INTERACTION REGION CONSIDERATIONS FOR A B-FACTORY*

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ABSTRACT

A number of machine-detector interface issues are mentioned, with an emphasis on detector backgrounds.

1. INTRODUCTION

The goal of the project is to observe CP violation in the $\overline{B}B$ system. This machine is supposed to be a factory for high energy physics, not an R&D project for accelerator physics. (The necessary R&D is supposed to be done before the machine is built.)

There are a number of interrelated design issues arising from the different desires of the detector and the machine, some of which are listed below.

A number of background and beampipe issues are mentioned. The emphasis is on calculations. Any satisfactory design will combine measurements on existing machines with calculations pertaining to the measurement conditions as well as to the proposed machine.

2. DETECTOR REQUIREMENTS

- Many events are required, which implies high luminosity (this means high L_{ave} , not only high L_{peak}), which, in turn, implies high current and small spots. High current is achieved with customary bunch population but much closer bunch spacing. Small spots imply small β^* which, in turn, implies short bunches and fairly large IP angles.
- Good vertex resolution is required, which implies a small, thin beampipe. The IP beampipe will be the smallest physical aperture in the machine.
- Luminosity requirements are reduced by having a moving center of mass, which implies unequal beam energies, which requires two rings. Even with equal energies, two rings are necessary to eliminate the effects of parasitic bunch crossings.
- There is competition between the detector and machine for the scarce real estate near the IP. (Don't forget space for cables and services.)
- The detector will have a solenoidal field of 1-1.5 T extending over ± 2 m.
- The detector must experience acceptable backgrounds during luminosity running. For the detector, this means a design relatively insensitive to backgrounds. For the machine, this means a number of masks (both near and far from the IP), an appropriate optics design that minimizes background problems, and a pressure profile that reduces backgrounds.

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- Frequent and rapid injection is required to keep L_{ave} high. This obviously constrains the machine. The detector must be insensitive to radiation damage during injection, and it must go quickly from data taking to injection and back again. Some kind of rapidly insertable and removable shielding to protect the detector against injection and poor machine performance might be useful.
- Radiation damage to the detector from commissioning and machine physics work should be small compared with the inevitable amounts during luminosity running. The detector will undoubtedly be absent during initial commissioning, but it will be present during the final stages of commissioning, since it is the best instrument to measure backgrounds, and it will be present during recommissioning following
 shutdowns.
 - The design of the detector/machine should be flexible, for example to accomodate different headon or crossing angle geometries at the IP, or changes in the energy asymmetry.
 - Special IR instrumentation is needed. For tuning, whether by operator or by computer, prompt signals proportional to background and to luminosity are needed. Radiation detectors near masks and limiting apertures would be useful in identifying sources of background, as would detectors that were sensitive to only one beam. Since some bunches might contribute more background than others, it might be very educational to be able to identify individual bunches, or at least sync the background detectors to the revolution frequency. Possibly special BPMs should be added.

3. SYNCHROTRON RADIATION BACKGROUND

Bends and quads near the IP are the main sources of synchrotron radiation that cause background problems. For **headon** collisions with unequal energy beams, bends are needed near the IP to separate the beams to avoid parasitic bunch collisions. Bend magnets are required to get the beams into the arcs; the final bending should be done at low field to reduce the characteristic energy of the SR.

Masks shield the IP beampipe from direct SR as well as from scattered SR. Only the higher energy photons that eventually can cause problems in the detector are of interest. The SR background can always be reduced by increasing the inner radius of the IP beampipe, but at the expense of degrading detector resolution. Almost all the SR photons go through the IP beampipe without hitting any masks, but they all eventually interact somewhere.

Appendix A contains some synchrotron radiation formulas.

3.1 SOURCES OF SR

A bend magnet produces a fan of radiation with the extreme rays being the incoming and outgoing beam trajectories. Usually the bend angle is large enough so it determines the width of the SR swath. Perpendicular to the bend plane the height of the swath is determined by the size and angular divergence of the radiating beam plus the intrinsic angular distribution of the SR photons relative to the radiating trajectory.

A quadrupole produces a much more complicated beam of SR than a bend magnet. A program commonly in use at SLAC that calculates radiation from quadrupoles, and traces the photons through a series of masks, QSRAD,⁵ makes various approximations: (a) each ray of the beam emits a flat fan, (b) a single value of B characterizes the SR, derived from an average offset, and (c) the intrinsic angular spread in the beam is neglected. The four-dimensional integral over the beam distribution (x, x', y, y') is reduced to an integral over only x, y. Evenly spaced rays are traced through the system and the photons from each ray are weighted by the chosen beam density at that x, y. Or an external ray distribution file from an optics calculation may be used as input to QSRAD. A partial check on the approximations can be made by dividing physical quadrupoles into a number of shorter quads for computational purposes.

The distribution of photons from a quad depends on the transverse distribution of the beam, which often becomes more poorly known the farther one gets from the beam axis (see Sec. 6). This is especially true for the outer part of the photon beam which is most likely to hit masks and cause detector background.

3.2 MASKING AND MASK RERADIATION

Masks shadow the detector beampipe from photons coming directly from the magnets. Unfortunately, there is no such thing as a perfectly black mask; that is, every photon hitting a mask has some probability of reradiation, depending on energy, angle, material, and geometry. So frequently secondary masks shadow primary masks, and so on. Table 3.1 gives some representative reradiation probabilities calculated with EGS4⁷ for forward scattering fro-m a mask. A photon beam with $k_c = 15 \text{ keV}$ and width 1 cm is incident on a rectangular mask, starting from the edge. All photons are scored that scatter out with $\theta < 11.5$ '. K-shell fluorescent radiation is included. All emerging photons had k > 30 keV.

