FCC Collimation System Study Plans in the US

FCC-hh Collimation System Session

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Rome — FCC Week 2016 *2016 April 12*

Possible US Studies for FCC Collimation

- Collimation System Development
  - Admittedly, commitment of effort up to this point has been harder, with other present priorities in the U.S. program
  - But, there is interest, there is experience and expertise, and a strong willingness to participate
- Energy Deposition computational tools continue to be developed, relevant to FCC

Possible US Studies for FCC Collimation

- ***Machine-Detector Interface***
- ***Lattice and Layout Optimization*** for betatron, momentum collimation systems
- Energy Deposition code development (MARS), and general simulations
    - Steady-State vs. Single-Event
        - synchrotron rad., beam-gas, IP debris, etc.
        - abort kicker module failures, etc.

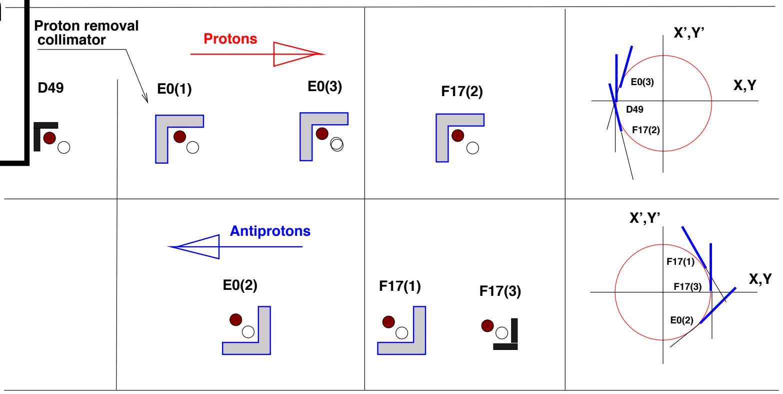
A History of Past Studies in US

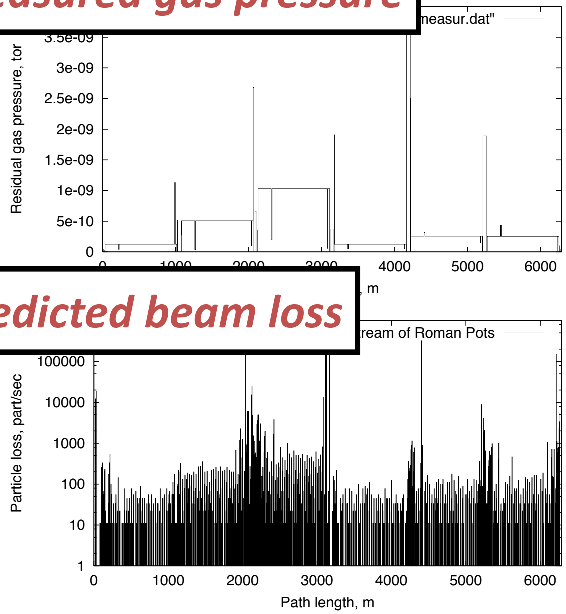
- Tevatron
- LHC/LARP
  - collimator project
- SSC
- VLHC

- Long history of general energy deposition computational development

Tevatron Collider Collimation System

Eventual 2-stage approach taken, adopted from SSC system development



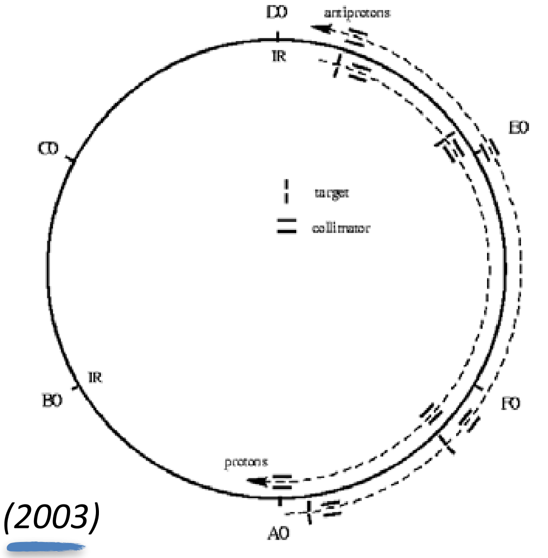


measured gas pressure

predicted beam loss

FIGURE 3. Measured residual gas pressure (*top*) and STRUCT-calculated beam loss distribution from nuclear elastic beam-gas scattering (*bottom*).

alignment of models with operational data is a continuous process

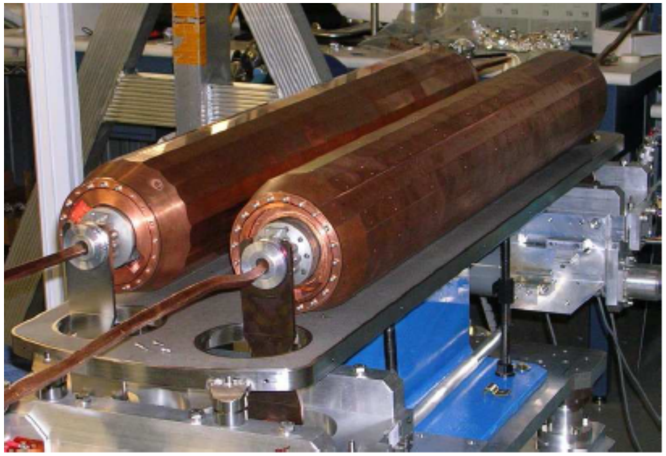


from Mokhov, *AIP* ***693,*** *14 (2003)*

LHC Collimation System Studies

In addition to general beam (halo) cleaning, LHC implemented modern IR protection schemes and stronger protection against beam accidents

LARP program also involved in collimator hardware studies as well as energy deposition calculations



AIP Conference Proceedings

Beam Collimation at Hadron Colliders

N. V. Mokhov

Citation: AIP Conference Proceedings **693**, 14 (2003); doi: 10.1063/1.1638313

View online: http://dx.doi.org/10.1063/1.1638313

LHC

At nominal operation parameters, each of the 7 TeV circulating beams of the LHC contains approximately 334 MJ of energy, which is enough to cause severe damage to the expensive machine and detector equipment. An extremely reliable abort system will use fast extraction to divert the beam to an external graphite absorber at the end of a normal fill or in case of a detected anomaly in beam behavior. There are three collimation systems implemented into the complex: high-luminosity interaction region protection, beam cleaning system and protection at beam accidents.

The high-luminosity IR protection system on each side of the IP1 and IP5 has been designed over the years on the basis of comprehensive MARS calculations [19]. It includes:

- The TAS front copper absorber at L=19.45 m from the IP (1.8 m long, 34-mm ID, 500-mm OD).
- A 7-mm thick stainless steel (SS) liner in the Q1 quadrupole.
- The SS absorber TASB at L=45.05 m (1.2-m long, r=33.3-60 mm).
- A ∼3-mm thick SS liner in the Q2A through Q3 quadrupoles.
- 40-cm long SS masks at L=23.45 m, r=250-325 mm to protect the Q1 slide bearings.
- The neutral particle 3.5-m copper absorber TAN at 140 m from the IP.
- The 1-m long TCL SS collimator at 191 m from IP.

