Quench levels and transient beam losses at HERA

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Abstract

The talk recalls the main parameters which defined the expected (in 1985) beam loss generated quench levels and compares the results with measurements of loss induced quenches at HERA in 1994-2005. The parameters of the BLM system (e.g. calibration, positioning, alarm level, etc.) are discussed and the response of the system to beam loss induced quenches with different time constants are analyzed.

Introduction

The electron-proton collider HERA started its operation in 1992. The HERA proton ring has more than 1000 superconducting (s.c.) magnets: 422 s.c. main dipoles, 224 s.c. main quadrupoles and 600 s.c. correction coils. The momentum of the protons spans 40 GeV/c at injection to 920 GeV/c (820 GeV/c from 1993 – 1998) at top energy. The magnetic field in the superconducting dipoles reaches 5.1 T at 920 GeV/c (4.7 T at 820 GeV/c). Studies were done during the design phase of HERA to guarantee a stable operation of the s.c. magnets without a significant number of quenches. One of the tasks was to establish a reliable beam loss monitor (BLM) system to avoid beam loss induced quenches of the magnets. Details of the BLM system can be found in Refs. 1-4. In this report the basic parameters of the system will be extracted and compared with data taken over the HERA running period between 1993 to 2005. The emphasis is on the comparison between the expected and measured beam loss rates which were below and above the quench level.

Originally the maximum momentum of HERA was designed to be 820 GeV/c, in 1998 the maximum momentum was increased to 920 GeV/c. This increase required a reduction of the liquid Helium temperature from 4.4 K to 4.0 K and an increase of the maximum current from 5025 A to 5500 A. The main parameters of the BLM system were calculated for a maximum momentum of 820 GeV/c but no major changes were necessary for the increased momentum.

In the context of this workshop, this report will give an idea of how the HERA BLM parameters were determined. Therefore all calculations in this report are based on the knowledge of the years before 1990. Since the BLM system has worked over the HERA operation time as expected and without significant changes, no other parameter settings were necessary and therefore no subsequent calculations have been done.

Energy deposition in magnets due to beam losses (quench level)

Quench level of a cable at 820 GeV/c

The HERA s.c. cables are built of NbTi filaments in a copper-matrix with a superconducting fraction of the cable of $\varepsilon = 0.36$ and with a cross section of $\approx 10 \times 0.15$ mm^2 (Rutherford type cable, 24 strands, 10-12 µm filament size). The magnetic field at the dipole coil is B = 5 T (4.7 T in the gap) at 820 GeV/c. The coils are cooled by liquid supercritical Helium with a bath temperature of $T_b = 4.4$ K (820 GeV/c operation). The typical critical values for quenching such a cable are (Refs: 5, 6):

Critical Magnetic field:	$B_c = 14.5$ T,
Critical current density[1]	$J_c = J_c$ (B, T)
HERA operating current:	$J_{op} \approx 0.7 \cdot J_c = 5025$ A
Critical Temperature:	T_c (B=0, I=0) = 9.2 K;
	$T_c (B, I=0) = T_c (0) \cdot (1- (B/ B_c))^{0.59}$

Current sharing temperature:

$$T_{cs} (B,I) = Tb + (T_c(B, I=0) - Tb) \cdot (1 - J_{op}/J_c)$$

⇨ $T_{cs} (B, J_{op}) = 5.2$ K

Therefore the temperature difference between the He-bath T_b and the critical temperature T_{cs} is:

$\Delta T_c = T_{cs} - T_b = 0.8$ K

The heat capacity c_p of the Copper-NbTi cable is (Ref. 6):

$c_p = 10^{-3} \cdot \varepsilon \cdot \{(6.8/\varepsilon + 43.8) \cdot T^3 + (97.4 + 69.8 \cdot B) \cdot T\}$ [mJ/cm^3 · K]

⇨ $c_p = 2.63$ mJ/cm$^3 \cdot K^{-1}$ (at 4.4 K)

An energy deposition of

⇨ $E_{dep} = 2.1$ mJ/cm^3

is needed for a temperature increase of $\Delta T_c = 0.8$ K (at 820 GeV/c) which will lead to a quench of the cable.

The calculated value of $E_{dep} = 2.1$ mJ/cm^3 was compared with other s.c. magnets from various references (before 1990):

(at nom. energy of the accelerator) (cable parameters: $\rho = 7.9$ g/cm^3, area = 0.15 cm^2)

Tevatron:	$\Delta T_c = 1$ K;	Edep = 0.5 mJ/g	= 3.9 mJ/cm3;	Ref. 7
SSC Magnets:	$\Delta T_c = 0.6$ K ;	Edep = 0.2 mJ/g	= 1.6 mJ/cm3;	Ref. 8
Fermilab Energy Doubler:	$\Delta T_c = 1.4$ K ;	Edep	= 9.8 mJ/cm3;	Ref. 9

The enthalpy H for the HERA s.c cables at all beam energies can be calculated by

$H(T) = \int_0^T c_p \, dT$ [mJ/cm^3]

while the difference of the enthalpy ΔH at T_{cs} and T_b gives the energy density which is required to quench a cable (Ref. 10, 11):

$\Delta H = H(T_{cs}) - H(T_b)$;

Fig 1 shows the result for the HERA cable within HERA's beam energy range.

