Prospects for the Use of Internal and External Coils on ITER

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ITER Organization

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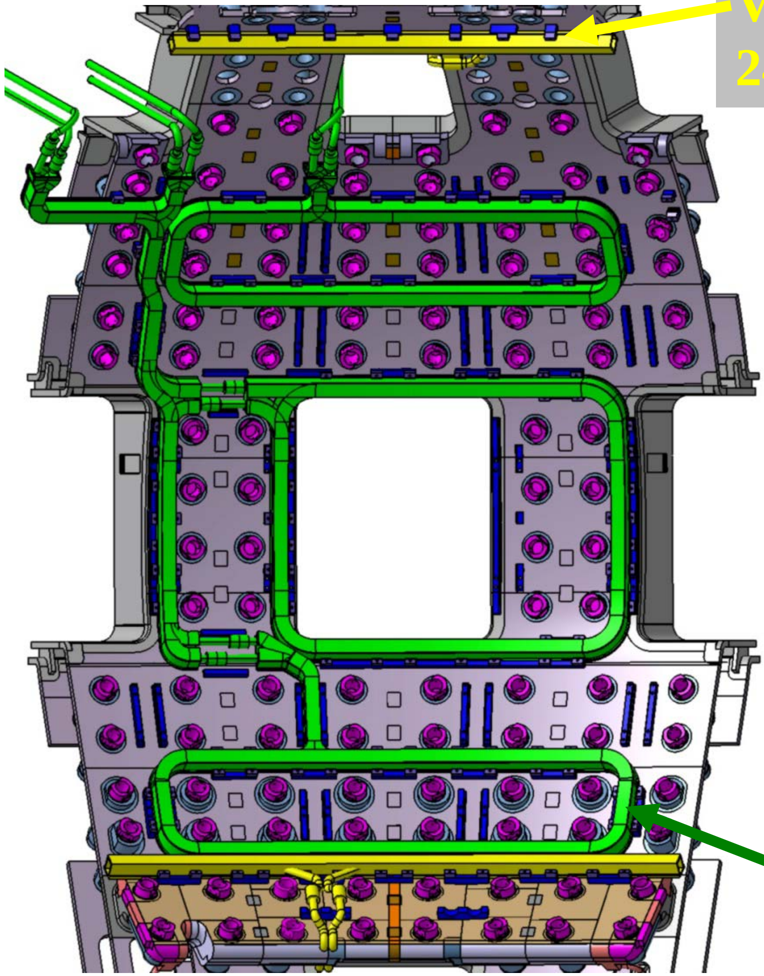
Outline

- Internal vertical stability and ELM control coil descriptions
- ELM control with magnetic perturbations
- External error field correction coil description
- Error field control
- Resistive Wall Mode control
- Plasma rotation control
- Conclusions

Magnetic Actuators (Still) Include In-Vessel Coils



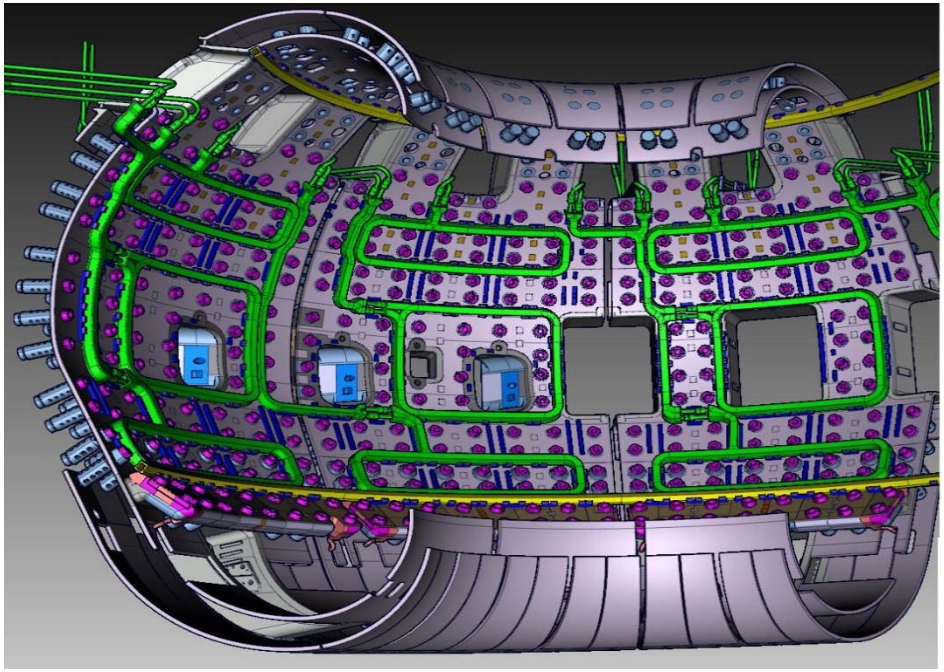
VS coils (4 turns, 40 kAturns RMS, 240 kAturns peak, 2.3 kV)

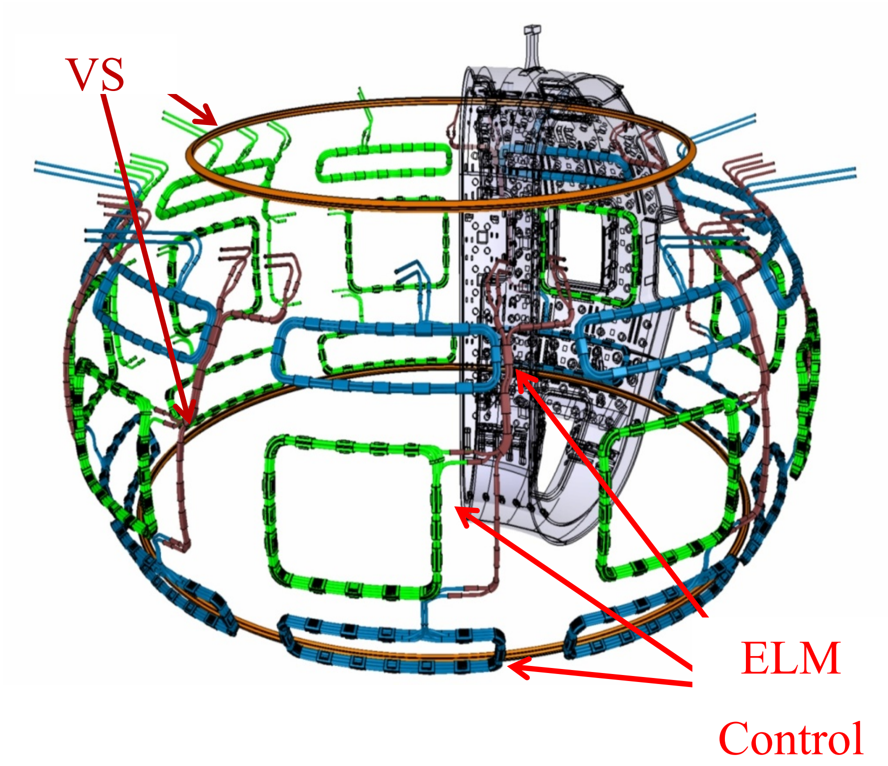
- **A set of in-vessel resonant magnetic perturbation (ELM) and vertical stability (VS) coils is being designed:**
  - 9 toroidal × 3 poloidal array on outboard internal vessel wall
  - vertical stabilization coils upper & lower loops form a saddle coil

ELM coils (3 sets of 9 coils)
6 turns up to 90 kAturns

ITER ELM Control Coils : Design

- 3 coils per Vacuum Vessel Sector (40º) → 27 ELM Control Coils (Tor. Symm.)
- ELM Control Coils located between BSMs and VV (integration complexity)
- 6 turns/coil → I_{coil}^{max} = 90 kAt (H_2O-cooled CuCrZr + with MgO + SS jacket)
- Operating conditions : DC → AC (5 Hz)





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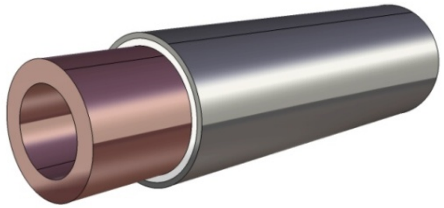
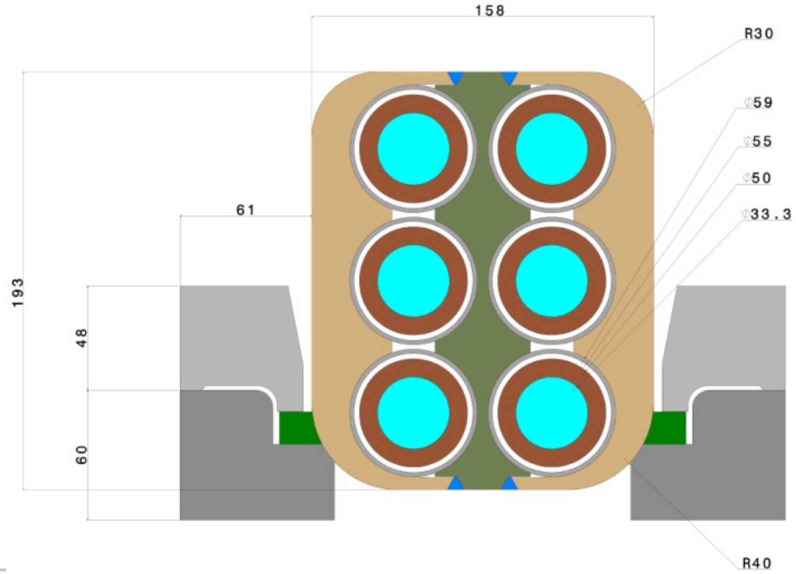
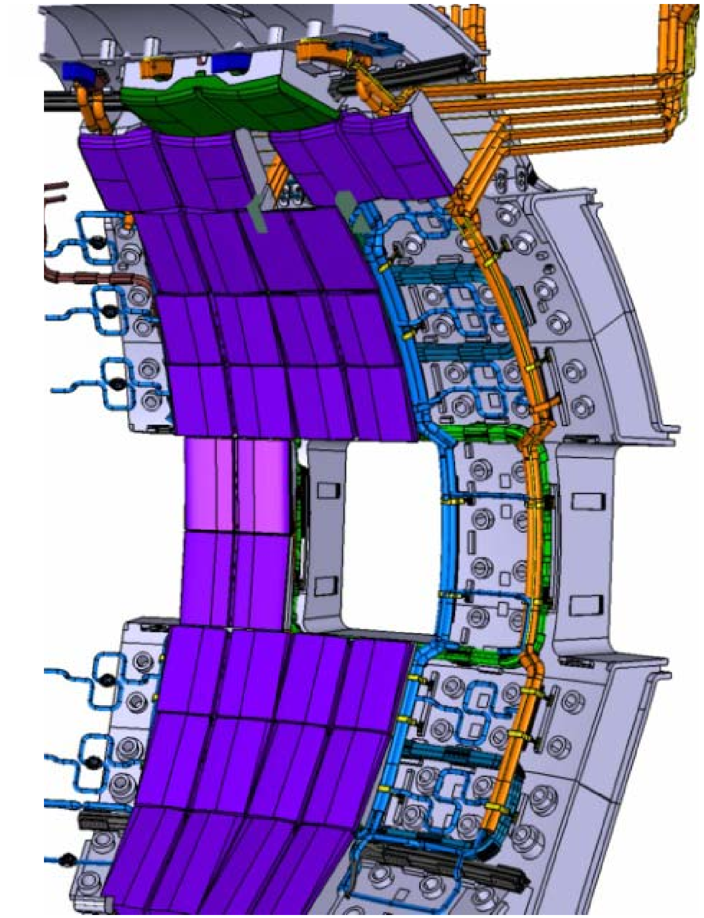


