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Surveillance Protection of a 150 kW Proton Beam Dump

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Abstract. The 72 MeV beam dump of the PSI Injector 2 cyclotron was replaced in the 1999 shut-down. It has since been operated with currents up to 2 mA and a beam power density up to 300 W/mm^2. The beam is stopped at the trumpet-shaped inner surface of six successive water cooled copper blocks. Excessive focusing as well as large transversal displacements of the beam have to be prevented in order to protect the dump. This is provided mainly by monitoring the currents to each of the stopper blocks and to a 4-segment secondary emission foil in front of the beam dump. In addition a sensitive but slow control of beam alignment is provided by four thermocouples positioned circumferentially in one of the stopper blocks. The evaluation of the measured parameters is outlined and the data acquisition and processing by in-house developed programmable CAMAC devices is described.

INTRODUCTION

The first 72 MeV beam dump BX2 went into operation in 1984 together with the Injector 2 cyclotron [1] and has been operated during beam development at currents up to 2 mA. The integrated beam current amounts to several thousand mAh. In the 1998 shutdown the conical surface of the 2nd and 3rd of three copper blocks was recognised to be heavily damaged. The surface had been melted, probably due to excessive focusing of the beam (Figure 1). Since the inclination of the stopping surface is essential to the distribution of beam power, further damage leading to loss of functionality was to be expected. The dump, together with its vacuum vessel and its local lead and concrete shielding, was replaced in the 1999 shutdown. The thermal load capacity [2] and the surveillance protection of the dump were improved. It has since been operated with currents up to 2 mA.

The beam leaving the cyclotron is surrounded by a thin halo. The need to transport this halo to the beam dump (aperture 20 cm) avoiding activation of the beam pipe, together with the lack of focusing elements on the last 8 metres of transport, prohibits a large widening of the beam. This leads to an approximately round beam with a relatively high maximum power density normal to the beam cross section (~240 W/mm^2 at a beam power of 125 kW).

As a consequence of the high power density, a rotational symmetric stopper surface was chosen over a planar geometry, although this introduces the need to center the beam on the stopper. The beam is stopped at the trumpet-shaped inner surface of 6 water cooled stopper blocks made from OFHC copper (Figure 2). Surface shape, wall thickness and dimensions of the cooling water grooves are carefully adjusted to the beam profile in order to limit the maximum temperature in the blocks and the maximum heat flux at the copper-water boundary. (Typical values are 230 °C and 1 W/mm^2 at a centered nominal beam of 125 kW and a maximum heat flux normal to the copper surface of 12 W/mm^2 at a different longitudinal position.) In case of an intolerable overload, the melting of the surface and film boiling of cooling water will take place approximately at the same heat load. In practice much lower temperatures are envisaged in order to avoid mechanical stress and possible fatigue related damage. The intrinsic advantage of the conical geometry is not fully exploited in order to retain a safety margin against a misaligned and sharply focused beam.

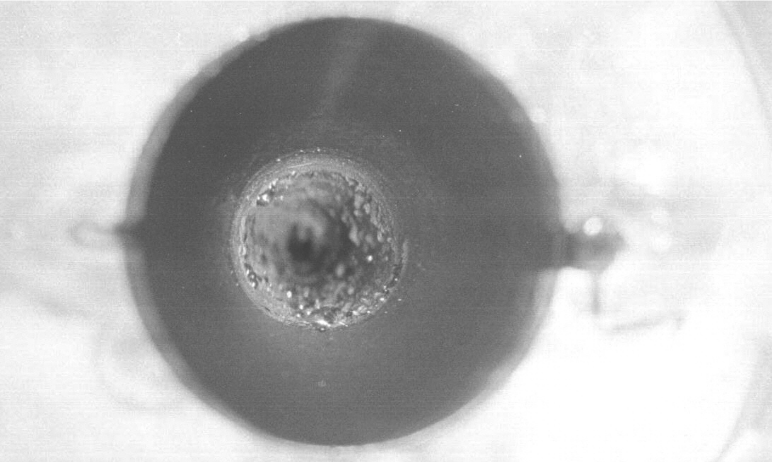

FIGURE 1. Head-on view (via mirror) into the cone of the old BX2. The overly focused beam has cut into the 25 mm thick water cooled aperture in front of the three conical stopper blocks. Pearls of melted copper cover the inner surface of the rear two stopper blocks. Observation in the remote processing facility revealed no cracks and indicated a limited extension of the melted area into the bulk copper.