[1] For detail of J_c(B,T) see Ref. 5

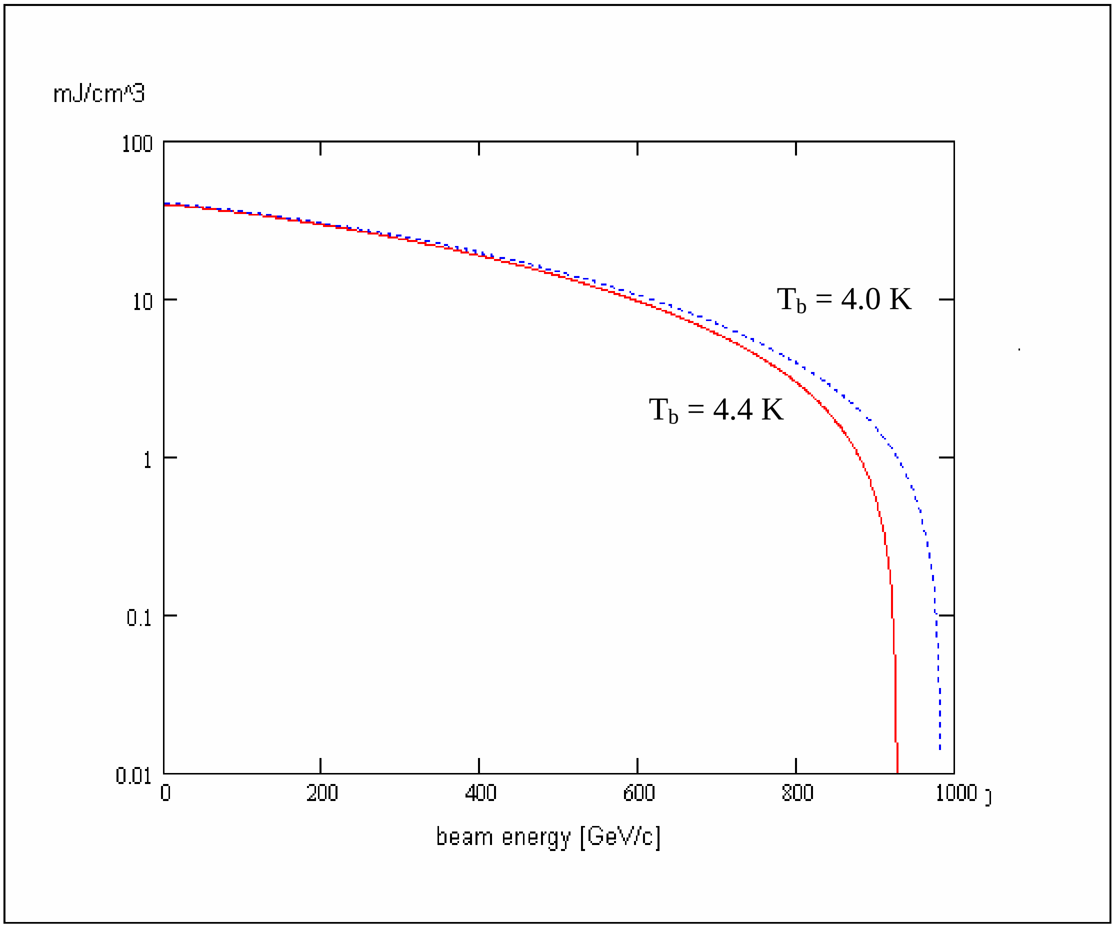


Fig. 1: Energy density required to quench a s.c. HERA cable. Two different He-bath temperatures were assumed to show the necessary reduction of Tb for the 920 GeV/c upgrade.

More detailed calculations done later (Ref 12) with the concept of a minimum propagation zone led to the result that “an energy of 1 mJ would be sufficient to heat a 12 mm long section of the HERA cable above the critical temperature”. This gave an energy deposition of E_{dep} = 6.6 mJ/cm^3. For the calculations of the BLM parameters this value was not used and was kept as a safety margin.

Tolerable beam loss rates, energy deposition due to beam losses

Monte Carlo calculations were performed to simulate beam loss and the corresponding energy deposition in the coils. The critical loss was determined from the critical energy deposition in 1 cm^3 coil volume (the hot spot at the ends of the coil). Note that the calculations in the previous chapter assumed an instantaneous energy deposition. A BLM system always needs some kind of continuous losses which are integrated by the BLM system over a small time period before any action from the BLM system can be taken. A BLM system cannot protect against instantaneous losses. Therefore an experience from Tevatron was taken into account (Ref. 13) in which beam loss induced quenches had been observed at a continuous loss dose (/s) of 16 times higher than the instantaneous loss dose[2]. This factor of 16 was used to define a critical continuous proton loss rate [p/s] from the calculated critical instantaneous loss (see Fig. 2). But note that this factor was never verified for the HERA magnets.

