

ITER High Priority Research Needs 2009-2011

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ITER Organization

Acknowledgements:

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ITPA experts and many members of the international fusion community

Synopsis

- Scope of Physics programme within ITER construction
- Structure of ITER Physics programme
 - relation to ITER project needs
 - overview of main lines of activities within Physics research programme
 - possible implementation mechanisms
- Key elements of Physics research programme for 2009-2011
- Overview of longer term research priorities
- Summary

ITER Physics Programme - Scope

- We foresee the ITER scientific programme developing along 3 major lines:
 - provision of the necessary technical support to the ITER construction project - **next few years**
 - development of plans for ITER plasma commissioning and exploitation phases - **accompanying construction**
⇒ scientific framework and programme for ITER exploitation
 - implementation of an extensive programme of experimental, modelling and theory research to exploit the ITER device
- **exploitation phase**

ITER Physics Programme - Structure

1. Relation to Project Needs

- **Development of the ITER Physics programme has focussed on identifying priorities for coming 3 years based on expected requirements from project:**
 - supporting implementation of Design Review outcome (PF system, RMP coils ...)
 - issuing of Procurement Arrangements (Vacuum Vessel, Divertor, Disruption Mitigation System, H&CD ...)
 - collaborate with Members' fusion communities to resolve key R&D issues on timescale required by ITER construction schedule (scenarios, T-retention, dust, TBM-related issues ...)
 - support the project's licensing application
 - defining requirements for ITER plasma control system:
develop physics definition of control strategies and algorithms
 - developing a comprehensive modelling capability - builds on activities in Members' programmes
 - development of ITER Research Plan

ITER Physics Programme - Structure

1. Relation to Project Needs - STAC Issues

- **Key Issues on which STAC recommended further analysis:**

- – Vertical stability/ PF Control/ Flux consumption
- – ELM control
 - Remote handling
 - Blanket manifold remote handling
- – Divertor armour strategy
- – Capacity of 17MA discharge
 - Cold coil test
- – Vacuum vessel/ blanket loading conditions
- – Test blanket modules strategy
 - Hot cell design
- – Heating and current drive strategy, Diagnostics and Research Plan

⇒ **Solutions developed largely endorsed by STAC and recommended to ITER Council - accepted without prejudice to cost implications**

ITER Physics Programme - Structure

1. Relation to Project Needs - PAs

- **Key Physics-related Procurement Arrangements:**
 - PF/ CS conductors (Sep08); PF/CS coils (Nov08)
 - VV shielding/ ferromagnetic inserts (Jan09)
 - Error field correction coils (Feb09)
 - Divertor HHF (Feb09)
 - Diagnostics: DNB (Jan09-Jun09); Diagnostic systems (Jul09)
 - H&CD systems: ICRF (Apr09-Dec09); ECRH (Mar10-Jan11); NB (Sep08-Apr10)
 - PF/ CS power supplies (Feb10)
 - Fuelling systems (May10-Jul10); Vacuum system (Jul11)
 - In-vessel coils (Sep10)
 - Tritium plant (Dec10-Jun11)
 - Blanket and First Wall (Jul11)
 - Disruption Mitigation System (Dec12)
 - TBM port frames (Dec12)
 - CODAC (to be defined)

ITER Physics Programme - Structure

2. Main lines of Activities

- **Analysis of Physics workprogramme is structured in parallel with FST WBS, but integration is also included:**
 - Transport and Confinement Physics (includes pedestal)
 - Plasma Stability (MHD, PF scenarios and control)
 - Divertor and Plasma-Wall Interactions
 - Plasma Operations (integrated scenarios, integrated plasma control, energetic particles, physics operations aspects)
 - Integrated Modelling

ITER Physics Programme - Structure

3. Possible Implementation Mechanisms

- **There are several instruments for interaction with fusion community, defining implementation mechanisms for Physics workprogramme:**
 - International Tokamak Physics Activity (ITPA, ITPA/IEA)
 - R&D Tasks (via DAs)
 - Design Tasks (via DAs)
 - Integrated Modelling Programme
 - External service contracts
 - Visiting Researchers (via DAs)
- **We are still in the process of identifying the appropriate mechanisms to meet all of our research needs**

