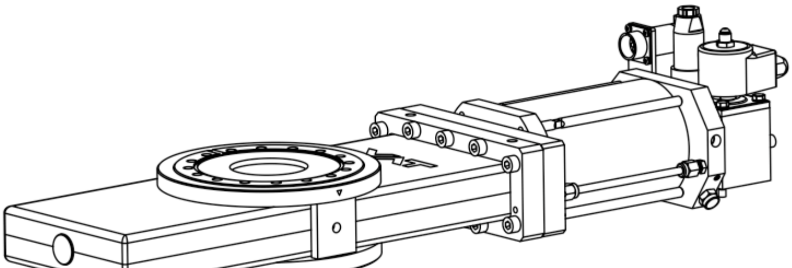
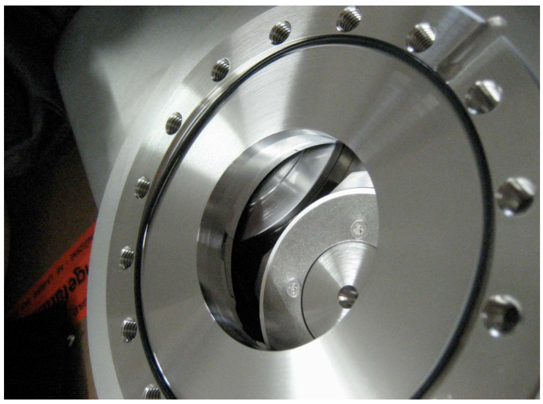
Section 0 - Introduction

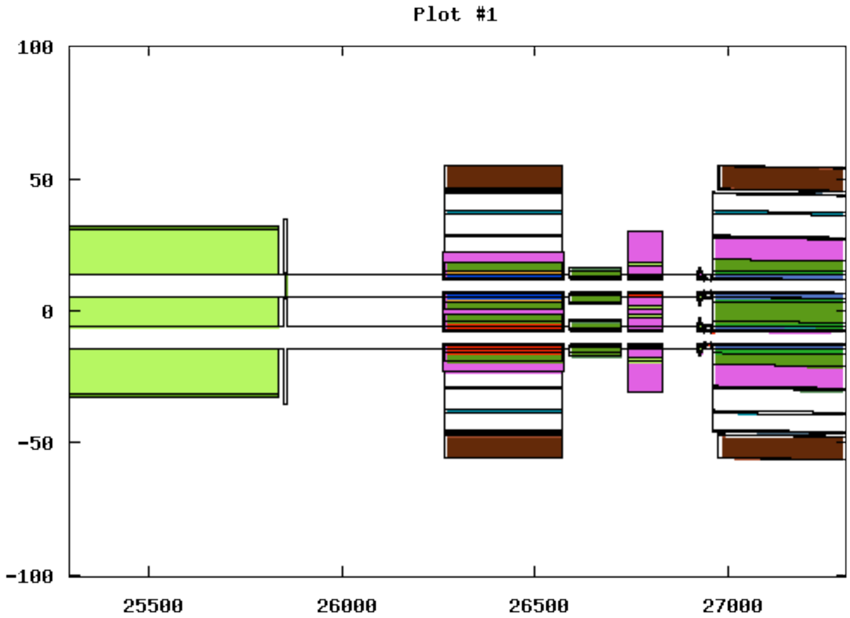
The LHC sector valves are located in the LSSs and sectorize the LHC vacuum, closing in 3s (5s) for a valve with aperture 60mm (100mm). This gives a closure speed of 0.02 m/s. The closing valve should trigger a beam dump request, which will occur in a few turns after the request. This work studies what would happen if this request was not made and the closing valve scrapes the beam, in terms of downstream magnet quenches and BLM signals. The LHC vacuum valve design is shown below for the 60mm variant. The steel door closed across the beam, leading with a steel flange of approximately 1.8 cm thickness. This amount of material initially seen by the beam is greater than the ultimate door thickness. There fore the simulation models the valve door as a homogeneous piece of 1.8 cm thick steel.





The studies were made in the right-hand side of IR7 for beam 1, with a candidate valve located in the region just before MQ7, which is just before the arc. Between MQ6 and MQ7 there are two valve locations, one in the drift before MQ7 and one just after MQ6 (but separated from the cold elements by several other elements). This gives the opportunity to study valve-magnet longitudinal layouts. The valve before MQ7 will be studied as the main valve. Furthermore, a study valve location located immediately before MQ7 will also be considered to check the impact of a valve immediately before a cold element, although this does not correspond to a valve in IR7 in the real machine. This study valve also allows comparison to previous studies of point-like losses in quadrupoles as a validation of the calculations. The losses on the valve are assumed to be a pencil beam, with a proton beam energy of 7 TeV, 3.5 TeV and 5 TeV. The pencil beam is used in place of the real beam distribution and should correctly give the location and magnitude of the shower peak. The valve is taken to be in the closed position, or in an open position with a beam grazing the edge of the material. For the latter, the impact parameter is taken to be 1, 5 and 10 turns times the valve speed, giving 2 um of valve movement per turn (the valve speed is approximately 6cm/3s, or about 2um per turn).

The layout in this region is shown below, with the MQ7 located around 26500 cm, the bend at the left of the plot is MBA8 and the target valve is located just after the green box.



The energy deposition is scored in the coils of the quadrupoles, the trim quadrupoles and the dipoles, mainly MQ7, MQ8, MBA8 and MBB8. The BLM energy deposition along a theoretical BLM gives the expected BLM signal. The MB and MQ quench level at 7 TeV is taken to be 1mJ /cc for transient losses, with the peak estimated from a binning of the magnet coils. This quench level is taken to be 3 mJ /cc at 5 TeV and 9 mJ /cc at 3.5 TeV. The FLUKA shower analysis gives GeV /cc /p, which is scaled to mJ /cc for the coil deposition. For the case of the BLMs, the energy deposition per cc is scaled to nC by a factor of 0.16/34.8 nC/GeV and also for the volume ratio for a BLM (1537.42 cm3) to the volume ratio in the simulation (2837.25 cm3 for a MB and 567.45 cm3 for a MQ).

For the target valve, the elements from the valve to MQ8 are the following:

246	**VDUM.7R7.B1**	VDUM7R	E	0.000	0.000	25856.
247	**MQ.7R7.B1**	MQ7R	E	0.000	0.000	26417.
248	MQTLI.7R7.B1	MQTLI7R	E	0.000	0.000	26654.800
249	MCBCH.7R7.B1	MCBCH7R	E	0.000	0.000	26783.800
250	MCDO.8R7.B1	MCDO8R	E	0.000	0.000	26924.500
251	IC1.DS1R7.B1	IC1DS1R	E	0.000	0.000	26944.213
252	**MB.A8R7.B1**	MBA8R	E	-1.823	0.000	27673.397
253	IC1.DS2R7.B1	IC1DS2R	E	-3.697	0.000	28398.381
254	MCS.A8R7.B1	MCSA8R	E	-3.786	0.000	28415.793
255	IC3.DS1R7.B1	IC3DS1R	E	-4.082	0.000	28473.805
256	**MB.B8R7.B1**	MBB8R	E	-9.810	0.000	29239.370
257	IC1.DS3R7.B1	IC1DS3R	E	-15.381	0.000	29964.336

258 MCS.B8R7.B1 MCSB8R E -15.559 0.000 29981.747
259 IC2.DS2R7.B1 IC2DS2R E -15.906 0.000 30015.746
260 **MQ.8R7.B1** MQ8R E -19.053 0.000 30324.329
where the last column shows the centre of the element.

