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Recommended Locations of Beam Loss Monitors for the TOTEM Roman Pots

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Summary

This note presents results from simulations of losses on the TOTEM Roman Pot stations located close to 150m and 220m from IP5. These results are used to evaluate suitable locations to position beam loss monitors to monitor these losses, and help to avoid quenches of the super-conducting magnets downstream of the roman pots. The results presented in this note indicate the locations where the BLMs should be installed. A more detailed note on the topic will follow later.

Introduction

Roman pots for the TOTEM experiment [1] are to be installed on both sides of IP5, in "stations" close to 150m and 220m from the IP. The Roman pots contain detectors which, during stable operation, will approach very close to the beam axis. Depending upon the operational condition, this may be even as close as 10 sigma from the beam. As extra elements in the beamline, there will be an aperture change within the vacuum chamber when they are inserted. This implies that there will be additional losses from protons in the beam halo striking the pots. In the positioning of the Beam Loss Monitors (BLM) for the machine [2, 3], this loss mechanism has not been taken into account, therefore it is necessary to evaluate the topology of these additional losses and use it to evaluate suitable locations where the additional BLMs, which are already foreseen for the TOTEM RPs [4], can be positioned to have sensitivity to this type of loss.

The purpose of installing the BLMs is not only for monitoring the impact of the losses – it is also active protection of both machine and detector, for example, in the catastrophic case of the pot approaching too closely the beam, arising from either movements of the pot or of the beam. In this event, there is potential for damage – as demonstrated by the incident at FERMILAB, where a CDF roman pot approached the beam, causing extensive damage to collimators and magnets downstream [5]. The BLMs should help guard against quenches induced by these losses, dumping the beam before any magnet quenches or damage to the detector occurs, hence minimising machine inefficiency and downtime.

Presented here are the results from a simulation of losses on the Roman Pots, based upon interactions with pots at 147m and 220m from IP5. These results are used to determine suitable positions to install BLMs to detect these losses. A more detailed note on this loss mechanism and its potential effects on the magnets downstream will be available at a later stage; in particular, to extend these studies beyond the topology of the losses to predict energy deposition patterns and their normalisation and relation to the quench levels of the magnets, and examine BLM threshold levels that might be appropriate for the initial commissioning.

1 TOTEM Roman Pots

The TOTEM RP stations that are envisaged to be installed for the LHC startup phase are located close to 150m and 220m. The locations of these stations in the long straight section 5 (LSS5R) are shown in Figure 1. Each of these stations then comprises of a number of pots on the outgoing beam. Figure 2 shows the anticipated layout for the 150m station. The 220m station will be similar.

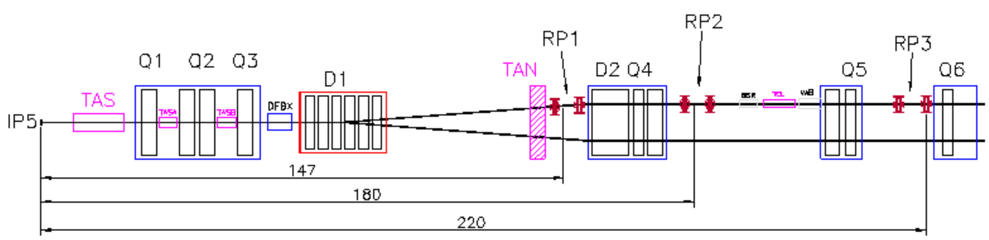

Figure 1: Machine Elements in LSS 5. RP1 indicates the location of the 150m station, and RP3 indicates the location of the 220m station. RP2 represents a possible station for TOTEM Roman Pots, which maybe installed at a later stage.

Each pot contains either vertical or horizontal detectors; the pots containing vertical detectors have detectors both above and below the beam; whereas the pots containing horizontal detectors have just one detector unit, which is placed on the outer side of the ring. The locations, as distance from IP5, and the orientations of the detectors for both the 150m station and the 220m station are shown in Table 1.

The geometry of the pot, containing the detector, which is inserted into the beampipe in shown in Figure 3. The inner edge of the Roman Pot will be parallel to the beam, and for a proton in the halo will present a stainless steel target of 5cm in depth.

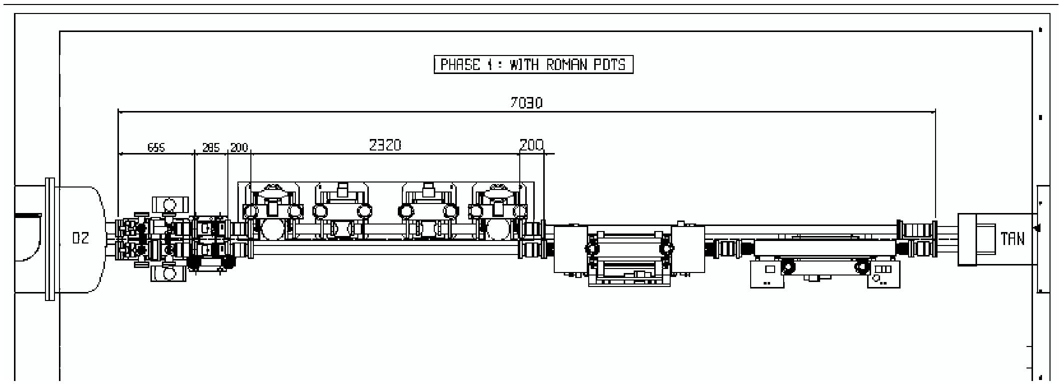

Figure 2: Drawing of the TOTEM 150m station showing the details of the integration between TAN and D2. From [6].

