History and Lessons from Existing and Studied High Energy Hadron Machines

*FCC-hh: **Beam Dump** Concepts Session*

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Rome — FCC Week 2016 *2016 April 13*

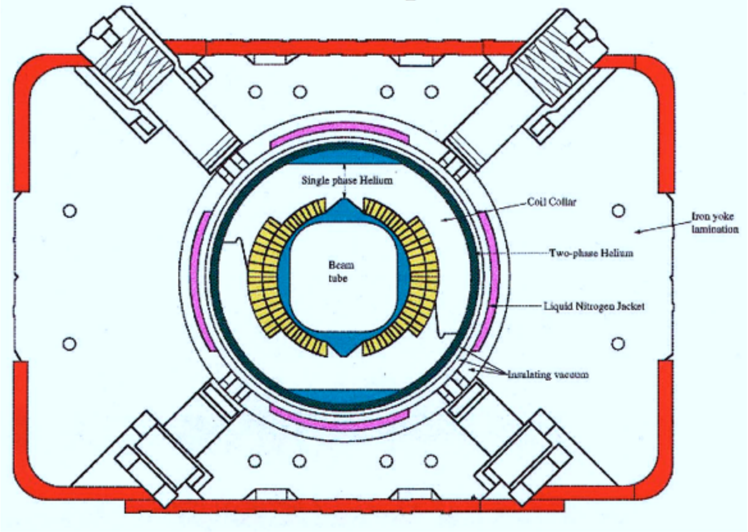
Historical Perspective

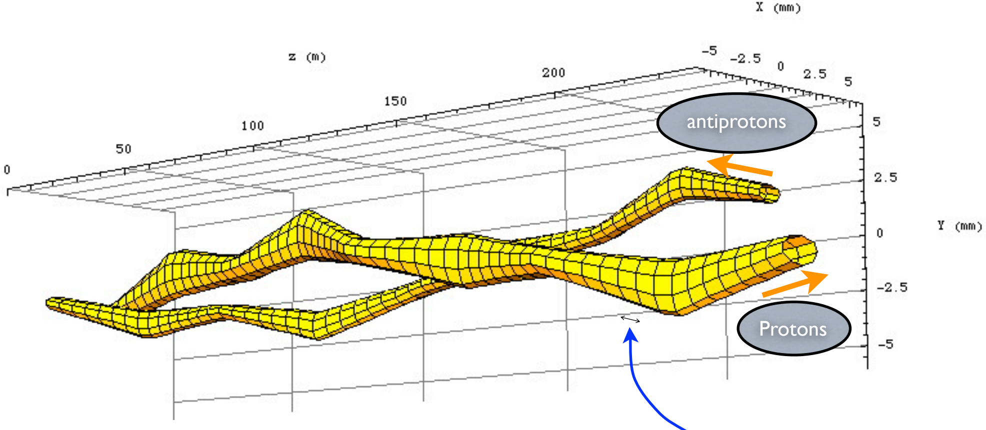
- The Tevatron
- The Superconducting Super Collider (SSC)
- The Large Hadron Collider (LHC)
- The Very Large Hadron Collider study (VLHC)
- The Future Circular Collider study (FCC)

The Tevatron

- 1st superconducting synchrotron
- 4.4 T magnets; 4°K
- collide protons w/ antiprotons
- common beam pipe

Tevatron Dipole





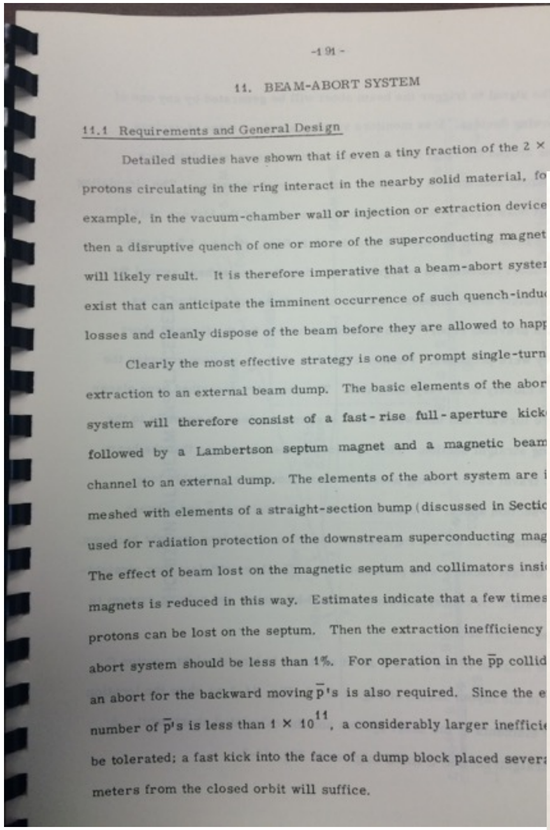
bunch length

Helical orbits through 4 standard arc cells of the Tevatron

Tevatron Abort System

- Prior to Tevatron, the original “Main Ring” at Fermilab existed in the same tunnel
  - 400 GeV beam, ~3 x 10^{13} p, 10 s cycle
  - corresponds to ~2 MJ beam energy
- Tevatron originally ran as fixed target synchrotron, with 800 GeV beam
  - ~2 x 10^{13} p, 30 - 120 s cycles; 2.6 MJ
- When reconfigured for colliding beams, the beam abort system was changed to an “internal abort”; re-use the “C0” straight section for a possible new interaction region
  - 980 GeV, ~1 x 10^{13} p —> ~ 1.5 MJ
  - less for antiprotons (eventually, up to ~0.75 MJ)

The Energy Doubler (a.k.a., Tevatron)



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11. BEAM-ABORT SYSTEM

11.1 Requirements and General Design

Detailed studies have shown that if even a tiny fraction of the 2×10^{13}
protons circulating in the ring interact in the nearby solid material, fo
example, in the vacuum-chamber wall or injection or extraction device
then a disruptive quench of one or more of the superconducting magnet
will likely result. It is therefore imperative that a beam-abort syster
exist that can anticipate the imminent occurrence of such quench-induc
losses and cleanly dispose of the beam before they are allowed to happ

Clearly the most effective strategy is one of prompt single-turn
extraction to an external beam dump. The basic elements of the abor
system will therefore consist of a fast-rise full-aperture kick
followed by a Lambertson septum magnet and a magnetic beam
channel to an external dump. The elements of the abort system are i
meshed with elements of a straight-section bump (discussed in Sectic
used for radiation protection of the downstream superconducting mag
The effect of beam lost on the magnetic septum and collimators insi
magnets is reduced in this way. Estimates indicate that a few times
protons can be lost on the septum. Then the extraction inefficiency
abort system should be less than 1%. For operation in the $\bar{p}p$ collid
an abort for the backward moving $\bar{p}$'s is also required. Since the e
number of $\bar{p}$'s is less than 1×10^{11}, a considerably larger inefficie
be tolerated; a fast kick into the face of a dump block placed sever
meters from the closed orbit will suffice.

Energy Doubler Design Report, 1979

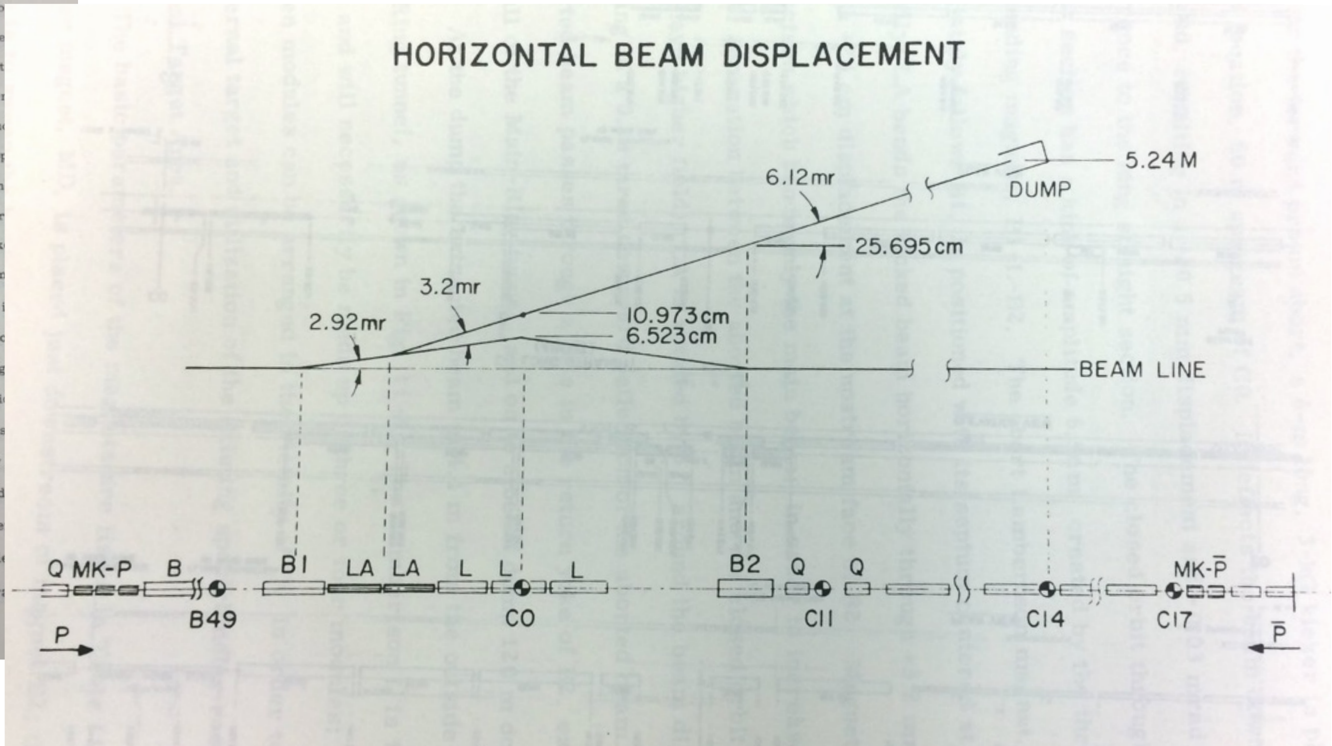
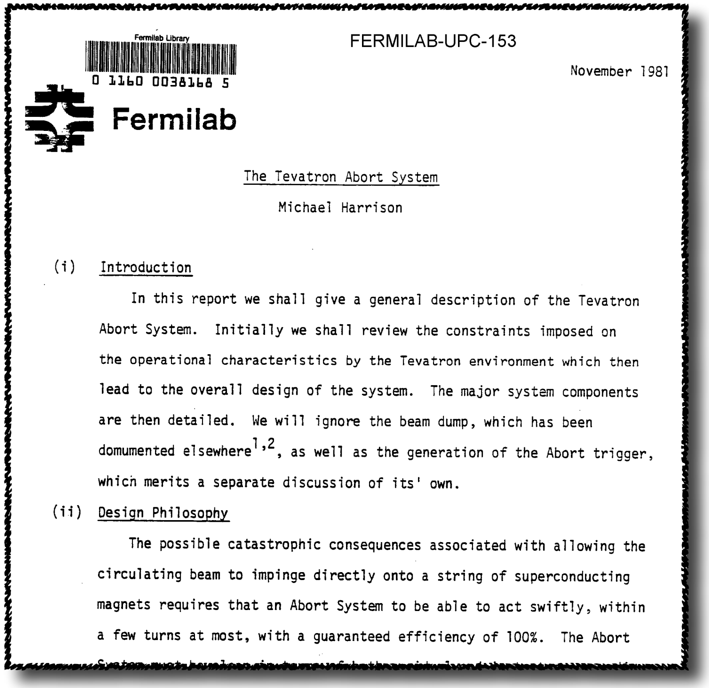


Fig. 11-1. Location of abort-system elements and displacement of aborted beam.

