STATUS OF THE FCC-ee INTERACTION REGION DESIGN

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Abstract

The FCC-ee project is a high-luminosity circular electron-positron collider envisioned to operate at center-of-mass energies from 90 to 350 GeV, allowing high-precision measurements of the properties of the Z, W and Higgs boson as well as the top quark. It is considered to be a predecessor of a new 100 TeV proton-proton collider hosted in the same 80 to 100 km tunnel in the Geneva area.

Currently two interaction region designs are being developed by CERN and BINP using different approaches to the definition of baseline parameters. Both preliminary designs are presented with the aim of highlighting the challenges the FCC-ee is facing.

INTRODUCTION

FCC-ee is foreseen to run at four different center-of-mass energies: the Z-pole at 90 GeV, the W pair production threshold (160 GeV), Higgs resonance (240 GeV) and $t\bar{t}$ threshold (350 GeV). From the accelerator point of view, the Z-pole and $t\bar{t}$ threshold are the most challenging setups due to the high number of bunches per beam and high luminosity target (Z) and beamstrahlung ($t\bar{t}$) so these will be the driving forces of the lattice design. In Table 1 the relevant baseline parameters for the 100 km option of FCC-ee are shown. The parameters are in part determined by the design limit of 50 MW of synchrotron radiation per beam. Another constraint for the design of FCC-ee, in particular of the Interaction Region (IR), is the required compatibility with a possible proton-proton collider (FCC-hh) in order to allow a reuse of the tunnel for both machines. Since not only length, but also diameter of the tunnel are a major cost driver of projects of that kind, the design of both machines has to be closely connected and optimized.

Table 1: FCC-ee Baseline Parameters at Z and $t\bar{t}$ Energy for CERN Design at the 100 km Option [1]

	Z	$t\bar{t}$
Beam energy [GeV]	45.5	175
Crossing angle [mrad]	11	
Bunches / beam	16700	98
Bunch population [10^{11}]	1.8	1.4
Energy loss / turn [GeV]	0.03	7.55
Beta function at IP β^*		
- horizontal [m]	0.5	1
- vertical [mm]	1	1
Transverse emittance ϵ		
- horizontal [nm]	29.2	2
- vertical [pm]	60	2
Beam size at IP σ^*		
- horizontal [µm]	121	45
- vertical [µm]	0.25	0.045
Luminosity / IP [10^{34}cm^{-2}s^{-1}]	28.0	1.8

CERN IR DESIGN

The CERN interaction region design is based on a generic lattice originally designed for linear accelerators [2]. This is in part due to the fact that the strong focusing required to reach the high luminosity goals induces high chromaticity that will require a local correction, especially in the vertical plane. The design is shown in Fig. 1 together with the optical functions. It consists of a Final Focus System (FFS), Vertical and Horizontal Chromatic Correction Sections (CCSV, CCSH) and a Matching Section (MS). Each chromatic correction section consists of 4 FODO cells forming two opposed missing dipole dispersion suppressors. All functions are spatially separated which makes the whole lattice very modular. In addition to the sextupoles for chromaticity correction, weaker sextupoles for local correction of nonlinearities were inserted. Currently the CERN design is still in a very early stage of development and only the $t\bar{t}$ settings have been matched.

In the final focus quadrupole, the chromaticity is proportional to $\xi_{x,y} \sim \frac{L^*}{\beta^*_{x,y}}$, thus the length of the last drift L^* should be as small as possible while still leaving enough space to host the detector. At this stage of the design, $L^* = 2$ m is considered reasonable.

