SYNCHROTRON RADIATION ISSUES FOR THE CEPC IR*

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Abstract

This is a preliminary investigation of some of the issues concerning Synchrotron Radiation (SR) generated in and nearby the Interaction Region (IR) of the CEPC e+e- Higgs Factory design. Background issues are discussed as well as power levels and power absorption of the SR in this region. Implications as to final focus magnet parameters, including L*, and nearby bending magnet strengths and positions are explored.

INTRODUCTION

The IR of any collider is one of the more difficult sections of the accelerator. There are several conflicting requirements related to this area that need to be satisfied. The ultimate performance of the accelerator (the luminosity) is manifest here by the event rate of the physics coming out of the collision between the beams. Low β* values are needed which in turn requires large beta functions in the final focus magnets (usually a doublet). The distance from the final focus magnets and the Interaction Point (IP) called L* plays an important role. The physics detector prefers as much space as possible around the collision point in order to collect as much physics as it can. However, areas close to the beams and to the vacuum beam pipes are populated with backgrounds from the beam particles directly (lost beam particles through various mechanisms: Beam-Gas scattering (BGB), Coulomb scattering, Touschek scattering, Inter-bunch scattering (IBS), beamstrahlung, to name a few. In this paper, I will concentrate on the backgrounds and implications of the large amount of SR generated in this area.

CEPC INTERACTION REGION

The high energy of the colliding beams (120 GeV) makes high power fans and beams of SR. This radiation must be controlled and designed to either be absorbed in local masks and shields or to pass harmlessly through the IR to be absorbed at some location away from the IP. The intensity of the SR generated in this area is high enough to instantly (seconds to minutes) destroy unprotected detectors if it is not properly controlled. Usually at least 4 orders of magnitude (and in some cases much more) suppression is needed in order to create an environment suitable for detectors to collect the physics from the collision point.

Table 1 lists some of the accelerator parameters important for the study of SR backgrounds in the IR. This is not a complete parameter list but emphasizes features important to IR designs.

Table 1: Some accelerator parameters important for SR background studies in the interaction region.

Accelerator Parameters related to IR designs	
Beam energy (GeV)	120
Current (mA)	16.6
Number of bunches	50
Particles/bunch	3.79×10^{11}
L* (m)	1.5
Emittance x/y (nm-rad)	6.12/0.018
β* x/y (mm)	800/1.2
QD0 L(m) and G(T/m)	1.25/300
QF1 L(m) and G(T/m)	0.72/300

SYNCHROTRON RADIATION SOURCES

The sources of SR come from nearby magnets. The important magnets are the final focus magnets and the last bend magnet before the collision point. We will first take a look at the last bend magnet in the design.

Last Bend Magnet before the IP

In an earlier design, the last bend magnet from the local chromaticity correction block had the following parameters: length 3.375 m and a bend angle of 4.416 mrad. These values gave a field strength of 5.275 kG for this bend magnet. This is a very intense magnetic field for this beam energy (the arc bend magnets have a field strength of about 600 G). This bend magnet would have generated 8965 kW of SR power. This was quickly recognized as too much local power and a new design has emerged in which the bend magnet has been lengthened to 15.5 m and the strength has been reduced to 1 kG. This reduces the SR fan power from this magnet to 47 kW, still a significant amount of power, but greatly reduced from the initial design. The new bend magnet also starts 30 m from the IP which is about 15 m farther away from the IP.

Figure 1 shows a drawing of a possible beam pipe with a 2 cm radius for the pipe outboard of the final focus (FF) quads. There is a 1.5 cm radius cryogenic pipe under the final focus quads and the collision point beam pipe has a 1.5 cm radius and is ±0.1 m long. As one can see, the SR fan from the last bend magnet passes entirely through the region and the detector beam pipe and the cryogenic beam pipes under the FF quads must be shielded from this fan. The power incident on the beam pipe from the SR fan is shown. The power density for each section of the fan and for various surfaces of the beam pipe is listed in Table 2. For reference, an acceptable beam pipe surface power is usually about 10 W/mm. The highest beam pipe wall power that can be absorbed is about 20 W/mm and a material called GlipCop™ which is dispersion strengthened copper is one of the few materials that can stand up under this power density.

