Interaction Region Designs for Electron Colliders

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A Brief History of e+e- Colliders and Backgrounds

- The very first e+e- collider was AdA – made here at Frascati and later moved to Orsay (1961-1964)
    - Beam related backgrounds were not considered
    - Touschek scattering was discovered due to the poor lifetime and increased instability of the stored beam – not because it was a background source
    - Beam energies and beam currents were low, making synchrotron radiation unimportant as a background – it was much more important as a damping mechanism – and as visible observation of the beam

Other colliders in the 60s

- **There were a few more colliders in the sixties**
  - **Stanford – Princeton collider (e-e-) (1962)**
    - **Vacuum “scrubbing” (photon desorption) was discovered and with it the need for ultra-high vacuum chambers**
  - **VEPP-1 (e-e-) (1964)**
  - **VEPP-2M (1965)**
- **All still had low beam currents and beam energies**
- **The fixed target electron colliders of the 60s were CEA (1963?) (6 GeV) and SLAC (1966) (25 GeV)**

Colliders of the early 70s

- **ADONE (1969)**
- **SPEAR (1972)**
- **CEA (1970)**
- **VEPP-2M (1974)**
- **DORIS (1974)**
  - **Beam energies reached the several GeV level and IR beam pipes started to get thinner**
  - **The higher beam energies reduced the effects of Touschek scattering**
  - **Vacuum technology was improving**
  - **Beams had high emittance in order to store as much charge as possible in one or two bunches – RF power was not a limitation**
  - **SR was still not a major issue except for the bending radiation that came from the last arc magnets**
  - **Beam-gas Bremsstrahlung (BGB) and Coulomb scattering became the dominant detector backgrounds**

Colliders of the late 70s and early 80s

- **PETRA (1978)**
- **CESR (1979)**
- **PEP (1980)**
  - **Beam energies ranged from 5 GeV (CESR) to 21 GeV (PETRA)**
  - **Beam currents were still relatively modest (10s of mA)**
  - **Further improvements in vacuum technology improved BGB and Coulomb backgrounds**
  - **IR beam pipes became thinner with low Z materials**
  - **SR from the final focus magnets and from upstream correctors became a background issue for the first time – SR became a dominate background if not properly masked and had to be carefully studied**

Other colliders of the 80s

- **Tristan (1986)**
  - Beam energies were the highest of the time (32 GeV) and SR backgrounds had to be carefully modeled and masked as well as BGB and Coulomb scattering
- **BEPC (1989)**
  - An e+e- collider in the charm region 1-2 GeV beam energy
- **HERA (Primarily an e^+P collider (1992)**
  - The positron beam (14-28 GeV) generated significant SR in the interaction region that had to be masked away from the detector beam pipe. The proton beam was 40-920 GeV.

LEP (1989) and SLC (1988)

- These colliders had to contend with new background sources
  - Highest beam energies to date (50-100 GeV)
  - Muon generation from upstream collimators
  - Hard x-rays from SR causing pair production in the vacuum beam pipe

B Factories (late 90s to 2010)

- Beam energies moved back down to several GeV but beam currents were higher than any previous machine and collision luminosities were (and still are) the highest
- First double ring asymmetric-energy e+e- colliders
- Luminosity backgrounds became a new issue
  - Two-photon e+e- production
  - Radiative Bhabha production
- Wake field losses and RF heating became important for vacuum chamber design

DAΦNE

- DAFNE is the first low-energy (0.5 GeV) high-current (1-1.4A) collider
  - The primary detector background is from Touschek scattered beam particles
  - The low beam energies make very little SR which is good for detector backgrounds but makes it more difficult to effectively “scrub” the vacuum chambers
  - Scrubbing can help reduce backgrounds from BGB and Coulomb scattering and also improves beam lifetime and stability

BEPC-II

- BEPC-II is the other present low-energy collider. It has SPEAR, VEPP-2, DORIS and ADONE-like beam energies (1-2 GeV) but with beam currents of nearly an Ampere (0.91A)
  - BEPC-II has two separate storage rings and collides with a crossing angle (nn mrad)
  - The high beam currents make SR, BGB, Coulomb and Touschek backgrounds important

New Collider Designs

- There are three major categories of new electron collider designs
  - Moderate-energy high-luminosity colliders
    - Super B-factories (SuperB and superKEKB)
  - Very high-energy colliders
    - Linear colliders (CLIC and ILC)
    - Muon collider
  - eP (and e-ion) colliders
    - JLAB – MEIC
    - BNL – eRHIC
    - CERN – LHeC

Interaction Regions

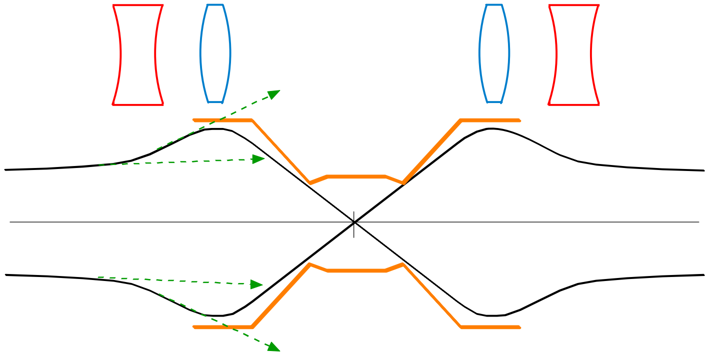
- **All interaction Region (IR) designs hinge on controlling machine induced backgrounds for the detector**
- **In addition, the IR design has to incorporate important machine requirements that are needed to deliver the design performance**
  - **Final focus optics**
  - **Beam trajectories**
  - **Collision frequency…**

New designs

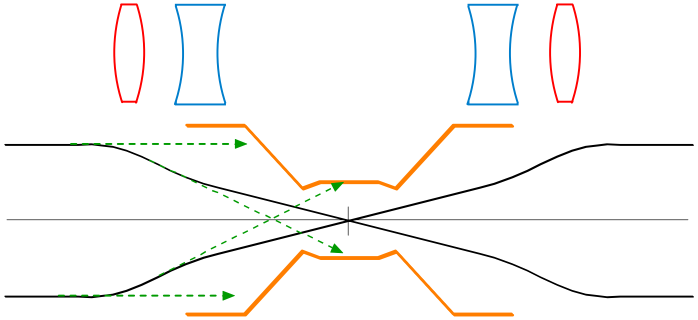
- Essentially all new designs call for high beam currents or high beam bunch charge
  - This means high luminosity
- Hence luminosity backgrounds are beginning to dominate other backgrounds
- SR must still be carefully checked as this background has the steepest dependence (both geometrically and as a function of beam energy)
  - Power from SR becomes an important design feature
- Wake field and HOM losses are also important because of the high beam currents

Issues for Modern IR Designs

- **Control of SR backgrounds from the final focus magnets and other upstream sources like the last bend magnet**
  - **Soften the last bend magnet as much as possible**
  - **Move it as far away as possible**
  - **Too far away can increase backgrounds**



Vertical beam focusing
(side view)



Horizontal beam focusing
(plan view)

IR Design Concerns (2)

- Beam apertures (beam pipe sizes)
  - Large enough to minimize local hits from off-energy beam particles
    - Sources are: BGB, Touschek, Coulomb
  - Smooth (gentle, slow) size transitions to minimize RF heating from wake fields, especially heating of the thin central chamber
  - For storage rings the size must be large enough to accommodate the initial injection orbit
  - The IR beam pipes should not be the limiting aperture of the accelerator (usually measured in beam sigmas)

IR Final Focus Magnets

- **Final focus magnets need to be close enough to the collision point to keep the maximum beta function values "reasonable"**
  - **Less than 5000m for storage rings (I personally prefer < 2500 m)**
  - **Less than 10000m for single pass machines (ERLs, etc.)?**

- **The final focus design is an integral part of any Interaction Region**
  - **The magnet placements strongly influence detector acceptance for physics (usually something has to be given up or compromised since detectors want 4π SA)**