To help with the plots, the centres of the relevant elements are:

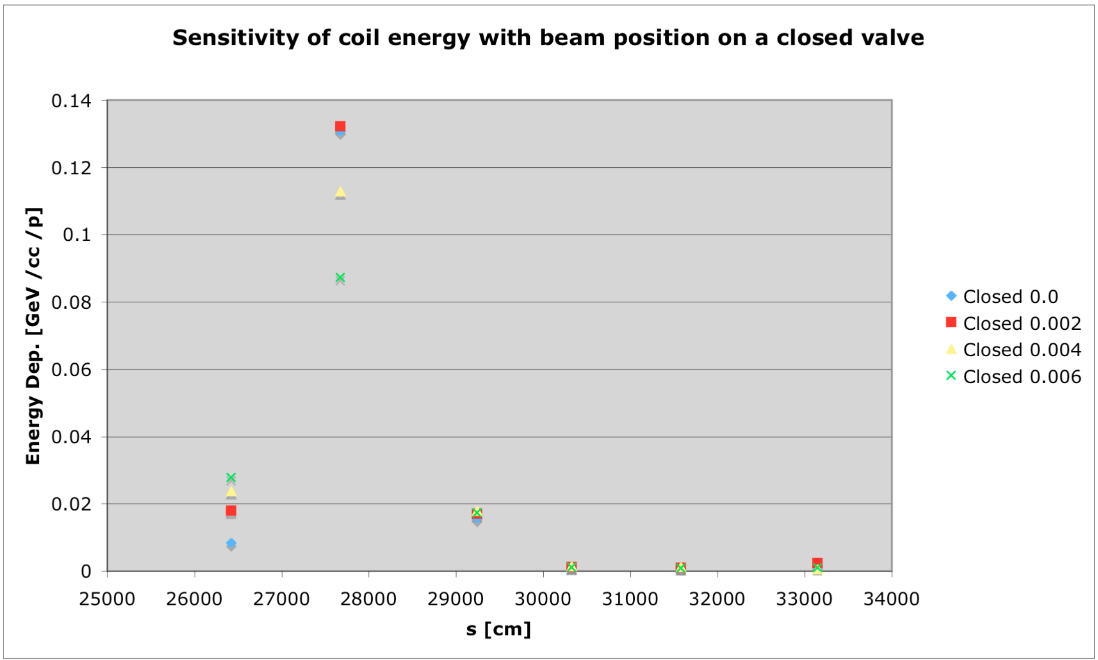
Main target valve	25856.65 cm
Second target valve	23526.15 cm
Study valve	26233.760 cm
MQ7	26417.9 cm
MBA8	27673.397 cm
MBB8	29239.37 cm
MQ8	30324.329 cm

The rest of this note is organised into 3 sections and a conclusion. The first is a detailed study of the 'study' valve located immediately before MQ7. This includes sensitivity studies of beam initial conditions, both for a valve in the closed and open configurations, and studies of the BLM signal at the downstream magnet quench level. The next section makes the same calculations for the target valve located in the drift before MQ7 at 7 TeV. Finally, section 3 makes a study of alternative configurations and of the target valve at 3.5 TeV and 5 TeV.

Section 1 – the study valve immediately before MQ7 at 7 TeV

1.1 Sensitivity study 1 – Closed valve position scan

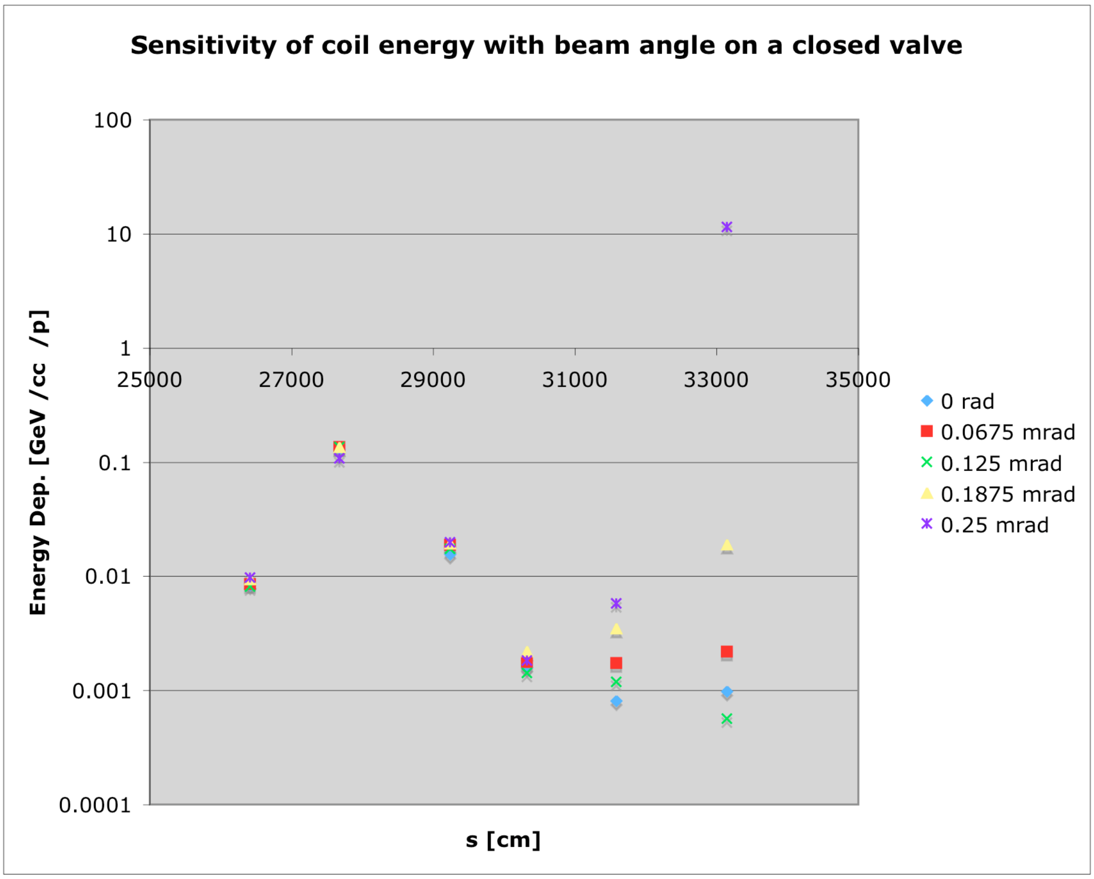
To assess the dependence on pencil beam initial position, a sensitivity study on the closed study valve was made for a selection of initial beam horizontal position and the dependence on the coil energy deposition (GeV /cc /proton) calculated.



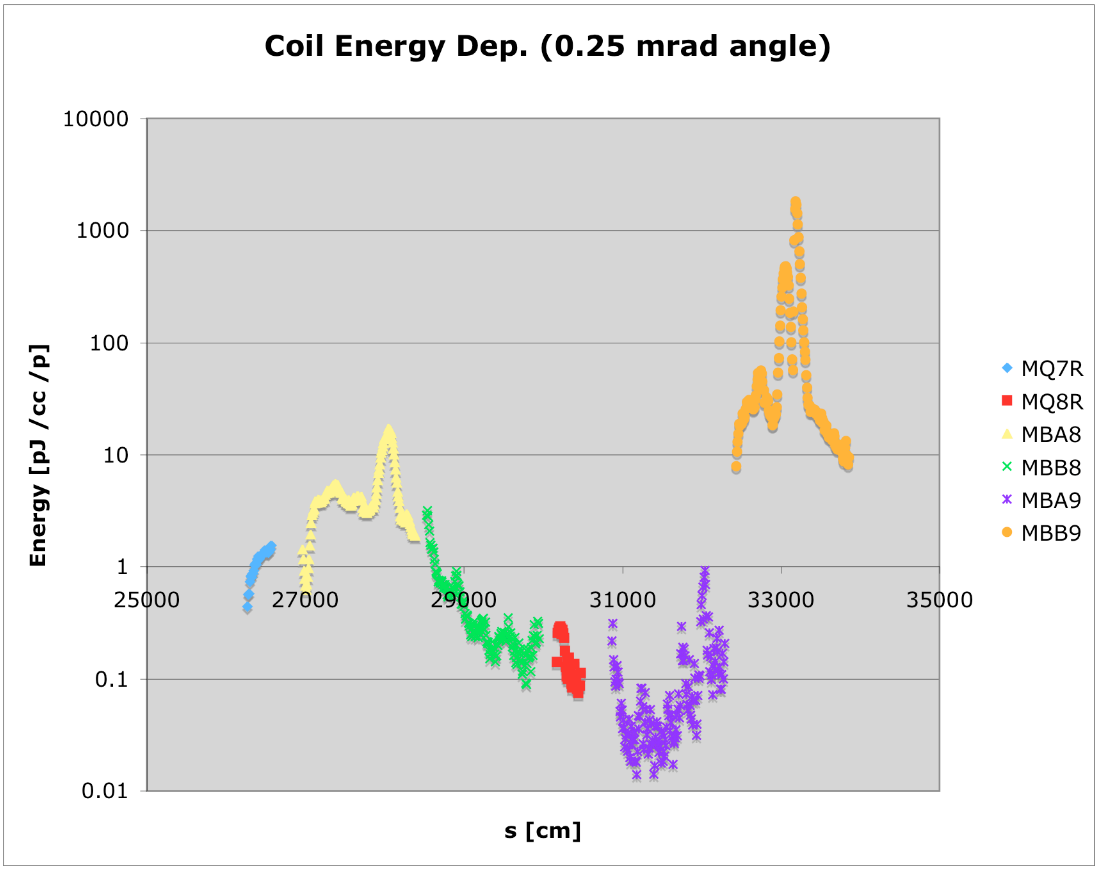
The peak energy deposition along s is plotted, and the valve is located at 26233.76 cm. The first point corresponds to loss in MQ7, and the peak to loss in MBA8. The magnitude of the peak shows some dependence on the initial position, but the peak deposition drops as the beam moves off-axis.

