

# 3. 物理検討について

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検討状況1: プラズマ運転シナリオ

検討状況2: ELM時のダイバータ熱負荷の低減の必要性

検討状況3: TBM (Test Blanket Module)の影響

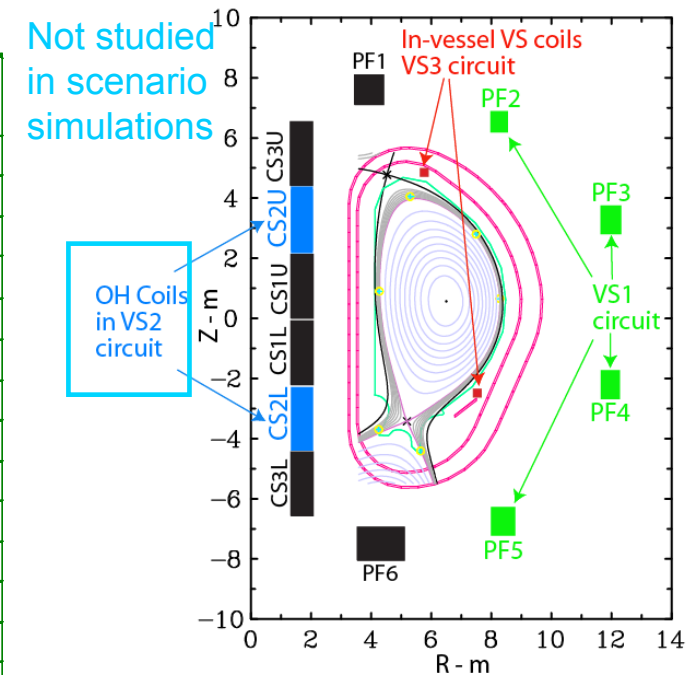
# 検討状況1:プラズマ運転シナリオ

・15MA, Q=10での数100秒燃焼シナリオ、多岐にわたるオーミック、ハイブリッド及び非誘導DTシナリオの検討(多様なプラズマ形状、プラズマ立ち上げ立ち下げ)が進められている。

- Analysis of scenarios with Baseline PF coils, Vacuum Vessel, Power Supplies, in-vessel coils, .... (VS1-6 kV & VS1-6 kV + VS3-2.3kV)
- Work carried out by IO & DAs through ITA tasks (EU, JA, RF, JA) on-going
- Reference DT scenarios and non-active scenarios are being analyzed

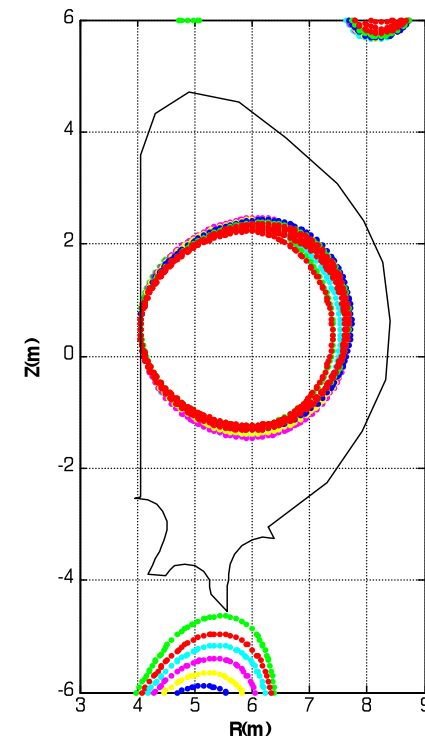
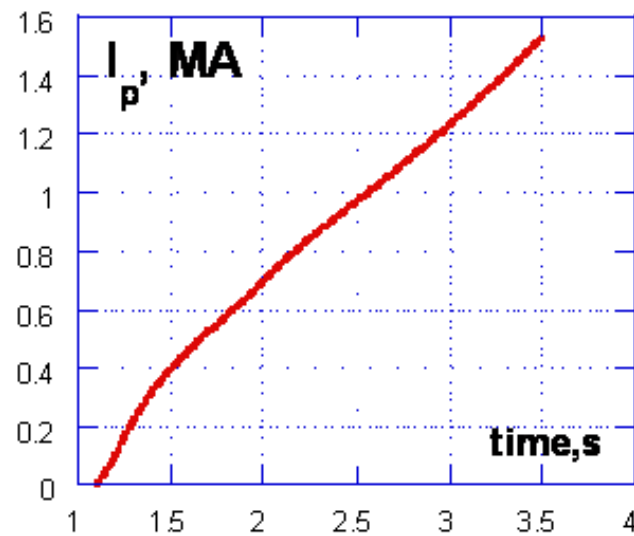
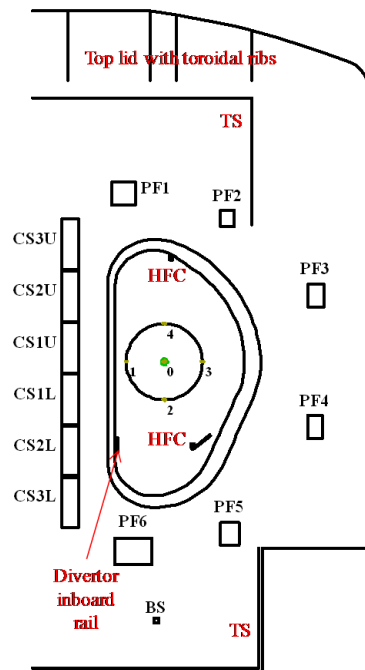
Table 1.1 Nominal plasma parameters for the three ITER reference scenarios

Parameter	1. Inductive operation	2. Hybrid operation	3. Non-inductive operation
R/a (m/m)	6.2 / 2.0	6.2 / 2.0	6.35 / 1.85
Toroidal field, $B_T$ (T)	5.3	5.3	5.18
Plasma current, $I_p$ (MA)	15.0	13.8	9.0
Elongation, $\kappa_x/\kappa_{y5}$	1.85 / 1.7	1.85 / 1.7	2.0 / 1.85
Triangularity, $\delta_x/\delta_{y5}$	0.48 / 0.33	0.48 / 0.33	0.6 / 0.4
Fusion power, $P_{fus}$ (MW)	500	400	356
$P_{add}$ (MW)	50	73	59
Energy multiplication, Q	10	5.4	6
Burn time (s)	300 - 500	1000	3000
Minimum repetition time (s)	1800	4000	12000
Total heating power, $P_{TOR}$ (MW)	151	154	130
L-H transition power, $P_{L-H}$ (MW) (note 1)	76	66 <td 48	
Plasma thermal energy, $W_{th}$ (MJ)	353	310	287
Maximum fuelling input ( $Pa \cdot m^3/s$ )	200	160	120



