BPO Inputs to ITER Design Review on
Pellet Pacing, RMP and RWM Coils, and Disruption Mitigation

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by

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presented at

Town Meeting on ITER Design Review

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International Collaboration Essential Ingredient

Contributions to Pellet Pacing

USBPO: L. Baylor and P. Parks
EU: P. Lang, A. Loarte, K. Gal, L. Garzotti, G. Saibene, and M. Valovic
JA: Y. Kamada
IO: A. Polevoi, A.Kukushkin, M. Sugihara, and M. Wykes

Contributions to RMP and RWM Coils

USBPO: J. Bialek, T. Evans, M. Fenstermacher, A. Gorofalo, D. Loesser, J. Menard, G. Navratil, M. Okabayashi, S. Sabbagh, M. Schaffer, T. Strait, J. Smith, and R. Stambaugh
EU: M. Becoulet, A. Loarte, E. Nardon, and P. Thomas
IO: D. Campbell, Y. Gribov, and G. Johnson

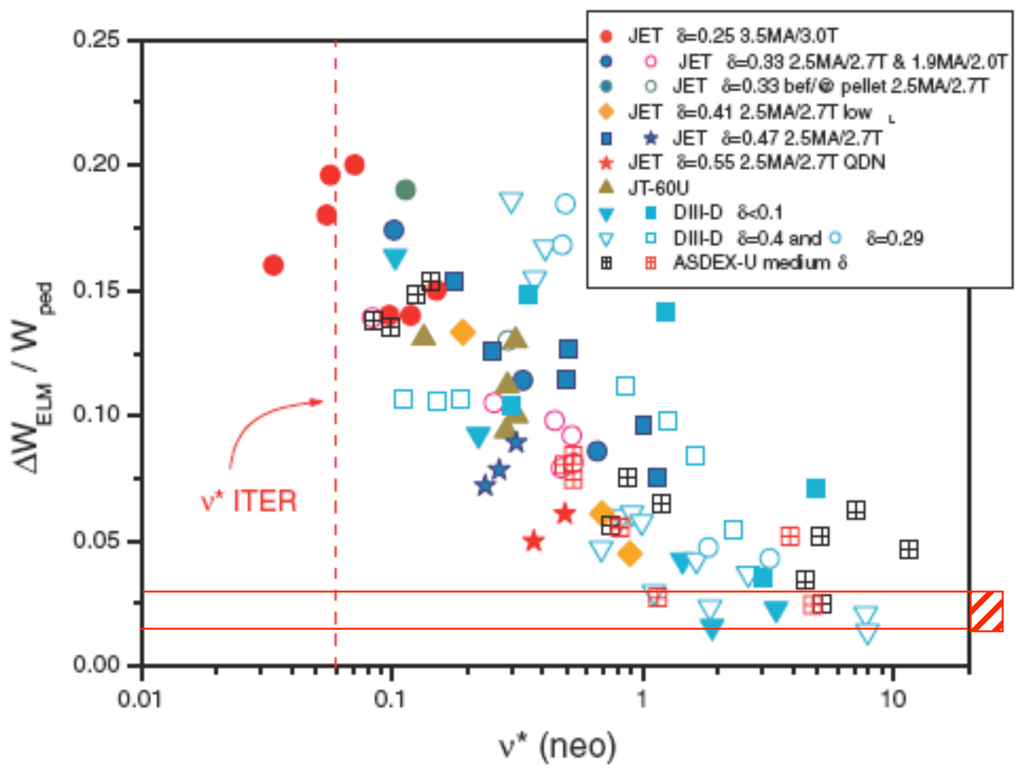
Contributions to Disruption Mitigation

USBPO: L. Baylor, R. Granetz, D. Whyte, and J. Wesley
IO: M. Wykes

Apologies in advance for failing to recognize your contributions.

Control of Type 1 ELMs Is a Pressing Issue for ITER

Loarte et al., Nuclear Fusion, ITER Physics Basis,Chapter 4



Acceptable Value ~1MJ

Recent results reduced the acceptable energy loss from ELMs. Reducing the energy loss to <1MJ using pellet pacing is challenging. DIII-D experiments have demonstrated that ELMs can be stabilized by RMP coils.