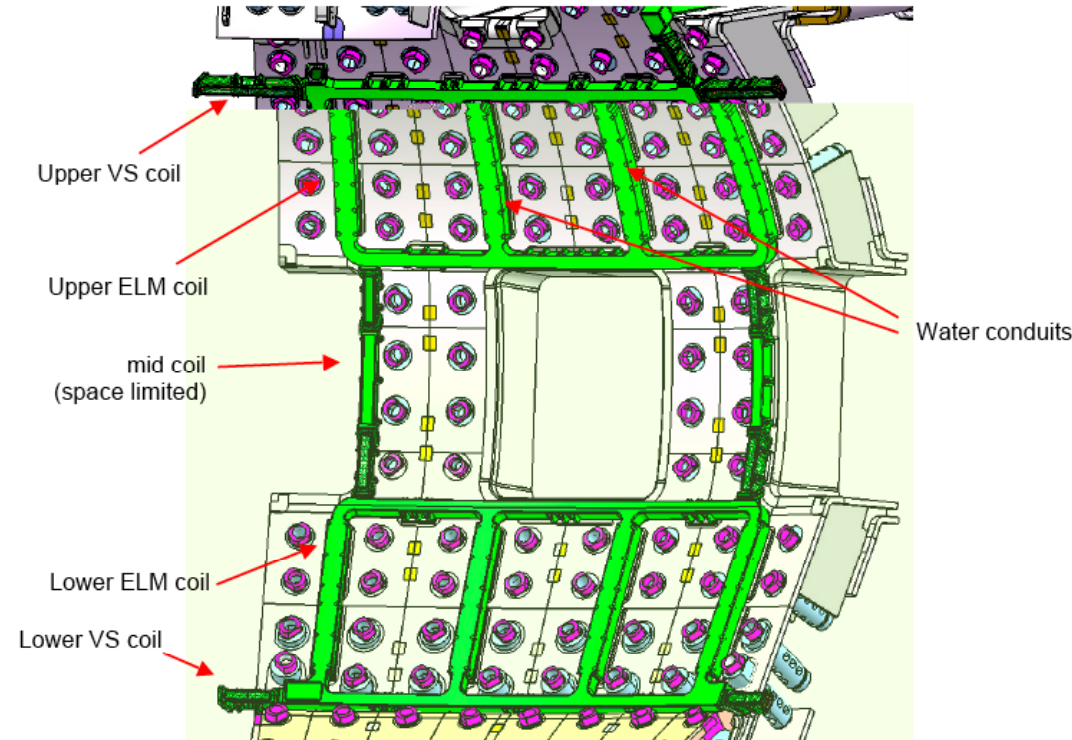
Key elements of Physics research programme, 2009-2011

Transport and Confinement

- **Key elements - predominantly voluntary R&D:**
 - Transport and confinement during transient phases
 - Access conditions for high confinement regimes
 - ELM control schemes and compatibility with ITER requirements
 - Toroidal field ripple effects and implications for ITER performance/ fast particle losses
 - Particle transport and fuelling relevant to ITER reference scenarios
- **Longer term R&D activities include:**
 - H-mode pedestal characteristics
 - Development of alternative ELM regimes
 - Investigation of alternative ELM control schemes
 - Momentum transport/ intrinsic plasma rotation in ITER

ELM Control/ Mitigation

- **Design of in-vessel RMP coil set for ELM control is underway**
 - design is in progress
 - technology R&D to be launched
- **An extensive physics R&D programme is required to confirm suitability of this approach for ITER**
- **Key issues include:**
 - applicability at ITER pedestal/ edge parameters
 - interaction with other plasma control techniques



ELM Control/ Mitigation

- **It is essential to demonstrate that ITER will have adequate ELM control capability**
- **An extensive R&D programme proposal has been prepared to address the key physics issues in this area, including:**
 - confirmation that the systems foreseen for ITER can provide required control at ITER parameters
 - impact of control techniques on ITER fusion performance is acceptable
 - exploration of alternative approaches to ELM control to provide backup techniques in case limitations found in primary techniques
- **When are results required?**
 - to give confidence that ITER has adequate ELM control capability, R&D results needed in next 2-3 years - feeds back to high level decision making
 - if alternative approaches require system upgrades, results probably needed in next 2-3 years

ELM Control/ Mitigation

- **Typical R&D questions in programme assembled by Pedestal TG:**
 - specification of requirements for RMP suppression of ELMs in ITER
 - requirements for pellet parameters for ELM pacemaking in ITER
 - interaction between different ELM control techniques
 - impact of ELM control on edge pedestal and resulting core plasma performance (Note: $P_{\text{sep}}/P_{\text{LH}} < 2$)
 - analysis of potential deleterious effects on fuel, impurity and energy transport, core rotation, mode locking ...
 - quantitative analysis of potential of alternative ELM control techniques
- **An integrated and focused R&D programme will be required to establish a conclusive case that ITER has robust ELM control capability**