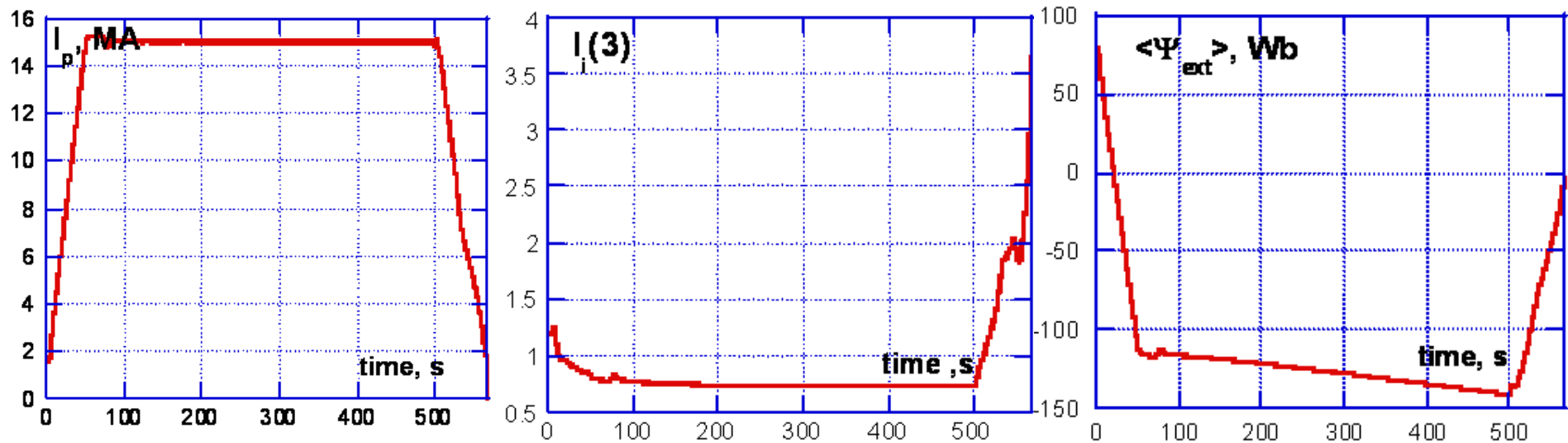
# Plasma initiation studies

- Initiation studies carried out taking into account conducting structures and Power Supplies (Switching Networks, Converters, ..)
- For 15 MA :  $\Psi_{\text{pre-mag}} = 118 \text{ Wb} \rightarrow \Psi_{\text{break}} = 111 \text{ Wb} \rightarrow \Psi_{0.5\text{MA}} = 104 \text{ Wb}$
- DINA simulations with plasma control up to 1.5 MA with  $\Psi_{1.5\text{MA}} = 89 \text{ Wb}$



## 15 MA $Q_{DT} = 10$ Scenario

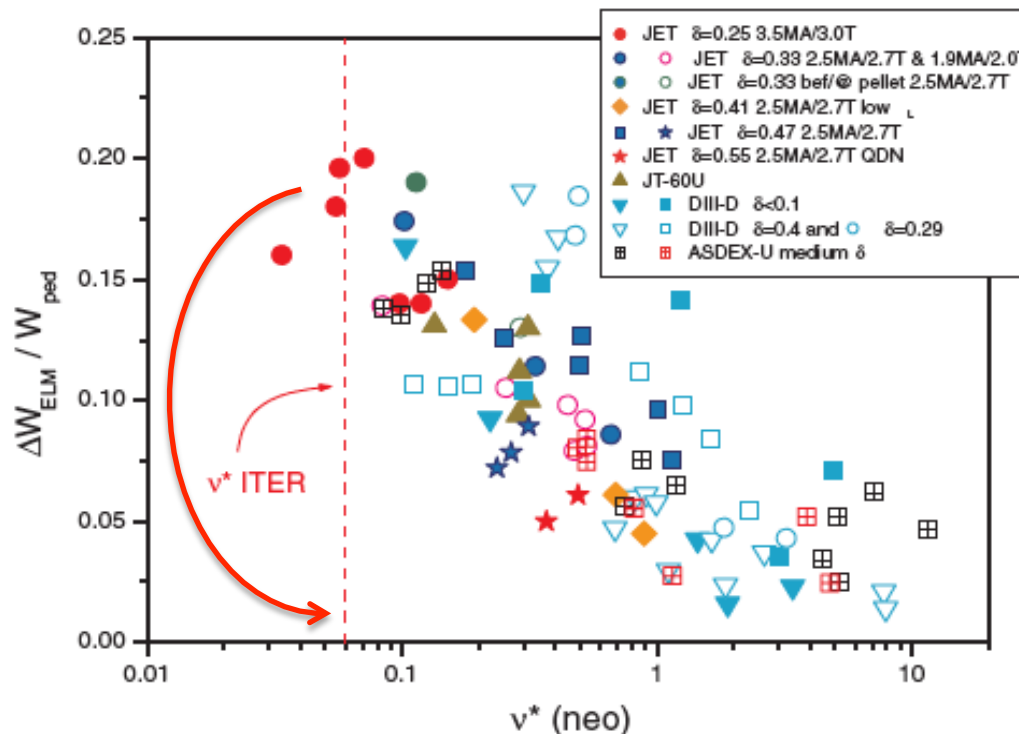
- Simulations of scenario with noise : VS1 (6 kV) or VS1 (6 kV) + VS3 (2.3 kV)
- If noise is low and  $I_i$  remains controlled  $\rightarrow$  VS 1 is sufficient
- $Q_{DT} = 10$  for 400 s starting from  $\Psi_{1.5MA} = 80$  Wb (<89 Wb from initiation studies)



- Recovery of burn flux to CS-2008 levels achievable by larger  $P_{aux}$  in ramp-up and higher ramp-rate (5-7 Wb)
- Similar results with DINA and CORSICA

