Fusion Reactor Technology I
(459.760, 3 Credits)

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Introduction:
Engineering Issues for Physicists

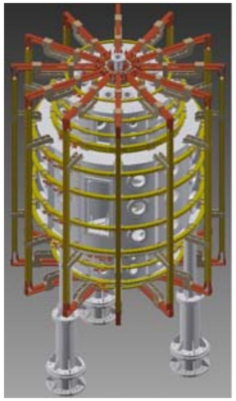
- To allow a physicist to understand the mix of physics and engineering which has to come together to achieve some desired level of machine performance or to match some resource investment

- Generic issues: finding a machine size, plasma current, heating power and so on consistent with the broad objectives and overall budget available
- Specific issues: machine topology, conditioning processes, control system and design options for the key components of the load assembly and power supplies, permitting the physicists and engineers to converge upon a workable design

Project Aims and Constraints

- The level of machine sophistication required varies with the real purpose of the device.

- Establishing national plasma physics centre?
- Enhancing the training of the nation's plasma physicists?
  → Large enough machine to have interesting plasma parameters
  Ex) a tokamak of ≥ 5 kA plasma current



- Creating national expertise in tokamaks
  → a tokamak of ≥ 150 kA plasma current,
  probably with some specific design features
  to address certain key issues
- Time scale and budgetary constraints

Machine Size

- Plasma current range determined by considering the purpose and resource constraints
  → other leading parameters and cost related with the current

$$q_a = \frac{5a^2 B}{RI}\left(\frac{1+\kappa^2}{2}\right)\left[1+\left(1+\frac{\Lambda^2}{2}\right)\right]\left[1.24-0.54\kappa+0.3\left(\kappa^2+\delta^2\right)+0.13\delta\right]$$

$$\approx 6a^2 B\kappa / RI$$

$$\approx (6\sim 12)a^2 B / RI = (6\sim 12)\varepsilon^2 RB / I$$

$$\geq 2$$

$$\Lambda = \beta_p + \frac{l_i}{2}$$

$$\Rightarrow \quad \varepsilon^2 RB \approx qI/(6\sim 12)$$

$$\varepsilon^2 RB \geq I/(3\sim 6)$$

- The cost of the device rising with *R* and *B*, but also *ε* due to engineering difficulties at the central region of the machine

Machine Size

- A set of scalings developed from JET cost analysis and benchmarked against the LHD

  - Load assembly: $\$17\text{M} \times aR\kappa^{1/2}$
  - Pumps and cooling system: $\$16\text{M} \times aR\kappa^{1/2}$
  - Power supplies: $\$2.6\text{M} \times a^2 B^2 \kappa$
  - Auxiliary heating: $\$2\text{M} \times P_{aux}$
  - Buildings: $\$0.2\text{M} \times \text{number of professional staff}$

  not including factors such as existing building availability, problematical special design features

- The number of professional people-years required to implement the device can be very roughly estimated by dividing the resulting total by $150k.

Auxiliary Heating

- Aim

- Bulk plasma heating
- Bulk current drive
- MHD instability control

→ determining the choice of a suitable scheme
  and the likely power requirements

Auxiliary Heating

- Bulk plasma heating

- Required power = stored energy / energy confinement time

$$\beta \approx 3.5 I / aB$$

$$\tau_E^{ITER89P} = 0.038(M/Z)^{0.5} I^{0.85} B^{0.2} R^{1.2} a^{0.3} \kappa^{0.5} \overline{n}_{19}^{0.1} P_{tot}^{-0.5}$$

