Tools and Approach of the PEP-II IR Design

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SLAC
April 25, 2023

PEP-II Parameters

PEP-II TIMELINE

1987: Particle physicists determine that asymmetrical beam energies are preferred.
1991: First PEP-II CDR.
1993: Second PEP-II CDR.
1994: Construction started
1997: First HER stored beam 6:30 am June 5.
1998: First LER stored beam 2:49 am July 16.
1998: First collisions 12:05 pm July 23.
1999: BaBar placed on beam line in May.
1999-2008: Collisions for BaBar.
2000: Design luminosity achieved ($3x10^{33}$) Oct. 29.
2006: Luminosity $1.2x10^{34}$ achieved 8 pm Aug. 17.
2008: PEP-II turned off 23:22 pm April 7.

Table 1 : PEP-II Collision Parameters

Parameter	Units	Design	April 2008 Best	Gain Factor over Design
I+	mA	2140	3213	x 1.50
I-	mA	750	2069	x 2.76
Number bunches		1658	1732	x 1.04
β_y*	mm	15-25	9-10	x 2.0
Bunch length	mm	15	10-12	x 1.4
ξ_y		0.03	0.05 to 0.065	x 2.0
Luminosity	10^{34} /cm^2/s	0.3	1.2	x 4.0
Int lumin per day	pb^{-1}	130	911	x 7.0

*Supported by US DOE contract DE-AC02-76SF00515.
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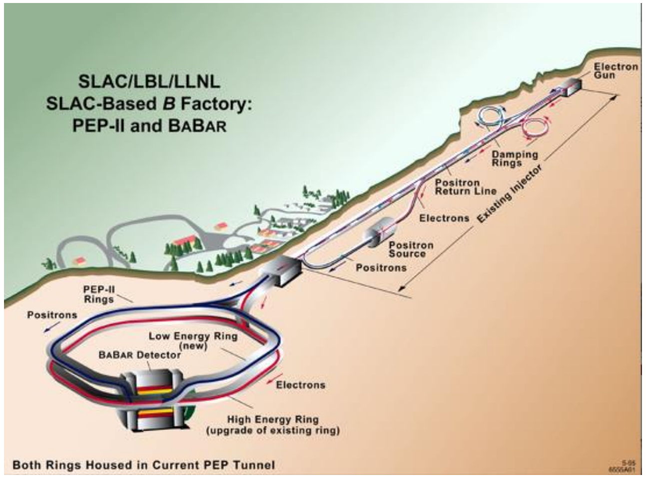


HER = 9 GeV, LER = 3.1 GeV for CM boost

PEP-II IR Beam Trajectories

PEP-II has LER above the HER in the ARCs.

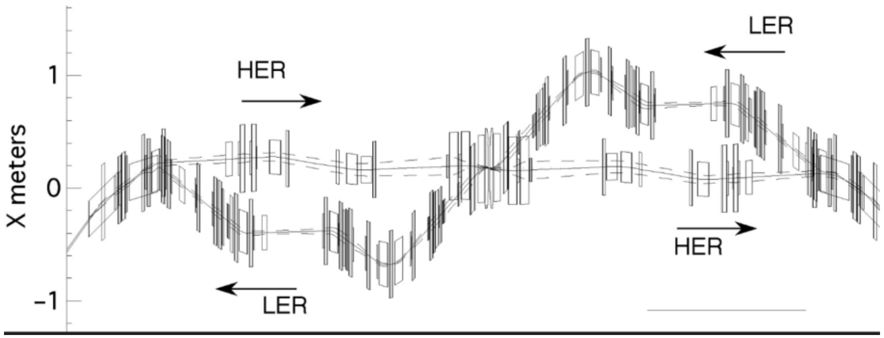
In the IR LER comes down to the HER.

In the IR HER bends much less than LER to reduce the synchrotron radiation generated.

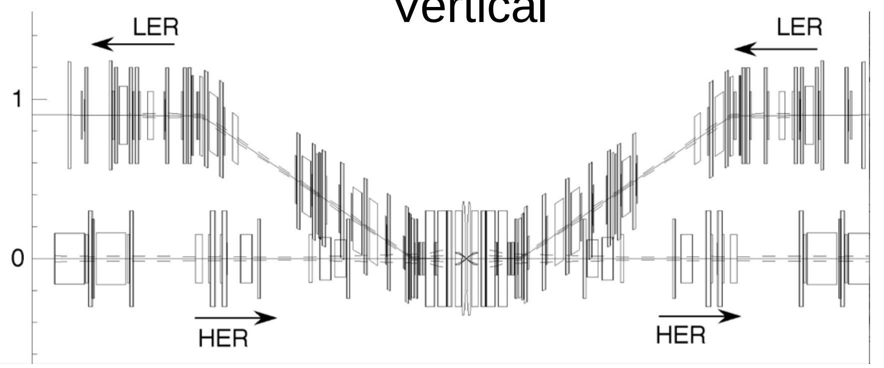
Head-on collisions with dipoles near the IP (0.5 m).

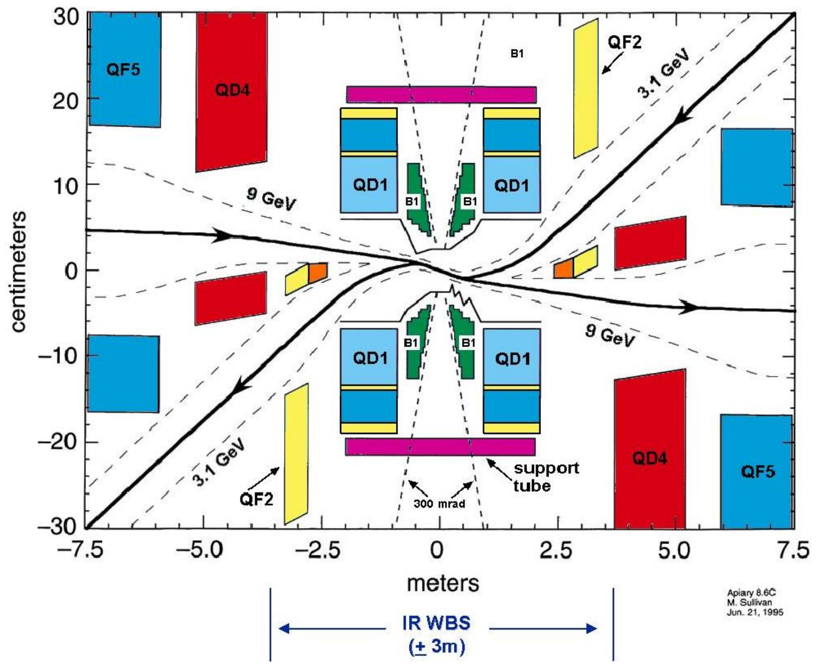
Strong forward radiation lands downstream of the detector.

Horizontal



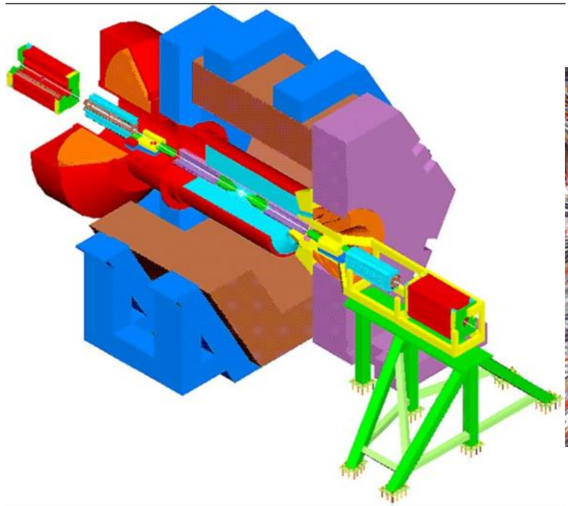
Vertical

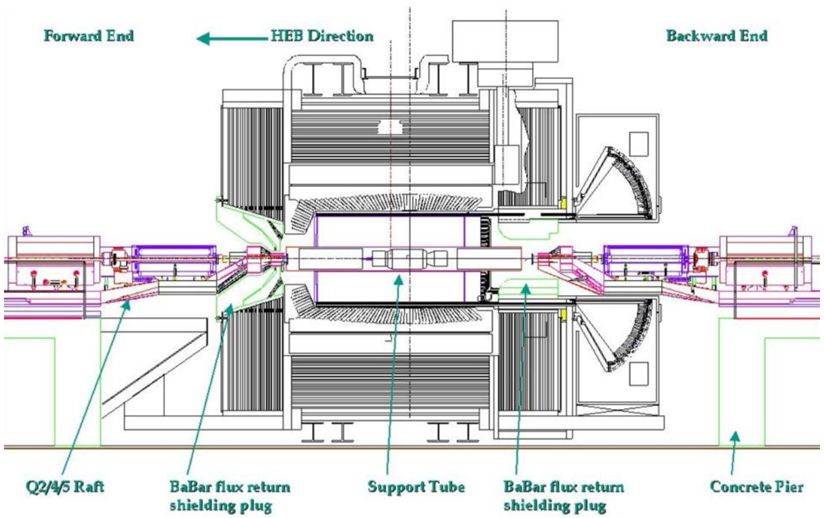




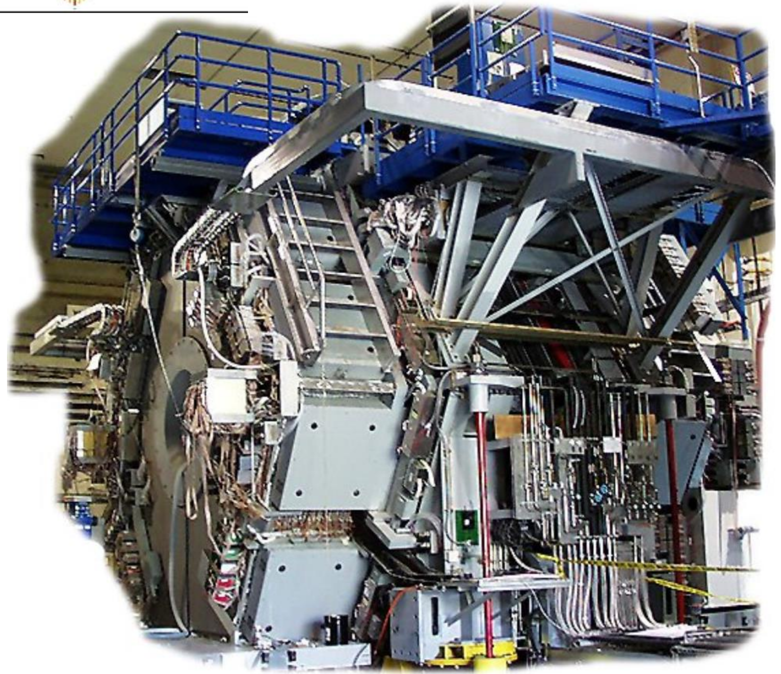
PEP-II and BaBar Schematic Drawing

BaBar detector has a full acceptance but there is a CM boost 9x3.1 GeV. Separation cone angles for Babar are 350 mrad forward direction and 400 mrad backward. For PEP-II B1 Dipole, the cone angle is 300 mrad. Permanent magnet IR dipoles and quadrupoles and silicon vertex tracker (SVT) are mounted in a support tube to where technicians can connect it without a "magic vacuum flange". BaBar solenoid has field 1.5 T.