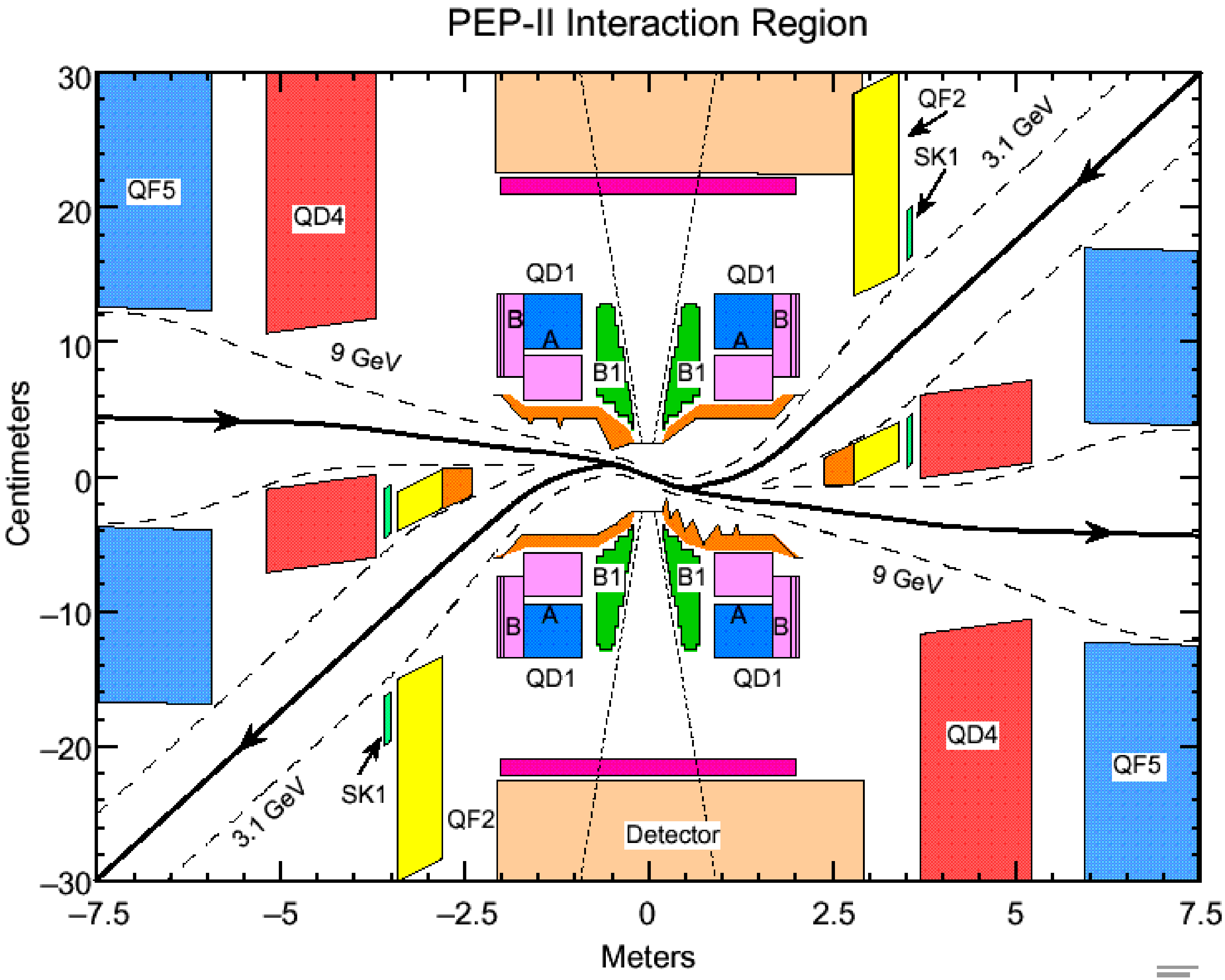
The Final Focus magnets (2)

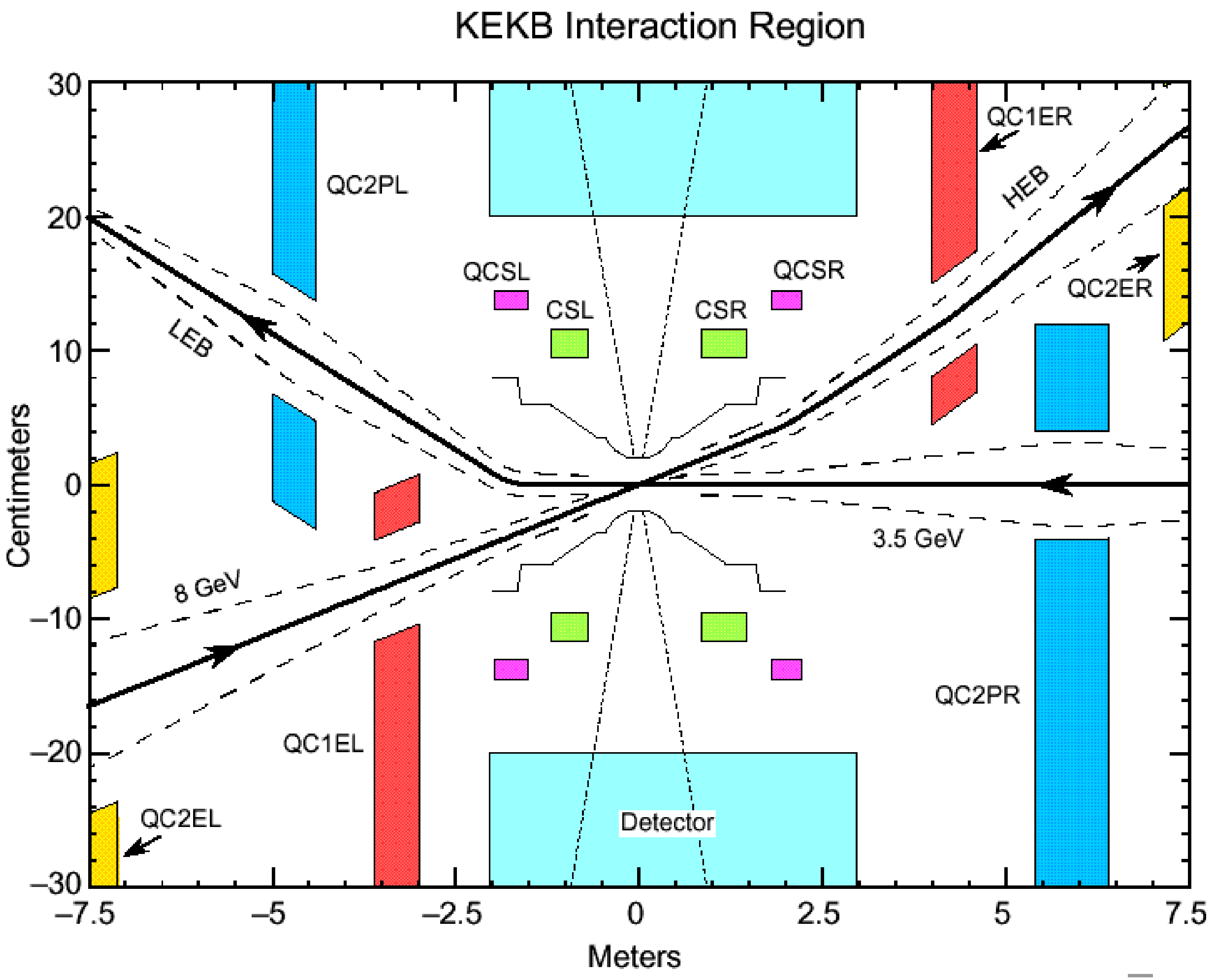
- Flat vs Round beams
  - For storage rings, flat beams have so far proven to be the preferred final focus design
    - SR backgrounds are easier to control (see 3 slides back)
    - Magnet strengths are lower
  - For single pass colliders round beams have been preferred and proton and ion storage rings also prefer round beam collisions
    - Usually a triplet is needed for the final focus and the magnet strengths are considerably higher
    - SR backgrounds are more difficult with round beam optics

More IR Design Issues

- Minimal bending of the beams near the IR
  - Before the collision to minimize steering off-energy beam particles into the detector and minimize upstream SR sources
  - After the collision to minimize steering the off-energy radiative Bhabha beam particles into the nearby beampipe

- One might argue that the two B-factories narrowly escaped the radiative Bhabha luminosity background source
  - As the first accelerators to successfully collide independent storage rings – both had strong bending on the outgoing beam fairly close to the IP
  - PEP-II had the strongest bending both just before and after the collision


PEP-II Interaction Region
Centimeters
Meters
30
20
10
0
–10
–20
–30
–7.5
–5
–2.5
0
2.5
5
7.5
QF5
QD4
QD1
B
A
B1
QF2
SK1
3.1 GeV
9 GeV
Detector


KEKB Interaction Region
Centimeters
Meters
30
20
10
0
–10
–20
–30
–7.5
–5
–2.5
0
2.5
5
7.5
QC2PL
QC1ER
HEB
QCSL
QCSR
CSL
CSR
QC2ER
LEB
3.5 GeV
8 GeV
QC2PR
QC1EL
QC2EL
Detector

Still More IR Design Issues

- **Aim for the best vacuum one can achieve on the upstream section of the beam pipe for each beam**
  - **This minimizes BGB and Coulomb backgrounds created between the last bend magnet and the IP**
- **Collimators for these beam particle backgrounds and for Touschek scattered events that occur around the rest of the storage rings need to be far enough upstream of the detector to not be a new source of backgrounds from shower debris**
  - **One can also consider using collimators that are downstream of the detector for a tighter collimation than can be made to work on the upstream side. These would reduce multi-turn events.**

Backgrounds

- We now have several backgrounds that modern IR designs must control
  - SR
  - BGB, Coulomb
  - Touschek (at lower energies or very high bunch charge)
  - Luminosity related
  - More exotic
    - eP collisions
    - ILC - CLIC (very high beam energies)
    - Muon collider