Material	$rac{1}{n_{ m in}} rac{dn_{ m out}}{d\Omega} ({ m sr}^{-1})$
Та	3×10^{-6}
c u	4×10^{-5}
Al	7 x 10 ⁻⁴

Table 3.1

High Z masks are better because all the cross sections per atom increase with Z, and in addition the major absorption cross section (photoelectric effect) grows more rapidly with Z than the scattering cross sections. The probability of fluorescence radiation following photoelectric absorption increases with Z. Fortunately, it is not as severe for the softer spectra characteristic of B-factories as it is at linear colliders, for example. Often, masks are coated with thin layers of lower Z materials on top of higher Z to optimize the competition between absorption and reradiation. This applies as well to the inside of the IP beampipe.

4. BACKGROUND FROM LOST BEAM PARTICLES

Beam particles hitting the masks and beampipe near the detector will send degraded shower debris into the detector. As is well known, there are no black masks for high-energy beam particles. IR masks honor a beam-stay-clear that is supposed to keep beam tail particles from hitting them. This means that a-distant mask system shadows the masks close to the IP. However, beam-gas interactions relatively close to the IR may cause beam particles to hit the inner masks depending on details of optics, masking, and residual pressure.

4.1 BEAM-GAS BREMSSTRAHLUNG

The cross section for fractional energy loss u by radiation is approximately'

$$\frac{da}{du} = 4\alpha r_e^2 Z (Z+1) \frac{4}{3u} (1-u+.75u^2) \ln\left(\frac{183}{Z^{1/3}}\right)$$
(4.1)

$$u = \frac{k}{E} . (4.1a)$$

The Z + 1 takes approximate account of radiation from the atomic electrons." Note that the radiated photons themselves may be a noticeable source of background, even though their average energy is only afraction of the energy of the beam. The angular distribution of the radiation process is usually neglected in this application. The angular distribution has characteristic angle $1/\gamma$ (that is, the transverse momentum is about mc).¹³

4.2 BEAM-GAS NUCLEAR COULOMB SCATTERING

The cross section for Rutherford scattering at polar angle θ (taken much less than 1) is⁸

$$\frac{d\sigma}{d\Omega} = 4r_e^2 Z^2 \frac{\left(\frac{m}{p}\right)^2}{(\theta^2 + \theta_1^2)^2} , \qquad (4.2)$$

$$\theta_1 = \alpha Z^{1/3} \left(\frac{m}{p}\right) \ . \tag{4.2a}$$

The screening of the atomic electrons is accounted for by the angle θ_1 . Any nuclear form factor effects are neglected, which requires $q \approx E\theta < q_{\text{max}} = 137 \text{ m}/A^{1/3}$. The energy lost by the beam particle is $q^2/2A$ which can safely be neglected.

4.3 COULOMB SCATTERING FROM ATOMIC ELECTRONS

This is Rutherford scattering of the beam particles from free electrons. Changing Z^2 to Z(Z + 1) in Eq. (4.2) will roughly take account of this. One might worry that the fractional energy loss on a light target, which is approximately

$$u = \frac{q^2}{2m} \frac{1}{E} \frac{1}{2} = \frac{\theta^2 \gamma}{2} , \qquad (4.3)$$

might be a concern. However, calculations show that energy losses greater than the natural energy spread correspond to a small scattering cross section.

4.4 NUMBER OF BEAM PARTICLES HITTING MASKS

The products of beam-gas interactions are transported through the optical system to well beyond the IP. It is convenient to use the program **DECAY TURTLE'** to track the beam-gas interaction products through a system of optical elements and masks. Note that in SLC calculations it was found that including sextupoles affected the tracking results, presumably because large amplitude particles are important.¹² The source probability is weighted according to the pressure profile and the composition of the residual gas.

The rate of particles hitting masks can be estimated as follows: Take 6.25 x 10^{12} beam particles (corresponding to 1 A for 1 μ sec) traversing 10 m of CO (37.42 g/cm² radiation length)¹⁴ at a pressure of 10^{-8} Torr, which comes to 4.1 x 10^{-13} radiation lengths. Consider all bremsstrahlung collisions that radiate more energy than 10 times the natural energy spread in the beam, taken as 10^{-3} . The rate is (6.25 x 10^{12}) x (4.1 x 10^{-13}) x 4/3 x $\ell n(100) = 16$.

4.5 RERADIATION OF SHOWER DEBRIS INTO THE DETECTOR

The reradiation probability into the detector is greater for particles that hit near the IP, but distant sources must be evaluated numerically. Reradiation is also greater for particles that hit the face or near the edge of a mask. The shower debris also has to be transported through the lattice, the masks, the detector'magnetic field and into the detector. $EGS4^7$ can be used to follow the shower debris through the beampipe into the detector.

5. OTHER SOURCES OF BACKGROUND

5.1 INJECTION SHIELD

Radiation damage during luminosity running is likely to be significant, so it is important to reduce damage during injection **as** much as possible. An attractive idea is a massive shield that can be quickly inserted inside the main drift chamber to provide protection to all the detector elements except the silicon vertex detector. This would supplement any other possible protective measures.

