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Beam-Induced Energy Deposition in a LHC Quadrupole Magnet

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Abstract

We present the results of a simulation of the energy deposition in a low-beta superconducting quadrupole magnet in the Large Hadron Collider (LHC). The dependence of the energy deposition was studied in the inner quadrupole-triplet system on the LHC. Monte-Carlo simulations were performed using PYTHIA to generate 7 TeV × 7 TeV proton-proton events and GEANT(+FULKA) to follow hadronic and electromagnetic cascades. The total energy deposition in the inner quadrupole-triplet system was 17% of a 7-TeV proton. The average energy depositon per unit length was 8.8 W/m in the inner quadruple-triplet system. The maximum energy deposition density was 8 mW/cm^3, which was reduced to about 50% by increasing the beam pipe wall thickness by 5 mm. The energy deposition due to the beam-gas interaction was indicated to be negligible compared to the effect of the beam-beam interaction under the normal operating condition.

1 Introduction

High-energy accelerator superconducting magnets are occasionally subjected to beam-induced quenches. In order to avoid beam-induced quenches, an estimation of the energy deposition in the coils is important. The LHC is designed to provide proton-proton collisions at $E_{\rm CM}$=14 TeV and $L = 1.65\times10^{34}$ cm^{-2}s^{-1}[1]. The circulating current per beam is 0.56 A, and the designed value of the vacuum is 10^{-9} Torr. In the LHC energy deposition was mainly induced by secondary particles at an interaction point and beam loss with a beam-gas interaction. The increasing refrigerator heat load causes a rising temperature in the superconducting magnet coil and induces quenches. At the closest regions to the interaction point, very strong low-beta superconducting quadrupole triplet magnets will be installed in order to obtain a large luminosity. Therefore, it is very important to estimate the energy deposition in the superconducting coils. We have carried out an estimation of the energy deposition using well-known computer codes, PYTHIA[2] and GEANT[3]. The total cross-section and elastic cross-section were assumed to be 101.5 mb and 22.2 mb at

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E_{CM}=14 TeV, while in proton collisions with air the total cross-section was assumed to be 400 mb at E_{beam} = 7 TeV. This paper describes the simulation model, energy deposition under normal operating condition and a suggestion to reduce the energy deposition to the magnet system.

2 Computer Modelling

The LHC low-beta insertion region is shown in Fig.1. A model of the LHC inner quadrupole-triplet system is shown with the scale ratio $R : Z$ = 1:100. The closest magnet system to the interaction points is an inner triplet quadrupole system which consists of four identical superconducting high-gradient quadrupole magnets ($\partial B_x/\partial y = \partial B_y/\partial x$ = 235 T/m) with a coil inner diameter(d_{in}) of 7.0 cm and an outer diameter (d_{out}) of 18.4 cm, respectively. They are arranged as a focusing magnet (Q1 and Q4) and as a defocusing one (Q2 and Q3). The dipole magnet (D) is placed behind the triplet. A 2.0 m long copper absober is placed in front of the triplet. The proton-proton collisions and showers were simulated with the PYTHIA event generator and the GEANT code, respectively. The magnet coils were simulated as a homogenous material with copper (ρ= 8.93 g/cm^3). The parameters of the inner triplet for the simulation are given in Table 1. The quadrupole magnetic field was taken into consideration to calculate the circumferential dependence of the energy deposition.

Table 1: Size and field gradient of the Inner Triplet Quadrupole System

Model	Material	R_{in}(cm)	R_{out}(cm)	Z(m)
Coil	Cu	3.5	9.2	6.0×4
Yoke	Fe	9.2	23.5	6.0×4
Beam Pipe 1	Fe	1.4	1.5	—
Beam Pipe 2	Fe	2.05	2.3	—
Collimator	Cu	1.5	23.5	2.0

$\partial B_x/\partial y = \partial B_y/\partial x$ = 235 T/m

3 Results of Simulation

3.1 Beam-Beam Interaction

At the interaction point a beam-beam interaction was simulated using the PYTHIA event generator. An example event in the ATLAS detector generated by PYTHIA is shown in Fig.2. Also hadronic and electromagnetic cascades were calculated by GEANT(+FULKA). At E_{CM} = 14 TeV the cross-section was calculated to be σ_T =101.5 mb and the luminosity was calculated to be 1.65×10^{34} sec^{-1} in the LHC. Therefore, the total number of collisions was shown to be 1.67×10^9 sec^{-1}($N_T = L\ \sigma_T$). The parameters of the LHC are given in Table 2. The average energy deposition per event in the quadrupole magnet has been calculated and the z-dependence is shown in Fig.3. Also, the r-dependence of the energy deposition is shown in Fig.4. The azimuthal-angle dependence of the energy deposition has four peakes due to the quadrupole magnetic field, as shown in Fig.5. The maximum value of energy deposition in the superconducting coil was calculated in the shaded region shown in Fig.1. The total energy deposition in the inner triplet system was estimated to be 211 W. Thus, the average energy deposition per length is 8.8 W/m. The maximum energy depostion density is 8 mW/cm^3. For studying the effect of an internal absorber, the wall thickness of the beam pipe was varied. The result of the dependence on the wall thickness is shown in Fig.6. Increasing the wall thickness caused a reduction in the energy deposition. For example, we can reduce it by about 50% by increasing the wall thichness by 5 mm.

