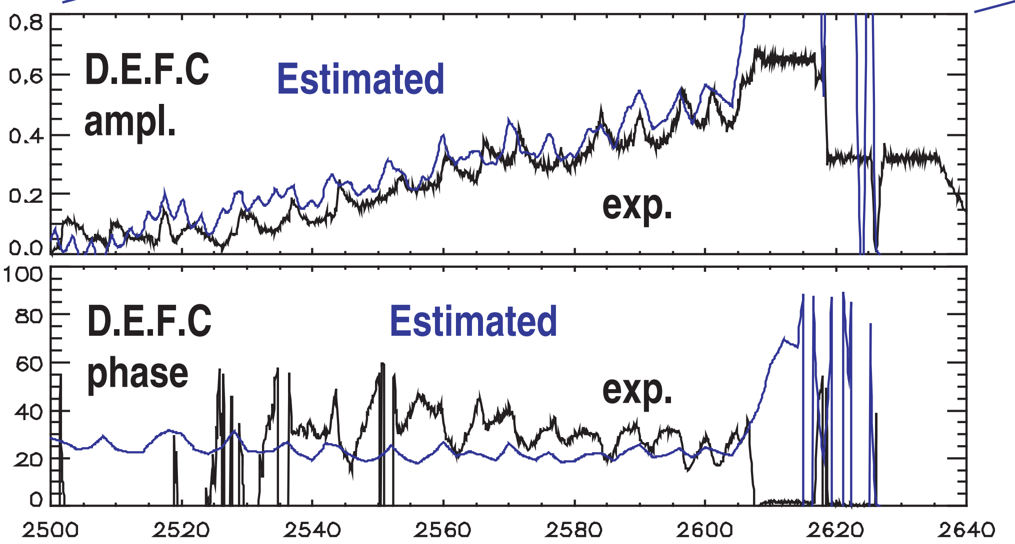
ELM-Modulated rotation affects the coil current.
$-\square_{rot}$ May be Needed as an input for Refining Dynamic Error Field Correction.

- **Pre-programmed error field correction**
  External-coil cur. (kA)
- **Dynamic error field correction**
  Internal -coil cur.(kA)
- **Plasma rotation** (km/s)

H-alpha



- I-coil was affected by the rotation modulation
- Rotation was modulated by ELM events



- Estimate by "Extended lumped parameter model" including $\square_{rot}$ explains I-coil modulation

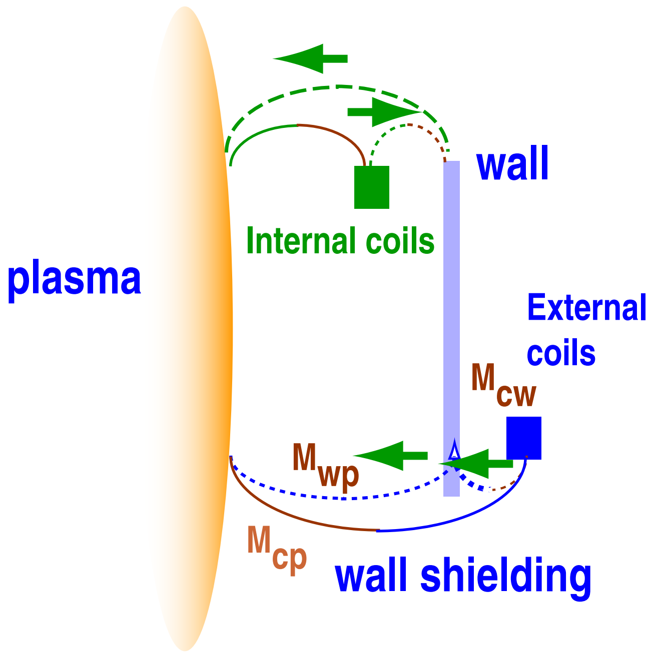
-> need of sensors of $\square_{rot}$ for optimzing the process