Station	Orientation			
	Vertical	Horizontal	Horizontal	Vertical
	Distance from IP5 (m)			
150m Station	148.944	149.393	150.027	150.476
220m Station	214.628	215.077	219.551	220.000

Table 1: Locations and orientations of midpoints of the TOTEM RP stations.

2 Machine Equipment surrounding TOTEM Roman Pots

As the Roman Pots are installed on the outgoing side of the IP for each beam, only the machine elements downstream (further from the IP) of the pots are potentially affected. Figure 1 shows a diagram of the magnetic elements in the Long Straight Section for IP5. It can be seen that the magnetic elements closest to the 150m station are D2 and Q4. Downstream of the 220m station is Q6. Additionally between D2 and Q4 and within the Q6 cryostat are the correctors MCBY and MCBC respectively. All of these are super-conducting magnets, operating at 4.5K, so therefore, in danger of quenching if the energy deposition in the coils becomes too large.

3 Beam Loss Monitors

At the LHC, Beam Loss Monitors will be installed close to all known potential loss locations, to monitor and diagnose the levels of losses from the beam, and used to provide protection against magnet quenches which could be induced by these losses. As such, to provide active protection, the BLM system will be connected to the beam dump system, via the Beam Interlock System (BIS), so that the beam can be dumped in a timely manner (within three turns), if the levels of losses are approaching the quench levels of the magnets.

The standard LHC beam loss monitors are cylindrical ionisation chambers, 60 cm in length with a diameter of 9 cm. Their response to different particle species and energies

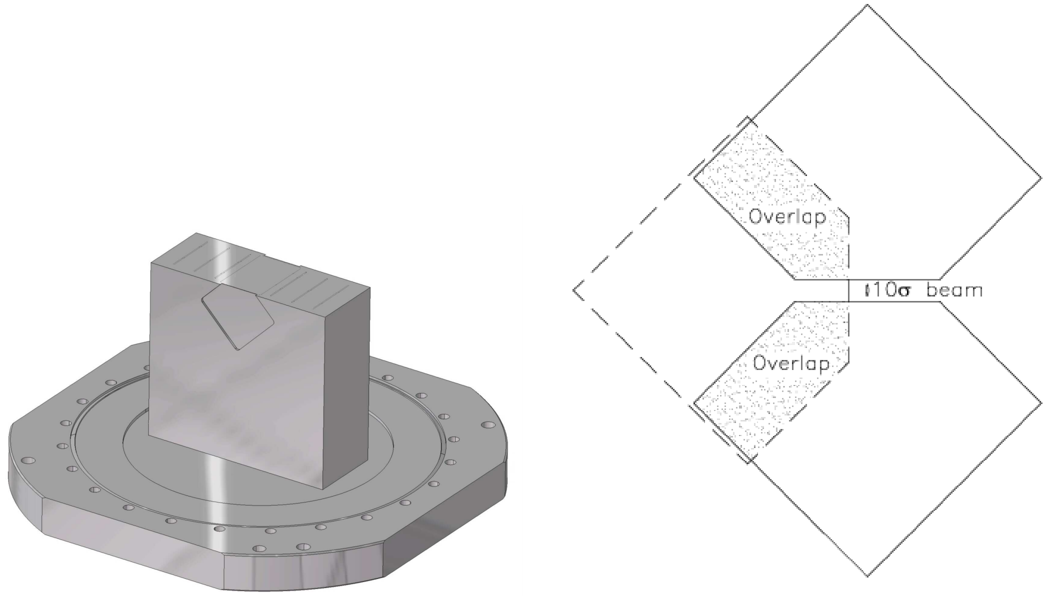

Figure 3: Geometry of Detector Pot to be inserted close to the beam (left). The detector configuration (right) consists of 2 vertical detectors (solid lines) at the same location in s, and 1 horizontal detector (dashed lines), offset by $\sim$ 90cm in s.

is highly non-linear, as can be seen from Figure 4. However, their response to charged hadrons is much larger than that of other particles in the energy range of interest here ($\sim$MeV–GeV), and so in the studies presented here, charged hadrons are assumed to be the dominant contribution to the signal.