5.2 MULTIPLE REFLECTIONS OF SYNCHROTRON RADIATION

The calculations in Sec. 3 typically take account of 2 or 3 photon reflections. One always worries that there is some efficient mechanism involving multiple reflections for transporting SR over long distances to the IP. I do not know of such a process. Total external reflection¹⁵ requires exceedingly smooth surfaces and only occurs for photon energies that are quite low by our standards. Multiple forward Rayleigh scattering is diminished by the competition with photoelectric absorption; any fluorescence reradiation is isotropic. X-ray diffraction scattering from the polycrystalline wall of the beampipe is also in competition with photoelectric absorption.

5.3 Gas Interactions near the IP

Section 4 dealt with beam-gas interactions fairly far from the IP which caused beam particles to hit masks near the IP. There are also interactions near the IP (within the z acceptance of the detector) that send background particles directly into the detector. Consideration of these processes may set a restrictive limit on the IP pressure.

- (a) Some convenient FORTRAN programs calculate a number of e and γ interactions on nuclei, including quasi-elastic and inelastic electron scattering and various photopion reactions.¹⁶ These are a useful supplement to rates measured with random triggers on existing machines. The recoil proton cross sections agree with measurements.^{26,27}
- (b) SR photons can scatter into the detector by Compton or Rayleigh scattering; photoelectric fluorescence is not a problem from C and 0 because the K edges are below 1 keV. For $x \equiv k/m < 1$ Compton scattering per free electron is approximately⁵⁷

Scattered Angle (degrees)	$d\sigma/d\Omega~(r_e^2/{ m sr})$	k'/k
0	1	1
90	0.5/(1 + 2x)	1/(1 + x)
180	1/(1 + 4x)	1/(1 + 2x)

Table 5.1

Rayleigh scattering in our energy range is a more complicated function of k and Z. Useful fits to the cross sections based on a Fermi-Thomas atom ¹⁷ are

$$\text{MOI} = \frac{8\pi}{3} Z^2 r_e^2 \left[1 + \left(\frac{B}{1.394}\right)^{1.162} \right]^{-1.628}$$
(5.1)

$$B = \frac{2k}{\alpha m Z^{1/3}} = \frac{k (\text{keV})}{1.865 Z^{1/3}}.$$
 (5.1*a*)

and

$$\frac{da}{d\Omega} = Z^2 r_{\rm e}^2 \, \frac{1 + \cos^2 \theta}{2} \left[1 + \left(\frac{U}{1.186} \right)^{1.199} \right]^{-2.436} \,, \tag{5.2}$$

$$U = B\sin\frac{\theta}{2} \,. \tag{5.2a}$$

The fit ranges are 0 < B < 10 and 0 < U < 40. The Fermi-Thomas model is pretty good for high Z. But, for example, Eq. (5.2) overestimates the cross section for C and 0 by about a factor of 2 at U = 12, and a factor of 5 at U = 40.

As an order-of-magnitude estimate of this background, consider a beam of 1 A for 1 μ s with 1 photon per electron, a pressure of 10^{-8} Torr N₂, an acceptance of 1 m and 2π sr, and evaluate the cross sections at 90". The results are shown in Table 5.2. A proper calculation would integrate the SR fluxes from both beams over the actual cross sections and acceptances, and include absorption in the beampipe.

	Number of Scattered Photons		
k(keV)	Rayleigh	Compton	Total
5	0.9	0.7	1.6
10	0.3	0.7	1.0
20	0.06	0.7	0.8

Table 5.2

5.4 SR-BEAM INTERACTIONS

The bunches of synchrotron radiation photons and the charged beam bunches collide at the IP and at $s_b/2$. Most of the interactions are Compton scattering, like a back-scattered laser beam,¹⁸ although some of the highest energy photons will make pairs.¹⁹ The interaction rates are not high, and the reaction products have low p_t and make small angles with the beam axis.

5.5 PHOTON RADIATION FROM A TRANSVERSE CRAB CAVITY ·

Both synchrotron radiation from the transverse kick, and Compton scattering from the RF photons in the $cavity^{20}$ are very weak.

5.6 BACKGROUND FROM RF CAVITIES

At PEP, the DELCO detector experienced background from the RF cavities in a nearby straight section, apparently from field emitted electrons that were accelerated in the cavities. These were eliminated by putting a weak magnetic bump on the IP side of the closest cavity.²¹ DELCO was an open detector with little selfshielding; the other PEP detectors with adjacent RF, MkII and MAC, had no such problem.

5.7 PHOTO HADRONS AND PHOTO MUONS

Is it possible that the effects of hadronic/muonic debris from lost particles hitting near the detector could be more severe than the electromagnetic debris, possibly in causing triggers? It doesn't seem likely, but I don't see how to rule it out. So one should check.

6. BEAM SHAPE

The beam distribution near the IP affects both the SR and lost particle backgrounds. The beam size in the final quads affects the distribution of SR photons in number, energy, and spatial extent that the masks are designed to cope with. The lost particle rate depends on the beam distribution through over-focusing of low-energy particles in the final quads. It is useful, although somewhat artificial, to divide the beam into a central Gaussian core plus a halo or tail extending to many sigma.

