Scientific Status of ITER

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Acknowledgements:
Many colleagues in the ITER IO, ITER Members and ITPA

Summary of Presentation

- What are the main changes resulting from the ITER Design Review?

- What is our present vision of the ITER research programme?

- What are the major physics R&D issues which need to be resolved?

Synopsis

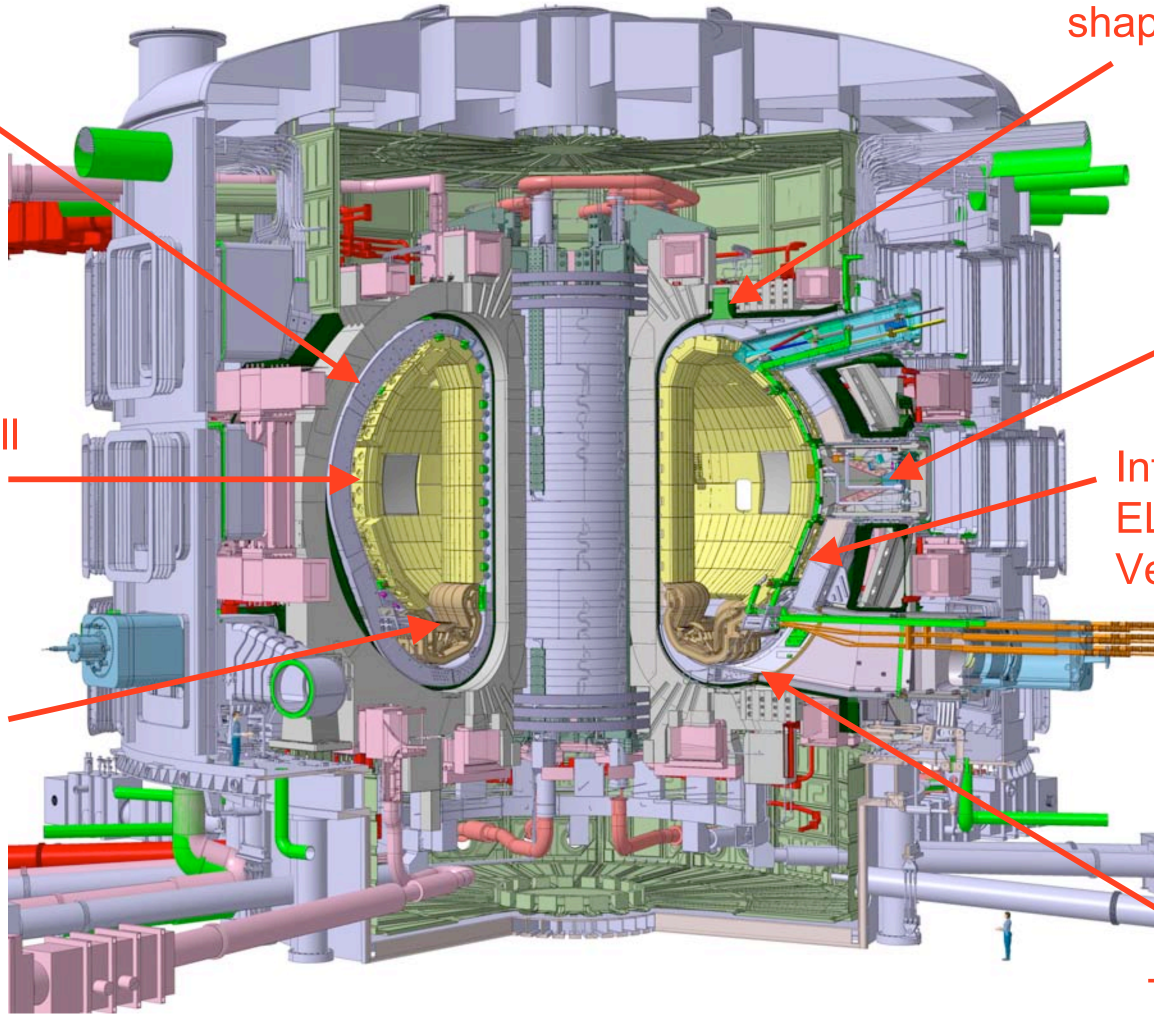
- **Major physics & technology developments through the Design Review**
- **ITER Research Plan**
- **Major outstanding physics R&D issues:**
  - ELM control
  - Access to high confinement
  - Disruption/ runaway electron mitigation
  - Key PFC material and PWI issues
  - Plasma scenarios
  - Integrated Modelling
- **Conclusions**

What are the main changes resulting from the ITER Design Review?

Key Design Review Issues - Tokamak

Vacuum vessel em-loads

PF/CS performance: shape and vert. stability



H&CD Systems

Blanket/ First Wall design and RH
- Heat Loads

Internal coils: ELM & RWM control, Vertical stability

Divertor material strategy

TF performance: fusion gain

"STAC Issues" - Major Risk Reduction

- **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**

What is our present vision of ITER research?

