

## PROGRESS IN THE FCC-ee INTERACTION REGION MAGNET DESIGN

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### Abstract

The design of the region close to the interaction point (IP) of the FCC-ee [1] [2] experiments is especially challenging. The beams collide at an angle ( $\pm 15$  mrad) in the high-field region of the detector solenoid. Moreover, the very low vertical  $\beta^*$  of the machine necessitates that the final focusing quadrupoles have a distance from the IP ( $L^*$ ) of 2.2 m and therefore are inside the main detector solenoid. The beams should be screened from the effect of the detector magnetic field, and the emittance blow-up due to vertical dispersion in the interaction region should be minimized, while leaving enough space for detector components. Crosstalk between the two final focus quadrupoles, only about 6 cm apart at the tip, should also be minimized. We present an update on the subject since the work reported last year [3].

### INTRODUCTION

FCC-ee incorporates a “crab waist” scheme to maximize luminosity at all energies [4]. This necessitates a crossing angle between the electron and positron beams which is  $\pm 15$  mrad in the horizontal plane. No magnetic elements can be present in the region approximately  $\pm 1$  m from the interaction point (IP) to leave space for the particle tracking detectors and the luminosity counter. Therefore, beam electrons experience the full strength of the detector magnetic field close to the IP. The resulting vertical kick needs to be reversed and this is performed in the immediate vicinity. This vertical bump, however, leads to vertical dispersion and an inevitable increase of the vertical emittance of the storage ring. Since FCC-ee is a very low emittance machine (with an emittance budget of about 1 pm), the emittance blow-up in the the IP region needs to be minimized. The effect is most important at the Z energies (45 GeV beam energy).

The luminosity counter, a compact electromagnetic calorimeter with a depth of about 20 cm, needs to satisfy the following criteria: the overall rate from Bhabha events at the Z peak cannot be too much smaller than the Z to hadrons rate. This effectively means that the total cross section of the luminometer should not be smaller than about 15 nb. The luminometer will be of a conical design symmetric around the outgoing beam pipe (due to the boost of the Bhabhas from the 30 mrad crossing angle). These requirements fix the position of the front face of the luminometer at a distance of 100 cm from the IP and the back face at 120 cm. This forces the first magnetic element to start at a distance of 125 cm from the IP. This is 25 cm downstream of our early design [3] and since the emittance

blow up is a very steep function of the position of the first magnet element, the whole design had to be readjusted.

Furthermore, the magnetic elements cannot occupy a space outside the acceptance of the luminosity counter (140 to 170 mrad) as this would impact the physics performance.

Another requirement comes from the magnitude of the solenoid field that leaks in the area of the final focus quadrupoles. For a field of 0.03 T the vertical emittance blow up is 0.05 pm. The effect is quadratic. Therefore it is desirable to keep the final focus quadrupoles in a well-compensated longitudinal field region of below 0.05 T.

Field quality in the vicinity of the final focus quadrupoles plays an important role and the requirements are stringent: all normal and skew multipoles should be kept below the  $10^{-4}$  level (1 unit). Furthermore, the upstream and downstream edges of the quadrupoles, where the presence of multipoles is strongest, should give integral multipole fields less than one unit on their own and not by integrating through the whole length of the final focus quadrupole. The reason is that the final focus quadrupoles sit in an area of rapidly changing optics functions. A special programme has been developed to design quadrupoles with very small edge effects.