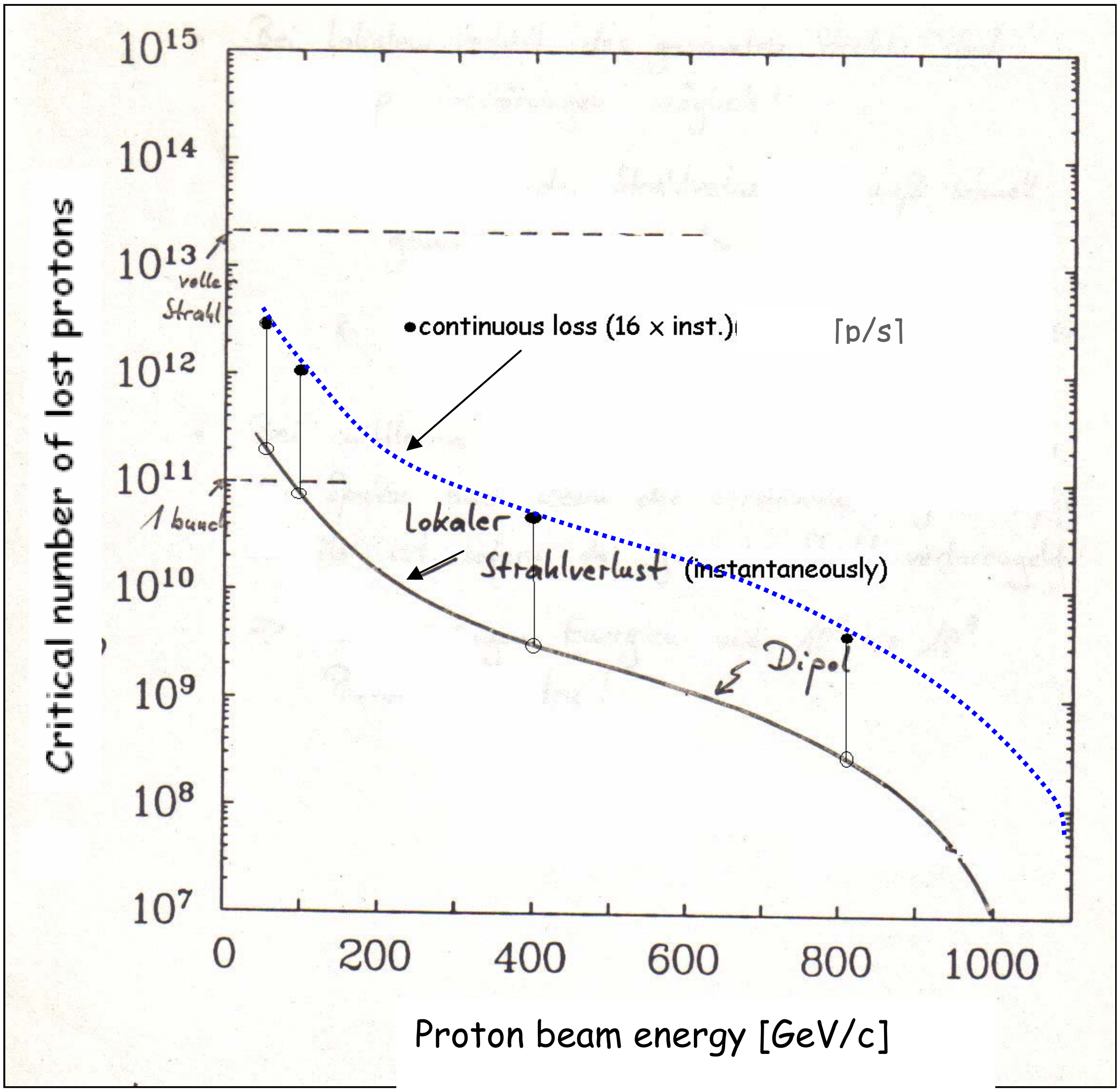


Fig. 2: Critical instantaneous proton loss calculated by Monte Carlo calculations (Ref. 14). The dotted line represents the factor 16 higher continuous proton loss rate [protons/s] as measured at FERMILAB (Ref.13).

Some additional safety margins were assumed:

- So far all calculations were valid for dipoles, but losses are expected mainly in quadrupoles (Ref. 1). However, since the quadrupoles are constructed with the same cable, they have the same cryogenic system and therefore the same temperature, it is expected that the maximum excitation current will be the same but at the coil one expects a smaller magnetic field B (=> increase T_{cs})

[2] This factor of 16 was verified during this workshop by a talk and comments of N. Mohkov, –FNAL-

- The quench current of all magnets was measured at 4.75 K:
  Mean (± σ): Dipoles 6458 A (± 114 A); Quads: 7383 A (± 148 A).
  Weakest: Dipole: 6154 A; Quad: 6518 A.
  Calculated with previous formulas: J_c = 6340 A.
- The accepted loss rate should be ≤ 1/10 of the critical loss rate.

The BLM time response was chosen to match the cryogenic time constant of the magnets. This time constant was measured at the TEVATRON to be 16 ms (Ref. 13). The decision for HERA was to measure continuous loss rates in 5.2 ms intervals (= alarm time binning). This number was chosen to avoid potential 50 Hz noise integration.

Response, calibration and settings of BLMs

The BLM system of HERA is described elsewhere in detail (Ref. 1-4). The basic idea of the system is to count the loss rate in the quadrupoles and on other locations where the aperture is limited. The maximum count rate of a BLM depends on the bunch repetition rate of HERA (maximum = 10.4 MHz). The PIN diode BLMs are located near the end of the quadrupoles and are sensitive to charged particles crossing the diodes. Charged particles are generated by beam losses inside the quadrupoles. Monte Carlo calculations with the Gheisha 8 code were made to simulate such losses and the number of charged minimum ionizing particles (MIPs) crossing the BLM detector area was computed (Ref 3). Fig. 3 shows results of the Monte Carlo calculations for the superconducting quadrupoles of HERA.

