Heating and current drive

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Previously...

- We've looked at equilibrium plasma configurations: Linear machines, tokamaks, and stellarators
- Mentioned in passing some means of sustaining these configurations, but in this lecture we'll go into some more details
- One class of methods uses radio-frequency waves to inject energy into the plasma, so we'll study these in the next two lectures
- Some of this will be familiar from fusion technology, but this time we'll go more into the plasma physics of these systems

Heating and current drive

- In all fusion reactors, we need to get the core of the plasma to $\sim 10 - 20$keV i.e. around 100 million ^{o}C
- Heating is needed during startup before alpha heating can take over
- In tokamaks we need to drive a toroidal current to create the rotational transform
- Currents are also key to some plasma instabilities such as NTMs (later in the course) so targetted current drive is being investigated for instability control

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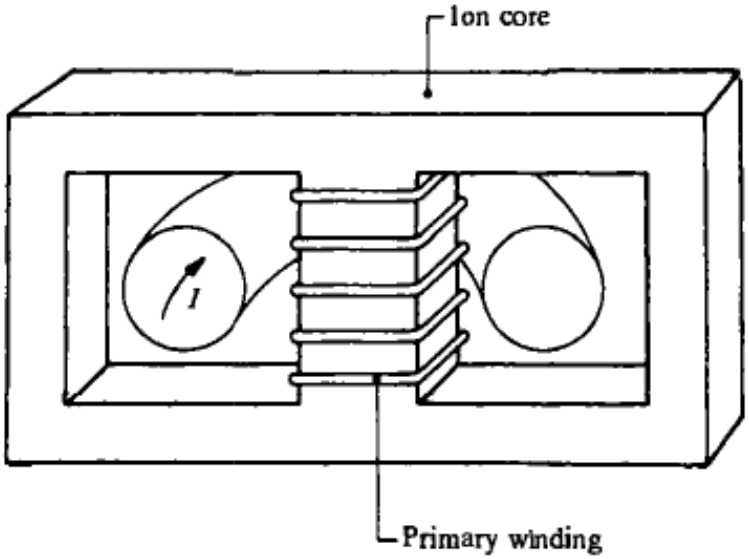
Mechanisms:

- Ohmic: use a transformer to create a toroidal electric field and drive a current
- Radio-frequency (RF) injection
- (Neutral) beam injection (NBI)

Transformer action

A toroidal electric field is produced by changing the magnetic flux through the centre of the machine



$$\oint \underline{E} \cdot d\underline{l} = -\frac{\partial}{\partial t} \int \underline{B} \cdot d\underline{S}$$

The field in a solenoid is given by

$$B = \frac{\mu_0 \mu_r N}{L} I$$

where N is the number of turns and L is the length of the solenoid. The toroidal electric field E_ϕ is therefore given by

$$2\pi R E_\phi = -\frac{\mu_0 N A}{L} \frac{\partial I}{\partial t}$$

where A is the cross-sectional area of the solenoid.

Current evolution

In a plasma a simplified form of Ohm's law is

$$\underline{E} + \underline{v} \times \underline{B} = \eta \underline{J}$$

Assuming a stationary plasma, take the curl of this equation

$$\nabla \times \underline{E} = -\frac{\partial \underline{B}}{\partial t} = \nabla \times (\eta \underline{J})$$

Taking the curl again, and taking η as a constant

$$-\frac{\partial}{\partial t} \nabla \times \underline{B} = \eta \nabla \times \nabla \times \underline{J} = \eta \left[\nabla (\underbrace{\nabla \cdot \underline{J}}_{=0}) - \nabla^2 \underline{J} \right]$$

$$\Rightarrow \frac{\partial \underline{J}}{\partial t} = \frac{\eta}{\mu_0} \nabla^2 \underline{J}$$

This is a diffusion equation for current

Current evolution

If the resistivity η is not constant then the equation looks like

$$\frac{\partial \underline{J}}{\partial t} = \frac{1}{\mu_0} \nabla^2 (\eta \underline{J}) - \nabla [\nabla \cdot (\eta \underline{J})]$$