Elevation View of PEP-II I.R. and BaBar



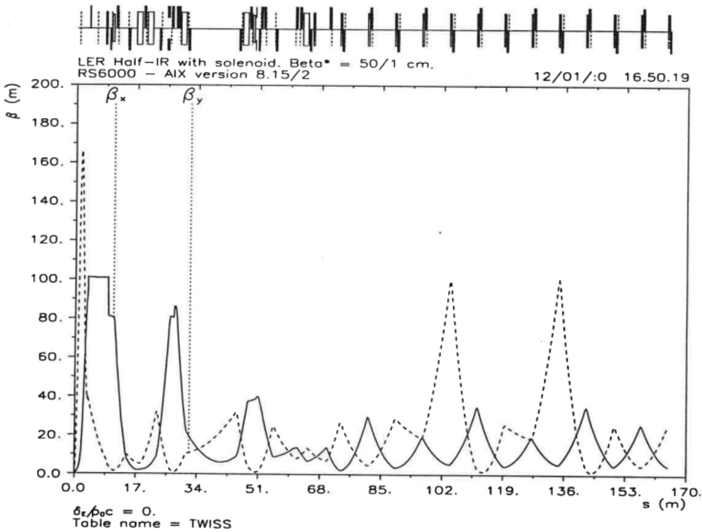
PEP-II IP Optical Lattice Functions (Donald, Garren)

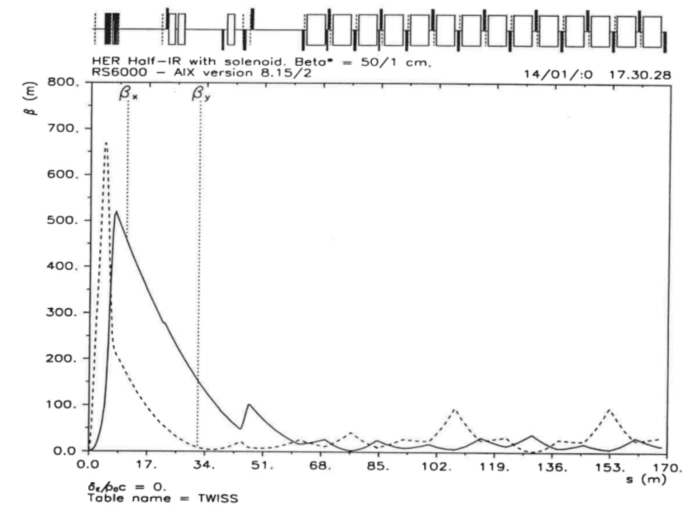
Accelerator optics done with MAD (Donald, Garren, Helm) and LEGO (Y. Cai).

IP quadrupole chromatic corrections were done by adding beta beats in x and y to allow the sextupoles to have smaller strengths.

Dynamic aperture tracking was done to verify the beam-stay-clears distances.

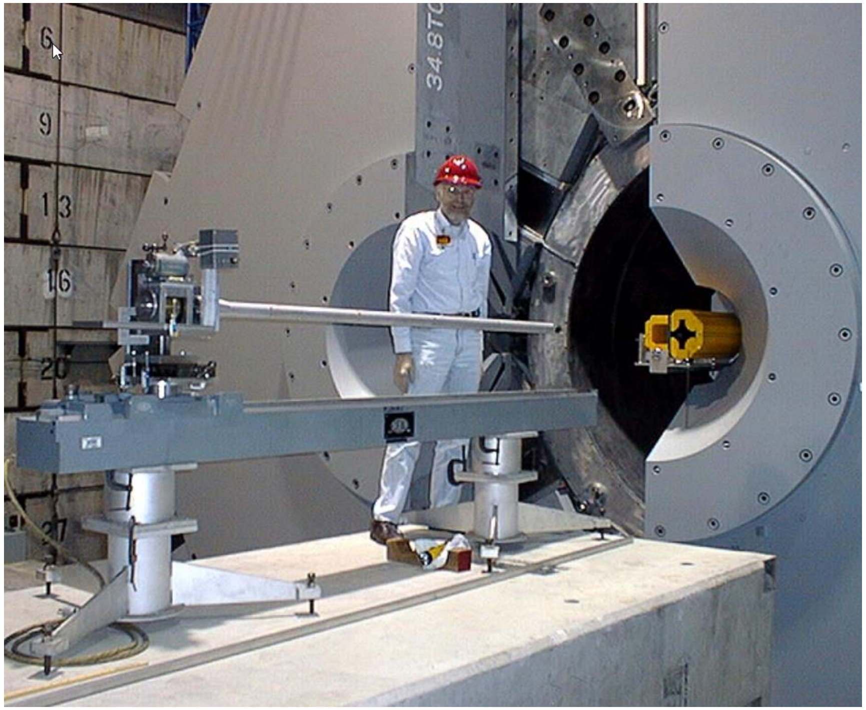
Parameter	PEP-II Design	PEP-II Present
HER Vertical tune	23.64	23.61
HER Horizontal tune	24.62	24.503
LER Vertical tune	36.64	36.59
LER Horizontal tune	38.57	38.505
HER current (mA)	750	1776
LER current (mA)	2140	2950
Number of bunches	1658	1722
Ion gap (%)	5	1.6
HER RF klystron/cav	5/20	10/26
HER RF volts (MV)	14.0	15.6
LER RF klystron/cav.	2/4	4/8
LER RF volts (MV)	3.4	4.35
β_y* (mm)	15-25	9-10
β_x* (cm)	50	40-105
Emittance (x/y) (nm)	49/2	30-50/0.8
σ_z (mm)	11	11-12
Lum hourglass factor	0.9	0.82
Crossing angle(mrad)	0	<0.05
IP Horiz. size Σ (μm)	222	160
IP Vert. Size Σ (μm)	6.7	6.9
HER Horizontal ξ_x	0.03	0.113
HER Vertical ξ_y	0.03	0.062
LER Horizontal ξ_x	0.03	0.027
LER Vertical ξ_y	0.03	0.047



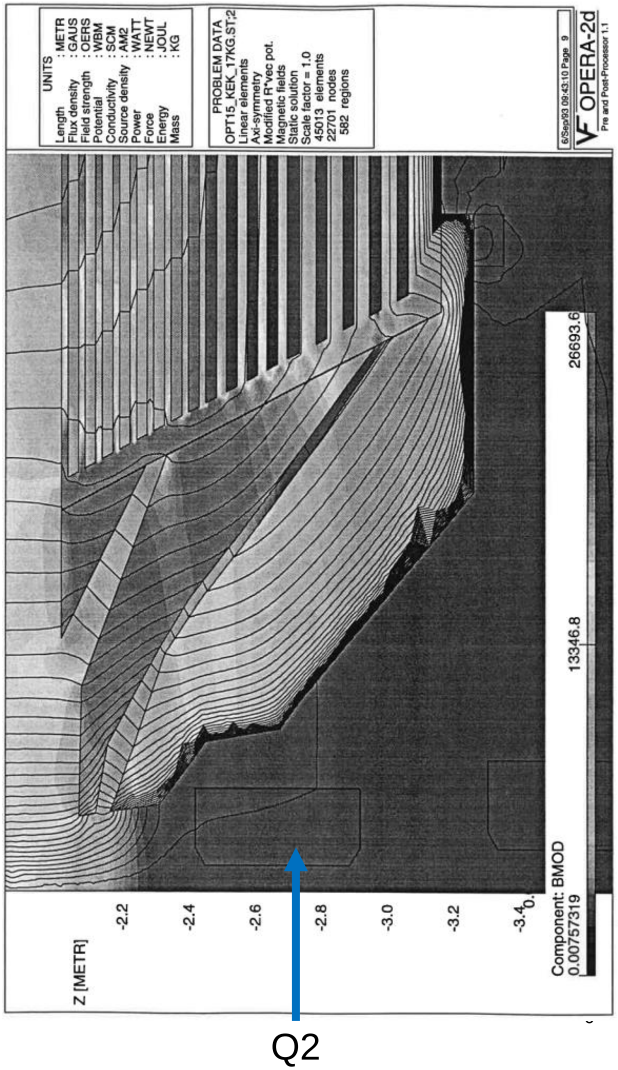


Detector magnetic fields near PEP-II

Permanent magnets were used inside of BaBar.
Outside quadrupoles were steel magnets.
We calculated the solenoid field escaping outside the central hole using OPERA-2d to see if the near steel magnets would saturate. OK in end.
Measured fields in the hole were measured.



OPERA-2d field calculations.