SR

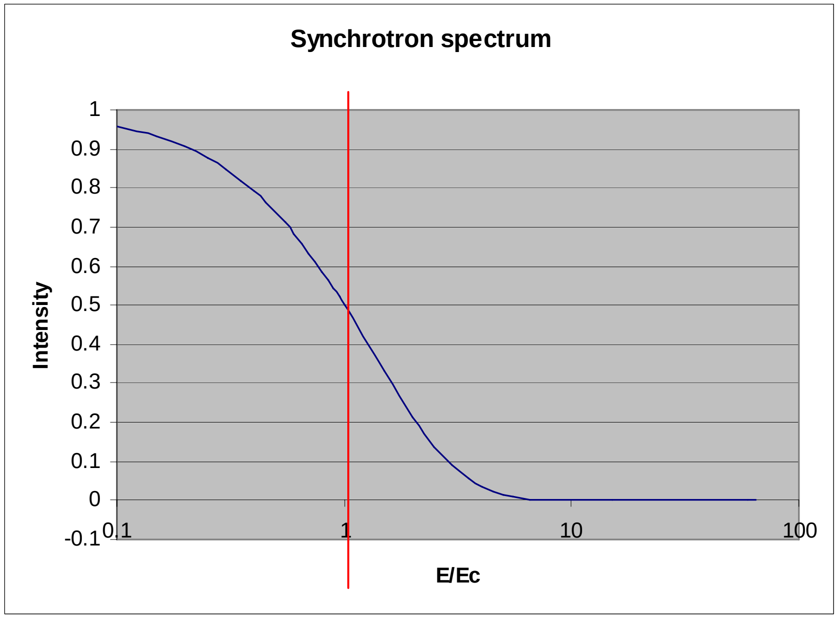
- Photon Energy Spectrum
  - Critical Energy
- Masking
  - Shielding the IR beam pipe from the generated photons
- Scattered photons
  - Masks may be necessary to protect the detector from backscattered as well as forward scattered photons (one-bounce photons)

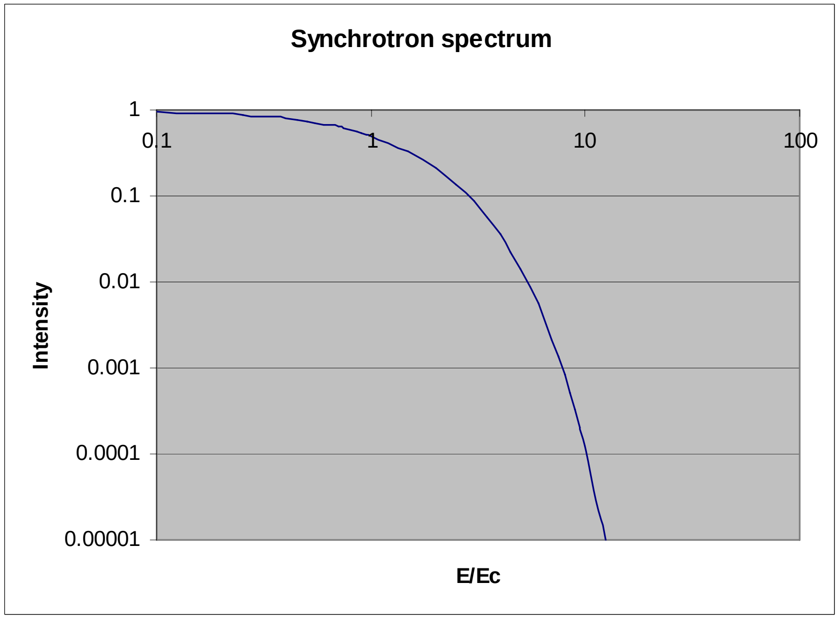
Photon Energy Spectrum

Critical Energy

$$E_c = 6.66\,(\text{keV})\left(\frac{E_{beam}}{10\,(\text{GeV})}\right)^2 B\,(\text{kG})$$

$$= 0.666\,(\text{keV})\,E_{beam}^2\,(\text{GeV})\,B\,(\text{T})$$





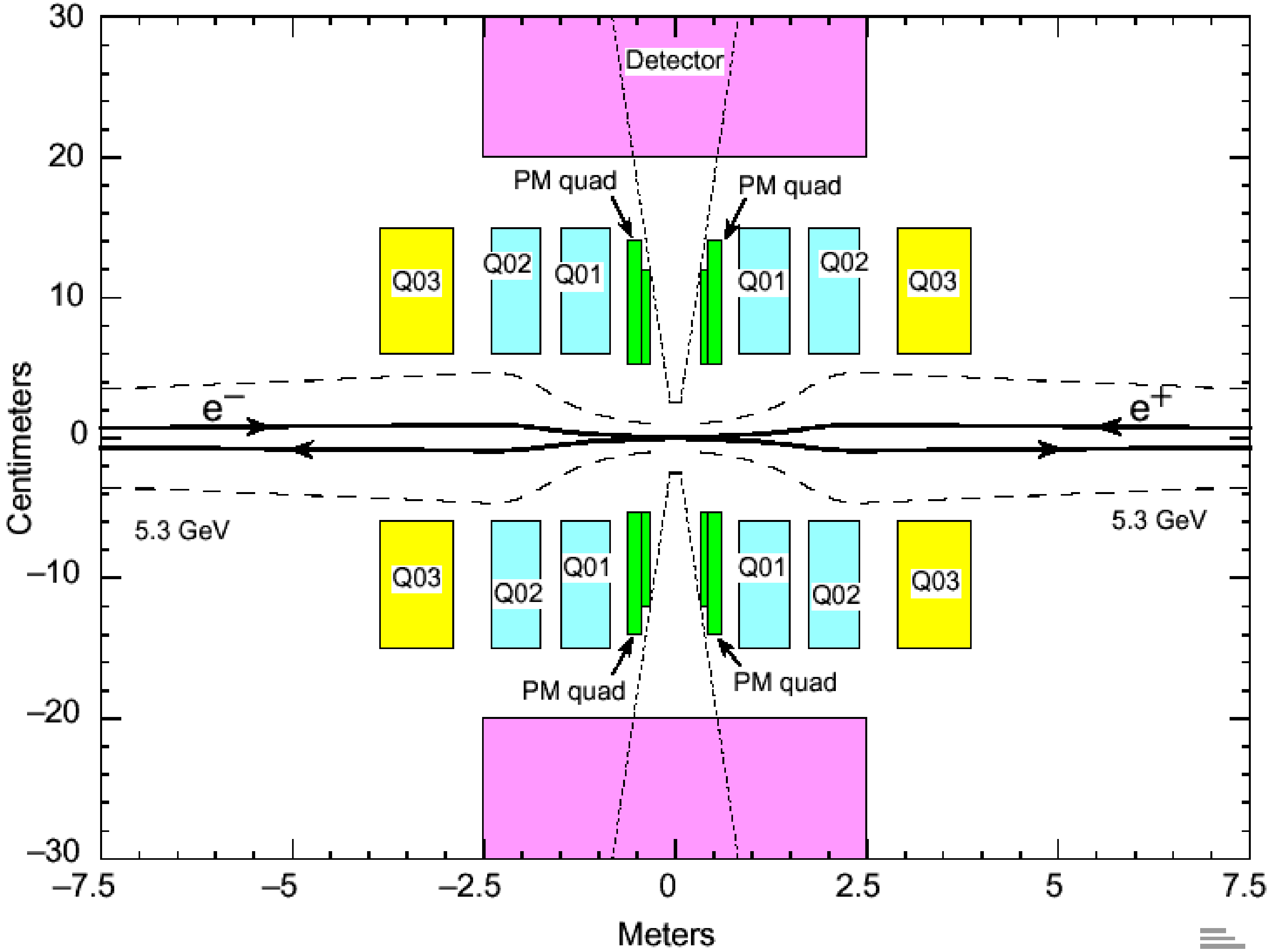
The photon energy spectrum cuts off very suddenly. The critical energy is the half intensity point.

As the beam energy increases the critical energy goes up as the cube of the beam energy.

SR Masking

- Machines before the B-factories were mostly symmetric energy machines and most had both beams in the same beam pipe (CESR)
  - Symmetric energy colliders have limited options when it comes to masking the beam pipe
  - Care must be taken to make sure a mask for one upstream beam does not become a background source for the other beam
  - One-bounce photon scattering from the IP side surface of a mask is one of the primary sources to watch (see slide 14)

CESR-III Interaction Region



Masking (2)

- With asymmetric-energy colliders (which also means separate storage rings), masking can be designed for each beam almost independently
  - Even the head-on design of PEP-II had separate masking designs for each beam
  - The separation magnets (B1) generated different beam trajectories shortly after the collision

Scattered photons

- SR photons that scatter from downstream surfaces can be a significant source of detector background
  - HERA was perhaps the first accelerator to encounter this background
- This is generally not a problem for symmetric colliders
- The B-factories had to control this possible source of background

Scattered photons (2)

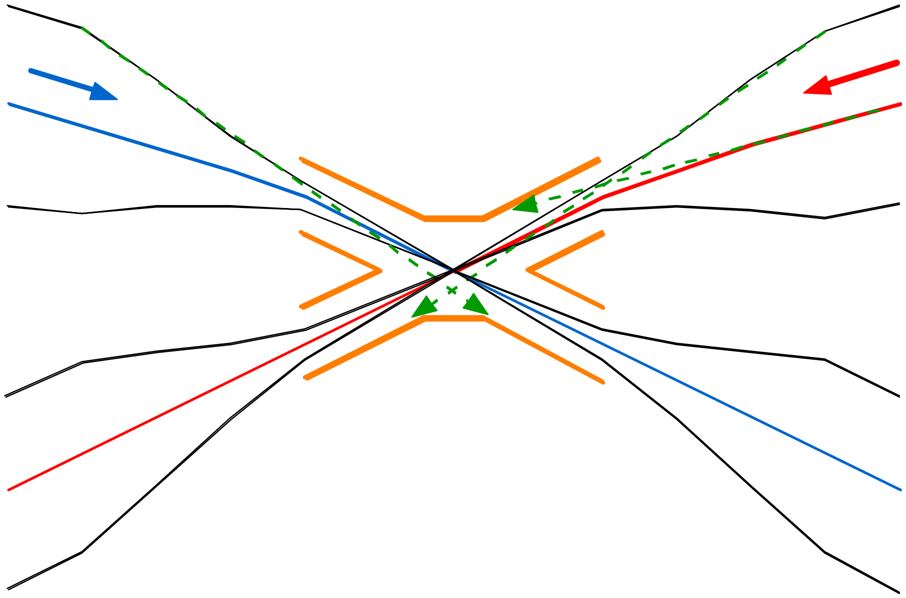
- The ILC design for the beam dumps has to control the backscattered rates from these high energy beams

