ITER High Priority Research Needs 2009-2011

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ITER Organization

Acknowledgements:
Staff of FST and CHD Departments, Contributors to ITER Design Review, 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
    $\Rightarrow$ 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**

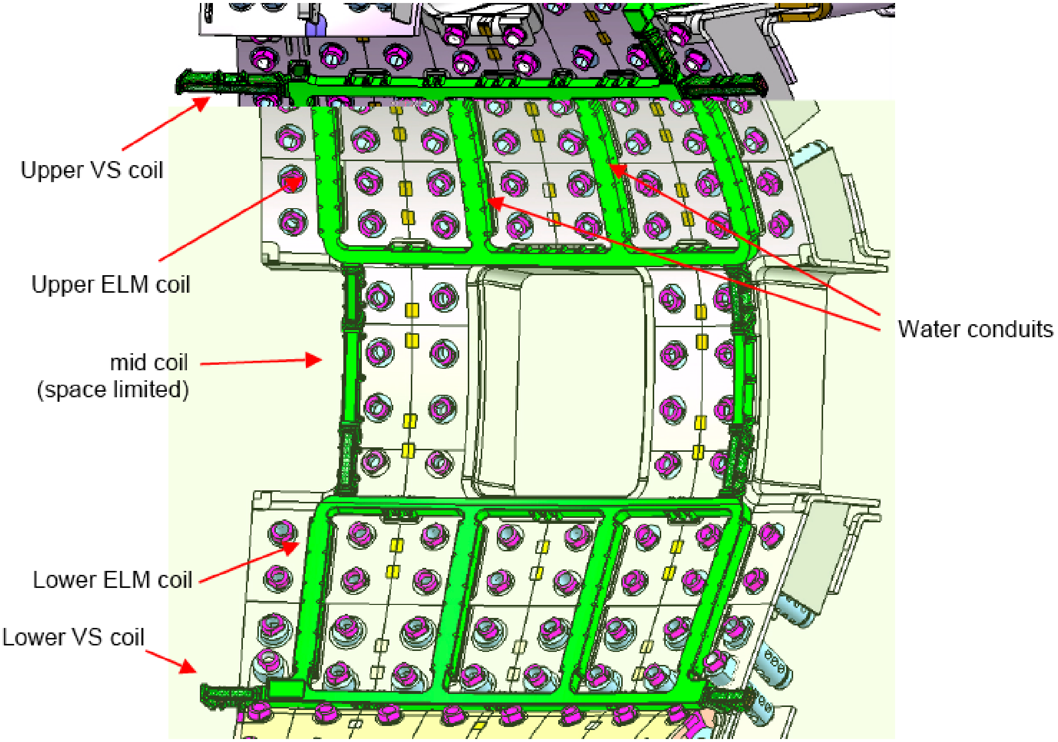
Key elements of Physics research programme, 2009-2011

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: $P_{sep}/ P_{LH} < 2$)
  - analysis of potential deleterious effects on fuel, impurity and energy transport, core rotation, mode locking …
  - quantitative analysis of potential of alternative ELM control techniques