From the high number of bunches at lower energies, it is clear that a crossing angle is required to ensure an adequate bunch separation after the IP. While the crossing angle must be large enough to separate the bunches to several σ_x, a large crossing angle requires either a broad tunnel -a major cost driver- or strong dipole magnets close to the IP bending the beam back. The latter will produce high doses of synchrotron radiation close to the detector, increasing the background noise and potential radiation damage. Thus a compromise has to be found.
A first approach is to choose the crossing angle as small as possible to achieve a certain beam separation and have both beams share the same quadrupoles of the final focus system. In this case, the beams pass the first quadrupole off axis and are deflected due to the magnetic field being non-zero, producing considerable amounts of synchrotron radiation. In

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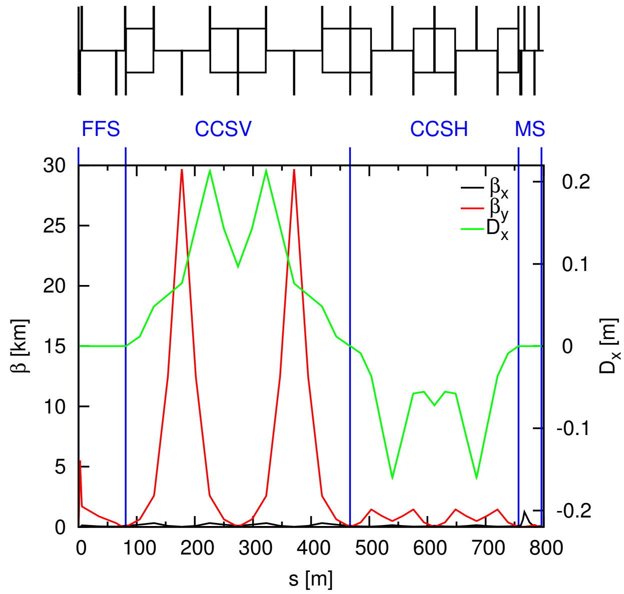

Figure 1: Optical functions of the CERN IR design.

Table 2 the average radiation power is shown, based on calculations with the current CERN IR design and an angular beam separation as small as $6\,\sigma_{P_x}$. Even for this absolute minimum crossing angle, the radiation power produced in the shared quadrupoles is prohibitively high. Given the fact that there will be little room for absorbers after the last quadrupole, the shared quadrupoles scheme must be considered unfeasible.

Table 2: Average synchrotron power radiated from the shared final focus quadrupoles at an angular beam separation of $6\,\sigma_{P_x}$. Values are per beam and per quadrupole.

	Z	**$t\bar{t}$**
average power from Q1 [kW]	96.8	3.5
average power from Q2 [kW]	423.0	15.1

For a final focus system with separate apertures for each beam, the crossing angle is determined by L^* and the minimum separation of the magnetic axes of the last quadrupoles that is technically feasible. Design studies of FFS magnets for SuperB [3] and a prototype design by BINP [4] suggest that quadrupole magnets with an axis separation of $\approx$ 22 mm are possible. With an L^* of 2 m this implies a minimum crossing angle of 11 mrad which is used in the current CERN design.

BINP IR DESIGN

While the CERN design focuses mainly on the feasibility of the high energy option, BINP uses a different approach. The philosophy of the BINP interaction region design is to apply a crab waist collision scheme [5] in order to increase luminosity at low energies (Z,W) by increasing the vertical tune shift. To achieve this the baseline parameters where altered according to Table 3. The parameters where chosen to use the advantages of the crab waist scheme, but at the same time allow running at all energies with the same lattice. At low energies, the crab waist scheme aims at luminosities that are higher by a factor of 8 (Z) and 3 (W) compared to the head-on collision scheme. However, at high energies (H, $t\bar{t}$) the crab waist scheme has no considerable advantages since the beam-beam tune shift, and thereby the luminosity, is limited by beamstrahlung.

Since the BINP design makes use of the crab waist scheme the crossing angle is not chosen as small as possible but to provide an interaction length of the bunches roughly equal to the vertical beta function at the IP for both, Z and W setup. In the case of the BINP design, it is 30 mrad.

The general layout [6] and the optical functions are shown in Fig. 2. Again, a final focus system and vertical and horizontal chromaticity correction sections can be seen as well as a CRAB section providing the necessary phase advance and optical functions for the crab sextupoles. The chromaticity correction sections are much shorter than in the CERN design but this advantage is accomplished at the price of much stronger dipoles. To mitigate the effects of synchrotron radiation at the IP (background in the detector), the first dipole has a rather low magnetic field.