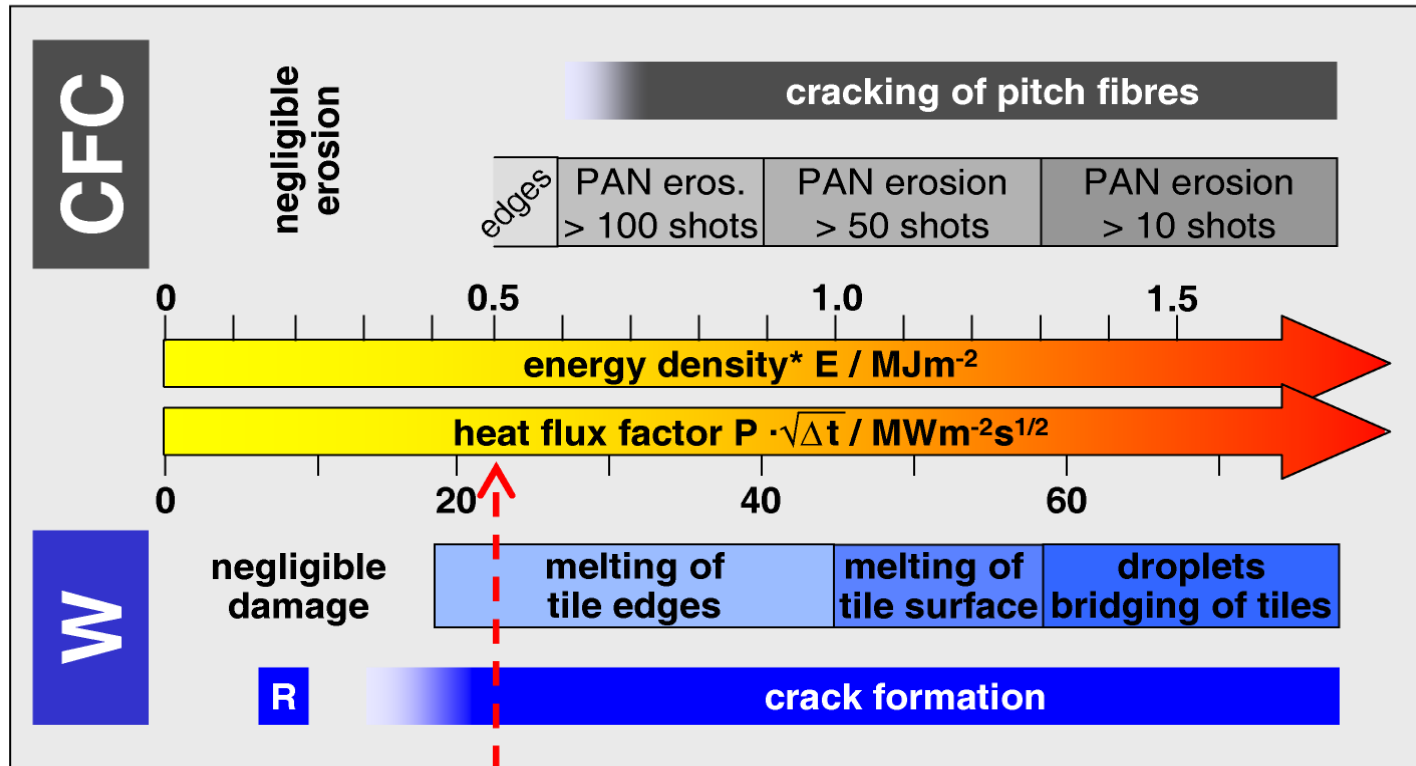
## 検討状況2:ELM時のダイバータ熱負荷の低減の必要性

1. ダイバータ材料の耐熱パルス特性の評価(プラズマガン実験)より、限界値 $0.5\text{MJ}/\text{m}^2$ 。(過去の「均質材料+理想状態」での計算予測は $1\text{-}1.2\text{MJ}/\text{m}^2$ )
2. ELM時のダイバータ熱負荷に関する実験結果
  - 2-1. ELM熱流束幅は広がらない(従来はELM間での熱流束の1.5倍としていた。)
  - 2-2. 内側ヒットポイントでの熱流束は外側ヒットポイントの2倍
  - 2-3. 放出エネルギーが平均値を大きく越えるELMが発生する(頻度 $\sim 10\%$ )



- Permissible for ITER ELMs  $\sim 1\%$  of the pedestal energy.
- Expected not mitigated ELMs for ITER low collisionality plasma are  $\sim 20\%$  of the pedestal energy .
- Mitigation is necessary by  $\sim 20$  times

# Material Issues are Very Serious



J. Linke et al.

**mitigated ELMs in ITER**

\*  $\Delta t = 500 \mu\text{s}$

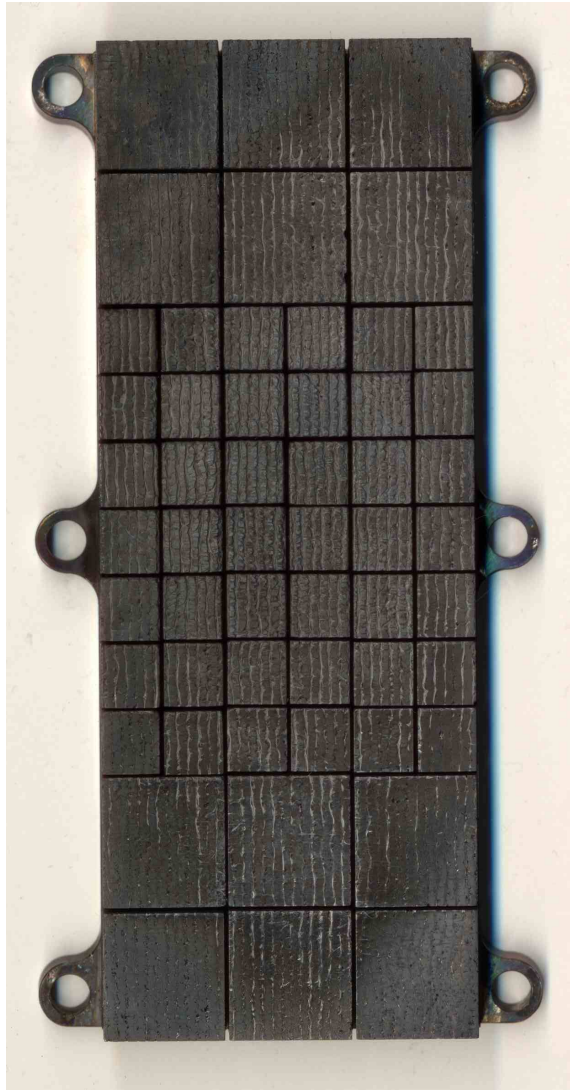
**R** cracking of recrystallized tungsten at 420.000 shots

Unmitigated ELMs correspond to  $\sim 10 \text{MJ/m}^2$

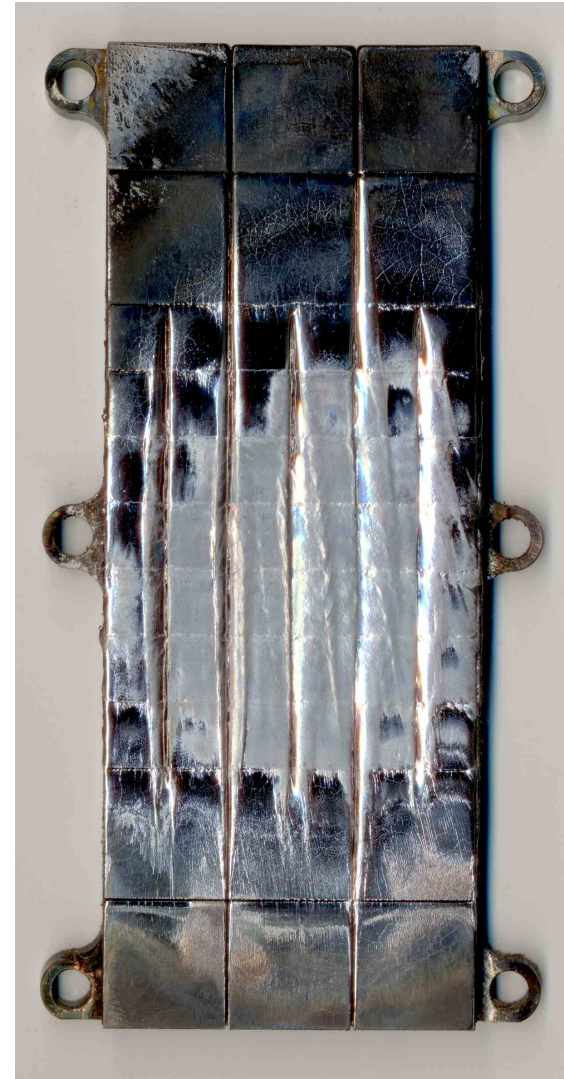
If ELMs are reduced from 20MJ to 1MJ ( $.5 \text{MJ/m}^2$ ), need to control >99% to <2MJ out of  $10^4$  ELMs per pulse to achieve a divertor lifetime of 100-1000 shots.