6.1 GAUSSIAN CORE

For a single beam, the core size is set by the emittance (SR fluctuations) and the optics. However, the beam-beam interaction increases the core size, especially in the vertical direction (for flat beams), and this is seen in the luminosity.⁵⁰ A simulation of a PEP-like machine gave an increase in sigma of 5% in the horizontal and 10% in the vertical.⁴⁷

6.2 HALO OR TAIL

The halo is generated by beam-gas interactions, the beam-beam interaction, nonlinear aspects of the optics encountered at large excursions, and the resonant and tune structure. (It seems to be the conventional wisdom that when beams are first brought into collision after a fill, the backgounds get worse, implying that gas scattering alone does not set the halo.) The halo distribution is in dynamic equilibrium between the processes tending to kick particles out, and radiation damping tending to bring them back. Beam lifetime is related to the distribution near the limiting aperture.⁵⁵

There are several approaches to arriving at a model to use for the halo distribution, but, to my mind, none is completely satisfactory. This is unfortunate because a bold SR masking scheme would depend critically on the halo distribution.

(a) Computer Tracking Simulation

One might think that the halo could be calculated since all the processes are known, with the possible exception of nonlinearities at large radius. Simulations for the core seem relatively satisfactory, but the present beam-beam codes are not designed to accurately predict the small population ($\sim 10^{-5}$) in the halo.

(b) Fit a Model to Measurements

Measurements at CESR of the vertical beam distribution clearly showed a tail. 52 This was fit to the following forms

$$\frac{1}{n} \frac{dn}{dy} = \frac{1}{\sigma\sqrt{2\pi}} \left[\exp\left\{\frac{-y^2}{2\sigma^2}\right\}, \text{ or } 3.7 \times 10^{-6} \exp\left\{-1.2\left(\frac{y}{\sigma} - 5\right)\right\} \right], (6.1)$$

depending whether y/σ is less than or greater than 5, and used for subsequent SR calculations.

Background measurements at PEP, assumed to come entirely from SR, were used to adjust the parameters of an assumed Gaussian tail,⁵⁴ which was used for subsequent SR calculations.⁵⁶

The problem with the first approach is the basic assumption that the vertical distribution will be the same in the new machine of interest. But the beam-beam simulations indicate significant sensitivity to various machine parameters. To use this approach with confidence, one should demonstrate scaling.

The second approach suffers the same shortcomings as the first, and in addition, it is only an integral measurement.

(c) Semiquantitative (Qualitative?) Approach

Ritson argues that the relative population in the halo should be roughly the ratio of damping time to beam lifetime, and it should fall off relatively slowly, say, as a power ~ 4 or so, rather than as an exponential or Gaussian.⁴⁹

(d) Conservative Approach

Assume a flat background out to the limiting aperture with a population larger than is implied by beam lifetime. Since presumably this is a worst case, it is useful to at least check a mask design against it. What to do if the worst-case backgrounds are too high is another question.

6.4 LIMITING APERTURES

As masks get closer to the IP, their size in sigma units should increase. The limiting apertures should be far from the IP, designed to shadow the IP region.

7. HEATING AND COOLING

The heat loads on various beampipes, masks, and surfaces need to be specified so that adequate cooling can be provided. Possible problem areas are cooling the IP beampipe, which will decrease the IP resolution, and high SR power densities. Allowable temperature rises need to be established and the consequences of thermal expansion investigated. The final temperature of a object depends on the relative rates of heating and cooling.

7.1 SR HEATING

SR heating of masks near the IP is usually small, since a significant heat load would be an intolerable background source $(1W = 6.25 \ 10^{15} \ \text{keV/s})$.

Machines with headon collsions and small bunch separations (l-2 m) produce dozens of kW of SR from the bend magnets initiating the orbit separation and in beams off-axis in common quadrupoles. (The irreducible SR from the quad focusing is roughly 10 times less.) This power must be conducted to a water-cooled dump, possibly first going through a very thin window in the vacuum pipe. The transverse power density can be high, and the initial rate of energy absorption is also high.

7.2 IMAGE CURRENT HEATING

All beampipes are heated on the inside by image currents flowing in the skin depth. This is basically a bunched beam pulse heating. The appropriate formula for a Gaussian beam is^{22}

$$\frac{dP}{dz} = -\frac{\Gamma(3/4)}{4\pi^2 a} \frac{s_b}{\sigma_z^{3/2}} \sqrt{\frac{\mu Z_0}{2\sigma(Z)}}, \qquad (7.1)$$

$$= 2.75 \left(\frac{W}{m}\right) \left(\frac{2cm}{a}\right) \left(\frac{1cm}{\sigma_z}\right)^{3/2} \left(\frac{s_b}{1m}\right) \left(\frac{\langle I \rangle}{1A}\right)^2 \left[\frac{\mu \,\sigma(Cu)}{\sigma(Z)}\right]^{1/2} \quad (7.1a)$$

7.3 HOM HEATING

A more serious source of heating comes from the RF power radiated by the beams as they traverse changes in size and shape of the beampipe. This is frequently referred to as higher order mode power (HOM) because the RF cavities are a major discontinuity in the beampipe and the radiated energy typically has higher frequencies than the cavity fundamental. There are two fairly separate parts to the problem: how much HOM power is radiated, and where is it absorbed. All the HOM power is absorbed somewhere. It's just a question of providing enough cooling at the right places.

