ITER operation

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ITER

Some key statistics for ITER are:

Parameter	ITER	JET
Fusion power	500MW	$<$ 16MW
Burn time	400s	
Plasma current	15 MA	3.2 - 4.8MA
Major radius	6.2m	2.96m
Minor radius	2.0m	1.25/2.10m
Elongation	1.70 / 1.85	1.6
Plasma volume	840 m^3	100 m^3

Some key issues to achieve this are

- **Confinement**: Last lecture we looked at H-mode, needed to achieve the Q=10 design goals
- **Disruptions**: The plasma has to avoid major instabilities which lead to complete loss of confinement
- **Power handling**: Limits to the power on material surfaces

Confinement: H-mode

As we discussed last lecture, high confinement mode (H-mode) is the standard ("baseline") operation scenario for ITER.

- The standard H-mode will have ELMs, which need to be mitigated[1]
- Approximately doubles confinement time τ_E relative to H-mode
- Design objective for ITER is to achieve

$$Q = \frac{\text{Fusion power}}{\text{Heating power}} = 10$$

- The transition to H-mode is poorly understood, but can be routinely reproduced in modern tokamaks

[1] Lots of effort going into RMP coils, vertical kicks, pellets etc.

Getting into H-mode

- The amount of power needed to get into H-mode can be estimated using existing machines: an empirical scaling law e.g. [2]

$$P_{LH} = 0.048 e^{\pm 0.057} n_{e20}^{0.717\pm 0.035} B^{0.803\pm 0.032} S^{0.941\pm 0.019}$$

  where n_{e20} is density in units of $10^{20}\mathrm{m}^{-3}$, B is in Tesla and S is the plasma surface area in m^3.
- For ITER, $n_{e20} \simeq 0.5$, $B \simeq 5.3\mathrm{T}$, $S \simeq 678\mathrm{m}^2$ then $P_{LH} \simeq 55\mathrm{MW}$, but high uncertainty
- Note: $P_{LH} \propto nB$ is not dimensionally correct, and dimensional constraints are usually applied in modern scaling laws.

[2] Y.Martin *et.al.* IAEA technical meeting on H-mode Physics and Transport Barriers

Getting into H-mode

This scaling law gives an estimate of the minimum level of heating power needed to get into H-mode

- ITER expects to achieve 500MW of fusion power, and $1/5^{th}$ of this will be in alphas and contribute to heating
  - This should be easily enough to get into H-mode
  - but ITER must get into H-mode before it can get this power
- If more power is needed than the scaling law predicts (and is available on ITER), an option is to enter H-mode at low density, then slowly increase density while staying in H-mode

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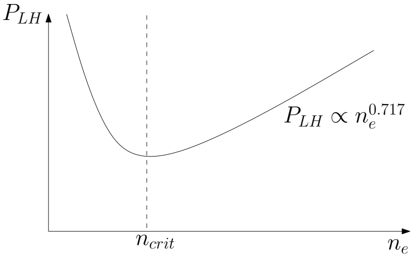
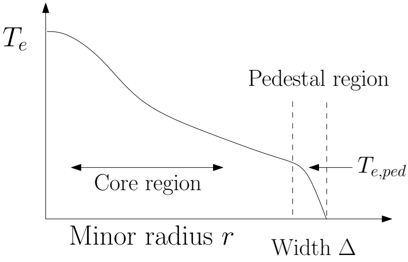
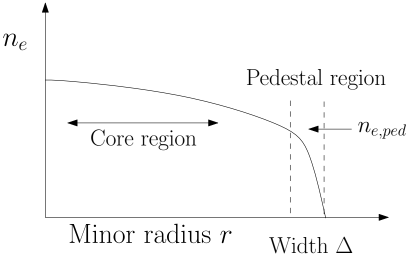
- There is an added twist: the power threshold rises at low density



H-mode profiles

In H-mode operation, the plasma profiles look something like:





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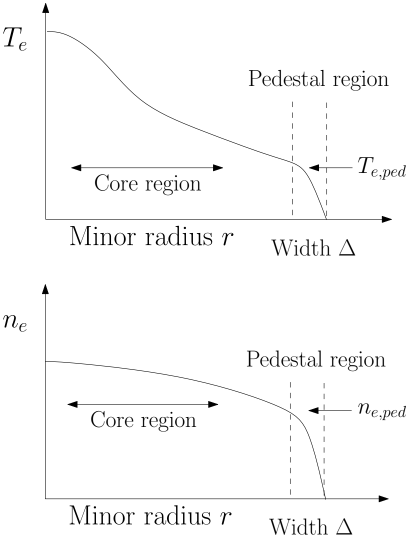

