IR Design Issues for High Luminosity and Low Backgrounds

for the

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Outline

- Very brief e+e- collider history
- Some new designs
- High currents
- Beam halos/tails
- High luminosity
- Backgrounds
- Summary
- Conclusions

Very brief history

- e+e- colliders at the energy frontier of new particle production
  - AdA, Doris, SPEAR, PEP, PETRA, Tristan, LEP
- PP colliders at the energy frontier
  - Only possible because the proton contains some anti-matter
  - RHIC, SPS, LHC
- Tevatron PPbar collider
- e+e- colliders moved to the luminosity frontier with the B-factories, Tau-Charm factories and Phi factories
  - First high current (> 1 A) colliders
- New designs now have high currents (EIC, STCF…) and some also have high energies (FCCee, CEPC)
  - LHC is still at the energy frontier

New Designs

- SuperKEKB
  - Machine is already running and gradually improving performance
  - This machine has the highest design currents
    - 3.6 A for the 4 GeV e+
    - 2.6 A for the 7 GeV e–
  - Smallest diameter IR beam pipe
    - 20 mm
  - Largest crossing angle
    - 83 mrad
  - Design luminosity
    - 5-6x10^{35}
    - Nano-beam collision scheme

FCCee and CEPC

- Multiple beam energies
  - FCCee — CEPC
  - 45, 80, 120, 182.5 GeV — 45.5, 80, 120, 180 GeV
- Currents are:
  - 1.4, 0.135, 0.0267, 0.005 A — 0.8035, 0.0841, 0.0167, 0.0033 A
- Luminosities are:
  - 18.1, 1.73, 0.72, 0.125×10^{35} — 11.5, 1.6, 0.5, 0.05×10^{35}
- The lowest beam energy (Z-Factory) design has high beam currents and a very high luminosity making this machine very similar to the SuperKEB but with a much higher beam energy

EIC

- Also a multiple energy machine
    - Proton beam energy range is 40 – 275 GeV
- The electron beam also has several energies
    - The electron beam energies are 5, 10, 18 GeV
    - The electron beam currents are 2.5, 2.5, 0.27 A
    - Luminosity of $1x10^{34}$
- The EIC has the highest design current for a 10 GeV beam
    - The PEP-II B-factory achieved 2.07 A at 9 GeV and 3.21 A at 3.1 GeV
    - KEKB achieved 1.2 A at 8 GeV and 1.6 A at 3.5 GeV
    - The SuperKEKB design currents are 2.6 A at 7 GeV and 3.6 A at 4 GeV

High Current Issues

- SR critical energy values for the main bend magnets of various machines
- The PEP-II B-factory HER had a bend magnet critical energy of 9.8 keV
- SuperKEKB bend magnet critical energy for the HER is 2.6 keV
- FCCee and CEPC bend magnet critical energy for the Z running is about 20 keV
- The EIC bend magnet critical energy for the 10 GeV beam is about 6.2 keV and 36 keV at 18 GeV
- The new machines (FCCee, CEPC and EIC) will need to go through significant beam pipe “scrubbing” time before being able to achieve their design high current values
  - The superKEKB has been scrubbing the beam pipe (especially in the new LER beampipe) for more than 2 years. They now are reaching beam currents above 1 A.