The locations for these BLMs around the LHC ring have been chosen by simulating different loss-types, and the topology of the resulting showers evaluated [2, 3]. Typically the loss locations are aperture restrictions. For both the arcs and the LSS, the peak of the energy response from a loss location on the beam screen has been found to be similar – the maximum of the loss observed on the outer wall of the cryostat occurs approximately 1m after the loss location in the beam direction, s, and is approximately on a horizontal plane from the beam position, on the side of the cryostat nearest the beam from which the loss originated. So, detectors should be situated approximately 1m after loss locations, and on an approximately horizontal plane with the beams, to minimise cross-talk from differing loss locations in the BLMs response. This choice leads to the BLM closest to the loss location giving a response which is as independent as possible from losses elsewhere. The position around the cryostat, "ϕ", is indicated in Figure 5.

Several sets of BLMs are already envisaged to be installed near to the 150m and 220m TOTEM stations. Downstream of the 150m station, a set of 6 BLMs are foreseen to be installed on the Q4 quadrapole, 3 providing coverage for each beam. It is not presently foreseen to install BLMs on D2 as it is not thought to be a major loss location. Similarly, downstream of the 220m station, a set of 6 BLMs are foreseen to be installed on the Q6 quadrapole, 3 providing coverage for each beam.

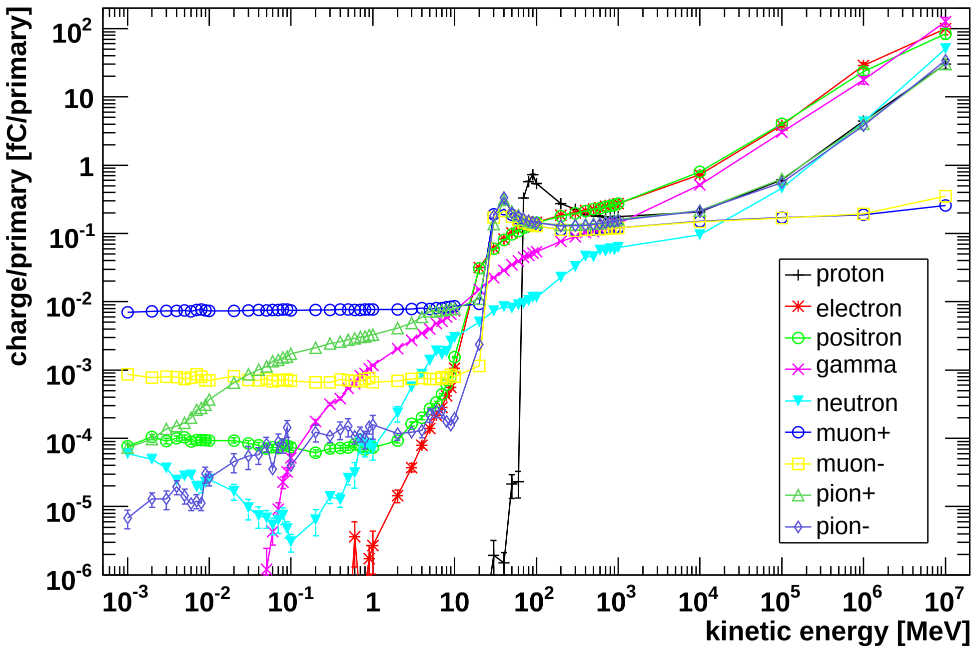

Figure 4: BLM response to different particle species as a function of incident energy of the particle. From [7].

4 Simulation of Showers from TOTEM RP Loss Mechanism

The beamline downstream of the 150m and 220m stations was simulated using the IHEP MARS program [8]. In the case of the simulation of the TOTEM 150m station, showers from inelastic interactions of a 7 TeV proton with a silicon nuclei [1] were traced from their origin at 147m, along 23m of beamline, until the beginning of the magnetic length of Q4. The simulation includes the details of the beampipe and the beam screen, the D2 magnet coils and yoke and the corrector coils and yoke. The cryostat material is not included in this version of the simulation. However, the amount of cryostat material is significantly smaller than the material in the magnet coils and yoke, and so can safely be neglected without a significant effect on the results of the simulation. The magnetic fields in the magnets were included in the simulation, using the values from the nominal optics. Particles yielded from the showers are then scored as they pass through a cylinder of radius 32cm from the centre of the outgoing beampipe – this corresponds approximately to the outer radius of the cryostat. The interaction was assumed to take place at the centre of the outgoing beampipe, making the results equally applicable to both the horizontally and vertically orientated pots. This is because a displacement of a few mm is negligible compared to the geometry of the beamline,

[1] The material in the pot closest to the beam is 5cm stainless steel, not silicon. However, as discussed later, the simulation for the 150m station of silicon rather than steel changes only the normalisation of the results, and not the topology of the shower.