Table 2: LHC parameters

Proton-proton energy	$E_{CM} = 14$ TeV
Luminosity	$L = 1.65 \times 10^{34} cm^{-2}$
Proton-proton total cross-section	σ_T(p-p) = 101.5 mb
Beam energy	$E_{beam} = 7$ TeV
Circulating current per beam	$I_b = 0.53$ A
Proton flux	$n_p = 3.3 \times 10^{18}$ protons/sec
Vacuum	$P_{vac} = 10^{-9}$ Torr
Gas density	$\rho_{air} = 1.56 \times 10^{-15} g/cm^3$
Proton-air total cross-section	σ_T(p-air) = 400 mb

3.2 Beam-Gas Interaction

To study the beam-gas interaction, the energy deposition in the inner triplet system magnet was simulated with GEANT. The circulating current per beam was assumed to be 0.53 A with a 10^{-9} Torr vacuum. At $E_{\rm beam}$= 7 TeV, for the total cross-section of a proton in air 400 mb was used. Therefore, total-reaction number per meter is 8.5 $\times 10^4$ sec^{-1} m^{-1}. The total energy deposition with the beam directed from and to the interaction point was estimated to be 69×10^{-3} W and 61×10^{-3} W, respectively. The estimated energy deposition for one event is larger than one event of the beam-beam interaction. However, the accumulated energy deposition is smaller, because the event number is smaller than the beam-beam interaction. Comparing the energy deposition of 5 mW/m per event with the beam-beam interaction, we concluded that the value of the beam-gas interaction is negligible. Being cautions, the energy deposition with the beam-gas interaction was calculated assuming a pencil beam and a beam with a divegence of 36 μrad., as shown in Fig.7. The effect of the beam-gas interactions should be reduced with beam scrapers along the way.

4 Discussion

In the LEP collider, the beam-induced quench at the superconducting magnet was measured by a cryogenic microcalorimeter[4]. The experimental results indicated that induced quenches took place when the copper microcalorimeter received more than about 5 mJ/cm^3 within 300 ms. Our result of 8 mW/cm^3 for the maximum energy deposition is close to the quenching value for the superconducting magnet. It is suggested that absorbers might be necessary at the low-beta insertion region in the LHC. The effect of an absorber is big, because the incident particle trajectory has a long path length in the beam-pipe wall. The effect of a variable beam-pipe thickness is shown in Fig.6. To reduce the energy deposition in the superconducting magnet-coil, an internal absorber could be placed between the magnet coil and the beam pipe. Another problem is that there is a big uncertainty concerning the effect of the vacuum. When a particle hits the beam-pipe wall, the vacuum suddenly becomes worse, with gas evaporated from ice on the wall. It is clear that the energy deposition is proportional to the vacuum value. In this paper we can not estimate the effect, because it depends on the conditon of accelerator operation. In this simulation at $E_{\rm CM}$ = 14 TeV, we used a cut energy of 50 MeV, because the computer had a finite memory space. In the Tev energy region, a secondary particle could have a similar behaviour, except for the produced particle number. For testing this effect of the cut energy, a simulation at E_{CM} = 1 TeV was performed, as shown in Fig.8. The results indicate an increase of about 10% correction, where the cut energy changed to 1 MeV from 50 MeV. However we keep the value of energy deposition with no correction because there is more uncertainty concerning the geometry and reaction cross-section. A summary of results, the total energy deposition (Q_T), the average energy deposition per meter ($< Q/m >$) and maximum energy deposition density (q_{max}) are given in Table 3.

Table 3: Summary of the results

Thichness of the beam pipe	Q_T	$< Q/m >$	q_{max}
Beam-bean interaction			
2.5 mm	211 W	8.8 W/m	8.0 mW/cm^3
7.5 mm	123 W	5.1 W/m	3.1 mW/cm^3
Beam-gas interaction			
2.5 mm	131×10^{-3} W	5.5×10^{-3} W/m	—

5 Conclusions

For 7 TeV× 7 TeV proton-proton collisions at the LHC collider, the distribution of the energy deposition is shown in Fig.9. The energy balance for 7 TeV protons was 27% in the detector system including the collimator, 17% in the inner quadrupole-triplet system, and 42% in the dipole magnets behind the inner triplet system. Also the other parts are due to neutal particles escaping to the outside of the system. Due to the beam-beam interaction, the total energy deposition in the inner quadrupole-triplet system was 211 W. The average energy deposition per length was 8.8 W/m. Especially in the maximum energy deposition, the energy deposition density was about 8 mW/cm^3. This estimation suggests that some absorbers should be installed between the superconducting magnet and the beam pipe in order to reduce the effect of energy deposition. The amount of energy deposition was reduced to half the value by increasing the wall thickness of the vacuum pipe from 2.5 mm to 5.0 mm. With the beam-gas interaction, the total energy deposition was about 130 mW, which is negligible compared to those with the beam-beam interaction. The energy deposition in the beam-pipe wall is big, even if we take into consideration of a correction with cut energy. Therefore, this simulation suggests that the beam-pipe must also be cooled .