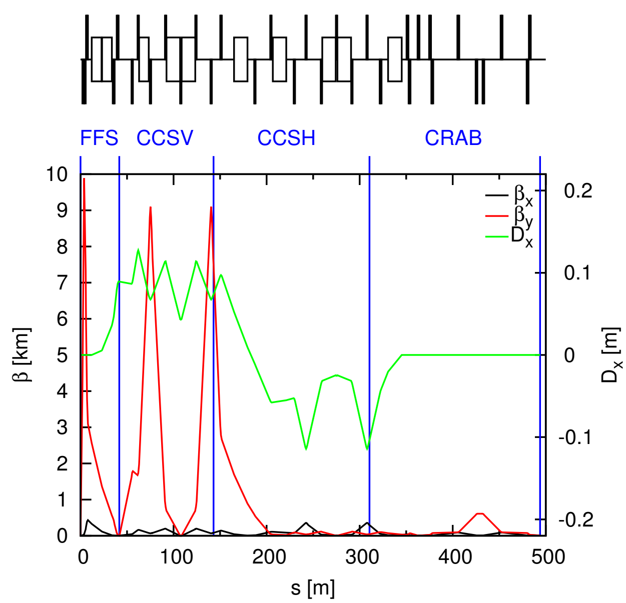

Figure 2: Optical functions of the BINP IR design.

COMPARISON AND DIFFICULTIES

In Fig. 3 the geometry of both FCC-ee designs are shown, together with the FCC-hh design for $L^* = 36$ m. Both FCC-ee designs require approximately the same tunnel diameter of about 2 m, which is reasonable.

The shown IR for FCC-hh is 540 m long, although this value may increase for a longer L^* (current aim $L^* = 46$ m) and depending on the choice of the dispersion suppressor design. The current design specification for the length is

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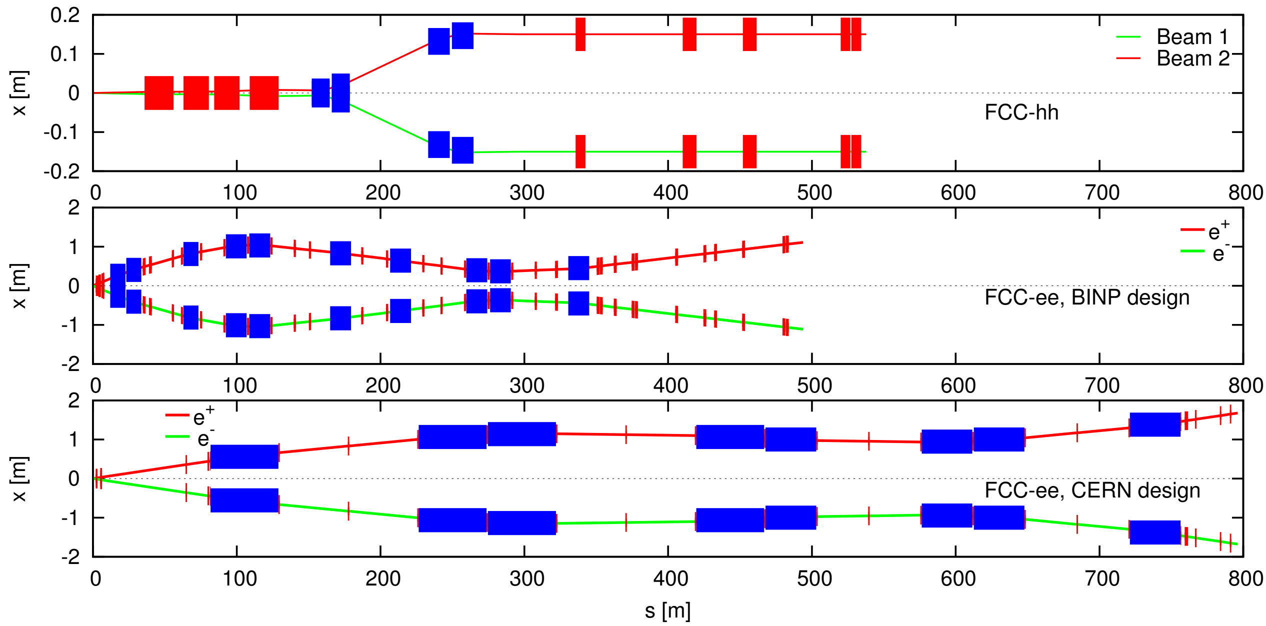