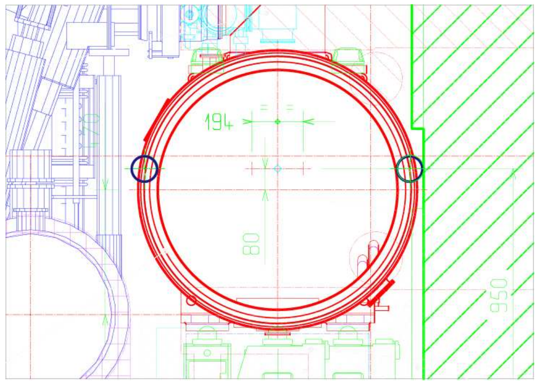

Figure 5: Cross-section of the cryostat, indicating where the BLMs will be positioned. The proposed location to install the BLMs is indicated by the solid black circles. The green hashed area to the right-hand side indicates the space reserved in the tunnel for transport.

coils and cryostat.

Studies [9] were done into the suitable energy cut-off for scoring particles, and it was decided that 100 MeV was most appropriate for evaluating the effective signal seen in the BLMs, from consideration of both the energy response of the BLMs and the energy spectrum of the particles in the shower. One hundred MeV is just above the threshold detection of protons in the BLMs. There are, however, small amounts of material in the cryostat missing from the simulation, but despite this, the conclusions of the studies do not change if instead, 20 MeV or 1 GeV, is used as the energy cut-off for particle scoring [9]. The flux of the following particle species were chosen to evaluate their relative contribution: protons, neutrons, charged pions and kaons, electrons and photons, and muons.

The location of the interaction for the simulation of the 150m station corresponds to the intended previous location of the Roman Pots. The pots will not now be installed at this location, as it is needed for tertiary collimators on the incoming beam to shield the interaction point and to prevent the inner triplet (Q1-3) from quenching, and have instead been shifted by a few metres further away from the IP. However, for the purpose of evaluating the topology of the shower that develops, this change should not be critical. The geometry will be updated in the next stage of simulation, also taking into account the geometry in the TAN region which has also recently undergone slight changes [10, 11].

For the simulation of the 220m station, showers from an inelastic interaction of a 7 TeV proton with a iron nuclei were traced from their origin at 220m, through 11.2 m of beamline from the origin, which corresponds to the end of the magnetic length of the Q6 magnet. The simulation includes the details of the beampipe and the beam screen and the Q6 magnet coils and yoke. As for the simulation of the 150m station, the cryostat material is not included in this version of the simulation. Particles yielded from the shower are then scored as they pass through a cylinder of radius 32 cm from the centre of the outgoing beampipe – which corresponds approximately to the outer radius of the cryostat. The starting location at 220m is the location of the furthest set of Roman Pots in this station. As the results of the 150m simulation were already available when this simulation was done, only protons, charged pions, charged kaons and neutrons were scored. Whilst the collision material simulated for the 150m and 220m stations differed (silicon and stainless steel respectively), the innermost material of the detector inserted into the beamline will be the stainless steel edge of the detector unit for all pots. The validity of the simulation of silicon target, was checked against the stainless steel target results – in similar solid angle regions close to the interaction the outgoing flux from the simulation differed, as expected, by the relative inelastic cross sections of the 2 materials, indicative of a change in normalisation of the particle fluxes, whilst the shower shape remains similar. This gives confidence in the validity of the topologies predicted by the simulations.

The co-ordinate system used in the results shown here is as follows: s is in the outgoing direction of the beam, with the origin at IP5, and ϕ is the azimuthal angle around the beam, in radians, defined such that 0 corresponds to ring outwards, $\pm\pi$ to ring inwards, $\pi/2$ as up and $-\pi/2$ down.

5 Results of Simulation

5.1 TOTEM 150m Station

Figure 6 shows the particle flux recorded in the simulation across the cylindrical scoring plane at radius 32cm as a function of s. It can be seen that there are significant variations in flux over the length included in the simulation.

