IR Design Issues for High Luminosity and Low Backgrounds

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Outline

- Some standard MDI issues
  - Detector acceptance
    - Maximum
  - Final Focus elements
    - High luminosity constraints
  - Backgrounds
    - Synchrotron Radiation
    - Beam particle
    - Luminosity related (radiative Bhabhas, e+e- → e+e-e+e-, etc.)
  - Other (heating, HOM, vacuum, …)

Outline (2)

- Specific SR issues for high luminosity large machines
  - Last bend magnet before the IP
    - Specular reflection
  - Small spot size at IP
    - Strong FF quads
    - Large beta functions in FF quads
  - Beam Tail distributions
  - High beam currents
    - Crossing angle
- Summary
- Conclusion

MDI issues

- Up to now, factories have been lower energy machines (<~10 GeV) with very high beam currents (>1 A)
- However, new *ee* machines are now all essentially factory designs
- Also, current and future *ee* machines are aiming for higher energies and unprecedented luminosities

MDI concerns stem from factory designs

- Detector acceptance
  - Final Focus elements are as close to the IP as possible
  - Low angle detector acceptance is reduced
    - Pushes the design dimensions of FF quads to be as small as possible
- The last bend magnet always sends SR into the IP
  - Most designs make this magnet as low a field as reasonable – grazing angles for incident radiation

Synchrotron radiation sources

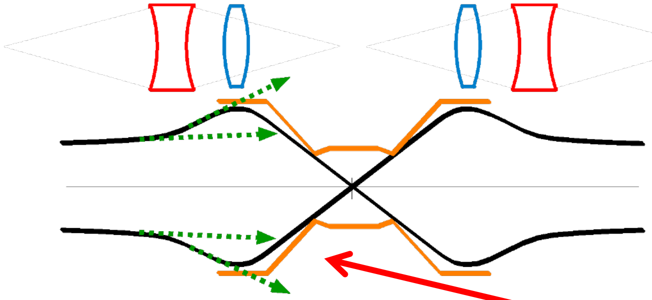
- Close final focus elements mean stronger magnetic fields in the final focus quads
  - SR from the FF magnets (quadrupole radiation) becomes an important detector background
  - Beam tail distributions become important – more on this
  - FF magnets close to the IP mean less space to design masking solutions
  - In addition, the downstream FF magnets have to be protected from the upstream FF SR (especially if they have cold bores)

Primary SR sources

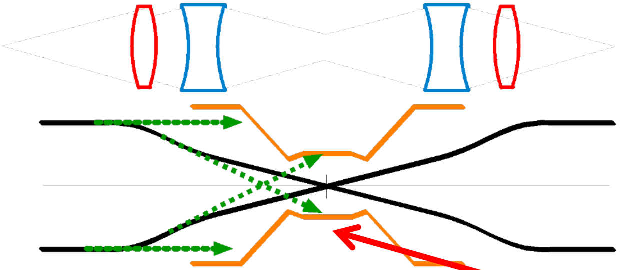
- The new and current machines have higher energy beams or higher beam currents (or both!)
- This means that SR intensity and energy spectra are higher than before in almost all cases
- Blocking the SR sources from directly hitting the detector (mainly the central beam pipe) is the first step

Secondary SR sources

- But then secondary radiation (one bounce and/or tip scattering) becomes the dominant source of SR background in the detector and this can be a high rate source
- This also includes backscattered photons (HERA)
- The newer, larger accelerator designs have another possible source of SR background coming from low-energy photons that have "mirror reflected" by hitting upstream beam pipe inner wall surfaces with a small grazing angle
  - This source is geometry dependent but high luminosity designs usually want an as small as possible central beam pipe in order to maximize the physics reach and this can lead to exposure from this source



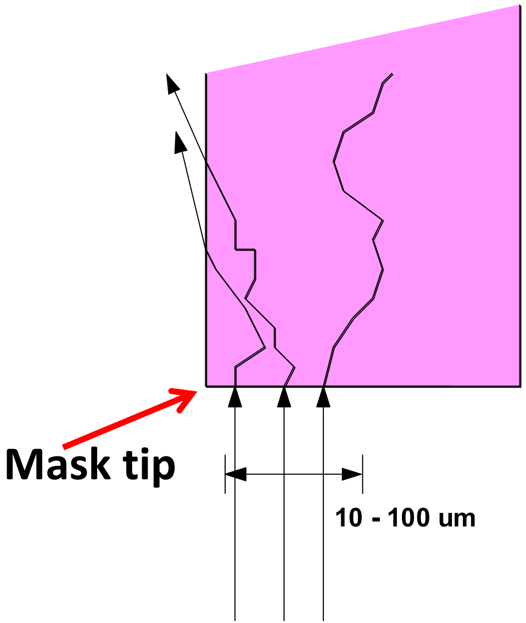
Vertical beam focusing
(side view)



