Asymmetric e^+e^- B-Factory Machines

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for the

30^{th} Anniversary of BaBar

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Matter Anti-matter Colliders

- Before the asymmetric energy B-factories the only e^+e^- colliders were ***single ring***, ***equal energy*** colliders
  - AdA, ADONE, SPEAR, VEPP-2, VEPP-2M, ACO, DCI, DORIS, PETRA, PEP, CESR, TRISTAN, LEP
    - These were mostly energy frontier colliders looking for new particles
  - Also, the SLC – not a ring but an equal energy collider
  - BEPC and BEPC-II, the Beijing e^+e^- collider started out single ring and has now converted to a double ring with equal energies
- Pier Oddone pioneered the concept of an asymmetric energy e^+e^- collider to study CP violation and the unitarity triangle
  - E_{cm} at the Upsilon 4S
  - Need a moving CM frame
  - Need high luminosity

Asymmetric energy collider

- This was a new idea that:
  - Requires separate rings
  - Complicates the collision
    - Head-on – requires bend magnets close to the collision point (PEP-II)
    - Crossing angle – had been tried earlier with very little success (KEKB)
- But separate rings allows for many more bunches
    - More luminosity
    - Most previous pushes toward higher luminosity had been the highest possible single bunch current (lumi increases as the single bunch current squared)
    - More bunches increase the lumi as the number of bunches (linear)
    - Beam currents would move into the multi-Ampere range
    - Need much more powerful RF systems
    - Previous and current machines were in the 10s of mA range

Asymmetric colliders (2)

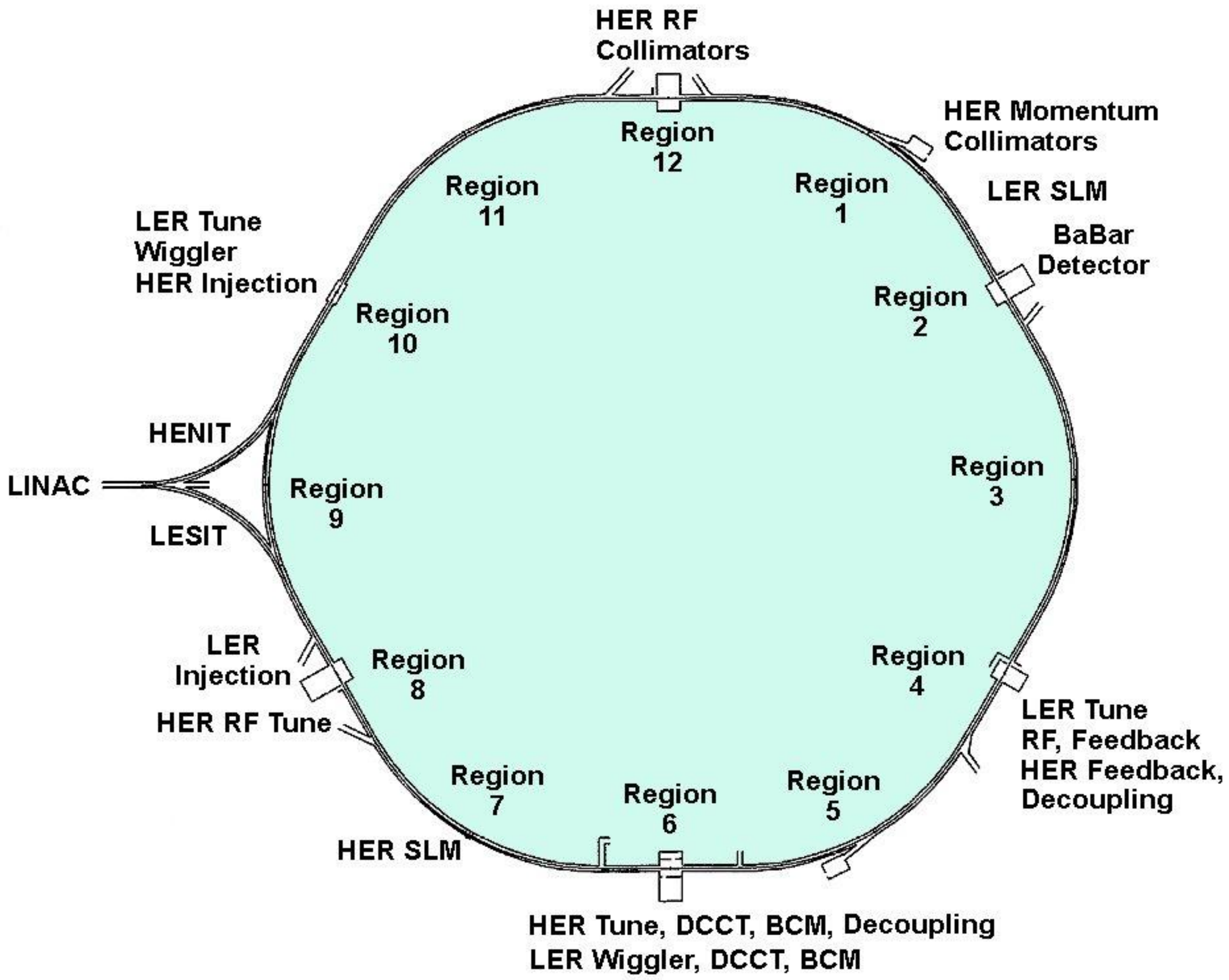
- This was a first major push into the luminosity frontier
  - Very high lumi produces a very high data rate allowing for the measurement of and the search for rare decay channels
- Not on the energy frontier
  - The SLC and LEP were on the energy frontier at the time
  - CESR at Cornell was doing B physics at this time but not with a moving CM frame and hence could not measure the separate decay times of the B mesons produced by the Upsilon 4S decay
- The B-factories would be a serious Standard Model stress test

PEP-II

- Used the PEP tunnel and infrastructure
  - Used the PEP magnets for the HER (9 GeV beam)
  - New ring and magnets for the LER (3.1 GeV beam)
  - New vacuum chambers for both rings
  - New RF systems for both rings
  - Feedback systems for both rings
    - New accelerator development – controlling bunch-to-bunch perturbations
- Injector was the SLAC LINAC
  - Used much of the SLC infrastructure
    - Damping rings were very important in generating very low emittance bunches
  - Powerful injector for both the HER and the LER

PEP-II ring

- The PEP-II B-factory had two rings – one on top of the other in a 2200 m tunnel
- The HER reused the PEP-I magnets
- The LER was a completely new ring



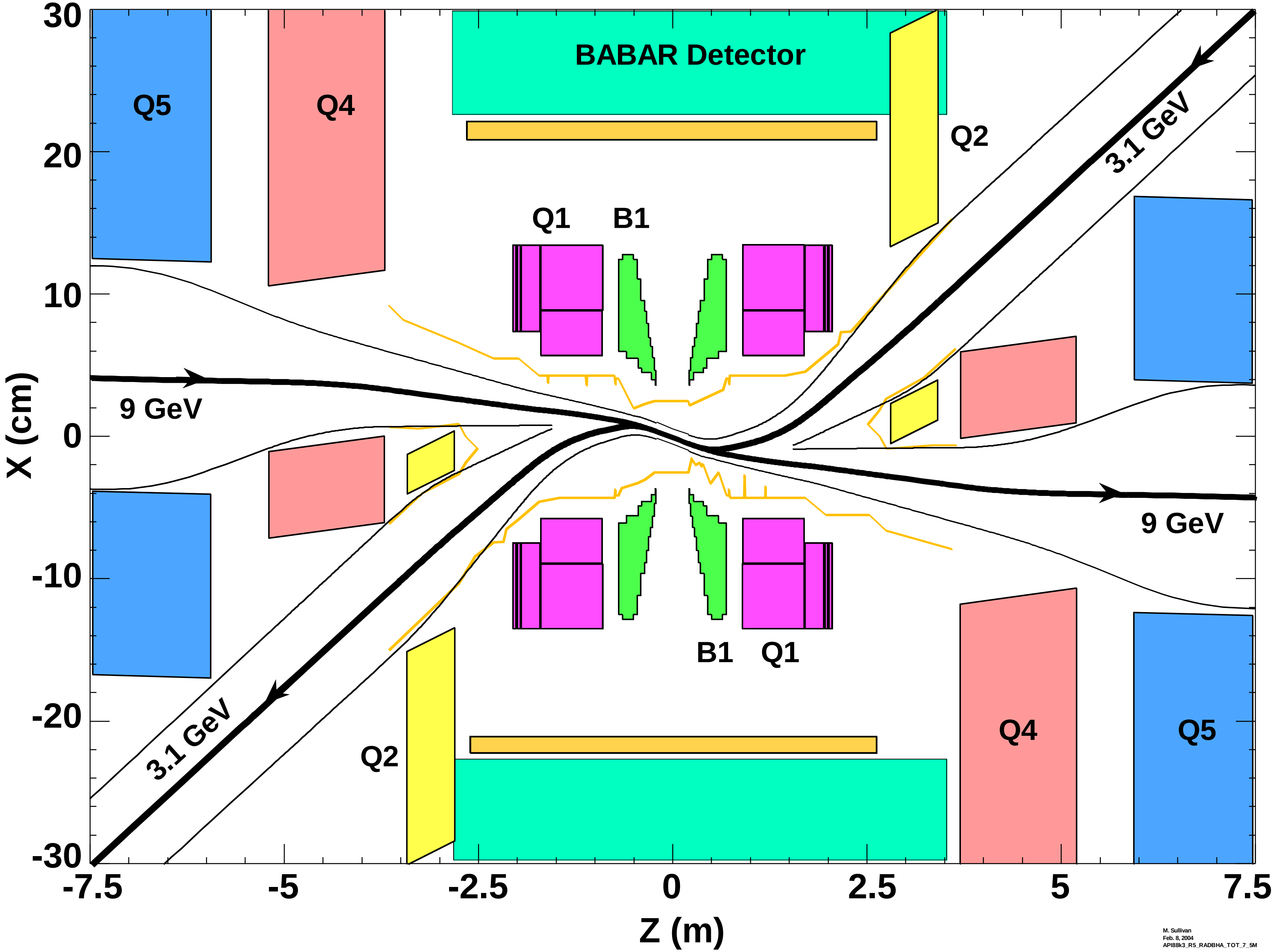
PEP tunnel

- One of the first pictures taken of PEP-II with both rings installed

PEP-II Interaction region

- The B1 bending magnets were the strongest bend fields in the entire ring
- They generated overlapping 40 kW beams of SR in the HER

