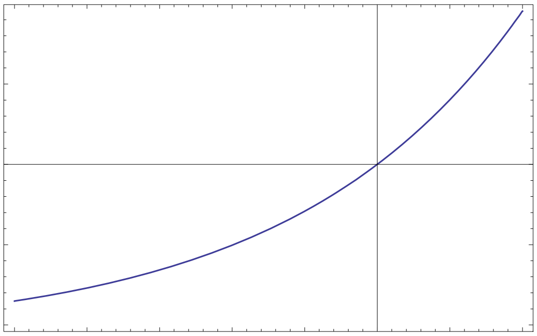
Cumulative Integrated Performance on ITER that allows Q=10

M. Kotschenreuther, S. Mahajan, P. Valanju; *Oral*-Boundary and Core Simulation Panels

The displayed plot highlights the sensitivity fusion gain Q to the (confinement) H factor, using the H-mode scaling law preferred in the ITER physics basis (ITER98(y,2)). If H=1 corresponds to an energy gain of 10, then a 15% reduction in H brings down Q by almost a factor of 2. For ITER, this reduction will also drop the net heating power ($P_{net}=P_{aux}+P_{alpha}-P_{radiation}$ for the core) below the L-H mode threshold; Q ~ 1-2 for L-mode on ITER. The huge sensitivity of Q to H may seem surprising, but it is a simple consequence of the fact that fusion power ~ the *square* of the stored energy (which is ~ H), together with the fact that as stored energy decreases, the heating power also decreases, that further reduces stored energy.

Commendably, ITER was designed with some conservatism in confinement requirements. Despite the caution, we will show *there is good reason to expect that this conservatism is inadequate to meet ITER objectives.* The ITER conservatism was enforced in a rather obscure way: the radiation power is subtracted from the assumed heating power. However, according to the rules used to develop and apply ITER98(y,2), radiation power should not be subtracted, since this fits the data much better as long as one is above the L-H threshold (physical reasons for this are beyond our scope, but the fact is well justified). The upshot is that, if the strict rules of the scaling law are followed, ITER needs an H factor of only 0.82 for 500MW of fusion power at Q =10 (with low impurity dilution and 50 MW of heating power). In what follows, we strictly adhere to rules of the scaling law formulation, and credit the assumed conservatism expressed as follows: ITER's H-factor under "ideal" conditions is 18% higher than needed to obtain Q=10.



With this preamble, consider the implications of operating with a radiating divertor. Recent projections of SOL width (~ 1mm for ITER) imply that over an order of magnitude reduction in plate heat flux is required, compared to an ordinary H-mode. Present experiments attain such performance with puffing and impurity seeding, but there is a dilution penalty. For nitrogen, an increase in core Z_{eff} results, with ΔZ_{eff} ~ 1. Appling this level of dilution to ITER, the fusion power drops, reducing the heating power, etc.,; the upshot is that, for a simple model based on ITER98(y,2), all conservatism of the ITER design is almost completely "used up" by this dilution, and Q = 13 results *if H=1*.

Let us consider a second factor than is likely to arise. Radiative divertor operation typically results in a drop of H factor by ~ 10-15% *compared to the confinement before puffing and seeding*. Experiments starting out with H> 1 can get H ~ 1 after this confinement penalty on present experiments. Assuming ITER starts with H=1, applying a 15% confinement penalty, *together with dilution*, Q drops to ~ 6.7. Any further small degradation of confinement or core radiation is catastrophic.

IF *any three* of the following factors are taken into account (each of which has substantial support from experiments, modeling or theory), *very* low Q results on ITER:

1) Low core velocity shear in the core (expected on ITER) relative to most present day experiments: can reduce H by ~ 10-15%
2) Recent experiments on JET with an ITER like wall find non-stationary conditions due to growing core radiation (likely from tungsten). This could portend higher core radiation on ITER, or the need for more extreme divertor detachment on ITER and/or more extreme ELM mitigation measures, with greater confinement degradation.
3) Initiation of Neoclassical Tearing Modes - the rho* of ITER implies these are much easier to initiate than on present devices. The “seed island” width is proportional to ρ*, which is several times smaller on ITER. An m=3 NTM reduces confinement by ~ 20%, an m=4 by ~ 10-15%. Localized EC can stabilize one rational surface (likely at q=2, the most dangerous spot), but an m=3 or m=4 islands can form at several surfaces. Seed islands can arise from many sources, including: MHD events (including those initiated by pellet injection) or non-axisymmetirc perturbations (including RMPs). It must be stressed that events that are much too small to trigger NTMs on present devices *can* trigger them on ITER, so any optimistic experimental experience today for a particular seeding event cannot be taken as a reliable guide to the future.
4) Radiative divertors - require a delta Z_{eff} ~ 1 for order of magnitude reductions in heat flux
5) Confinement reduced by ~ 10-15% *compared to starting value* for order of magnitude reduction in heat flux
6) Strong ELM mitigation or total suppression: reduces pedestal (and potentially core) confinement by ~ 10-15%. (For pellets, possibly RMP.)

To combat the combined deleterious effects of the above- mentioned processes, satisfactory ITER operation will *likely require* either or both of the following:

A) Operating modes on ITER which, in “ideal” conditions, give H *well above* 1. This might be possible on ITER using Li injection similar to present experiments, or perhaps, accessing newly predicted “super-H-modes” (based on the EFIT model). Other possibilities should also be devised. The H factor should be high enough so that, after the decrements above are accounted for, performance is still adequate. This would be analogous to operation in present experiments on radiative divertors that attain H~1 *by starting with* H above one before puffing and seeding.
B) Operation with novel divertor modes, such as the X-divertor configuration. This is possible on ITER within coil design limits and with the baseline cassette. This may allow satisfactory divertor operation with significantly less degradation from dilution and/or confinement reduction.

Research to consider the implementation of such advanced modes on ITER should commence as a matter of urgency; *it is likely that such advancements will be crucial to ensure satisfactory performance*. If, very fortuitously, the indicated degradations do not occur, even then, the implementation of advanced modes would be very worthwhile: it might allow ignition on ITER. *Furthermore, integrated simulations should be performed with available models to obtain ITER’s projected performance including the likely degradations including those noted above.*