MICHIGAN STATE UNIVERSITY

Very Large Hadron Collider

Lessons from SSC and VLHC

Optics Design and Layout

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NSCL

CERN | FCC hh ee he

U.S. DEPARTMENT OF ENERGY | Office of Science

FCC Week
24 March 2015

Acknowledgments

- The SSC lattice design was many-year effort, involved many individuals over ~10-year period:
  - A. Chao, S. Chattopadhyay, E. Courant, D. Douglas, D. Edwards, M. Furman, D. Johnson, S. Peggs, M. Syphers, R. Talman, … *many more*
  - I know I risk not including many important names here, so my sincere apologies — there were MANY others with much detailed input (and, it's been over 20-25 years!)
- A very important contributor to me was: Al Garren
  - SYNCH code was used throughout most of the final design work, along with MAD (survey function)
  - Al had many important innovations during those years and was an inspiration to me and many others

SSC Design Requirements

- Center-of-Mass Energy of 40 TeV
- Initial luminosity of $10^{33}/cm^2/s$
- Average of 1 event per bunch crossing
- 80% Overall Reliability

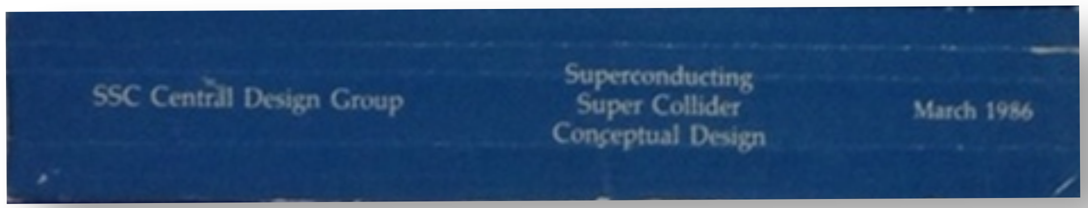
- Cosine-theta magnet design chosen, with field of order 6-7 T; led to circumference of about 87 km
- Luminosity and events/crossing led to 5 m bunch spacing (16.7 ns)

The Superconducting Super Collider

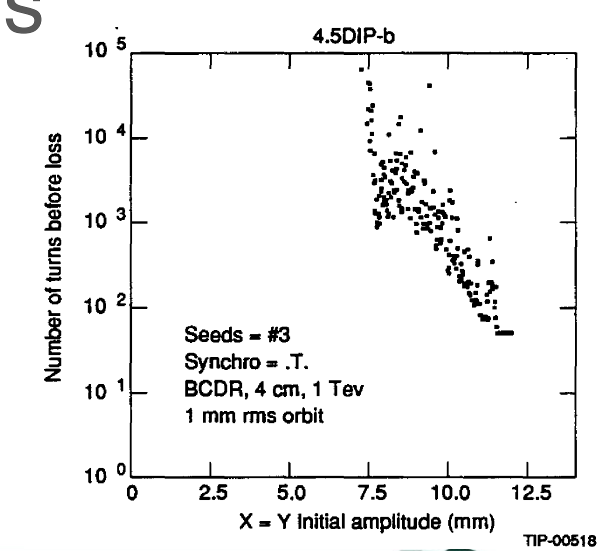
- CDR, SCDR, Retrospective Summary, …
- Technical Reports, Project Documents, …
- Web page of documents and links to many documents: » http://lss.fnal.gov/archive/other/ssc/

SSC Conceptual Design

- The 1986 report reads like a textbook in accelerator physics and technology

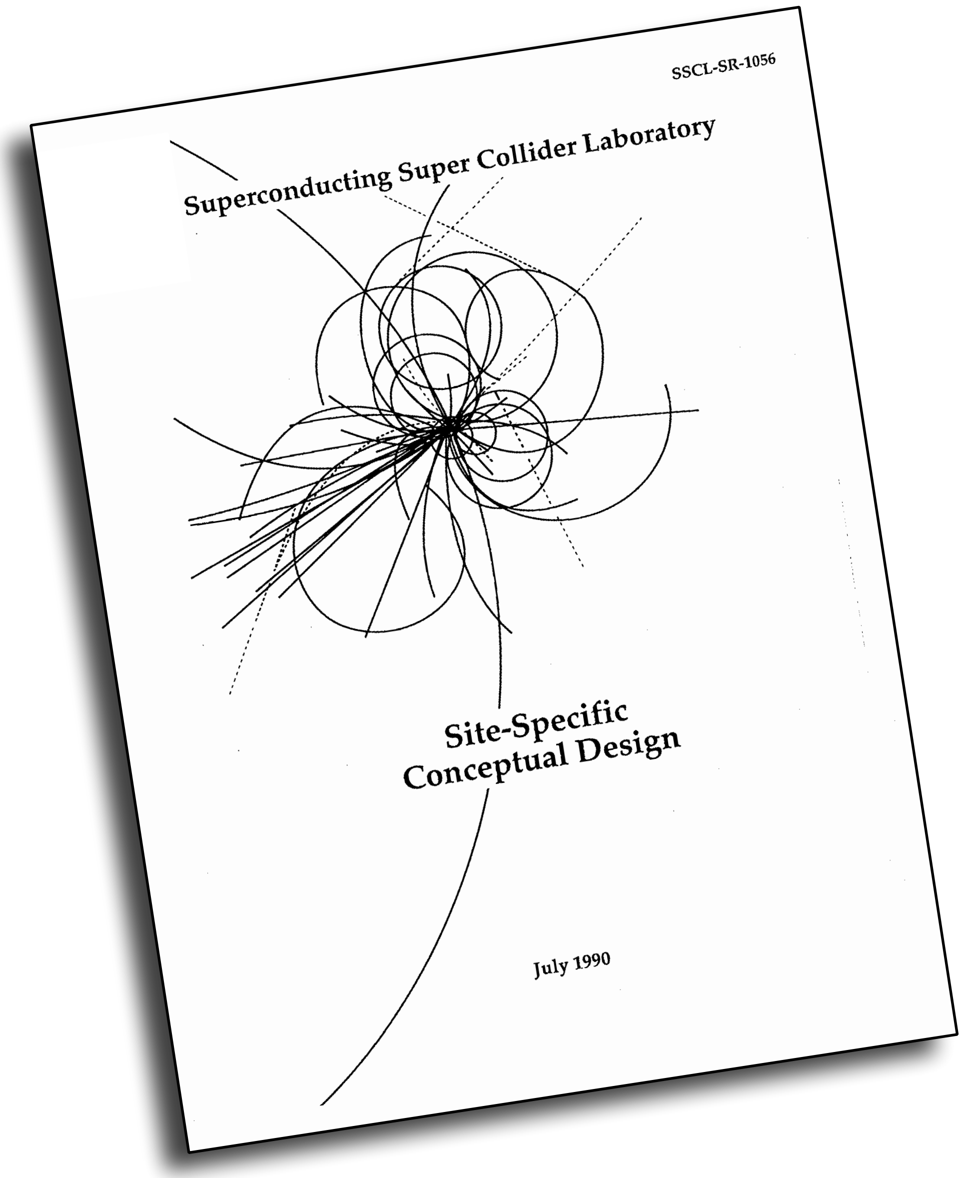


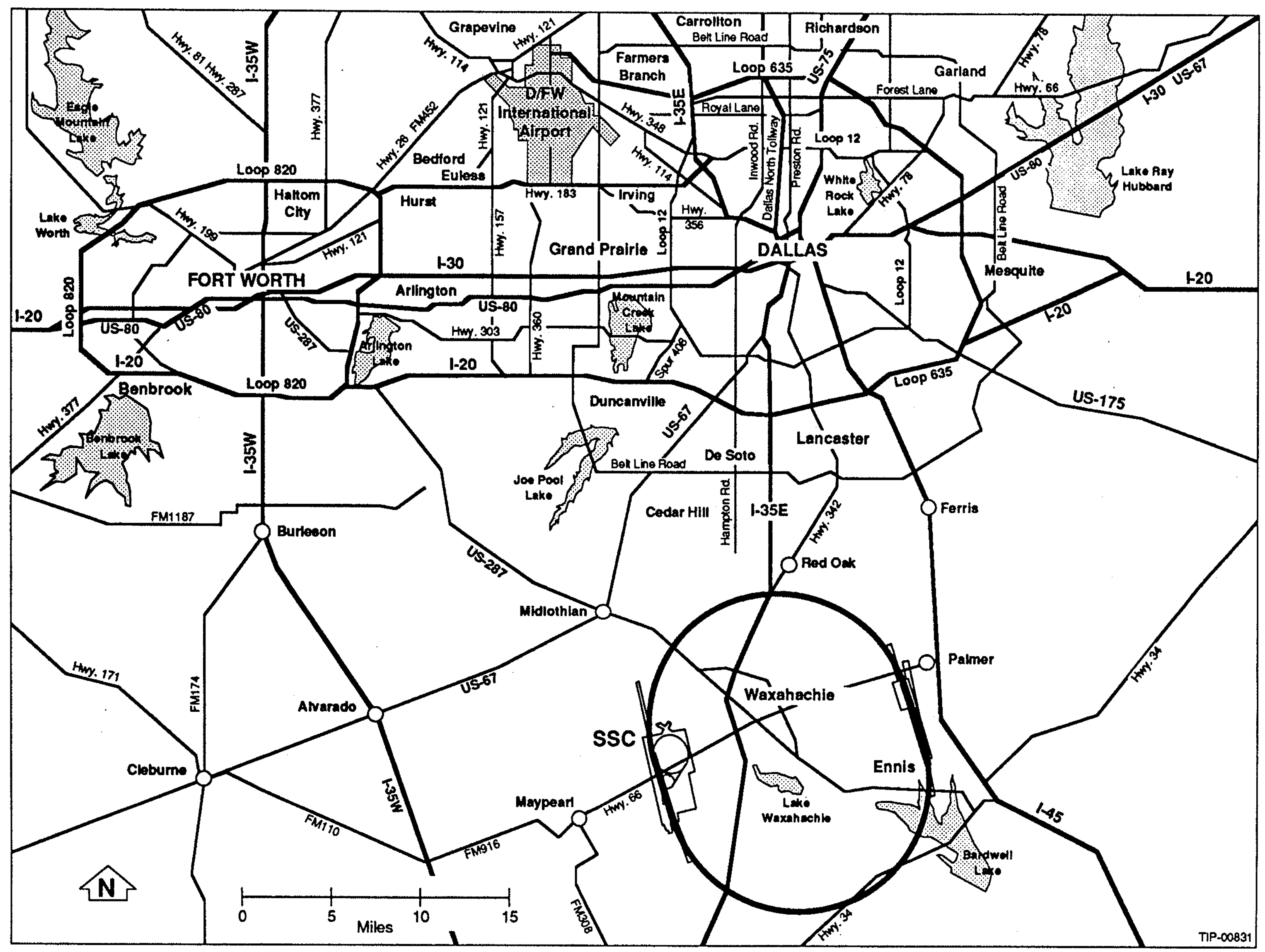
- The Central Design Group (CDG) and SSC studies world-wide initiated many first looks, including …
  - various magnet technologies, designs, systems; snap-back
  - intensive particle tracking studies of dynamic aperture
  - luminosity evolution in high-energy hadron colliders
  - PACMAN bunches, detailed beam-beam studies
  - experimental beam dynamics studies
  - large-scale modular lattice design
  - many, many, many others…