1.2 Sensitivity study 2 – Closed valve angle scan

The sensitivity to initial angle was checked in the same way.



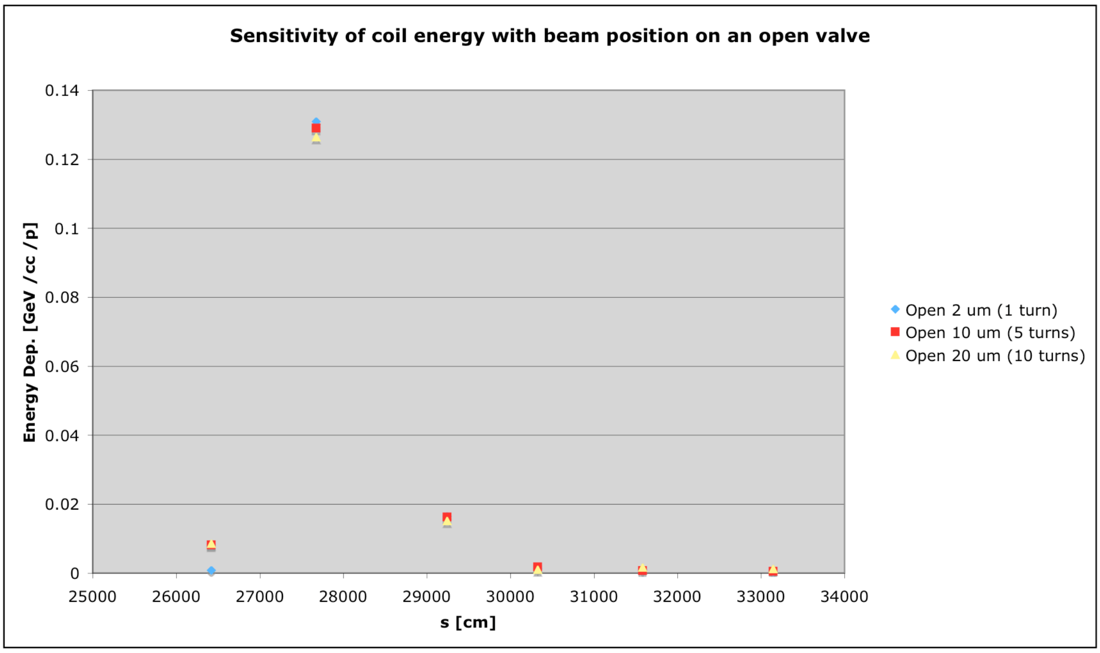
The peak energy deposition in s was calculated for a scan of initial angles for a closed valve configuration. The dependence on initial angle is weak at small beam angles. The large growth in the peak around 33000 cm, corresponding to MBB9, is from direct beam impact at large angles, which can be seen from a detailed coil energy deposition for this case.



The shower peak in MBA8 is still present, but a much larger peak in MBB9 (around 33mmm cm) now appears due to direct beam impact in the coils. However, an angle of 0.25 mrad is many angular sigma's at this point, and so a very large angle.

1.3 Sensitivity study 3 – Open valve and impact parameter scan

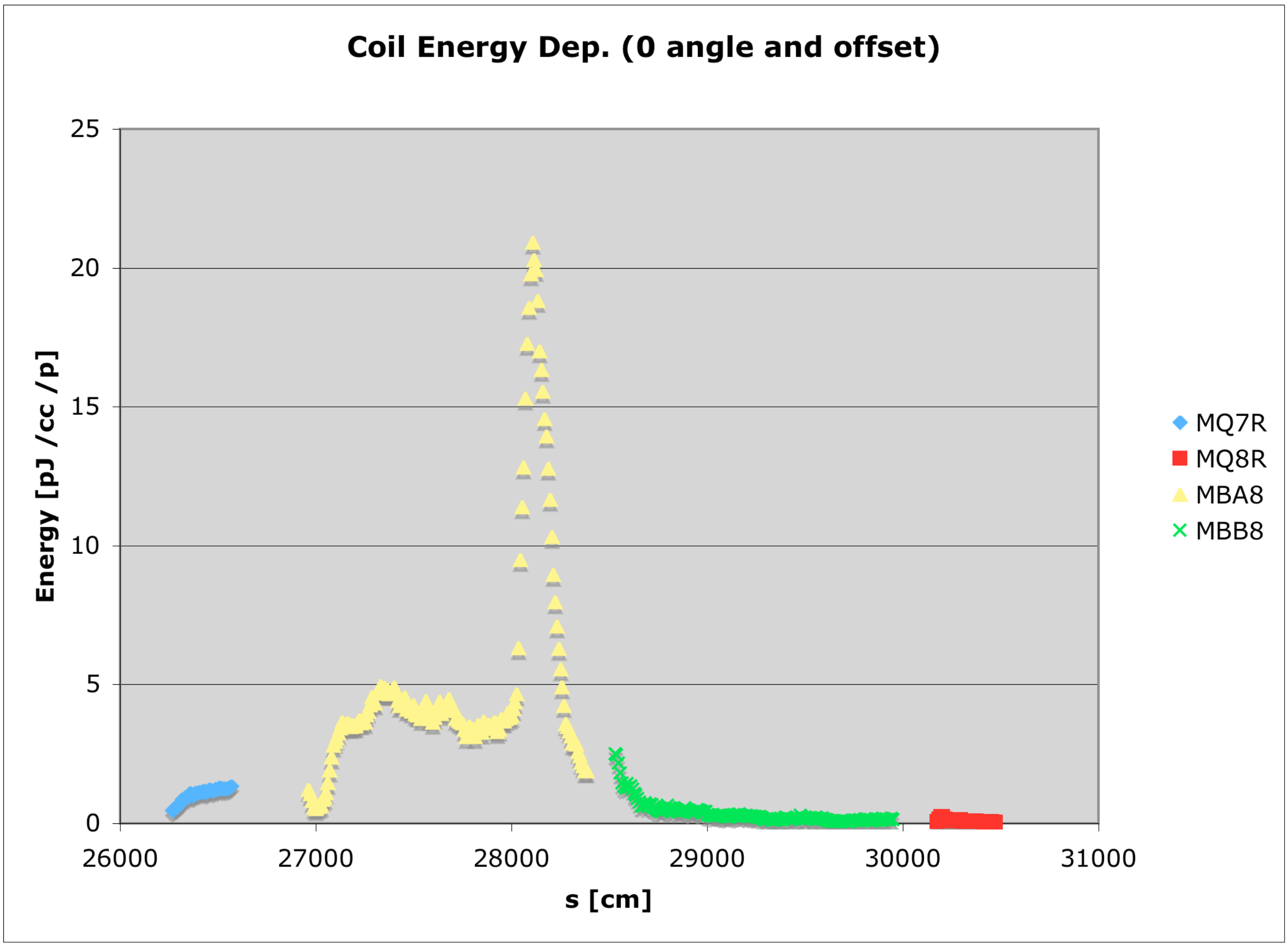
The final sensitivity study concerns an open valve and variation of the impact parameter of the beam. The cases chosen correspond to the valve movement in 1, 5 and 10 turns (2 um, 10 um and 20 um).