Taking the toroidal (ϕ) component of this, then assuming axisymmetry

$$\frac{\partial J_\phi}{\partial t} = \frac{1}{\mu_0} \nabla^2 (\eta J_\phi)$$

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- When driving current using a toroidal electric field, current is initially driven at the surface and then diffuses into the plasma
- Diffusion coefficient $D_J \simeq \eta/\mu_0$ m^2/s
- Plasma resistivity (Spitzer) $\eta \simeq 10^{-4} Z \ln\Lambda\, T^{-3/2}\Omega\mathrm{m}$ so $D_J \sim 10^3\, T^{-3/2}\mathrm{m}^2/\mathrm{s}$
- For a plasma on the scale of meters, at 10eV the timescale is $\sim$ 10ms and at 1keV it's 10s of seconds

Current evolution

- During plasma startup, the current quickly diffuses into the plasma
- Resistive heating ηJ^2 raises the temperature
- As the discharge goes on, current tends to diffuse into the plasma core and the safety factor q falls
  $\Rightarrow$ has implications for plasma stability
- In steady state, $\eta J_\phi =$const so $J_\phi \propto 1/\eta$ and most current flows in the hot core of the plasma

Ohmic heating limits

The resistivity of a plasma decreases with temperature $\eta \propto 1/T^{3/2}$

- As the plasma heats up, the amount of energy which can be injected into the plasma drops
- For typical reactor parameters, this limits the temperature to $T \sim 3\text{keV}$
- At this temperature the alpha heating won't be sufficient
- $\Rightarrow$ additional heating is needed to get to burning reactor temperatures

Ohmic engineering limits

There are engineering limits to Ohmic heating

- To create a constant electric field, the current must vary at a constant rate. There is a limit to how much current can be driven
- Running a current through a solenoid will heat it, so eventually there is an I^2R limit

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- Spherical tokamaks will have to operate entirely without a solenoid as there is insufficient space for the shielding needed $\Rightarrow$ solenoid-free startup is being investigated on MAST and NSTX

Neutral Beam Injection

We need another way to get energy into the plasma. Due to the magnetic field, we can't inject charged particles as they'll just be deflected.

As neutral atoms are unaffected by magnetic fields, they will travel through a plasma until they are ionised by collisions

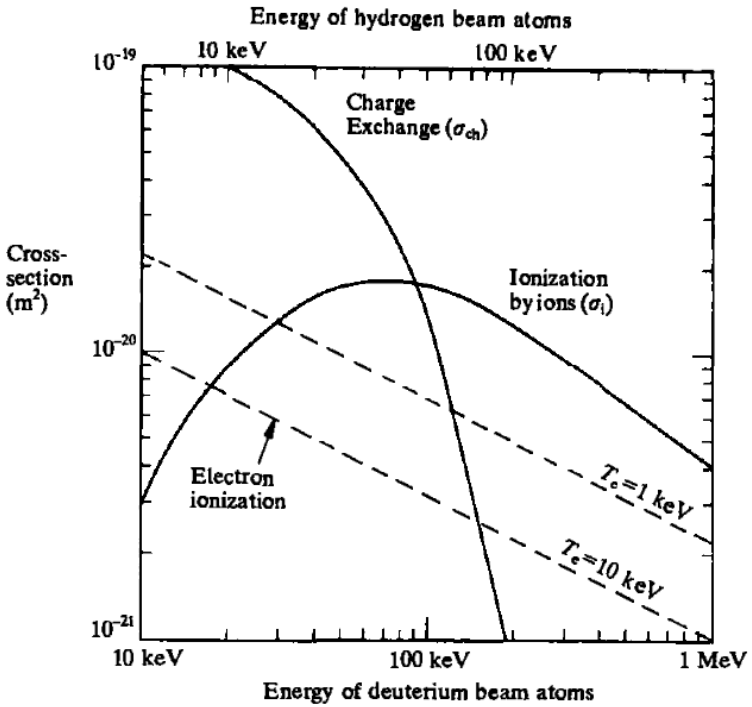

Figure : [Wesson fig 5.3.1]