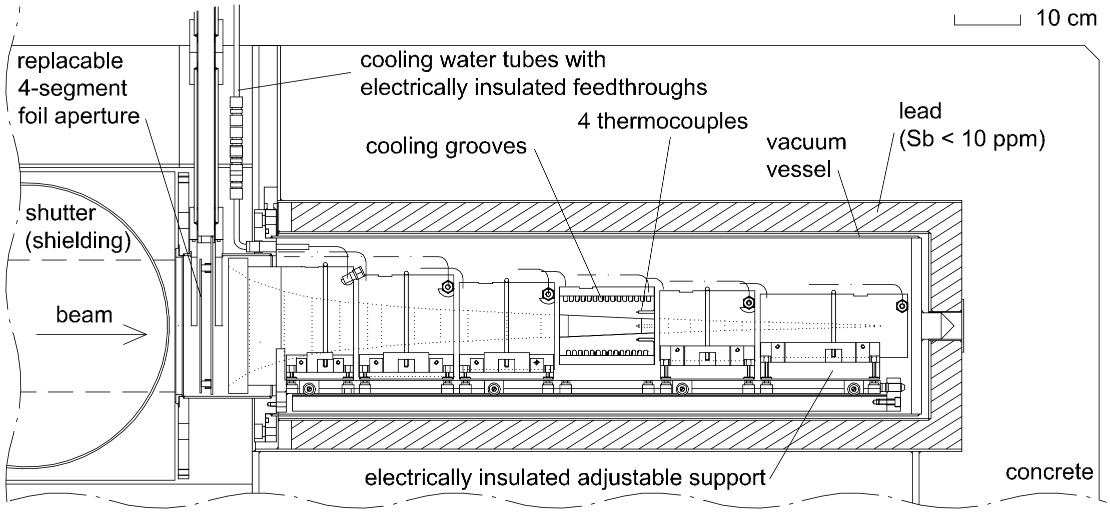

Figure 2. Layout of the new BX2 and its local shielding.

SURVEILLANCE PROTECTION

The temperature of the stopper blocks should stay as low as possible and in any case should not exceed 400 °C. This requires a well centered, round and not too strongly focused beam at the stopper as well as sufficient cooling water flow. With increasing beam current, the beam requirements become more strict. Most of the time an acceptable beam is delivered by the transfer beam line due to the closed loop beam centering (based on inductive beam position monitors and steering magnets) and narrow limits to the allowed quadrupole settings. Nevertheless, extreme and fast varying beam conditions produced during beam development shifts, require an independent and fast surveillance protection of the beam dump.

In our case, neither the surface temperature distribution nor the 2-dimensional beam current density distribution are measured directly during normal operation. Therefore the fast surveillance protection has to rely on the measurement and evaluation of the currents to the six stopper blocks and to a 4-segment foil aperture in front of the stopper blocks. It is supplemented by slower temperature measurement with four thermocouples in the 4th stopper block and the surveillance of cooling water flow and temperature (Figure 3).