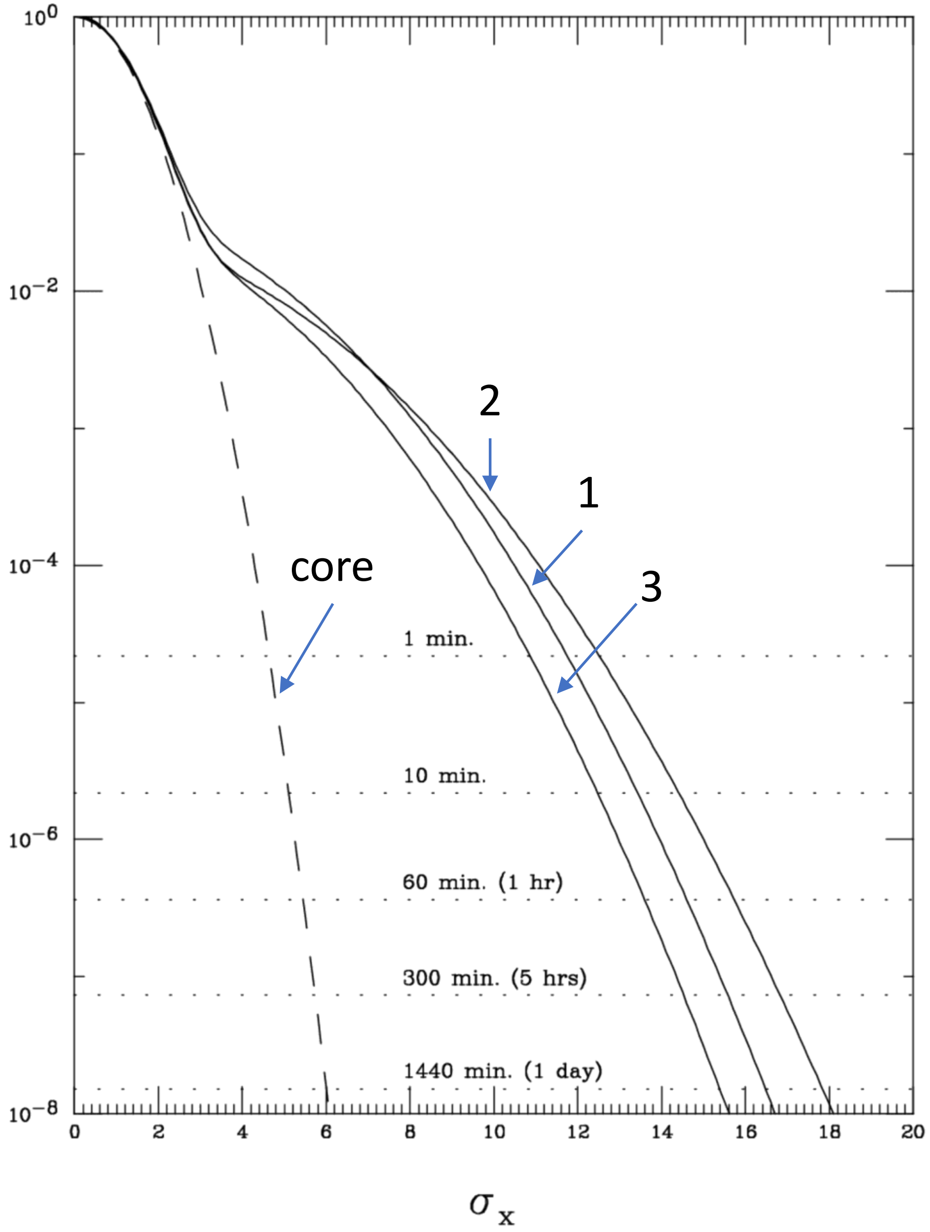
More on High Currents

- The higher SR critical energies for the FCCee and CEPC at the Z pole running could mean that the beampipe scrubbing time may be longer
- The higher energy photons can penetrate more deeply into the beam pipe wall thereby dislodging more gas molecules located farther inside the material
- As more current is stored in the ring more gas molecules are dug out of the wall and the dynamic gas pressure increases which shortens the beam lifetime
- The beam develops non-gaussian tail distributions in X and in Y from scattering off of gas molecules and collimator settings or actual beam pipe apertures or the dynamic aperture of the ring will cause beam particles in these tails to be lost
- If the perturbations generated by the gas pressure is often enough then the size of the core of the beam can increase lowering the expected luminosity

Beam tail distributions

- ANY perturbation of the particles in a stored beam will populate a non-gaussian tail
- Because the non-gaussian beam tails are generated by a large number of possible sources it is difficult to calculate an overall tail distribution
  - The source terms also vary with time – some are more important when the vacuum pressure is high while others can become important if the bunch charge is large
- A beam tail distribution coming from a particular source can be calculated but it is difficult to get all of the source terms correct at the same time
  - Source terms can come from the beam being near instability thresholds
- I use a second, wider gaussian beam tail distribution to model a real tail distribution
  - A second gaussian distribution is a reasonable approximation as the tail distribution is semi-stable
- The second gaussian has two unknowns in each transverse dimension
  - The width which is given by a factor times the core sigma
  - The height as compared to the core gaussian
- This is done separately in both dimensions (X and Y)
  - I ask that the horizontal height and the vertical height of the tails be the same – reducing our 4 unknowns to 3
- This model can then be used to calculate SR backgrounds, and the entire beam transverse distribution is the sum of these four gaussians

