CONSTRAINTS ON THE FCC-*ee* LATTICE FROM THE COMPATIBILITY WITH THE FCC HADRON COLLIDER

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Abstract

Following the recommendations of the European Strategy Group for High Energy Physics, CERN launched the Future Circular Collider Study (FCC), a design study for possible future circular collider projects to investigate their feasibility for high energy physics research. The FCC Study covers three different machines with a circumference of 100 km: an electron positron collider with collision energies in the range of 90 GeV to 350 GeV (FCC- ee), a proton proton collider with a maximum energy of 100 TeV (FCC-hh) and an electron proton option (FCC-he). This paper will present the constraints on the design of the FCC-ee lattice and optics from geometry and lattice considerations of the hadron machine.

INTRODUCTION

With the discovery of a Higgs boson all particles of the standard model of particle physics have been found. In order to discover new physics CERN started to study a future discovery machine called FCC-hh with proton proton collisions at 100 TeV center of mass energy. Considerations presented in this paper will show that such a machine will need to have a circumference of 80 km-100 km given by the achievable technology. Having this tunnel available it is obvious to think about an electron positron collider for precision measurements as well [1]. The large circumference allows operation with an acceptable amount of synchrotron radiation losses and the costs for a second machine decrease drastically, as no extra tunnel has to be built. However straight sections for RF installation have to be provided to deal with the synchrotron radiation loss in such a storage ring. This part of the design study, earlier known as TLEP, is called FCC-ee. The third part of the study, FCC-he, covers the investigation of future electron proton collisions in order to study deep inelastic scattering. This comprises two options: a LHeC like linac-ring option and, in case FCC-hh and FCC-ee can be hosted and operated in the tunnel at the same time, a ring-ring option. Each machine of the FCC study has special requirements, that have to be considered in the design phase. This paper focuses on the constraints on the FCC-ee lattice design from the compatibility with FCC-hh. Contrary to FCC-ee, for a beam energy of 50 TeV in the hadron machine a new magnet technology has to be developed. The maximum bending radius in the arcs and consequently the circumference of the machine directly depends on the achievable magnetic field. The length of the long straight sections needed for insertions also contributes to the circumference. They must provide enough space to house RF installation, collimators, kickers for injection and beam dump and the detectors. If LHC is used as an injector, the circumference and harmonic number of FCC should be rational multiples of the LHC's to allow bunch to bucket transfer. Furthermore the FCC-hh and LHC tunnels should be close to each other to guarantee a reasonable length of the transfer lines. For locating a 100 km circular collider also geologic aspects play a major role. The constraints arising from the requirement of hosting both machines in the tunnel at the same time and from the compatibility with FCC-he are not covered in this paper.

BENDING RADIUS AND CIRCUMFERENCE

The beam rigidity of a 50 TeV proton beam is

$$B\rho = p/e \approx 1.67 \times 10^5 \text{ Tm}. \tag{1}$$

To bend such a stiff beam in a reasonable radius a new technology of superconducting magnets needs to be developed. A prototype dipole based on Nb_3Sn technology could reach a magnetic field of B =16 T [2]. Such a magnet would define a bending radius of ρ = 10.7 km. If even higher magnetic fields of B =20 T could be achieved, the bending radius could be reduced to ρ =8.5 km. Assuming 16 T magnets and 67 % of the whole circumference including long straight section being occupied by bending magnets the circumference C would approximately be 100 km. As mentioned before, if LHC is used as an injector, the circumference of FCC should be a multiple of the LHC circumference, which is 26.66 km [3]. For 16 T magnets approximately 106.64 km should be taken as circumference and 79.98 km for the 20 T version. Both possibilities are studied, the final choice will depend on the technical progress in magnet technology.

Table 1: Circumference and Ending Radius for Different Magnetic Felds of the Bending Magents

B in T	ρ in km	C in km
16	10.7	106.64
20	8.5	79.98

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LAYOUT OBJECTIVES AND SHAPE OF THE MACHINE

The maximum momentum of the particle beam in a hadron machine is limited by the bending radius of the dipoles. Therefore the design aims to maximize the integral magnetic dipole field around the machine

$$\oint B(s)\,\mathrm{d}s. \tag{2}$$

Practically that means highest possible dipole fill factor and avoiding sections without full strength bending magnets as far as possible. This includes straight sections but missing bend or half-bend dispersion suppressors as well. The energy in a lepton machine on the contrary is limited by synchrotron radiation. The energy loss per turn is given by [4]