Tevatron *Fixed Target* Abort Layout



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The Tevatron Abort System

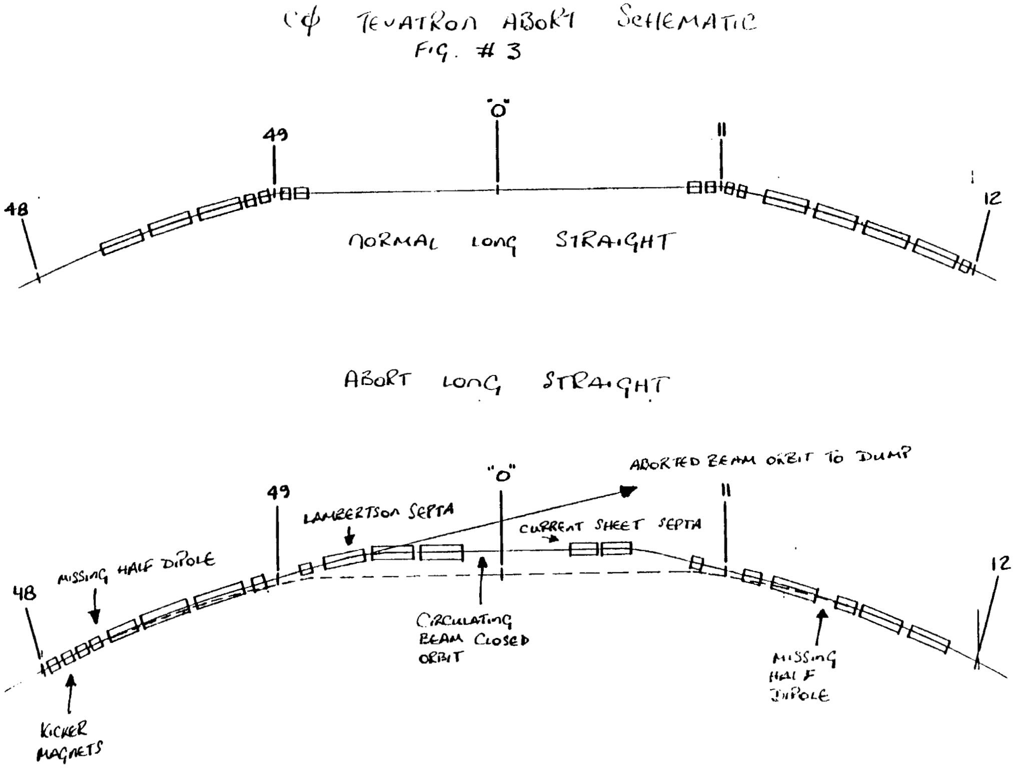
Michael Harrison

(i) Introduction

In this report we shall give a general description of the Tevatron Abort System. Initially we shall review the constraints imposed on the operational characteristics by the Tevatron environment which then lead to the overall design of the system. The major system components are then detailed. We will ignore the beam dump, which has been domumented elsewhere[1,2], as well as the generation of the Abort trigger, which merits a separate discussion of its' own.

(ii) Design Philosophy

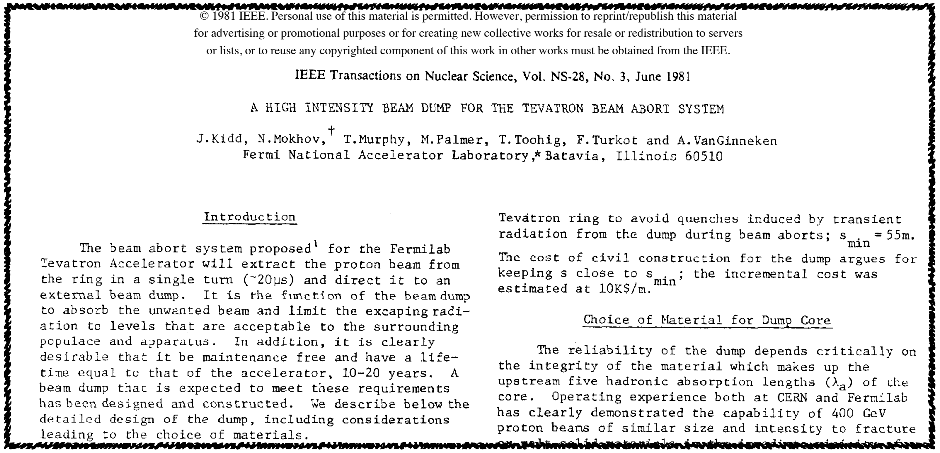
The possible catastrophic consequences associated with allowing the circulating beam to impinge directly onto a string of superconducting magnets requires that an Abort System to be able to act swiftly, within a few turns at most, with a guaranteed efficiency of 100%. The Abort



Aborted beam moves through field-free region of the Lambertson septum.
Warm bending magnets incorporated, on the same bus as SC magnets.

Tevatron *Fixed Target* Beam Dump

- Designed for 3.2 MJ over 21 μs
- 10-20 yr lifetime



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IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

A HIGH INTENSITY BEAM DUMP FOR THE TEVATRON BEAM ABORT SYSTEM

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Introduction

The beam abort system proposed[1] for the Fermilab Tevatron Accelerator will extract the proton beam from the ring in a single turn (~20μs) and direct it to an external beam dump. It is the function of the beam dump to absorb the unwanted beam and limit the excaping radiation to levels that are acceptable to the surrounding populace and apparatus. In addition, it is clearly desirable that it be maintenance free and have a lifetime equal to that of the accelerator, 10-20 years. A beam dump that is expected to meet these requirements has been designed and constructed. We describe below the detailed design of the dump, including considerations leading to the choice of materials.

Tevatron ring to avoid quenches induced by transient radiation from the dump during beam aborts; $s_{min} = 55$m.

The cost of civil construction for the dump argues for keeping s close to s_{min}; the incremental cost was estimated at 10K$/m.

Choice of Material for Dump Core

The reliability of the dump depends critically on the integrity of the material which makes up the upstream five hadronic absorption lengths (λ_a) of the core. Operating experience both at CERN and Fermilab has clearly demonstrated the capability of 400 GeV proton beams of similar size and intensity to fracture

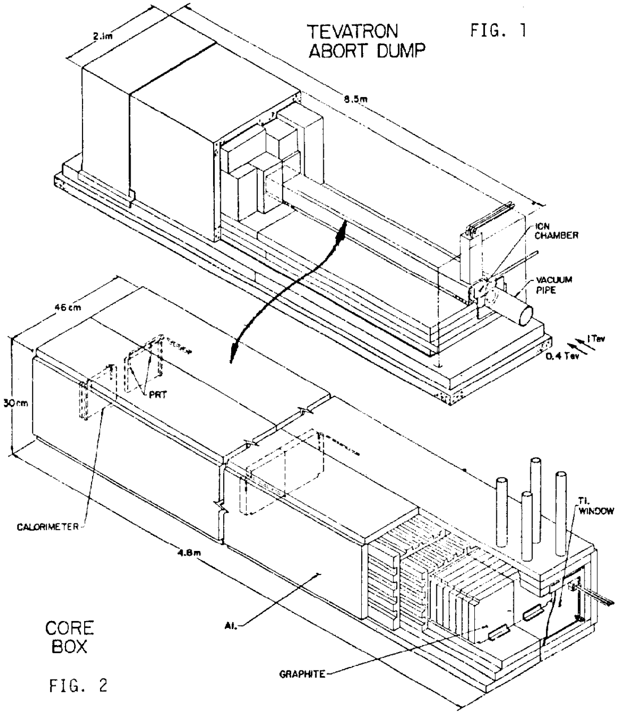

FIG. 1

FIG. 2

Tevatron *Collider* Abort System

- After being reconfigured for colliding beams, the beam abort system was soon changed to an "internal abort"; desire was to re-use the "C0" straight section for a possible new interaction region
    - 980 GeV, ~1 x 10^{13} p —> ~ 1.5 MJ
    - for antiprotons, eventually, up to ~0.75 MJ

Tevatron Internal Abort

eceedings of the 1988 Summer Study on HEP in the 1990's, Snowmass, CO, June 6-Jul 15,

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INTERNAL BEAM ABORT SYSTEM FOR THE TEVATRON UPGRADE

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INTRODUCTION

In this note we shall examine the
of an internal beam dump system for t
running in the pbar-p collider mode.
that the beam energy can be as high
The motivation behind this report co
fact that the present proton abort syst
single-turn fast-extraction system, wh
progressively more difficult to perf
beam energy is raised without leng
straight section. We examine thre
designs (Fig. 1). The first is a syste
of two beam dumps at each end of t
straight section, the second dump
absorber for the secondary particles

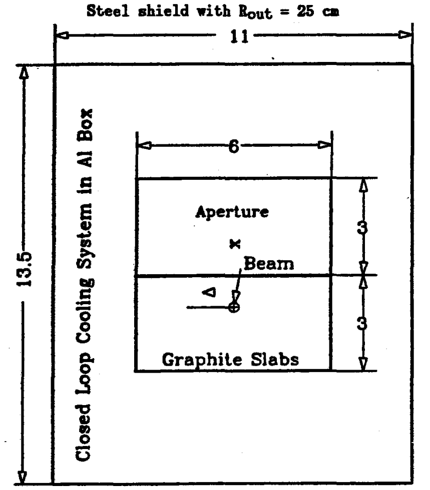


Figure 6 Core of the internal beam abort dump, Scheme 1(B). All dimensions are in cm.

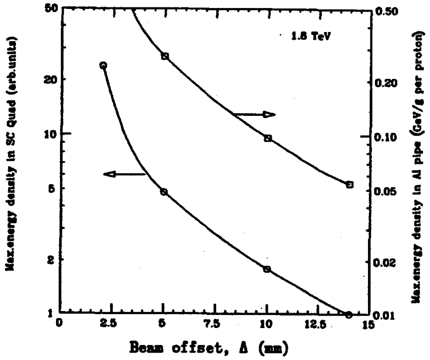


Figure 7 Maximum energy deposition density in the first downstream quadrupole superconducting coils and in the aluminum beam pipe inside the internal abort dump versus beam displacement in the dump.

