SSC Parameter Review

Tanaji Sen
FNAL

Joint Snowmass-EuCARD / AccNet-HiLumi LHC workshop
February 21-22, 2013

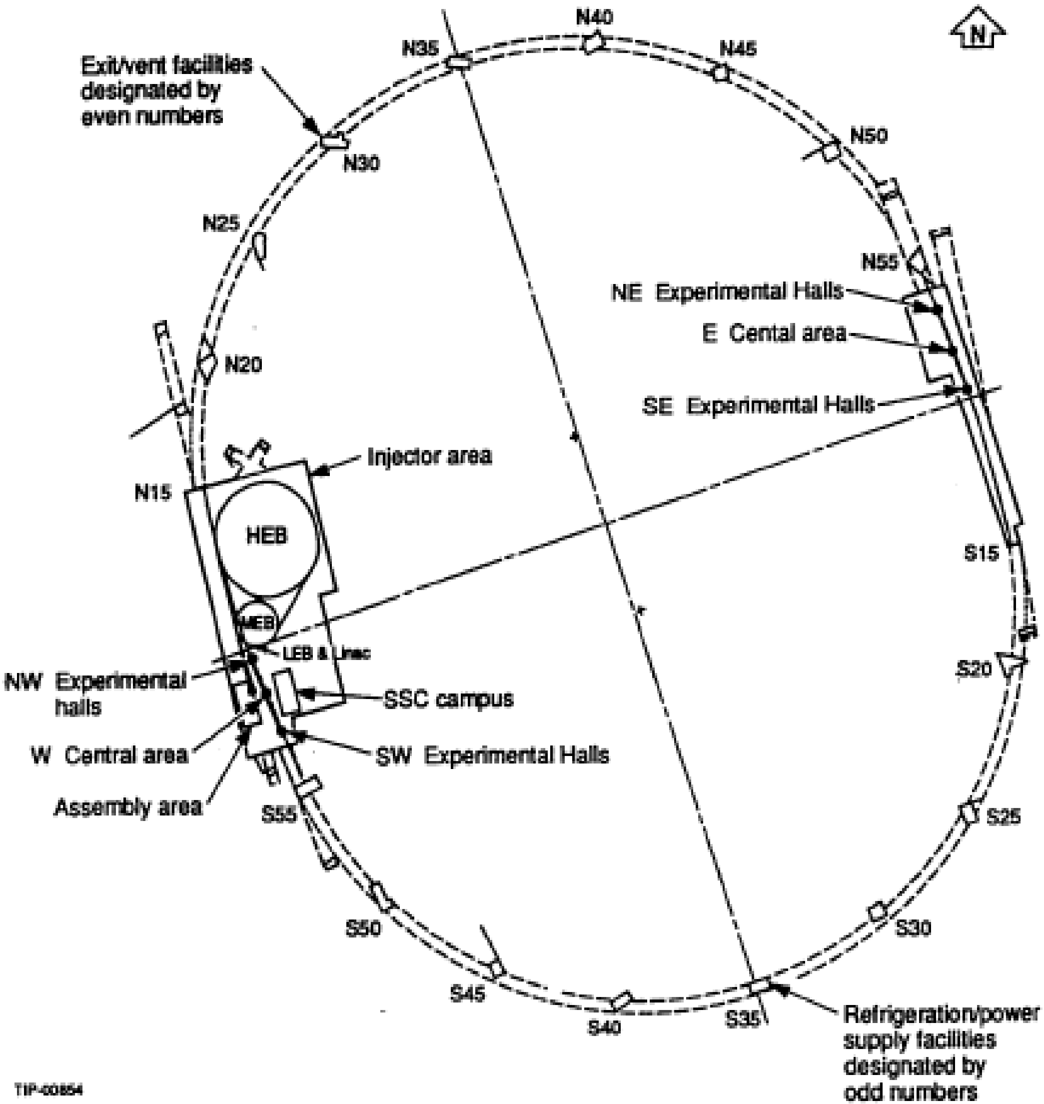
SSC Timeline

- 1984 : Central Design Group forms at LBL
- 1986 : Conceptual Design Report
- 1989 : Waxahachie, TX picked for SSC site. Start of SSC Laboratory
- 1990 : Site Specific Conceptual Design Report
- 1991 : Construction of Magnet Development Lab and other sites
- 1992 : Successful test of a half cell
- Oct 1993 : SSC terminated. Tunnel construction about 20% complete.

Main Parameters

	Value
Beam energy [TeV]	20
Initial Luminosity[$cm^{-2}s^{-1}$]	10^{33}
Circumference [m]	87120
Bunches/beam	17240
Particles /Bunch	0.75×10^{10}
Beam current [mA]	71
Bunch spacing [m] / [ns]	5 / 16
Cycle time [h]	24
Trans. norm. emitt [mm-mrad]	1
Beta at IP [m]	0.5
Synch. rad. power/beam [kW]	8.75
Beam stored energy [MJ]	418

SSC Ring



Collider

- Two arcs, each 35 km, 196 FODO cells
- Interaction Regions with up to 4 IPs, two on each side.
- Two utility sections, on the east and west sides for IRs, beam injection, Rf, collimation etc

Choices of select parameters

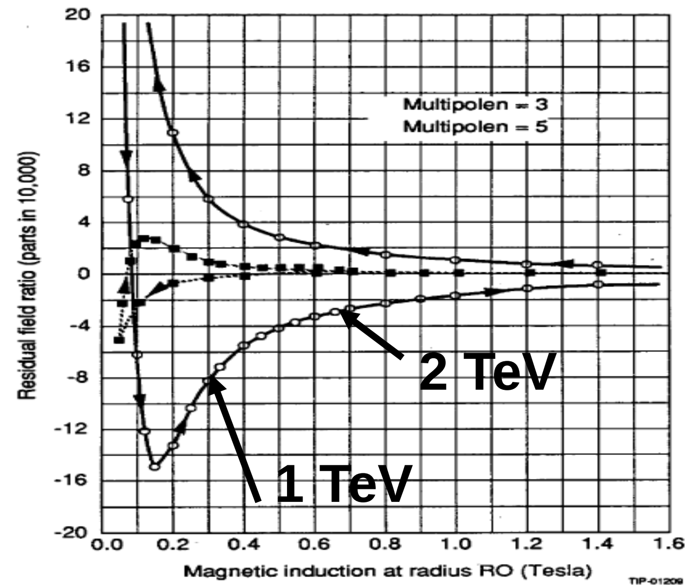
- Cell length
- Injection Energy
- Dipole coil aperture

Cell length

- Initial (1986) half cell length = 114.25m, phase advance = 60^o
- In the SCDR (1990) half cell length shortened to 90m, phase advance = 90^o
- Beta function ~ L, dispersion ~ L^2, so beam size with energy spread reduced by 20%.
- Tune shift due to systematic error multipoles ~ L^n, n > 2; e.g. chromaticity from systematic sextupoles ~ L^3. So, this chromaticity was halved. Larger effect with higher order multipoles.
- Shorter cell length with stronger focusing increased the number and length of quadrupoles.