Internal-coil is more effective in reducing ELM induced n=1 RWM

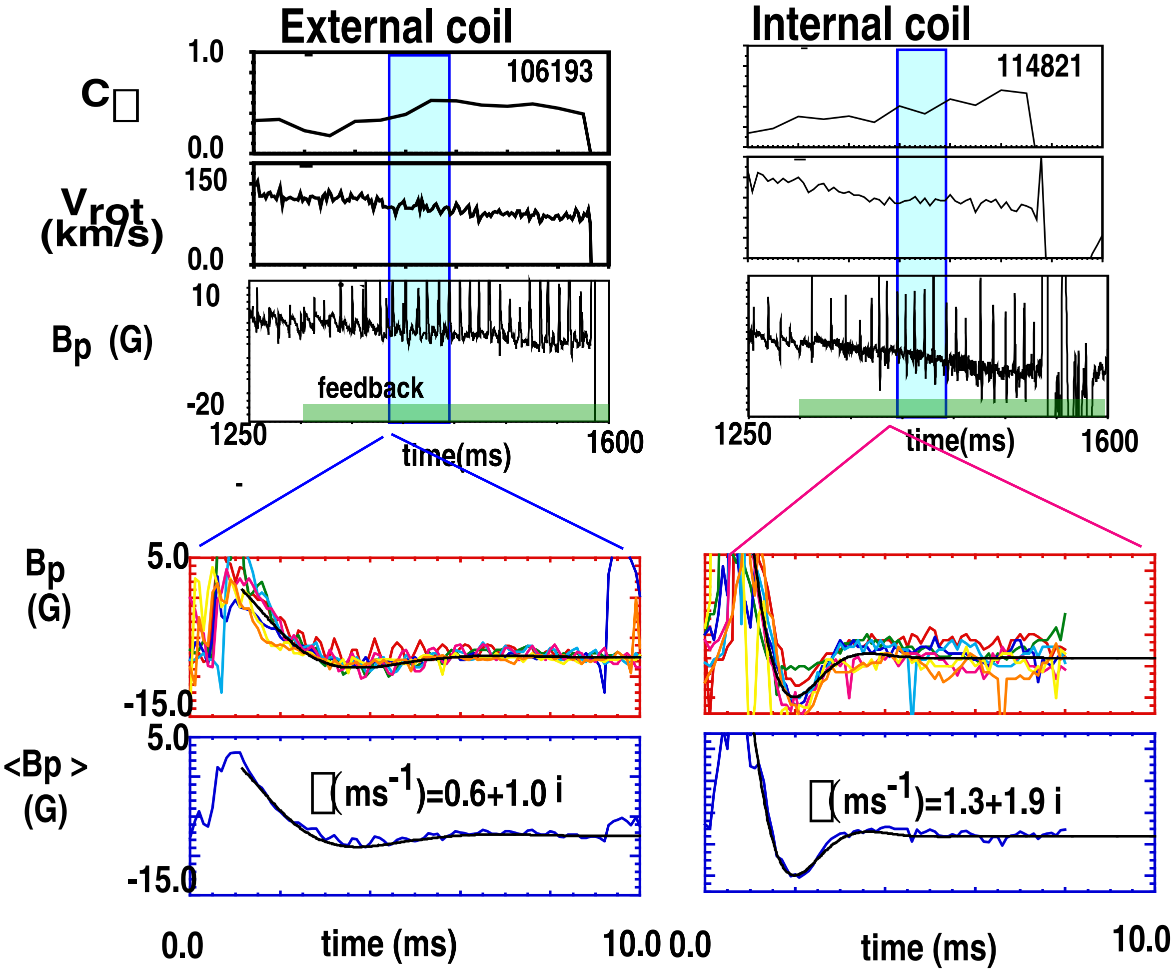
- n=1 component of ELM events excites n=1 RWM
- Internal-coil feedback reduces the n=1 RWM by a factor of 2 faster than with C-coil