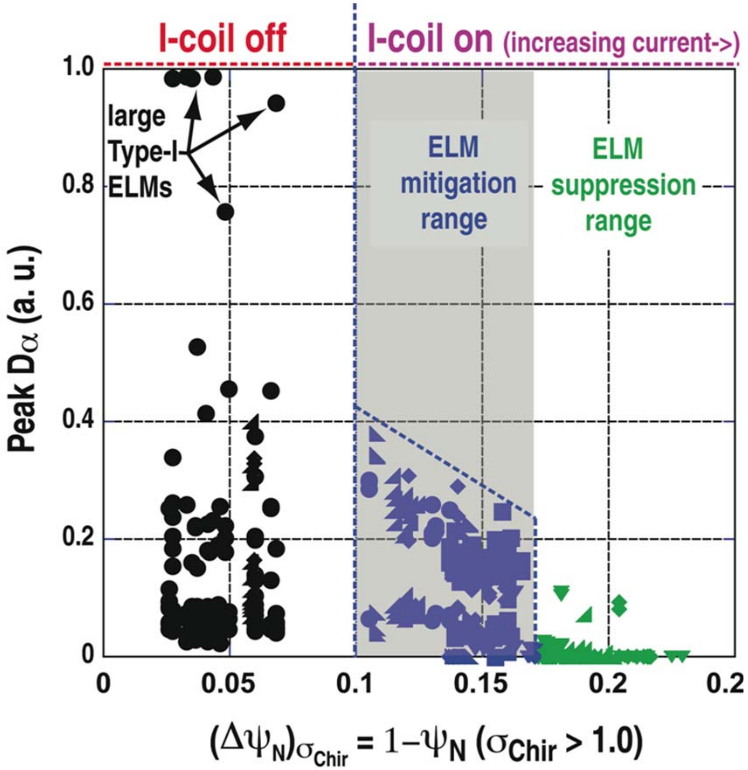




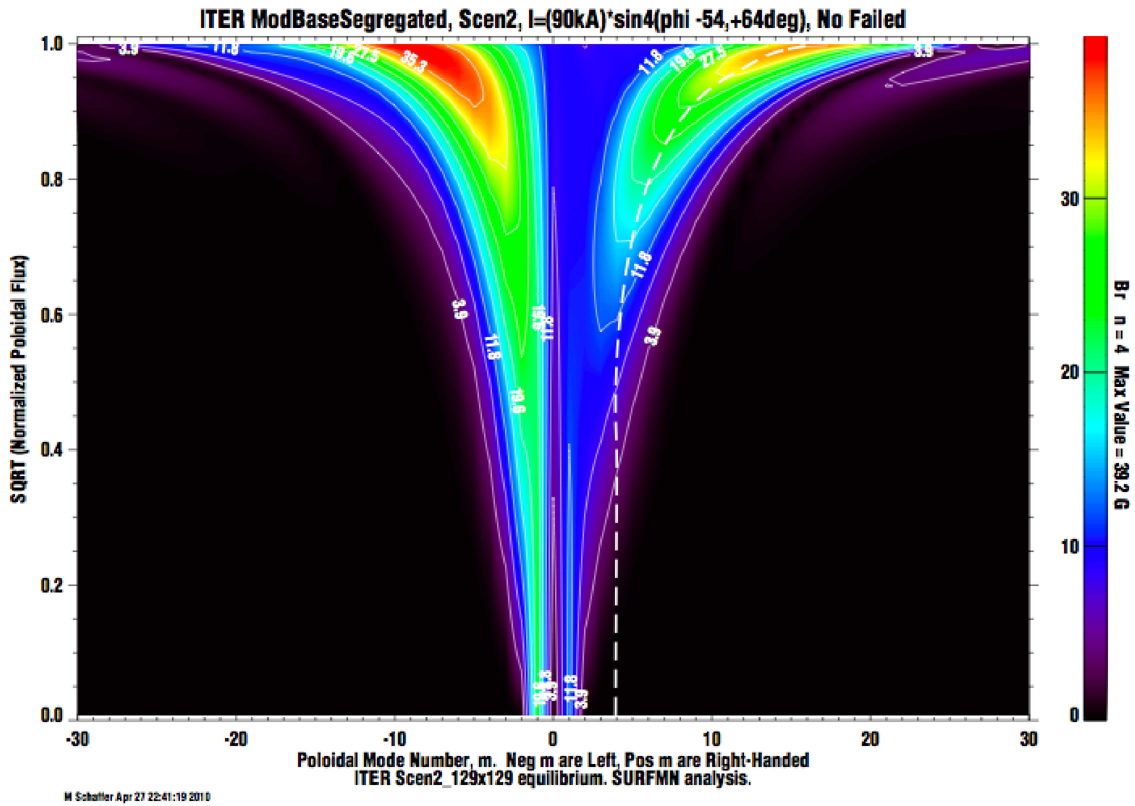
ITER ELM Control Coils : Design Guidelines (I)

- Guideline → vacuum field island overlap criterion for ITER-like shots at DIII-D
- n = 4 → smaller core plasma disturbance → $I_{coil}^{required}$ = 75 kAt for I_p = 15 MA
- I_{coil}^{max} = 90 kAt = 1.2 $I_{coil}^{required}$ 20% design margin
- Every coil powered independently → required for flexibility across ITER operational scenarios (advanced Q_{DT} = 5 → q_{95} ~ 5)

DIII-D-Fenstermacher PoP 2008



ITER – Schaffer 2009 90 kAt & n=4 → $|b_r|/B_{T,0}$ ~ 6.2 10^{-4}



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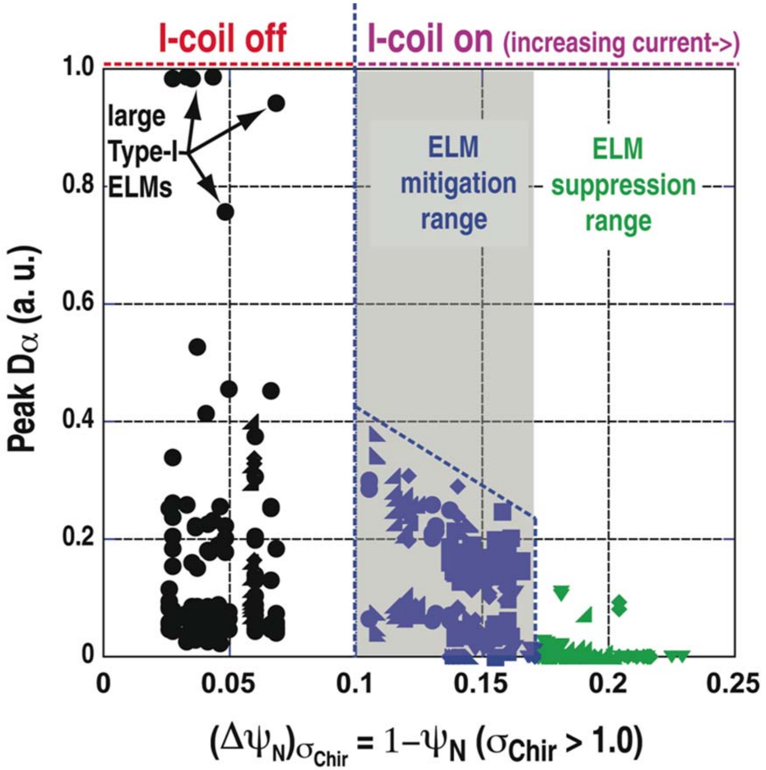

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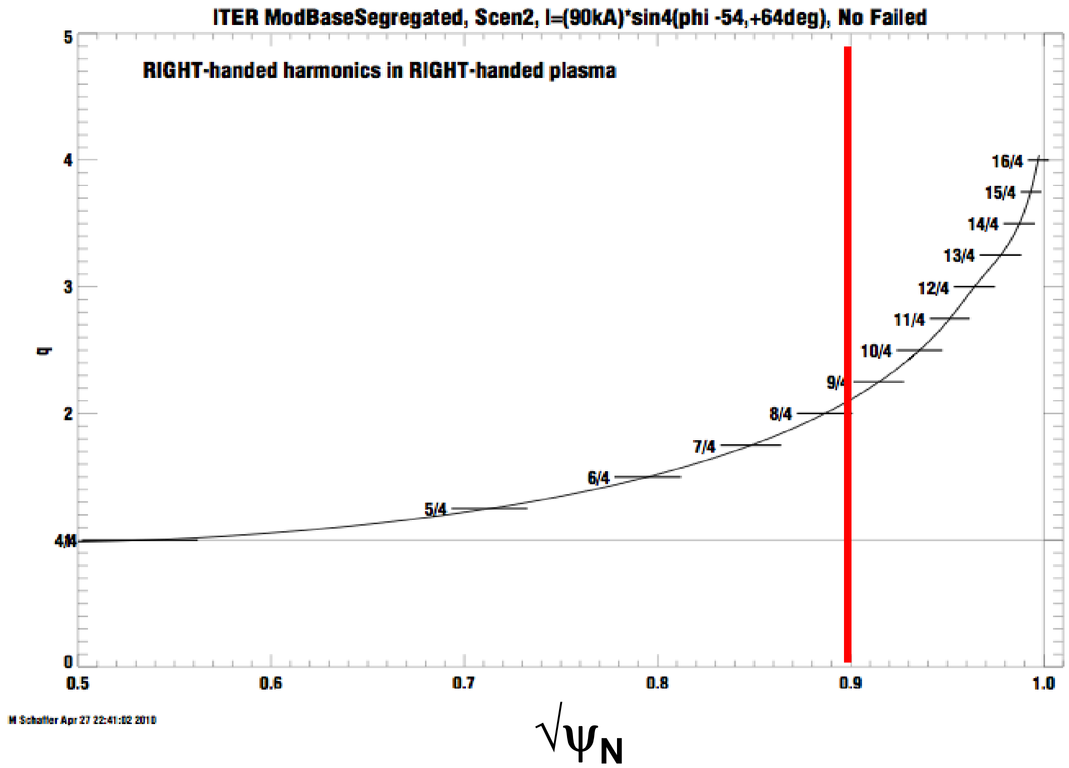
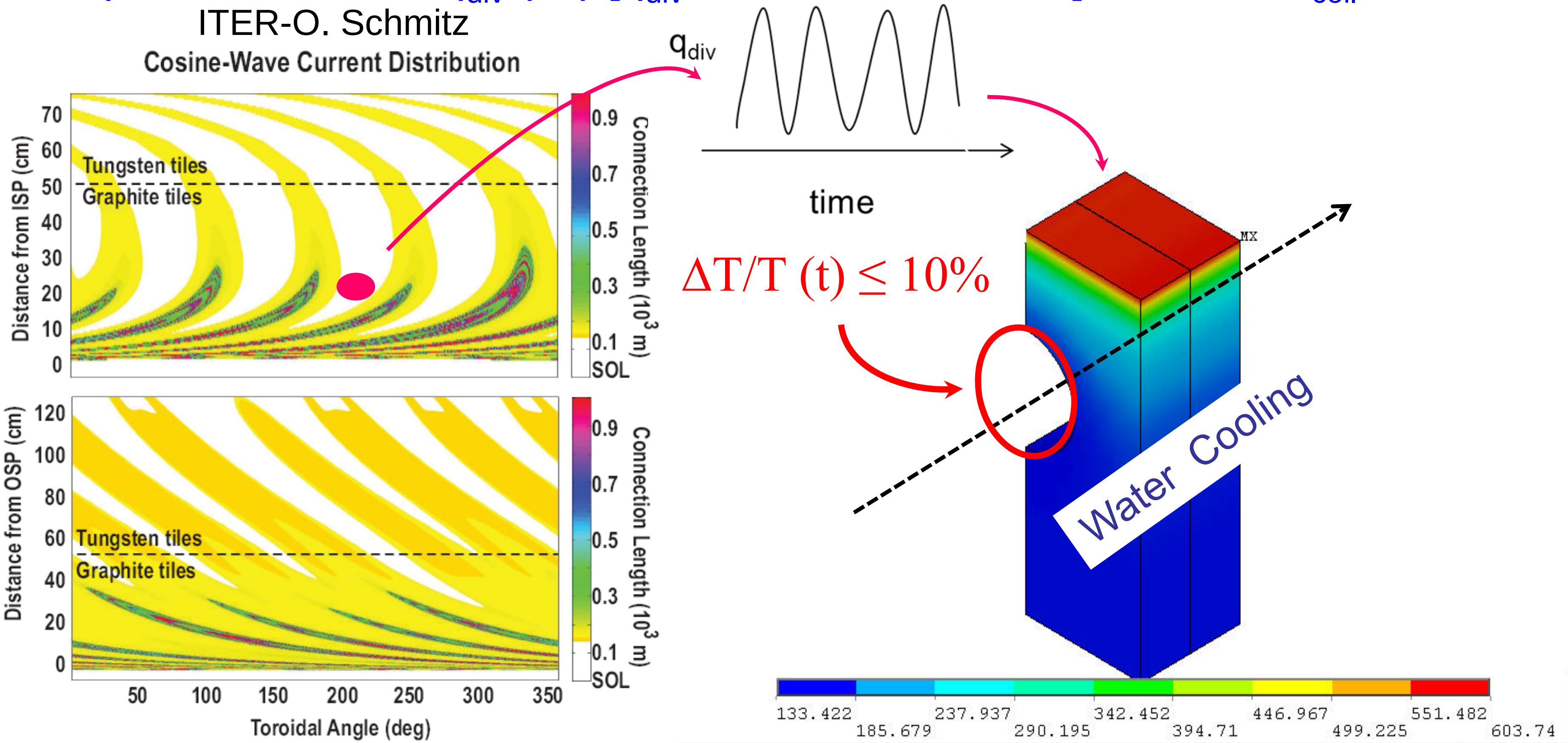


ITER ELM Control Coils : Design Guidelines (II)

