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# Ionizing Radiation Dose in the SSC Dipole Magnet Correction Coils

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Energy deposition in SSC dipoles due to beam loss around the ring has been simulated by Alberto Fassò, using the CERN cascade simulation program FLUKA. Only very early results are available at this time. They have yet to be checked, the model (first collision on the beam pipe rather than on-axis on the gas) is not quite appropriate, and correction coil dose must be inferred from the dose in the nearby main superconducting coils. With these caveats and with an assumed loss rate of $3.7 \times 10^{15}$ protons/year for 30 years, the maximum dose in the correction coils is 1 MGy.

## 1. Introduction

During his one-month visit with the SSC last fall, Alberto Fassò (CERN) worked on a Monte Carlo simulation of beam loss in SSC magnets, with particular emphasis on the peak energy deposition in the superconducting coils. There were some formidable program bugs in the newly upgraded version of FLUKA, as well as technical obstacles special to this problem. Everything started working (we think) just before Christmas, during the last week of his stay, and first results were obtained. A great many checks remain to be made, and the problem needs to be modified somewhat to answer our specific questions.

A detailed discussion of the work will appear under Fassò's name in the near future, after the appropriate checks and modifications have been made. However, there is some urgency to understanding the radiation environment of the correction coils, in connection with the *SSC Workshop on Distributed Multipole Correction Coils*,* and I attempt in this Note to interpret Alberto's results for the needs of the Workshop.

## 2. The Model

Calculations were made with the current version of FLUKA, using a cylindrically symmetric idealization of an SSC dipole. The model is shown in Fig. 1, and parameters (radii, composition, densities) are given in Appendix 1, which is a note from Alberto to me summarizing what he had done.

The modelling combined cylindrical geometry ($r$, $z$; no $\theta$) with "combinatorial" geometry, which permitted superposition of a rectangular grid. Experiments

* SSC Central Design Group report SSC-SR-1032, R. Sah, Ed., (1988).

were made to establish the necessary bin size. As it turned out, the radial dependence of the dominant electromagnetic part of the cascade was so steep that 1 mm $\times$ 1 mm binning was necessary. The $z$ binning for the results reported here was 1 cm. To save computing time, results were scored only over the rectangle shown in Fig. 1.

20 TeV protons struck the beam pipe at grazing incidence, so that the cascade originated in the beam pipe. A vertical 6.6 T magnetic field (uniform over the entire rectangle!) bent the charged particles to the right or left, so that they cascaded in the magnet structure in roughly the horizontal plane. Graphics output is available for longitudinal bins near shower maximum in this plane.

For purposes of the Workshop report, on-axis collisions with residual gas would be more appropriate. Since vertical spreading would be greater in this case, the radiation density would be lower that is indicated by the present results. Beam-gas collisions have high priority for the next round of simulations.

Substantial radiation densities occurred only in the superconducting coils, and only data for this region is available. Within 50%, $dE/dx$ is the same in the correction coils and main coils when expressed in MeV/(g cm$^{-1}$), so, if the density of shower electrons bent into the correction coil region is comparable to that in the first radial bin of the copper, the dose expressed in energy per unit mass will be the same. In any case, the dose in the first bin in the copper coil provides an upper limit.

### 3. Results

Fig. 2 shows the energy density in the innermost coil bin as a function of longitudinal distance ($z$) from the impact point. The scatter results from the extremely small bin size, but in exchange the large number of points defines the shape rather well. I have hand-drawn three straight lines on the plot in order to estimate the area, which is needed to interpret the results. The final segment has a rather ill-defined slope, and the integral under this segment must be taken to $z = \infty$. Fortunately, the area under this part is only about 15% of the total. I estimate that the slope uncertainty contributes at most about 10% uncertainty to the total, which is 3650 GeV cm$^{-2}$ for this bin. The overall uncertainty is about 15%.

The maximum occurs $\sim$ 40 cm from the cascade origin. An example of a radial distribution near the maximum (for $z$ = 38.5 cm) is shown in Fig. 3. Typically, the first bin receives the largest dose.