- **Internal coil advantages**

- Closer to Plasma
- Wall shielding can be compensated by higher feedback gain



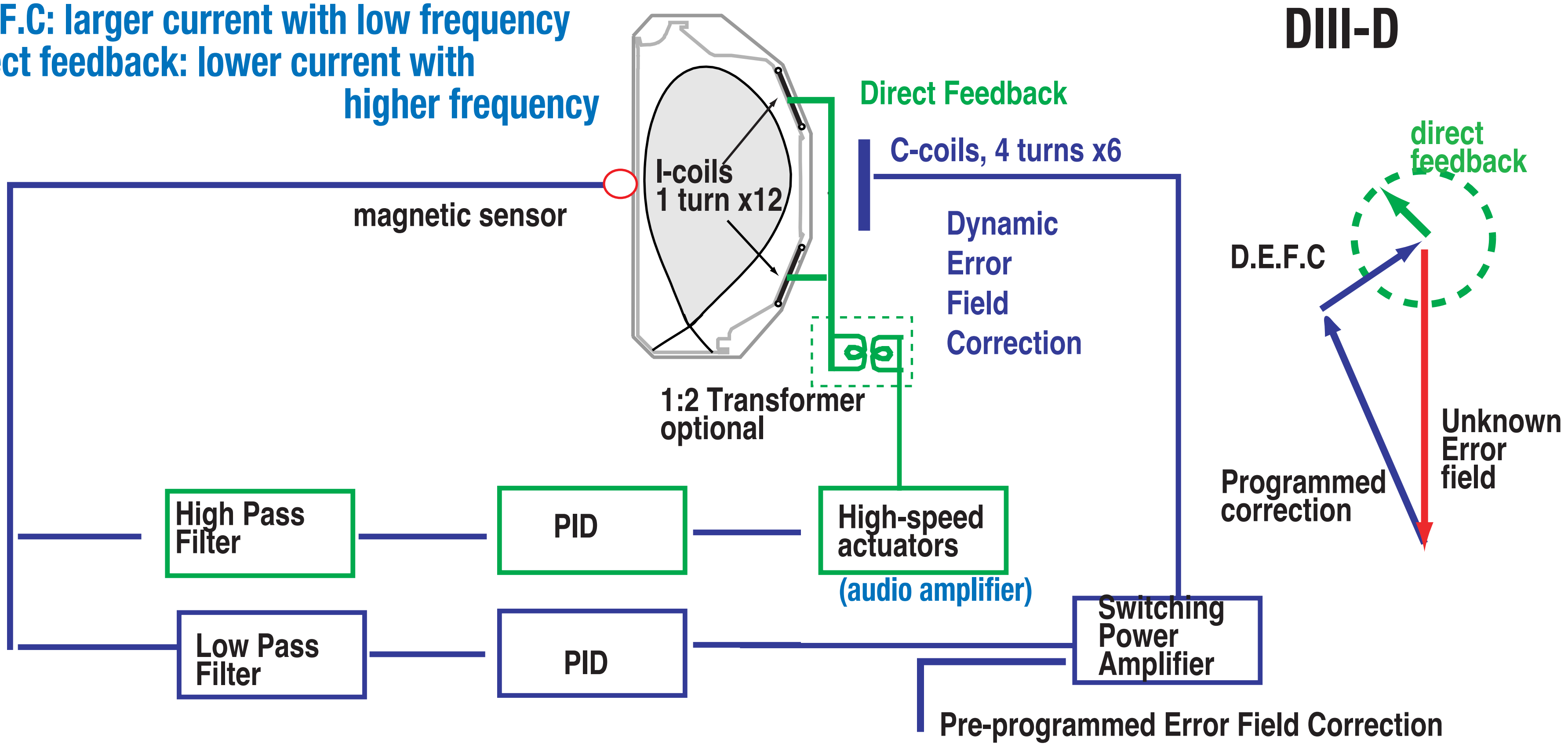
Feedback Performance



Independent Operation of Dynamic Error Field Correction and Direct Feedback is More Efficient and Effective

- D.E.F.C: larger current with low frequency
- Direct feedback: lower current with higher frequency