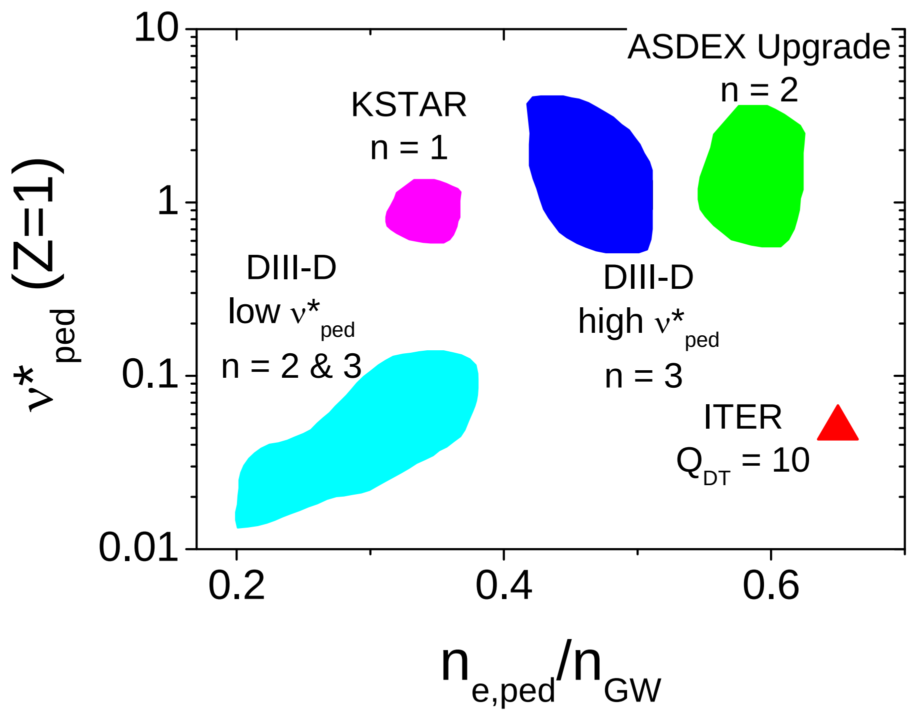
- Significant modifications of footprint at divertor for I-coil required for ELM suppression → non-toroidally uniform particle and power fluxes may arise
- Possible localized net erosion spots and high q_{div} → smoothing by rotation of perturbation in toroidal direction ($f_{rotation} = f_{coil}/n$, n =4)
- Required rotation of q_{div} (x,t) [$q_{div}^{max\text{-}local}$ = 20 MWm^{-2}] = 1 Hz → f_{coil} ~ 5 Hz



ELM Control by in-vessel Coils has been Demonstrated

- ELM control and complete Type I ELM elimination by B_{edge} perturbation demonstrated in several devices DIII-D, ASDEX-Upgrade and KSTAR
- Toroidal mode number of perturbation can be low n but operational space decreases at lower n due to mode locking

Operational space of plasmas without Type I ELMs



DIII-D - Evans

ASDEX-Upgrade – W. Suttrop

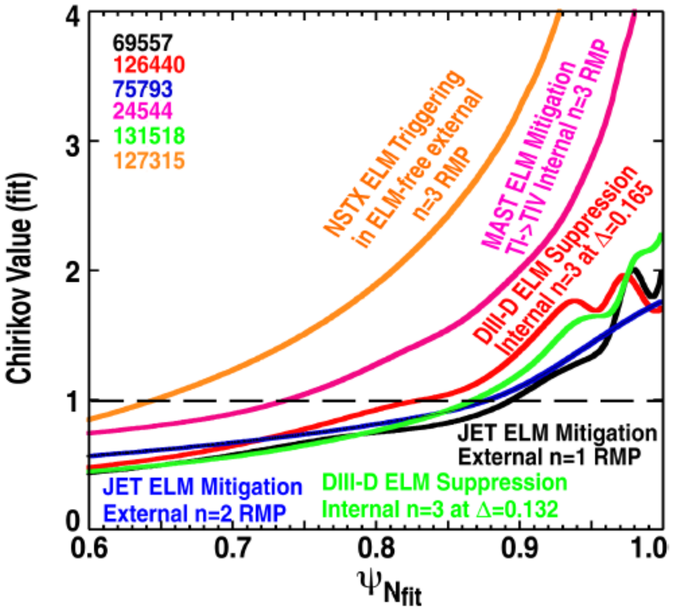
KSTAR – Y. M. Jeon

- Physics of processes leading to ELM suppression not yet understood (including plasma response to external B_{edge} perturbation) → ITER coil system will be flexible with every coil being powered independently

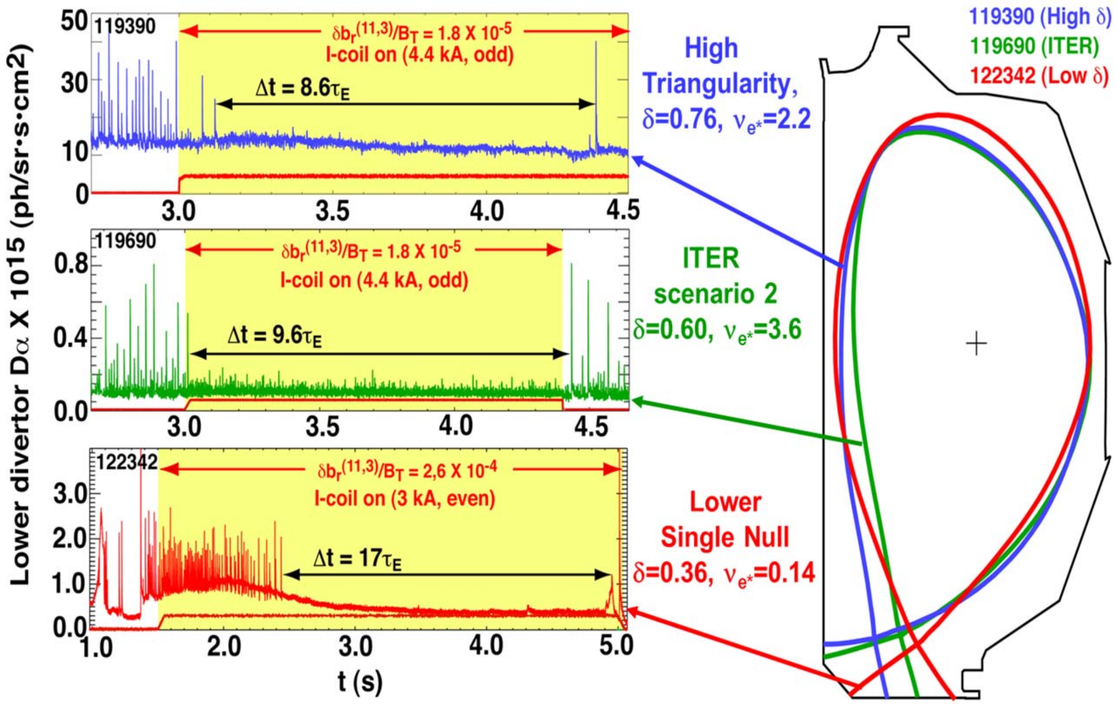
Required B_{edge} perturbation and spectrum for ELM control/suppression

- ITER design guideline not a universal criterion for ELM suppression → Physics-based criterion for ITER required
  - ✓ Is n=4 cosine wave the best choice for ITER ?
  - ✓ Is I_{coil}^{max} = 90 kAt sufficient to achieve ELM suppression in ITER?
- DIII-D experiments require B_{edge} perturbation to be resonant (Δq_{95} = 0.1-0.5) to have effect on ELMs both for high & low ν^*_{ped} → is this required in ITER ?

ITPA-Fenstermacher IAEA'10



DIII-D-Evans



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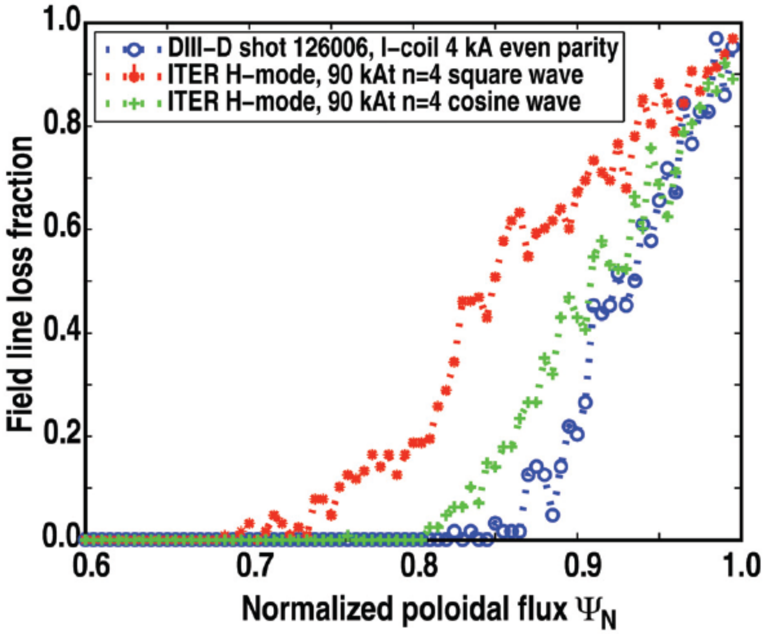
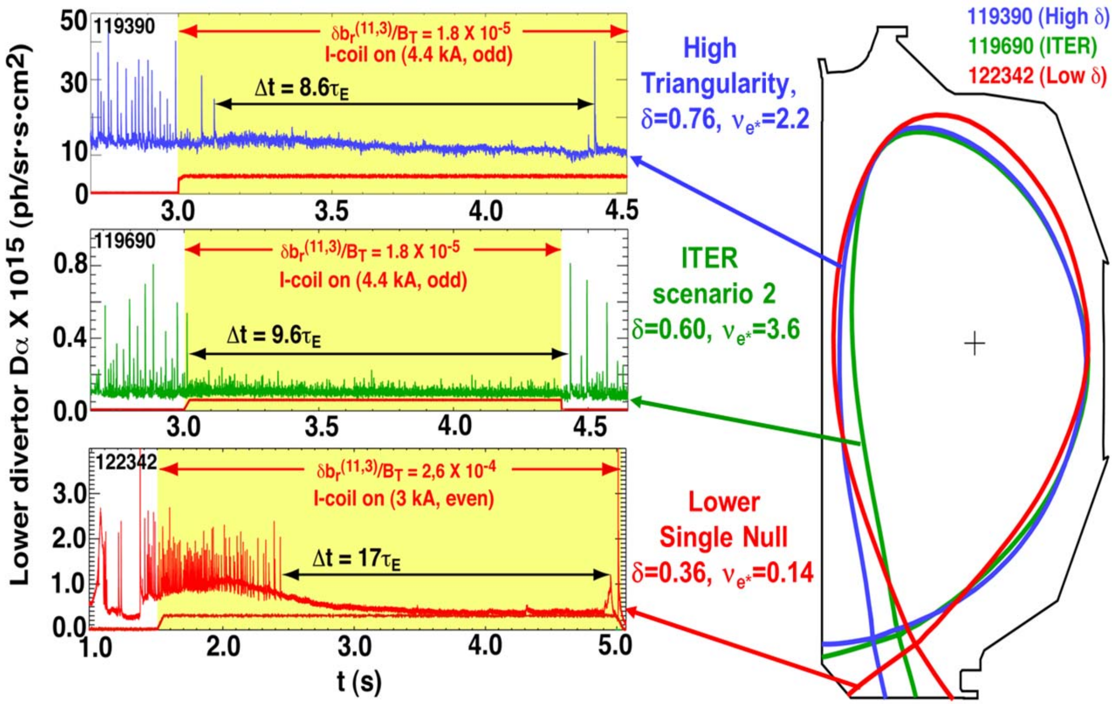
ITER-Orlov EPS 2010



DIII-D-Evans



ITER ELM Control Coil System : Status

- Preliminary Design Review in October 2010 → OK to go ahead
- Funding for Final Design Review approved (March 2011) → FDR expected to be completed by mid 2013
- Funding for prototype and tests of VS and ELM coils approved (March 2011)
  - ✓ 1 Prototype equatorial ELM control
  - ✓ Aim to produce ~ 60 m conductor length (avoidance of in-coil joints)
  - ✓ Check of manufacturing tolerances & techniques + Magnet assembly
  - ✓ Accelerated testing → lifetime under cycling
  - ✓ Additional small prototypes (coil joints) for other tests
- Formal decision to request funding approval to ITER Council to build ELM and VS coils expected by end of FDR at the latest
- ITER Design & Construction : Blanket Shield Modules, Cooling Manifolds, Vacuum Vessel, etc., include interfaces for VS & ELM coils

ELM suppression by B_{edge} perturbation : Outstanding Issues for ITER

Physics basis for ELM suppression and mitigation with Bedge perturbation remains under development → extrapolation to ITER uncertain

- Magnitude and spectrum of $|b_r/B_{T,0}|$ for ELM suppression/mitigation in ITER?
  - ✓ What is required in terms of resonant and non resonant perturbation at the ITER edge plasma to get ELM suppression and mitigation ?
  - ✓ Can we reliably predict the modification to B_{edge} in ITER ?
  - ✓ What is the optimum spectrum (ITER : 9 x 3 coils → flexibility) ?
  - ✓ Is maximum current in ITER coils sufficient (90 kAt) and how can spectrum be optimized to reduce maximum current required per coil ?
- Compatibility of ELM suppression and mitigation with B_{edge} perturbation with ITER scenario requirements ?
  - ✓ Radiative divertor operation with B_{edge} perturbation ?
  - ✓ ELM power fluxes for mitigated ELMs with B_{edge} perturbation ?
  - ✓ Fuelling of plasmas to high density with B_{edge} perturbation ?

