ITER Hybrid Regime: Modelling Requests

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Outline

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Hybrid operation space

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Summary

ITER's Definition of Hybrid Operation

An intermediate step between inductive operation and steady-state:

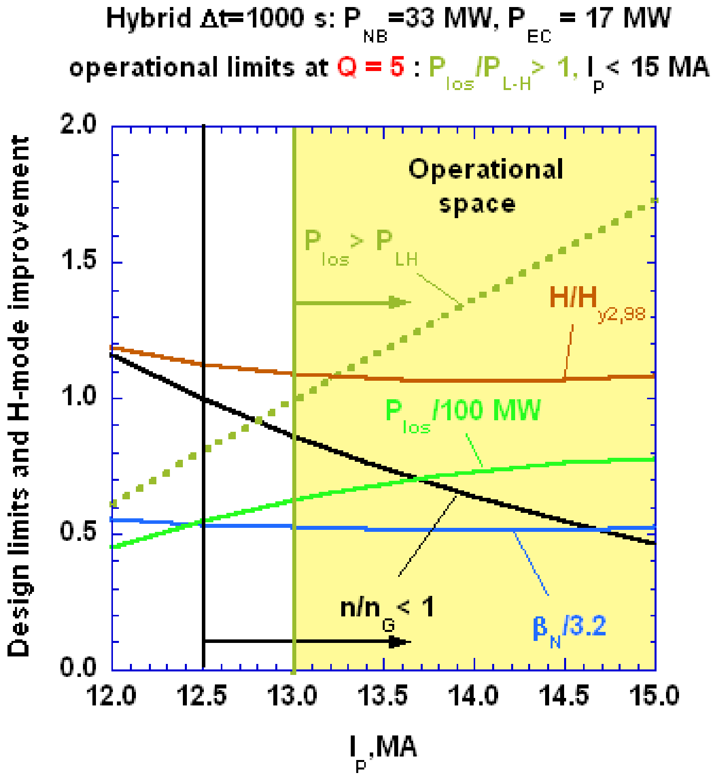
- Extended pulse length of ~1000 s
- Q ~ 5

To achieve these conditions, requires:

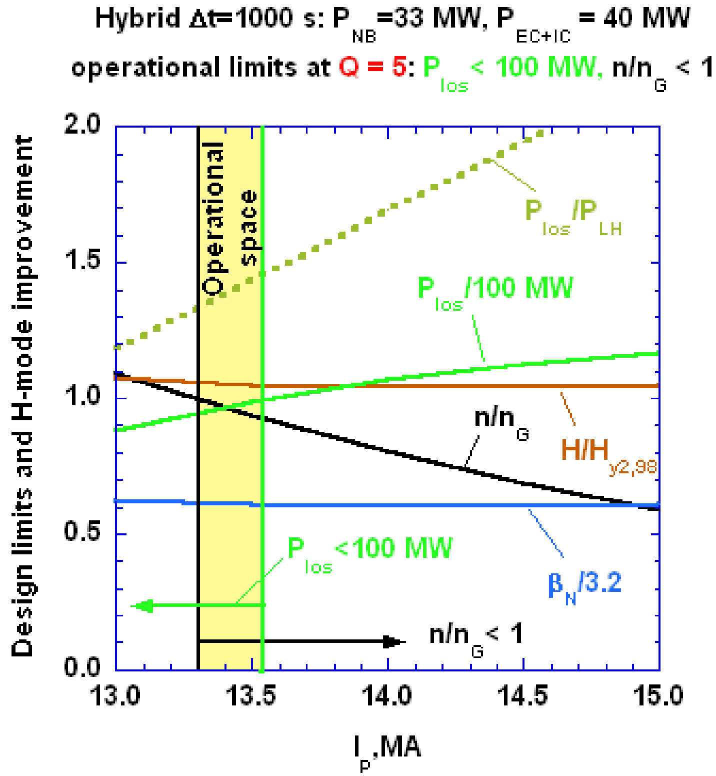
- Reduced plasma current to extend pulse
  - Less inductive current
  - Perhaps more non-inductive current
- Improved confinement to compensate for reduced current (based on expected H-mode scaling)
  - ITBs?
  - Advanced Inductive?
  - Other approaches?

