Domanda 1

Physics of NBI HDC
Match the following sentences concerning NBI and beam fast ions with the corresponding categories (current tokamaks experiments(cte) and future fusion reactors(ffr))

a)Dominant electron heating (ffr)
b) generation of suprathermal particle population (cte ffr)
c) plasma rotation control by relevant torque injection (cte ffr)
d) necessity of accelerating negative ions in the injector (ffr)
e) possible presence of lower particle-energy components in the injected beam (half and third of the nominal injection energy) (cte)
f) "beam halo" generation in the plasma (especially for D0 injection) (cte)
g) larger effect of multi-step ionization process from excited states (ffr)
h) larger banana orbits of trapped beam ions for tangential injection (ffr)
i) larger current-drive efficiency for tangential injection (ffr)

Domanda 2

Pedestal physics
Which of the following statements describes best the EPED model for pedestal predictions?

- The pedestal width is determined by turbulent transport, via the expression $w_{ped} = 0.076\sqrt{\beta_\theta^{ped}}$ (KBM constraint) and the ELM is triggered by peeling-balooning instabilities (PB constraint)

Domanda 3

Pedestal Physics

Ballooning modes are driven by:

- pressure gradients

Domanda 4

Sol and Divertor
Alternative divertor configurations are under consideration:

- In the super-X divertor the target is foreseen to increase because $n_e^t \propto R_t^2$
- X-divertor solution will exploit the poloidal flux expansion to increase the flux-tube area at equivalent upstream λ_q upstream

Domanda 5

Sol and Divertor

Considering the physical description of the sheath close to a material wall pick up the correct answer:

- electron density at the sheath entrance is equal to $\frac{n_0}{2}$
- At the sheath entrance ions coming from upstream can have velocity higher than the ion speed sound

Domanda 6

Pedestal physics

Which of the following statements can describe the characteristics of type-I ELMs:

- They occur in plasma with input power significantly higher than the LH power threshold ($P_{sep} >> P_{LH}$)
- The ELM frequency increases with increasing P_{sep}
- They can be triggered by ballooning instabilities (they are triggered in general by ideal MHD instabilities)

Domanda 7

SOL transport

Consider an ITER size device with:

$$P_{SOL} = 10^8 W \cdot A_{SOL}$$

$$A_{SOL} = 1m^2$$

$$n_u = 6 \times 10^{19} m^{-3}$$

$$L \parallel = 100m$$

and a deuterium plasma and a sheath-transmission factor:

$$\gamma = 7$$

Assuming negligible power and momentum losses compute the expected temperature at the separatrix and density and temperature at the outer strike point. Provide a qualitative description of the methodology which are routinely implemented to ensure heat flux mitigation.

Answer:

In order to derive the required quantities we use the two point model. This way we can determine the temperature and densities upstream, correlating them to the ones at the target.

$$T_u = \left(\frac{7}{2} \frac{q_{\parallel L_{\parallel}}}{\kappa_{0,e}} \right)^{7/2}$$

where:

$$q_{\parallel} = \frac{P_{sol}}{A_{\parallel}} \quad and \quad \kappa_{0,e} = 2000$$

While, the temperature at the target can be expressed as:

$$T_t = \frac{m_i}{2e} \frac{4q_{\parallel}^2}{\gamma^2 e^2 n_u^2 T_u^2}$$

and the density at the target is:

$$n_t = \frac{n_u^3}{q\,\|^2}\left(\frac{7}{2}\frac{q_\parallel L_\parallel}{\kappa_{o,e}}\right)^{6/7}\frac{\gamma^2 e^3}{4m_i}$$

The deuterium mass is $m_D = 3.34 \times 10^{-27}\,\mathrm{Kg}$ and the electron charge is $e = 1.6 \times 10^{-19}\,\mathrm{C}$

Qualitative Answer:

heat flux mitigation can be achieved via:

- Impurity seeding
- Operations at higher densities, which ensure also larger fusion power production, the density at the target is strongly correlated to the upstream density and also the temperature at the target behaves as $\sim 1/n_u^2$
- New geometrical divertor configurations (snowflake, X-divertor)
- Any process ensuring a loss of momentum and velocity is acting in reducing the flux and by extension the heat flux at the target.