- In addition, all designs must take care to ensure that SR photons that hit beam pipe surfaces upstream of the detector can not one-bounce to the central thin detector chamber (second order SR background source)

BGB, Coulomb and Touschek

- **These I call the classic background sources. They were the first backgrounds that were seriously calculated.**
- **BGB and Coulomb depend on storage ring vacuum quality**
- **It is interesting to note that for a while when beam energies increased above 1 GeV in the 70s Touschek scattering as a background went away. However, modern designs now call for very low emittance beams and very high beam currents both of which have brought back Touschek scattering as an important beam lifetime issue and background source.**

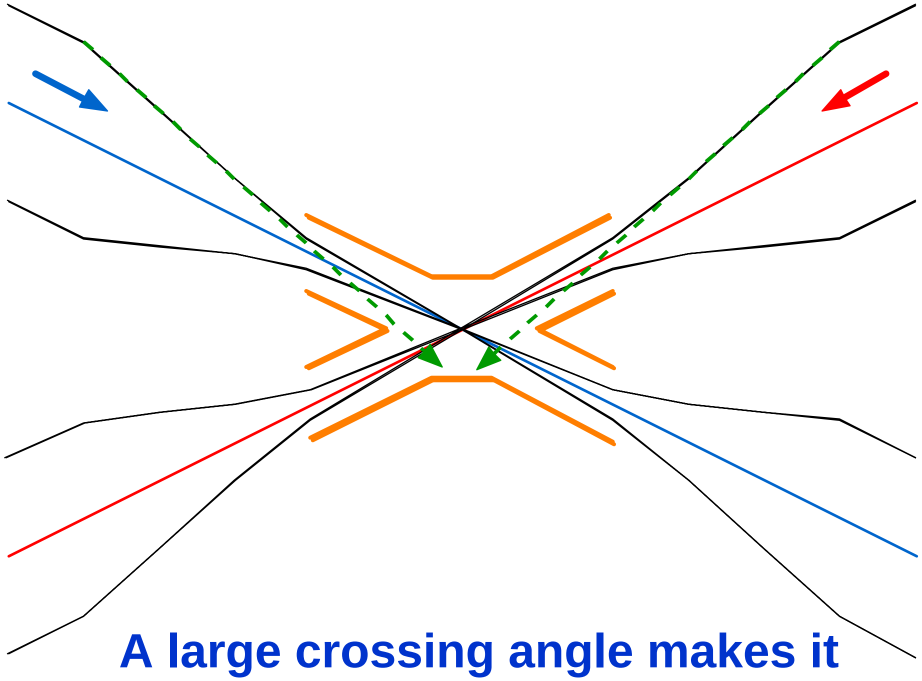
Crossing Angle Collisions



One way of improving the background rate is to introduce a small bend in the incoming beams. This effectively reduces the crossing angle for SR.

However, this bend must not introduce new background sources due to scattered photons from the bend hitting nearby surfaces.

This technique was successfully used for the incoming HER in PEP-II.

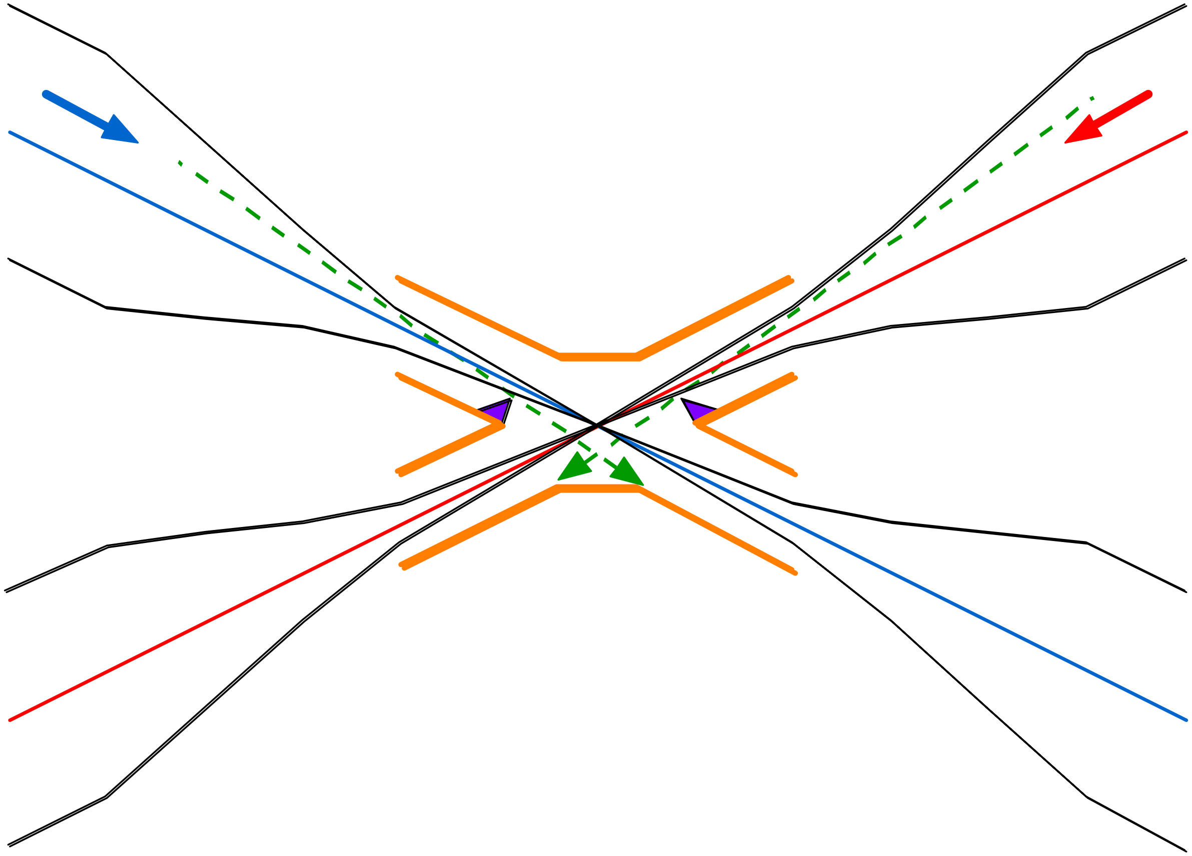


A large crossing angle makes it more difficult to protect the central chamber from direct SR hits

Large Crossing angle

Another way of shielding the central chamber is to put masks in the beam pipe. These masks have to be fairly close to the beam because they must be positioned where it is difficult to intercept the photons of interest.

The Super KEKB design has adopted this technique which includes a larger beam pipe on the outgoing side to let local HOM power escape.



Design Techniques

- SR is the first background to get under control

- First rule for SR backgrounds
  - No SR photons directly strike the central thin detector vacuum chamber

  - Any non-zero rate on this vacuum chamber can change by several orders of magnitude if beam conditions deteriorate. This can sometimes cause nearly instantaneous damage to the detector.
    - Modern detectors have safety systems to abort the beams