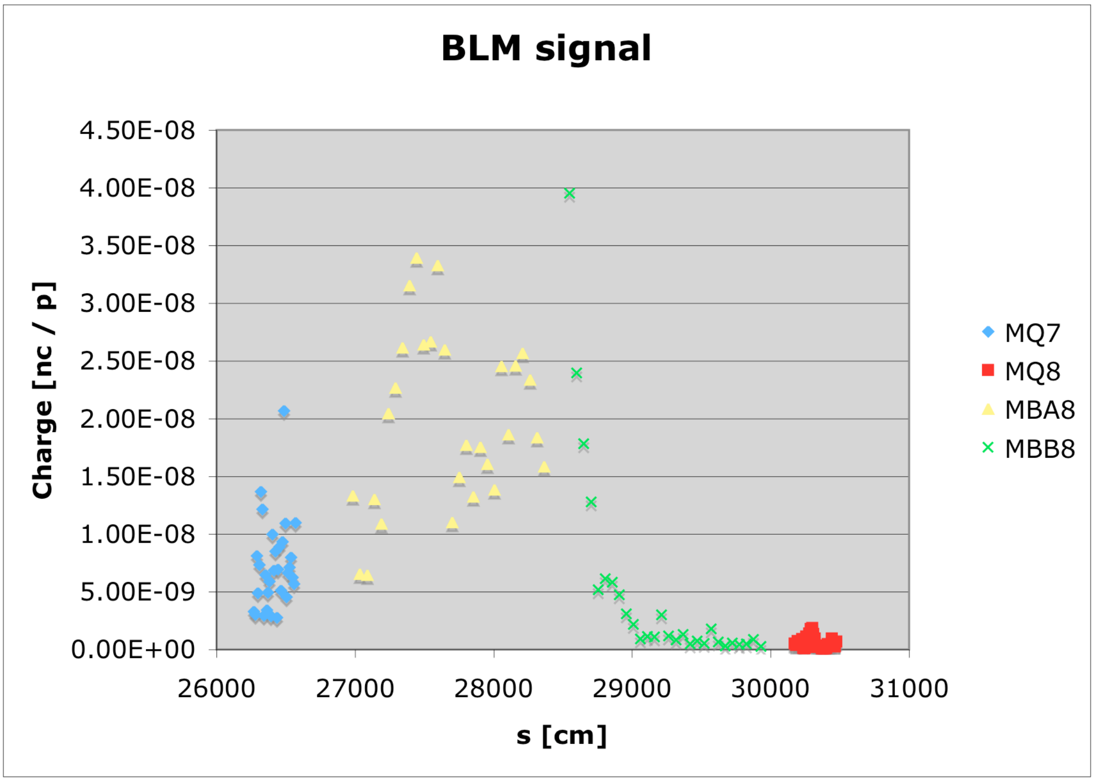
The dependence on impact parameter is weak, and considering the case of 2um impact parameter is sufficient. Also, the 2um open valve case gives similar results to the x=0 closed valve case.

1.4 Detailed study 1 – closed valve at 7 TeV for the study valve

The valve in the closed configuration and an incident pencil beam was simulated to check the MQ and MB coil energy deposition and BLM signal at 7 TeV. The beam is located at x=0. The energy deposition scored in the downstream magnet coils is:



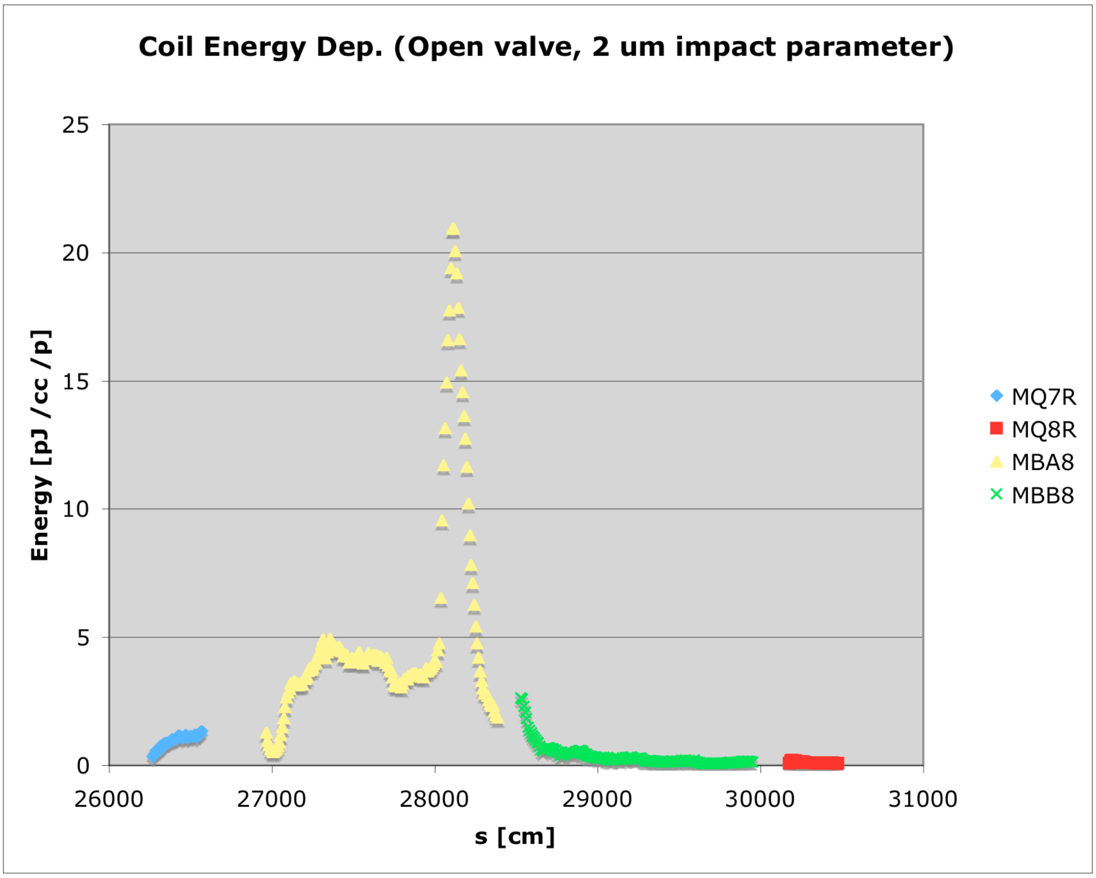
The further downstream elements are not shown, as the energy deposition is very small. The peak corresponds to the coils of MBA8, with a peak valve of 20.9 pJ /cc /proton hitting the valve, with an error of 2.6%. Therefore MBA8 will reach the quench level of 1 mJ /cc when 5E7 protons are incident on the valve face. The peaks in the magnet coils exceeds the peaks in other locations e.g. in the interconnects. The associated BLM signal, scored along the length of all relevant magnets is:



