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IR DESIGN ISSUES FOR HIGH LUMINOSITY AND LOW BACKGROUNDS*

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Abstract

New e^+e^- accelerator designs aim for factory-like performance with high-current beams and high luminosities. These new machines will push interaction region designs to new levels and require a careful evaluation of all previous background sources as well as introduce possibly new background sources. I present here a summary of standard background sources and also suggest a new possible background source for Synchrotron Radiation (SR) namely, specular reflection. In addition, one will have to pay closer attention to the beam tail particle distribution as this may become a significant source of SR background from the high-current and high-energy beams of these new designs.

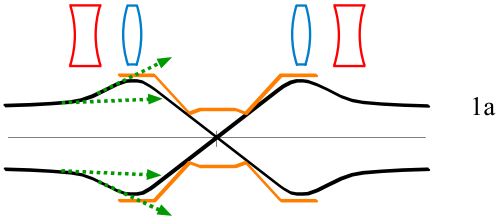
INTRODUCTION

The Interaction Region (IR) of a colliding beam e^+e^- accelerator is always one of the more challenging aspects of the collider design. In order to obtain a high luminosity, usually done by having many beam bunches, nearly all designs now have a separate storage ring for each beam. This in turn means that the collision has a crossing angle (only the PEP-II B-factory had separate storage rings and a head-on collision through the use of strong bending magnets close to the Interaction Point (IP)). Crossing angles for new or recently completed designs range from ±15 mrad (FCCee [1,2]) to ±41.5 mrad (superKEKB [3]). The demand for high-luminosity (~10^{34}-10^{36} cm^{-2}s^{-1}) requires the final focus magnets to be close to the IP (~1 m) in order to get the necessary small spot size at the collision point. I will first discuss some of the standard layout issues for a collision point and how these affect the background studies. Then I will concentrate on the various background issues related to SR and, in particular, discuss the potential for specular reflection to become a possible new SR background source. I will then look more closely at the issue of the beam tail particle distribution and how this distribution can become an important source of SR backgrounds. Finally, I will mention the standard beam particle backgrounds that must always be studied along with some of the other accelerator related issues that must be evaluated before an IR design can be accepted.

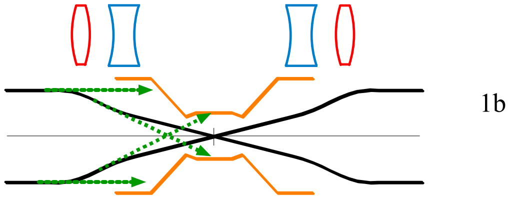
THE IR DESIGN

Final Focus Quadrupoles

As mentioned above, modern factory designs have a crossing angle between the beams at the collision point. The crossing angle is imposed by the requirement that the focusing elements in each beam are independent (i.e. there are no shared magnets – no quadrupoles that have both beams). In addition, the Final Focus (FF) magnets are placed close to the IP. The short L* values (~1-2 m) in these designs mean that these FF quadrupoles are quite strong and that the beta functions in these quads tend to be large. This makes the FF magnets an important source of SR production. This is especially true of the high-energy (FCCee and CEPC) designs. Here the FF magnets are focusing a very high-energy beam and the SR energy spectrum from these magnets is well into the MeV range. The photons from this higher energy spectrum need to be masked and the high energy of these photons make this more difficult. Figures 1a and 1b illustrate the masking issues for SR that comes from the FF magnets.



Vertical beam focusing (side view)



Horizontal beam focusing (plan view)

Figure 1: Illustration of the primary issues in shielding a central beam pipe from the SR coming from final focus magnets. 1a: Vertical view of the FF magnets and IP. The SR generated in the vertical comes from the beam when it is defocused in X-focusing magnet (red outline) which is usually before the Y-focusing magnet (blue outline) the last magnet before the IP. The X-focusing magnet generates fans of SR that are between the two green dashed arrows in the drawing. There is another fan from the Y-focusing magnet that is between the outside green dashed arrows and the beam envelope that hits the IP. This radiation is easier to shield than the radiation shown in 1b. 1b: Plan view showing the horizontal radiation fans generated by the beam in the X-focusing magnet which is before the Y-focusing magnet. This radiation is more difficult to

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shield as the SR fans cross-over the beam axis because of the over-focusing nature of this magnet. The horizontally focusing magnet must over-focus in order to compensate for the defocusing that comes from the Y-focusing magnet. This can be seen from the outline of the beam envelope (black lines) in the drawings.