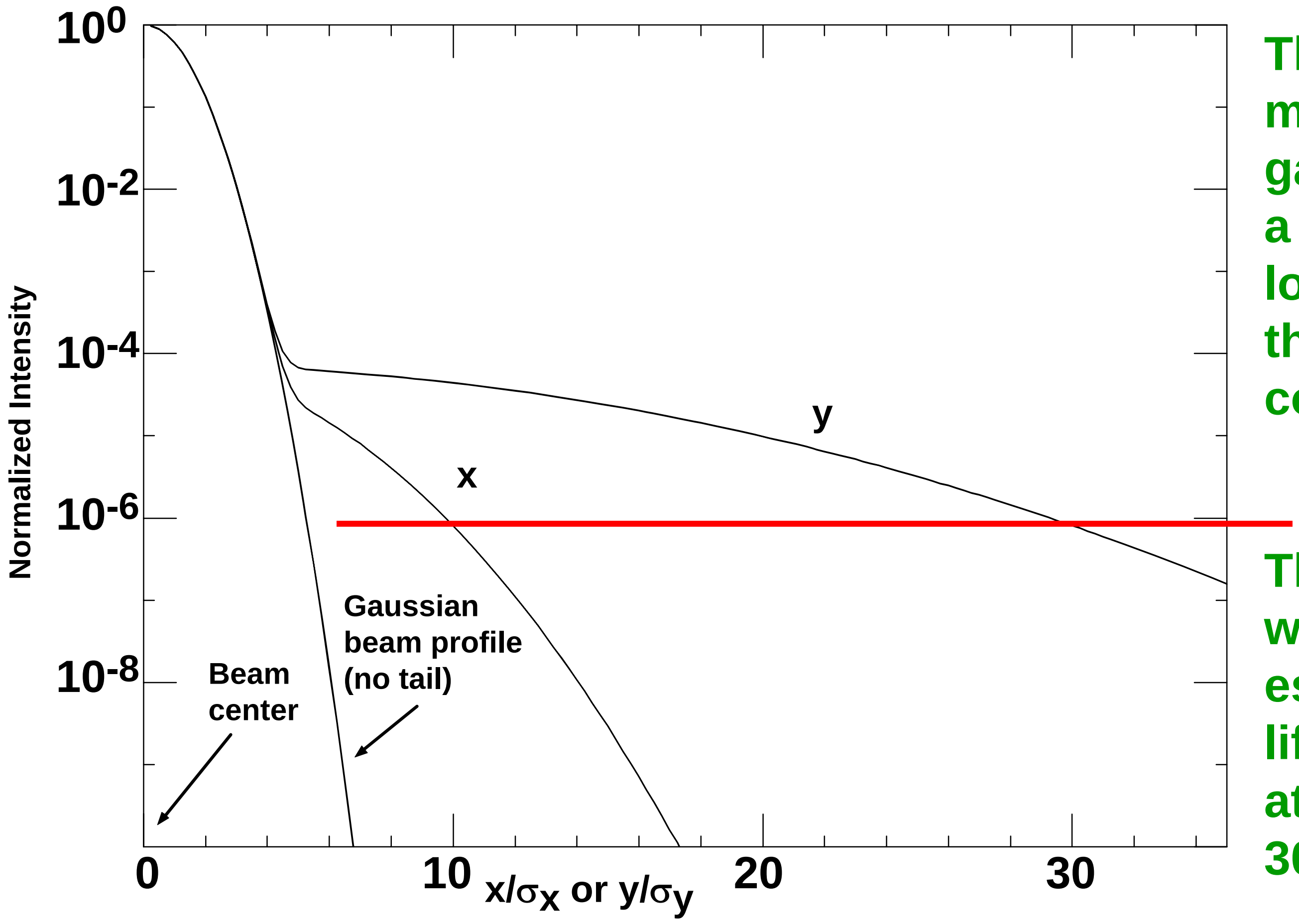
Techniques (2)

- The first SR rule is not exactly rigid
  - Depends on how far out in transverse beam size dimensions (x,y) one tracks the beam particles
  - Also depends on the estimation of beam particle density in the “high beam sigma region” (beam–tail distributions)

Beam tails

- Estimates of the beam tail distribution can be made using lifetimes and beam collimator transverse settings
- Modern background code for lost beam particles can predict the beam tail distributions based on beam lifetime calculations
  - Some caveats:
    - Background simulations do not include all beam tail generators (no beam-beam for instance)
    - Background simulations generally use a perfect machine

Beam tail distribution used in the PEP-II design



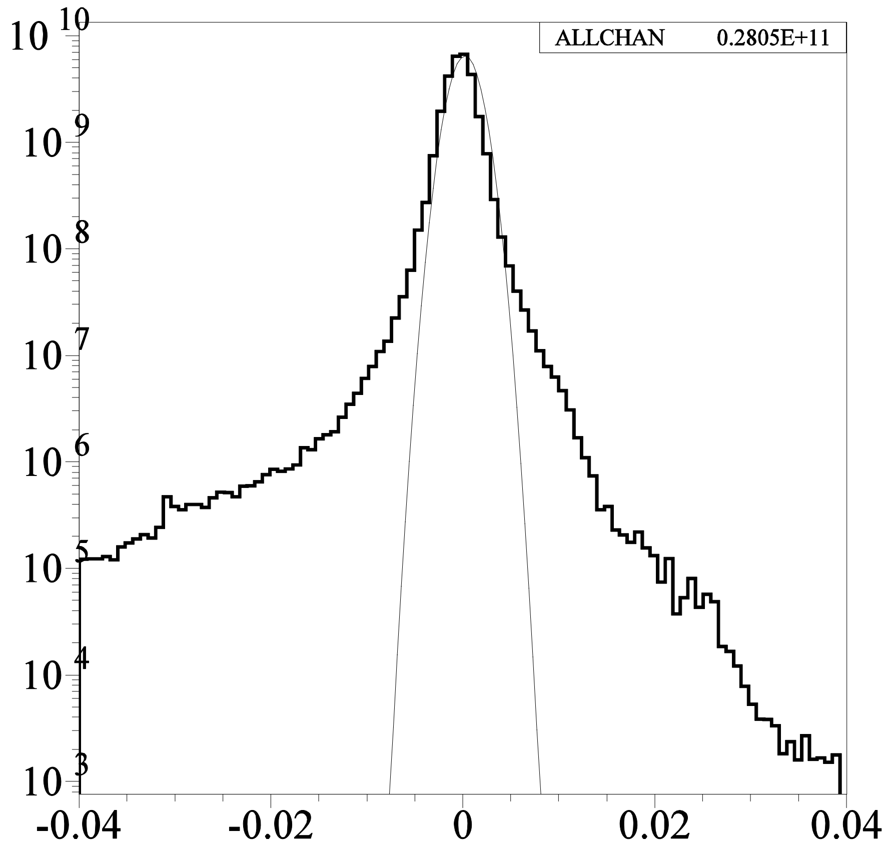
The tail distribution is modeled using a gaussian function with a larger sigma and lower peak value than the gaussian beam core.

The 2D tail distribution was based on an estimated 1-2 hr beam lifetime for the beam at 10σ in x and about 30σ in y.

Predicted beam tail distribution for the SuperB LER

This is an estimate of the beam tail distribution in the x direction for the low-energy ring of the SuperB design.

The tails are the result of Touschek and BGB interactions (Courtesy of M. Boscolo)



Techniques (3)

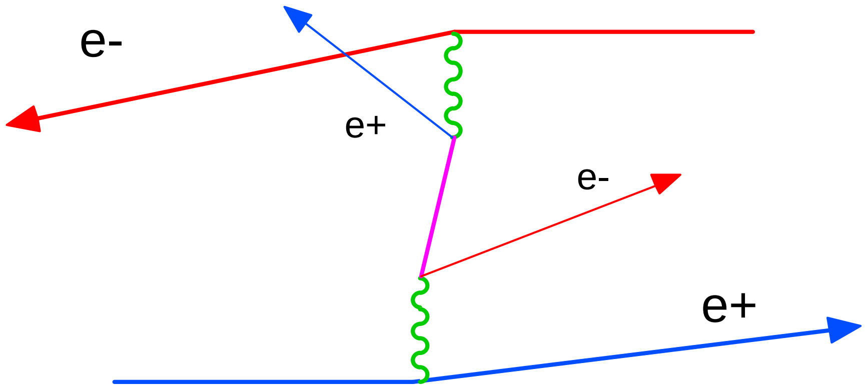
- **Fast turn around development code**
  - **Ability to adjust the position and strengths of the final focus magnets**
  - **Test the beam geometry quickly**
  - **Measure the SR backgrounds relatively quickly**

- **It is still generally difficult to use full geometry packages with MC generators. This method has a difficult time producing the needed statistics at large beam sigmas especially for SR**

Luminosity backgrounds

- Two-photon e+e- pairs
  - SuperB designs
  - LC designs
- Radiative Bhabhas
  - SuperB designs
  - LC designs
  - LHeC
  - MEIC
  - eRHIC
- Beam disruption

Low-energy e+e- pair production

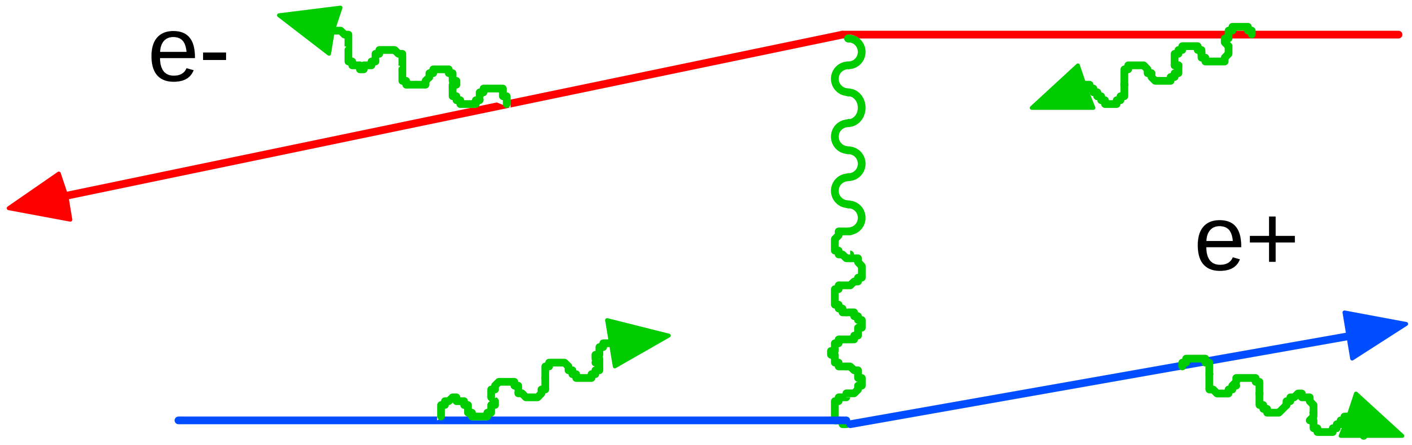


- **Any lepton pair can be created but electrons are the lightest charged leptons**
- **This diagram has a singularity at a scattering angle of zero degrees**
- **The low-energy produced pair start to cause backgrounds in the detector when the transverse bending radius (Larmor radius) from the detector solenoidal field exceeds the radius of the beam pipe**

