Thrust 4: Develop and qualify operational scenarios and the supporting physics basis for achieving a wide range of burning plasma regimes in ITER

Ron Parker and Craig Petty

For Theme 1 Panels 2 & 3

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Accessing high performance states in ITER presents many challenges and research opportunities (1)

Plasma initiation: What wall cleaning methods will be used for ITER? Can techniques be developed to remove tritium from the walls without major loss of operating time?

Transient phases: What are the energy and particle transport coefficients during rampup and rampdown and how do they depend on the evolving current profile?

H-mode access: What is the physical basis for extrapolating H-mode power thresholds accurately and evaluating Pin/Pth for ITER in initial H/He and eventual nuclear phases?

H-mode sustainment: What is the physical basis for extrapolating H-mode confinement to conditions with low torque injection and equilibrated electron/ion temperatures at low collisionality (i.e. dominant electron heating)?

Accessing high performance states in ITER presents many challenges and research opportunities (2)

H-mode pedestal: What is the physics of the H-Mode pedestal and how does it integrate with core models of heat and momentum transport?

Heating: How effective will the 20 MW of ICRH heating planned for ITER be, especially in transient phases and considering plasma-antenna interactions?

Fueling: What particle transport coefficients and what pellet ablation and fuel deposition models are appropriate to predict ITER density profiles and performance?

Pulse length extension: What is the physics basis of hybrid modes and do they extrapolate favorably to ITER? What is the optimum path to an AT SS mode and what tools are needed to access it?

Wall preparation and tritium removal

Most of the wall preparation techniques used on present day tokamaks are not applicable to ITER due to its steady-state high field

An attractive approach to cleaning the walls of the ITER chamber would be to use electron cyclotron discharge cleaning at 5.3 T.

ECDC cleaning has been successfully used on Alcator C-Mod, but at low field, and with the field swept to spread interaction region over chamber walls.

A thrust element addressing this issue would be to develop variable frequency gyrotrons in the 170 GHz, 1 MW class.

Intense ECDC would not only clean walls of lightly bound impurities, it might be useful in removing tritium, thermally and/or by isotope exchange.

Transport during transient phases

Simulations of the current profile evolution during ramp-up and ramp-down, which are important for assessing MHD stability, depend sensitively on poorly known properties of the thermal electron transport during these transient states.

Uncertainty in transient transport can be greatly reduced by a thrust element on this topic. To be most relevant to ITER it is desirable to use dominant electron heating, likely from RF sources.

Sawtooth ‘mixing’ and temperature recovery between sawtooth crashes is a ‘transient’ condition that may be of more importance in ITER than present-day devices. To study sawtooth transport, high time resolution diagnostics are required for measurements of magnetic pitch angle, ion temperature, and flow speed.

Experiments need to vary between thermal (e.g. Ohmic or ECH) and fast-ion heating to validate models of the effect of sawtooth stabilization by suprathermal particles.

H-Mode access and sustainment

Access to H-mode is essential for ITER to fulfill any part of its experimental mission. A high-priority thrust element is the determination of auxiliary power required for obtaining several H-mode regimes in ITER-like plasma conditions and developing strategies for the minimization of that power:

- **H-mode transition threshold**
- **Steady Type III H-mode operation**
- **Steady H98 = 1 H-mode**
- **H-mode access during plasma current ramp-up/down phases**

The isotope mass and species scaling (H and He plasmas) of required power for the above regimes is also of high value, when considering ITER’s non-nuclear phase.

Ample heating power should be available in multiple forms (e.g. NBI, ICRF, ECH). Efforts should be made to resolve differences in power threshold results that may arise between different heating schemes.

H-Mode access and sustainment (cont'd)

Plasma conditions in ITER will differ from most present-day tokamaks with dominant electron heating, electron-ion temperature equilibration, low collisionality and low torque injection. Additionally, ITER is expected to require a radiative divertor and ELM mitigation. *What is the physical basis for extrapolating H-mode confinement to this reactor-relevant condition?*

Confidence in this transport extrapolation can be obtained by determining the scaling with relative gyroradius (ρ^*), and perhaps neoclassical collisionality (ν^*), while keeping the other dimensionless variables fixed.

A high priority for future transport experiments is to use dominant RF heating to better simulate the burning plasma regime with strong electron heating and low torque injection.

H-Mode access and sustainment (cont'd)

It is important to determine the origin of spontaneous rotation and validate its size scaling as it can affect confinement, the H-mode transition, and MHD.

Pure electron heating cases are the most relevant to ITER, and further work with all forms of RF heating should be pursued as potential profile control tools.

Experiments also need to document and model the effects of resonant and non-resonant drag from non-axisymmetric magnetic fields, as well as the counter-current offset to rotation from neoclassical toroidal viscosity.

H-Mode Pedestals

The ability of the ITER device to achieve its Q=10 mission depends on having an edge pedestal sufficient to maintain high core confinement. *What is the physics of the H-Mode pedestal and how does it integrate with core models of heat and momentum transport?*

Models of the H-mode pedestal structure, and of the complete ELM cycle, need to be further developed and thoroughly tested against experiment. This includes the effect of pellet fueling and low flow/torque.