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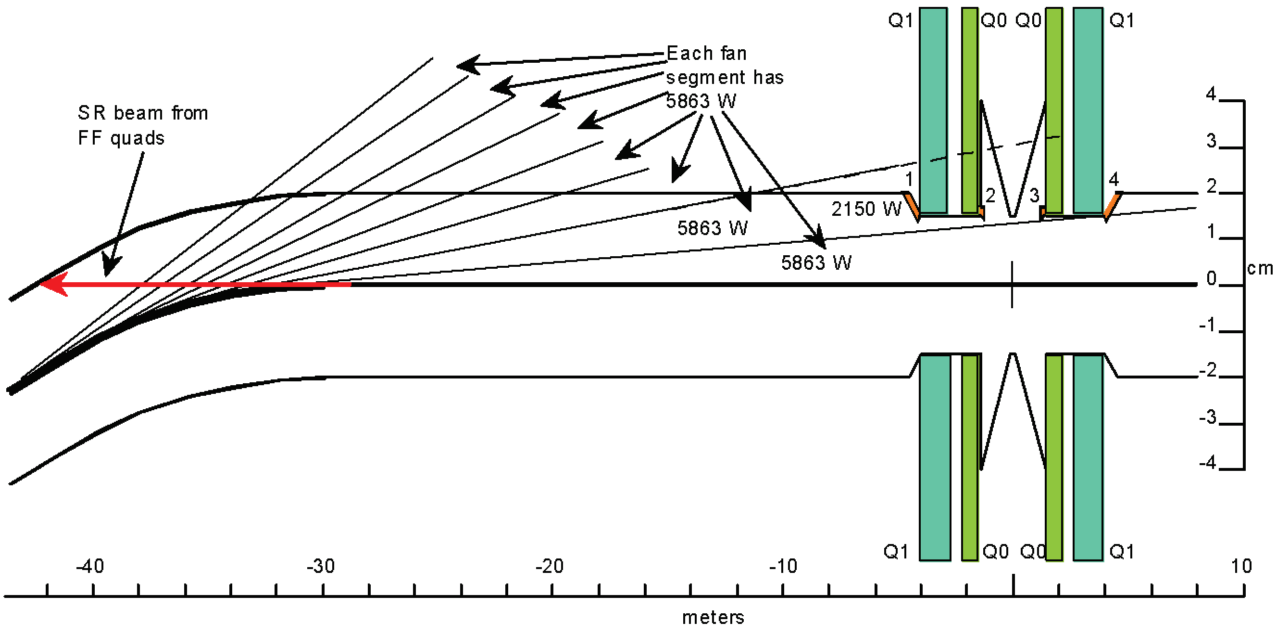

Figure 1: Drawing of the synchrotron radiation fan from the last bend magnet coming from the beam that enters from the left side of the picture. This layout reflects the latest IR design. The SR fan from this magnet is shown in 8 sections. Each section generates 5.863 kW of power. The critical energy of these fans is 958 keV. The amount of SR power to strike mask #1 is estimated to be 1250 W. Assuming the shield is stretched out over 0.5 m (as drawn) then the power density on this surface is 2.5 W/mm which is an acceptable number. This surface as well as all of the upstream beam chamber surfaces (from both sides) will have to be water cooled. The large red arrow to the left indicates where the intense SR beam generated by the FF quads will hit the beam pipe. In this picture, the SR power in the red arrow comes from the other beam.