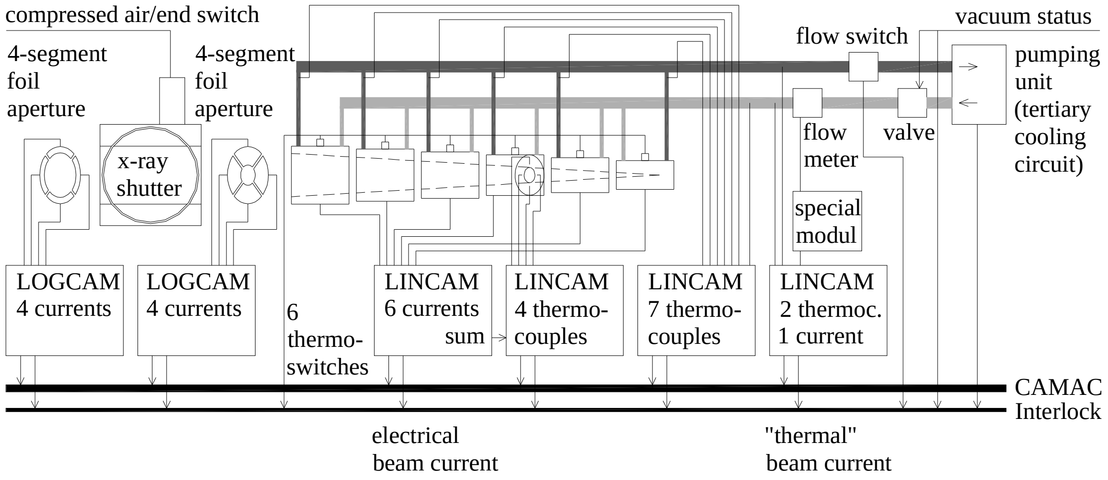

Figure 3. Block diagram of surveillance instrumentation

Evaluation of the Currents to the Six Stopper Blocks

The current to a single stopper block is given by the integral over a ring shaped sector of the beam current density distribution. For a centered rotational symmetric beam, the beam profile can be roughly deduced from the six partial currents but this is obviously not the case for a displaced beam. Nevertheless, with the assumption of a "normally shaped" beam profile, some indications can be drawn from the measurement. In particular, a set of criteria can be set up which indicate if an untolerable state of the beam is likely to be present or not.

This was done with the help of numerical simulations of the temperature distribution in the stopper blocks and the cooling water, caused by circular symmetric beams of arbitrary given profile and displacement. (Similar simulations were used for the design of the stopper blocks.) Starting from measured beam profiles, the beam diameter was varied as well as beam current and misalignment. The maximum temperature and the occurence of film boiling of the cooling water were evaluated together with the six partial currents to the stopper blocks. An example is given in Figure 4. The criteria were chosen such that larger but only slightly smaller beam diameters as presently observed are tolerated, in order to allow for future improvements.

Four criteria were chosen (adjusted to the present block separations at inner surface radii of 6, 11, 17, 24, 35, 90 mm):

1. "Total current (= sum of partial currents): maximum 3000 μA." This prevents overload in the presence of a well shaped beam. (Not needed up to now.)
2. "Partial current: maximum share of total current from 0.68 at 25 μA to 0.21 at 3000 μA, same for all blocks." This secures a broad beam at least at high currents.
3. "Sum of two currents: maximum share of total current from 0.91 at 25 μA to 0.64 at 1000 μA total current, same for all blocks." This prevents an overly focused beam at small currents. (Above 1000 μA total current obsolete due to criterium 2.)
4. "Maximum fraction $I_{\text{outer block}}/I_{\text{inner block}}$ of currents to neighboring blocks: 6.4 for outermost blocks to 2.3 for innermost blocks. Independent of total current." This prevents larger beam misalignment (by requiring the fictitious beam profile derived from the six partial currents to decrease steadily with radius).

Below a total current of ~10 μA, no damage can occur even at the smallest beam diameter compatible with the beam emittance.