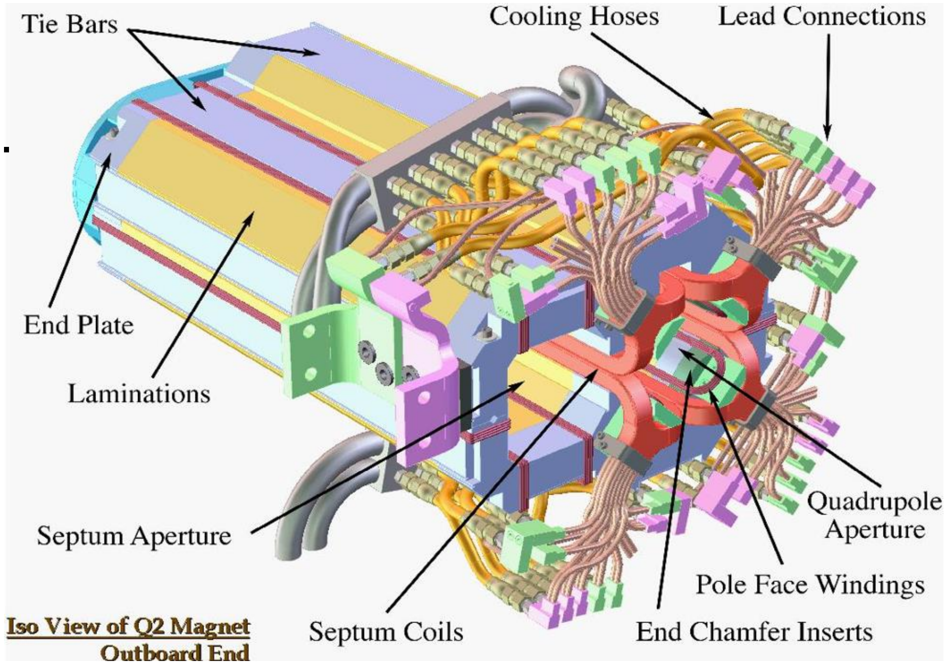


PEP-II conventional quarupole magnets

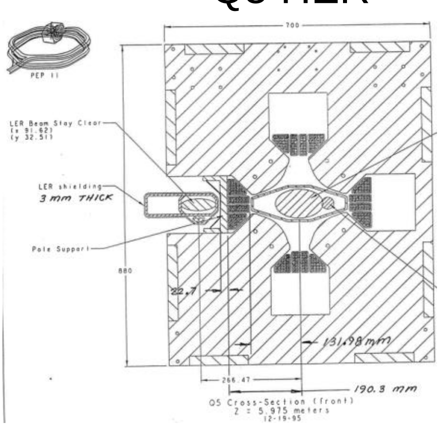
Al of the nearby steel magnets had
to accommodate the two beam chambers.

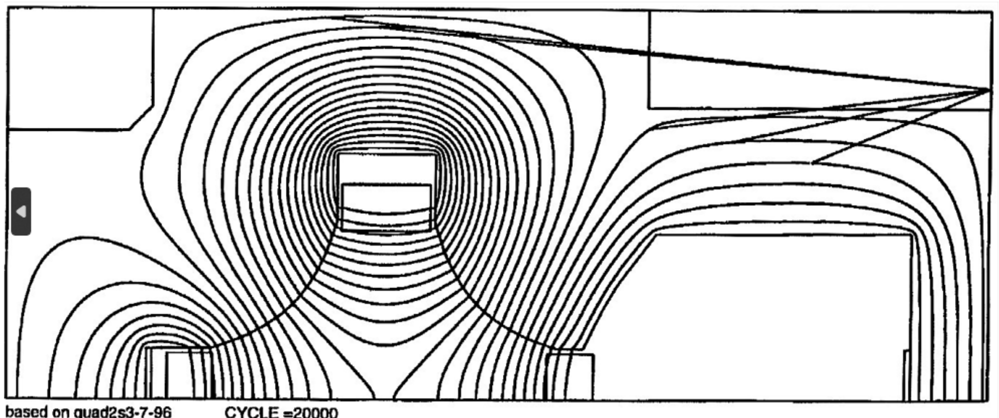
Prototypes were made and measured
both in the high field region and the
“zero” field region for the adjacent beam.

Permendur steel



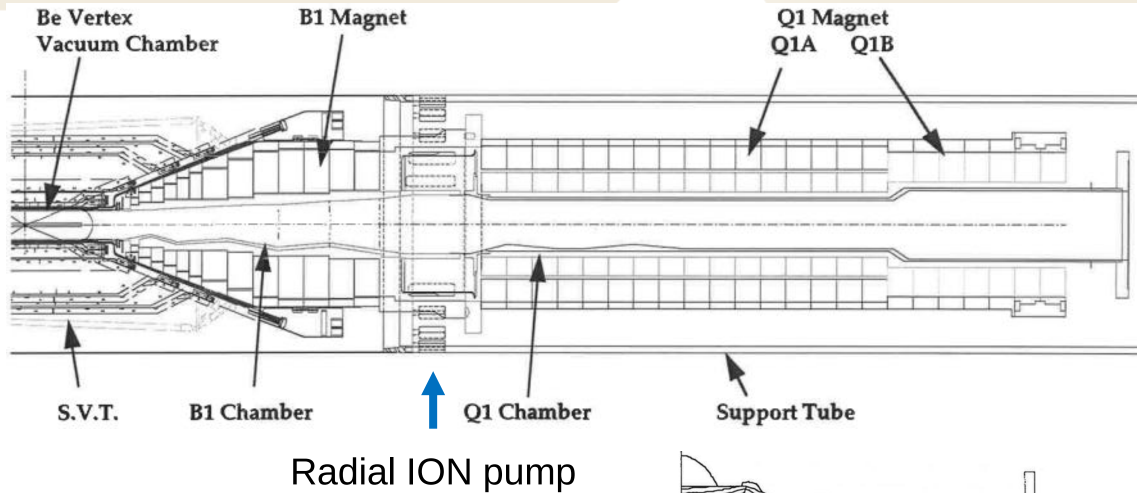
Q5 HER

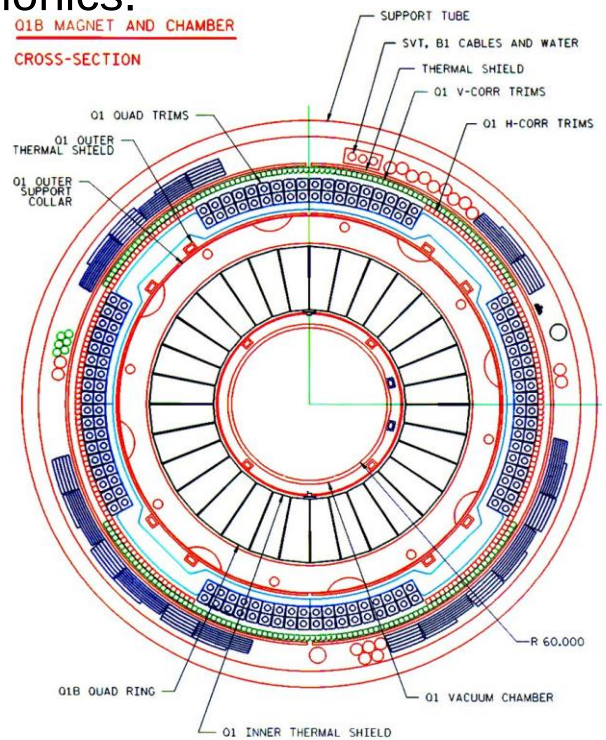


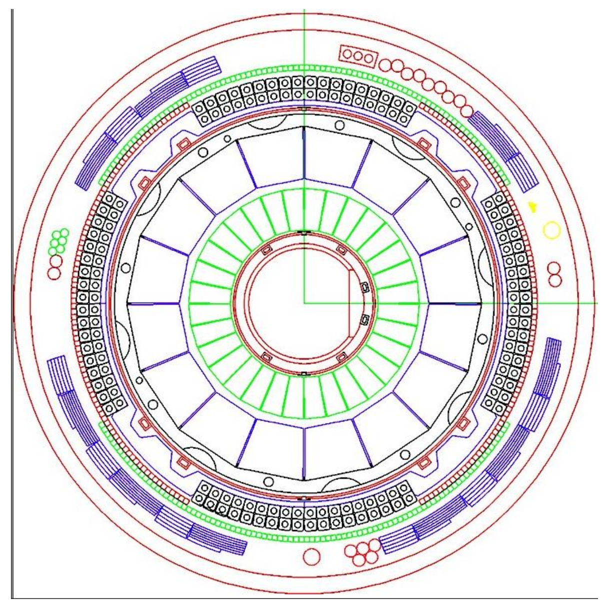


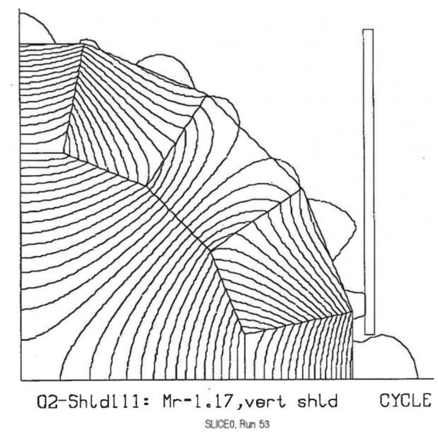
PEP-II Permanent Magnet Design

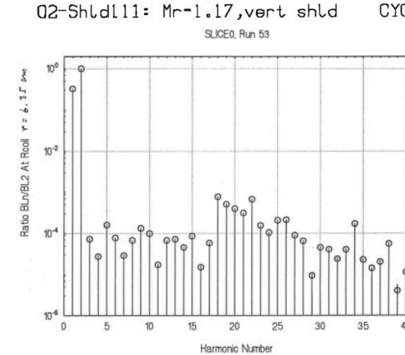
The permanent magnets in the IR had three segments: B1 dipole first, Q2 dipole+quad second and only a (Q2) quad third.
Fields were calculated by “MBUILD” (Sullivan) using Halbach formulae to determine field strengths and harmonics.