Horizontal beam focusing
(plan view)

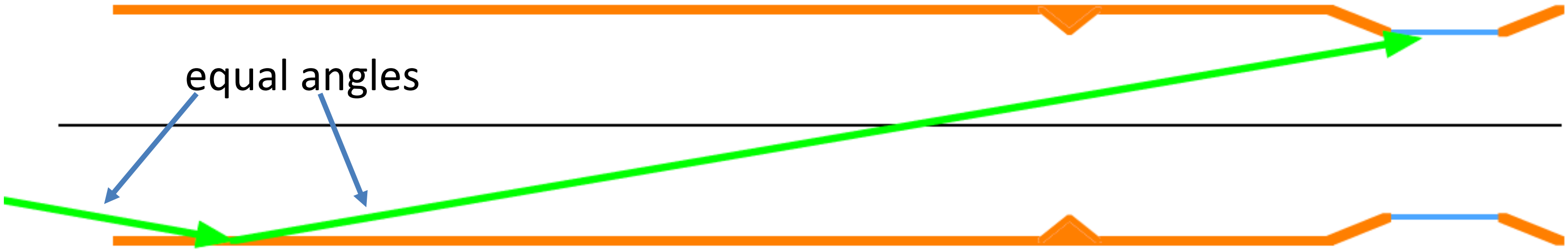
Photons generated from the final focus quadrupoles have to be masked away from the central beam pipe. The vertical focusing element is usually closest to the IP and easier to mask.

The horizontal focusing magnet is farther back and must over-focus in order to compensate for the defocusing of the vertical focusing magnet. These photons are more difficult to mask.



Photons that strike near the tip of a mask have a chance to scatter through the tip and then hit the central beam pipe

Specular reflection



SR photons from far upstream can possibly mirror scatter (specular reflection) off of the inside wall of the beam pipe. The angle of incidence needs to be small (~few mrad) and usually the photon energy is low (~<10 keV) but if the incident photon rate is high this can be a potential background issue. The reflection rate for this process can be >10% (see next slide)

Reflection (2)

94 *D.H. Bilderback, S. Hubbard / X-ray mirror reflectivities II*

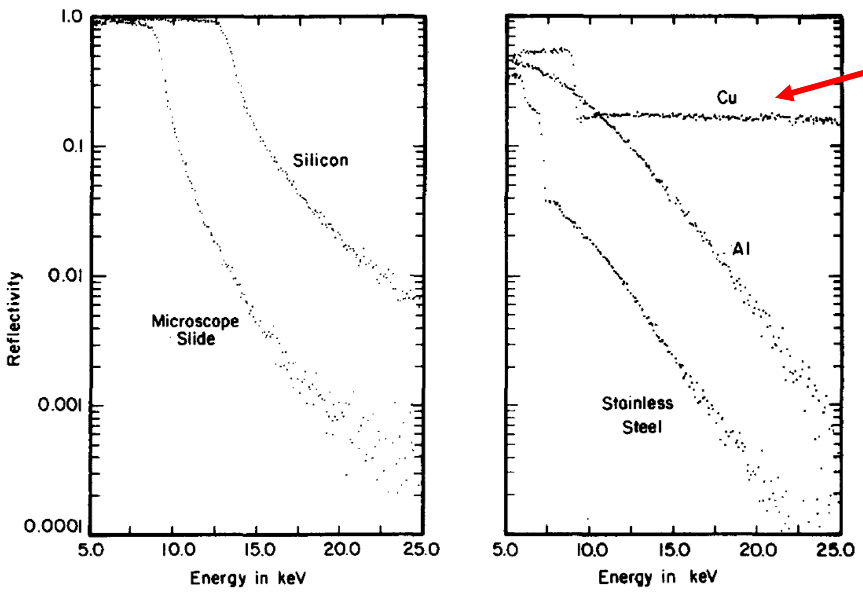


Fig. 3. Reflectivity of a (111) silicon wafer set at an angle of 2.3 mrad and a microscope slide set at 3.5 mrad. The reflectivities of rolled but not polished sheet metal strips of copper, aluminum and stainless steel set at a 3.5 mrad angle.