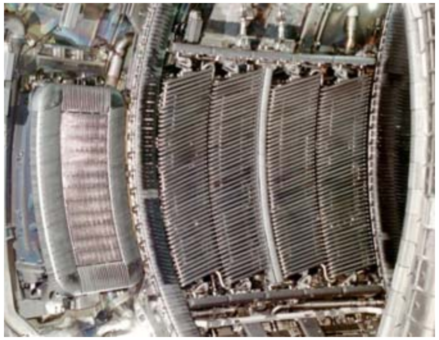
$$P_{tot} = \frac{a^2 R \kappa B^2 \beta}{8.49 \tau_E^{ITER89P}}$$: total power required to attain a given β

$$P_{tot} \approx \frac{118 a^{1.4} \kappa B^{1.6} I^{0.3} Z}{R^{0.4} n_{20}^{0.2} M}$$: required maximum power

Auxiliary Heating

1. ICRH, ECH

- Constraint on *B* to match the favoured heating frequency (*f*) at a chosen harmonic number (*l*)



ICRH: $B \approx (M/Z) f / 15l$

$$\omega_c = l \frac{qB}{m}$$

ECRH: $B \approx f / 28l$

- HFS for X mode fundamental: $\bar{n}_{e19} \leq 6(f/60)^2$
- LFS for O mode: $\bar{n}_{e19} \leq (f/60)^2$

  X mode second harmonic: $\bar{n}_{e19} \leq 1.3(f/60)^2$

2. LH

- Access criterion to reach the core of the plasma

$$B/(n_{e19})^{1/2} \geq 2N_{\|} / \left(N_{\|}^2 - 1\right), \quad N_{\|} = c / v_{phase} \sim 3$$

Auxiliary Heating

3. NBI

- Plasma line averaged density has to be large enough to stop the majority of the beam.

$$\text{beam path length} \times \bar{n}_{e19} \approx 22(E_{beam} / M_{beam})^{2/3}[2.3 - \ln(F / 0.1)]$$

F: shine-through fraction

- The plasma current has to be large enough to confine the resulting fast ions: to keep the full banana orbit widths at some prescribed small fraction of the minor radius.

$$I \geq 2.0(\varepsilon M_{beam} E_{beam})^{1/2} / [Z(\Delta_{banana} / a)], \quad \Delta_{banana} / a \leq 1/3$$

$$\Rightarrow \quad I \geq 6(\varepsilon M_{beam} E_{beam})^{1/2} / Z$$

HW: plasma current .VS. fast ion confinement

- Density limit

$$1.5 \times 10^{-14} \leq \frac{I}{\pi a^2 \kappa \bar{n}} \leq 1.5 \times 10^{-13}$$

disruptions runaway electrons

Auxiliary Heating

- Bulk plasma current drive (CD)

- Theoretical current drive scaling by considering electron scattering processes

$$I = k\frac{PT_e}{Rn\ln\Lambda}, \quad \Lambda \sim 16$$

1. LHCD

$$k \propto 1/N_{\parallel}^2 T_e$$

$$P_{LHCD} \approx (0.3 \sim 2) IRn_{19}$$

2. NBCD

$$k \approx \text{constant}$$

$$P_{NBCD} \approx 5IRn_{19}/T_e \cos\phi_{beam} \text{ for } Z_{eff}/Z_{beam} \approx 2$$