Site-Specific Conceptual Design

- The "White Book" (SCDR)





Superperiodicity

- Racetrack vs. multiple superperiods

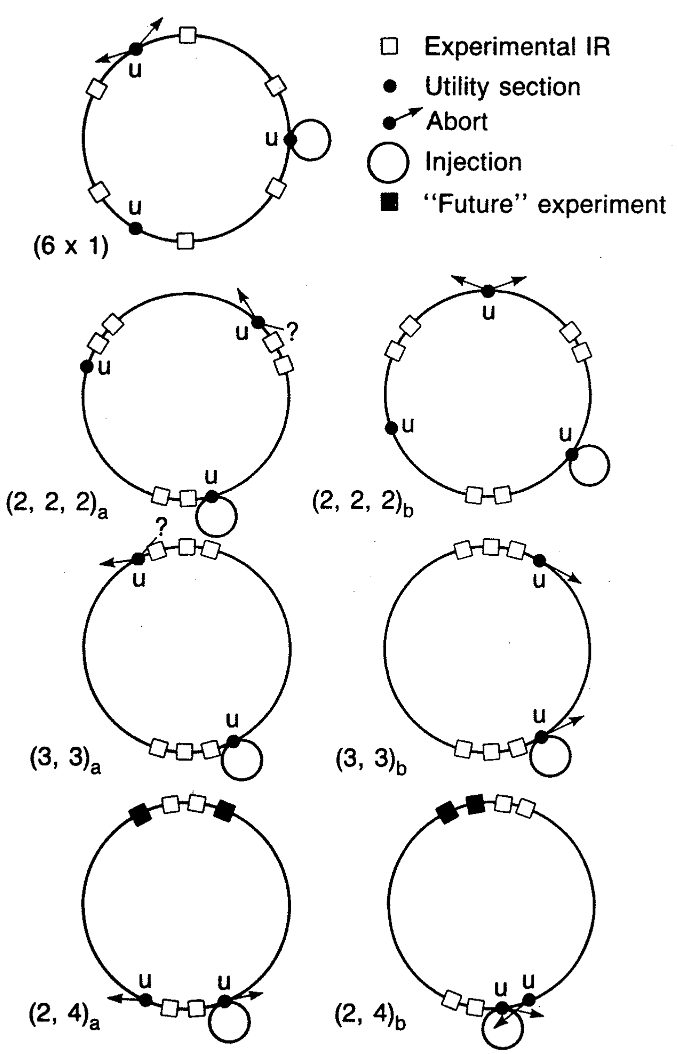


Figure 4.2-1. Various possible IR clustering arrangements for the SSC.

from CDR (1986)

However, the clustered scheme is more cost effective because of considerations concerning the conventional facilities and so was recommended for the SSC conceptual design.

Generally speaking, evenly distributed IRs permit a higher superperiodicity and thus fewer resonances in the tune space. For the case of SSC, this means a superperiodicity of 6, if the utility sections and crossings are ignored. Realization of the consequences of high superperiodicity requires correlation of particle motion in magnets that are separated by 1/6 of the ring circumference, i.e., about 14 km. Because of various magnet field and alignment errors, correlation over this long distance is not likely to be maintained. The superperiodicity is thus broken in reality and all low-order resonances, systematic and accidental, need to be avoided.

The fact that a high superperiodicity is not very important for the SSC is demonstrated by particle tracking using the programs PATRICIA [4.2-8] and RACETRACK [4.2-9] on

eral was found to deteriorate as compared with the two-family scheme.

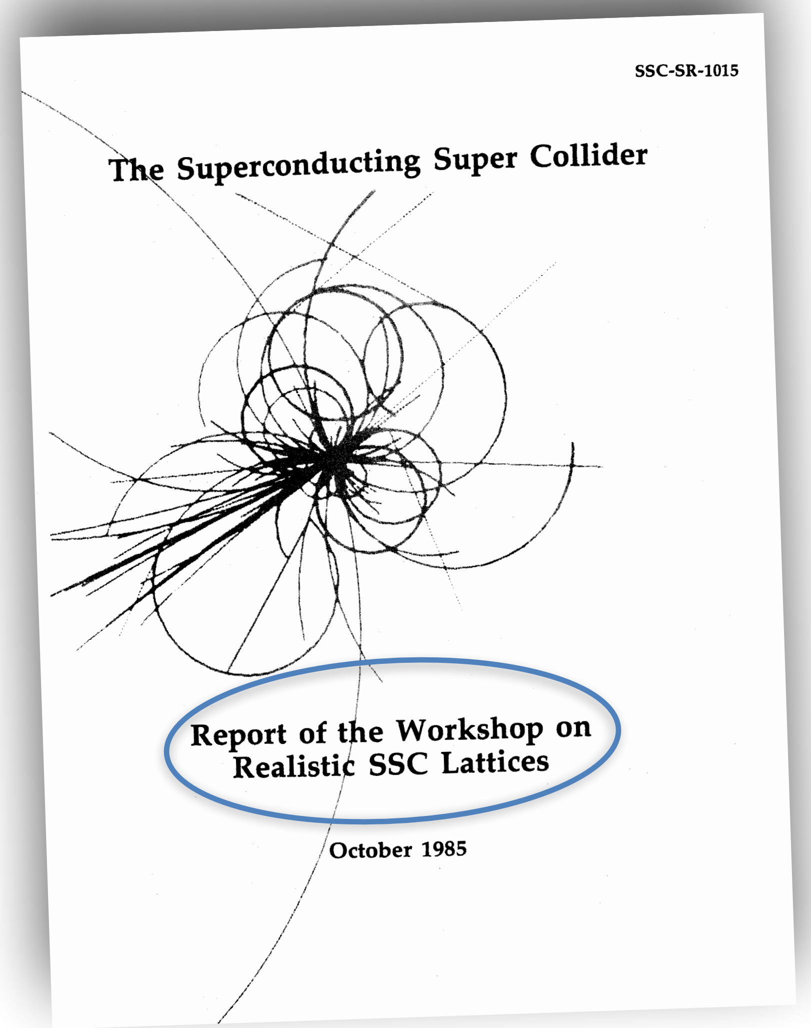
There is a potential optical advantage of IR clustering. Compared with distributed IRs, clustered IR lattices have one more variable to control the optical quality, namely, the betatron phase advance μ between adjacent IPs in a cluster. The optimum value of μ is found to be an odd multiple of $\pi/2$ [4.2-7, -11, -12]. By pairing IRs in a cluster and setting μ to the optimum value, one minimizes the chromatic aberrations of particle motion. This optimum phase also helps to reduce the orbit effect from long-range beam-beam interactions and to suppress some of the incoherent beam-beam resonances.

To be more specific, the tune dependence on momentum is described to first order by

FNAL: original Main Ring had $P = 6$;
Tevatron: $P = 1$!

Magnet Arrangement: 2-in-1 / 1-in-1 / H / V

- Vertical 1-in-1 chosen for the SSC, following extensive studies and workshops



SSC-SR-1015

The Superconducting Super Collider

Report of the Workshop on Realistic SSC Lattices

October 1985

The beams are separated vertically by 70 cm in the arcs. The magnets in the arcs are arranged in an over-under configuration rather than side by side. The 70 cm separation allows the magnets of the two rings to be decoupled cryogenically as well as magnetically. The over-under arrangement has the advantages that the tunnel space can be utilized more effectively and that the path lengths between collision points in the two rings can be more easily equalized. The decoupled magnets allow separate operation of the two rings. This makes it possible to perform accelerator physics studies on one ring when the other ring is not available [4.2-3].

In a side-by-side arrangement, the horizontal dispersion introduced by the separation section can be removed by the horizontal dispersion suppressor already incorporated in the lattice. In an over-under arrangement, the vertical dispersion caused by the vertical separation section has to be compensated by an additional vertical dispersion suppressor. This can be done in two ways, depending on whether the beam separation starts immediately after the IR triplets (the early separation scheme) [4.2-2] or about 200 m after the triplet (the late separation scheme) [4.2-4]. The former allows more flexibility for operating and making corrections on the two rings separately and it minimizes the long range beam-beam perturbations. Early separation also makes it easier to remove the forward secondary particles that are generated by beam collisions. The latter has the advantage that the beta functions are more easily controlled, giving smaller beta function values in the matching quadrupoles beyond the main triplets.

The present conceptual design adopts the early separation scheme. The vertical dispersion suppression is accomplished by dividing the 70 cm separation into two steps and then introducing a FODO section which has 180 degree phase advance between the two steps. The vertical dispersion contributions from the two steps cancel outside the separation region.

Collider Parameters

- From the SCDR

Table 4.1.1-1
SSC Parameters

Energy	20 TeV
Particles/bunch (N)	0.75×10^{10}
Circumference	87,120 m
No. of bunches (B)	17,424
NB	1.3×10^{14}
f_{rot}	3.4 kHz
$f_{collisions}$	60 MHz
S_b	5.0 m
ε_N (σ)	1 π mm-mrad
β^*	1/2 m
σ^* (μm)	5
Luminosity ($\mathcal{L}$)	1×10^{33} cm^{-2} s^{-1}
$\mathcal{L}/_{hit}$	1.6×10^{25} cm^{-2}
$\Delta\nu_{HO}$ (total)	0.003
$\Delta\nu_{LR}$ (total)	0.004
Sync. rad. power at $NB = 1.3\times10^{14}$	8.75 kW/ring

Collider Lattice Parameters
(Footprint Version)

Energy: injection, collision (TeV)	2	20
Magnetic radius (m)	10187.1896	
Magnetic field (T)	6.55	
Rigidity (T-m)	66712.8	
Gradient (T/m)	205.6	
Circumference (484 cell lengths) (km)	87.12	
Arc length, cluster length (km)	35.28	8.28
Half-cell length, arc sector length (m)	90	4320
Long straight section length, bypass length (m)	1350	4770
Drift lengths at IP: low-β, medium-β IRs (m)	±20	±120
Drift lengths in utility straight: center, ends (m)	500	161
IP-IP distance: inner, outer (m)	2160	2520
IP-IP bending angle (mrad)	40	
Minimum IP to muon beam clearance (m)	34	
Vertical beamline separation (m)	0.80	
Cell phase advance (deg)	90	
Betatron tune: outer, inner bypass branch	123.28	123.78
Phase advance between IPs: outer, inner branch	$4.25 \times 2\pi$	$3.75 \times 2\pi$
Chromaticity: collision, injection optics	–250	–173
Transition energy-γ_T	105	
Momentum compaction (α)	0.000091	
Crossing angle (μrad)	<150	
Bunch spacing (m)	5	
rf wavelength (m)	0.8333	
Lengths of cell dipole, quadrupole (effective)* (m)	12.7	5.2
Bend radius, average arc radius (km)	10.187	12.032
Bend angle per arc, per cluster (deg)	168	12
Maximum number of IRs: simultaneous, total	5	9
Cells per arc, cluster length in equivalent cells	196	46
Number of dipoles per cell, per ring (outer)	12	5040
Number of dipoles per arc, per cluster (outer)	2352	168
Number of dipoles per bypass inner branch	104	
β_{max}, β_{min} in arc (m)	305	53
η_{max}, η_{min} in arc (m)	1.82	0.8
β^* in low-β IR: injection, collision (m)	8	0.5
β^* in medium-β IR: injection, collision (m)	60	10
β_{max} in low-β, medium-β IRs (collision) (m)	7990	2657
β_{center}, β_{max} in utility straight (m)	300	970

*See Tables 4.1.1.1-3 and 4.1.1.1-7.