The close FF quadrupoles will obscure more of the low angle acceptance of the detector. In order to minimize this the outer radius of these quadrupoles is minimized. The large beam size in these magnets and the need to minimize the outer radius tends to push the magnet design to a cold bore configuration. This can be okay, but the SR generated by the upstream FF magnets must then not strike the inner bore of the downstream FF magnets in each beam line. If masking the downstream magnet bores is needed, this mask can become a backscatter source of SR photons for the detector and care must be taken to minimize this potential source of background.

OTHER SR BACKGROUNDS

Secondary SR Sources

Once primary strikes of SR photons on the central beam pipe have been masked away it becomes necessary to consider all possible cases of secondary radiation coming from one bounce and/or mask tip scattering. The high-energy beams of new accelerator designs have higher energy photon spectra, and this will increase the rate of secondary sources. In addition, the high-current beams of all designs also increase the secondary source rates.

Tip scattering is an unavoidable source of secondary SR background. The SR photons that strike near an edge or near the corner of a mask have a chance of scattering through the mask material and striking the central detector beam pipe. The tip scattering rate increases as the incident photon energy increases (higher energy photons have a greater chance of scattering through the material). Figure 2 illustrates this source of SR background.

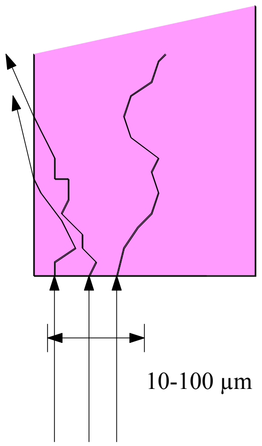

Figure 2: The SR photons that strike a mask either near a tip or near an edge have a chance of scattering through the material. Some fraction of these forward-scattered photons will strike the central beam pipe.

Tip scattering can be minimized through material selection for the mask. A high Z material is usually better, and this choice is also usually better for beam particle backgrounds. When possible, moving the mask tip back away (in Z) from the central beam pipe reduces the solid angle acceptance to the central beam pipe for the scattered photons. This can sometimes be done with an upstream mask intercepting the majority of the incident radiation and the closer mask then receiving a reduced incident photon rate.

Backscatter from either downstream beam pipe surfaces or downstream masks can be a serious source of detector background from SR. Here again, keeping these sources as far away as possible from the IP will reduce the solid angle acceptance back to the central beam pipe and keep these backgrounds low. Also, the choice of mask material can be tailored to a specific photon energy spectrum and this can help reduce the rate from this downstream secondary source.

Coating the central beam pipe (which is invariably made of Be) with a thin layer of high Z material (i.e. Au), can significantly cut down the penetration rate of incident photons if the photon energy is low enough (usually <10-20 keV). However, at the very high energy machines (i.e. the FCCee at the top energy), it is not so clear that a thin layer of high Z material helps since the photon energies are so much higher. In this case, a lower Z material (i.e. Cu) may be selected for conductivity issues rather than for SR photon absorption. The lower Z material of course reduces the track multiple scattering – a feature generally desired by the detector team.

Upstream Last Bend Magnet

The last bend magnet before the IP always sends SR into the IR. This radiation must always be masked away from the central chamber. All designs strive to make this last bend magnet weak and as far from the IP as reasonable. The number of photons decreases with increasing distance and the energy spectrum of the SR photons diminishes linearly with the magnetic field strength. A soft energy photon spectrum is much easier to mask away from the central beampipe but the increase in low energy photons and the large distance from the IP together can make a possible new source of detector background (see below).