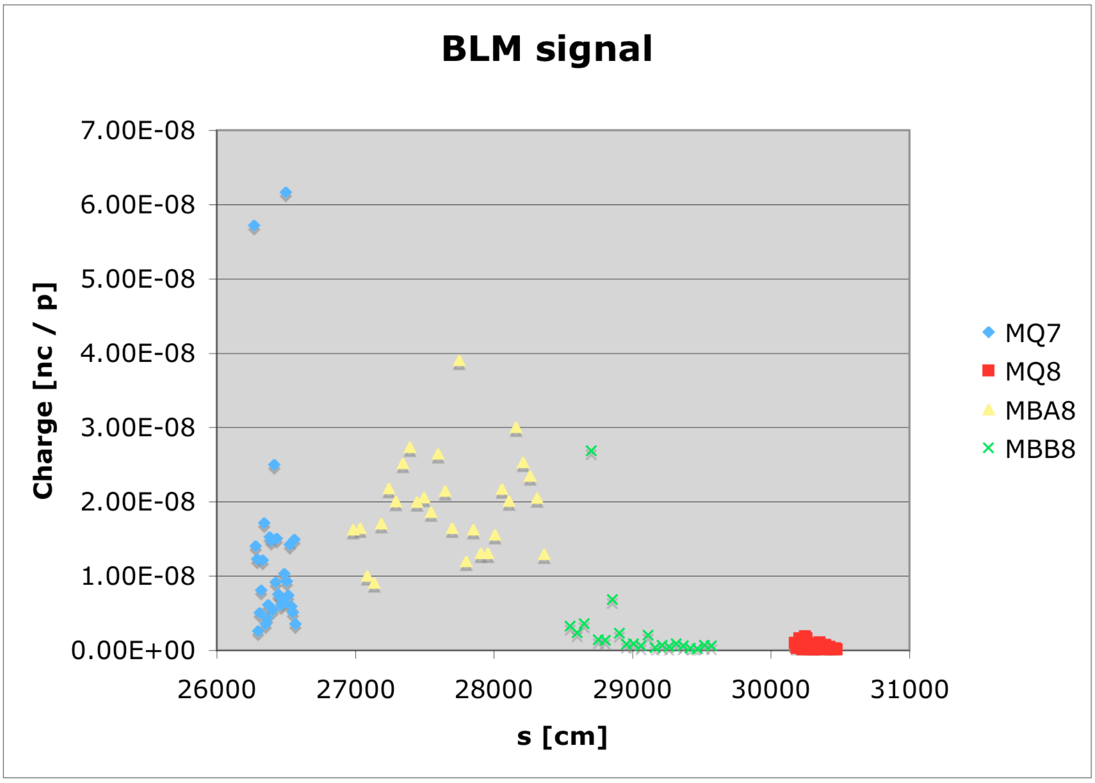
The peak BLM signal of 4E-8 nC /proton is seen in the BLM system of MBB8, with a second peak of 3E-8 nc /proton seen in the BLM system of MBA8. This corresponds to a peak in a theoretical BLM stretching along the length of the magnet and may be slightly larger than the signal seen in the physical BLM. At the quench level of 1 mJ /cc in the coils of MBA8, the BLM signal in MBB8 is 1.9 nC and in MBA8 is 1.6 nC. This is in excess of the BLM threshold and observable.

1.5 Detailed study 2 – open valve at 7 TeV for the study valve

This study was made with an impact parameter of 2 um, corresponding to the distance the valve will close in 1 turn. This was done at 7 TeV. The energy deposition scored in the downstream magnet coils is:



The further downstream elements are not shown, as the energy deposition is very small. The peak corresponds to the coils of MBA8, with a peak valve of 21.0 pJ /cc /proton hitting the valve, with an error of 2.0%. Therefore MBA8 will reach the quench level when 5E7 protons are incident on the valve face. The peaks in the magnet coils exceeded the peaks in other locations e.g. in the interconnects. The associated BLM signal, scored along the length of all relevant magnets is:

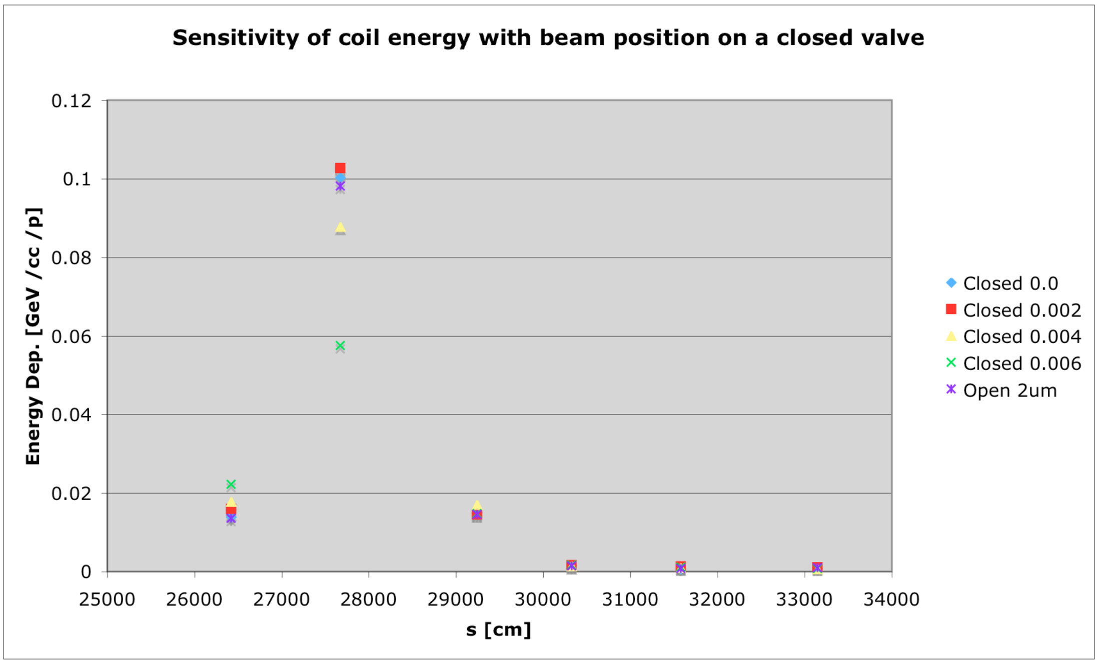


In contract to the closed case, the peak BLM signal of 6E-8 nC /proton is seen in the BLM system of MQ7, with a second peak of 4E-8 nc /proton seen in the BLM system of MBA8. This corresponds to a peak in a BLM stretching along the length of the magnet and may be slightly larger than the signal seen in the physical BLM. At the quench level of 1 mJ /cc in the coils of MBA8, the BLM signal in MQ7 is 2.9 nC and in MBA8 is 1.9 nC. This is in excess of the BLM threshold.

Section 2 – the target valve in the drift before MQ7 at 7 TeV

2.1 Sensitivity study – Closed valve position scan

To assess the dependence on pencil beam initial position, a sensitivity study on the closed study valve was made for a selection of initial beam horizontal position and the dependence on the coil energy deposition (GeV /cc /proton) calculated.