Modularity

- Length of Standard Half-Cell was in units of bunch spacing (5 m)
  - *L* = 90 m, for example
- Then, Utility Regions, IRs, *etc*., each in units of *L*
- By adding *L* at ends of straight section regions could maintain anti-symmetry of optics

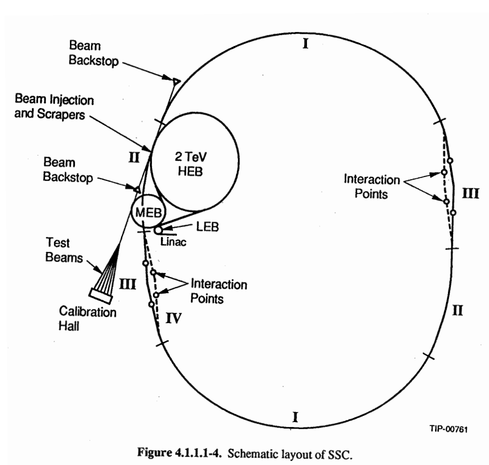
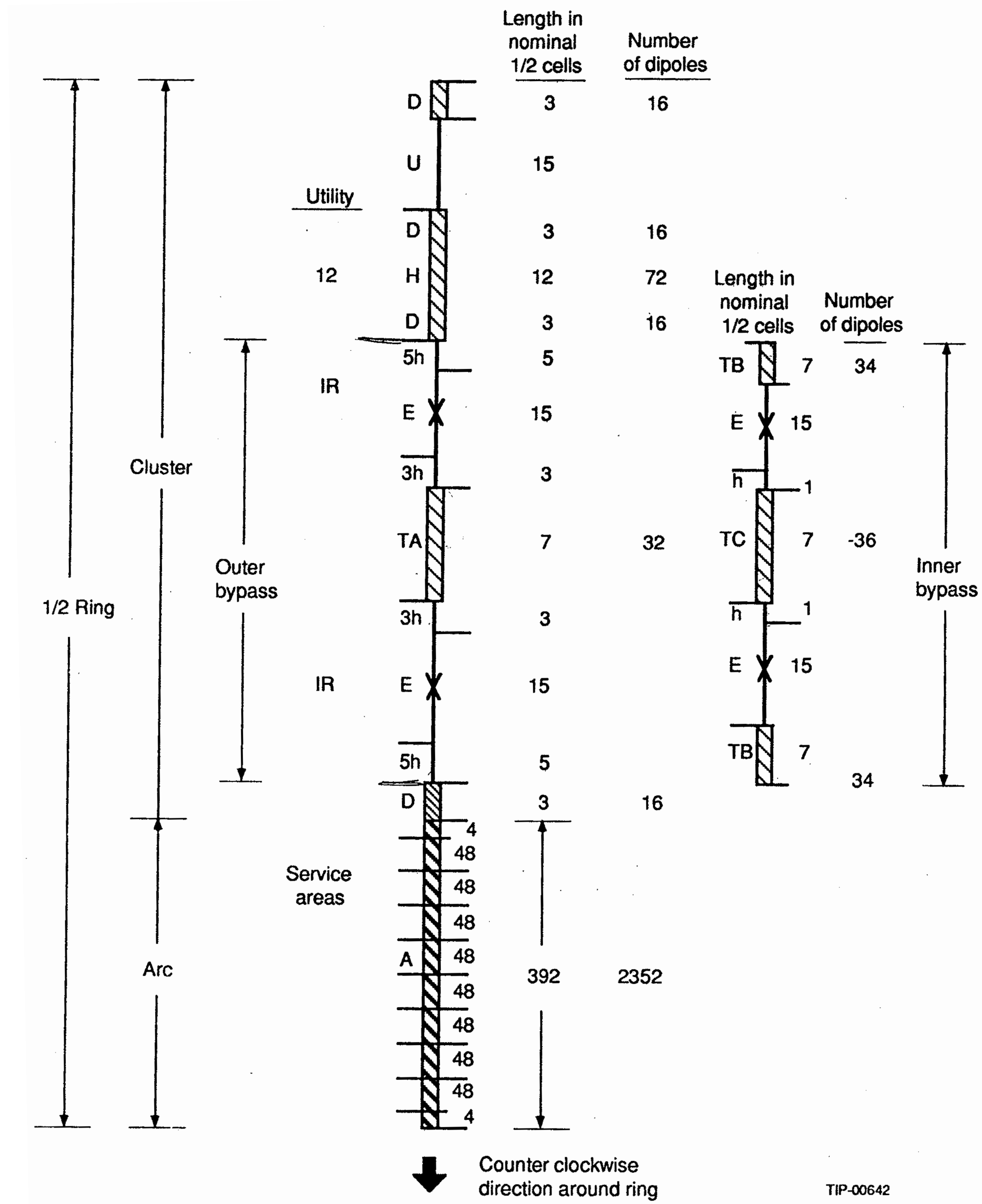


Figure 4.1.1.1-4. Schematic layout of SSC.

Modular Approach:



The Diamond Bypass

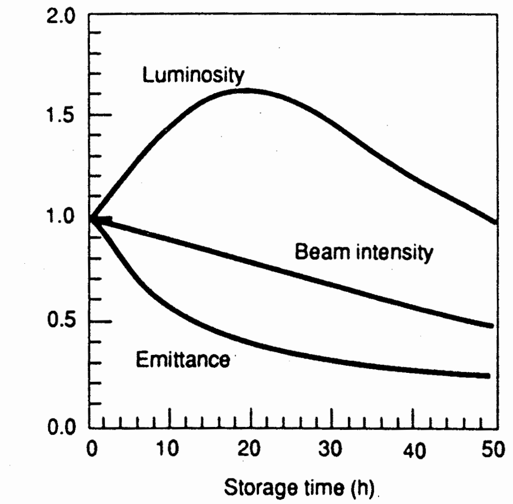


Figure 5.2.2 Collider luminosity, beam intensity, and emittance as a function of time for the parameters given in Table 5.2.1. The value of 1.0 on this scale corresponds to the design values (10^{33} cm^{-2} sec^{-1} luminosity).

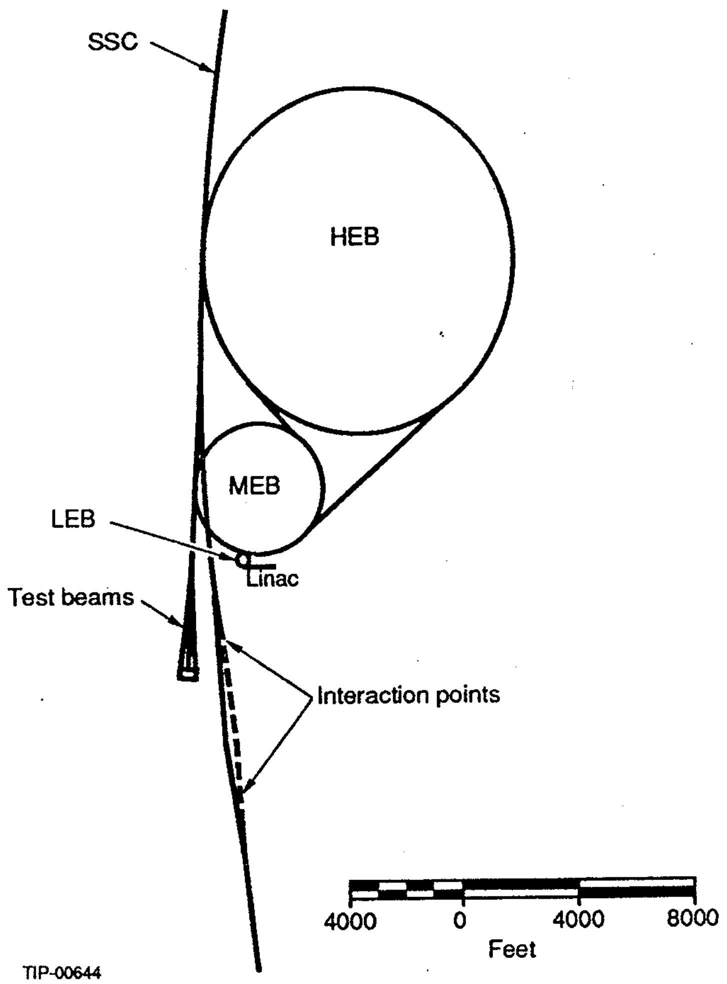


Figure 4.1.1.1-2. Layout of west campus region.

