DESY visit on machine protection issues

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HERA-p parameters

- Injection energy: 41 GeV.
- Top energy 820-920 GeV.
- Proton beam current up to 100 mA, 180 bunches.
- The luminosity is on average 300-400 nb^{-1} /day, with 500-800 nb^{-1} for a good day.

Recalling HERA I protection issues

The machine protection systems implemented from the start-up were appropriate for HERA I. The BLMs have an integration time of 5 ms, and beam losses faster than 5 ms were not (or very rarely) observed. There was no need for very fast processing of alarms (alarms at HERA are similar to interlocks leading to a beam dump request at the LHC). After the luminosity upgrade from HERA I to HERA II fast beam losses became a concern.

Overview of HERA II protection issues

HERA is equipped with a so-called alarm-loop that has a similar role to the beam interlock loop of the LHC (more details below). The main clients of the loop in the HERA I period were the MPS (Main Power Supply) and BLM systems, and the two systems worked to satisfaction. Not all failures could be caught, for example warm low-beta quadrupoles with time constants of ~20 ms, but such failures were rare.

With HERA II, the number of critical circuits with small time constants was increased from 6 to 14. Only quadrupole magnets in the low-beta sections of the machine are critical. The time constants for the warm quadrupoles is in the range of 20-100 ms. Warm dipoles have time constants of ~500 ms. In addition to the increased number of critical circuits, the reliability of the PCs was degraded due to aging / insufficient maintenance. The MTBF for the ensemble of these critical circuits was down to ~300 hours. Simulations of PC failures show that for a certain time (few ms) not much happens, but that at a certain moment the beam becomes unstable~~-~~: closed orbit distortions and losses increase exponentially and the beam is lost within 0.5-1 ms (at HERA 1 turn ~ 25 μs). The simulations show that with an interlocks on the beam position (3 mm window) and the BLM system, 83% of the fast failures can be 'intercepted' in time before the beam is lost. The efficiency depends however critically on the collimator settings. Presently the collimators are set to 7σ for physics. They are left open at injection and closed to 10-11σ during the ramp. The fast failures are due to a combination of optics instabilities, tune shifts (fractional tunes 0.28-0.30) and orbit offsets in the quadrupole whose PC fails.

To improve the overall situation, the following actions are/were implemented:

- The MTBF of the critical circuits was increased to 1000-2000 hours by a regular inspection / revision / maintenance of the critical PCs. Extended maintenance procedures are followed for such power converters.
- The processing time of internal alarms (interlocks) in the PC was reduced to 200 μs by generating the interlock signal directly from the gate electronics of the thyristors instead of going via the controlling PLC (which implies longer cycle times).
- An external surveillance of the PC currents is in the development phase ('Magnet Current Alarms').
- A fast interlock on the beam lifetime was developed and made operational.
- The delays in the alarm loop and beam dumping system were minimised.

As a consequence of all those actions, the estimated rate for this fault should decrease to 1 failure in 5 years.

The old distributed BLM system is still sufficient for most slow circuits (the BLM system was designed for a mostly cold machine):

- One BLM per quadrupole, about 1.5 m downstream from the magnet centre
- Dump level depends on energy, changed in the BLM system
- The dump is triggered when losses above the threshold level are observed at a number (5) of BLM stations simultaneously
- Dump levels do not depend on loss duration
- BLMs are used to adjust the collimator positions.

No fast BLM system was designed/added near collimators: there are fast loss transients (duration of a few turns) that could potentially trigger a dump by such a system. The transients disappear again after a couple of turns and may lead to a considerable reduction of the reliability of the machine. The size of the losses can reach up to 0.1% of the total beam intensity. They mainly affect the drift chambers of the experiments. The detectors in the experiments are the only monitors that can monitor losses with a resolution better than 5 ms. The spikes may be due to transients on the mains and to messages sent over the electrical network by the electricity companies. Transients of the order of few 10^{-4} are visible on the PC currents despite filtering. The frequency of the messages is ~ several times per hour. Another source is cultural noise (clearly seen in the background of the experiments). There are no problems on the SC main circuits due to the large inductance.

