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Beam Dynamics Issues in Very High Energy Circular p-p Colliders

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Northern Illinois University

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NAPAC2016

Collider Requirements

- When discussing issues for future colliders, must place establish a range of basic parameters to consider as our goals —
  - maximum energy
  - maximum instantaneous luminosity, integrated luminosity goals
  - bunch length, spacing, events per bunch crossing, energy spread at collision
  - and other other impacts that come into play:
    - » crossing angle and beam-beam effects, etc.
    - » cost-effective hardware design; real estate; etc.

- Today's Frontier Parameter Set
  - Energy: ~ 100 TeV (*i.e.*, 50 TeV per hadron beam)
  - Luminosity: *peak* ~10^{35} cm^{-2} s^{-1}, ~ 100's fb^{-1}/year, 1000's fb^{-1} total data set
  - Events per bunch crossing: ~200
  - Bunch spacing: ~10 ns (5-25 ns)

attempting to be general, but will easily recognize FCC-type parameters

The Super Proton Proton Collider (SPPC)

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CEPC –SPPC Site Selection

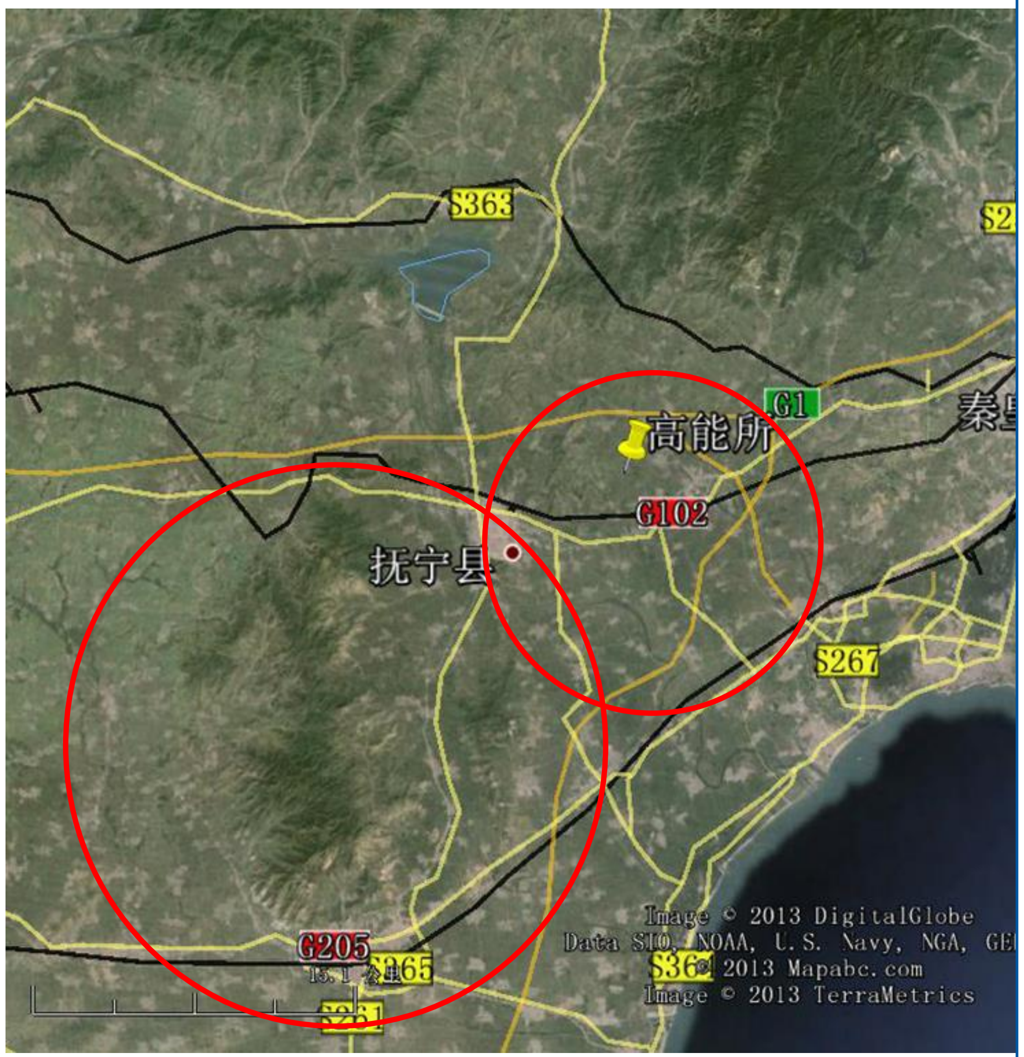
A candidate is QinHuangDao (秦皇岛)

300 km from Beijing

3 hours by car; 1 hour by high-speed train

J. Tang

from talk at FCC Week 2015



SPPC main parameters

Parameter	Value	Unit
Circumference	54.36	km
C.M. energy	70.6	TeV
Dipole field	20	T
Injection energy	2.1	TeV
Number of IPs	2 (4)	
Peak luminosity per IP	1.2E+35	$cm^{-2}s^{-1}$
Beta function at collision	0.75	m
Circulating beam current	1.0	A
Max beam-beam tune shift per IP	0.006	
Bunch separation	25	ns
Bunch population	2.0E+11	
SR heat load @arc dipole (per aperture)	56.9	W/m

The Future Circular Collider Study

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hadron collider parameters

parameter	FCC-hh		SPPC	HE-LHC* (*tentative)	(HL) LHC
collision energy cms [TeV]	100		71.2	>25	14
dipole field [T]	16		20	16	8.3
circumference [km]	100		54	27	27
# IP	2 main & 2		2	2 & 2	2 & 2
beam current [A]	0.5		1.0	1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25	25
beta* [m]	1.1	0.3	0.75	0.25	(0.15) 0.55
luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	20 - 30	12	>25	(5) 1
events/bunch crossing	170	<1020 (204)	400	850	(135) 27
stored energy/beam [GJ]	8.4		6.6	1.2	(0.7) 0.36
synchrotr. rad. [W/m/beam]	30		58	3.6	(0.35) 0.18

Future Circular Collider Study
Michael Benedikt
2nd FCC Week, Rome, April 2016
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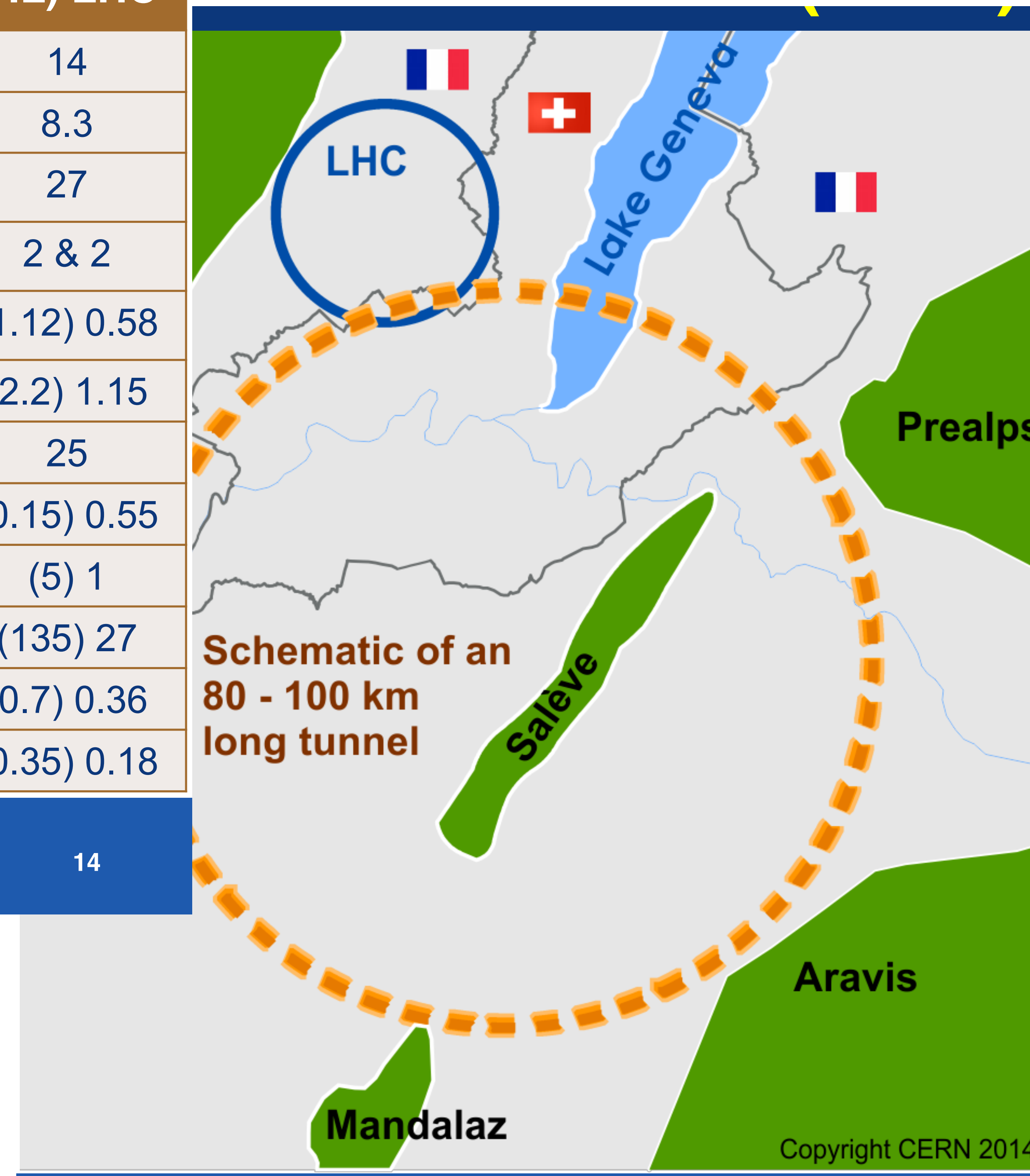

M. Benedikt
from talk at FCC Week 2016

Technology Limitations and Challenges

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- Today's (or next year's) technology limitations will determine the engineering solutions used in a future collider — many years to complete
- For a *large* hadron collider, it's the **Magnets**
  - Tevatron ~ 4 T; (SSC ~ 6 T); LHC ~ 9 T;   FCC ~ 16 T
  - today's limit in model accelerator magnets ~ 13-14 T
    - still ways to go to make reproducible, but getting closer — should get there
    - note: will actually need 18-20 T, to include operational margin, etc.
- So, let's assume ~16 T — sets scale of the collider circumference

$$\rho = \frac{p}{e\,B}\ ; \quad R = \rho/f \quad (f \approx 0.8 - 0.9)$$

leads to ~ 100 km circumference

- Many other important technology considerations, with actual feedback into the beam dynamics issues: beam pipe design (synch rad, vacuum, impedance), energy deposition mitigation, controls/feedback systems, …

Magnets

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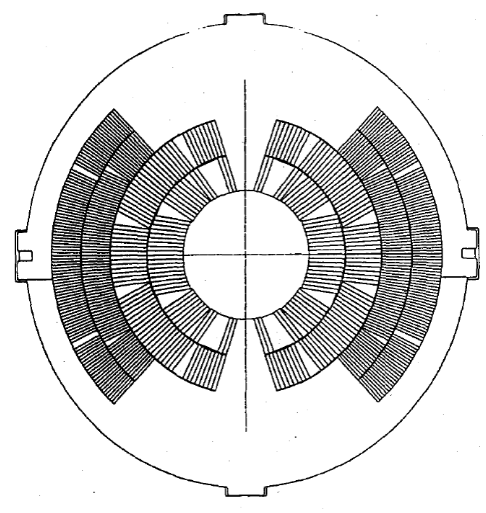
Cos-θ (D20, achieved bore field 13.5 T at 1.9 K)



D. Dell'Orco et al., IEEE Trans. Appl. Supercond., Vol. 3, No.1, 1993

Block (HD2c, achieved bore field 13.8 T at 4.3 K)

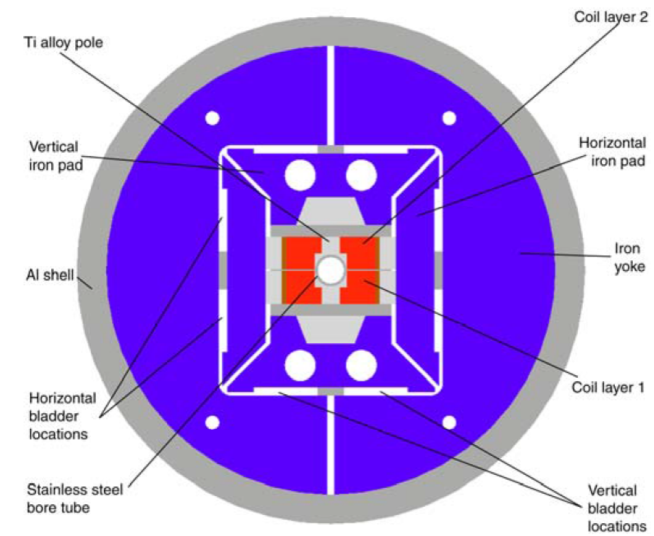


Fig. 2. HD2 cross-section.

P. Ferracin et al., IEEE Trans. Appl. Supercond., Vol. 19, No.3, 2009

Common coil (Rd3d, achieved bore field ~11 T)

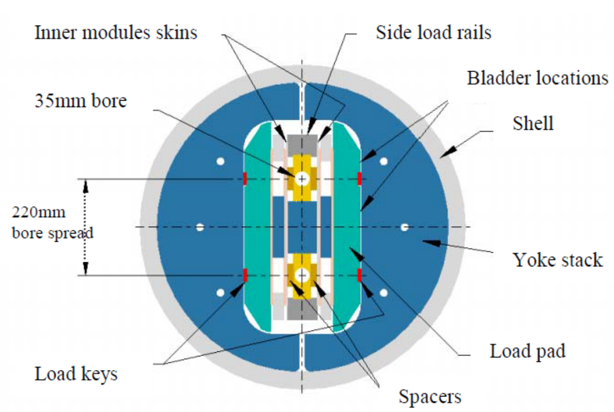
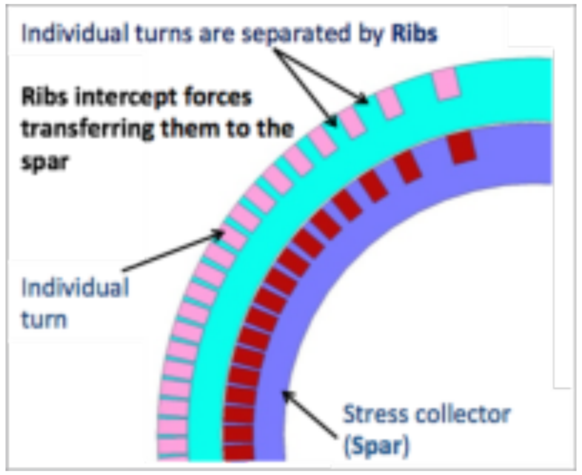
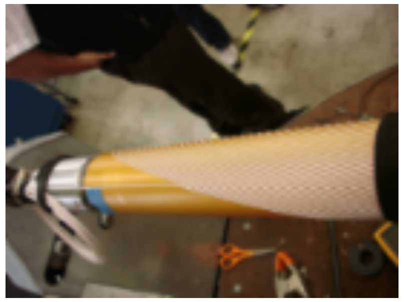


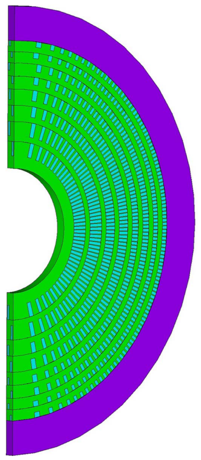
Figure 1: The magnet cross-section for RD3c.

A.F. Lietzke, IEEE Trans. Appl. Supercond., Vol. 13, No.2, 2003

Canted-Cos- θ (concepts)







S. Caspi, FCC kick-off meeting, SC Magnet Development Toward 16 T Nb3Sn Dipoles

L. Brouwer, IEEE Trans. Appl. Supercond., Vol. 25, No. 3, 2015

Courtesy Daniel Schoerling (CERN)

Luminosity

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- One could argue that with a factor of 7 in beam energy (14 to 100 TeV) should come a factor of ~50 in luminosity — 5x10^{35}cm^{-2}s^{-1}
  - Remember that LHC luminosity was picked to compete with the SSC (14 rather than 40 TeV —> 10^{34} rather than 10^{33}). If SSC were scaled to 100 TeV, then would want ~10^{34}

$$\xi = \frac{r_0 N}{4\epsilon_n}$$

(beam-beam "tune shift" parameter)

- In round numbers, …

$$\boxed{\mathcal{L} = \frac{fN^2}{4\pi\sigma^2} \longrightarrow \frac{\gamma\xi}{r_0\beta^* t_b}\ N\ \mathcal{F}(\alpha)}$$

$$\mathcal{F}(\alpha) \approx \frac{1}{\sqrt{1+(\alpha/2)^2(\sigma_s/\sigma_x)^2}}$$

$(5\ 10^4)(0.005)$ / $[(1.5\ 10^{-16}\ \mathrm{cm})(100\ \mathrm{cm})(25\ 10^{-9}\ \mathrm{s})] * 10^{11} * (9/10)$

$\sim 5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (FCC-hh early-stage design goal)

- These basic parameters could be viewed as "modest", and upgraded values would lead into the 10^{35} luminosity regime

Beam Dynamics Issues at 50 TeV

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- What are the beam dynamics issues at 20-50 TeV/beam?
  - aperture and single-particle stability
  - synchrotron radiation, luminosity development/optimization
  - energy deposition — beam loss rates, heating, etc.
  - beam stored energy — abort and accident protection
  - beam-beam interactions, crossing angles, tune spread, PACMAN effects
  - coherent instabilities
- Same issues (by name) now as in 1986; but…
  - …technology & materials — the field has continued to evolve
  - …computing power — VERY different that 30 years ago
  - …*and*, we now have ***experience*** at ~1-7 TeV

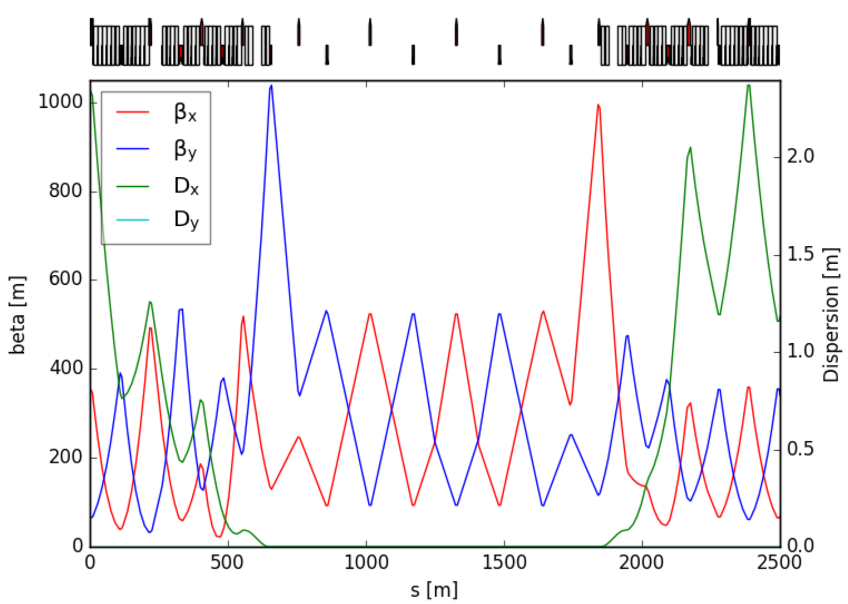
can only discuss a few issues here, in any small amount of depth

Start with Linear Optics

- For a given technology, can scale the optics (focal lengths, spacing, etc.) with the momentum. Hence, often adapt layout of present systems into newer systems, taking into account improvements in technologies

$$N_{cells} \sim \sqrt{C} \;, \quad etc.$$

- Note: superconducting technologies have enabled much higher fields, however the "warm" components still dictated by 2 T technologies:
  - kickers, septum magnets, separation magnets, etc.
  - as particle energy increases, space required for injection, extraction, etc., increases proportionally (assuming similar transverse constraints)



Recent FCC straight section design iteration
(courtesy A. Chance)

Linear Optics

- Straight Section Insertions
  - Extraction typically requires long nearly-uninterrupted space
    - » protection of elements during atypical beam abort
  - Interaction regions — next longest (typically for final focus, beta-squeeze)
  - Shorter regions for injection (maybe not so short), RF, instrumentation
  - Becoming ever more important for higher energies: energy deposition mitigation
    - » beam scraping/collimation — transversely and longitudinally
- At issue:
  - IR placement, clustering
  - modularity, circumference control
  - dispersion control, suppression (and, in some cases, enhancement)

Superperiodicity

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- Racetrack vs. multiple superperiods

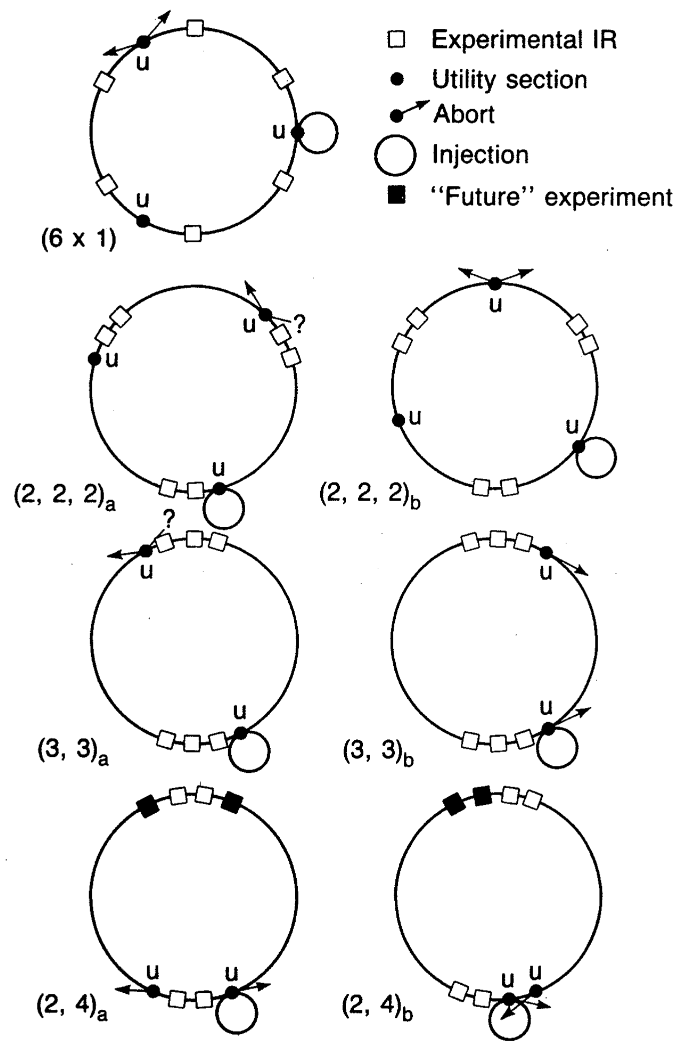


Figure 4.2-1. Various possible IR clustering arrangements for the SSC.

from the SSC 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: $P = 1$!