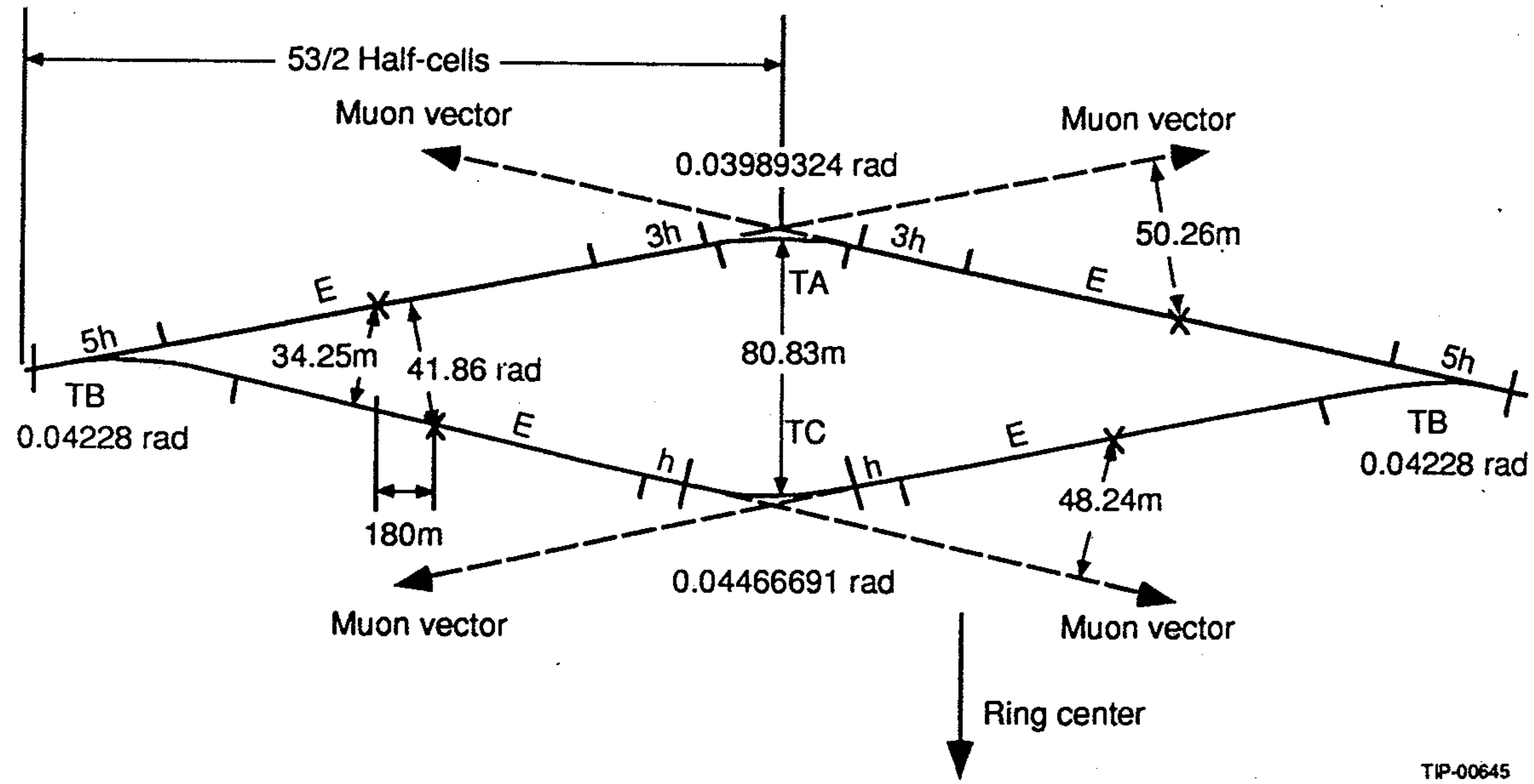


Figure 5.2.1 The diamond bypass arrangement. In the initial configuration, the outer legs (farther from ring center) will be instrumented.

Lattice Decisions

- 1-in-1 assured can operate one ring without the other
  - *except*: the IR triplets were “shared” by both
  - desire was to be able to commission one ring if the other was not ready
  - Vertical “-*I* ” beam lines made IR tuning transparent
- IR designs were still being finalized at project end


Nuclear Instruments and Methods in Physics Research A 346 (1994) 448–460
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Principles of interaction region design in hadron colliders and their application to the SSC

Y. Nosochkov *, T. Sen, E. Courant [1], A. Garren, D.M. Ritson [2], R. Stiening, M.J. Syphers
[a] *Superconducting Super Collider Laboratory +, 2550 Beckleymeade Avenue, Dallas, TX 75237, USA*

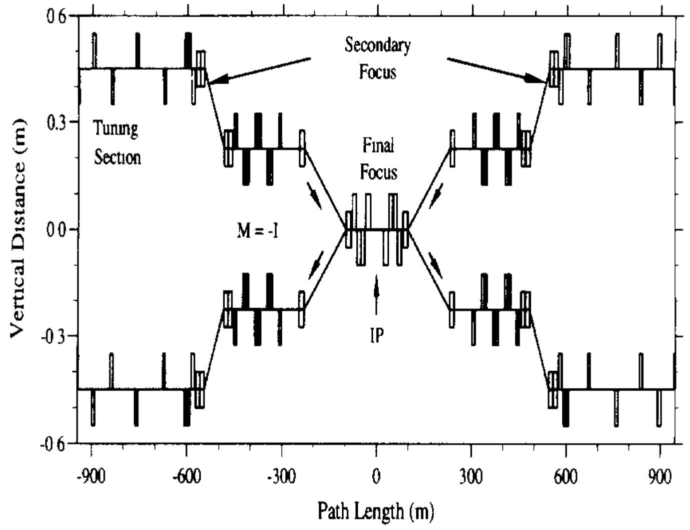


Fig. 1. Vertical view of an IR.

Dispersion Suppressor

keep $L\theta = \frac{1}{2}$ for 90° dispersion suppression by making $L = 3L_o/4$ and $\theta = 2\theta_o/3$

Required second length of dipole magnet

Later, this magnet was also used at power feed locations to create extra space
(every six cells throughout an arc)

5, 15-m dipoles

$\theta_d = 2\theta_0/3 = \theta_0 \times 4/5 \times 5/6$

4, 13-m dipoles

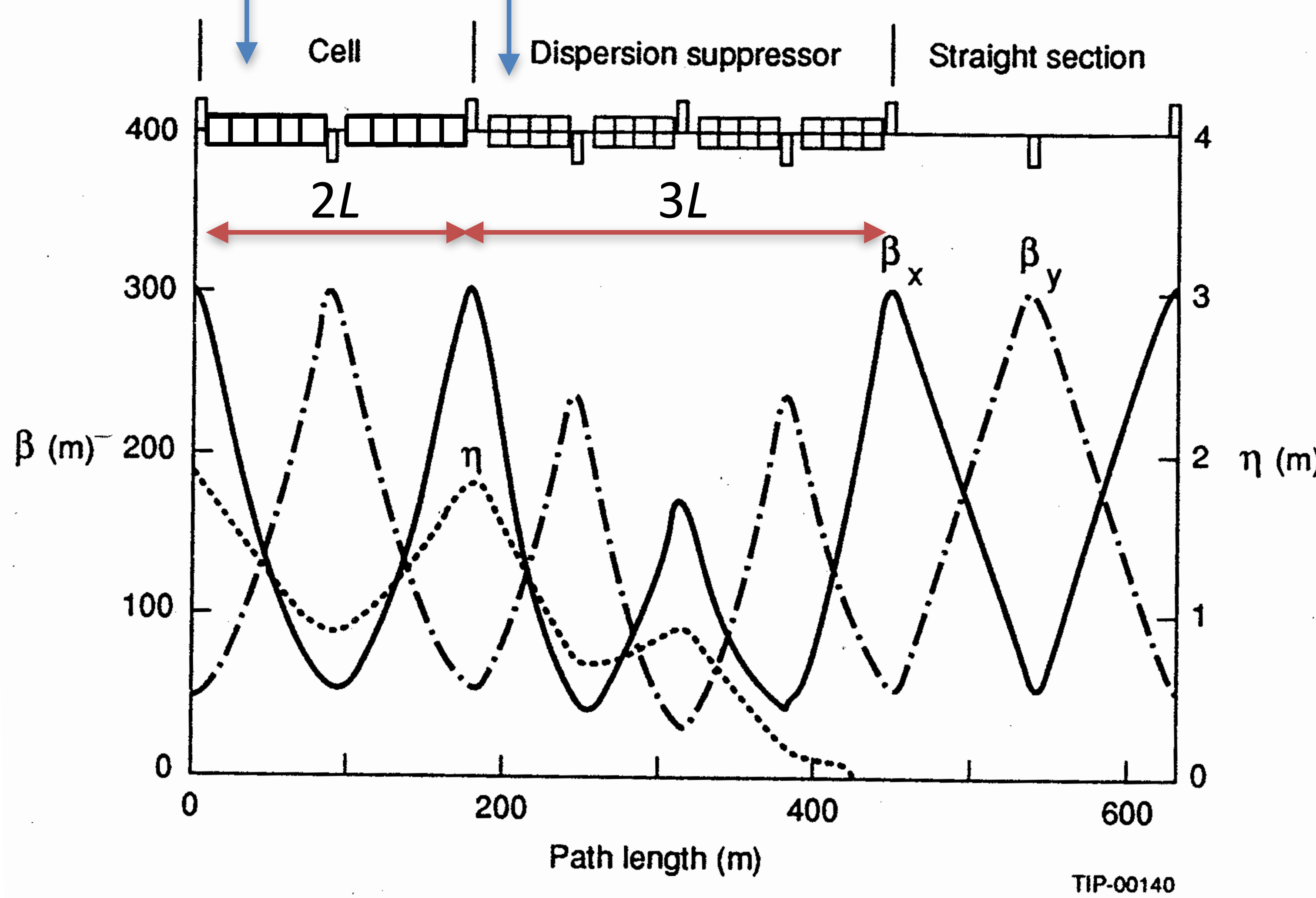
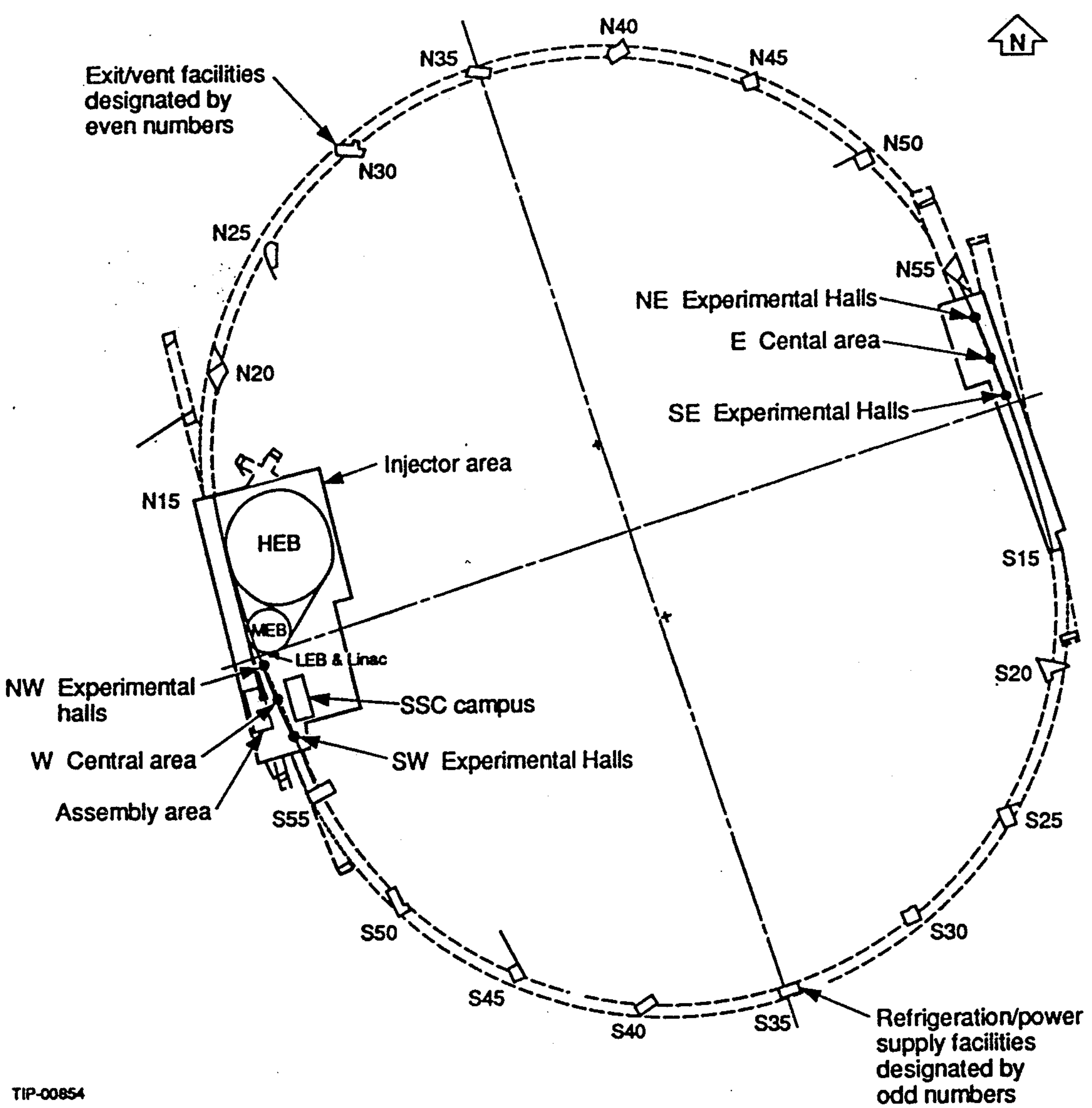


Figure 4.1.1.1-8. Lattice functions of the normal cell *C*, the dispersion suppressor *D*, and empty cell *CO*.