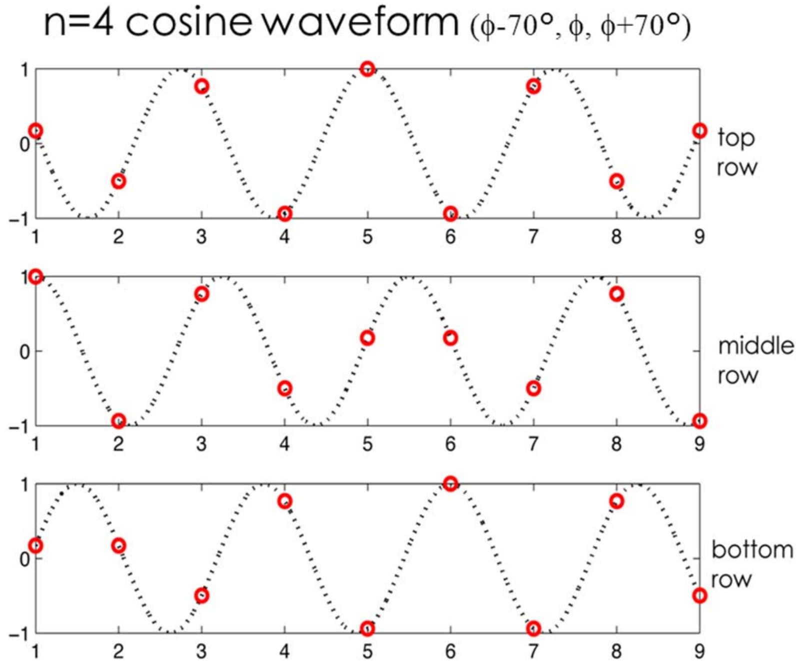
What is the Optimum ELM Coil Current Distribution?

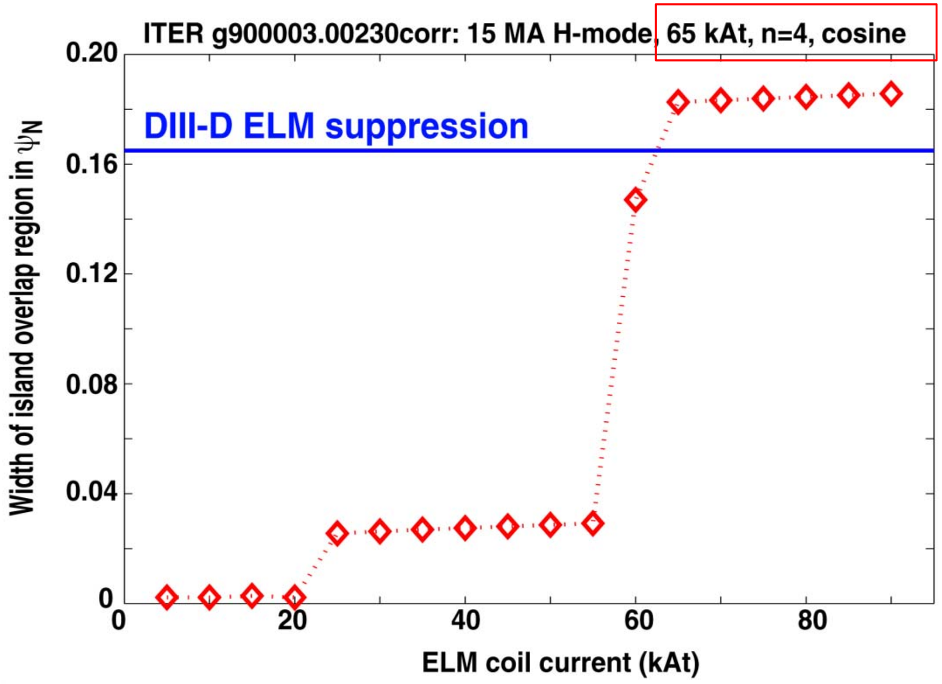
- Effects of 3-D fields on stationary energy/particle fluxes

  - Study edge vacuum field structure in ITER for relevant scenarios and waveforms to optimize current distribution to experimental guideline

DIII-D Chirikov criterion → island overlap criterion (ITER n=4 with 27 coils)

ITER-Evans

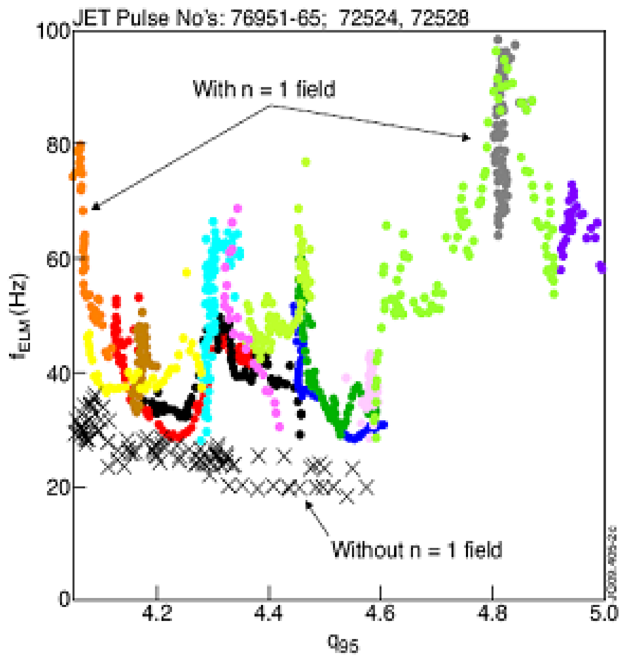




Required B_{edge} perturbation and spectrum for ELM control/suppression

- Resonant effects on ELMs found in other experiments (JET, MAST) <u>but not in ASDEX-Upgrade with large ELM mitigation at high n_{ped}-ν^*_{ped}</u>
- ✓ Need for B_{edge} perturbation & q_{95} alignment has to be assessed → important practical consequences for ITER operation & extrapolation of experiments :
  - ✓ ELM control in H-mode before/after I_p = 15 MA flat top (q_{95} (t) : 4.5 ←→ 3)
  - ✓ Robustness of system for ELM control to coil failure (resonant vs. non-resonant)
  - ✓ Magnitude of the required B_{edge} due to shielding of resonant perturbations

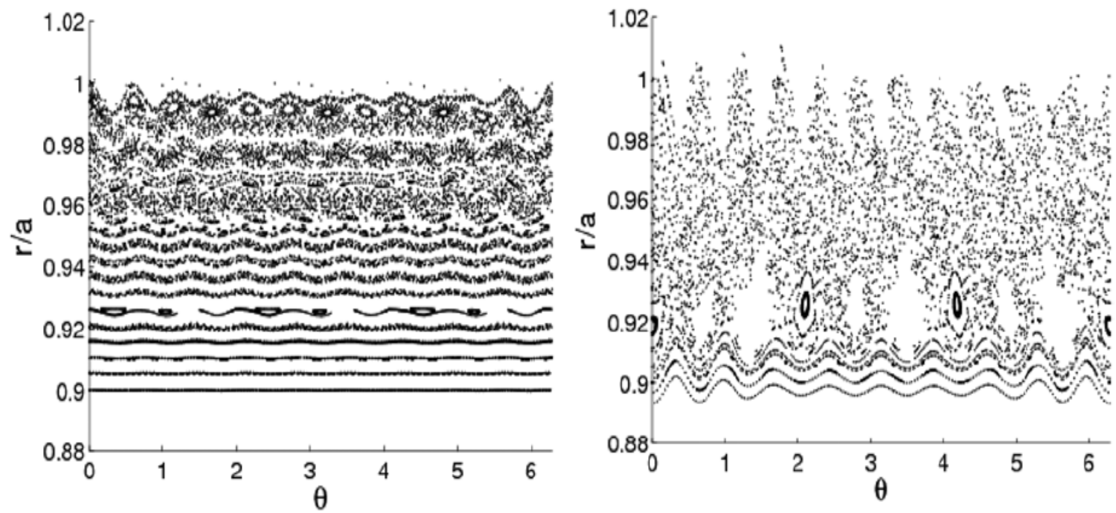
JET - Liang



Nardon – NF '10

Vacuum Approximation

With Plasma Response

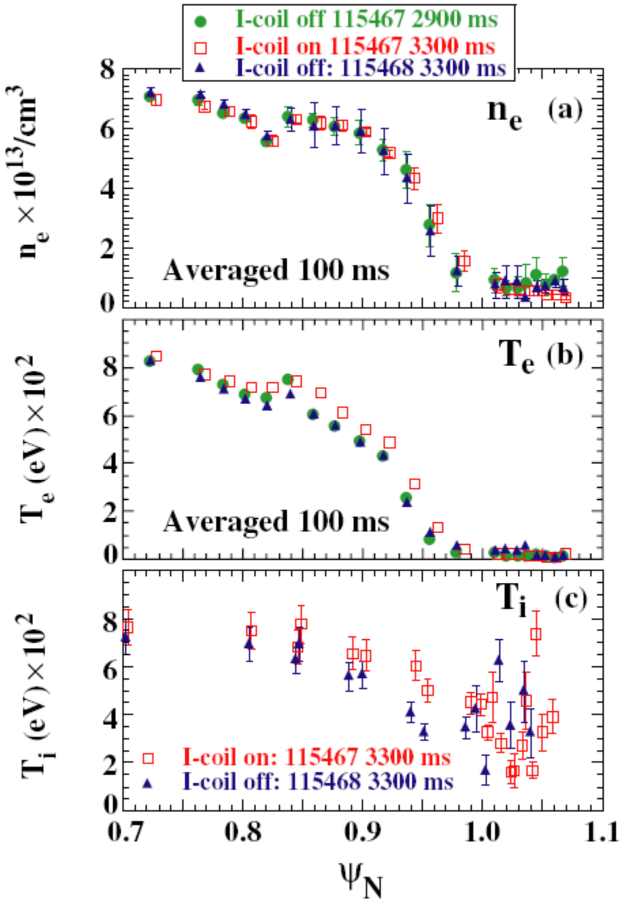


ELM Control by B_{edge} Perturbation : Effect on Pedestal Plasma

- High Q_{DT} operation requires high $<P_{ped}>$
- Understanding of B_{edge} perturbation effect on n_{ped} and T_{ped} in ITER required → Range of different experimental behaviours depending on n_{ped}/ν^*_{ped} and characteristics of B_{edge}