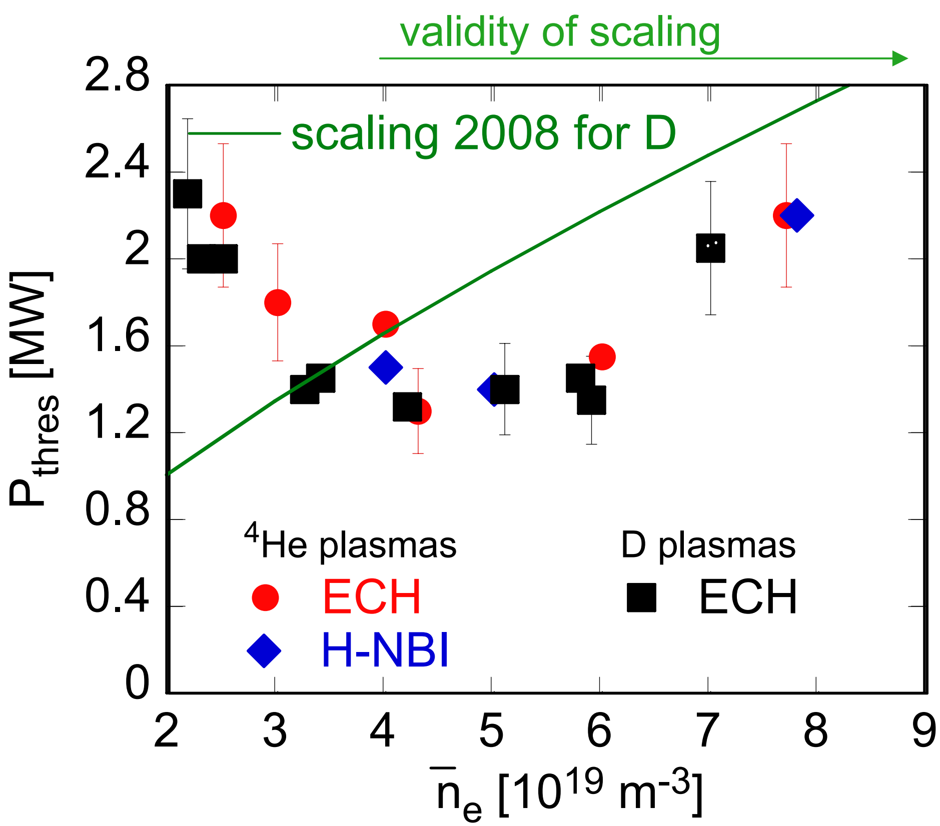
- **An integrated and focused R&D programme will be required to establish a conclusive case that ITER has robust ELM control capability**

Access to High Confinement

Helium H-modes

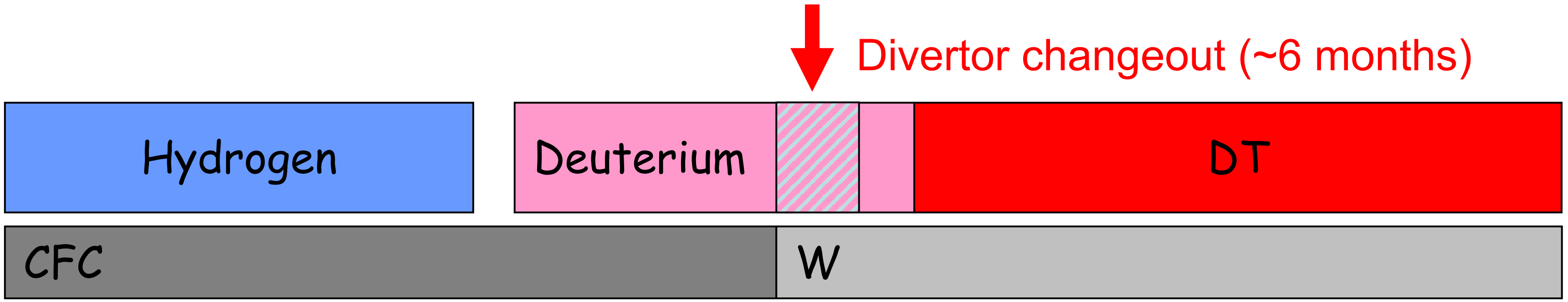
- **Access to type-I ELMy H-modes during the non-active phase would have a significant impact on the ITER IRP:**
  - would allow, eg investigation and demonstration of ELM control
  - impacts on divertor changeout and deuterium operation ⇒ accelerates progress towards DT plasmas