## Material Erosion by ELM-like Energy Fluxes

CFC : 100 ELMs @  $1.5 \text{ MJm}^{-2}$



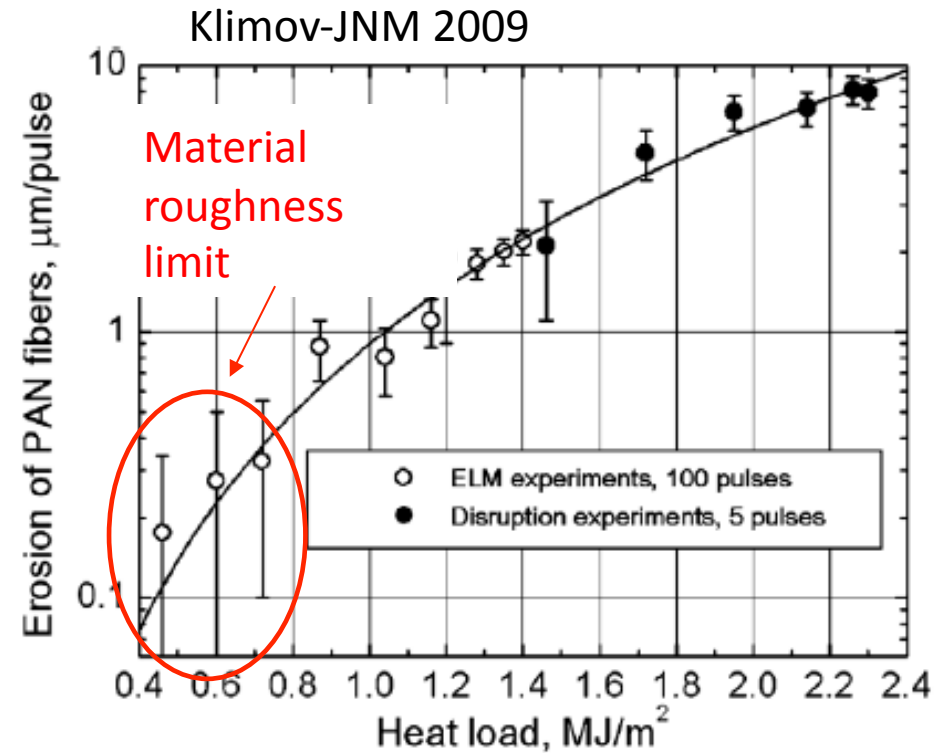
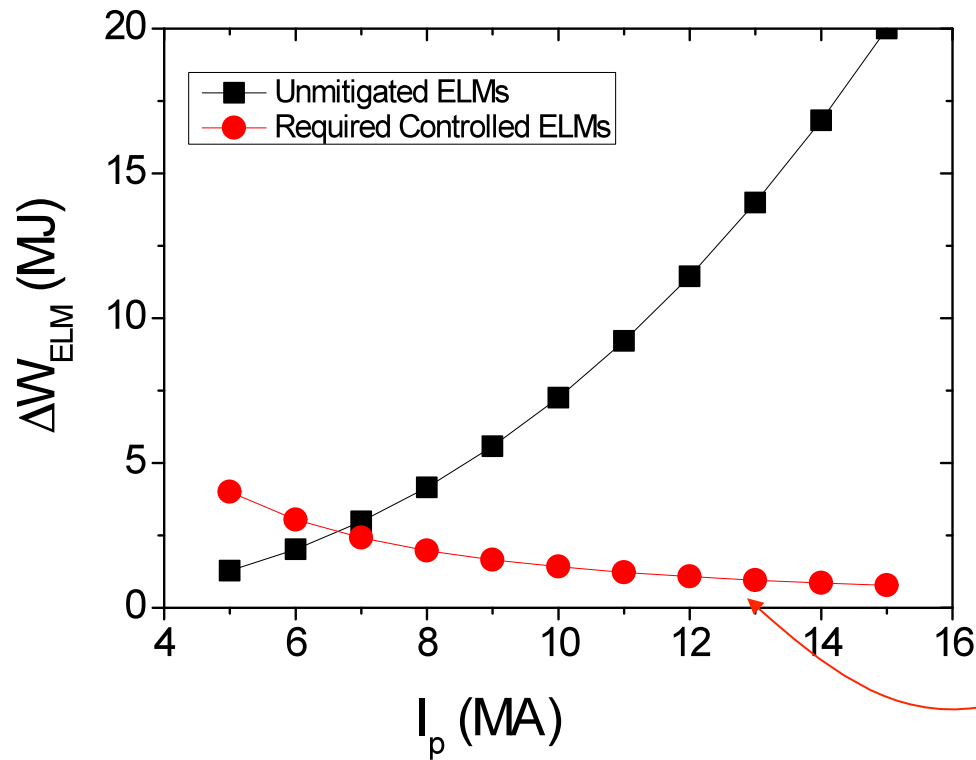
W : 100 ELMs @  $1.5 \text{ MJm}^{-2}$



# ITER ELM Control Requirements

Determined by material limits → ELM erosion negligible for divertor lifetime ~ 1000s  
 $Q \sim 10$  pulses (several  $10^6$  ELMs)

Operation of ITER without active ELM control and adequate divertor lifetime only viable for low  $I_p \sim 5$  MA