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References

[1] The LHC Study Group, The Large Hadron Collider Conceptual Design, CERN/AC/95-05(LHC)(1995).

[2] T. Jostrand, PYTHIA 5.7 and JETSET 7.4 Physics and Manual, CERN-TH. 112/93.

[3] Application Software Group, GEANT ver.3.21 CERN(1994).

[4] Ph. Lebrun, H. Blessing, T. Taylor and L. Walckiers, Cryogenic Microcalorimeter for Measurement of Energy Deposition by Beam Losses in Superconducting Accelerator Magnets, HEACC '92, Vol.2 p.592 Hamburg

Figure Caption

Fig.1 Inner triplet quadrupole system in the LHC. The shaded areas indicate the maximum energy-deposition region.

Fig.2 Example of an event in the ATLAS detector generated by PYTHIA.

Fig.3 Energy deposition per event vs Z in the Q-magnet. The shaded band corresponds to the maximum energy deposition area.

Fig.4 Energy deposition per event vs R in the Q-magnet.

Fig.5 Energy deposition per event vs ϕ in the Q-magnet.

Fig.6 Total energy deposition vs the beam pipe thickness.

Fig.7 Energy deposition vs the beam pipe length.

Fig.8 Ratio of the energy deposition vs cut energy at $E_{CM} = 1$ TeV.

Fig.9 Energy balance of 7 TeV $\times$ 7 TeV p-p collisions.