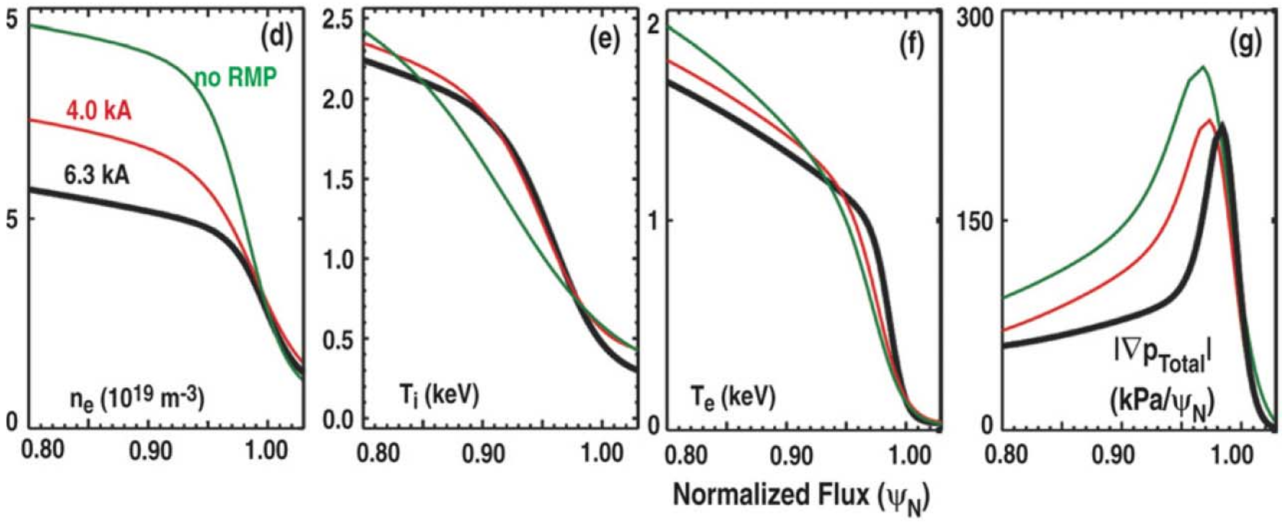
DIII-D-Evans NF '05

Non-res B_{edge} & High ν^*_{ped}



DIII-D-Evans NF '08

Res B_{edge} & Low ν^*_{ped}

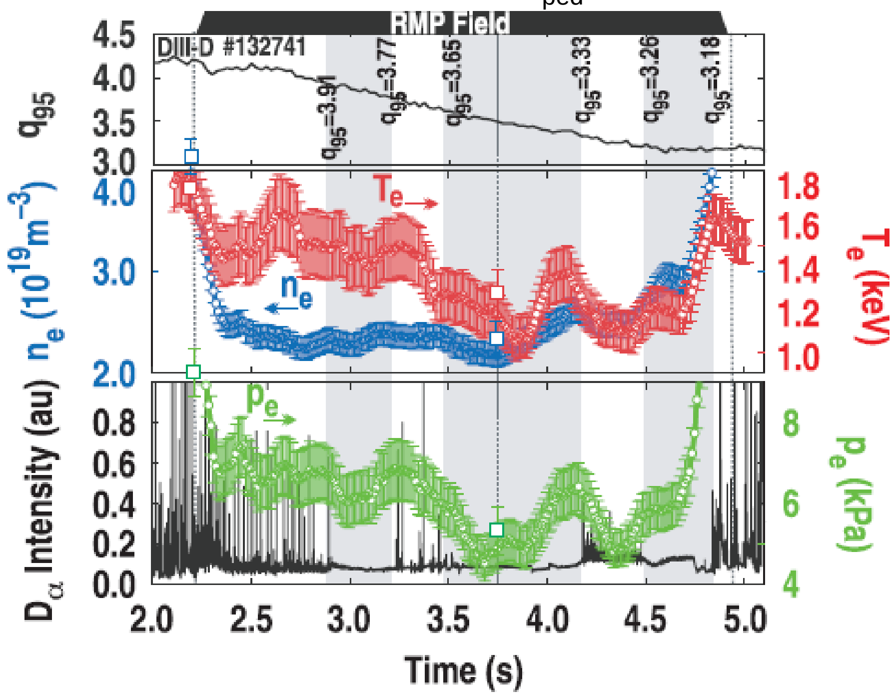


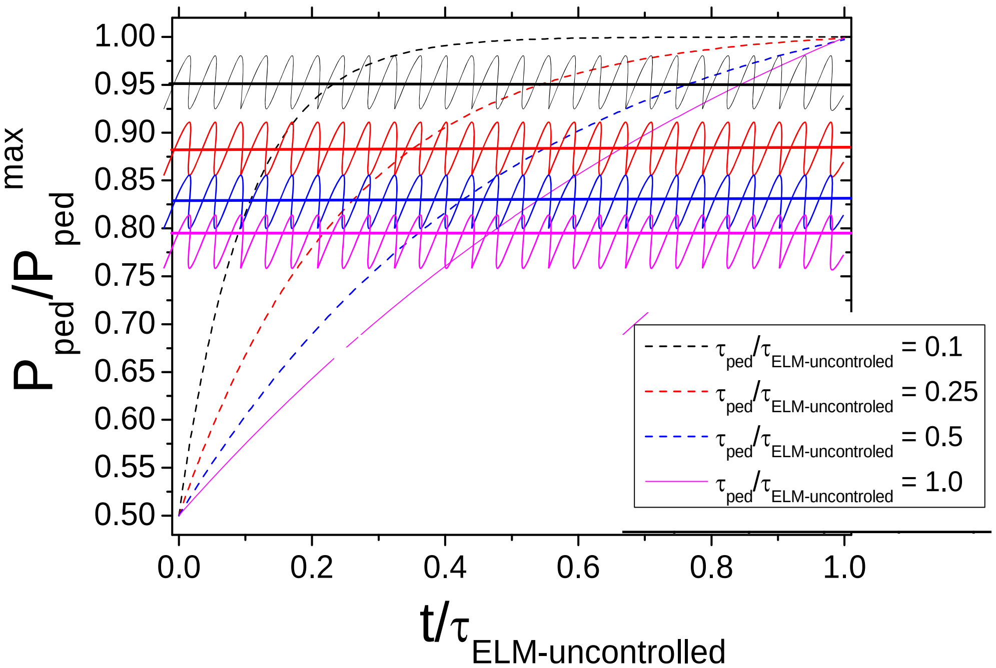
ELM Control by B_{edge} Perturbation: Effect on Pedestal Plasma

- Role of thermal transport in ergodized edge for ELM mitigation/suppression? (seen in high δ–low ν^*_{ped} not in low δ–low ν^*_{ped})
- Mechanisms driving additional particle transport and dependence on B_{edge} characteristics and ν^*_{ped} and expectations in ITER ?
- To which level is reduction of $<P_{ped}>$ controllable ? More systematic quantification of effect on τ_E required

DIII-D-Schmitz PRL'09

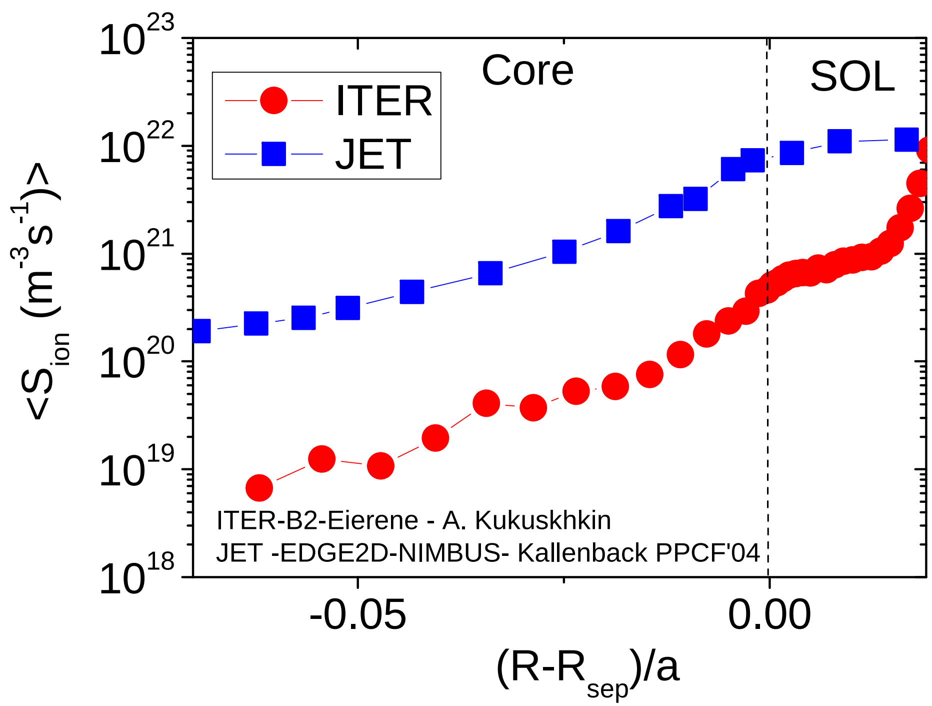
Low ν^*_{ped}



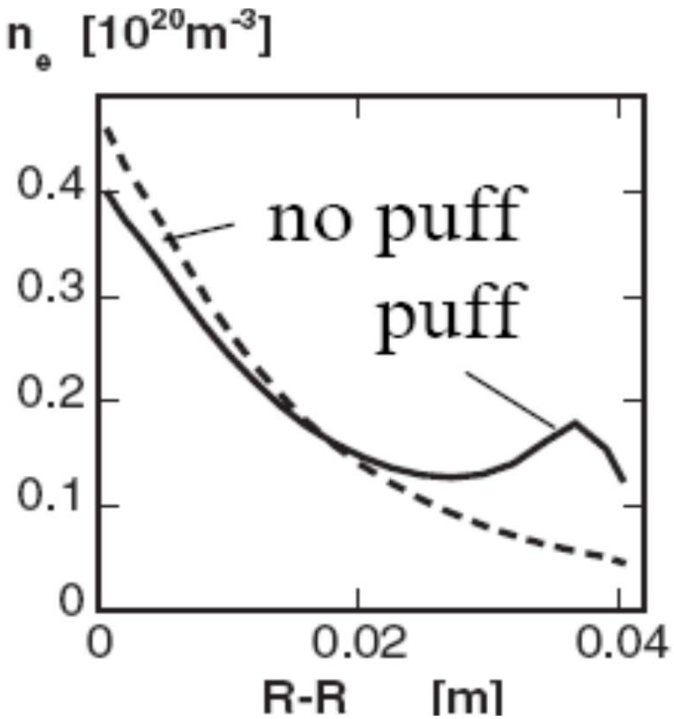


ELM Control by B_{edge} Perturbation: High $\langle n_e \rangle$ operation

- High Q_{DT} ITER operation requires high $\langle n_e \rangle / n_{GW}$ and $n_{sep}/\langle n_e \rangle$ ~0.3
- Plasma Fuelling/Pumping in ITER → unlike today's experiments
  - ✓ Fuelling efficiency by recycling neutrals ITER very low → $\langle n_e \rangle$ to be controlled by pellet fuelling
  - ✓ Pumping requirements driven by He removal and limited by T recirculation to low levels (typically ~1% of divertor recycling flux)



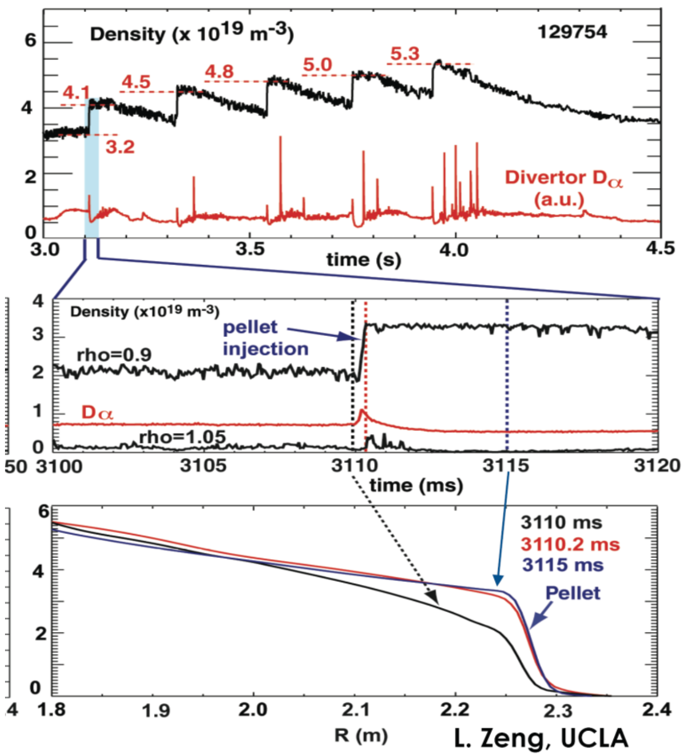
ITER-B2 Eirene- Kukushkin



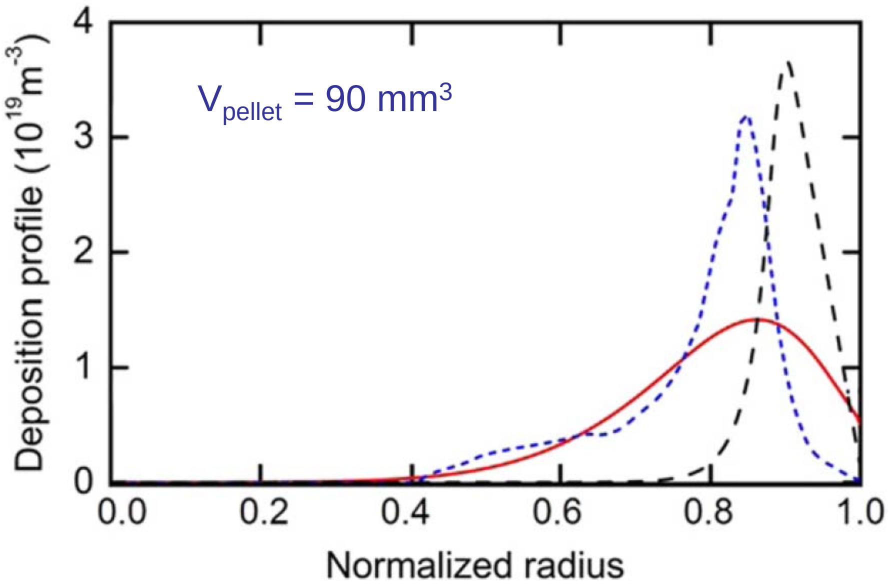
ELM Control by B_{edge} Perturbation : High $<n_e>$ operation

- Fuelling of ELM-controlled H-mode plasmas with pellets in ITER ?
  - Is it possible to achieve required density while avoiding Type I ELMs and/or large transient fluxes after pellet injection (~4-8 Hz)?
  - Effectiveness of peripheral pellet fuelling & under controlled-ELM conditions (depth of increased $nv_{eff}^{out}|_{edge}$ vs. pellet deposition depth)