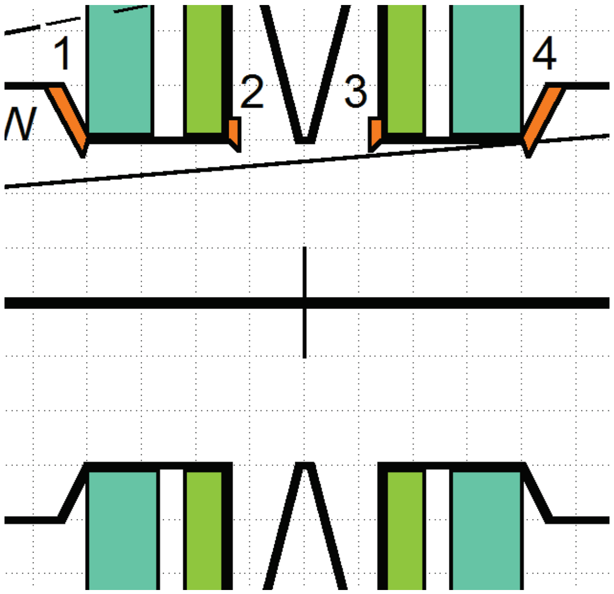

Figure 2: Close up of the IR region. This shows more clearly the suggested masking needed to shield the cryogenic beam pipes inside the final focus magnets from the bend radiation of the last horizontal dipole magnet. The masking is necessarily right/left symmetric in order to shield the cryogenic beam pipes from the bend radiation coming from the other beam (not shown in this picture). So, masks 1 and 3 are used to protect the beam pipes from the left beam fan and masks 2 and 4 are needed to shield the beam pipes from the right beam fan.

The depicted masking scheme in Figs 1 and 2 is only a suggested solution. A detailed simulation of the photons coming from this bend magnet needs to be done to insure that the shielding is adequate. As we see from the example here, there will be forward and backscattering from these masks and that will also have to be carefully modeled. In addition, because the energy spectrum is high, many photons will penetrate most masking schemes and a tally of these photons will also be needed in order to correctly estimate the background rate in the detector and onto the cryogenic beam pipes.

Table 2: Power levels on the beam pipe from the last bend magnet SR fan. The fan is broken into 8 separate fans of equal SR power (5683 W) in order to more correctly estimate the surface power on the beam pipe.

Fan number	Est. beam pipe length (m)	Power density (W/mm)
1	2.0	2.93
2	2.2	2.67
3	2.2	2.67
4	3.1	1.89
5	4.4	1.33
6	8.6	0.68
7	5.9	0.38*
8	>20	0.29#

*This is only part of a fan section. See Fig 1.

#This fan segment travels completely through the IP and strikes downstream surfaces.

Final Focus Quadrupoles

The final focus quadrupoles are the last magnets before the collision point. They generally have fairly high magnetic field strengths and perform the final focus of the beam to the small β values at the IP. Table 3 lists the parameters of the final focus quads for the CEPC design.

Table 3: Parameters for the Final Focus Doublet

Magnet	QD0	QF1
Length (m)	1.25	0.72
Z of Face (m)	1.5	3.25
Gradient (T/m)	300	300
Beam pipe radius (mm)	16	16
Coil radius (mm)	20	20

As we can see from the table the magnet strengths are quite high. Since the beam energy is also very high, these magnets will generate significant SR.

Beam-stay-clear and Beam Tails

A crucial aspect of finding out whether or not the beam produces background SR from these magnets is the definition of the Beam-Stay-Clear (BSC) and the beam particle population in the high beam sigma region. The BSC is defined as the transverse region around the beam where no physical object can intrude. This means all beam pipes and other physical objects must be outside of this boundary. Most storage ring beams require a minimum of 10 σ_x and 10 σ_y. A storage ring collider needs more vertical space because high luminosity means a high vertical tune shift. This means that more beam particles are pushed vertically out away from the beam core, hence the necessity of more vertical aperture. The vertical BSC is usually described as between 35 and 60 σ_y depending on the accelerator emittance ratio. In addition, the BSC definition has a dispersion term to account for regions of high dispersion. The equations describing the BSC are:

$$BSC_x = n\,\sigma_x + COD_x \;\; and \;\; BSC_y = m\,\sigma_y + COD_y$$

$$where \;\; \sigma_x = \sqrt{\varepsilon_x\beta_x + \left(D_x(\delta p/p)\right)^2}$$

$$and \quad \sigma_y = \sqrt{\varepsilon_y\beta_y + \left(D_y(\delta p/p)\right)^2}$$

COD_x and COD_y are the allowed orbit differences from ideal (typically between 0.5 and 1 mm) and n and m are the number of agreed upon beam sigmas. The distribution of beam particles in the high sigma region is the next important piece of information. Figure 3 shows the assumed transverse beam distribution that was used to simulate the beam profile for the PEP-II B-Factory.