View is inside the ring looking out

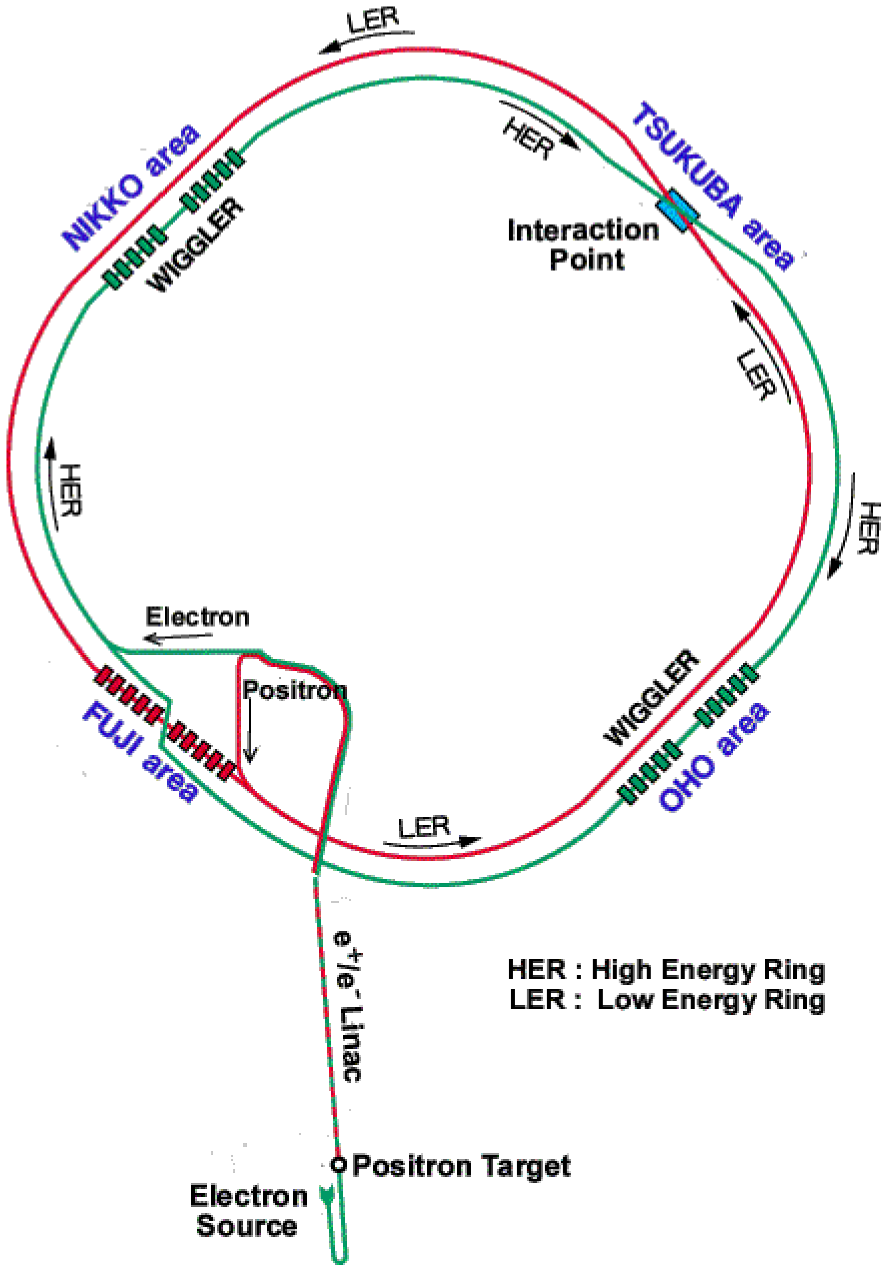


KEKB

- Used the TRISTAN tunnel and infrastructure
  - Much of the TRISTAN magnets were used for the HER 8 GeV beam
  - New magnets for the LER 3.5 GeV beam
  - New vacuum chambers for both rings
- KEK injector was originally a 3 GeV injector for TRISTAN
  - Upgraded the injector to 8 GeV

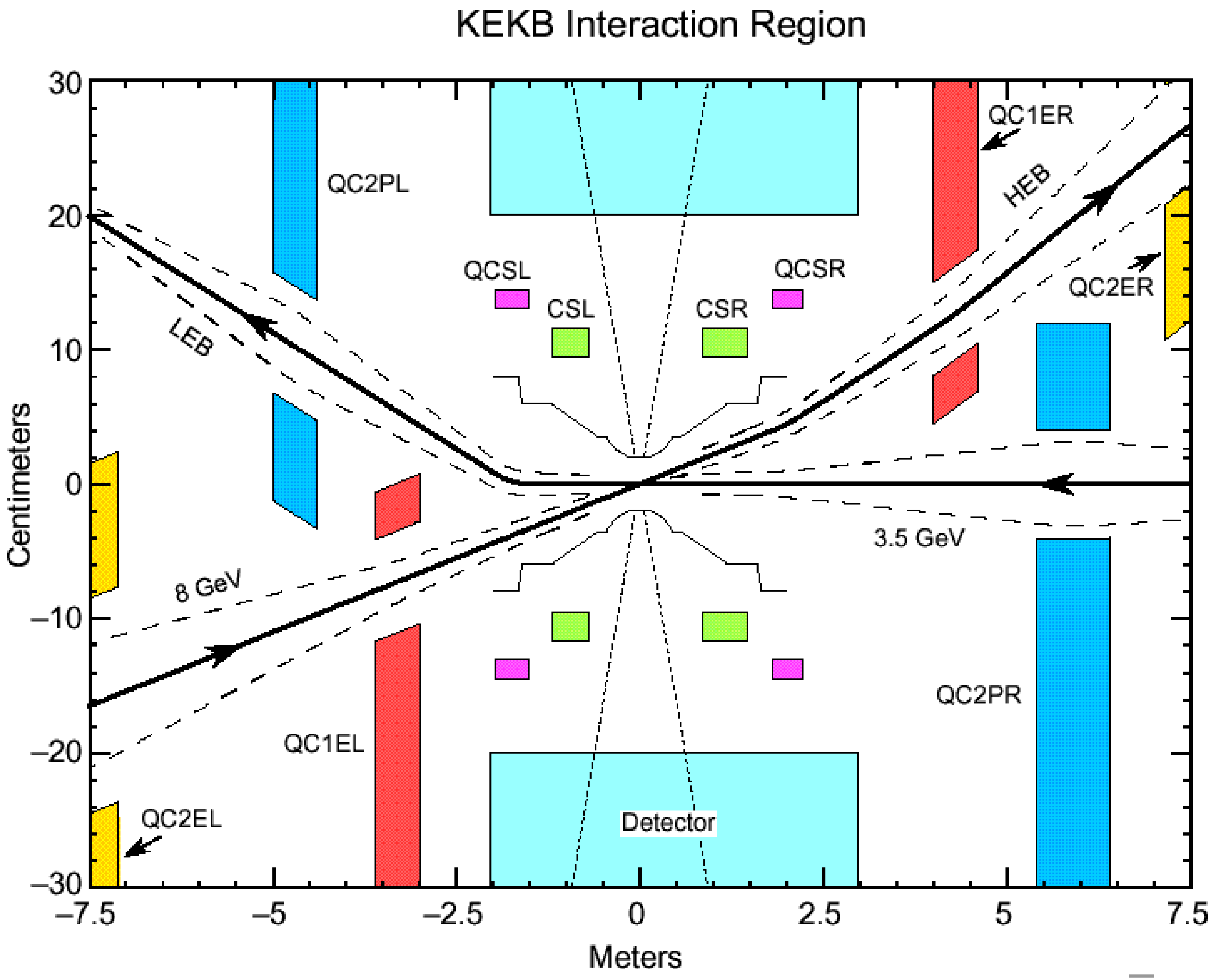
KEKB ring

- The Tsukuba hall was (is) where the Belle (Belle II) detector was (is) located
- This is the TRISTAN 3000 m ring



KEKB Interaction region

- The crossing angle collision made it possible for the design to have no incoming nearby bend magnets



Achievements

KEKB records	
Luminosity 21.1×10^{33}	2x design
Her current 1188 mA	
LER current 1637 mA	
Bunch currents 1.03 mA LER and 0.75 mA HER	
Total Int. Lumi 1.041 ab^{-1}	

PEP-II Records

Last update: April 8, 2008

Peak Luminosity

4x design

12.069×10^{33} $cm^{-2}sec^{-1}$ — August 16, 2006

1722 bunches 2900 mA LER 1875 mA HER

Integration records of delivered luminosity

Best shift (8 hrs, 0:00, 08:00, 16:00)	339.0 pb^{-1}	Aug 16, 2006
Best 3 shifts in a row	910.7 pb^{-1}	Jul 2-3, 2006
Best day	858.4 pb^{-1}	Aug 19, 2007
Best 7 days (0:00 to 24:00)	5.411 fb^{-1}	Aug 14-Aug 20, 2007
Best week (Sun 0:00 to Sat 24:00)	5.137 fb^{-1}	Aug 12-Aug 18, 2007
Peak HER current	2069 mA	Feb 29, 2008
Peak LER current	3213 mA	Apr 7, 2008
Best 30 days	19.776 fb^{-1}	Aug 5 – Sep 3, 2007
Best month	19.732 fb^{-1}	August 2007