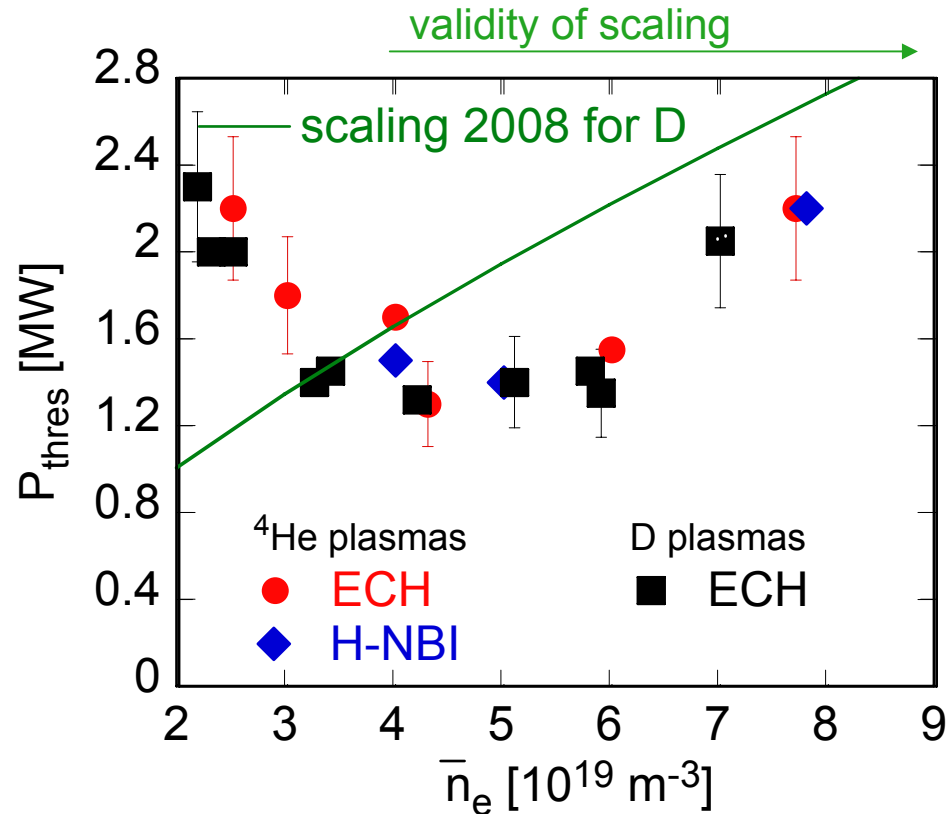
Access to High Confinement Helium H-modes

- **Access to type-I ELMy H-modes during the non-active phase would have a significant impact on the ITER IRP:**

- would allow, eg investigation and demonstration of ELM control
- impacts on divertor changeout and deuterium operation \Rightarrow accelerates progress towards DT plasmas

- **Detailed studies of helium H-modes support this planning:**

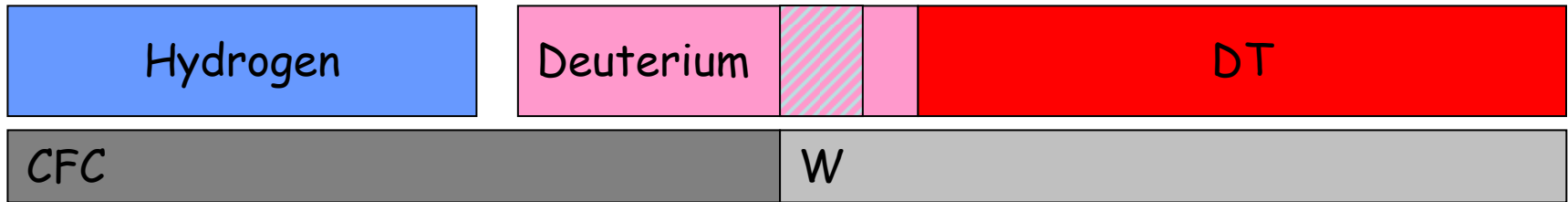
- need to characterize ELM behaviour and response to ELM mitigation



F Ryter et al, IAEA-FEC2008, PD-1-1

Proposed Schedule of Divertor Changeout

↓ Divertor changeout (~6 months)



- **Advantages:**

- Time to learn how to mitigate ELMs and disruptions – CFC more robust to type I ELMs
- Characterize hydrogenic retention for CFC in H-mode
- Physics programme with W-divertor ideally can start from point left at the end of CFC, eg already with knowledge of how to ameliorate the ELMs and mitigate disruptions

- **Impact on ITER Research Plan:**

- Delay of physics programme – defined by conditions to commission W-divertor, possibly including time for additional hydrogen operation (detritionation, recommissioning)