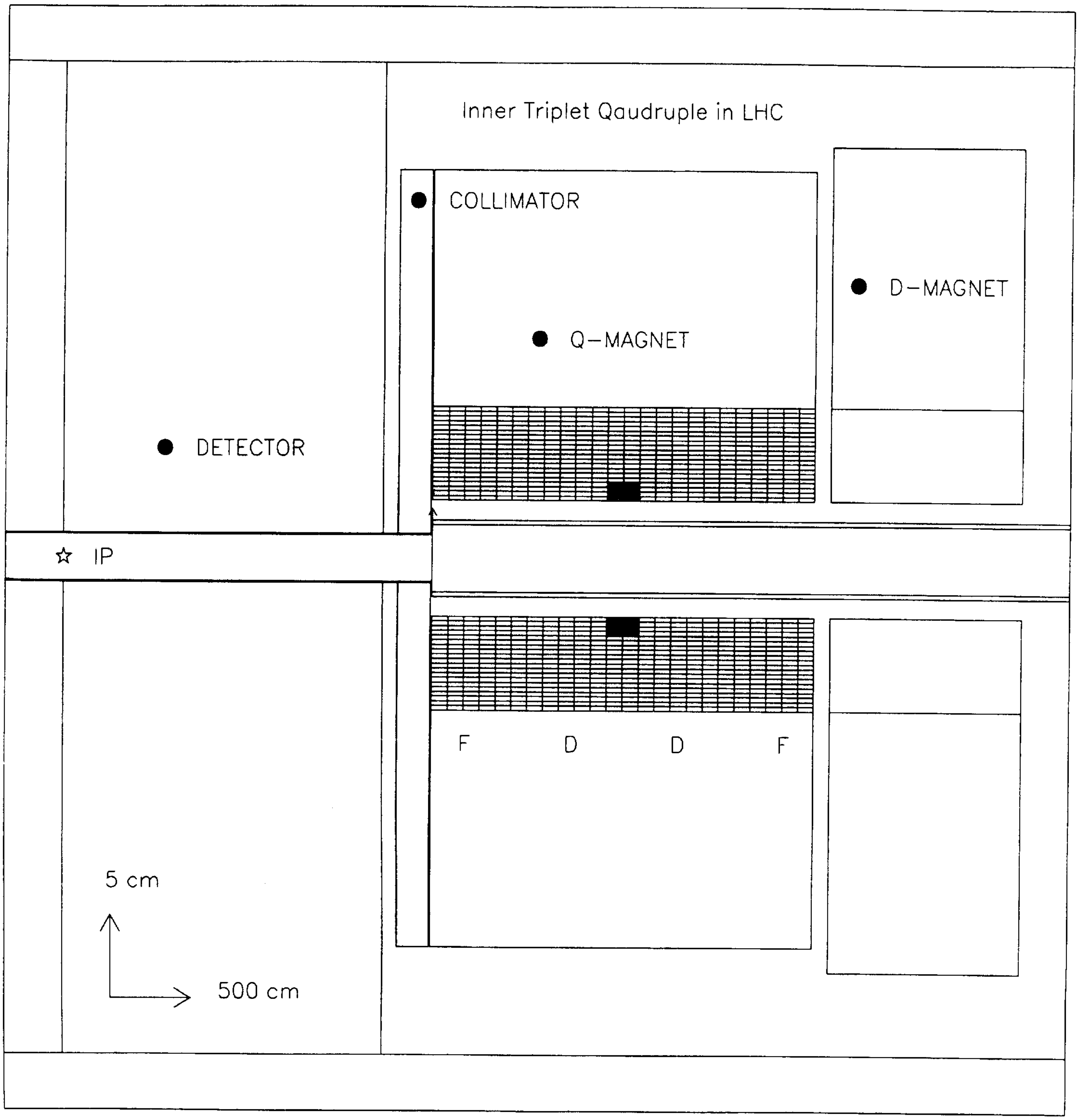

Fig.1 Inner triplet quadrupole system in the LHC. The shaded areas indicate maximum energy deposition region.

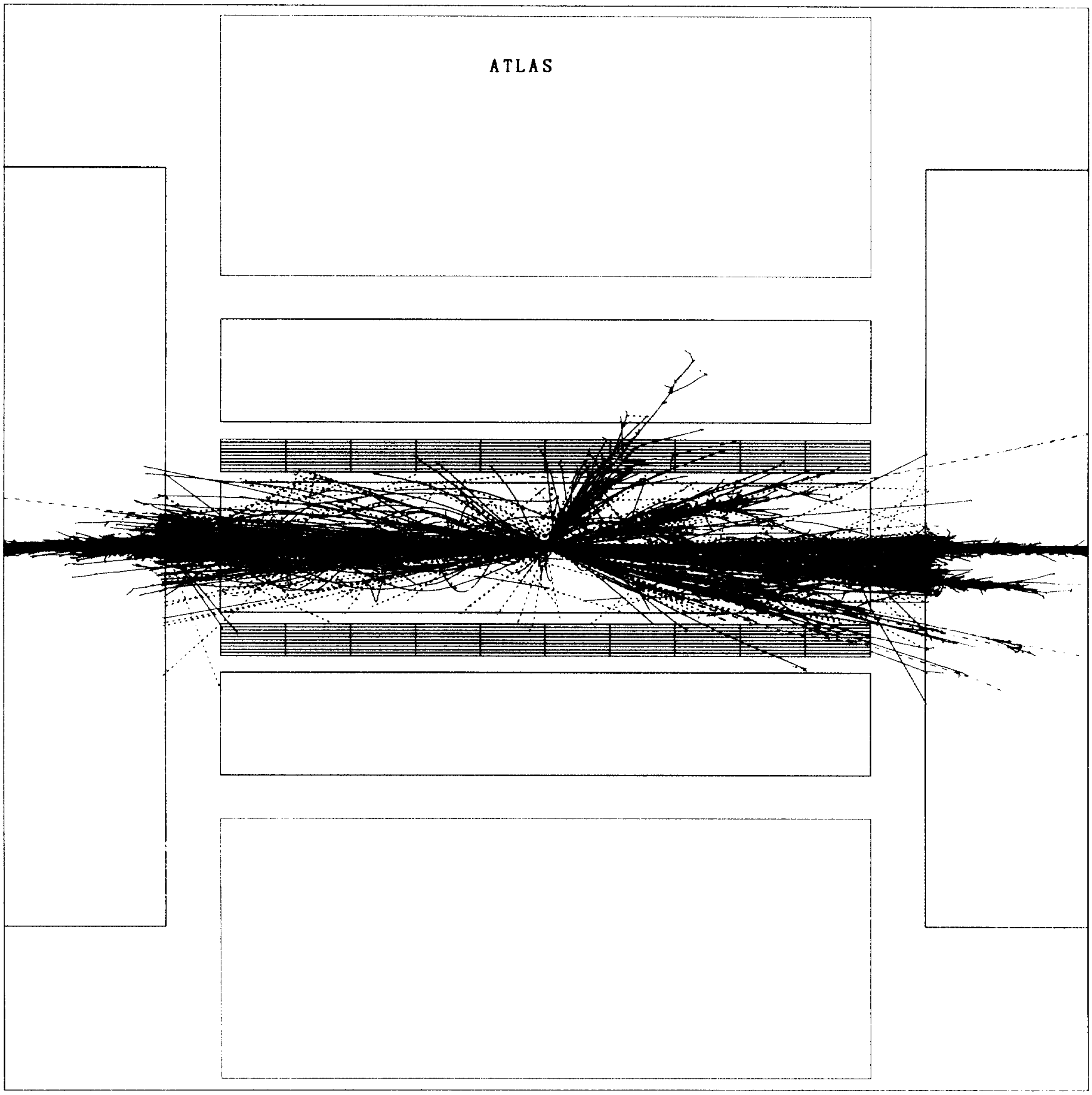

Fig.2 An example of event in ATLAS detector generated by PYTHIA.