Injection Energy

- Injection energy in CDR was 1 TeV
- In the SCDR, raised to 2 TeV for:
  - Persistent current multipoles decrease
    e.g. sextupole comp b_3 reduced by 2, Including cell length decrease, chromaticity at injection due to persistent current b_3 reduced from 3400 to 700 units.
  - Relaxed alignment tolerance of dipoles eliminated need of bore tube correctors in dipoles. Only lumped correctors in cell.
  - Smaller beam size
- But increased size of HEB injector
- Larger quad aperture and different tunes increased DA and possibility to lower injection energy to 1.5 TeV



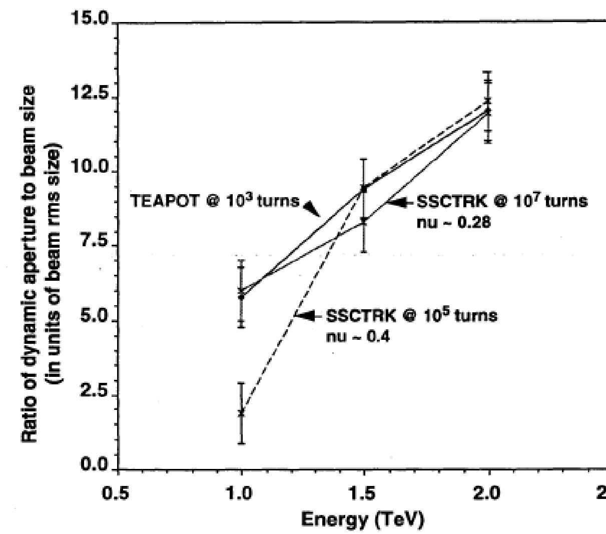
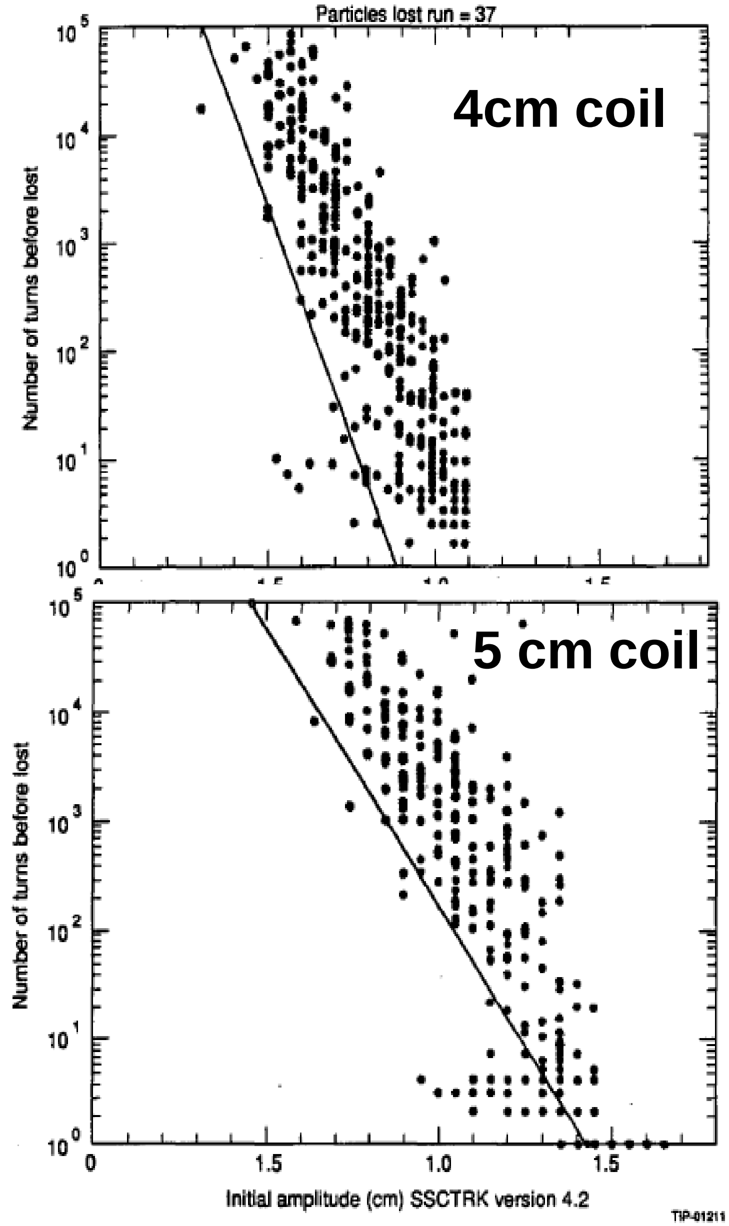


Figure 8-1. Graph of Calculated Dynamic Aperture versus Injection Energy.

Dipole Coil Aperture

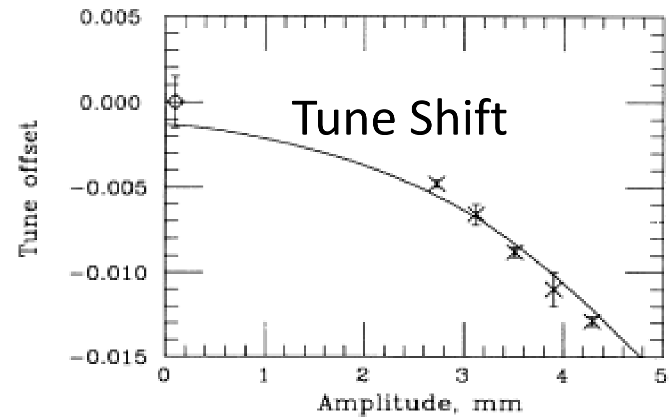
Survival Plots

- Systematic multipoles in dipoles scale with coil radius R_0 as $b_n \sim 1/R_0^{(n-1)}$ European
- Tevatron and HERA dipoles were used to generate multipole tables.
- Tracking simulations showed that going from 4cm to 5cm coil aperture, the dynamic aperture increased 1.6 times
- Dipole aperture raised to 5 cm in 1990 from 4 cm (CDG value)
- Increased operational margin due to lower current density
- Hotly debated issue. Increased cost by $1B.

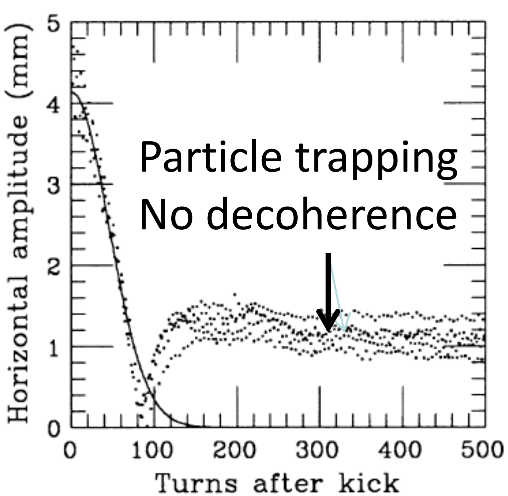


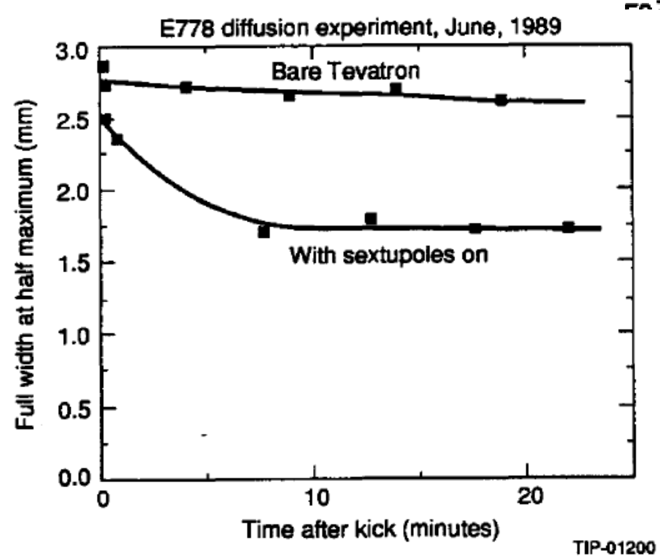
E-778 – testing magnet aperture criterion

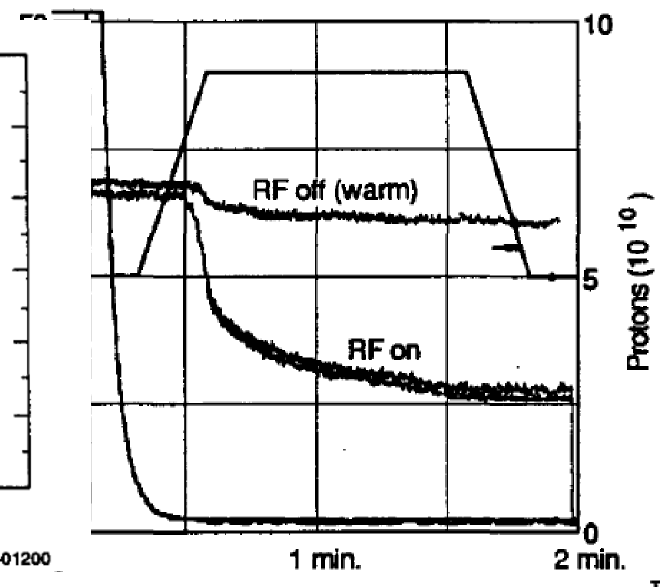
- Experiments in the Tevatron, at the request of HEPAP
- 16 strong sextupoles powered, beam excited with a pulsed kicker
- Compared tune shift and smear with theory
- Observed particle trapping in resonance islands
- Observed effects of modulation diffusion on beam lifetime