Protection at beam accidents. A beam loss, caused by an unsynchronized abort launched at abort system malfunction, can cause severe damage to collider inner triplet components and the CMS detector near-beam elements. A set of stationary collimators for the IP5 interaction region has been proposed in [21] to protect its elements and mitigate consequences to the detector. Fig. 4 gives details of the MARS model of the system. The first collimator is positioned at $21\sigma_{collis}=10.3\sigma_{inject}=10$ mm from the beam orbit (11.8 mm from the beam pipe center). Second and third collimators are used to protect magnets from secondary particles emitted from the first one. The collimator configuration, materials and dimensions have been carefully optimized to provide reliable protection of the inner triplet and to ensure collimator survivability. Combined with an unsynchronized abort, such a system reduces peak energy deposition in the IP5 inner triplet quadrupoles by almost six orders of magnitude compared to the disastrous case of a 1-module prefire.

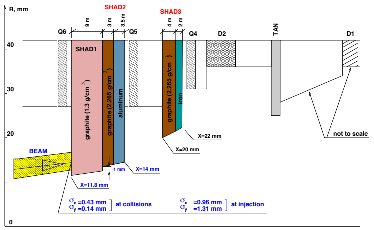


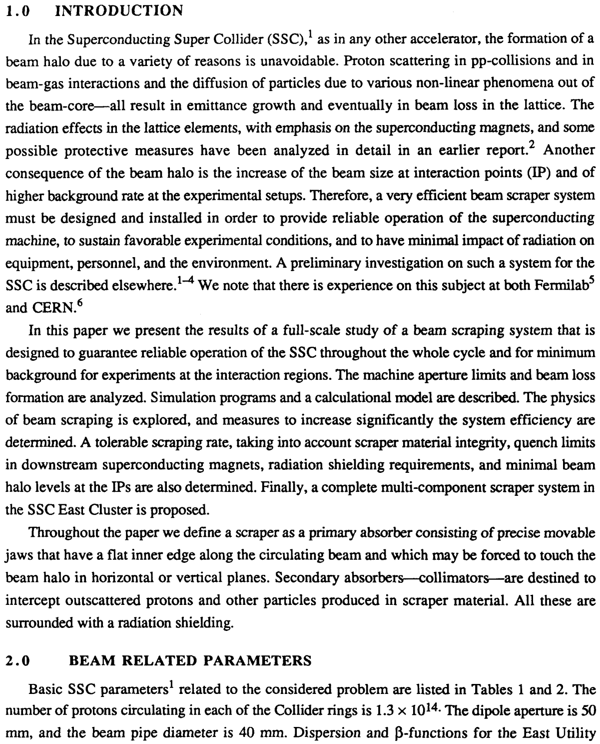
FIGURE 4. Stationary collimators in the LHC IP5 outer triplet.

SSC Collimation/Protection

The SSC Beam Scraper System

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

June 1991



1.0 INTRODUCTION

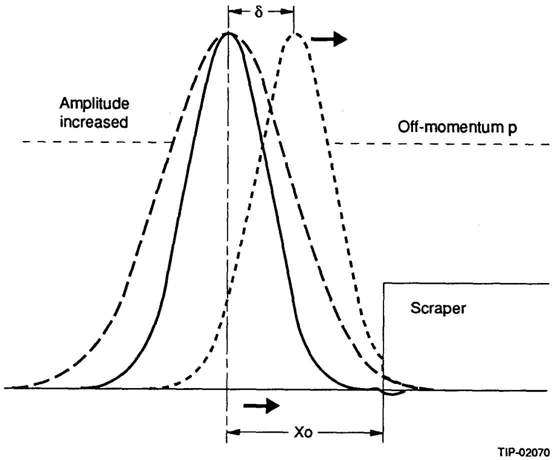
In the Superconducting Super Collider (SSC),[1] as in any other accelerator, the formation of a beam halo due to a variety of reasons is unavoidable. Proton scattering in pp-collisions and in beam-gas interactions and the diffusion of particles due to various non-linear phenomena out of the beam-core—all result in emittance growth and eventually in beam loss in the lattice. The radiation effects in the lattice elements, with emphasis on the superconducting magnets, and some possible protective measures have been analyzed in detail in an earlier report.[2] Another consequence of the beam halo is the increase of the beam size at interaction points (IP) and of higher background rate at the experimental setups. Therefore, a very efficient beam scraper system must be designed and installed in order to provide reliable operation of the superconducting machine, to sustain favorable experimental conditions, and to have minimal impact of radiation on equipment, personnel, and the environment. A preliminary investigation on such a system for the SSC is described elsewhere.[1–4] We note that there is experience on this subject at both Fermilab[5] and CERN.[6]

In this paper we present the results of a full-scale study of a beam scraping system that is designed to guarantee reliable operation of the SSC throughout the whole cycle and for minimum background for experiments at the interaction regions. The machine aperture limits and beam loss formation are analyzed. Simulation programs and a calculational model are described. The physics of beam scraping is explored, and measures to increase significantly the system efficiency are determined. A tolerable scraping rate, taking into account scraper material integrity, quench limits in downstream superconducting magnets, radiation shielding requirements, and minimal beam halo levels at the IPs are also determined. Finally, a complete multi-component scraper system in the SSC East Cluster is proposed.

Throughout the paper we define a scraper as a primary absorber consisting of precise movable jaws that have a flat inner edge along the circulating beam and which may be forced to touch the beam halo in horizontal or vertical planes. Secondary absorbers—collimators—are destined to intercept outscattered protons and other particles produced in scraper material. All these are surrounded with a radiation shielding.