Note the high rate (~20%) of reflectivity up to 25 keV for a 3.5 mrad incident angle on a rolled but NOT polished surface of Cu (typical inside wall beam pipe material)

from “X-ray Mirror Reflectivities from 3.8 to 50 keV” Pt. II, NIM 195 (1982) by Bilderback and Hubbard

Reflection Summary

- The amount of x-ray reflectivity is highly dependent on:
  - The surface material and roughness
  - The x-ray energy
  - The angle of incidence
- The above are all difficult to accurately simulate unless the surface is fully specified

Reflectivity Conclusion

- Construct a beam pipe and masking scheme design that eliminates the possibility of small incident angle one-bounce reflectivity as a background
  - Even better is to make all 2nd bounce photons have a high incident angle (~>15 mrad?) on the 2nd surface

Reflectivity Update

- There are some new codes working to simulate this process more generally
  - H. Burkhart mentions specular reflection as a G4 upgrade (mainly w.r.t. x-ray mirrors)
    - https://indico.cern.ch/event/497514/contributions/1177065/attachments/1231011/1804574/G4dev_FW_Options_2016_02_18.pdf
  - There is a paper on specular reflection as a means of "piping out" the SR power from the arcs of the FCC-hh machine
    - http://dx.doi.org/10.1103/PhysRevLett.115.264804
    - Also there is a similar study for the SSC: L. Jones, T. Dershem, "Synchrotron Radiation from protons in a 20 TeV, 10 Tesla superconducting super collider", Prod. Of the 12th International Conference on High-Energy Accelerators, 1983, pg 138.
  - Two papers on the program synrad3D which simulates diffuse and specular reflection
    - http://dx.doi.org/10.1103/PhysRevAccelBeams.20.020708
    - http://dx.doi.org/10.1103/PhysRevSTAB.18.040704
  - I understand that Roberto Kersevan has used Synrad+ to simulate specular reflection in order to study electron cloud effects with Eleonora Belli

Beam Tails

- Some slides on the beam tail simulation
- All stored beams have a non-gaussian tail distribution. The tail is populated by:
  – Quantum SR fluctuations
  – Beam-gas scattering
  – Beam-beam interactions
  – Magnetic nonlinearities
  – IBS interactions
  – Other……

Beam tails (2)

- The integral of the tail distribution generally should be lower than a few (~2%) percent of the entire bunch
  - The tail distribution does not contribute to the luminosity and hence we would start to see a systematic discrepancy in the luminosity calculation if the tail distribution is too large
- The particle density at large sigma cannot be too high or the beam lifetime becomes too short
  - However, many new accelerator designs rely on continuous injection in order to improve luminosity (peak and integration) and/or maintain polarization
  - This means that shorter beam lifetimes (~10-15 min) are acceptable

Beam Tails (3)

- These constraints still leave quite a bit of variation for tail distributions
- Matt Sands (UCSC) makes an estimate of beam life time based on an aperture cutoff of the gaussian distribution.* He says that 6σ is the critical sigma for a 1 day lifetime and 12σ is a reasonable aperture size.
- Accelerator experience tends to agree with this estimate. We usually have collimator limits of about 8-10σ in X.
- At machine start up we may need larger limits due to initial beam gas scattering which increases the tail population.

*SLAC-121 (1979) sect. 5.7 pg 141

Beam Tails (4)

The tails in the plots here are the ones I use for synchrotron radiation background calculations