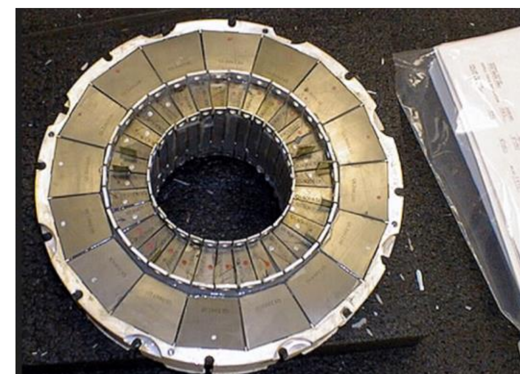


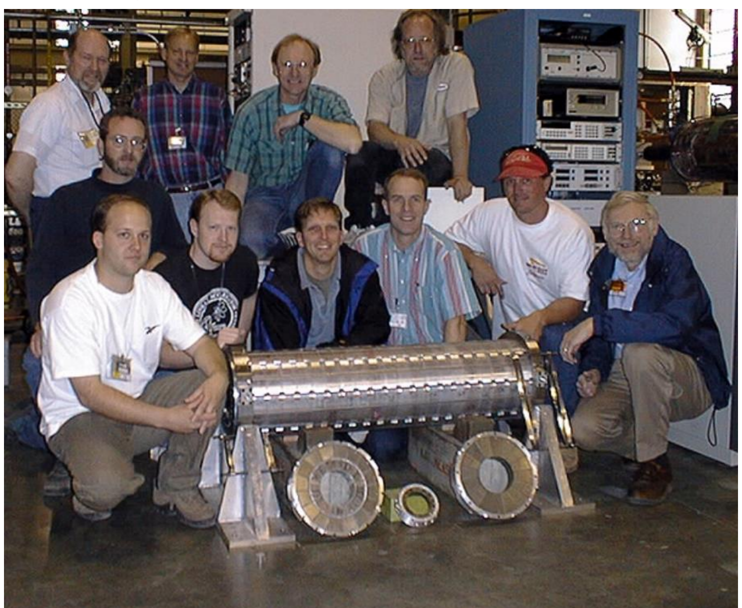


PEP-II IR Permanent Magnet Construction (A. Ringwall)

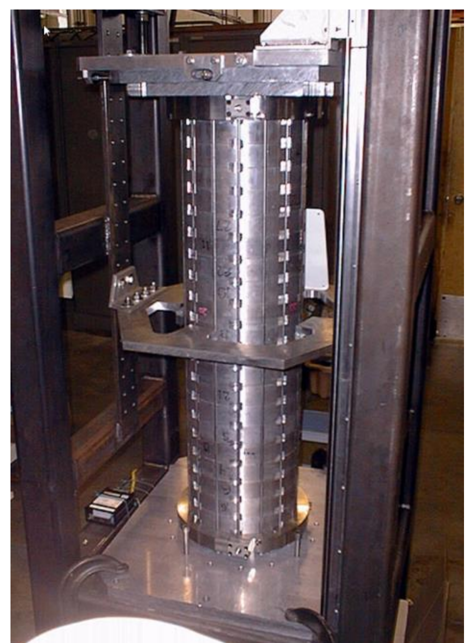
Permanent magnet blocks were made of Cm_2Co_{17} for strength and radiation hardness.
Each block was glued to a holder and manipulated into place. The field harmonics were measured and the errors were fixed by block movements. Once the fields were good (10^{-4} at quad radius) the blocks were epoxied in place and the fixtures removed. One ring was made at a time then stacked.

1S_002 Capacitive Sensors measure block motion 02/04/98





Permanent Magnet Crew 04/09/98



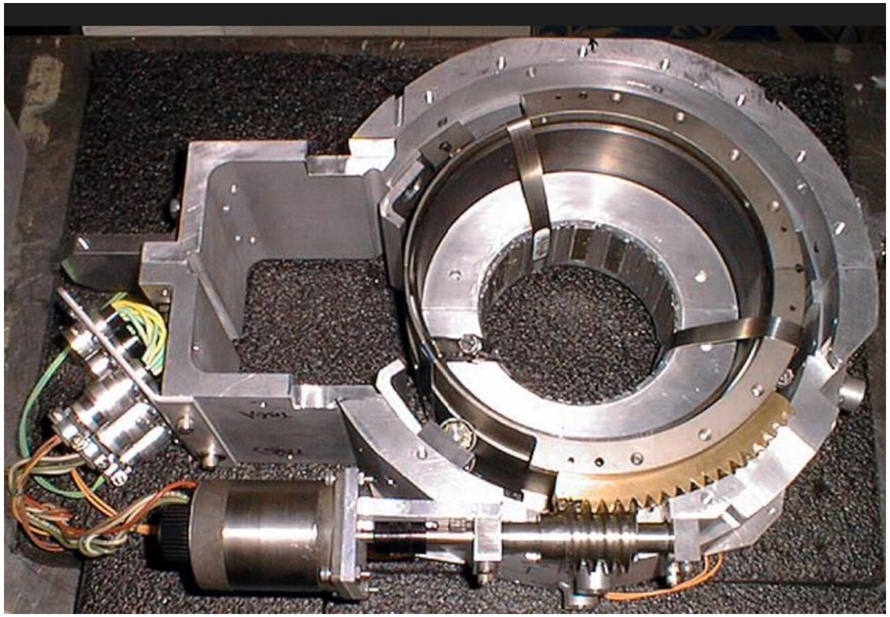
Solenoid Compensation by Skew Quadrupoles

Solenoid compensation was done by skew quadrupoles upstream and downstream of the detector, 12 in LER and 12 in HER.

A rotating mechanical fixture (shown here) could rotate two PM rings if additional skew quad strengths (left+right) were needed.

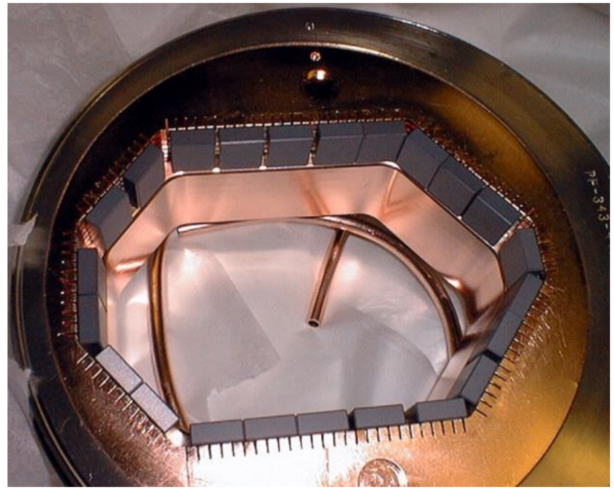
Table 1. List of old and new skew quad strengths.

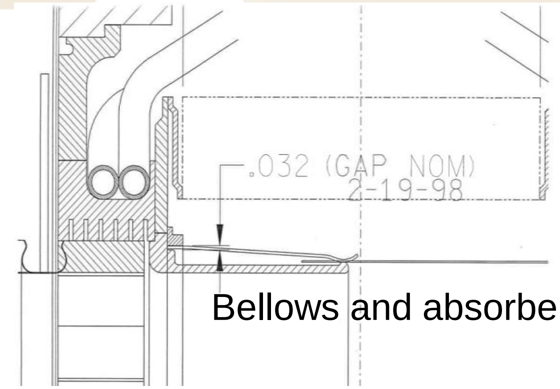
	Previous skew quad values	Present skew quad values
KSK1	0.806009876244 (pure skew)	0.972818713731(Mag., θ = 35.9°)
KSK2	-0.173274815633	-0.186464739573
KSK3	0.048822132989	0.0547721272
KSK4	-0.041635888106	-0.039915415564
KSK5A	-0.120312163391	-0.11662876396
KSK6A	-0.055326692406	-0.046045943936
KSK1L	-0.227809073954 (pure skew)	0.972818713731(Mag., θ = -9.1°)
KSK2L	0.095793356267	0.103047415341
KSK3L	-0.03273305964	-0.038225284655
KSK4L	0.032536374504	0.032596355015
KSK5AL	0.104318429692	0.107104279199
KSK6AL	0.04902251173	0.042797156312

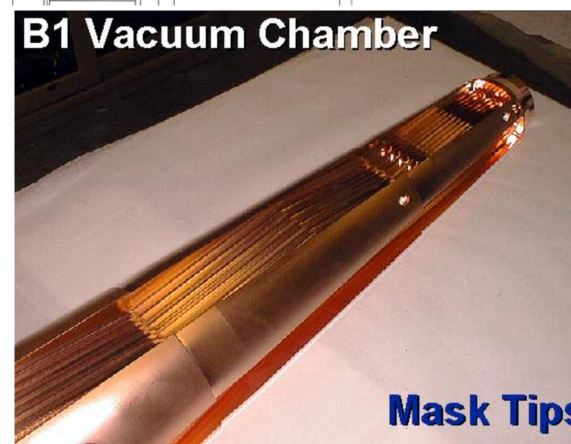


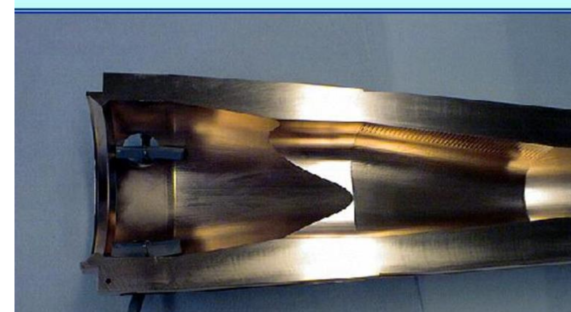
PEP-II IR Be IP Chamber

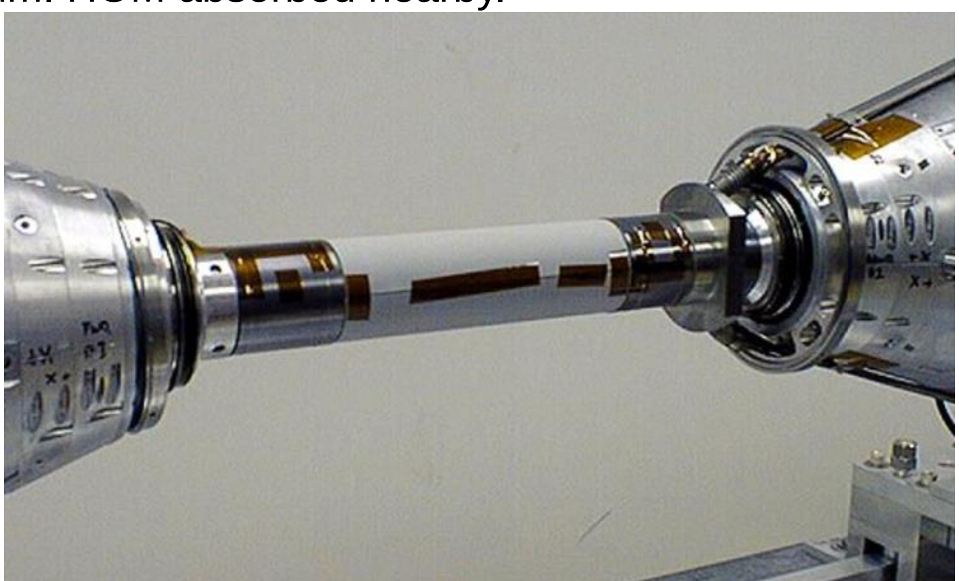
Be chamber was ~40 cm long.
Two layers: 0.8 mm and 0.4 mm wall Be tubes with 1.5 mm gap for de-ionized water cooling with ~1 gpm. Negative H_2O pressure to prevent leak problems.
Be material protected by aircraft BR-27 epoxy (K. Scarpass-VIII).
Background protection layers on Be: 4 microns Au, 7 microns Ni, 7 microns Ni, 75 micron, tantalum. HOM absorbed nearby.