Low-energy e+e- pair production

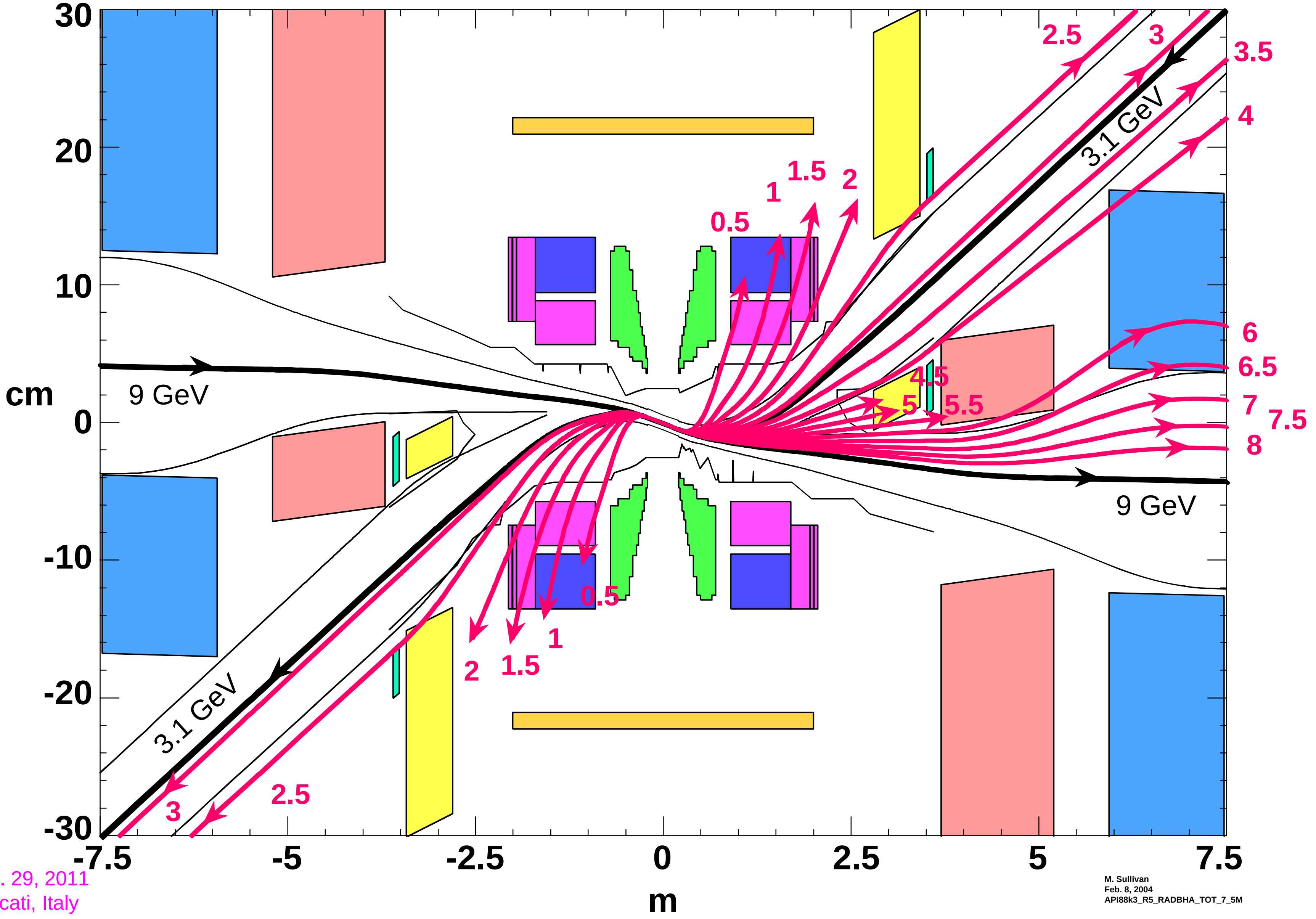
- **This reaction is starting to set constraints on modern electron-positron collider designs**
  - **The SuperB designs are finding predicted rates that are close to defining the minimum acceptable radius of the detector beam pipe**
  - **This reaction rate already sets the minimum acceptable size of the ILC detector beam pipe**

Radiative bhabhas



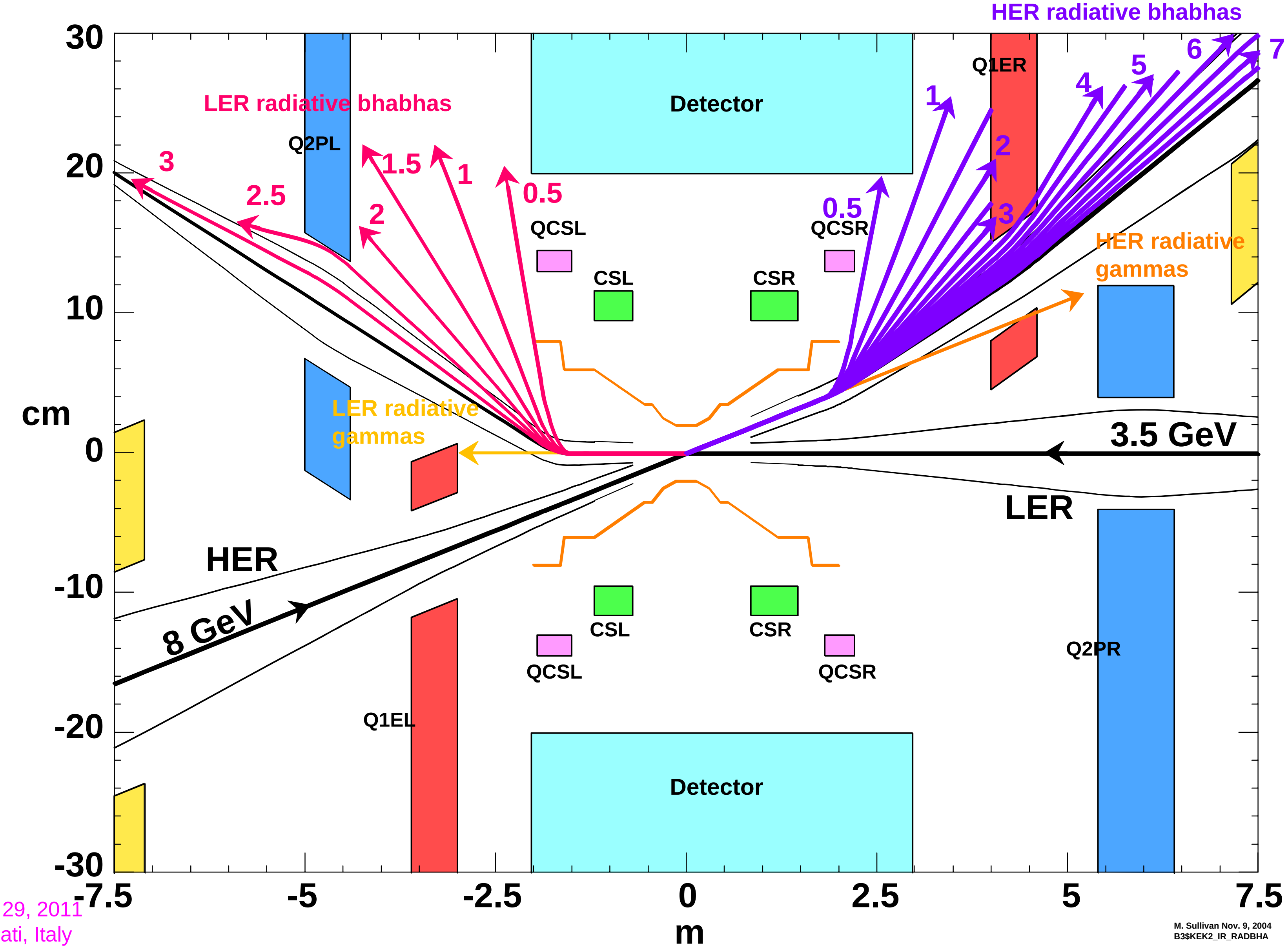
- **The figure summarizes four possible Feynman diagrams, two are initial state radiation and two are final state radiation. All four change the energy of a beam particle and hence can generate backgrounds if that particle loses enough energy to be over-bent in the outgoing final focus magnets and crash into the local beam pipe.**