2.0 BEAM RELATED PARAMETERS

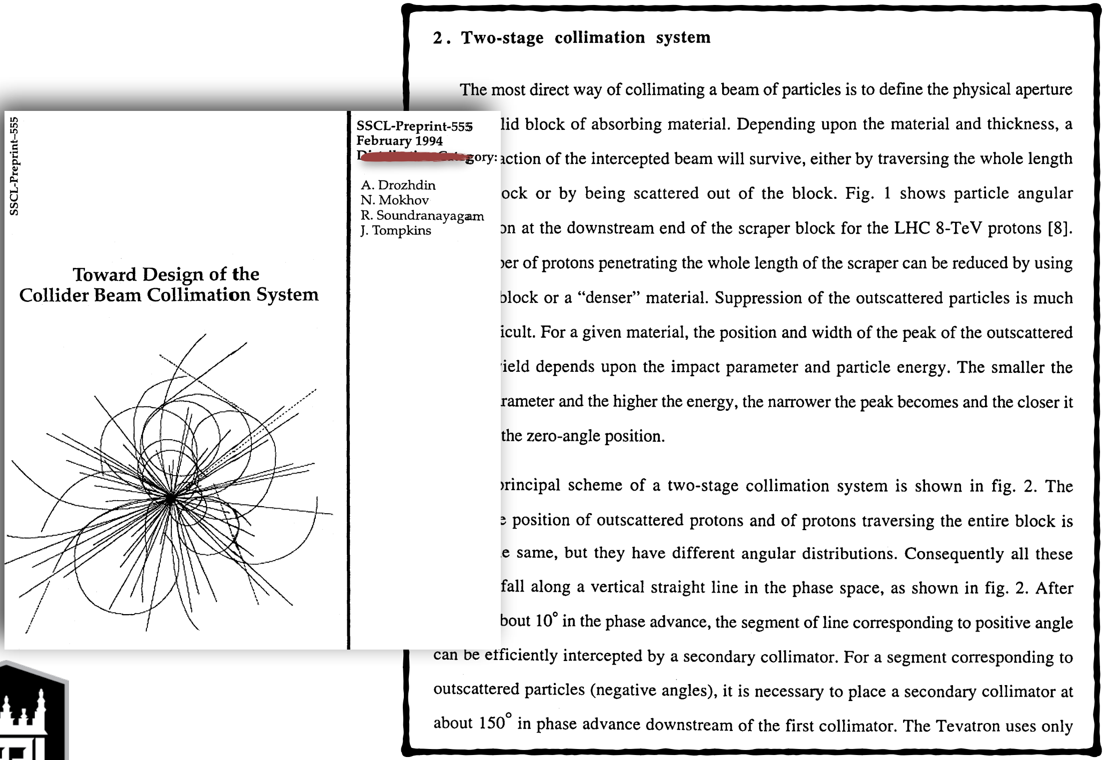
Basic SSC parameters[1] related to the considered problem are listed in Tables 1 and 2. The number of protons circulating in each of the Collider rings is 1.3×10^{14}. The dipole aperture is 50 mm, and the beam pipe diameter is 40 mm. Dispersion and β-functions for the East Utility



ure 4. Dynamics of Beam Halo-Scraper Interaction: 1) Beam Lead Up to the Scraper (Solid); 2) Large Amplitude Protons (Long Dash); 3) Off-Momentum Protons (Short Dash).

Introduction of a "2-Stage" Collimator System

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



SSCL-Preprint-555

SSCL-Preprint-555
February 1994
D[redacted]gory:

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].
er 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
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

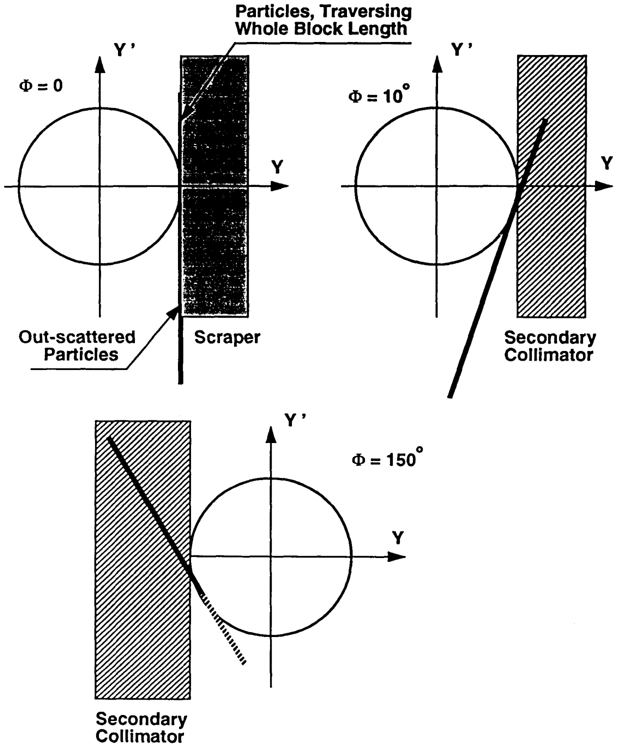


Fig. 2. Principal scheme of a two-stage collimation system.

SSC Beam Cleaning

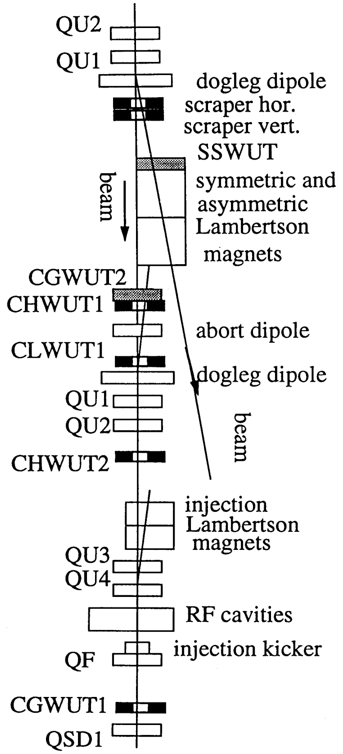


Fig. 8. Scraper and collimator positions in the Collider West Utility.

The SSC Beam Scraper System

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

June 1991

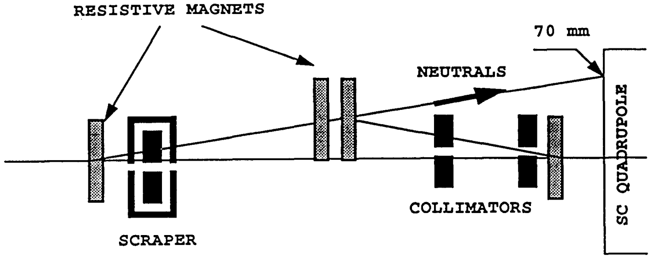


Fig. 19. Principal scheme of beam cleaning for off-momentum protons in the East Utility.

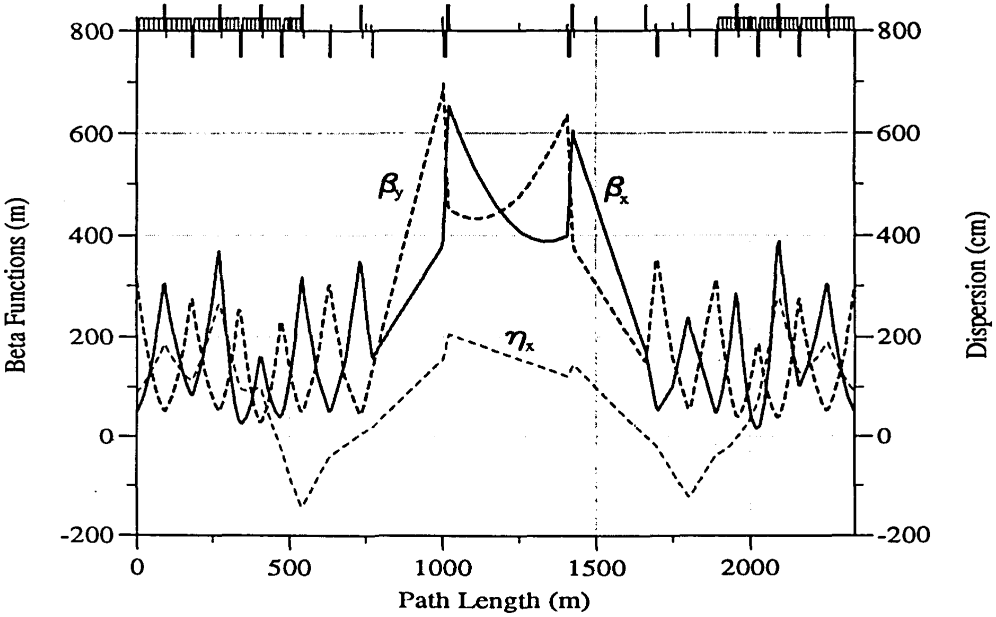


Fig. 18. Lattice functions in the East Utility.