- Charge exchange
  $D_b + D_p^+ \rightarrow D_b^+ + D_p$
- Ionisation by ions
  $D_b + D_p^+ \rightarrow D_b^+ + e + D_p^+$
- Ionisation by electrons
  $D_b + e \rightarrow D_b^+ + e + e$

'b' = beam, 'p' = plasma

Neutral Beam Injection

Neutral beam systems provide three things:

- Heating: these systems usually supply $\sim$ MW of power
  Need to get energy into the plasma core: too high cross-section and just the edge will be heated, too low and the beam could "shine through" the plasma

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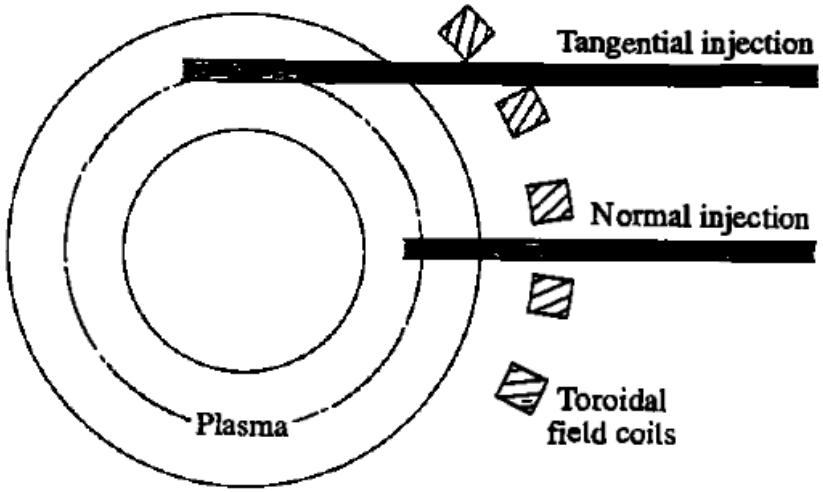

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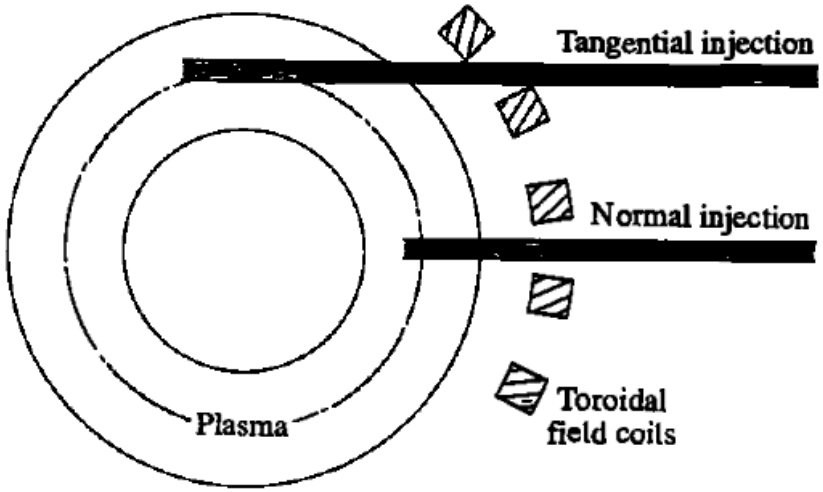

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- Current: drive a net current in the plasma

Neutral Beam Current Drive (NBCD)

- After ionisation, the electrons and ions in the beam collide with the background plasma and slow down
- This happens faster for electrons than for ions (due to their smaller mass) and so a net current is produced in the direction of the beams
- Collisions with between beam ions and electrons produce an electron beam which partly cancels the ion current
- Because the fast ions travel around the torus multiple times the current "stacks up"
- A complicated process involving particle collisions and trapping. In general codes needed to calculate current deposition
- As the plasma spins up this also reduces the efficiency