Modularity

- Length of SSC Standard Half-Cell was in units of the bunch spacing (5 m)
- 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

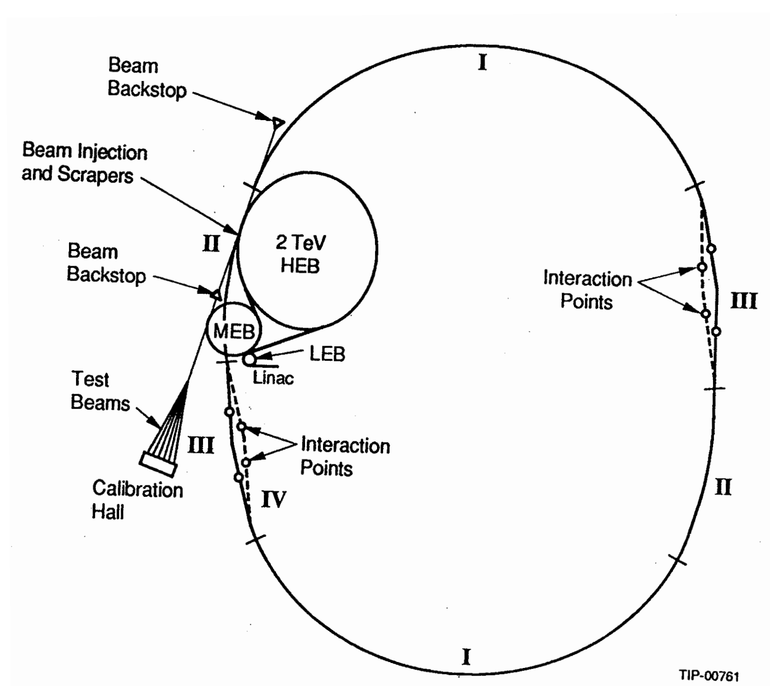
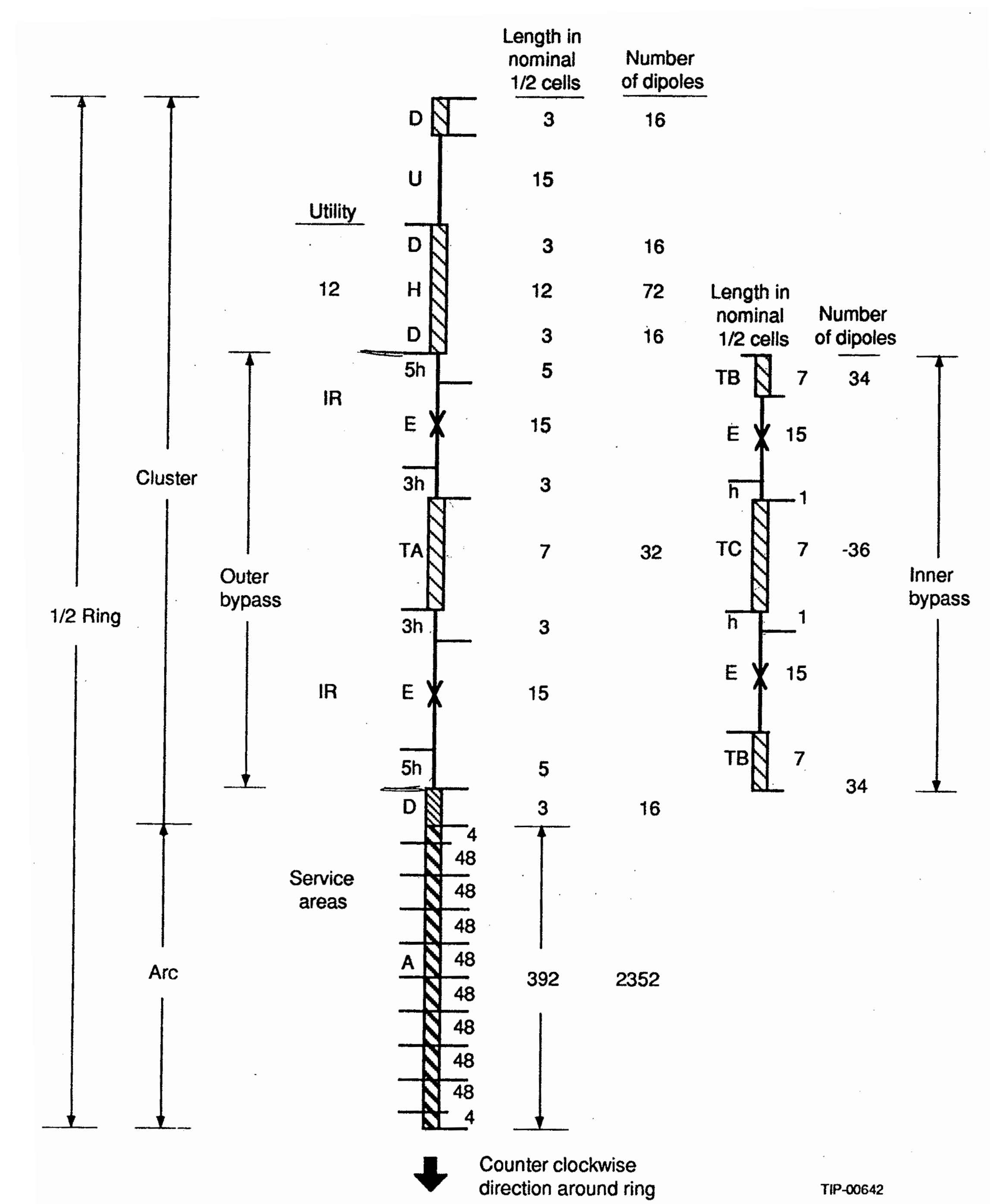


Figure 4.1.1.1-4. Schematic layout of SSC.

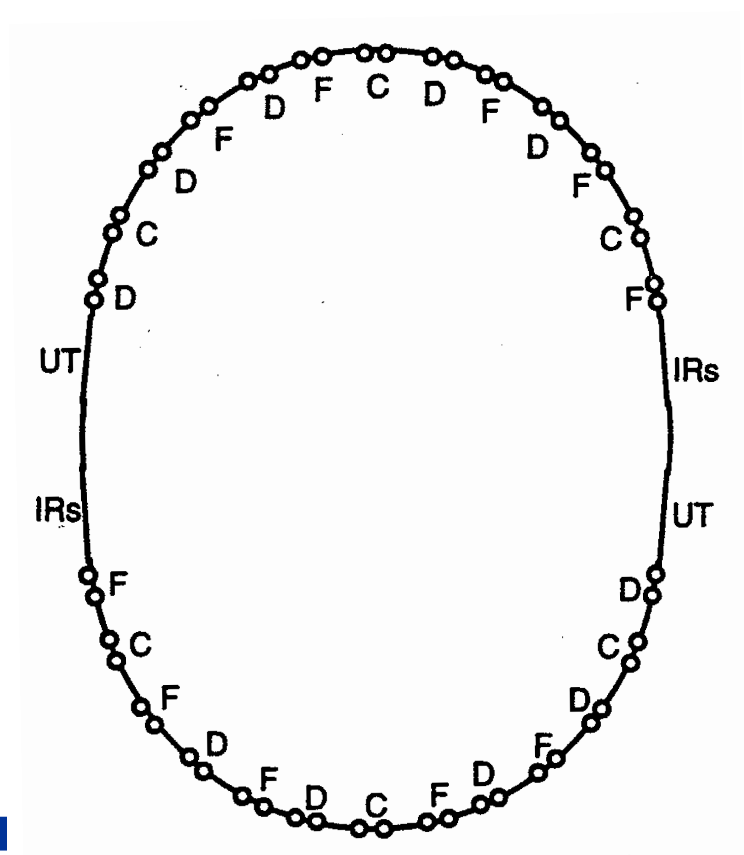


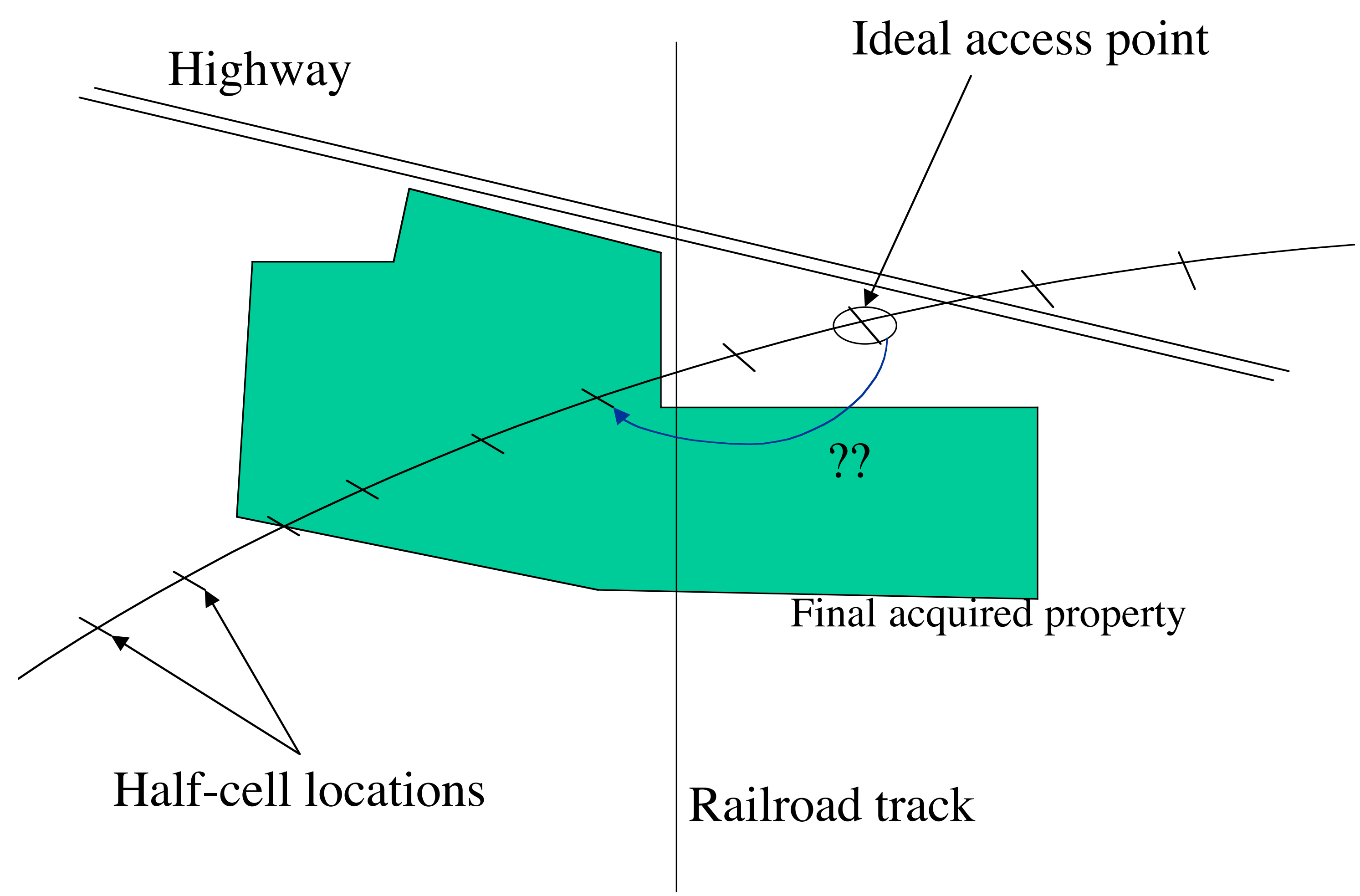
Basic SSC modules

Modularity and “free space”

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

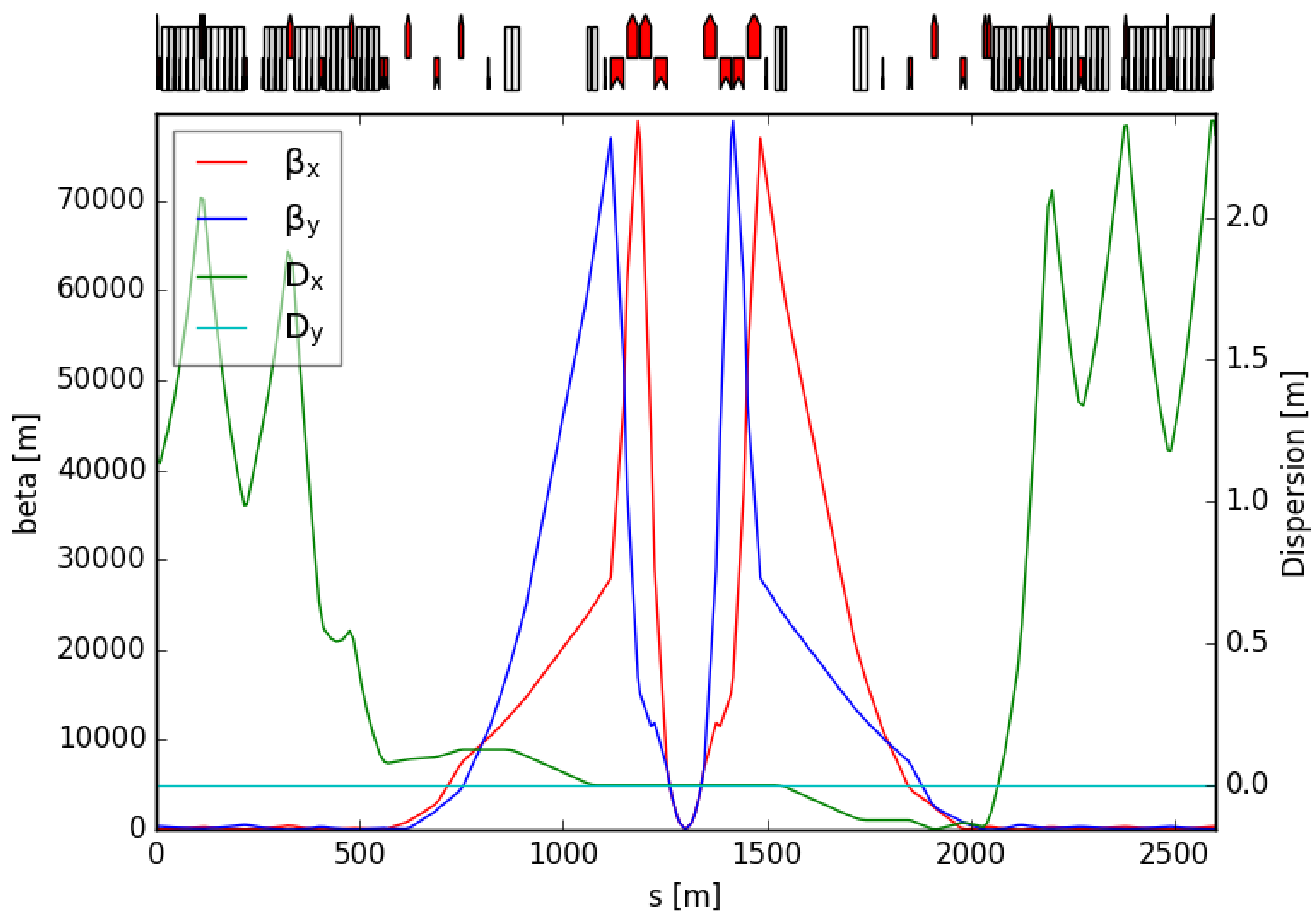
- “free space” created in arcs
  - “missing” dipoles in cells





Interaction Region Design

- Machine-Detector Interface
  - inclusion of shielding, sweeping dipoles, etc.
- Issues will extend beyond the IP/IR — arc interface
  - dispersion suppressors at entrance/exit of IRs will require attention



Recent FCC design iteration
$\beta^* = 0.3$ m
(courtesy A. Chance)

Momentum Collimation

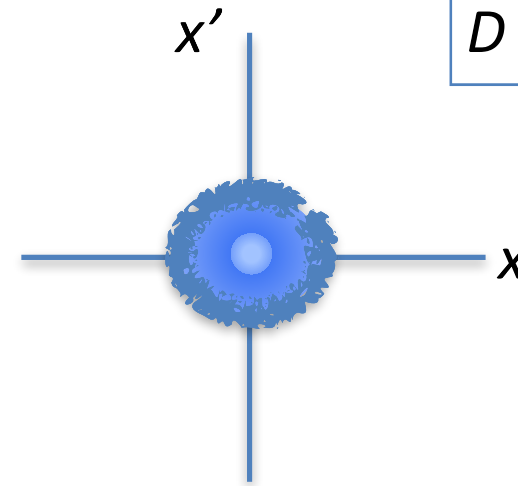
- Note: momentum spread goes down; but dispersion remains ~ the same
  - *D* always on the scale of ~1-2 m or so

$$D_{max} = \frac{L\theta_{hc}}{\sin^2 \mu/2}\left(1 + \frac{1}{2}\sin\mu/2\right)$$

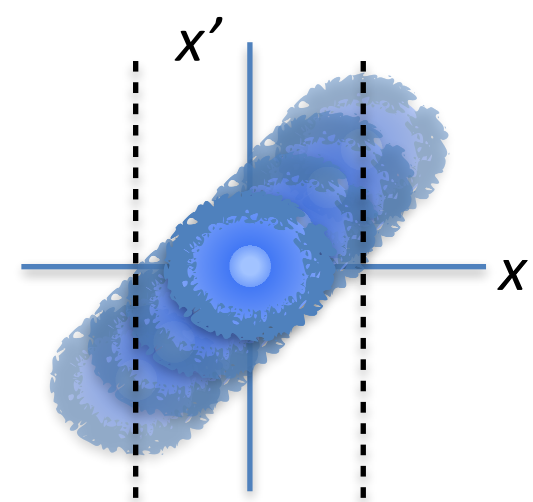
$$\sigma(s) = \sqrt{\beta(s)\epsilon_N/\gamma + D(s)^2\sigma_p^2}$$

- Momentum spread decreases for higher energies, and dispersion harder to generate in a short space
- Look to improve momentum cleaning through optical designs

D = 0



D ≠ 0



thus, optimize $\dfrac{D}{\sqrt{\beta}}$

Momentum Collimation

optimize $\dfrac{D}{\sqrt{\beta}}$ to discriminate during collimation

- Create insertion with
  - "low-beta" optics, and
  - larger dispersion

Suppose want

$$D\sigma_p \geq 2\sqrt{\beta\epsilon_N/\gamma}$$

Then, for FCC-like parameters,

$$\frac{D^2}{\beta} \geq \frac{4(2.2\cdot 10^{-6}\mathrm{m})}{(2\cdot 10^{-5})^2(5\cdot 10^4)} \approx \frac{1}{2}\ \mathrm{m}$$

About the middle of a straight section with a focus,

$$\frac{D^2}{\beta} = \frac{D^{*2}}{\beta^*}\ \underline{\frac{1}{1+(s/\beta^*)^2}}$$

for $s < \beta^*/2$, this factor > 0.8

Lattice Design Investigations

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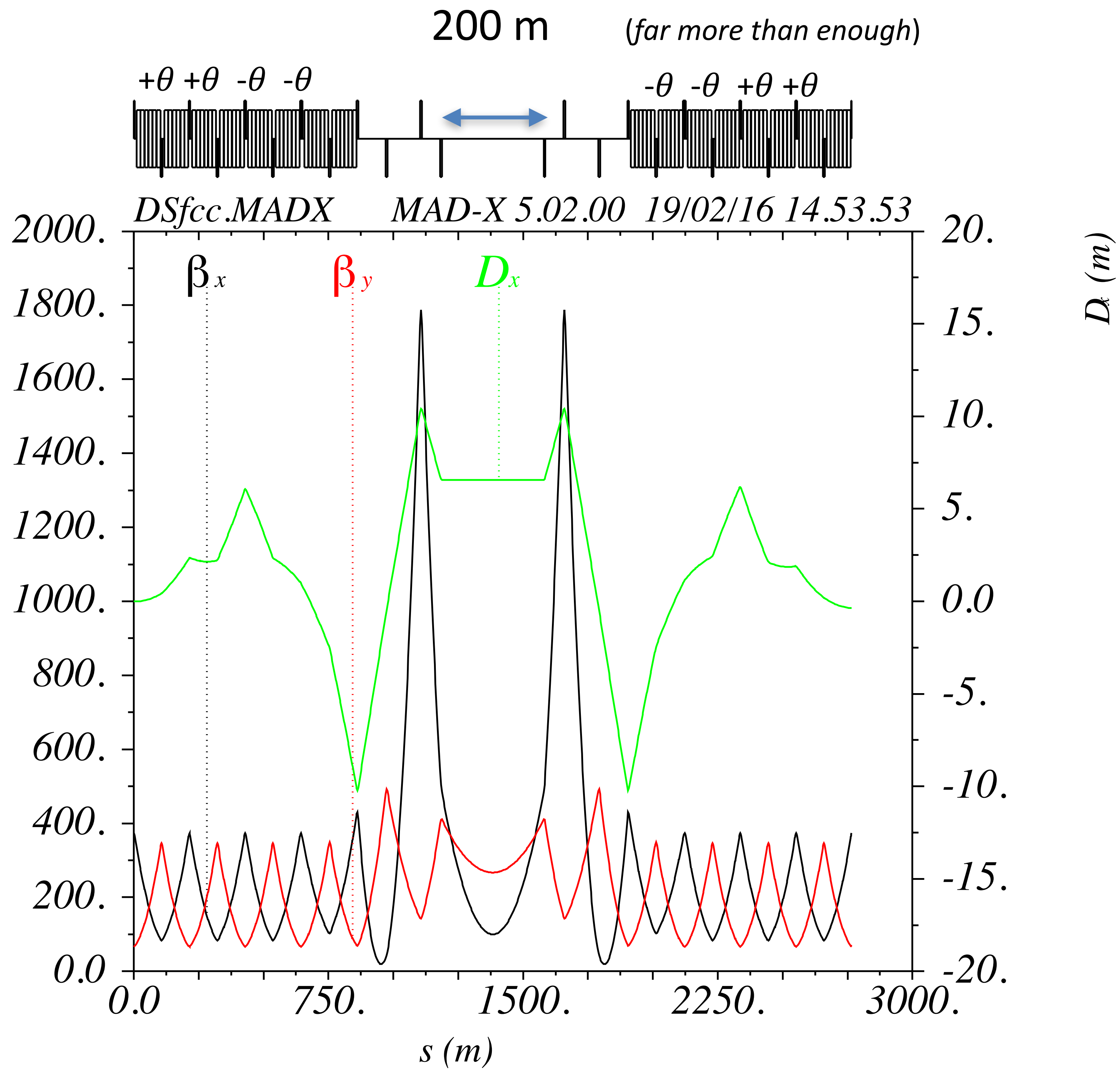
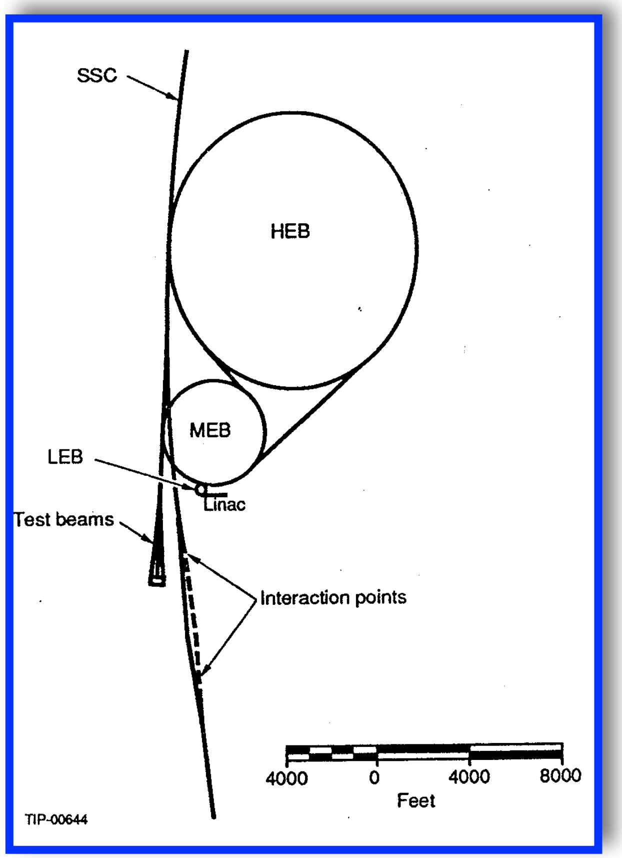
optimize $\frac{D}{\sqrt{\beta}}$ using reverse bending

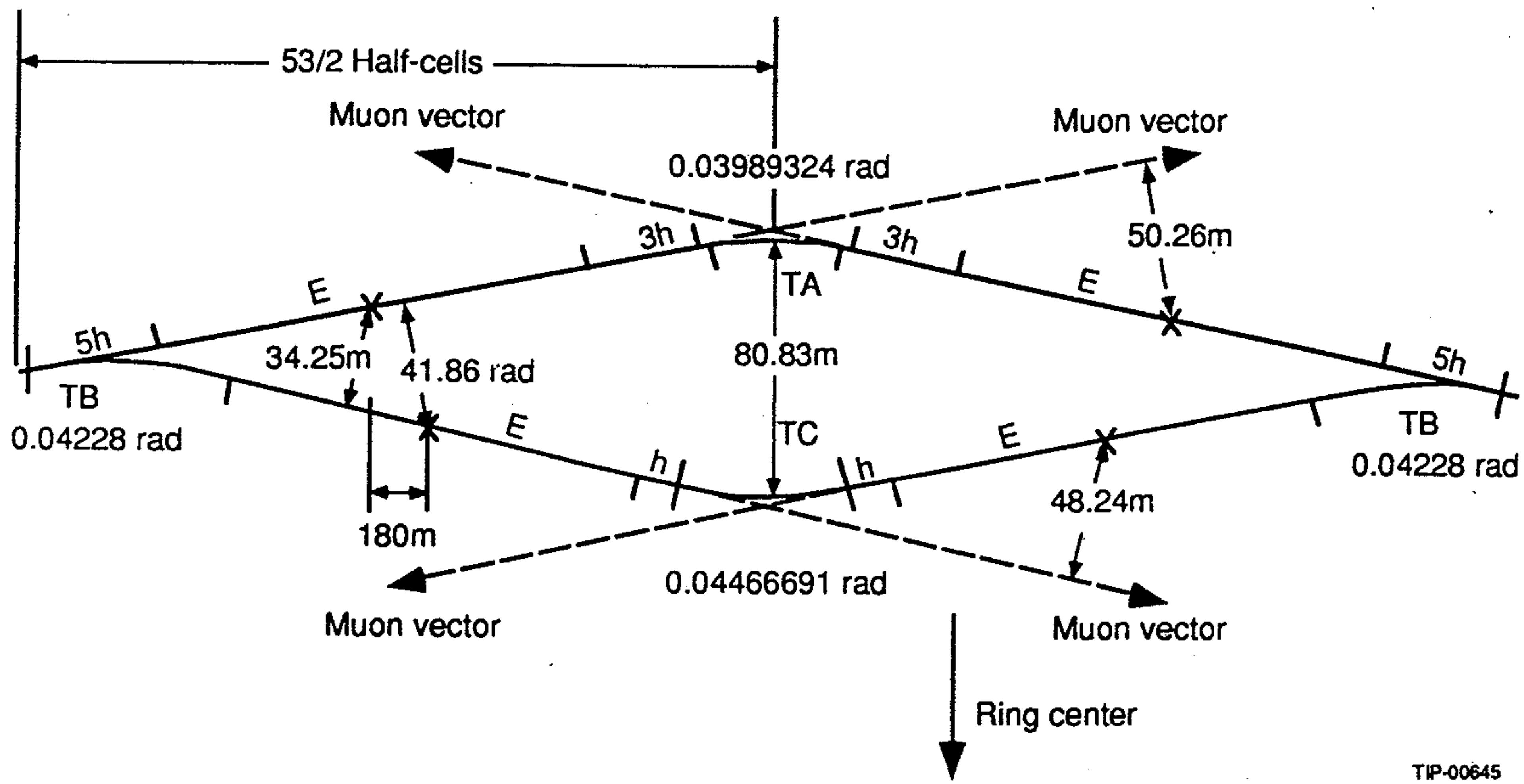
- Produce an insertion with "low-beta" optics (β^* ~ 100 m) and a larger dispersion (D^* ~ 5-10 m), created by appropriately phased anti-bending
- Concept is still under investigation, including geometric implications, etc.
- Again, similar scheme was applied in the SSC lattice, for different purpose