⇒ ITER Research Plan

ITER Research Plan

- **The ITER Research Plan (IRP) is a component of the new ITER Baseline Documentation, complementing Integrated Project Schedule (IPS)**
- **The ITER Research Plan provides a framework linking and integrating the current priorities of the programme with the preparation for future commissioning and exploitation**
- **A major aim of the Research Plan is to integrate the researchers in the Members' fusion communities into the planning and preparation for ITER operation:**
  - encourage active participation in current R&D activities required to prepare for successful implementation of ITER operation and exploitation

ITER Research Plan v1.0

Contents

- Introduction
- R&D during construction
- Hydrogen (non-active) phase
- Deuterium phase, including divertor changeout
- DT1 phase, including development of inductive and non-inductive scenarios
- Analysis of possible upgrades
- Priorities for DT2 phase

Four Phases of ITER Operation

- **To develop a first analysis of the operational aspects of the IRP, the first 10 years of ITER operation have been divided into four phases:**
  - Hydrogen/ Helium (non-active) operation
  - Deuterium operation
  - Inductive DT operation
  - Non-inductive (steady-state) DT operation

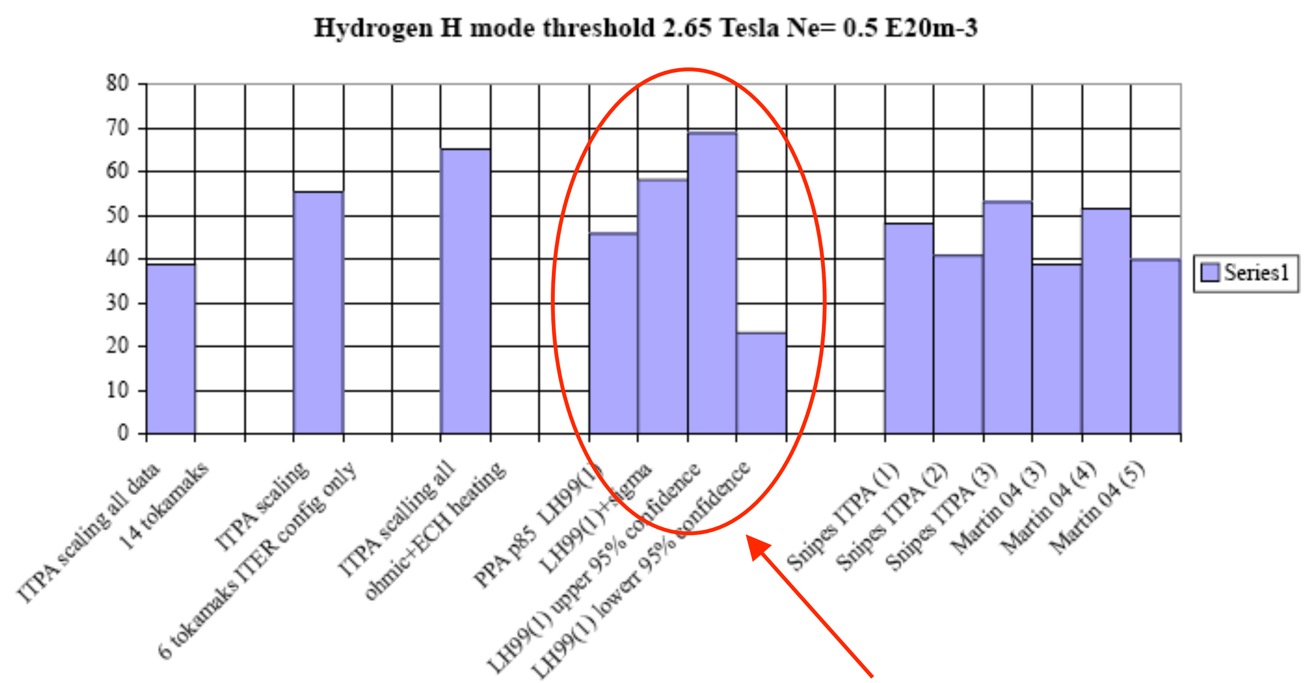
- **Each of these phases have been analyzed to establish:**
  - Facility requirements
  - Goals
  - Main elements of experimental programme
  - Issues to be resolved in programme planning
  - Approximate duration
  - Some implications for adequacy of present design

Major Objectives for H/He-Phase

- Commission installed heating and diagnostic systems with plasma
- Commission/ integrate installed control and safety related systems
- Demonstrate critical system performance
  - eg shape control, vertical stabilization, divertor loads …
- Demonstrate plasma operation to full technical performance (15MA/ 5.3T)
- Validate licensing assumptions concerning disruptions
  - commission disruption avoidance/ mitigation system
- Characterize operational boundaries and off-normal events
- Analyze hydrogen retention and characterize dust production
  - develop operational experience and control of PWI issues in unique mixed material environment
- Demonstrate, to the extent possible, plasma performance and scenarios relevant to D and DT operation

H-mode Access in H/He-Phase

- Access to the H-mode in the non-active phase is problematic, with significant implications for overall structure of the ITER Research Plan:
  - Robust H-modes probably not achievable in hydrogen plasmas
  - Confirmation of results from helium H-mode studies in JET ($P_{LH,He}$ ~ 0.7×$P_{LH,H}$), would open access to H-mode operation in the non-active phase - recent results from AUG provide encouragement!