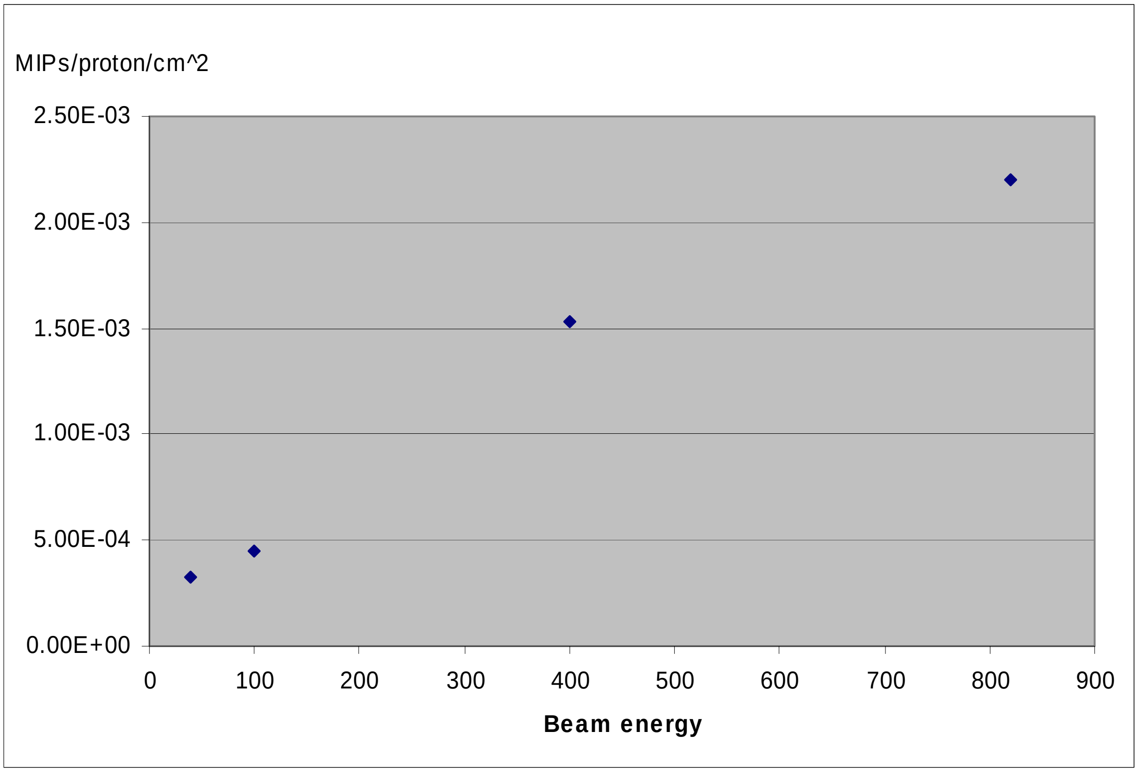


Fig. 3. Number of MIPs crossing 1 cm^2 BLM detector area. The area of the PIN diode is 2.75 x 2.75 mm^2.

The result is a mean value over a length of about 2 meters since the shower which reaches the outside of the cryostat is distributed approximately over this length. This means on the other hand that the beam loss location can vary within this length without changing the response of the BLM very much. Typical losses were expected to occur within the first half of the quadrupole (approx. 1 m). The radial distribution of the MIPs at the BLM position was found to be isotropic. It should be noticed that at that time the code Gheisha 8 was not able to handle magnetic fields in the simulation. Therefore all calculations were done without magnetic field in the quadrupole. This may change the Monte Carlo result due to asymmetries in the magnetic field.
The sensitivity of the BLM to MIPs was measured to be $\varepsilon_{blm} = 0.348 \pm 0.019$ counts/MIP (Ref. 3, 4)[3]. The sensitivity of the BLM to a lost proton was given by a simplified fit to the data:

1 count = $1.5*10^7/p$ [lost protons] with p = momentum of lost proton [GeV/c].

Fig. 4 shows the expected critical proton loss rate together with the threshold settings of the BLM system in terms of lost protons and in the related count rates of the BLM on a superconducting quadrupole. The allowed count rate (threshold) was set somewhat arbitrarily fulfilling the requirement of $\leq 1/10$ of the critical loss rate.