Plasma Stability: Plasma Control

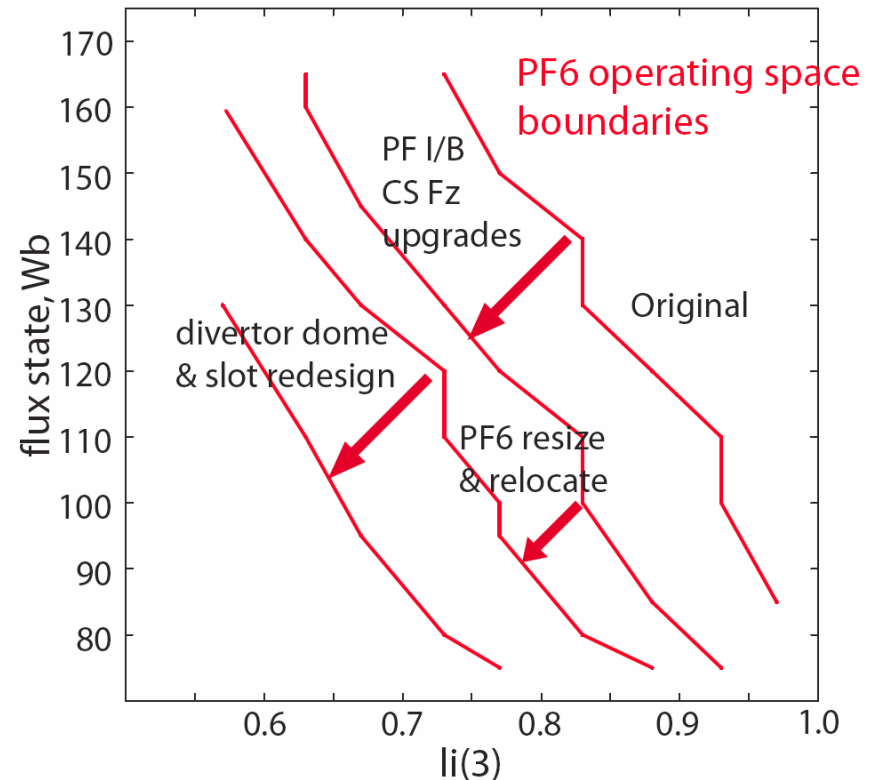
- **Significant Design activity required in short-term:**
 - Analysis and specification of plasma reference scenarios, including plasma initiation, start-up and ramp-down scenarios
 - Specification of TF ripple requirements
 - Control of plasma current, position and shape
 - Magnetic reconstruction of plasma boundary
 - Error field correction
 - Analysis of magnetic field distribution in Tokamak Complex
- **R&D activities include (some funded, some voluntary):**
 - Validation of plasma reference scenarios, including disturbances
 - Error field measurement and correction techniques
 - RWM control

Scenarios: Operating Space Improvements

- Design Review analysis has focussed on expanding 15MA operating space
- Now need to move beyond “design basis” scenarios to put ITER experimental capability on firmer basis:
 - some aspects (eg OH/ L-mode transport, current ramp-down) of 15MA scenario required
 - non-active/ deuterium scenarios must be detailed
 - state-of-the-art approach to hybrid and steady-state scenarios required - key question for prioritizing upgrades
 - quantitative input on plasma disturbances required for control analysis

15 MA Operating Space

Evolution of Operating Space with Design Changes



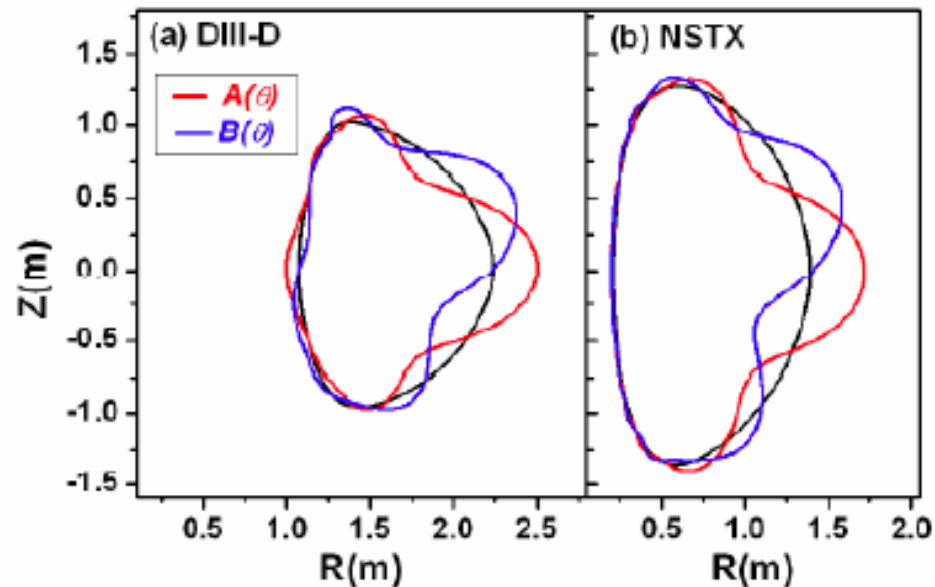
C Kessel et al, IAEA-FEC2008, IT-2-3

Error Field Detection and Correction

- **Error field detection and correction can have a significant impact on the planning of ITER commissioning and initial operation**
 - Long recognized that ITER plasmas are likely to be very sensitive:
 $\delta B_r/B_\phi \sim 5 \times 10^{-5}$
- **We need to develop schemes for error field detection and correction**
 - could impact on magnetic measurement requirements
 - need to establish appropriate formalism for the analysis
 - require comparative analysis of possible non-plasma/ with plasma detection techniques