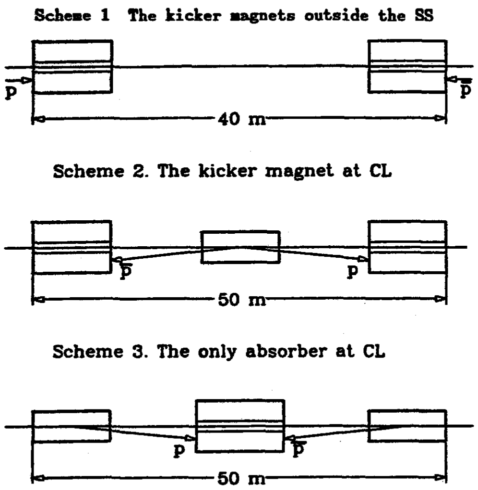


Figure 1 Three examined designs for the Tevtron internal beam dump system.

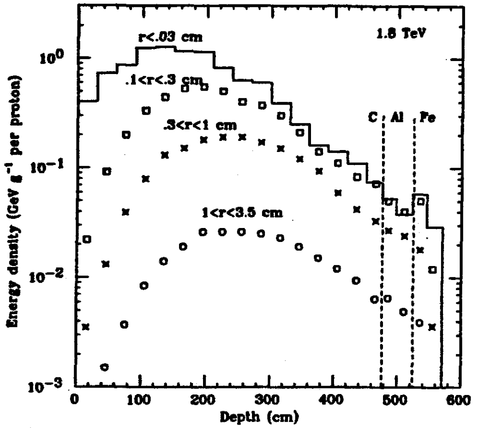
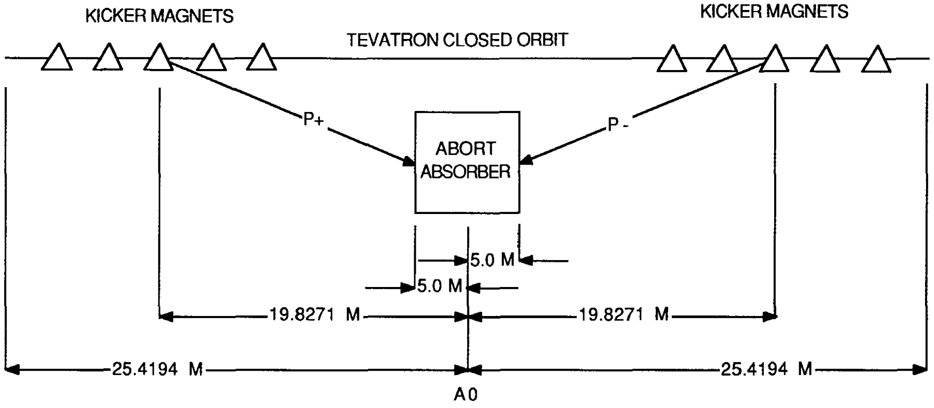


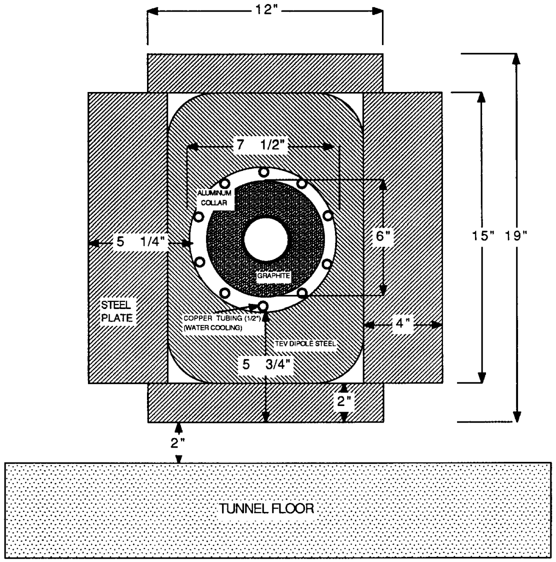
Figure 3 Longitudinal distributions of energy deposition density in the various radial bins of the core of the internal beam dump at the 1.8 TeV proton abort with a beam spot of 0.48*0.34 mm (H*V) rms.

Tevatron Collider Abort System



FLANGE TO FLANGE LENGTH OF EACH MAGNET IS 2.2369 METERS

FIGURE 1. TEVATRON UPGRADE ABORT LAYOUT

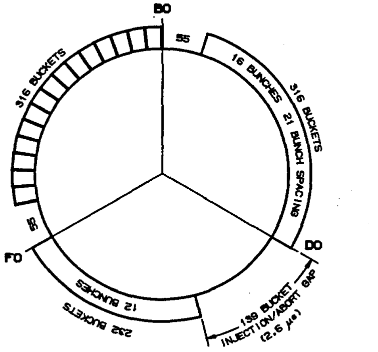


LENGTH OF RECTANGULAR STEEL SHELL IS 3 METERS

LENGTH OF DIPOLE STEEL IS 4.5 M

VACUUM TUBE IS 2.5" OD X 0.060"WT

FIGURE 9. CROSS SECTION OF THE GRAPHITE PORTION OF THE ABSORBER

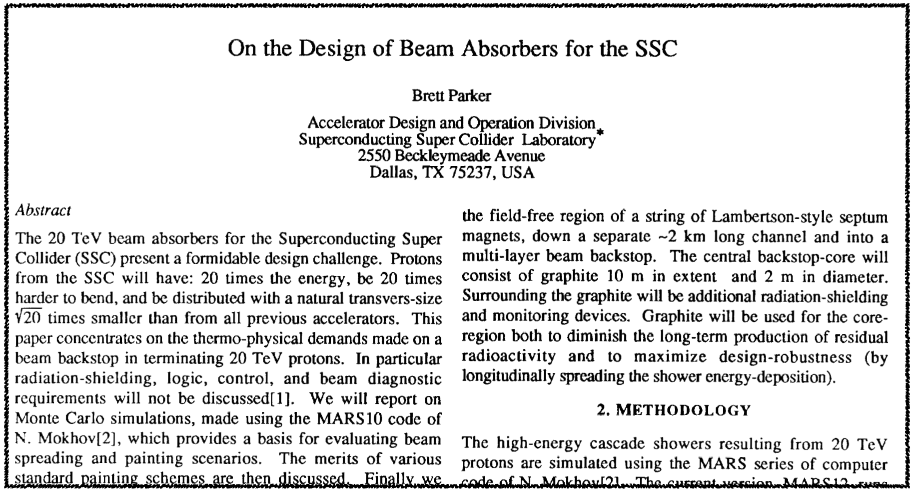


ALTERNATE 44 BUNCH INJECTION PATTERN

C. Crawford, 1989

The SSC Beam Abort System

With 20 TeV per beam, and 1.3×10^{14} p per beam, yields stored beam energy of 400 MJ



On the Design of Beam Absorbers for the SSC

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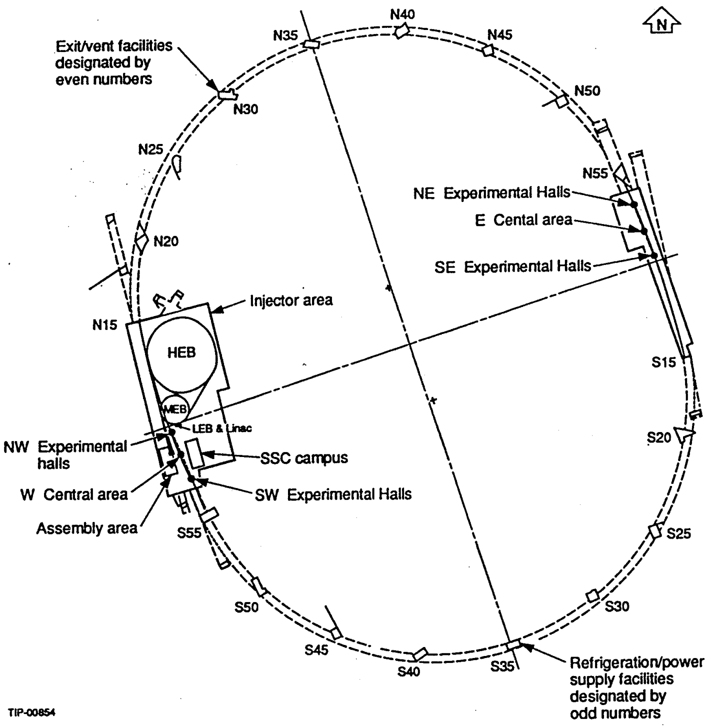
Abstract

The 20 TeV beam absorbers for the Superconducting Super Collider (SSC) present a formidable design challenge. Protons from the SSC will have: 20 times the energy, be 20 times harder to bend, and be distributed with a natural transvers-size $\sqrt{20}$ times smaller than from all previous accelerators. This paper concentrates on the thermo-physical demands made on a beam backstop in terminating 20 TeV protons. In particular radiation-shielding, logic, control, and beam diagnostic requirements will not be discussed[1]. We will report on Monte Carlo simulations, made using the MARS10 code of N. Mokhov[2], which provides a basis for evaluating beam spreading and painting scenarios. The merits of various standard painting schemes are then discussed. Finally we

the field-free region of a string of Lambertson-style septum magnets, down a separate ~2 km long channel and into a multi-layer beam backstop. The central backstop-core will consist of graphite 10 m in extent and 2 m in diameter. Surrounding the graphite will be additional radiation-shielding and monitoring devices. Graphite will be used for the core-region both to diminish the long-term production of residual radioactivity and to maximize design-robustness (by longitudinally spreading the shower energy-deposition).

2. METHODOLOGY

The high-energy cascade showers resulting from 20 TeV protons are simulated using the MARS series of computer code of N. Mokhov[2]. The current version MARS12 runs



The SSC Beam Abort System

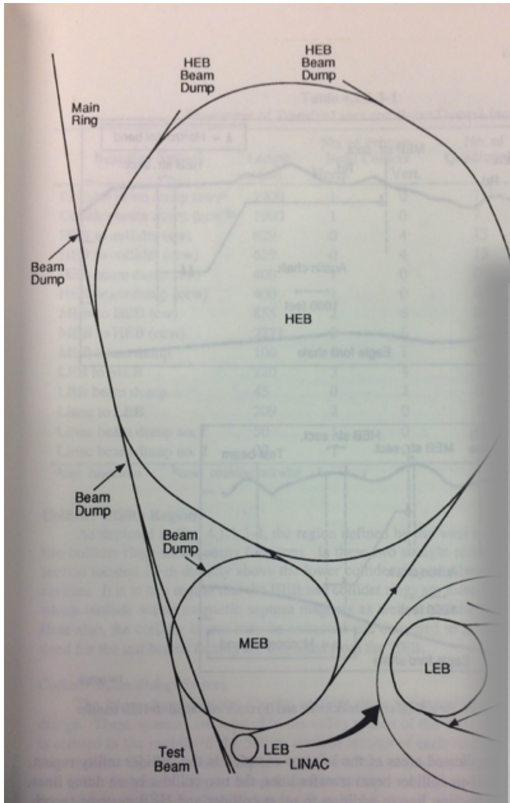


Figure 4.1.1.3-2. Plan view of injector complex indicating beam transf
insert shows a blow-up view of the linac and LEB area (not to scale).