This was the era in which beam optics designs tailored to collimation system started to be investigated, and in which suitable materials were more thoroughly explored.

Much of this work came near the ***end*** of the project, hence were not flushed out entirely.

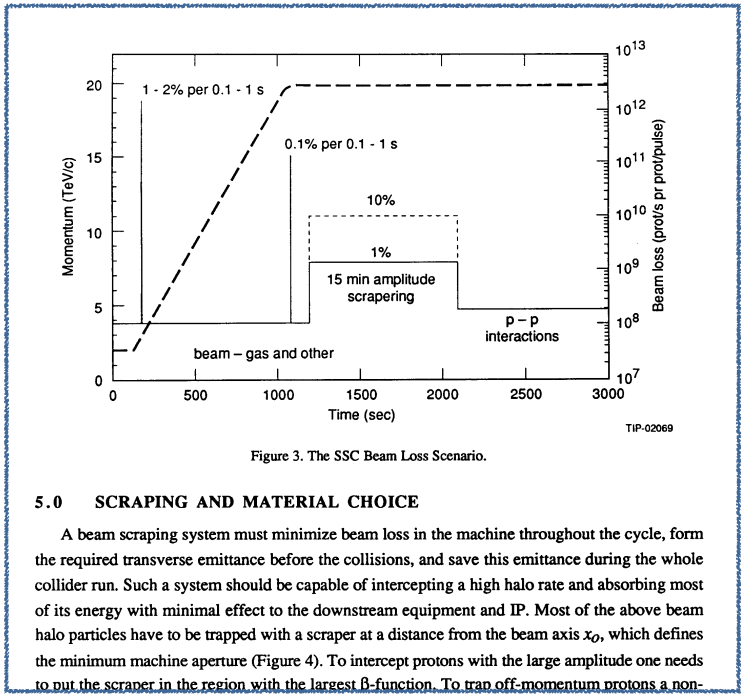


Figure 3. The SSC Beam Loss Scenario.

5.0 SCRAPING AND MATERIAL CHOICE

A beam scraping system must minimize beam loss in the machine throughout the cycle, form the required transverse emittance before the collisions, and save this emittance during the whole collider run. Such a system should be capable of intercepting a high halo rate and absorbing most of its energy with minimal effect to the downstream equipment and IP. Most of the above beam halo particles have to be trapped with a scraper at a distance from the beam axis x_0, which defines the minimum machine aperture (Figure 4). To intercept protons with the large amplitude one needs to put the scraper in the region with the largest β-function. To trap off-momentum protons a non-

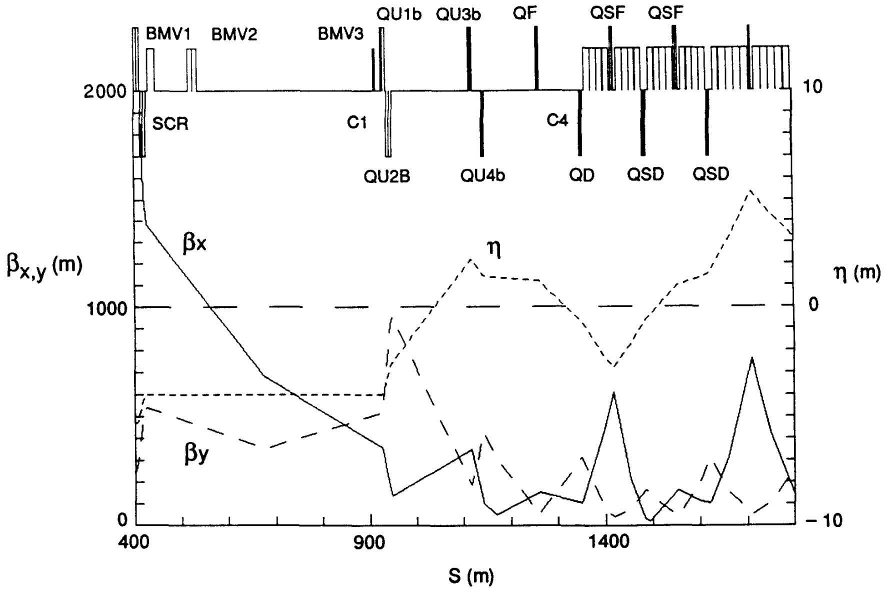


Figure 26. Lattice Functions and Schematic Magnet Layout for an East Utility Straight Section Scraper System.

Table 11. Scraper System Parameters: Dogleg Magnets.

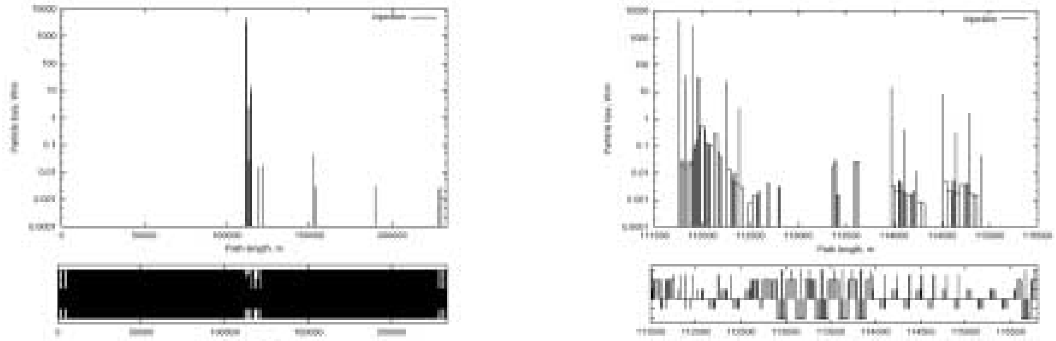
No.	Element	S (m)	L (m)	B (kG)
Asymmetric Dogleg				
1	BM1	426.5	15	–20
2	BM2	521.0	20	+20
3	BM3	916.5	5	–20
Dogleg with Lambertson				
1	BM1	428.5	27.5	–17.1
2	BM2	628.0	94.0	10.0
3	BM3	894.0	27.5	–17.1

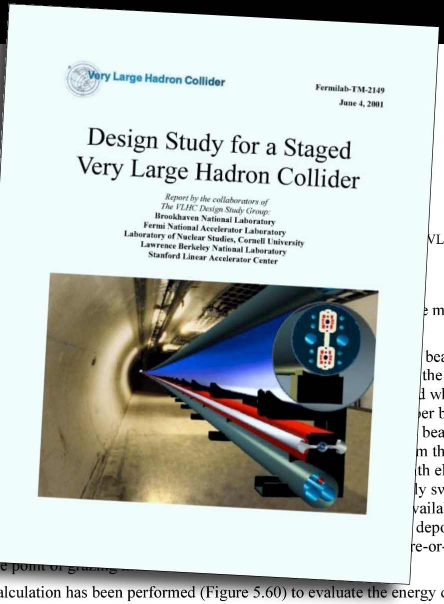
VLHC Collimation

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

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.