ITER Hybrid Operation Space (Polevoi *et al* 2010 EPS)

P_{aux} = 50 MW



P_{aux} = 73 MW



Physics Issues for Hybrid Operation – 1

Clarify access conditions to Advanced inductive/Hybrid operation across devices:

- What are the requirements on the q profile?
- What are the requirements for heating during the current ramp?
- What are the requirements on the density during the current ramp?
  - Low n and high T to reduce resistivity?

Is off-axis CD necessary to raise q0?

- If so, how much will be required on ITER?
- How effective are ECCD and LHCD in achieving these conditions?
  - Possible basis for upgrade options

How can the required q profile be maintained for more than a current relaxation time?

- Can the q profile be maintained spontaneously by the plasma through MHD modes?
- Can theory explain this?
  - Is it scalable to ITER?

Physics Issues for Hybrid Operation – 2

Are current profiles more susceptible to island formation?

- If stable, how do they affect the current evolution and transport properties?
- If unstable, are they helpful in maintaining a favorable q profile?

How much density peaking is there?

- What does it depend upon?
- Is impurity accumulation an issue?
  - Can it be resolved with on-axis heating?
  - Can it be resolved with counter ECCD?
    - Will more EC power be needed on ITER to handle this?

Can transport models be validated across multiple AI/Hybrid experiments?

- Need to assess scalability to ITER
  - Collisionality
  - Dominant turbulence characteristics
  - MHD activity

Control Issues for Hybrid Operation

Can plasma control algorithms be built into the transport models to ensure:

- The ramp up can reach the required q profile and maintain it with the available CD power
- The L-H and H-L transitions will occur when expected by the model
- The divertor exhaust power can be controlled within melting/sublimation limits
- The core and edge density and pressure profiles can be maintained with the available fueling and heating systems
- The impurities from He ash, puffed in for divertor detachment control, and evolved off of the walls and divertor can be controlled
- The fusion burn can be well controlled with core pellet fuelling
- The plasma position and shape can be controlled throughout all of the regime changes
- MHD stability can also be maintained with the available heating and current drive power
- The plasma can be safely ramped down to ~1 MA with the available heating power

Example Study from Plasma Scenario Tasks

Examples of Hybrid studies from work of C. Kessel *et al,* targeted at PF system analysis

Codes:

– TSC and TRANSP

Hybrid scenario, DT, 12-13 MA, 5.3 T, ~50% non-inductive current, 1000 s pulse:

– Core transport with prescribed and theory based predictive models

– Determine criteria for access to ~1000 s flattop times

– Evaluate equilibrium operating space

Physics Models (C. Kessel *et al*) – 1

Energy transport (being applied in these studies):

- Coppi-Tang modified for pedestal and ITBs
- Bifurcation ITB model
- MMM08
- GLF23

Bootstrap current:

- Sauter
- NCLASS

H/CD sources:

- TORIC (full wave ICRF)
- FP on resonant species, equivalent Maxwellian on other fast species
- LSC (ray-tracing 1D FP)
- TORAY (ray-tracing 1D FP)
- NUBEAM (MC orbit following)
- Alpha particles (MC orbit following, and Bosch-Hale formulation)

Physics Models (C. Kessel *et al*) – 2

Particle transport:

- Prescribed density profiles
- Hydrogen (DT) derived from quasi-neutrality
- He density derived from τ_{He*}/τ_E

Sawtooth model:

- Porcelli/hyper-resistivity

Impurities:

- Prescribed magnitude and profile

Radiation (targeting 25-45 MW):

- Cyclotron (Trubnikov)
- Bremsstrahlung
- Line (Coronal equilibrium)

Pedestal:

- Prescribed χ_{ped}
- Pedestal model (EPED1)

Hybrid Scenario Scans (C. Kessel *et al*)

Hold T_{ped} ~ 3.9-4.5 keV, ρ_{ped} ~ 0.94 (from EPED estimate)