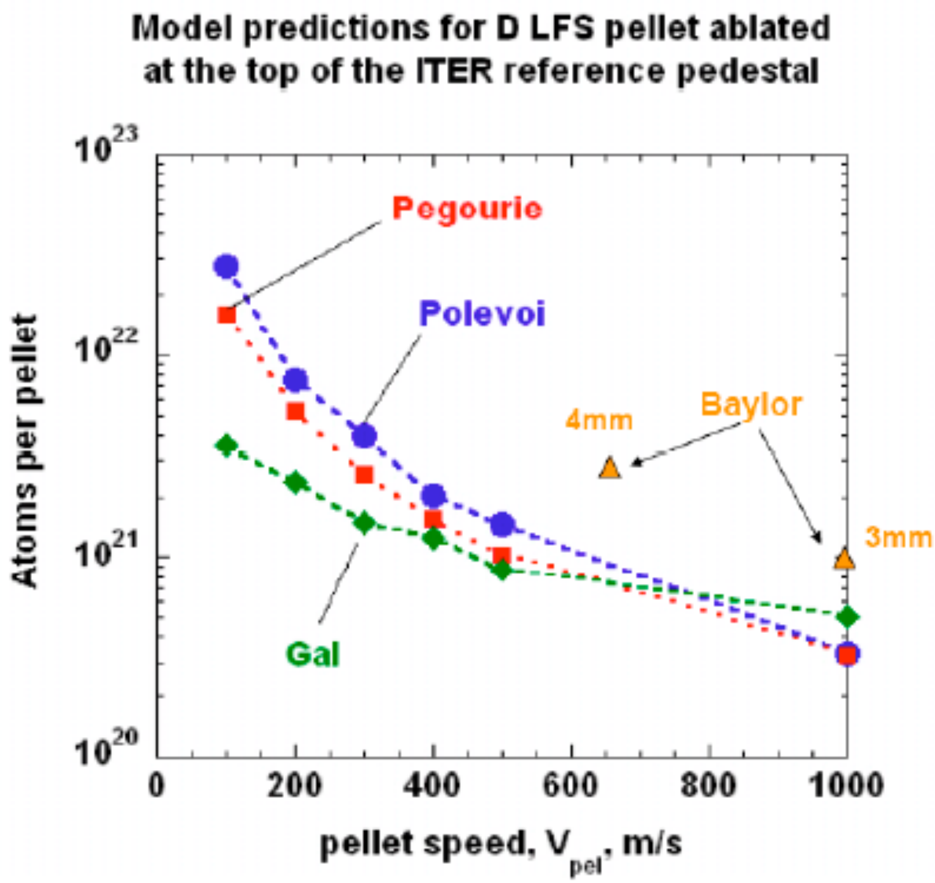
Is Pellet Pacing Consistent with the Fueling and Pumping Requirements for ITER?

- Pellet pacing is planned to control ELMs.
  - For <1MJ ELMs, estimate 40 Hz compared with ~4Hz in in current design.
  - Review of ASDEX data motivates injection of the pellet to the top of the pedestal instead of half way up the pedestal.

- According to the ITER requirements documents, the maximum throughput of DT fuel is 120 Pa•m^3/s.

- Requirements should be based on a self- consistent model of:
  - pellet ablation and redistribution
  - particle transport in the core and the pedestal
  - impact on temperature of the pedestal
  - divertor behavior
  - *A benchmarked model was not available.*
  - *Experimental data not available for repetition rates and pellet sizes required to simulate ITER.*

Pellet Pacing Benchmarking Exercise Identified Differences in Code Simulations



Polevoi

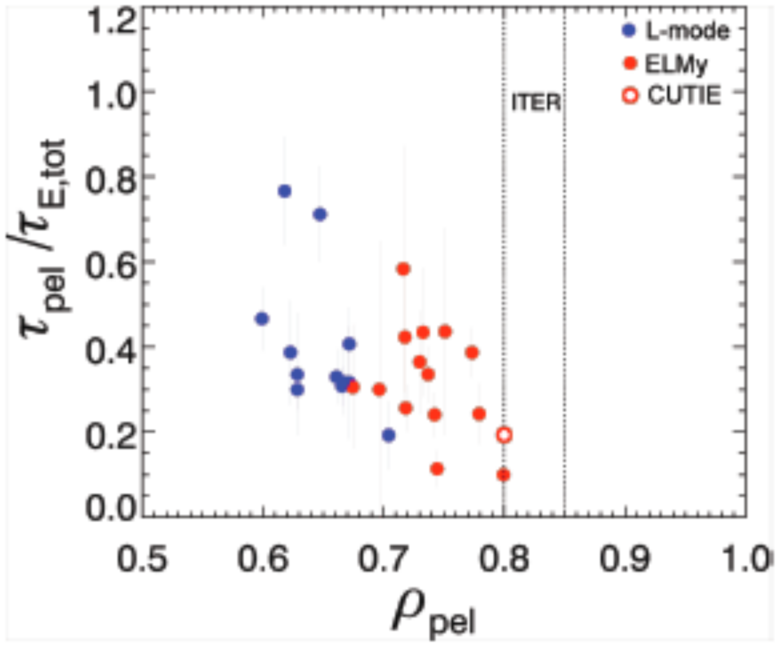
- Implies 4 10^{22} to 1.2 10^{23} atoms/s, ignoring loss in flight tube at 500m/s.
- Benchmarking of drift/redistribution of pellet mass has not been completed.