A. Chao et al, PRL, **61**, 2752 (1988)



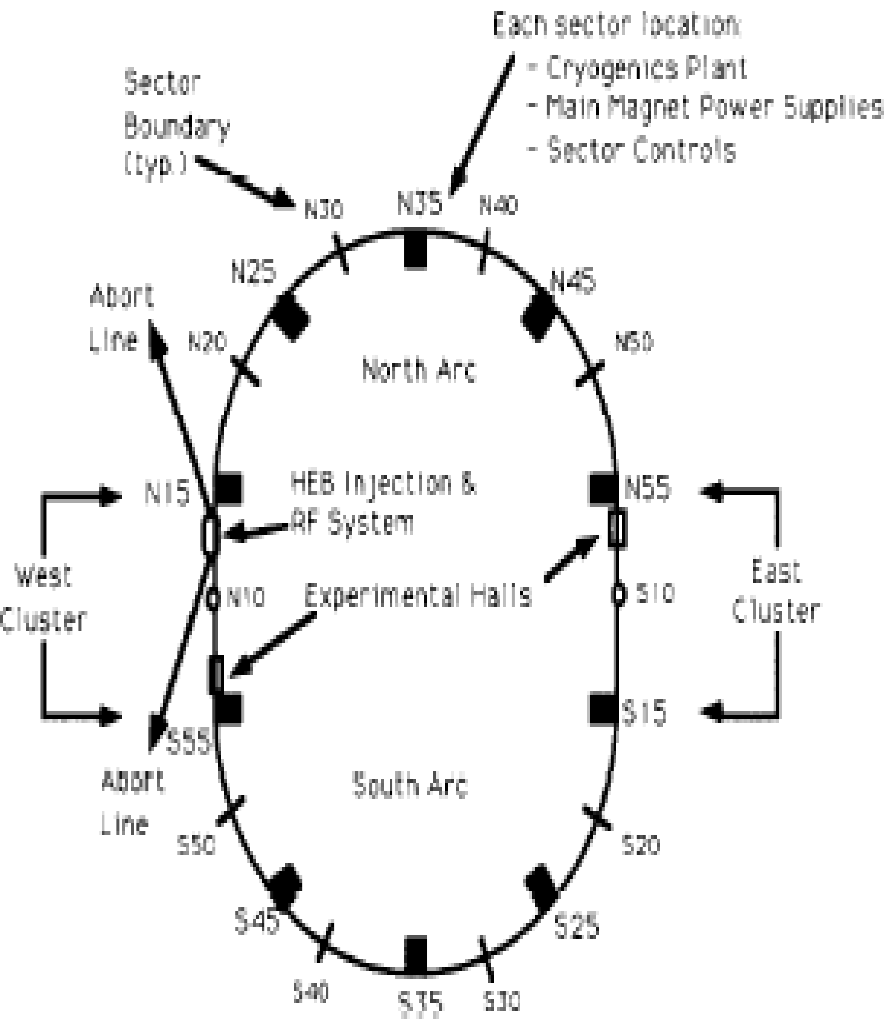




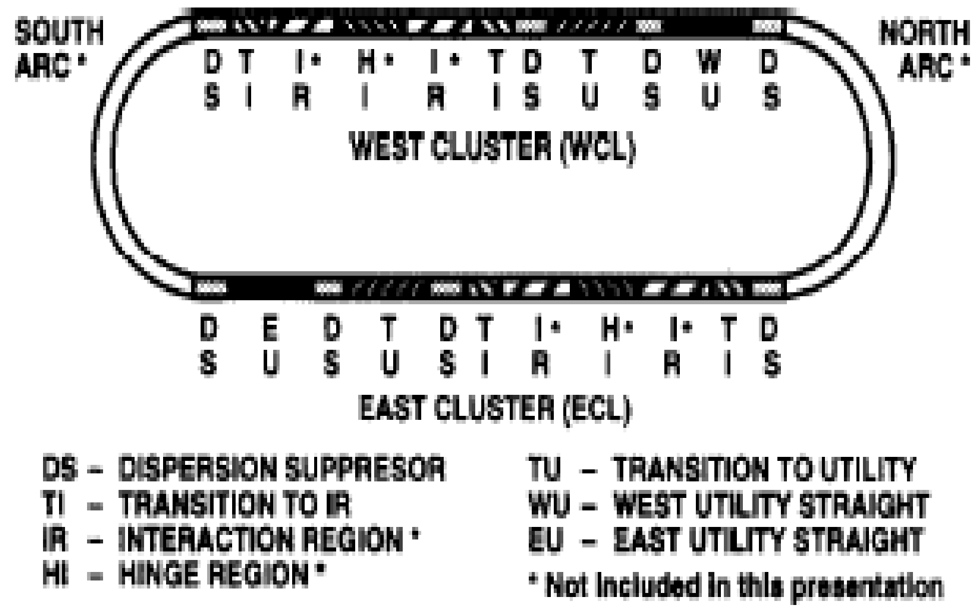
Evolution of Collider Arc Parameters

	1993	1990 SCDR	1986 CDR
Injection Energy [TeV]	2	2	1
Circumeference [m]	87120	87120	82944
Half Cell Length [m]	90	90	114.25
Cell phase advance [^{0}]	90	90	60
Dipole coil diameter [cm]	5	5	4
Dipole field [T]	6.79	6.6	6.6
Quad coil diameter [cm]	5	4	4
Quad field]T/m]	194	206	212
Total crossing angle [μrad]	135	135	75

Straight Sections



15 Service areas, 1 or 2 shafts at each



- West Utility straight had: beam injection from the High Energy Booster, Rf cavities, scrapers for removing beam halo, damper systems, beam extraction, beam instrumentation
- East cluster had the low-beta IRs. Momentum collimation & crystal extraction envisaged.

Selected optics & dynamics issues

- IR design
- IR chromaticity correction
- Beam-beam interactions
- Synchrotron radiation and vacuum
- Luminosity evolution

