Alcator C-Mod

Mini-Proposal

MP No. 524

Subject: Development of ITER relevant current rise phase

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1. Purpose of Experiments

The experiments are aimed to find out what is required for the current rise in ITER.

Experiment in C-Mod will be coordinated with work at ASDEX Upgrade, JET and DIII-D to obtain an optimum set of data in the first half of 2008. Despite C-Mod’s relatively small size, key/unique contributions are expected resulting from (1) operation at ITER toroidal field values (5.3T-5.4T), (2) the high ohmic power contribution, (3) operation with all metal walls, (4) high density operation (giving ITER relevant high equipartition) and (5) the issue of real-time reconstruction of the true shape in the presence of large vessel currents and the flux consumption by these vessel currents.

In validating the proposed ITER ramp-up phase to 15MA, with $0.7<l_i(3)<1.0$ throughout the current rise phase, several important questions need to be answered:

- What are the important ingredients to achieve this (plasma shape, current ramp rate, temperature, plasma purity, etc)?
- Is the plasma stable? If not, what are the (MHD) limitations?
- How much additional heating power is required, is it possible with ohmic heating alone?
- What range of plasma density is possible or optimal?
- What are the heat loads to the first wall and divertor?
- What tools are available to control $l_i(3)$?
- What transport model describes the experimental data?

The results of these experiments can be used to benchmark the transport models used in the current rise simulations for ITER. TSC/TRANSP interpretation of the experimental results obtained will directly benefit simulations for ITER with TSC/TRANSP.

2. Background

In ITER, routine operation at 15MA is required, with a robust current rise phase. The proposed current rise phase for ITER has to stay within several constraints of the device, given by the poloidal field set and first wall components. The operational margins are small, compared to today's experiments, due to strict budget constrains. One example of the reduced operation space is the requirement to stay within a range of $l_i(3)$=0.7-1.0.

Simulations of the ITER current rise phase are available, but need to be validated by experiments. The ITPA topical group on steady State Operation has initiated a coordinated set of experiments to document the requirements for the current rise phase in ITER, and to maximize the input to the simulation codes by providing data from several experiments.

ITER now plans to ramp to 15MA at 80 seconds, achieving 1.5MA after 3.5 seconds, and diverting just after 4.5MA (15s.) is reached. The plasma configuration is mainly large bore with a_{min}~2.0m and preliminary transport code predictions give $\langle T_e \rangle$ ~1.3-1.4 keV.

Uncertainties (mainly due to transport assumptions) in the prediction of the electron temperature profile in ITER give substantial uncertainty in the prediction of the $l_i(3)$ evolution for ITER, the amount of heating required, or the current ramp rates required in ITER to stay within $0.7<l_i(3)<1.0$. Hence, it is difficult to give conclusive statements on the need to upgrade the poloidal field set or first wall components of ITER

Large vessel currents at breakdown and during the early rise phase: The ITER team has raised this issue when discussing the control of the plasma configuration/position in the early current rise phase. In other experiments, vessel currents soon become irrelevant after the breakdown phase. Hence, C-Mod can make a unique contribution in the issue of real-time reconstruction of the true shape in the presence of these currents and the time scale of control given the relative resistivity of the vessel and the plasma. A clear summary of the measurement requirements needed on C-Mod would be very helpful. Correlated with this would be a determination of the flux consumed by the vessel resistivity as a check on the magnitude of the vessel currents. In ITER, the additional passive stabilizers under discussion will have significant currents and likely lead to higher flux consumption.

At this stage of the design, "the ITER team does want to have contributions on what is possible; more on what is not possible is counterproductive"

3. Approach

For the ITER relevant current rise experiments in C-Mod we propose:

- To perform the experiments at 5.4T.
- To have the current ramp in C-Mod at relatively low density to keep the temperature high (~20% of the Greenwald density, 0.65 10^{20} at 0.5MA, 1.65 10^{20} at 1.2MA).

- Develop in a first series of discharges the required shape evolution. This implies diverting relatively early and using an "ITER" plasma shape or a relaxed shape that is still close enough to ITER.
- Do the first few pulses with a ramp to 1.0-1.2MA but then push I_p up to get to $q_{95} \leq 3.5$ (I_p close to 1.4MA).