B-factories: PEP-II



M. Sullivan
Feb. 8, 2004
API88k3_R5_RADBHA_TOT_7_5M

B-factories: KEKB



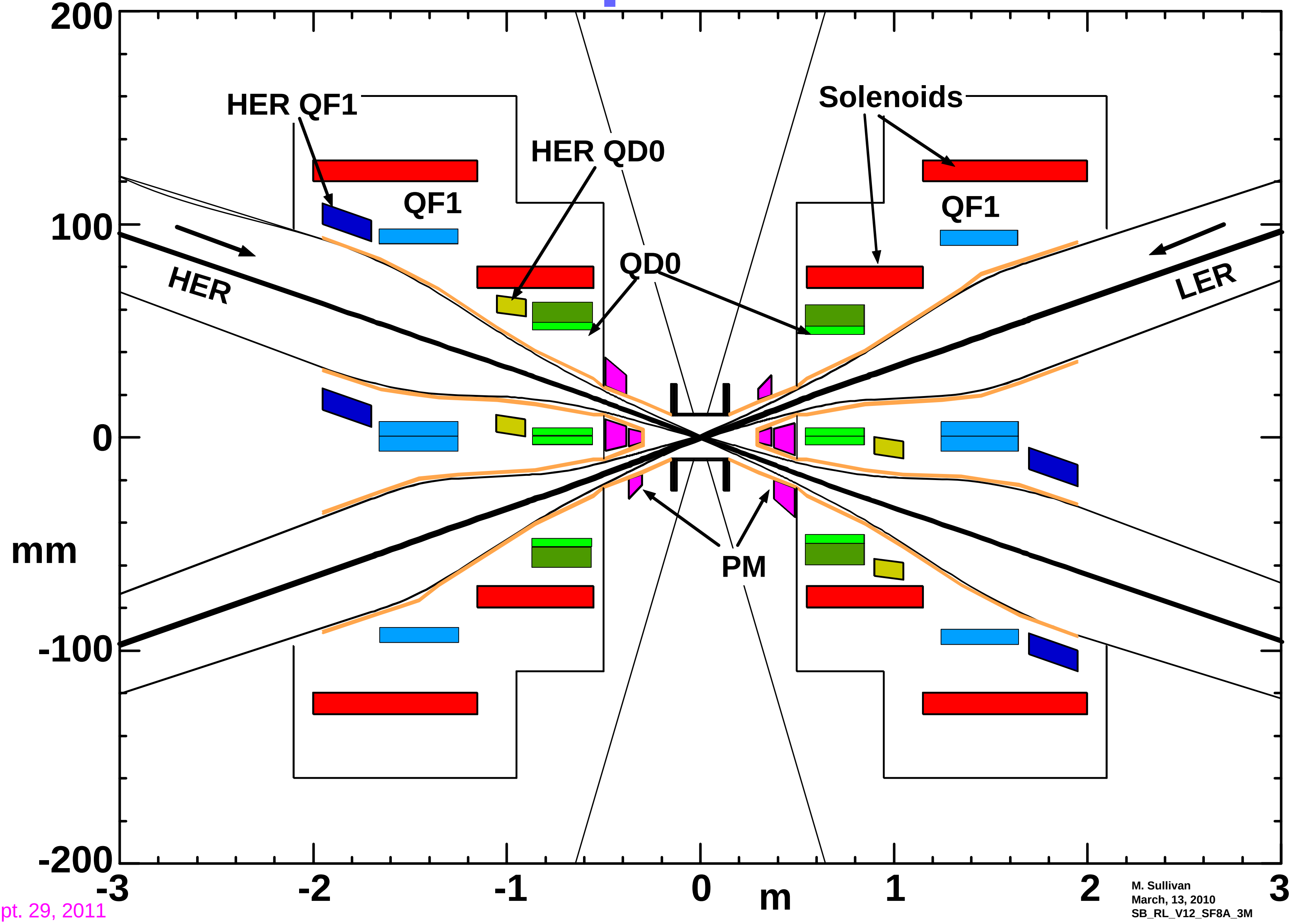
M. Sullivan Nov. 9, 2004
B3$KEK2_IR_RADBHA

Super B-factories and the LCs

- **Both super B-factory designs (luminosities of 50-100 times the B-factories) are concentrating on minimizing any bending of the incoming and outgoing beams near the IP**

- **The ILC and CLIC designs have a bigger effect to control than radiative bhabhas and that is beam disruption from the collision. This dominates the size of the exiting beam and drives the size of the outgoing beam pipes and the geometry of (and distance from) the beam dump.**

SuperB IR


HER QF1
HER QD0
Solenoids
QF1
QF1
QD0
HER
LER
PM
mm
m
200
100
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-100
-200
-3
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2
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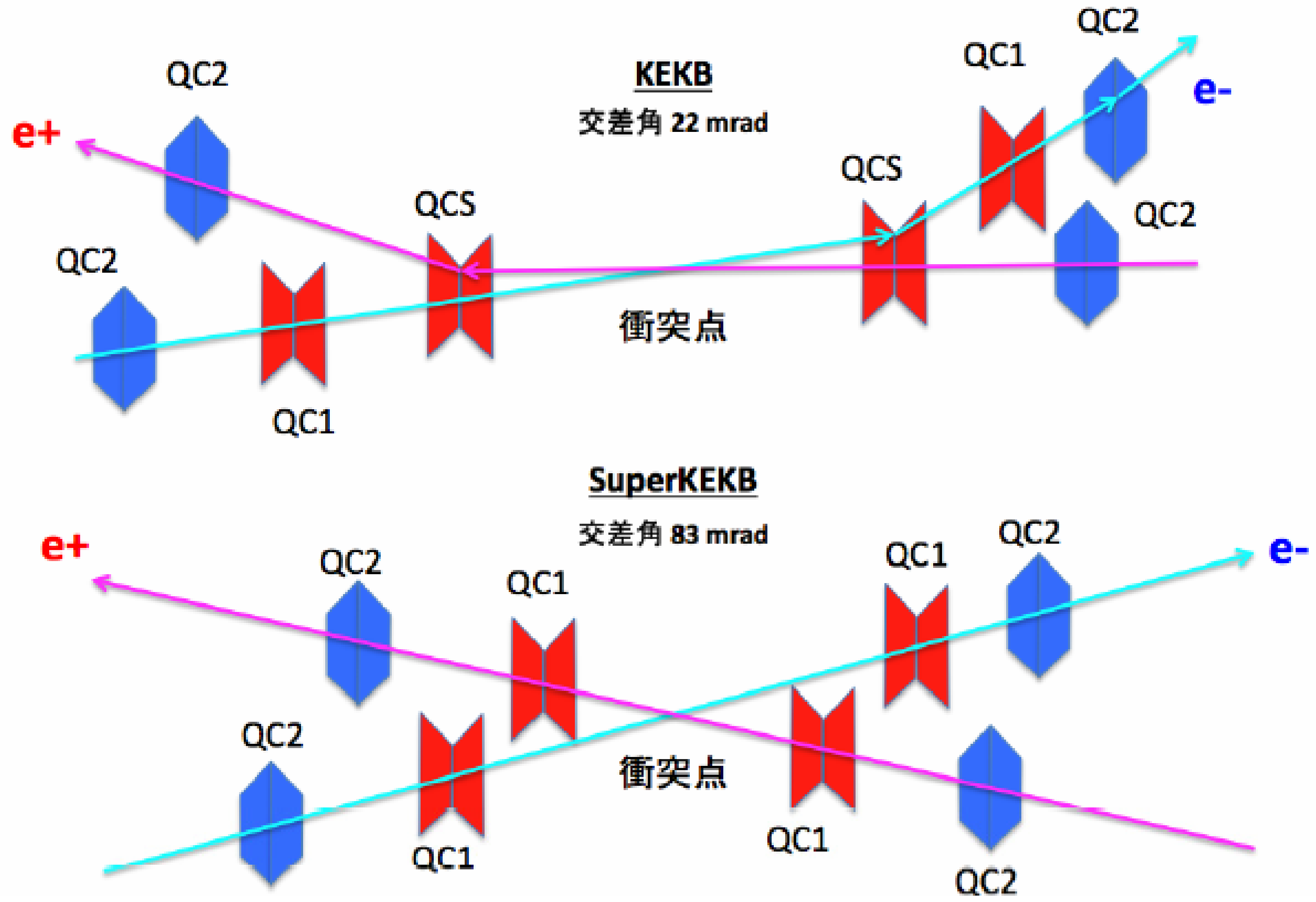
M. Sullivan
March, 13, 2010
SB_RL_V12_SF8A_3M

SuperKEKB IR design



eP Colliders

- **The first eP collider was SLAC which ran a 25 (later 46) GeV electron beam into a hydrogen (and deuterium) target**

- **HERA was the next eP collider of note with beams of 28 GeV (e-) and 920 GeV (proton)**

- **There are now three new eP collider designs (MEIC, eRHIC and LHeC). All three plan to explore different regions of the scattering phase space.**