- **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



- **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

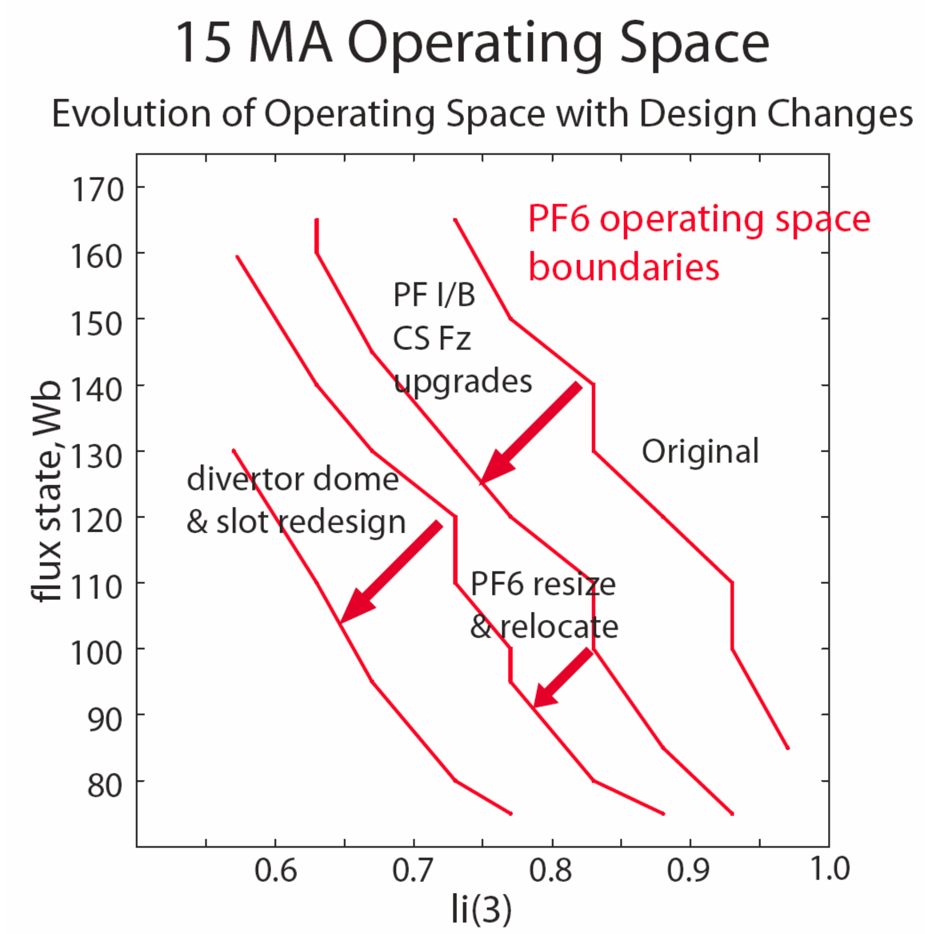
- **Impact on ITER Research Plan:**
  - Delay of physics programme – defined by conditions to commission W-divertor, possibly including time for additional hydrogen operation (detritiation, recommissioning)

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



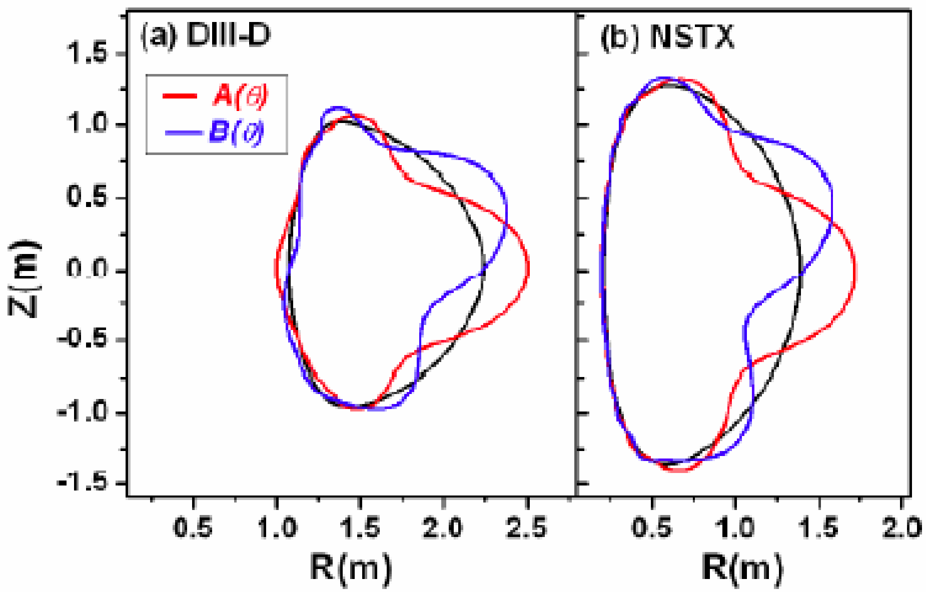
C Kessel et al, IAEA-FEC2008, IT-2-3

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: $\delta B_r/B_\phi \sim 5\times10^{-5}$
- **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