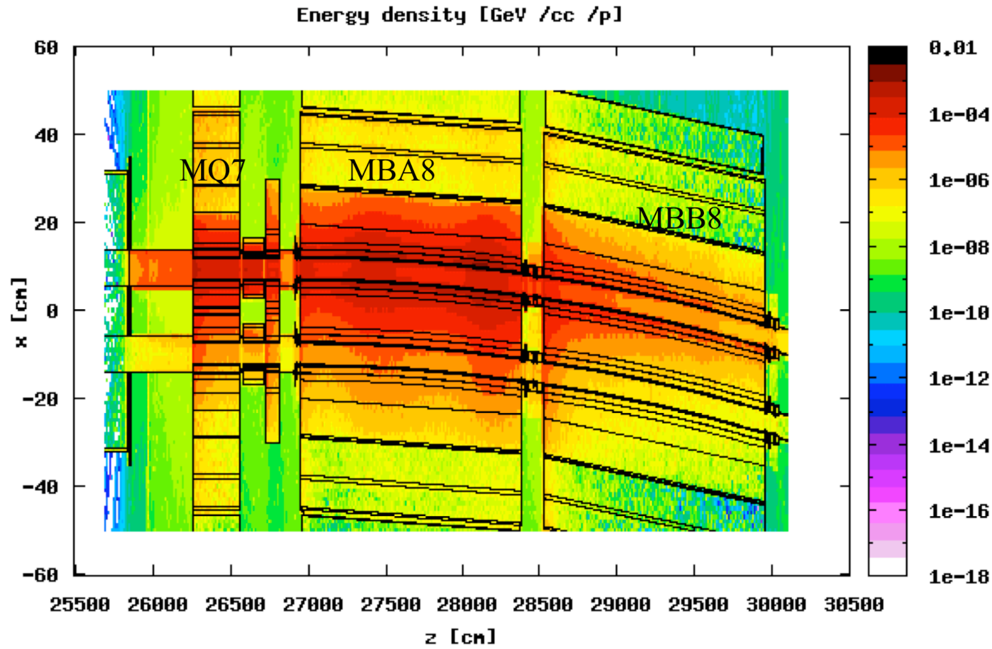


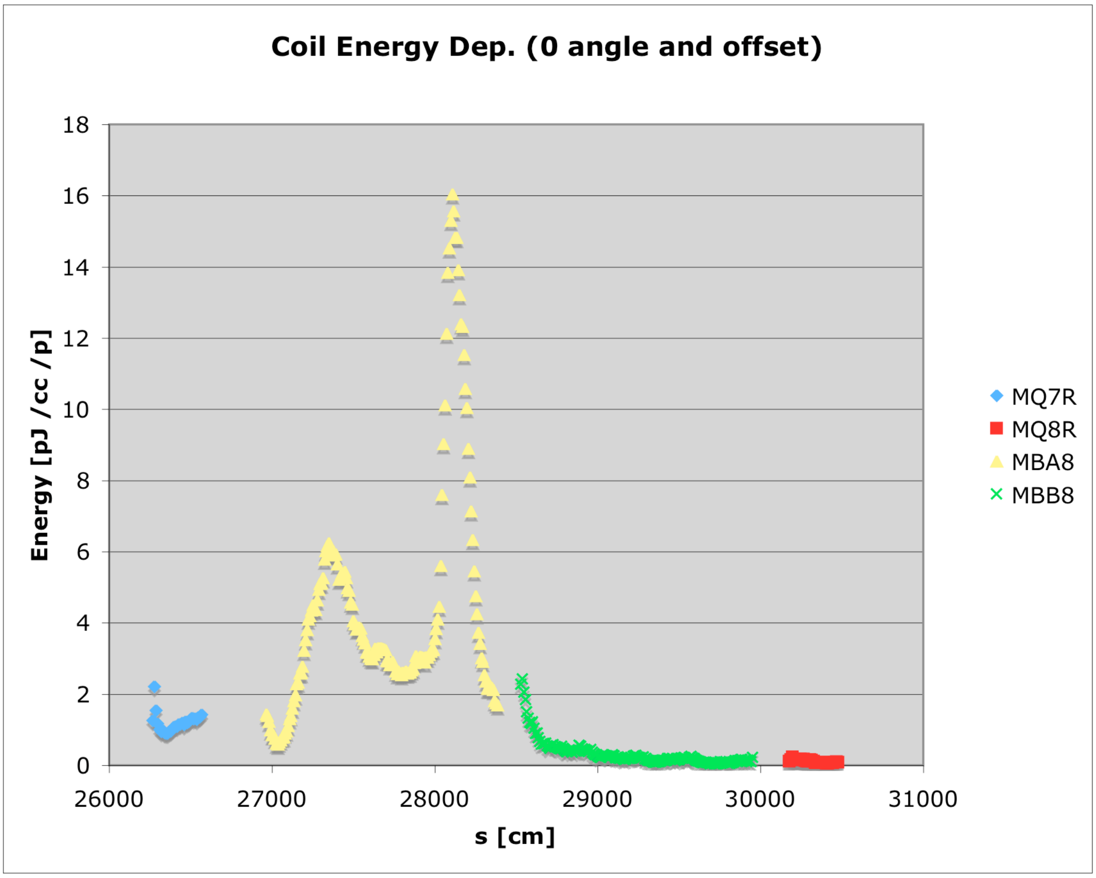
The peak energy deposition along s is plotted, and the valve is located at 25856.65 cm. The first point corresponds to loss in MQ7, and the peak to loss in MBA8. The magnitude of the peak shows some dependence on the initial position, but the peak deposition drops as the beam moves off-axis. The study also shows finds the same conclusion as for the study valve, and the beam incident on an open valve gives very similar peaks to the beam incident on a closed valve.

2.2 Detailed study 1 – closed valve at 7 TeV for the target valve

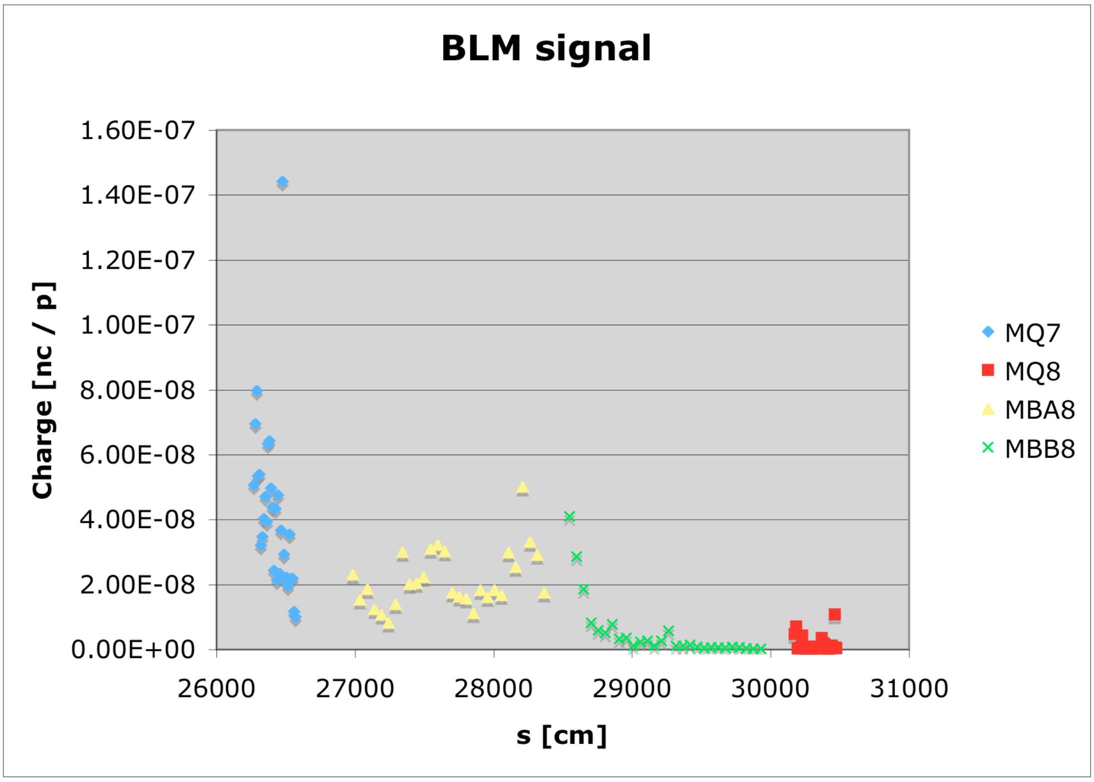
The valve in the closed configuration and an incident pencil beam was simulated to check the MQ and MB coil energy deposition and BLM signal at 7 TeV. The beam is located at x=0. The energy deposition, with the peak in MBA8 looks like:

The energy deposition scored in the downstream magnet coils is:





The further downstream elements are not shown, as the energy deposition is very small. The peak corresponds to the coils of MBA8, with a peak valve of 16.1 pJ /cc /proton hitting the valve, with an error of 3.6%. The energy deposited into MBA8 is reduced for the case of the target valve, as this valve is further from MBA8 than the study valve. However the energy deposited into MQ7 has increased by a factor of 2 for the target valve case. MBA8 will reach the quench level of 1 mJ /cc when 6E7 protons are incident on the valve face. The peaks in the magnet coils exceeds the peaks in other locations e.g. in the interconnects. The associated BLM signal, scored along the length of all relevant magnets is:



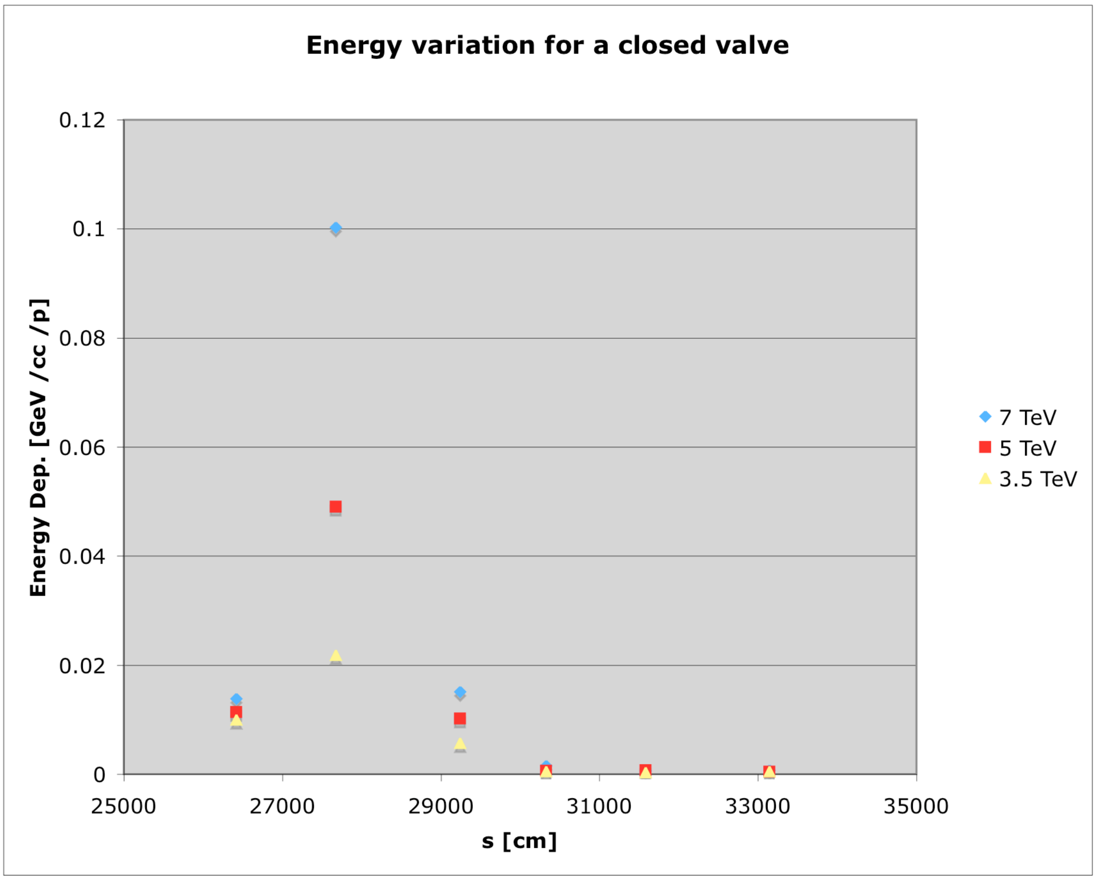
The peak BLM signal of 1E-7 nC /proton is seen in the BLM system of MQ7, with a second peak of 5.E-8 nc /proton seen in the BLM system of MBA8. This corresponds to a peak in a BLM stretching along the length of the magnet and may be slightly larger than the signal seen in the physical BLM. Note the BLM peak is seen in the BLMs of MQ7 for the target valve, as opposed to in MBA8 for the study valve. At the quench level of 1 mJ /cc in the coils of MBA8, the BLM signal in MQ7 is 9.0 nC and in MBA8 is 3.1 nC. This is in excess of the BLM threshold. Note the BLM threshold is also exceeded in the BLM of MBA8. The conclusions for the closed valve will also apply for the open valve with an impact parameter of 2um, as found for the study valve case.

The BLMs can see a signal of pCs, for an integration time of 40 us. For this case, the BLM sees 1E-7 nC / proton, and so will reach the BLM threshold when 1.E5 protons are incident on the valve, which is 8.E-7 of a nominal bunch (1.3E11 protons). Similarly, the quench level is reached when 6E7 protons are lost on the valve, which is 5E-4 of a nominal bunch. The beta-function here is 112m in the horizontal plane, so assuming a normalised emittance of 3.75E-6 m.rad and a Gaussian distributed bunch, the number of incident protons reaches the BLM threshold level when the valve is 1.2mm from the beam-pipe centre, and the magnet quench level when the valve is 0.78mm from the beam-pipe centre (assuming a centred beam). In this time between these events the valve moves 4.2E-4/0.02 m/s, which is 21 ms. Therefore the BLM sees a signal 21 ms (236 turns) before the quench level is reached. This crude calculation assumes a perfectly Gaussian bunch but shows there is sufficient reserve.