The most sensitive external field at the plasma boundary

$$(\delta \mathbf{B}^{\text{ext}})_b(\theta, \varphi) = \mathbf{A}(\theta) \cos \varphi + \mathbf{B}(\theta) \sin \varphi$$



J-K Park et al, APS2008

Plasma Stability: Disruptions

- **Essential R&D activities include:**
 - Development of improved electromagnetic models of disruptions/ VDEs and experimental validation
 - Refined definition of requirements for disruption/ RE mitigation
 - Studies of alternative approaches to RE mitigation/ control
- **Supporting experimental/ modelling activities include:**
 - Characterization of runaway electron generation in disruptions
 - Development of improved models of runaway electron loss and resultant heat loads
 - 3D modelling of disruptions/VDEs

Disruption/ Runaway Mitigation

Disruption/ VDE Impact

- **High energy loads during disruption thermal quench or VDE drift:**
 - tungsten divertor lifetime ≤ 20 full power disruptions
 - beryllium wall lifetime $\leq 20-30$ full power VDEs
- **Electromagnetic loads on vacuum vessel due to halo currents:**
 - category II event implies $TPF \times I_h / I_p \leq 0.6$
- **Runaway electron impact on first wall:**
 - up to 10MA of REs with energies in the 10s of MeV range
 - loss processes and parameters uncertain
 - depth of FW melt layer up to 2.5mm/ event under “reference” (1° intersection angle) assumptions - could reach 7.5mm for 3° intersection angle on FW at top

Disruption/ Runaway Mitigation

- **MGI is promising, but application to ITER problematic:**
 - injecting gas quantity required (500 - 1000g) for runaway suppression requires technological R&D - even if physics allows
 - implications for ITER pumping systems imply very substantial interference with ITER operation - aim at 3 hour recovery time
 - possibility of localized melting of first wall
- **Three key questions:**
 - is Rosenbluth density required for runaway suppression?
 - if so, is “killer pellet” a viable alternative to MGI (higher assimilation)?
 - are other alternatives, eg stochastic magnetic fields, effective and viable?
- **Need to understand:**
 - quantitative extrapolation of technique to ITER
 - reliability of routine use
 - implications for use in ITER - technology R&D? impact on operations?
 - first wall heat loads produced - experimental evidence and modelling required
 - influence on runaway electron generation/ suppression

Disruption/ Runaway Mitigation

- **What is required?**

- experimental demonstration that a technique or combination of techniques allows reliable mitigation of disruption effects
- “mitigation” implies:
 - heat loads, runaway electrons: reduction by more than 1 order of magnitude
 - forces: reduction by factor of 2 to 3
- key effects are:
 - local heat loads
 - vertical/ horizontal forces
 - runaway electron currents (energies ?)
- significant modelling development to provide basis for ITER extrapolation

- **When are results required?**

- present ITER construction schedule requires physics preliminary specification of DMS in late 2009
 - ⇒ Procurement Arrangement issued in 2012
- new technology R&D will be time-consuming

Disruption/ VDE/ RE Modelling

- Improved modelling in several areas could have a significant impact on the project
- There are several issues where improved results are important now:
 - a more complete validated modelling capability for VDEs, including halo currents, to strengthen the basis for predicting **vertical and horizontal forces**
 - a validated modelling capability for runaway generation and loss to allow an improved **assessment of first wall energy deposition**
 - A validated modelling capability for MGI, including toroidal asymmetries, to allow **analysis of implications for first wall**
 - an improved assessment of **SOL width and local power deposition** during disruptions/ VDEs, including limiter plasmas
- **When are results required?**
 - Licensing discussions have already begun - vacuum vessel loads are a key question
 - improved data and analysis within the next 1-2 years would be invaluable