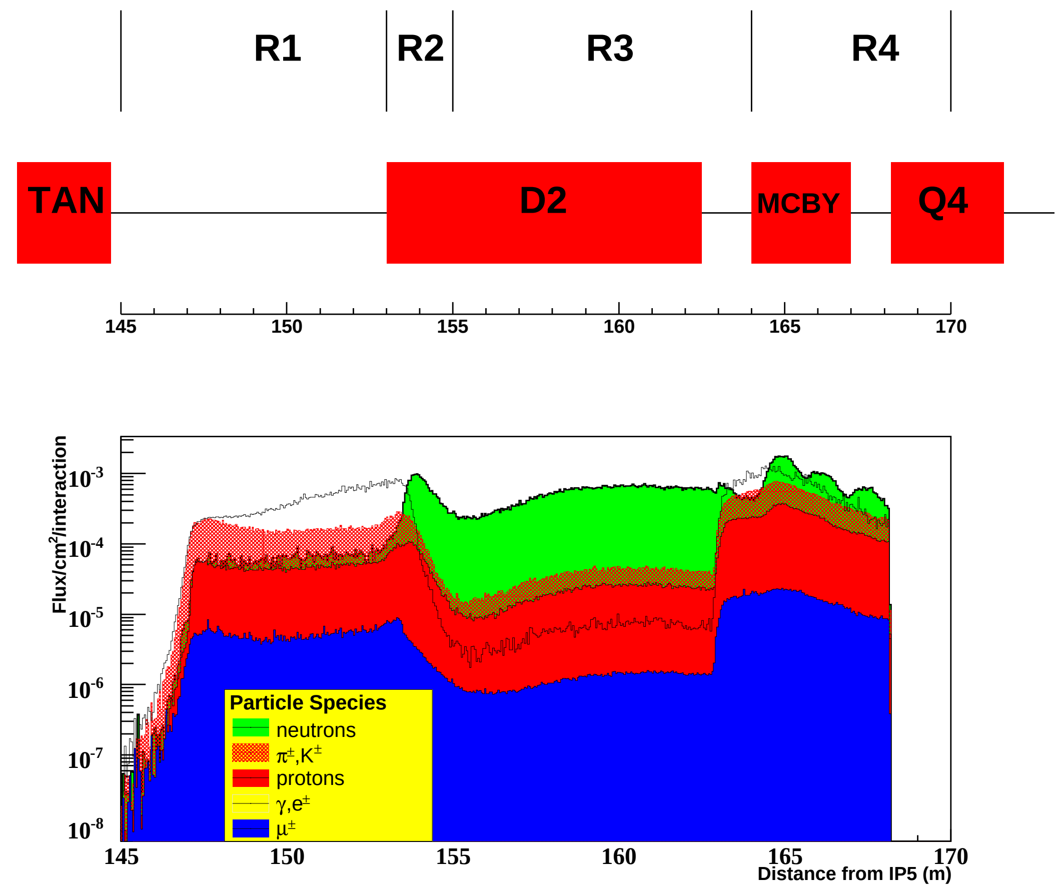

Figure 6: Particle flux density recorded across the scoring plane as a function of distance from IP5 for simulation of the 150m station. The particle species shown are: neutron (green histogram), proton flux (red histogram), muon flux (blue histogram), charged pion and kaon flux (red line), and the photon and electron flux (black line). The regions of interest, defined later in the text, and the positions of the magnetic coils are indicated at the top of the figure.

After the origin of the interaction, the fluxes of all particle species rise up to a plateau, corresponding to the region up to the start of the D2 cryostat. After about 2m of beamline the flux rises up to plateau. This is because, in this region, the beampipe is bare, i.e. the beampipe is warm, and there are no magnetic elements/cryostat surrounding it. The plateau in the flux in this region verifies that the shift in Roman Pot location from that simulated here will not affect the flux significantly, as it is determined predominantly by presence of the bare beampipe in this region. At the beginning of the cryostat, between 153 and 155m, there is a peak in the neutron, proton and pion fluxes. Further inside the D2 magnetic length, the neutron flux dominates, and the charged hadron fluxes are suppressed, due to the material in the core of D2. In the region of the correctors, the charged hadron flux again becomes large. Part of the reason for the subsequent rise in the charged hadron flux is because of the change in aperture of the beampipe and beam-screen between D2 and the correctors.

Considering that the charged hadron flux will dominate the signal detected in the BLM, it would appear that they should be located at any position up the beginning of the magnetic length in D2, or in the corrector region of the D2-Q4 cryostat. However, the present proposed geometry for the TOTEM 150m RP station, as shown in Figure 2, differs from the geometry in the simulation used here: the interaction in the simulation occurs at 147m, the originally envisaged location of the 1st Roman Pot. As seen from Table 1, Roman Pots now will be installed in the second half of the TAN-D2 gap, between 148 and 151m. This therefore suggests that the preferred location for the BLM would be as close to the front of the D2 cryostat as is feasible. The corrector region of the D2-Q4 cryostat remains an attractive secondary location for placing a BLM.

To continue further with the studies, the simulated section of the beamline was divided up into 4 regions of interest in s. These regions of interest were decided by considering both Figure 6 and the geometry of the region. The regions chosen were:

1. Region 1: Before the D2-Q4 cryostat (8m long).
2. Region 2: Start of the D2-Q4 cryostat (2m long).
3. Region 3: D2 (9m long).
4. Region 4: Correctors (4m long).

These locations are also indicated in Figure 6.

	R1 (8m)	R2 (2m)	R3 (9m)	R4 (4m)	Total
$\pi^{\pm}, K^{\pm}$	21.48	5.97	15.32	40.66	83.44
Protons	5.91	2.61	7.67	19.29	35.48
Neutrons	7.78	20.7	97.42	75.64	201.54
$\gamma, e^{\pm}$	50.29	12.28	15.35	55.39	133.31
$\mu^{\pm}$	0.66	0.16	0.56	1.38	2.76
Total	86.13	41.72	136.33	192.36	456.53

Table 2: Flux of particles from showers from an interaction with a Roman Pot at 147m. The flux is given as numbers of particles expected crossing the scoring plane within the region indicated, per incident proton interaction with a silicon target. The length of each region is indicated by the number in parentheses next to it.