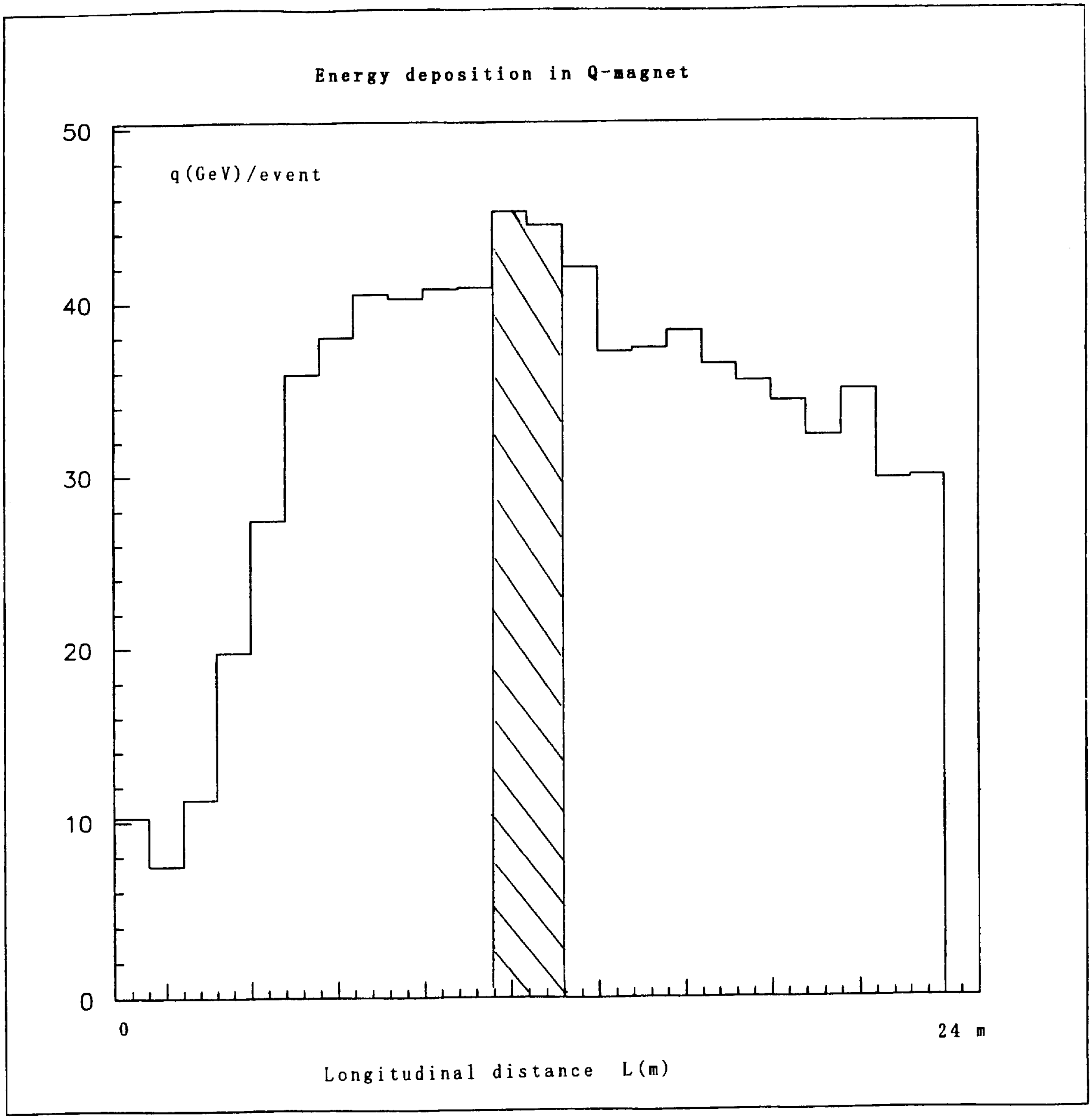

Fig.3 Energy deposition per event vs Z in Q-magnet. The shaded band is corresponding to maximum energy deposition area.