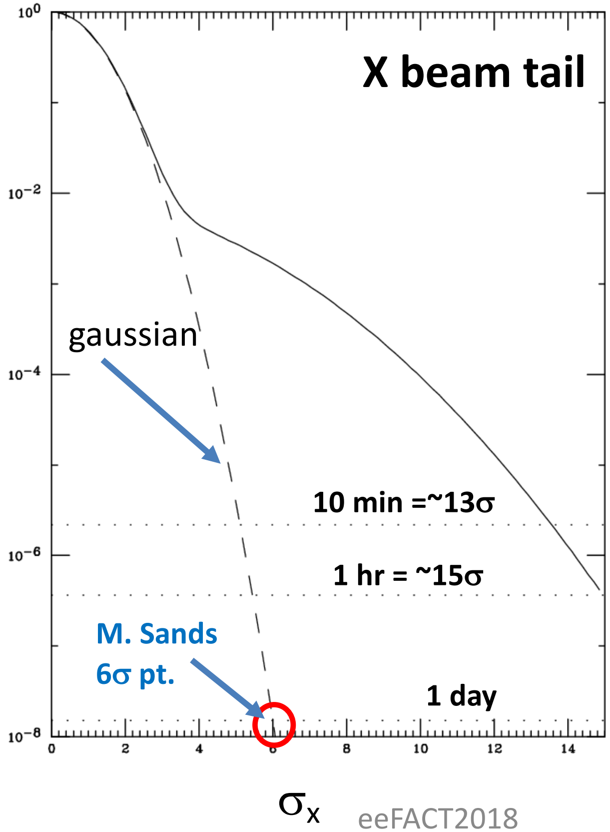
The background distribution is a 2nd lower and wider gaussian

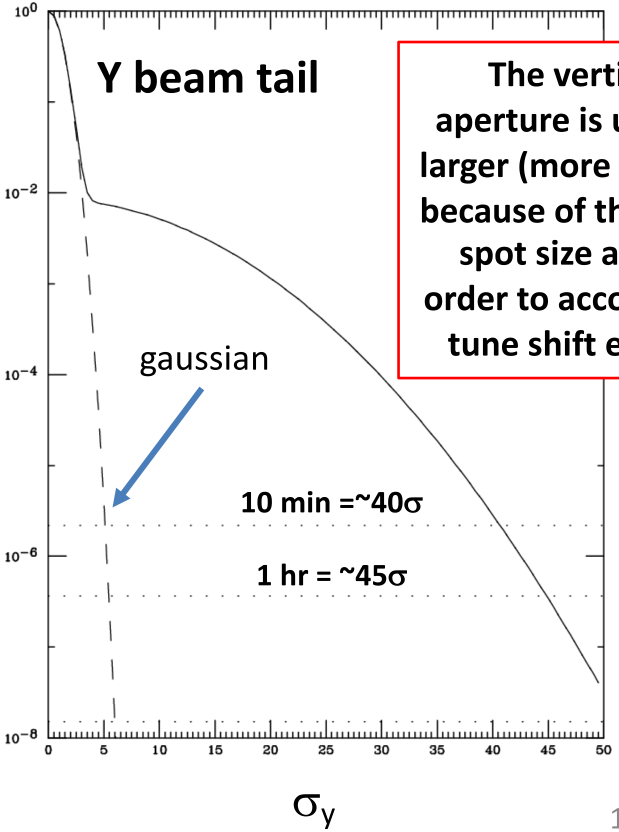
$$e^{-\left(\frac{x^2}{2\sigma^2}\right)} + ae^{-\left(\frac{b^2x^2}{2\sigma^2}\right)}$$

Where $a = 8.5 \times 10^{-3}$ and
b = 0.3 for x and
0.1 for y

The integral of the background distribution is about 0.3% of the total.

This might be on the low side especially for a new accelerator.





The vertical aperture is usually larger (more sigmas) because of the small spot size and in order to account for tune shift effects

Beam Tail summary

- The particle density in the intermediate (4-8σ) range can be a significant source of SR background if not properly masked
  - In this region there may be beam particle densities as high as 0.1-2% of the main bunch gaussian which will make significant levels of SR
- Masking designs need to be made that account for the possibility of a high beam particle density here