Figure 3: Comparison of the geometry of the current FCC-hh design and both FCC-ee designs. Dispersion suppressors are not included. Red rectangles represent quadrupoles, blue rectangles dipoles. Note the different scales for hadron and electron machines.

Table 3: FCC-ee Baseline Parameters at Z and $t\bar{t}$ Energy for the 100 km Option in the Crab Waist Scheme [7]

	Z	**$t\bar{t}$**
Beam energy [GeV]	45.5	175
Crossing angle [mrad]	30	
Bunches / beam	29791	33
Bunch population [10^{11}]	1	4
Energy loss / turn [GeV]	0.03	7.7
Beta function at IP β^*		
- horizontal [m]	0.5	
- vertical [mm]	1	
Transverse emittance ϵ		
- horizontal [nm]	0.14	2.1
- vertical [pm]	1	4.3
Beam size at IP σ^*		
- horizontal [µm]	8.4	0.3
- vertical [µm]	0.03	0.07
Luminosity / IP [10^{34}cm^{-2}s^{-1}]	212	1.3

700 m. The designs for FCC-ee have lengths of 500 m (BINP) and 800 m (CERN). Due to the high synchrotron radiation in the arcs, an RF section has to be included in the interaction region, requiring an additional dispersion free straight section somewhere between the dispersion suppressors and the IP. Furthermore, both designs presently end with diverging beams and a beam separation of ≈ 2 m. It is not yet clear if they can be bent back together in the dispersion suppressors (which means different dispersion suppressors on each side of the IP) or if this recombination requires a dedicated matching section which will add several hundreds of meters to the overall length of the straight sections. If FCC-hh becomes the driving force for building the tunnel, the BINP design might still work out but the CERN design will be too long. Hence, in further steps shortening the IR in order to ensure recombination within a comparable length will be considered. At the Z-pole, the crab waist scheme promises a luminosity almost one order of magnitude higher than the head-on scheme, 3 times higher at the W energy and 1.6 times higher at Higgs energy. On the other hand, the synchrotron radiation produced is also much higher as can be seen in Table 4. The total average power radiated in 4 IRs sums up to 5.6 MW per beam which accounts for more than 10 % of the overall synchrotron radiation budget. The average powers radiated from the dipoles closest to the IP are comparable in both designs, with the crab waist scheme having a higher critical energy. Further studies are needed to determine whether this radiation crosses the detector without hitting the walls of the vacuum chamber or whether it needs to be shielded.

FIRST TRACKING STUDIES ON THE 100 km RING

First tracking calculations with the full 100 km arc lattice for high energies (Higgs, $t\bar{t}$) [8] were conducted for both designs. All simulations were performed for on-momentum particles, 500 full turns with four IPs and without radiation by MADX and PTC. For these early studies the matching

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Table 4: Characteristics of the Synchrotron Radiation in the Interaction Regions

	Z	$t\bar{t}$
Average total power per IP [kW]		
- CERN	138	138
- BINP	1460	1410
Energy loss per particle per IP [MeV]		
- CERN	0.8	168
- BINP	2.0	440
Average power in last dipole [kW]		
- CERN	7.3	7.3
- BINP	8.2	8.0
Critical Energy in last dipoles $\hbar\omega_c$ [keV]		
- CERN	8.8	503
- BINP	20	1100

of arcs and interaction region was rather preliminary. The machines do not yet fully close, no RF section around the IR was included and the Montague W functions have not yet been aligned. The aim of these studies is to provide a first look at the dynamic aperture.