Beam profiles for the HERA proton ring depend on the operational state. Without beam-beam effects, with fresh beam, tails can be suppressed. During beam-beam operation there is the tendency that tails exceeding Gaussian tails develop. Simulations of failure scenarios by F. Willeke assume always Gaussian distributions and a linear machine.

There are indications that about 0.1 % of the beam is lost during such fast beam losses.

Power Converters (J.P. Jensen MKK)

Two types of PCs are in use: PCs using thyristors and switched mode PCs. There are many different sources of PC failure: connections, temperature, external sources (electrical network), aging, problems with component, water and humidity, insulation and air/water filters.

The DESY electrical network is sensitive to thunderstorms with a distance of 200 km. There are regular power sags (10%-20% for up to 120 ms) occurring every day (this corresponds to a regular operation of the power grid). Even distant faults and the following disconnection of power lines will always be seen in the form of voltage sags in the complete grid. Power converters at HERA seem to be particularly sensitive to such voltage sags due to possibly insufficient filtering in the output stages. This is a problem, in particular for the converters powering normal conducting magnets. Changes of the tap changer in the main transformers can result in magnet current variations as high as 10^{-4}.

The PC converter reliability was increased by performing more preventive maintenance, and not just reactions on faults. One day per month is spent on PC maintenance, with generally another day lost to recover from it. There is clearly a balance between maintenance and not touching a running system.

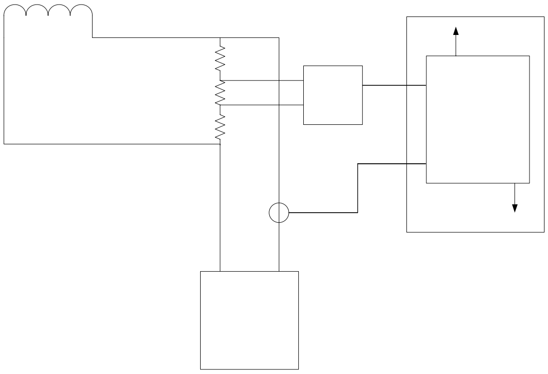
PCs were analysed by thermography using infrared cameras to detect hot or cold spots – indicators for faulty components or bad connections. Another problem is quality control by engineers, in particular after maintenance.

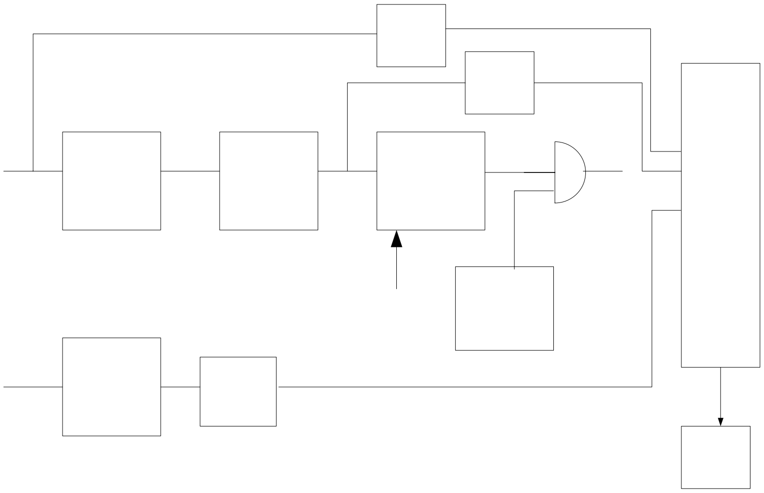
At the level of the PC interlocks, the aim is now to run the PC as long as possible when a fault is detected to make sure that the beam is dumped before the PC is switched off. The PLC timings and trigger generation was therefore re-optimized, and the PC faults now trigger the beam dump directly, rather than switching the supply off and waiting for a secondary effect to trigger the dump. Fast internal faults are detected and interlocks are generated within 200 μs directly from the gate electronics of the converters. The system is very reliable.

Logging of failures using the electronics logbook is very helpful, since it allows identifying recurrent problems on one power converter.

PC Surveillance (M. Werner MDI)

An external system for PC surveillance is presently in the design stage. The voltage over the circuit is used to simulate the current signal (after low/high pass filters) as shown in the figures below. The aim of the high pass filtering is to extract the high frequency (i.e. fast) current changes and transients that are compared to a threshold value and used to generate a dump signal. The information is also digitized and stored inside a FPGA for post-mortem diagnostics. The actual current setting (Initialise Protection) is used as a mask to avoid problems during PC switch on.