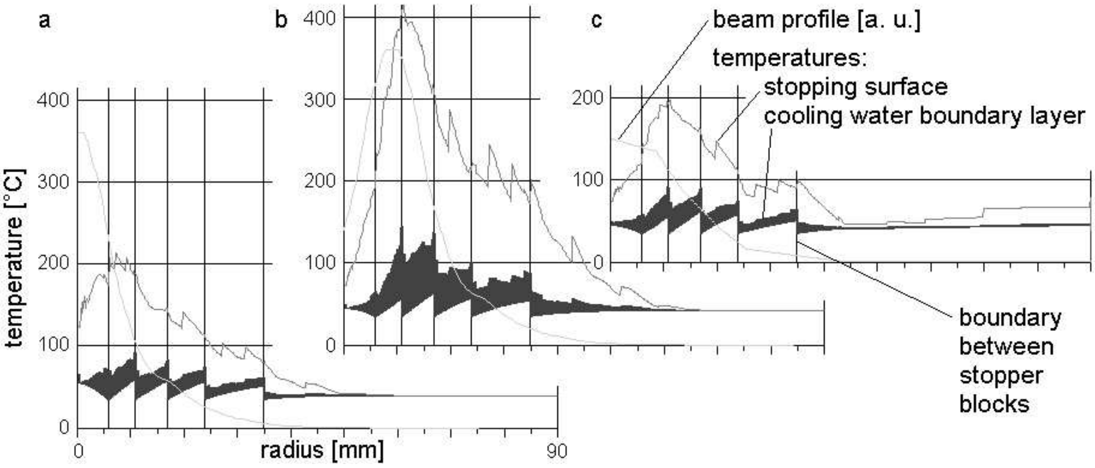

Figure 4. Radial beam profile at the beam dump and deduced temperatures (correlated to stopping surface radius). Beam current 1500 μA. Water flow 6 x 800 l/h. a: Centered beam (profile derived from measurements with upstream wire scanners by inverse Abel-transformation). b: Same with assumed misalignment of 9 mm. At this point an interlock is generated due to criterium 4. c: Same for a fictitious beam profile derived from the six currents of case b by a simple model which uses the (false) assumption of a centered beam.

4-Segment Foil Apertures

A 4-segment aperture made from 35 μm molybdenum foil with an inner radius of 25 mm is located at the entrance of the dump. Limiting the allowed fraction of the secondary emission current which leaves a single segment to the total beam current prevents large misalignments (or a too broad beam profile). A more sensitive detection of beam misalignment would result from comparison of the currents to opposite segments. Nevertheless this implicates a more significant fraction of the beam hitting the aperture, requiring a smaller inner radius than the present one.

Another 4-segment aperture in front of the x-ray shutter with much lower current limits prevents the beam or its halo from hitting the shutter or the beam tube in front of it.

Thermocouples in the 4th Block

A more sensitive control of horizontal and vertical beam alignment is provided by thermocouples positioned circumferentially at four locations in the 4th stopper block, 9 mm below the inner surface (Figure 5). $\Delta T_{\mathrm{opposite}}/I_{\mathrm{beam}}$ is approximately linear with beam misalignment up to 6 mm but gives much too low values above 8 mm. The measurement is slow due to a temperature relaxation time of ~2.7 s. Nevertheless, this may be fast enough to protect the dump in case of a moderately misaligned but not overly focused beam. The maximum allowed temperature difference $\Delta T_{\mathrm{opposite}}$ between opposite thermocouples is set to 40 °C.

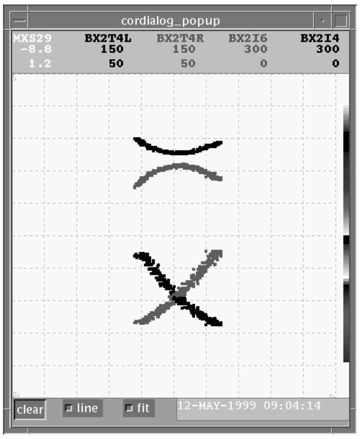

Figure 5. Temperature of left and right thermocouples in the 4th block (lower traces, 50 to 150 °C) and currents to the 4th and 6th blocks (upper traces, 0 to 300 μA) as a function of the horizontal beam position (-7 to 7 mm) varied by an upstream steering magnet (vertically centered beam, I_{beam}=1000 μA).

Other Surveillance

An independent flow switch in the cooling water circuit and thermoswitches mounted to the outside of each stopper block are connected to the interlock system. In addition, the flowmeter and the thermocouples in the cooling circuit, providing independent information on partial and total beam currents, are monitored. The maximum allowed outlet temperatures are 150 °C, the maximum inlet temperature is 40 °C. The minimum allowed water flow is 4000 l/h.

ELECTRONICS

The measurement of the currents, thermovoltages and output current of the flowmeter, the evaluation and the connection to the interlock system and via CAMAC bus to the accelerator control system are performed by standard in-house developed data acquisition modules (in part extended from 4 to 8 channels).

The data acquisition modules LOGCAM and LINCAM (Figure 6) are CAMAC modules built around the 16-bit ROMless microcontroller HPC46004 from National Semiconductor. The controller has fast hardware multiply and divide and runs at 16 MHz. It has on-chip 512 bytes of RAM, eight 16-bit timers, serial I/O interface, and numerous general purpose I/O lines. The program code is stored in external EPROM memory. The processor controls the multiplexer, reads the ADC and processes the data according to the requirements of the application with a typical refresh time of 250 μs. It generates an interlock to shut down the beam if the measured values surpass the limits saved in the EEPROM or if derived values are incompatible with the limits. The measured data are written into the output registers which are asynchronously accessed by the accelerator control computers through the CAMAC data transmission system. The communication with CAMAC is done with one 16-bit input register, used to set actual limits and working parameters, and with 32 16-bit output registers holding measured and derived values and status information. All these values present at the last generated interlock are also stored in these registers as well as the actual limits and working parameters for verification.