Interaction Region Layout

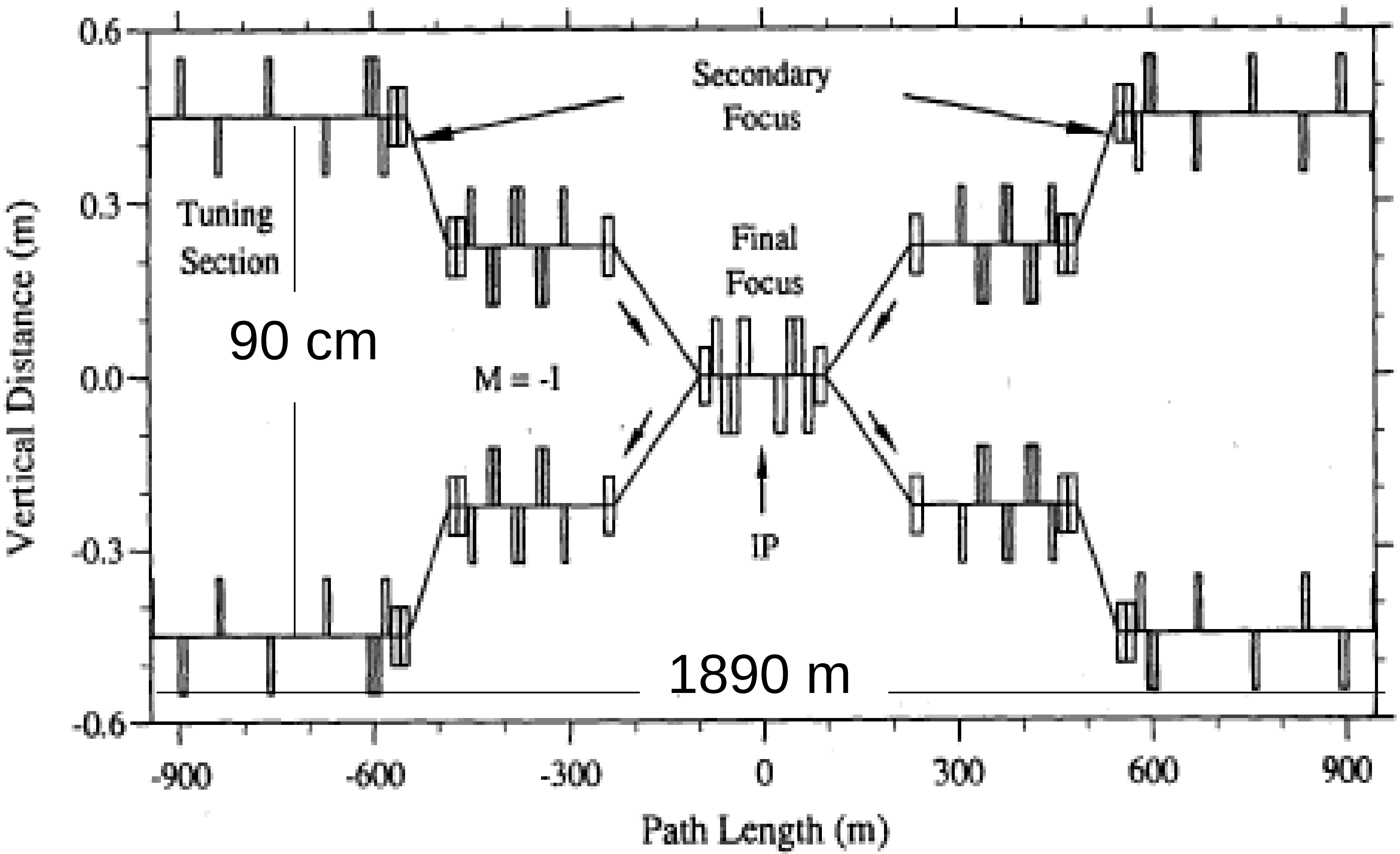
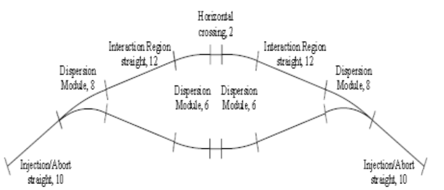


Figure 9-1. General Layout of the Interaction Region.

Features of the IR Design

- Independent tuning section for the beta squeeze in each ring. Inner triplets do not change during squeeze.
- Phase advances μx and μy and transfer matrix across IR kept constant during squeeze.
- A secondary focus on both sides where IP is imaged, 2 π from IP. Possibilities for diagnostics & halo collimators.
- Optimum phase advances for local IR correction
- Values of L* from 20.5m to 90m with corresponding β* from 0.25m to 1.95m. (Lengths, positions) of inner triplets and positions of adjacent dipoles adjusted.
- 2 in 1 magnets for the M=-I section. This section zeros the vertical dispersion at the IP.
- Phase advance of π/2 between adjacent IPs for chromaticity cancellation.
- Diamond bypass in each cluster for 2 additional IRs



IR chromaticity correction

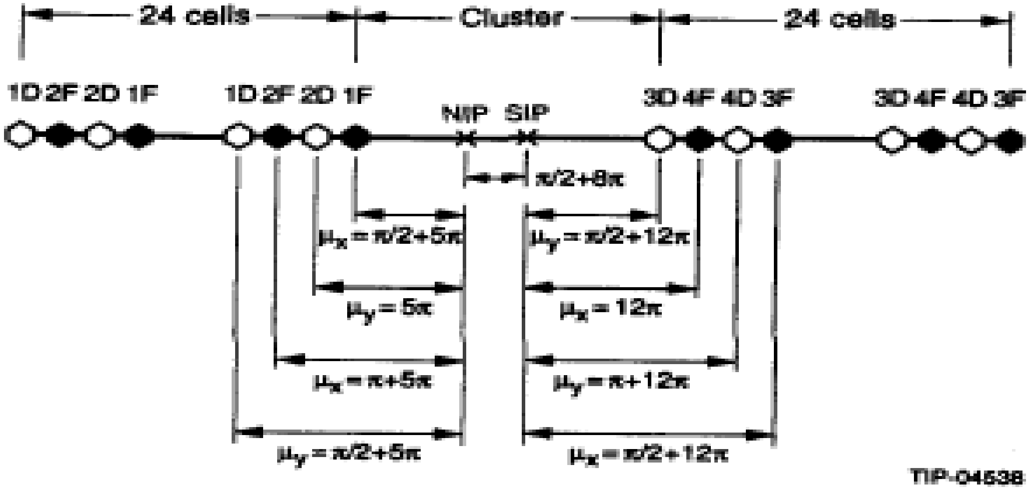


Figure 1. Local Sextupole Distribution.

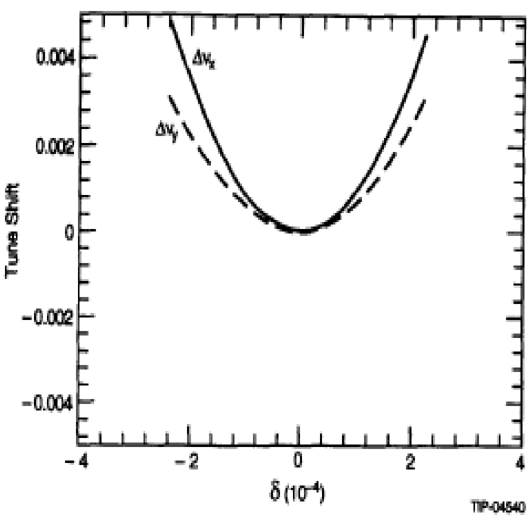


Figure 3. Tune variation with δ : Global correction.

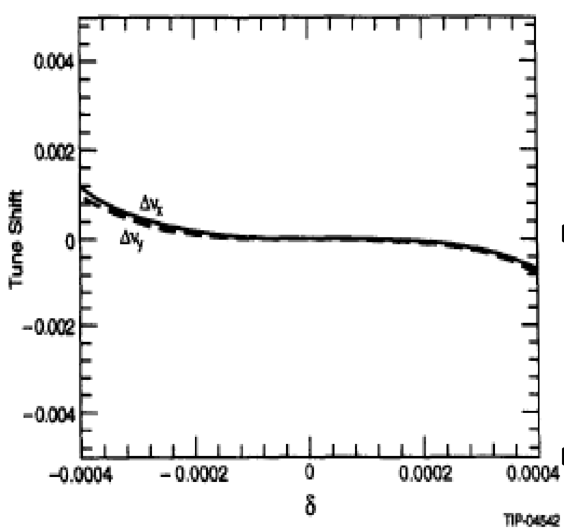


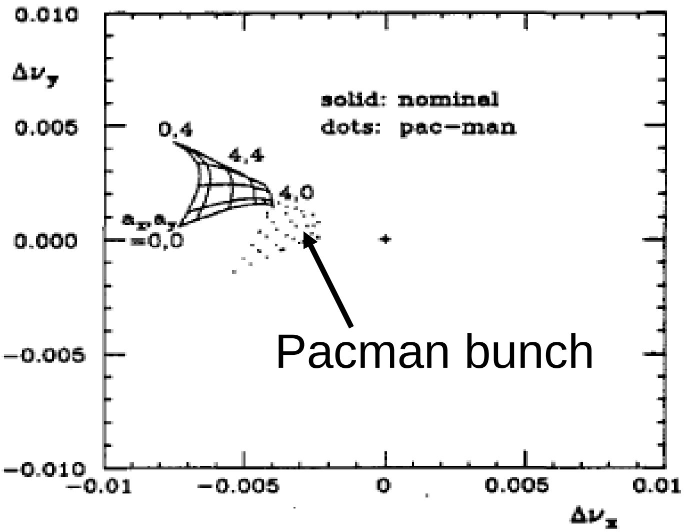
Figure 5. Tune variation with δ : Local correction.