- Edge Transport Barrier leads to steep gradients of temperature and density
- The density tends to be very flat in the core:
  $$\frac{n_0}{n_{e,ped}} \sim 1.2 - 1.3$$
- Steep gradients at the edge can drive ELMs
- Flush out impurities, and control density
- ELMs in ITER could do a lot of damage to vessel components unless they are adequately controlled

Core transport: stiff profiles

- In the core plasma, small-scale instabilities such as ITG tend to limit the gradients
- Both theory and experiment find that core gradients are "stiff", and it's hard to change the temperature gradient away from
$$\frac{a}{T}\frac{dT}{dr} = -\lambda$$
where λ is an $O\left(1\right)$ constant, and $r = a$ is the plasma edge.
- Solution to this is
$$T = T_0 \exp\left(-\frac{\lambda r}{a}\right)$$
Therefore $T_0/T_{ped} = e^{\lambda} =$ constant, and the core temperature is proportional to the edge temperature.

ITER baseline scenario

The baseline scenario for operating ITER and achieving $Q = 10$ is ELMy H-mode:

- Power threshold $P_{LH} \sim 55$MW, marginal with existing heating. Lower density reduces threshold (up to a point).
- Once in H-mode fusion power provides more than enough to stay in H-mode
- The core temperature strongly depends on edge temperature, so a huge effort being put into understanding and predicting pedestal properties.
- ELMs provide density and impurity control, but are potentially damaging if not controlled
- Current diffuses into the core, dropping q to just below 1, so these plasmas will have sawteeth.

Power handling

In this course I've concentrated on the plasma physics aspects, and have left most of the more engineering aspects to the Fusion Tech course. There are some major issues which have implications for plasma operations though:

- The energy which leaves the core plasma has to go somewhere
- This will come from both heating input and α heating power
- Given 50MW of heating power, and $1/5^{th}$ of 500MW fusion power, the power output to divertors on ITER is around 150MW

Power handling

- Taking the simplest geometry, the area of the divertor is given by $2\pi R\lambda$ where λ is the width of the Scrape-off layer (SOL)
- The width of this SOL is highly uncertain, but simple estimates give $\lambda \sim 3$cm
- This gives $\sim 1.2\text{m}^2$, and so a power flux of over 125 MW/m^2
- This is totally unacceptable, and something more like 10MW/m^2 is needed

[3] G.F.Matthews "Plasma detachment from divertor targets and limiters" J.Nucl.Mat. 220-222 (1995) 104-116

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Several approaches are used including:

- Tilting target plates to spread the power over a larger area
- Magnetic geometries like Super-X and Snowflake
- The primary method to reduce the power reaching the divertor targets is currently **detachment**[3]

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- When plasma hits the divertor plates, it cools and recombines
- As the plasma density at the targets is increased, this neutral gas starts to interact with the incoming plasma

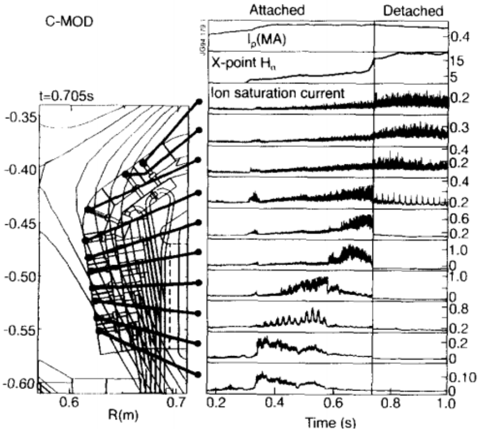

Figure : Divertor I_{SAT} on C-MOD. B.LaBombard *et.al.* Am.Phys.Soc.Conf. 1993 3S6

Divertor detachment

- To get this detachment, neutral gas needs to be retained close to the strike point
- On MAST getting divertor detachment is much more difficult due to the open geometry, but possible on the inboard leg [4]

[4] J.R.Harrison *et.al.* "Characterisation of detached plasmas on the MAST tokamak" J. Nucl. Mat. 2011 (in press)

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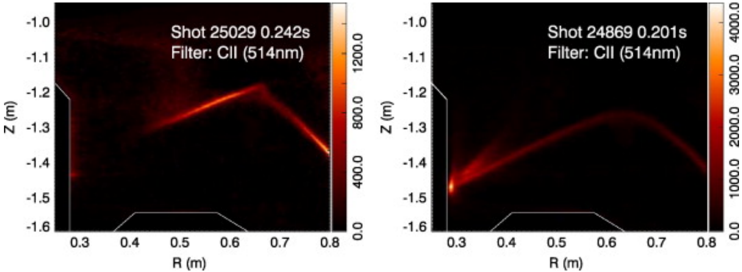

Figure : Filtered camera images from inner MAST divertor leg[2]. **Right**: standard operation, **Left**: Detached.