Confinement H_{98} ~ 1.25, based on GLF23

Coppi-Tang L-mode χ, modified to produce a pedestal, scaled to produce τ_E

Vary I_p ramp time 60, 100 and 150 s

Vary heating in ramp phase to get q(0) to reach 1 at approx end of ramp

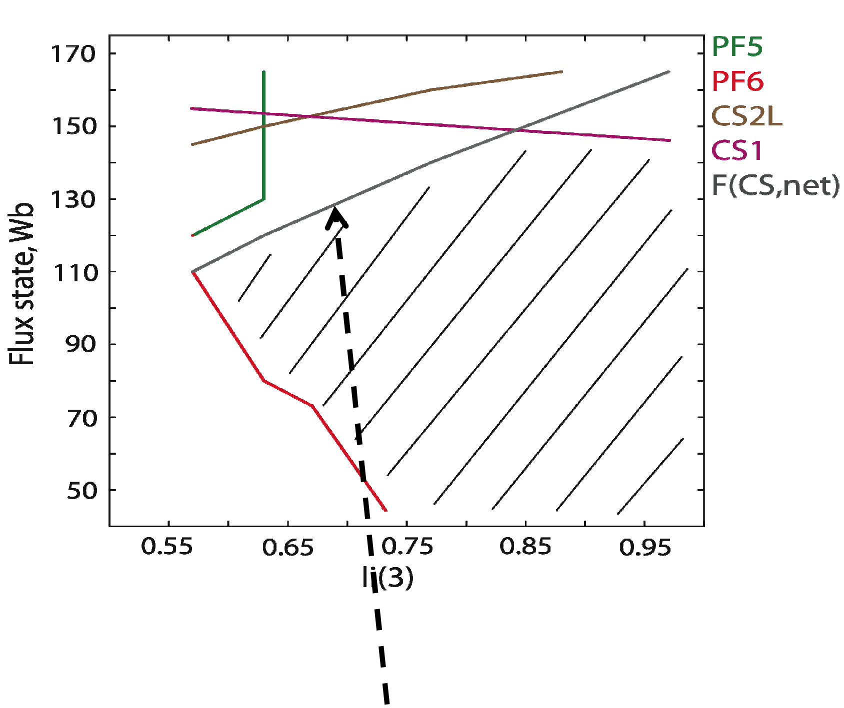
Presently using 20 MW ICRF, and 33 MW NB

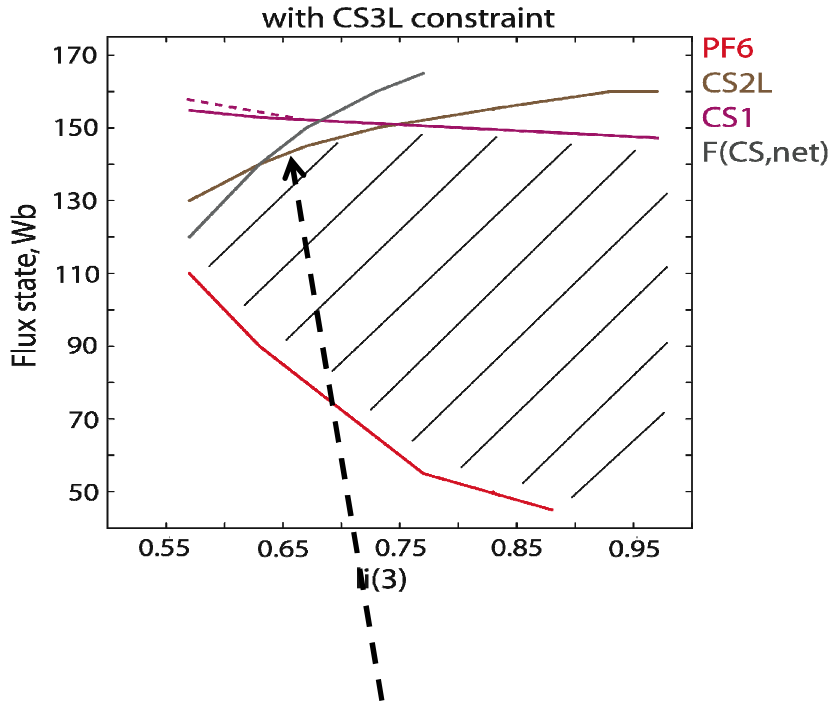
30 Wb pre-magnetization advance is used as reference

