Fusion Reactor Technology I
(459.760, 3 Credits)

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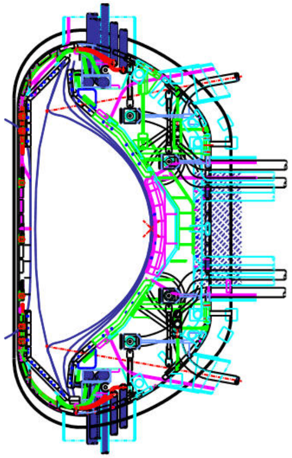
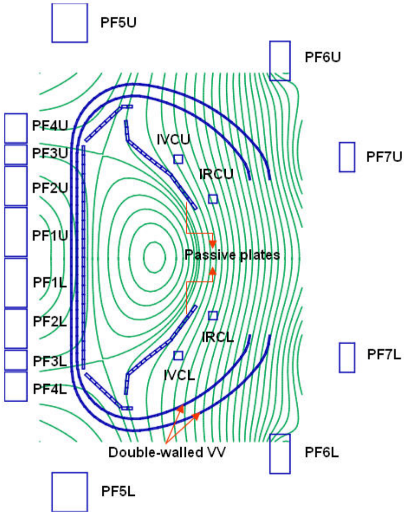
- Which coils are nearest to the plasma, those producing the toroidal (TF) or the poloidal field (PF)?

- Fast control coils close to the plasma
- Typically solenoid windings and main equilibrium field coils placed remotely

Discussion Time (5 min)





KSTAR

Topology

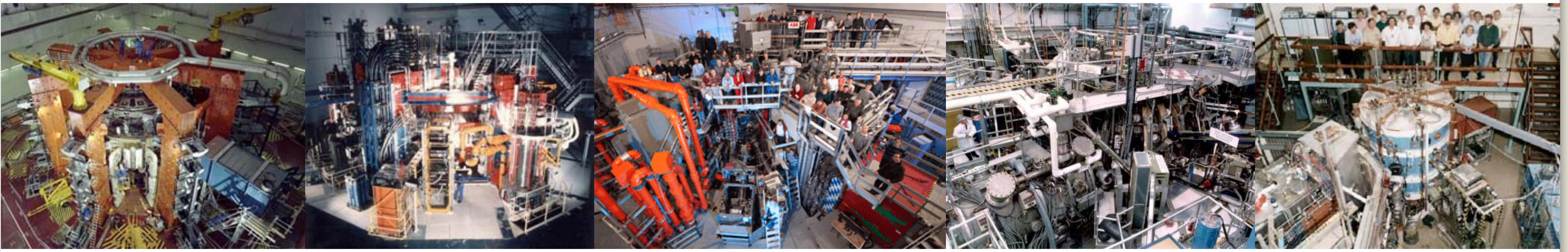
- Which coils are nearest to the plasma, those producing the toroidal (TF) or the poloidal field (PF)?

Coils nearest plasma	Advantages	Disadvantages
Toroidal field	- Smallest possible stored magnetic energy - No interlinking of coils	- Many coils needed to avoid severe ripple - Restricted OH solenoid diameter if air-cored - Difficult to get strong plasma shaping
Poloidal field	- Easy to shape plasma - Possible gain in plasma vertical stability - Largest possible (air-cored) OH solenoid diameter - Can use fewer TF coils - Good access for (small) diagnostics	- Interlinked coils, therefore joints somewhere - Larger TF stored energy