Neutral beam injection systems

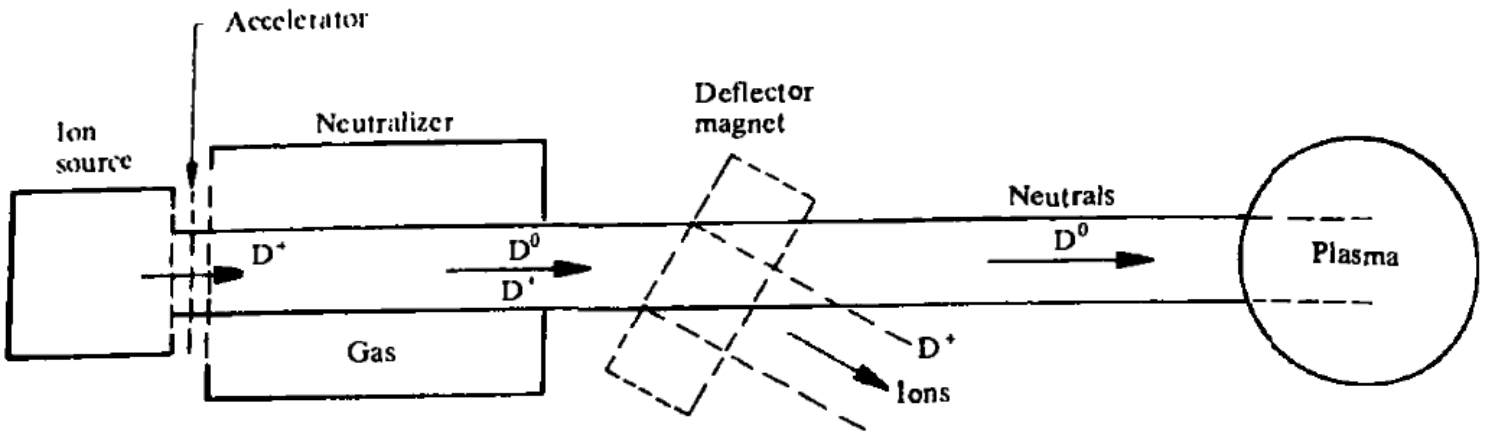

Figure : Layout of NBI system [Wesson fig 5.5.1]

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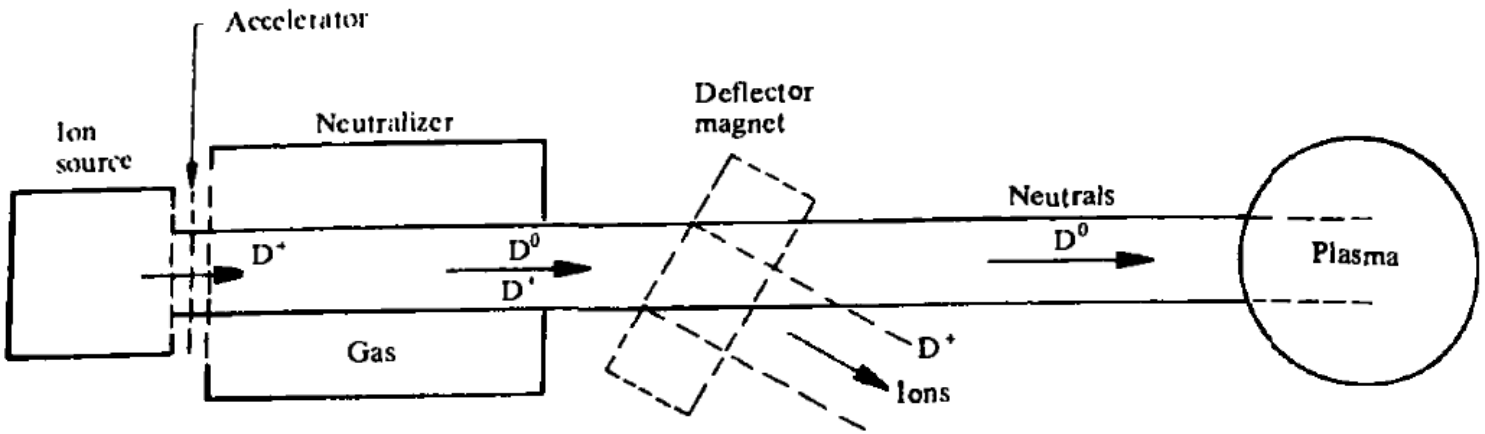