The "10F" Lattice

i.e., Version 10, sub-version F (1993)

- "holes", and the role of modularity in the final layout



- "free space" created in arcs
  - "missing" dipoles in cells

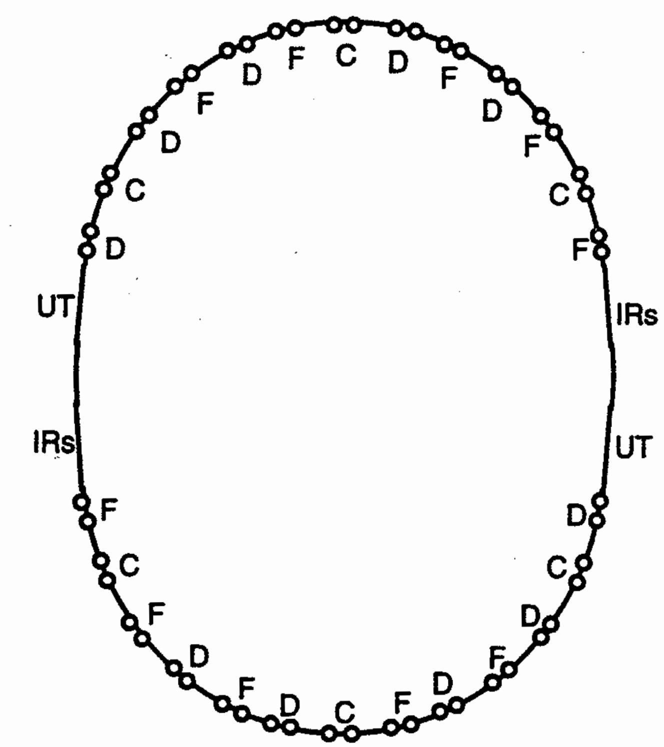
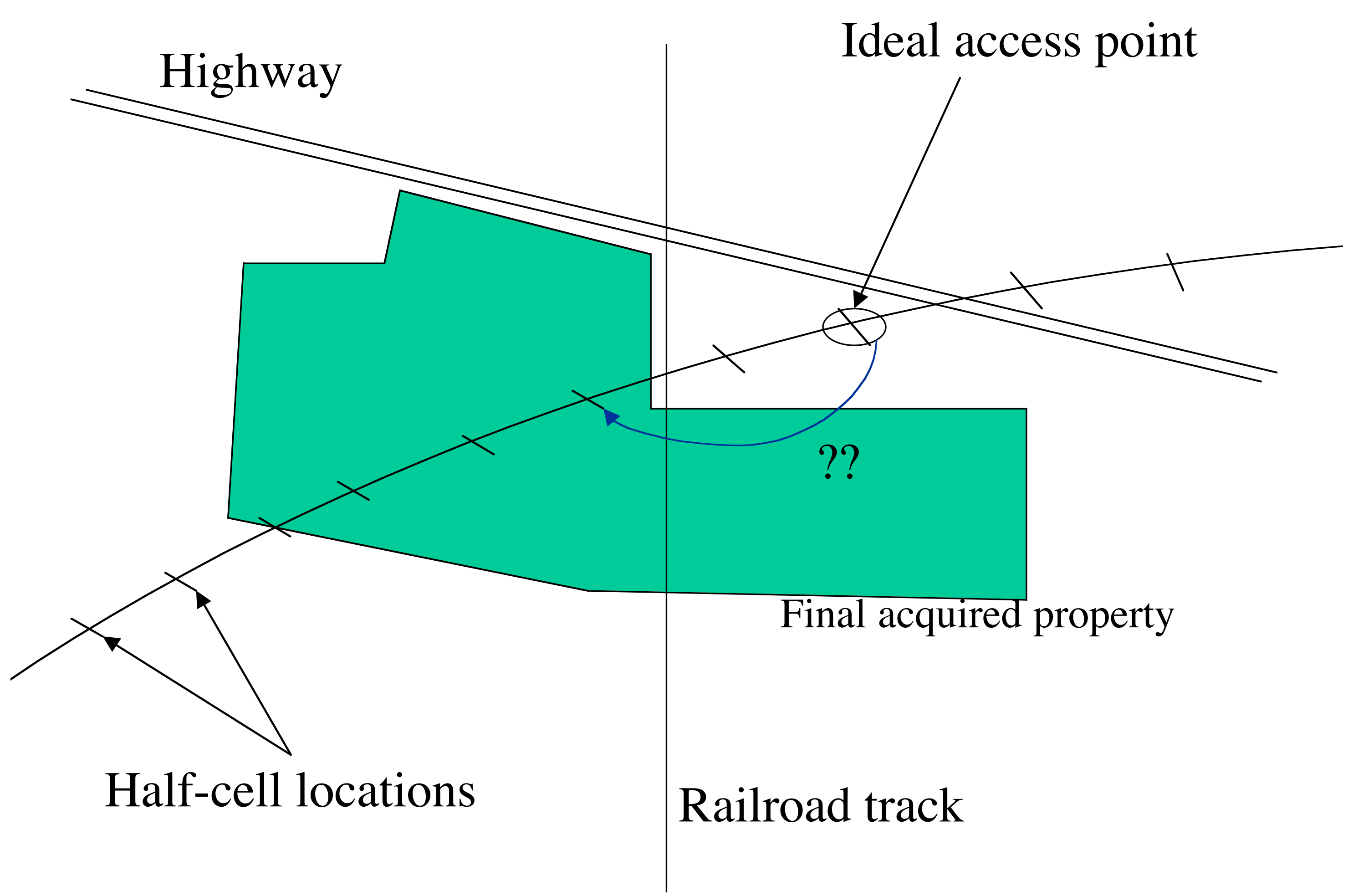


Figure 7-1. Schematic Layout of the Free Space in the Collider.

Modularity and “free space”

- Modularity and “free space” became very useful when finalizing the exact locations of shafts, utilities and service buildings



Close-Out…

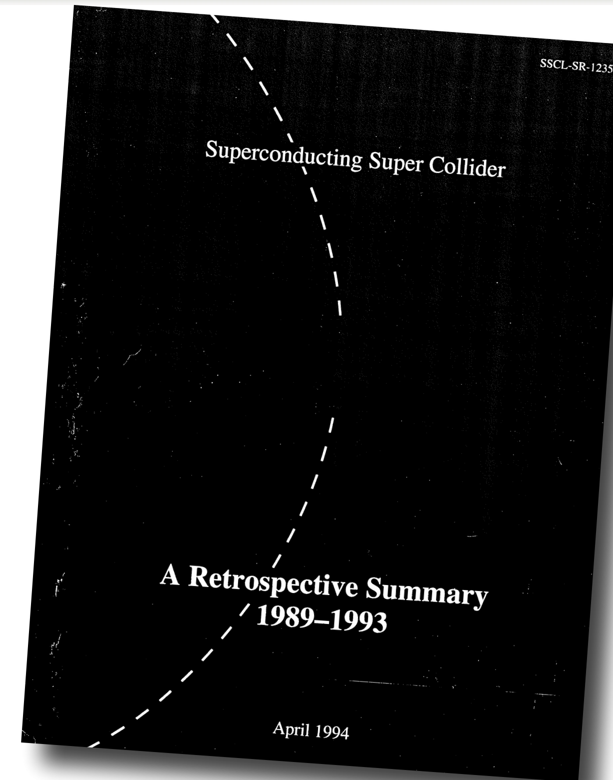


Table 7-1. Collider Parameters.

	1993	1990 SCDR	1986 CDR	UNITS
Injection Energy	2.0	2.0	1.0	TeV
Circumference	87120	87120	82944	m
Cell length	90	90	96	m
Cell phase advance	90	90	60	deg
Dipole Coil Diameter	50	50	40	mm
Dipole Field	6.79	6.60	6.60	T
Quad Coil Diameter	50	40	40	mm
Quad Field	194	206	212	T/m
β^*	0.5	0.5	0.5	m
Crossing angle	<150	<150	<150	μrad

Table 7-2. Changes of Relevant Parameters for One Ring.

	1992	1990
15 m free spaces (arc)	26	0
2.5 m free spaces (arc)	26	34
15 m spaces (cluster)	2	0
2.5 m spaces (cluster)	0	2
Long Dipoles (15 m)	3972	3978
Short Dipoles (13 m)	196	252
Standard Quads	848	832
Dispersion Suppresser Quads	40	60
Bend Field Increase	1.27%	0
Max. Dispersion in arc		
Top Ring	2.26 m	1.87 m
Bottom Ring	2.26 m	1.81 m
Max. Dispersion in ring		
Top Ring	2.85 m	1.87 m
Bottom Ring	2.85 m	1.81 m

Note: Tevatron beam energy was 0.98 TeV

Lessons Learned [MJS]

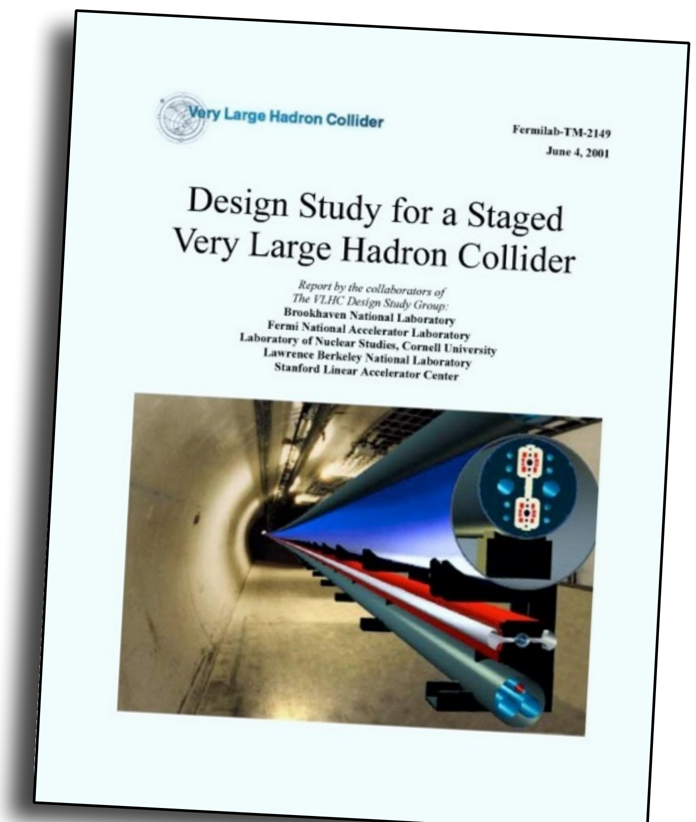
- Modularity in the optics design and layout was VERY important; "saved the day" several times
- A certain amount of "free space" in the arcs will be very important — diagnostics, collimators, other?
  - avoid MANY km of solid cryostat
  - build in at the beginning — avoid later complications in meeting goals (e.g., magnetic field)
- Payoffs of higher superperiodicity not practical for such large rings; even the Tevatron had P = 1
- 2-in-1 magnets (rather than 1-in-1) now a proven success
- Build off of an existing site and its infrastructure/assets