Layout based much on Tevatron design

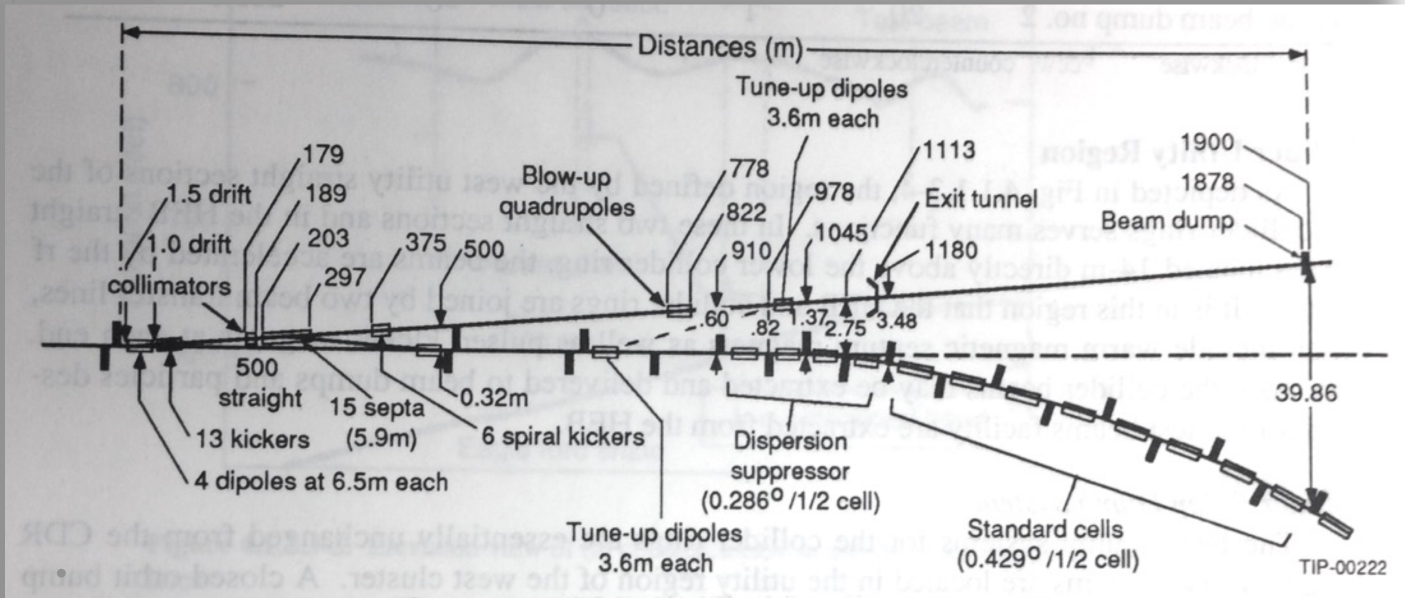


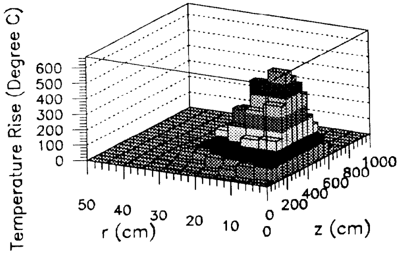
Figure 4.1.1.3-5. Collider dump schematic (not to scale).

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 *ΔT(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

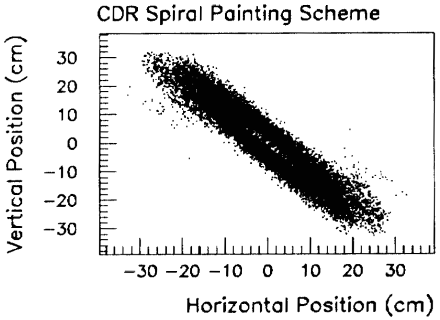


Fig. 5. CDR spiral painting with phase slippage.

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.

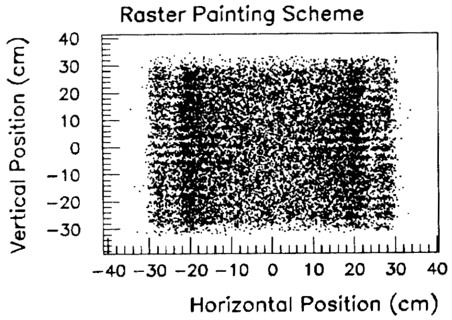
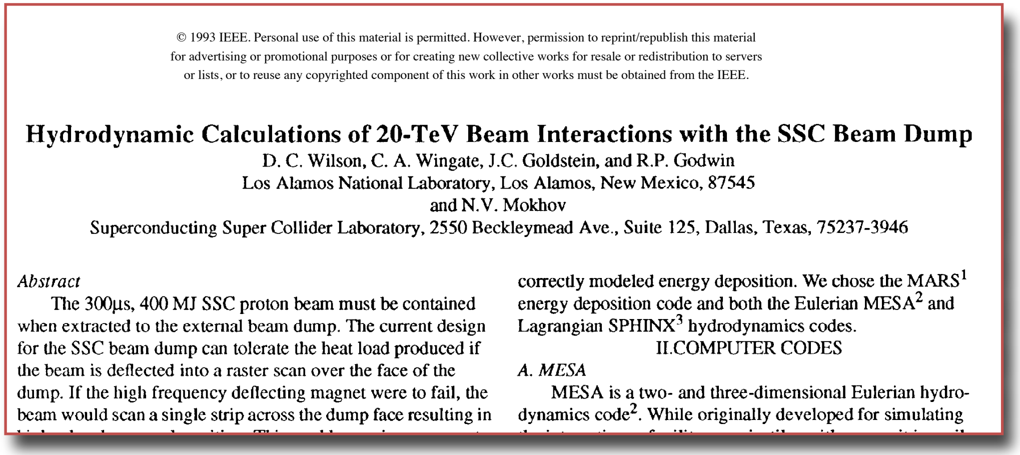


Fig. 6. Beam profile for raster painting scheme.

Hydrodynamic Calculations

- Early hydrodynamic computations of beam interacting with matter (beam pipes, magnets, tunnel walls!!, …) began in the early 1990s with the SSC



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Hydrodynamic Calculations of 20-TeV Beam Interactions with the SSC Beam Dump

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Abstract

The 300µs, 400 MJ SSC proton beam must be contained when extracted to the external beam dump. The current design for the SSC beam dump can tolerate the heat load produced if the beam is deflected into a raster scan over the face of the dump. If the high frequency deflecting magnet were to fail, the beam would scan a single strip across the dump face resulting in

correctly modeled energy deposition. We chose the MARS[1] energy deposition code and both the Eulerian MESA[2] and Lagrangian SPHINX[3] hydrodynamics codes.

II.COMPUTER CODES

A. MESA

MESA is a two- and three-dimensional Eulerian hydrodynamics code[2]. While originally developed for simulating

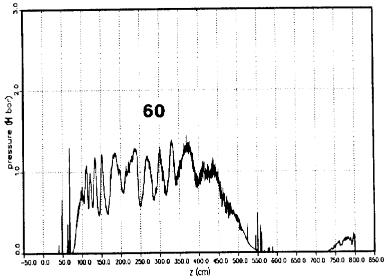

Figure 3 Axial Pressure from 2D MESA at nominal fluence

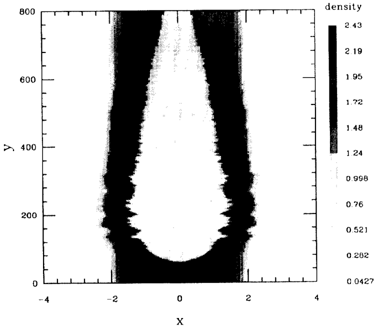

Figure 4 Density from 2D SPHINX at high fluence

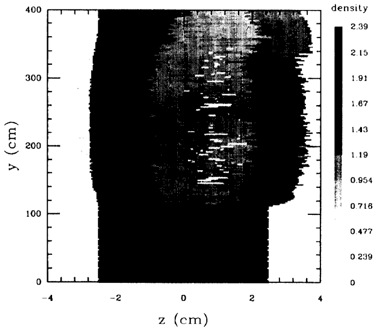

Figure 5 Density from 3D SPHINX at high fluence

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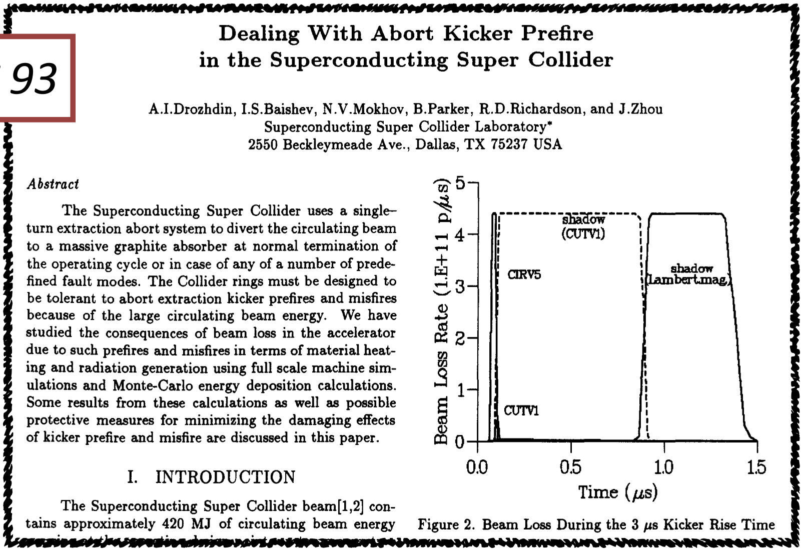
PAC 1993

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

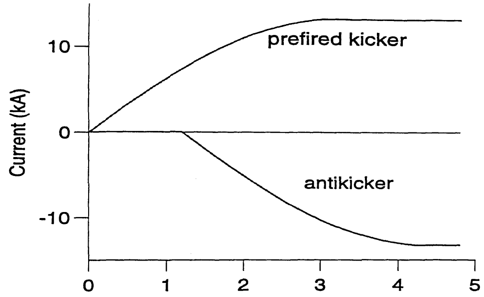
The Superconducting Super Collider uses a single-turn extraction abort system to divert the circulating beam to a massive graphite absorber at normal termination of the operating cycle or in case of any of a number of predefined fault modes. The Collider rings must be designed to be tolerant to abort extraction kicker prefires and misfires because 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.