DIIID-Evans-IAEA'08



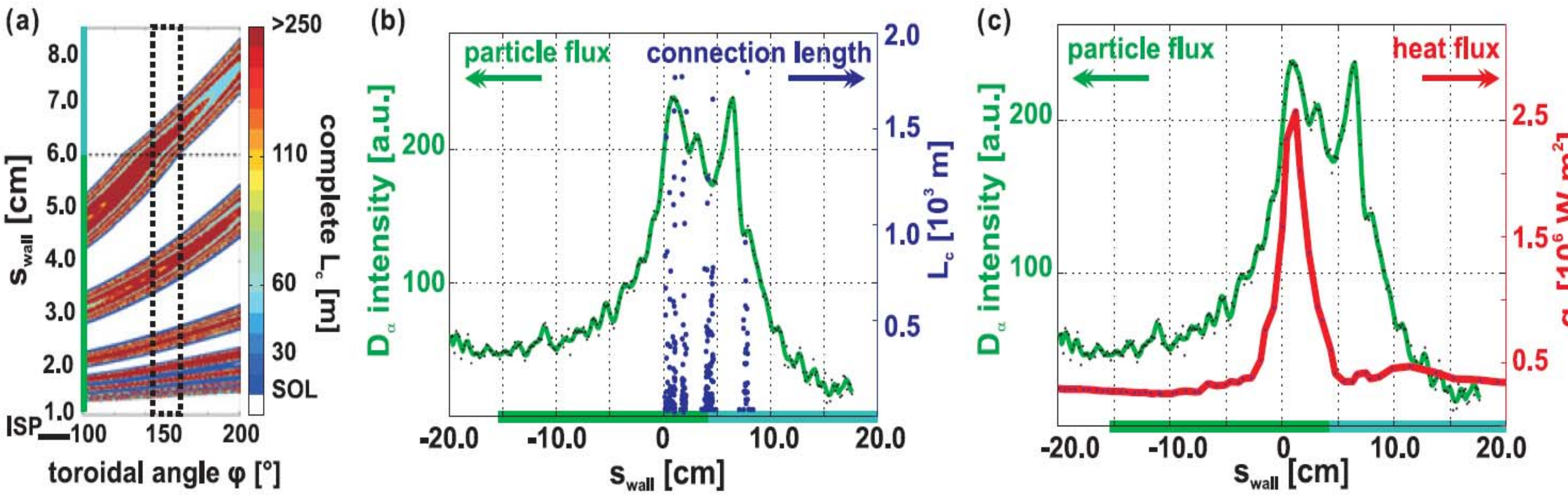
ITER-Pegourie – PPCF 2009



ELM Control by B_{edge} Perturbation : Fluxes to PFCs

- B_{edge} perturbation : Experiments → effects on power & particle fluxes to PFCs
  - ✓ Non toroidally symmetric patterns of Particle Fluxes
  - ✓ Non toroidally symmetric patterns of Power Fluxes (high ν^*_{ped})
- Understanding of energy/particle transport at plasma edge with perturbed B_{edge} required to predict effects/consequences in ITER & mitigation strategies

DIII-D - Schmitz – PPCF 2009



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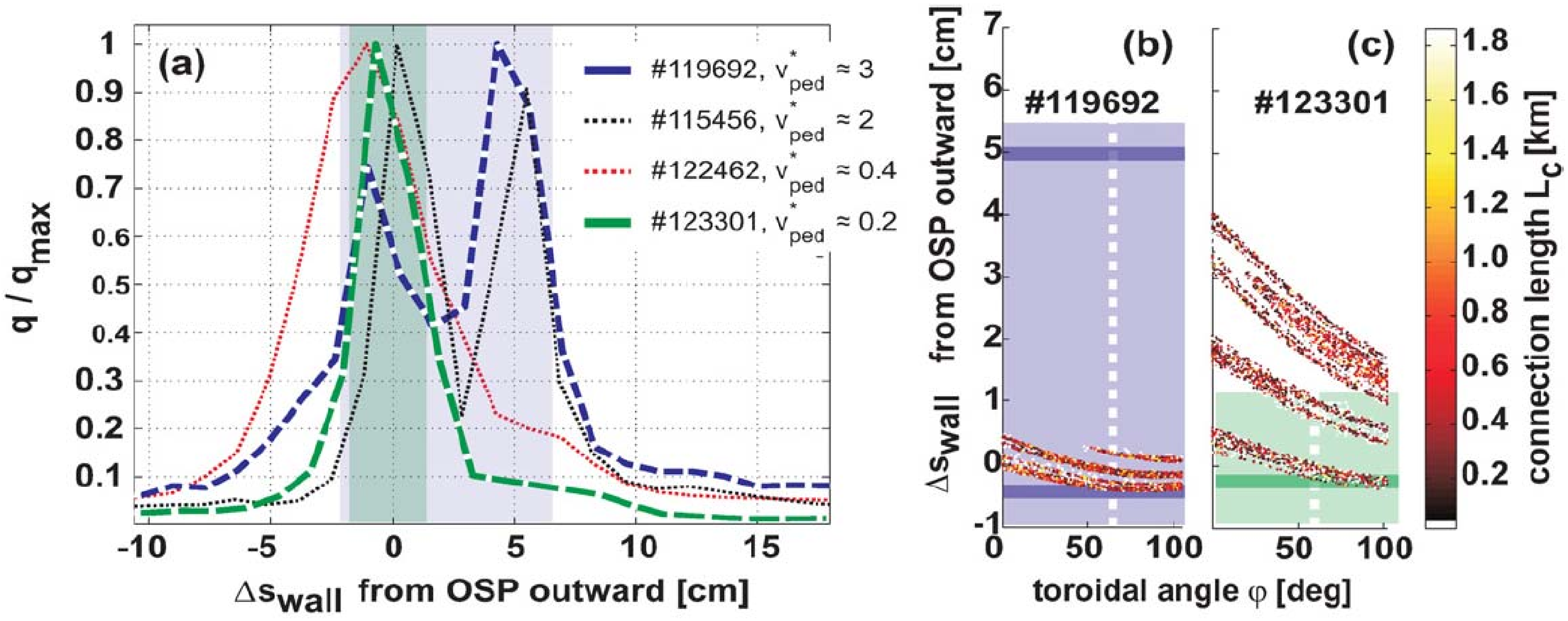
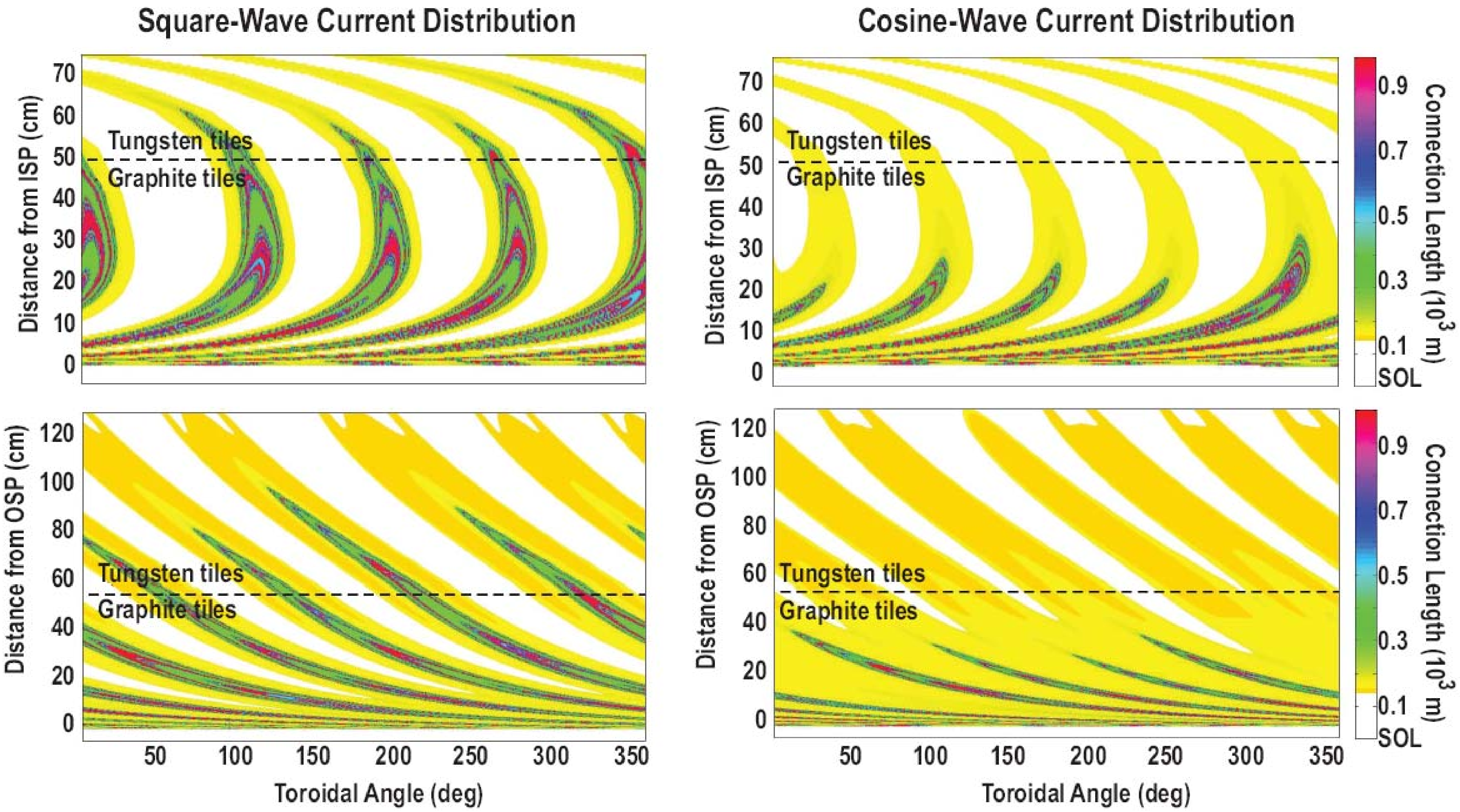
DIII-D - Jakubowski – NF 2009



How does the divertor footprint change with scenarios?

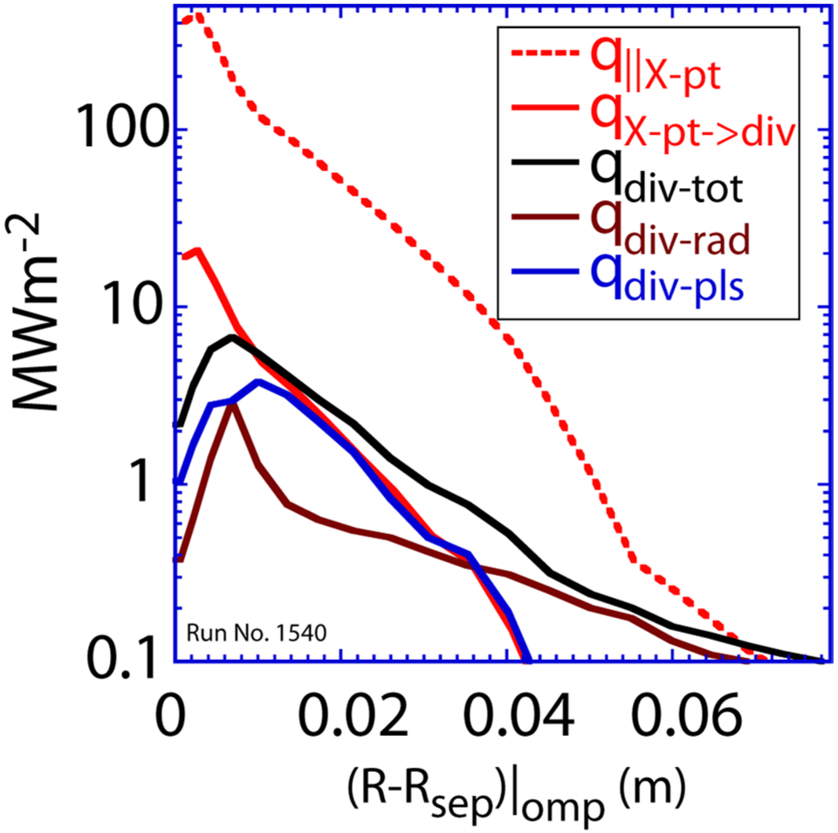
Study footprint structure and heat/particle fluxes with EM3C-Eirene for range of scenarios

