Exercise 5.1:

The HE-LHC operation would allow to push the energy frontier of the LHC to 27 TeV, but avoiding to incur in some of the practical problems of the FCC-hh. The increased energy allows to increase sensitivity to high mass new physics (e.g. SUSY particles, resonances, top-partners, ...). The high luminosity allows to increase sensitivity to light and weakly coupled new physics (e.g. Higgs couplings and self-coupling).
The access to SUSY is the most appealing feature of the HE-LHC, in fact the only fermion superpartner that can be eventually detected directly at the LHC energy with the statistic of tens of fb^{-1} is the gluino. All the other fermion superpartners with mass above 1 TeV can be detected at higher energies only.

The similarity of many aspects of the HE-LHC with respect to the HL-LHC, including size,, assure that many of the required technologies will be already developed at the start of the construction.

The key beam parameters to compare the three projects are reported in the table below:

<table>
<tr><th>Parameter</th><th>(HL) LHC</th><th>HE-LHC</th><th colspan="2">FCC-hh</th></tr>
<tr><td>√s [TeV]</td><td>14</td><td>27</td><td colspan="2">100</td></tr>
<tr><td>Dipole field [T]</td><td>8.3</td><td>16</td><td colspan="2">16</td></tr>
<tr><td>Bunch intensity [10^{11}]</td><td>(2.2) 1.15</td><td>2.2</td><td colspan="2">1 (0.5)</td></tr>
<tr><td>Bunch spacing [ns]</td><td>25</td><td>25 (12.5)</td><td colspan="2">25 (12.5)</td></tr>
<tr><td>Norm. emittance [μm]</td><td>(2.5) 3.75</td><td>2.5 (1.25)</td><td colspan="2">2.2 (2.2)</td></tr>
<tr><td>IP β* [m]</td><td>0.3</td><td>0.25</td><td>1.1</td><td>0.3</td></tr>
<tr><td>Luminosity [10^{34} $cm^{-2}s^{-1}$]</td><td>(5) 1</td><td>25</td><td>5</td><td>30</td></tr>
<tr><td>peak #events / bunch Xing</td><td>(135) 27</td><td>800 (400)</td><td>170</td><td>1000(500)</td></tr>
<tr><td>Stored energy / beam [GJ]</td><td>(0.7) 0.36</td><td>1.4</td><td colspan="2">8.4</td></tr>
<tr><td>SR power / beam [kW]</td><td>(7.3) 3.6</td><td>100</td><td colspan="2">2400</td></tr>
<tr><td>Proton burnoff time [h]</td><td>(15) 40</td><td>3.0</td><td>17.0</td><td>3.4</td></tr>
</table>

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The key idea is to replace the LHC dipoles with new units, realised with the technology of FCC-hh and capable of reaching a field of 16 T. This approach has number of practical advantages, such as avoid to bore a new 100 km tunnel to host the FCC-hh and to keep operating the LHC as injector, reducing costs and energy consumption. This also would allow to keep pushing the physics frontier in case the FCC magnet technology is available, but for external (e.g. political, ...) reasons the realisation of FCC is not possible.

The desirable high luminosity will reach 5 times the HL-LHC, determining a pileup up to 800 in the detectors. A consistent development in the detector technology is required to face this challenge and assure a high event reconstruction efficiency. Considering that by the construction of the HE-LHC the detector will be completely rebuilt because of aging and obsolescence of the components, a strong R&D effort is required to face the pileup challenge.
Such high luminosity is reached both through a small β* and the bunch structure. The β* is chosen to be similar to the HL-LHC, but with a 1.9 times more energetic beam. This value

seems reachable using the Niobium-Tin magnet technology while matching the required aperture of the quadrupoles of the final triplet.
The bunch structure is similar to the HL-LHC, with a bunch spacing of 25 ns and same intensity and emittance. The LHC Injectors Upgrade program is currently running to assure that such beams are producible in the current acceleration chain. The HE-LHC injection energy is around 1.2 TeV, that requires an upgrade of the SPS or an additional pre-acceleration ring sitting in the LHC tunnel. The latter option is challenging because of the reduced size of the LHC (well, LEP ...) tunnel that was not designed to host two rings. Anyway after the abortion of the PS2 and SPL program, it is likely that another upgrade of the current injectors is required to fill the HE-LHC.

The radiated power by synchrotron radiation is higher than the other two machines in exam, but cannot reach the LEP levels. Therefore, the state of the art materials are suitable to realise the beam pipe. The beam pipe heating has to be controlled, but the current LHC cryo plant is sufficient to handle the excess of heat. On the beam dynamics side, the high radiated power cause an emittance shrinkage in all the three planes, inducing possible instabilities. This can be cured inserting random noise in case of need to stabilise the beam, determining a controlled blowup. This procedure can be also controlled in order to level the luminosity.
To face the energy irradiated and accelerate the beam, the accelerating voltage will be doubled with respect to the LHC, to 32 MV.

The machine protection issues are not negligible, since the stored energy per beam is going to be twice the HL-LHC. Anyway the machine is going to be the same size of the HL-LHC, so similar system can be involved. Particular attention has to be paid to the collimator materials, that have to be resistant to beams of twice the energy. In this sense the R&D program should give hint on the feasibility.

The short proton burnoff time allow to increase the integrated luminosity collected. A gain of more than 3 times with respect to HL-LHC is expected, taking into account the turnaround time.

Ultimately the beam parameters of the HE-LHC look very similar to the HL-LHC, and the project offer the possibility to access higher energy and luminosity in a much shorter timescale and with a reduced budget than the FCC-hh. Furthermore, the luminosity of the HE-LHC is far beyond the baseline of FCC-hh. Clearly the HE-LHC cannot access processes at higher energies than 27 TeV, that are accessible with FCC-hh. So if the physics interest is in studying heavy particle production, especially using high-threshold processes, the higher energy the better. In this sense the FCC-hh can access some physics that is not accessible by the HE-LHC.
On the other hand, handling a 100 TeV beam is problematic on the machine protection side, also because of the size of the machine. The synchrotron radiation power would be huge and require an incredible amount of energy from the RF systems. Cryogenics and vacuum are also challenged by SR emission. The focusing magnets technology will be also stressed in order to provide very high gradient fields while maintaining a practical aperture. The production of a beam with half the intensity and similar emittance of HE- and HL-LHC does

not seem to be a challenge for the injectors. A controlled emittance blowup, similar to HE-LHC, could be beneficial for luminosity leveling and instabilities control.