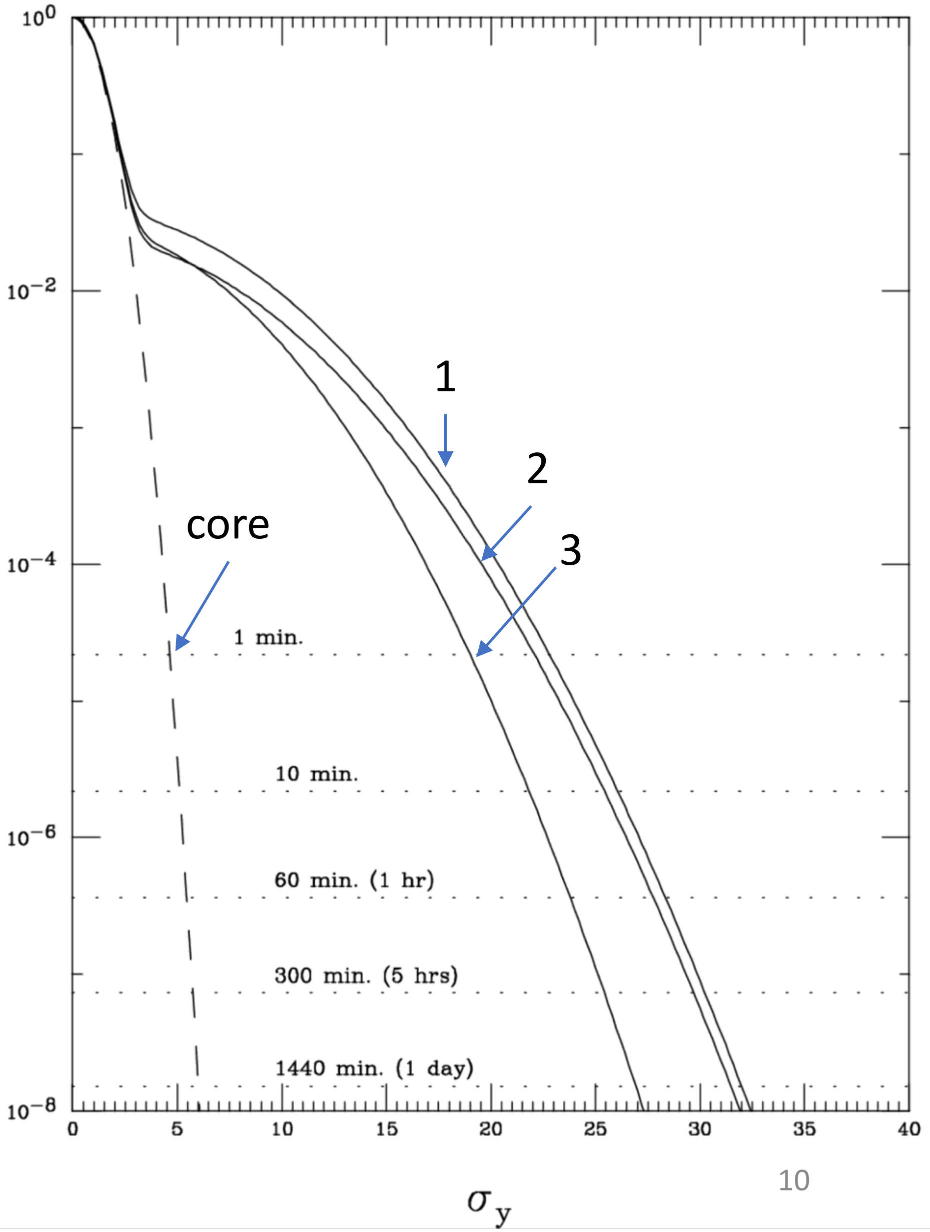
Beam transverse distribution plots for superKEKB



Tail distributions that can generate the background level seen in the superKEKB pixel detector (PXD) during early running.