The proposal is now being designed within an electronic board, fitted into the crate of the concerned power converters. Once the hardware is finished, an extensive test series will reveal the most appropriate detection principle. Beside the passive electronics for protection, all signals are digitized and available within the FPGA for possible later usage and monitoring. A defined interface will allow for possible later combination of the HERA and the CERN approach to provide the expected monitoring possibilities of the CERN solution also for the HERA board.

Normal Conducting M

Alarm Loop (R. Bacher)

The HERA quench protection system reacts within ~10 ms to a magnet quench, a time scale similar to the BLM system (5 ms). Both systems were designed with similar reaction times. The HERA alarm loop (1.6 A / 100 V current loop) had a typical transmission delay of ≤ 1 ms during the HERA I phase. Recently the reaction time of the system was reduced to ≤ 100 μs (relays were replaced by opto-couplers…). The loop does not implement any logic. BLMs and other equipment can 'manipulate' the line to reduce the current: at 920 GeV the manipulation of the line by 5 BLMs produces a beam dump. The system is democratic, i.e. every BLM (or other input channels) has the same weight. The change induced by a BLM is different at injection and during the ramp/collisions: more BLMs are therefore needed to dump the beam at injection. Equipment currently connected to the alarm loop are BLMs, experiments, power converters and the RF.

The alarm loop fires the dump typically once per day, while the BLMs typically dump the beam 1-2 times per week.

Lessons to be learned:

- Do not build a purely analogue system.
- Provide some form of logic to 'condition' the client signals.

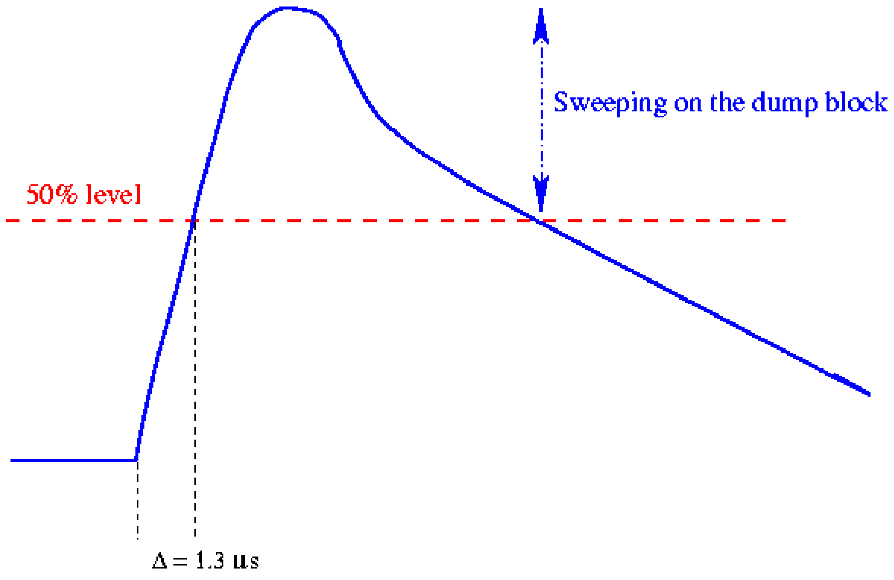
Quenches are not considered to be a major problem: there are no many quenches, and a quench is not considered to be dangerous. Quenches from showers generated by the collimators are not frequent, and if they happen, it is usually the first dipole magnet downstream that quenches.

Beam Dump (M. Schmitz)

The HERA beam dumping system uses 8 kicker magnets and an internal beam dump block. Parameters for the beam dump system:

- Kickers with spark gap switch, U=25 kV, I=20 kA
- Operational voltage at about 88% of self triggering level
- 15 free bunch spaces for beam abort gap
- Rise time 1.3 μs to 50 %
- Beam energy tracking uses 1 DCCT, with no redundancy or cross-checking
- Pre-firing of 1 kicker triggers all others within about 1 μs.
- Constant spark-gap voltage to keep triggering delay constant
- Kick waveform sweeps beam across absorber block for dilution
- Internal synchronisation mechanism in case external clock is lost

One kicker pre- / asynchronous firing does not damage the machine (the beam remains within the vacuum chamber). 7 kickers are sufficient to safely dump the beam.