Divertor and Plasma-Wall Interactions

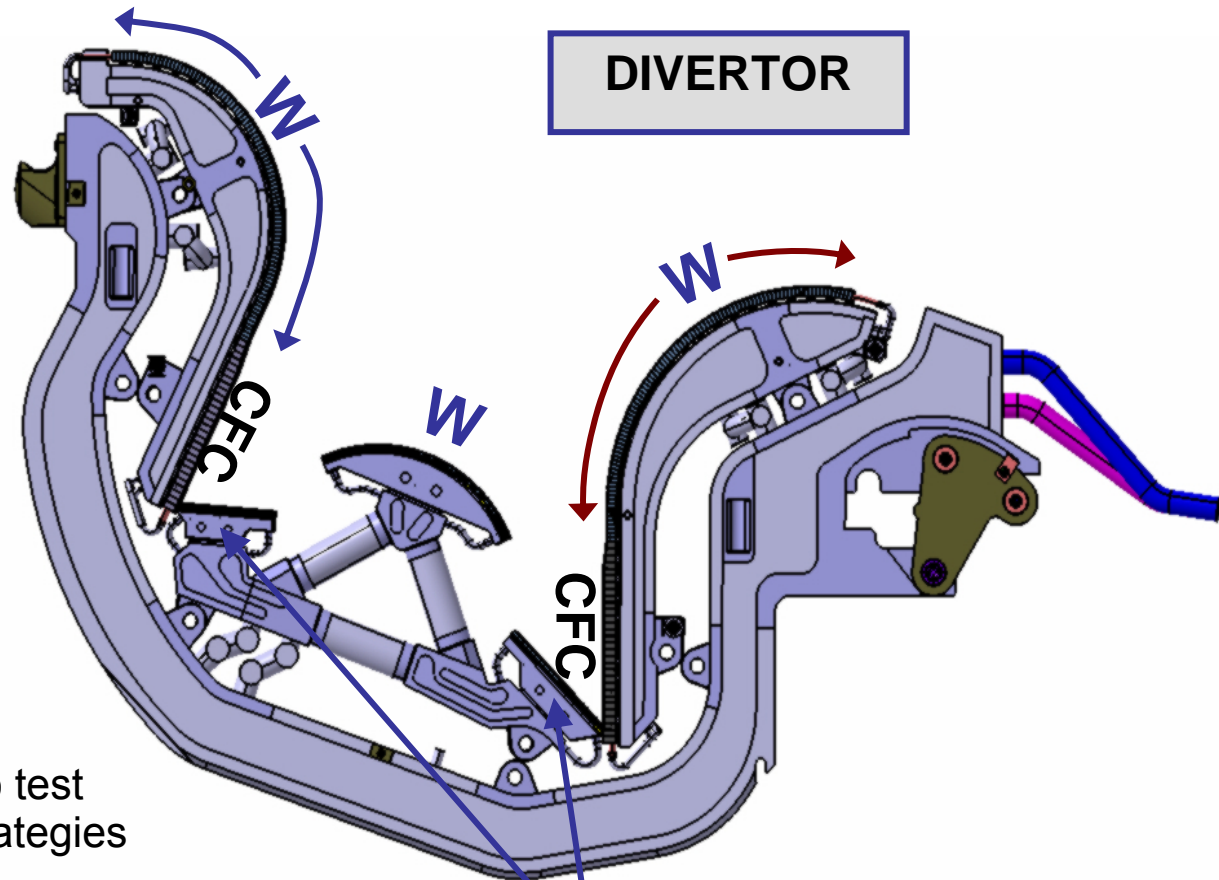
- **Key elements - predominantly voluntary R&D:**
 - Analysis of tritium retention/ development of tritium removal techniques
 - Improved definition of requirements for RF conditioning
 - Expansion of operational experience with tungsten divertor - includes operational scenarios, effect of transients (dust), tritium retention ...
 - Quantitative characterization of dust production/ distribution
 - Improved characterization of first wall/ divertor heat loads, particularly during ELM/ disruption mitigation
 - Quantitative analysis of erosion/ redeposition phenomena
- **Longer term R&D activities include:**
 - Influence of all-metal walls on plasma-wall interaction phenomena in ITER-relevant regimes
 - Development of improved modelling capability for PWI phenomena

Materials choice – big R&D driver

In the current ITER baseline:

CFC at the strike points, W on the baffles through the H and D phases

All-W from the start of DT operations



DIVERTOR

W – “reflector plates”

Rationale:

- Carbon easier to learn with ...
- Lack of melting makes it easier to test ELM and disruption mitigation strategies
- T-retention expected to be too high in DT phase with CFC targets
- Dust probably a big issue with CFC, even in steady state
- But (limited) DT operations with CFC target still in place not excluded

Plasma Facing Materials - Scenarios

- **Extensive R&D required to establish physics basis for ITER reference scenarios with W/ Be PFCs:**
 - development of current ramp-up/ ramp-down scenarios (with/ without additional heating and impurity seeding)
 - high performance H-mode scenarios with impurity seeding, ELM control etc
 - core impurity control, particularly in ITB scenarios
 - impurity production with ICRF
 - control of ELM-produced impurities
 - operation with melt-damaged tungsten components
- **When are results required?**
 - basic elements of operational scenarios should be assessed on 2-3 year timescale
 - more detailed aspects would need answers on 3-5 year timescale to allow time to analyze implications for ITER operation