The predicted particle fluxes in each of these regions for the different particle species is shown in Table 2 and Figure 6. Examination of the fluxes shows that muons can be neglected from further consideration – they are a tiny contribution to the overall flux. The electromagnetic component of the flux ($\gamma, e^{\pm}$) is dominated by photons - typically they compose 75% of this component of the flux, the rest being approximately equally electrons or positrons. So, whilst the contribution of photons and neutrons is significant, they are highly suppressed by the response function of the BLM, as shown in Figure 4. Furthermore, the energy spectra of photons and neutrons is softer than that of the charged hadrons, suppressing their contribution further. This confirms the assumptions made earlier about the contributions of different particle species to the signals in the BLMs. However, at a later stage, when determining appropriate levels for setting the thresholds of the BLMs, the signal induced in the BLMs by the electromagnetic and neutron flux should be taken account of.

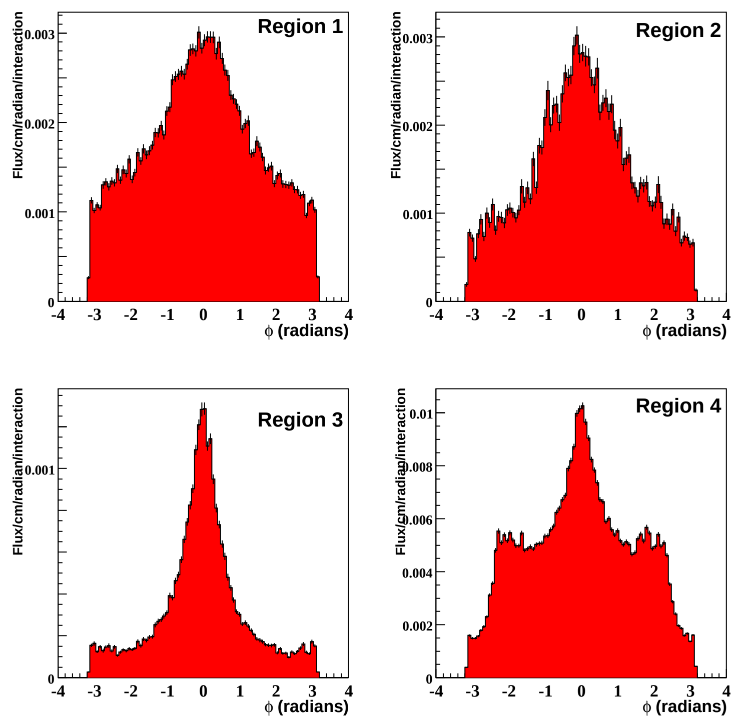

Figure 7: ϕ dependance of particle flux for the simulation of the 150m station. ϕ, in radians, is defined so that 0 corresponds to ring outwards, $\pm\pi$ to ring inwards, $\pi/2$ as up and $-\pi/2$ down.

To determine the best location around the cryostat to locate the BLMs, the angle of exit on the cylindrical scoring plane for the particles from the shower is recorded. The distribution in ϕ for charged hadrons from the simulation of the 150m station, for the regions defined above, can be seen in Figure 7. It can be seen that in all cases the ϕ distribution of the showers are peaked towards zero, which corresponds to ring outwards. At IP5, on both sides, the outgoing beam from the IP is on the outside of the ring, so the peak at ϕ of zero is due to the lower material thickness and distance on this side of the cryostat. Additionally, the ϕ distributions of positive and negative particles, in particular for charged pions, were checked, and no significant differences were found. This is indicative that the dominant influence on the shower topologies comes from the materials close to the beamline, and not the fields within the magnet, implying that the details of the optics should not affect significantly the results from the simulation. Therefore the best location to position the BLMs for the Roman Pots is approximately on the horizontal plane, on the outer side of the ring.

This location in ϕ, on the horizontal plane is the same optimal position as was found for the BLMs to be positioned elsewhere in the LHC ring. A BLM placed on the outside of the cryostat subtends about 3-4 % of azimuthal solid angle towards the beamline. A BLM at these locations on the horizontal plane will be sensitive to between 8 % and 11 % of the signal for regions 4 and 2 respectively [9].

