

**Nuclear Engineering 180**  
**Fall Semester, 2003**  
**Final Examination**

THREE HOURS, CLOSED BOOK. TWO:  $8 - \frac{1}{2}'' \times 11''$   
 SHEETS OF NOTES ALLOWED. PLASMA FORMULARY ALLOWED.

1. The ITER tokamak design has the following parameters.

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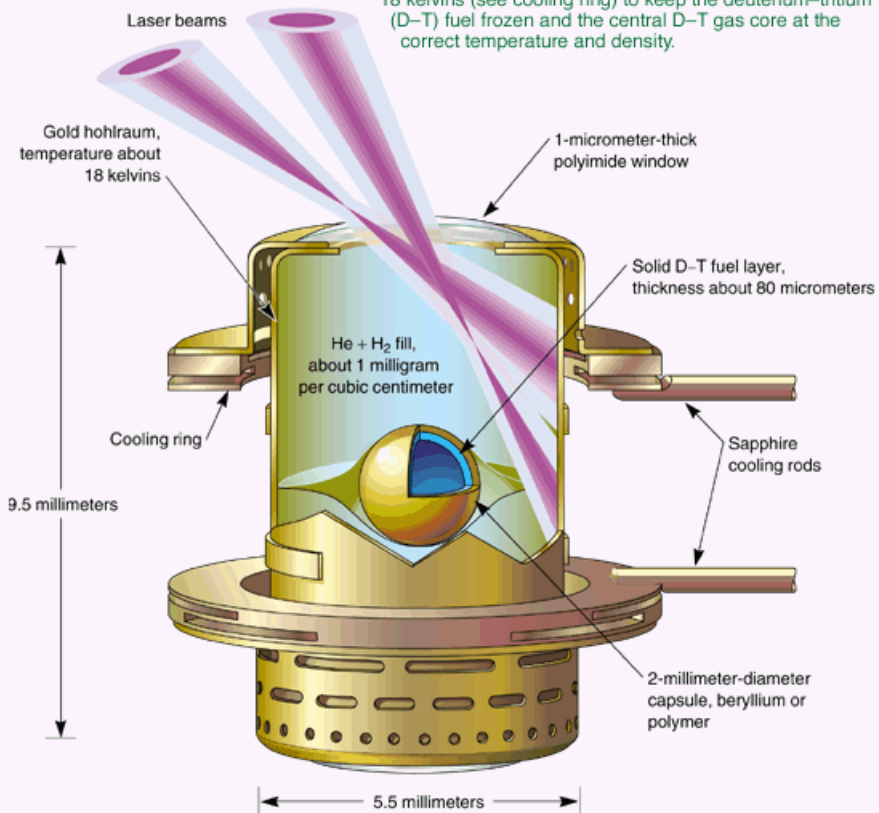
Plasma volume $V$	$837 \text{ m}^{-3}$
Toroidal magnetic field $B_\phi$	5.3 T
Volume-averaged density $\langle n_e \rangle$	$1.019 \times 10^{20} \text{ m}^{-3}$
Radiated power $P_{rad}$	48 MW
External heating power $P_h$	40 MW
Averaged fusion reactivity $\langle \sigma v \rangle$	$6.8 \times 10^{-23} \text{ m}^3 \text{ s}^{-1}$
Plasma major radius $R$	6.2 m
Plasma minor radius $a$	2.0 m
Averaged ion temperature $\langle T_i \rangle$	8.1 keV
Averaged electron temperature $\langle T_e \rangle$	8.9 keV

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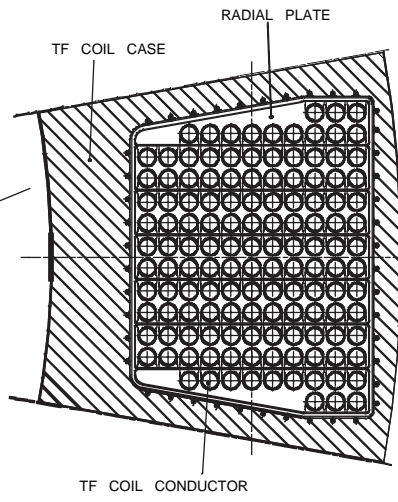
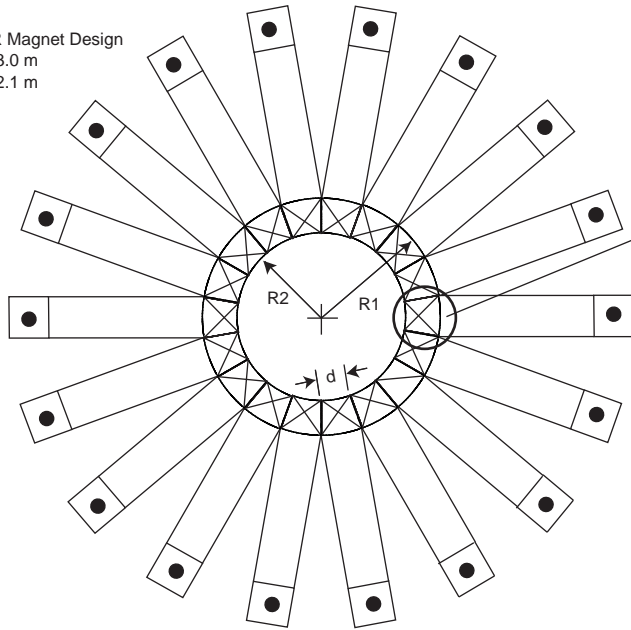
- a. The density profile in ITER is nearly flat. Assuming this and using the averaged reactivity given above, find the fusion power produced (assume 50-50 D-T).
- b. Find the alpha heating power in the machine.
- c. Find  $Q$ .
- d. Find the energy confinement time  $\tau_E$ .
- e. Find the averaged toroidal beta,  $\langle \beta_T \rangle$ .
- f. Assuming that the plasma cross section is elliptical, find the elongation factor  $\kappa = b/a$  consistent with the given plasma volume, where  $b$  is the major radius in the  $z$ -direction.
- g. Find  $Z_{eff}$  assuming that 30 MW of the radiative power is bremsstrahlung and that  $\langle T_e^{1/2} \rangle^2 = 15 \text{ keV}$ .

