

1. **(Just for fun)** (2p)

Assuming the simple  $1/R$  dependence for the toroidal magnetic field, calculate the expression for the corresponding gradient drift (a vector) in terms of the perpendicular velocity.

2. **(Magnetic mirror in a tokamak)** (6p)

Since the magnetic field strength in a tokamak increases towards the symmetry axis and field lines are helical, a particle moving along a field line sees a non-uniform field and, when moving towards a higher field strength, can get reflected if its parallel velocity is not sufficiently high. We say that the particle encounters a magnetic mirror.

- (a) Assuming that the field strength has the simple  $1/R$  dependence, find the expression for  $R_b$ , the value of major radius at which a particle bounces, i.e., gets reflected, in terms of the magnetic moment  $\mu$ , the magnetic field strength on the magnetic axis  $B_0$ , the major radius of the plasma  $R_0$  and the particle energy  $E$ . (3p)
- (b) Show that the condition for a particle to get reflected is given by  $\mu B_0/E > 1 - a/R_0$ , where  $a$  is the minor radius of the plasma. (3p)

(Hint: Like with the magnetic bottle, use the conservation of energy and magnetic moment.)

3. **(How many bananas in a tokamak?)** (6p)

Use now the slightly more informative expression for the magnetic field strength, 'derived' during the lecture,  $B \approx B_0(1 - \epsilon \cos \theta)$ , where  $\epsilon = r/R_0$  and  $\theta$  is the poloidal angle. Assume a large aspect ratio, i.e., that  $R_0/r \gg 1$ .

- (a) Show that for a particle to get reflected somewhere in the plasma it has to satisfy  $\frac{v_{\perp,0}^2}{v^2}(1 + 2\epsilon) > 1$ , where the sub-index 0 refers to values at the low-field side equator, i.e., where the magnetic field has its lowest value. (4p)
- (b) Using the result of (a), show that the condition for reflection can also be written as  $\frac{v_{\parallel,0}}{v_{\perp,0}} < \sqrt{2\epsilon}$ . (2p)

(Hints: Use the conservation of energy and magnetic moment, and the fact that the last possible point to get reflected is at  $\theta = \pi$ .)

4. **(Food for thought: Stellarator)**

During lectures we have discussed only tokamaks when considering toroidal magnetic confinement of plasma. There is an even older concept, called a stellarator, that is making its second coming these days. Find out what a stellarator is, how it differs from a tokamak, why it has been inferior to tokamaks, and why there is suddenly a renewed interest in this concept.