Φ_{beam}: angle between the beam and the magnetic field

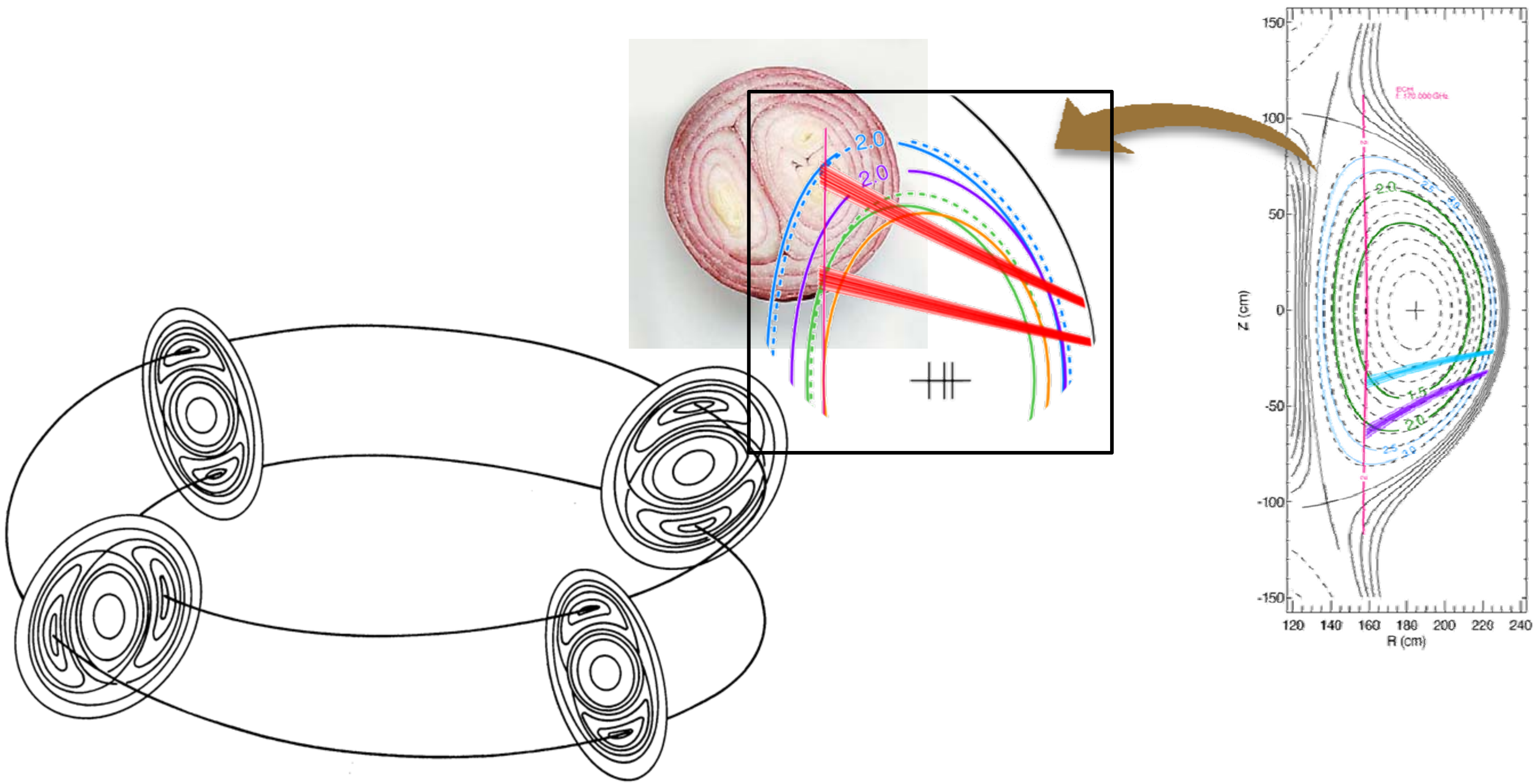
Auxiliary Heating

- MHD stability control

- Perturbing the plasma pressure or current profile by localised heating or CD
- Necessary power estimated as a small fraction (10 or 20%) of that required to perform the gross heating or CD
- In the special case of stabilising a low-*m* mode with CD localised to the region of the mode resonance and synchronised to the mode phase, a still smaller fraction suffice, ≤ 1% of the total plasma current needed to be driven.