Specular Reflection

When the photon energy spectrum is soft, and the angle of incidence is small many of the incident photons can actually mirror reflect (specular reflection) off of a surface. See Fig. 3. The number of mirror-reflected photons can be much higher than the number of photons that scatter out of the incident surface. I have found one reference where a surface of *unpolished* Cu had a reflection coefficient of nearly 20% for incident photons up to 25 keV at an incident angle of 3.5 mrad [4]. The material tested was similar to the type of inside surface found in a Cu beam pipe.

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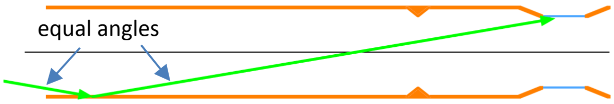

Figure 3: Photons from specular reflection off of a beam pipe surface that is far upstream of the IP might be able to avoid the local masking scheme and strike the central beam pipe.

This background source is particularly difficult to simulate. One has to know a great deal about the inner surface of the vacuum chamber as well as some information on the reflection coefficient as a function of incident photon energy and incident photon angle. Special cases have been simulated and work is ongoing to put specular reflection into several codes [5-8].

The best procedure to check for specular reflection is by inspecting the geometry of the design. If it is possible for reflected photons to strike the central beam pipe, then proceed to install masking or rearrange the geometry so that specular reflection photons can no longer strike the central chamber. This may have to include the study of multiple bounces as parallel beam pipe surfaces may be able to "pipe" the reflected photons over long distances [9].

BEAM TAILS

All stored beams have a non-gaussian beam tail. The particle distribution comes about from several different factors, 1) quantum fluctuations in SR emission, 2) beam-beam interactions, 3) beam-gas interactions, 4) Inter-beam scattering to name a few. This tail distribution can contribute to detector backgrounds by two methods: 1) the high sigma particles may get lost inside the IR and 2) the high sigma particles can emit SR inside the final focus quads generating steep angle photons that have a chance of getting around the masking scheme and either hitting the central detector beam pipe directly or hit nearby surfaces that can one bounce to the central beam pipe. The number of beam particles in the tail distribution should not be more than about 1-2% of the total. Anything much above this number would start to be noticeable as a discrepancy in the calculation of the luminosity since the tail particles do not contribute to the luminosity [10]. On the other hand, there cannot be too many particles at very high sigma or out where there is a physical aperture as these particles would be scrapped off and cause beam lifetimes that are too short. M. Sands [11] has made an estimate of the particle density at an aperture limit as a function of lifetime and concludes that a particle density equivalent to the 6σ value of the standard beam gaussian sets a lifetime of about 1 day. New accelerators accept lifetimes of less than 1 hr and in some cases as little as 10 min. This means the particle density at an aperture limit (like a collimator) can be quite a bit higher. Figures 4a and 4b show plots of the tail distributions used by the SR background simulation program SYNC_BKG [12]. The tail is a second flatter gaussian compared to the primary beam gaussian (shown with a blue line). In addition, the plot shows the particle density levels for several beam lifetime estimates based on the calculation made by Sands.