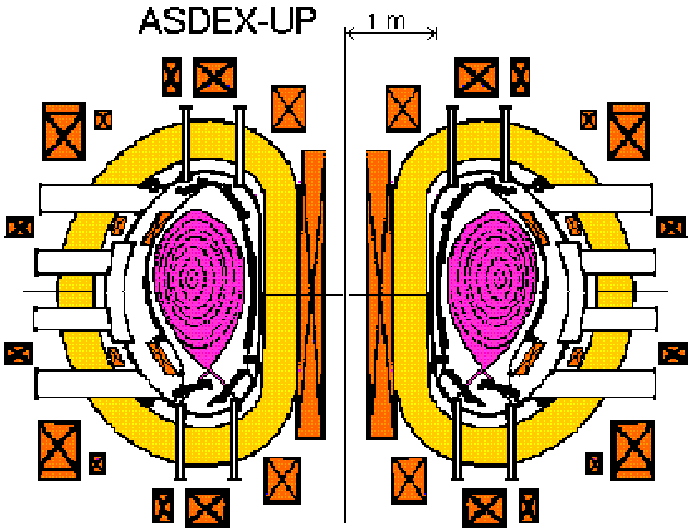
Topology

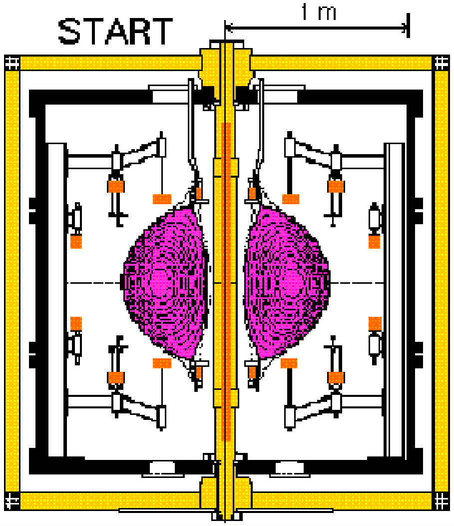
- Which coils are nearest to the plasma, those producing the toroidal (TF) or the poloidal field (PF)?

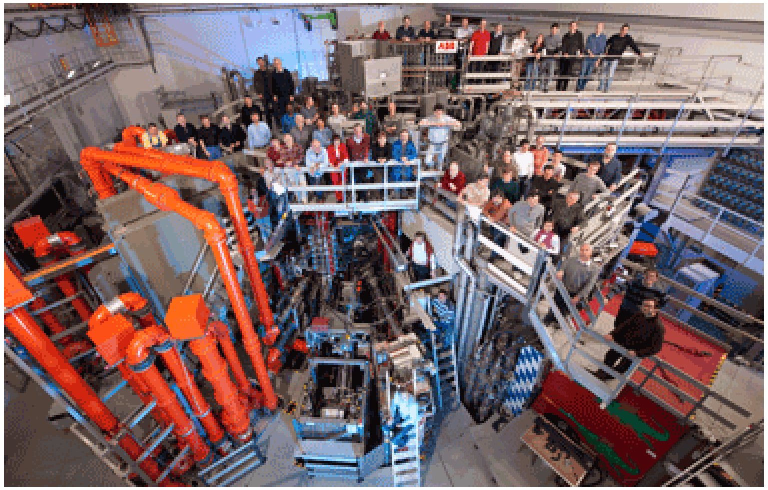
- Fast control coils close to the plasma
- Typically solenoid windings and main equilibrium field coils placed remotely
- JET, TORE SUPRA: iron-cored
- ASDEX Upgrade: air-cored
- DIII-D: air-cored with the PF coils all interlinking the TF coil set
- START: no solenoid, a single turn TF coil arrangement
  and jacketted PF coils inside the vacuum vessel
  (pursuit of minimum possible plasma aspect ratio)