Very Large Hadron Collider

Fermilab-TM-2149
June 4, 2001

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

collateral dam … magnet. This
is not our bigg

A second … beam vaporizes
a small chann … the beam were
perfectly extr … d when the beam
is normally in … er block.
However at g … beam impact
point (due to … m the tunnel
wall. This sp … th electron
beams [100] … ly sweeps fresh
material acro … vailable to initiate
the shower, … deposition can
be calculated … re-or-less fixed
position near the point of grazing

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.

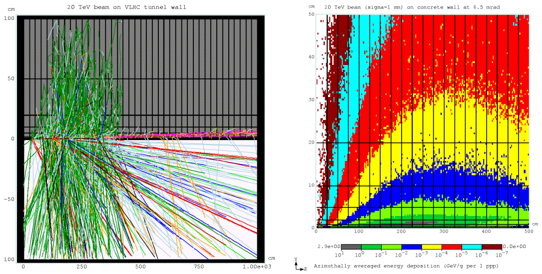


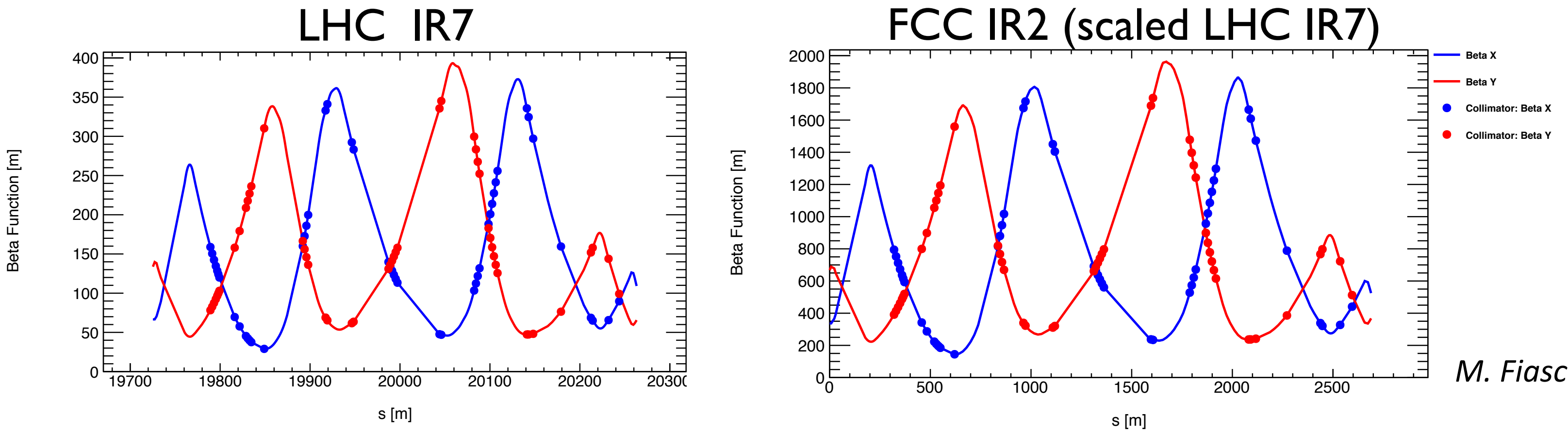
Figure 5.60. Stage-1 VLHC beam at 6.5 mrad grazing incidence on tunnel wall. The left picture shows particle tracks; the right picture is a map of energy deposition.

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

Lattice Design Investigations

- Looking at optical design options to enhance collimation and protection systems
- Betatron cleaning scales well from LHC; can always look for improvements

FCC betatron cleaning


LHC IR7

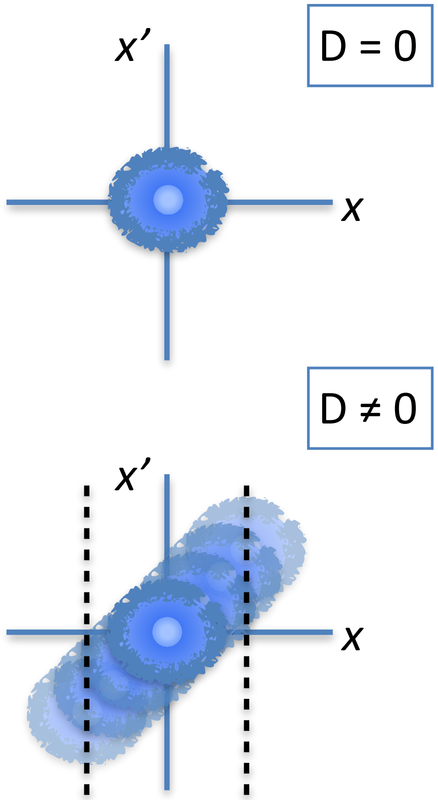
FCC IR2 (scaled LHC IR7)