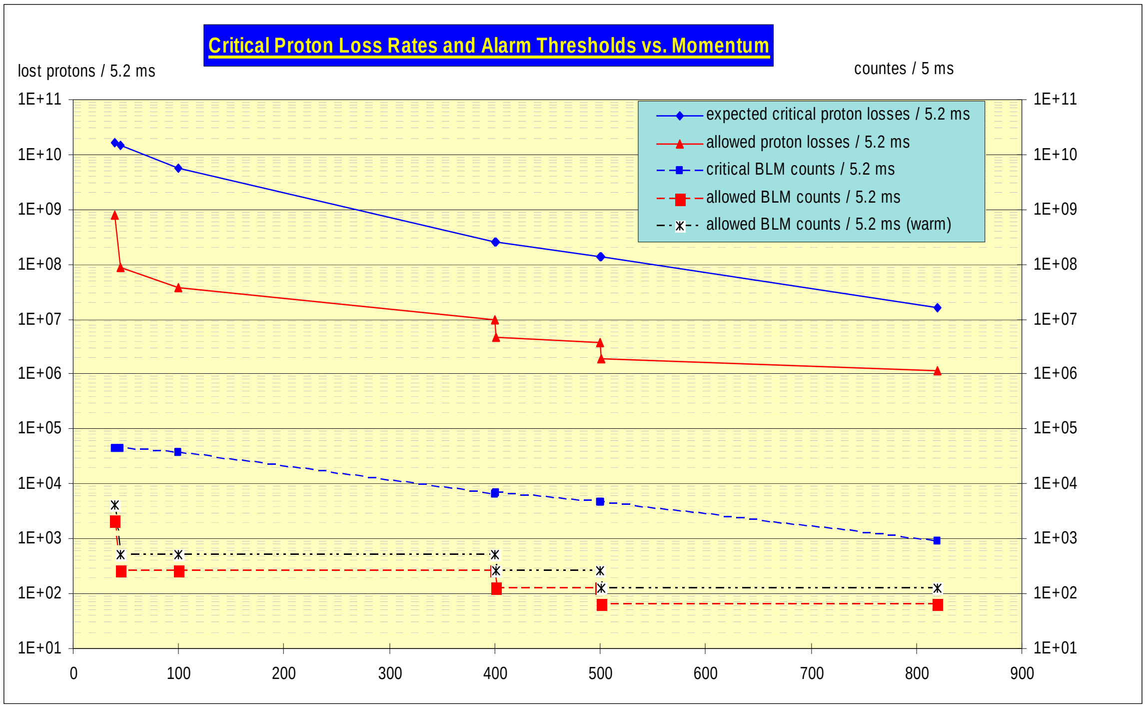


Fig. 4: Critical Loss rates and alarm thresholds versus momentum. The count rates already include the sensitivity of the BLM to lost protons at certain energies.

The HERA alarm system was set to accept 4 different BLM count rates above the threshold (p > 40 GeV/c) within a 5.2 ms interval before firing the beam abort system. The main idea behind this was to be insensitive to failure readings of a single BLM and

[3] Note that the given sensitivity of Ref. 3 had to be corrected due to the measurements of Ref. 4 to the value given above.

the expectation that losses will always occur at several aperture limits in the machine. Note that the aperture limits in HERA are located in the “warm” (room temperature) parts of the machine, where no danger of quenches exists. Therefore the thresholds of the “warm” BLMs were set a factor 2 higher. Over the years and with increasing experience with the system, some BLMs at specific (mostly in warm) locations required individual threshold settings to cover typical loss patterns. The whole BLM system covers the cold part of the machine, the warm parts around the interaction point (IP) and the collimators, all with individual thresholds and BLM sensitivities.

Experience with beam loss induced quenches (1994-2005)

The BLM alarm system has worked very reliable since the beginning of the HERA operation. Until the end of 2004 about 1000 BLM induced beam aborts occurred without quenching a magnet. However, 205 additional beam loss induced quenches occurred due to various problems. A detailed analysis of the problems can be found in Ref. 15. 64% of the beam loss induced quenches occurred due to beam losses with a time scale faster than 5.2 ms. These very fast losses were caused by injection errors, trips of special power supplies (Mini-β quadrupoles) and RF trips and were often located in the superconducting part of HERA. These losses occurred faster than the response time of the BLM alarm system; therefore the system was not able to dump the beam before a quench occurred. In the following, these types of losses were not analyzed, because of probable saturation of the BLMs within the unknown short time period of the beam loss.

The remaining 36% of the beam loss induced quenches are caused by losses which occurred over much longer time periods. In principle the BLM system should avoid these type of quenches but there are two different kinds of problems which had prevent the system to abort the beam in time:

1) The alarm system of HERA “lost” its threshold of 4 BLMs and was erroneously set to a much higher value. Therefore not enough BLMs gave an alarm signal to abort the beam.
2) Less then 4 BLMs were affected due to very localized beam losses. Such localized losses occurred due to unwanted local beam bumps and at the first superconducting magnets after the collimating section of HERA. Unwanted beam bumps were driven by erroneous automatic or operator induced orbit corrections or by longitudinal beam instabilities in the (unfortunately) cold dispersive sections of HERA. The quenches just behind the collimator were driven by accidental motion of the collimator jaws very close to the beam core.

The archive system of the BLMs and of the HERA control system stores the BLM count rates of the last 128 x 5.2 ms = 666 ms and, with a larger time resolution, also the rates of the last 128 x 666 ms = 85 s before any alarm. Since a detection of a quench causes also an alarm (and of course a beam abort), most of the BLM data in these cases can be used to analyze the beam loss rates which had caused the quench. Fig. 5 shows an example of archived BLM data. To compare the measured data with the calculated (expected) count rates (Fig. 4), two values were extracted from the data:

1) The highest mean count rate R_{mean} over all 666 ms intervals (long mode).
2) The maximum count rate R_{max} within a 5.2 ms interval (short mode)

In the example of Fig. 5 R_{mean} = 580/5.2ms (from long mode display) while R_{max} = 1300/5.2ms (from short mode display). Fig. 6 shows the sampled data of R_{mean} and R_{max} of 75 beam loss induced quenches between 1994 and 2005. The results show that the lowest measured rates are about a factor 5 – 10 smaller than the expected rates, for all energies.