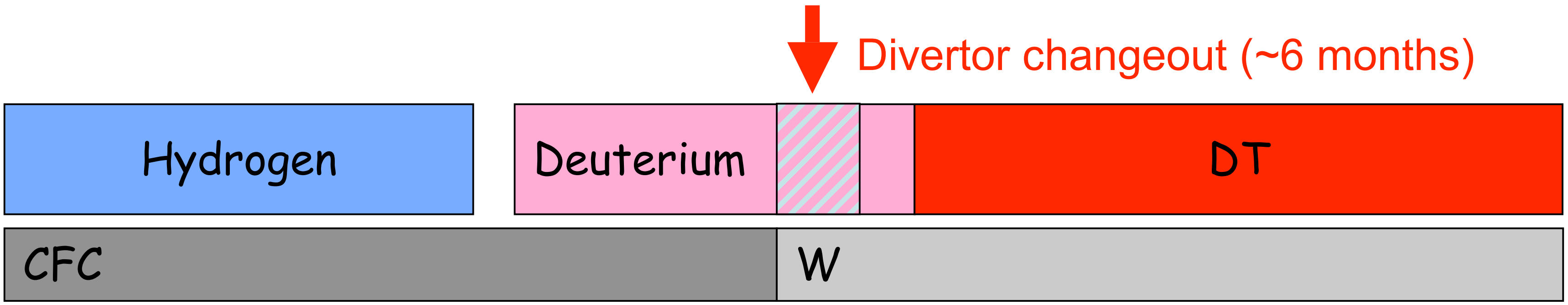


Current ITER performance assessment basis

Major Objectives for D-Phase

- Commission H&CD and diagnostics systems with deuterium plasmas
- Demonstrate and characterize H-mode operation at ITER scale:
  - H-mode power threshold and confinement
  - explore power and particle exhaust
  - divertor and FW performance with ELMs
  - develop ELM avoidance/ mitigation to routine level
  - characterize disruptions and demonstrate disruption avoidance/ mitigation
  - characterize hydrogenic retention and dust production
  - demonstrate NTM suppression with ECCD
  - explore DT-relevant scenarios (H-mode, hybrid, steady-state candidates) - characterize current drive efficiency
- Implement CFC/W divertor changeout and re-establish plasma scenarios with W-divertor
- Initiate trace tritium experiments for particle transport, fuel retention …

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

ITER DT Scenarios

- **Baseline scenarios:**

Single confinement barrier

- ELMy H-mode:
  - Q=10 for ≥300s
  - well understood physics extrapolation to:
    - control
    - self-heating
    - α-particle physics
    - divertor/ PSI issues
  - physics-technology integration
- Hybrid:
  - Q=5 - 50 for 100 - 2000s
  - conservative scenario for technology testing
  - performance projection based on extension of ELMy H-mode

- **Advanced scenarios:**

Multiple confinement barriers

- satisfy steady-state objective
- prepare DEMO
- develop physics in a range of scenarios:
  - extrapolation of regime
  - self-consistent equilibria
  - MHD stability
  - controllability
  - divertor/ impurity compatibility
  - satisfactory α-particle confinement

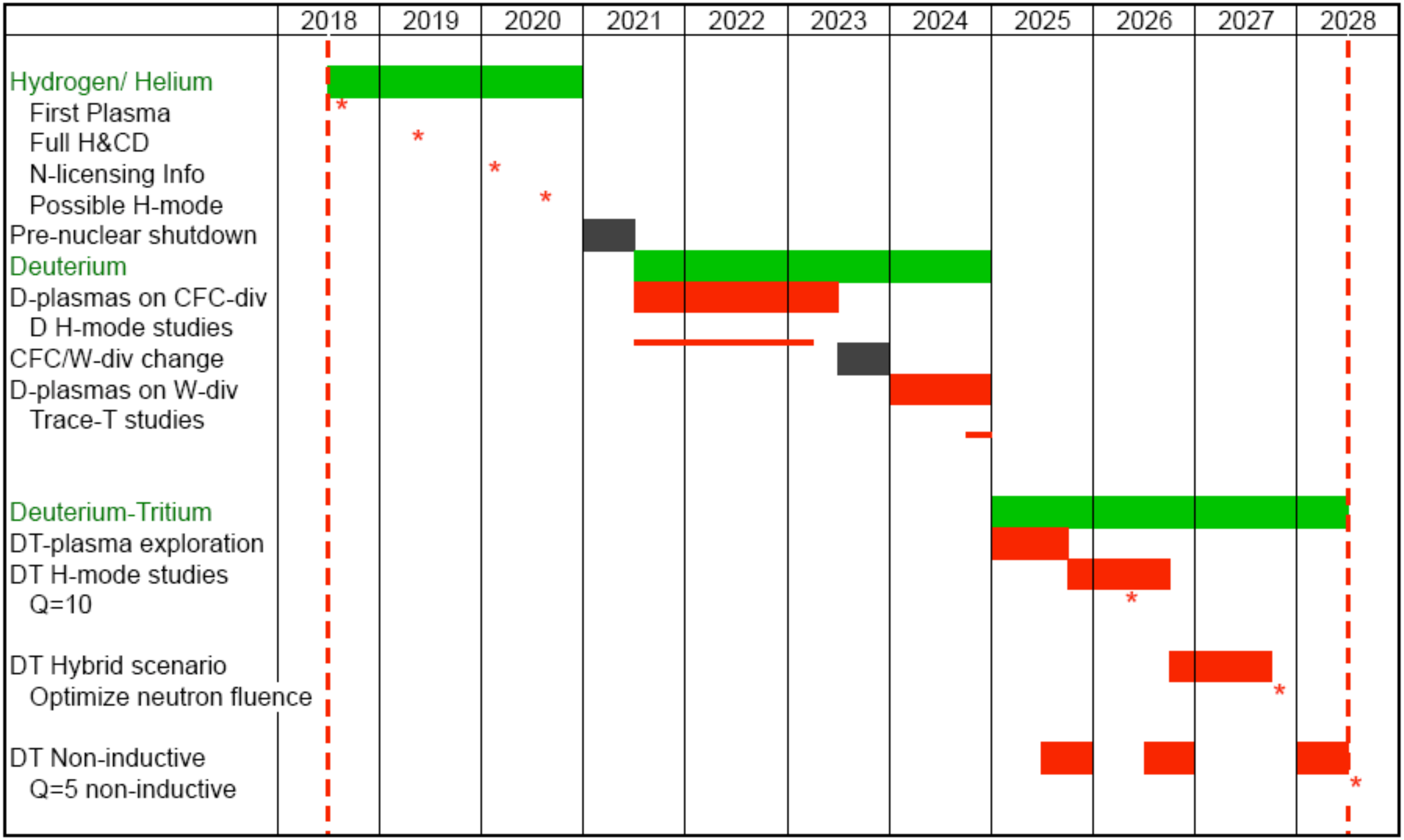
Major Objectives for DT-Phase (inductive)

