THE MULTILEVEL PROTECTION SYSTEM FOR THE VACUUM CHAMBERS OF THE HIGH-INTENSITY 590 MEV PROTON BEAM LINES

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A multilevel protection system developed by many specialists and in operation since decades has constantly been upgraded to the needs of the today's high-intensity 590 MeV beam (N > 1 MW), which is very demanding on the reliability of diagnostic elements and electronic equipment in order to avoid long and costly shut-downs caused by a damaged vacuum chamber in a highly radioactive environment.

INTRODUCTION

The range of 590 MeV protons in steel is about 28 cm. Therefore, the PSI proton beam with its small diameter and with more than one megawatt of power acts like a welding torch when it hits the steel walls of a vacuum chamber. At the Targets M and E for example, the diameter of the beam is as small as 4 mm ($\sigma_x \approx \sigma_y \approx$ 1 mm). For this case, the time to heat up steel to its melting point as a function of beam intensity is given in Fig. 1. For a 2 mA beam, the machine interlock system has to switch-off the beam in less than about 5 ms to avoid a damaged vacuum chamber or seal where the beam diameter is small. It should be pointed out here, that a hole in one of the vacuum chambers in the Target E region could cause a shutdown of up to one year duration. In order to protect the p-channel vacuum-chamber system from being damaged by the proton beam, five different classes of devices or services are installed (see also [1]):

1. Watchdog for magnet currents.
2. Monitoring the beam losses.
3. Monitoring the beam halo.
4. Monitoring the beam transmission.
5. Controlling correlated magnets at Target E.

A simultaneous effectiveness of 2-3 of these functions at most locations along the beam line is desired for redundancy.

WATCHDOG FOR MAGNET CURRENTS

The actual values of the currents of all bending-magnets along the 590 MeV proton beam line between the ring extraction and the SINQ-target are permanently monitored by their local COMBI-controllers, when a magnet's value exceeds it's individually programmed upper or lower limit, then the beam is switched off via the machine interlock system. If this function would be absent, then the beam could easily drill a hole into the vacuum chamber of this magnet, because the produced spill by a wrongly steered beam is usually well shielded by the iron yoke and therefore, the spill's intensity may be too weak to be monitored as dangerous by the nearby ionisation chamber. The widths of the windows created by the upper and lower limits for each magnet have to be wide enough to allow set-up and tuning sessions with a certain variability of the beam energy and direction at the accelerator exit. The back-readings (measured in volts) of the lower and upper limits of the 9 bending-magnet's currents vary from magnet to magnet. Each COMBI-controller is also permanently comparing (with a hardware-comparator) the magnet's set-point value with its actual value and generating an interlock if it is incorrect.

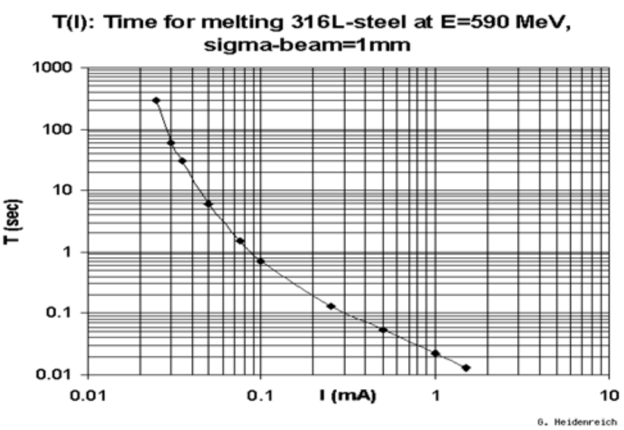

Fig. 1: Intensity-dependence of melting-down time

MONITORING THE BEAM LOSSES

The backbone of the proton beam line's protection system is an array of 29 ionisation chambers [IC] lined up, at an average distance of about 4 meters, along the beam line and close to the beam tube. They are arranged in 4 interlock groups:

From:	To:	# of ICs
Accelerator exit	Target M	9
Target M	Target E	6
Target E	Beam-dump	5
AHL-Bend	SINQ-target	9