Estimates Constrained by Energy Loss

- Loarte estimated the maximum fueling rate consistent with a convective power loss corresponding to 3-5keV temperature of 0.8 to 2.8×10^{22} atoms/s

- Since part of the pellet may not penetrate to the top of the pedestal and some of the mass will be prompt loss associated with redistribution, a maximum fueling rate of 5×10^{22} atoms/s appears appropriate.
  - near the lower end from the fueling estimates of low field side injection.
  - upper end of estimates constrained by convective heat loss.

Core Fueling Requirements



- MAST experimental simulations of pellet fueling indicate a relatively short particle confinement time.
- According to Valovic this extrapolates to 3.7 10^{22} atoms/s
  - Major extrapolation from MAST to ITER.
- Convective power loss constrains to 5.4 10^{22} atoms/s consistent with Q=10 performance.

A Design Change Request (DCR) on Pellet Pacing has been Submitted

- Recommend increasing the fueling and pumping requirement to accommodate:
  - Total pumping and fueling requirement 1.1 10^{23} atoms/s or 210 $Pa{\cdot}m^3s^{-1}$ compared with the present requirement of 120 $Pa{\cdot}m^3s^{-1}$.

- Opportunity for BPO to address uncertainties in how the present results extrapolate
  - Depth of pellet penetration
  - Mass retained (drifts/redistribution) and convected power
  - Particle transport coefficients.
  - Recyling and divertor behavior.
  - Need for a consistent edge-core simulation.
  - *Impact on edge pedestal parameters when pellet repetition time corresponds to 1% of τ_E.*
  - *Can we preserve good H-modes?*

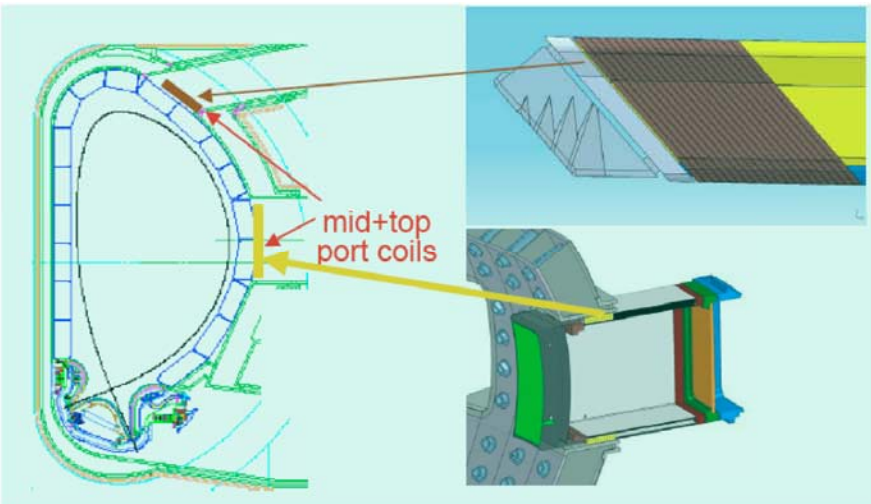
- Engineering assessment of proposed change is “on-going” due to implications on pumping, fueling and tritium systems.

Can Resonant Magnetic Perturbation (RMP) and Resistive Wall Mode (RWM) Coils Be Incorporated into the Design?