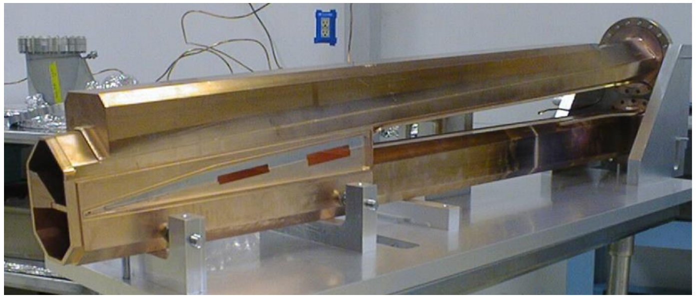


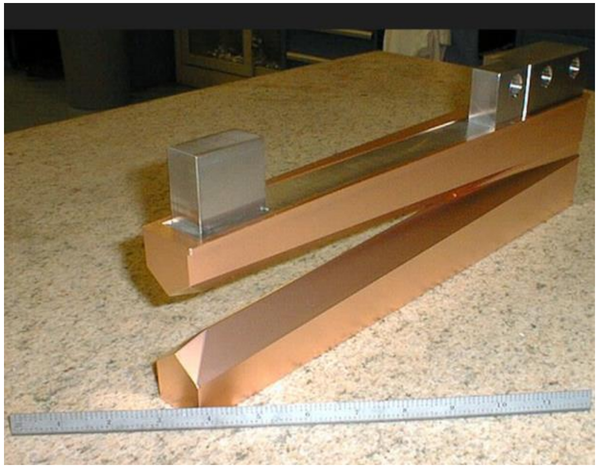


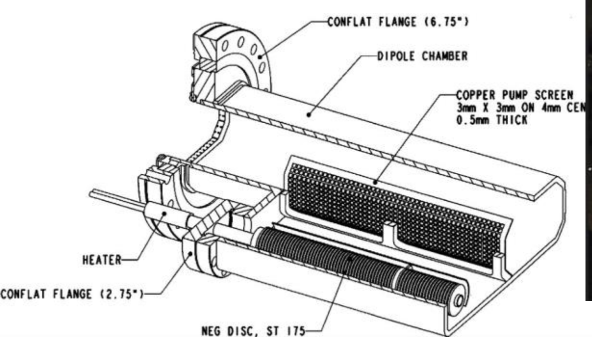
PEP-II Near IP Vacuum Chambers

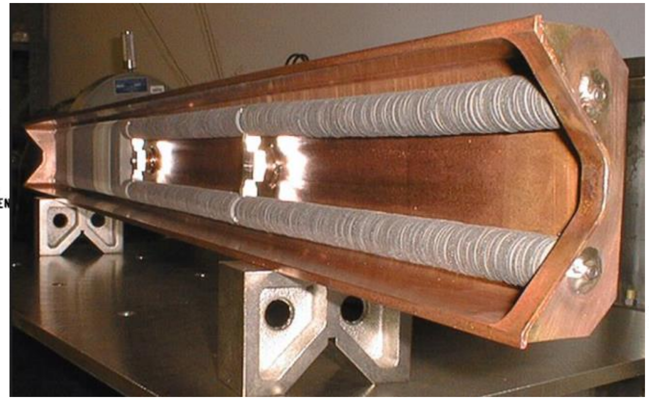
IR chambers made of GlidCop for strength. Special NEG and radial ion pumping. 3-D surfaces for synchrotron power absorption and to reduce HOM generation.

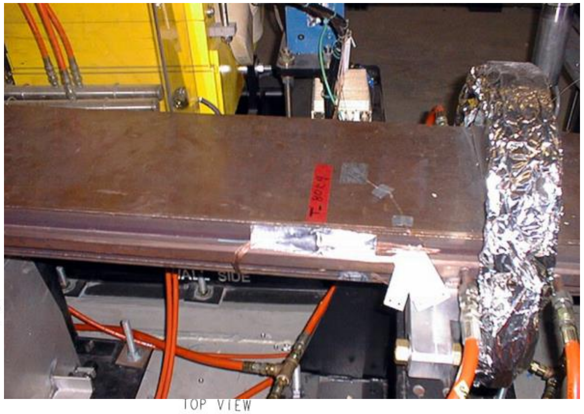
HER downstream high power dump was ~4 m long tapered copper, absorbing 90 kW at 1.8 A.

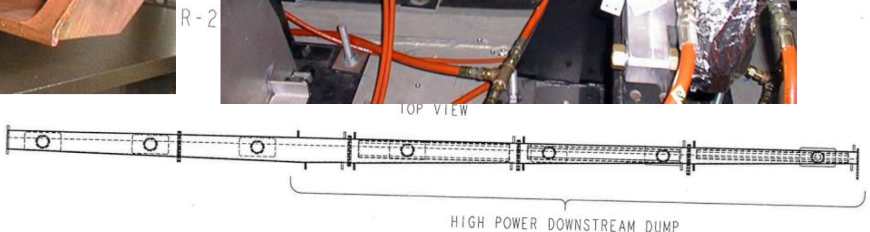






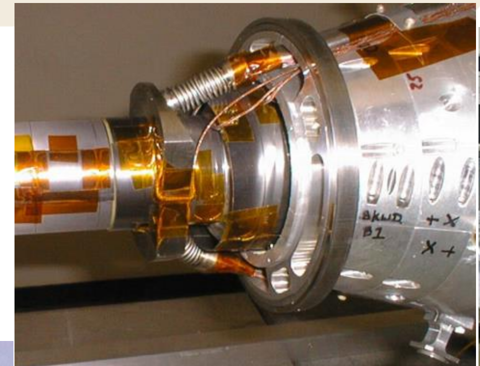
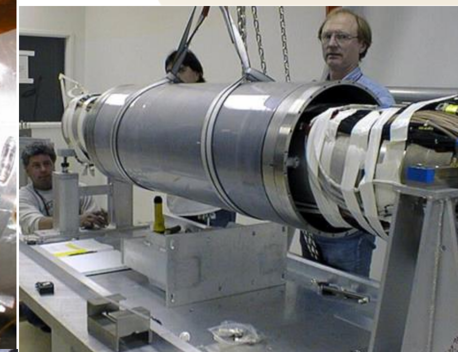






Support Tube Assembly

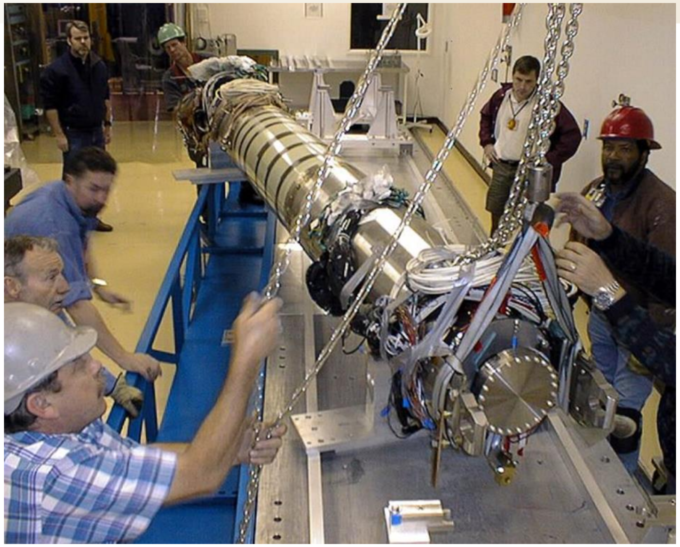
Support tube assembly started with vacuum chambers, then permanent magnets, Be chamber, silicon tracker (SVT), all cables, outer SS cylinders and then carbon fiber central tube. All components were alignment during assembly.