Total delivered 557 fb^{-1}

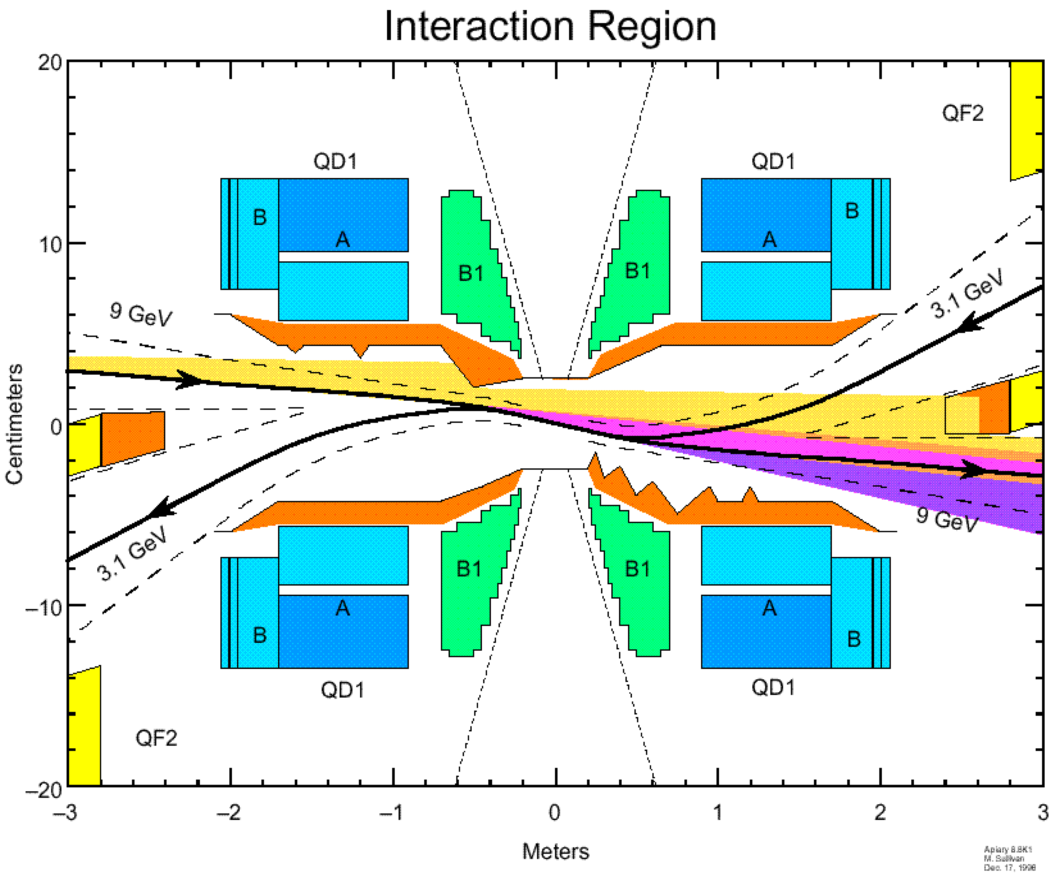
PEP-II turned off April 7, 2008

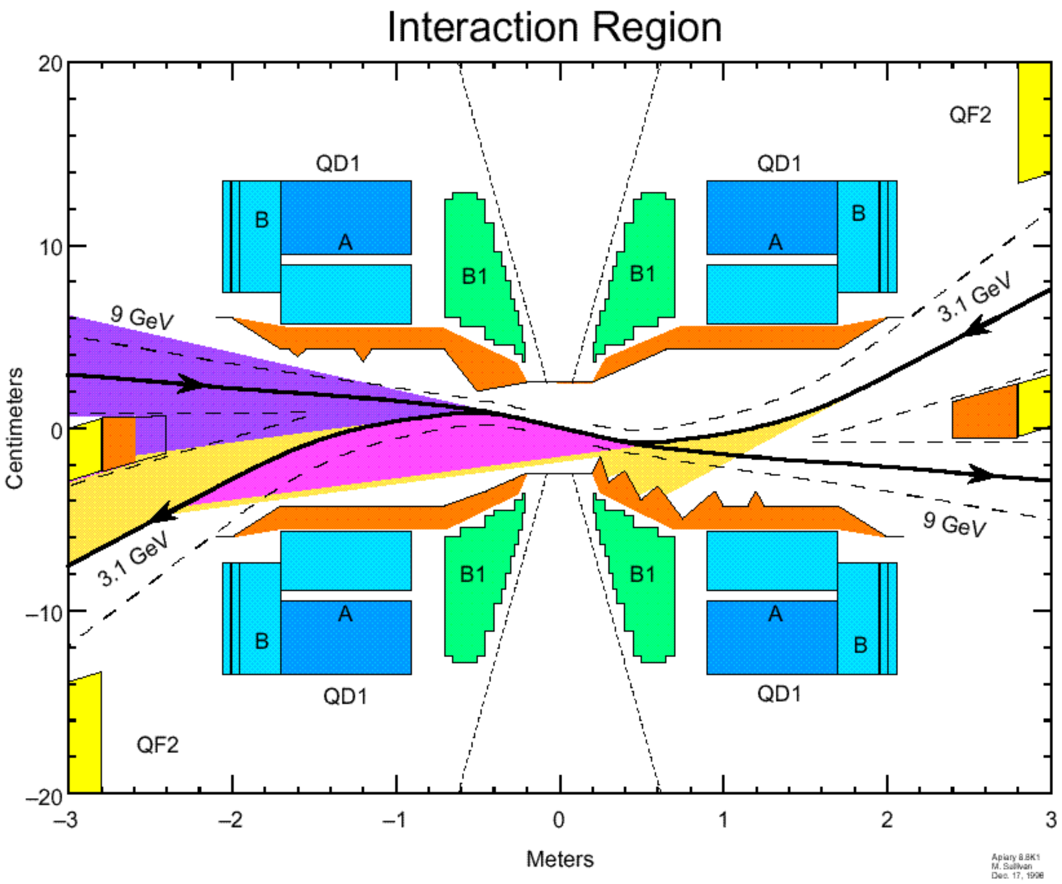
Some high-current beam issues

- Here are some of the issues that result from multi-bunch high-current beams
  - Synchrotron radiation
  - Radiative Bhabhas
  - Electron cloud (close bunch spacing)
  - RF heating
  - Sudden beam losses

PEP-II IR SR fans

HER SR fans



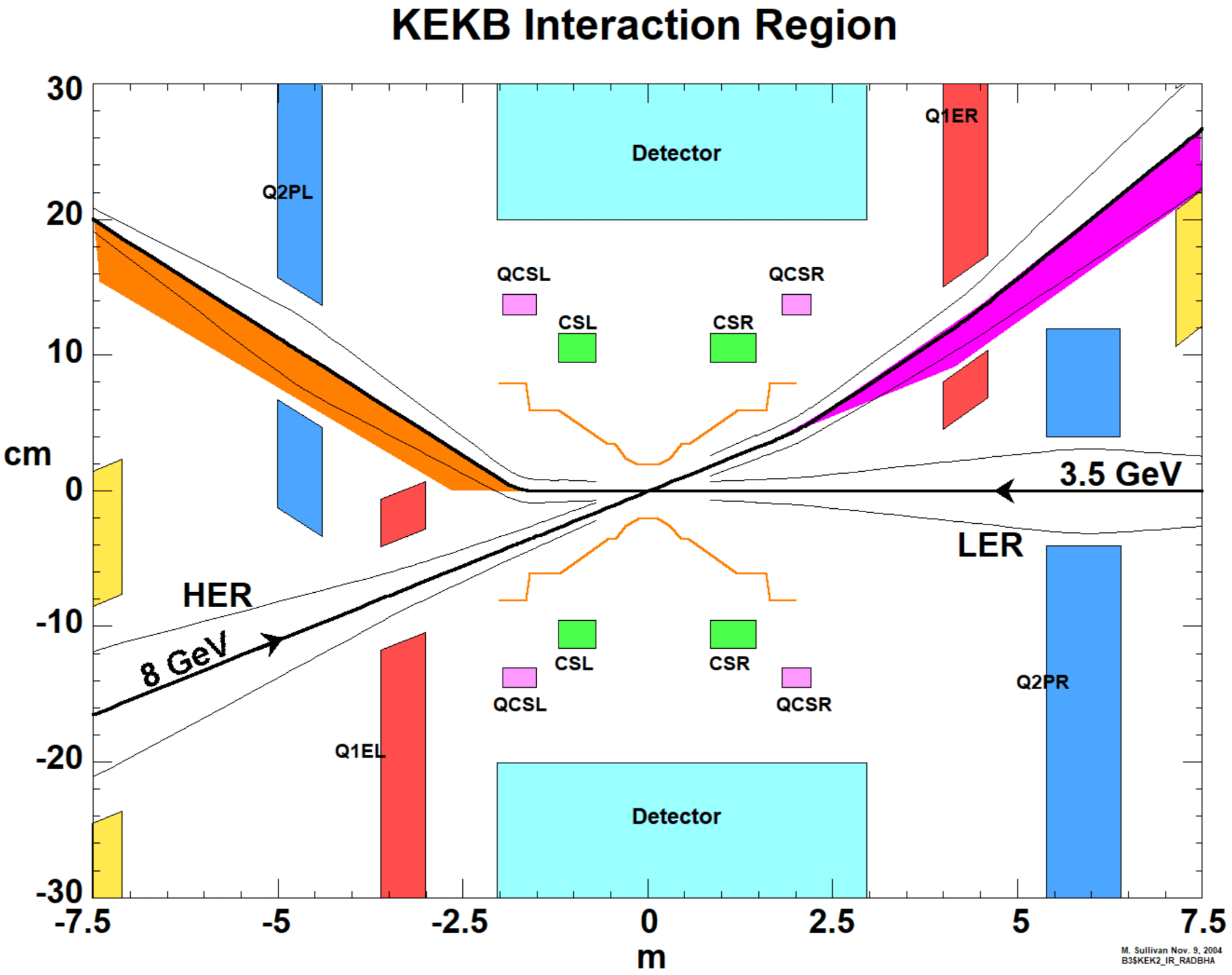


LER SR fans

This intense outgoing and overlapping fan from the B1 magnets intercepted the beam pipe wall from 10-20 m away and was a noticeable source of neutrons