To estimate the requirement for these experiments in C-Mod, we assume the current diffusion rate to scale as: $a_{min}^2 \langle T_e \rangle^{1.5}$. With a_{min}=2m and $\langle T_e \rangle$=1.35 keV for ITER, the following table indicates the requirements for the plasma current rise, as a function of the plasma temperature. Based on C-Mod data and data from other devices (ASDEX, JET), $\langle T_e \rangle$ is assumed constant in time for the latter half of the current rise phase. Calculated are the time I_p=1.2MA should be reached, and the linear current rise rate (dI_p/dt) after the initial plasma formation phase (400kA, at t=0.065s).

$\langle T_e \rangle$ during ramp-up	**T_{e0}, (~2.2x$\langle T_e \rangle$)**	**Time of I_p=1.2MA**	**dI_p/dt, after breakdown phase**
0.5 keV	1.1 keV	0.18 s.	7.0 MA/s
0.6 keV	1.3 keV	0.24 s.	4.6 MA/s
0.7 keV	1.5 keV	0.29 s.	3.6 MA/s
0.8 keV	**1.8 keV**	**0.35 s.**	**2.8 MA/s**
0.9 keV	**2.0 keV**	**0.42 s.**	**2.3 MA/s**
1.0 keV	**2.2 keV**	**0.49 s.**	**1.9 MA/s**
1.1 keV	**2.4 keV**	**0.56 s.**	**1.6 MA/s**
1.2 keV	**2.6 keV**	**0.65 s.**	**1.4 MA/s**
1.3 keV	2.9 keV	0.73 s.	1.2 MA/s
1.4 keV	3.1 keV	0.81 s.	1.1 MA/s
1.5 keV	3.3 keV	0.90 s.	0.96 MA/s

In this table we assume T_{e0}~2.2$\langle T_e \rangle$, which is correct for ohmic plasmas at low $l_i(3)$<1.1. At high plasma inductance however, the temperature profile is much more peaked with T_{e0}~4$\langle T_e \rangle$. The peaked temperature profile will tend to maintain a peaked current profile during the current rise phase. This route to peaked current profiles can only be broken if the current density profile is relatively flat in the initial current rise phase, or off-axis additional heating is used to broaden the temperature profile (in some transport simulations this is done by making a transition to H-mode).

In order to stay within realistic current rise parameters for C-Mod (indicated in blue), the electron temperature needs to be T_{e0}~1.8-2.6 keV, achievable at low density in C-Mod or some (few MW) addition heating during the current rise phase. A recent example discharge that come close to these parameters is #1080108024.

Additional comments:

- Early diversion, when the current is in the range Ip=400-500kA, is desirable for the best match to the ITER reference scenario, and for reduction of impurity influx and improved density control during the ramp. Diversion at such current or lower has been achieved in the slow ramp startups (MP#522, e.g. 1080118006). However for the fast current ramp case proposed here this may lead to excess stress (>300kN) on OH2L, depending on the relative currents in OH1, OH2L and EF1L. Simulations of the ITER scenario also encounter a limit of this nature on the corresponding coil CS3L (ref: Gribov, et al., SSO ITPA Topical Group Meeting (Dec 2007)). Therefore, this aspect of the proposal should be pursued only up to the point that the OH force calculator (Burke) allows. The main purposes of this experiment can still be met if the discharge remains in a full bore limiter configuration up to ~700kA or somewhat higher.

- Breakdown + limiter phase: As standard for C-Mod, limiter configuration should be as full bore as possible, could limit on inner wall.
- MSE measurements would be useful but not essential to perform these experiments. Another powerful indicator for the q-profile evolution is the onset of sawteeth.
- In these experiments the plasma could be terminated with an ITER relevant current decay phase; slow current decay keeping divertor shape. This could be suggested as a piggy back experiment. However, it poses a risk that too many experiments are done in one discharge type, leading to diminishing returns for the main experiment.