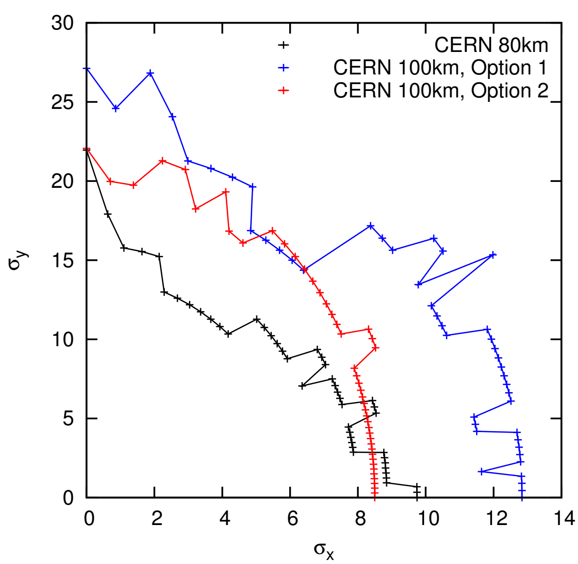

Figure 4: Dynamic apertures of the CERN design for 80 km option and two 100 km options at different working points.

The results for two different working points for the CERN IR are shown in Fig. 4 together with the earlier results with an 80 km arc lattice [9]. The largest dynamic aperture found so far is about 13 σ in the horizontal plane and 25 σ in the vertical plane. The other two options have dynamic apertures of about 9 σ horizontaly and 20 σ vertically. For the CERN IR, the aim right now is to find a working lattice with acceptable dynamic aperture and momentum acceptance. Further improvements and refinements are to be considered. For example, the tune will be set to minimise the adverse effects of the beam-beam interaction.

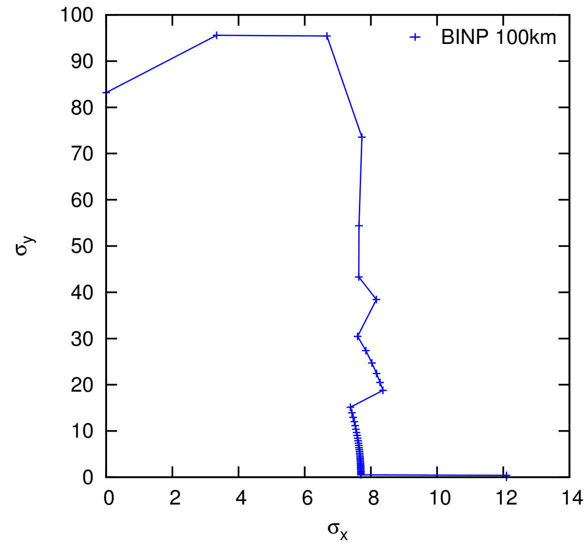

Figure 5: Dynamic aperture of the BINP design for the 100 km option.

Figure 5 shows the tracking results for the BINP design at the 100 km option. It has a dynamic aperture of 8 σ horizontaly and almost 100 σ vertically. The latter is a very important property because the vertical beam size is rather small so even small errors in the magnetic fields will have a large relative impact.

Table 5: Non-integer Part of the Phase Advance between the IPs for the Tracked Lattices

	ψ_x	ψ_y
CERN, 80 km	0.77	0.61
CERN, 100 km, Option 1	0.48	0.23
CERN, 100 km, Option 2	0.77	0.11
BINP, 100 km	0.54	0.57

Recent beam-beam simulations at $t\bar{t}$ energy suggest beam lifetimes of $\tau_{BS} = 0.39$ min at a momentum acceptance of $\Delta p/p = \pm 1.5\,\%$ or $\tau_{BS} \approx 6$ min for $\Delta p/p = \pm 2.0\,\%$. For lower energies, the requirements are more relaxed [10]. The momentum acceptance of FCC-ee should at least lie between these values, the exact minimum value will depend on the performance of the top-up injection scheme planned for FCC-ee. Although the Montague W functions have not yet been matched to the arcs, preliminary momentum scans were conducted in order to get a first notion of feasibility of these momentum acceptances. The scans (Fig. 6 and Fig. 7) were performed within an intervall of $\Delta p/p = \pm 1.5\,\%$ for the CERN IR lattice at the aforementioned 80 and 100 km options and the BINP lattice at 100 km. The CERN design at 100 km (option 1), which had the largest dynamic aper-