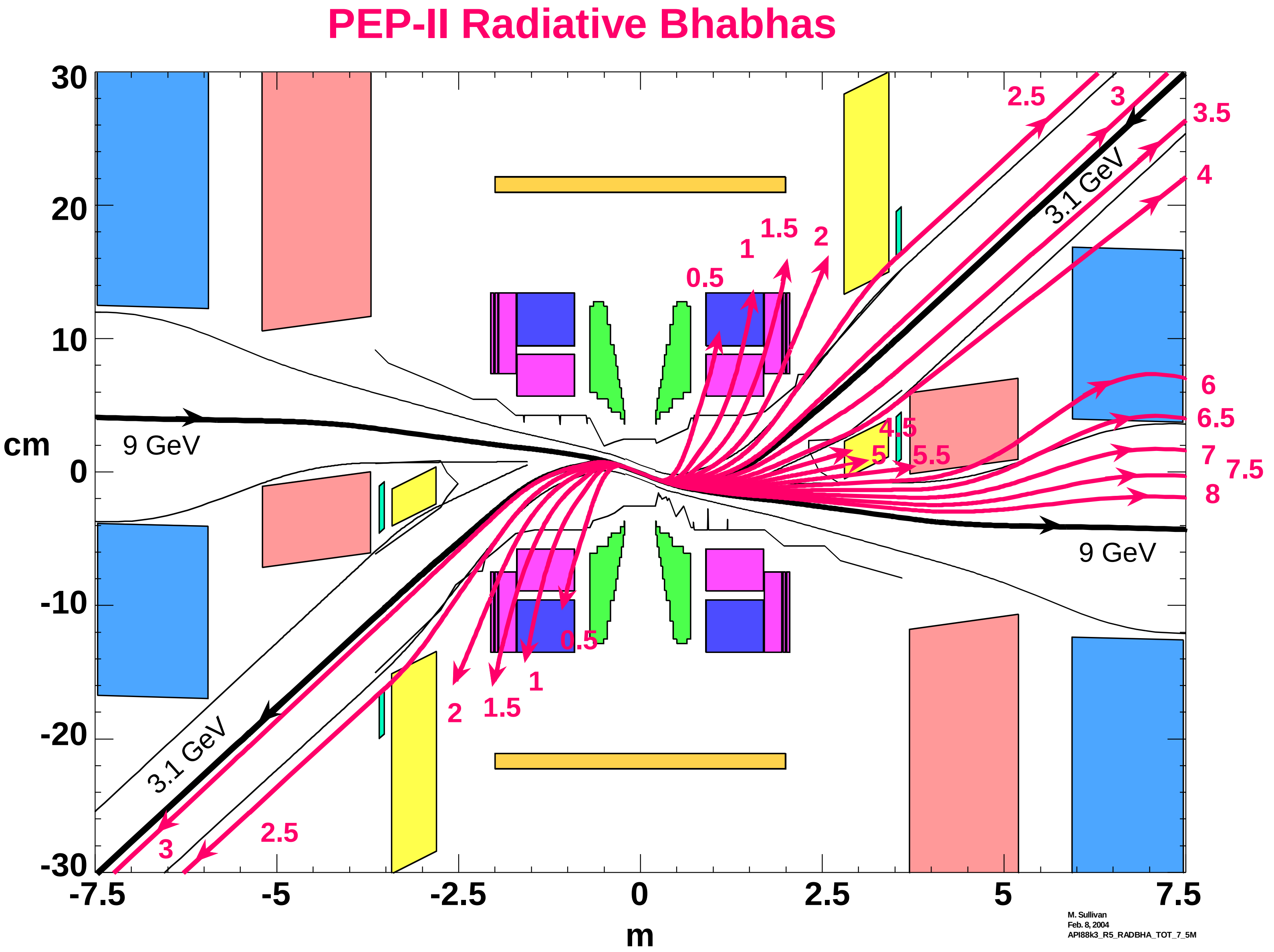
KEKB IR SR fans

- KEKB had a much simpler IR wrt to SR fans
- The exiting beams received a fairly sharp bend from the shared final focus quads
- The outgoing fans did generate significant power – especially in the HER



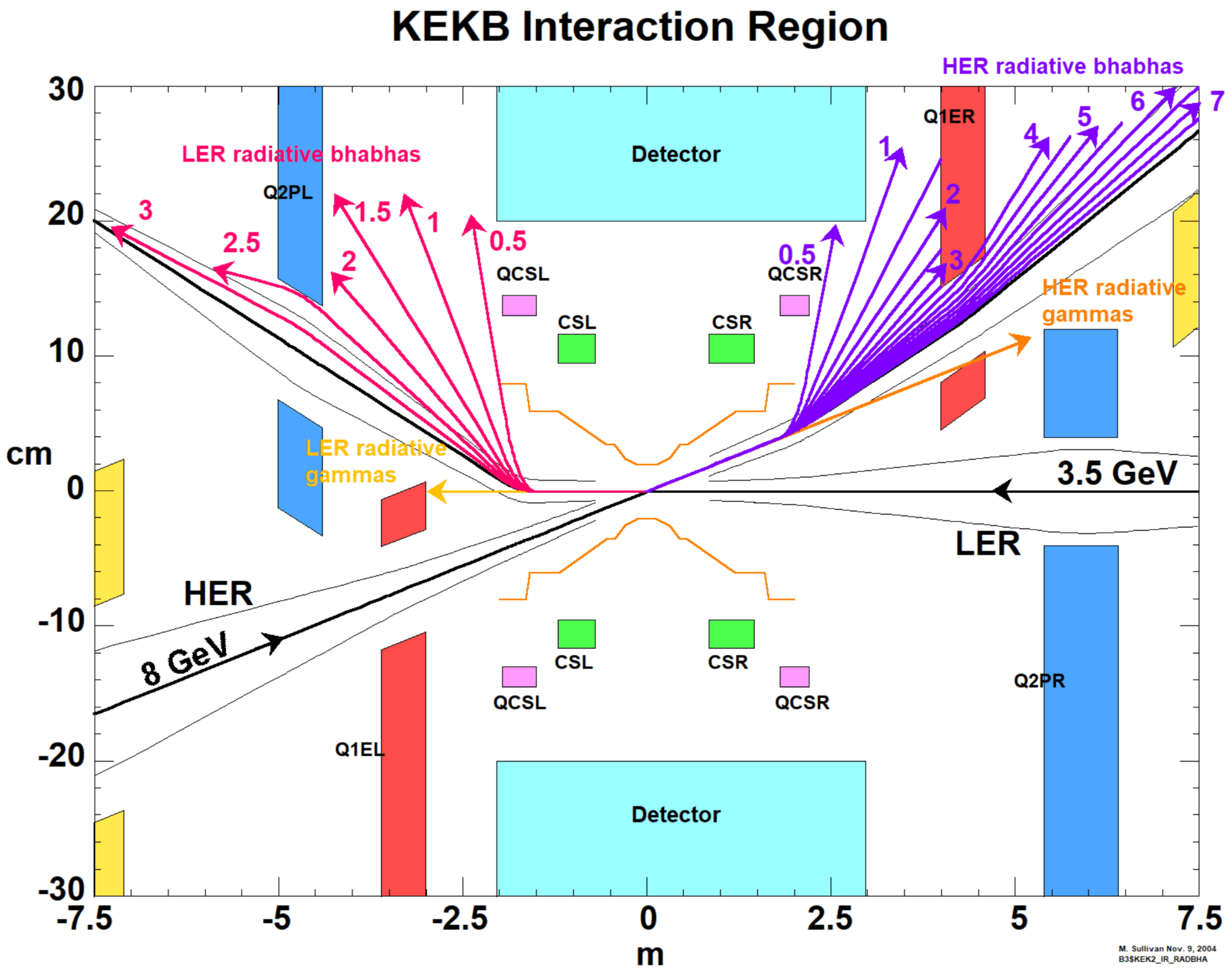
PEP-II radiative Bhabhas

- The very strong B1 bending magnets swept the radiative Bhabhas into the Q1 permanent magnets
- The magnets shielded some of this, but it was still an annoying background
- Because of the B1 bend magnets we were able to get the gamma from this reaction out of the beam pipe just after Q5 magnet giving us an excellent real-time luminosity monitor for every bunch



KEKB radiative Bhabhas

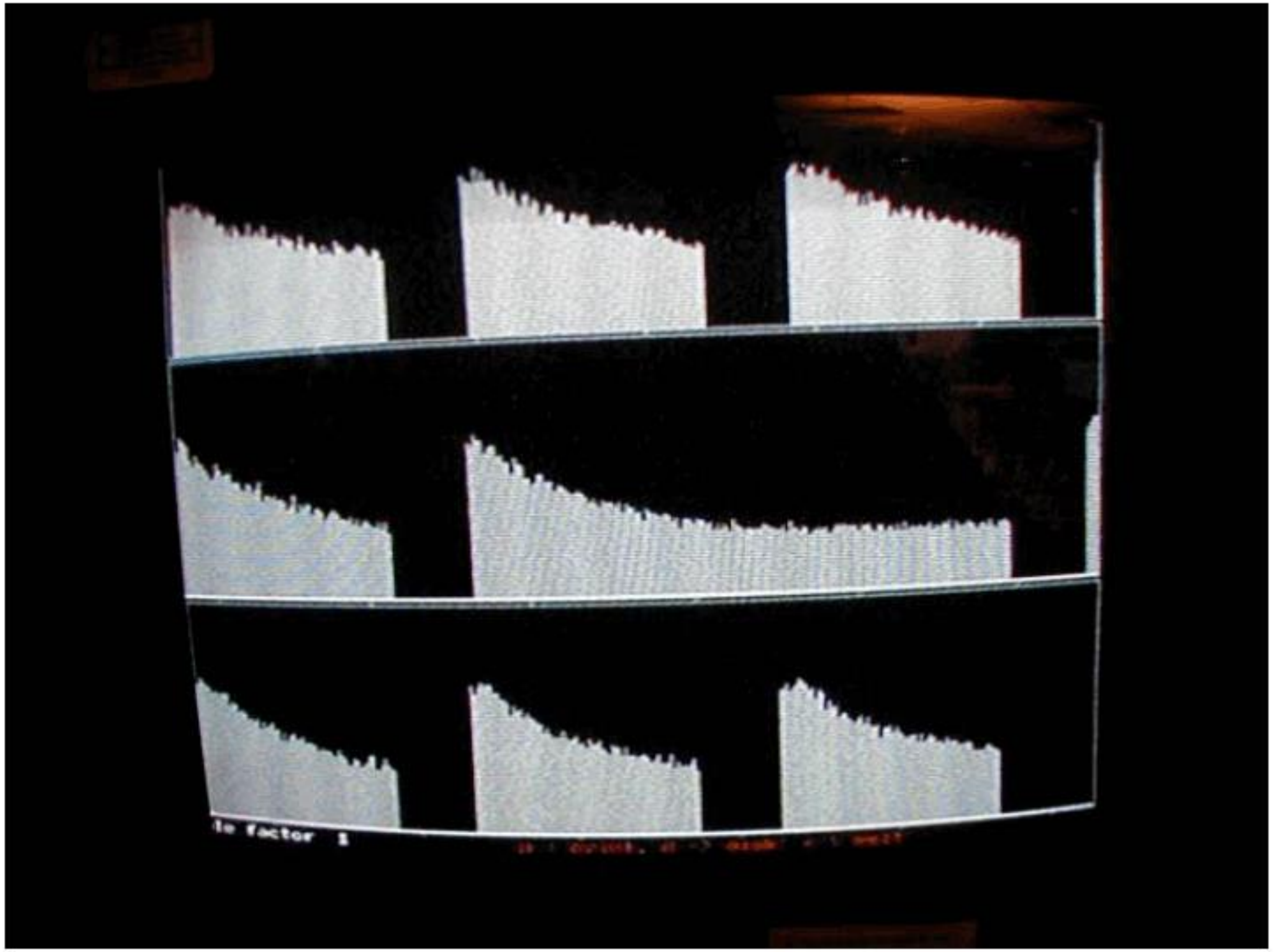
- KEKB had no close bending magnets and hence did not see much of a radiative Bhabha background initially
- The outgoing beams do get a strong bend from the off-axis orbits in the quads making a radiative background that was seen as the luminosity increased



Evidence of the electron cloud effect on the LER

- Very dramatic effect of the electron cloud on following bunches
- After a gap, the cloud has dissipated
- The first few bunches are then OK again
- We went to small bunch trains with small gaps until we could add winding coils around most of the LER