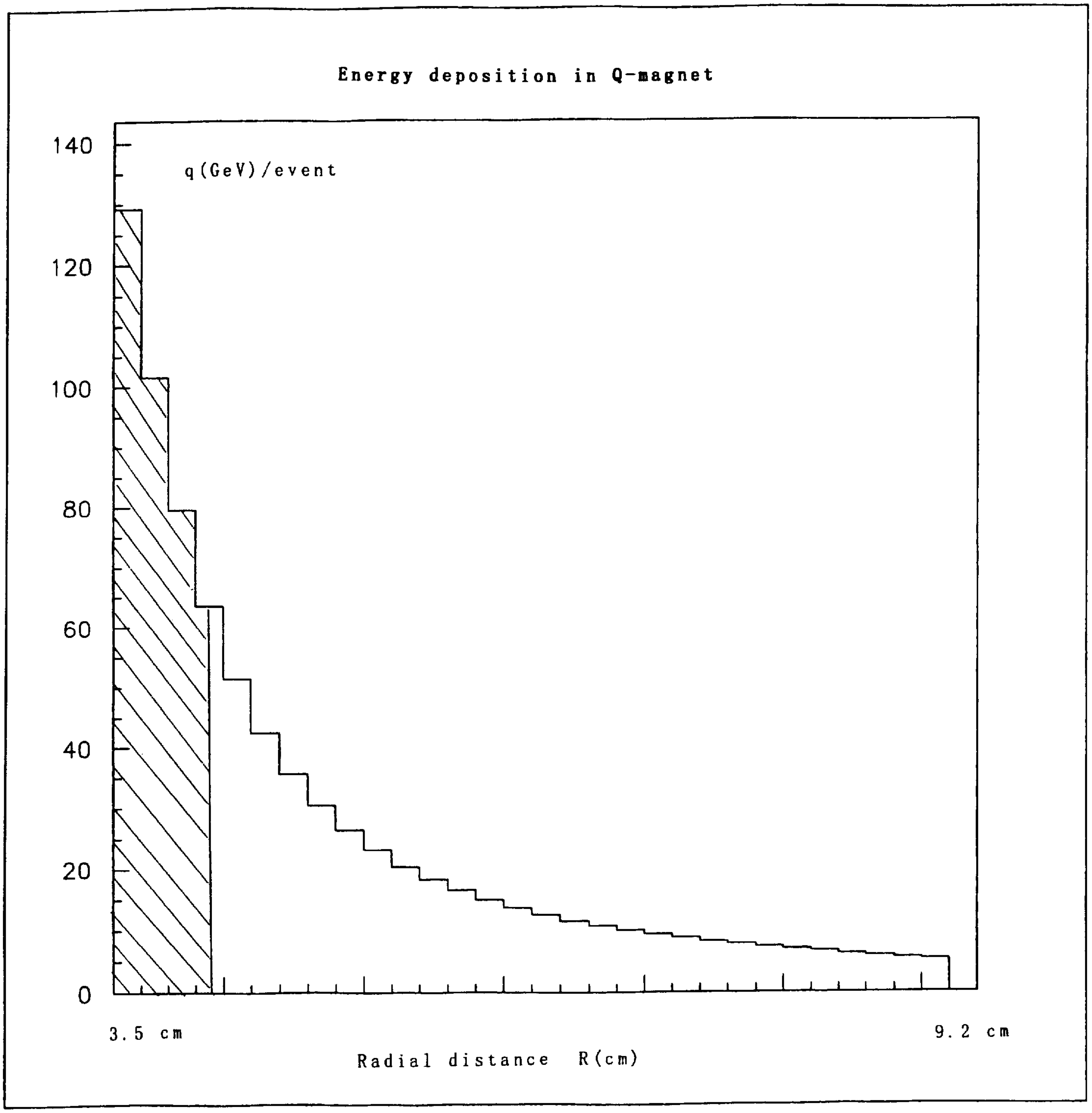

Fig.4 Energy deposition per event vs R in Q-magnet.