5.2 TOTEM 220m Station

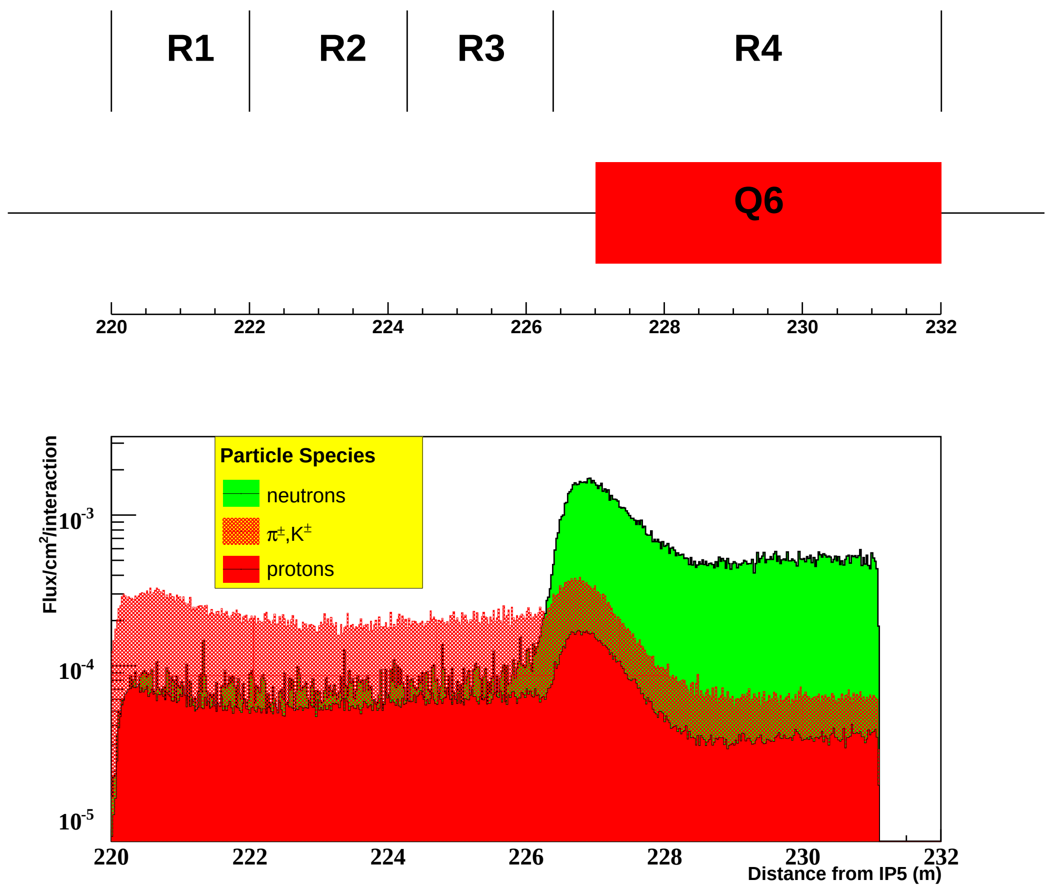

Figure 8: Particle flux density recorded across the scoring plane as a function of distance from IP5 for simulation of the 220m station. Charged pions and kaons are represented by the red line, protons by the red histogram, and neutrons by the green histogram. The regions of interest, defined later in the text, and the positions of the magnetic coils are indicated at the top of the figure.

The particle flux recorded in the simulation across the cylindrical scoring plane for the 220m station is shown in Figure 8 for charged hadrons and for neutrons. It can again be seen that there are significant variations in flux over the length included in the simulation.

Within 1m of the interaction, the charged hadron flux from the showers has reached a peak. After this initial peak, the charged hadron flux then remains approximately constant along the entire length of bare beampipe and throughout the region at the beginning of the Q6 cryostat. The charged hadron flux again peaks at the position of the beginning of the Q6 magnetic length, before being strongly attenuated by the material in the coils and yoke for Q6. In contrast the neutron flux is negligible until the beginning of the magnetic length of Q6, where it very strongly peaks. Throughout the magnetic length of Q6, the neutron flux remains larger than the charged hadron flux.

These results from the simulation suggest that there are two locations to position BLMs to be sensitive to the interactions with the TOTEM Roman Pots at 220m. The first position would be as close as possible to the last 220m detector plane of the Roman Pots. As shown by the simulation, this BLM would have sensitivity to all of the detector planes here. This position has a further advantage that the BLM can be placed closer to the beamline than the radius of the cryostat. The second suggested location would be just before, or around the start of the magnetic length of Q6. Again, this location would be sensitive to all of the detector planes in the 220m station, however it is also likely to be sensitive to other sources of losses too.

To continue further with these studies, the simulated section of the beamline was divided up into 4 regions of interest. These regions of interest were decided by considering both Figure 8 and the geometry of the region. These regions are:

1. Region 1: Bare beamline immediately after last detector plane (2m).
2. Region 2: Second half of the bare beamline up to the Q6 cryostat (2.3m).
3. Region 3: Beginning of Q6 cryostat (2.1m).
4. Region 4: Q6 magnetic length (4.8m).

These locations are also indicated in

	R1 (2m)	R2 (2.3m)	R3 (2.1m)	R4 (4.8m)	Total
$\pi^{\pm}, K^{\pm}$	9.79	8.35	8.42	11.31	37.87
Protons	2.18	2.33	2.48	5.42	12.41
Neutrons	2.62	3.11	4.14	65.86	75.73
Total	14.59	13.79	15.04	82.59	126.01

Table 3: Fluxes of particles from showers from an interaction with a Roman Pot at 220m. The flux is given as numbers of particles expected within the region indicated per incident proton interaction with a stainless steel target.

The predicted particle fluxes in each of these regions for the different particle species are shown in Table 3 and figure 8. Examination of the fluxes shows that except for region 4, the flux is dominated by charged particles.