The VLHC Study

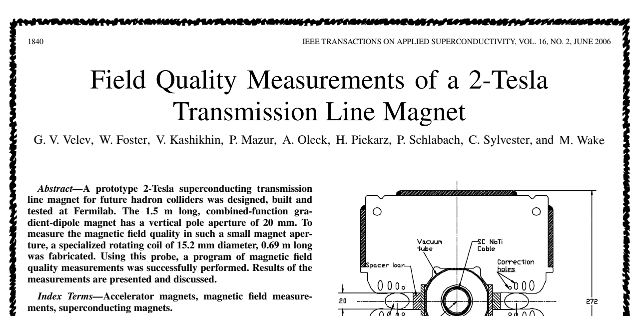
http://vlhc.org

- Study performed *primarily* from 1998-2001, with certain R&D efforts extending from 1995 ~ 2006
- Steering Committee formed in 1998
  - http://vlhc.org/vlhc/index.html
- Resulted in 270-page report in 2001
  - http://inspirehep.net/record/559461
- Snowmass Working Group in July 2001
  - http://vlhc.org/snowmass.html
- Transmission Line Magnet Efforts
  - continued until ~2006

Very Large Hadron Collider
Steering Committee for a Future Very Large Hadron Collider



(Much info taken from P. Limon talks on VLHC circa 2003)


1840 IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 16, NO. 2, JUNE 2006

Field Quality Measurements of a 2-Tesla Transmission Line Magnet

G. V. Velev, W. Foster, V. Kashikhin, P. Mazur, A. Oleck, H. Piekarz, P. Schlabach, C. Sylvester, and M. Wake

***Abstract*—A prototype 2-Tesla superconducting transmission line magnet for future hadron colliders was designed, built and tested at Fermilab. The 1.5 m long, combined-function gradient-dipole magnet has a vertical pole aperture of 20 mm. To measure the magnetic field quality in such a small magnet aperture, a specialized rotating coil of 15.2 mm diameter, 0.69 m long was fabricated. Using this probe, a program of magnetic field quality measurements was successfully performed. Results of the measurements are presented and discussed.**

***Index Terms*—Accelerator magnets, magnetic field measurements, superconducting magnets.**

VLHC involved many of same people:

M4 Participants

Snowmass, 2001

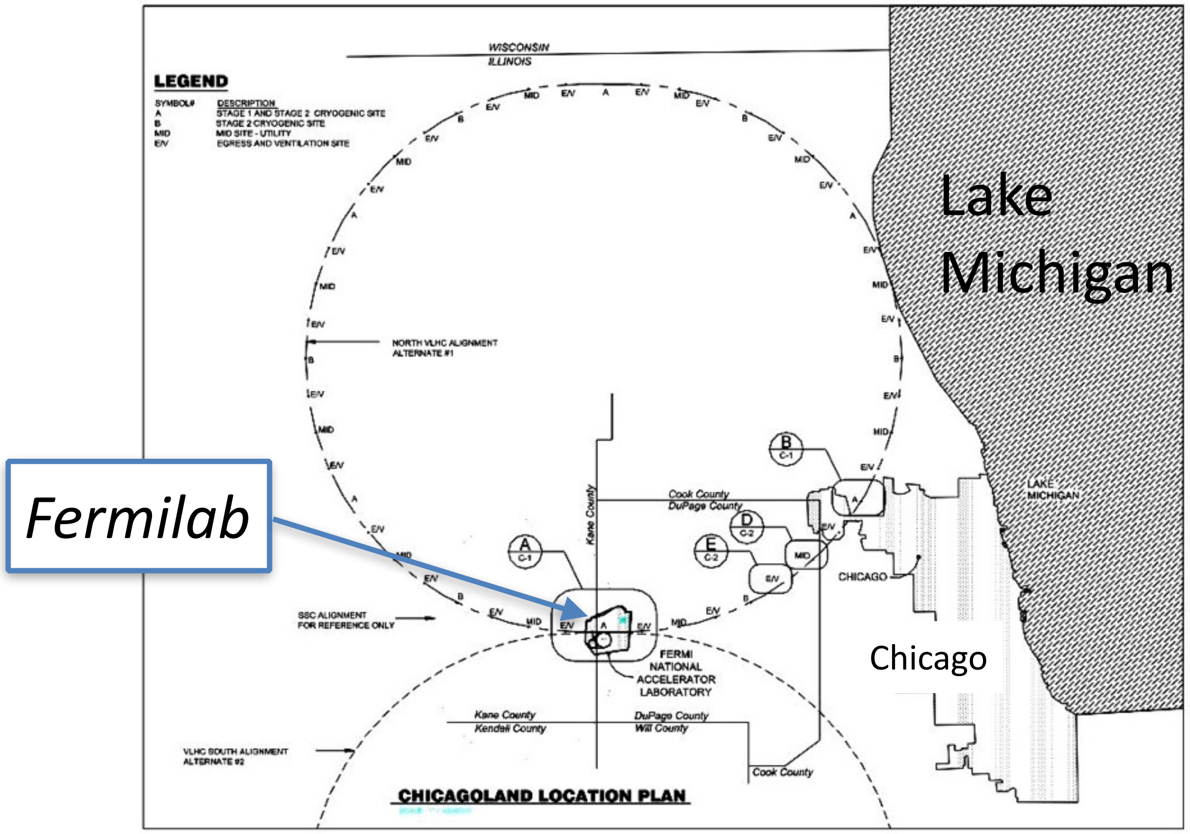
- Convenors: Peggs, M.Syphers
- Participants (50+)

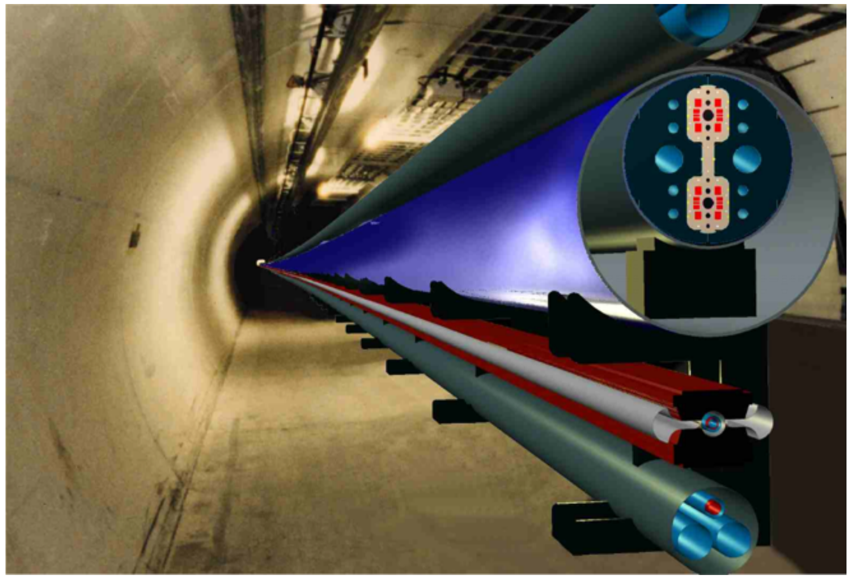
•R.Baartman	•R.Diebold	•E.Keil	•B.Parker	•K.Takayama
•W.Barletta	•J.Ellison	•B.King	•R.Pasquinelli	•T.Toyama
•P.Bauer	•G.W.Foster	• M.Lamm	• F.Pilat	•M.Wake
•M.Blaskiewicz	•J.Fox	• P.Limon	•M.Pivi	•P.Wanderer
•A.Burov	•M.Furman	•E.Malamud	•R.Roser	•M.Watanabe
•J.Cardona	•P.Garbincius	•A.McInturff	•M.Ross	•R.Webber
•A.Chao	•H.Glass	•P.McIntyre	•A.Sattarov	•K.Wittenberg
•J.Corlett	•R.Gupta	•N.Mokhov	•T.Sen	•M.Xiao
•L.Cremaldi	•R.Johnson	•T.Murphy	•Y.Shimosaki	•R.Yamada
•D.Denisov	•J.Johnstone	•R.Palmer	•J.Strait	•V.Yarba
	•H.Jostlein		•D.Summers	•A.Zlobin

plus others we missed…??

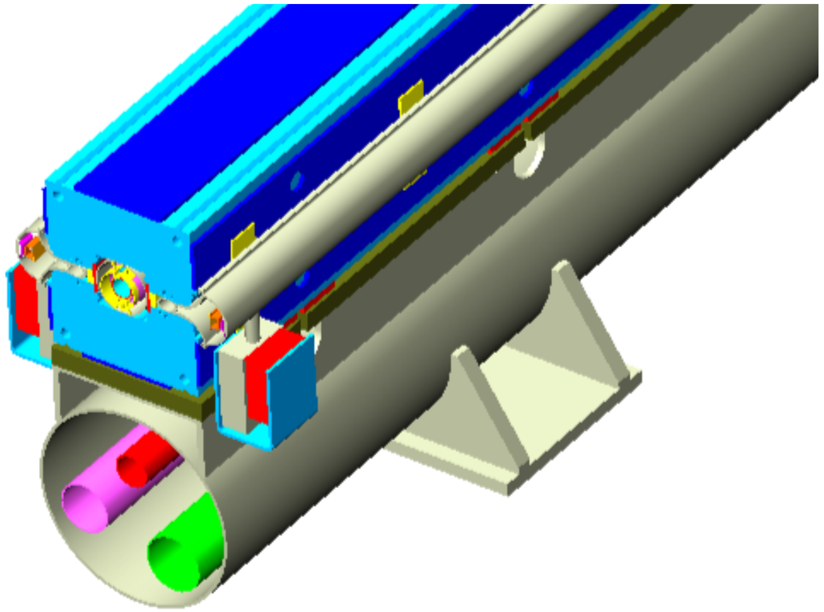
VLHC Concept

- Build a BIG tunnel. (230 km!)
- Fill it with a less-expensive 40 TeV collider
  - ~2 T transmission line magnet
- Use combined-function magnets to improve packing fraction, reduce field
- Later, upgrade to a 200 TeV collider in the same tunnel.