They also approximately agree with the measured beam lifetime.

The one-day lifetime is derived by Matt Sands, "The Physics of Electron Storage Rings an Introduction", 1970, SLAC-121



EIC beam tail

With 1.7×10^{11} particles/bunch we have about 1.7×10^{4} particles at the blue lines

- This is the beam tail I used for an EIC study
- It is what I call a “mid-range” tail
- With collimators set at the BSC, the beam lifetime is about 2-3 hrs (red lines)
- The fraction of the core that is in the tail is 0.14 %

0			Fraction (%)
Total particles/bunch (integral) is		1.720100E+11	99.9999951716
Number of particles > 4 sigma	=	1.956130E+08	0.1137218698
Number of particles > 6 sigma	=	7.809452E+07	0.0454011513
Number of particles > 8 sigma	=	3.565942E+07	0.0207310180
Number of particles > 10 sigma	=	1.444567E+07	0.0083981560
Number of particles > 12 sigma	=	5.090714E+06	0.0029595456
Number of particles > 15 sigma	=	8.207671E+05	0.0004771625
Number of particles > 20 sigma	=	1.658588E+04	0.0000096424
0			Fraction (%)
Number of particles in the tail	=	2.453745E+08	0.1426513028
Tail particles > 4 sigma	=	1.428411E+08	0.0830423134
Tail particles > 6 sigma	=	7.809176E+07	0.0453995485
Tail particles > 8 sigma	=	3.565942E+07	0.0207310180
Tail particles > 10 sigma	=	1.444567E+07	0.0083981560
Tail particles > 12 sigma	=	5.090714E+06	0.0029595456
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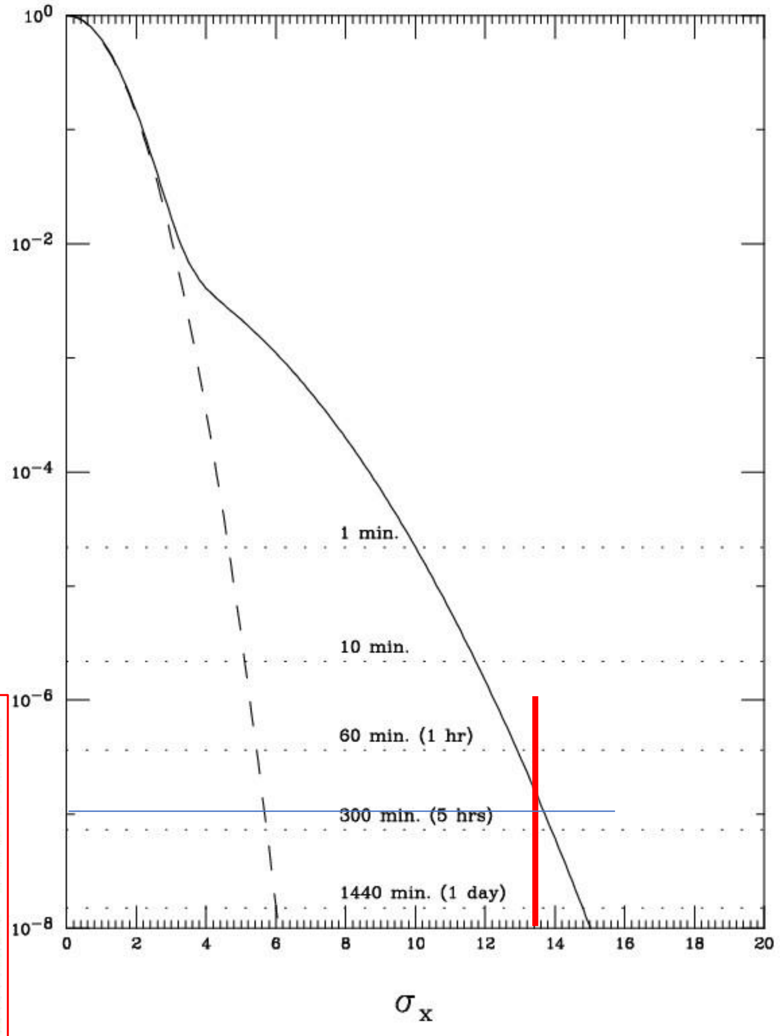
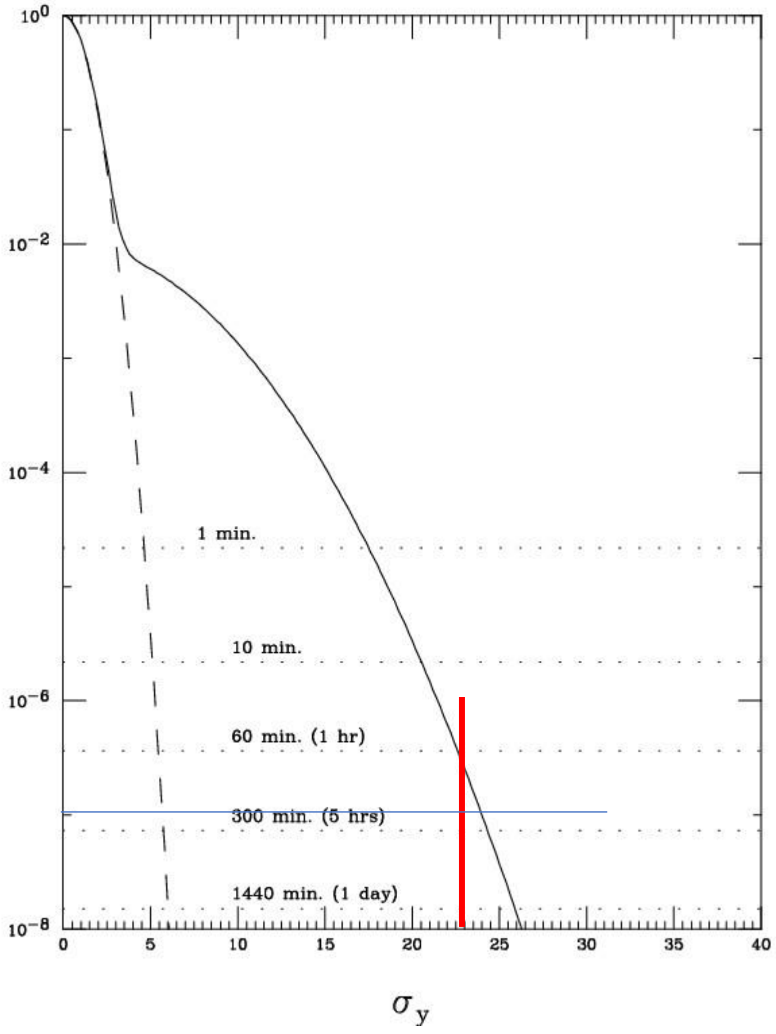