Producing equilibrium operating space

- – CS and PF coil limits

Hybrid Equilibrium Operating Space (C. Kessel et al)





Found that the CS net force could dip down and restrict operating space

CS coils are all negative making a large net force

By changing the weights to make CS3L positive over more of the flux state space, the boundary was moved out of the way

Time dependent trajectories (C. Kessel et al)

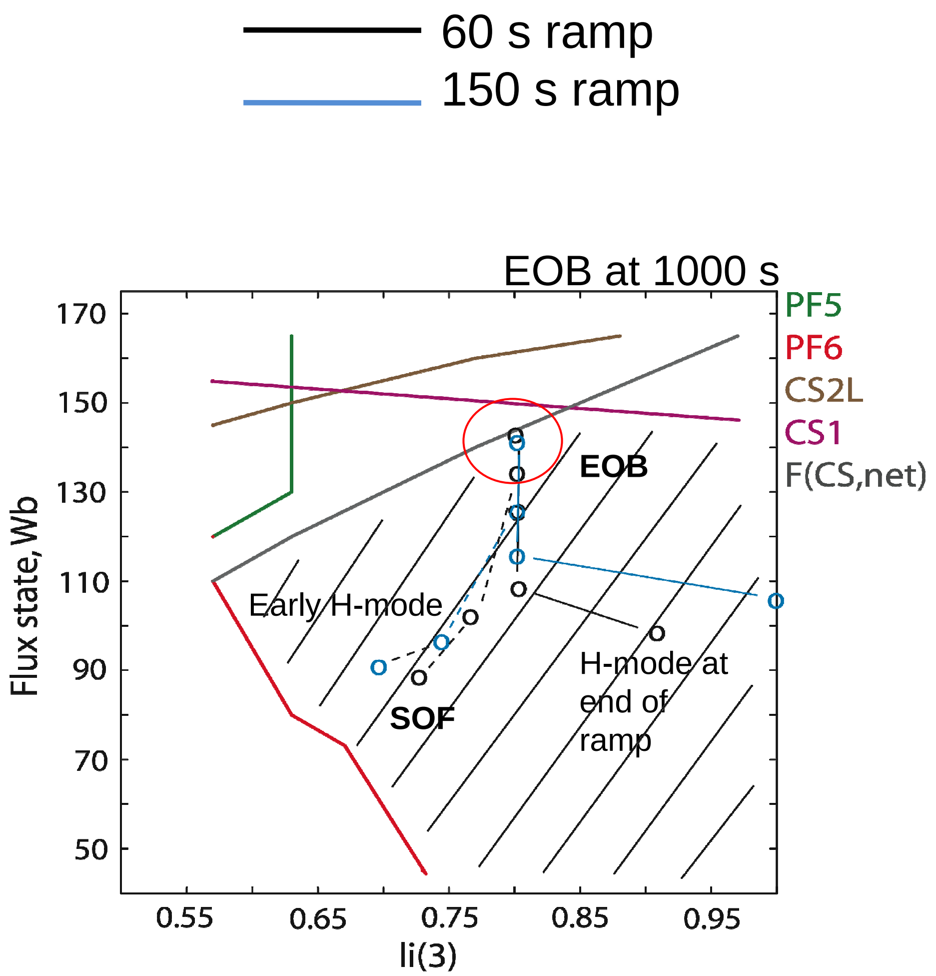
2 ramp rates shown – 60 and 150 s

60 s ramp uses 2.5 MW heating in the ramp

150 s ramp uses 10-15 MW heating in the ramp

Induced H-mode at end of ramp, or 2/3 of the way up the ramp

60 s ramp case with later H-mode gets close to the net CS force limit



Summary

A major goal of ITER physics studies is to identify optimal performance characteristics for a DEMO:

- Hybrid operation is viewed as a step in the direction of steady-state operation

The main objectives of studies of Hybrid operation in the present program:

- Clarify access conditions to enhanced confinement regimes
- Examine robustness through inter-machine studies
- Evaluate control requirements
- Determine scaling characteristics

Projections to ITER:

- Propose start-up scenarios and possible operating windows
- Provide guidance for upgrades (particularly CD)