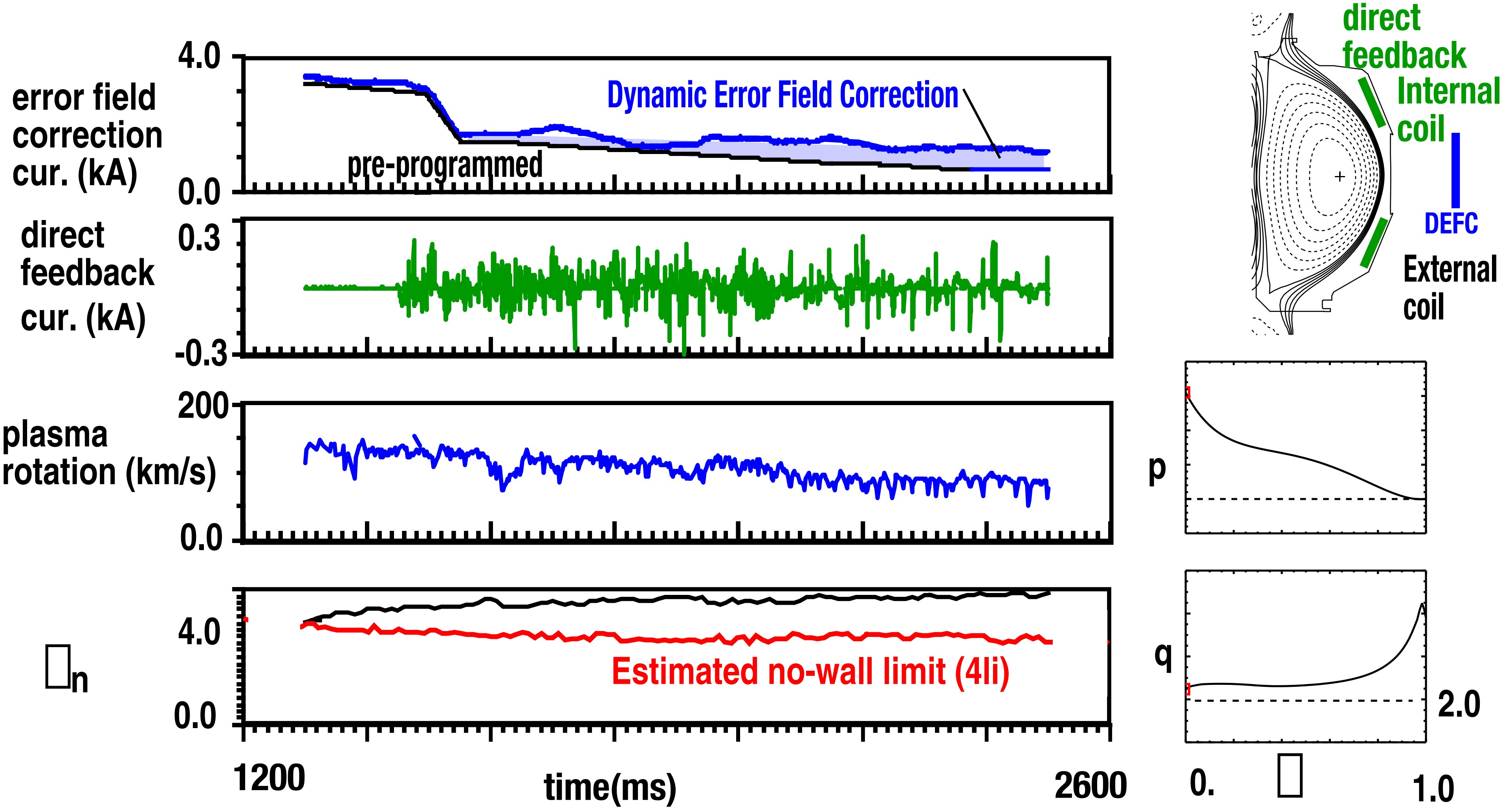
DIII-D



Coil	Inductance	Resistance incl. leads	Power Supply	volt and current	Freq. range
I-coil	10μH(quartet)*	4 mΩ	High-speed actuators	400 A x 140 V (quartet)	DC-50 kHz
C-coil	170 μH(pair)*	10 mΩ	Switching Power Amplifier	3.5kA x 250 V (pair)	DC-1.5 kHz