As an example, Fig. 2 shows the operator console's display screen of the 9 ionisation chamber readings for the beam line to SINQ for a proton beam intensity of 1.8 mA being extracted from the ring cyclotron. The ionisation chambers exist in three shapes (square box, cylinder or ring) and have an active volume of about one litre each. The applied voltage over the plates inside is 200 volts and the filling gas is normal air. They are manufactured at PSI and consist of metal and ceramic insulator material only. There are two basically different programs residing in the ionisation chamber electronics (LOGCAM2 CAMAC unit developed at PSI) to detect measured values exceeding limits and therefore triggering a machine interlock in as short a time as 5 ms:

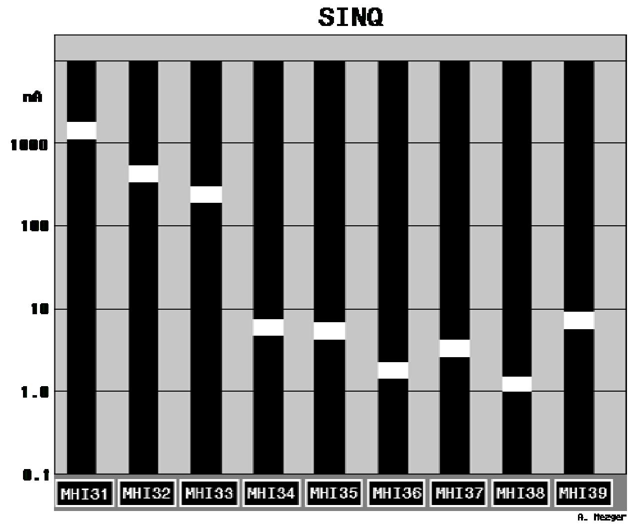

Fig. 2: Beam-spill display along the SINQ beam line

Program A: (see Fig. 3)
As soon as a measured IC current exceeds a hardware (HW) limit, a machine interlock signal is produced by the electronics. At low beam intensities this limit may be too far away to detect a miss-steered beam and to turn off the beam before a vacuum leak is created. Experience showed, that already with beam intensities as low as 10 μA, a leak at a vacuum seal may occur after overheating it for only a few seconds.
Program B: (see Fig. 4)
Because of the scattering of protons passing through target material, the beam spill measured with ionisation chambers down-stream from the target is proportional to the beam intensity as long as the beam remains on axis. Therefore, the quotient of the measured IC currents (I) divided by the actual beam current (I_0) remains constant over the whole range of beam intensities above 50-100 μA (see Fig. 5). This fact is exploited by the programmed electronics in comparing this ratio with individually set upper and lower limits and triggering an interlock in case of out-of-limit values. Additionally, the hardware limit mentioned above is also supported by this program.