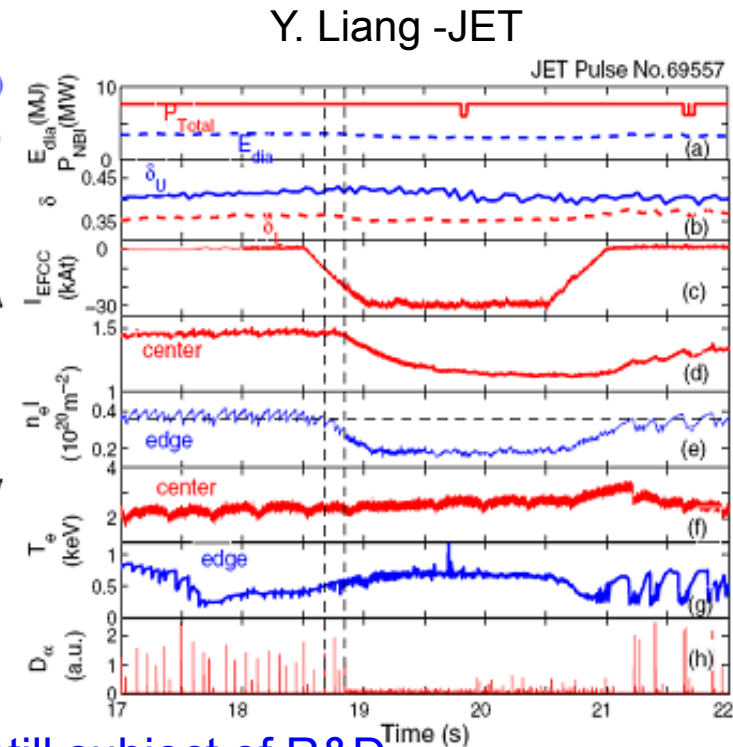
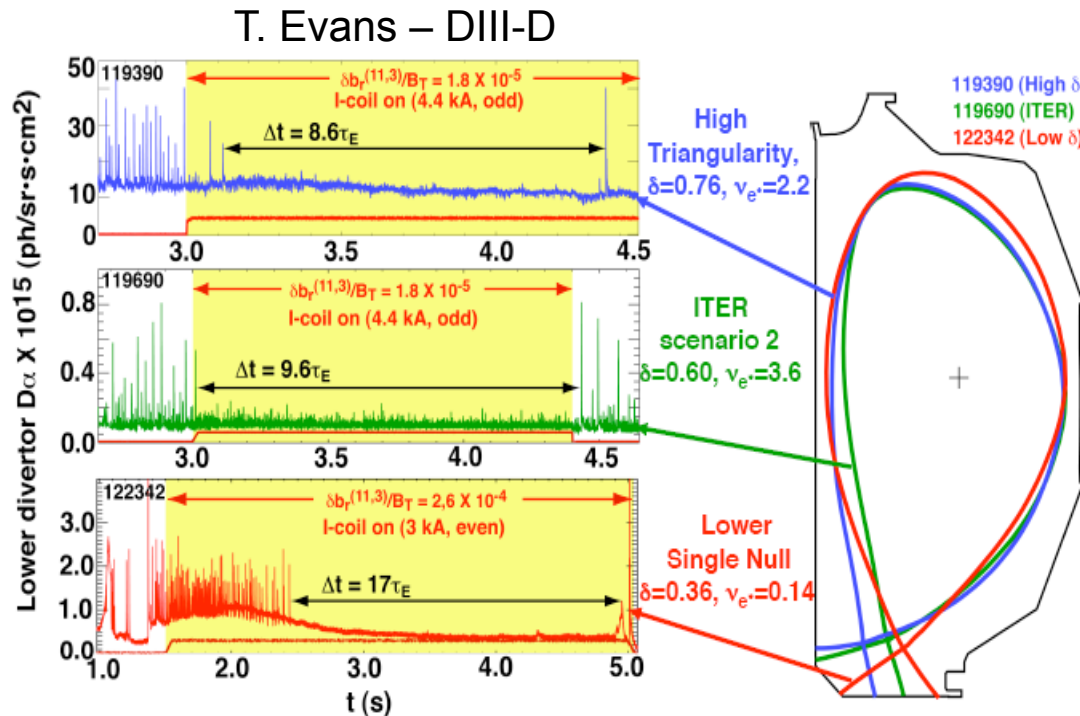
Exceeding material erosion limit decreases divertor lifetime drastically

$E_{ELM} = 1 MJm^{-2}$  ( $Q \sim 10$ ) →  $1 \mu m$  CFC erosion/ELM → Lifetime  $\sim 2 \cdot 10^4$  ELMs = 1-10 pulses



# ELM Control by $B_{\text{edge}}$ perturbations : Experiments DIII-D & JET

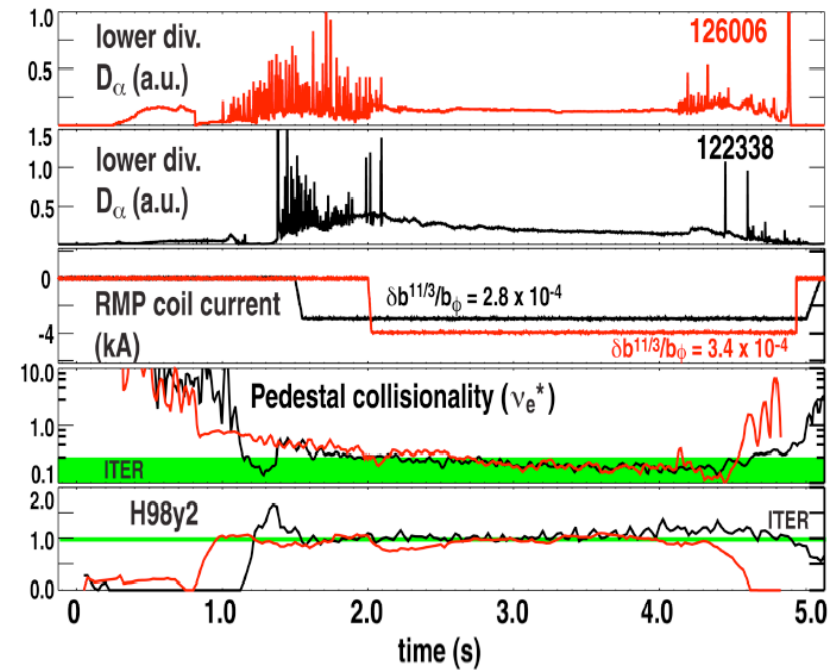
- ELM control/suppression by edge magnetic field perturbation
  - ✓ Large effects on ELM behaviour for  $|b_r^{\text{res}}/B_{\text{t}}|_{\text{edge}} \sim \text{few } 10^{-4}$
  - ✓ Most experiments  $\rightarrow f_{\text{ELM}} \uparrow \Delta W_{\text{ELM}} \downarrow$  & DIII-D also sees ELM suppression