Plasma Facing Materials - PWI

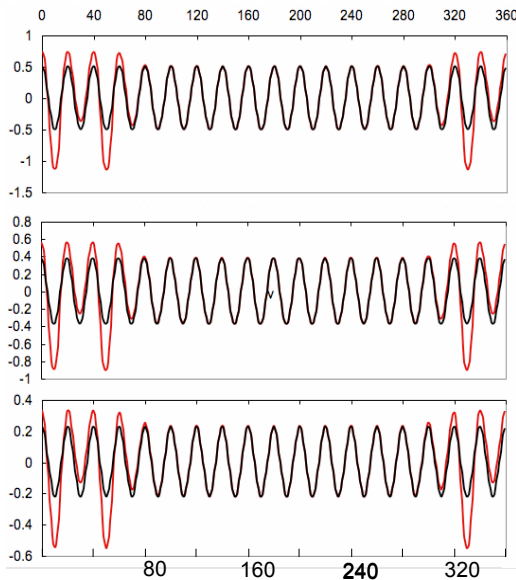
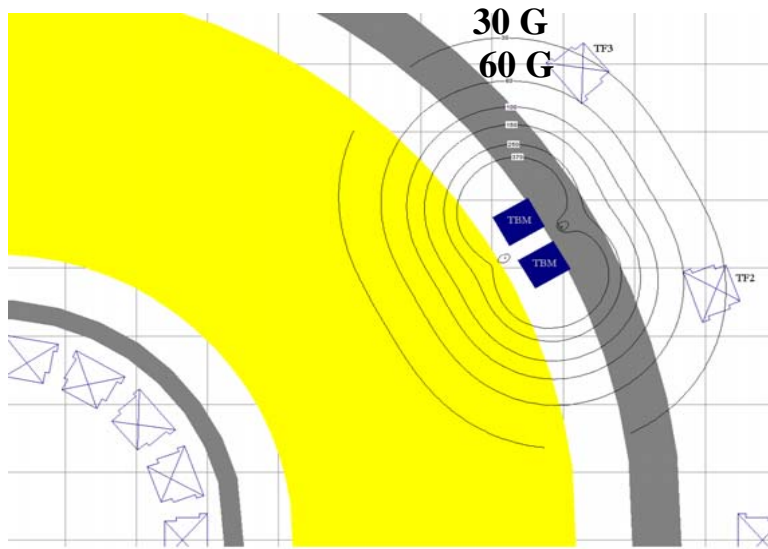
- **A range of PWI issues will need to be resolved to build confidence that **reliable operation can be sustained**:**
 - establishment of requirements for **carbon/ carbidic compound removal** at divertor changeout (eg need to identify distribution of redeposited material)
 - **T-retention** in W/ Be and their compounds, including role of retention in first wall and neutron irradiation effects
 - tungsten/ beryllium material damage and **dust production rates** (steady-state, transients)
 - performance of **Be-coated tungsten PFCs**
 - development of modelling capability for **beryllium and tungsten PWI simulation**
- **When are results required?**
 - early quantitative information on key safety-related questions (T-retention, dust production) would be important - ie 2-3 years
 - should aim for a complete picture of W/ Be PWI issues on 5 year timescale

Plasma Operations

- **Key elements - predominantly voluntary R&D (except TBM effects):**
 - Development of non-active and deuterium phase plasma scenarios
 - Redefinition of hybrid/ steady-state plasma scenarios and experimental validation
 - Development of integrated plasma control strategies and requirements
 - Assessment of H&CD system performance in ITER scenarios
 - TBM influence on plasma performance
- **Longer term/ accompanying R&D activities include:**
 - Modelling of energetic particle confinement/ MHD processes
 - Development of ITER Research Plan
 - Establishing basis for H&CD upgrade programme

TF Ripple Effects

TBM-induced ripple



- Recent JET/ JT-60U experiments have revealed influence of TF ripple on H-mode confinement
- TBMs produce a localized ripple at 3 port locations which is larger than background TF ripple (0.4%)
 - correction measures under review with TBM community
- Need to quantify effect of localized ripple on confinement:
 - probably requires a dedicated experiment with “TBM-like” perturbation
 - progress on understanding physics basis also important
 - timescale for TBM design decisions 1-3 years

ITER Heating and Current Drive

Heating System	Stage 1	Possible Upgrade	Remarks
NBI (1MeV Sive ion)	33	16.5	Vertically steerable (z at Rtan -0.42m to +0.16m)
ECH&CD (170GHz)	20	20	Equatorial and upper port launchers steerable
ICH&CD (40-55MHz)	20		$2\Omega_T$ (50% power to ions Ω_{He3} (70% power to ions, FWCD)
LHH&CD (5GHz)		20	$1.8 < n_{\text{par}} < 2.2$
Total	73	130 (110 simultan)	Upgrade in different RF combinations possible
ECRH Startup	2		126 or 170GHz
Diagnostic Beam (100keV, H^-)	>2		

- **ITER has a range of options for H&CD upgrades**
 - Experimental and modelling studies required to determine most appropriate upgrades
 - Physics and Technology R&D on LHCD necessary if a necessary upgrade

Integrated Modelling

- **A proposal for an Integrated Modelling Programme is under development to support Physics R&D activities, preparation for operation and operational phase**
- **Programme will be launched in 2009 with initial emphasis on**
 - Establishing advisory group to define programme and infrastructure requirements
 - Provision of software/ hardware infrastructure
 - Implementation of first phase in integration of component modules in IM suite
- **IM activities will rely heavily on voluntary contributions from fusion community, with financial resources focussed on development of infrastructure**