VLHC Concept [2]



- Physics sooner, allowing time to develop cost-reducing technologies for Stage 2
- Stage 1 becomes high-energy full-circumference injector for Stage 2
- **Stage 1:**
  - 2-in-1 warm iron
  - Superferric: 2 T bend field
  - 100 kA Transmission Line
  - alternating gradient (no quadrupoles needed in FODO cells)
  - 65 m Length
  - Self-contained, including Cryogenic System and Electronics Cabling
  - Warm Vacuum System

VLHC Parameters

	Stage 1	Stage 2
Total Circumference (km)	233	233
Center-of-Mass Energy (TeV)	40	200
Number of interaction regions	2	2
Peak luminosity ($cm^{-2}s^{-1}$)	1×10^{34}	2.0×10^{34}
Dipole field at collision energy (T)	2	11.2
Average arc bend radius (km)	35.0	35.0
Initial Number of Protons per Bunch	2.6×10^{10}	5.4×10^{9}
Bunch Spacing (ns)	18.8	18.8
β^* at collision (m)	0.3	0.5
Free space in the interaction region (m)	± 20	± 30
Interactions per bunch crossing at L_{peak}	21	55
Debris power per IR (kW)	6	94
Synchrotron radiation power (W/m/beam)	0.03	5.7
Average power use (MW) for collider ring	25	100

Some VLHC Conclusions (*2001*)

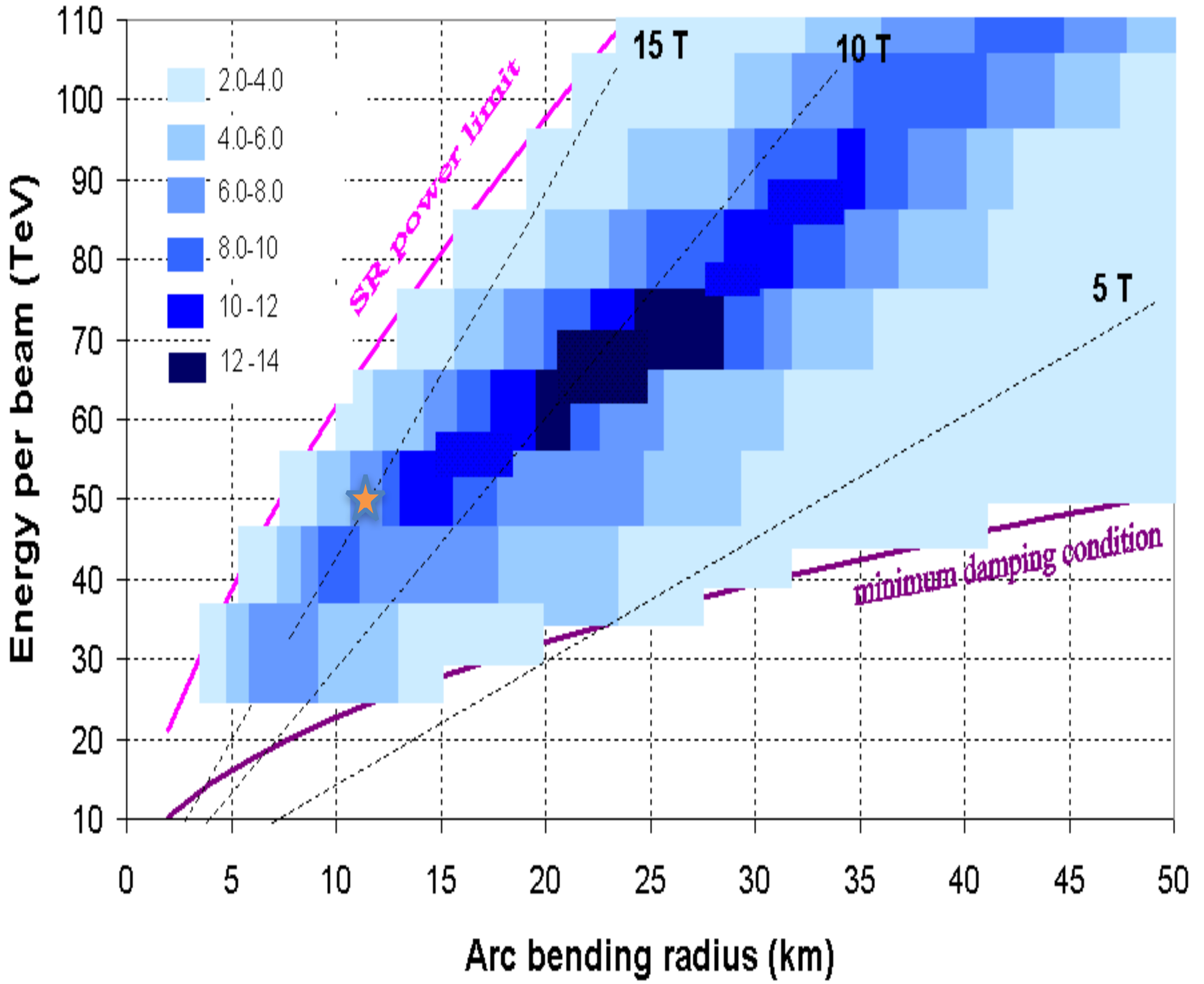
- No serious technical obstacles to the Stage-1 VLHC at 40 TeV and 10^{34} luminosity.
- The existing Fermilab accelerator complex was an adequate injector for the Stage-1 VLHC, but lower emittance would have been better.
- From this and previous studies, surmised that the cost of a collider of energy near 40 TeV is almost independent of magnetic field
  - even lower fields (10-12 T) efficient for high-energy
- Building the VLHC at an existing hadron accelerator lab saves significant money and time.

Some VLHC Conclusions (*2001*) [2]

- The Stage 2 VLHC could reach 200 TeV and 2×10^{34} or possibly significantly more in the 233 km tunnel.
  - A large-circumference ring is advantageous for the high-energy Stage-2 collider. High-energy VLHC with small-circumference may not be realistic.
  - Optimum field for a 100-200 TeV collider is less than the highest field attainable because of synchrotron radiation, total collider cost and technical risk.
  - Minimum magnet aperture determined more by beam stability & synchrotron radiation, much less by field quality.

VLHC Optimum Field (*2003*)

P_{SR}<10 W/m/beam peak $t_L > 2\ t_{sr}$ Int/cross < 60 L units 10^{34} $cm^{-2}s^{-1}$



P. Bauer, *et al.*

U.S. Experience

- The U.S. has much to convey to the FCC studies, including accelerator physics and design optimization
  - 25 years of 2-TeV collider operation (Tevatron)
  - 10 years studying, designing, and (partially) constructing a ~90 km, 40 TeV collider project (SSC)
  - >5 - year study of a 40-200 TeV-scale collider (VLHC)
  - 10-15 years with LHC (LARP, in the least)
- Technology challenges should be the main thrust in the U.S., as well as Accelerator Physics efforts that will help to guide these future activities of the FCC

Outlook

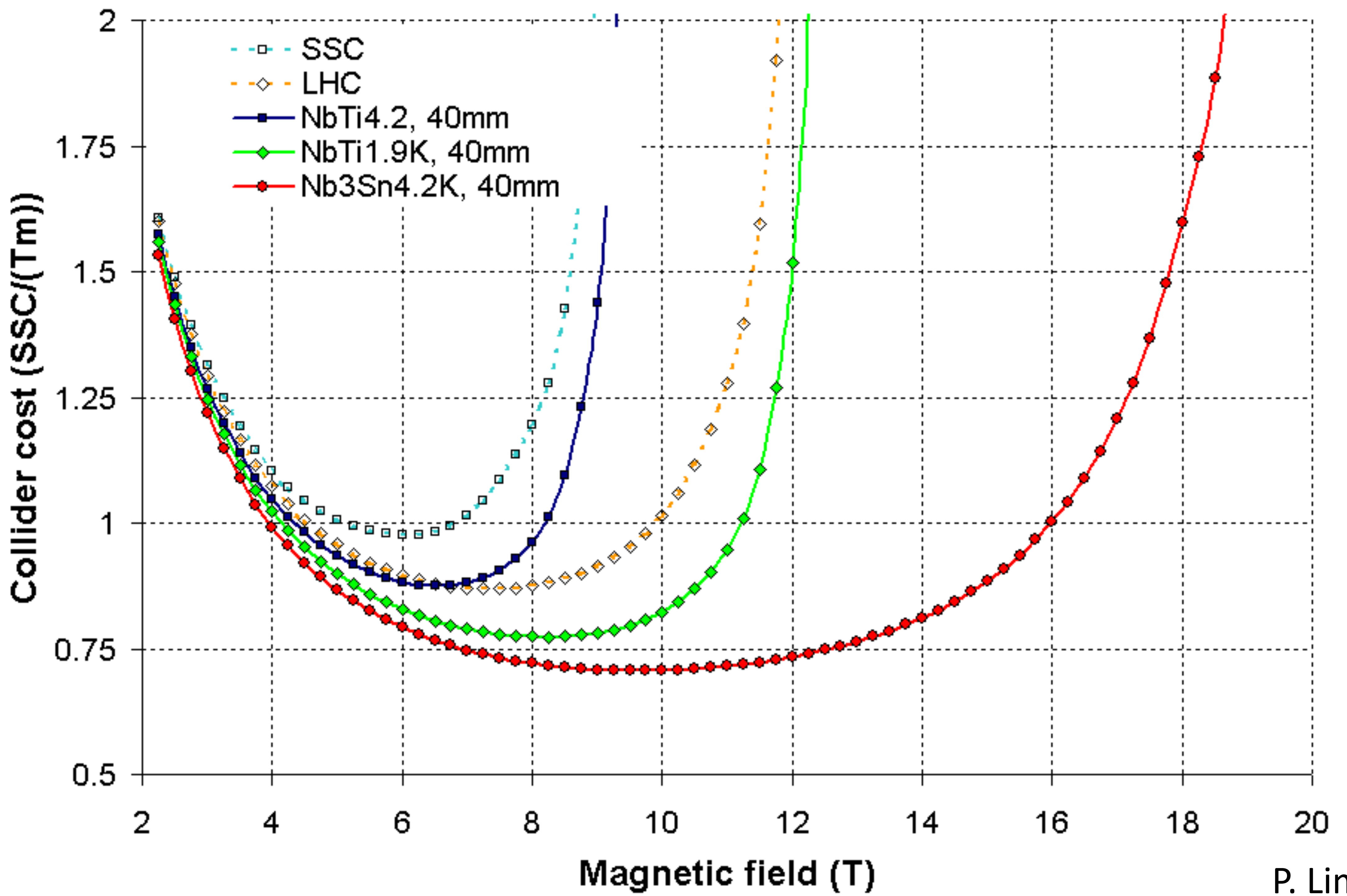
- While many issues still facing us today were first examined 15-30 years ago, much has changed and much has been learned
  - faster computing, newer/better technologies, …
  - the LHC!
- Must find balance between past and present
  - much was learned, much was written, but…
  - do not restrict ourselves: look at what has been done in the past, but feel free to challenge!
  - reasons for past decisions may/may not be as relevant today
    - SSC: http://lss.fnal.gov/archive/other/ssc/ VLHC: http://vlhc.org

Very Large Hadron Collider

Thanks for your attention!