The SSC Diamond Bypass



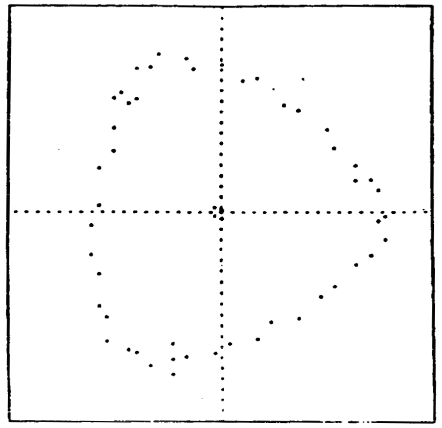
Was to utilize reverse-bending sections to create equal path length modules to separate future IR regions from the early-commissioned IRs



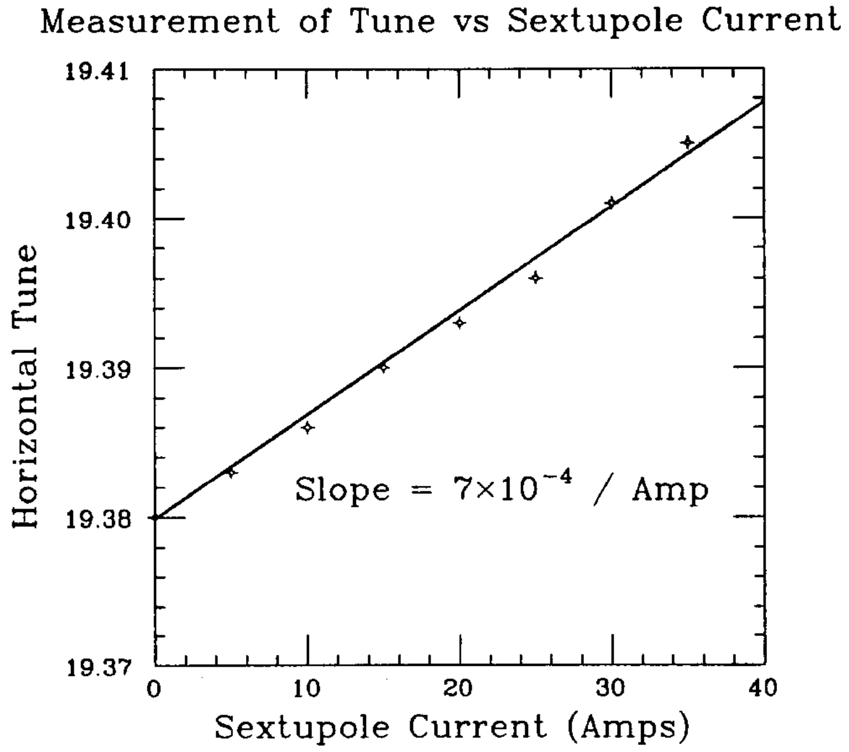
A. Garren design

Dynamic Aperture and Design Criteria

- Computations of dynamic aperture began in earnest with the Tevatron design studies
  - Early verification of nonlinear dynamics
    - » measured phase space; tune vs. amplitude
    - » measured dynamic aperture vs. predictions



early Tevatron data



L. Merminga, et al., Tev Expt. E778

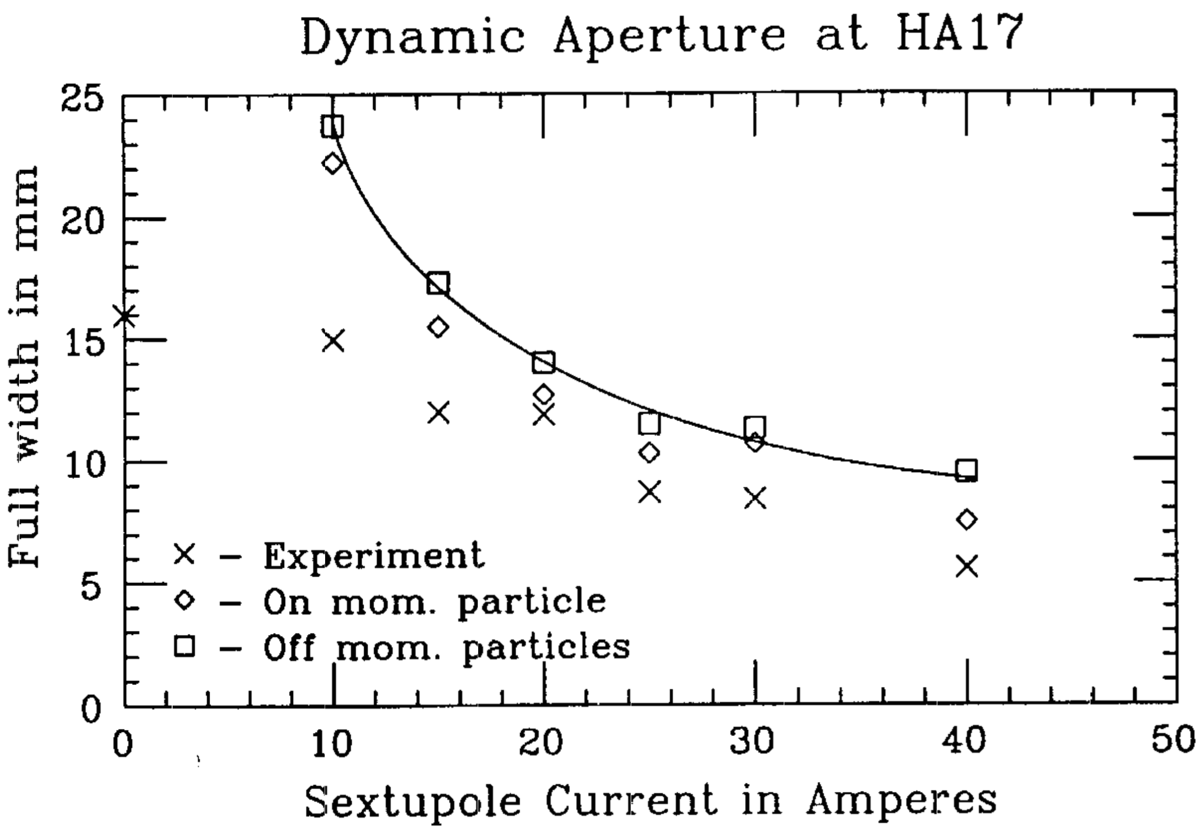


Figure 7.5: Dynamic aperture at HA17. The smooth curve is a fit to the simulated results for off-momentum particles.

Dynamic Aperture and Design Criteria

- SSC Design Study, LHC design study:

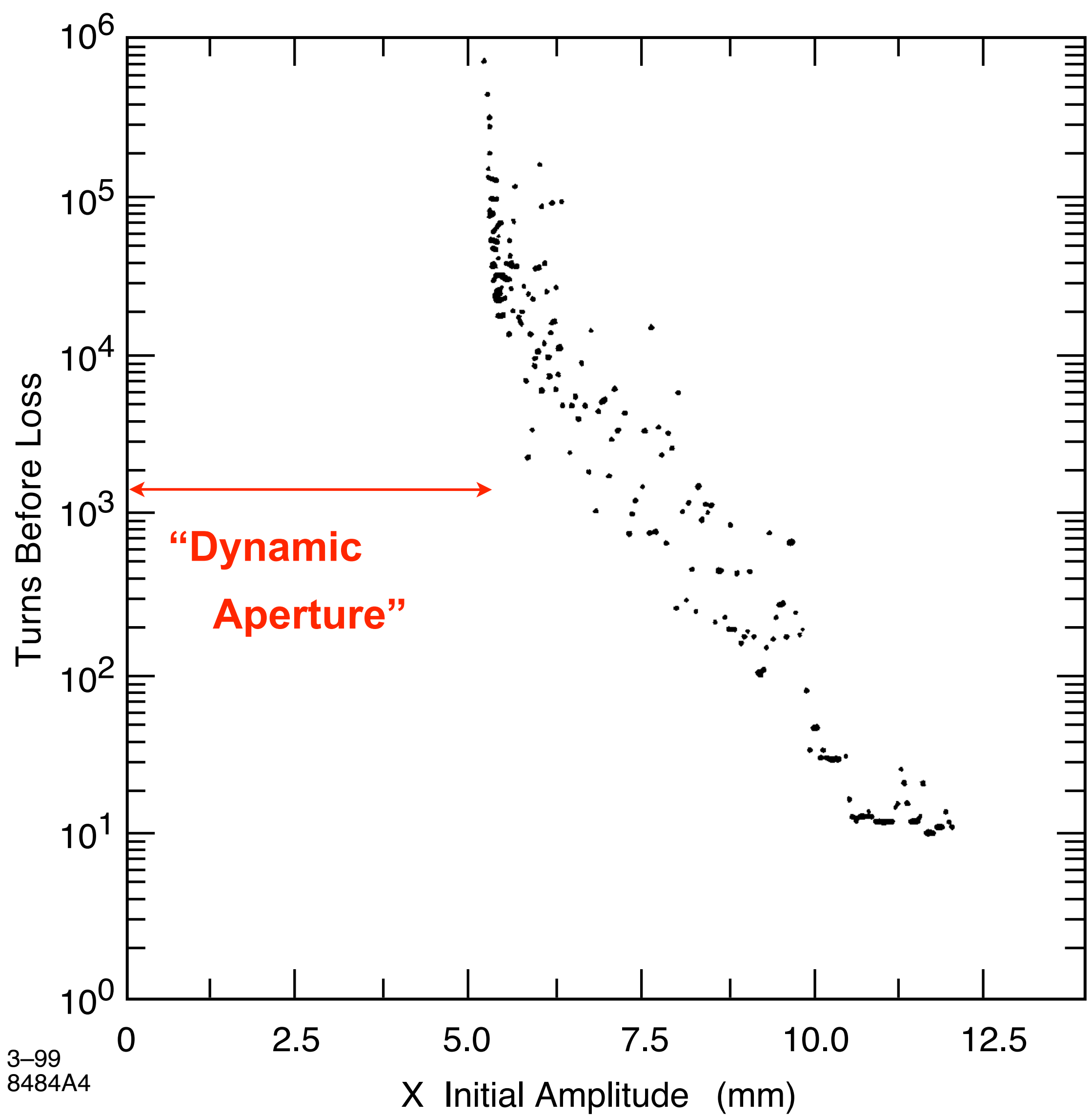


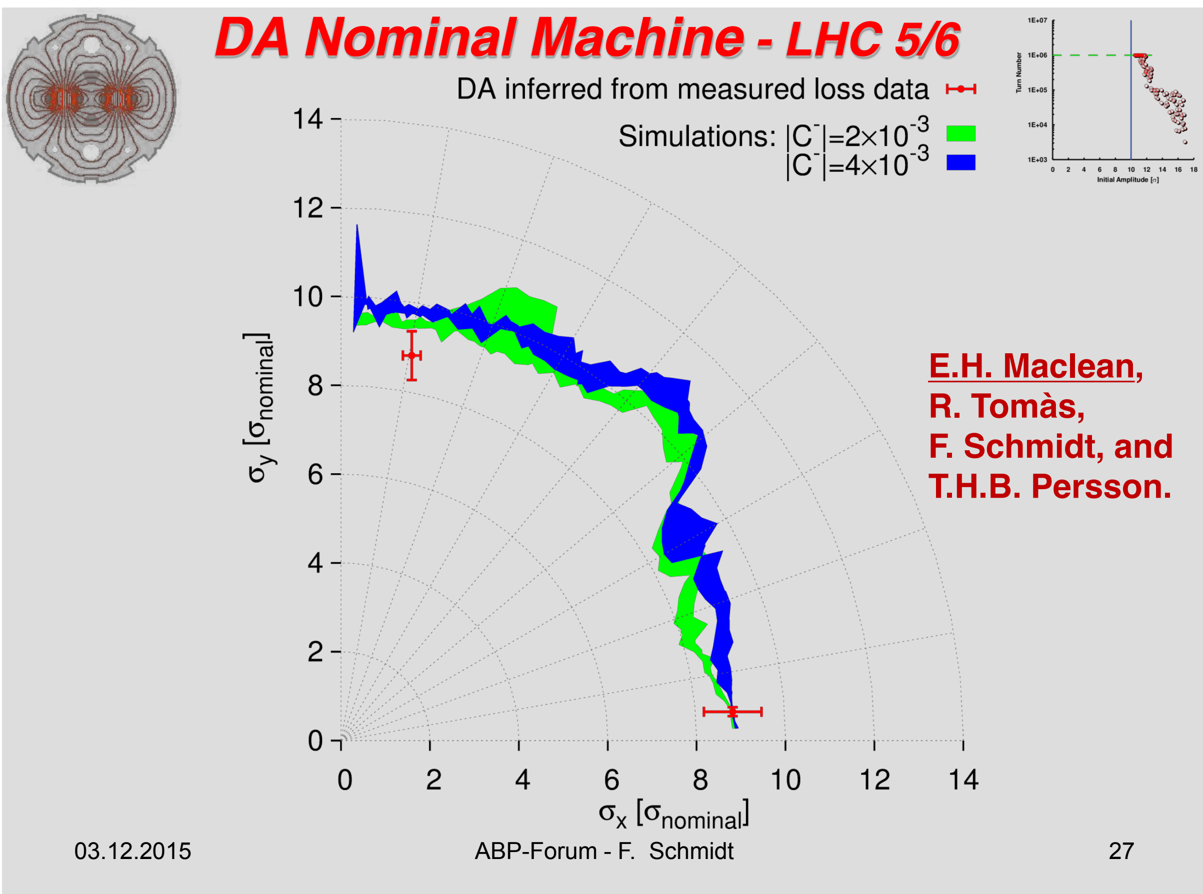
Figure 3. Survival plot for an SSC model.

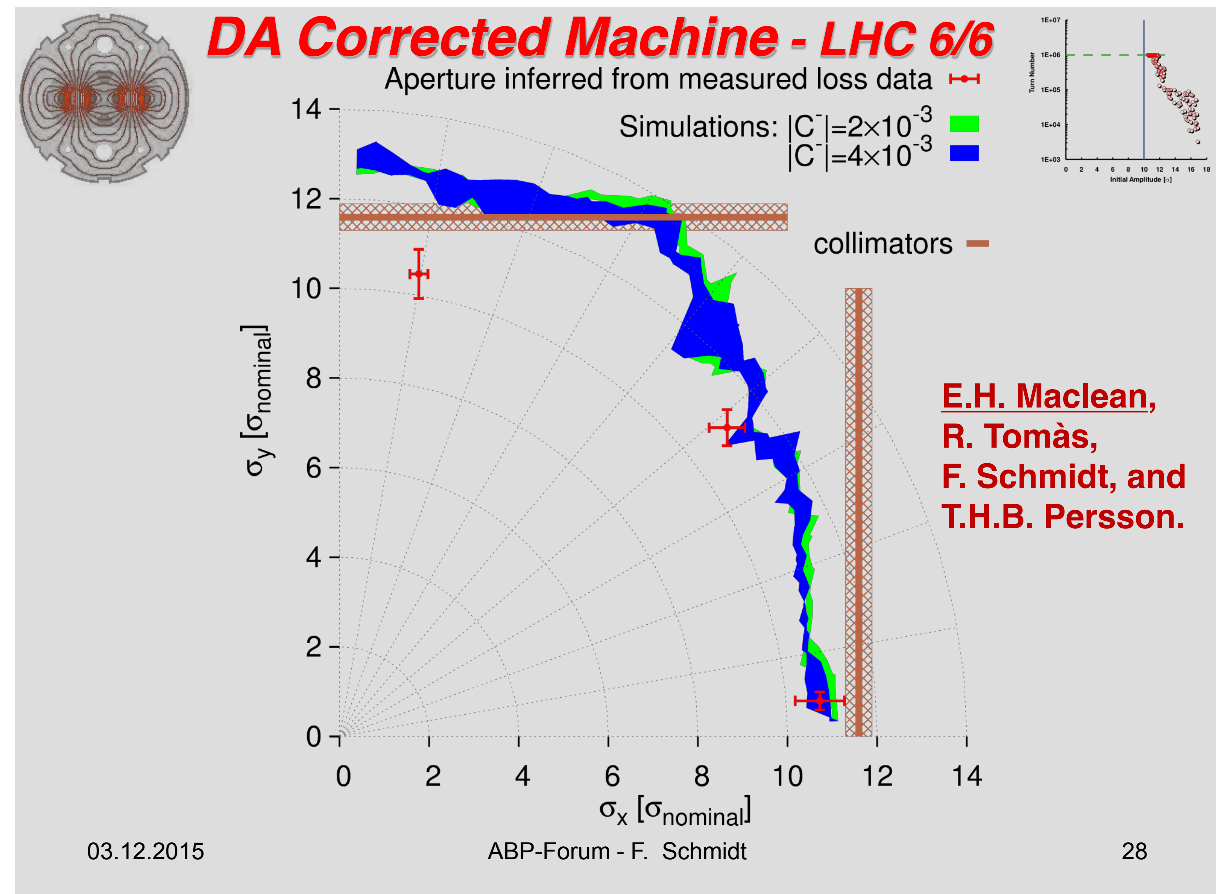
- Initial long-term tracking codes for the SSC and for early LHC design work struggled to be able to track for 10^6 turns — for a single particle!
- Led to many, often conservative, decisions to be made during these times

Y. Yan, *et al.*,SSCL Report 303 (1990)

Single Particle Stability

- Today, times are different. Computers are MUCH faster and simulations can be much more complete.
- And, we now have a well-operating LHC with which to compare!





- Tracking sufficient number of particles for sufficient turns will require continued efforts, but recent history provides confidence in the techniques

Synchrotron Radiation

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- In the SSC design, electron cloud effects were just becoming realized as an issue
  - this generated the need for a liner
  - SSC was cancelled, but became even more important for LHC
- LHC studies drove understanding of liner impedance and requirements of coatings and interfaces
- For SSC, and especially for LHC — SR no longer a “nuisance”, but rather a significant operational issue
  - parameter choices with beam screen considerations
  - SR can be exploited to optimize integrated luminosity
  - impedance, e- cloud, instabilities will need further study

Early FCC Beam Screen Studies

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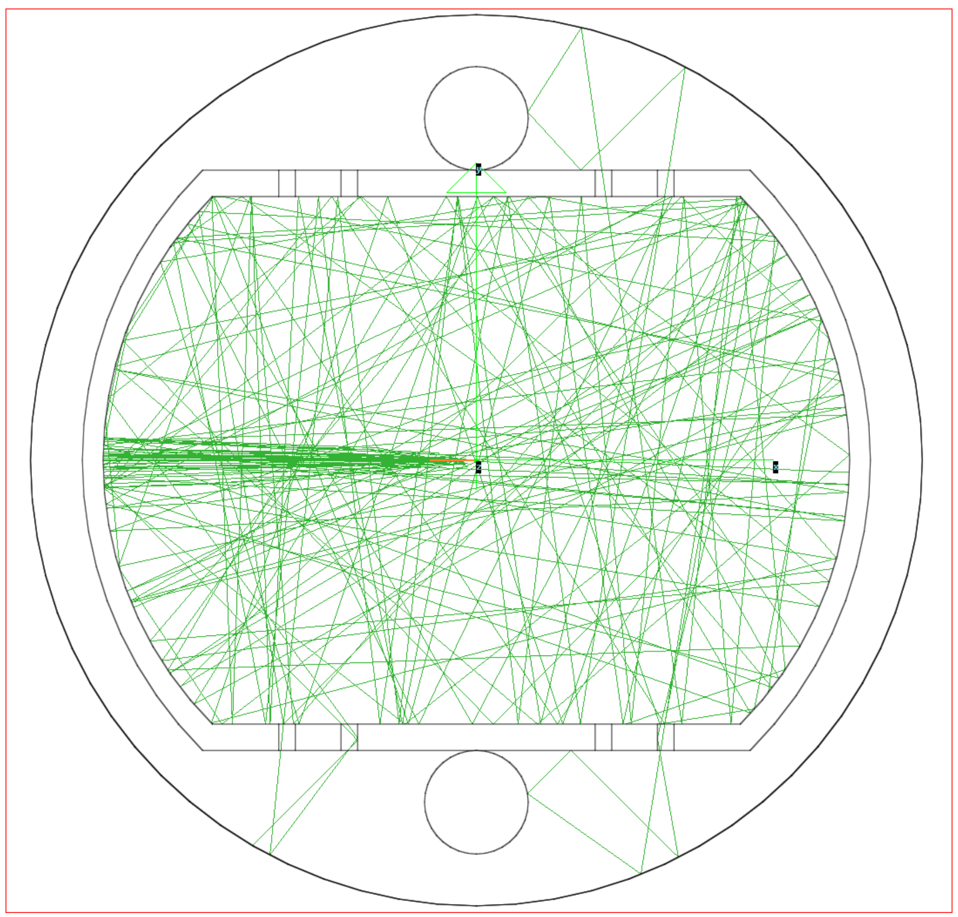
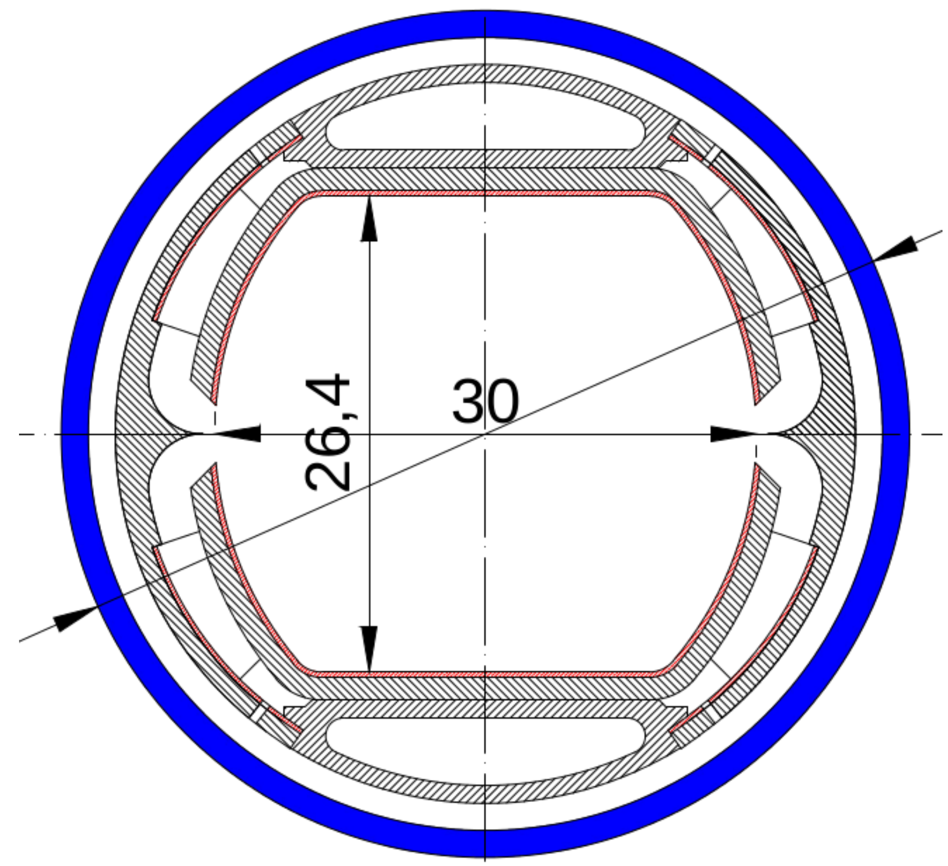
SR Ray-Tracing (Synrad+):

The high-energy small vertical angle opening of the primary SR fan passes almost unscathed inside of the 2x 1.57 mm-high continuous slot



All SR-induced gas load may interact with the beam



More recent beam screen design, R. Kersevan, C. Kotnig, et al.