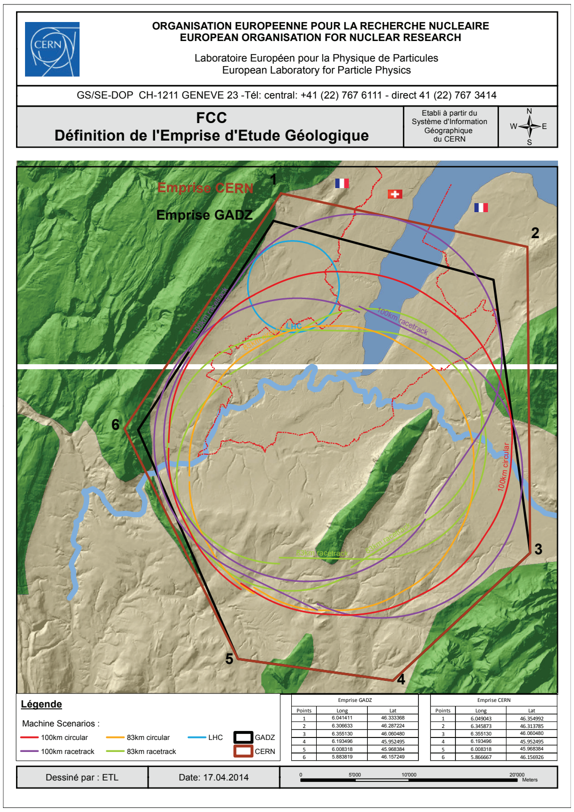
$$U_0 = \frac{4\pi}{3}\alpha\hbar c\frac{\gamma^4}{\rho}. \tag{3}$$

The lost energy needs to be fed back to the beam in straight sections with RF installation. Those cavities must be positioned in dispersion free sections to avoid coupling between the longitudinal and transversal planes. The design for a lepton machine not only aims for maximum dipole fill factor in order to maximize the bending radius and minimize the radiation power, but contrary to a hadron machine also for a high number of straight RF sections to narrow down the energy sawtooth of the orbit. This is important because particles with large energy deviations will move on dispersion orbits with large amplitude and cross strong non-linear fields or even get lost while hitting the geometric aperture. Those layout requests end up in different shapes of the machine: in case of a hadron machine, the minimal number of dispersion suppressors is given by a racetrack design, where all infrastructure like injection, ejection, RF and interaction regions is concentrated in two very long straight sections which are connected by two arcs. In case of a lepton machine a circular design with equally distributed straight RF sections is preferred. The more dispersion free RF sections are provided the smaller is the energy sawtooth.

In general it is useful to ensure a phase advance of $(n + 1/2)\pi$ with n being an integer between two interaction points to correct higher order chromaticity. In a racetrack like geometry with clustered interaction regions the preservation of the phase advance is easier than in a circular layout because of the smaller distance between those points (e. g. SSC design [5]). Still measurements at LHC have shown, that the phase advance can be kept stable between the two high-luminosity experiments ATLAS and CMS, which have a distance of ca. 13.3 km. So clustering the interaction points is not a compulsory requirement from an optics point of view.

LOCATION OF THE FCC TUNNEL

A variety of boundary conditions has to be considered in context of a possible location of FCC.



Emprise GADZ		
Points	Long	Lat
1	6.041411	46.333368
2	6.306633	46.287224
3	6.355130	46.060480
4	6.193496	45.952495
5	6.008318	45.968384
6	5.883819	46.157249

Emprise CERN		
Points	Long	Lat
1	6.049043	46.354992
2	6.345873	46.313785
3	6.355130	46.060480
4	6.193496	45.952495
5	6.008318	45.968384
6	5.866667	46.156926

Figure 1: The geological study area with some proposals for the location for both circular and racetrack shaped machines with the circumference 80 km and 100 km (Defined by the FCC Civil Engineering Group chaired by J. Osborne).

Geology

Building a tunnel with the length of 100 km is a civil engineering challenge. The geology of the area plays a major role and must be studied carefully before deciding the exact location. The geological study area defined by the FCC Civil Engineering Group is shown in figure 1. Its borders are defined by the surrounding area: the Pre-Alps in the East and South-East, the Jura Mountains in the West, Mount Vuache in the South and Lake Geneva to the North. The mountains consist mostly of Limestone, with some Karstic features, making the risk of encountering water very high. Tunnel excavation in this type of rock can be complicated and expensive due to stored water in the rocks. The depth of the access shafts needs to be minimized to facilitate the installation of services and optimize the safety paths. As far as possible, the tunnel should be housed in the Molasse Rock, a sedimentary rock made up of sandstone and marls.

Tilting the Tunnel

For finding an appropriate location for the future FCC tunnel it is considered to tilt the tunnel plane. This was already done when the LHC tunnel was built for LEP. The median plane was tilted with respect to the horizontal by 1.42 % [6] to maximize the tunnel extent in Molasse Rock environment and to minimize the depth of the access shafts.