- **Goals:**
  - Suppress ELMs with RMP coils
  - Increase β_N with RWM coils for steady-state operating mode

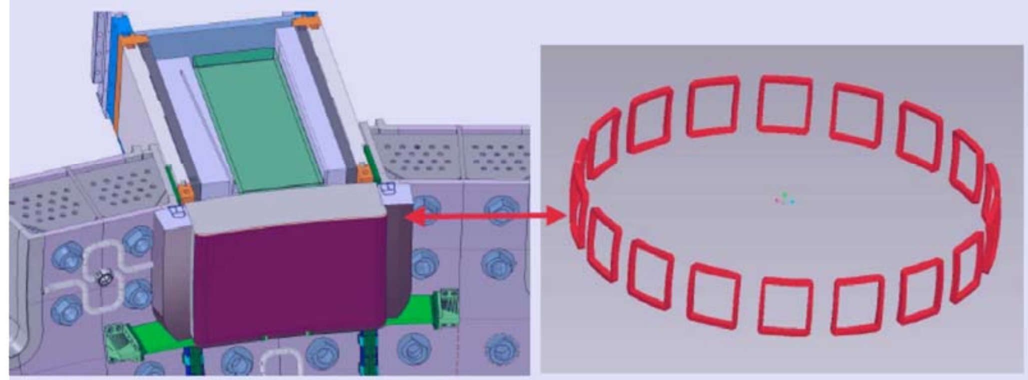
- **Physics analysis has been performed and updated.**
  - DIII-D results indicate that the Chirikov parameter be > 1 into normalized poloidal flux = 0.85.
  - Performed non-resonant braking calculations upto n=20.
    - Non-resonant braking is a concern because it can lead to the growth of locked modes in the presence of error fields.
  - Reviewed world-wide experimental results.

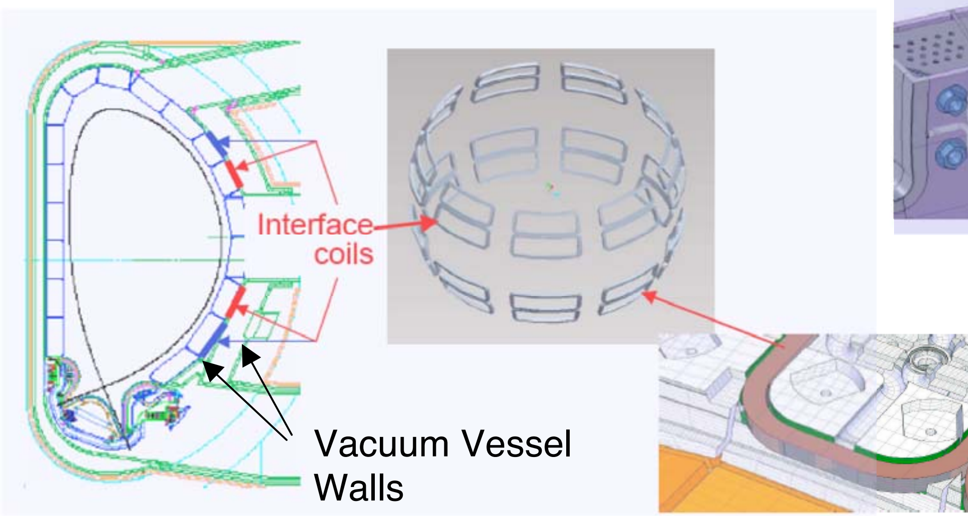
Minimum Island Overlap Region Width Requirement Used to Estimate Current Requirements



14 Outer Midplane Port Plug Coils
300 kAt required

18 Outer Midplane Port Frame Coils
100 kAt required





(4 rows x 9 toroidal) Blanket-Vessel Interface Coils
55 kAt required

D. Loesser and J. Smith

Various Coil Options Were Examined

Some Indicators of Side Effects of ELM Control Coils[1] for the 2007 Sept ITER DCR Review					
For Indicator Name	DIII–D[2] ELM Suppressed by I-coil (n=3), C-coil + Errors	Vessel Wall 4 rows of 9 coils[3] n=4 55 kA·t peak	Vessel Wall 18 Picture Frame around ports, n=4 100 kA·t peak	0.5 m coils on 14 Mid Port Plugs n=4 310 kA·t peak	14 Mid & 18 Top Port Plugs[4] n=4 300 kA·t pk
B_{res} [10^{-4} T][5]	6.5	26	26	25	26.5
B_{res}/B_0 [[10^{-4}]][5]	3.5	4.9	4.9	4.7	5.0
Radius for half B_{res}[6] [$\sqrt{\psi}$]	0.68	0.77	0.61	0.60	0.64
q at half B_{res}[8]	1.25	1.45	1.05	1.05	1.1
B_{res} at $q = 2$[7] [10^{-4} T]	4.9	20	21	21	21.5
NonResBrakeFact.[7] ($n \leq 10$) [10^{-8}]	380	525	750	1200	1500
NonResBrakeFact.[7] ($n \leq 20$) [10^{-8}]	400	595	2900	3100	3200