In the standard version of LOGCAM, the analog front end signal conditioner is a 4-channel logarithmic current-to-voltage converter. It has a very wide dynamic range from 1 nA to 4 mA. The precision is better than 1% and the resolution after analog to digital conversion is 0.5% of the measured value over the entire dynamic range. The frequency bandwidth of up to 100 kHz is good enough for our applications. If a higher precision is required, the front end is equipped with a multichannel linear current-to-voltage converter with a single fixed range and a precision better than 0.1 %. The resolution is 0.025% of the full scale.

The temperatures are measured with thermocouples. In this case, the front end uses a multichannel low-voltage amplifier with very good stability and low offset. The microcontroller can correct the non-linearity of the thermocouples and, if necessary, compensate for the reference junction temperature.

The front end electronic is powered by an insulated DC-DC converter to allow grounding at the signal source. The signals are then transferred to the ADC via differential instrumentation amplifiers.

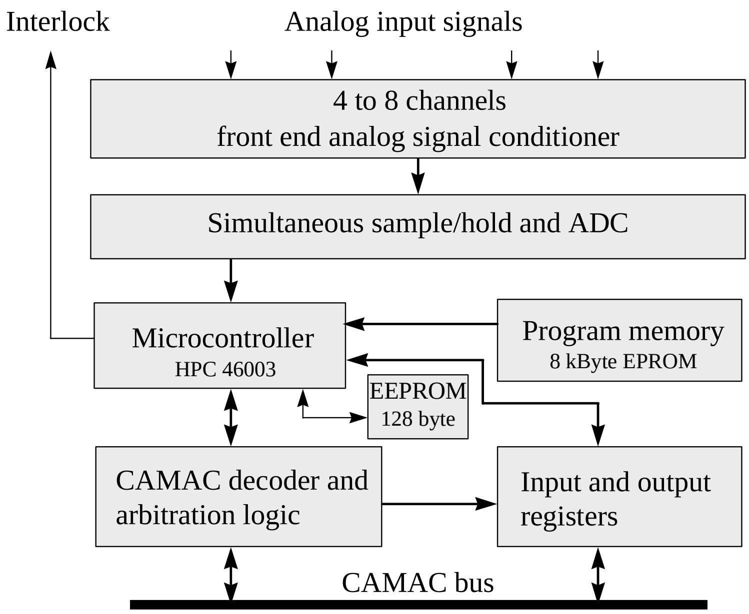

Figure 6. Block diagram of LOGCAM and LINCAM modules