In case of FCC such a tilt could allow passing Lake Geneva further in the North without increasing the depth of the access shafts to the Southern part of the machine.

Location Relative to LHC

With the LHC, CERN already has a high energy hadron machine available that could be used as injector for FCC-hh. Below 3.5 TeV the power converters and the cooling system allow to ramp the LHC bending magnets with up to 50 A/s. Combined with its double ring layout LHC would be a very efficient injector delivering up to 2800 bunches per beam. To keep the transfer lines reasonably short the FCC tunnel should overlap or cross one LHC straight section. Nevertheless there is a minimum horizontal distance between the LHC extraction point and a possible FCC injection point, which is necessary to overcome the difference in depth. Due to maintenance and engineering reasons the slope of the transfer line tunnel should not be larger than 5 %. Thus the required distance depends on the beam energy, the magnet technology used and the difference in depth. Figure 2 shows this dependency for a beam energy 3.5 TeV and a dipole filling factor of 0.75, which leaves enough space for machine protection elements. The different lines correspond to different vertical distance between the LHC and the FCC tunnels, which is labeled on the right. Obviously the transfer line must be longer, if the vertical distance of the tunnels is larger or the magnetic field of the dipoles is smaller. So choosing normal conducting magnets will elongate the transfer line. Assuming a difference of depth of less than 200 m and reasonable dipole fields the LHC extraction point and FCC injection point need to have a distance between about 0.5 km and 1.5 km.

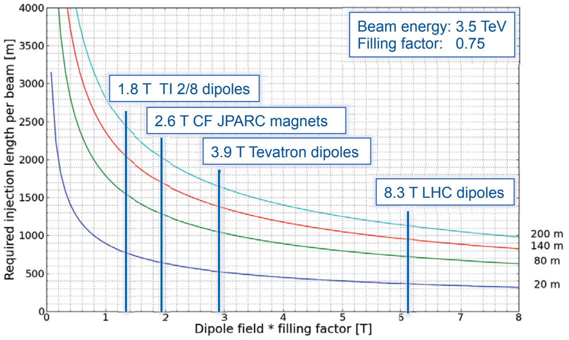


Figure 2: The plot shows the required horizontal distance between the extraction point at LHC and a future injection point at FCC-hh ring as a function of the magnetic field of the used bending magnets. Each line stands for a certain vertical distance of the two tunnels, which is labeled on the bottom right of the plot.

LENGTH OF LONG STRAIGHT SECTIONS

Long straight sections are used for various purposes: RF installation, injection, beam dump, collimation and mini-beta insertions for the experiments. For the injection of pre-accelerated beams from the arriving transfer line to the main ring, septum magnets are used followed by kicker magnets. Additionally machine protection elements will be needed to prevent damage in case of failure. For the injection of a 3.3 TeV proton beam into FCC-hh these group of elements will require space with the length of 600 m, corresponding to about three FODO cells, that will have to be modified. The extraction to the beam dump line uses the same scheme, but it has to be laid out for up to 50 TeV beam energy. Though longer kicker rise times can be accepted, more space will be necessary. First estimates predict a length between 800 m and 1000 m. For the collimation system two 2.8 km long straight sections are foreseen.

INTERACTION REGION

The biggest experiment at LHC is the ATLAS detector with about 45 m length and 25 m height. However for particle detection at 100 TeV center of mass energy even larger detectors are needed, because the particle jets penetrate deeper before the particles are absorbed in the calorimeter. The current FCC-hh interaction region design therefore assumes an L^* of 46 m, which corresponds to a 92 m long drift space for the detector. The length of the complete FCC-hh interaction region including matching sections and dispersion suppressors is approximately 1100 m long. The interaction region layout for FCC-ee is completely different: In the FCC-hh final focus system a very tiny crossing angle of ca. 70 μrad is used. In the FCC-ee design the ambitious request for the vertical beta function at the interaction point $\beta^* = 1$ mm needs to be combined with a small L^* of 2 m to prevent the beta function from growing to unreasonable size. To minimize synchrotron radiation the two beams must be focused by separated quadrupoles, thus the crossing angle is defined by the quadrupole's aperture and the size of the coils. The CERN interaction region design is based on a crossing angle of 11 mrad, while the final focus system designed by the Budker Institute of Nuclear Physics (BINP) is based upon 30 mrad [7]. In combination with a local chromaticity correction scheme this leads to different geometries of the interaction regions, that are shown in figure 3. While in the FCC-hh design the two beams are separated by 40 cm in the matching sections, the ones for FCC-ee have a distance up to 2 m. Including matching sections and dispersion suppressors the FCC-ee interaction region will probably be longer than the one for FCC-hh. So the dimensions of the straight sections next to the experiments will be defined by the requests of FCC-ee.