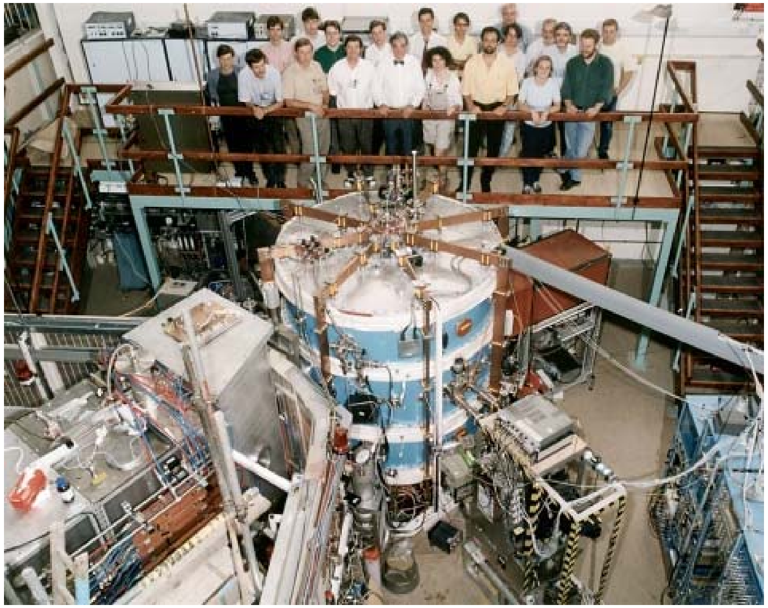


Topology

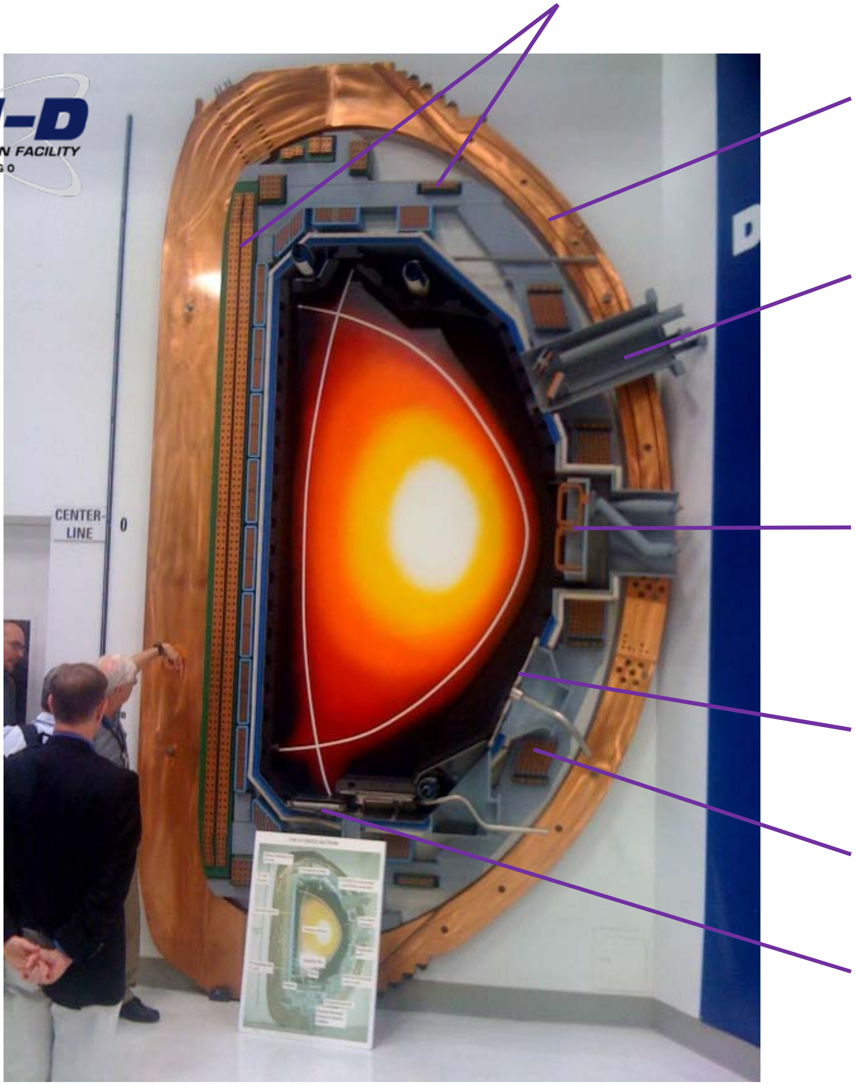








Topology



OH heating coil

Toroidal field coils

Port access

Limiter (pumped)

Vacuum vessel

Poloidal field coils

Divertor

Toroidal Field Coils

- TF coils system has to be strong enough to tolerate the forces imposed on it.