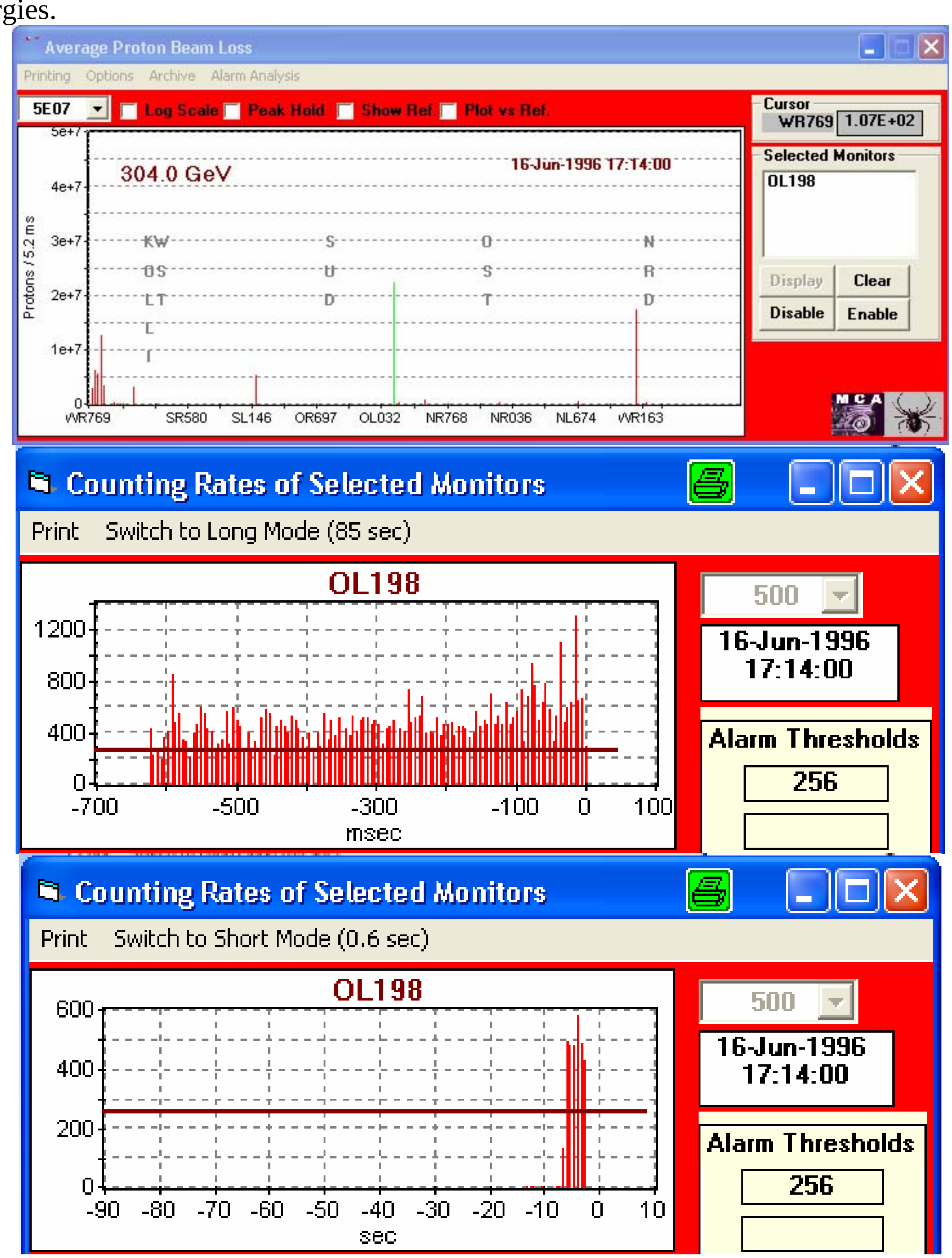
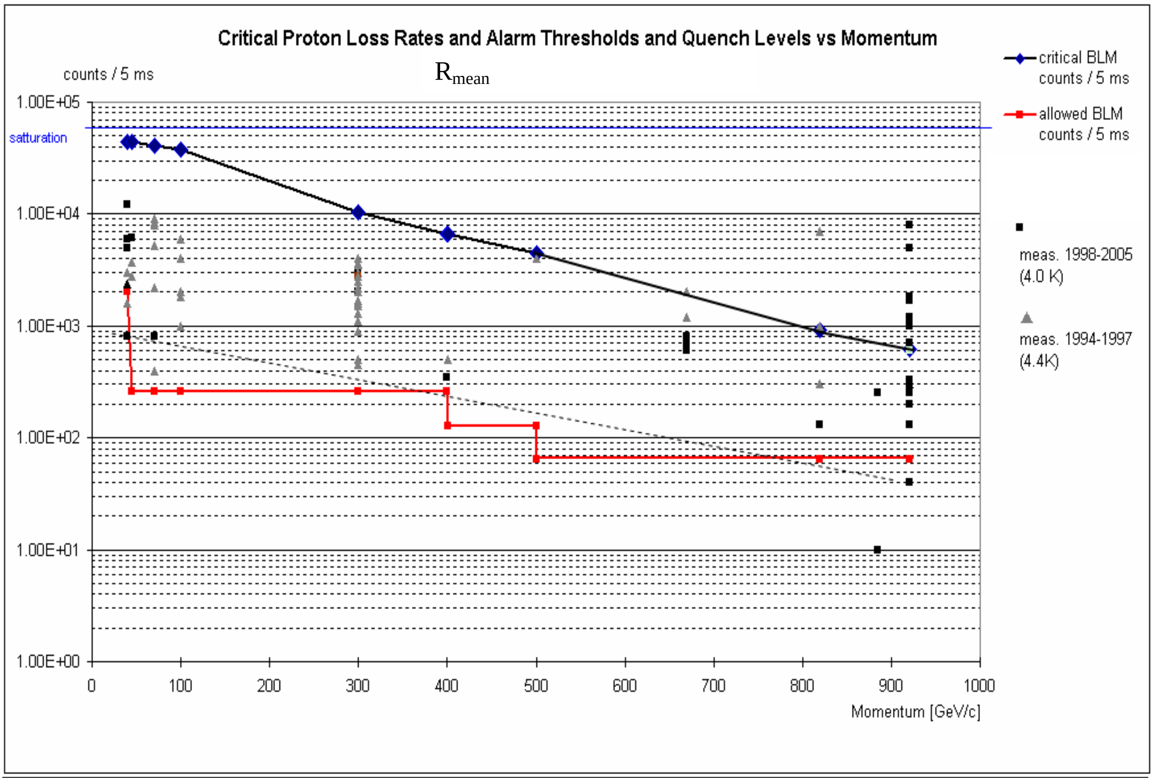


Fig. 5: The upper picture displays the loss distribution around the HERA ring. This example shows a localized loss at the BLM-location at east left 198m (OL198). The picture in the middle shows the OL198 BLM count rates during the last 666 ms (short mode) before the quench alarm at time=0 while the lowest picture shows the mean OL198 BLM count rates over the last 85 s (long mode).