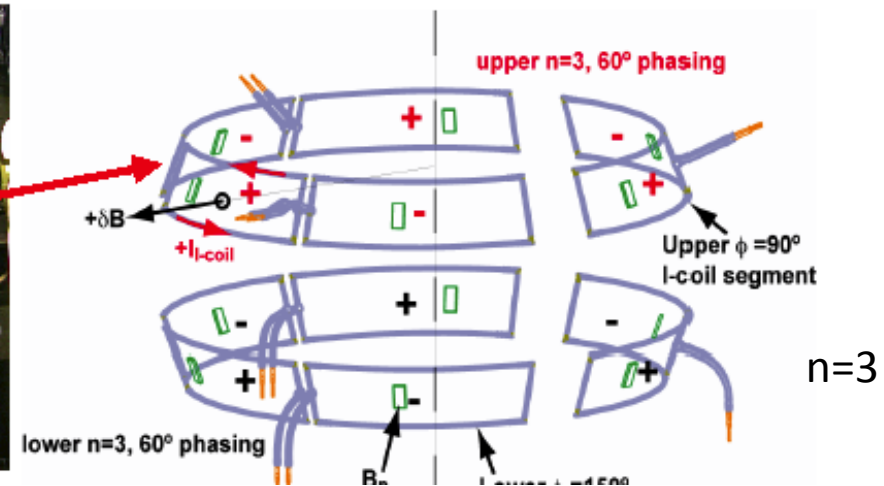
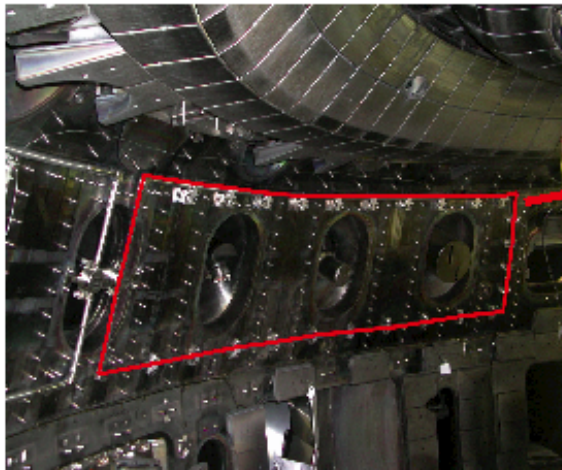
- Processes leading to ELM control & suppression still subject of R&D
  - ✓ Enhancement of edge transport by ergodic layer (O. Schmitz-DIID PRL09) for ELM suppression
  - ✓ Interaction of external field with peeling mode stability for  $f_{\text{ELM}}$  enhancement & ELM control/suppression (Y. Liang - JET- sub PRL10)

# ELM suppression by ergodization

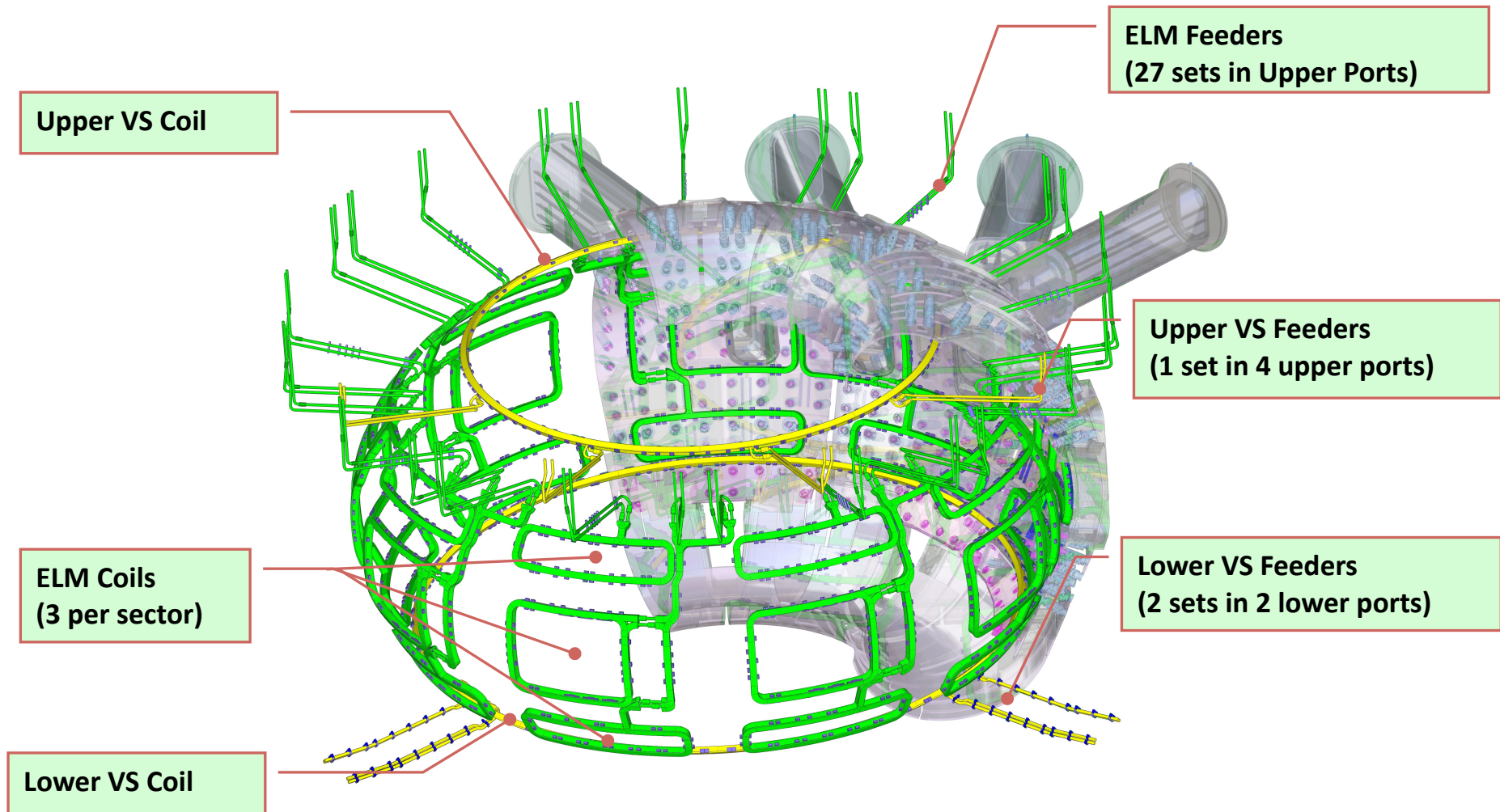
- Ergodization works for DIII-D and JET.
- WG-1 has proposed to use a set of 36 Resonant Magnetic Perturbation coils.