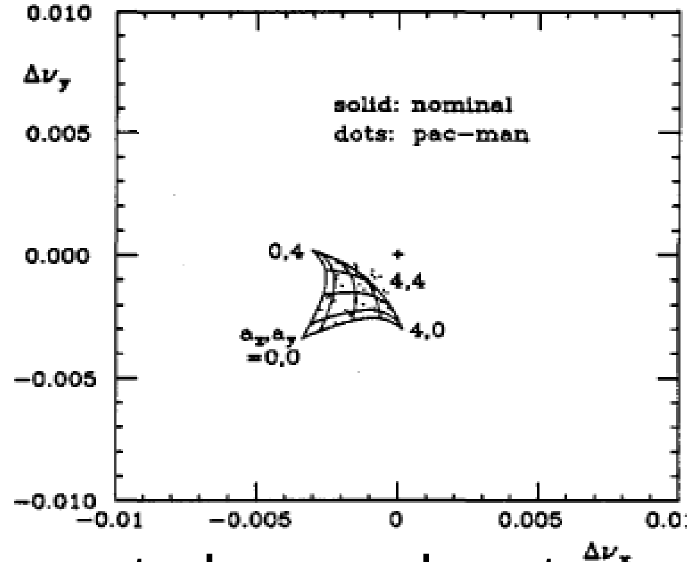
- Global sextupoles correct for linear chromaticity.
- Local scheme corrected for 2nd order chromaticity with zero linear chromaticity
- Phase slip between local sextupoles gives better cancellation of chromatic beta wave
- Momentum aperture increased more than 3-fold
- Correction worked with unequal β* at adjacent IPs

Beam-beam issues

- Beam-beam parameter=0.001
- Total head-on tune shift=0.004, long-range tune shift=0.007, long-range tune spread=0.002
- Pacman effect named for outlier bunches
- Synchro-betatron resonances due to crossing angles
- <u>Diffusion due to long-range interactions</u>
- Coherent beam-beam effects
- Head-on beam-beam compensation with electron lens proposed

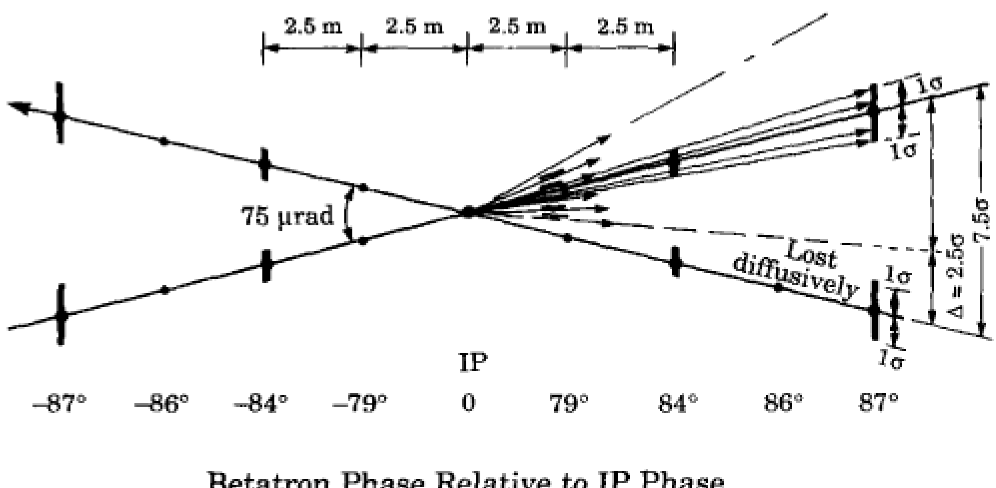
Beam-beam effects



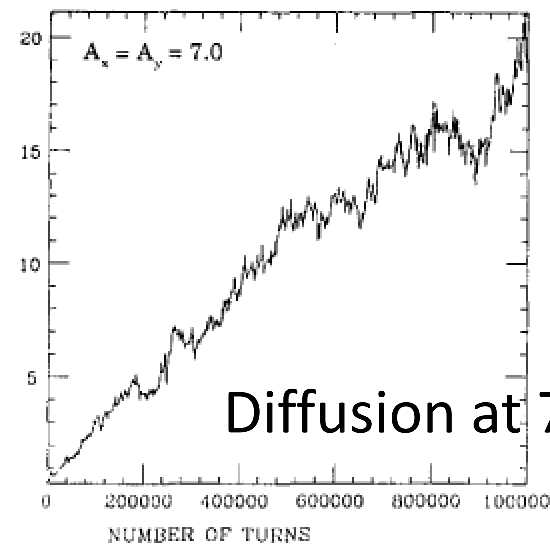


Vertical crossing at 4 IPs

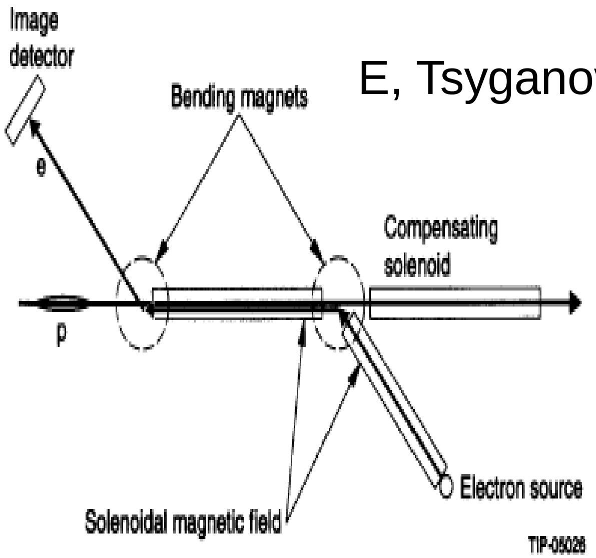
Alternate hor. and vert. crossings



Number of LR interactions on each side ~ 30



Head-on beam-beam compensation



E, Tsyganov et al

Figure 5. Schematics of a beam-beam compensating device. A low-energy electron source collides with a bunch of protons. Electrons are kept stable in space by a solenoidal magnetic field. After collision with the proton bunch, an electron beam is deflected to the image detector, which is used to steer the electron beam relative to the proton bunch.

- Proposed use of a low energy electron beam to compensate kicks of opposing proton beam
- Transverse distribution of e-beam should match that of p-beam
- 10 keV e-beam pulse 2m long, 32 mA
- 2T solenoid field for transverse stability of e-beam. Compensating solenoid acts on p-beam

Synchrotron Radiation and Vacuum

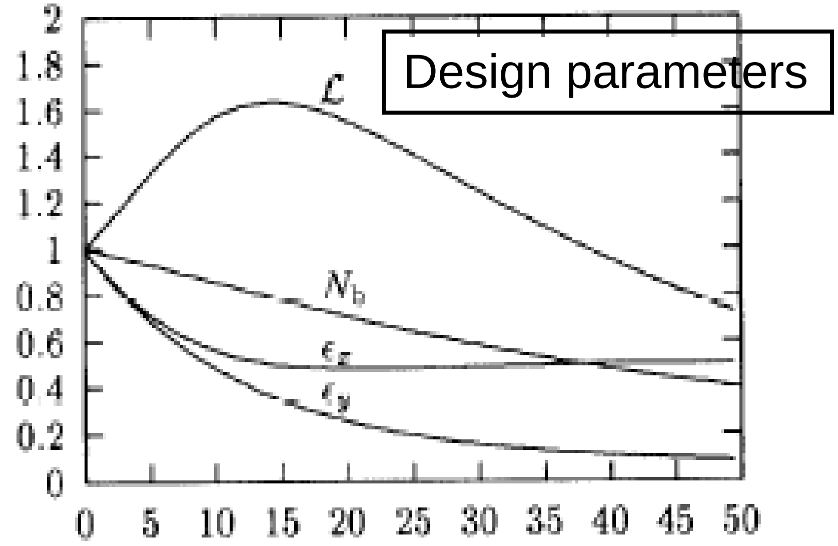
	SSC	LHC
Top Energy [TeV]	20	7
Energy lost/turn [keV]	127	6.7
Synch. Rad. Power/beam [kW]	9.9	3.6
Power density in dipoles [W/m]	0.16	0.21
Critical energy [eV]	292	44
Long. Emit. Damping time [h]	6.3	13
Trans. Emit. Damping time [h]	12.7	26