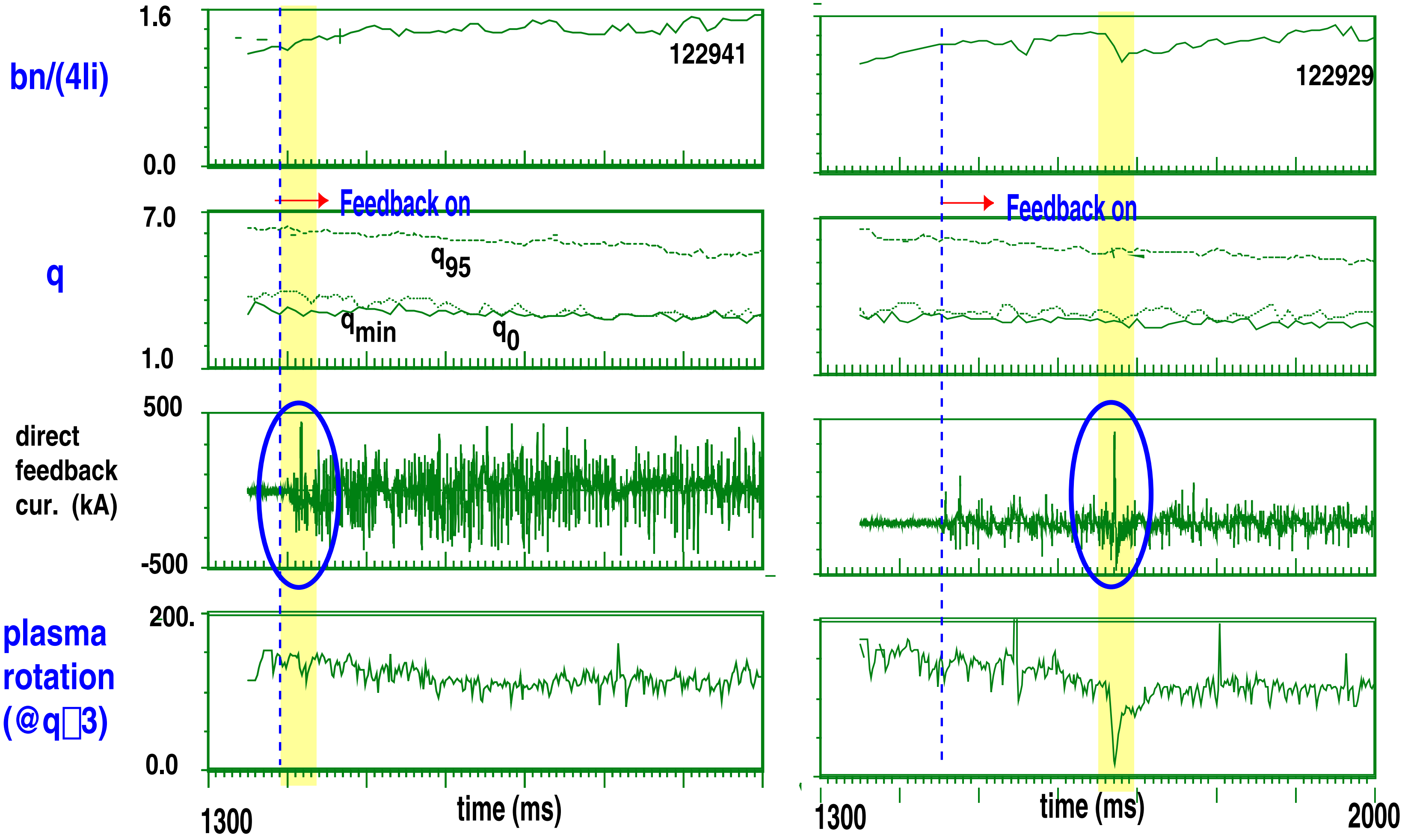
* including lead inductance 50μH

Combination of External and Internal Feedback Assists Achievement of High β_n AT Plasmas



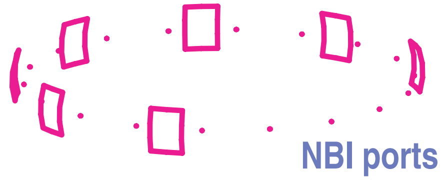
Unstable RWM is Excited in An Predictable Manner

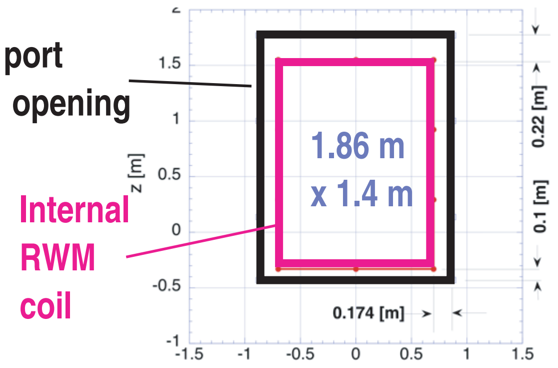
- Occasionally RWM stabilization by combined rotation and feedback becomes marginal; requesting large feedback current.