Beam particle Backgrounds

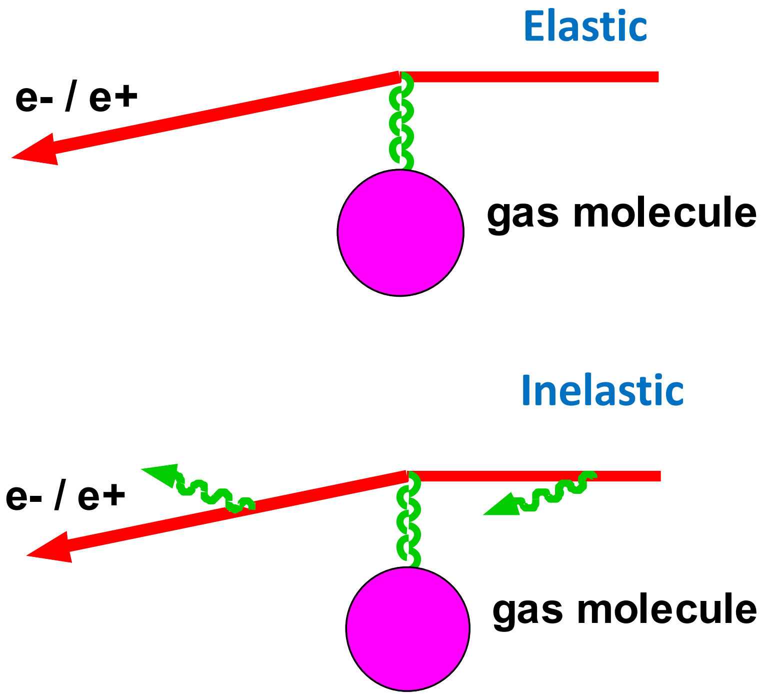
- There are several processes that need to be calculated that all involve backgrounds from a beam particle
  - Particle – particle interaction inside a beam bunch
    - Touschek
    - Inter-beam scattering (IBS)
  - These scattering events populate the large sigma region of a beam bunch (beam tails) with particles that tend to get lost in the IR because the beta functions are largest in the final focus magnets
    - Careful beam tail collimation at places outside of the IR are needed

Beam Beam

- Beam-beam tune shift also puts beam particles into the high sigma regions
  - Collimation should help this but one must watch the beam lifetime
- Luminosity lifetime
  - This is essentially the above point again.
  - Beam particles are shoved out into the high beam sigma regions
    - Mostly in Y, but it takes several turns to damp down and these beam tail particles will move into the X plane before being damped
    - Top up injection needed

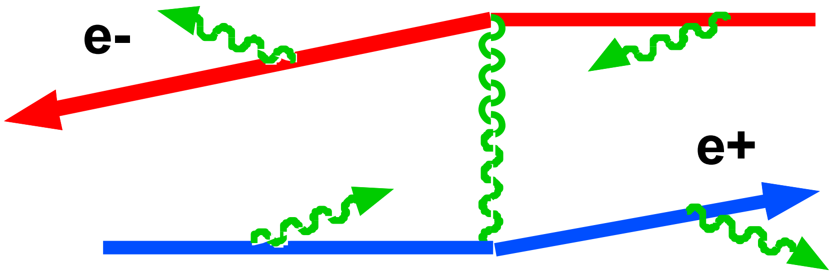
Beam-gas particle bkgds

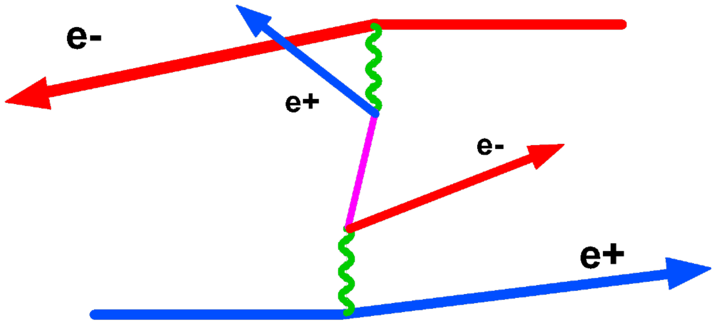
- Beam particle interaction with a gas molecule
  - Coulomb scattering (elastic)
  - Beam-Gas interaction (inelastic)
    - A carefully constructed collimation scheme is needed to minimize these backgrounds
    - Also as good a vacuum as possible around the ring and especially upstream of the detector



Luminosity backgrounds

- The B-factories were the first to encounter significant backgrounds from luminosity
  - Radiative Bhabhas
    - Low angle γs and off-energy beam particles
  - Two-photon $e^{+}e^{-}$
    - Sets the inner radius of the beam pipe
- These bkgds increase with increasing luminosity