\- Primary self- (i.e. bursting) force

$$F_{self} \approx 2.5 B_{\phi 0}^2 R_0^2 / NR$$

In each of the *N* limbs, and the toppling force due to the interaction with the PFs

\- Often worst immediately following a disruption, due to the vertical field in the absence of toroidal current in the plasma (and vessel)

$$F_{toppling} = \frac{5 B_0 R_0}{N} \times B_v \approx \frac{B_0 I}{2N} \ln\left(6R_0 / a\right)$$

HW: Detailed forces acting on TFCs and PFCs

→ Tensile and bending stresses

→ Can be reduced to pure tension for the self-force on a D-shaped coil

→ Finite element modelling needed to determine the stress distribution

Toroidal Field Coils

- Requirements

KSTAR: 50,000 pulses, 1,000,000 s of total operation
5,000 pulses/year, 100,000 s operations/year

- Cycle lifetime: 10 times the number of machine shots envisaged
  keeping below ~30 MPa for conventional copper (OFHC)
  ~200 MPa for special copper alloys

- Compromise between strength and conductivity
  Alloying the copper to produce a high strength material increases its resistivity.
  Cf. The state of work-hardening of the delivered material may not be very critical due to an annealing effect during operation.
  Avoiding using a high resistivity conductor due to:
    extra power and energy demanded to produce B_t
    various thermomechanical and thermohydraulic problems caused by the temperature rise of the coils and their insulation

Toroidal Field Coils

Ohmic heating rate in a conductor $\dot{\theta} = \eta J^2 / \rho S$

For warm copper $\dot{\theta} \approx 0.6 J^2$

Range of J to run copper coils in steady state using water cooling, while otherwise intershot cooling is usually required: $J \leq 2 \sim 3\ \mathrm{kAcm}^{-2}$

If the vault of inner TFC limbs has a copper fraction f_c, and inner and outer radii r_1 and r_2, respectively,

$$J = \frac{0.5 B_0 R_0}{f_c \pi \left(r_2^2 - r_1^2\right)}$$

Use of insulation of the epoxy-resin-glass type:

upper temperature limit ≤ 100 °C
a rise during the shot of ≤ 80 °C

$$\int J^2 dt \leq 133\,\mathrm{kA}^2\mathrm{cm}^{-4} s$$

$$\left(r_2^2 - r_1^2\right) \geq \frac{0.5 B_0 R_0 \left(T_{pulse}\right)^{1/2}}{f_c \pi (133)^{1/2}} \rightarrow \left(r_2^2 - r_1^2\right) \geq \frac{B_0 R_0 \left(T_{pulse}\right)^{1/2}}{73 f_c}$$

Determining the necessary extent of the TFC vault in major radius

Toroidal Field Coils

- Superconducting coils
- Modest power supply required
- Need for liquid He and liquid N_2 refrigeration plant and its power consumption (10-20 MW for a big machine)
- The space demands in the overall conductor pack for the cryostats and thermal insulation
- Need for detailed analyses of eddy current and neutron heating
- Requirement for quench stabilisation in terms of J_{crit}: a great deal of copper (or aluminium) and liquid He to the conductor CX

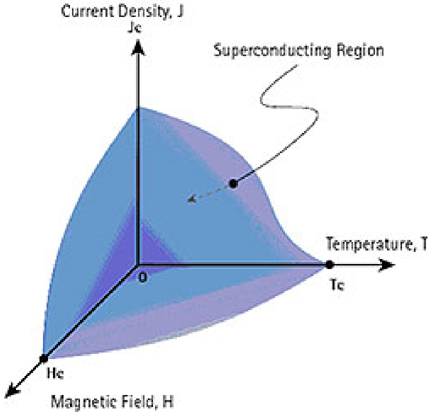
Ex. NbTi (peak field of 6.1 T):

122.5 $\mathrm{kAcm^{-2}}$ in the NbTi alone

21.0 $\mathrm{kAcm^{-2}}$ in the cable

6.8 $\mathrm{kAcm^{-2}}$ in the overall conductor

$$J = \frac{0.5 B_0 R_0}{f_c \pi \left(r_2^2 - r_1^2\right)} \rightarrow \left(r_2^2 - r_1^2\right) \geq \frac{0.5 B_0 R_0}{f_c \pi J_{crt}}$$



Toroidal Field Coils

- Superconducting coils

KSTAR의 냉동기 power는 4.5K에서 9kW입니다.
즉, 외부에서 9kW의 열침입이 있어도 전체 시스템을 4.5K으로 유지할 수 있는 능력입니다.
액체헬륨을 만드는 것은 기체 헬륨을 잔뜩 압축했다가 갑자기 여러단계로 단열 팽창해서 온도를 내리는 것이기 때문에…
압축기 (Compressor)가 전기를 많이 잡아 먹습니다.