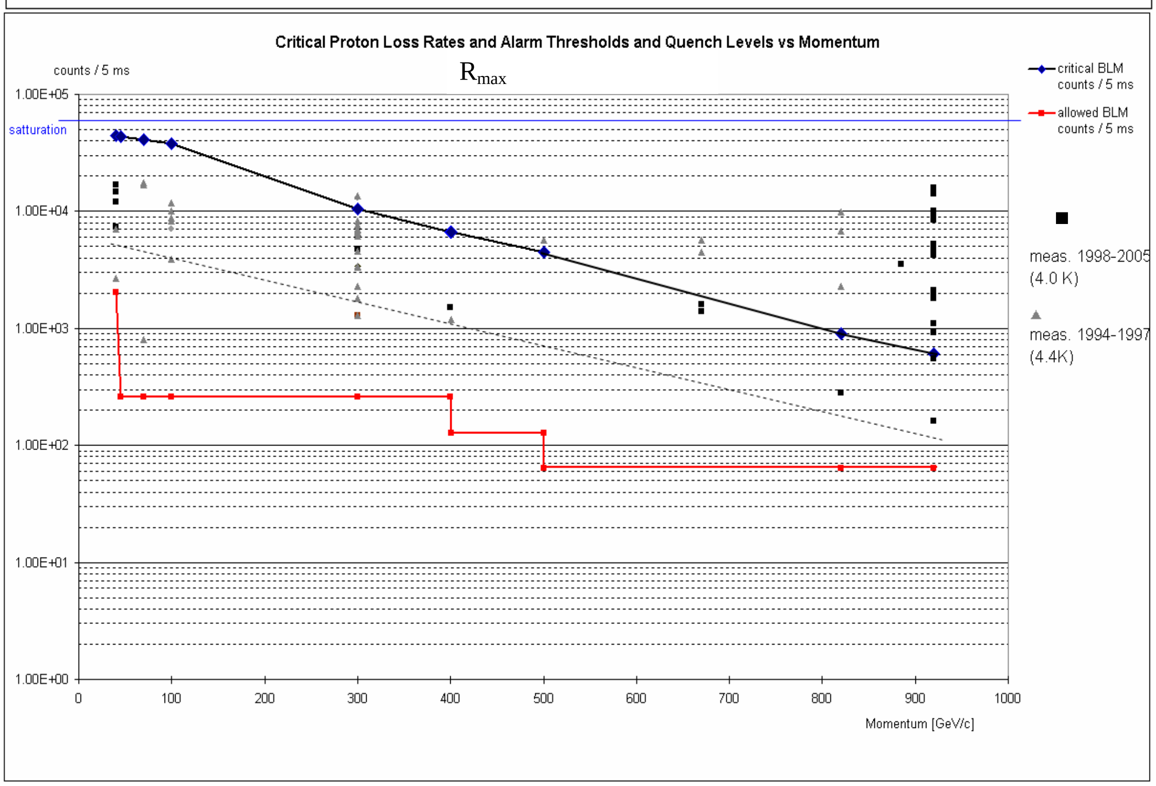


Fig. 6: R_{mean} (upper) and R_{max} (lower) extracted from 75 beam loss induced quenches between 1994 and 2005. The dotted line in both pictures marks the lowest measured value of R_{mean} and R_{max}, respectively.

No differences were observed between the 4.4 K (820 GeV/c) and the 4.0 K (920 GeV/c) bath temperature. The band of data points at certain beam energies are a result of the special operation of HERA. Most of the problems occurred at certain break points in the ramp procedure of HERA (typ. 70 and 300 GeV/c), at the start of the ramp (40 GeV/c) or at maximum momentum (820 or 920 GeV/c). Very few data points (2-3) lie much outside (below) the dotted line. No clear explanations were found for those rare events. But one should note that a detailed analysis of the events was not possible with the limited information in the archive system and with the sometimes rough comments in the logbook.

Note again that the Monte Carlo calculations were done with a code which was not able to include magnetic fields in the tracking of the shower particles. This might be one of the main reasons for the discrepancies between the expected and measured minimum critical loss rates.

The beam loss induced quenches were distributed over the whole HERA ring (Fig. 7). A significant accumulation of quenches occurred at the 198m left locations where HERA has its largest dispersion. Therefore these locations are mainly affected by longitudinal instabilities of bunches. The magnets in the region between WL162 and WL 251 are mainly affected by faulty collimator operation; scattered particles from the jaws of the collimators at WL153 were mainly lost in these following superconducting magnets.