- Development of burn control techniques for DT plasmas, including power and particle exhaust, active mhd control
- Achievement of fusion power of several hundred MW
- Demonstration of Q=10 for several hundred seconds
- Exploration of high-Q operation in conventional H-modes
- Development of a hybrid mode of operation to longer burn durations or higher fusion performance
- Exploration of hybrid regime operating space
- Pursue programme of burning plasma research based on Q≥10 operating scenarios - confinement, stability, helium exhaust, impurity control, Alfvén modes …

Major Objectives for DT-Phase (non-inductive)

- Extension of current drive studies to DT plasmas - quantify off-axis CD capability
- Building on DT-inductive programme, establish range of target q-profiles with early heating and current ramps
- Commission feedback control algorithms for H&CD, MHD stability control, fuelling and divertor power handling in relevant regimes
- Explore control algorithms in presence of strong α-heating over current relaxation time - validate models for control algorithms
- Develop scenarios close to MHD limits and explore stability/ control
- Develop fully non-inductive plasmas and extend performance to Q=5
- Extend pulse length towards 3000s at Q=5
- Pursue burning plasma physics studies in non-inductive scenarios

Experimental Programme Overview



Plans for further development of IRP

- **The first version of the IRP allowed an initial review of issues associated with ITER experimental programme:**
  - IRP working group brought current experimental expertise into the ITER planning process
  - Allowed an early identification of certain issues not previously considered, eg H-mode access in non-active phase
  - Stimulated thinking about how certain design issues emerging from Design Review (eg PFC strategy, H&CD strategy) could impact on operational planning
  - Provided a basic framework for future more extensive development of IRP

Plans for further development of IRP

- **We are preparing to launch the next phase of the IRP analysis with several goals in mind:**
  - Integration of:
    - Operations planning constraints (availability, shutdown requirements)
    - TBM programme: development programme, testing requirements, changeout schedule
  - Incorporation of Physics Work Programme 2009-2011
    - possible contribution from ITPA to expanded “construction phase” programme
  - Acceleration of programme to DT operation
    - include options for alternative paths, eg with helium H-modes
  - Detailed specification of plasma scenarios
  - Elaboration of Burning Plasma Physics programme
    - possible contribution from ITPA
  - Development of upgrade options and associated research programme

Plans for further development of IRP

- **Framework for future development:**
  - Aim to launch proposal for activity in coming weeks with aim of presenting a revised IRP to the ITER STAC in May 2009
  - Activity would initially be launched through Domestic Agencies:
    - form small working groups of experts in areas outlined
    - involve ITPA and TBM communities
    - define initial aims of programme in each area - allow working groups to develop more extensive programme
    - progress work programme through regular teleconferences
    - foresee one or two working sessions in Cadarache to exchange ideas on developing plans
  - Target date for integration of revised document would be end-April 2009

What are the major physics R&D issues which need to be resolved?

⇒ Key elements of Physics research programme, 2009-2011

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

2. Relation to Project Needs - PAs

- **Key Physics-related Procurement Arrangements:**
  - PF/ CS conductors (Sep08); PF/CS coils (Nov08)
  - VV shielding/ ferromagnetic inserts (Jan09)
  - 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

ITER Physics Programme - Structure

3. Main Lines of Activities

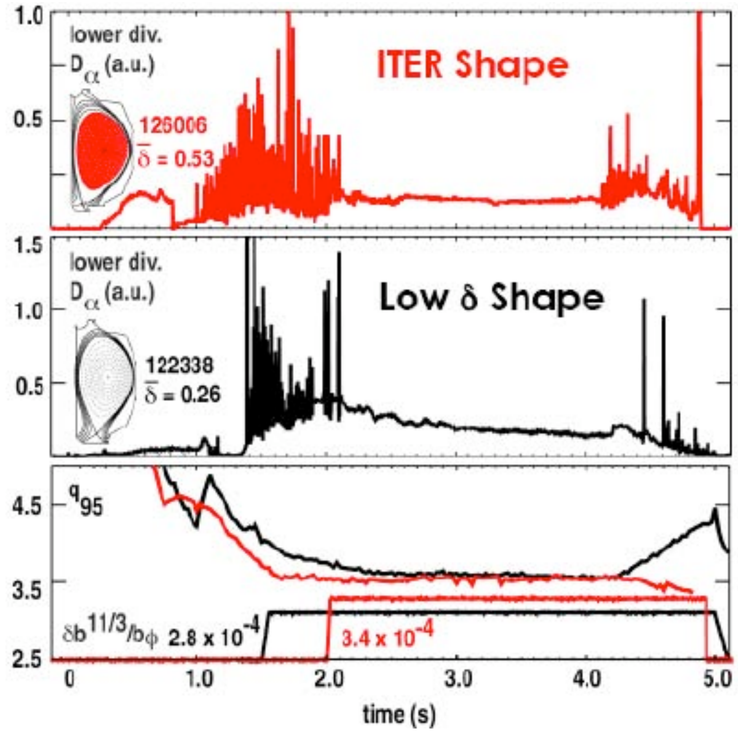
- **Analysis of Physics workprogramme is structured in parallel with FST WBS, but integration is also included:**
  - Transport and Confinement Physics (includes pedestal)
  - Plasma Stability (MHD, PF scenarios and control)
  - Divertor and Plasma-Wall Interactions
  - Plasma Operations (integrated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