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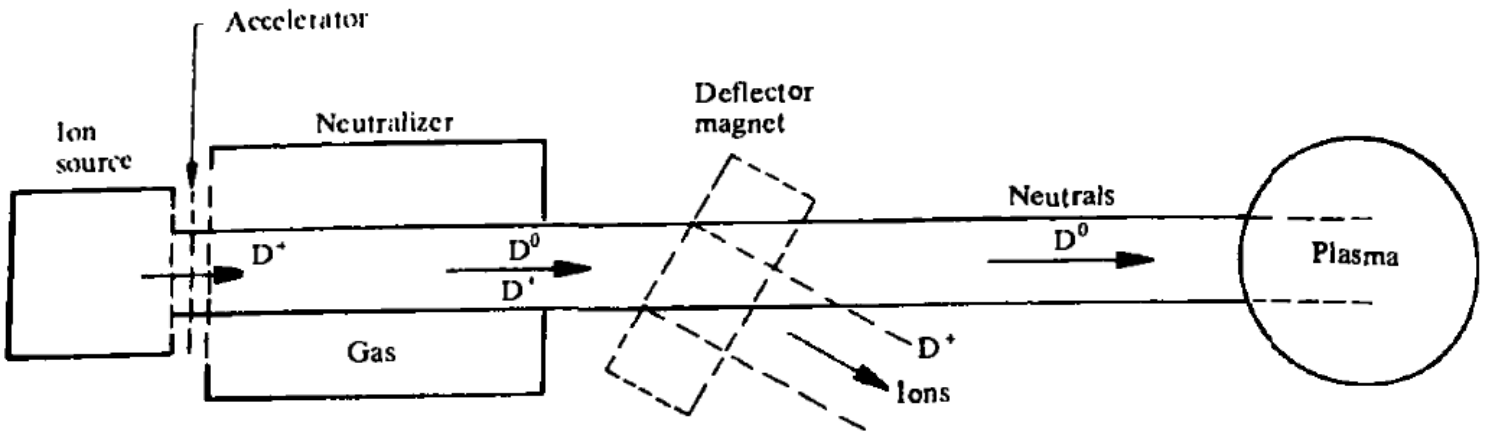

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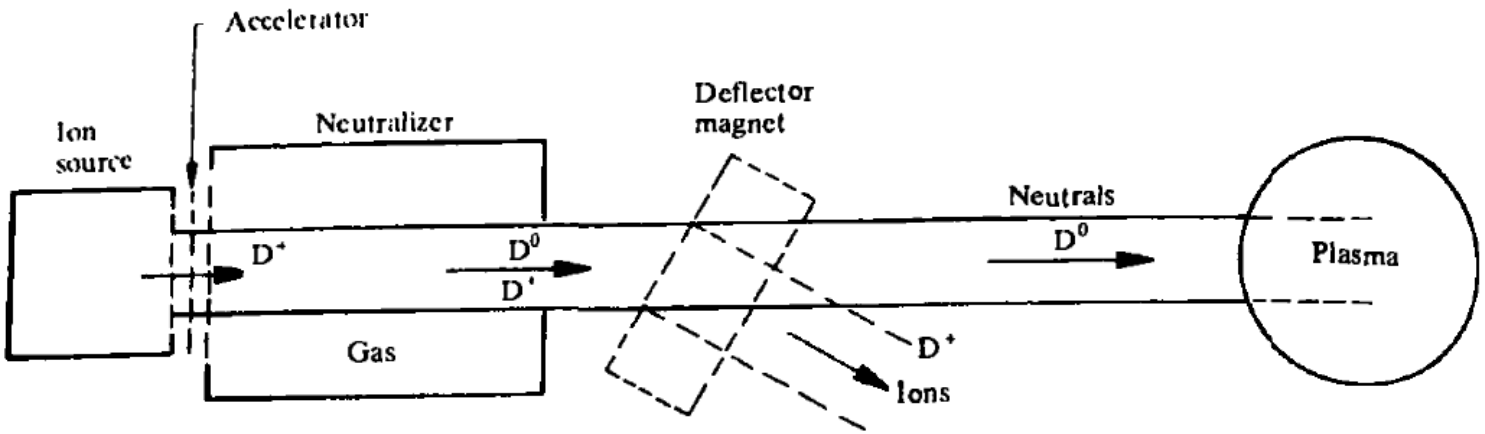