Auxiliary Heating

- MHD stability control: neoclassical tearing mode (NTM) by ECCD



Auxiliary Heating

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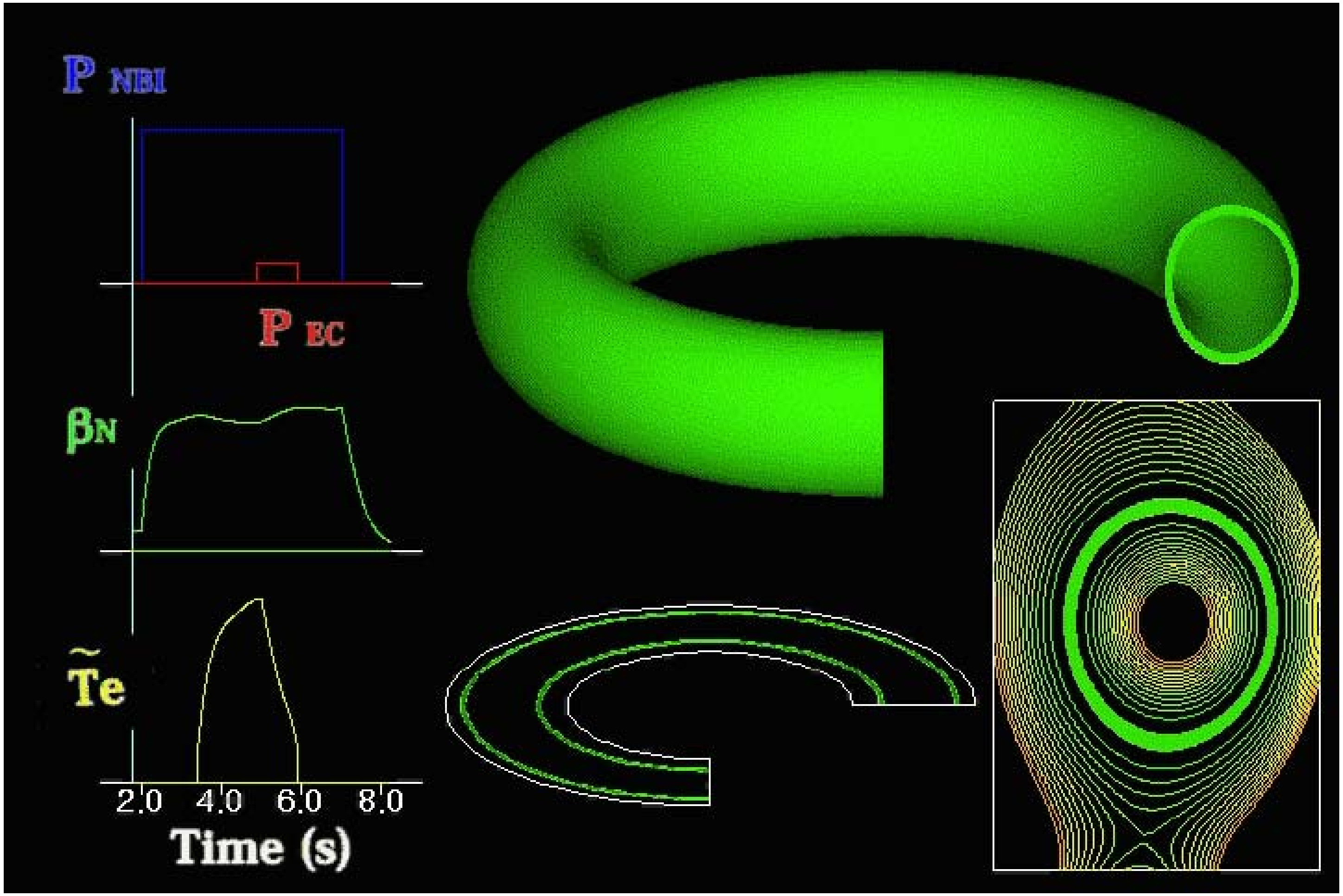

Auxiliary Heating

- Consideration of the effects required of the auxiliary heating system and the overall consistency of the machine parameters will lead to the selection of one or more schemes and the necessary power in each one.

- Construction costs: $(1~4)/watt-at-the-plasma

- Power demand: typically a factor of 2~5 greater than the power-at-the-plasma

- A team dedicated to run the auxiliary heating system required