1. Transport and Confinement

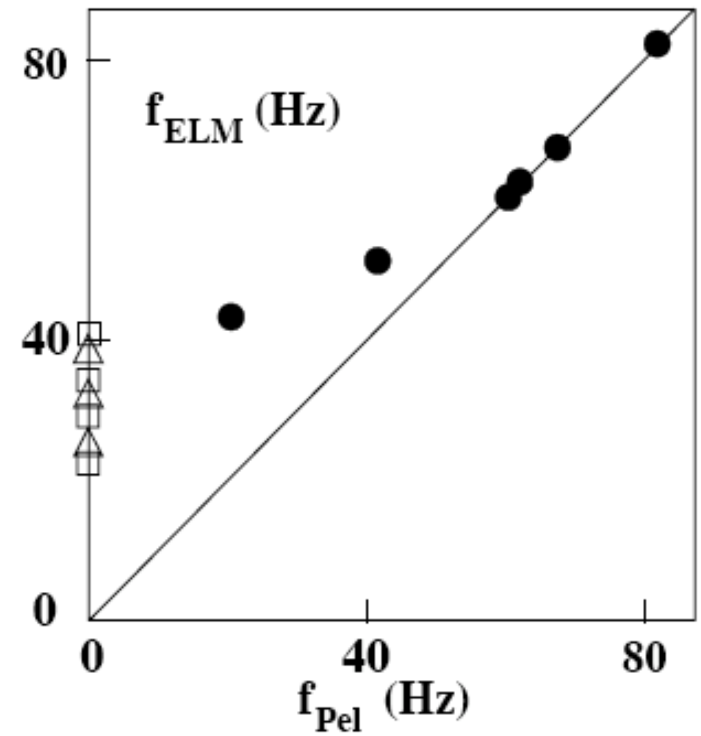
- **Key elements - predominantly voluntary R&D:**
  - Transport and confinement during transient phases
  - Access conditions for high confinement regimes
  - ELM control schemes and compatibility with ITER requirements
  - Toroidal field ripple effects and implications for ITER performance/ fast particle 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 Techniques