Early FCC Beam Screen Studies

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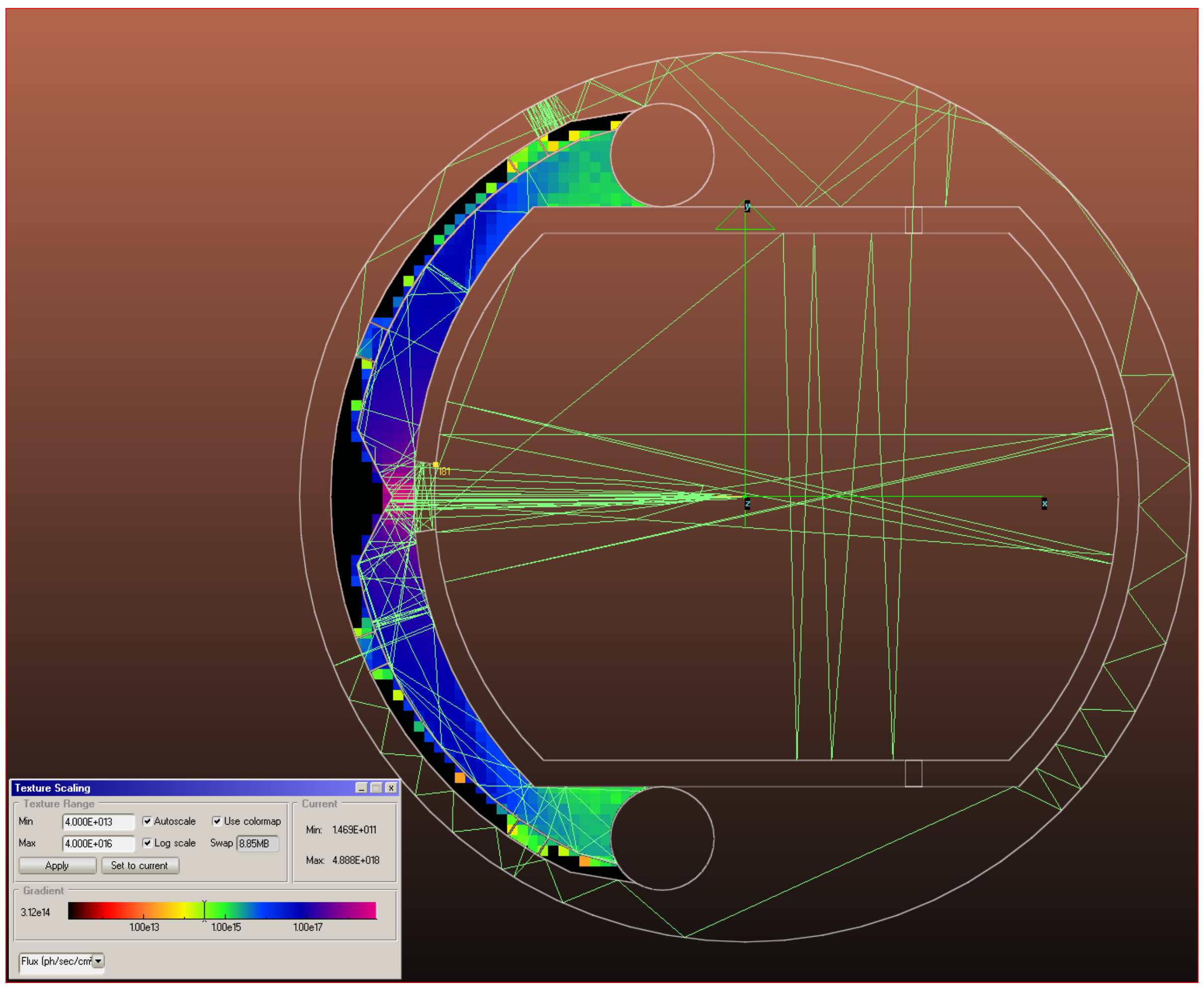

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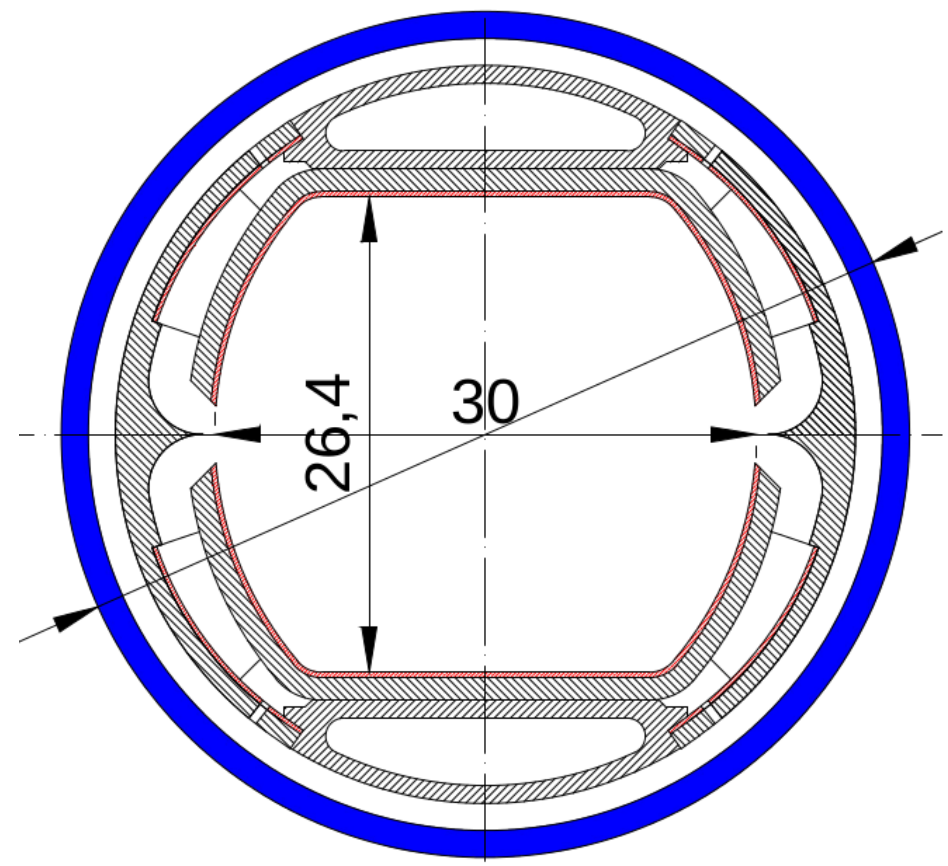

More recent beam screen design, R. Kersevan, C. Kotnig, et al.

Energy Deposition and Collimation

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- Example: FCC parameters
- >8 GJ kinetic energy per beam

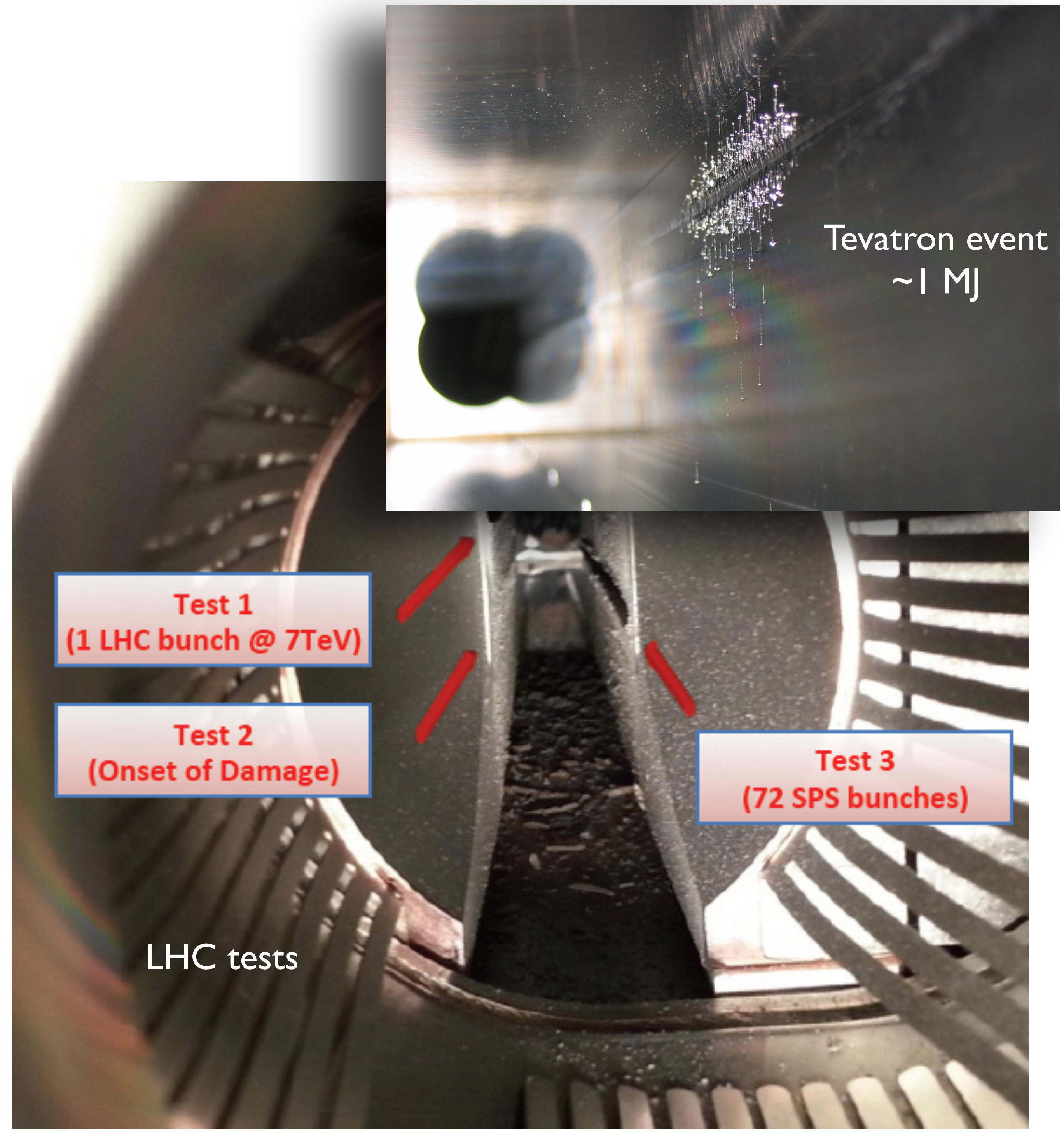
beam loss of ~10^{-4} = ~1MJ

- **Airbus A380 at 720 km/h**
- 24 times larger than in LHC at 14 TeV
- Can melt 12 tons of copper
- Or drill a 300 m long hole

⇒ Machine protection

- Also *small* loss is important
- *e.g.* beam-gas scattering, non-linear dynamics
- Can quench arc magnets
- Background for the experiments
- Activation of the machine

⇒ Collimation system



Introduction of “2-Stage” Collimator System

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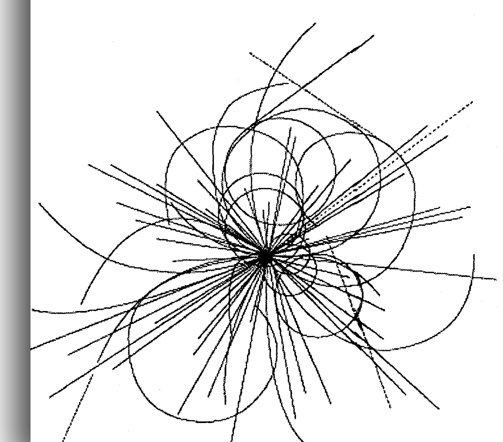
- First investigated in detail during the SSC site-specific design development, later implemented in the Tevatron, LHC

SSCL-Preprint-555

SSCL-Preprint-555
February 1994
Distribution Category:

A. Drozhdin
N. Mokhov
R. Soundranayagam
J. Tompkins

Toward Design of the
Collider Beam Collimation System



2. Two-stage collimation system

The most direct way of collimating a beam of particles is to define the physical aperture ...lid block of absorbing material. Depending upon the material and thickness, a ...action of the intercepted beam will survive, either by traversing the whole length ...ock or by being scattered out of the block. Fig. 1 shows particle angular ...on at the downstream end of the scraper block for the LHC 8-TeV protons [8]. ...ber of protons penetrating the whole length of the scraper can be reduced by using ...block or a “denser” material. Suppression of the outscattered particles is much ...icult. For a given material, the position and width of the peak of the outscattered ...ield depends upon the impact parameter and particle energy. The smaller the ...rameter and the higher the energy, the narrower the peak becomes and the closer it ... the zero-angle position.

...rincipal scheme of a two-stage collimation system is shown in fig. 2. The ...e position of outscattered protons and of protons traversing the entire block is ...e same, but they have different angular distributions. Consequently all these ...fall along a vertical straight line in the phase space, as shown in fig. 2. After ...bout 10° in the phase advance, the segment of line corresponding to positive angle can be efficiently intercepted by a secondary collimator. For a segment corresponding to outscattered particles (negative angles), it is necessary to place a secondary collimator at about 150° in phase advance downstream of the first collimator. The Tevatron uses only

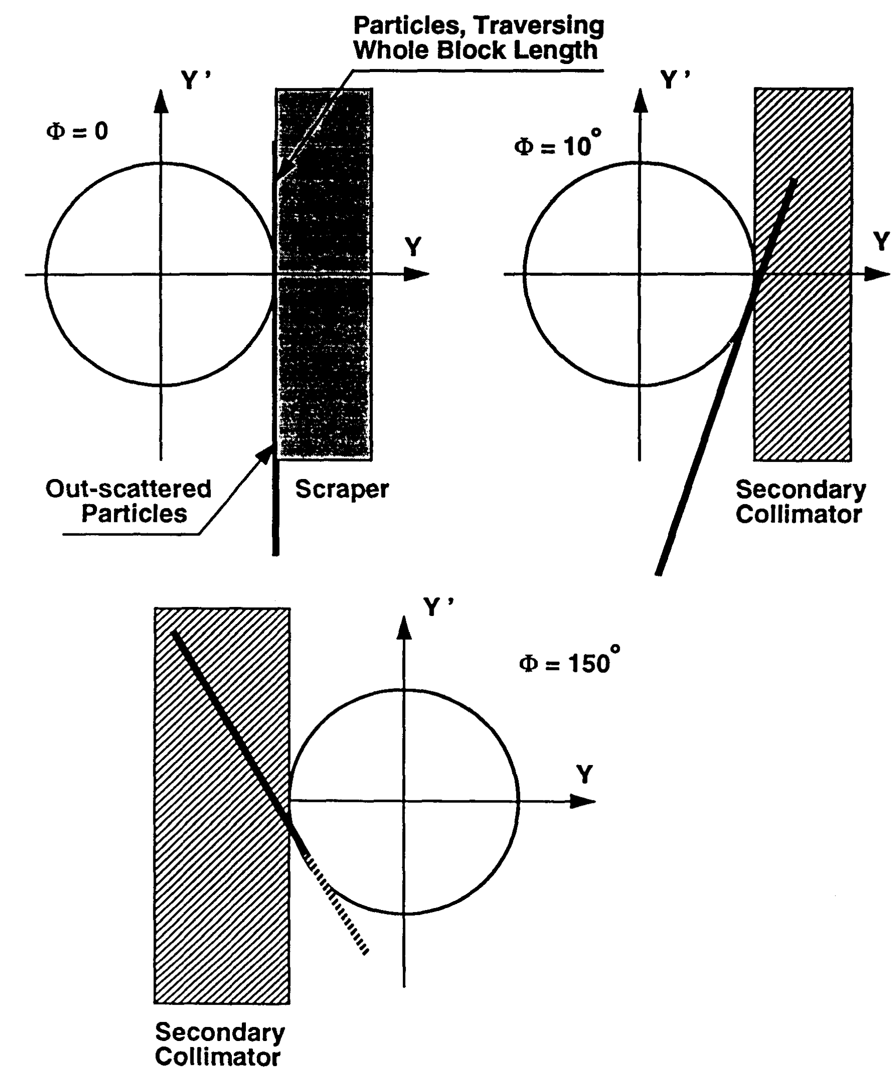
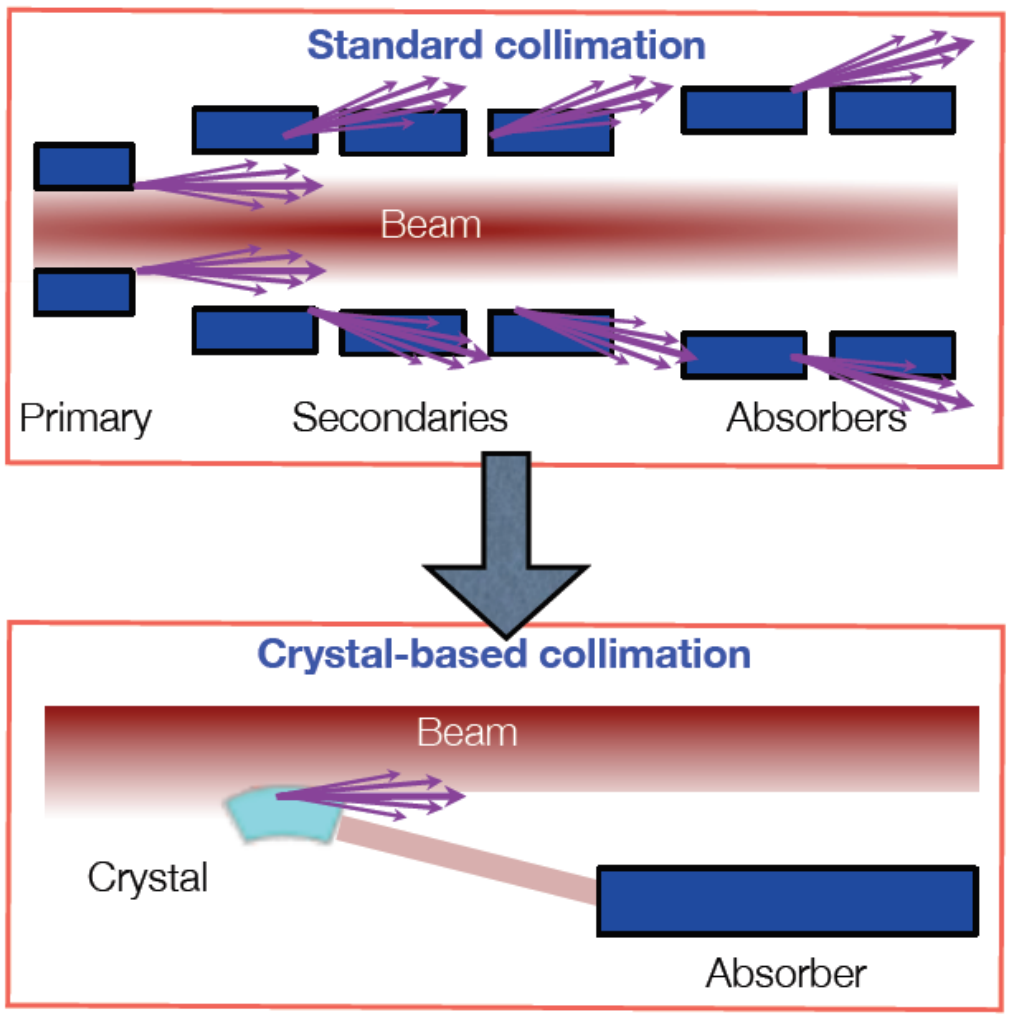


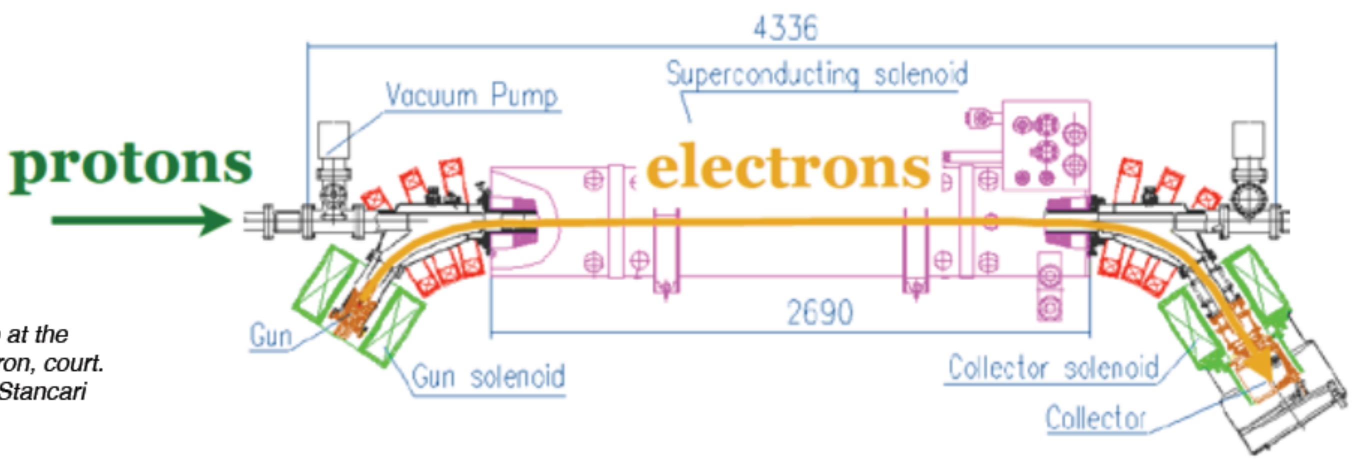
Fig. 2. Principal scheme of a two-stage collimation system.

Beam Collimation

Can make an LHC-type solution, but other solutions need to be investigated

- hollow beam as collimator
- crystals to guide particles
- renewable collimators





Setup at the Tevatron, court. of G. Stancari

Beam Abort — 8.4 GJ all at once

Northern Illinois University

- SSC work led to the use of a spiral kicker system, eventually implemented in the LHC design
  - full hydrodynamic calculations of energy deposition began at this time as well

- Beam Abort System kicker misfiring will be even bigger issue
  - segmentation; aperture and system protection
  - beam spreading
    - spiral, raster, etc.
  - sacrificial components — first examined during **VLHC study**

The requirements for the reliability of a one-turn extraction mechanism are comparable to the SSC [90] and LHC [91]. The extraction kicker is broken into 10 independent modules, with any 7 out of 10 sufficient for a safe abort. Solid-state pulsers (as opposed to Thyratrons) will be used to minimize accidental prefires. Three Musketeer logic ("All-for-one, and one-for-all!") guarantees that any single module firing will automatically trigger the rest of the modules.