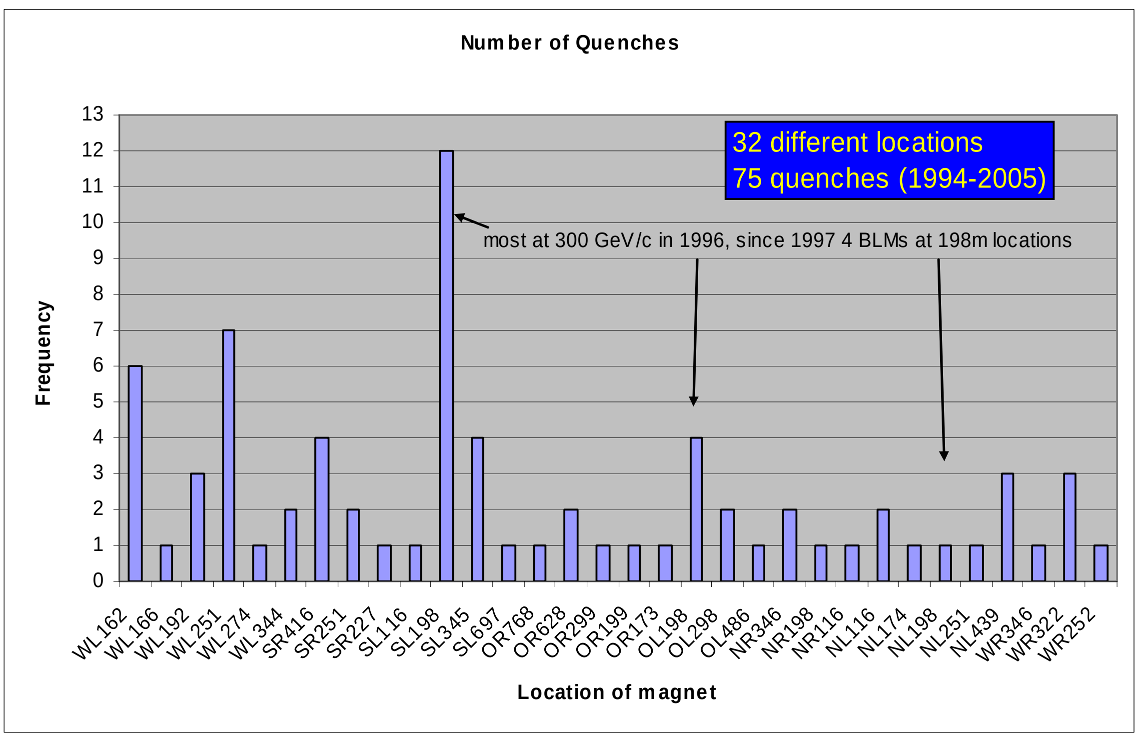


Fig. 7: Distribution of analysed quenches around the HERA ring.

Conclusions (avoiding quenches at LHC)

Calculated and measured beam loss induced quench levels at HERA were compared. The required energy to quench a superconducting cable was calculated as a function of the temperature, current and magnetic field at the magnet coil. These values were used to calculate the maximum allowed beam loss rate inside a superconducting magnet (using the Monte Carlo code Gheisha 8) which led to a critical energy deposition in the coil. The same code was used to calculate the response of beam loss monitors (BLMs) due to beam losses (but unfortunately by different persons without any time overlap), with the assumption that losses will mainly occur in the quadrupoles. These calculations, together with some experiences from TEVATRON, defined a critical signal rate of the BLMs while the threshold of the BLM system was set about a factor 10 below this critical rate. 10 years of experience of the HERA BLM system had shown that this system worked very reliable and within its expected performance. More than 1000 beam aborts were activated by the BLMs, always due to a too high beam loss induced signal rate, but without a quench. However also about 205 beam loss induced quenches occurred. About 64% of these events happened on an unexpected fast time scale of < 5.2 ms, for which the BLM system was not designed for. The remaining 75 beam loss induced quenches happened due to malfunctions of the HERA alarm system and due to very localized losses which affected less than 4 BLMs at the same time. These events were used to compare the expected critical loss rates with measured (quench-) rates. It was found, that the measured critical rate is about a factor 5-10 below the expected critical rate, but various uncertainties have to be to taken into account:

- All Monte Carlo calculations were done without magnetic field. This certainly will influence the calibration of the BLM.
- Tevatron experiences gave a factor of 16 difference between critical instantaneous beam losses and continuous losses. This factor was never verified for the HERA magnets but it was implemented in the HERA BLM design.
- The required energy deposition for quenching a coil was calculated for superconducting dipole magnets while beam losses occurred mainly in quadrupole magnets.

Such a factor 5 – 10 uncertainty is probably not sufficient to design and run a reliable BLM system to avoid dangerous beam losses and quenches at the LHC. Therefore one should learn from the HERA experiences:

- Need of precise Monte Carlo calculations (which include magnetic fields) for energy deposition in superconducting coils and **at the same time** the response of the BLM system.
- Need of precise beam loss scenario calculations with beam loss patterns (place and time) around the ring.

Some general experiences of quenches in HERA:

- Very short losses (<5ms) are possible.
- Very localized losses (long- and short- term) are possible.
- Need of increased weight of BLM thresholds at collimators and other aperture limits (e.g. dispersion).
- Need of flexible thresholds on all BLMs.
- Need of a very reliable alarm system.
- Block injection into a not well prepared machine.
- Beam loss induced quenches can occur everywhere in the ring, no significant dependence on weak magnets was observed.
- Threshold of 4 BLMs is not save enough; sometimes only 1 BLM is affected. But a single BLM alarm might produce to much false beam aborts…

- Other technical subsystems (magnets, RF, …) should give in case of a failure a dump signal.
- Archiving of as much as possible data (Cryo, BPMs, BLM, RF, …) is most helpful for post mortem analysis of events.

Acknowledgements

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