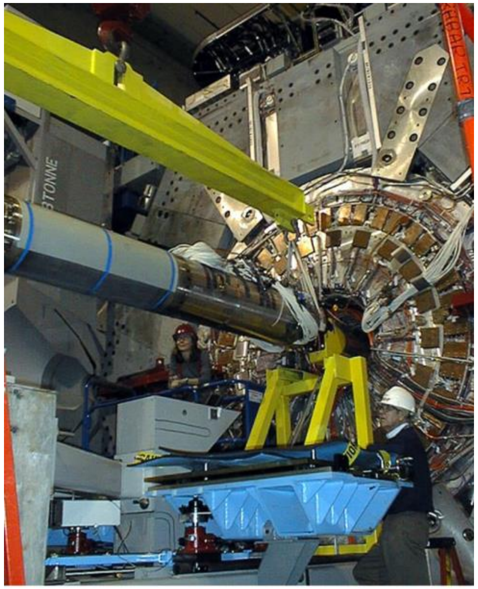





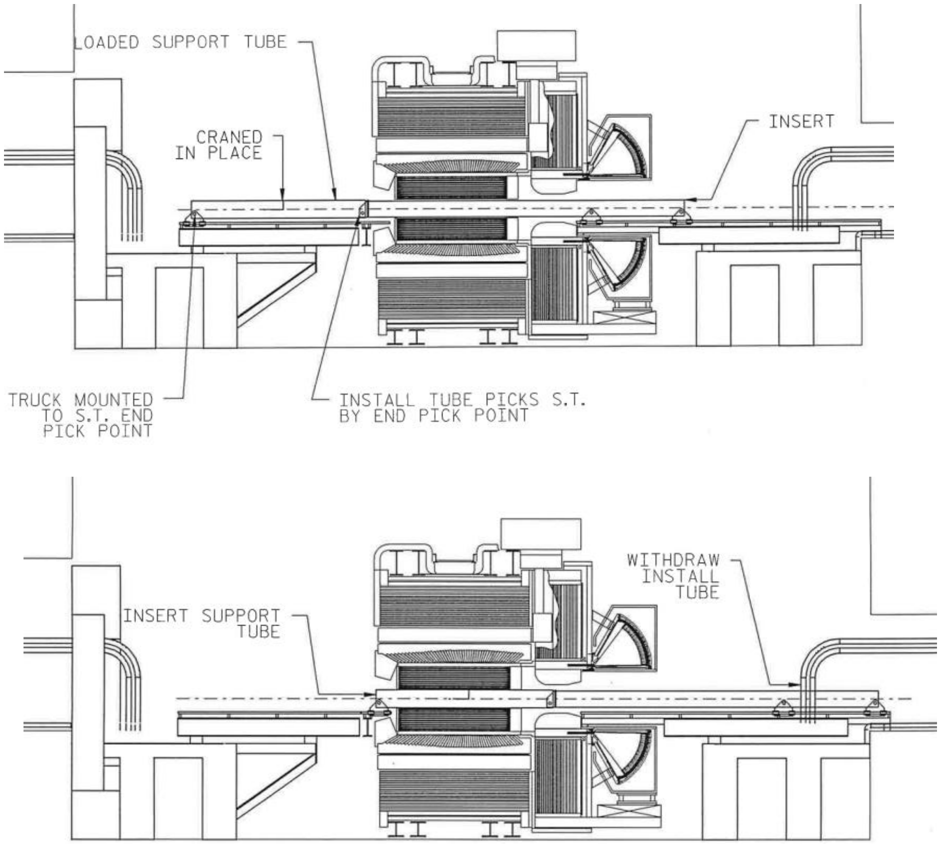



PEP-II IR Support Tube Installation



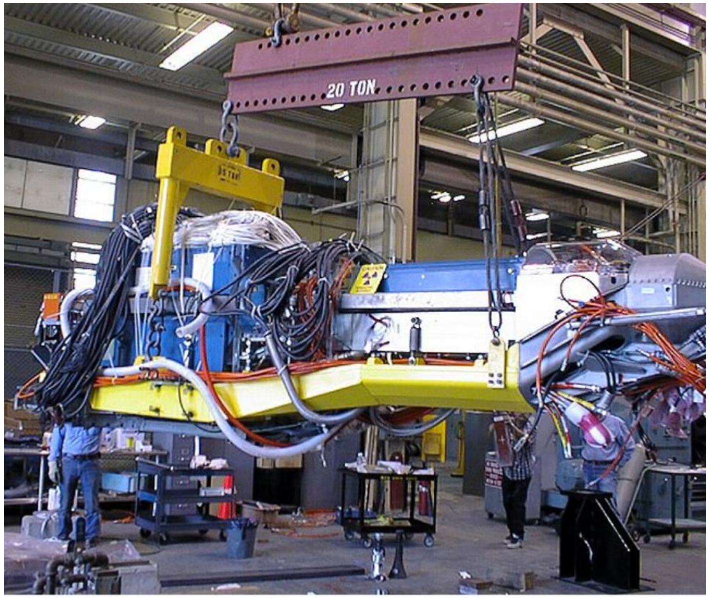


Support tube inserted with long install/withdraw tube. Tube then removed. Then left and right Q2/Q4/Q5 rafts were installed.

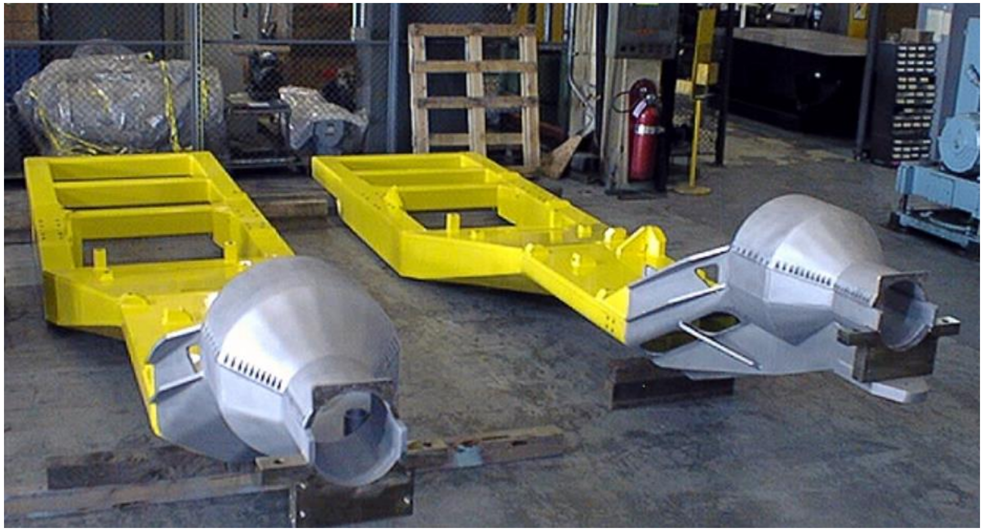


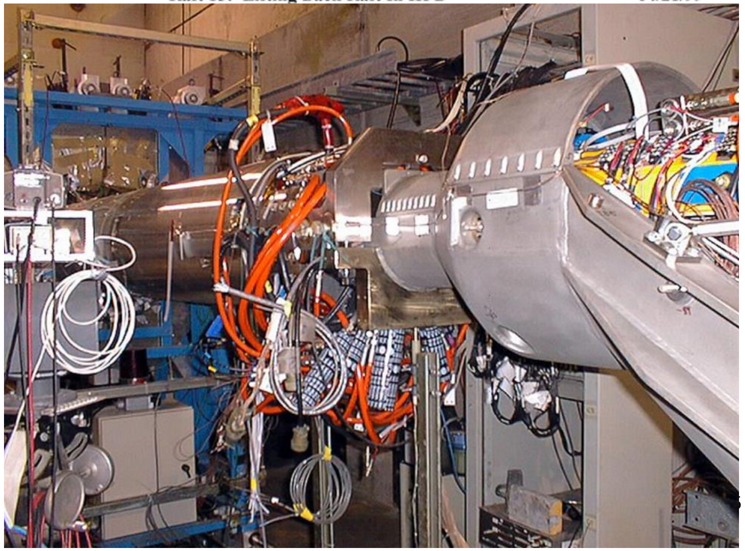
IR Raft Layout and Assembly

Q2, Q4, Q5 rafts were assembled in the shop and then installed by the overhead crane in the IR hall. These cantilevered supports were vibration sensitive and much work was invested in damping them.



Raft 15: Lifting Back Raft In HFB 04/21/99

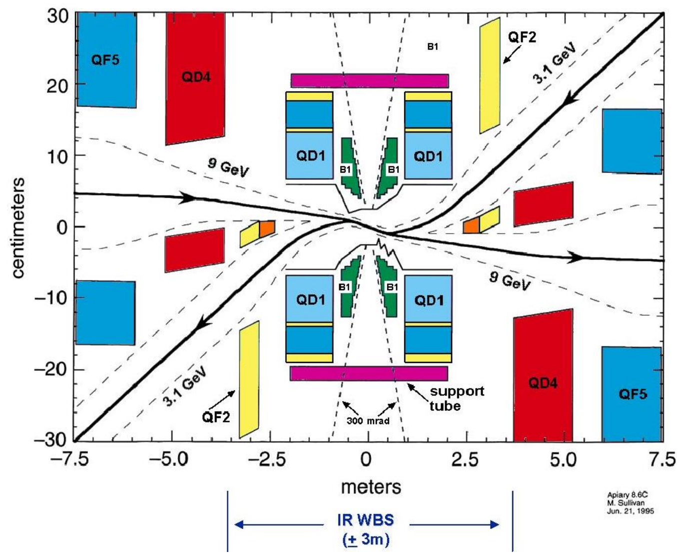




MDI background calculations (Sullivan)

Background sources: synchrotron radiation, particle losses, X-ray scattering, beam gas, mask tip scattering.

Mitigations: minimize bends, reduce vacuum pressure, collimation, masking, vacuum chamber apertures.
Codes used: EGGS4 and MAGBENDS (Sullivan)



SR power on forward Q2 mask. S.J.Metcalfe, 8/27/01
Data from MAGBENDS file dated 17 Oct '96

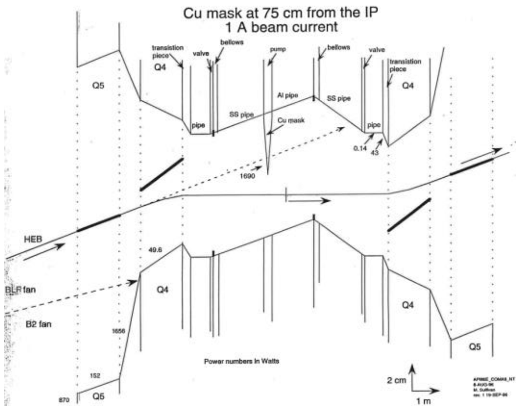
1) Radiation from Backward Q4

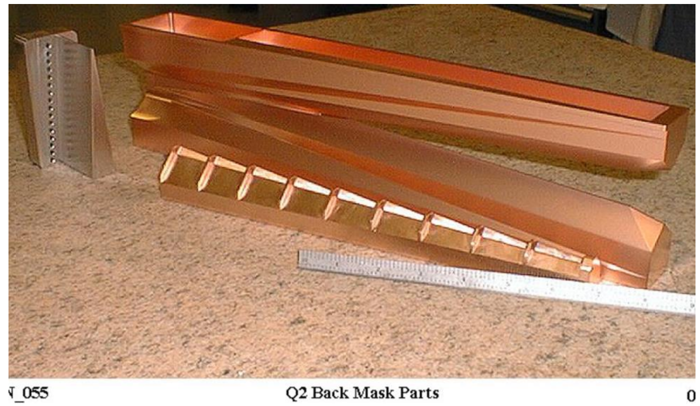
	HEB Power levels at 1A					
	X watts	Y watts	X + Y watts	Distance cm	w/cm @1A	w/cm @2A
QD4.3	293.9	5.7	299.6			
QD4.4	260.2	6.2	266.4	5.59	47.66	95.31
QD4.5	228.8	6.7	235.5	5.71	41.24	82.49
QD4.6	202.3	7.2	209.5	5.2	40.29	80.58
QD4.7	177.4	7.7	185.1	4.85	38.16	76.33
QD4.8	154.9	8.2	163.1	1.69	96.51	193.02
Q4 Totals			1359.2	23.04		