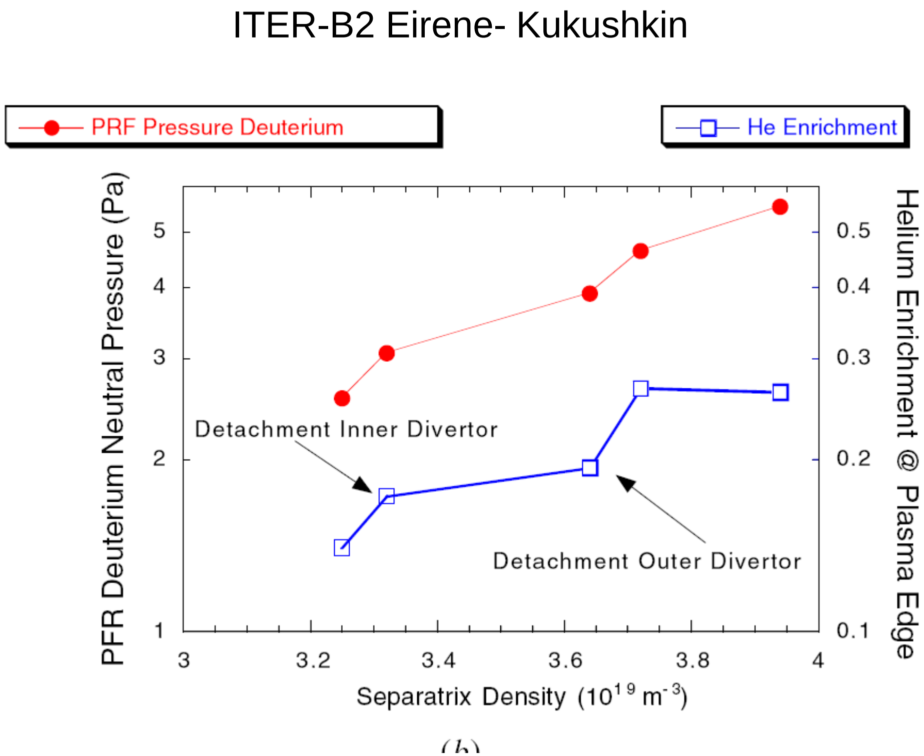
ITER-O. Schmitz



ELM Control by B_{edge} Perturbation : Fluxes to PFCs (II)

- ITER high Q_{DT} requires divertor operation with low T_e and high n_e for divertor power flux control and He pumping
- Compatibility of ELM-controlled regimes by B_{edge} perturbation with high density/radiative divertor conditions (Z-seeding) remains to be demonstrated





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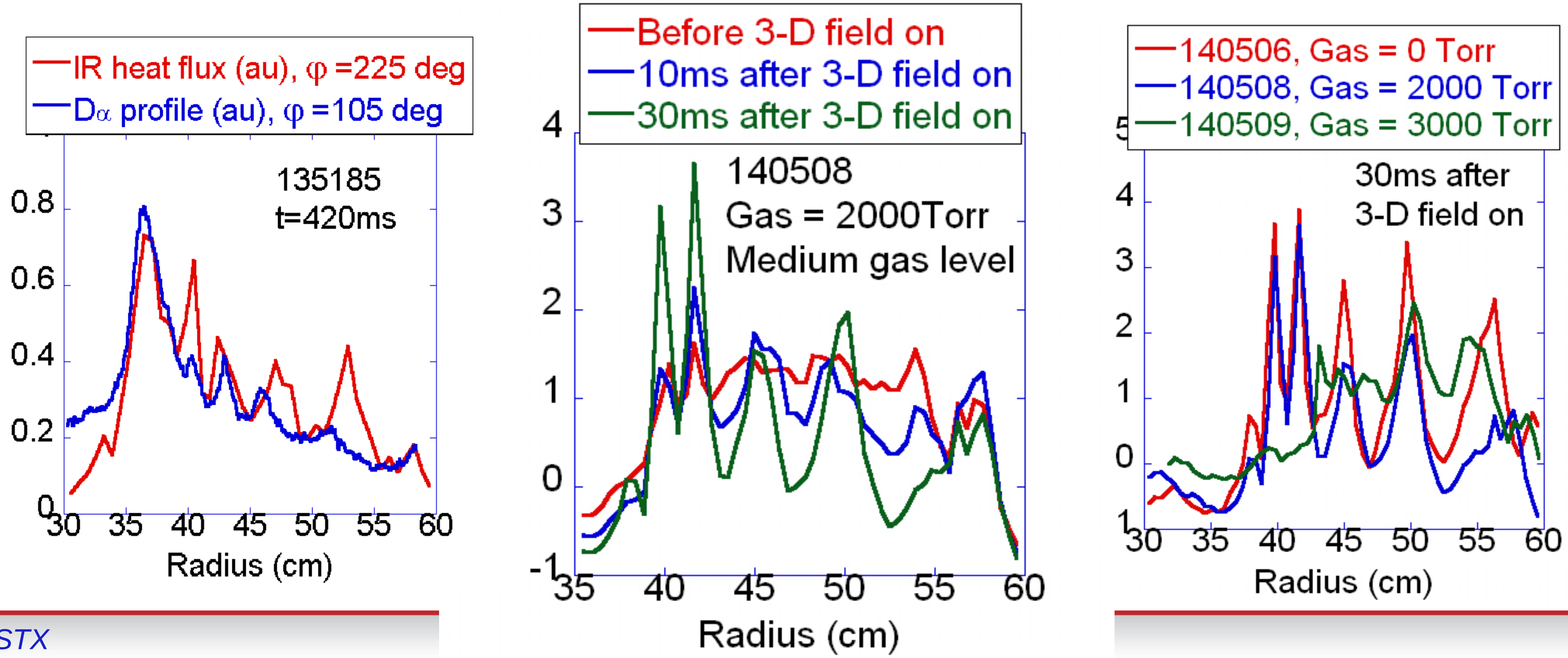
NSTX – Ahn – APS 2010 (ELMy H-mode-between ELMs)

Attached Plasma	Detached Plasma	Detached Plasma
with B_{edge}	no B_{edge} → attached with B_{edge}	no B_{edge} → detached with B_{edge}

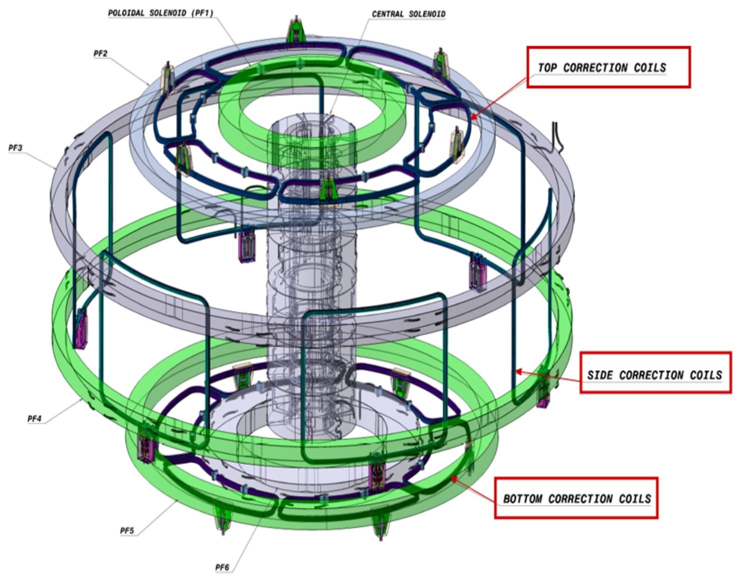


NSTX

2. Error field control

Error Field Control with External Correction Coils

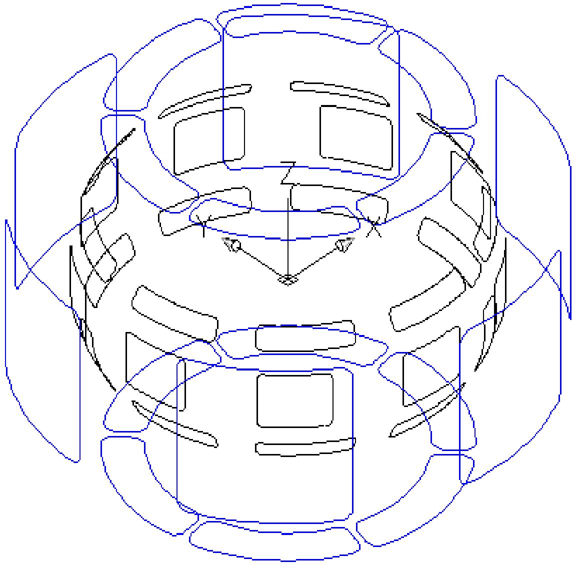
- Error fields come from CS, PF, and TF coil misalignments and feeds
- Error fields also from ferromagnetic materials especially Test Blanket Modules (TBMs)
- Error fields induce a torque slowing down the plasma toroidal rotation

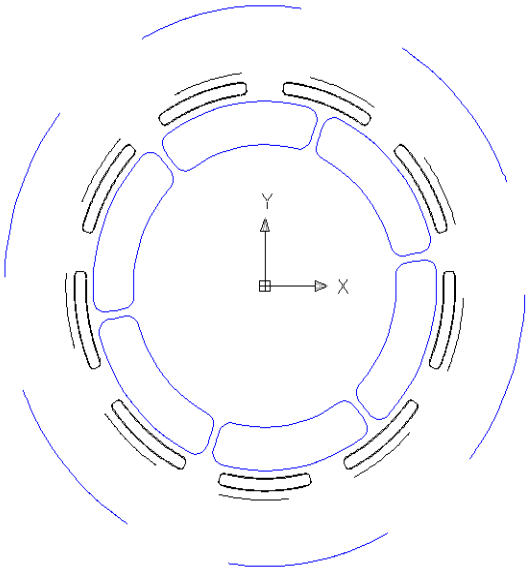


External Correction Coils

- Reduced rotation can lead to more locked modes and disruptions
- Error fields also enhance resistive wall modes (RWMs) at high β
- Three sets of 6 top, bottom, and side external correction coils will be used within the 320 kAt top & bottom and 200 kAt side current limits together with in-vessel ELM coils to correct a broad error field spectrum

Correction coils and ELM coils





- The primary objective of ELM coils (shown in black) is control of ELMs. However, in combination with Correction coils (shown in blue), these coils are a unique tool for control of error fields.
- The whole coil system, comprising 27 ELM coils with 27 independent power supplies and 18 Correction coils with 9 independent power supplies, allows a very high flexibility in production of different modes of non-axisymmetric magnetic fields.

Error fields expected in ITER

- Criteria were used in the studies of ITER error fields:

1) **"3-mode"** error field criterion, recommended in "ITER Physics Basis"
2) **"overlap"** error field criterion ("overlap external field"), developed recently for three ITER plasmas with the IPEC code (*J.Menard, J-K.Park, et al., 2010*)

- Plasmas considered:

1) **Plasma 1** – low β plasma at the start of current flattop in 15 MA scenario (l_i = 0.94, β_p = 0.056, q_{95} = 3.1)
2) **Plasma 2** – high β plasma at the state of burn in 15 MA scenario (l_i = 0.76, β_p = 0.77, q_{95} = 3.2)
3) **Plasma 3** – high β plasma at the state of burn in 9 MA steady-state scenario (l_i = 0.72, β_p = 1.88, q_{95} = 5.9)

Error fields expected in ITER

Error fields expected in ITER in 10^{-5} of the toroidal magnetic field, 5.3T

Type of analysis ==>	"3-mode"	"overlap" error field			Comments
Source of error field	**Plasma 1**	**Plasma 1**	**Plasma 2**	**Plasma 3**	
misalignments of TF, CS and PF coils	< 12.6	< 8.87	< 4.34	< 1.89	for the given tolerances
joints and busbars of TF, CS and PF coils	1				
six Test Blanket Modules	1.0	3.02	4.15	2.45	$\mu_0 M_s$ = 1.6 T
irregularity of Ferromagnetic Inserts (FI)	1.1	1.89	1.51	1.51	$\mu_0 M_s$ = 1.6 T
scattering in FI saturated magnetization	< 1				±2.5% of $\mu_0 M_s$ = 1.6 T
NBI Magnetic Field Reduction Systems	1.2				2 Heat.NBI + 1 Diag.NBI
Bioshield	< 1				
Tokamak Complex	0.2				
Cryostat and Cryostat Thermal Shield	< 0.04	< 0.19	< 0.15	< 0.11	$\mu_0 M_S$ = 7 mT, $\mu \le 1.05$
Criterion:	**5.0**	**11.5**	**6.4**	**4.9**	

- The main uncertainty - error fields from misalignments of TF, CS and PF coils. At present the tolerances in CS coils has been increased.
- Among the sources of error fields studied using the IPEC approach, the highest ratio of the "***overlap***" error field for **Plasma 2** to the corresponding "***3-mode***" error field for **Plasma 1** has error fields caused by the Test Blanket Modules (**4.15**)

Error fields expected in ITER

Error fields expected in ITER in 10^{-5} of the toroidal magnetic field, 5.3T

Type of analysis ==>	"3-mode"	"overlap" error field		
Source of error field	**Plasma 1**	**Plasma 1**	**Plasma 2**	**Plasma 3**
misalignments of TF, CS and PF coils	< 12.6	< 8.87	< 4.34	< 1.89
joints and busbars of TF, CS and PF coils	1		4.3	
six Test Blanket Modules	1	3.02	4.15	2.45
irregularity of Ferromagnetic Inserts (FI)	1.1	1.89	1.51	1.51
scattering in FI saturated magnetization	< 1		< 4.3	
NBI Magnetic Field Reduction Systems	1.2		5.16	
Bioshield	< 1		< 4.3	
Tokamak Complex	0.2		0.86	
Cryostat and Cryostat Thermal Shield	< 0.04	< 0.19	< 0.15	< 0.11
Total (simple summation)	**< 19**		**< 29**	
Criterion:	**5.0**	**11.5**	**6.4**	**4.9**

- The numbers marked in **red** were obtained assuming the ratio of "***overlap***" error field for **Plasma 2** to the corresponding "***3-mode***" error field for **Plasma 1** equal to **4.15** (**upper estimate**).
- Expected error field should be reduced by about a factor of 4.