## 4. Interpretation

1. Following the argument given elsewhere,* the *average* energy density at the inside edge of the coil from the loss of a proton anywhere in the ring is $(3650 \text{ GeV cm}^{-2})/(83 \text{ km}) = 4.40 \times 10^{-4} \text{ GeV cm}^{-3}$.

2. We assume a current lifetime against beam-gas loss of 300 hr, and a stored beam containing $4 \times 10^{14}$ protons. The loss rate under these conditions is then $4 \times 10^{14}/300 \text{ hr} = 3.7 \times 10^{8} \text{ sec}^{-1}$.

   Note that this current is three times the design current, and so represents a conservative worst-case estimate. We will assume below that this current is present for an average of $10^7 \text{ s yr}^{-1}$, or that $3.7 \times 10^{15}$ protons collide with gas in the beam pipe every year.

3. The average energy deposition is then $1.63 \times 10^{5} \text{ GeV cm}^{-3}\text{s}^{-1}$.

4. Multiplying by $1.6 \times 10^{-10}$ to convert GeV to joules and dividing by $\rho = 7.0$ to convert $\text{cm}^{-3}$ to $\text{g}^{-1}$, we obtain

$$3.72 \times 10^{-3} \frac{\text{J}}{\text{kg}} \text{s}^{-1} = 3.72 \times 10^{-3} \text{ Gy s}^{-1}$$

5. For an assumed $10^7$ second year at this current, the dose is $3.72 \times 10^{4}$ Gy, or 1.1 MGy over a 30-year lifetime.

We once again emphasize that this estimate is for the inner edge of the superconducting coil and represents an upper limit for the correction coils, that on-axis production should result in some reduction, and that the preliminary simulation results have not yet been adequately verified.

* T. A. Gabriel, F. S. Alsmiller, R. G. Alsmiller, Jr., B. L Bishop, O. W. Hermann, and D. E. Groom, "Preliminary Simulation of the Neutron Flux Levels in the Fermilab Tunnel and Proposed SSC Tunnel," SSC Central Design Group Report SSC-110 (1987).

A. Fassò Dec. 22, 1987

## ENERGY DEPOSITION CALCULATIONS IN SSC DIPOLE COILS
First results

### 1. Geometry

The dipole has been described geometrically by 7 concentric cylinders. Although cylindrical R-Z geometry would have been sufficient for that purpose, I have preferred combinatorial geometry because it leaves the possibility open for a more detailed description if necessary. Also, combinatorial geometry has allowed me to "cut out" a portion of the structure by including it in a "box". In this first series of computer runs, particles have been tracked only inside the box, all histories being terminated when crossing its boundaries. This approximation should not affect the results by more than a few percent (although this has still to be confirmed), but reduces computer time considerably.
In the next runs, I plan to increase the box size: if non negligible differences are found, the whole dipole can eventually be included.
The geometry and the box are displayed in Fig. 1

The cylinder's length was 11 m (10 downstream the proton impact point and one upstream). The radial configuration was as follows:

0 to 1.693 cm: vacuum
1.693 to 1.727 cm: nitronic (Mn 9%, Cr 20.3%, Ni 6.5%, Fe 64.2% - density 7.83 g/cm3)
1.727 to 2.000 cm: spacer (C 21.7%, O 72.3%, Cu 6% - density 0.76 g/cm3)
2.000 to 2.974 cm: first coil (Cu - density 7.0 g/cm3)
2.974 to 4.019 cm: second coil (" " " " )
4.019 to 5.558 cm: nitronic
5.558 to 13.81 cm: iron (Fe - density 7.83 g/cm3)
a further cylinder (a "blackhole") surrounded the above structure, as required by combinatorial geometry conventions.

### 2. Transport

Protons of 20 TeV energy were assumed to impinge on the internal surface of the nitronic vacuum chamber in the horizontal plane at an angle of 0.2 mrad. This angle has no particular justification: it is just what was used for LHC. That machine, however, has very different characteristics. It would be good to use a more realistic value when doing the final calculations.