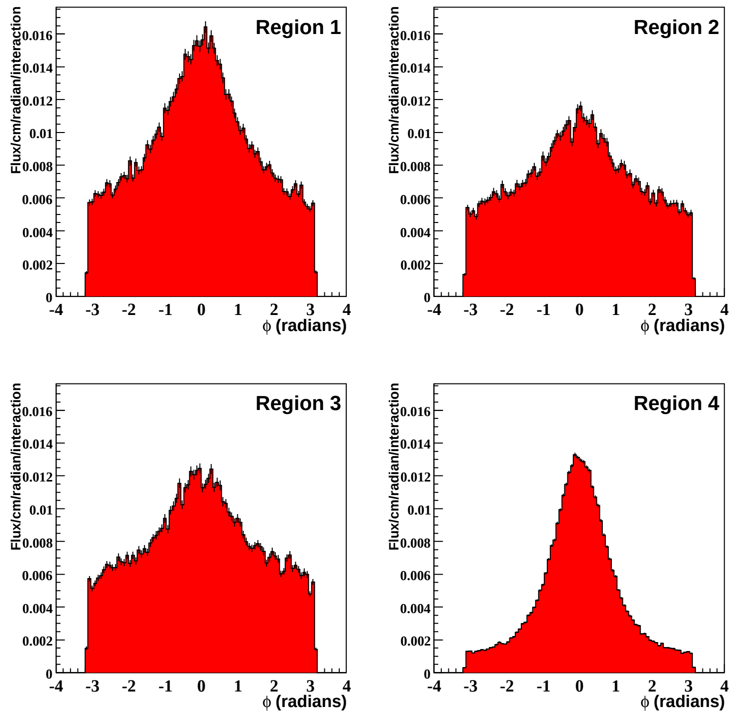

Figure 9: ϕ dependance of particle flux for the simulation of the 220m station. ϕ, in radians, is defined so that 0 corresponds to ring outwards, $\pm\pi$ to ring inwards, $\pi/2$ as up and $-\pi/2$ down.

Again, to determine the best location around the cryostat to locate the BLMs, the angle of exit on the cylindrical scoring plane for the particles from the shower is recorded. The distribution in ϕ for charged hadrons from the simulation of the 220m station for the regions defined above can be seen in Figure 9. It can be seen that in all cases the ϕ distribution of the showers are peaked towards zero, which corresponds to ring outwards. The tendency with increasing distance from the interaction for the ϕ distribution to become more peaked is more pronounced for the 220m station than for the 150m station. In summary, for the 220m station as well as for the 150m station, the optimal location to position the BLMs for the Roman Pots is approximately on the horizontal plane with the beams, on the outer side of the ring.

Conclusion

Results have been presented here from a simulation of proton interactions with the material of the TOTEM Roman Pots in the 150m and 220m stations, as a model of the losses of proton-halo on these pots, with the aim of determining the optimal location for the positioning of LHC BLMs for detecting the magnitude of these losses. The optimal locations were determined by considering both the particle flux originating from these interactions passing through the radius of the exterior surface of the cryostat and the machine elements nearby that may quench as a result of these showers. Two standard LHC BLMs were foreseen by the BLM group to be available for each TOTEM RP station – this study suggests that they should be positioned and installed as follows:

- **150m station:**

  BLM A: At the beginning of the D2 cryostat, before the D2 coils start **(s=±153m)**.

  BLM B: Within the region of the correctors within the D2-Q4 cryostat **(s=±164m)**.

- **220m station:**

  BLM A: As close as possible in s to the last detector plane **(s=±221m)**.

  BLM B: Just before, or at the start of the magnetic length of Q6 **(s=±226.5m)**.

The distances within parentheses indicate the approximate distance of the suggested location from IP5.

A 150m and a 220m TOTEM RP station will exist on both beam 1 and beam 2 outgoing from IP5, i.e. for beam 1 the TOTEM RPs will be on the RHS and for beam 2 the TOTEM RPs will be on the LHS. Therefore BLMs need to be placed near to the stations in both directions, as indicated in the list above by the '±' notation on the distances from IP5.

In all cases, the BLMs should be positioned on a horizontal plane with respect to the beams, as close as possible to the beamline as is feasible – i.e. on the outside of the cryostat or bare beampipe. The outgoing beam at IP5 is, for both beams, on the outside of the ring, and therefore the BLMs should be placed on the "ring-out" side.

This information is summarised in the table below:

IP5		**LHS**	**RHS**
Station	BLM	Beam 2	Beam 1
150 m	BLM A	-153 m	+153 m
	BLM B	-164 m	+164 m
220 m	BLM A	-221 m	+221 m
	BLM B	-226.5 m	+226.5 m

Whilst the results suggested here are from a preliminary simulation, they are expected to be robust to changes in the details of the geometry. The optics is also expected to have a small effect upon the loss topology. Therefore, they can be taken with confidence as the appropriate locations of BLMs. The final locations for installation of the BLMs will be determined in consultation with the BLM group and the integration team.

Acknowledgements

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