CONCLUSION

The compatibility of the FCC-ee lattice with FCC-hh requires the same layout and geometry given by the tunnel. While the magnetic fields for FCC-ee can easily be obtained (see Table 2), the circumference and the bending angle for the FCC-hh machine are defined by the achievable magnetic fields. The length of the straight sections depends on the re-

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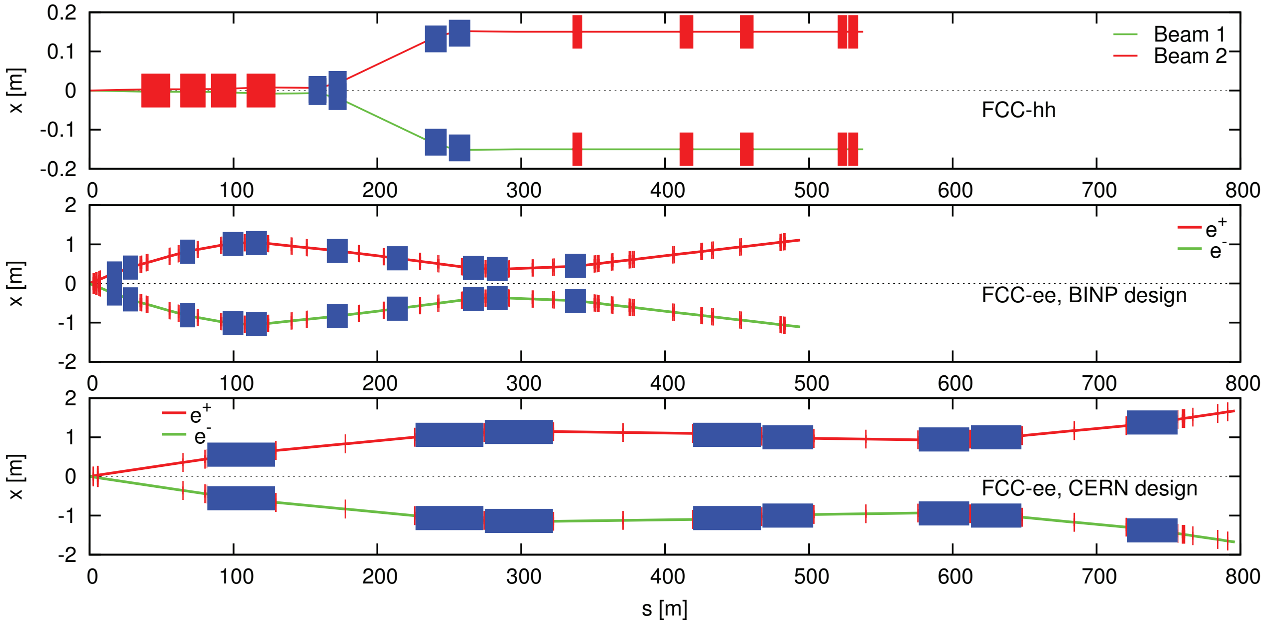

Figure 3: Comparison of the Geometry of the Interaction Region Designs for FCC-hh and FCC-ee [7].

Table 2: List of Baseline Parameters for FCC-hh and the Different Physics Programs of FCC-ee ([8], [9])

	FCC-hh	**FCC-ee Z**	**FCC-ee W**	**FCC-ee H**	**FCC-ee tt**
Beam energy (GeV)	50000	45.5	80	120	175
Circumference (km)	100 (80)	100	100	100	100
Dipole field	16 (20)	0.014	0.024	0.036	0.053
Arc filling factor	0.79	0.84	0.84	0.84	0.84
Number of IPs	2+2	4	4	4	4
Peak luminosity (10^{34} $\mathrm{cm^{-2}s^{-1}}$)	5	28.0	12.0	5.9	1.2
Betatron function at IP β^* (m)					
- Horizontal	1.1	0.5	0.5	0.5	1
- Vertical	1.1	0.001	0.001	0.001	0.001

quirements for the injection, extraction, collimation regions. While the size of the caverns housing the experiments is defined by the FCC-hh detectors, the straight sections for the final focus system must provide enough space for the geometry of the FCC-ee design. The possible location of a future FCC tunnel depends on geological aspects but also on the already existing infrastructure. The LHC would be a very effective pre-accelerator for FCC-hh, so a possible injection point at FCC-hh should be located close to a LHC straight section but keep a minimum distance to overcome the difference in depth.

Especially in this early stage of the FCC study it is important to consider the compatibility of the sub-studies with each other to ensure a successful development of the project.

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