Other MDI issues

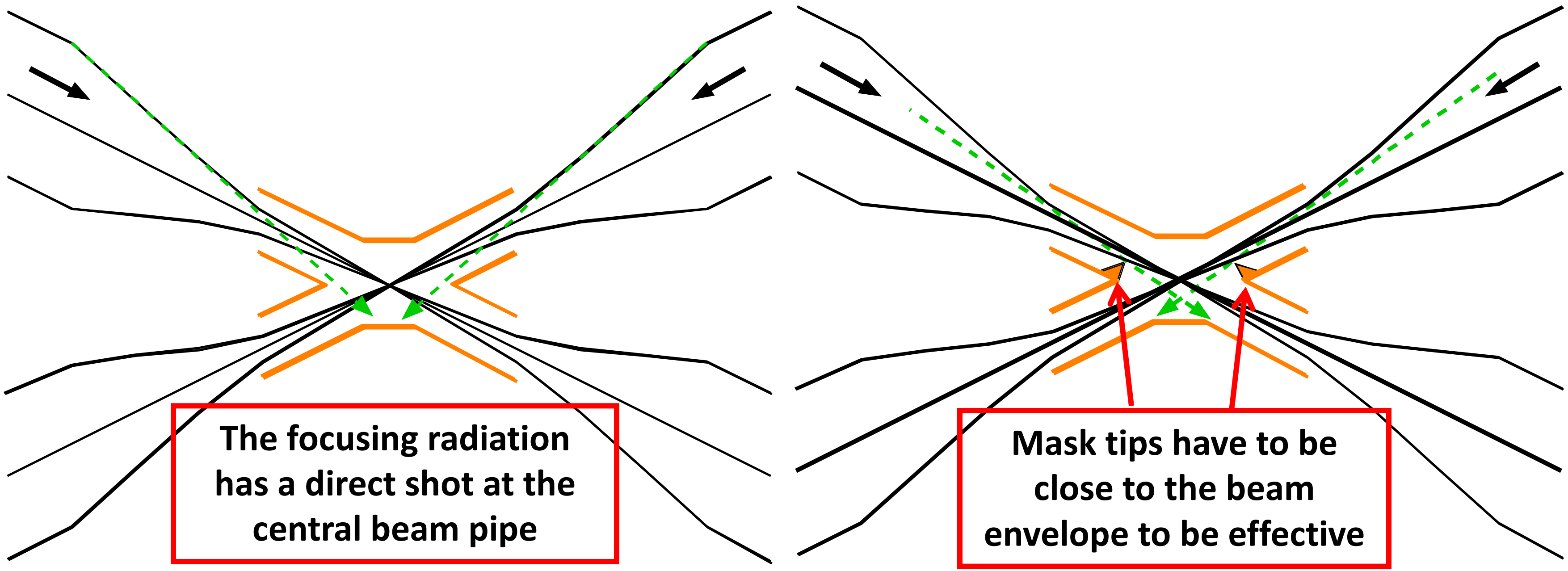
- HOM heating
  - This is always an issue especially for crossing angle or separate storage ring collider designs
  - There is always a place that has the largest inside volume which is where the low frequency HOM gets trapped
- Image current heating
  - The beam produces an image charge on the walls that travels with the beam. This image current has an I^2R power loss based on the resistivity of the wall which is a function of frequencies related to the bunch length

More MDI issues

- **Vacuum pressure**
  - **As low as reasonably possible upstream of the IR**
  - **The beam pipe from the last collimator to the IR must have very good vacuum as all gas interactions in this region will tend to crash into the detector (a bend magnet can help – especially BGB but Coulomb can still be a problem)**
- **Injection backgrounds**
  - **Continuous injection can double and perhaps triple the integrated luminosity compared to a coast and fill method (luminosity lifetime) but then one needs to make sure the detector can survive with continuous injection**

Crossing angle masking

- **A large crossing angle makes shielding the central chamber from direct SR hits more difficult**
  - **SuperKEKB has the largest crossing angle of 83 mrad**



Summary

- The Interaction Region is one of the more interesting parts of an accelerator
  - There are many conflicting requirements that need to be optimally resolved
  - The accelerator needs to be able to **produce the luminosity**
  - The detector needs to be able to **collect the physics**

Summary (2)

- A good IR design should try to be as **"flexible"** as possible in order to **"bend"** and not **"break"** when slightly different running conditions or circumstances turn out to produce better machine and/or detector performance

- One needs to study around the large multi-parameter space near the design choices in order to find out where the **"breaking points"** are located

Conclusion

- Start with a reasonably good IR design
- Then check for robustness
- Re-optimize
- Check again for robustness
- Keep iterating and rechecking especially after even small changes in the machine or detector design occur

Thank you!