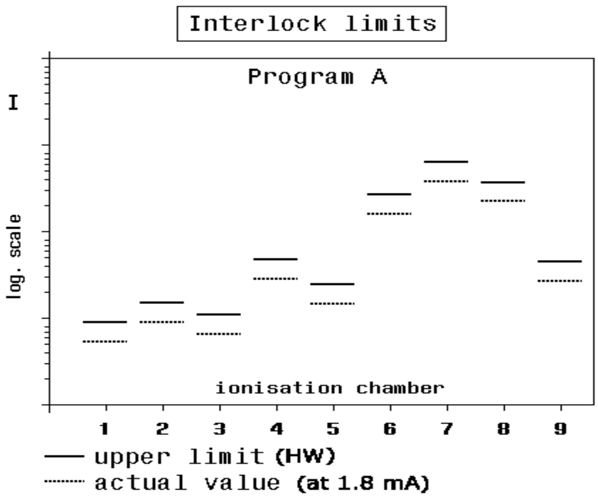

Fig. 3: Standard HW interlock level scheme for ionisation-chambers

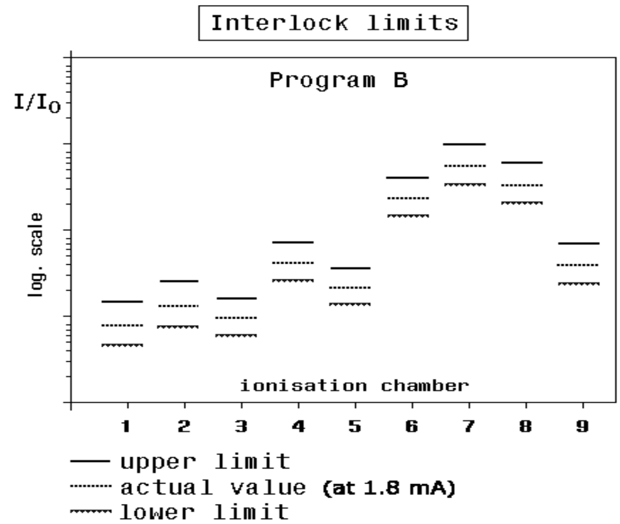

Fig. 4: Special SW-interlock level scheme

At the moment, only the LOCAM2-units of the beam line sections behind Target E are equipped with program B. It is planned to investigate, if also the section between Target M and E may be equipped with program B. This would improve the usefulness of the ionisation chambers at low intensities, which is quite important for protecting the vacuum chambers of Target E and just in front of it with more redundancy (see also Fig. 1 and 10).

MONITORING THE BEAM HALO

Behind Target E and in front of the SINQ-target several beam-halo monitors are installed. They consist of 2 or 4 segments of thin sheet-metal (0.1 mm Nickel) mounted with insulators in front of the slits or collimators. If protons are hitting the copper of the slits or collimators, then while they pass through one of the segments and with an efficiency of about 5 % they produce a current flowing to the measuring device (LOGCAM2). These currents are processed with program B described for the ionisation chambers. Additionally, a too high left-right or up-down asymmetry also produces an interlock. At the operator's console, the actual currents collected at the different segments of the 8 halo monitors may be displayed with a repetition rate of 1 Hz (see Fig. 6). This display is an important tuning tool for optimising

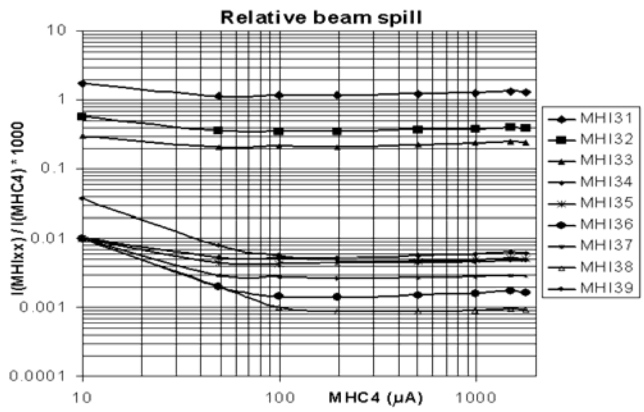

Fig. 5: Beam-current dependence of relative beam spill

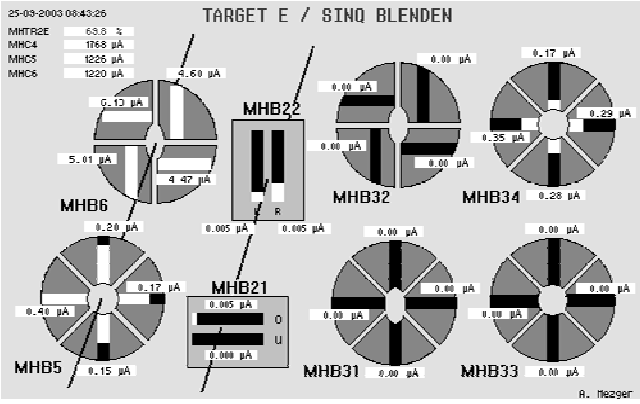

Fig. 6: Halo-monitor display for TE and SINQ-target

the passage of the proton beam through the Target E station and for adjusting the beam centring at the SINQ-target.