Estimated lifetime for this beam tail is 3-4 hrs (red lines)

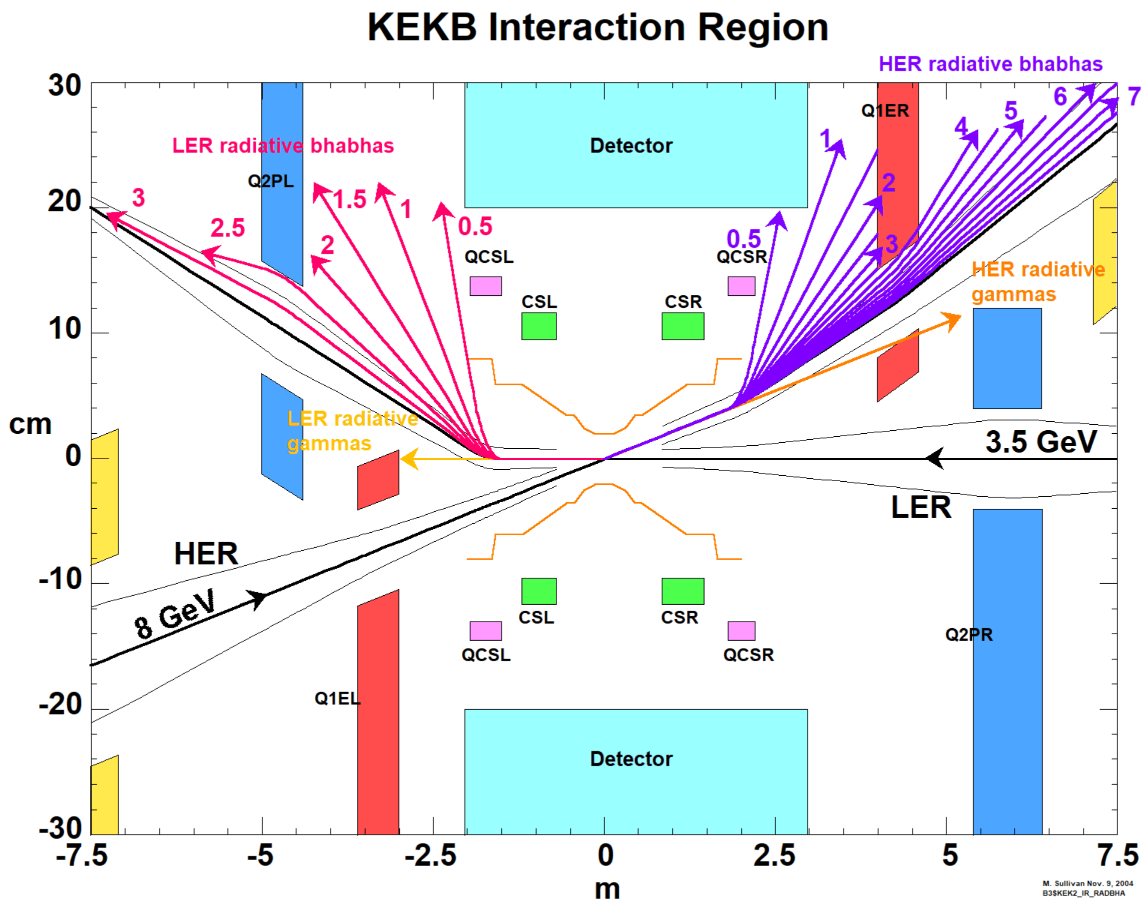
High Luminosity Issues

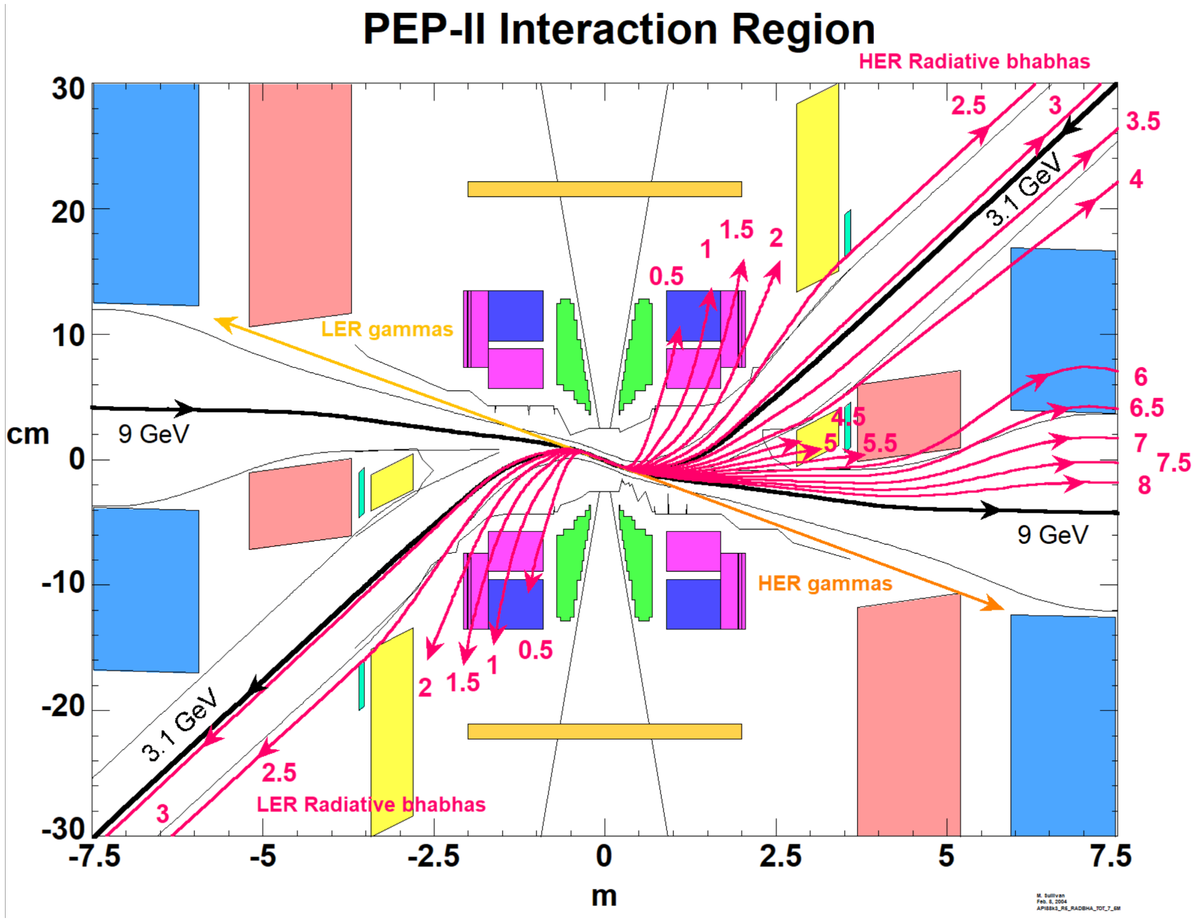
- When the design luminosity is 1×10^{34} or higher for e^+e^- machines the collision begins to affect the detector through additional background sources
  - Radiative Bhabhas
  - Two-photon → $e+e-$ (low energy pair)
  - Tune shifts
  - Beamsstrahlung
    - First studied in Linear Collider designs
    - Is now important in the FCCee and CEPC as a collision background while running at the Z pole
- The high luminosity machines (superKEKB, FCCee and CEPC at the Z) have lifetimes that are dominated by the collision itself (less than 30 min)

Luminosity backgrounds

- Radiative Bhabhas