The FLUKA87 program was used to simulate production and transport of hadrons and muons, with the usual cut-off at 50 MeV kinetic energy. Multiple scattering was not considered for those particles: I have found confirmation that the existing code contains an error in the part dealing with that effect (as already pointed out by some users).
Rather than trying to correct it, I have started preparing a new version, based on the NSW theory of Nigam, Sundaresan and Wu as modified by Marion and Zimmerman (Nig59, Mar67). That should lead to a more accurate treatment, while at the same time saving computer time. In fact, the Marion and Zimmerman version of the theory allows one to sample the random scattering angle from a distribution depending on a single





adimensional parameter, what can be efficiently made by table look-up. The work on this part is near to completion: I have managed to reproduce the numerical values of the distribution published by Marion and Zimmerman, but I have not yet done the integration necessary for Monte Carlo sampling. For this reason, the effect was not considered in the present calculations.

Electrons and photons were transported by EGS4. A cross section data set has been prepared by the pre-processor PEGS for the materials listed above. A cutoff of 1 MeV (total energy) for electrons and 0.1 MeV for photons was applied.

A 6.6 T vertical magnetic field has been assumed everywhere (directed downwards - the beam grazing the external part of the vacuum chamber).
A different algorithm for tracking in the magnetic field has been used in FLUKA and EGS.

FLUKA uses the exact solution of the Lorentz force differential equation and transports the charged particles on their actual curved path. A surface boundary crossing point is found by iteration. The particle energy is assumed constant along each step, whose size is determined by the ionization step length requested in input.
No magnetic field option is available in the compiled version of EGS included in the FLUKA package; however, an example of implementation is given in the EGS manual for the simple case, identical to the one of interest here, of a uniform magnetic field aligned with one of the axes. The successive positions of the particle are calculated correctly, but transport is performed in many small rectilinear steps and boundary crossing takes place in the usual way (intersection of a straight line with a body surface).

Either method has its advantages in different circumstances: FLUKA can be faster in vacuum or in regions where no detailed energy binning is required, while the technique suggested for EGS works better in problems with many boundaries close in space. Since it is not clear which one should preferred in the present case, both schemes have been kept. The results should not be affected by this choice, since for very small steps (0.5 mm here) they should be regarded as equivalent. In further calculations, however, it may be worth investigating their relative efficiency.

### 3. Scoring

Energy deposition has been scored in rectangular volume bins 1 cm long in the longitudinal direction, and 1 mm in the radial and in the vertical direction. The whole bin array included 300 bins longitudinally (in total 3 m from the proton impact point), 20 radially (in total 2 cm from the inner coil surface) and 2 vertically (plus or minus 1 mm from the horizontal plane).

### 4. Biasing

The leading particle biasing option was applied in EGS, i.e. only one particle was followed out of two left after each interaction. Higher energy particles are preferentially selected, and their weights properly adjusted.
A similar technique is available in FLUKA, where two particles are kept after each interaction, the so-called leading particle (of highest

energy) and one of the other secondaries selected randomly with a probability proportional to its energy. This scheme, particularly appropriate for deep shielding calculations, was found too crude for the present problem; on the other hand, a complete analog simulation of a 20 TeV cascade would take much computer time even within the reduced geometry described above. A compromise was found in rejecting each secondary (leading particle excluded) with a 50% probability. At very high energy, several tens of particles are still selected per event, thus insuring that all kind of particles are correctly represented, but computer time per incident proton is considerably decreased. To reduce fluctuations, the weight of the particles retained has been adjusted so that energy is conserved not only on average, but also on an event-by-event basis. This technique seems to give good results, but more tests must be done by comparing with full analog calculations (possibly at lower energies), to make sure that no significant bias can affect the results.

## 5. Results

Fig. 2 shows the longitudinal dose distribution in the innermost radial bin, 1 mm from the inner surface of the coil. The values refer to one incident proton. The error bars show the spread (standard deviation of the mean) in a set of 12 30 min runs on the IBM 3081. Each run provides two equivalent distributions (upper and lower vertical bin).
The following figures show the radial distribution at selected longitudinal depths (with more detail in the peak region 30 to 50 cm from the impact point.