Notes:
(1) All cases have Chirikov $\sigma > 1$ at $\sqrt{\psi} > \sqrt{0.85}$ (ψ = normalized poloidal flux). ITER cases use Scenario 2 H-mode equilibrium.
(2) DIII-D plasma, ITER-similar shape and pedestal collisionality; different q95 and q profile. I-coil plus C-coil and error field contributions. $\sigma > 1$ at $\sqrt{\psi} > \sqrt{0.90}$. DIII-D indicators should not be compared too closely with the ITER ones.
(3) Current distributions phased to make main toroidal harmonics spectral peak with $m = qn$ resonance.
(4) Attempted to align spectral peak with $m = qn$, but there are always larger non-resonant peaks.
(5) Determined by meeting the Chirikov condition (1).
(6) Higher is better.
(7) Lower is better.
(8) Information.

T. Evans and M. Schaffer

Evaluation Parameters Were "Calibrated" to Cases from DIII-D and NSTX

Reference parameters for RMP Control Coils on current tokamaks[1] (rev. 1, Sept. 11. 2007, 18:30 PDT)					
Indicator Name	DIII-D I-coil + C-coil 3 rows of 6 coils **n = 1** 7.2 kA·t peak[2] 128947:02320	DIII-D I-coil + C-coil 3 rows of 6 coils **n = 1** 6.5 kA·t peak[2] 128946:02500	DIII-D I-coil 2 rows of 6 coils **n=3** 3.9 kA·t (4.4 kAt n=1 C-coil) 126006:04400	DIII-D I-coil 2 rows of 6 coils **n = 3** 4.0 kA·t (4.6 kAt n=1 C-coil) 125900:04400	NSTX RWM/EFC coil 1 row of 6 coils **n = 3** 4.9 kA·t peak 124350
B_{res} [10^{-4} T][3]	3.1	3.0	6.5	6.2	5.6
B_{res}/B_0 [[10^{-4}]][3]	1.6	1.6	3.5	3.2	11.4
Radius for half B_{res}[6] [$\sqrt{\psi}$]	n.a.	n.a.	0.68	0.63	0.66
q at half B_{res}	n.a.	n.a.	1.25	1.33	6.0
B_{res} at q = 2 [10^{-4} T]	3.3	3.1	4.9	4.5	0.2
Non resonant Braking Factor [10^{-8}], *scaled	**86.5** (n≤10), **96.4** (n≤20)	**75.6** (n≤10), **84.3** (n≤20)*	**380** (n≤10), **400** (n≤20)	**337**[4] (n≤10), **363** (n≤20)	**4800**[4] (n≤10), **4920** (n≤20)
Edge Rotation Prior to RMP (km/s)	75	62	74	63	135
Minimum Edge Rotation During to RMP (km/s)	0	44	4	45	0
Core Rotation Prior to RMP (km/s)	242	277	207	no data	255
Minimum Core Rotation During to RMP (km/s)	24	165	-25	no data	0
Locked Mode	**Yes**	**No**	**Yes** (ctr-NBI phase)	**No** (ctr-NBI phase)	**No**

Implications of Recent Physics Analysis for ITER RMP Coils

- Upper port plugs do not provide sufficient benefit for RMP.

- The depth of penetration of the perturbed field is minimized for the blanket-vessel interface coils.
  - Less likely to lock the plasma or destabilize NTMs

- The non-resonant braking associated with the equatorial and picture frame coils is substantially higher than from the blanket-vessel interface coils.
  - Further analysis required to take into account different plasma parameters including collisionality.

- Midplane coils on DIII-D, JET, NSTX, and MAST did not stabilize ELMs
  - Only successful coil configuration to date for ELM suppression has been the DIII-D I-coils, two rows of off mid-plane coils.

- Best option for ELM control is blanket-vessel interface coils.
  - Concluded that we do not have an experimental or theoretical basis for equatorial (or equatorial plus upper) coils to suppress ELMs.