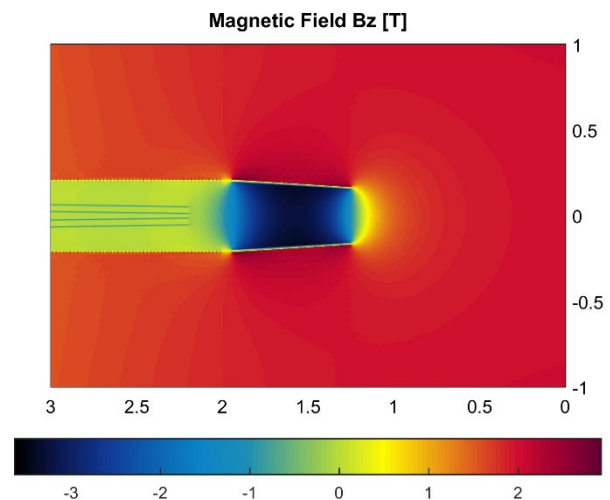


Figure 1: The longitudinal component of the magnetic field in the region  $x=(-1, 1$  m) and  $z=(0, 3$  m) in the vicinity of the compensating solenoid (blue, -3T), screening solenoid (yellow, 0T), final focus quadrupoles (in blue), all in the +2T solenoidal field of the experiment (red).

This analysis is performed for the immediate region around the IP of  $\pm 3$  m. It does not deal with the upstream edge of the detector solenoid and the absence or not of a return yoke at the end caps of the detector, It is assumed

that the challenges in that region are much less important than the region of interest of this paper ( $\pm 3$  m from the IP) and will be dealt with at a late stage.

## THE REQUIREMENTS

We here summarise the list of requirements for the magnetic elements close to the IP:

- $L^*$ , the distance of the final focus quadrupoles to the IP is fixed at 2.2m. this is defined by the optics.
- Emittance blow up (cumulative for all IPs, currently two) much smaller than 1 pm.
- Maximum amplitude of the solenoid field at the tip of the final focus quadrupole less than  $\sim 50$  mT.
- Field quality at each end and everywhere along the final focus quadrupoles smaller than  $\sim 10^{-4}$  for all multipoles.

## THE MAGNETIC ELEMENTS AROUND THE IP

The beam-stay-clear (b-s-c) area in the vicinity of the interaction region has been computed to be  $\pm 12$  mm. This allows for a compact *beam pipe* of 30mm in diameter. The improved conceptual design of the magnetic systems close to the IP which fits our requirements comprises the following elements:

The *detector solenoid* is a cylinder with an inner radius of 376cm and an outer radius of 382cm. Its half-length is 400cm. There is no iron yoke at the moment for cost saving reasons but one can be fitted at the upstream edges of the solenoid without affecting the philosophy of the current design. The adoption of a realistic detector solenoid represents an improvement of our earlier design [3], where the detector solenoid field was assumed to have a uniform value everywhere.

The *screening solenoid* is a thin solenoid producing a field equal and opposite to the detector solenoid and screens the final focus quadrupoles from the detector solenoid field. It starts at 200cm from the IP and extends all the way to the endcap region of the detector. Its inner radius is 20cm and its outer radius 22cm. Since the original design, two more degrees of freedom have been added in the form of two corrector solenoids to deal with the fact that the detector solenoidal field varies along Z (in the original design it was assumed to be constant). One can envisage more degrees of freedom to be added in the future by splitting the screening solenoid into a series of screening solenoids.

The *compensating solenoid* sits in front of the screening solenoid, has a field higher than that of the detector solenoid, so that the magnetic field integral seen by the beam is zero. The length of this solenoid is 70cm, its front face is at 125cm from the IP and its back face at 195cm, and its strength is approximately -5T. It is tapered and its outer diameter at the front tip is 17cm and at the back tip 22cm. This corresponds to an angle of 136mrad for the front face and 113mrad at the back face. Note that this is

worse than the original design, where all elements were within a 100mrad angle from the IP.

Since large fields are required, the coils mentioned in this work will make use of Nb-Ti superconducting wire technology. This results in a need for cryostats and the infrastructure and service associated with them, which also take space. Space, therefore is the biggest challenge in this work.