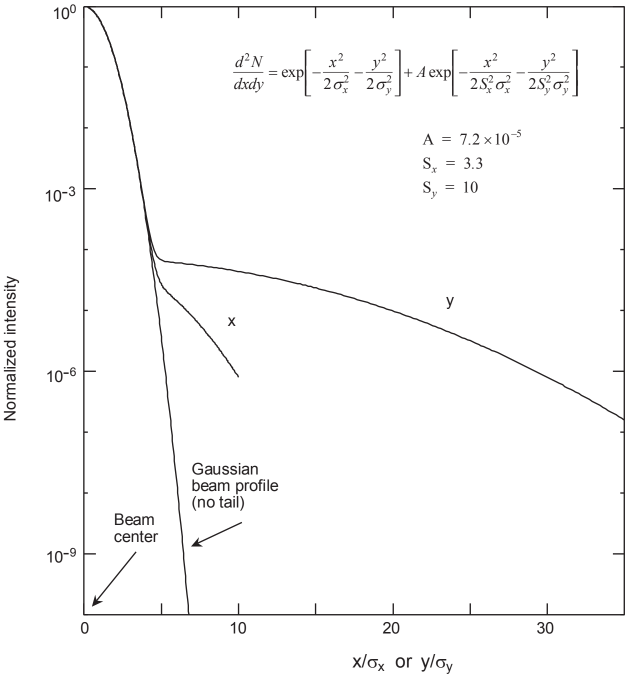

Figure 3: Transverse beam profile plot that was used in the PEP-II B-Factory background simulations for SR. The particle density at the ends of the tail distributions reflect an approximate beam lifetime of 1 hour assuming the beam particles at a distance greater than 10 σ_x and 35 σ_y are lost either through collimation or through dynamic aperture limits. The emittance ratio for the PEP-II B-factory was about 0.05. This was significantly larger than the proposed emittance ratio of the CEPC design which is 0.003.

Final Focus Synchrotron Radiation

In the CEPC design, the final focus quadrupoles produce a synchrotron radiation beam of gamma rays (here we define a gamma ray as a photon that is > 1 MeV) along the colliding beam axis. The intensity of this beam grows rapidly as the distance to the beam axis decreases. Table 4 shows the photon rate per bunch crossing as a function of radius at the IP (Z=0.0). The photon values in the larger radii data points are dominated by the choice of beam tail parameters. One can see from the table that the photon rate and the power density climb rapidly as the radius gets smaller. Near the beam axis nearly all of the particles in the beam are contributing to the generation of SR.

Table 4: Photon rates and power densities of the synchrotron radiation photons from the FF quads. The photon numbers are for each bunch crossing. Each row of numbers in the table are for an annulus with an inner radius given by R1 and an outer radius given by R2. This table shows the numbers for one beam. These numbers double for both beams. The values in this table come from a beam profile distribution shown in Figure 3. The beam profile is traced out to 12 σ_x and 65 σ_y for the CEPC FF design. There were no photon hits above 23 mm radius at the IP for this particular scenario.