4. Resources

4.1 Machine and Plasma Parameters

Toroidal Field:	5.4T
Plasma Current:	Ramp to I_p=1.2MA, push to 1.35MA when required
Working Gas Species:	D_2, Hydrogen minority (~5%)
Density:	~20% of the Greenwald density during the ramp
Equilibrium configuration:	Starting point: Discharge 1080108024, which gets to 1.2MA at 0.4s, keeps 0.9<li(3)<1.0 from 0.08<t<1.3s (according to EFIT), T_{e0}~2.2keV at 0.4sec (ohmic), $<n_e>$~1.6e20. This shot continues on up to 1.35MA, q_{95}=3.4, kappa=1.8.

4.2 Auxiliary Systems

RF Power, pulse length, phasing:	ICRH: 2-3 MW, H-minority 80 MHz, LH: Standby (experimental plan steps 2, 4b)
Pellet Injection (species):	None
Impurity blow-off injection:	None
Diagnostic Neutral Beam:	Desirable
Cryopump:	Desirable

4.3 Diagnostics

MSE measurements would be useful but not essential to perform these experiments, high frequency magnetic pick-up coils. Thomson and ECE to monitor the electron temperature profile. Diagnostics for impurity survey: Z_{eff} and Mo influxes. PCI to observe Alfvén Cascades in case a reversed q-profile is formed during the current rise phase.

5. Experimental Plan

5.1 Run sequence Plan:
These experiments require 1 run day (20-25 shots).

5.2 Shot sequence plan
Rationale:

- Step (1): The initial scenario development needs some time to obtain a stable ohmic discharge that diverts around 500kA, with a fairly fast ramp to at least 1.2MA. The shape does not need to be exactly matched to ITER. As noted in section 3, keeping a full bore limiter up to ~700kA (to stay within the OH force limits) and then diverting would be fine as well. The plasma current ramp rate is important. Some time needs to be taken to obtain the fastest possible rate while still in control of the shape or position. One can always go slower when required.
- Steps (2) and (3) in the table below are parametric scans. These are geared to assess what is important for the current profile evolution. They will data for the code benchmarking and comparisons to results of other experiments.
- Step (4a): When the experiments above are successful ($l_i(3) < 1$), then we need a demonstration discharge (push to full current I_p~1.35MA) with the optimum current ramp rate, plasma density and additional heating for $l_i(3)$ ~0.85 during the current rise phase.
- Step (4b): When access to $l_i(3) < 1$ is not possible due to MHD then this needs to be documented. In case the plasmas are stable but always have $l_i(3) > 1$, a few pulses with LHCD should be done.

Step	**Subject**	**shots**
(1)	Develop current rise scenario (ohmic): I_p waveform, early divert, shape evolution, low density, at low $q_{95} \leq 3.5$. This step: Maximum I_p ~1.2MA.	8-10
(2)	Input heating power scan (not changing the density waveform): Ohmic to 2-3 MW ICRH. To increase the temperature and access low $l_i(3)$. Is H-mode possible in current rise to broaden the temperature profile? Back-up: LHCD in case $l_i(3)$ does not respond to central heating.	4-5
(3)	Scan plasma density: Lower and higher density compared to density used in step 1. Trade-off between plasma purity and requirement to use more additional heating to maintain desired temperature.	3-5
(4)	<u>(a) When successful:</u> ITER demonstration with $l_i(3)$~0.85 (q_{95}=3-3.5). <u>(b) Severe limitations:</u> Document limitations to achieve $l_i(3)$<1.0, use LHCD when required.	5

6. Anticipated Results

The development of ITER relevant current rise phase in C-Mod:

- Will indicate the feasibility of obtaining $0.7<l_i(3)<1.0$ at low $q_{95}=3\text{-}3.5$, and the important ingredients to achieve this (plasma shape, current ramp rate, temperature, plasma purity, etc)?
- Document the plasma stability.
- Obtain results for benchmarking (transport) simulations of the current rise phase.

Collaboration:
These experiments are done in collaboration with other experiments (ITPA).

Publications:
Contribute to a joint paper (ITPA) proposed for the IAEA 2008.
Stand alone publication (on the C-Mod results themselves) in a journal.