MONITORING THE BEAM TRANSMISSION

There are 4 locations along the 590 MeV proton beam line, where the beam current transmissions are monitored:

Location:	expression to evaluate:
HE-beam splitter	I(MHC1)-I(MHC2)-I(MBC1)
target station M	I(MHC3)-I(MHC4)-Losses @TM
target station E	I(MHC4)-I(MHC5)-Losses @TE
Drift-tube to SINQ	I(MHC5)-I(MHC6)

The beam currents are measured with the monitors (50 MHz high-frequency cavities) MHC1 to MHC6 and MBC1 (measures the peeled-off beam current for PIREX), which have only an accuracy of around 1 % and have also to be re-calibrated (done manually by operators, which is considered by experts as a main security risk) from time to time. The four transmissions are computed with local processors with a repetition rate of 200 Hz. Because of the limited accuracy of the beam intensity measurements, the allowed losses are dependent on the beam currents. At Target E (TE) e.g. the permitted width of the window is ±5 μA near 0 μA and ±90 μA at 2 mA beam current (see Fig. 7). In order to reduce the amount of spurious interlocks produced by beam current fluctuations, a beam current dependent time constant for the integration of the measured current values is applied. This time constant varies between 110 ms for 0 μA and 10 ms for beam currents larger than 1.5 mA (see Fig. 8). The losses at TM are 1.6 % over the whole range of beam currents, whereas for the Target E (length = 4 cm graphite) the losses are 28 % + 1.3 % per mA beam current (i.e. 30 % at 1.8 mA).

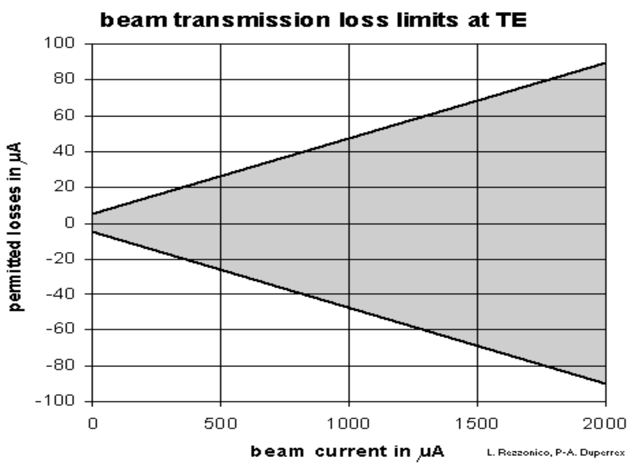

Fig. 7: Window of allowed beam-transmission losses

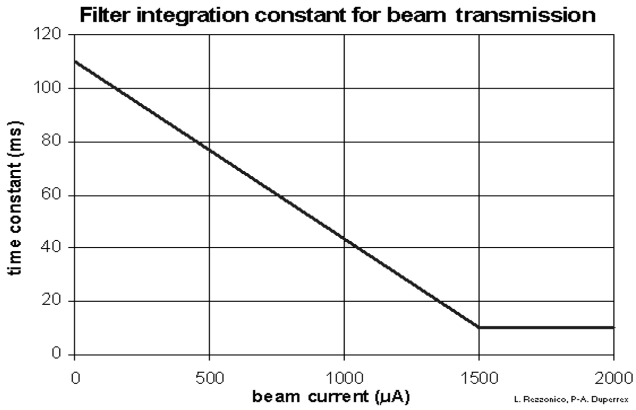

Fig. 8: Filter-function for the beam-transmission at TE

The most important motivation for introducing the transmission monitoring at Target E was to prevent the possibility of too much beam bypassing the graphite target material (rotating wheel of 6 mm width). This non-scattered beam passes through the beam line to SINQ with a higher momentum and generates a considerably smaller spot at the SINQ-target, which may be harmful for it (e.g. liquid metal target for the MEGAPIE experiment). Fig. 9 shows a Monte-Carlo simulation (with the program TURTLE) of the 2 beam spots (scattered and non-scattered beam) at the location of the SINQ-target. In order to have more redundancy for protecting the MEGAPIE-target from being hit by too much of the narrow non-scattered beam, an additional protection-method has been presented [2]. The proposed slit will be put in place during the shutdown 2004 and its usefulness tested during the HE-beam period 2004.