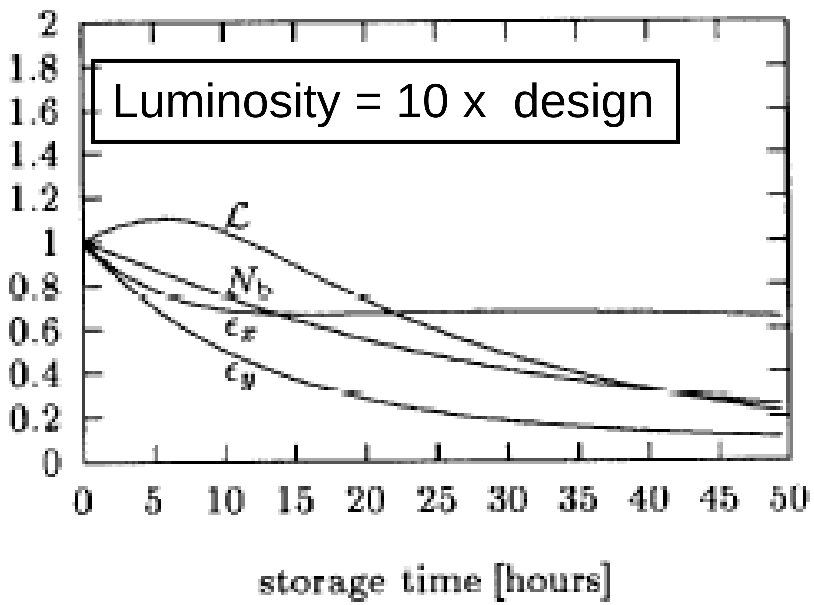
Vacuum

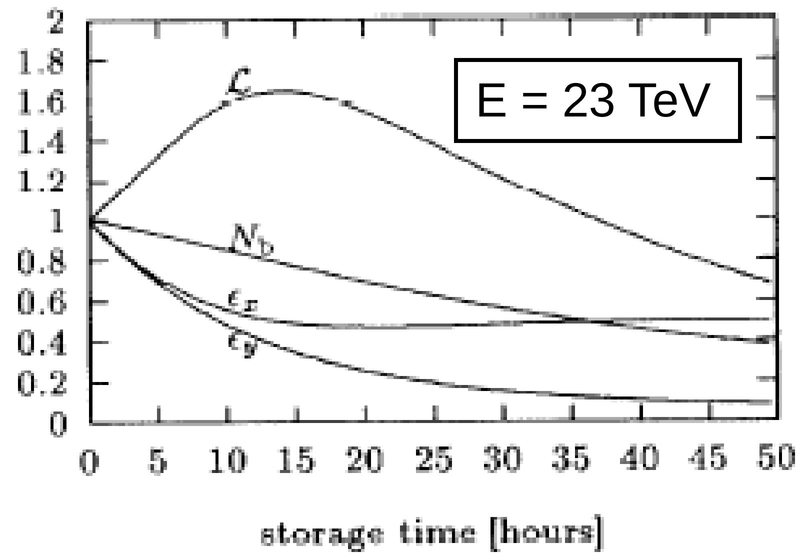
- CDG data on photo-desorption suggested feasibility of a liner at 80K. Engineering design of a liner at 80K was done.
- Later experiments showed that liners at 4.2K and 20K would mostly work better. Their design was under development

Parameter Evolution During A Store

Model included
- pp scattering
- Synchrotron radiation
- IBS
- Rest gas scattering
- Other sources for 10% of total beam loss
- Beam-beam tune shift increases initially







Electron Cloud	SPS	SSC Store	LHC Inj/Store	VLHC - II Inj/Store
Machine radius [m]	1100	13201	4243	37089
Energy [TeV]	0.026	20	0.45/7	10/87.5
N_b [$x10^{10}$]	6	0.75	10	0.9
Chamber half height [mm]	22.5	16	17.4	10
Beam radius [mm]	3.2	0.126	1.1 / 0.29	0.21/0.074
Bunch length [ns]	1.0	0.24	0.43/0.25	0.27/0.087
Bunch spacing [ns]	25	16	25	18.8
Av. elect. energy gain [eV]	112	8.3	727/1093	24/31
Beam potential well [kV]	0.52	0.58	2.7 / 6.5	0.5 /2.0

- Not considered during the SSC
- Post analysis during the VLHC design phase
- Most likely would not have been an issue

Other Beam Physics Research at the SSC

- Slow extraction using bent crystals
- Echo effect in accelerators
- Differential algebraic methods and Taylor maps for long term particle tracking
- Noise and modulation effects on emittance growth, luminosity
- Longitudinal dynamics with rf noise
- Effects of ground motion
- ……

Rf system

- Peak voltage = 20 MV
- Frequency = 360 MHz
- 10 single cell Nb cavities per ring
- 2 cavities fed by a 200 kW klystron
- Accelerating voltage during ramp = 5.23 MV
- Accelerating voltage at store = 0.123 MV
- Design evolved from room temperature PEP style to superconducting LEP style cavities

Early Dipole Magnet Designs

P.F. Dahl, SSCL-220 (1990)

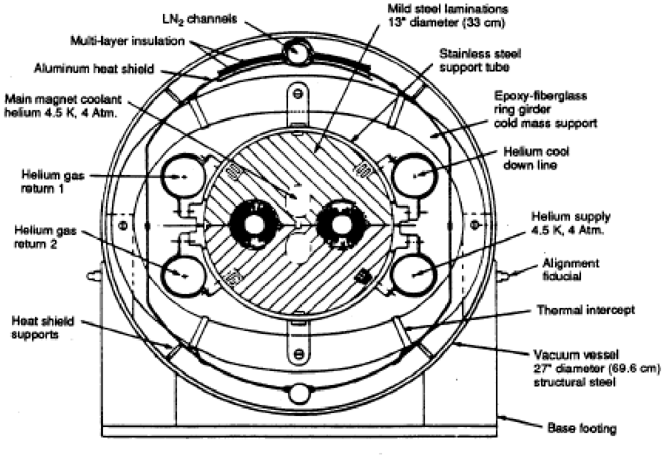


Figure 2-1. Cross section of Reference Design A dipole, including cryostat and support assembly.

A: 2-in-1, cold iron, no collar; 6.5 T

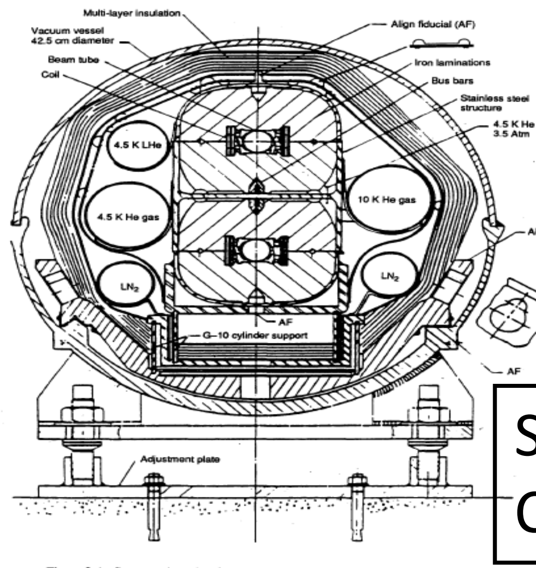
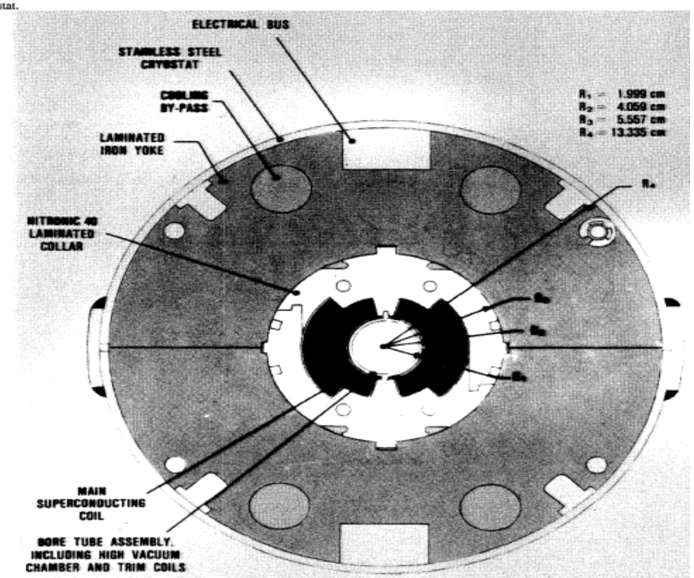


Figure 2-4. Cross section of Reference Design C superferric dipole and cryostat.