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ture, has a momentum acceptance of only $\approx \pm 0.1\,\%$ with some stable orbits for higher momentum deviation after a resonance crossing. This is mainly due to the fast change of the β functions with $\frac{\Delta p}{p}$ and likely to increase, once the Montague W functions are properly matched to the arcs. The scan for the 80 km option showing a momentum acceptance from $-0.6\,\%$ to $0.9\,\%$ before crossing the first integer resonance, as well as the scan for 100 km option 2 ($-0.4\,\%$ to $0.8\,\%$) reinforce this assumption. The BINP design already offers a considerabe momentum acceptance ranging from $-0.6\,\%$ to $1.2\,\%$. Considering the preliminary nature of the matching of arcs and IR, the scans give hope that the required momentum acceptance can be achieved by both design principles.

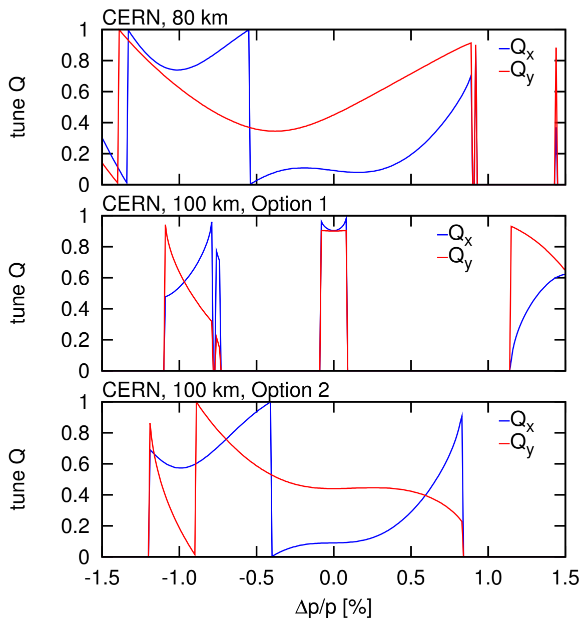

Figure 6: Variation of non-integer part of the horizontal and vertical tunes Q_x and Q_y versus relative momentum deviation $\frac{\Delta p}{p}$ for the CERN designs (80 km and 100 km). For empty sections no stable orbit was found.

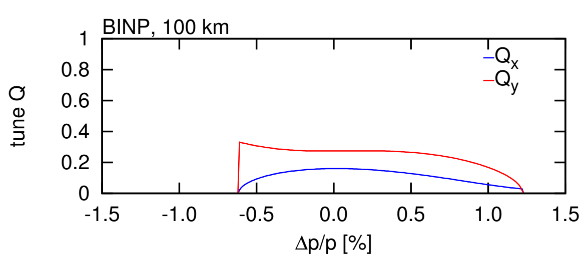

Figure 7: Variation of non-integer part of the horizontal and vertical tunes Q_x and Q_y versus relative momentum deviation $\frac{\Delta p}{p}$ for the BINP design (100 km). For empty sections no stable orbit was found.

OUTLOOK

The matching sections connecting arcs and interaction region will be refined to properly match the Montague W functions in order to allow optimization of the momentum acceptance. Both designs will be rematched to the arc lattice for lower energies and dynamic aperture and momentum acceptance studies will be performed for these setups. The CERN interaction region is still in a very early stage, currently it still inherits several shortcomings of the generic lattice it is based on. This means there is a lot potential for necessary optimization, especially concerning the dynamic aperture and the momentum acceptance. Different concepts for chromaticity correction will be tested in order to reduce the length of the overall interaction region. The correction of higher order chromaticities will be refined by varying the dipole scheme and adding sextupoles closer to the IP. For both designs, the evolution of the dynamic aperture for changing momentum deviation will be studied, as well as possibilities of shielding the synchrotron radiation from the IP.

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