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Advanced scenarios

To operate a tokamak in steady state, we need to move away from inductive current drive

- Maximise the bootstrap current I_{bs}

$$\frac{I_{bs}}{I_p} \propto \beta_N q_a \qquad \beta_N = \frac{\beta\,[\%]}{I\,[\mathrm{MA}]\,/\,(a\,[\mathrm{m}]\,B\,[\mathrm{T}])}$$

  Need high edge q and high β_N
- MHD instabilities limit β_N to ~ 3 (see lecture 13), in particular Resistive Wall Modes, and NTMs.
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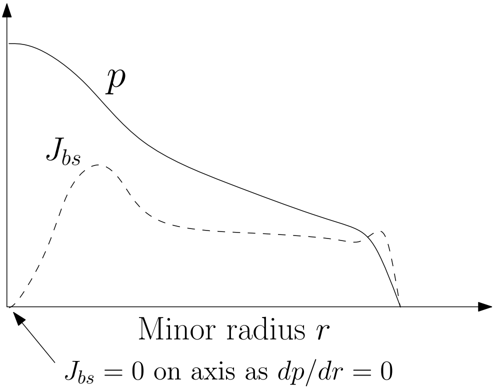
- MHD instabilities limit β_N to ~ 3 (see lecture 13), in particular Resistive Wall Modes, and NTMs.
- Need to optimise plasma for stability. Ongoing research area
- High edge q means low current ($q \propto 1/I_p$)
- From last lecture, $\tau_E \propto I$, so low current means low confinement
- Need to improve confinement beyond standard H-mode

Negative or reverse shear

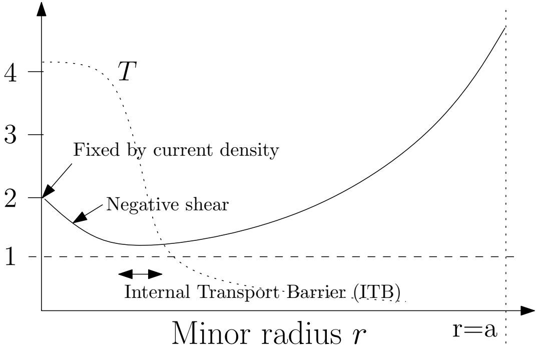
Recall that the bootstrap current density $J_{bs} \propto \frac{dp}{dr}$

- For a typical H-mode pressure profile, the bootstrap current is mainly driven off axis



Negative or reverse shear

Current driven off axis raises the q on axis (for fixed total current), as q_0 is set by the current density on axis.



- For reasons we don't understand, an Internal Transport Barrier (ITB) can form near to the region of zero shear.
- This can then provide the improved performance beyond H-mode

Challenges for Advanced Scenario

Although ITBs can provide the higher confinement that compensates for operating at lower current, there is a problem:

- A plasma with a steep pressure gradient in a region of zero shear is vulnerable to an ideal MHD instability when the minimum q is close to rational
  $\Rightarrow$ requires fine-tuning of the current distribution to avoid instabilities
- At high performance ($\beta_N \sim 3 - 5$), the plasma is unstable to Resistive Wall Modes (RWMs).
  - The plasma must be kept rotating to stabilise these
  - It's not clear that ITER will rotate sufficiently fast
- There is much current research on optimising stability to maximise pressure, and understand the formation of ITBs
- On ITER, the target is $Q = 5$ in the Advanced operation mode

Summary of ITER operation

- ITER baseline operation is ELMy H-mode, with $q \sim 1$ in the core, sawteeth and ELMs.
- In this mode ITER is designed for $Q = 10$ performance
- This is strongly dependent on the characteristics of the ITER pedestal
- Advanced scenarios aim for steady-state operation at $Q = 5$, by maximising the bootstrap current fraction and producing an ITB
- These need to operate above the no-wall stability limits, so optimisation of plasma parameters is key
- "Hybrid" scenario is somewhere in between, keeping q_0 just above 1. Objective is to get very long H-mode pulse lengths on ITER

Summary of the summaries

Optimising scenarios and solving the issues for ITER (and later DEMO) requires understanding many aspects of MCF physics:

- Plasma equilibrium and neoclassical physics, particularly bootstrap currents. Long pulse operation without solenoids.
- Plasma instabilities and performance limits. Find ways to maximise fusion yield without risking damage to the machine
- Heating an current drive methods which can be used to adjust pressure and current profiles and optimise performance
- Plasma transport, both neoclassical and turbulent

Many of these areas are still quite poorly understood. Hopefully this course has given you some background in each of these areas so that you can get into the literature and start to solve some of these problems!

Thank you!