Plot of the luminosity of the individual bunches



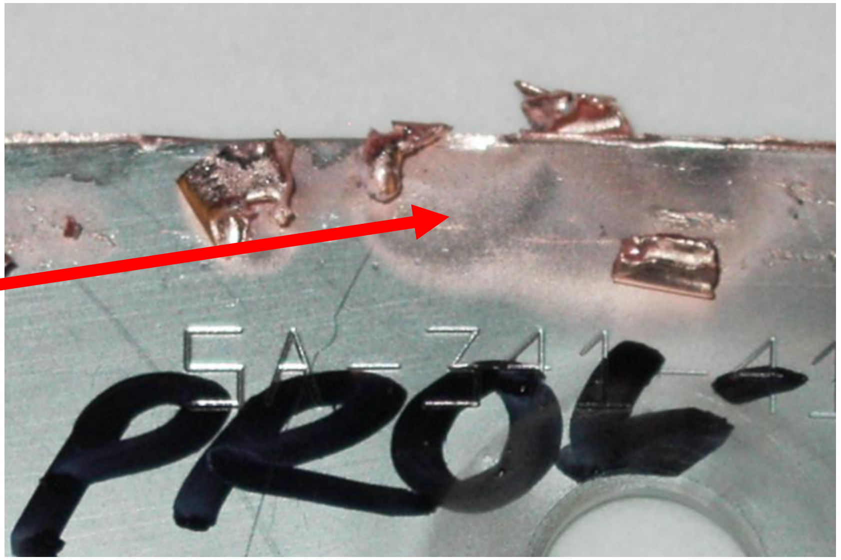
RF heating

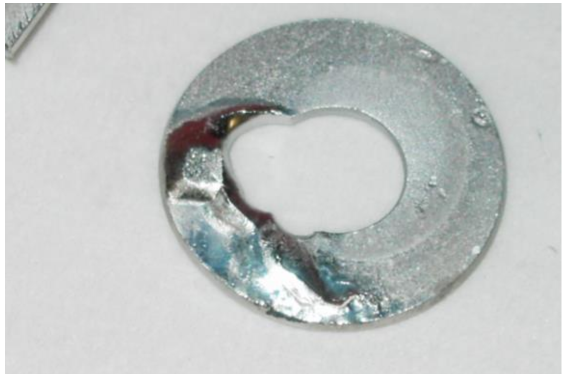
- In the PEP-II machine we encountered several issues of RF heating and/or arcing
- In one case, we had made very sure that we had very good vacuum pumping in the upstream part of the LER
  - However, we discovered that the RF screens separating the beam from the NEG pumps were too thin
  - RF power penetrated the screens and was absorbed by the NEG pumps warming them up to where they started to outgas creating backgrounds in the detector
  - We ended up having to remove a lot of the high-capacity NEG pumps in this region

Arcing

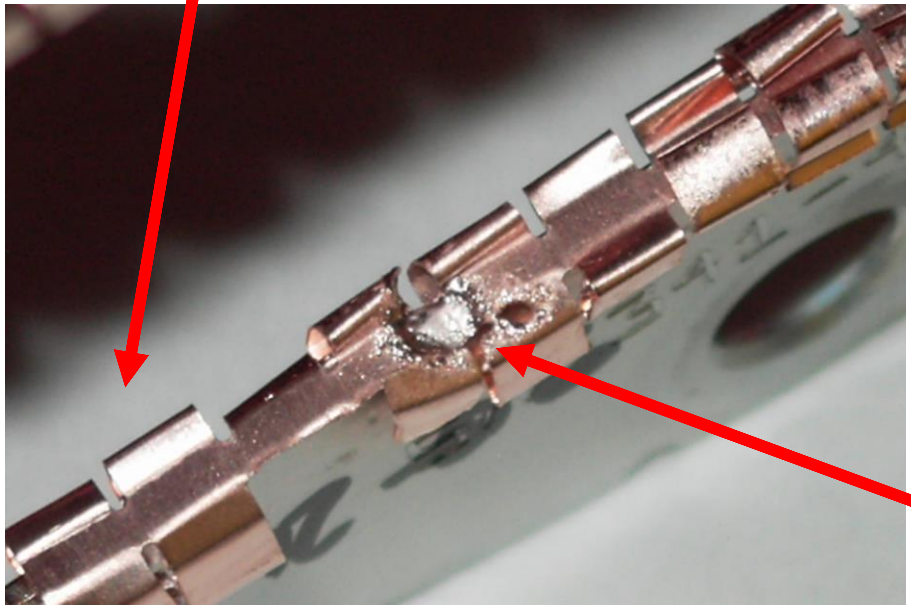
- There were several issues with arcing and RF seal failures. Here is one.
- In the HER, we found that the 192 RF seals between the bend magnet chamber and the quad chamber around the entire ring had failed and were letting RF power into an uncooled part of the vacuum chamber. The failed seals also started to arc and ended up vaporizing some of the Cu seal.
- We replaced all of these RF seals in the summer of 2007
- There was only one seal out of 192 that looked OK

This is supposed to look like this





Partially melted a SS washer



A hole dug into the SS sheet holding the Cu fingers through arcing

Sudden beam losses

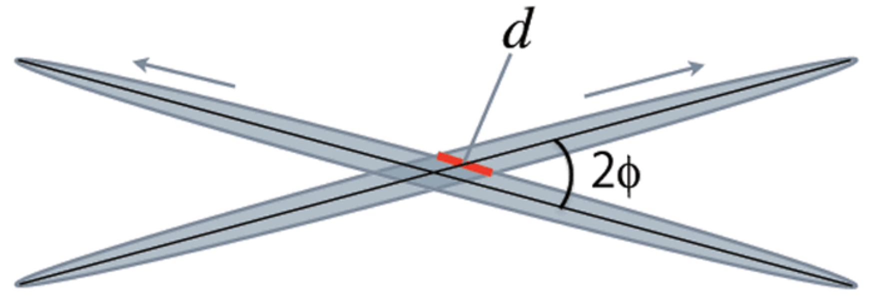
- PEP-II would have several sudden beam losses every day
  - The beam aborts were (mostly) initiated by the radiation monitors inside BaBar designed to protect the vertex detector
  - We could see confirming evidence that the beam was going unstable after the event through stored orbit information
  - We never detected any damage to the accelerator or the detector
  - So, as soon as the RF stations reset themselves, we would fill the rings back up as fast as we could
  - The operators got very good at this, and I believe some of the shortest downtimes from these events were on the order of a few minutes between beams lost and back to delivery
- KEKB did not seem to have this issue or at least it was much rarer for them
  - They had many days with no beam aborts while we had only a handful of days with no beam aborts (<10?)

New machines

- I believe experimental HEP scientists have the following saying:
  - “Yesterday’s sensation is today’s calibration and tomorrow’s background”
- I think we can paraphrase that for accelerator physicists:
  - “Yesterday’s record is today’s operating point and tomorrow’s minimal design parameter”
- Present and new machines are using the high-current success of the B-Factories as starting points for their designs
  - SuperKEB
  - FCCee
  - EIC