Domanda 8

Anomalous transport equation
Provide a qualitative description of the mechanisms leading to ion temperature gradient instabilities and indicate typacl expected features (including expected scale and instability condition)

Answer

ITG turbulences are instabilities arising from temperature gradients, indeed they are called ion temperature gradient modes.
Perturbations in the temperature gradient

A qualitative description of the mechanism associated with ITG is the following: temperature is not uniform across the plasma, a temperature gradient exists, with higher temperature regions close to the plasma core and low temperature regions localized near the edge. A gradient of

the magnetic field is also existing along the x direction and then we have an initial perturbation of the ion temperature in the direction perpendicular to this gradient of the magnetic field.
The gradient of the magnetic field is causing a grad B drift that is charge dependent and proportional to the temperature:

$$v_{\nabla B} = \pm \frac{v_\perp}{\omega_c} \frac{\mathbf{B} \times \nabla \mathbf{B}}{B^2} \propto T$$

This means that the particles (which are sitting in the hot or colder regions) because of the initial perturbation have different grad B drifts. This grad B drift builds up a local perturbation of the densities leading to a charge separation which in turn creates an electric field E. Due to this electric field an ExB drift arises enhancing the perturbation.
This is a typical example of turbulence we can have because of the presence of gradients inside a tokamak.
The ITG turbulence do have a clear ballooning character, meaning that they occur only in the bad curvature region (low field side).

ITG exhibit a critical threshold, it builds up only if we have a critical scale length of the local gradient:

$$r/L_{Ti} > \frac{4}{3}\left(1 + \frac{T_i}{T_e}\right)$$

considering the indicative turbulence scale ITG exist in a range where $0.1 < k_\theta \rho_s < 1$.

CHATGPT Enhancement:
Ion temperature gradient (ITG) instabilities arise due to steep ion temperature gradients in magnetically confined plasmas. These gradients introduce free energy that drives the instability. Qualitatively, the mechanism is as follows:

The plasma has a non-uniform temperature distribution, with hotter regions near the core and cooler regions near the edge. Alongside the temperature gradient, there exists a gradient in the magnetic field strength. If a small perturbation occurs in the ion temperature perpendicular to the magnetic field gradient, it creates localized regions of slightly hotter or cooler ions.

Because the grad-B drift depends on the ion temperature (v∇B∝Tv_{\nabla B} \propto Tv∇B∝T), ions in hotter regions drift differently from those in cooler regions. This difference in grad-B drift creates a local charge separation, as ions move more quickly than electrons. The resulting charge separation generates an electric field (E\mathbf{E}E), which in turn drives an E×B\mathbf{E} \times \mathbf{B}E×B drift. This drift enhances the original perturbation, leading to a positive feedback loop.

Additionally, in a toroidal magnetic geometry, regions of bad curvature amplify this effect. The combined influence of temperature gradients, magnetic field gradients, and curvature results in the exponential growth of ITG instabilities. Over time, nonlinear interactions between these modes lead to turbulence, causing significant transport of heat and particles across magnetic field lines. This turbulence tends to flatten the temperature gradient, reducing the drive for further instability.

Domanda 9

MHD equilibrium
Assume a tokamak with a circular cross section and main parameters:

$$a = 0.5m$$

$$R/a = 3$$

$$B_t = 3\,T$$

Compute the limit in plasma current due to current driven

external kink.
Which part of the potential energy determines stability.

Answer

The limit in plasma current can be estimated by the kruskal shafranov limit, it states that the plasma current must satisfy the condition:

$$I_p < \frac{2\pi a^2}{\mu_0 R_0} B\phi$$

Using the given parameters we calculate the limit as:

$$I_p = 0.61 \times 0.5 \times 3 \times 3 = 1.3675 \, \mathrm{MA}$$

therefore the limit in plasma current due to current driven external kink is the one above.
The part of the systems potential energy determining the stability is the W_b that is the potential energy at the boundary.

Domanda 10

MHD equilibrium

Linear MHD theory is a powerful tool for quickly assessing the global stability properties of a plasma.
Describe the main source of instability in a fusion relevant plasma and what is the role of curvature in toroidal systems

Answer

concerning fusion relevant plasma devices we can have different instabilities that are mainly due to plasma current and plasma pressure gradients.
it is helpful to think about energy conservation and in particular about the potential energy W in order to analyze the main sources of instability. As we previously discussed there are current driven instabilities which depend on the parallel current density and the equilibrium field B_0.
Examples of this instabilities are the sausage instability

and current driven kink.
On the other hand the pressure driven instabilities depend on both pressure gradients and magnetic field curvature. Since in a toroidal system the inner part has a good curvature while the outer part has a bad curvature,that's why pressure driven instabilities are more likely to develop on the outer side of tokamaks. Moreover, this curvature difference introduces an outward force: since the flux surfaces of B are concentrated in a small area (inward), the pressure from inside is higher than outside, and a force directed outward is generated (hoop force).