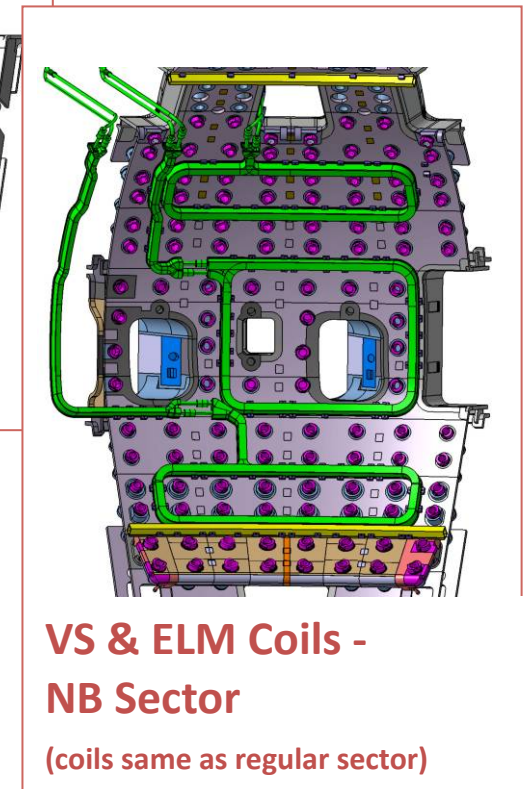
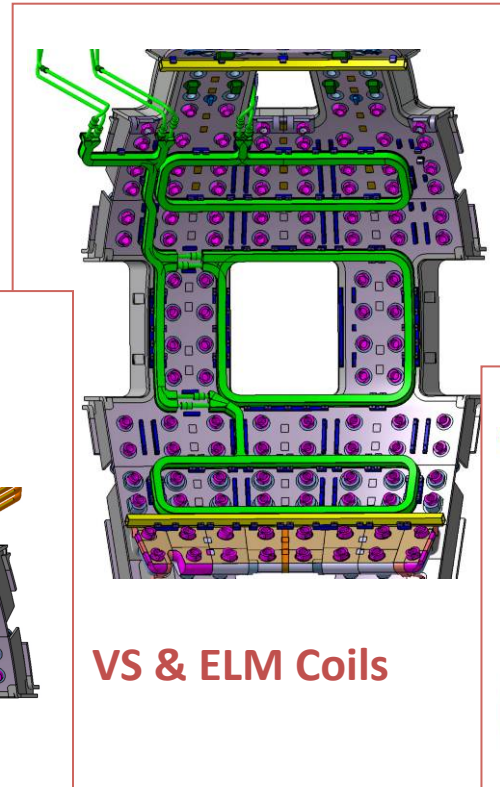
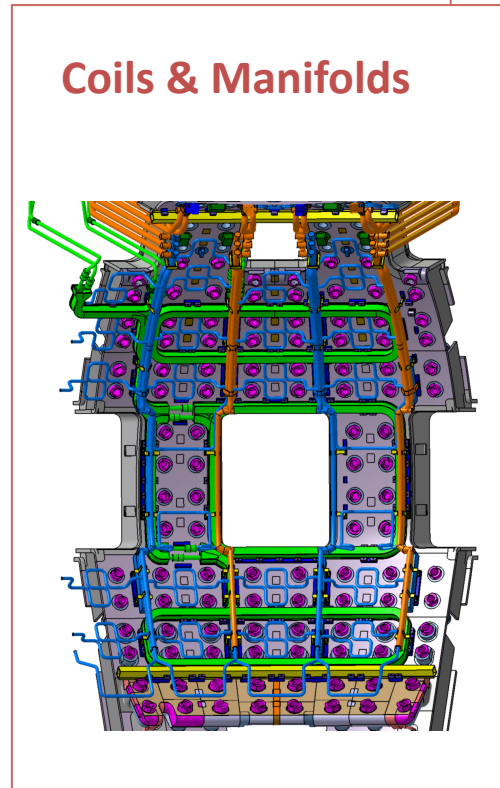
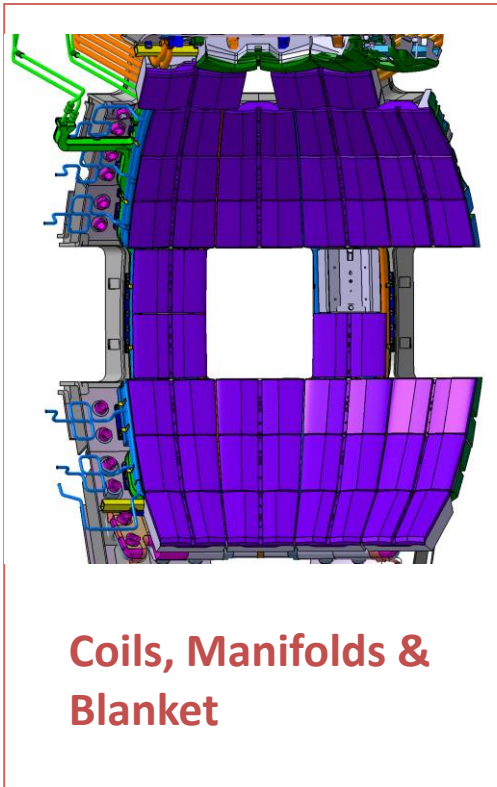
DIII-D



# In-Vessel Coil Arrangement



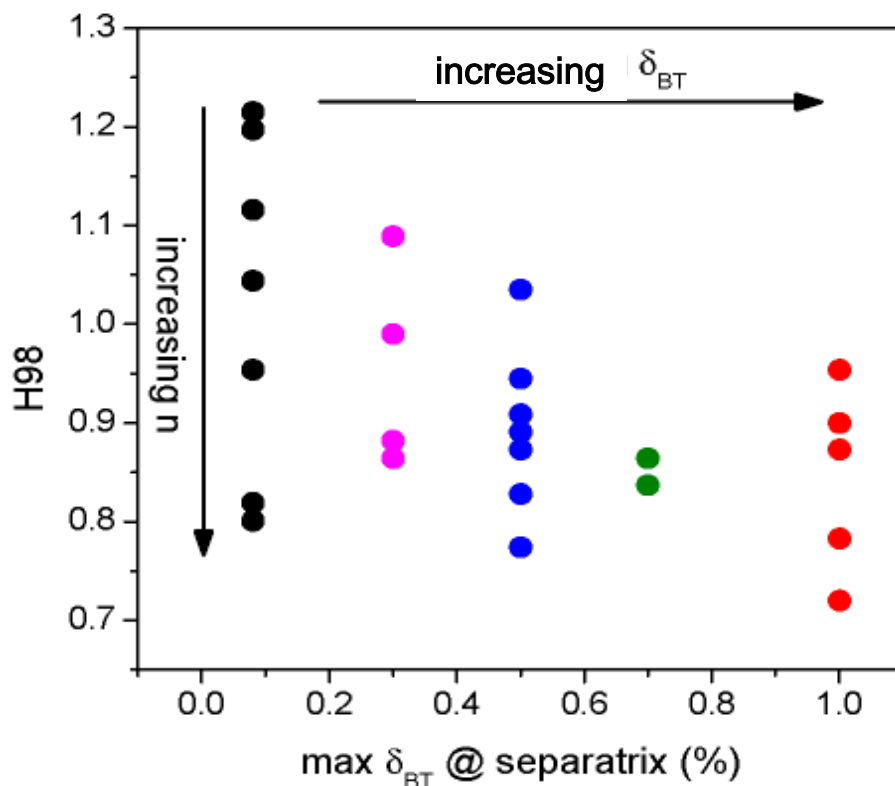
# Overall In-Vessel Coil Arrangement



- 継ぎ手の構造、コイルの取り付け、遠隔保守、故障対策配線・関連機器の配置など、解決すべき課題が多い。
- ELMコイルによるELM周波数の制御やプラズマへの影響についてもR&Dが要。