DIII-D Magnetic Control

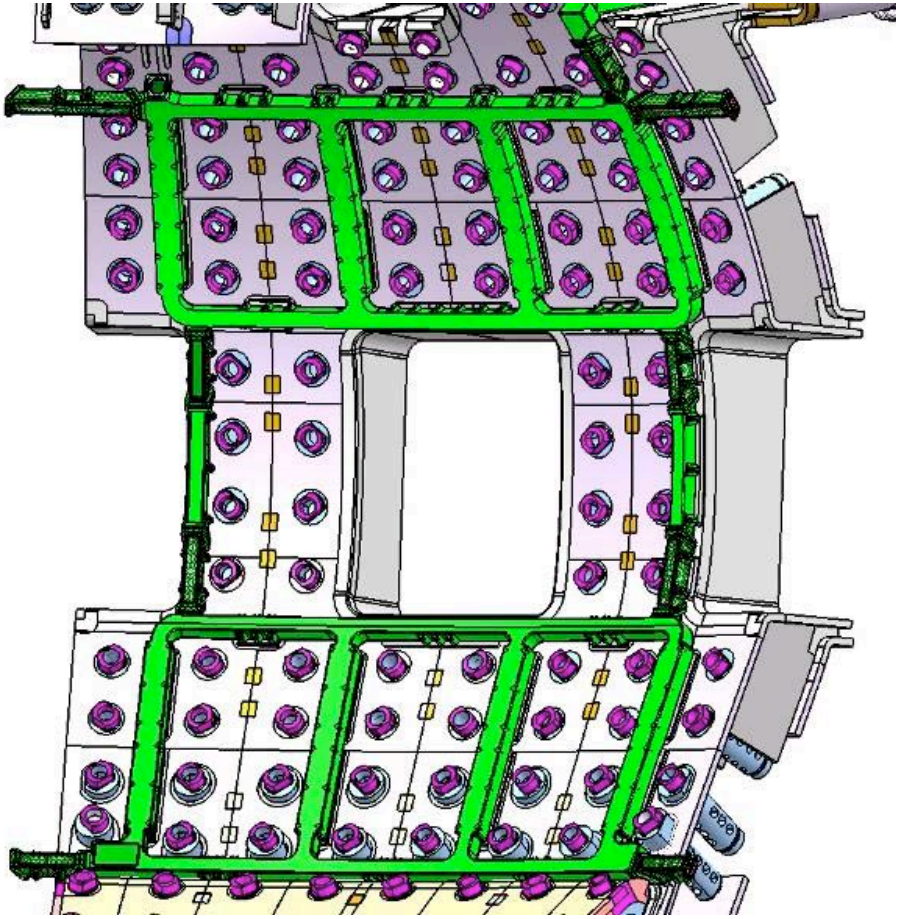


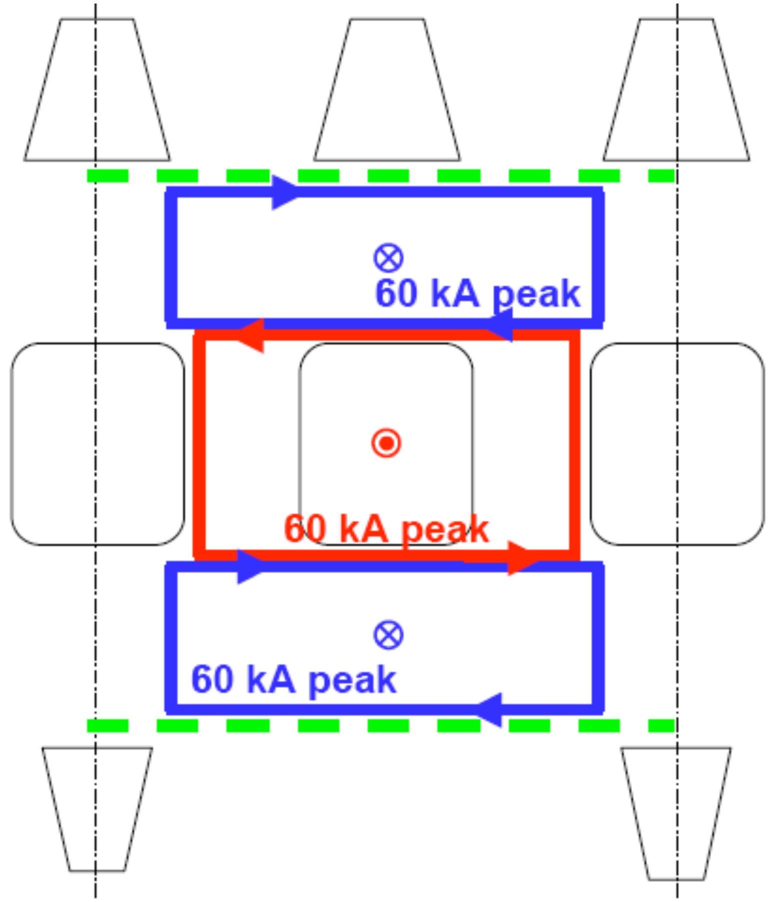
AUG Pellet Pacemaking



- **Two principal approaches are currently under development for ITER:**
  - edge ergodization by RMP coils
  - pellet pacemaking

ELM Control by RMP Coils in ITER





P R Thomas et al, IAEA-FEC2008, IT-1-5

- **A set of resonant magnetic perturbation (RMP) coils under design:**
  - consists of 9 toroidal x 3 poloidal array on internal vessel wall

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

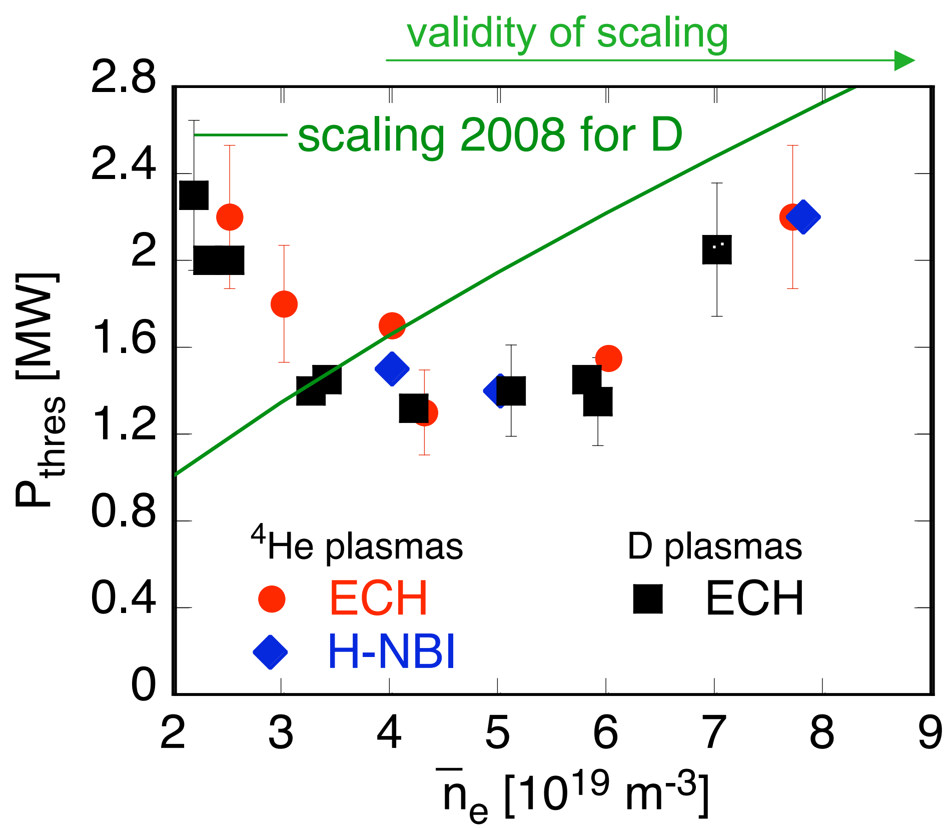
- **Typical R&D questions in programme assembled by Pedestal TG:**
  - specification of requirements for RMP suppression of ELMs in ITER
  - requirements for pellet parameters for ELM pacemaking in ITER
  - interaction between different ELM control techniques
  - impact of ELM control on edge pedestal 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

2. Plasma Stability: Plasma Control

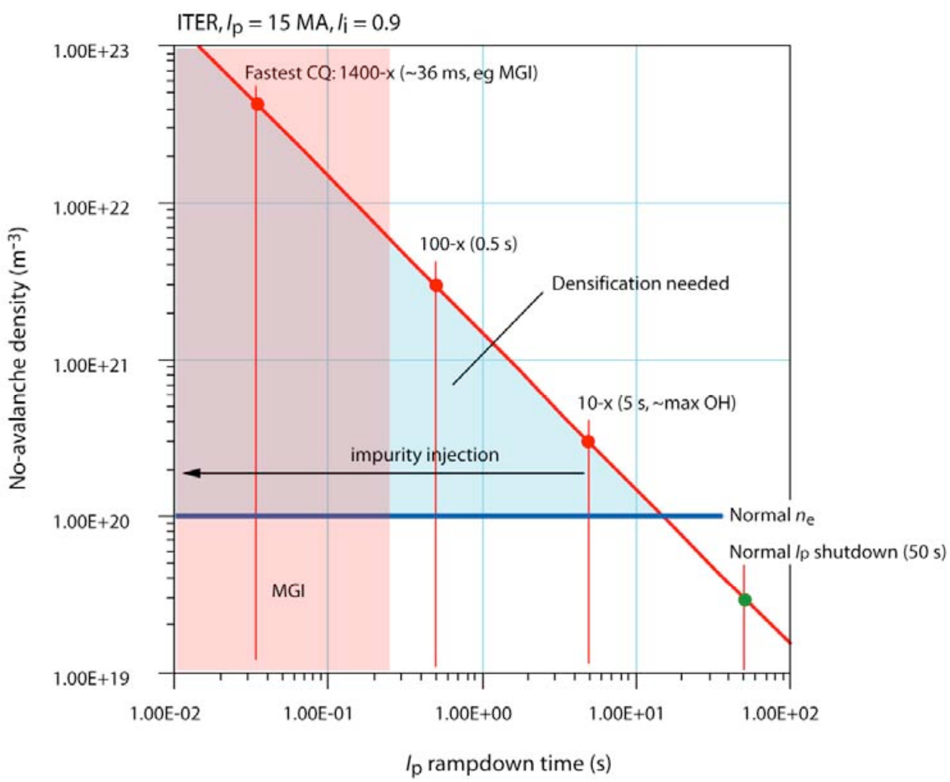
- **Significant Design activity required in short-term:**
  - Analysis and specification of plasma reference scenarios, including plasma initiation, start-up and ramp-down scenarios
  - Specification of TF ripple requirements
  - Control of plasma current, position and shape
  - Magnetic reconstruction 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