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



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 disurptions/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 ≤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" (1º intersection angle) assumptions - could reach 7.5mm for 3º 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 - <u>aim at 3 hour recovery time</u>
  - 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 peliminary specification of DMS in late 2009
    $\Rightarrow$ 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 <u>now</u>:**
  - a more complete validated <u>modelling capability for VDEs</u>, including halo currents, to strengthen the basis for predicting vertical and horizontal forces
  - a validated <u>modelling capability for runaway generation and loss</u> to allow an improved assessment of first wall energy deposition
  - A validated <u>modelling capability for MGI, including toroidal asymmetries,</u> 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

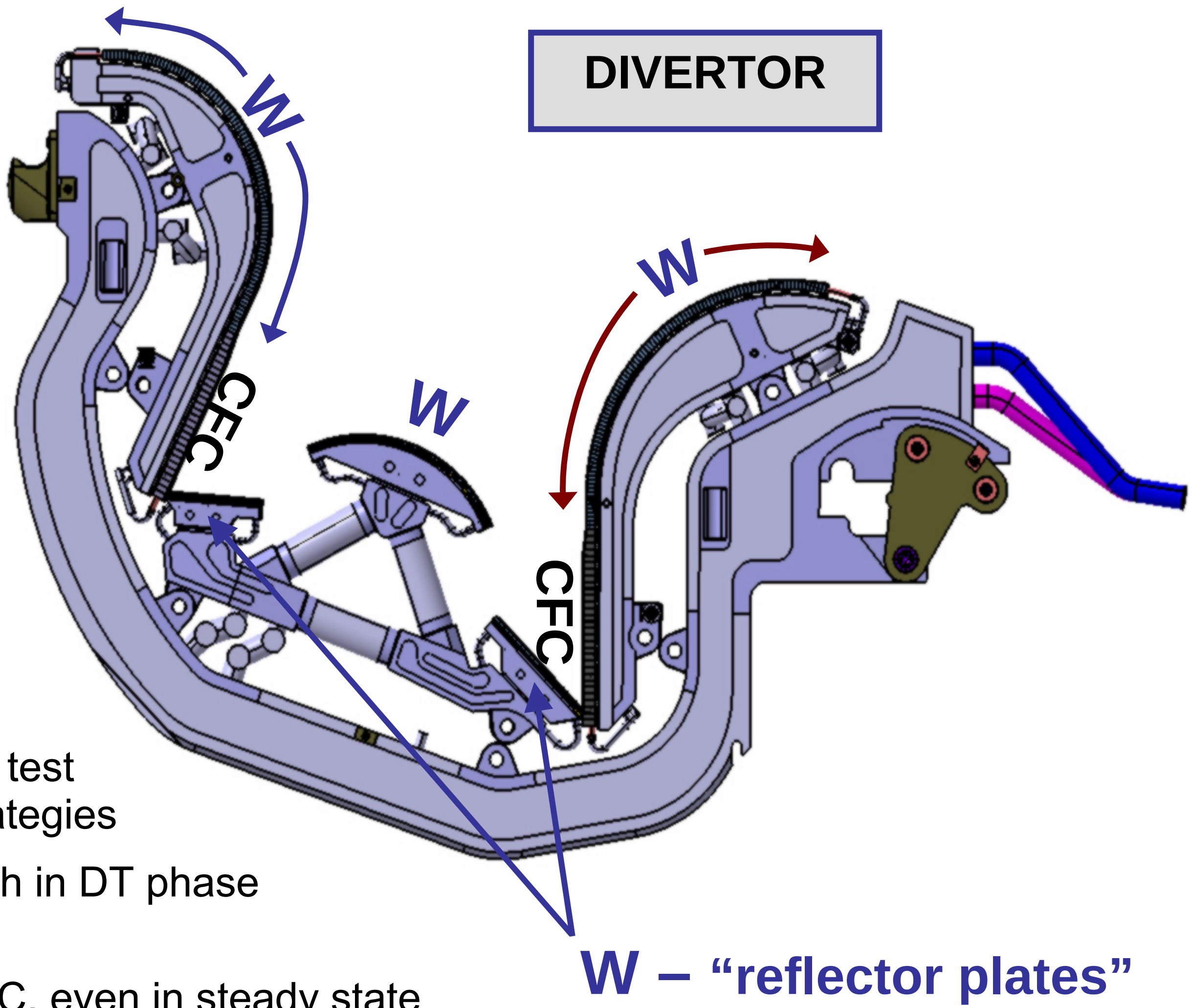
- **Key elements - predominantly voluntary R&D:**
  - Analysis of tritium retention/ development of tritium removal techniques
  - Improved definition of requirements for RF conditioning
  - Expansion of operational experience with tungsten divertor - includes operational scenarios, effect of transients (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