C: super-ferric; 3T

SSC Design: Collared Coils Cold Iron; 6.6 T



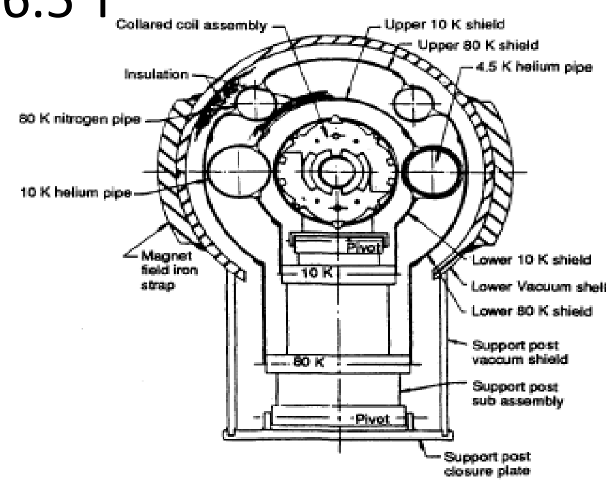


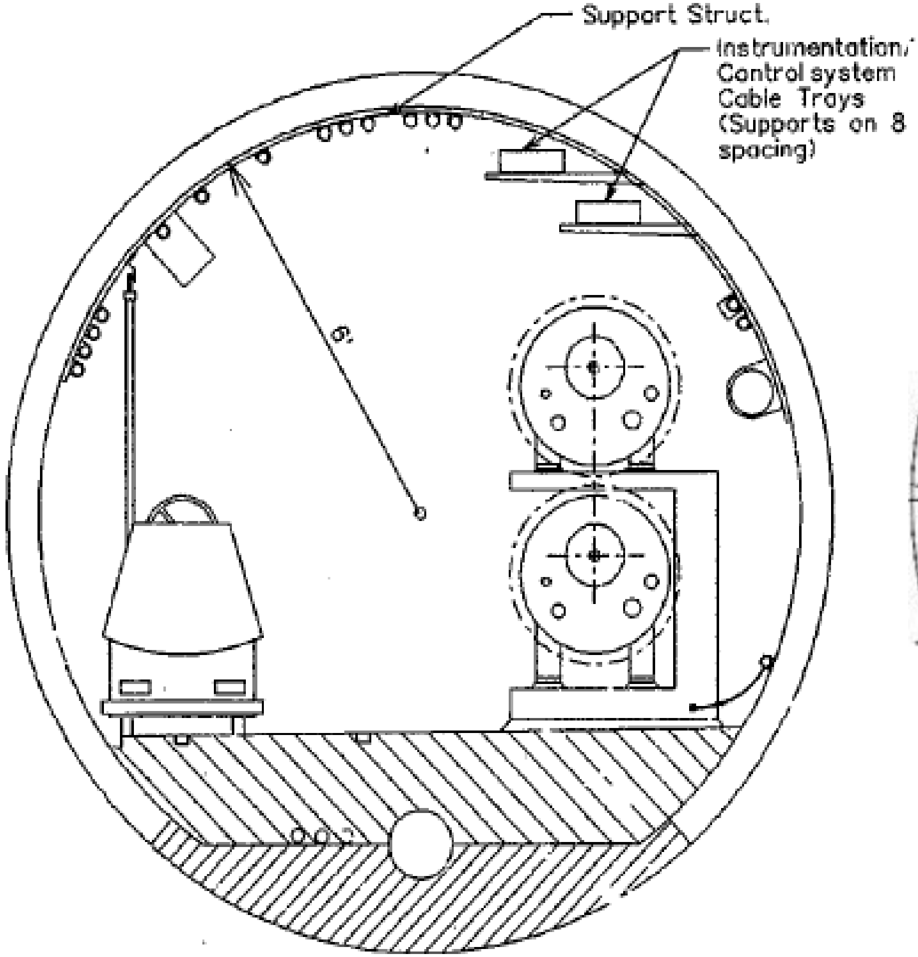
Figure 2-3. Reference Design B dipole and cryostat cross section.

B: collared coil, no cold iron; 5 T

Magnets and Tunnel

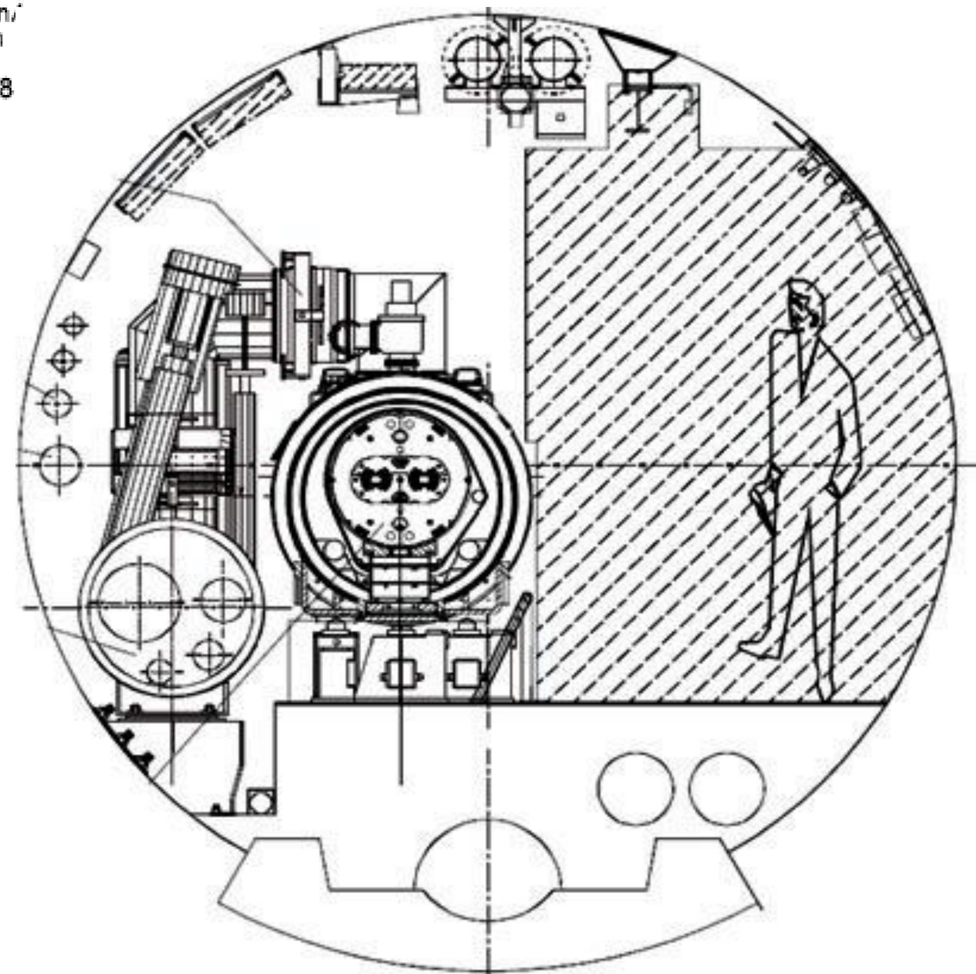
- Magnets were in separate cryostats
- Magnets in the 2 rings separated vertically
- Required a tunnel to accommodate both sets of cryostats and a transport vehicle
- Tunnel dimension: 12 ft inner diameter
- 18 shaft locations. Magnet shafts had 55 ft diameter, others were 30 ft and 15 ft.