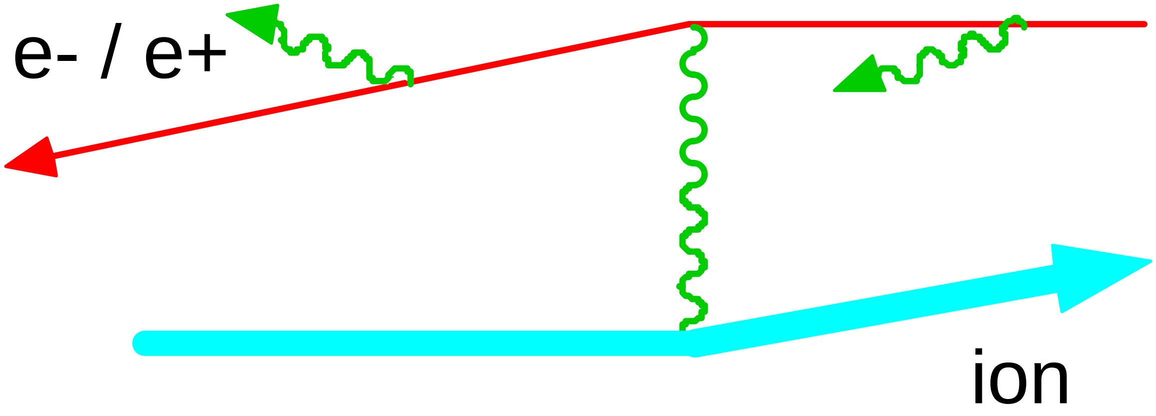
eP Design Concerns

- All of the new designs are attempting to get significant increases in luminosity

- This means much higher electron beam currents than previous eP colliders as well as minimal beam emittance

- All the standard electron backgrounds become important again, especially SR power issues as the electron beam needs to get into and out of collision with the ion beam

Radiative bhabhas for eP colliders

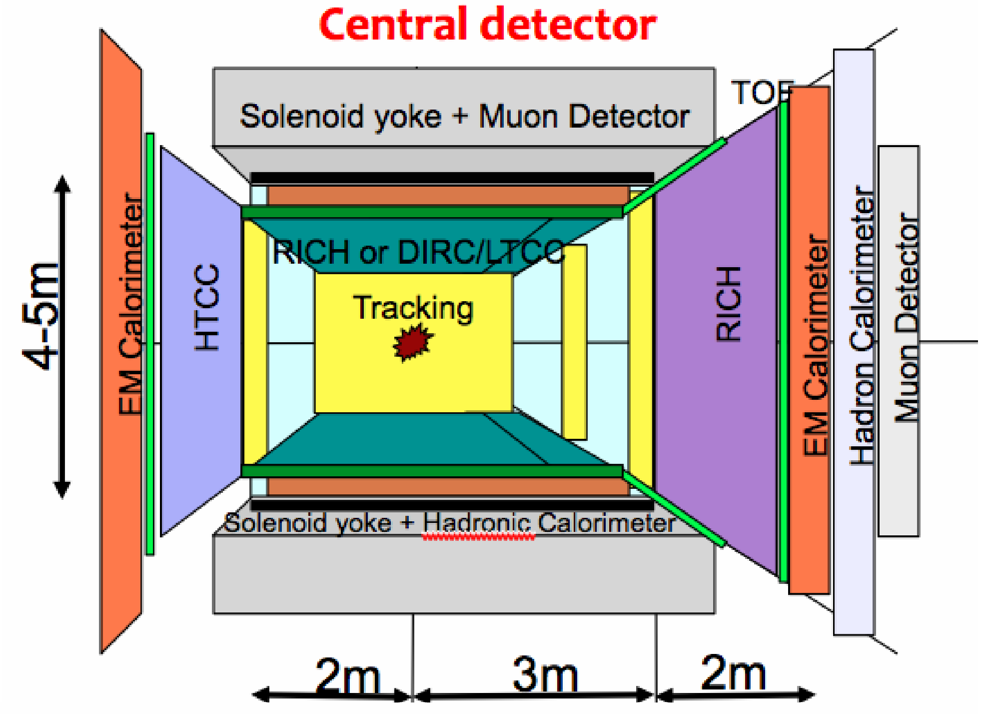


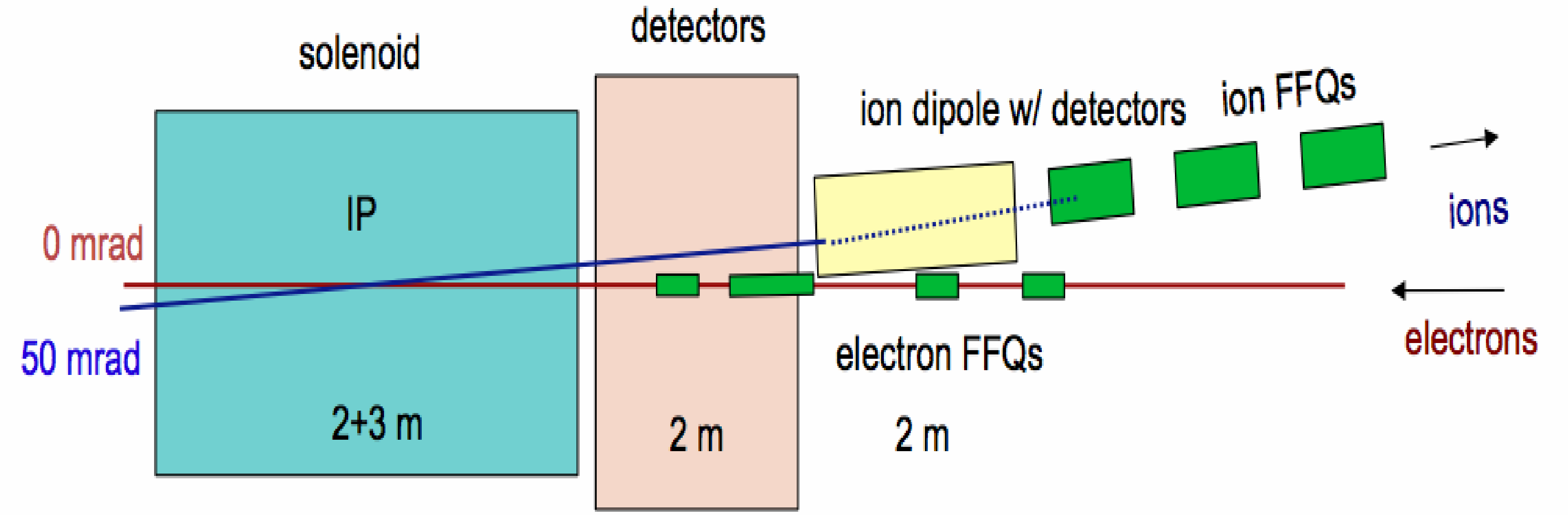
- **EP colliders do have to worry about radiative bhabhas from the electron beam**
- **Again, this reaction causes off-energy electrons to be bent out of the beam and crash into nearby beam pipes**
- **Most eP colliders need fairly strong bending magnets to get the electron beam into and out of collision**

eP Designs

- MEIC
  - This design collides a 12 GeV electron beam with a 30 GeV proton (ion) beam
  - The detector would like all of the solid angle possible especially along the direction of the proton (ion)
  - The design is attempting to make as short a proton bunch as possible. This permits the collision to have a crossing angle allowing the electron beam to get into and out of the collision with minimal bending.

MEIC IR Design





eP Designs (2)

- eRHIC
  - The proposed electron beam is 3-20 GeV and the RHIC proton beam is 50-250 GeV
  - They are also offering eAu collisions with 50-100 Gev Au ions
  - The collision is head-on and is either an ERL or a new storage ring
  - The head-on collision means that the electron beam will need to be quickly bent into and out of the proton (ion) beam producing powerful SR fans of radiation (see LHeC)

eP Designs (3)

- LHeC
  - This design wants to collide a 100 GeV electron beam with the 7 TeV proton (and ion) beam
  - The proton beam has a long bunch length and this forces the design to have a close to head-on collision in order to be at all efficient at generating luminosity (the same as eRHIC)
  - The (at best) small crossing angle means the electron beam must be bent to near the proton axis and then bent out of the proton beam between the final focus magnets of the proton beam generating strong SR fans of radiation. These high powered fans must not strike the cryo beam pipes of the proton beam final focus magnets as well as be controlled as the beam enters and exits the IR.

Muon Collider

- Only some thoughts
- For a 2 TeV CM muon collider we have 1 TeV muons in the final focus magnets. These magnets must be quite strong, especially to achieve the required small spot size at the IP.
- A point to keep in mind is that some fraction of the beam will decay in and just before the FF magnets producing electrons with ~0.5 TeV energy. These will be the highest energy electrons of any accelerator. These electrons will be strongly bent in these FF magnets generating considerable SR that is directed at the detector. This radiation will be very high energy photons and will be very difficult to mask or shield.
- The electrons themselves will of course also be a significant background
- BGB and Coulomb reactions are probably not very important (assuming the vacuum is decent) as well as luminosity related backgrounds

Summary

- All new collider designs involve at least one electron beam (muon collider excepted)
- Backgrounds from electron beams are still an important part of any collider design
- SR has continued to be an important source of concern for any design of an IR and this has been especially true as beam energies have gone up and beam currents have increased
- The new designs require high-current, low-emittance electron beams to maximize the luminosity and this means that all the beam particle related backgrounds (BGB, Coulomb, Touschek) are important sources (linear colliders to a lesser extent but these sources need to be checked carefully even there)

Conclusion

- It looks like background sources from electron beams will continue to be involved in any future design of a collider interaction region

- We will need to continue to study the old classic backgrounds (BGB, Coulomb, Touschek and SR) as well as keep thinking about how new regimes of machine parameters (higher-energy, higher-currents, lower-emittances, higher luminosity, etc.) can generate new sources of detector backgrounds

Backup Slides

AdA

The AdA storage ring. The first beams were produced by shooting gamma rays into the beam pipe and letting the magnetic field and RF capture the e+ and e- pairs created inside the pipe.