압축기의 전력소모량은 4MVA (MW하고 거의 비슷한 단위기는 한데 압축기의 모터가 인덕턴스 성분을 잔뜩 가지고 있으므로 전압, 전류의 위상차가 달라지는 시스템에서는 이렇게 표기) 정도 됩니다. 그래서 24시간 운전 때는 하루에 전기료만 1500만원 ~ 2000만원 정도 가죠..

- 양형렬 박사 (NFRI)

Toroidal Field Coils

- Power supply demand

\- Reactive power producing the stored magentic energy in the required rise time

$$P_{reactive} = \frac{2.5 B_0^2 R_0^2 h \ln\left(R_2 / R_1\right)}{T_{rise}}$$

h, R_2, and R_1: height, major radii of the outer and inner TFC limbs

\- Resistive power (assuming warm copper, rectangular coil)

$$P_{resistive} \approx \frac{0.3 B_0^2 R_0^2 \left(h + R_2 - R_1\right)}{f_c (r_2^2 - r_1^2)}$$

Toroidal Field Coils

- Power supply options

Type	Advantages	Disadvantages
Capacitor banks	Very low mains power demand; simple and very cheap	Very poor control of current waveform
Inductive storage	Cheaper than capacitor bank systems at very large energies	Switching problems
Flywheel motor generators	Low (pony motor) mains demand; optional stator field control; very large powers and energies readily available	Output frequency falls during pulse

Toroidal Field Coils

- Power supply options

Type	Advantages	Disadvantages
Steady state motor generators	Some flywheel effect to accommodate transients; clean DC output with optional feedback control by stator field	Severe mains demand; feedback response time can be slow
Thyristor rectifier	Fairly fast if multiphase (e.g. 12 or 24 phases); natural inversion available	Ripple and noise in load current; worst possible option for mains demand; large signal BW poor, particularly for turn-off; four-quadrant versions 'messy'
Thyristor chopper	Very fast; can run from capacitor bank(s); readily made multiple-quadrant	Ripple and noise in load current (and or complexity if multirail)
Transistor amplifier	Linear, clean output, very fast four-quadrant feedback control	Limited to a few hundred kilowatts per unit; expensive

Stray Fields

- Two categories
  - Average perpendicular fields, which inhibit plasma breakdown and may cause plasma motion during the plasma discharge
  - Resonant magnetic perturbations (RMPs) which tend to create magnetic islands in the plasma region, possibly affecting plasma confinement and stability (e.g. via ‘mode lock’ phenomena)
- Perpendicular field
  - Originating from systematic (or net) tilt errors in the placement of the coils, or from the interconnection scheme if this is not well thought out
  - Constraint on the permissible construction error tilt angles in radians: $B_\perp / B_\phi << 10^{-3}$

Ex) COMPASS

aligned during assembly to ~ 0.4 mm, coils size ≈ 1.5x1.0 m^2

axisymmetric field ≤ 0.1 mT at 1.75 T

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Ex) KSTAR: 모든 초전도자석의 설치오차는 6축 공차기준으로 최대 변위가 1mm입니다. 즉, x, y, z 축상 변위오차와, 세 축을 중심으로 회전하는 결과의 오차에서 가장 변위가 큰 지점에서의 오차를 말하는 것입니다.

- 양형렬 박사 (NFRI)

Stray Fields

- RMPs

- Originating from random differences in placement from coil to coil and from nonaxisymmetric stray fields generated by the feeder bars
- Forming a magnetic island at the relevant resonance ($q = m/n$)
- Island width

$$\frac{W}{a} = \left(\frac{16}{n} \frac{\tilde{b}_r}{B_0} \frac{R}{a} \frac{r_q}{a} \right)^{1/2} \leq 0.1, \quad r_q = q / \nabla q$$

$$\frac{\tilde{b}_r}{B_0} \leq 0.1^2 \times \frac{1}{16} \times \frac{1}{3} \times 1 \approx 2 \times 10^{-4}$$

→ Quite demanding!

- Careful alignment of the coils during assembly
- Correction coils
- Rotation