2. 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

- **Several issues need to be addressed:**
  - electromagnetic forces
  - thermal loads
  - runaway electrons
- **The development of high pressure gas injection (MGI) looks promising for disruption mitigation (and machine protection!)**
- **The critical problem relates to suppression of runaway electrons**
  - gas requirements based on achieving "Rosenbluth density" imply need to inject several hundred grams of gas



Disruption/ Runaway Mitigation

- **MGI application to ITER problematic:**
  - injecting gas quantity required 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>
  - we are still analyzing suitable gas species

- **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
  - 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 (energy/ current): 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

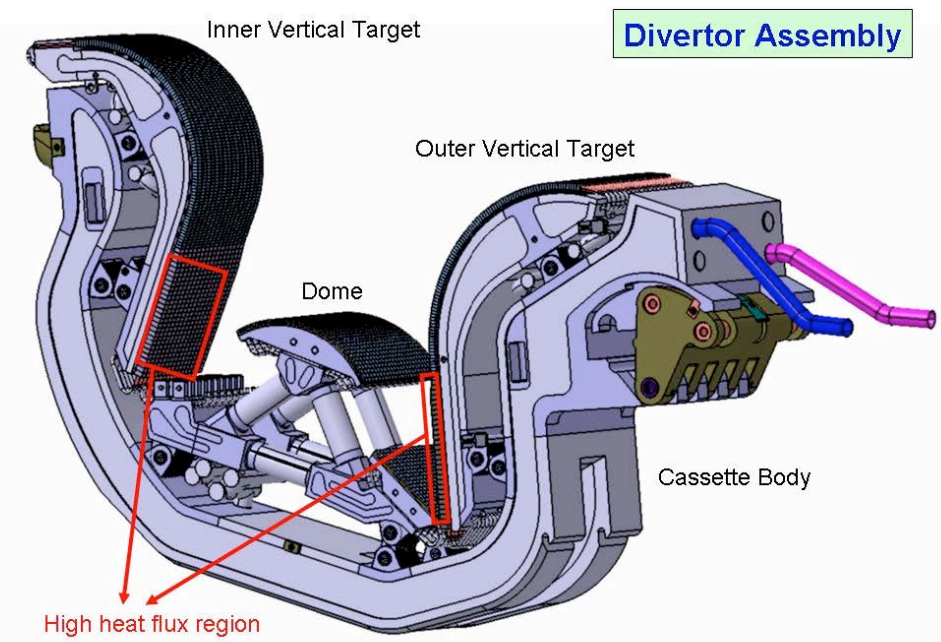
- **When are results required?**
  - present ITER construction schedule requires physics specification of DMS in 2009 ⇒ Procurement Arrangement issued in 2012
  - new technology R&D will be time-consuming

3. 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

Plasma Facing Material Strategy



- **Strategy for use of plasma facing materials in ITER revised:**
  - CFC will be used for high heat flux regions of divertor in advance of DT phase
  - tungsten targets will be installed before DT operation
- **Substantially reduces potential limitations in operation due to tritium co-deposition with carbon**
  - important implications for operating licence
- **Physics R&D required:**
  - to develop relevant plasma scenarios
  - to quantify tritium retention in W/ Be environment

Plasma Facing Material - 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 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