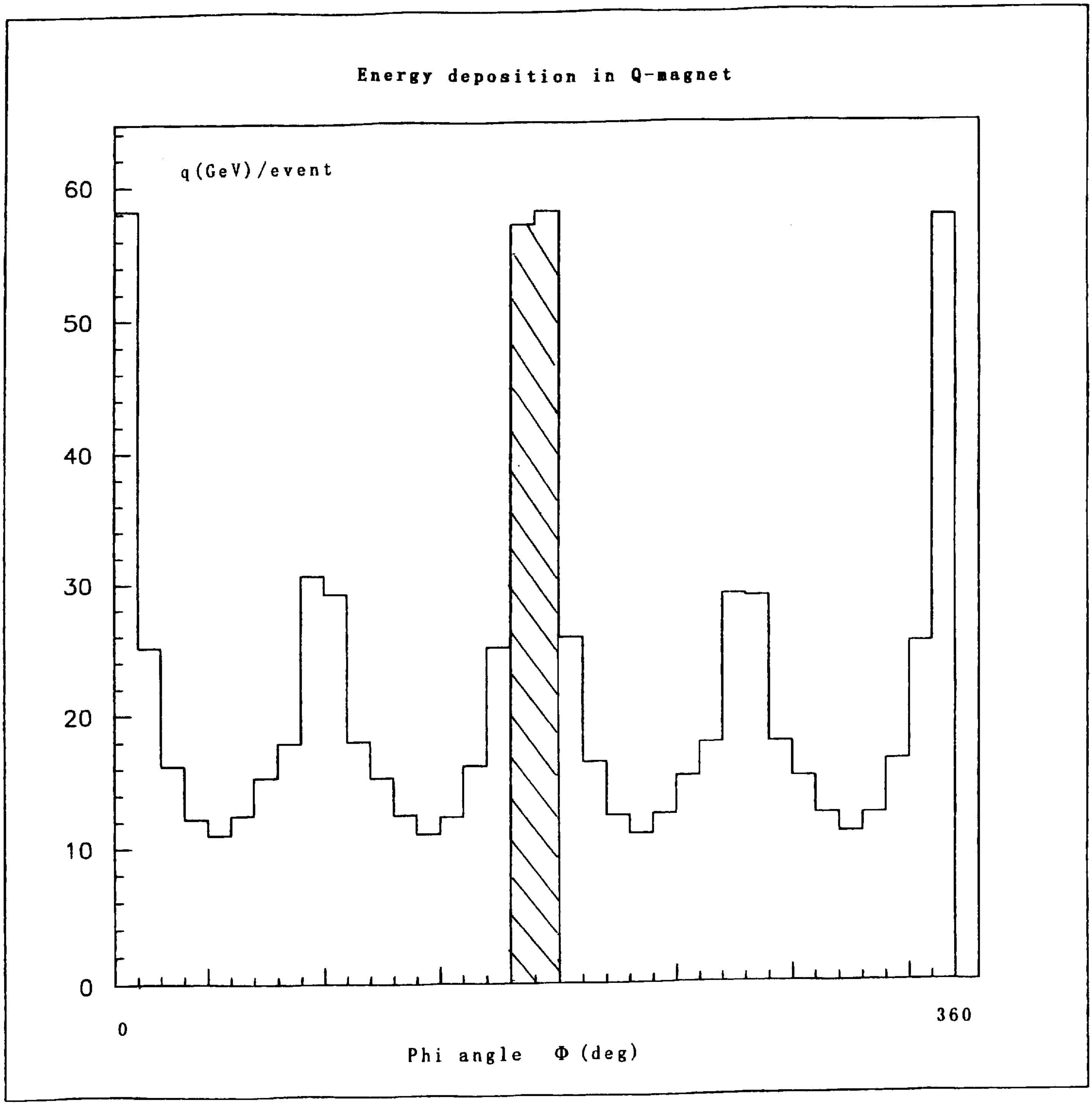

Fig.5 Energy deposition per event vs ϕ in Q-magnet.