There are typically 1-2 pre-firings of one of the kicker magnets per year. They never observed a missing kicker. A fast change of the energy signal used to determine the kick strength induces a beam dump request. There is no defined procedure what to do when the beam dump would not fire, but such event never happened.

Beam Intensity Surveillance (M. Werner)

The fast surveillance of the beam current/lifetime is based on the fast (bunch by bunch) ACCT (in CERN language the FBCT [Fast Beam Current Transformer]). The transformer signal is filtered (low pass 700 kHz) to extract the 10.4 MHz bunch frequency signal which is digitized with a 12 Bit AD converter and 8 MSamples/s and summed over approximately one turn. The one-turn-sum is compared to moving sum and threshold signals to take into account the normal decay of the beam current. The system was put into operation on 18th December 2003 and it seems to perform well. The maximum tracking rate of the average current is 0.7 mA/ms (the total current is presently around 100 mA) and the threshold for beam dump is 0.5 mA below the average. If the beam current decay is faster than the tracking rate, the system eventually dumps the beam, with a delay that depends on the difference between the tracking rate of the threshold and the actual decay of the current. The turn-by-turn resolution of the system seems to be around 0.3%.

BPM Surveillance (S. Herb)

The possibility to dump the beam with the BPM system was implemented by hardware right from the beginning of HERA, but that functionality was never used until recently. The properties of the system are:

- The allowed position window is centred around the electrical centre of the BPM.
- The system reacts when the position exceeds a settable threshold.

- The system responds within a single turn.

In order to use the BPMs in operation for 2004:

- Only healthy arc monitors are used.
- The BPMs were added to the BLMs for the dump trigger. Every BPM is independent and has the same weight. A BPM has also the same weight than a BLM. At 920 GeV the beam is dumped when the total number of BPMs and BLMs that exceed the threshold reaches 5.
- Non-uniform windows are used to take into account BPM offsets (respectively the reference orbit position).

The system should be complementary to the BLM system. An important issue concerns the reliability of the system that must still be determined. The reliability of the BPMs is rather poor (aging of the electronics installed in poorly ventilated shafts below the tunnel floor).

For the HERA electron ring an orbit feedback operating at about 1 Hz is used. For the proton ring, there is not such system. However, the orbit is very stable.

Other issues

HERA very much relies on post mortem recording, and they understand the reason for abnormal ends of nearly all fills.

Data retrieval is efficient and fast. Together with our colleagues from DESY we scanned through many recordings of BLMs and Quenches after of beam aborts – the software that has been developed is quite impressive.

Most beam losses are around collimators, but in general, there are also losses around the entire ring. The threshold for quenches is in the order of 10^{-4} of the total beam intensity a fast loss (number to be confirmed by K.Wittenburg). At injection energy, there are in general no quenches, except in the cases where the injection is badly configured (e.g. injecting into a machine at tope energy, bad timing,incorrect injection settings). There is no dedicated protection system to ward against injection kicker failures.

800 power converters are used for the proton machine. The complexity of the machine is one of the reasons for failures and operational inefficiency. Part of the electronics is installed in the tunnel, under 20 cm of concrete.

Several ideas for future collaborations were discussed:

- Understanding of fast losses of a small fraction of the beam at HERA (such beam losses could limit LHC performance, and could be a threat for the collimation system)
- Installation of LHC BLMs at HERA
- Collaboration in the development for detection systems of fast magnet failures
- Collaboration in the development for fast lifetime measurements using ADCCTs
- Studies on mechanisms for fast beam losses using software that has been developed at CERN
- The archiving system is impressive, what could we learn?

HERA will switch off in 2007. Priority today is operation for luminosity. We cannot expect to profit from manpower at DESY, nor can we expect MDs at HERA. However, our DESY colleagues are very open for collaborating on issues of common interest. In particular, passive monitoring during regular operation using systems foreseen for LHC protection would allow validating our choices on an accelerator similar to the LHC.