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- The ions are passed through a grid and accelerated across a high voltage
- Ions pass through a box of neutral gas. Inelastic collisions lead to charge exchange
- Remaining ions are deflected onto beam dumps

Neutral beam injection systems

Tend to be large and complex systems

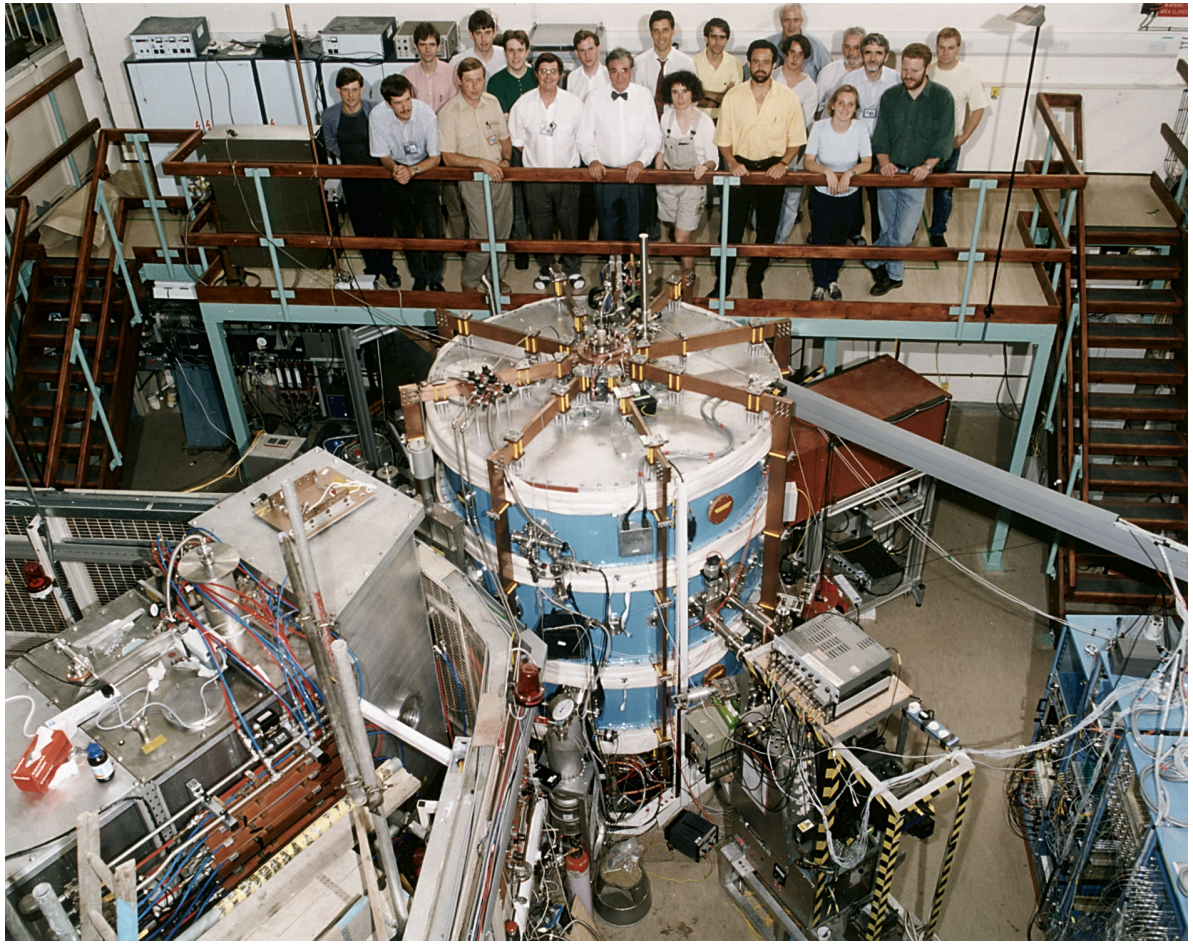

Figure : START tokamak, NBI system lower left

Positive ion beam limits

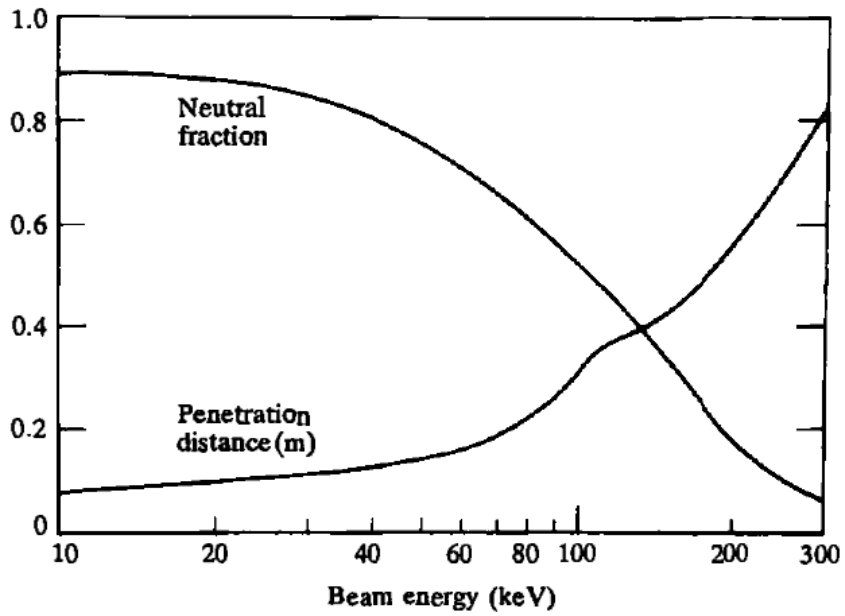

Figure : Fraction of neutrals in the beam and penetration distance into the plasma [Wesson fig 5.5.3]

- At higher energies neutrals penetrate further into the plasma
- It also becomes harder to neutralise the ion beam so the efficiency drops at higher energies
- ITER and fusion reactors are bigger, and have higher density and temperature and so need beams of $\sim$ 1MeV neutrals.

Negative ion beams

Positive ion beams can't be used in ITER, so several groups are developing negative ion beam systems

- In negative ions the extra electron is only weakly bound
- This makes neutralising the beam easier
- Result is that the efficiency is much better at high energy (e.g. 1MeV)
- Problem is generating negative ions, which is more complex than positive ions

Summary

- Transformer action can be used to produce a toroidal electric field and drive an **Ohmic** toroidal current
- This current diffuses through the plasma, tending to concentrate in the hot core where the resistivity is lower
- Because resistivity drops with temperature, Ohmic heating is limited to $\sim$ 3keV, too low for alpha heating to take over
- There are limits to how long Ohmic current drive can operate
- Neutral beam systems can be used to provide additional heating, momentum input and current drive
- Current systems are positive ion, but ITER and future reactors will need more complex negative ion systems
- Other issues: fast particles from NBI can also interact with MHD waves and instabilities e.g. drive fishbone instabilities and affect sawteeth