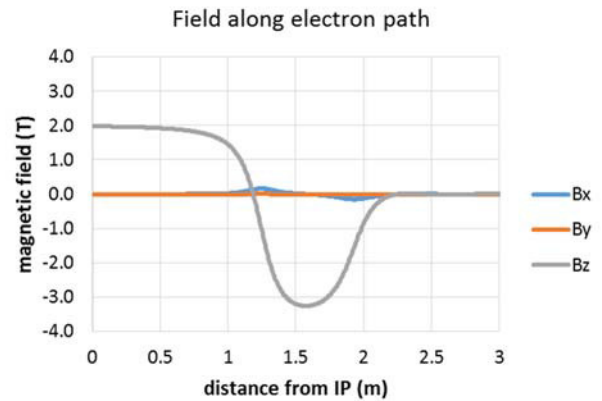


Figure 2: The field profile seen by an electron from the IP up to a distance of 3m (still inside the detector solenoid). During the first meter or so the electron sees the full detector solenoid field, then the field reverses thanks to the compensating solenoid and it finally approaches zero at the tip of the final focus quadrupoles (at 2.2m from the IP).

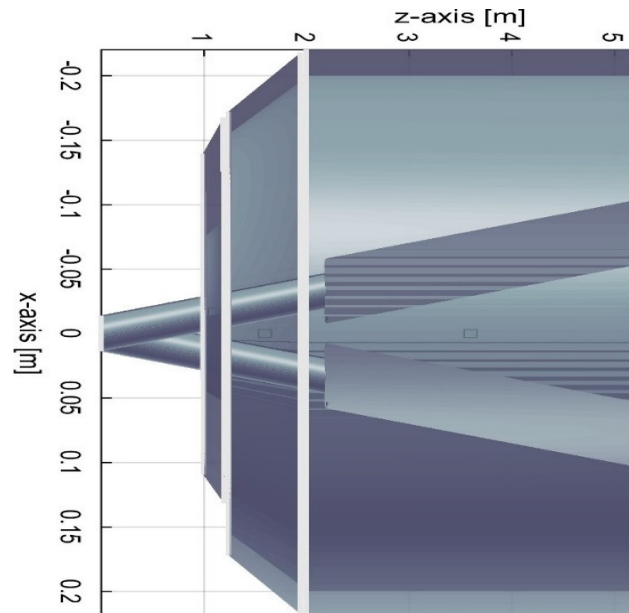


Figure 3: The conceptual design of the magnetic elements close to the IP, looking on the x-z plane (from above). The detector solenoid has been omitted for clarity. The IP is at (0,0). Please note the elongated scale in x. The compensating solenoid is tapered and is in front of the screening solenoid. The luminosity counter is centred around the outgoing beam pipe and sits at a distance of 100 to 120cm from the IP.

The *final focus quadrupoles* in our current design sit at a distance of 2.2m from the IP and are 3.2 m long. The focusing strength in the current design is about 100T/m at 175GeV [5]. The distance between the centres of the two quadrupoles is 6.6 cm at the tip closest to the IP and 16.2cm at the far end.

The different elements of the design can be seen in Figure 3, as seen looking down on the detector. Please note the elongated view along the x-axis. Figure 1 shows the longitudinal component of the magnetic field and Figure 2 the field components in the x, y and z direction along the direction of the electron. All analysis described here was done using the *Field* suite of programs [6].

## EMITTANCE BLOW-UP

The vertical emittance increase close to the IP,  $\Delta\epsilon_{y,IP}$ , is given by

$$\Delta\epsilon_{y,IP} = 3.83 \times 10^{-13} \frac{\gamma^2 I_{5,IP}}{J_v I_2} \quad (1)$$

Where  $\gamma$  is the relativistic  $\gamma$  of the beam,  $I_2$  is the second synchrotron radiation integral which can be approximated by

$$I_2 \cong \frac{2\pi}{|\rho_{bend}|} \quad (2)$$

(equal to about  $6 \times 10^{-4}$  for FCC-ee with bending radius in the arcs  $\rho_{bend} = 11$  km.  $J_y = 1$ . The fifth synchrotron radiation integral is

$$I_{5,IP} = \int_{-d}^d \frac{\mathcal{H}_y(s)}{|\rho|^3} ds \quad (3)$$

where  $\rho$  is the bending radius due to the magnetic field along the path of the electrons in the area of interest,  $-d$  to  $d$ , in our case -3 to 3 m.