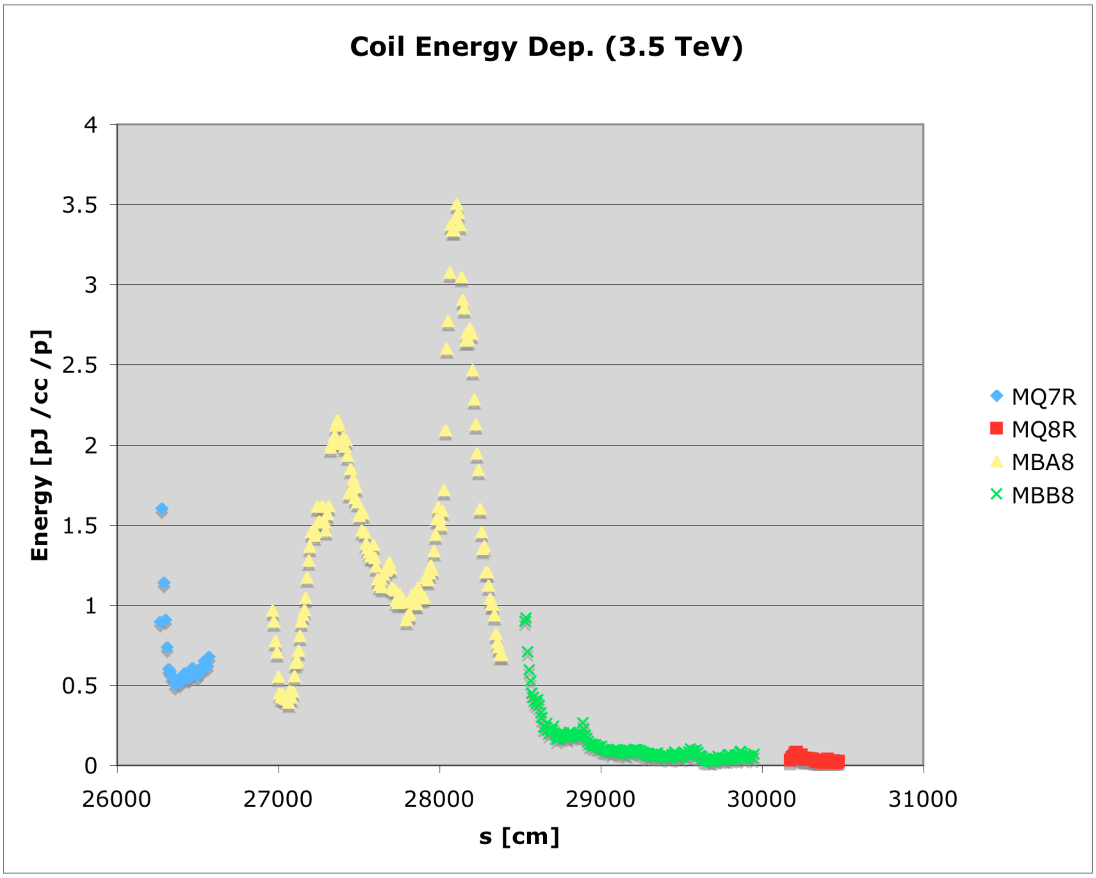
Section 3 – other cases of interest

3.1 The target valve at 3.5 TeV and 5 TeV

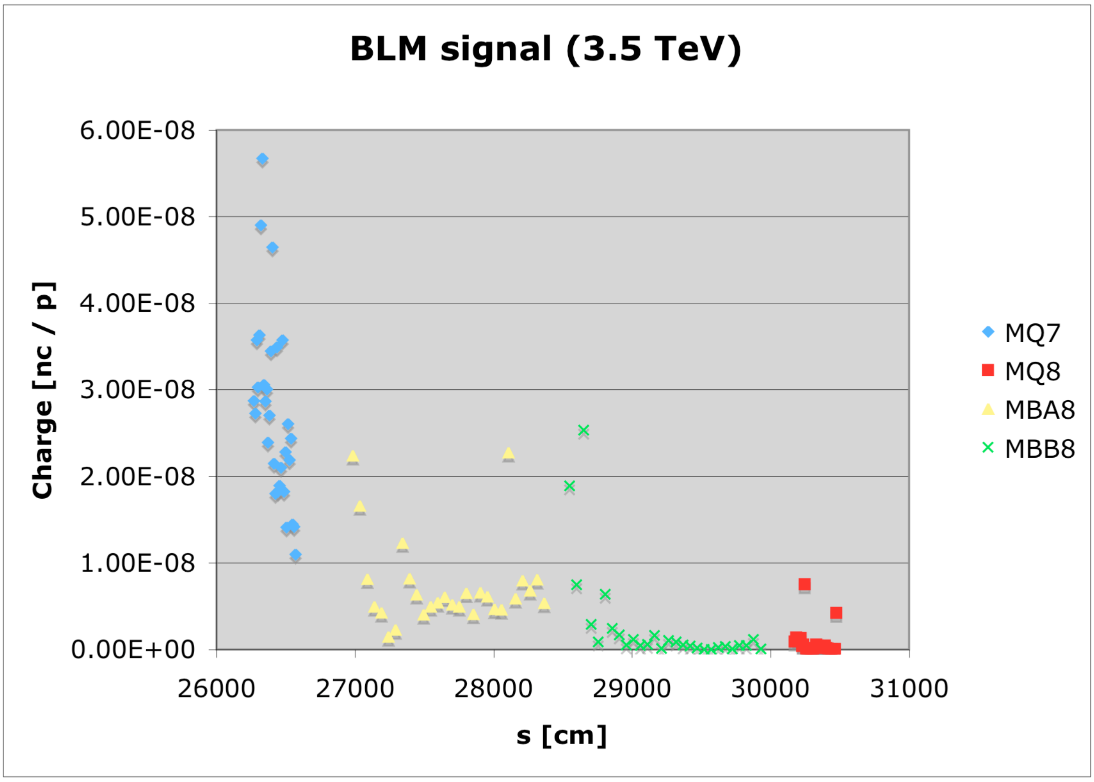
In this section, the target valve in the drift immediately before MQ7 is studied at beam energies of 3.5 TeV and 5 TeV for the case of a closed valve and a central beam position. For these energies the quench levels are taken to be 3 mJ /cc at 5 TeV and 9 mJ /cc at 3.5 TeV. For the lower energy cases the fields in the magnets and beam energy were scaled by the appropriate amount, but all other normalisation factors remain the same. The location of the coil energy deposition peak for the three energies is:



The first point corresponds to MQ7, and the peak is located in MBA8 for all three energies. The magnitude of the energy deposition falls with decreasing beam energy. The detailed longitudinal energy deposition scored in the downstream magnet coils is for the case of 3.5 TeV beam energy is:



The further downstream elements are not shown, as the energy deposition is very small. The peak corresponds to the coils of MBA8, with a peak valve of 3.5 pJ /cc /proton hitting the valve, with an error of 2.8%. Therefore MBA8 will reach the quench level of 9 mJ/cc when 3E9 protons are incident on the valve face. The peaks in the magnet coils exceeds the peaks in other locations e.g. in the interconnects. The associated BLM signal, scored along the length of all relevant magnets is:



The peak BLM signal of 6E-8 nC /proton is seen in the BLM system of MQ7, with a second peak of 3E-8 nc /proton seen in the BLM system of MBB8. This corresponds to a peak in a BLM stretching along the length of the magnet and may be slightly larger than the signal seen in the physical BLM. Note the BLM peak is seen in the BLMs of MQ7 for the target valve at 3.5 TeV, in agreement with the 7 TeV case and opposed to the peak seen in MBA8 for the study valve case. At the quench level of 9 mJ /cc in the coils of MBA8, the BLM signal in MQ7 is 146 nC and in MBB8 is 65 nC. This is well in excess of the BLM threshold. Note the BLM threshold is also exceeded in the BLM of MBA8. The conclusion of an easily seen BLM signal at the quench level has been made for the 7 TeV case and for the 3.5 TeV case, and hence applies at the 5 TeV case also. Finally, the conclusions for the closed valve will also apply for the open valve with an impact parameter of 2um, as found for the study valve case.

3.2 Studies at the second (far) valve location at 7 TeV

In this section the second target valve, located after MQ6 at 23526.15 cm, is studied. This valve is relatively far from the cold elements, and separated from the cold MQ7 by the TCLA collimator. For the case of a 7 TeV beam incident on a closed valve, the energy deposition peak is in MQ7 and MBA8, both with 5.4 pJ /cc /p and errors 8.2% and 3.7% respectively. Therefore to reach the quench level 2E8 protons needs to be incident on the valve. The peak BLM signal is seen in BLMs of the TCLA, where BLSA7R1 sees 7.5E-8 nC / p, and so a signal of 15 nC.

Section 4 – conclusions

A summary of the results are:

i) The case of 7 TeV beam with a closed valve located immediately before MQ7. MBA8 receives a peak of 20.9 pJ /cc /proton with an error of 2.6%, and so MBA8 will reach the quench level of 1 mJ/cc when 5E7 protons are lost on the valve. At this level the BLM on MBB8 sees 1.9 nC of charge, and the BLM on MBA8 will see 1.6 nC of charge.

ii) The case of 7 TeV beam with an open valve located immediately before MQ7. MBA8 receives a peak of 21.0 pJ /cc /proton with an error of 2.0%, and so MBA8 will reach the quench level of 1 mJ/cc when 5E7 protons are lost on the valve. At this level the BLM on MQ7 sees 2.9 nC of charge, and the BLM on MBA8 will see 1.9 nC of charge.

iii) The case of 7 TeV beam with the closed valve located in the drift before MQ7 (target valve). MBA8 receives a peak of 16.1 pJ /cc /proton, with an error of 3.6%, and so MBA8 will quench when 6E7 protons are lost on the valve. At this level the BLM on MQ7 sees 9.0 nC of charge, and the BLM on MBA8 will see 3.1 nC of charge.

iv) The case of 3.5 TeV beam with the closed valve located in the drift before MQ7 (target valve). MBA8 receives a peak of 3.5 pJ /cc/ proton, with an error of 2.8%, and so MBA8 will quench when 3E9 protons are lost on the valve. At this level the BLM on MQ7 sees 146 nC of charge and the BLM on MBB8 sees 65 nC of charge.

Valve location	Config	Energy	Peak	mJ /cc /p	Error %	Quench level mJ /cc	# p's to quench	BLM sig.	BLM sig. nC /p	nC	Time
Study	Closed	7 TeV	MBA8	20.9	2.6	1	5E7	MBB8	4E-8	1.9	2.3 ms
Study	Open	7 TeV	MBA8	21.0	2.0	1	5E7	MQ7	6E-8	2.9	2.4 ms
Nominal	Closed	7 TeV	MBA8	16.1	3.6	1	6E7	MQ7	1E-7	9.0	2.6 ms
Nominal	Closed	3.5 TeV	MBA8	3.5	2.8	9	3E9	MQ7	6E-8	146	4.1 ms
Nominal	Closed	5.0 TeV	MBA8	7.8	2.5	5	4E8	MQ7	8E-8	32	3.3 ms

The conclusions of this study are

1) For the case of a valve located inside MQ7, the results are consistent with previous studies made of a point-like loss inside a quadrupole leading to a quench. A complete study would include a real particle distribution, but a pencil beam analysis is sufficient to draw order of magnitude conclusions.
2) For the case of a valve located close to a SC element, or located several metres before a SC element, the quench levels in the coil are not sensitive to a beam incident on a closed valve, or a beam incident onto an open valve with range of impact parameters. The location of the BLM peak signal at the quench level may change, but this is not significant.
3) For the valve longitudinal locations considered, the quench levels in the coil are not sensitive to a beam position on the valve, or to the initial beam angle within limits. This is consistent with previous studies.
4) The number of 7 TeV protons needed to quench a downstream magnet when the closed valve is located immediately before MQ7 is the order of 1.E7. This is consistent with previous studies of objects left in the beam, and the BLM

current level is consistent with the studies of the energy deposition into the Lyra.

5) When a valve immediately before a SC magnet impinges on the beam, the signal seen in the downstream BLMs exceeds the threshold of the BLM well before the quench level is reached on the downstream magnets.
6) When the valve is located in the drift before the SC magnet, the BLMs still see signal before any downstream magnets quench. The precise geometry of the BLM signal and the coil energy deposition depends on the relative positioning the valve, the magnets and the BLMs, but is safe in the typical geometries considered.
7) The BLM will see a signal 2.1 ms before the quench limit is reached, for a 7 TeV beam impinging on a closed target valve.
8) The BLMs close to the TCLA will see a signal before the quench limit, for the case of a 7 TeV beam impinging on a closed distant valve.
9) The margin of BLM sensitivity is larger for the 3.5 TeV and 5 TeV cases.