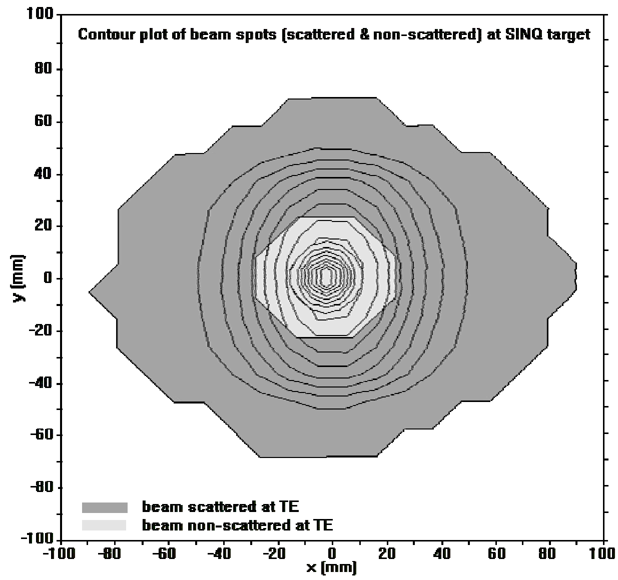

Fig. 9: Scattered an non-scattered beam-spot at SINQ.

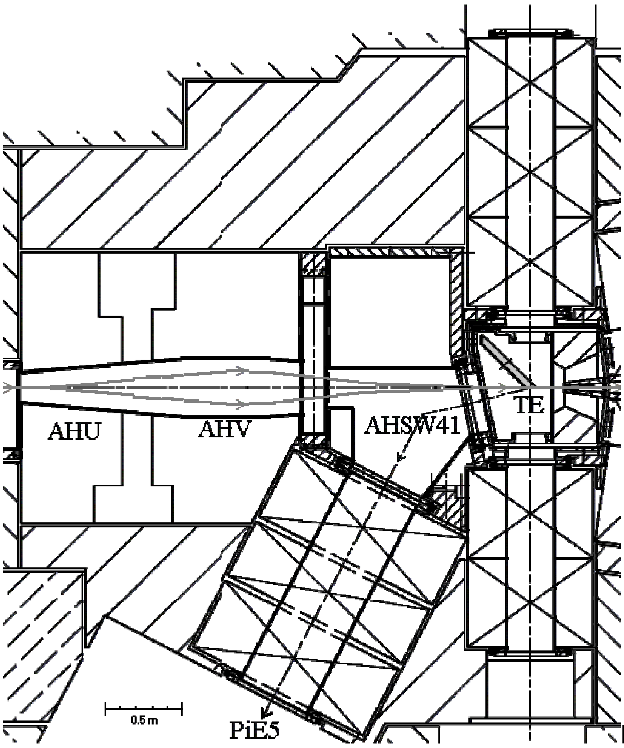

Fig. 10: AHU/AHV/AHSW41-magnets layout at TE

CONTROLLING CORRELATED MAGNETS AT TE

The magnetic fringe field of the (backwards) extraction magnet AHSW41 of the πE5 secondary beam line (starting at Target E) is also deflecting the proton beam in front of the Target E. In order to compensate this effect, 2 additional bending magnets named AHU and AHV are required (see Fig. 10). In this figure, the 2 grey curves show the central trajectories of the proton beam (coming from the left) for 120 MeV/c ±μ-beams being extracted into the πE5 beam line. In order to hit the Target E at the centre and keeping the proton beam parallel to the axis, the current settings for the 2 compensation magnets AHU and AHV have to be chosen for the different AHSW-currents (proportional to the momentum of the extracted myons with 3.529 A/MeV/c) from the curves shown in Fig. 11. To avoid wrong settings of these 3 magnets, which could lead very easily to a hole in one of the nearby vacuum chambers, (see Fig. 10 and assume e.g. the current of the magnet AHV has the wrong sign) their