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

I. INTRODUCTION

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

developed the notion of an “anti-kicker”



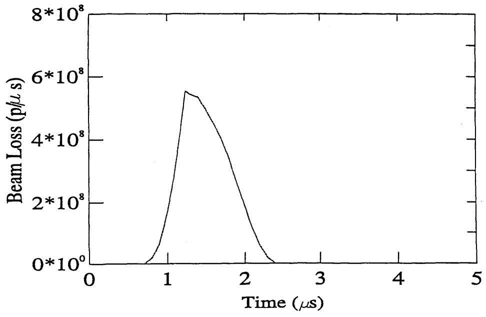
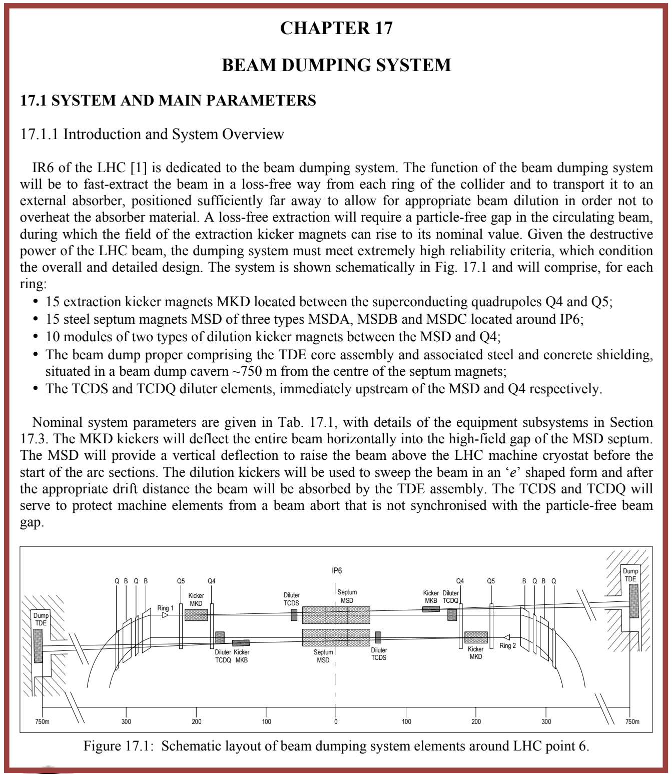


Fig. 7.   Beam loss vs time for 1.2 µs antikicker delay.

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

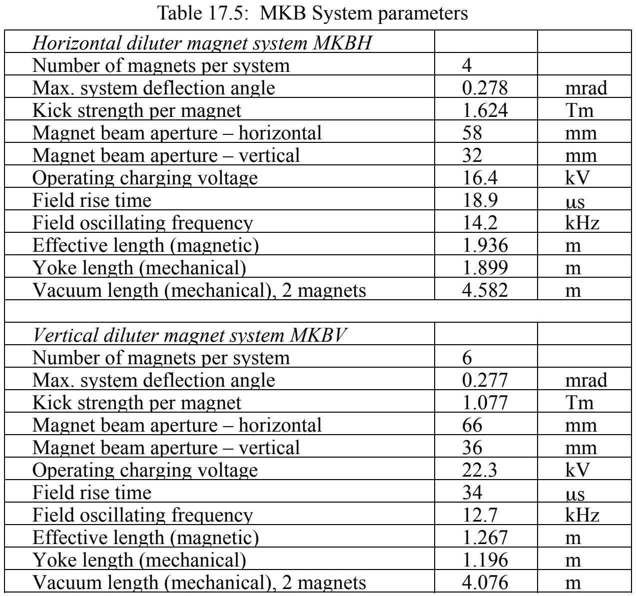
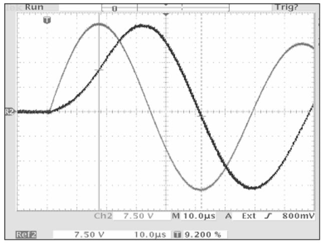


Table 17.5: MKB System parameters

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



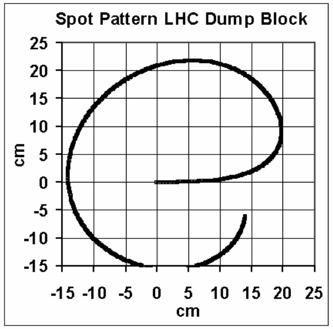


Figure 17.6: Beam spot figure on absorber block.

The LHC Abort System

- As this system has actually been constructed(!), many more details exist for the LHC than were developed and executed for the SSC hardware

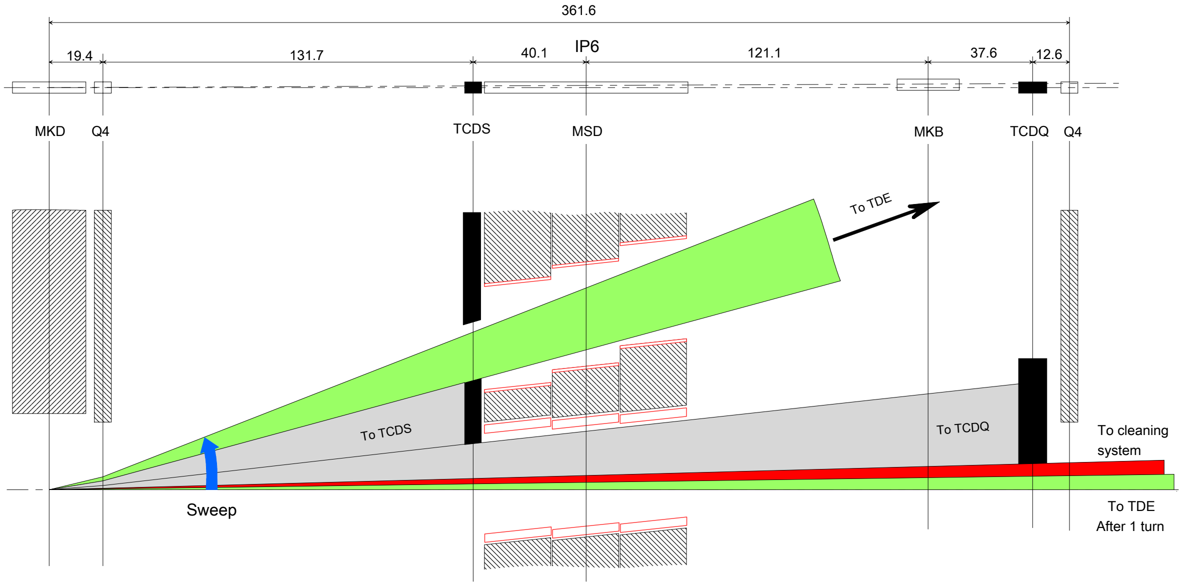
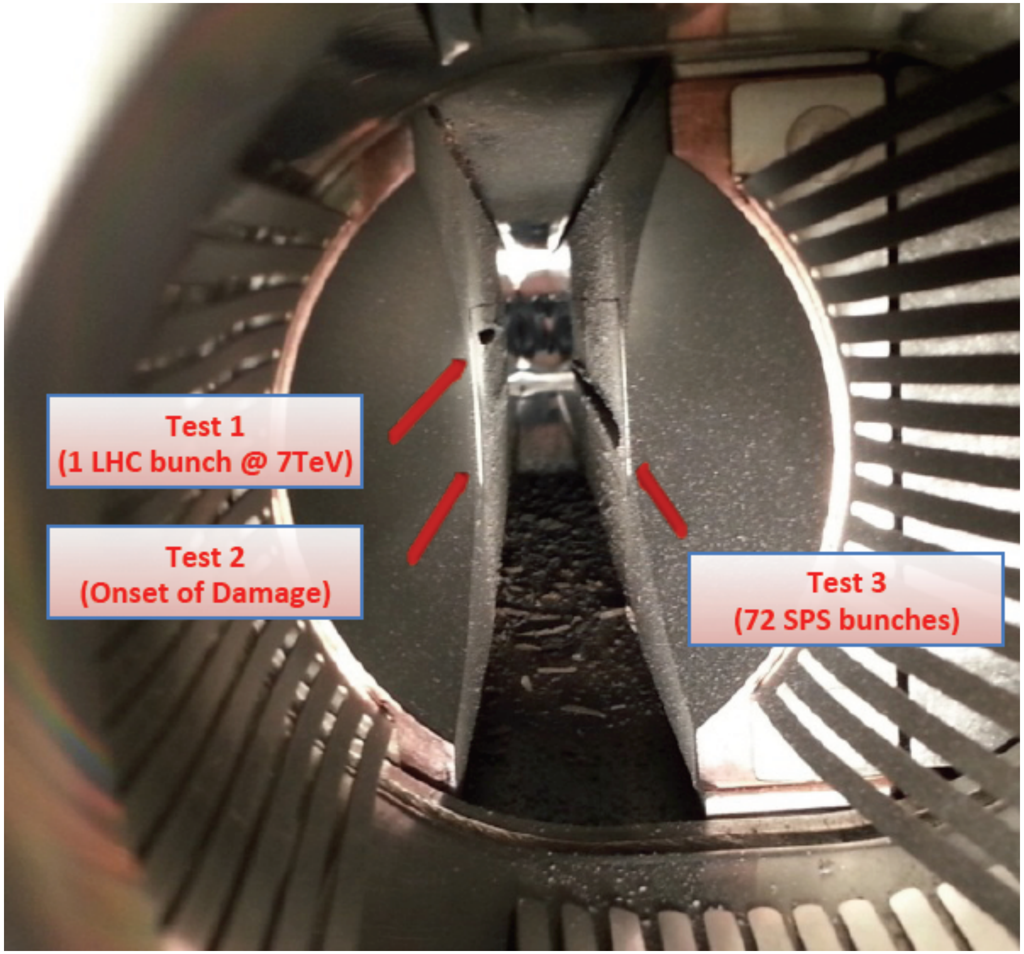


Figure 17.11: Schematic and functional layout of TCDS and TCDQ diluter systems.