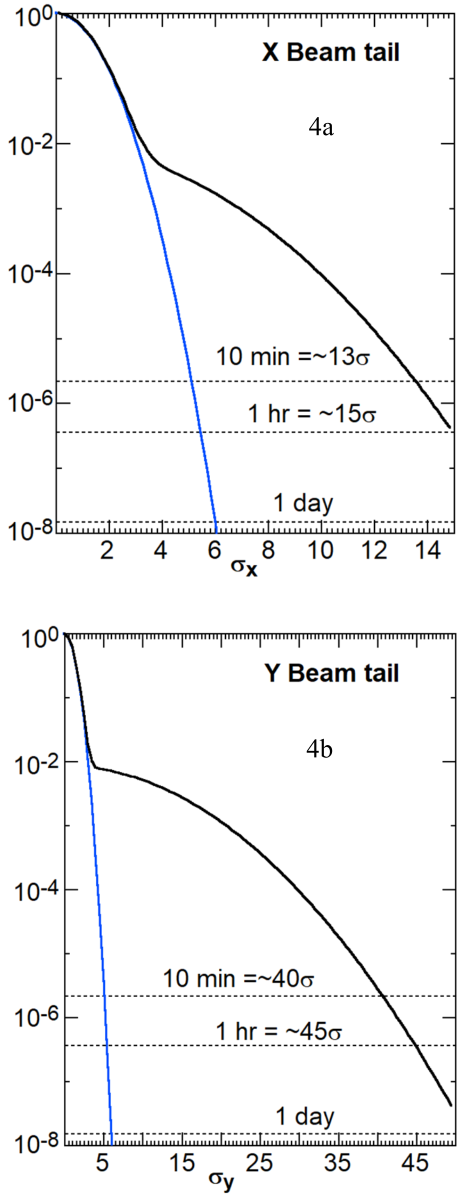

Figure 4: Figure 4a is a plot of the X tail distribution with dashed horizontal lines indicating approximate beam lifetimes based on the estimate by M. Sands. The blue lines in 4a and 4b are the profile of the main beam gaussian. Figure 4b is the vertical tail distribution. Here we assume the main beam bunch vertical sigma is smaller than the horizontal sigma and subsequently increase the aperture out to about 50σ. The vertical tail is consequently depicted as being flatter than the horizontal beam tail. The 2D integral of the tail distribution shown in these plots above leads to a sum of about 0.3% or almost 10 times lower than the estimated upper limit.

The estimates listed previously concerning the possible range of the beam tail distribution still leaves a lot of room. The tail distributions above might be called too small for an initial commissioning accelerator since there is a lot of outgassing from any new machine when beam is first stored in a ring and this should contribute significantly to the beam tail. The background study for an IR should include rather conservative estimates of the beam tail (i.e. a low lifetime or close to our 2% upper limit for the integral or perhaps both).

Equation (1) is the formula used to generate the core and tail distributions shown above where $a = 8.5\times10^{-3}$ for both plots and $b = 0.3$ for the X plot and 0.1 for the Y plot.

$$e^{-\left(\frac{x^2}{2\sigma^2}\right)} + ae^{-\left(\frac{b^2x^2}{2\sigma^2}\right)} \qquad (1)$$

LUMINOSITY BACKGROUNDS

The initial B-factories (PEP-II and KEKB) were the first machines to encounter issues from luminosity related backgrounds in e^+e^- circular colliders. There are two main luminosity backgrounds; radiative Bhabhas and low-energy e^+e^- pair production with the primary beam particles from the interaction going down the outgoing beam pipes and not being seen by the detector.

Radiative Bhabhas

The radiative Bhabhas produce a photon which lowers the energy of the outgoing beam particle that radiated. This off-energy beam particle is then mis-focused in the downstream final focus magnets and can be lost in the nearby downstream beam pipe. The PEP-II and KEKB B-factories both had designs with shared outgoing quadrupole magnets which meant that the outgoing beam was bent by the quadrupole field due to the beam being offset in this downstream quad. The off-energy radiative Bhabha beam particles were then swept out of the beam pipe close to the detector causing a significant increase in the overall background rate. All present and future IR designs for e^+e^- ring colliders do not have any shared magnets for this reason. Figure 5 illustrates the radiative Bhabha process.

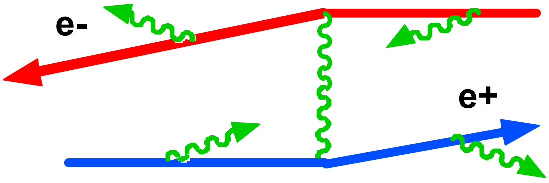

Figure 5: Depiction of the radiative Bhabha process. A radiative Bhabha interaction has only one photon in the final state. We show here the first four Feynman diagrams together for brevity. The interactions that occur from this process with a small scattering angle are the ones that tend to contribute to detector backgrounds.

Low-energy e^+e^- *Pair Production*

The 2nd luminosity background is the soft e^+e^- pair production. Here the low energy e^+e^- pair tend to curl up in the detector solenoid field. However, if the energy of the pair is high enough then these low-energy electrons can get just outside of the central beam pipe and then travel in a path that runs through the first layer of the vertex tracker. This small-radius helical track will leave an enormous amount of ionization in the first layer effectively disabling large sections of the inner layer of the vertex tracker. The rate for this process tends to set the minimum radius of the central beam pipe. This rate is also dependent on the strength of the detector magnetic field. Figure 6 shows the Feynman diagram for this process.