M. Fiascaris, et al.

Lattice Design Investigations

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

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



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

Lattice Design Investigations

optimize $\frac{D}{\sqrt{\beta}}$

- Create insertion with
  - “low-beta” optics, and
  - larger dispersion

Suppose want

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

Then, for FCC 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,

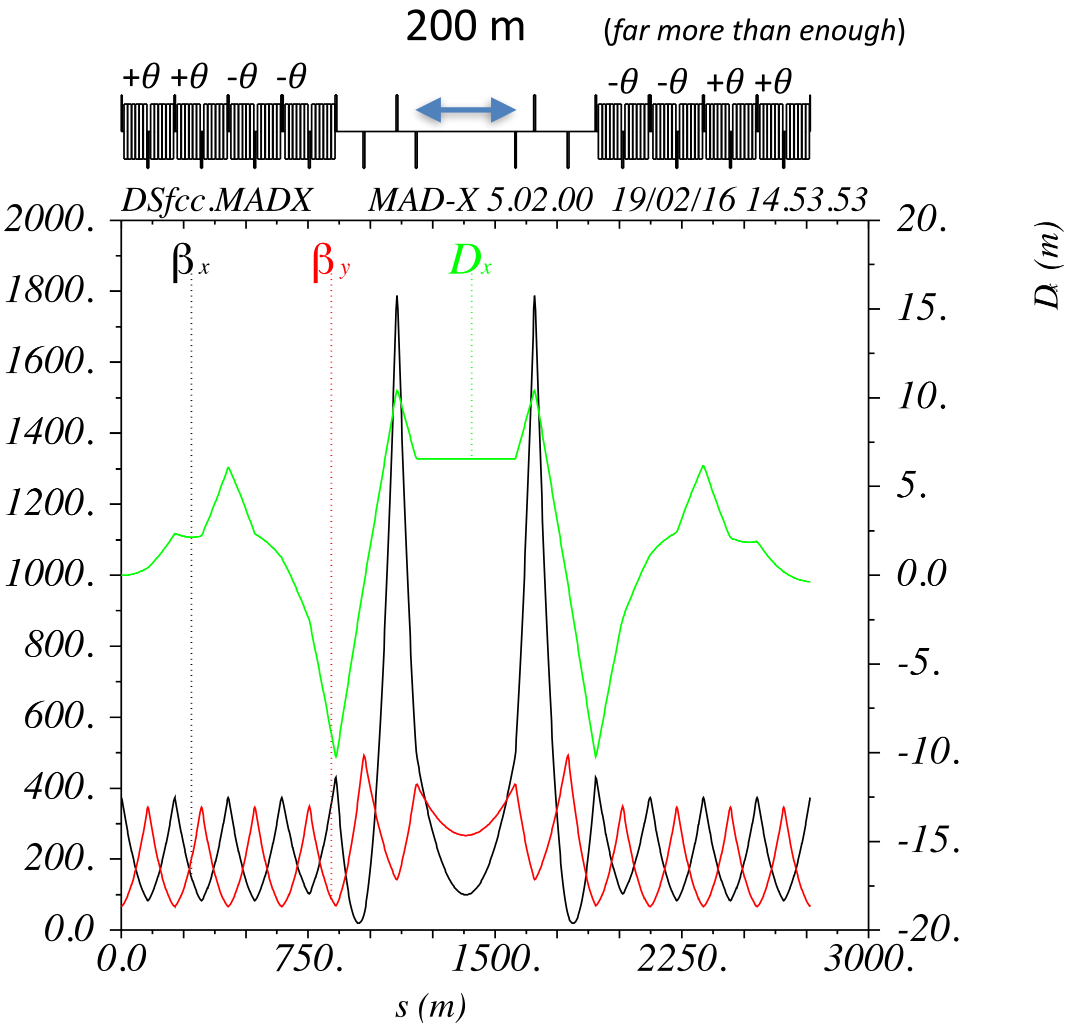
$$\frac{D^2}{\beta} = \frac{D^{*2}}{\beta^*}\ \underline{\frac{1}{1+(s/\beta^*)^2}}$$

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

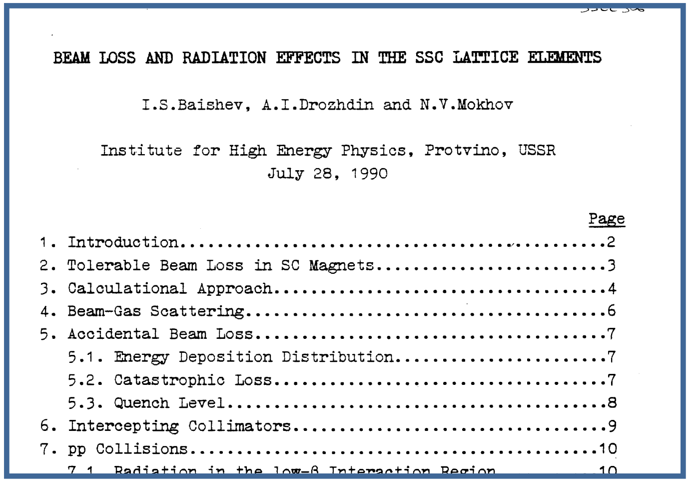
Lattice Design Investigations

optimize $\frac{D}{\sqrt{\beta}}$

- Produce an insertion with "low-beta" optics ($\beta^* \sim 100$ m) and a larger dispersion ($D^* \sim 5\text{-}10$ m)
- Concept is still under investigation, including geometric implications, etc.



Early SSC "Accident" Calculations

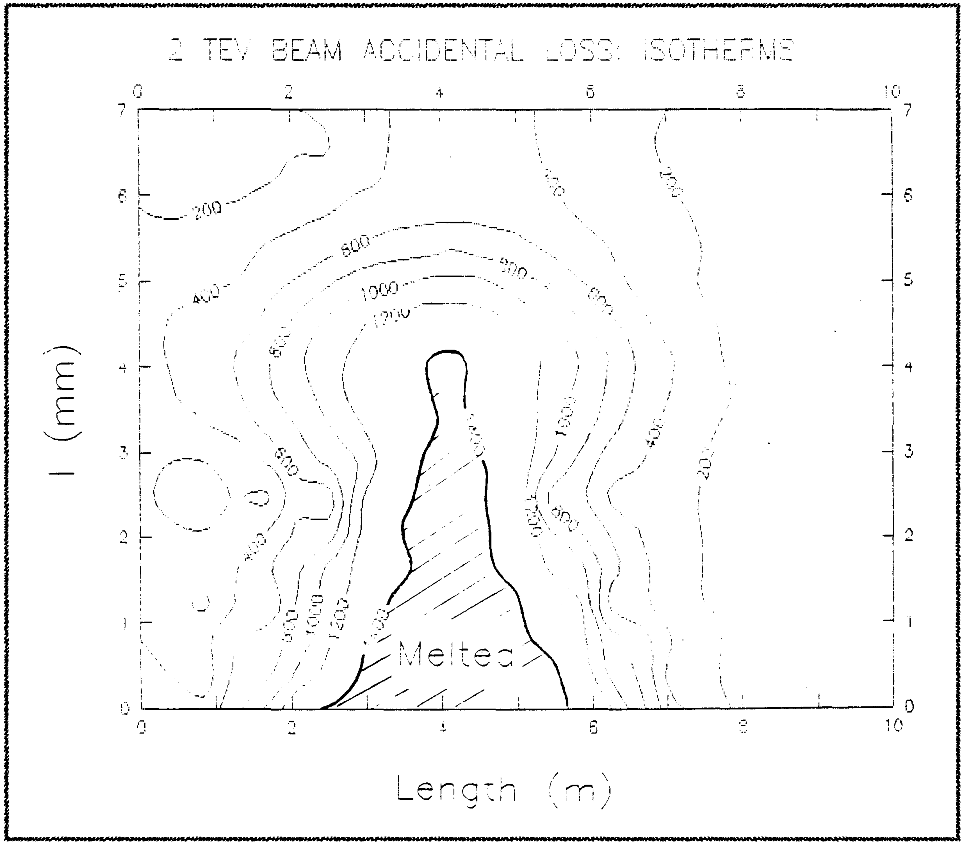


BEAM LOSS AND RADIATION EFFECTS IN THE SSC LATTICE ELEMENTS

I.S.Baishev, A.I.Drozhdin and N.V.Mokhov

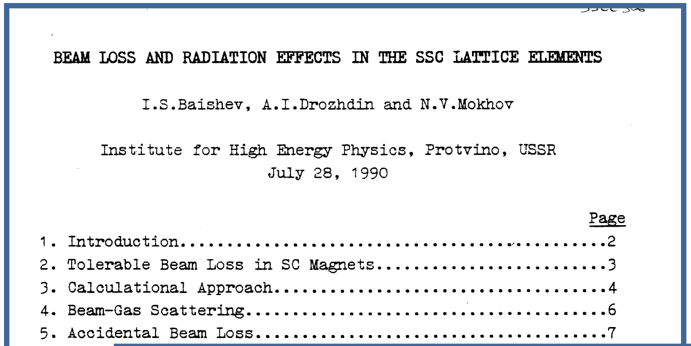
Institute for High Energy Physics, Protvino, USSR
July 28, 1990