Correction of error fields expected in ITER

Currents (kAturns) in Correction coils required for reduction of "**3-mode**" error fields expected in ITER (*Plasma 1*)

Source of error field	Top CC	Side CC	Bottom CC	Comments
misalignments of TF, CS and PF coils	165	80	250	reduction to 5×10-5
joints and busbars of TF, CS and PF coils	15	9	23	reduction to 0.01×10-5
six Test Blanket Modules	10.3	1.2	18.3	reduction to 0.01×10-5
irregularity of Ferromagnetic Inserts (FI)	1.6	6.7	3.6	reduction to 0.01×10-5
NBI Magnetic Field Reduction Systems	4	5	9	reduction to 0.1×10-5
Bioshield	5	3	4	reduction to 0.01×10-5
Total:	**201**	**105**	**308**	simple summation
Nominal current in CC:	**320**	**200**	**320**	

- Correction coils are capable to reduce expected "3-mode" error fields with some margin (particularly in Side CC).

Correction of error fields expected in ITER

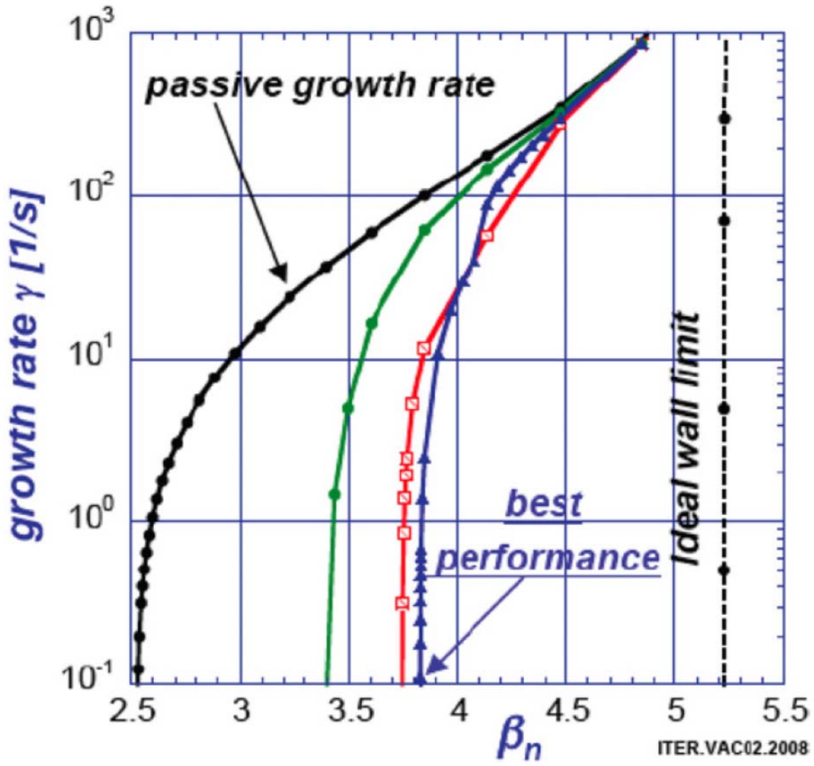
Currents in Correction coils required for reduction of "**overlap**" error fields expected in ITER (*Plasmas 1, 2, 3*)

Source of error field	Top CC	Side CC	Bottom CC	Comments
misalignments of TF, CS and PF coils				
joints and busbars of TF, CS and PF coils				
six Test Blanket Modules	6.8	26.2	3.3	to 1% of threshold
irregularity of Ferromagnetic Inserts (FI)	2.7	12	1.2	to 0.2% of threshold
NBI Magnetic Field Reduction Systems				
Bioshield				
Total:	**10**	**38**	**5**	simple summation
Nominal current in CC, kAt	**320**	**200**	**320**	

- So far only two sources of error field were analyzed using the "overlap" error field approach. More studies are needed.
- What should be the proper statement of problem?
- These estimates have major implications for the coil manufacturing and installation tolerances

Resistive Wall Mode Control Allows High β Operation

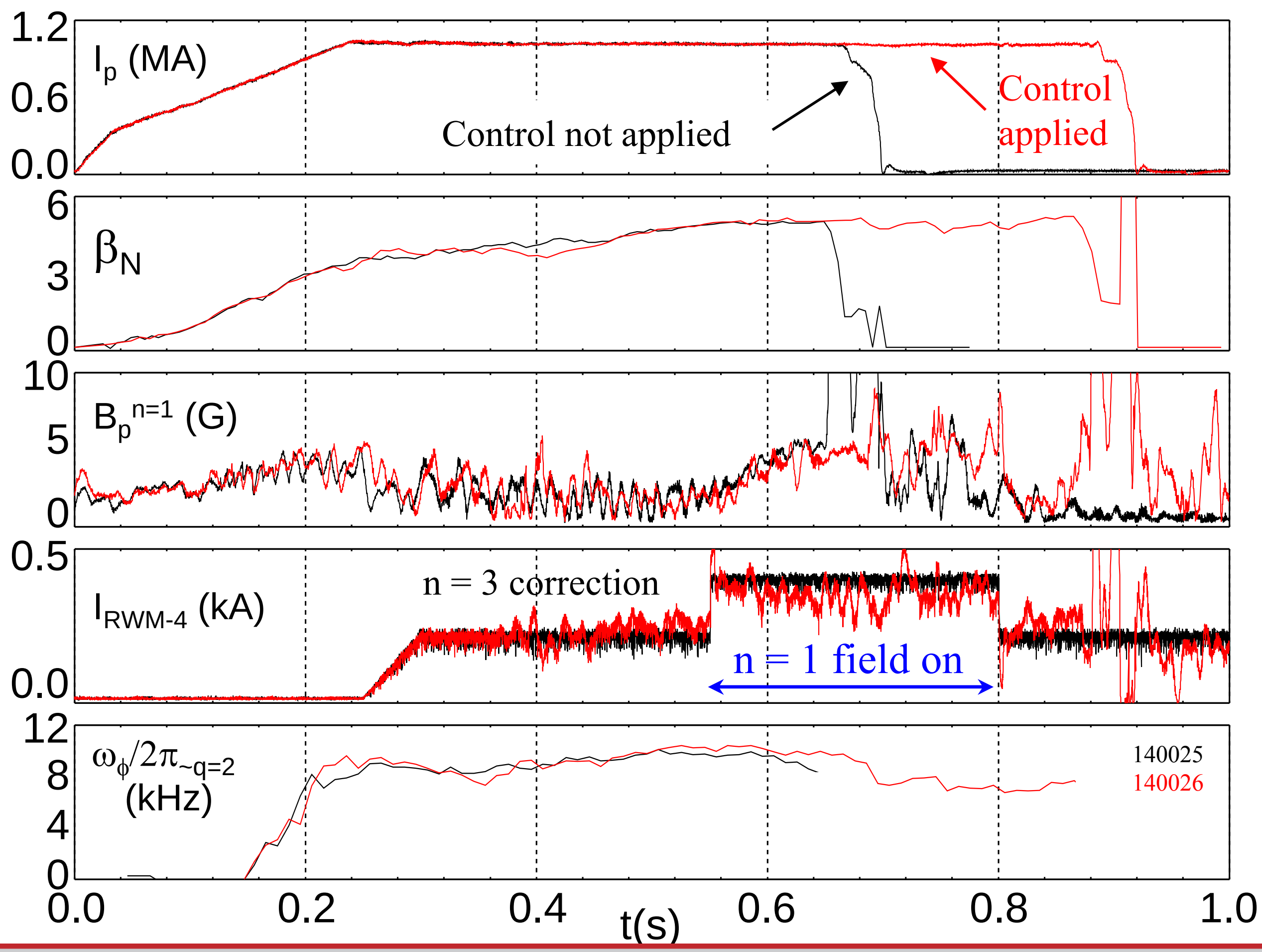
RWM Control: Hawryluk, NF 2009



- RWM control may be required as an upgrade at high β using internal ELM coils to reduce RWMs and external correction coils + ELM coils to reduce error fields
- VALEN code calculations indicate that the ELM coils can stabilize RWMs for $\beta_N < 3.7 - 3.8$ in ITER
- The ELM coils will be phased with the slow rotation of the RWM
- Power supply characteristics will be defined after initial ITER operation

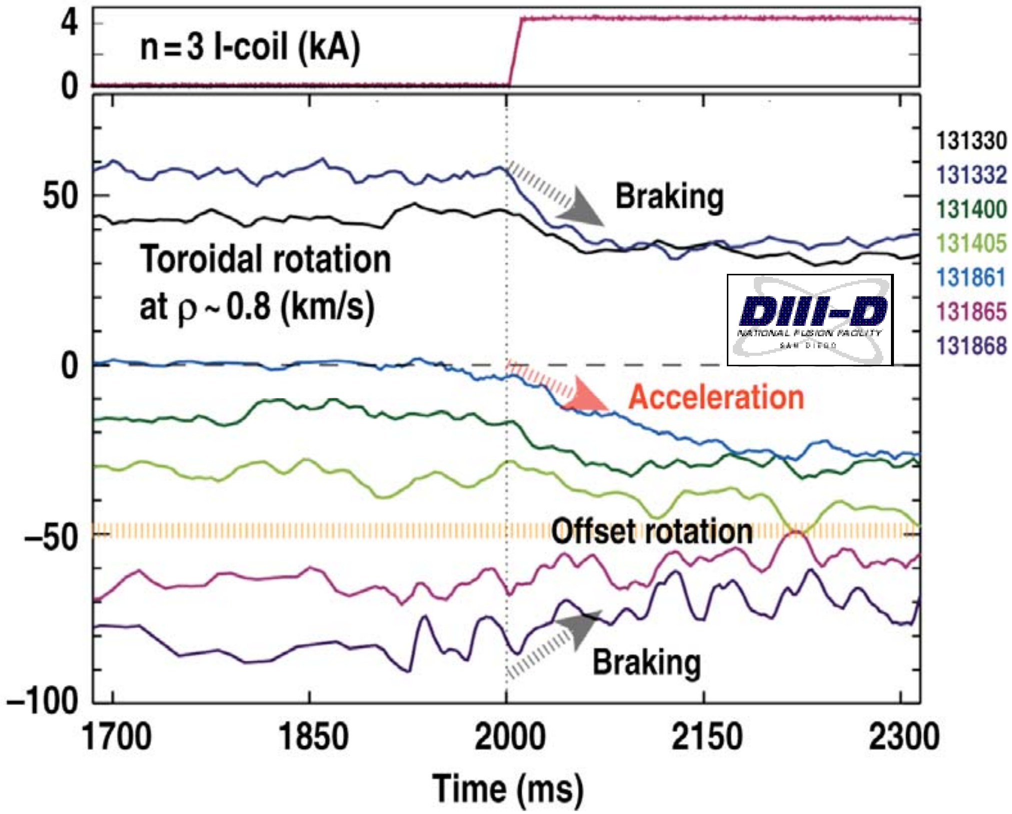
RWM state space controller sustains otherwise disrupted plasma caused by DC n = 1 applied field

RWM state space feedback (12 states)



- n = 1 DC applied field test
  - Generate resonant field amplification, disruption
  - Use of RWM state space controller sustains discharge
- RWM state space controller sustains discharge at high β_N
  - Best feedback phase produced longer pulse, $\beta_N = 6.4$, $\beta_N/l_i = 13$

Error Fields Also Affect Plasma Rotation



- ➢ Plasma rotation can be substantially reduced through magnetic braking with magnetic field perturbations
- ➢ DIII-D finds substantial slowing down of the plasma toroidal rotation when they energize the n=3 I-coils to stabilize ELMs
- ➢ However, when the plasma rotation is already near zero, the same n=3 perturbation can accelerate the plasma in the cntr-Ip direction
- ➢ Can ITER's ELM coils and external correction coils be used to help control plasma rotation?

Conclusions

- ITER will have internal upper and lower VS coils and a flexible array of independently powered ELM coils 3 poloidal × 9 toroidal
- The ELM coils are primarily designed for ELM control with up to 90 kAturns
- When current headroom exists, the ELM coils may also be used for error field and RWM control ➔sophisticated actuator sharing
- More R&D on existing machines is required to better understand effects of 3D fields on ELMs and on the divertor heat flux
- There will also be an array of external error field correction coils 3 poloidal × 6 toroidal used for error field control
- More experiments and modeling are required to understand how to optimize error field control in ITER
- 3D fields may also be used to maintain some level of plasma rotation if this is sufficient to reduce locked modes or RWMs