The energy radiated when a bunch passes a discontinuity is

$$U = k q^2 , \qquad (7.2)$$

where q is the bunch charge, and k is a loss parameter depending on the geometry of the discontinuity and on the bunch length (frequency spectrum). k is usually given in pV/C. The power radiated is

$$P = f_b U = k \frac{s_b}{c} \langle I \rangle^2 , \qquad (7.3)$$

$$f_b = \frac{c}{s_b} , \qquad (7.3a)$$

$$\langle I \rangle = f_b q \quad - \quad (7.3b) \quad -$$

Analytic expressions for k are available for simple geometries. For more complicated (realistic) geometries, computer codes are available (for example, MAFIA, TBCI, URMEL).³⁴ These computer calculations are tending to replace the experimental determination of k values.

Consider a cylindrical pipe of radius a that abruptly increases to radius b for a distance g before returning to a. Approximate expressions for $k \operatorname{are}^{28,29}$

$$k = \Gamma\left(\frac{1}{4}\right) \frac{Z_0 c}{4\pi^{5/2} a} \sqrt{\frac{g}{\sigma_z}} = 1.023 \frac{Z_0 c}{2\pi^2 a} \sqrt{\frac{g}{\sigma_z}}, g < g_c \qquad (7.4)$$

$$k = \frac{Z_0 c}{2\pi^{3/2} \sigma_z} \ln \frac{b}{a} , \qquad g > g_c \qquad (7.5)$$

$$g_c \approx \frac{(b-a)^2}{2\sigma_z} \,. \tag{7.6}$$

Equation (7.4) corresponds to a pillbox, and Eq. (7.5) to a step down in radius (there is very little loss for a step up in radius). Reference 28 finds quite good agreement between Eqs. (7.4)–(7.6) and the code TBCI. Tapering the transitions in radius reduces k, but not in a simple way.²⁸

The above results are for a single bunch traversing a single cavity. For high enough Q and short enough bunch spacing, interference effects may become important.^{33,28}

7.4 Absorption of HOM

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All the HOM energy is absorbed somewhere, in a few skin depths on the inside surface of the beampipe. The absorption is more complicated than the generation, since it depends on the mode and frequency distribution of the energy. High frequencies can propagate down the beampipe. Low frequencies are trapped in the cavities or are rapidly attenuated in the beampipe. The critical wavelength is comparable with the diameter of the beampipe.^{31,2} The propagating energy is absorbed with a characteristic 1/e length of roughly

$$\lambda_e \sim (100 - 300 \text{ m}) \left[\frac{\sigma(z)}{\mu \sigma(Cu)} \right]^{1/2} \left(\frac{\text{radius}}{3 \text{ cm}} \right),$$
 (7.7)

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which depends on mode and also on frequency relative to cutoff.

The small IP beampipe could have the highest cutoff frequency, so it might absorb HOM generated far away. One might contemplate isolating the IP with a lossy section of ferromagnetic stainless steel.³²

Billing has discussed HOM generation and absorption in the context of CESR.³⁵ He reports k = 0.09 V/pC for a 2 inch ID SR mask in a 4 inch ID pipe with 27° tapers, and k = 0.014 V/pC for about 3 m of IP beampipe with gently tapered (2°-5°) transitions. He makes the interesting point that configurations with large k scale roughly as σ_z^{-1} , whereas those with small k scale roughly as $\sigma_z^{-(2-4)}$. Presumably as the scale of the geometrical irregularities approaches σ_z , the dependency on σ_z becomes stronger; however, for irregularities much smaller than σ_z , one would expect k to approach zero.

7.5 ACCEPTABLE TEMPERATURE RISE

Preliminary calculations indicate the necessity of active cooling of the beampipe at and near the $IP.^{36}$ Once this big headache is accepted, it's just a question of deciding how much cooling is needed and how to supply it. It is possible that very little of the beampipe anywhere can be adequately cooled simply by convection to ambient air.

Thermal expansion and stresses set limits to temperature rise. Also, thermal desorption increases with temperature (see Sec. 9 on vacuum).

8. ACCEPTABLE DETECTOR BACKGROUND

The effects of background on the detector elements are usually divided into three categories: radiation damage, extra hits (occupancy) which confuse tracking and pattern recognition, and false triggers.

The first is cumulative; the second two accumulate over resolving times of the order of a microsecond, and depend on the details of the detector. For radiation damage, one might design for a useful life of five years (of luminosity running plus injection and machine physics) wit'h some safety factor added.

8.1 SILICON VERTEX DETECTOR

The detector elements themselves are relatively insensitive to radiation damage with acceptable levels of the order of 1 Mrad.⁴¹ However, the associated electronics, which is mounted on or near the detector elements, is more sensitive by a factor of 10 or more.⁴² This is presently a field of active research for SSC applications and one can hope for increased radiation hardness on a time scale of interest to a *B*-factory.⁴³

There are so many channels in a pixel detector that occupancy is not the limit, and even in a strip detector occupancy is less of a limit than radiation damage. To see this, consider a strip 25 μ m wide by 20 cm long, uniformly irradiated by charged tracks. The flux that produces 0.1 Mrad/10⁷s is 3.1 10⁵ tracks/cm²-s corresponding to an occuapncy of 0.016/ μ s.

8.2 MAIN DRIFT CHAMBER

Avalanches at the sense wires cause the accumulation of deposits that degrade performance. This only occurs when the HV is on, so this is mainly a concern during luminosity running, assuming that a fast HV ramp is provided for injection. The degradation is proportional to the integrated charge density on the wire. Present limits are around 1 C/cm,^{44a} and encouraging progress is being made in identifying the role of trace impurities,^{44,45} so I believe one may reasonably take this as a design value for a B-factory. Note that 1 C/cm spread over a 1 m wire for five years of 10^7 s each corresponds to 2 μ A average current.