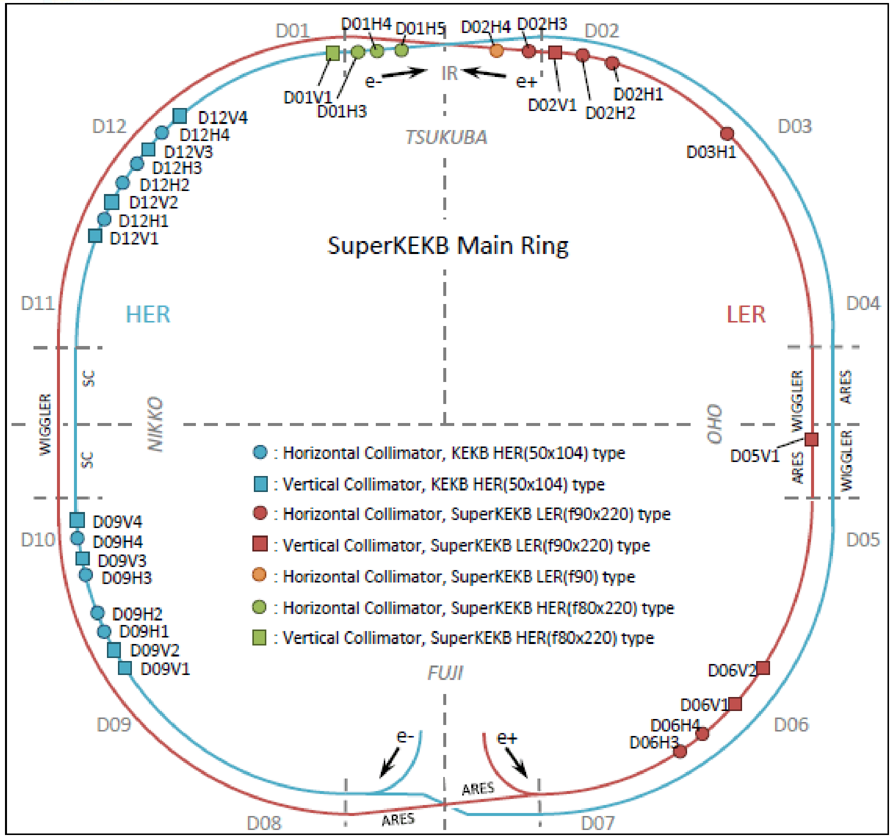
SuperKEKB

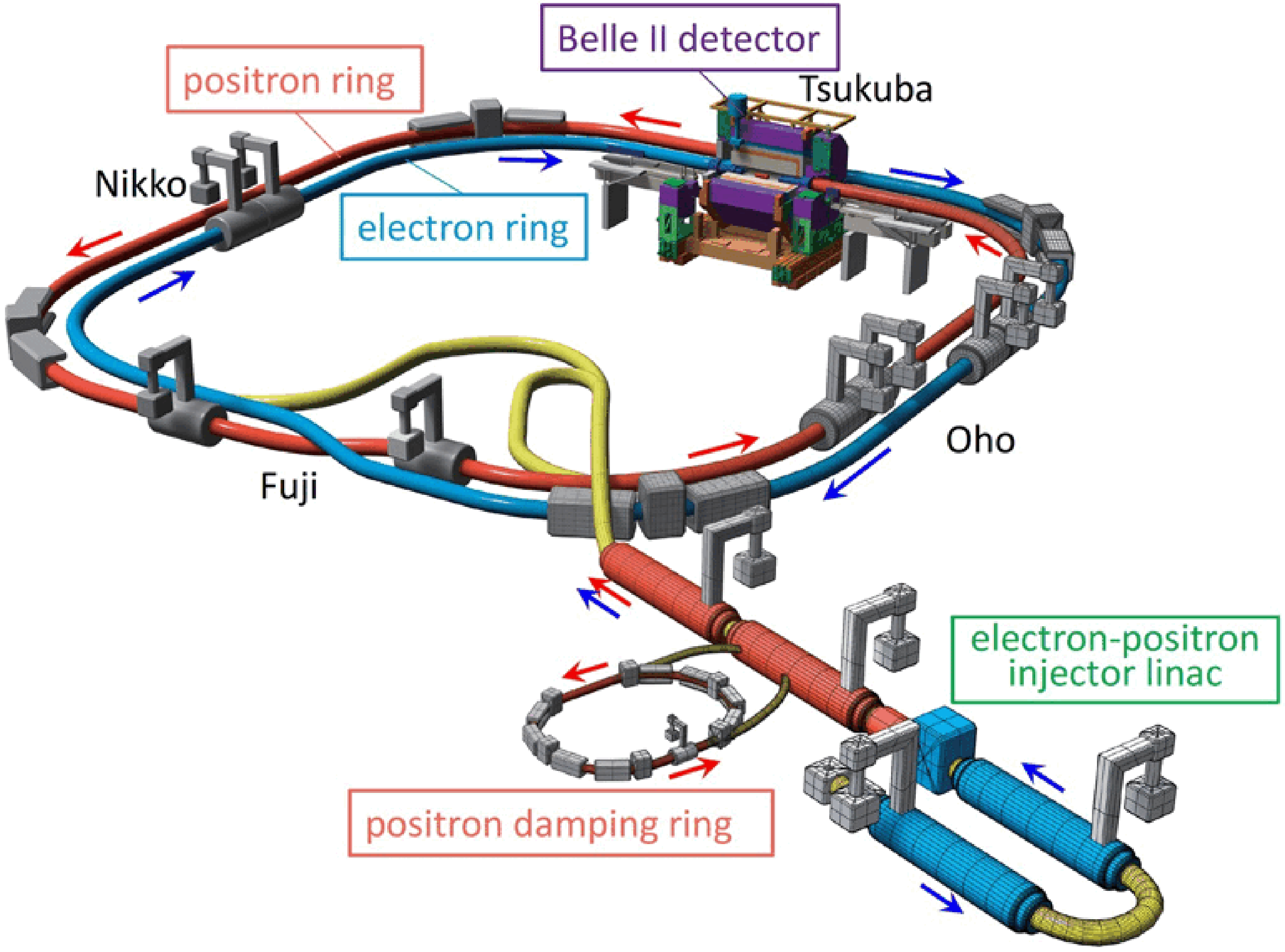
- Already up and running. Has achieved 4.65×10^{34}.
  - Is struggling with sudden beam losses that damage collimators
- SuperKEKB is aiming for a luminosity peak of 6×10^{35}
- And an integrated luminosity of 50 ab^{-1}
- They are using the nano-beam scheme pioneered by P. Raimondi in the design of the Italian SuperB design wherein the bunches are long wrt the β_y^* value (6 vs 0.3 mm)
  - The IR crossing angle in SuperKEKB is 83 mrad
- This has now been demonstrated at KEK
  - 6 mm long bunches and 1 mm β_y^*
- They also need high beam currents
  - 3.6 A LER and 2.6 A HER
  - Higher than anyone has achieved so far



SuperKEKB rings

Collimators



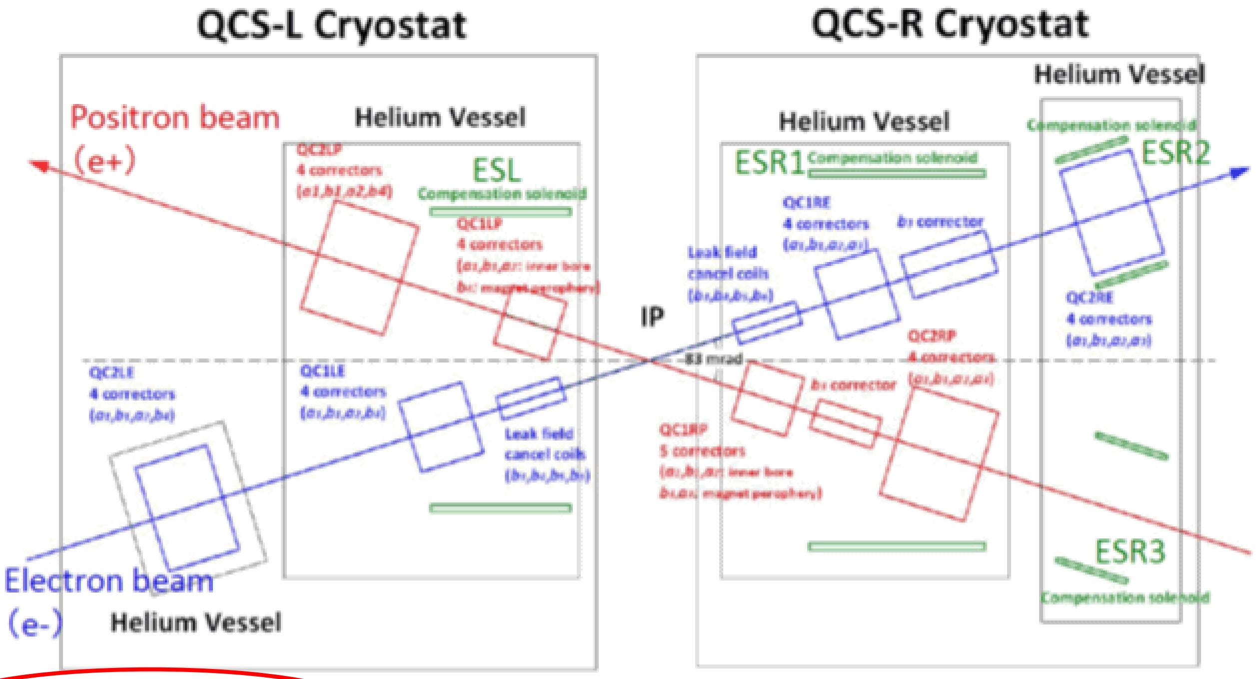


- SuperKEKB has added collimators to the LER. It is the LER that has most of the sudden beam loss events

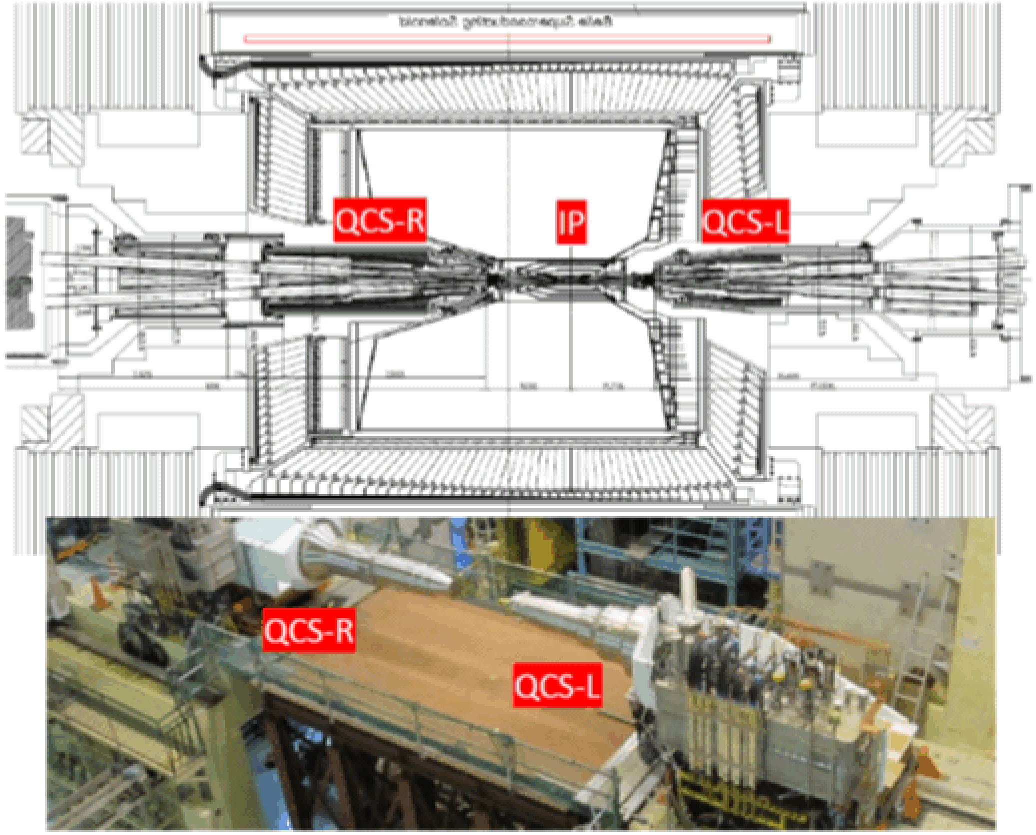
SuperKEKB IR and Belle II

The superKEKB crossing angle is 83 mrad
(complicates the central beam pipe – it cannot be very long)

e- beam line : 4 quadrupole magnets, 17 corrector coils, and 8 cancel coils
e+ beam line : 4 quadrupole magnets and 18 corrector coils
4 compensation solenoids are located on the outer surface of quadrupole magnets to cancel the influence of the Belle-II solenoid field on the collision beam.