## 6. Future calculations

These results should be regarded only as preliminary. More calculations are needed to validate the different approximations and biasing schemes applied. Magnetic field transport must be improved and tested more thoroughly (also by graphical means). In particular, it is necessary to confirm that the large number of low-energy electrons rejected by the geometry routines is not affecting the results in a significant way. Once these points have been clarified, a high-statistics set of computer runs can be made. However, it would be advisable beforehand to better define the problem: what loss scenario do we want to simulate? What information do we want to extract from FLUKA output in addition to that presented here?

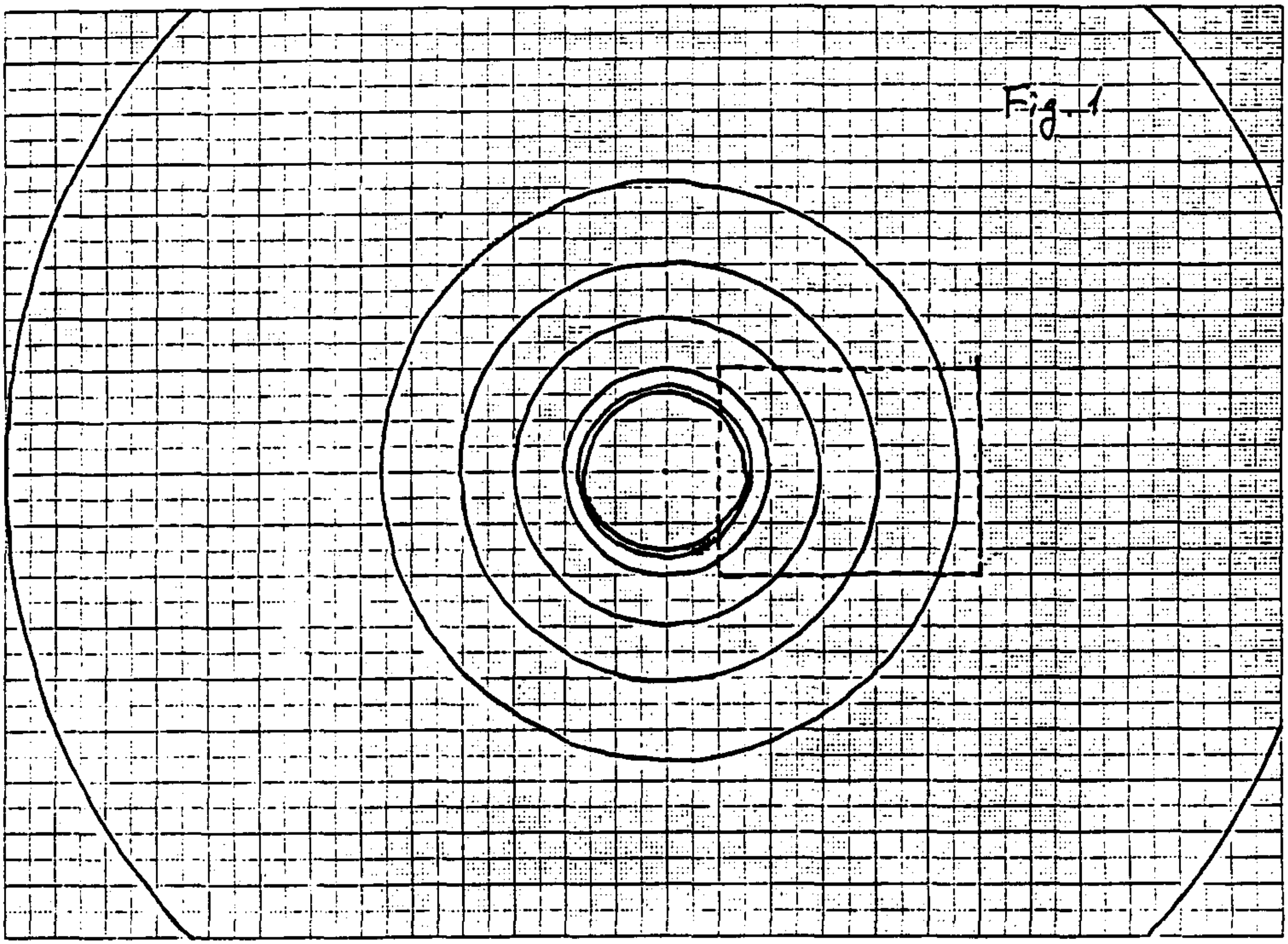


FIG. 1. Cylindrical idealization of SSC dipole discussed in Appendix 1.

