Basic Tokamak Operation Physical Quantities

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Outline of the talk

Content

Plasma heating power

- In the GOLEM tokamak the only heating mechanism of the plasma is **ohmic heating**.
- This is resulting from current flowing in a conductor with finite resistivity.
- The ohmic heating power can be calculated as:

$$P_{OH}(t) = R_{pl}(t) \cdot I_{pl}^2(t) \tag{1}$$

where R_{pl} is the resistance of the plasma and I_{pl} is the current flowing in the plasma.

Central electron temperature estimation I [3]

Specific resistivity of a fully ionized plasma only depends on:

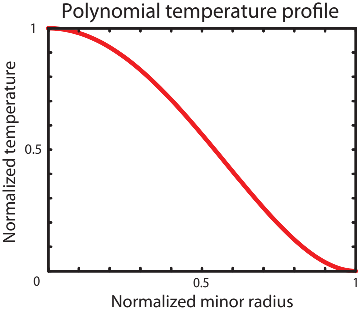
- electron temperature (T_e)
- effective charge number (Z_{eff})

This dependence is quantified by the Spitzer formula [**?**] and the **effective charge number** is assumed as $Z_{eff} = 2.5$.

Making estimation of the electron temperature from integrated value of resistivity ($R_{pl}(t)$) is ambiguous, because center of the plasma has

- Higher temperature
- Lower resistivity
- Higher current density

Central electron temperature estimation II [3]



However, if we use an equilibrium temperature profile (2) (Figure 6), measured in more detailed measurements [3], we can estimate one parameter of the profile, which is in this case the **central electron temperature** ($T_{e0}(t)$):

$$T_e(r, t) = T_{e0}(t) \left(1 - \frac{r^2}{a^2}\right)^2 \qquad (2)$$

Central electron temperature estimation III [3]

The central electron temperature (T_{e0}) is then calculated using Spitzer's resistivity formula. The current density of plasma is

$$j = E \cdot \sigma \tag{3}$$

where σ is the specific conductivity of plasma given by

$$\sigma(r) = 1.544 \cdot 10^3 \cdot \frac{T_e(r,t)^{3/2}}{Z_{eff}}, \qquad [\Omega^{-1}\mathrm{m}^{-1}, \mathrm{eV}] \tag{4}$$

and the electric field E is assumed constant in the poloidal cross-section:

$$E = \frac{U_{loop}}{2\pi R}. \tag{5}$$

Plasma current is obtained by integrating current density over the plasma column:

$$I_{pl} = \int_0^a E \cdot \sigma(r) 2\pi r dr. \tag{6}$$

Central electron temperature estimation IV [3]

Substituting (4) and (5) in (6) gives us the formula for the central electron temperature

$$T_e(0) = \left(\frac{R}{a^2} \frac{8 \cdot Z_{eff}}{1.544 \cdot 10^3} \right)^{2/3} \cdot \left(\frac{I_{pl}}{U_{loop}} \right)^{2/3} . \qquad (7)$$

For the CASTOR/GOLEM tokamak geometry with $a = 78$ mm :

$$T_e(0) = 89.8 \cdot \left(\frac{I_{pl}\ [kA]}{U_{loop}} \right)^{2/3} \approx 230\ eV. \qquad (8)$$

Electron density

The ideal gas law is used to give an order of magnitude estimate of the **electron density** (in particle/m^3):

$$n_{avr} = \frac{2p_{ch}}{k_B T_{ch}}. \tag{9}$$

where p_{ch} is the pressure of the chamber and T_{ch} is the chamber temperature, which is normally corresponding with the room temperatare.

This is a very rough estimate basically for two reasons:

- Plasma is not fully ionized, which makes us overestimate the electron density.
- Adsorbed gases are released from the surface of plasma facing components during the discharge. These atoms enter the plasma and can be ionized, thus making us underestimate the electron density.

Plasma energy

The **total energy** content can be simply calculated from the temperature, density and volume (V), based on the ideal gas law, taking into account the assumed (2) temperature profile:

$$W_{pl}(t) = V\frac{n_{avr}k_B T_{e0}(t)}{3}. \qquad (10)$$

The information that the magnetic field reduces the degrees of freedom of the particles to two has been used to derive this formula. Uncertainty of this formula is dominated by the uncertainty of our density estimate (9), which makes it good for only an order of magnitude estimate.

Energy confinement time

An important concept regarding the energy balance of the tokamak fusion reactor is the **energy confinement time** (τ_E). It is the characteristic time of energy loss:

$$P_{loss} = \frac{W_{pl}}{\tau_E}, \tag{11}$$

where P_{loss} is the power lost and W_{pl} is the total plasma energy.

Having an estimate for the plasma energy (10), the energy confinement time can be estimated at the point where the plasma energy has its maximum:

$$\tau_E(t_{top}) = \frac{W_{pl}(t_{top})}{P_{OH}(t_{top})}. \tag{12}$$

$$\frac{dW_{pl}}{dt}(t_{top}) = 0. \tag{13}$$

Safety factor

- The tokamak magnetic field consists of nested magnetic surfaces.
- **Safety factor** (q) gives the number of toroidal turns necessary for the magnetic field line at the given magnetic surface to reach its original position poloidally.
- On large aspect ratio circular tokamaks (like GOLEM), it can be approximated by:

$$q(r,t) = \frac{r}{R}\frac{B_t(t)}{B_p(r,t)}, \tag{14}$$

- where R is the major radius, (r_0) is the minor radius, $B_t(t)$ is the toridal and $B_p(r,t)$ is the poloidal magnetic field.

Safety factor - Illustration I

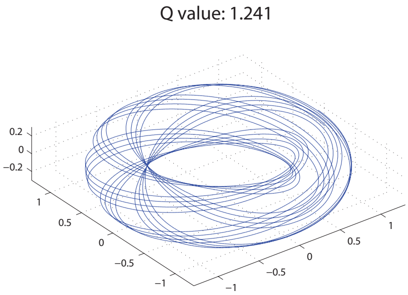


Figure: Magnetic field lines in a tokamak for different safety factors.

Safety factor - Illustration II

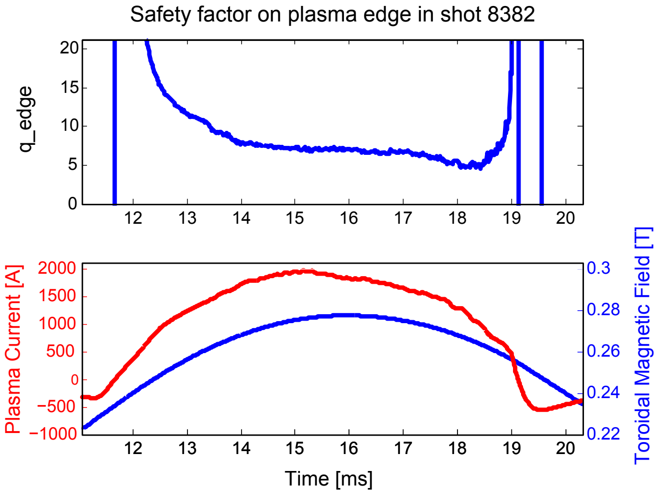


Figure: The time evolution of the safety factor on plasma edge.

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