Page



~40 MJ in this calculation

Early SSC “Accident” Calculations



BEAM LOSS AND RADIATION EFFECTS IN THE SSC LATTICE ELEMENTS

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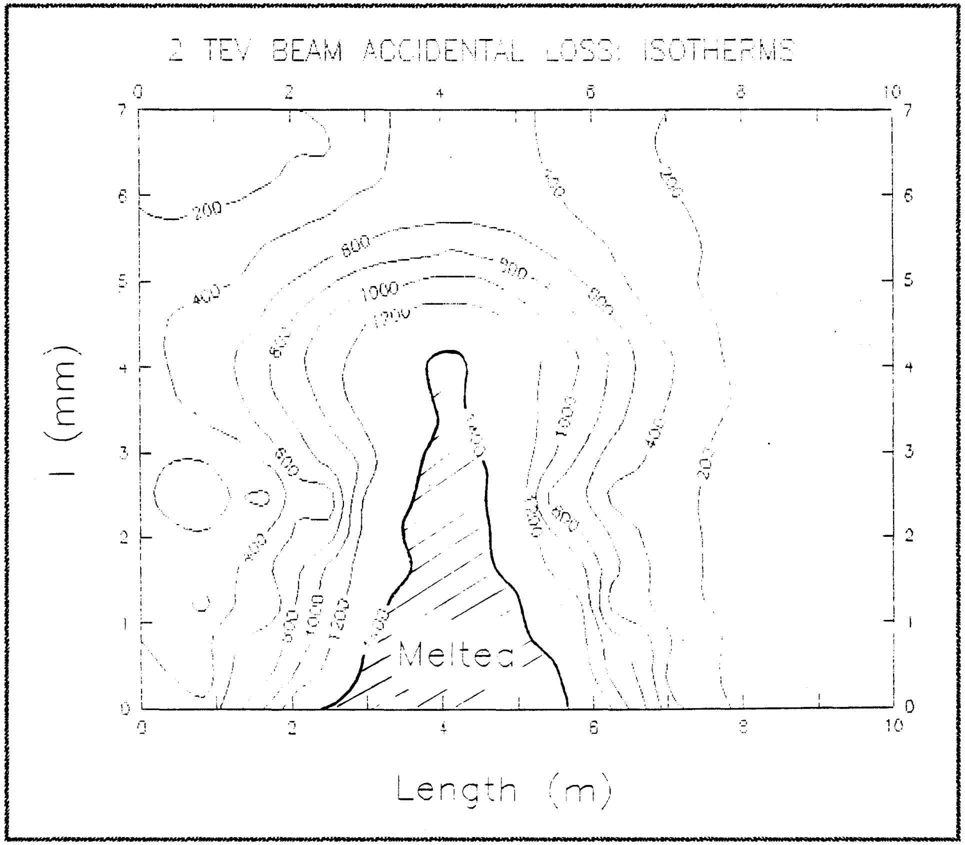
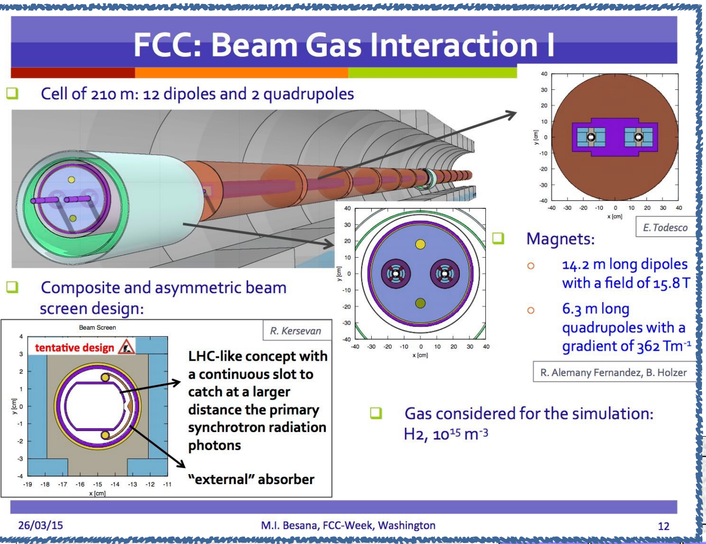
Tevatron Incident, 1 MJ, 2003



~40 MJ in this calculation

Energy Deposition Modeling (from *FCC Week 2015*)

M. Besana



FCC: Beam Gas Interaction I

- ☐ Cell of 210 m: 12 dipoles and 2 quadrupoles
- ☐ Composite and asymmetric beam screen design:

Beam Screen

tentative design

R. Kersevan

LHC-like concept with a continuous slot to catch at a larger distance the primary synchrotron radiation photons

"external" absorber

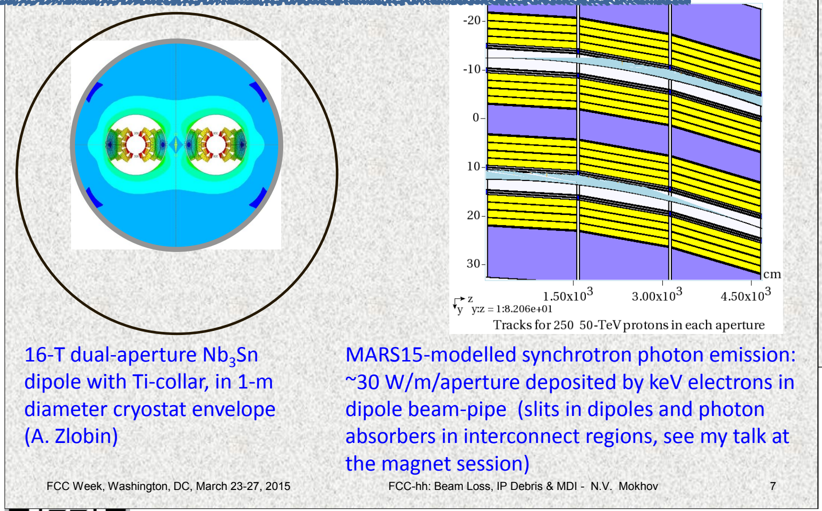
- ☐ Magnets:
  - ○ 14.2 m long dipoles with a field of 15.8 T
  - ○ 6.3 m long quadrupoles with a gradient of 362 Tm^{-1}