## 検討状況3： TBM (Test Blanket Module)の影響

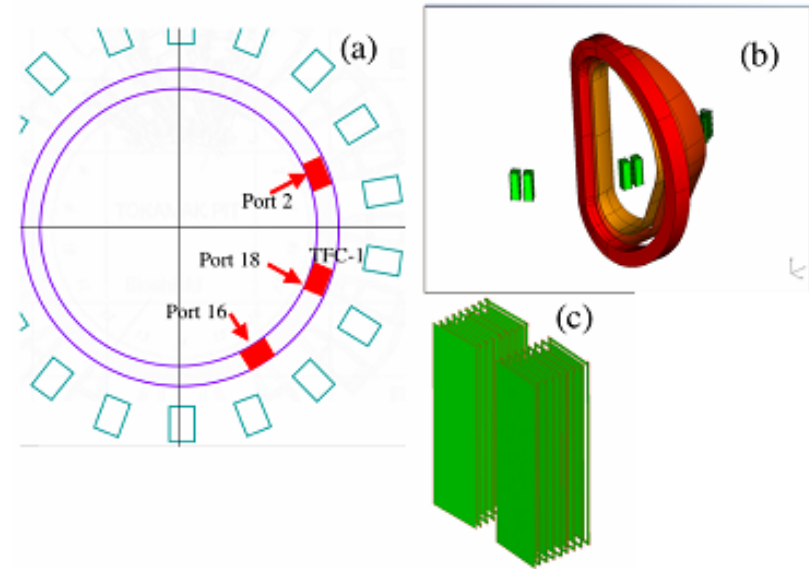
- TBMが作る磁場の擾乱の影響(トロイダル磁場リップル)について、プラズマ運転に対する影響の実験と数値解析が進んでいる。
- TBMを初期の水素及びヘリウム運転から据付けることについては、TBMのプラズマ運転上の影響は少なく問題が無い。
- 高出力運転時はTBMが誘導する磁場の誤差が $Q=10$ の達成に影響を与える可能性があり、ダミーTBMをD-T運転の最初から据付けるべきとの議論がある。
- さらなる検討・評価・対策が要とされている。



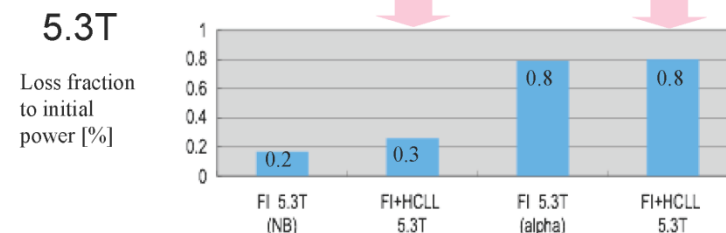
- JET experiments varying TF ripple show that energy and particle confinement can be degraded with increasing ripple in H-mode
- The degradation is strongest at the lowest density and lowest  $\nu^*$

# Energetic Particle Losses due to Ripple are Small

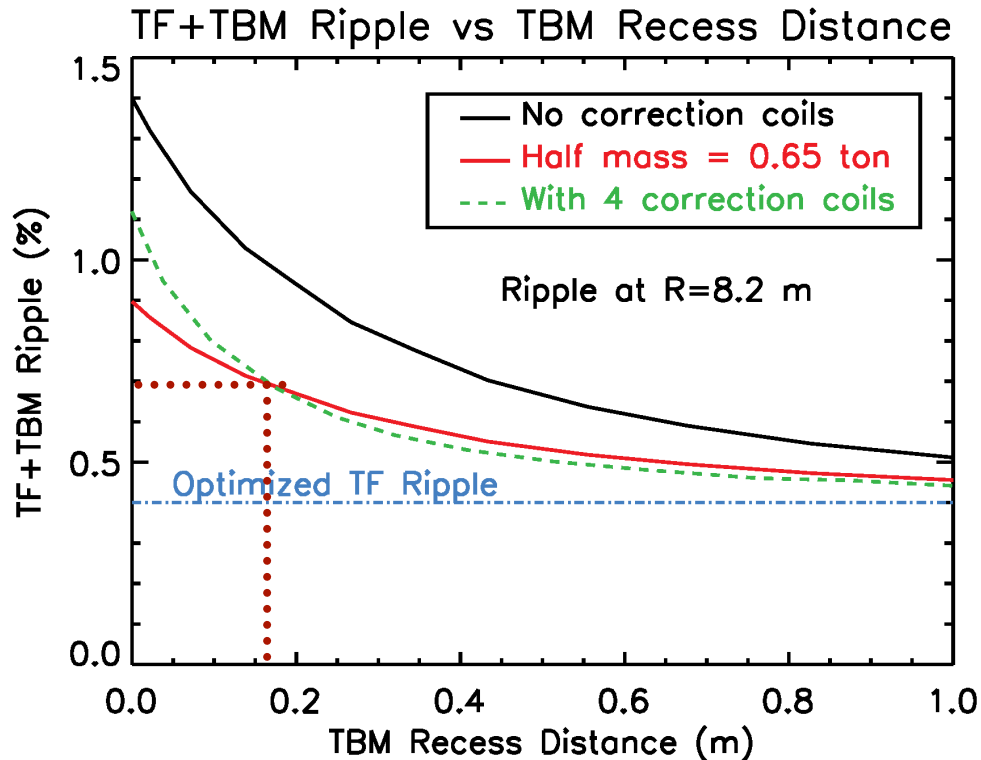
- TF ripple effects on fast ion losses
  - Expected TF ripple with ‘optimized’ ferritic inserts has  $\delta_{TF} \sim 0.4\%$
  - Worst expected fast ion heat loads  $< 0.5\text{MW/m}^2$  at 9 MA
- TBM magnetic perturbation could increase fast ion losses
- Calculations by Shinohara at 9 MA with 6 HCLL TBMs show the same  $\alpha$  particle losses and slightly more NB fast ion losses at 5.3 T
- At 15 MA, no significant fast ion losses due to the TBMs are expected
- More detailed calculations with a realistic first wall are ongoing



9 MA Scenario 4



## Effects of TBM Mass and Distance to Plasma



- Assuming an optimized TF ripple of 0.4%, the 1.3 ton HCLL TBMs will increase the TF+TBM ripple to ~1.3% with a 0.05 m recess
- Reducing the mass by a factor of two to 0.65 tons will reduce the TF+TBM ripple to ~0.8%
- Recessing the TBMs further reduces the ripple at the LCFS
- 0.65 ton  $\approx$  coil correction + 16 cm recess  $\approx$  0.7% TF+TBM ripple
- **Optimum TBM mass + recess + correction coils + TF ripple still needs to be determined**

# ITERでの研究課題

- ・ITER計画では、核融合炉に向けた技術取得の観点から、TBMの計画のほかにも進めなければならない多くの研究や技術の開発項目がある
- ・ITER装置を用いた研究開発を担う可能性を持つ若い研究者の方々にいろんな着想を持って取り組んで頂きたいと考えています。

<例>

- 核融合炉を想定して真空容器内に設置したコイルを使用しないでタイプ1 ELMの周波数を上げる制御手法の開発
- トカマクプラズマにおいて発生するディスラプションが核融合炉で起きないようにする運転技術の確立
- 真空容器内の機器を維持管理するための遠隔保守装置とホットセルや放射性廃棄物処理施設などを含めた核融合炉の装置・機器の維持・管理技術の確立
- 核融合炉で実装できる計測装置が限定されることを想定し、DT燃焼プラズマなどの実時間計算機シュミレータを内蔵した知能レベルの高いプラズマ制御系の構築