Recent Developments on RMP Coils for ITER

- Project decided to stop further work on blanket-vessel interface and picture frame coils.
  - Focus effort on port-plug coil.
  - Main reason was to avoid delaying the vessel procurement.
  - Remote maintenance of coils behind the blanket shield modules.

- ITER Scientific and Technical Advisory Committee met last week and recommended that coils located between the vessel walls be examined.
  - ITER Council and the IO will review this recommendation.

- Urgent need to address key scientific issues for ITER:
  - What determines the operating window to stabilize ELMs?
  - What is the impact of RMP coils on toroidal rotation, plasma braking and locked modes?
  - Compatibility with pellet fueling.

- BPO and EU made major technical contributions during the past several months.
  - Now we need to bring this effort to closure.

BPO Has Led the Effort on Analyzing RWM Stabilization

- Highest performance with 7 dedicated midplane and 9 upper coils.
  - β_N <3.8
  - upper coils may counteract effects of mode non-rigidity.
  - Need further effort to determine need for upper coils.

- Picture frame coils predicted to achieve β_N <3.6.

- Blanket-vessel interface coils predicted to achieve β_N <3.6.
  - Increased voltage insulation would be required to satisfy both functions.
  - Need to analyze the option of using the coils between the vessel walls.

- Most capable system would be a combination of 7 dedicated midplane and 9 upper coils dedicated to RWM stabilization.

- DCR submitted to ITER on RWM as well as RMP.

J. Bialek and S. Sabbagh

Massive Gas Injection Has Been Used to Successfully Mitigate Disruptions

- **Experiments on C-Mod and DIII-D have used massive gas injection to mitigate disruptions.**
  - **Accompanied by short current decay time and radiative loss of plasma and poloidal magnetic energy.**
  - **Detection of “control-issue” disruptions (e.g. VDE) should be reliable, and mitigation possible, due to long ITER timescales.**
  - **Necessary part of PFC/FW protection.**

- **The current and major radius of ITER is a substantial extrapolation from existing machines *- Research Opportunity for BPO***
  - **Are the runaways well confined, as implicitly assumed in the Rosenbluth-Wesley estimate?**
  - **Exact current quench rates (halo currents)**
  - **What fraction of the injected gas is “assimilated” into the plasma?**
  - **What is the optimal gas or gas mixture? Should pellets be used?**

Fueling Requirements to Mitigate a Disruption

Case by *atom fraction*	n_g 10^{22} m^{-3}	$N_{g,noble}$ 10^5 Pa m^3	$N_{g,H}$ 10^5 Pa m^3	c_{eff} m/s	L/R_{core} (ms)
100% He	4	6.3	-	1019	45
100% Ne	0.9	1.3	-	456	43
25% Ne, 75% D	2.5	1.0	1.5	593	40
10% Ne, 90% D	4	0.6	2.8	717	40
5% Ne, 95% D	6	0.5	4.5	799	36
100% Ar	0.8	1.3	-	322	22
10% Ar, 90% D	4.5	0.7	3.2	581	24
5% Ar, 95% D	5.5	0.4	4.1	689	24

- From D. Whyte based on a 20% assimilation factor and perfect confinement of runaways.
- J. Wesley has done an independent calculation and infers a similar fueling requirement.
- Experiments in the ITER hydrogen phase will be used to benchmark the models and refine the gas load.

A DCR Been Submitted on Disruption Mitigation

- **Analysis incorporated into the ITER physics guidelines.**
- **Significant programmatic and engineering implications.**
- **Michael Wykes has performed an initial assessment of the engineering implications at maximum gas load.**
  - **Substantial impact on the vacuum system**
- ***Recommended that the recovery time after a major disruption should be <3hr.***
  - ***That the system be capable of 4 major applications of MGI in a day.***
- **Due to the impact on the vacuum system the DCR was not accepted and is "in-formulation."**

Personal Observations on Design Review Process

- Project is interested in getting best technical input.
  - Pushback on incorporating new systems is to be expected.
  - Raises the threshold for a compelling case.

- Changes to ITER requirements need international support and IO support.
  - Need to work closely with IO.
  - Challenge to incorporate cutting edge results when an international consensus has not been achieved.

- BPO has been effective in providing input to IO
  - Need an ongoing long-term mechanism to work with IO during the construction phase.