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

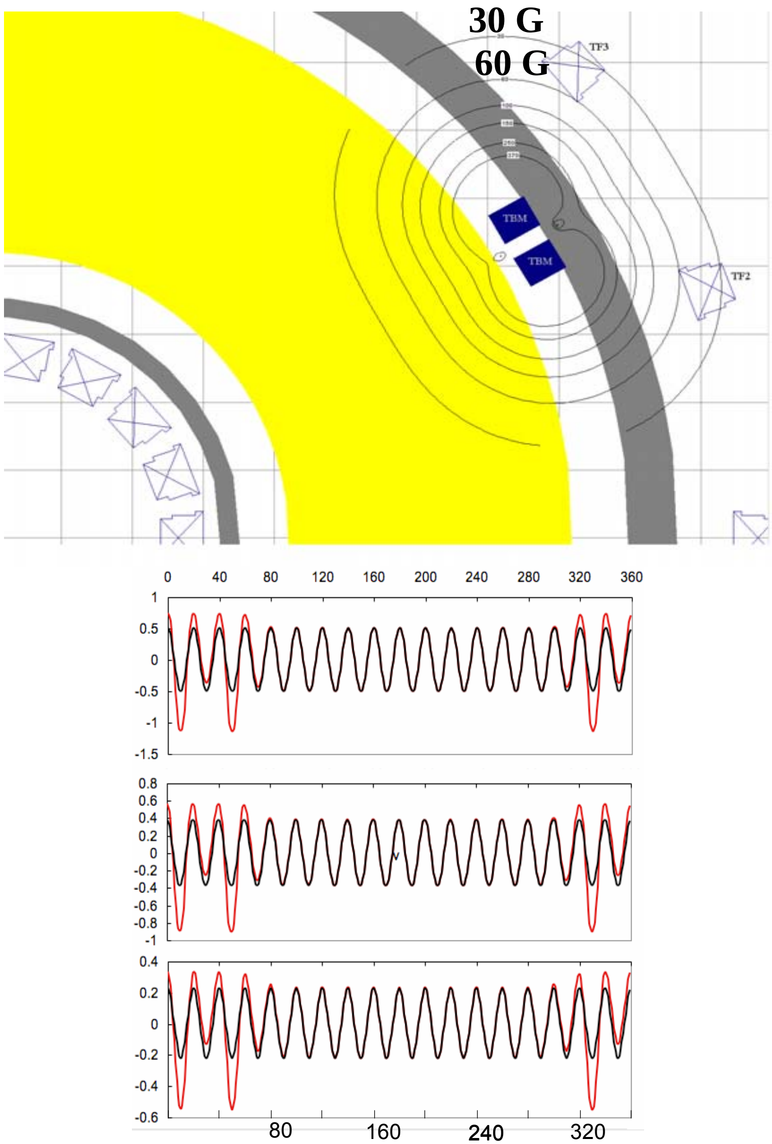
- **A range of PWI issues will need to be resolved to build confidence that reliable operation can be sustained:**
  - establishment of requirements for carbon/ carbidic compound removal at divertor changeout (eg need to identify distribution of redeposited material)
  - T-retention in W/ Be and their compounds, including role of retrention 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 Šive 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	$1.8<n_{par}<2.2$
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°C must be limited to <6kg 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