Totally 54 SC magnets



- SuperKEKB has eliminated all shared magnetic beam elements
  - This minimizes the radiative Bhabhas and the local synchrotron radiation
  - The radiative Bhabhas are a luminosity dependent background

FCCee

- Proposed next e^+e^- collider ring for CERN
  - ~100 km circumference
  - Will run at four different beam energies
    - 45.6 GeV "Z factory" – luminosity of 2.3×10^{36} – with beam currents of 1.39 A
    - 80 GeV "WW factory" – luminosity of 2.8×10^{35} – beam currents of 247 mA
    - 120 GeV "ZH factory" – luminosity of 8.5×10^{34} – beam currents of 29 mA
    - 175-183 GeV "Top factory" – luminosity of 1.7×10^{34} – beam currents of 6 mA
  - The Z factory is the closest to the B-factories
    - Over an Ampere of beam current at 45.6 GeV – 20.6 MJ/beam
    - High power SR fans in the IP region from the last bend magnets (softened)
    - Beamstrahlung (SR emitted by the interaction of a beam particle with the intense electromagnetic field of the other beam at the IP)
    - SR critical energies are high (photons from SR into the MeV energy range)

50 MW SR power limit

FCCee ring layout

- The LHC tunnel becomes the injector complex for the FCC

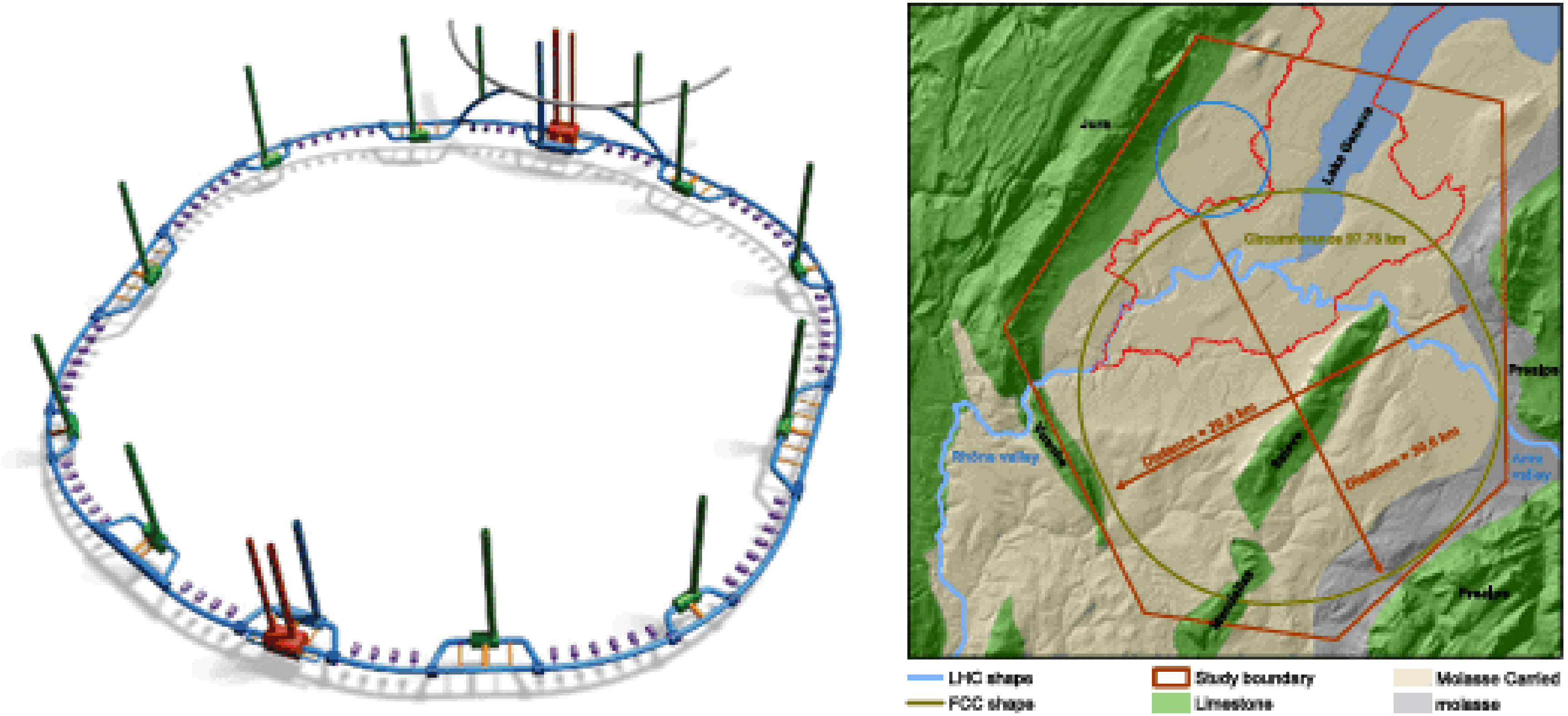
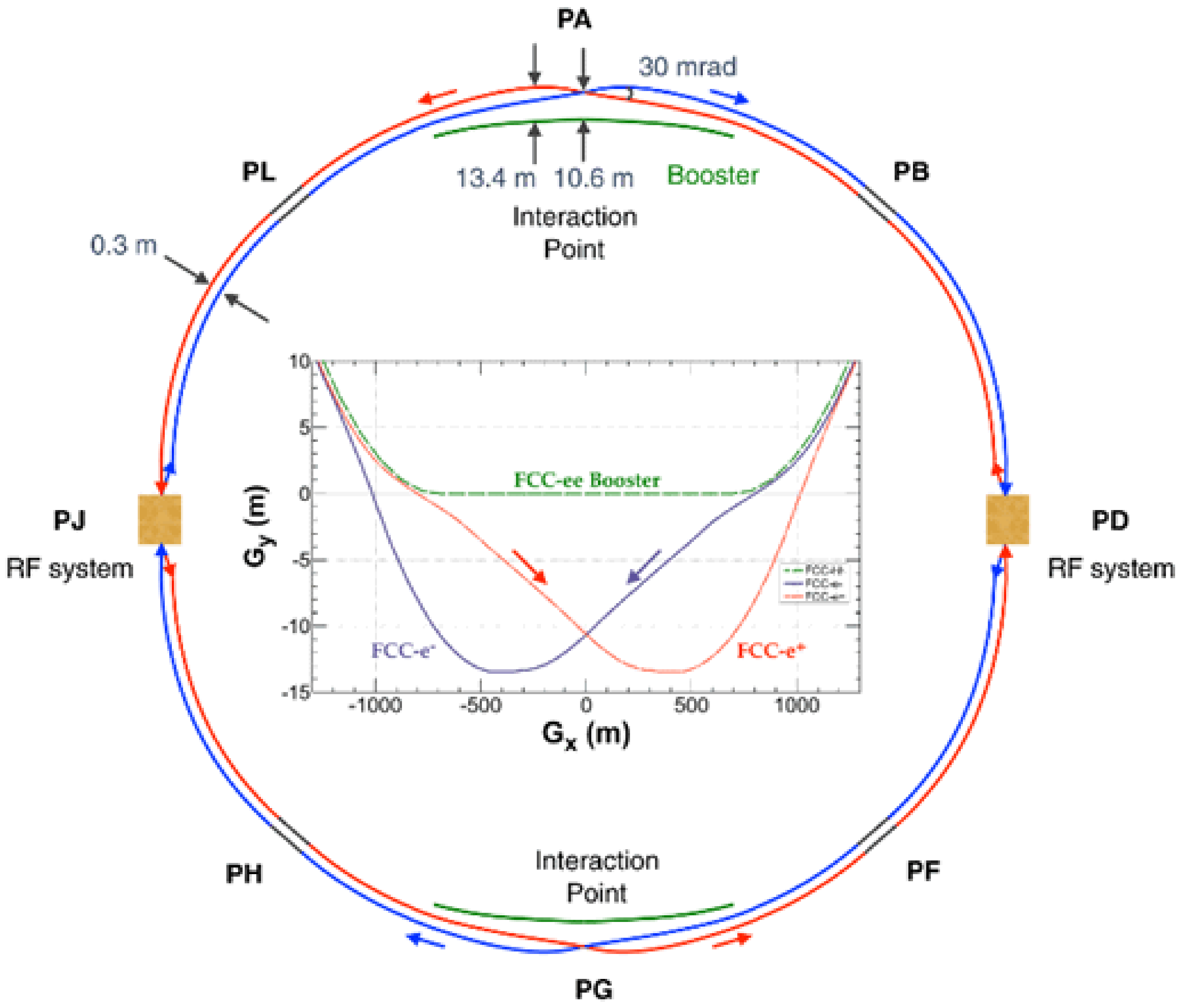


Fig. 5. Left: 3D, not-to-scale schematic of the underground structures. Right: study boundary (red polygon), showing the main topographical and geological structures, LHC (blue line) and FCC tunnel trace (brown line).

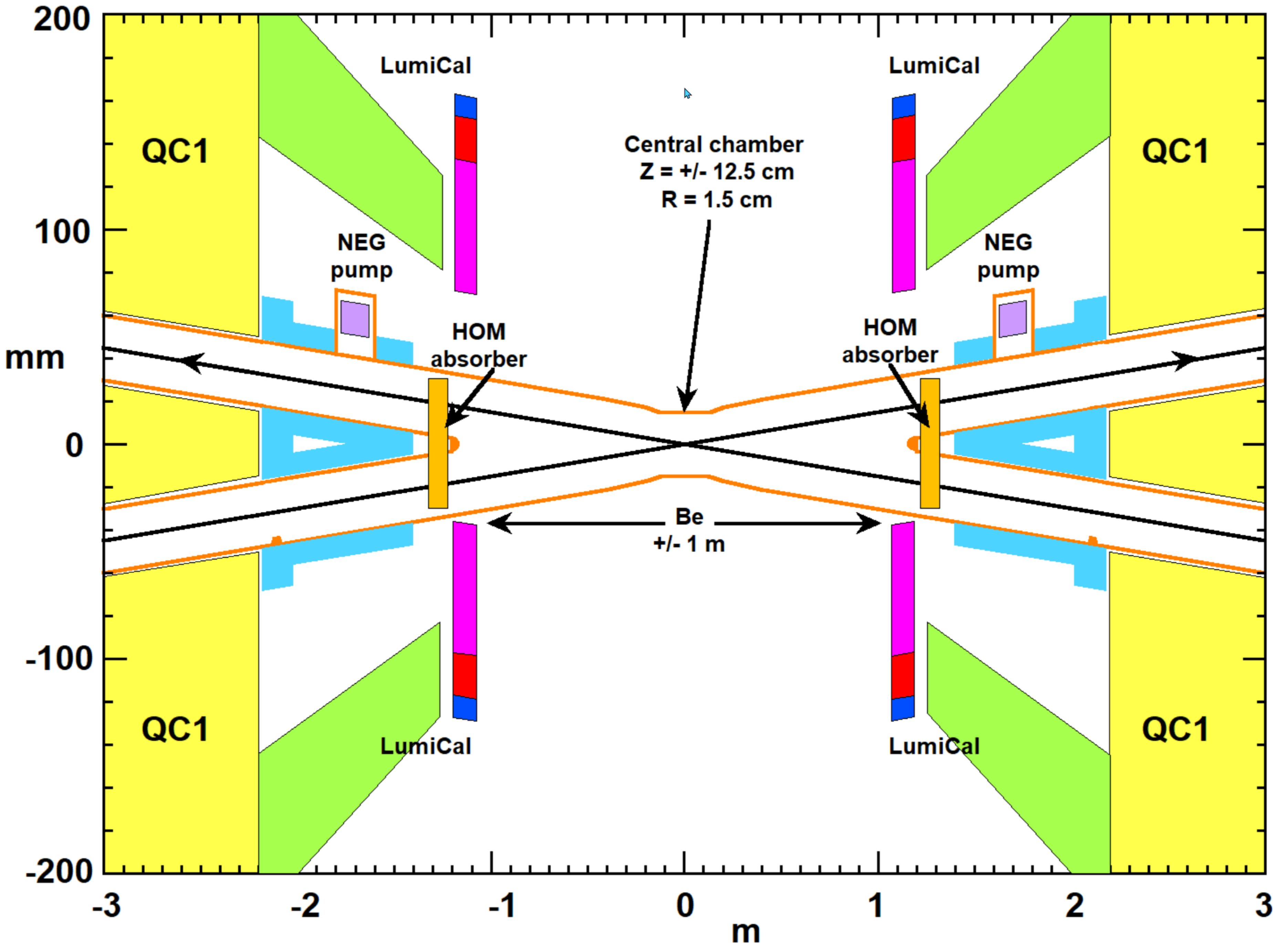
FCCee

- In order to inject continuously on energy, the design has a booster ring to accelerate bunches up to the stored ring energy
- Continuous top-off injection pioneered by the B-factories is now the norm in all new machine designs