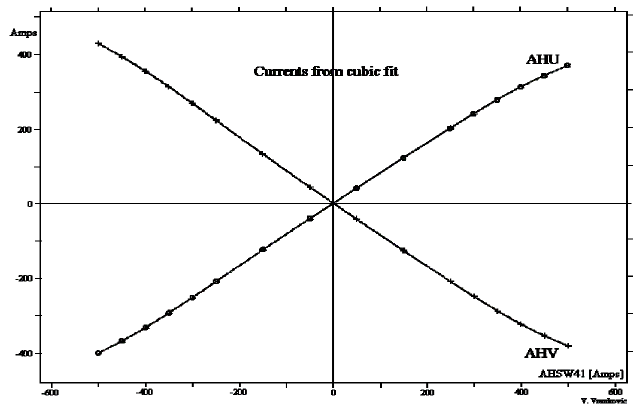

Fig. 11: Magnet-current correlation of the magnets AHU and AHV as a function of the AHSW41-magnet.

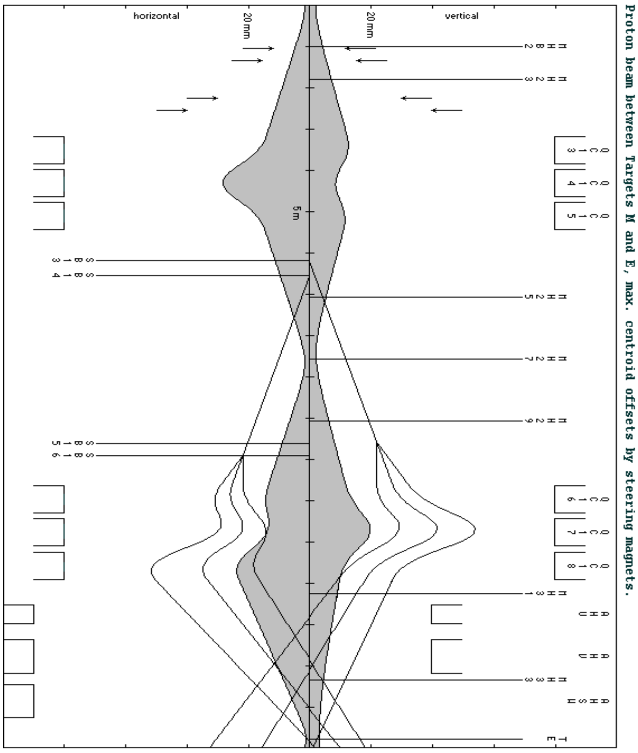

Fig. 12: Steering-magnet influence before TE

values cannot be set directly. Instead a super-combi device is used, which gets the myon-momentum (in MeV/c) as input (AHINP) and transforms it with the help of a lookup table (corresponding to Fig. 11) into magnet set-point values and then performs the magnet settings. Two additional super-combi input parameters allow similarly with AHPOS to shift the beam horizontally at Target E parallel to the axis within the range of ±5 mm and/or with AHWIN to vary the horizontal direction of the beam at Target E within the range of ±5 mr. Thus, as long as this super-combi device works properly, there is no chance, that the beam can hit a wall of a vacuum chamber near Target E. Between Target M and Target E there are also 2 horizontally and 2 vertically acting steering magnets with a maximum deviation power of ±5 mr (see Fig. 12). Comparing the drawn maximum possible (5 mr) beam centroid shifts reachable by these steering magnets, it is also obvious, that no vacuum chamber walls (see Fig. 10) can be hit with this 'worst-case' beam at regions where its spot size is small. In the near future it is planned to add a second identical (with the exception of disabled set-point channels) super-combi device to the existing one. This shadowing feature would certainly increase the safety, because if one of the 2 units is malfunctioning, the other would still be able e.g. to check the back-readings of the 3 magnets and generate an interlock in case of a magnet power-supply drop-out.

REFERENCES

[1] http://people.web.psi.ch/rohrer_u/protect.htm

[2] PSI Scientific and Technical Report 2001, Volume VI, p.34-35.