SSC and LHC Tunnels



3.7 m

SSC tunnel



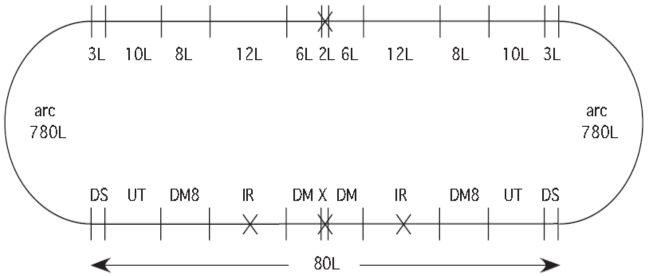
3.8 m

LHC tunnel

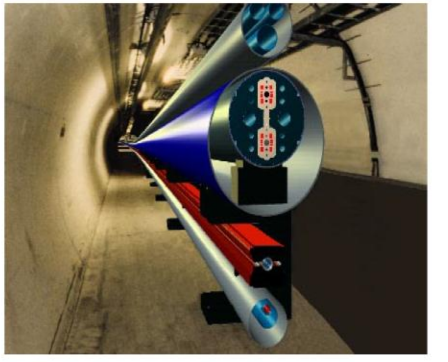
Injector Parameters

	Collider	HEB	MEB	LEB	Linac
Kinetic Energy[GeV]	20,000	2000	200	11	0.6
Circ [m]	87120	10800	3960	570	
SuperC/NC	SC	SC	NC	NC	NC
Bunch spacing [m]	5	5	5	5	5
Norm ε_T [π mm-mrad]	1	0.8	0.7	0.6	< 0.3
Protons/bunch [10^{10}]	0.75	1	1	1	

VLHC



- Design study in 2001
- All lattice sections: IRs, utilities, DSs had lengths in integer units of a half cell, a feature adopted from the SSC
- Super-ferric magnets for the 2 T low field, stage I
- NbTI magnets for 10T high field, stage II
- Very high beam stored beam energy (~ GJ) in both cases
- Energy deposition in IR magnets is a major issue
- Several instabilities incl. e-cloud, coupled-bunch, TMCI, need detailed study
- Synchrotron radiation useful in beam damping for stage II. Beam tube liner and photon stops required for protection.
- Operational aperture thought to be tight, perhaps requiring feedback on orbits, tunes, chromaticities
- Diffusion due to multiple sources
- e+e- collider in the VLHC tunnel



VLHC Parameters

	Stage I	Stage 2
Circumference [km]	233	233
Beam Energy [TeV]	20	87.5
Peak Luminosity [$cm^{-2}s^{-1}$]	10^{34}	2×10^{34}
Particles/bunch	2.6×10^{10}	0.75×10^{10}
Number of bunches	37152	37152
Beam current [mA]	195	57
Dipole field [T]	2	9.8
Trans. Emitt. (Norm) [mm-mr]	1.5	1.5
Beta* at IP [m]	0.3	3.7/0.37
Trans. Emitt. Damping time [h].	100	2.5
Synch Rad. Power/Ring [kW]	7.4	880
Stored Energy / Beam [GJ]	3.0	3.9

SSC and SHE-LHC parameters

Courtesy: F. Zimmermann

	SSC	SHE-LHC
Circumference [km]	87.1	80
Beam Energy [TeV]	20	50
Luminosity [x10^{33} $cm^{-2}s^{-1}$]	1	50
No. of events/crossing	1	193
Dipole field [T]	6.8	20
Number of bunches	17240	4210
Bunch population [x 10^{10}]	0.75	13.4
Beam current [mA]	71	338
β^* [m]	0.5	1.5
Rms bunch length [cm]	7.3	7.7
Rms norm. trans. emitt [mm-mr]	1	1.53
Total beam-beam tune shift	0.007	0.01
Stored beam energy [MJ]	418	4573
Transv. Emitt. Damping time [h]	12.7	0.6

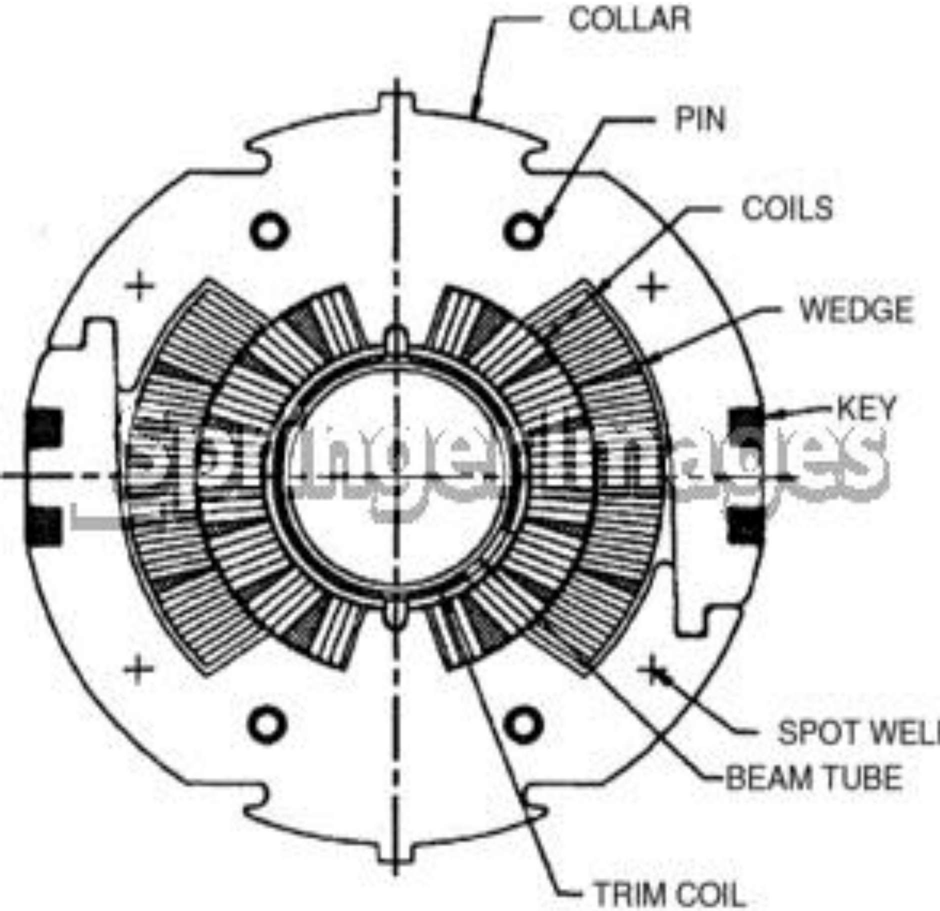
References

- J.R. Sanford and D.M. Mathews: Site Specific Conceptual Design Report", SSCL-SR-1056 (1990)
- G.F. Dugan and J.R. Sanford:"SSC: A Retrospective Summary 1989-1993", SSCL-SR-1235 (1994)
- D.A. Edwards and M.J. Syphers: "Selection of Basic Parameters for the Collider Rings", SSCL-297 (1990)
- Y. Nosochkov, et al: "Principles of Interaction Region Design in Hadron Colliders and their application to the SSC", NIM A346, 448 (1994)
- T. Sen, et al:"Chromaticity correction for the SSC collider rings", PAC1993, p 143
- B.Parker: "Design report on the collider utility straight sections", PAC1993, p 3775
- J.Irwin:"Diffusive losses from SSC particle bunches due to long-range beam-beam interactions", SSC-233 (1989)
- W. Chou, et al: "Emittance and luminosity evolution during collisions in the SSC collider", PAC1993,
- M. Blaskiewicz et al: "VLHC accelerator physics", FNAL-TM-2158 (2001)

SSC Campus, Waxahachie

Magnet Development Lab

SSC Dipoles



Dipole cross section and full length dipoles in the Magnet Development Laboratory

Inside the Collider Tunnel


THE
END


Thank You!