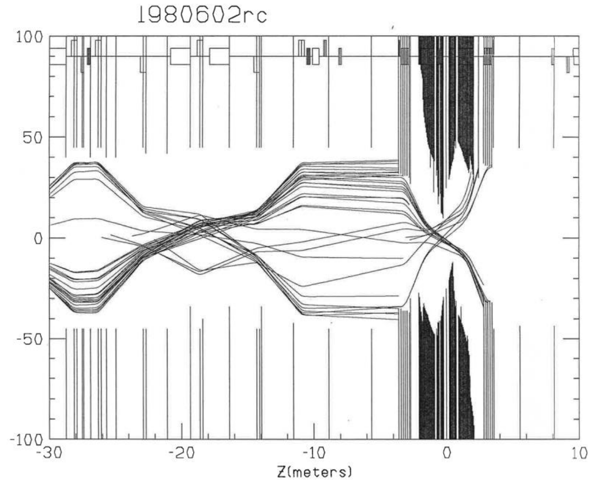
2) Radiation from Backward Q1

	HEB Power levels at 1A					
	X watts	Y watts	X + Y watts	Distance cm	w/cm @1A	w/cm @2A
QD1AM.24	6.47	2.8	9.27			
QD1AN.25	6.267	2.2	8.467	2.09	4.05	8.10
QD1AO.26	6.074	1.6	7.674	2.04	3.76	7.52
QD1AP.27	5.887	1.1	6.987	2.02	3.46	6.92
QD1BA.28	10.922	0.4	11.322	3.09	3.66	7.33
Q1 Totals			43.72	9.24		

Q1 + Q4 Total	1402.92







PEP-II HOM generation and damping (Novokhatski, Heifets)

HOM calculations for the IP region (Novokhatski code). IP wakes are in the range of about 5.3 (HER) + 13.7 (LER) = 19 kW at high currents. Measured overall HER HOM total power is about 2x expected. LER is about right. Measurements use the total RF power versus current. HOM ~ I^2.

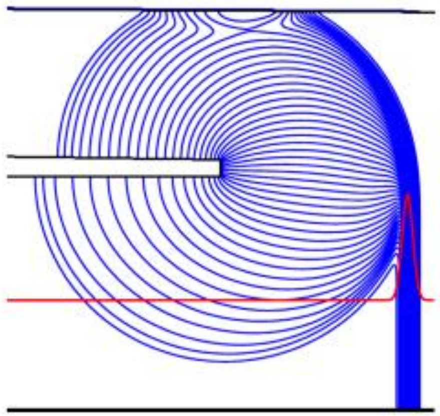
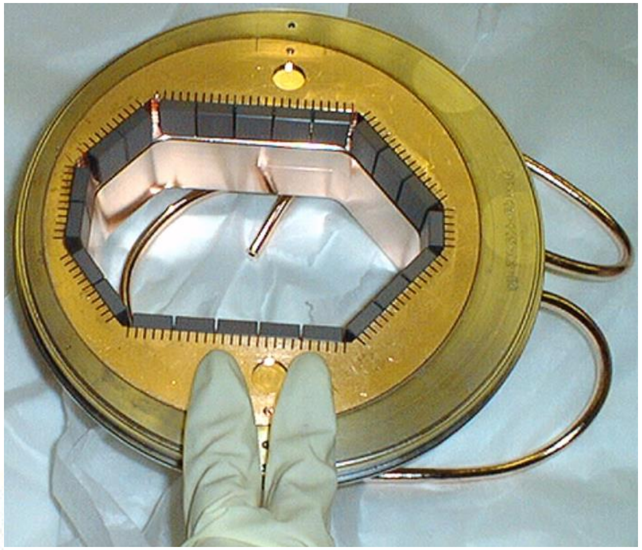


FIG. 1. Electric force field line distribution at the time when a relatively short bunch has just passed a pipe connection. The red line shows the bunch line charge density distribution and the bunch trajectory.



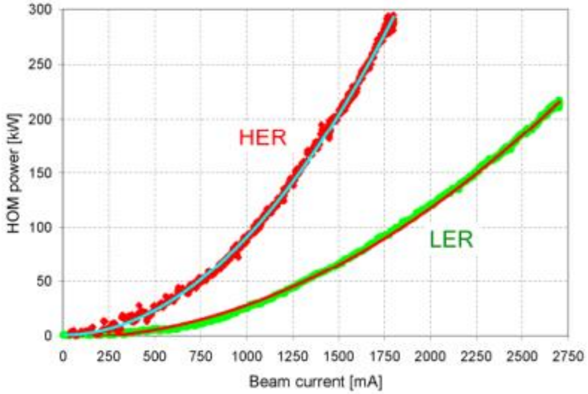


Figure 8: Total HOM power.

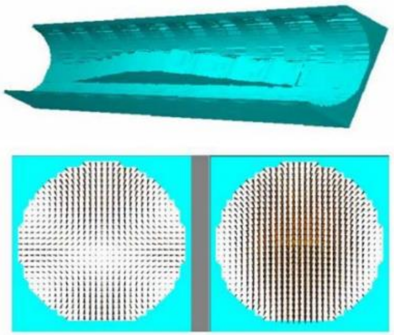


Figure 1: Collimator generates dipole and quadrupole fields after the passage of a 1.3 cm long Gaussian bunch. These are two snapshots at the same location separated in time.

Table 1: Calculated and Measured HOM Power in PEP-II

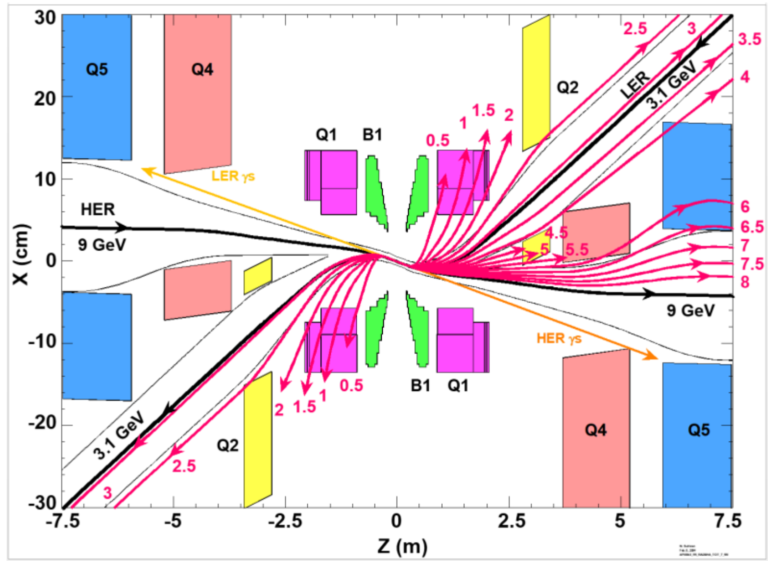
Vacuum element	LER 2900 mA Power [KW]	HER 1800 mA Power [KW]
RF cavities	63.46	76.16
Collimators	18.11	16.7
Kickers	17.3	6.08
Screens	1.24	5.5
BPMs	9.4	3.6
IR wakes	13.66	5.26
Resistive wall	71.74	36.15
Total power	195	167
Measured power	**210**	**298**

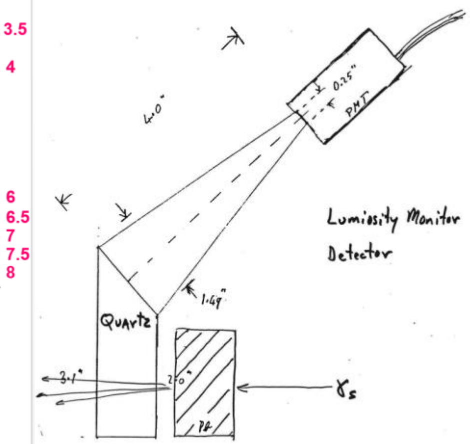
PEP-II Luminosity Measurements (C. Field, M. Sullivan)

Luminosity signal =
e+e- → e+e- γ (HER γ)

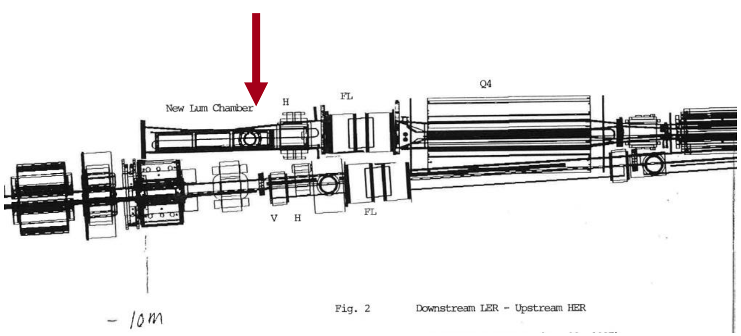
γs have energy from 1 to 5 GeV.
γ rate is ~1 MHz.
Luminosity was measured in each of the 1732 bunches to ~few % in 1 second, allowing real time tuning.

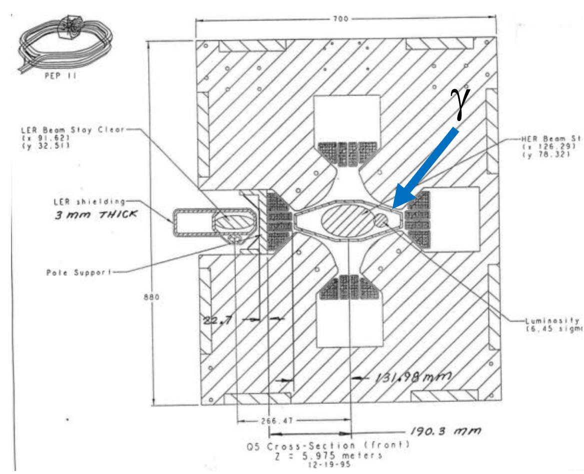
A very accurate luminosity measurement came from BaBar.