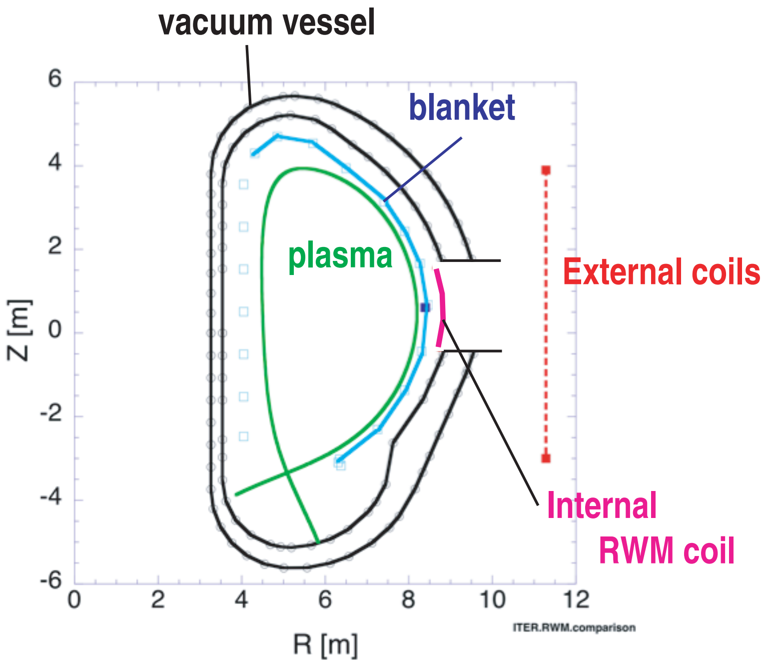


Internal 7 coils for RWM control in ITER

- RWM coils are located at every 40 degrees except NBI ports



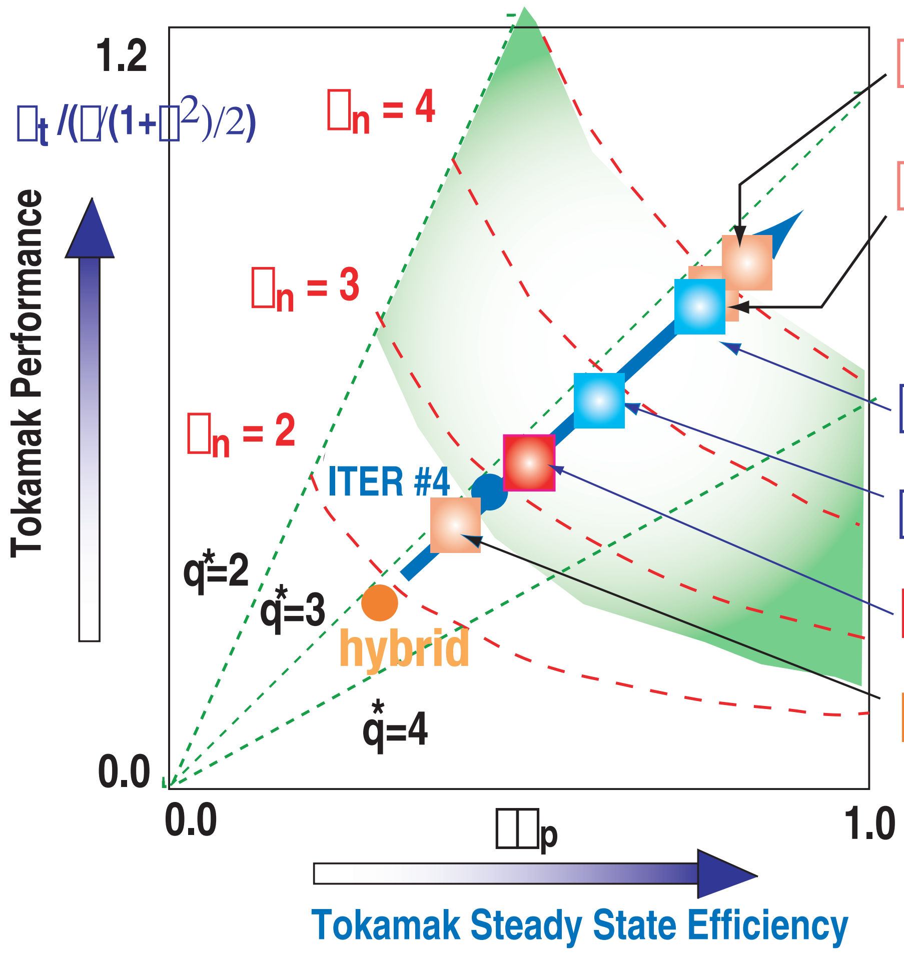




- Blanket without opening: 9 ms L/R time assumed
- Thin shell model

	T		L	R	□Bn (G/kA) pl.surface
Internal	1 turn	7 coils	3.6 □H	0.18 m-ohm	27.0
External	28 turn	3 pairs	39.2 mH	3.92 m-ohm	5.4

• Internal Coils Outperform External Coils in ITER



β_n = 5.20: Ideal β_n limit with blanket modules (coil ports covered)

β_n = 4.86: Ideal β_n limit with blanket modules (except coil ports)

β_n = 4.83: Internal 7 coils with blanket modules(except coil ports)

β_n = 3.94: Internal 7 coils blanket modules (coil ports covered)