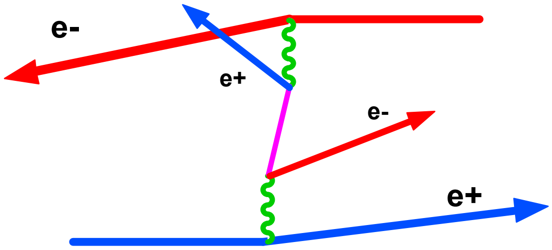

Figure 6: Illustration of the Feynman diagram for the low-energy e+e- pair production.

Of course, both of these luminosity backgrounds increase as the luminosity increases.

BEAM PARTICLE BACKGROUNDS

There are several general beam particle interactions that are standard detector background sources from stored beams. They are: 1) Beam-Gas interactions (BGB) where a beam particle interacts inelastically with a gas molecule and a high energy photon traveling along the beam particle trajectory is emitted along with an off-energy beam particle, 2) Coulomb scattering where a beam particle interacts elastically with a gas molecule resulting in a beam particle that is close to or outside of the storage ring phase space or dynamic aperture, 3) Inter-Bunch scattering (IBS) and Touschek scattering, interactions inside the beam bunch that kick beam particles out to high sigma values, 4) Beam-beam scattering where the interaction is at the collision point causing a shift in the tune of the stored beam particle which pushes it out to high sigma values (usually in the vertical plane), and 5) injection backgrounds where the injected bunch is inserted several beam sigmas off-axis with respect to the stored beam.

All of the beam particle interactions mentioned above generate beam particles out at high sigma values. The BGB and Coulomb scattering interactions are a linear function of the gas pressure and beam current. The IBS and Touschek interactions depend on the particle density in a bunch. High single bunch current and low emittance designs increase these interactions. However, low emittance and high single bunch current are directions machine people use to increase the luminosity. The backgrounds from beam-beam scattering due to the collision of course will tend to increase as the luminosity increases which usually means the tune shift increases.

A careful study of these interactions is necessary in order to develop a collimation system that can remove the majority of these particles before they enter the IR. There will still be a residual of the beam tail distribution that cannot be collimated away that is located in the region of about 4-8σ. These are generally too close to the main core of the beam to be able to effectively collimate away without losing to much beam lifetime.

As a machine continues to run, the beam-gas interactions should diminish as the vacuum improves and the inter-bunch interactions should also improve as the machine running conditions become more stable and tuned up. As the running conditions improve the beam tail generally reduces and lifetimes and luminosity performance both improve. The backgrounds that increase with increased luminosity will of course increase but these can also be ameliorated by improving the working point of the accelerator. Figs. 7 and 8 illustrate the two main beam-gas interactions.

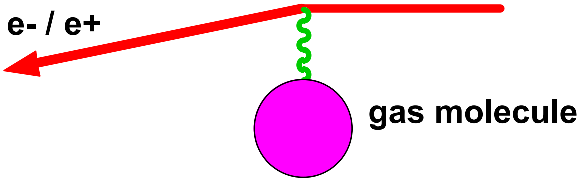

Figure 7: An elastic beam particle and gas molecule interaction. The beam particle retains all of the initial beam energy but has suffered a significant scattering angle. This places the scattered beam particle out into the high sigma region.

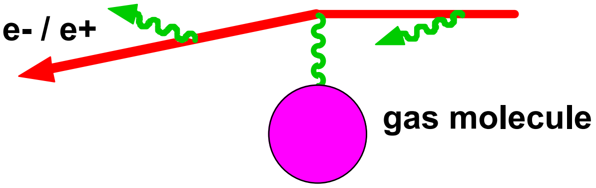

Figure 8: An inelastic beam-gas interaction. In this case an extra photon is emitted either just before the interaction or just after. The extra photon takes a significant amount of energy from the beam particle which usually places the beam particle outside of the ring dynamic aperture. This means the particle will get swept out of the ring upon encountering the next bend magnet. In addition, the photon (generally in the GeV energy range) will also leave the storage ring at the next bend magnet. All of the inelastic interactions that occur after the last bend magnet and before the IP will tend to cause significant backgrounds in the detector. It is important to minimize the vacuum pressure in the upstream beam pipe in order to minimize this detector background.