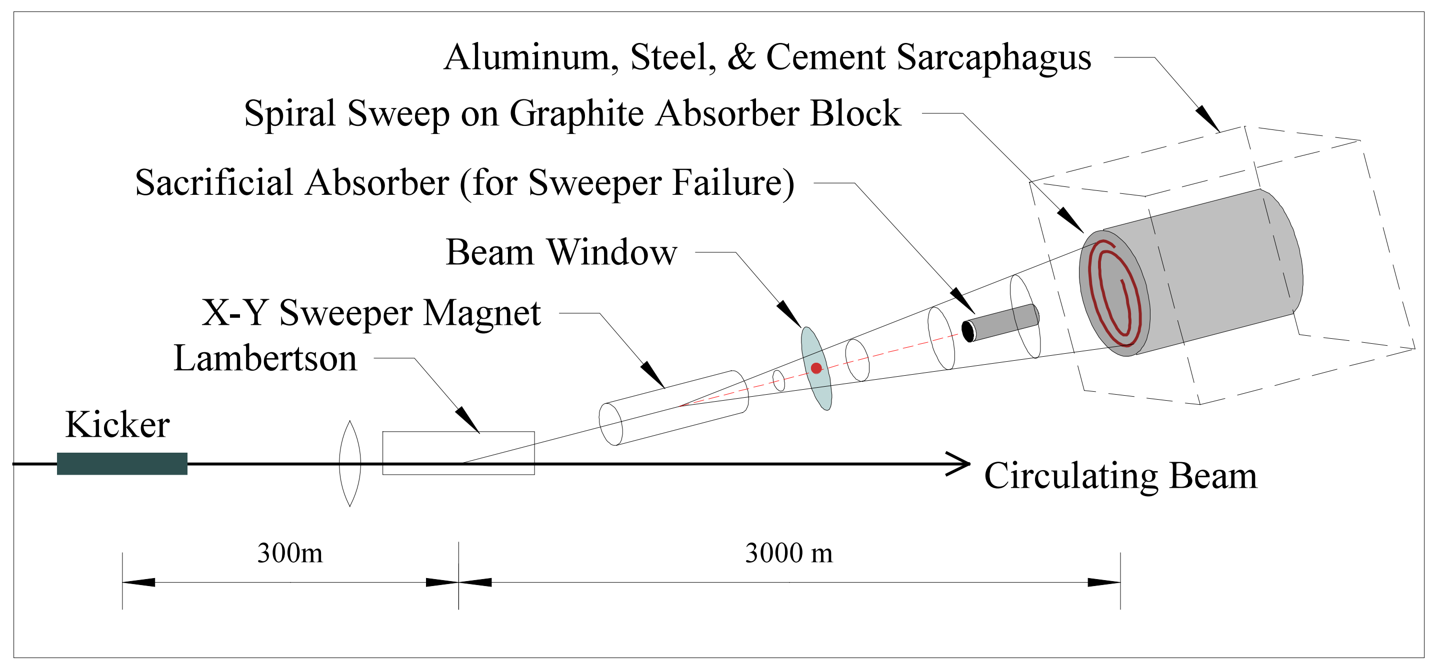
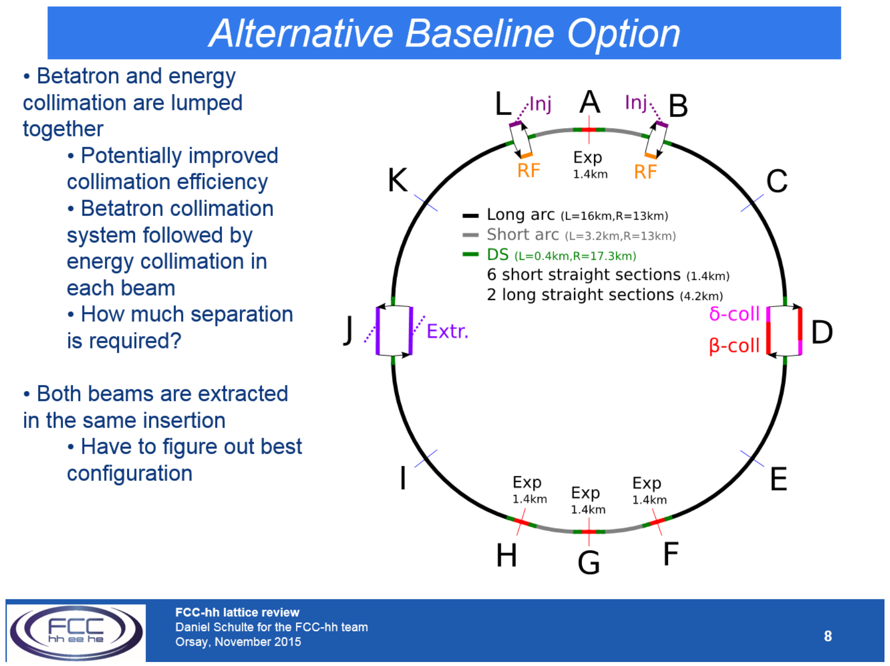
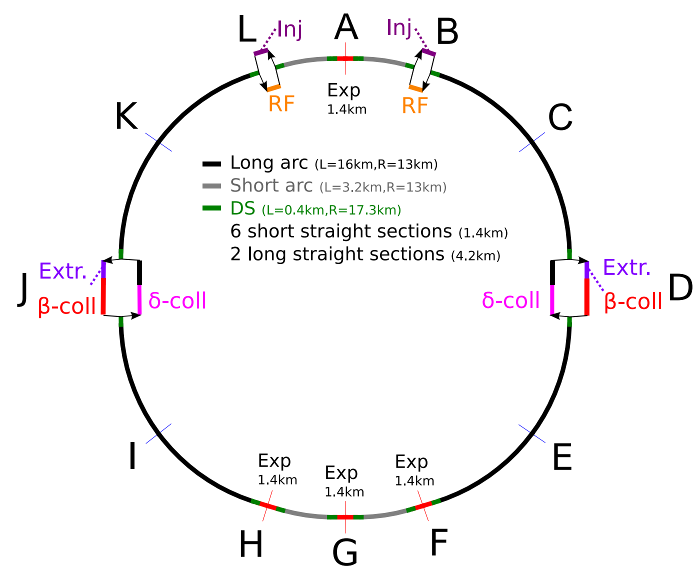


Figure 5.55. Schematic layout of beam abort channel including kickers, Lambertson septa, extraction beam sweeping, beam window, sacrificial rod, and graphite beam absorber. Under normal circumstances the extracted beam is swept in a spiral pattern to spread the energy across the graphite dump. If the sweeper magnet fails, the beam travels straight ahead into a sacrificial graphite rod, which takes the damage and must be replaced.

FCC Beam Abort — 8.4 GJ beams





FCC is looking at alternate layouts for collimation (betatron, momentum) and extraction systems

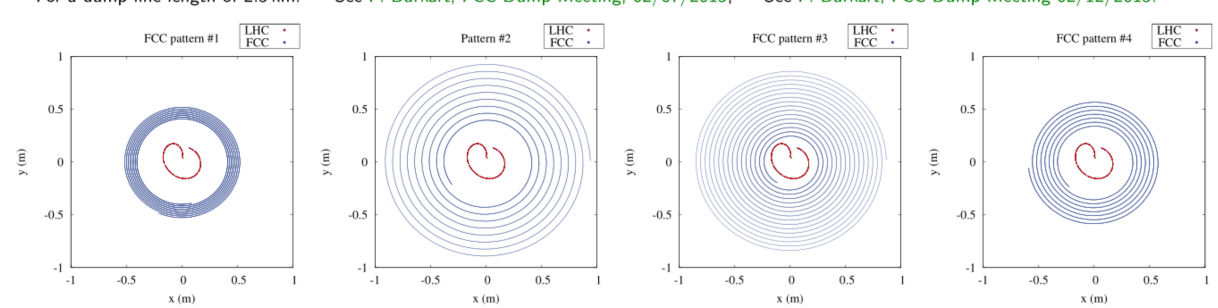
A. Lechner, FCC dump meeting, 20th Jan. 2016

Spiral dilution patterns appear to produce acceptable local energy density for FCC conditions; under study

Overview of multi-spiral dilution patterns (from F. Burkart)

	MKB frequency modulation	Frequency	B·dl [a]	Distance between neighbouring bunches	Distance between neighbouring branches
#1 [b]	No	32.8 kHz	34 Tm	2.00–2.64 mm	1.6 cm
#2	No	32.8 kHz	56 Tm	1.87–4.70 mm	6.5 cm
#3 [c]	No	50.9 kHz	53 Tm	1.83–6.95 mm	4.0 cm
#4 [c]	Yes	20–43 kHz	39 Tm	1.90 mm	3.7 cm

[a] For a dump line length of 2.5 km. [b] See F. Burkart, FCC Dump Meeting, 02/07/2015, [c] See F. Burkart, FCC Dump Meeting 02/12/2015.

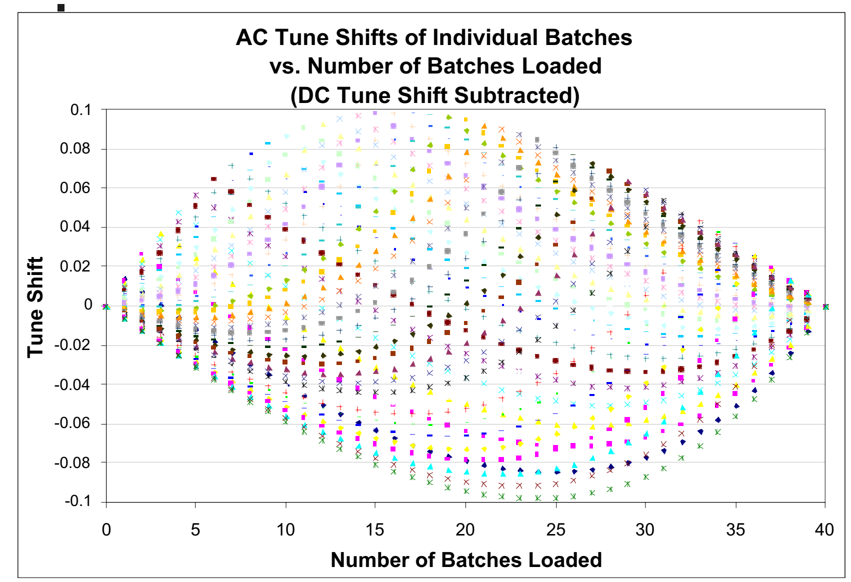


- Some remarks:
  - Pattern do not yet account for realistic filling schemes including gaps → this will still increase the total swep path length by several 10%
  - Only studied regular sweeps as shown above, but did not yet assess the consequences of failure scenarios for the different pattern/kicker parameters

A. Lechner (FCC Dump Meeting) Jan 20th, 2016 4 / 8

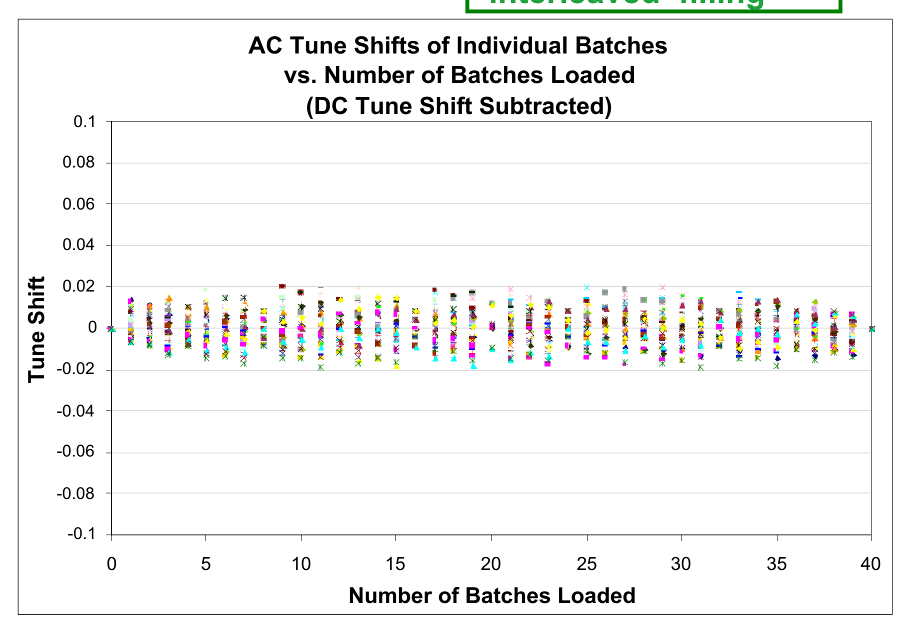
Multi-Particle Considerations

- FCC-type colliders maintaining bunch intensities at level of 10^{11}
  - not pushing the envelope here
- Multi-Particle Considerations
  - Beam-beam Interaction (HO, LR; PACMAN)
    - » lattice distortions
    - » luminosity limitations
  - Wake Field / Impedance
    - » intensity limitations
    - » injection schemes (interlacing, *a' la* VLHC)
    - » feedback system developments



STANDARD FILLING SEQUENCE --

BALANCED FILLING SEQUENCE -- interleaved filling



Foster, et al.,
*from **VLHC Study**, 2001*

Injection and Operations

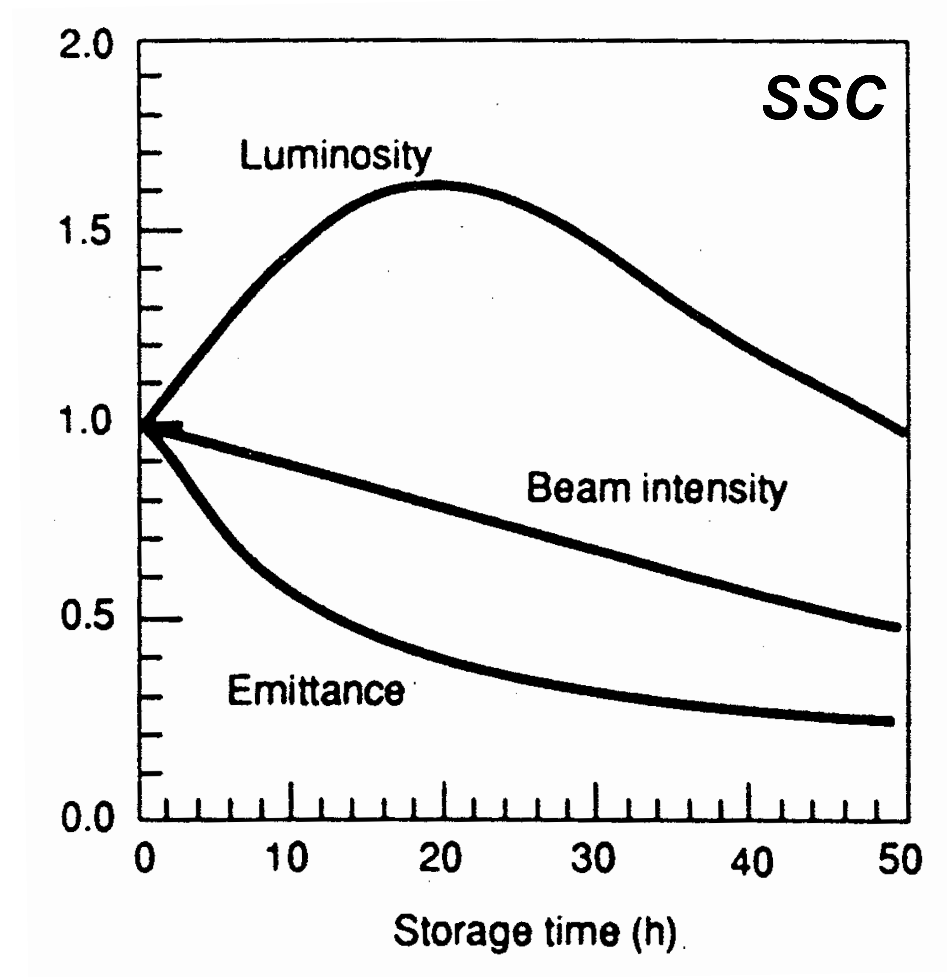
- Injector Chain
  - dynamic aperture at injection
  - choice of injection energy and injector system
  - filling times, turn-around times, scenarios; cogging and harmonics
  - sensitivities to injector emittance (RLHC), injection process
- $\tau_{lumi} \sim 5 \; \tau_{SR}$
  - luminosity leveling and integrated luminosity optimization
  - general parameter optimization for max integrated luminosity
- sensitivity of injector emittance to overall operation goals
  - see RLHC (precursor to VLHC)
- use of existing infrastructure vs. Green Field

Luminosity Optimization

Northern Illinois University

- Though synchrotron radiation is an operational issue for the LHC, the luminosity behaves in a traditional manner
- However, like the SSC design (see right), a 50-100 TeV collider will operate in an emittance-damped mode, leading to interesting optimization of the integrated luminosity

10^{33}cm^{-2}s^{-1},
10^{11},
μm



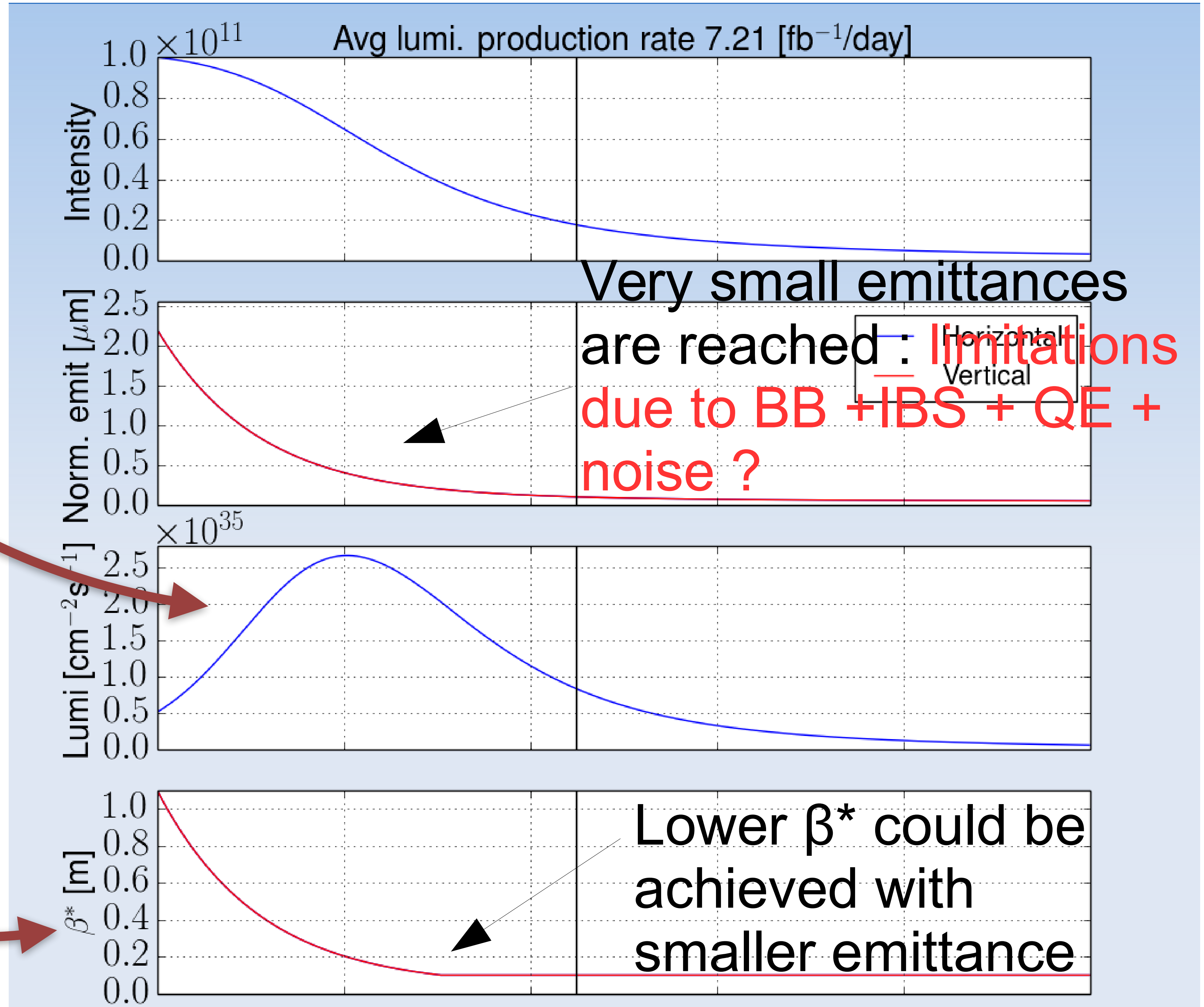
- Using dynamic crossing angle, β^* control, …
  - new operational scenarios will be explored
  - turn-around times, efficiencies will be ever more important
  - global optimization of the physics reach will be inevitable