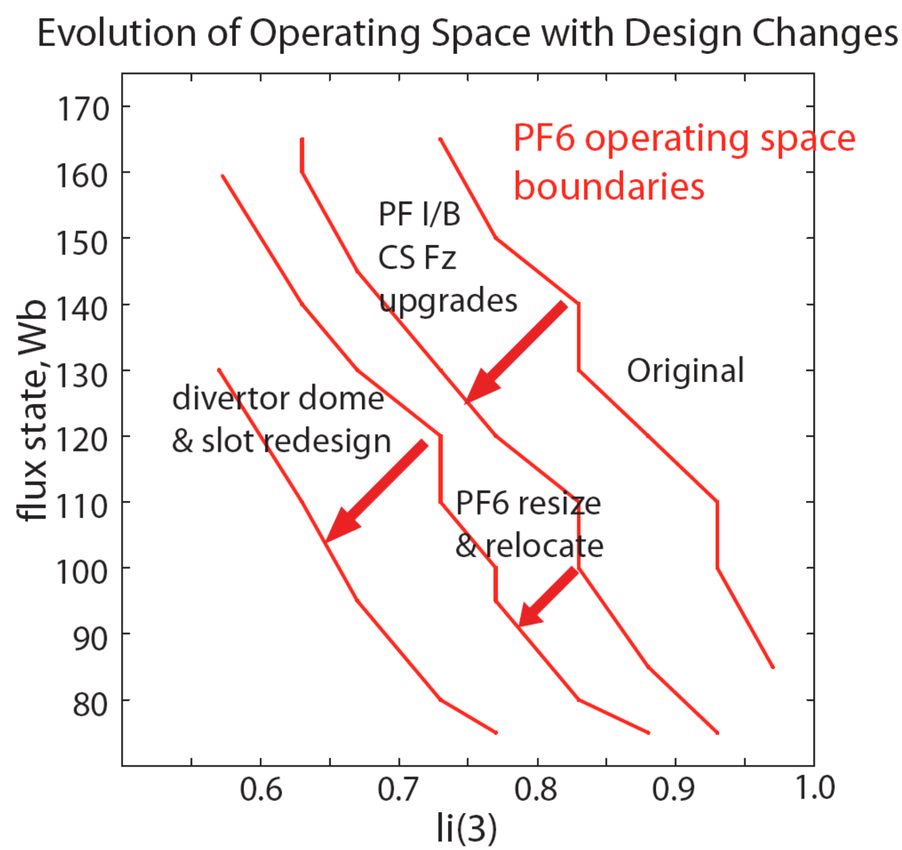
4. Plasma Operations

- **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

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



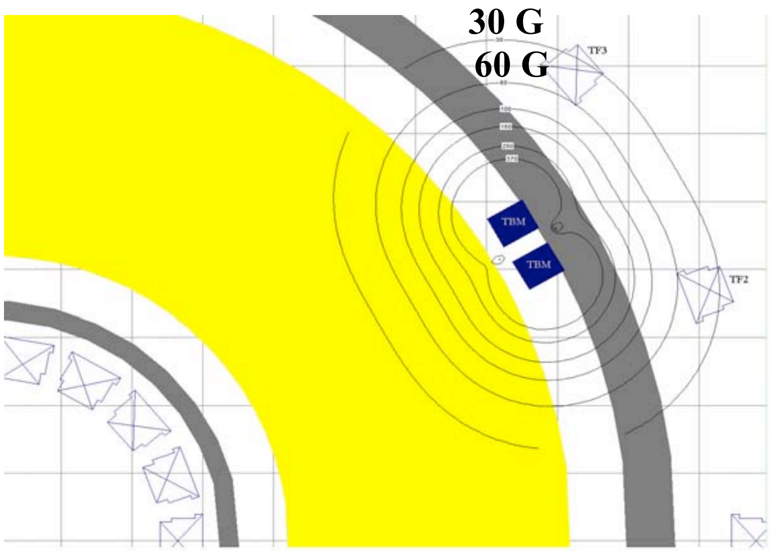
C Kessel et al, IAEA-FEC2008, IT-2-3

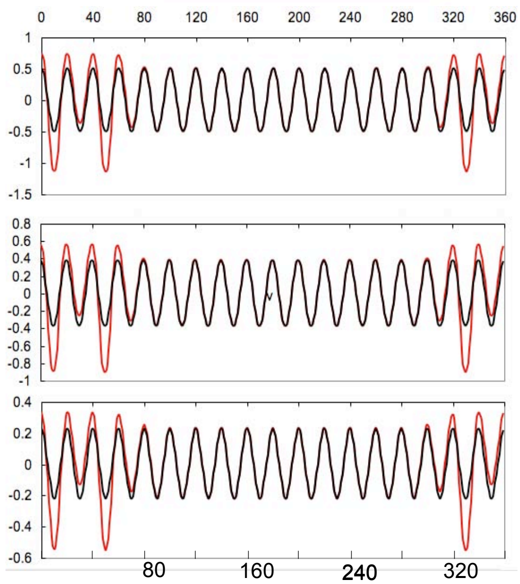
Integrated Scenario Development

- **Development of integrated scenarios which can be translated to the ITER environment will be a major research activity during construction**
  ⇒ realistic scenarios for ITER (including H/ He, D phases):
  - Need to use existing facilities to investigate ITER scenario development
    - various activities: plasma equilibrium development, H&CD exploitation, integrated control, power and particle exhaust, TF ripple effects …
  - ITER needs to handle range of scenarios robustly:
    - ohmic, non-active operation, L- and H-mode, Hybrid, non-inductive …
  - H&CD systems must be exploited efficiently:
    - start-up, heating, burn control, current drive, mhd control …
  - Plasma control possibilities need to be comprehensively explored:
    - robust implementation beyond proof-of-principle
    - physics of control algorithms must be demonstrated
    - need to develop good models of H&CD, diagnostics, fuelling …
    - self-consistent plasma and machine operating limits established
  - Power exhaust and particle fuelling/ pumping need to be self-consistent:
    - combination of good confinement and radiative regimes remains problematic
    - physics basis for fuelling/ pumping requirements is limited

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 –ive 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		

P_{aux} for Q=10 nominal scenario: 40-50MW

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

5. 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**

What are the major physics R&D issues which need to be resolved?

⇒ 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

Plasma Control Strategies

- **Plasma control in ITER is foreseen to consist of several main elements:**
  - Plasma equilibrium control: (routine and robust)
    - plasma shape, position and current
  - Basic plasma parameter control: (routine and robust)
    - plasma density
  - Plasma kinetic control: (exploratory to robust)
    - fuel mixture, fusion power, radiated power …
  - Control for advanced operation: (exploratory)
    - current profile, temperature profile
  - Active MHD stability control: (exploratory to established)
    - error field modes (EFMs), edge localized modes (ELMs), neoclassical tearing modes (NTMs), resistive wall modes (RWMs)
  - Disruption/ vertical displacement event (VDE) avoidance and mitigation (exploratory to robust)

- **Implementation on ITER will require both experimental development and a comprehensive modelling capability**

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

Through the Design Review analysis we have been able to incorporate many recent developments in the ITER design

- **ITER research requirements are dominated at present by need to resolve some tricky 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
- **We need to be imaginative about how ITER can be exploited**
  - advance development of fusion energy as rapidly as possible
  - extract maximum payoff from our major fusion physics research facility