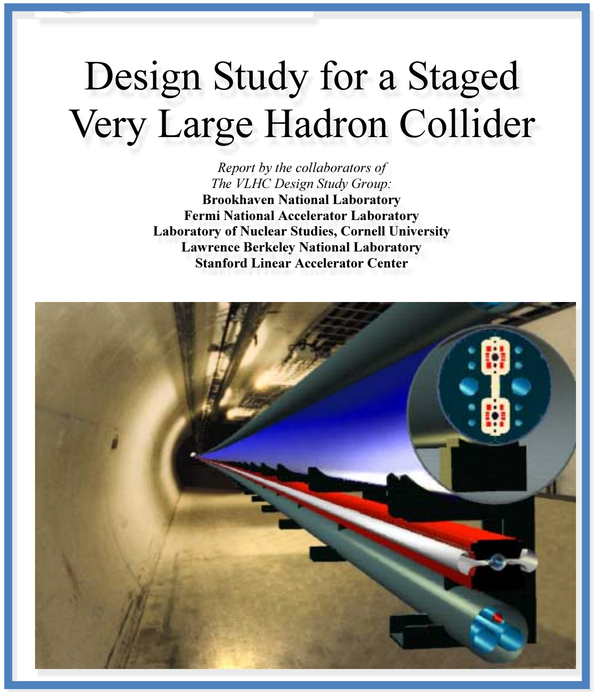
Machine Protection

Many tests were performed on the LHC system components, and undoubtedly much operational experience now exists that can be used to predict performance of future FCC systems

Will leave this to my CERN colleagues to discuss…



The VLHC Beam Abort Design

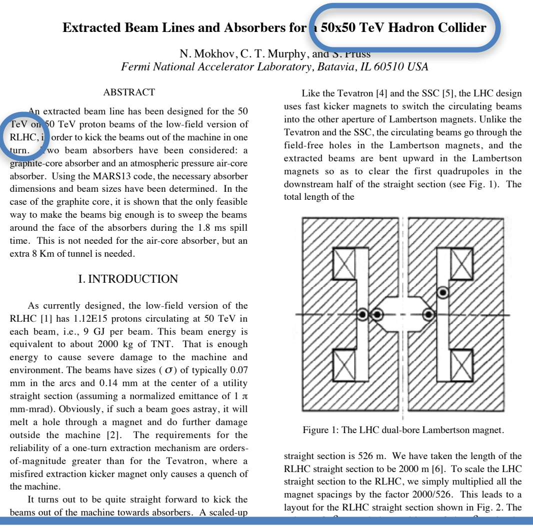


Design Study for a Staged Very Large Hadron Collider

Report by the collaborators of
The VLHC Design Study Group:
Brookhaven National Laboratory
Fermi National Accelerator Laboratory
Laboratory of Nuclear Studies, Cornell University
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center

Design studies for a *Really* Large Hadron Collider began in mid-1990s

Culminated in the **VLHC** (*Very* Large!) report of 2001



Extracted Beam Lines and Absorbers for a 50x50 TeV Hadron Collider

N. Mokhov, C. T. Murphy, and S. Pruss
Fermi National Accelerator Laboratory, Batavia, IL 60510 USA

ABSTRACT

An extracted beam line has been designed for the 50 TeV on 50 TeV proton beams of the low-field version of RLHC, i order to kick the beams out of the machine in one turn. wo beam absorbers have been considered: a graphite-core absorber and an atmospheric pressure air-core absorber. Using the MARS13 code, the necessary absorber dimensions and beam sizes have been determined. In the case of the graphite core, it is shown that the only feasible way to make the beams big enough is to sweep the beams around the face of the absorbers during the 1.8 ms spill time. This is not needed for the air-core absorber, but an extra 8 Km of tunnel is needed.

I. INTRODUCTION

As currently designed, the low-field version of the RLHC [1] has 1.12E15 protons circulating at 50 TeV in each beam, i.e., 9 GJ per beam. This beam energy is equivalent to about 2000 kg of TNT. That is enough energy to cause severe damage to the machine and environment. The beams have sizes (σ) of typically 0.07 mm in the arcs and 0.14 mm at the center of a utility straight section (assuming a normalized emittance of 1 π mm-mrad). Obviously, if such a beam goes astray, it will melt a hole through a magnet and do further damage outside the machine [2]. The requirements for the reliability of a one-turn extraction mechanism are orders-of-magnitude greater than for the Tevatron, where a misfired extraction kicker magnet only causes a quench of the machine.

It turns out to be quite straight forward to kick the beams out of the machine towards absorbers. A scaled-up

Like the Tevatron [4] and the SSC [5], the LHC design uses fast kicker magnets to switch the circulating beams into the other aperture of Lambertson magnets. Unlike the Tevatron and the SSC, the circulating beams go through the field-free holes in the Lambertson magnets, and the extracted beams are bent upward in the Lambertson magnets so as to clear the first quadrupoles in the downstream half of the straight section (see Fig. 1). The total length of the

Figure 1: The LHC dual-bore Lambertson magnet.

straight section is 526 m. We have taken the length of the RLHC straight section to be 2000 m [6]. To scale the LHC straight section to the RLHC, we simply multiplied all the magnet spacings by the factor 2000/526. This leads to a layout for the RLHC straight section shown in Fig. 2. The

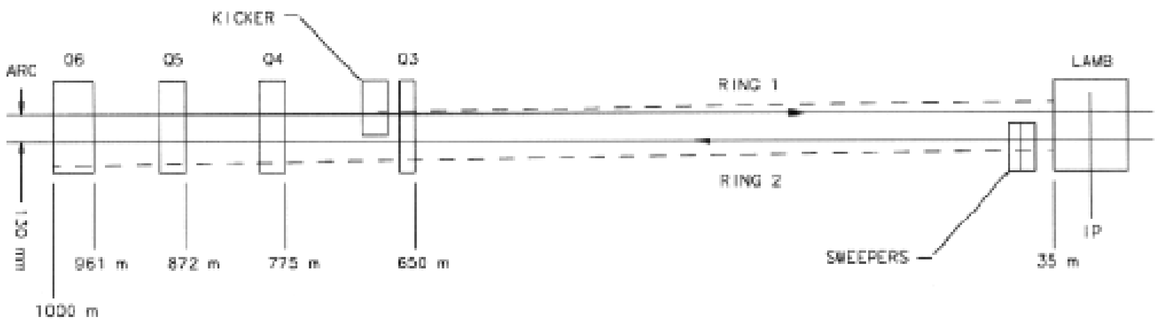


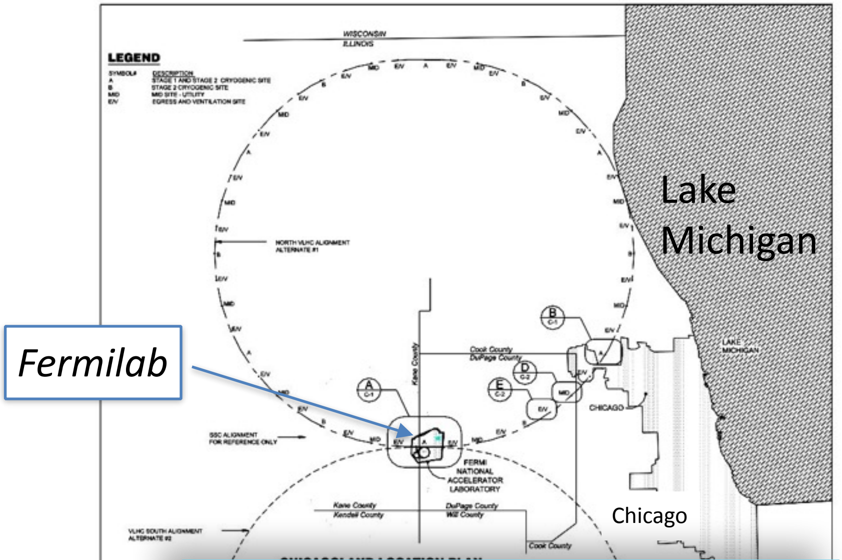
Figure 2: A possible layout of the utility straight. The dashed lines are the extracted beams.

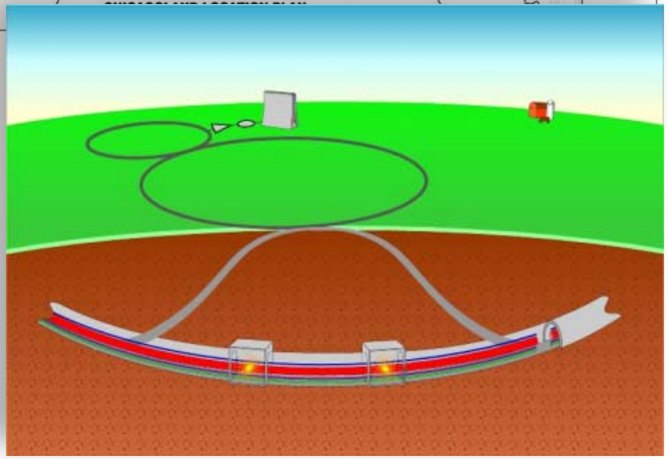
VLHC Parameters

- Stage 1: 20 TeV; 3.0 GJ
- Stage 2: 240 TeV; 3.9 GJ

Table 1.1. The high-level parameters of both stages of the VLHC.

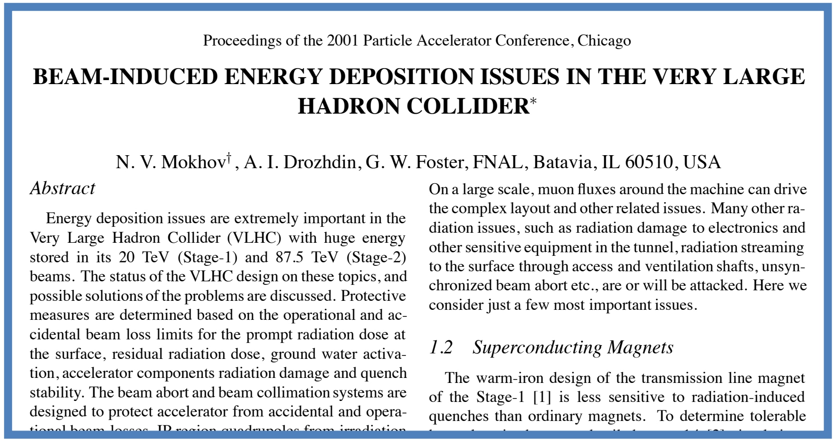
	Stage 1	**Stage 2**
Total Circumference (km)	233	233
Center-of-Mass Energy (TeV)	40	175
Number of interaction regions	2	2
Peak luminosity ($cm^{-2}s^{-1}$)	1×10^{34}	2.0×10^{34}
Luminosity lifetime (hrs)	24	8
Injection energy (TeV)	0.9	10.0
Dipole field at collision energy (T)	2	9.8
Average arc bend radius (km)	35.0	35.0
Initial number of protons per bunch	2.6×10^{10}	7.5×10^{9}
Bunch spacing (ns)	18.8	18.8
β* at collision (m)	0.3	0.71
Free space in the interaction region (m)	± 20	± 30
Inelastic cross section (mb)	100	130
Interactions per bunch crossing at L_{peak}	21	54
Synchrotron radiation power per meter (W/m/beam)	0.03	4.7
Average power use (MW) for collider ring	25	100
Total installed power (MW) for collider ring	35	250