Additional issues that need to be studied include the effect on the quality of the H-mode pedestal from (1) helium or hydrogen operation, (2) the near unity ratio of input power to H-mode threshold power, (3) the relatively small separation between the primary and secondary separatrices, and (4) high opacity to edge fueling.

Heating

The heating physics of the methods proposed for ITER is well understood; however there are uncertainties regarding the interaction of the ion-cyclotron antenna with the edge plasma. *What will be the nature of the RF sheaths formed by the ICRF antenna? What will be its effect in terms of impurity production? What will be the antenna impedance and will the required antenna voltage be acceptable?*

The proposed thrust element is a program focused on the interaction of ICRF antennas with the edge plasma, including development of validated models for RF sheaths and their effects. Closely coordinated work using experimental, theoretical and simulation tools is required.

Ideally, this activity will point toward advanced antenna designs. If so, they should be implemented and their performance validated in existing machines.

It is also expected that methods of reducing the antenna voltage below breakdown levels will be discovered and tested within the frame of this thrust element.

Fueling

Control of the density, and to the extent possible its spatial profile, is important to the transient and steady discharge phases. The limits of gas fueling at high neutral opacity and the role of transport in setting the density profile need to be explored. The fact that the particle transport differs among species could be leveraged to isolate control of particular species.

Questions to be resolved in this domain are: *What are the particle transport coefficients during these phases and what pellet ablation and fuel deposition models are appropriate? Can diagnostics be developed to determine the core D/T ratio which may serve as sensors for burn control, and as an adjunct to determining tritium retention*?

The specific activity in this thrust element involves measuring and characterizing particle transport in steady and transient phases and validating models of fueling via gas and (inside launch) pellet injection.

Existing tokamaks properly outfitted with inside launch pellet fueling and an appropriate diagnostic set should suffice for carrying out this mission.

Pulse length extension

Two modes of operation are foreseen in ITER for extending the pulse length: the "hybrid mode" and an "advanced tokamak" or AT mode.

The hybrid mode is characterized by a monotonically increasing q-profile with a central value ≥1. Improved stability and confinement occurs, allowing the current to be reduced below the value nominally needed for standard H-Mode.

While promising for ITER, the physics of the hybrid mode is incompletely understood, so the task is to develop predictive physics understanding of hybrid modes, including whether CD tools are needed to maintain q(0) > 1 with monotonic q profile and to determine if hybrid regimes extrapolate favorably to ITER.

Pulse length extension (contd)

Steady-state modes for ITER require further development. The preferred mode has nearly flat or slightly reversed shear, with the central safety factor ~ 2. As in the hybrid mode, enhanced stability and confinement are key features. Such AT modes have been obtained in existing tokamaks, but only for durations of a few resistive skin times.

The research required is to develop a predictive physics understanding of AT SS modes so that they can be confidently extrapolated to ITER. An important question to answer is: What tools are needed in ITER to assure access to Q = 5 steady-state scenarios?

It will also be important to demonstrate that high performance AT modes can be extended in duration for times long compared with the resistive diffusion time and can be integrated with other aspects of ITER operation.

Facility requirements

Much of the research required for extending the pulse length on ITER, and indeed for carrying out the research outlined in this thrust, can be initiated on the existing domestic tokamaks with enhanced capabilities.

As a first step, this can be accomplished by approximately doubling the ECH power on DIII-D, the NBCD power on NSTX, and the LHCD on Alcator C-Mod.

Additional contributions will be made by the international programs, in particular JET and the new superconducting Asian tokamaks, especially in the area of pulse length extension.

But in order to maximize the prospects for ITER's success, it is necessary as far as practical to develop *integrated* scenarios, i.e., scenarios which integrate core, edge and steady-state physics at high performance as measured by the standard dimensionless parameters (e.g., β, ν^* and ρ^*).

Attributes of a new facility, or facilities

Achieving integrated performance, and the underlying scientific understanding, may require new facilities. Needed attributes include:

- Sufficient electron heating to reproduce the main ITER operational scenarios (e.g. achieve the expected beta values; heat without torque injection)

- Sufficient mix of heating power to allow comparison of fast ion vs. thermal particle effects and study mode conversion flow drive.

- Sufficient current drive power to access the safety factor profiles for the main ITER operational scenarios and drive ≥ 50% of the total plasma current.

- Operation with truly equilibrated electrons and ions

- Extended capability to measure electron- and ion-temperature fluctuations.

Attributes of a new facility, or facilities (cont'd)

- Good particle control and different methods of pellet injection.
- Ability to operate with core particle source fully decoupled from edge fueling due to high neutral opacity
- Methods to mitigate/suppress ELMs in low collisionality plasmas.
- Radiative divertor operation.
- Sufficient plasma shape flexibility (encompassing ITER's shape) to determine optimal geometry.
- Pulse length many times the resistive diffusion time.

Conclusion

Ensuring that ITER will efficiently achieve its objectives requires a high level of support by the US tokamak program.

This requires:

In the near term, investing in the domestic tokamaks, e.g., with additional HCD and diagnostics, enabling a focused program of research addressing key ITER issues;

In the longer term, constructing and operating a new US tokamak -- an ITER Satellite Facility.