Neutrons

The interactions in the above two sections where we have off-energy beam particles or gamma-rays in the final state can all cause neutrons to be generated where these particles strike the beam pipe and begin an energy shower. If these particles are lost near the detector (~±20 m) then the neutrons generated by the shower can be a background for the detector. Both B-factory detectors observed a significant background from neutrons that had been generated locally.

In addition, the very high-energy accelerators will generate SR with photons in the MeV range from the final focus magnets and these high-energy SR photons can interact with the beam pipe and also produce neutrons through the large dipole resonance cross-section [13]. This is another new source of detector background coming from the very high-energy of the new accelerators.

LARGE CROSSING ANGLE AT THE IP

A large crossing angle between the two stored beams is very helpful in allowing the FF magnets to contain a single beam (no shared magnets) and to push the FF quads as close to the IP as possible in order to maximize the luminosity.

However, a large crossing angle can make it more difficult to mask the SR from the FF quads away from the central beam pipe. The difficulty occurs in the horizontal plane where the X focusing radiation must be over-focused in order to reach a minimum spot size at the IP. Figures. 9 and 10 show how the large crossing angle in an IR design can make in difficult to shield the central beam pipe from this final focus SR.

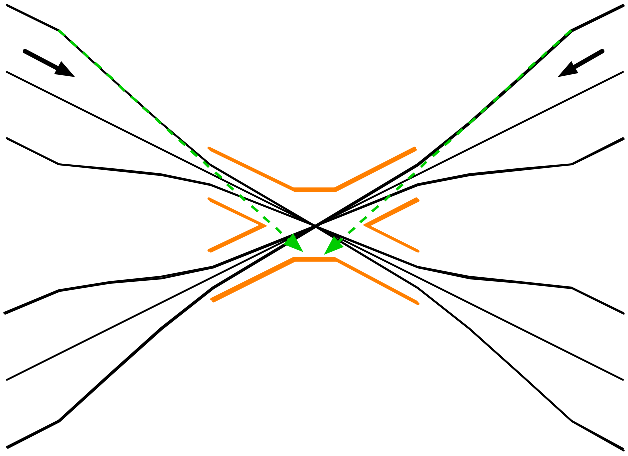

Figure 9: The SR from the over-focused beam in the X-focusing magnet (green dashed lines) actually crosses over the beam axis and then can directly strike the central Be chamber.

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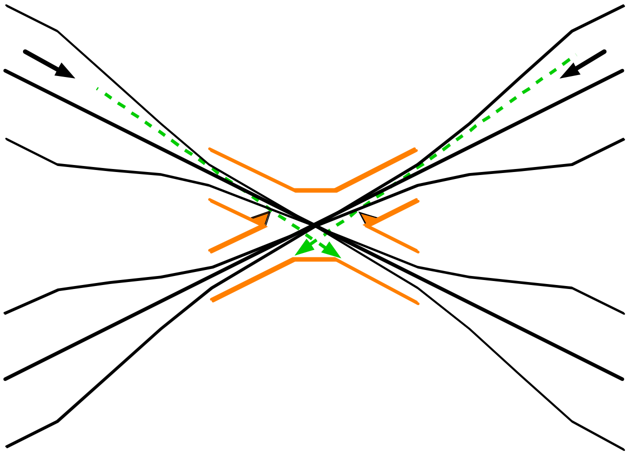

Figure 10: In order to mask the SR from the over-focused beam in the X plane, one must install very aggressive masking as close to the beam-stay-clear envelope as possible. Then the SR from the X-focusing quad will either hit the mask tip or will go past the central beam pipe. In this drawing we see the SR (dashed green lines) that just misses the mask tips and then is shown to just go past the central beam pipe.

