Execises for the LHC lectures - the order follows the complexity of the problems.

1) How many dipoles form the LHC lattice, knowing that at p=7 TeV each magnet has a field of B=8.33 T and a length of about L=14.2 m?

2) How many turns would take for a proton in the LHC to drop out of the LHC vertical aperture of 28 mm due to gravitation if there would be no vertical focusing or dipole corrector? The LHC revolution frequency is 11.245 kHz.

3) Compute the energy stored in the main dipoles at top energy, for an inductance of 98.7 mH and a current of 11850 A.

4) Compare the optics for IR1 for injection (450 GeV) and collision energy (7 TeV). The optics are available following the links:
http://proj-lhc-optics-web.web.cern.ch/proj-lhc-optics-web/
http://proj-lhc-optics-web.web.cern.ch/proj-lhc-optics-web/V6.500/
http://proj-lhc-optics-web.web.cern.ch/proj-lhc-optics-web/V6.500/IR1.html

Those web pages contain all the optics of the LHC which are included in the control system.
Select Injection and then Structured Spreadsheet (Excel format) to get the optics and do the same for the Collision optics, both only for Beam1. In the Excel sheets, one can find the optical beta vs s and the optical Dispersion (Dx or Dy). The interaction point is defined by the element name IP1.
The beam size at a given location s can be computed by:

$$\sigma(s) = \sqrt{\beta(s) \cdot \epsilon + \left(D(s) \cdot \frac{\Delta p}{p}\right)^2}$$

where ε is the physical emittance, β the beta function and D the dispersion.
Plot as function of s the beta function, the dispersion and the horizontal beam size dimension, considering a normalised emittance of 3.75 μm rad, both for injection and collision. Assume as $\Delta p/p=3.06*10^{-4}$ at injection and $1.129*10^{-4}$ at collision.
What would be the luminosity in units of [$1/cm^2/s$] if, instead of colliding at 7 TeV, one would collide at 450 GeV with the injection optics? Assume $1.15 *10^{11}$ proton per bunch, 2808 bunches, F=1 (no crossing angle), round beams ($\sigma_x = \sigma_y$) at the IP and a revolution frequency of 11.245 kHz. The relativistic gamma, if needed, is written in the header of the optics files.

5) During the LEP run, two bottles of beer have been found inside the vacuum pipe.
In the LHC, neglecting the problem of finding a bottle that can fit in the aperture, where would you place the bottle to minimise the emittance blow-up due to the multiple scattering introduced by the glass (Consider the collision optics)? At one of the IPs? In one of the collimation sections? In one of the arcs? Motivate the solution.

6) Moon tides can deform the circumference of the ring in such a way that the energy of the beam changes. Why a circumference change induces a beam energy variation? By how much the circumference has to vary to change the 7 TeV by 10 MeV knowing that the momentum compaction factor is $3.225 \cdot 10^{-4}$ and the circumference is 26.7 km? Is this energy variation during the day important for the experiments?

7) The Atlas cavern floor, due to weight the ATLAS weight during installation, is 5.5 mm deeper than the zero level fixed by the theoretical relative alignment between the IP and the LHC ring. Due to the hydrostatic pressure the cavern will lift by 1 mm every year. By using 4 dipoles, two at each side of the IP, 1 m long with a 3 T maximum field, build a system to shift up and down the beam trajectory, with the goal of compensating at first a negative vertical displacement of 4 mm at 7 TeV.

8) LEP used to be an e+e- collider installed in the LHC tunnel. Considering the formula given in the lecture about synchrotron radiation, compute the total power that was irradiated at LEP for a 100 GeV electron beam (10^{12} electrons) and in the LHC for the 7 TeV proton beam (10^{14} protons). What would be the energy per turn in eV irradiated in the LHC at 7 TeV by a single proton and by a single electron at 100 GeV and at 7 TeV? The classical radius of the electron is $2.81 \cdot 10^{-15}$ m, the electron mass is 511 keV, and the radius for proton is obtained by noticing that the classical radius is proportional to the inverse of the particle mass (mp=0.938 GeV). The bending radius equals to 2803 m and the revolution frequency is 11.245 kHz. (1 eV = $1.6 \cdot 10^{-19}$ joules, c = 300000 km/s)

9) The machine chromaticity gives the change of the total tune Q as a function of the momentum error of the beam:

$$\frac{\Delta Q}{Q} = (\xi_{nat} + \xi_{sext}) \cdot \frac{\Delta p}{p_0}$$

where ξ_{nat} defines the natural chromaticity which is generated by the linear quadrupoles of the machine. and ξ_{sext} the chromaticity which is generated by the sextupole field components in the machine. Derive a formula for ξ_{sext} which is generated by the sextupole field error (b3) of the LHC dipole magnets. The magnet field errors are measured in units of 10^{-4}. The chromaticity is generated by a quadrupole feed down field due to the dispersion orbit inside the sextupole fields:

$$b_2 = 2 \cdot b_3 \cdot \frac{D_x}{R_{ref}} \cdot \frac{\triangle p}{p_0},$$

where Rref is the reference radius for the field quality measurements (Rref =17 mm for the LHC dipole magnets). The normalized quadrupole gradient due to this feed down error is given by

$$\triangle k_2 = \frac{b_2}{R_{ref}\rho},$$

where ρ is the radius curvature inside the LHC dipole magnets ($\rho = 2804$ meter). The average dispersion in the LHC arcs is $< Dx >= 1.6$ meter and the average βfunction is $< \beta >= 108$ meter. The LHC has 1232 dipole magnets each having a length of $L = 14.3$ meter. Assuming a maximum sextupole field error of 11 units for the dipole field error by how much changes the machine chromaticity due to this error? (This exercise is taken from a CAS - CERN ACCELERATOR SCHOOL).