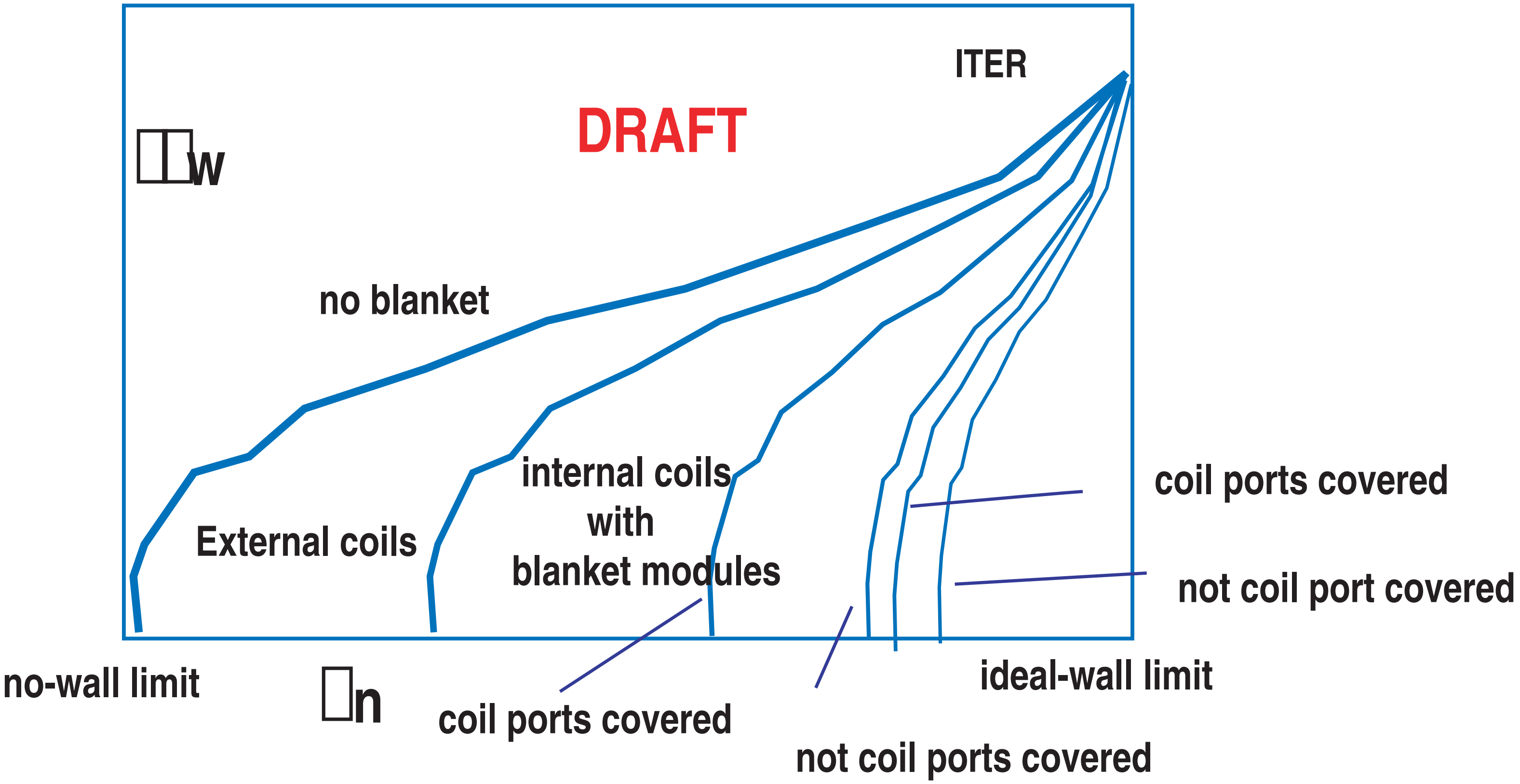
β_n = 3.18 : External 6 coils

β_n= 2.52 Ideal β_n limit without blanket modules

$\beta_n = \beta/(I_p/aB_t)$

Wide Range □$_n$ □ 2.5 -5.2 May be Sustainable with Internal Coils

- Achievability: depending on the effectiveness of blanket against external kinks



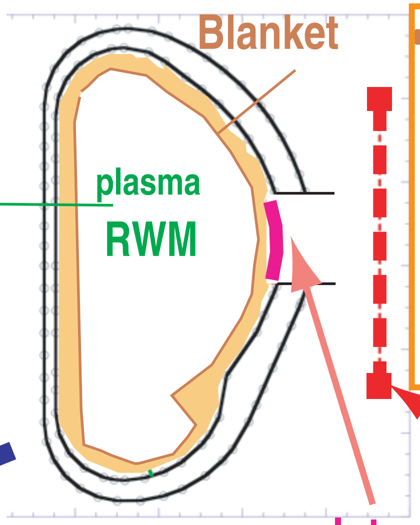
- Important factors :
  - Plasma-vacuum boundary physics
  - Thick shell RWM physics. ...

  - Joint experiments with various devices: essential to assess these issues

RWM Issues for Next Step

• RWM Physics

- *Critical rotation*
- *Stabilizing mechanisms*
- *Anomalous angular momentum loss*
- *Mode non-reproducibility*
- *Internal mode structure*



• Thick shell RWM physics

- *Range β_n = 2.9 - 5.2 achievability assessment*

• Plasma-vacuum boundary to global MHD

- *Divertor hardware, SOL currents*

• Dynamic error field correction

• Direct feedback

• Feedback signals

- *Plasma rotation,*
- *Improvement of magnetic sensors*

• Feedback logic

- *Mode identification (RWM, ELM,NTM)*
- *noise reduction (Kalman filter)*
- *Advanced feedback logic*

Plan for Addressing Open Issues

Subject	Contributions to Burning Plasmas
• RWM Physics	
- RWM damping mechanisms	
- quantitative comparison with numerical codes	
- critical plasma rotation	-> feedback necessity
- Mode rigidity	
- internal structure measurement by MSE	-> control logic
- RWM triggering mechanisms	
- RWM coupling to ELM and others	-> control logic
- Thick shell RWM physics	-> achievable β_n limit
- Plasma-Vacuum boundary to global MHD	-> control logic
• Feedback	
- Crucial test of feedback with	
- reduced NBI momentum input (DIIID)	-> achievable β_n limit
- Optimization of Internal and external coil combination	-> overall optimization
- Feedback optimization with internal coils	-> Internal control coils
- Non magnetic signal use for feedback	-> Improvement of dynamic error field correction