Diagnostics

- **Dust:**

- Validation of safe levels of dust in the vacuum vessel required for machine operation
- Need to test most promising diagnostic approach, a dust microbalance, in a tokamak
- Deliverable: develop, install, exploit and report on prototype
- Timescale: 2-3 years (by end-2011)

- **Hot Dust:**

- Be dust on PFCs with $T > 600^{\circ}\text{C}$ must be limited to $<6\text{kg}$ for safety
- Need to evaluate feasibility of significant quantities of dust being able to survive in regions of high heat flux using modelling and survey data from existing tokamaks
- Deliverable: provide an estimate of the quantity of hot dust in ITER, including quantitative evaluation of uncertainties
- Timescale: 1.5 years (end-2009)

Diagnostics

- **Divertor Erosion:**

- divertor erosion is expected to be the major source of impurities and dust, as well as limiting the divertor lifetime
- need to test most promising diagnostic approach to remote divertor erosion measurements, based on laser ranging techniques
- deliverable: develop, install, exploit and report on prototype remote divertor erosion measurement diagnostic using laser ranging
- timescale: 2-3 years (by end-2011)

- **Plasma facing mirrors and optical elements in divertor:**

- these components will likely have a finite lifetime, which will impact on reliability of optical diagnostics
- several developments are needed, including
 - models of erosion and deposition process
 - mitigation of erosion and deposition by design
 - development of shutters and baffles
 - in-situ calibration techniques
- deliverable: recommendation on most rugged first mirror arrangement for ITER, based on experiment and modelling
- timescale: several years

Diagnostics

- **Hydrogen background:**

- In non-active phase, outgassing and DNB will affect base level of hydrogen, influencing fuel retention studies
- need to assess evolution of hydrogen levels in existing devices and develop an appropriate model
- deliverable: estimates of hydrogen background in initial phase of ITER operation and assessment of required accuracy of gas balance measurements to permit analysis of fuel retention in non-active phase
- timescale: 2-3 years

- **Retained tritium:**

- require validated techniques for assessing level of retained tritium in vacuum vessel
- need to select and prototype candidate diagnostic techniques, including extrapolation from local to global measurements; also need to determine accuracy in estimate of T-burnup
- deliverable: validated technique for estimation of retained tritium in vacuum vessel
- timescale: 2-3 years

Longer term research priorities

ITER Physics Programme

Future Emphasis

- **Expect that community R&D will continue to support the ITER programme in core areas: confinement, mhd stability, divertor ...**
- **Need to expand activities in several areas to reflect the transition to construction and preparation for commissioning/ operation/ exploitation:**
 - integrated scenarios, including programme development
 - integrated modelling of burning plasmas
 - plasma control strategies
 - science of burning plasmas - α -particle physics
 - support to ITER licensing
 - developing upgrade paths
 - physics for fusion power plants
- **Continuing need to respond to key R&D issues emerging from the construction activities - supports timely transition to commissioning and operation**

ITER Physics Programme - Scope

Preparation for Operation

- **Development of plans for ITER plasma commissioning and exploitation phases**
 - ⇒ **scientific framework and programme for ITER exploitation:**
 - refined set of ITER reference plasma scenarios
 - ⇒ design basis for the tokamak/ auxiliary systems
 - ⇒ model plasmas for detailed study in the Members' programmes
 - define requirements for ITER plasma control system
develop physics definition of control strategies and algorithms
 - develop a comprehensive modelling capability - builds on activities in Members' programmes
 - lead programme of research in the fusion community to explore/
document ITER's potential as a burning plasma experiment
 - elaborate a detailed plan for commissioning and scientific exploitation of ITER in collaboration with Members' fusion communities
 - ⇒ ITER Research Plan

Developing Upgrade Paths

- **ITER is designed to allow upgrades to its capability throughout its lifetime**
- **Long lead-times for ITER system development necessitate R&D now to prepare basis for determining upgrade paths:**
 - H&CD can be upgraded to 130MW installed power
 - LHCD, improved antennas, more powerful/ flexible sources ...
 - Diagnostics capability can be extended through port-based systems
 - ongoing need for R&D to support baseline systems - first mirrors etc
 - key measurements (eg confined/ lost α 's may not be in baseline)
 - Control capability
 - need to establish reliability of novel techniques in accompanying programme
 - H&CD, fuelling systems offer possibilities for expanding control capability
 - PFC choice
 - need to support options for changes during operation

Conclusions

- ITER research requirements are dominated at present by need to resolve several long-standing R&D issues, finalize design and support construction progress
- Over coming ~3 years, procurement definition of auxiliary systems will be finalized
 - opportunities exist to influence performance specifications
- Focus of ITER research programme will gradually re-orient towards preparations for operation and exploitation
 - both experimental and theory/ modelling input will be essential
- Development of the longer term research plan is underway
 - involvement of the international fusion community is an essential element
- To make the most of the physics opportunities which ITER develops, there will be a continuing need for exploration in the R&D programme
 - in particular, need to develop the case for upgrades