First, compare radiation damage and occupancy for charged tracks. Assume that a track at normal incidence gives 0.8 pC at the wire (for example, 100 ion pairs with gain 5 $\times 10^4$; with 30 eV/ip, this corresponds to 3 keV deposited per track). Then 2 μ A corresponds to 2.5 $\times 10^6$ tracks/s or an occupancy of 250% per μ s. So occupancy sets a much more severe limit than radiation damage. This result is independent of gas and cell size through the assumption of constant charge per hit. Inclined tracks give more radiation damage for the same occupancy.

For SR photons, the relationship between radiation damage and occupancy is similar to that for charged particles, but there tends to be more radiation damage per unit occupancy. This arises from the energy spectrum of the photons, which interact mainly by photoelectric effect and, at higher k, Compton scattering. Low-energy interactions always produce damage, but may not trip a discriminator for a hit. High-energy interactions can produce much more pulse height (hence damage) than necessary for a hit. Note that for a given SR flux, a He-based gas will have many fewer interactions than an Ar-based gas.

Compton scattering at low energies is not very effective at transferring energy to the recoil electron. The average kinetic energy is approximately⁵⁷

$$(T) = k \frac{x}{1 + \frac{11}{5} x}, \qquad x = \frac{k}{m}.$$
(8.1)

8.3 CALORIMETER AND CRID

One must consider background effects in other detector elements. For example, CsI, **a** frequently considered material for an electromagnetic calorimeter, seems to be especially sensitive to radiation damage.

8.4 RARE EARTH PERMANENT MAGNETS

For relatively radiation hard material (Sm_2Co_{17}) , the tolerable exposure is roughly 10^{10} rad.⁴⁶

8.5 TRIGGERS

Triggers require one or two fairly high energy tracks and/or a significant energy 'deposition. These probably come only from lost particles. One needs a fairly detailed model of the detector to estimate the rate.

9. BEAMPIPE PRESSURE/VACUUM

Beam-gas interactions in the IR set limits on acceptable pressure. Residual gases are mostly hydrogen with a quarter to \mathbf{a} half of CO_2 and CO. Vacuum design for a storage ring seems to be at least as much art as science. *Caveat lector*.

9.1 SOME FORMULAS

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In a system, the rate of gas flow per unit pressure drop defines the conductance.^{37,38} (Note: the quantity of gas is measured in Torr-liter with 3.3 10^{19} molecules/Torr-1 at 20 C.)

Throughput = Pressure drop
$$\times$$
. Conductance (9.1)

$$Q$$
 (Torr-l/s) = **AP** (Torr) x F (l/s) . (9.1a)

Two simple but useful examples of conductance follow. For a small hole with area A

$$F = \frac{A\bar{v}}{4}$$
 or $F_0 = \frac{F}{A} = \frac{\bar{v}}{4}$, (9.2)

where $ar{v}$ is the average speed of the molecules. For a Maxwellian distribution

$$F_0 = \frac{1}{4} \sqrt{\frac{8}{\pi} \frac{kT}{M}} = 11.4 \left(\frac{1/s}{cm^2}\right) \sqrt{\frac{T}{293K} \frac{28}{M}}.$$
 (9.3)

For a round pipe with diameter d and length L

$$F = F_0 \frac{\pi}{4} d^2 - \frac{4}{3} \frac{d}{L}.$$
 (9.4)

The effective conductance of a pump (which conducts the gas to a land of no return) is called its pumping speed, S (liter/s), so a pump has associated with it a pressure drop

$$S = \frac{Q}{\Delta P} . \tag{9.5}$$

To get the pressure at a particular point, add up the values of **AP** from the pump to the point.

9.2 SOURCES OF GAS

(a) Thermal Desorption

The desorption rate depends on the material, how it has been cleaned, how clean it has been kept, and the temperature. A reasonable, ballpark value (at room temperature) is

$$q = 10^{-11} \text{ Torr-l/s-cm}^2$$
. (9.6)

This follows an Arrhenius temperature dependence. The effective binding energy can range from 0.1 to several eV,³⁸ which corresponds to an increase in desorption \cdot per 10 C from 15% to a factor of 50. In a mixed Al/SS system coming off bake, I observed a factor of 1.6 corresponding to 0.35 eV.

(b) Photo Desorption by Synchrotron Radiation

SR photons desorb gas from masks and beampipes. The yield of molecules/photon depends on photon energy 39a but usual practice seems to simply use an average value, for example, 39

$$\eta = 5 \times 10^{-6}$$
 molecule/photon, (9.7)

where only photons with k > 5-10 eV are included.

The value of η depends on the angle of incidence of the photons (90° is perpendicular incidence). The variation measured on Al with $k_c = 3 \text{ keV}$ is roughly^{40,39}

$$\eta(\phi) = \frac{\eta(90^\circ)}{\sqrt{\sin \phi}} . \tag{9.8}$$

Continued irradiation by SR photons ("scrubbing") reduces η approximately as the 2/3 power of the accumulated exposure.³⁹

10. OTHER ISSUES

10.1 SAFETY FACTOR

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What degree of conservatism is appropriate in designing the IP region? How much insurance should be provided against tolerances, misalignment, our imperfect understanding, possible machine upgrades, and the vagaries of the real world? Should one take seriously the goal of a turnkey B-factory, which implies a brief detector commissioning period, as apparently has happened at LEP? Or should one anticipate a period of development following first operation, with the possibility of significant modifications, as has often happened in the past?