E. Todesco

R. Alemany Fernandez, B. Holzer

- ☐ Gas considered for the simulation: H_2, 10^{15} m^{-3}

26/03/15 M.I. Besana, FCC-Week, Washington 12

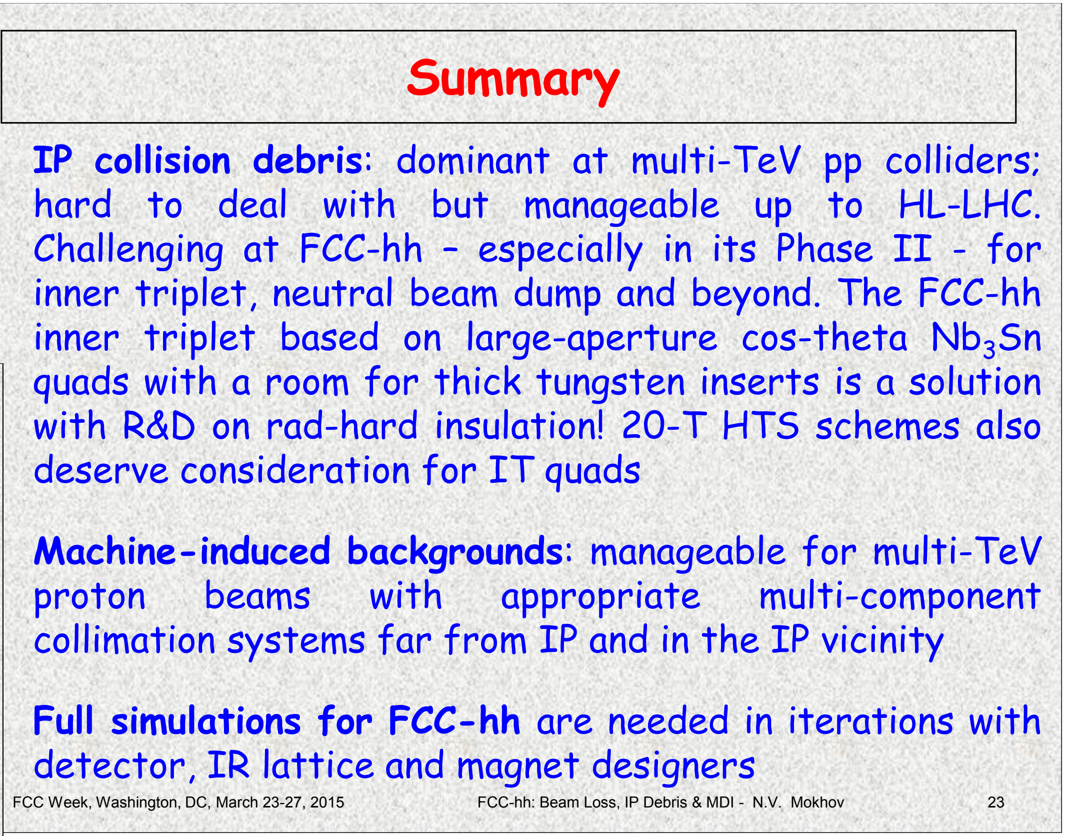


Tracks for 250 50-TeV protons in each aperture

16-T dual-aperture Nb_3Sn dipole with Ti-collar, in 1-m diameter cryostat envelope (A. Zlobin)

MARS15-modelled synchrotron photon emission: ~30 W/m/aperture deposited by keV electrons in dipole beam-pipe (slits in dipoles and photon absorbers in interconnect regions, see my talk at the magnet session)

FCC Week, Washington, DC, March 23-27, 2015 FCC-hh: Beam Loss, IP Debris & MDI - N.V. Mokhov 7



Summary

- **IP collision debris**: dominant at multi-TeV pp colliders; hard to deal with but manageable up to HL-LHC. Challenging at FCC-hh – especially in its Phase II - for inner triplet, neutral beam dump and beyond. The FCC-hh inner triplet based on large-aperture cos-theta Nb_3Sn quads with a room for thick tungsten inserts is a solution with R&D on rad-hard insulation! 20-T HTS schemes also deserve consideration for IT quads

  Machine-induced backgrounds: manageable for multi-TeV proton beams with appropriate multi-component collimation systems far from IP and in the IP vicinity

  Full simulations for FCC-hh are needed in iterations with detector, IR lattice and magnet designers

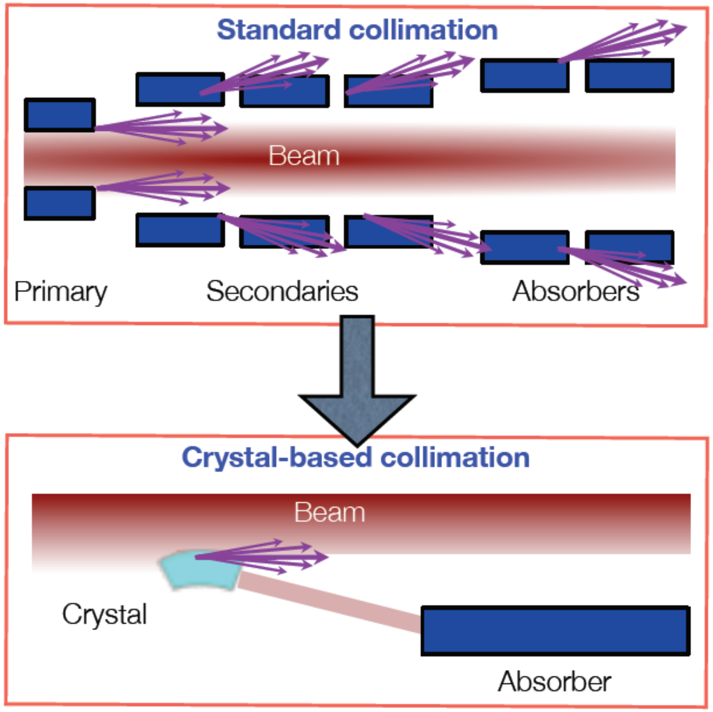
FCC Week, Washington, DC, March 23-27, 2015 FCC-hh: Beam Loss, IP Debris & MDI - N.V. Mokhov 23

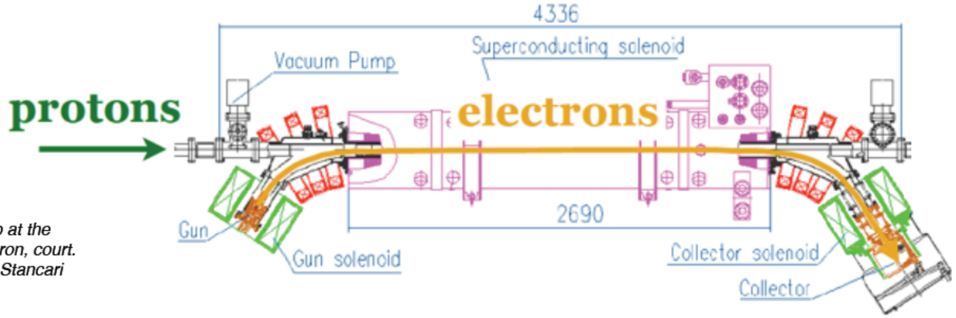
N. Mokhov

FCC Beam Collimation

LHC-type solution, but other solutions should be investigated

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





Setup at the Tevatron, court. of G. Stancari

Summary & Outlook

- Future Work in the US
    - optical layout, especially regarding momentum collimation
    - further MARS development
    - Investigations into fault scenarios and multiple stages of collimation
    - explorations into alternative methods (e-lenses, etc.)
- U.S. has been at frontline of energy deposition calculations and simulations for many decades; desire is to contribute further to future collider efforts at the energy frontier

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.

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Many thanks to Nikolai Mokhov for input and for the documents list!