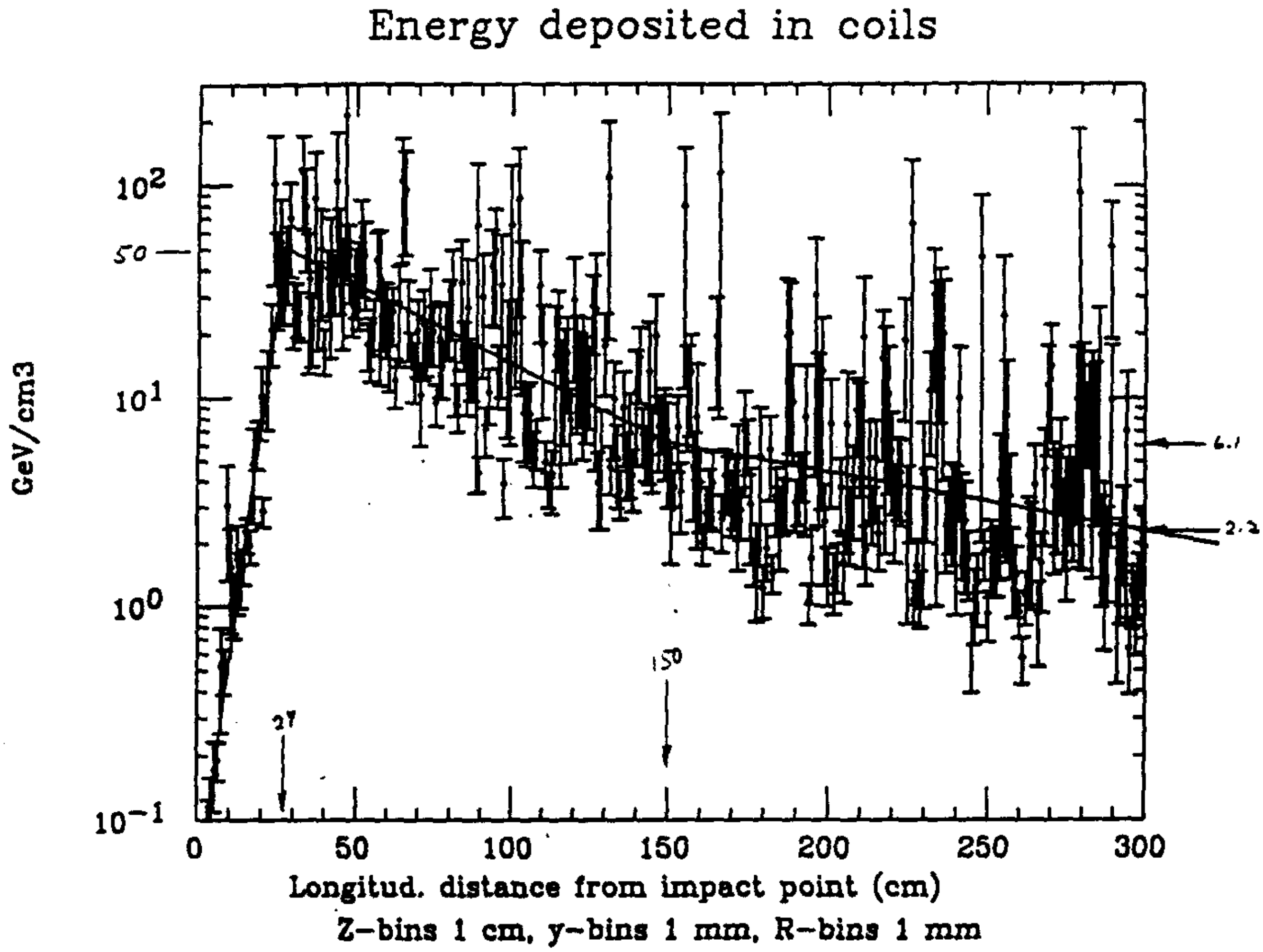


FIG. 2. Longitudinal distribution of energy deposition in innermost radial bin in the central plane of SSC dipole coils.