10.2 Approximations

Approximations enter in two ways, and we need to be sure they are adequate. Approximations are made in calculating a particular background process, although all the basic cross sections are well known. We also make approximations in deciding which are the dominant processes, and which can be neglected.

10.3 COMPARISON WITH ACTUAL EXPERIENCE

It is valuable, and possibly essential for a successful design, to compare our calculational techniques and procedures with data from a real detector at a real storage ring, to check whether our understanding is in tune with nature. Acceptable agreement does not assure success at a B-factory, of course, because scaling from one machine to another is imperfectly understood. But disagreement should surely cause hard thinking and lost sleep.

APPENDIX A: FORMULAS FOR SYNCHROTRON RADIATION

A.1 BEND MAGNETS

-These formulas pertain to electrons in circular motion.^{1,2,3} The average number of photons radiated in path length ds is

n = (n) = 20.6 E(GeV)
$$\phi$$
 (rad) = 0.618 B L(kG - m) . (A.1a)

The spectrum is a universal function of the characteristic energy

$$k_c = \frac{3}{2} \gamma^3 \frac{\hbar c}{\mathbf{P}} = \frac{3}{2} \frac{\gamma^3}{\alpha} \frac{r_e}{\rho} mc^2, \qquad (A.2)$$

$$= 2.22 (\text{keV}) \left(\frac{E}{10 \text{ GeV}}\right)^3 \left(\frac{1 \text{km}}{\rho}\right), \qquad (A.2a)$$

$$= 6.66(\text{keV}) \left(\frac{E}{10 \text{ GeV}}\right)^2 \left(\frac{B}{1\text{kG}}\right). \qquad (A.2b)$$

The normalized photon energy is

$$v = \frac{k}{k_c} . \tag{A.3}$$

The normalized number distribution of the photons is

- -

$$\frac{1}{n}\frac{dn}{dv} = \frac{3}{5\pi} \int_{v}^{\infty} K_{5/3}(y)dy , \qquad (A.4)$$

$$\approx 0.4105 \ v^{-2/3} (1 - 0.8438 \ v^{2/3} + 0 \ v^{4/3} + \dots) \qquad , \quad v \ll 1 \ (A.4a)$$

$$\approx \frac{3}{5\sqrt{2\pi}} \frac{e^{-v}}{\sqrt{v}} \left(1 + \frac{55}{72} \frac{1}{v} - \frac{0.9791}{v^2} + \dots \right) \qquad , \quad v >> 1 \ (A.4b)$$

Half of the energy is carried above v = 1, by only 8.7% of the photons. Half of the photons are above v = 0.078.

For convenience, Table A.1 lists some values for the spectrum (A.4) and its integrals.⁴ f_N is the fraction of the number of photons above v, and f_E is the fraction of the energy carried by photons above v.

V	dn/n dv	f_N	f_E
0.01	8.50	0.7381	0.9979
0.03	3.91	0.6277	0.9912
0.1	1.562	0.4628	0.9502
0.2	0.863	0.3483	0.9052
0.3	0.584	0.2775	0.8485
0.5	0.333	0.1896	0.7369
1.	0.1244	0.08677	0.5000
2.	0.0288	0.02326	0.2150
3.	0.00818	0.00703	0.0886
5.	0.00081	0.000737	0.0142

Table A.1

The energy loss per electron has average value

$$\langle U \rangle = \langle n \rangle \langle k \rangle , \qquad (A.5)$$

= 1.267 (keV)
$$\left(\frac{E}{10 \text{ GeV}}\right)^2 - \left(\frac{B}{10 \text{ GeV}}\right)^2 L(m)$$
, (A.5a)

= 140.8 (keV)
$$\left(\frac{E}{10 \text{ GeV}}\right)^4 \left(\frac{km}{\rho}\right) \phi(\text{rad})$$
, (A.5b)

and variance

÷ •

•

$$\operatorname{var}(U) = \left((U - \langle U \rangle)^2 \right) = \langle n \rangle \langle u^2 \rangle , \qquad (A.6)$$

$$= 11.17 (\text{keV}^2) \left(\frac{E}{10 \text{ GeV}}\right)^4 \left(\frac{B}{kG}\right)^3 L(m) , \qquad (A.6a)$$

$$= 414 \ (\text{keV}^2) \left(\frac{E}{10 \text{ GeV}}\right)^7 \left(\frac{km}{\rho}\right)^2 \phi(\text{rad}) , \qquad (A.6b)$$

where (v) = 0.3079 and $\langle v^2 \rangle$ = 0.4074 have been used.' Equation (A.6) arises because var(U) depends on fluctuations in n as well as in k; a Poisson distribution

for n has been used. The angular distribution of the radiated energy integrated over all k is

$$\frac{1}{U}\frac{dU}{dw} = \frac{21}{32}\frac{1+(12/17)w^2}{(1-w^2)^{7/2}}, \qquad -\infty \le w \le \infty, \qquad (A.7)$$

$$w = \gamma \psi , \qquad (A.7a)$$

where ψ is the angle perpendicular to the bend plane. For some cases of heating by bend SR, it is useful to have an approximate expression for the full double differential distribution. For fixed v, approximate the w dependence with a Gaussian. Then

$$\frac{1}{U} \frac{dU}{dvdw} \approx \frac{1}{U} \frac{dU}{d} \frac{1}{v} \frac{1}{\sqrt{2\pi\sigma_w}} \exp\left(\frac{-w^2}{2\sigma_w^2}\right) , \qquad (A.8)$$

$$\sigma_w \approx \left(\frac{0.363}{v}\right)^{0.44} . \tag{A.9}$$

This approximation is reasonable at the 10-20% level for 0.1 < v < 3. Outside this range, Eq. (A.9) overestimates the effective σ .