R1 mm	R2 mm	Total γ/bun xing	Watts	γ/bun xing > 10 MeV	Each ring W/mm^2
22	23	6.22E+02	2.45E-04	1.55E+02	0.0000
21	22	6.86E+03	2.72E-03	1.71E+03	0.0000
20	21	2.01E+04	7.71E-03	4.91E+03	0.0001
19	20	5.26E+04	1.94E-02	1.24E+04	0.0002
18	19	1.31E+05	4.61E-02	3.00E+04	0.0004
17	18	3.14E+05	0.105	6.94E+04	0.0010
16	17	7.18E+05	0.228	1.52E+05	0.0022
15	16	1.57E+06	0.474	3.19E+05	0.0049
14	15	3.30E+06	0.941	6.38E+05	0.0103
13	14	6.64E+06	1.79	1.22E+06	0.0211
12	13	1.28E+07	3.25	2.23E+06	0.0414
11	12	2.38E+07	5.64	3.88E+06	0.0781
10	11	4.23E+07	9.4	6.46E+06	0.142
9	10	7.26E+07	15	1.03E+07	0.251
8	9	1.20E+08	23.1	1.57E+07	0.432
7	8	1.93E+08	34.6	2.32E+07	0.734
6	7	3.02E+08	50.5	3.32E+07	1.23
5	6	4.66E+08	72.4	4.66E+07	2.09
4	5	7.01E+08	99.9	6.25E+07	3.53
3	4	9.99E+08	128	7.61E+07	5.82
2	3	1.56E+09	1667	8.98E+07	106.1
1	2	3.03E+10	1487	3.47E+08	157.7
0	1	4.87E+11	10803	7.72E+08	3438.7

It is possible that some rate of SR photons incident on the central detector beam pipe is acceptable. A simulation of the detector beam pipe and of the first layers of the silicon tracker is necessary to see what level of hit rate is acceptable. It is also possible that some shielding may be installed that can absorb some of the incident photons. Again, this needs to be simulated in detail to see if shielding can help.

Almost all of this radiation will travel through the nearby IP area and strike the beam pipe where the first bend magnet occurs for the outgoing beam. This is shown in Fig 1 by the large red arrow. The red arrow depicts the SR beam that comes from the opposite beam as it travels through both sets of final focus magnets. In this drawing, the beam pipe surface is sloped by about 3.4 mrad with respect to the collision axis and this means the power from this SR beam is spread out over as much as 0.3-1 m. Since both sets of FF quads contribute to the SR beam the total power striking the beam pipe surface is about 30 kW. The power density on the beam surface is then about 90-30 kW/m which is too high for any material to withstand. A careful beam pipe design will be needed in this area in order to properly control and absorb this radiation. Either a thin beam pipe that absorbs only part of the power and/or a more sloped surface are possible solutions but a detailed simulation will again be needed in order to properly design this beam pipe.

CHECKLIST FOR SR STUDIES

Below I have an incomplete list of items to investigate or check for any general SR design. There are bound to be topics missed in this list so the best a designer can do is to try to imagine where the photons might go after they strike a surface and to keep in mind that the answer is essentially all directions.

- The very first concern is the number of SR photons that directly strike the detector beam pipe and the cryogenic beam pipes under the FF quads. Ideally this number is zero after introducing appropriate shielding but some small number of hits per bunch crossing might be acceptable.
- The shielding used to protect these chambers from direct hits will now be a new source of SR photons through forward and back scattering photons from these shield surfaces.
- These now become significant new sources because they are relatively close to the chambers that need to be protected and these chambers hence have a fairly large solid angle acceptance for the scattered photons. These new source rates may force moving the shields farther upstream in order to decrease the solid angle acceptance. This may not always be possible and a careful choice of shielding materials may help.
- One may ultimately be forced to increase the radius of the chambers that must be protected from SR.
- The radiation from the last bend magnet is always an issue and introducing a very low field final section to this bend magnet can sometimes help.
- Allowances must be made for non-ideal beam orbits since this will most likely increase photon hits on sensitive beam pipe chambers.
- In addition, one must check for forward scattering photons from upstream beam pipes as far away as the last bend magnet before the IP.
- One must also check for backscattered photons coming from beam pipe surfaces as much as tens of meters downstream of the IP.

CONCLUSION

I have taken a very preliminary look at SR issues in the IR area of the CEPC accelerator design. There are several things to be aware of and many of the desires for both the detector and for the accelerator must be carefully checked to make sure these requests can survive the intense SR fans and beams in this area.

ACKNOWLEDGMENT

I would like to acknowledge the organizers of the workshop for setting up the program and presenting this very interesting accelerator design for a Higgs Factory. The IR has several very interesting design issues especially with respect to synchrotron radiation that must be addressed. The issues are challenging and this makes them all the more intriguing. I also want to thank the local CEPC design team for their help in giving me the details of the latest design. This has made this paper much more accurate and (I hope) helpful.