Example FCC Parameter Evolution

Northern Illinois University

luminosity rises, falls as in the SSC

actively vary the final focus optics to mitigate beam-beam interaction effects

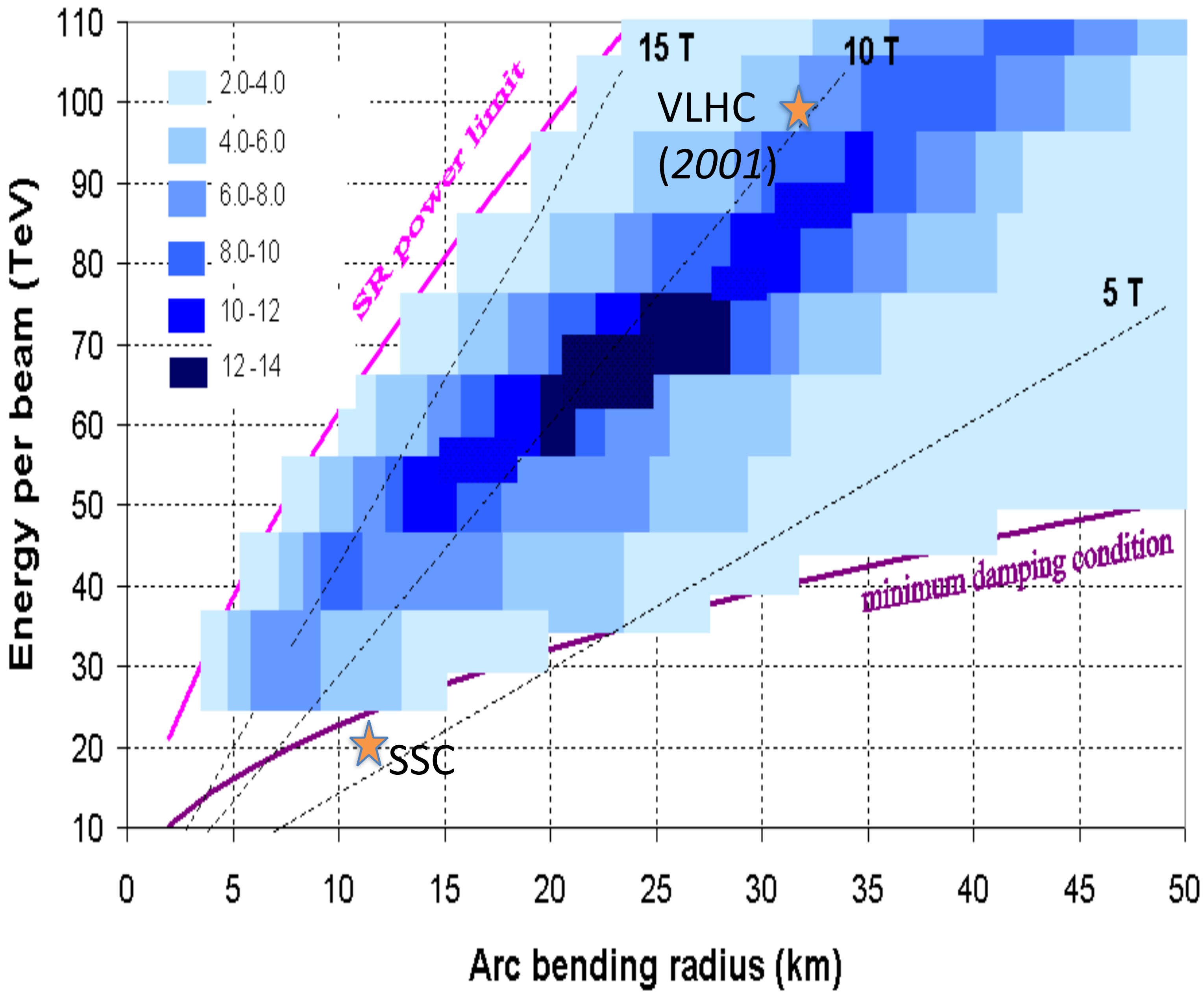


X. Buffat

Design Optimization for Luminosity

Northern Illinois University

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

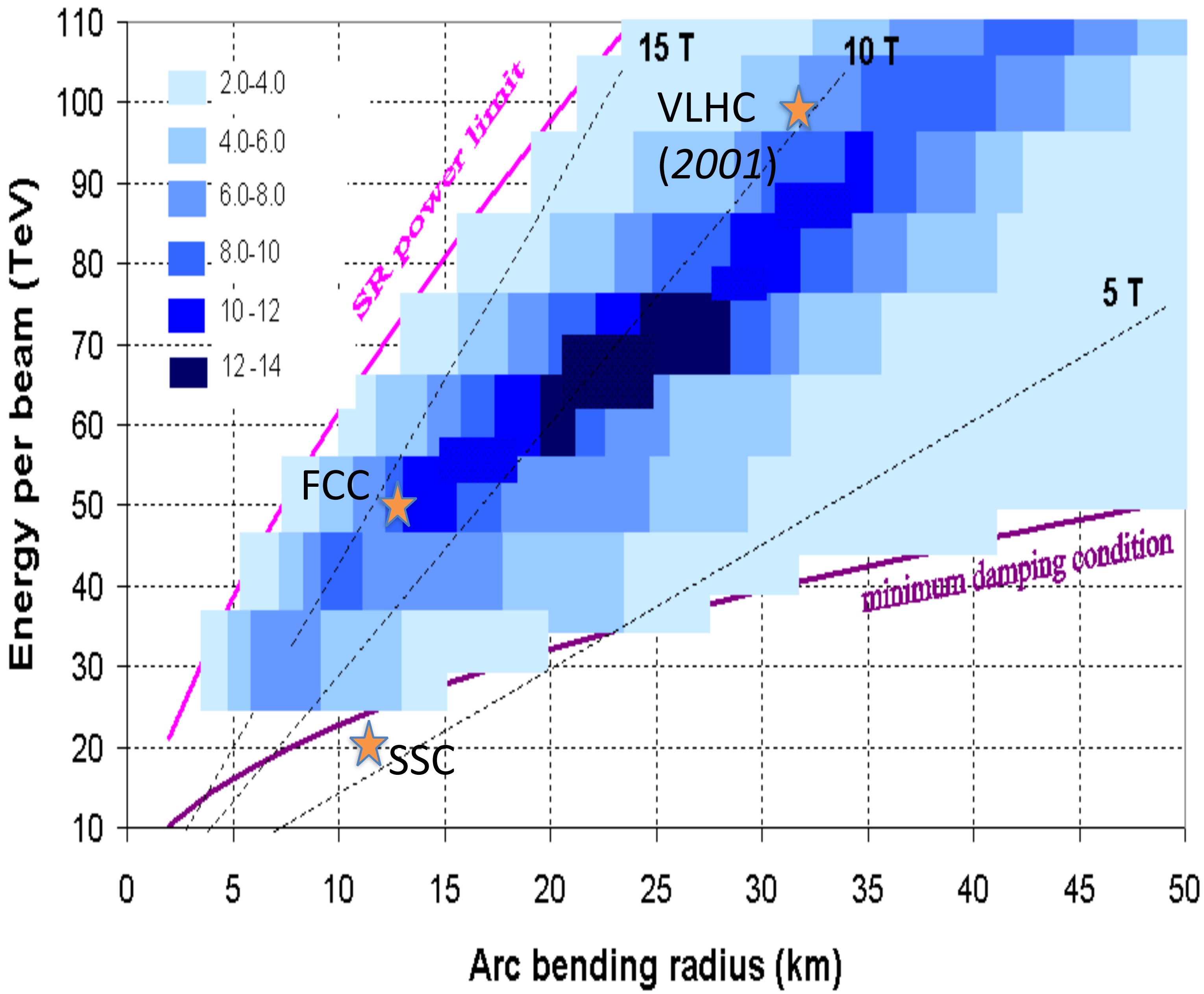


VLHC Study,
P. Bauer, *et al., 2002*

Design Optimization for Luminosity

Northern Illinois University

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



VLHC Study,
P. Bauer, *et al., 2002*

Design Optimization for Luminosity

Northern Illinois University

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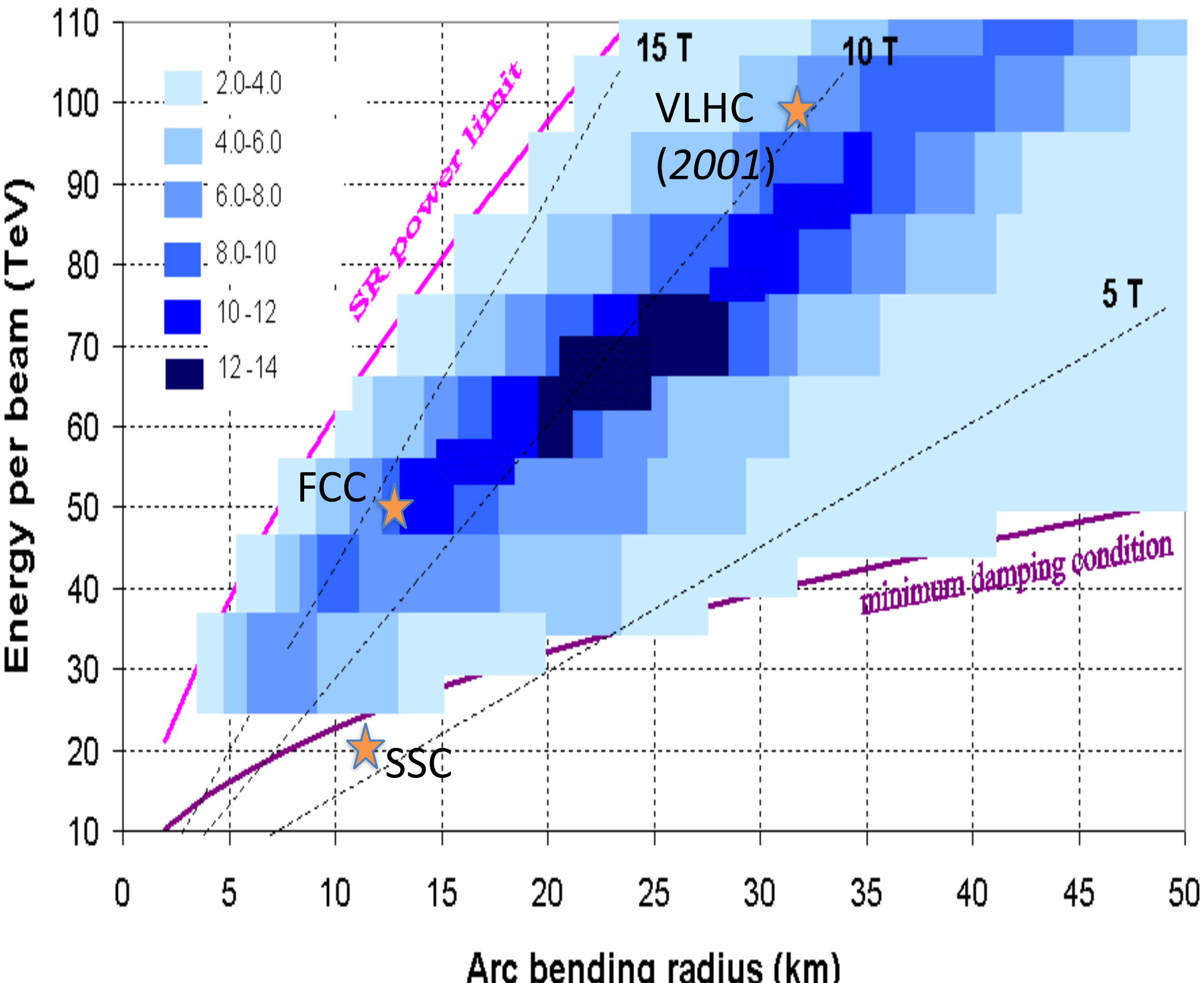


VLHC Study,
P. Bauer, *et al., 2002*

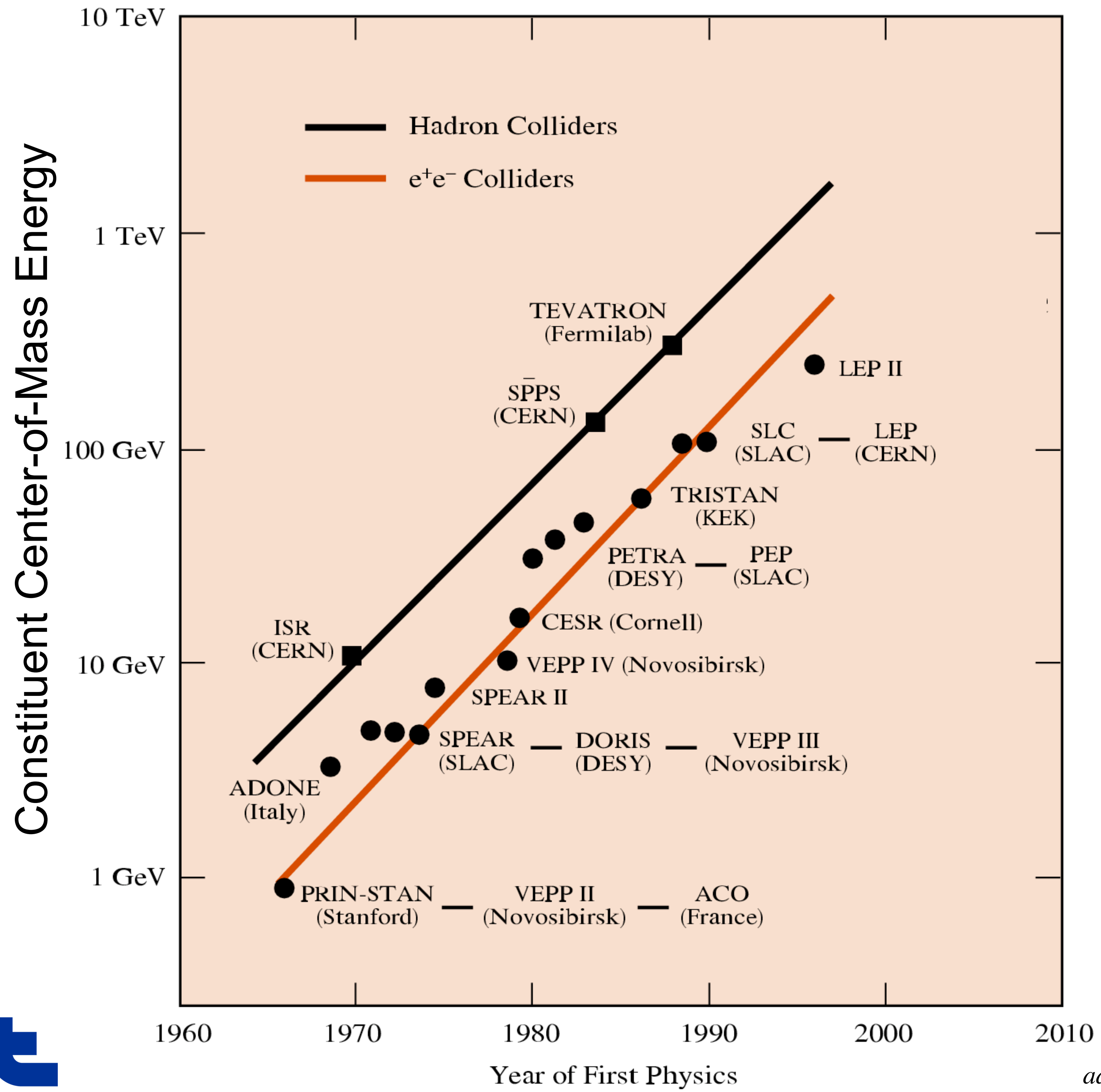
currently, radius of FCC is being constrained by CERN site and the Alps…

perhaps remove restrictions using the ocean?
see P. McIntyre, this session - MOB2

Collider History

Northern Illinois University

adopted from W. Panofsky. *Beam Line* (SLAC) 1997

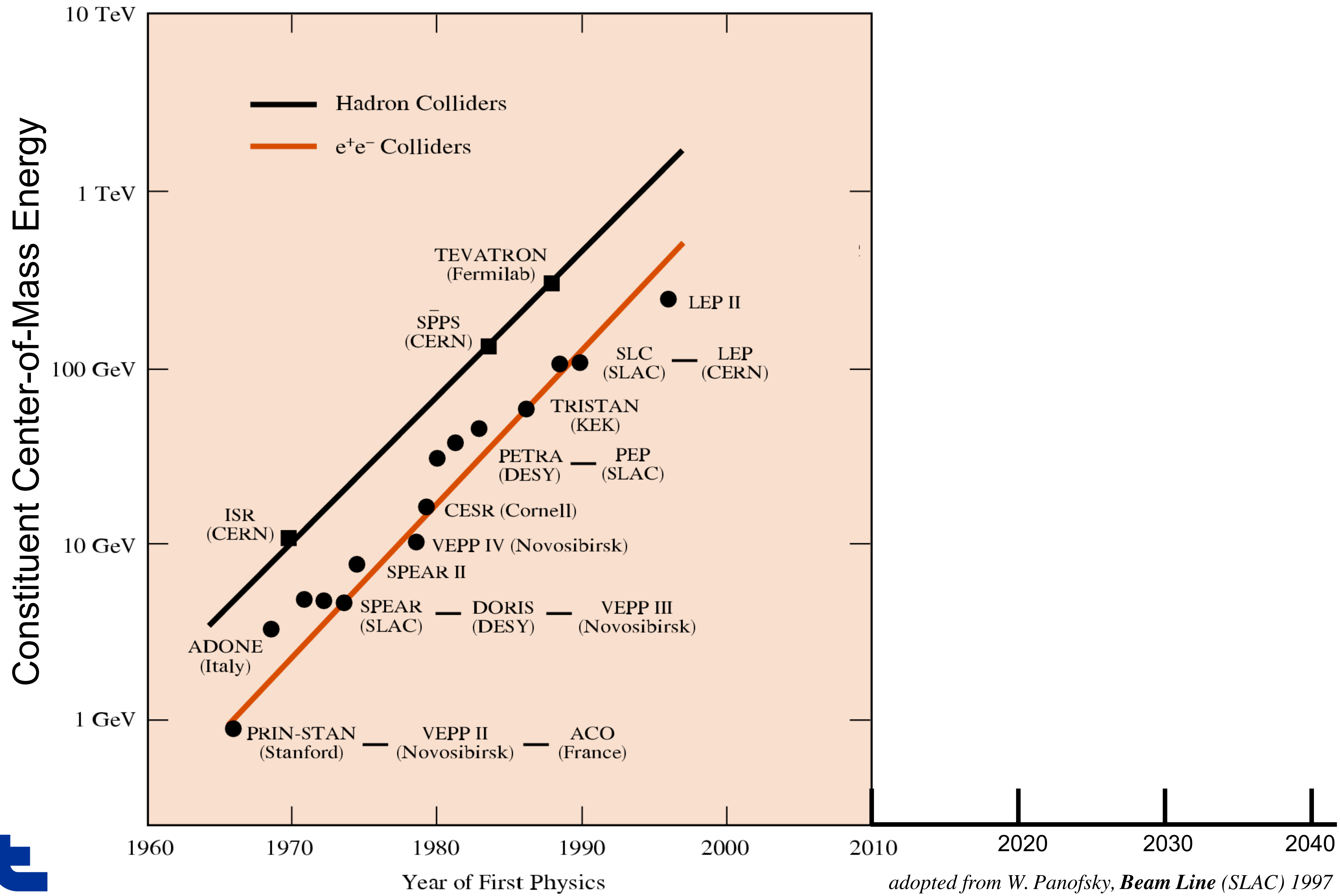


*adopted from W. Panofsky, **Beam Line** (SLAC) 1997*

Collider History

Northern Illinois University

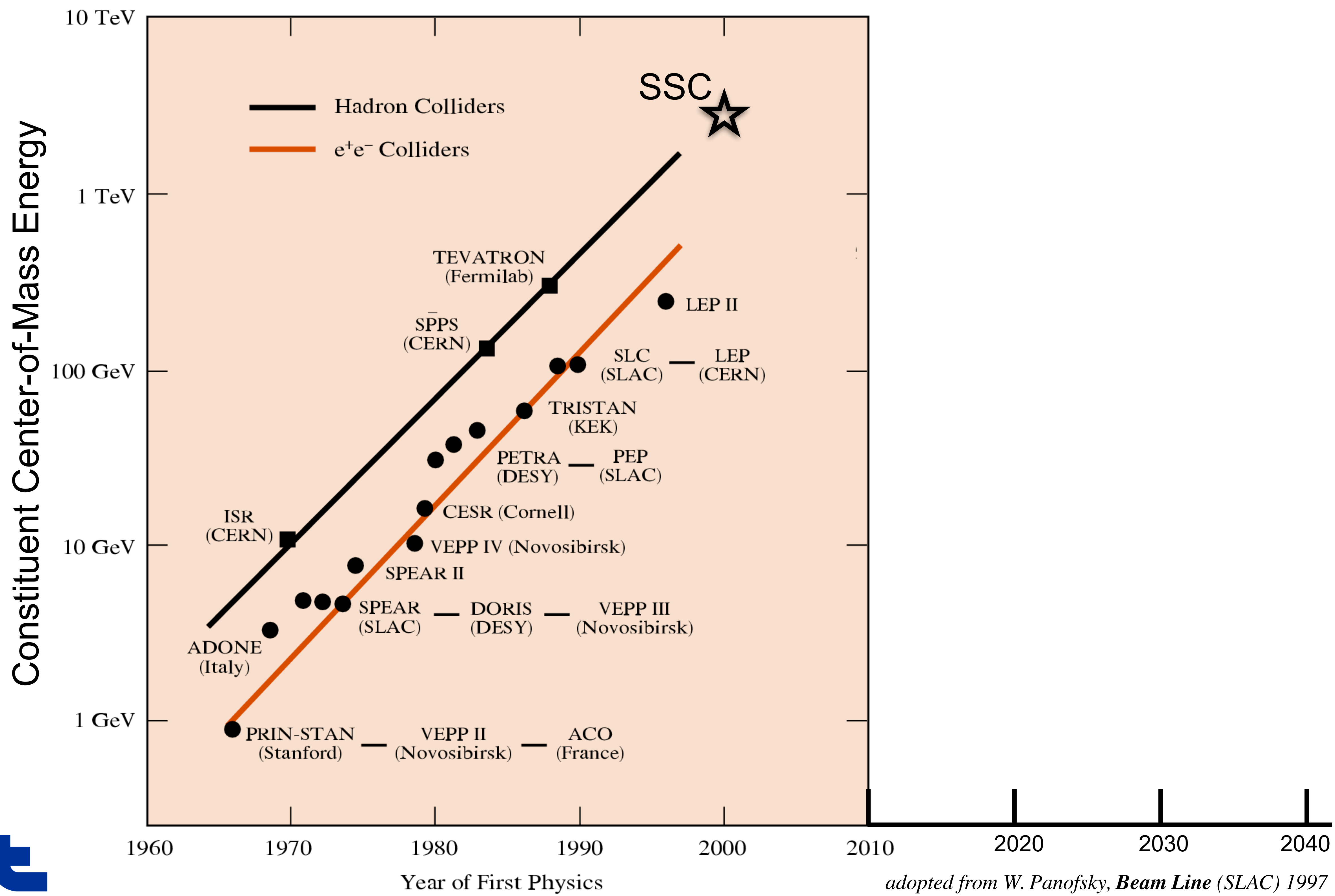
adopted from W. Panofsky. *Beam Line* (SLAC) 1997



*adopted from W. Panofsky, **Beam Line** (SLAC) 1997*

Collider History

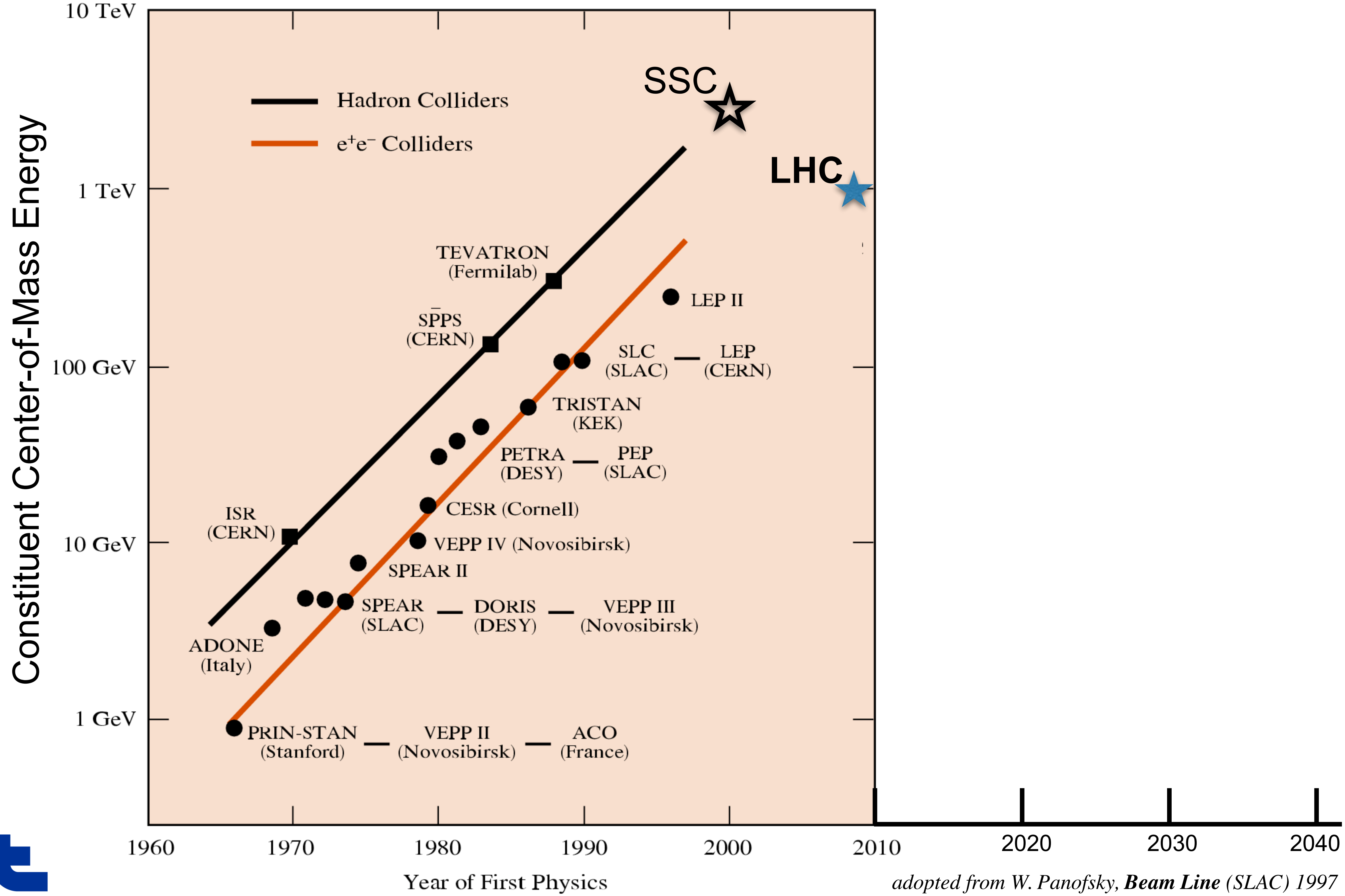
adopted from W. Panofsky. *Beam Line* (SLAC) 1997