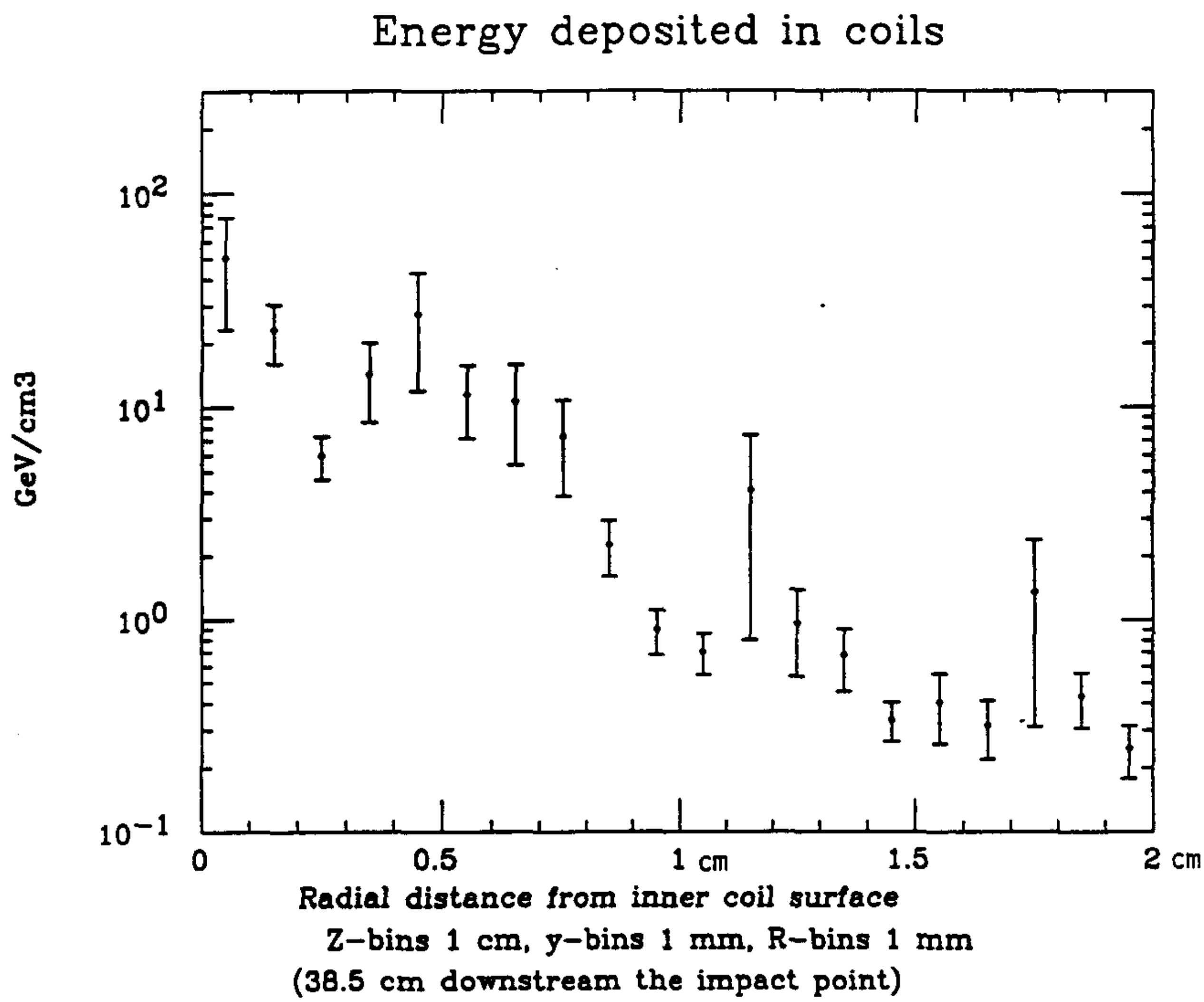


FIG. 3. Radial distribution of energy deposition in central plane of SSC dipole coils near cascade maximum.