  - This background was first appreciated by the B-factories (PEP-II and KEKB) when the luminosity got up to $1x10^{34}$
  - This interaction produces high energy gammas that travel along the beam axis and off-energy beam particles that get over focused in the final focus quads and crash into the local beam pipe producing shower debris in the detector
  - It was recognized that the gammas traveling along the exit beam axis would be an excellent signal of the luminosity of the collision
    - The high rate can produce a rapidly updating signal that can be applied to feedback programs as well as give the operators a signal to use to tune the machine
    - The rate is also high enough to give a measurement of the luminosity of each bunch

Radiative Bhabha tracks from the B-factories



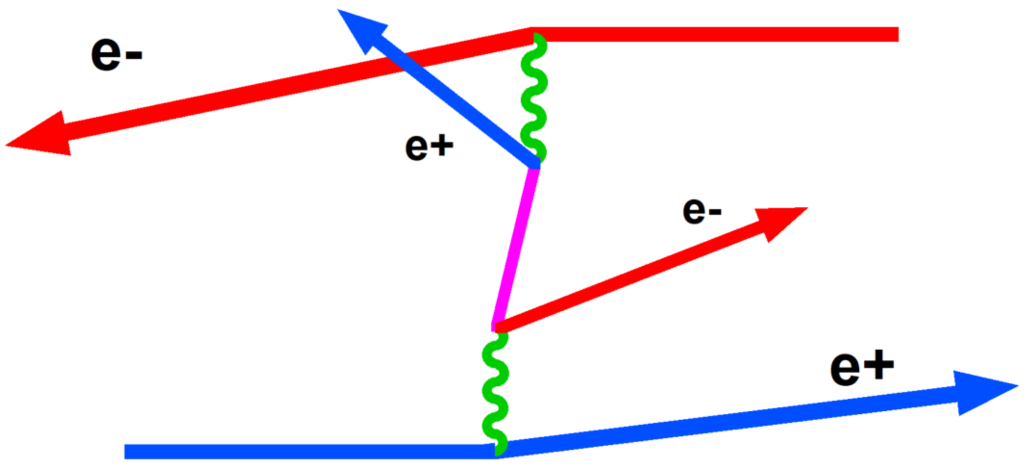


Radiative Bhabhas Cont.