2. Tungsten ( $Z = 74$ ) erodes from the divertor plates and walls of the ITER device.
  - a. Find the energy required to strip the last electron from  $W^{73+}$ . Do you expect that tungsten is fully stripped in the core of the ITER plasma, where  $T_e = 30$  keV?
  - b. Find the energy  $E_\gamma$  of a photon connected with a  $2p \rightarrow 1s$  transition in  $W^{73+}$ .
  - c. Suppose that the  $W$  impurity has an average charge state  $\langle Z \rangle$  of 50 over the plasma volume. Using this value of  $\langle Z \rangle$  for the entirety of the plasma, find the reduction in thermonuclear power output if the  $W$  impurity is 0.1 percent of the electron density, as opposed to a clean plasma with the same electron density.
3. Shown is a drawing of the NIF hohlraum. The laser light enters through two 2.8 mm holes at the two hohlraum end caps. The hohlraum is 5.5 mm in diameter and 10 mm in length. The laser light consists of a 1.4 MJ pulse of 0.35 micron wavelength. The pulse width is 3.5 ns.
  - a. Find the density  $\langle n_e^{crit} \rangle$  at which the laser light cannot propagate.
  - b. Suppose that there is a balance between the laser power entering the hohlraum ends and blackbody radiation leaving through the entrance holes. Find the blackbody temperature in eV.
  - c. The target capsule contains DT and is filled to 500 atmospheres at room temperature. The capsule has an interior diameter of 1.9 mm. Find the burnup fraction  $f$  of the DT fill if the yield is  $Q = 1$ , i. e. 1.4 MJ of fusion energy is released.
  - d. If all of this DT is compressed to a final density  $\rho$  of 1000 grams per cc, find the final  $\rho R_f$  at maximum compression.
4. The ITER toroidal field (TF) superconducting magnet set contains eighteen coils. The outer radius of the inner leg  $R1$  is 3.0 m and the inner radius of the inner leg  $R2$  is 2.1 m. The conductors are round annular and are cooled through the center and around the outside.
  - a. Find the side  $d$  of the coil module which meets this criterion.
  - b. The total number of conductors per coil is 134. Find the current per conductor if the total magnetic field  $B_T$  at  $R = 6.2$  meter is 5.3 T.
  - c. The diameter of each conductor is  $d/14$ . Find the safe allowable current for thermal stability if eighty percent of the conductor is copper ( $\rho_{Cu} = 3 \times 10^{-10}$   $\Omega$ -m at 4.2°K) and the conductor is hollow with an inner diameter equal to half of the outer diameter. Assume  $Q''_{crit}$  for He at 4.2°K is 4000 W m<sup>-2</sup>.
  - d. Find the force per unit length  $F'_1$  acting on each coil at radius  $R_1$ , treating the coil assembly as a single filament of current at radius  $R_1$ . (Hint: use  $d\vec{F} = Id\vec{l} \times \vec{B}$ .)

Figure 3. The hohlraum will be filled with hydrogen-helium gas (which will be contained inside polyimide windows) to minimize laser light scattering. The hohlraum will be maintained at 18 kelvins (see cooling ring) to keep the deuterium-tritium (D-T) fuel frozen and the central D-T gas core at the correct temperature and density.



ITER Magnet Design  
R1=3.0 m  
R2=2.1 m



5. The ITER device is designed to have a tritium inventory of up to 3.0 kg on site. Assume that one hundred percent inventory is being stored in a single location in twenty separate containers.
- Assuming that the average beta released in tritium decay is 5.5 keV, and the half-life of tritium is 12.3 years, how much heat was generated in one of these containers ?
  - Assume that the particle inventory lifetime is 10.0 s in the machine. How long could the machine be operated at 50-50 DT mixture without recycling of tritium into the fuel injection system?
  - If the United States were to donate this amount of tritium to ITER, what does this represent as an equivalent dollar amount?
  - If a worker accidentally ingested a one-curie dose of this tritium in the form of HTO, what would his dose be, in REM, if the worker was unaware of the exposure? What steps could be taken if the accidental ingestion was known?
6. When Saddam Hussein was captured in a small village outside of Tikrit, Iraq, he was clutching a satchel of his most valuable papers while he was hiding in an underground “spider hole”. Among these papers was a small drawing from the Ministry of Agriculture, which in the past has served as an organization for storage of critical nuclear production machinery. The drawing was a schematic of a small fusion reactor. It was labeled “Reactor for Iraq-Tikrit Exalted Ruler”, or ITER. The notes reveal that the machine had a blanket which could breed plutonium and that it had an output of 1000 MW and a major radius of 1.0 meter. The magnetic field was provided by a special assembly of superconductors insulated with woven coconut fiber which was stabilized by a team of camels which kept the magnets from crushing together. Tritium was sent through the machine and the residual was collected in an empty plastic bucket used to ship palm oil. The high-temperature blanket appeared to have hydrogen production as a part of its design. Describe: (1) the strengths and weaknesses of the engineering design, (2) whether or not this activity might be considered an attempt to develop weapons of mass destruction, and (3) if this activity were successful, how it might affect the oil-based economy of this war-torn country.