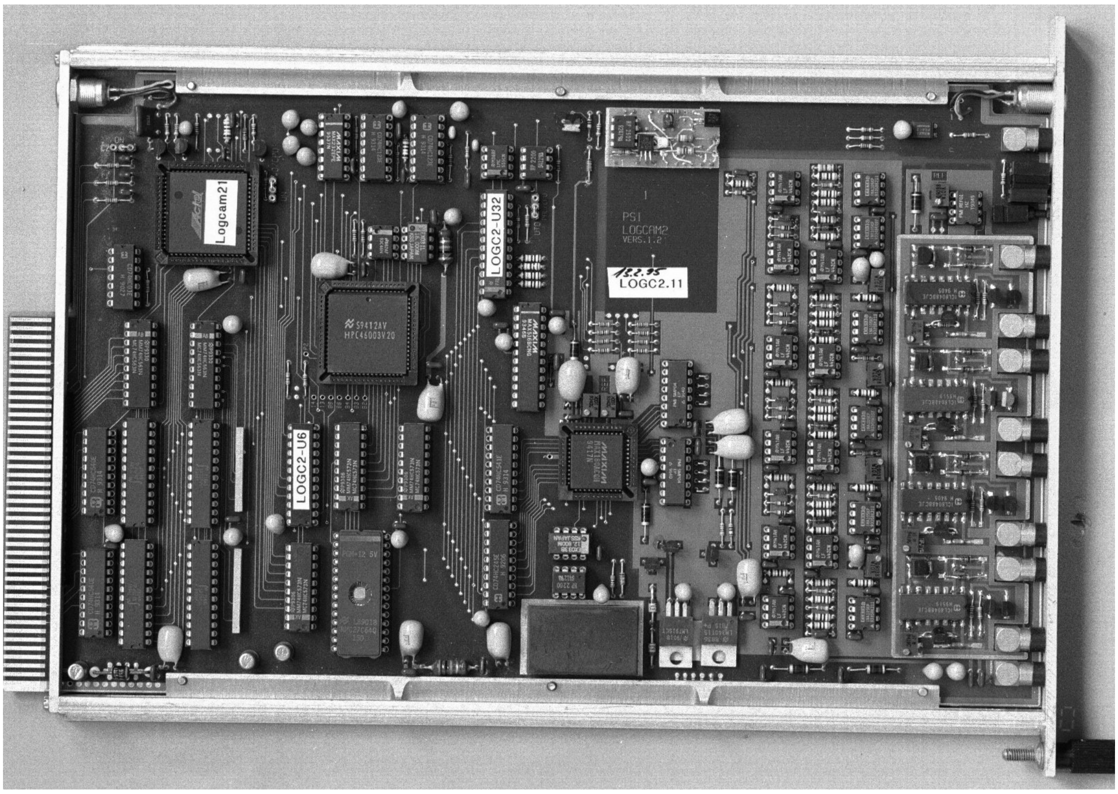

Figure 7. LOGCAM module

INTERFACE TO OPERATION

Most of the measured data, especially information on beam centering which is essential for operation and surveillance of the dump, is available at an online display in the control room (Figure 8). The display is generated by the generic display manager for the accelerator control system [3]. If an interlock is generated, its type is indicated at a separate display. Additional information on the LINCAM and LOGCAM status can be retrieved via another display.

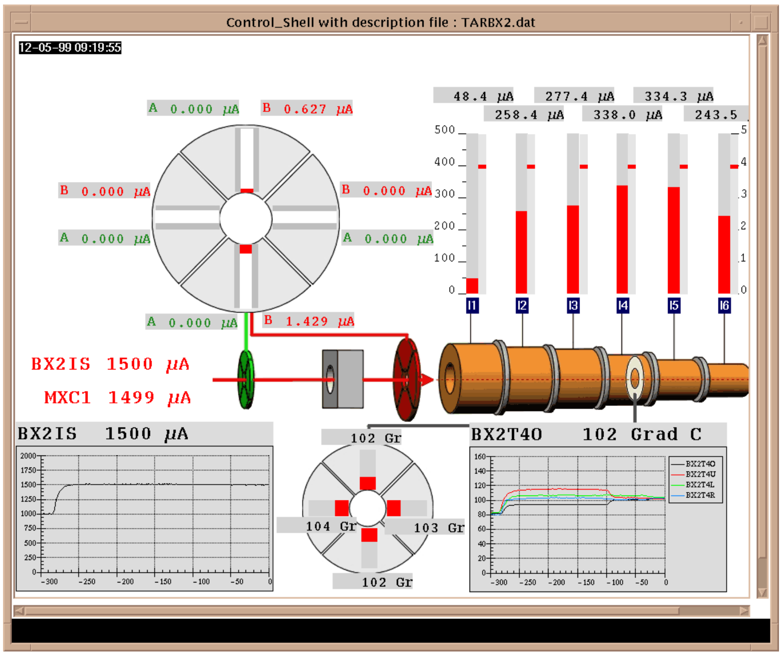

Figure 8. Status display at the control room console.

CONCLUSIONS

The short cylindrical symmetric beam dump sets narrow requirements upon beam centering and diameter. Sufficient surveillance of beam parameters is possible by measurement of the currents to the six stopper blocks and a 4-segment foil aperture and of the four temperatures in one of the blocks. These and other measurements are performed using standard in-house developed CAMAC modules.

REFERENCES

1. *SIN Jahresbericht* 1983, p. JB10 and *SIN Jahresbericht* 1984, p. JB5
2. Dölling, R., and Rezzonico, L., *PSI Scientific Report* 1999, Annex VI
3. Mezger, A., private communication