- Both B-factory designs had strong bending fields on the outgoing beam lines which made the backgrounds from this source worse
- SuperKEKB and all future ee designs now make sure that the outgoing and incoming beamlines have no nearby bending fields
    - Bending magnets are now much farther away from the detector
- Even so, this background source still ends up being the dominate detector background for SuperKEKB at design luminosity
    - The final focus quads overfocus these off-energy beam particles

Low energy e+e- pair production

- This interaction produces low energy e+e- pairs and these particles can cause a large increase in background hits in the vertex detector very close to the beam pipe
- The particles spiral in the detector magnetic field and circle around the vertex detector components closest to the beam pipe thereby generating an enormous number of hits
- This background can set a lower limit on the radius of the IR beam pipe
- A higher detector magnetic field can help to reduce this background source



General Background Issues

- Background levels are a continuing source of concern for the detectors of all new and present machines
- When an accelerator starts up and while the accelerator team is working on finding the optimum working point and ironing out initial difficulties the background level in the detector can be uncomfortably high
  - Many (almost all?) times the detector will stay offline during the initial startup and commissioning period
- This is also the time when instability thresholds are discovered and when the "scrubbing" of the beam pipe around the ring is generating a lot of gas molecules which increases the pressure in the beam pipe throughout most of the ring

Background Issues (2)
High backgrounds from high dynamic gas pressure

- As the rings become scrubbed and the dynamic pressure decreases then more current can be stored which will again increase the dynamic pressure
  - The background levels in the detector will remain high during this period
  - The acceptable background level set by the detector tends to limit the rate of current increase
  - But if the beam lifetime becomes too short, then the injection capability may be the limiting factor
- The luminosity remains low initially but as more current is added and as the machine gets tuned up the detector can begin to take data
- The backgrounds are still high but as the dynamic pressure improves the backgrounds do diminish and the lower ring pressure also tends to increase other beam instability thresholds allowing the accelerator team to improve the performance of the collider

Background Issues (3)
The downstream photon beam

- The high energy gammas from the radiative Bhabhas and from the Beamsstrahlung interaction as well as most of the quadrupole SR all travel down the axis of the outgoing beam line
    - This includes some remnant of SR from the last upstream bend magnet as well as whatever SR is generated by the detector magnetic field
- The high beam currents and the high luminosity of the collision together generate a significantly intense outgoing photon beam
- The energy from this photon beam will begin to strike the beam pipe at the first bend magnet after the collision
- The strike point must be carefully studied as the energy density can be high enough to melt most metals as well as create a significant source of neutrons
    - In the case of the FCCee the effort to control this photon beam is leading to a design of a beam dump for this intense beam
- These are all good reasons to move the downstream bend magnet as far as possible from the collision point

Summary

- The new and current e+e– accelerators are using the experience gained from the B-factories to push beam currents up into the multi-Ampere regime
- These high beam currents lead to extended beam pipe vacuum scrubbing and in turn large non-gaussian beam tail distributions which can influence the stored beam lifetime
- The high luminosity of these designs lead to increased detector background levels from the collision itself and the perturbations of the collision also populate the beam tails

Conclusions

- I have tried to touch on some of the important issues of high beam current, high luminosity machines and designs
- I have left out many topics that merit further discussions (apologies!)
  - HOM power issues is one in particular
- The future of e+e- colliders shows promise of being a very exciting time with the upcoming Higgs factories (FCCee, CEPC) and with possible other factories (STCF…)
- The EIC promises to be an equally exciting accelerator and will give us a much more detailed insight into how the proton is put together

- Thank You