*adopted from W. Panofsky, **Beam Line** (SLAC) 1997*

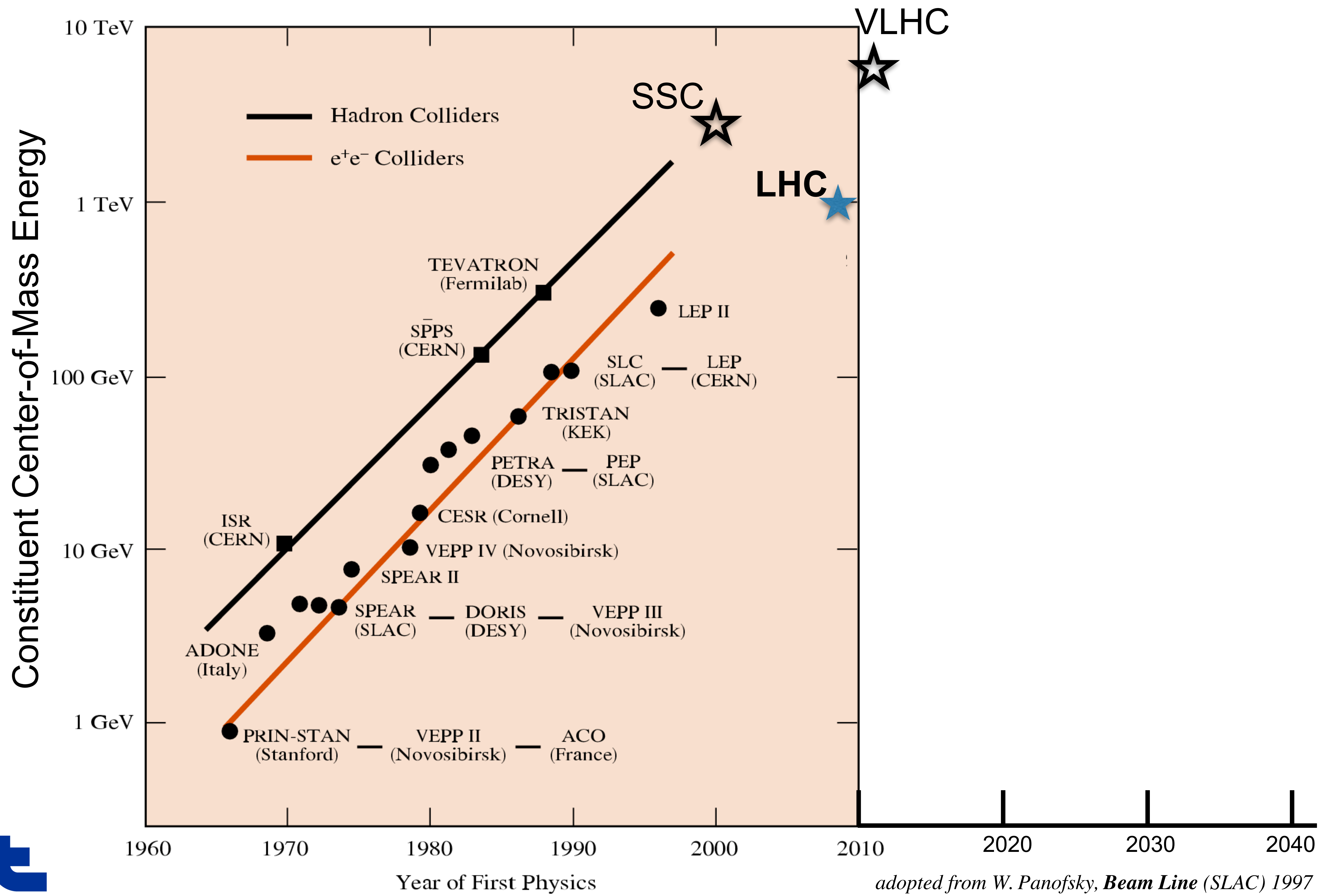
Collider History

adopted from W. Panofsky. *Beam Line* (SLAC) 1997



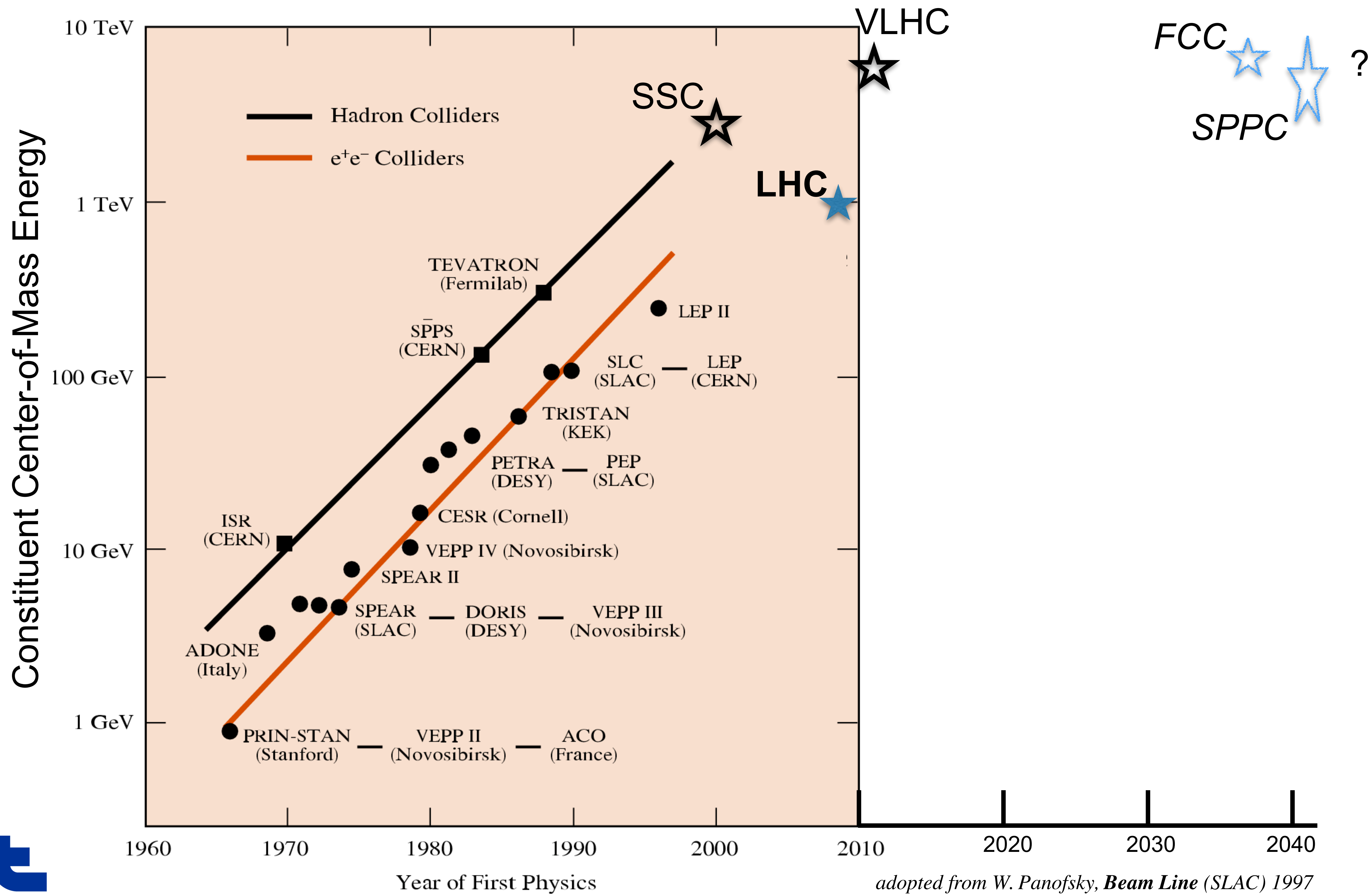
Collider History

adopted from W. Panofsky. *Beam Line* (SLAC) 1997



Collider History

adopted from W. Panofsky. *Beam Line* (SLAC) 1997



*adopted from W. Panofsky, **Beam Line** (SLAC) 1997*

Thank You!

- Other "Large hh Collider"-related talks:
  - *Collider in the Sea: A New Vision for a 700 TeV World Laboratory*
    Peter M. McIntyre (Texas A&M), this session - **MOB2**
  - *High Luminosity 100 TeV Proton-Antiproton Collider*
    Sandra Oliveros (U Miss), this afternoon - **MOB3**
  - Quench Training Analysis of Nb3Sn Accelerator Magnets - Strategy and First Results
    S. Stoynev, K.H. Riemer, A.V. Zlobin (Fermilab) - **MOPOB40**
  - Considerations on Energy Frontier Colliders After LHC
    V.D. Shiltsev (Fermilab) - **TUPOB07**
  - Persistent Current Effect in 15-16 T Nb3Sn Accelerator Dipoles and its Correction
    A.V. Zlobin, V.V. Kashikhin (Fermilab) - **THA1CO04**

- Bibliography

  - » For SSC CDR, and other documents: http://lss.fnal.gov/archive/other/ssc/
  - » LHC CDR, other documentation: visit http://home.cern/topics/large-hadron-collider
  - » *Design Study for a Staged Very Large Hadron Collider,* VLHC Design Study Group Collaboration (Giorgio Ambrosio et al.). Jun 2001. 271 pp. SLAC-R-591, FERMILAB-TM-2149
  - » Future Circular Collider Study web page: http://fcc.web.cern.ch
  - » For SppC, visit: http://cepc.ihep.ac.cn/preCDR/Pre-CDR_final_20150316.pdf

Back-Up

High Field *vs.* Low Field

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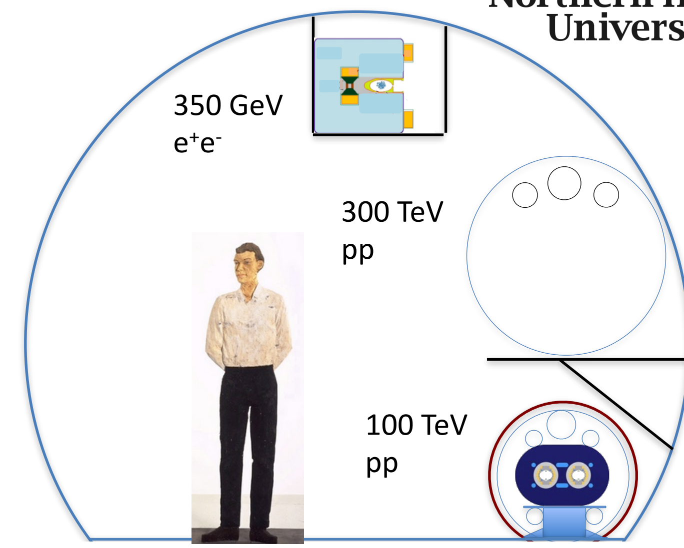
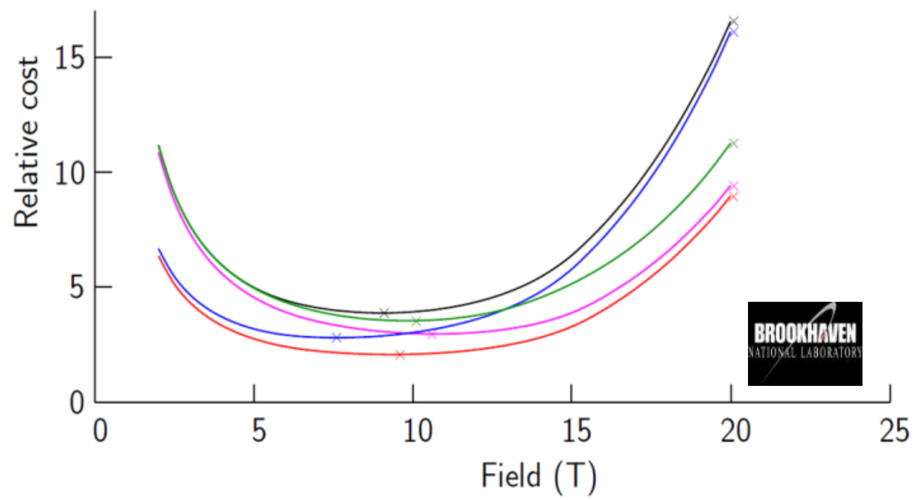
- Total costs of collider could be less, and leaves path for further upgrades



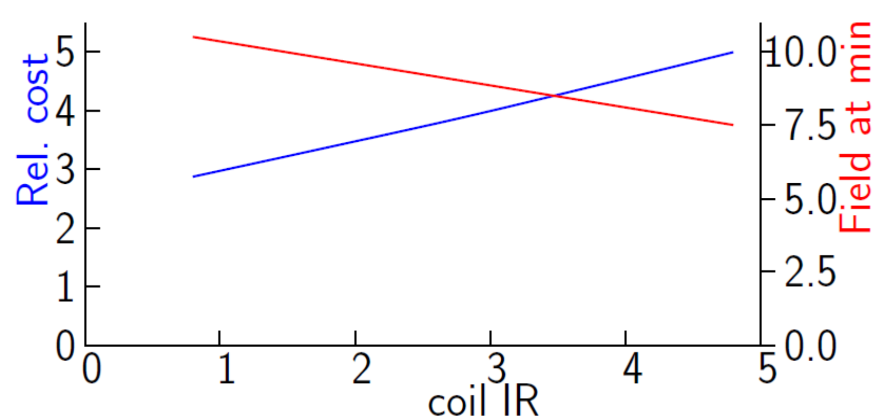
> *B. Palmer et al., "Accelerator Optimization issues of a 100 TeV collider", ARD panel meeting, BNL*

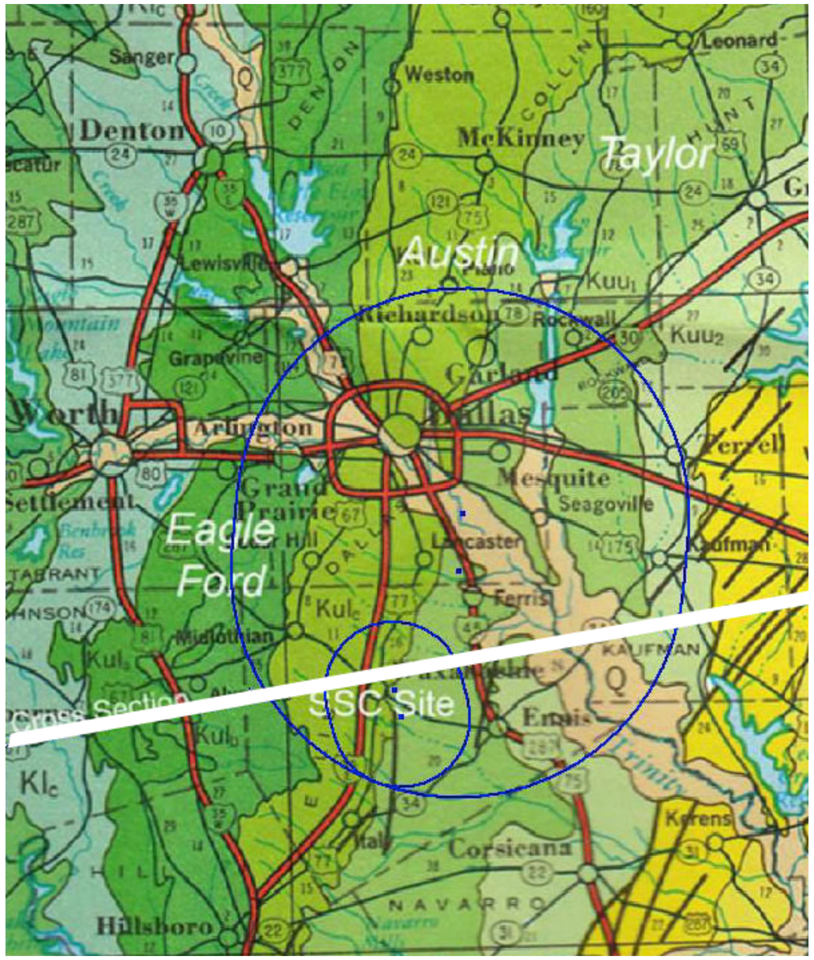
Updating/refining VLHC models

Sensitivity to different assumptions



Dependence on aperture





P. McIntyre

Dispersion Suppressor

Northern Illinois University

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

Required second dipole magnet length

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

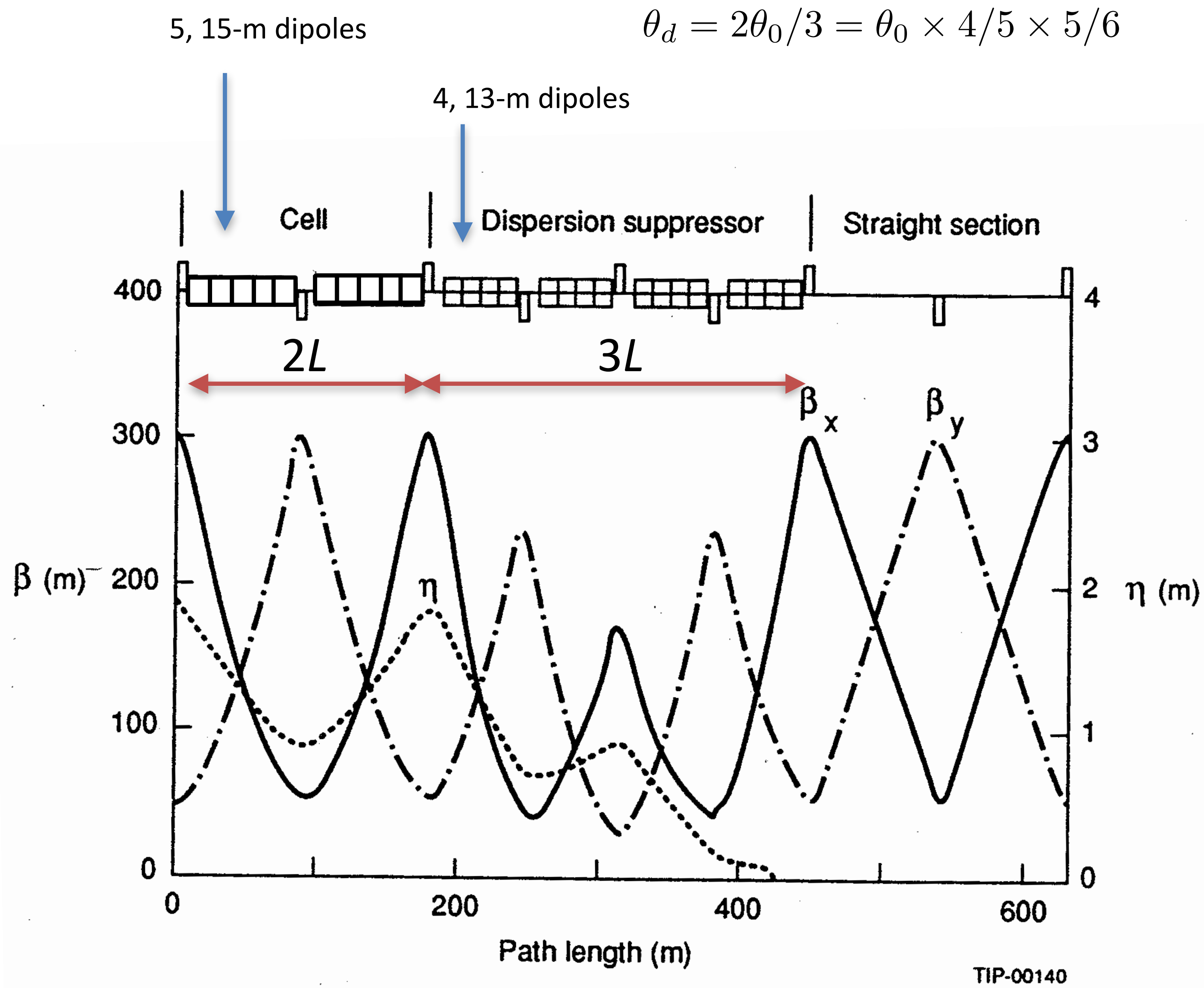


Figure 4.1.1.1-8. Lattice functions of the normal cell *C*, the dispersion suppressor *D*, and empty cell *CO*.

SSC Beam Cleaning

Northern Illinois University

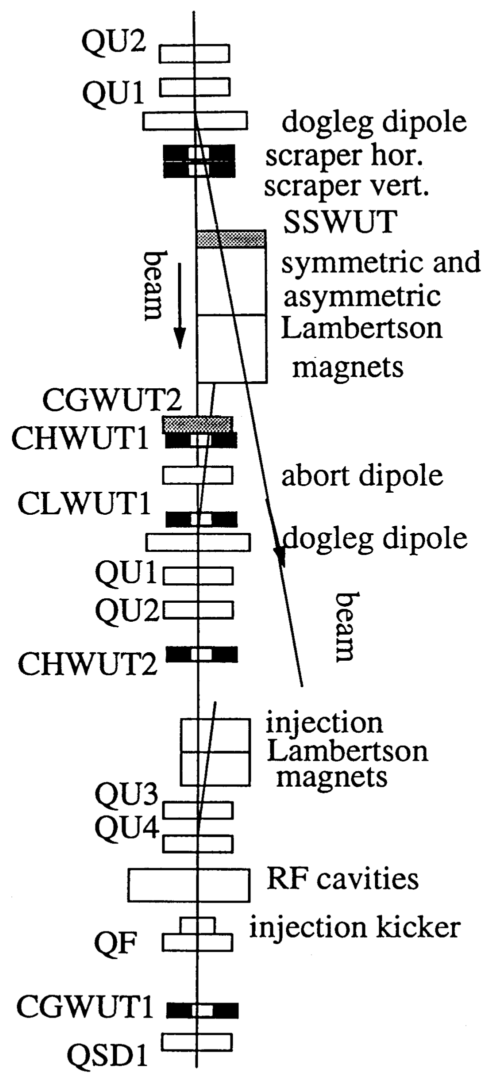


Fig. 8. Scraper and collimator positions in the Collider West Utility.


The SSC Beam Scraper System

M. Maslov, N. Mokhov, and L. Yazynin

June 1991

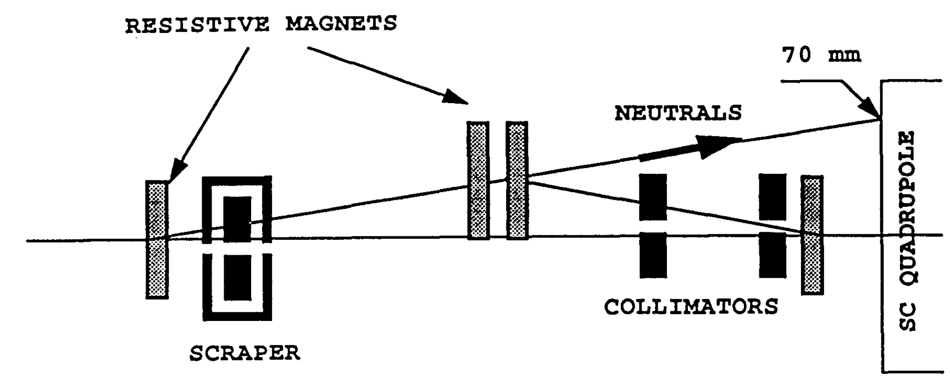


Fig. 19. Principal scheme of beam cleaning for off-momentum protons in the East Utility.

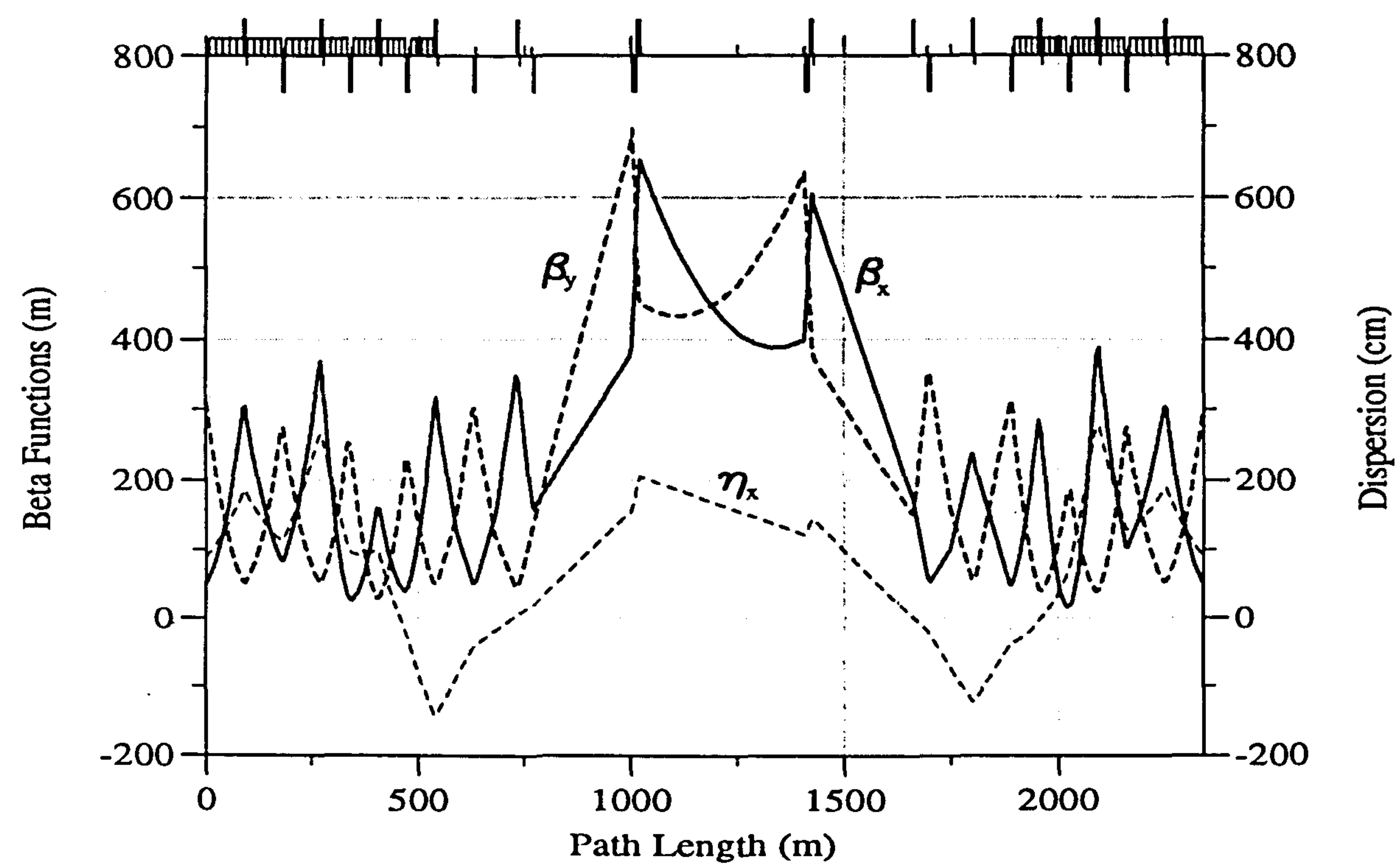


Fig. 18. Lattice functions in the East Utility.

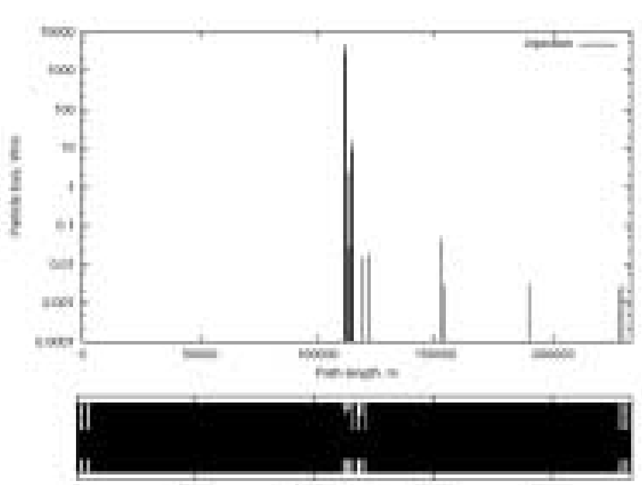
VLHC Collimation

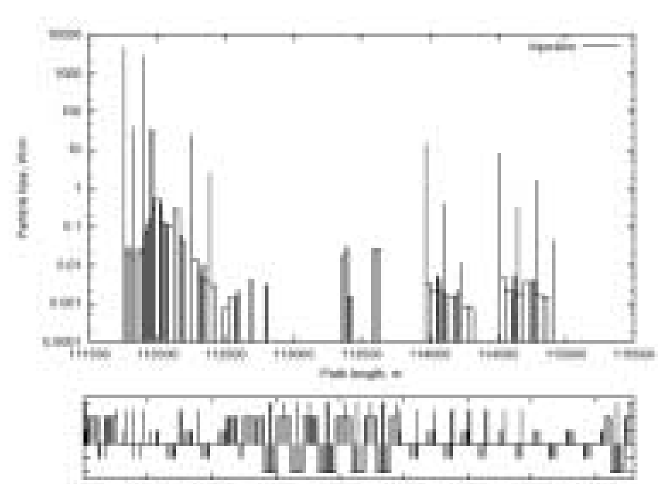
5.3.4 Beam Collimation System

Even in good operational conditions, a finite fraction of the beam will leave the stable central area of the accelerator aperture because of intra-beam scattering, small-angle beam-gas interactions along the circumference, collisions in the IPs, RF noise, ground motion and resonances excited by the accelerator imperfections. These continuously generate a beam halo. As a result of beam halo interactions with limiting apertures, hadronic and electromagnetic showers initiated in accelerator and detector components will cause accelerator related background in the detectors, magnet heating and accelerator and environmental irradiation. The design strategy of the VLHC is that the beam losses are controlled as much as possible by localizing them in a dedicated beam collimation system. This minimizes losses in cryogenic parts of the accelerator, and drastically reduces the source term for radiation hazard analysis in the rest of the lattice. The technology for these systems has been well developed for the Tevatron, SSC, and LHC.