FCCee IR

- The crossing angle is 30 mrad

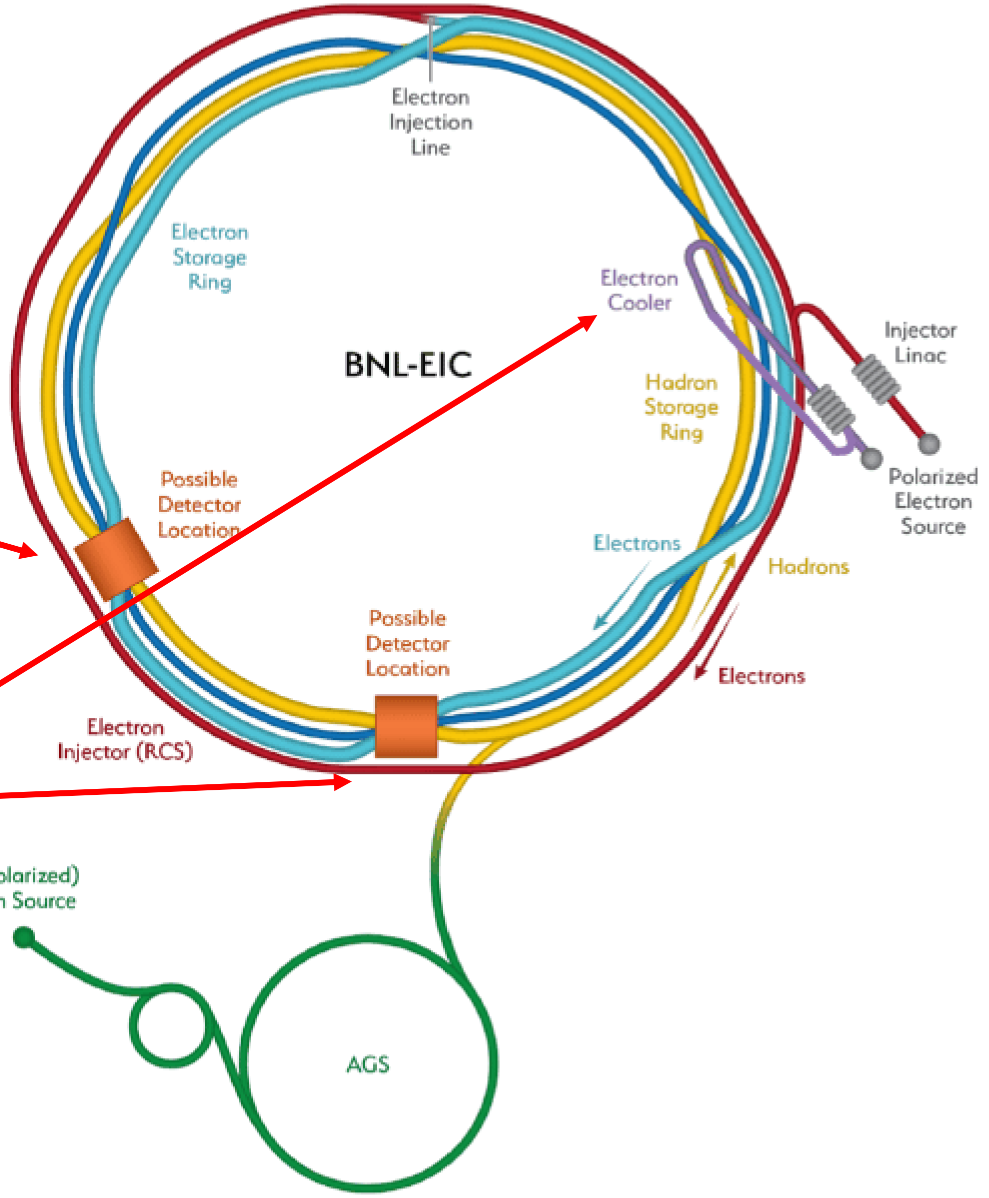


EIC

- The BNL Electron-Ion Collider is another machine that will run at several beam energies
  - For the ions (polarized beam):
    - 40 GeV
    - 100 GeV
    - 275 GeV
  - For the electrons (polarized beam):
    - 5 GeV, beam current of 2-2.5A, luminosity of ~0.4×10^{34}
    - 10 GeV, beam current of 2.5 A, luminosity of 1×10^{34} (very B-factory like)
    - 18 GeV, beam current of 227 mA, luminosity of 0.15×10^{34}
  - A rapid cycling synchrotron is used to ramp the electron energy up from 400 MeV to the stored beam energy prior to injection (continuous injection)

EIC layout

- The rapid cycling synchrotron must go around the detectors
- They anticipate needing an electron cooler for the hadron beam
- The tunnel is 3800 m

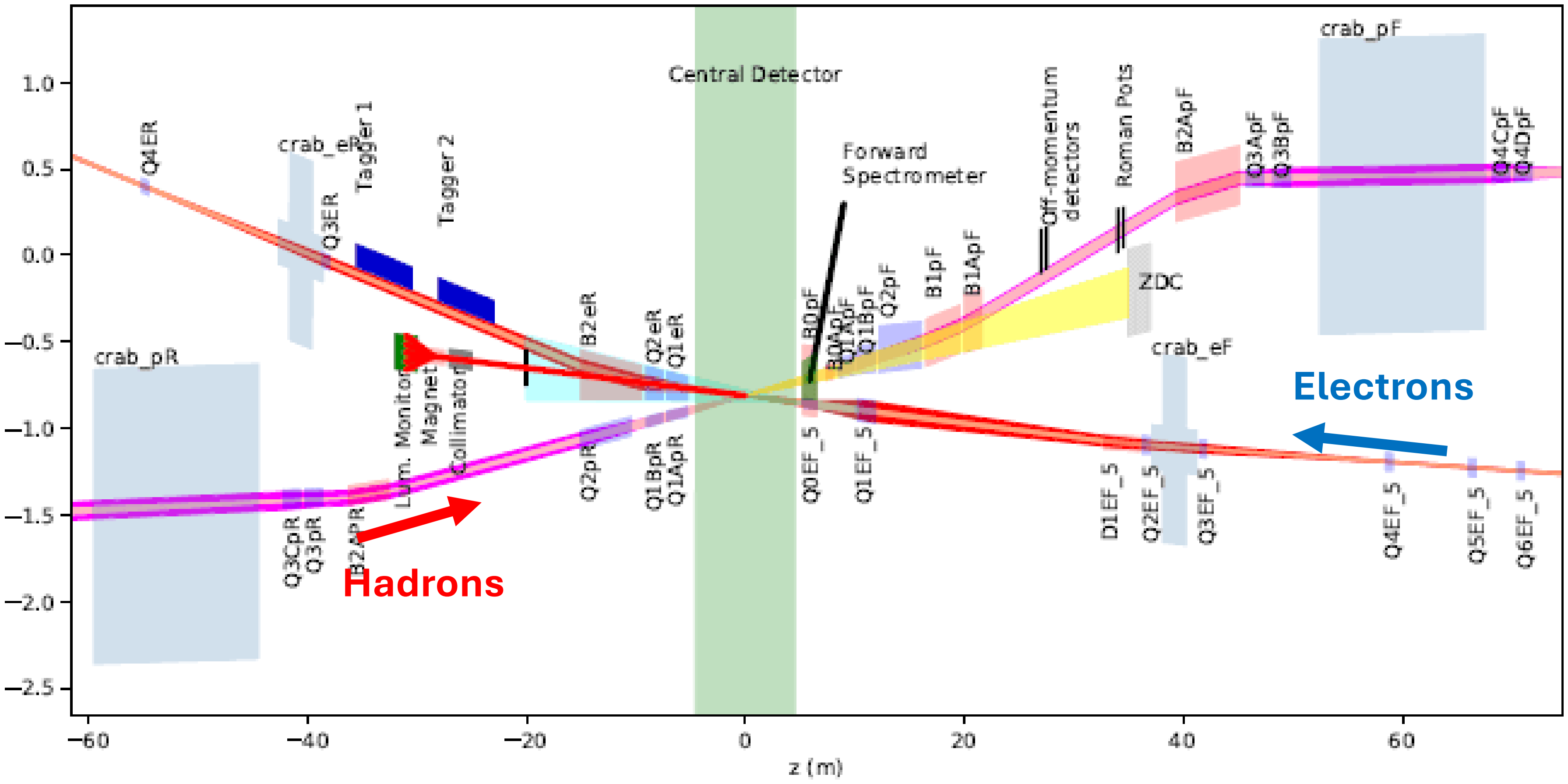


EIC detector

- They want to make the detector system as close to full 4π acceptance as possible
  - Very low angle and even some zero angle detectors
  - Roman pots in the hadron beam line
  - Very low Q^2 detectors in the electron beam line
- The aim is to get as much information as possible about the hadronic structure
  - From the surface to deep inside
  - By various collision energies as well as much of the entire Q^2 range as possible
- Both beams are polarized

EIC IR

- The crossing angle is 25 mrad
- There is a zero-degree luminosity monitor on the electron beamline
- There is a zero-degree detector for the hadron side



Summary

- The B-factories broke new ground in the accelerator field
- All current and new machines are using the legacy of the B-factories
  - High-current beams (multi-ampere)
  - Crossing angle
  - Continuous top-off injection
  - High luminosity
  - Many bunches
- Consequently, these machines will inherit and have to solve some of the B-factory headaches
  - RF wake-field heating and following bunch perturbations
  - High power SR (direct and scattered)
  - High luminosity backgrounds
  - Injection backgrounds

Summary (2)

- The new detectors want more solid angle acceptance
  - More hermeticity – improves the study of rare channels with missing energy/momentum
  - Better efficiency
  - They need to accept high data rates
  - Vertexing
  - …

Conclusion

- The SM has been shown to be quite robust and has held up in spite of the assault by the B-factories
  - There are a few hints that NP is possibly being seen but more data is needed
    - SuperKEKB
    - LHCb
  - NP has to be out there somewhere
    - Dark Matter
    - Muon g-2
    - …
- We must continue to push the energy and luminosity frontiers as well as any other avenues we can think of

Thank you!