The VLHC Beam Abort Design

- A new concept developed during the VLHC investigation:
  - a “graphite shadow”
    - sacrificial device



Proceedings of the 2001 Particle Accelerator Conference, Chicago

BEAM-INDUCED ENERGY DEPOSITION ISSUES IN THE VERY LARGE HADRON COLLIDER*

N. V. Mokhov†, A. I. Drozhdin, G. W. Foster, FNAL, Batavia, IL 60510, USA

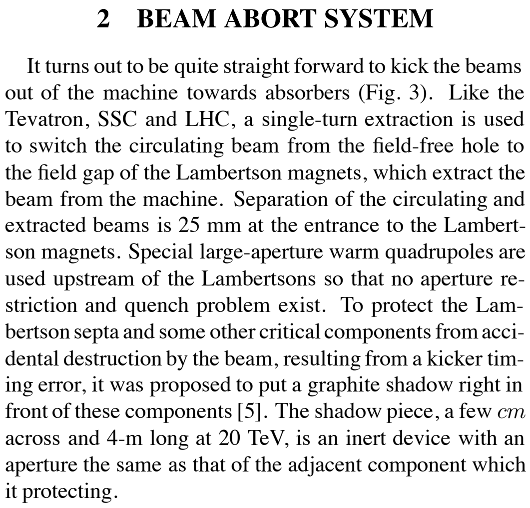
Abstract

Energy deposition issues are extremely important in the Very Large Hadron Collider (VLHC) with huge energy stored in its 20 TeV (Stage-1) and 87.5 TeV (Stage-2) beams. The status of the VLHC design on these topics, and possible solutions of the problems are discussed. Protective measures are determined based on the operational and accidental beam loss limits for the prompt radiation dose at the surface, residual radiation dose, ground water activation, accelerator components radiation damage and quench stability. The beam abort and beam collimation systems are designed to protect accelerator from accidental and operational beam losses, IP region quadrupoles from irradiation

On a large scale, muon fluxes around the machine can drive the complex layout and other related issues. Many other radiation issues, such as radiation damage to electronics and other sensitive equipment in the tunnel, radiation streaming to the surface through access and ventilation shafts, unsynchronized beam abort etc., are or will be attacked. Here we consider just a few most important issues.

1.2 Superconducting Magnets

The warm-iron design of the transmission line magnet of the Stage-1 [1] is less sensitive to radiation-induced quenches than ordinary magnets. To determine tolerable



2 BEAM ABORT SYSTEM

It turns out to be quite straight forward to kick the beams out of the machine towards absorbers (Fig. 3). Like the Tevatron, SSC and LHC, a single-turn extraction is used to switch the circulating beam from the field-free hole to the field gap of the Lambertson magnets, which extract the beam from the machine. Separation of the circulating and extracted beams is 25 mm at the entrance to the Lambertson magnets. Special large-aperture warm quadrupoles are used upstream of the Lambertsons so that no aperture restriction and quench problem exist. To protect the Lambertson septa and some other critical components from accidental destruction by the beam, resulting from a kicker timing error, it was proposed to put a graphite shadow right in front of these components [5]. The shadow piece, a few *cm* across and 4-m long at 20 TeV, is an inert device with an aperture the same as that of the adjacent component which it protecting.

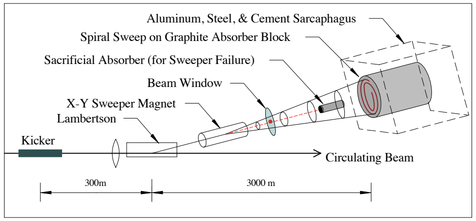
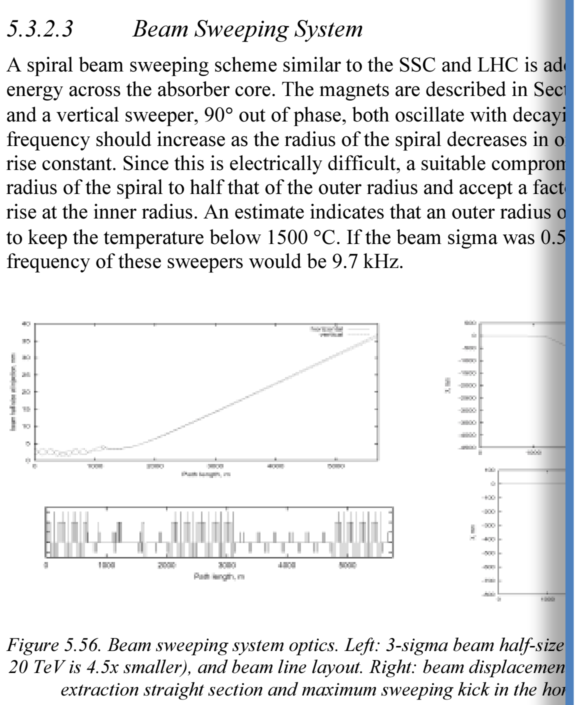


Figure 3: Schematic layout of beam abort channel.

For TeV beams, the natural choice for the absorber is

The VLHC Beam Abort Design



5.3.2.3 Beam Sweeping System

A spiral beam sweeping scheme similar to the SSC and LHC is ad
energy across the absorber core. The magnets are described in Sect
and a vertical sweeper, 90° out of phase, both oscillate with decayi
frequency should increase as the radius of the spiral decreases in o
rise constant. Since this is electrically difficult, a suitable compron
radius of the spiral to half that of the outer radius and accept a fact
rise at the inner radius. An estimate indicates that an outer radius o
to keep the temperature below 1500 °C. If the beam sigma was 0.5
frequency of these sweepers would be 9.7 kHz.

*Figure 5.56. Beam sweeping system optics. Left: 3-sigma beam half-size
20 TeV is 4.5x smaller), and beam line layout. Right: beam displacemen
extraction straight section and maximum sweeping kick in the hor*

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.

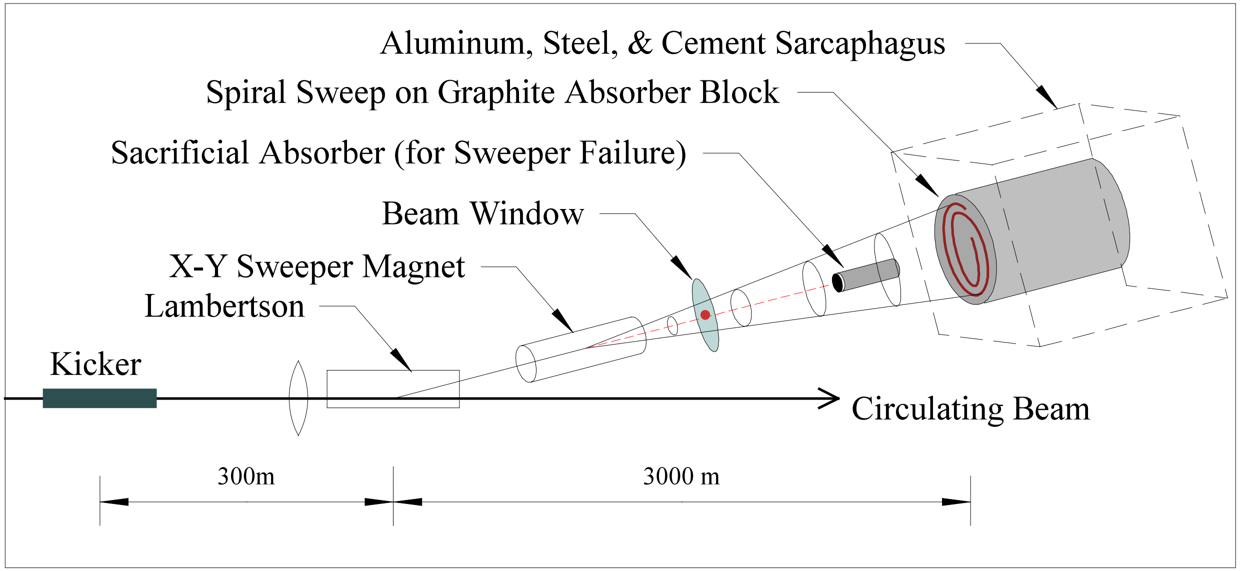
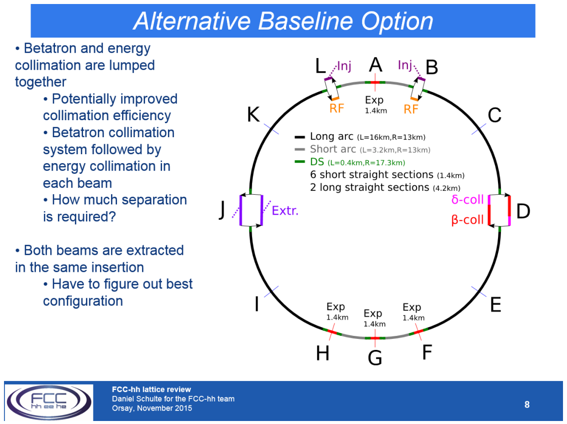


Figure 5.55. Schematic layout of beam abort channel including kickers, Lambertson septa, extraction beam sweeping, beam window, sacrificial rod, and graphite beam absorber. Under normal circumstances the extracted beam is swept in a spiral pattern to spread the energy across the graphite dump. If the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

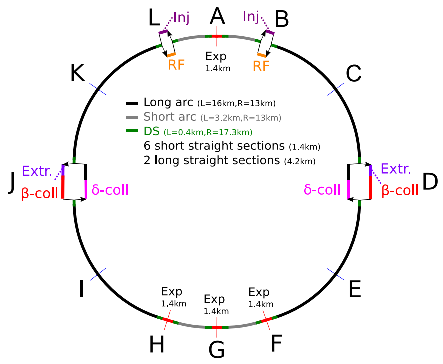
FCC Beam Abort — 8.4 GJ beams



Alternative Baseline Option

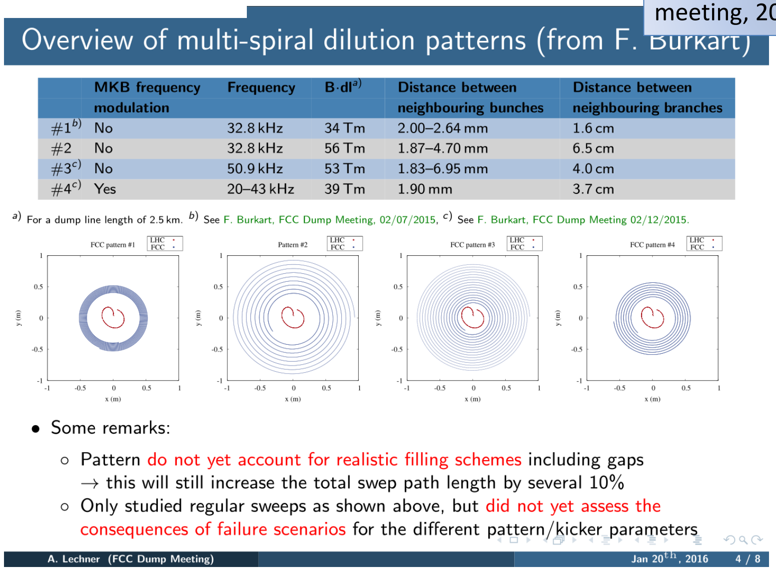
- Betatron and energy collimation are lumped together
  - Potentially improved collimation efficiency
  - Betatron collimation system followed by energy collimation in each beam
  - How much separation is required?
- Both beams are extracted in the same insertion
  - Have to figure out best configuration