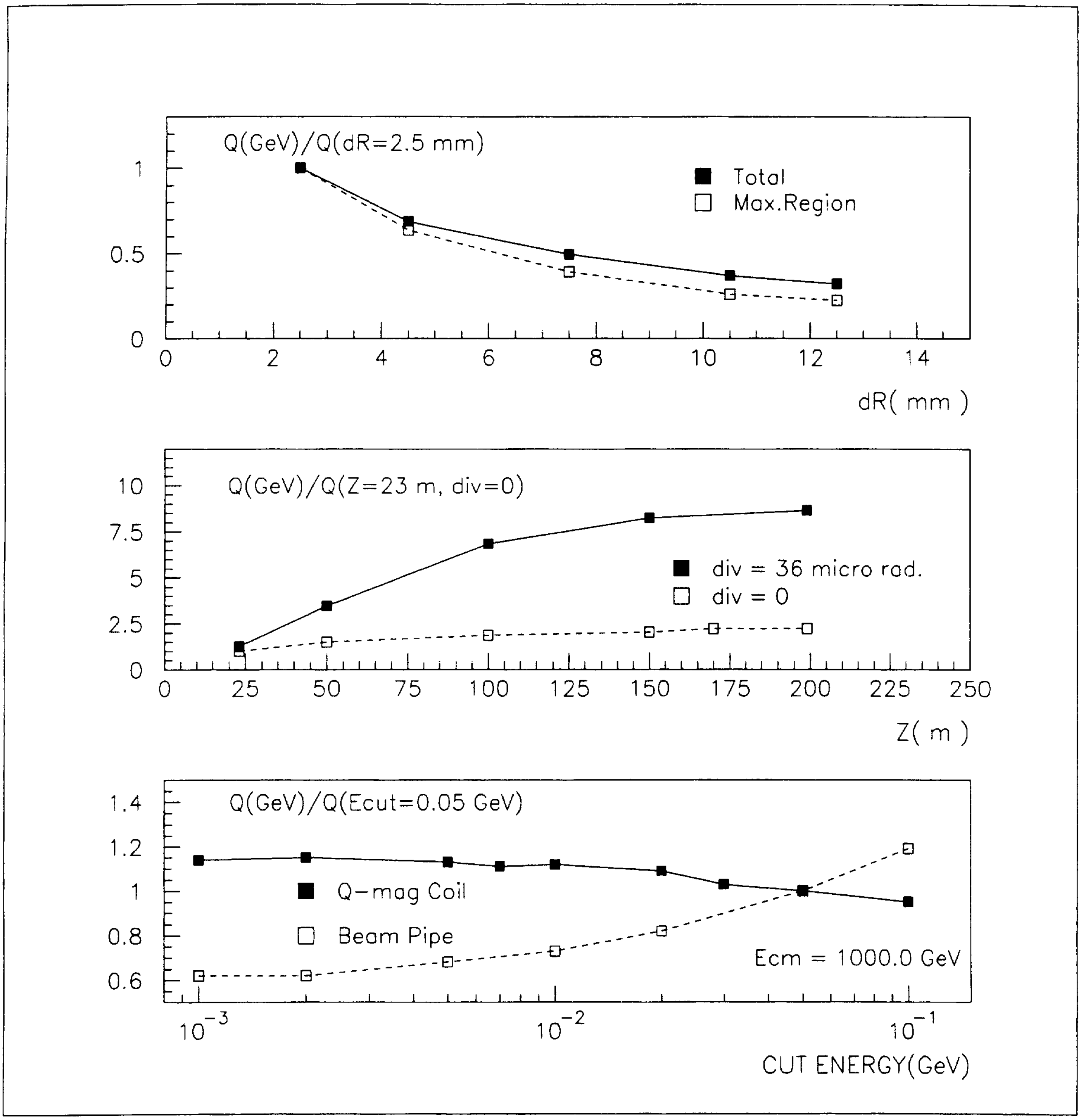

Fig.6 Total energy deposition vs beam pipe thickness.

Fig.7 Energy deposition vs beam pipe length.

Fig.8 Ratio of energy deposition vs cut energy at $E_{CM} = 1$ TeV.

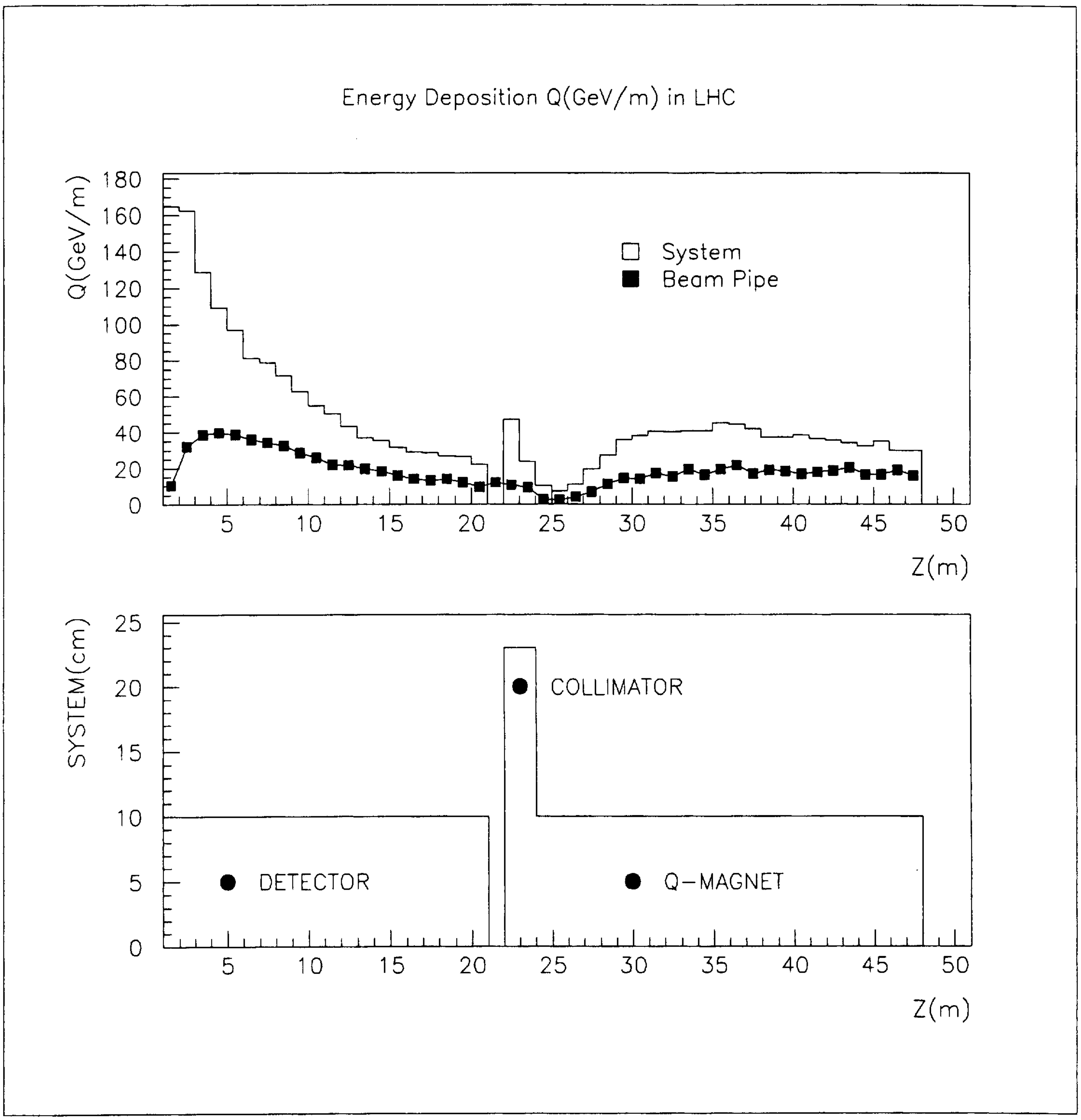

Fig.9 Energy balance of 7 TeV × 7 TeV p-p collisions.