NSCL

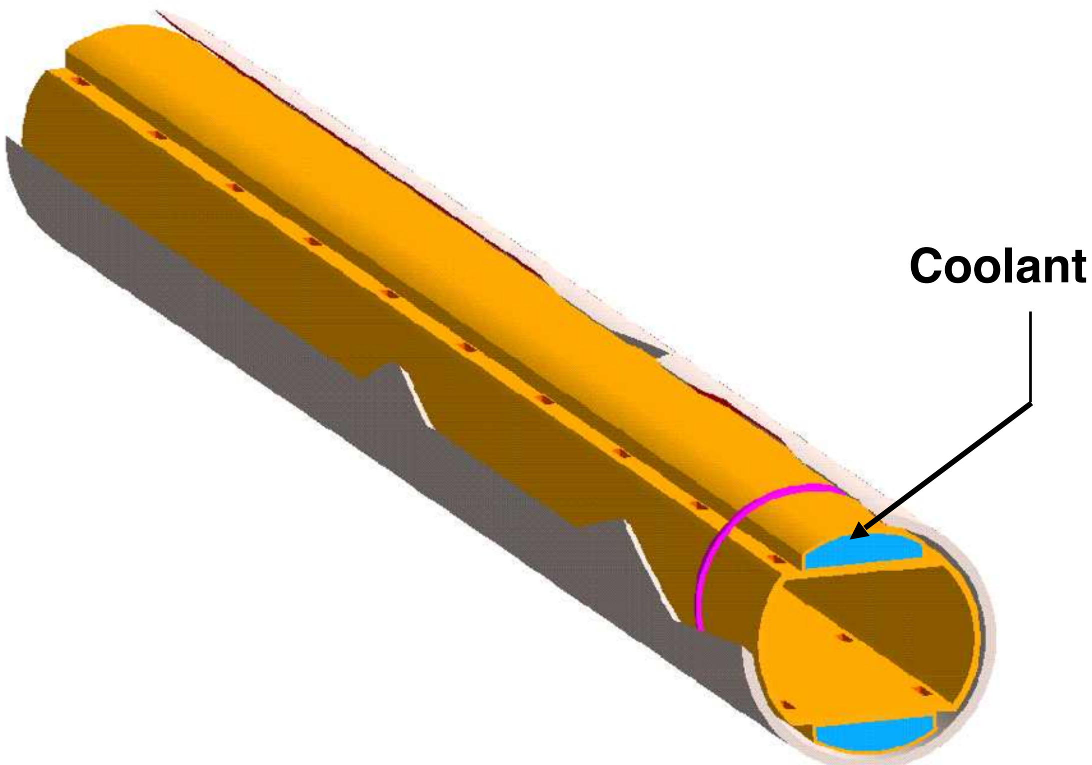
VLHC Cost based on SSC cost distribution



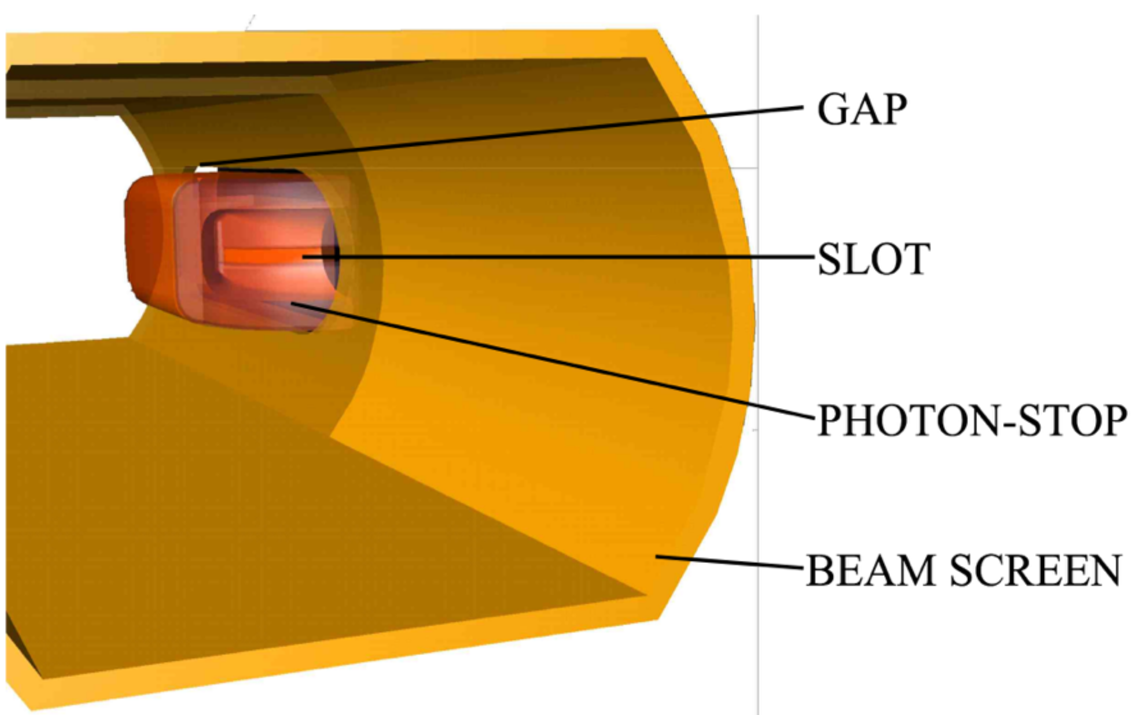
P. Limon, *et al.*

Synchrotron radiation

- Synchrotron radiation masks look promising. They decrease refrigerator power and permit higher energy and luminosity. They are practical only in a large-circumference tunnel.

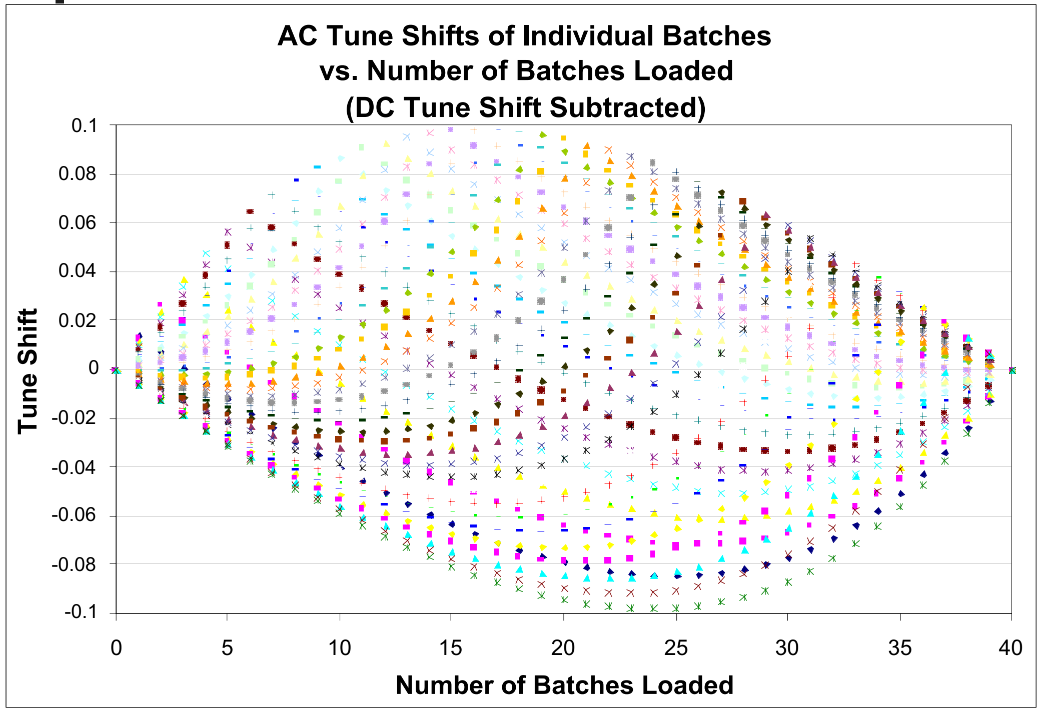


A "standard" beam screen will work up to ~200 TeV and ~2x10^{34}. Beyond that, the coolant channels take too much space.



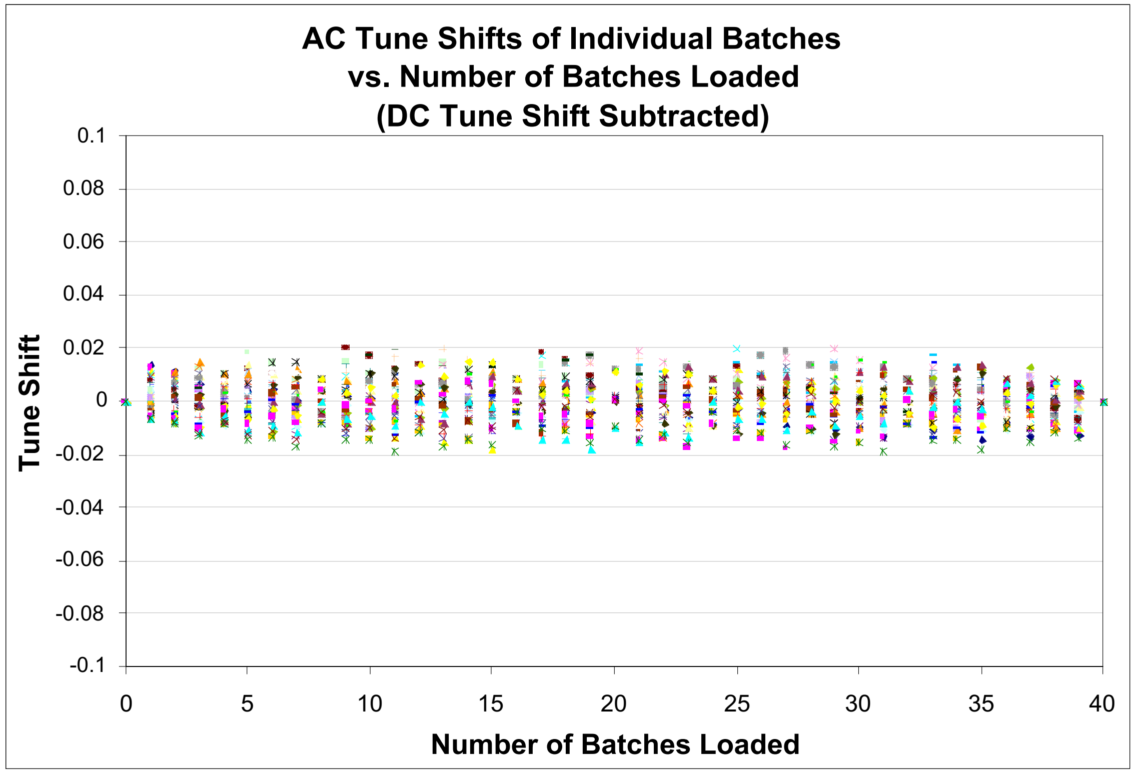
A synchrotron radiation "mask" will allow even higher energy and luminosity.

Filling patterns to reduce tune shifts



STANDARD FILLING SEQUENCE -- sequential filling

BALANCED FILLING SEQUENCE -- interleaved filling



W. Foster, V. Kashikhin