'A.2 QUADRUPOLES

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A photon spectrum integrated over a quadrupole field may be derived from (A.4).⁶ This spectrum is not very useful for background calculations because only the spectrum hitting the mask is interesting, not the spectrum going down the beampipe. The moments of a quad spectrum may be interesting for power reasons. For a Gaussian beam, the scale field is B_{σ} , the quad field at 1 σ of the beam. The number of radiated photons and the radiated energy in units of the values for a bend magnet with B_{σ} are, with b the beam centroid offset in σ units:

Table	A.2
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Gaussian Beam	Photon Number $\langle n angle / n_{\sigma}$	Radiated Energy U/U_{σ}
1-D	$\sqrt{(2/\pi)} + b$	$1 + b^2$
2-D (round)	$\sqrt{(\pi/2)}$ (b = 0 only)	$2 + b^2$

A.3 RANDOM SAMPLING FROM THE SYNCHROTRON RADIATION DISTRIBUTION

The nicest routine I know for random sampling from the spectrum Eq. (A.4) is due to Yokoya.¹⁰ RN is a random number uniform between 0 and 1 representing the integral number distribution between v and infinity. The returned values of v are within 0.05% of Mack's values,⁵ at least for 0.001 < v < 12.

```
DATA YA1/0.5352 /, YA2/0.3053 /, YA3/0.1418 /, YA4/0.4184 /,
% YB0/0.01192 /, YB1/0.2065 /, YB2/-0.3281 /,
% YC0/0.003314 /, YC1/0.1927 /, YC2/0.8877 /,
% YD0/148.3 /, YD1/675.0 /, YE0/-692.2 /, YE1/-225.5 /
```

```
IF(RN.GT..342)THEN
```

Pl=1.0-RN
P2=P1*P1
V=(((YA4*P2+YA3)*P2+YA2)*P2+YA1)*P2*P1
ELSEIF(RN.GT.0.0297)THEN
V=((YB2*RN+YB1)*RN+YB0)/(((RN+YC2)*RN+YC1)*RN+YC0)
ELSE
T1=-LOG(RN)
V=T1+(YD1*T1+YD0)/((T1+YE1)*T1+YE0)

A.4 SHORT BEND RADIATION

• A magnet in which the bend angle is less than $1/\gamma$ is called a short magnet; the spectrum does not follow Eq. (A.4) and depends on the z variation of B. The amount of energy is roughly the same as given in Sec. A.2, above but the scale or characteristic energy is greater,³ where with k_{c-long} given by Eq. (A.2),

kc-short
$$\approx k_{c-\log} \frac{\frac{\hat{z}}{\gamma}}{\phi}$$
 . (A.10)

A.5 GENERAL SR SPECTRUM

The spectrum in Sec. A.1 is for $k_c \ll E$. The general case is^{23,24,25}

$$\frac{1-dn}{n \ dy} = \frac{3}{5\pi} \frac{1}{(1+\xi y)^2} \left[\int_{\gamma}^{\infty} K_{5/3}(x) dx + \frac{\xi^2 y^2}{1+\xi y} K_{2/3}(y) \right] , (A.1 \ 1)$$

$$y = \frac{\frac{k}{k_c}}{1 - \frac{k}{E}} = \frac{v}{1 - u} = v(1 + \xi y) , \qquad (A.12)$$

$$\xi = \frac{k_c}{E} = \frac{3}{2} \Upsilon , \qquad (A.13)$$

where *n* is given by (A.1), and v only enters in the combination y. For $\xi = 0$, (A.11) reduces to (A.4). If fequently used as a measure of k_c/E rather than ξ .^{24.25} For Monte Carlo sampling of (A.11) see Ref. 10.

Radius а b Radius Velocity of light с Bunch crossing frequency, $f_b = c/s_b$ fь HOM loss parameter, usually pV/Ck Photon energy, usually **keV** k k'Scattered photon energy k_c Characteristic energy of synchrotron radiation Electron mass (energy or momentum, i.e., missing factors of c) _ mNumber of radiated SR photons n Momentum Р Bunch charge q q^2 (Momentum transfer)² Classical radius of electron, 2.82 $\times\,10^{-13}$ cm r_e Path length along orbit S Bunch spacing s_b Energy loss normalized to E, e.g., k/EU Normalized photon energy, k/k, V Angle nomalized to $1/\gamma$, w = γx angle W Distance along beam axis _ \boldsymbol{z} Α Atomic weight Magnetic field, usually KG В \boldsymbol{E} Beam energy Ι Beam current L Magnet length, usually mSR Synchrotron radiation Т Kinetic energy UEnergy radiated ZAtomic number Z_o 377 ohms 1/137 α E/m γ δ Skin depth, usually $\mu \mathbf{m}$ RF magnetic permeability relative to vacuum μ Bend angle ϕ Cross section σ Rms bunch length, Gaussian parameter σ_z $\sigma(Z)$ Dc electrical conductivity of material denoted by Zθ Scattering angle Radius of curvature ρ

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