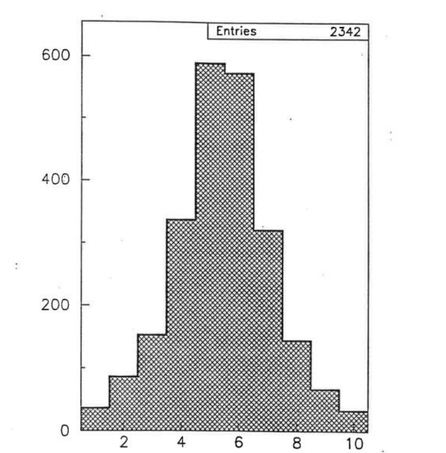


Fast luminosity monitor





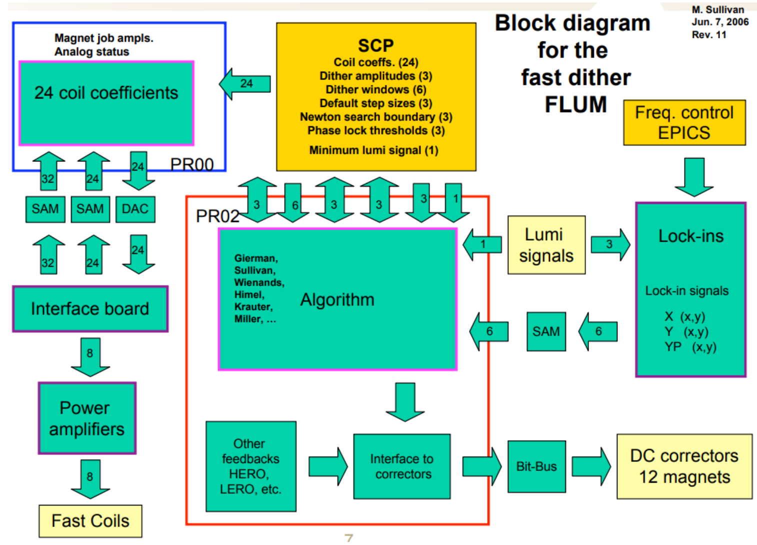
Number of hits in cells after 5 X0 at threshold 3. MeV



Dither IP feedback (~20 Hz) (Fisher, Hendricks)

Global steering kept the orbits stable on the minute time scale.

Fast IP luminosity feedback (1-10 Hz).
Feedbacks x, y, y' handled simultaneously but at different frequencies (~80 Hz). Air Core dipoles.
The luminosity signal was the input.
Rapid steering to maximize the luminosity.



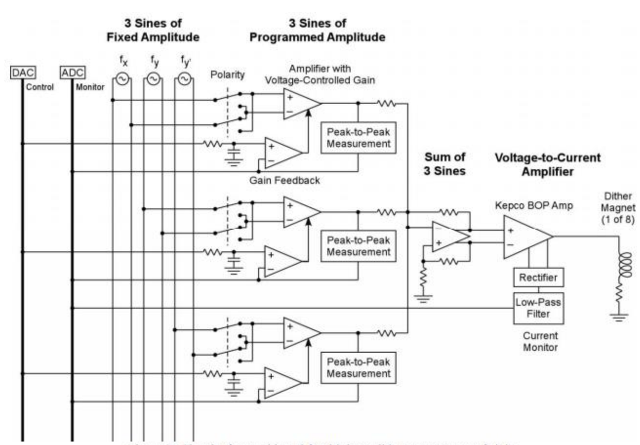


Figure 2: Sketch of control board for driving a dither magnet, one of eight.

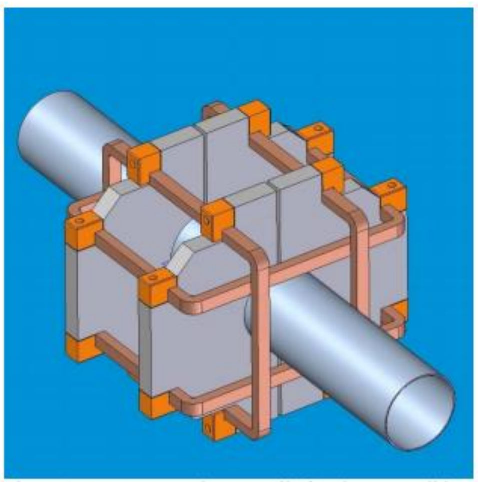
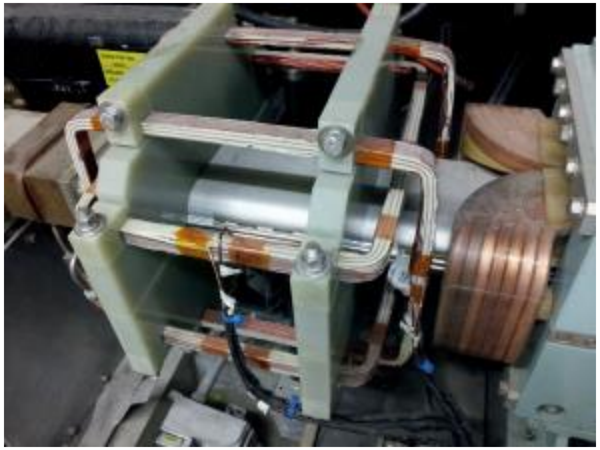


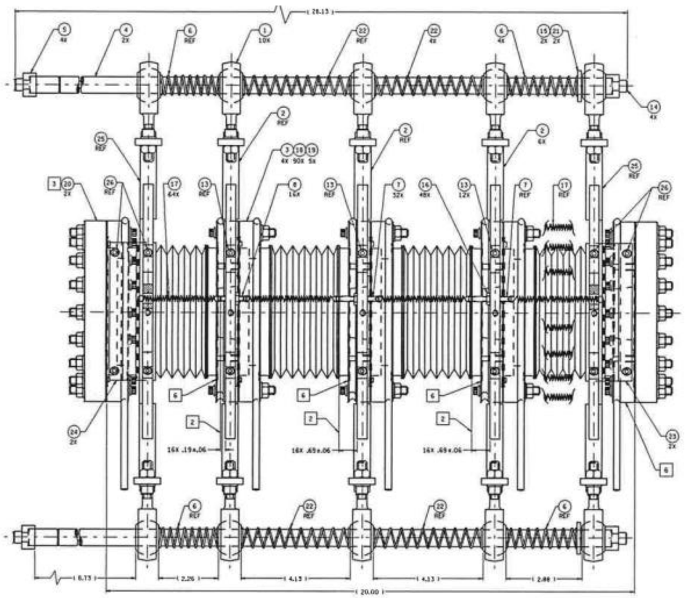
Figure 1: Low-power air-core coils for sine-wave dither, one of four installations.

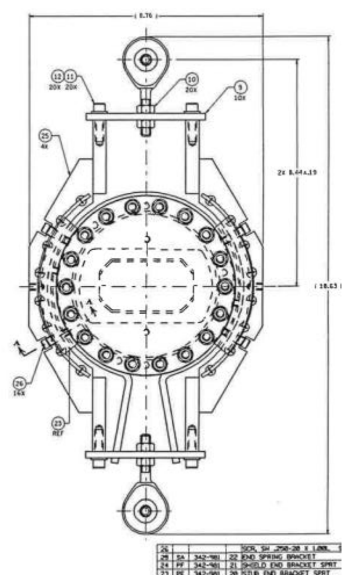


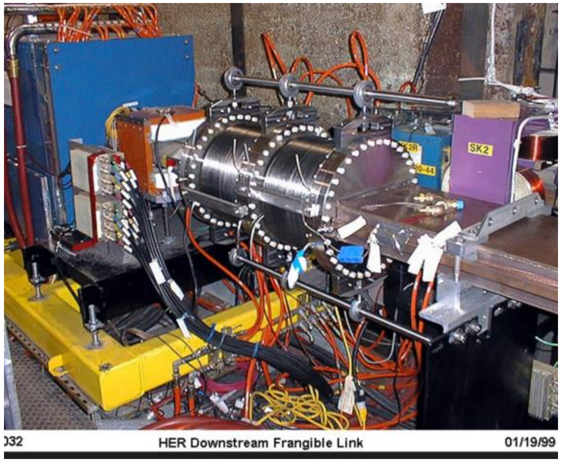
Earthquake Safety for BaBar and PEP-II

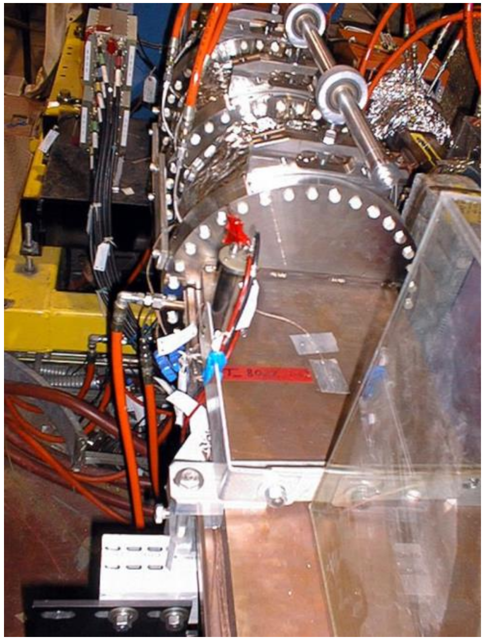
Goal: Protect BaBar and PEP-II from earthquakes.

BaBar is on earthquake isolators.
PEP-II accelerator tied to the ground.
To keep PEP-II from hurting BaBar, two HER and two LER disposable vacuum links on both sides of BaBar were made, called “Frangible Links”. Sturdy but compliant!
The allowed motion was +/- 0.3 m before major damage occurred.
The HER units had a large bore (~ 20 cm) and heavy of order 500 kg. See photos.









PEP-II IR Conclusions

Major topics for the PEP-II IR:

- Needed beam parameters (high currents, low β_y*, two rings, no dispersion)
- Optics with chromatic corrections
- Beam-stay-clears
- BaBar-PEP-II separation angle
- Quadrupoles and dipoles designs and inside BaBar
- Supports for accelerator components and minimize vibration
- Fast luminosity measurement (few % accuracy at ~1 Hz)
- Vacuum pumping and pressure
- HOM minimization and damping in the IR
- Vibration control of FF quadrupoles
- Background suppression (beam loss, injection, synchrotron radiation, collimation, masking)
- Beam diagnostics
- Beam steering
- Detector solenoid field measurements and compensation for PEP-II
- Keeping the beams in collisions with dither feedback
- Earthquake safety