For the VLHC a complete beam cleaning system which provides for both betatron and mo-

For the VLHC a complete beam cleaning system which provides for both betatron and momentum scraping has been designed and simulated [97,98]. The three-stage beam collimation system consists of 5 mm thick primary tungsten collimators placed at $7\sigma_{x,y}$ and 3 m long copper secondary collimators located in an optimal phase advance at $9.2\sigma_{x,y}$ and aligned parallel to the circulating beam envelope. Two more supplementary collimators are placed in the next long straight section to decrease particle losses in the low-β quadrupoles and in the accelerator arc. They are located at $14\sigma_{x,y}$ to intercept only particles scattered out from the secondary collimators.





collateral damage. It would probably not even be noticed from the outside of the magnet. This is not our biggest problem.

A second observation is that the "beam drilling" scenario (in which a stable beam vaporizes a small channel deep into the target) is impossible at grazing incidence, even if the beam were perfectly extracted on a fixed trajectory. This beam drilling scenario is expected when the beam is normally incident onto a semi-infinite slab of material such as a beam absorber block. However at grazing incidence, the imbalance of the mechanical forces near the beam impact point (due to local heating of the rock) will cause a rock chip to "spall" out from the tunnel wall. This spalling behavior has been observed during rock excavation tests with electron beams [100] and follows this simple mechanical model. This spalling effectively sweeps fresh material across the beam and guarantees that non-vaporized material will be available to initiate the shower, even if the beam is perfectly extracted. Thus the pattern of energy deposition can be calculated accurately enough by assuming that the shower initiates at a more-or-less fixed position near the point of grazing incidence.

A MARS calculation has been performed (Figure 5.60) to evaluate the energy deposition under the assumption that both the rock and beam position remain fixed. The simulation indicates that a region 8 meters long and about 15 cm in radius are heated to the melting point of dolomite. Obviously it will splatter to the floor. The next step in the calculation (in progress) is to use ANSYS to evaluate the thermal stresses in the surrounding rock and estimate the amount of rock that breaks off from thermal stress. The rise time of the heat pulse (1 machine revolution or about 0.8 msec) allows the mechanical stresses to relieve themselves on the scale of a couple of meters, so a static mechanical analysis is approximately valid.

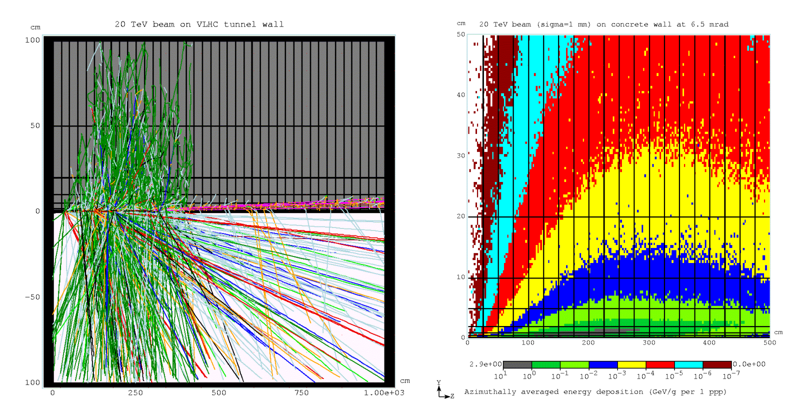


Figure 5.60. Stage-1 VLHC beam at 6.5 mrad grazing incidence on tunnel wall. The left picture shows particle tracks; the right picture is a map of energy deposition.

A more realistic situation in which the beam angle sweeps by even a few milliradians during extraction changes the situation significantly. In this case the heating is distributed into a large enough rock mass that the only a very small region (of order a centimeter wide) approaches the melting point. The picture becomes that of a destroyed magnet, a centimeter-wide

VLHC Collimation

Northern Illinois University

5.3.4 Beam Collimation System

Even in good operational conditions, a finite fraction of the beam will leave the stable central area of the accelerator aperture because of intra-beam scattering, small-angle beam-gas interactions along the circumference, collisions in the IPs, RF noise, ground motion and resonances excited by the accelerator imperfections. These continuously generate a beam halo. As a result of beam halo interactions with limiting apertures, hadronic and electromagnetic showers initiated in accelerator and detector components will cause accelerator related background in the detectors, magnet heating and accelerator and environmental irradiation. The design strategy of the VLHC is that the beam losses are controlled as much as possible by localizing them in a dedicated beam collimation system. This minimizes losses in cryogenic parts of the accelerator, and drastically reduces the source term for radiation hazard analysis in the rest of the lattice. The technology for these systems has been well developed for the Tevatron, SSC, and LHC.

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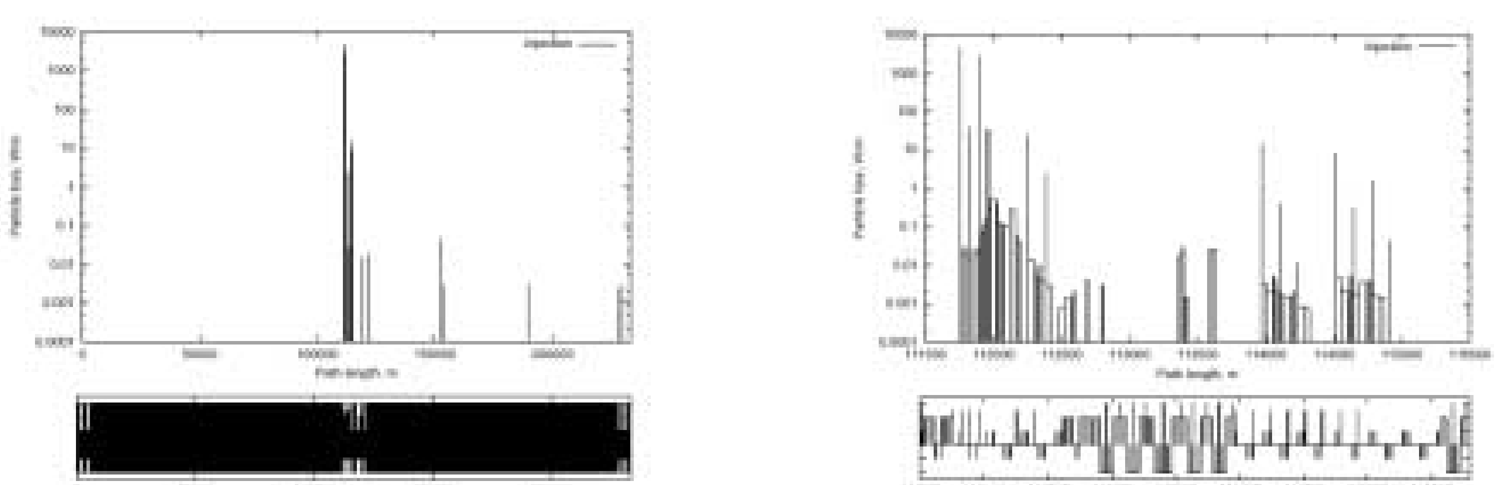

outside of the magnet. This

which a stable beam vaporizes dence, even if the beam were rio is expected when the beam a beam absorber block. orces near the beam impact "spall" out from the tunnel vation tests with electron lling effectively sweeps fresh erial will be available to initiate tern of energy deposition can itiates at a more-or-less fixed

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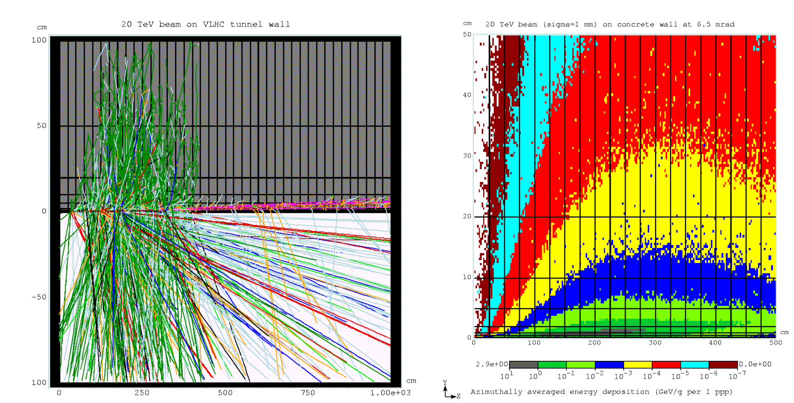

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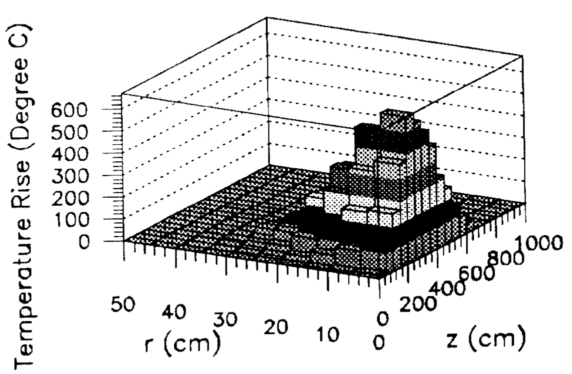
The SSC Beam Abort System

In addition to beam dump design development, the need was foreseen to spread out the beam via a sweeping or "raster" system

3. RESULTS

For the core of the beam backstop, it is desirable to choose a material with a high cracking/melting temperature and low density (to spread the shower longitudinally as much as possible); for these reasons, graphite is a natural choice. Carbon's low atomic number, also helps to reduce the amount of long-term induced radioactivity due to spallation fragments. A reference plot of $\Delta T(r,z)$, the radially-symetric temperature distribution, due to a round-Gaussian (σ=10cm) beam profile incident along the axis of a graphite core, is shown in Figure 2. for 1.3×10^{14} protons ($=10^{33}$ luminosity).



Original "blow-up lens" system was enhanced with a spiral kicker system

"Raster Scan" painting system, using two frequencies (H/V) was chosen in the end

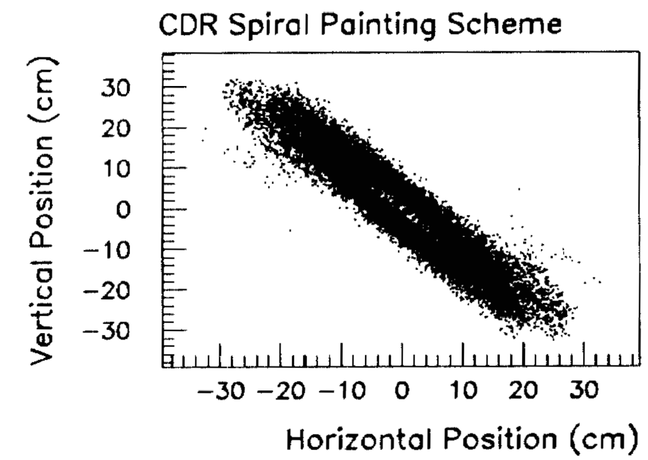


Fig. 5. CDR spiral painting with phase slippage.

A raster-pattern (shown in Figure 6) can be created via a combination of fast and slow kickers. Such a painting scheme with less needed fast-kicker strength and vastly reduced sensitivity to phase errors, is expected to be more reliable than the CDR spiral plan; however, there is some beam pile up near the outer edges of the raster pattern.

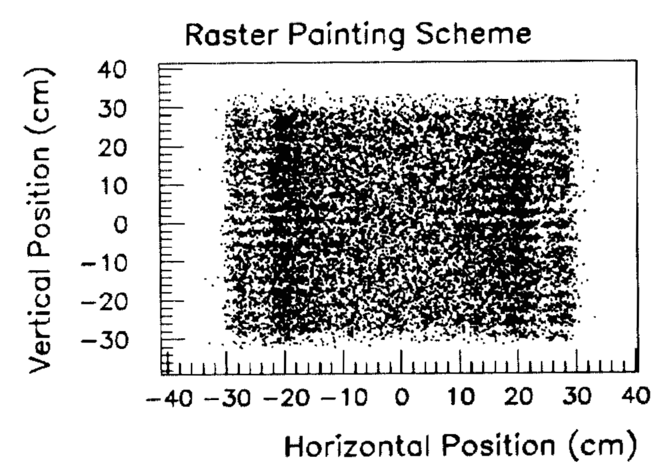
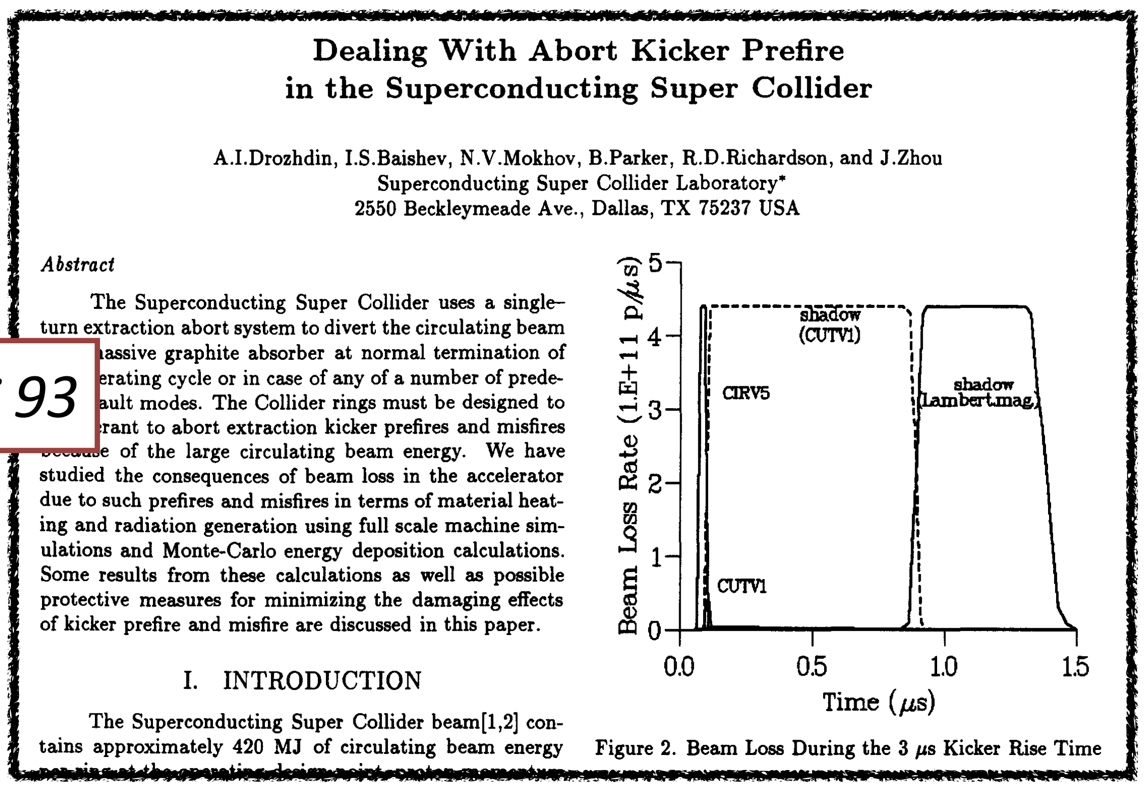


Fig. 6. Beam profile for raster painting scheme.

Reliability Issues — Abort Pre-Fire

- By 1990s the Tevatron had a good operational record, and a *history* of abort module pre-fires. Worried about this quite a lot at SSC

PAC 93


Dealing With Abort Kicker Prefire in the Superconducting Super Collider

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Abstract

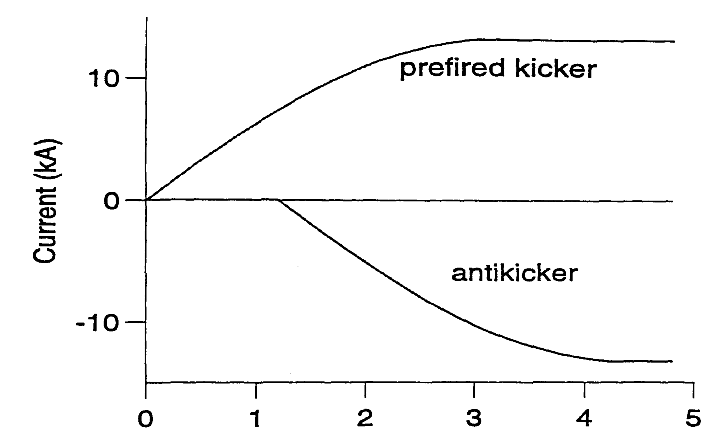
The Superconducting Super Collider uses a single-turn extraction abort system to divert the circulating beam ...assive graphite absorber at normal termination of ...erating cycle or in case of any of a number of prede... ...ault modes. The Collider rings must be designed to ...rant to abort extraction kicker prefires and misfires ... of the large circulating beam energy. We have studied the consequences of beam loss in the accelerator due to such prefires and misfires in terms of material heating and radiation generation using full scale machine simulations and Monte-Carlo energy deposition calculations. Some results from these calculations as well as possible protective measures for minimizing the damaging effects of kicker prefire and misfire are discussed in this paper.

I. INTRODUCTION

The Superconducting Super Collider beam[1,2] contains approximately 420 MJ of circulating beam energy

Figure 2. Beam Loss During the 3 μs Kicker Rise Time

developed the notion of an "anti-kicker"



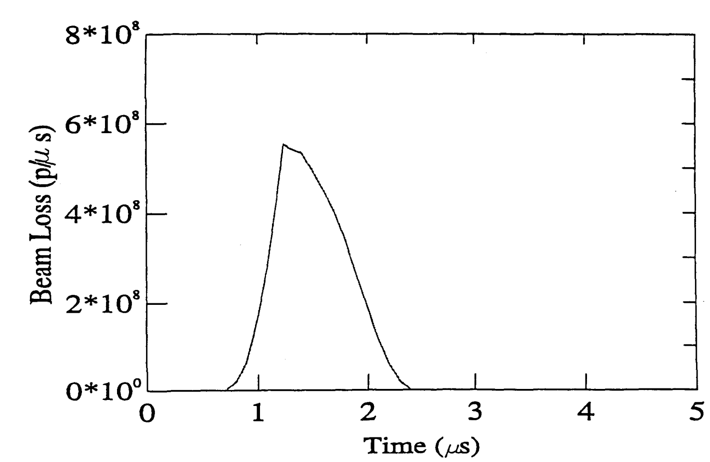


Fig. 7. Beam loss vs time for 1.2 μs antikicker delay.

The LHC Abort System

LHC Design Report

CHAPTER 17

BEAM DUMPING SYSTEM

17.1 SYSTEM AND MAIN PARAMETERS

17.1.1 Introduction and System Overview

IR6 of the LHC [1] is dedicated to the beam dumping system. The function of the beam dumping system will be to fast-extract the beam in a loss-free way from each ring of the collider and to transport it to an external absorber, positioned sufficiently far away to allow for appropriate beam dilution in order not to overheat the absorber material. A loss-free extraction will require a particle-free gap in the circulating beam, during which the field of the extraction kicker magnets can rise to its nominal value. Given the destructive power of the LHC beam, the dumping system must meet extremely high reliability criteria, which condition the overall and detailed design. The system is shown schematically in Fig. 17.1 and will comprise, for each ring:

- 15 extraction kicker magnets MKD located between the superconducting quadrupoles Q4 and Q5;
- 15 steel septum magnets MSD of three types MSDA, MSDB and MSDC located around IP6;
- 10 modules of two types of dilution kicker magnets between the MSD and Q4;
- The beam dump proper comprising the TDE core assembly and associated steel and concrete shielding, situated in a beam dump cavern ~750 m from the centre of the septum magnets;
- The TCDS and TCDQ diluter elements, immediately upstream of the MSD and Q4 respectively.

Nominal system parameters are given in Tab. 17.1, with details of the equipment subsystems in Section 17.3. The MKD kickers will deflect the entire beam horizontally into the high-field gap of the MSD septum. The MSD will provide a vertical deflection to raise the beam above the LHC machine cryostat before the start of the arc sections. The dilution kickers will be used to sweep the beam in an '*e*' shaped form and after the appropriate drift distance the beam will be absorbed by the TDE assembly. The TCDS and TCDQ will serve to protect machine elements from a beam abort that is not synchronised with the particle-free beam gap.

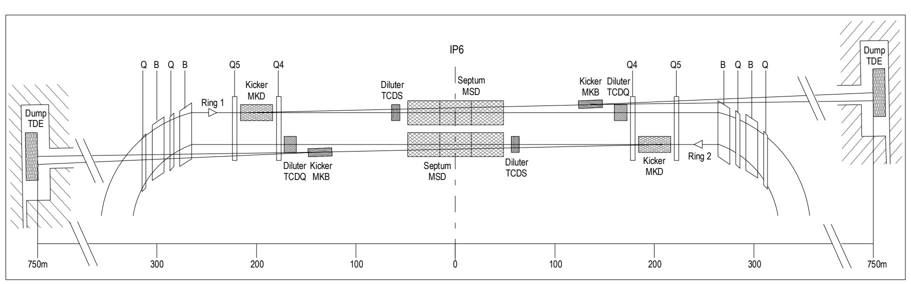
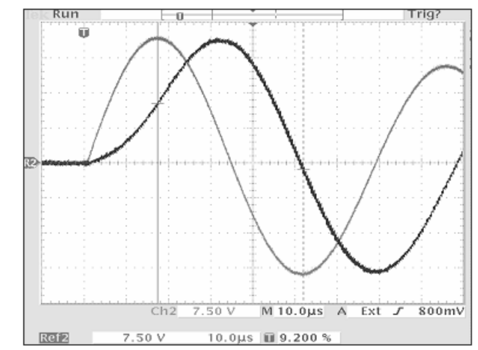


Figure 17.1: Schematic layout of beam dumping system elements around LHC point 6.

Very similar stored energy as in the SSC (0.4 GJ); incorporated spiral kicker system and many features that were envisioned for the SSC

Table 17.5: MKB System parameters

Horizontal diluter magnet system MKBH		
Number of magnets per system	4	
Max. system deflection angle	0.278	mrad
Kick strength per magnet	1.624	Tm
Magnet beam aperture – horizontal	58	mm
Magnet beam aperture – vertical	32	mm
Operating charging voltage	16.4	kV
Field rise time	18.9	µs
Field oscillating frequency	14.2	kHz
Effective length (magnetic)	1.936	m
Yoke length (mechanical)	1.899	m
Vacuum length (mechanical), 2 magnets	4.582	m
Vertical diluter magnet system MKBV		
Number of magnets per system	6	
Max. system deflection angle	0.277	mrad
Kick strength per magnet	1.077	Tm
Magnet beam aperture – horizontal	66	mm
Magnet beam aperture – vertical	36	mm
Operating charging voltage	22.3	kV
Field rise time	34	µs
Field oscillating frequency	12.7	kHz
Effective length (magnetic)	1.267	m
Yoke length (mechanical)	1.196	m
Vacuum length (mechanical), 2 magnets	4.076	m



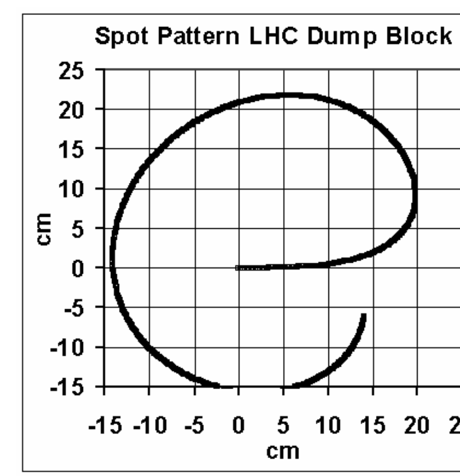


Figure 17.6: Beam spot figure on absorber block.