The superKEKB accelerator at KEK has a crossing angle of 83 mrad (±41.5 mrad) which is the largest collision crossing angle to date. Consequently, the design has followed the above description and has installed SR masking that tips starting at 0.245 m from the IP and have a radius of 4.5 mm. However, the superKEKB design calls for very small emittances and this means that this small radius mask tip is still more than 40σ away from the beam in the X plane.

OTHER IMPORTANT IR ISSUES

There are several more issues that need to be studied for all IR designs and some of these will need to be looked at more carefully due to the large beam currents and high beam energies. I will list some of these below with some comments.

HOM Heating

When the beams pass through the IR, they go from separate beam pipes to a shared beam pipe at the collision point. This means that there is a place on either side of the central beam pipe where the two separate beampipes join together. This region where the separate pipes come together always produces a region where the vacuum cross-section reaches a local maximum. The central beam pipe is usually as small as can be achieved based on backgrounds and other considerations which means we have two separate vacuum regions with a local maximum. This region will trap Higher-Order-Mode (HOM) RF energy with wavelengths that are too large to be able to travel down the outgoing beam pipes. This trapped RF power must be absorbed locally, and it is important to develop an absorbing mechanism [14]. This is especially true for high-current designs.

Image Current Heating

In addition to HOM heating there are heating issues coming from image currents. These currents travel along the inside wall of the beam pipe and can deposit power into the beam pipe material based on the I^2R losses in the material. Aside from the DC component in the power loss which is based on the average beam current, there is also an AC component related to the bunch length and to the bunch spacing. The AC part has a penetration depth into the material called the skin depth. For most accelerators this is on the order of a few microns. These losses are coming from both beams and that means that we can have a phase difference between the beams. In general, one does not know exactly what the phase difference will be between the beams, the best thing to do is to assume the power loss from each beam adds up in the central beampipe. Cooling for the central chamber is almost always necessary. For very high-energy configurations where the beam currents are significantly lower (i.e. FCCee running at the top energy) the power loss from both HOM and image current may be low enough to make beam pipe cooling unnecessary and this might allow for the possibility of installing an especially thin central beam pipe for this segment of machine running.

Vacuum Pressure

As mentioned earlier, it is important that the vacuum pressure upstream of the IP, between the collision point and the last upstream bend magnet, needs to be a low as reasonable. Preferably below 1×10^{-9} Torr. The vacuum pressure right at the IP does not need to be especially low as the volume of vacuum with a higher pressure is quite small and any beam-gas interactions from this region do not have a big impact on the detector background rate. This same argument is true for the downstream beam pipes.

Injection Backgrounds

The injected bunch that enters the stored beam comes in off-axis (either in X or in Y). This off-axis sub-bunch (usually less than 10% of the stored bunch, especially for continuous injection) damps down into the stored bunch after several turns. During the damping time, this part of the stored beam usually generates significantly higher backgrounds in the detector and in many cases, this particular stored beam bunch is blanked out from the detector trigger and data acquisition. For continuous injection designs it is important to estimate this increase in background and make sure that the added background levels are tolerable with regards to integrated radiation dosage.

CONCLUSION

There are always a large number of conflicting issues that need to be addressed in order for an IR design in a new accelerator to become feasible. The detector needs to be able to efficiently collect the physics and the accelerator needs to be able to achieve the luminosity. Both of these requirements are crucial in order for the overall design to be a success. High luminosity and large beam currents together with high-energy beams increase the importance of checking and cross-checking detector backgrounds as well as engineering feasibility of any particular IR design. The new factories (primarily Higgs factories) will push collider and IR designs into a new regime and new source terms for detector backgrounds as well as new issues affecting accelerator performance may come to light. It is important to continue to review past design decisions and to explore possible new issues that may come up especially as the overall design matures. Small changes in the accelerator running conditions can produce a significant impact on the IR design by requiring changes in the SR masking design or in the size of the central beam pipe or in the collimator scheme designed to protect the IR from beam related backgrounds.

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