$$\mathcal{H}_y(s) = \beta(s)D_y'^2 + 2\alpha(s)D_y D_y' + \gamma(s)D_y^2 \quad (4)$$

where  $D_y$  is the vertical dispersion (see Figure 4) and

$$\alpha(s) = -\frac{1}{2}\beta'(s); \gamma(s) = \frac{1+\alpha(s)^2}{\beta(s)} \quad (5)$$

Where  $\beta(s)$  is the vertical beta optics function. Emittance blow up is worse at low energies due to the  $\frac{\gamma^2}{|\rho|^3}$  dependence (the magnetic field of the detector is expected not to change at different energies).

A study of the above formulas reveals that to minimize the vertical emittance blow up one needs to (a) elongate the compensating solenoid in Z as much as possible and (b) increase its diameter as much as possible. These requirements are of course in conflict with the  $L^*$  of the machine (2.2m) and with the requirement that the magnetic elements should not be in the way of detector elements. A compromise of all requirements has given the layout described above. The overall emittance blow up for two IPs has been computed to be 0.3pm (Figure 5), or about 30% of our vertical emittance budget.

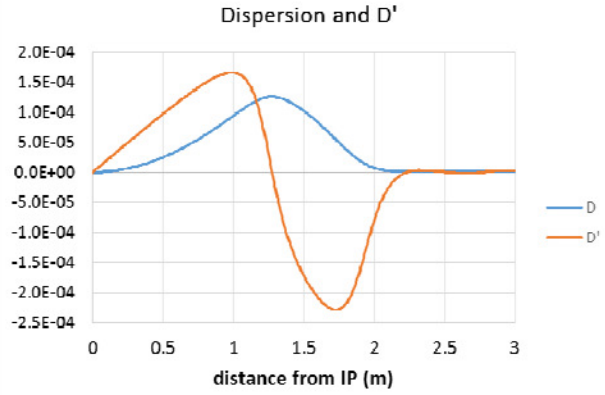


Figure 4: Vertical dispersion and its derivative close to the IP.

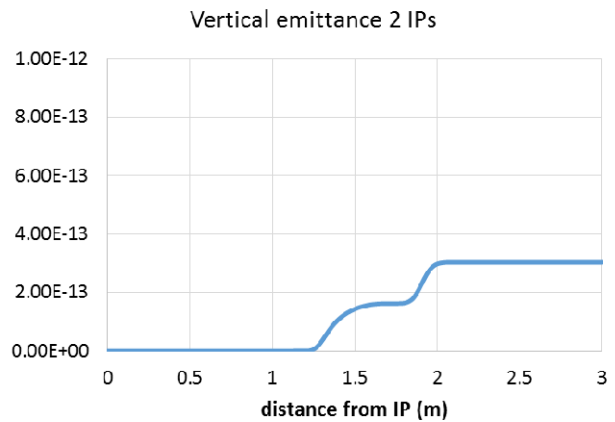


Figure 5: Vertical emittance blow up from the IP to 3m downstream multiplied by a factor 4 to give the total emittance blow up close to the IPs for a ring with two experiments.

## FINAL FOCUS QUADRUPOLES

The final focus quadrupoles have stringent requirements regarding cross talk and edge effects (less than 1 unit everywhere for all multipoles integrating only short regions (of the order of 20cm). We have a design based on CCT technology [7] [8] that satisfies these requirements, reported elsewhere [9] [10].

## CONCLUSIONS

We have demonstrated that the very stringent requirements for the magnetic systems around the IP of an FCC-ee detector can be met with a system comprising final focus quadrupoles, screening solenoids and a compensating solenoid. The emittance blow-up due to two interaction regions is computed to be 0.3pm, well within the desired range.

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