FCC-hh lattice review
Daniel Schulte for the FCC-hh team
Orsay, November 2015
8



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

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



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

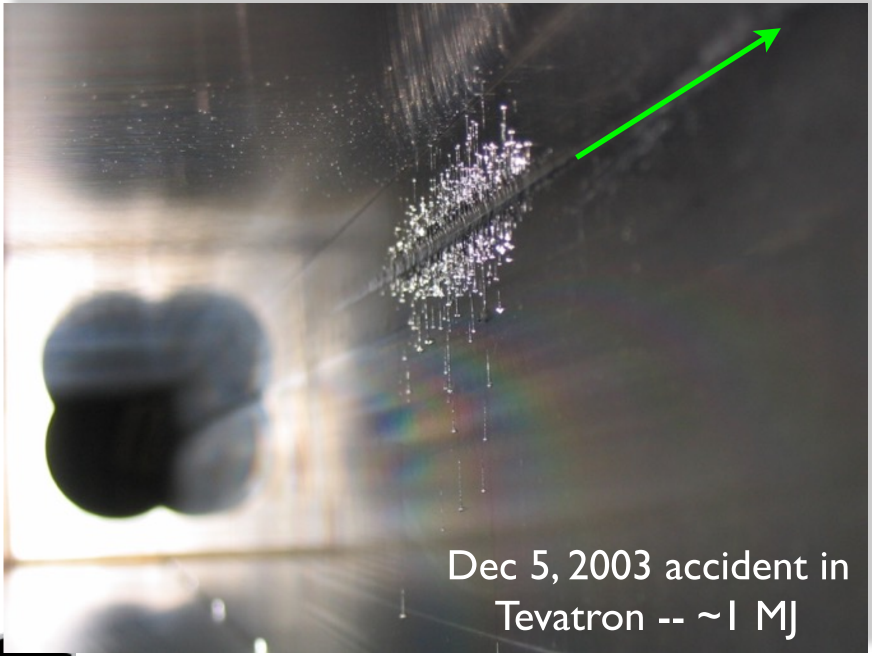
A. Lechner (FCC Dump Meeting) Jan 20th, 2016 4 / 8

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

(see talks later this session)

Tevatron Beam Incident of 5 Dec 2003

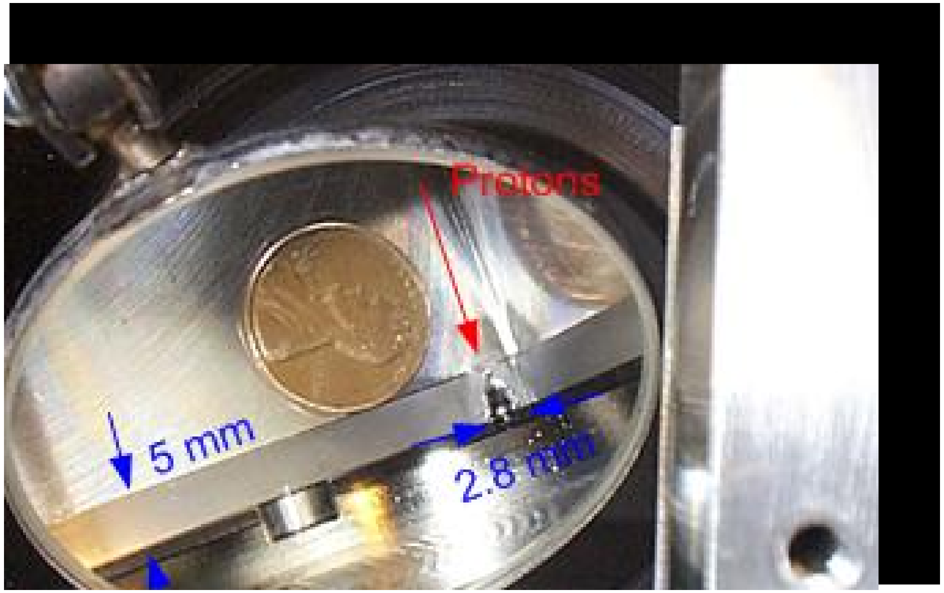
- The abort system fired, but not before the beam was moved to the edge of the collimator by a decaying power supply to a corrector magnet



Dec 5, 2003 accident in Tevatron -- ~1 MJ

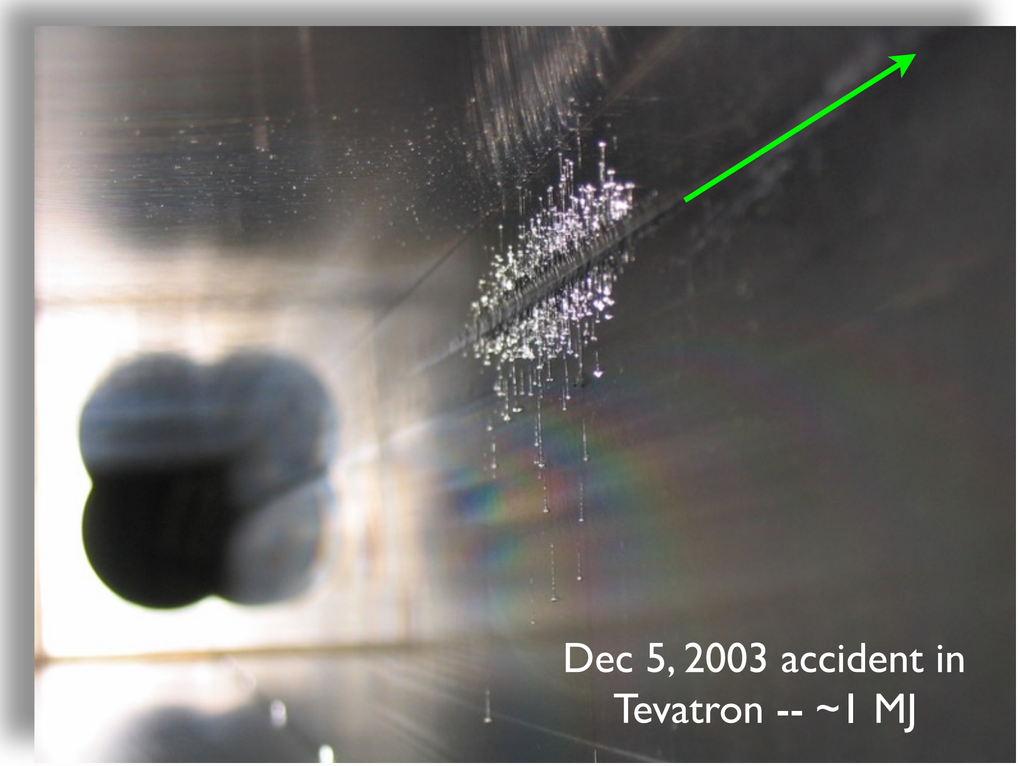
E03 1.5m collimator

~1 MJ beam stored energy, 0.98 TeV



D49 target

Note: this beam loss corresponds to 10^{-4} of total **FCC** beam energy!



Dec 5, 2003 accident in Tevatron -- ~1 MJ

Comments on FCC Beam Abort

- New, much higher level of beam energy
- SC magnet fields go up; NC fields have not
- thus, when incorporating NC magnets need much more space to create required angular deflections
- Possible to incorporate similar concepts into FCC design, but really in need of a new concept…
  - incorporating rad-hard HTS magnets ??

SSC Documents (full texts available on INSPIRE)

1. Beam Loss and Radiation Effects in the SSC Lattice Elements
   I.S. Baishev, A.I. Drozhdin, N.V. Mokhov (Serpukhov, IHEP). Jul 28, 1990. 92 pp.
2. Hydrodynamic calculations of 20-TeV beam interactions with the SSC beam dump
   D.C. Wilson, C.A. Wingate, John C. Goldstein, R.P. Godwin (Los Alamos), N.V. Mokhov (SSCL). 1993. 3 pp.
   Published in Conf.Proc. C930517 (1993) 3090-3092
3. 2-TeV HEB Beam Abort at the SSCL, R. Schailey, J. Bull, T. Clayton, P. Kocur, N.V. Mokhov (SSCL). May 1993. 3 pp., Published in **Conf.Proc. C930517 (1993) 1369-1371,** SSCL-PREPRINT-419, C93-05-17
4. Dealing with Abort Kicker Prefire in the Superconducting Super Collider
   A.I. Drozhdin, I.S. Baishev, N.V. Mokhov, B. Parker, R.D. Richardson, J. Zhou (SSCL). May 1993. 3 pp.
   Published in **Conf.Proc. C930517 (1993) 3772-3774,** SSCL-PREPRINT-329, C93-05-17
5. Consequences of Kicker Failure during HEB to Collider Injection and Possible Mitigation
   R. Soundranayagam, A.I. Drozhdin, N.V. Mokhov, B. Parker, R. Schailey, F. Wang (SSCL). May 1993. 3 pp.
   Published in **Conf.Proc. C930517 (1993) 1360-1362,** SSCL-PREPRINT-358, C93-05-17
6. Beam Loss Monitor System for the SSC, R.G. Johnson, N.V. Mokhov (SSCL). Oct 1993. 10 pp.
   Published in **In *Santa Fe 1993, Beam instrumentation* 191-200.** SSCL-PREPRINT-523, C93-10-20
7. Accidental Beam Loss in Superconducting Accelerators: Simulations, Consequences of Accidents and Protective Measures, A. Drozhdin, N. Mokhov, B. Parker (SSCL). Feb 1994. 31 pp.
   Published in **Submitted to: Nucl.Instrum.Meth.** , SSCL-PREPRINT-556

VLHC Documents (full texts available on INSPIRE)

1. Beam-induced energy deposition issues in the Very Large Hadron Collider
   N.V. Mokhov, A.I. Drozhdin, G.W. Foster (Fermilab). Jun 2001. 3 pp.
   Published in **Conf.Proc. C0106181 (2001) 3171-3173,** FERMILAB-CONF-01-135, PAC-2001-RPAH137

2. 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, SLAC-R-0591, SLAC-591, SLAC-0591, FERMILAB-TM-2149

see also: http://lss.fnal.gov/archive/other/ssc/

Thank you to Nikolai Mokhov for input and for the list of SSC/VLHC documents!