BEAM LOSS MONITORING AND CONTROL FOR HIGH INTENSITY BEAMS AT THE AGOR-FACILITY*

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Abstract

The experiments at the AGOR facility require intense heavy ion beams. Typical examples are 10^{13} pps of $^{20}Ne^{6+}$ at 23.3 MeV/A and $\geq 10^{12}$ pps $^{206}Pb^{27+}$ at 8.5 MeV/A. To prevent damage to components by the beam (power density up to 1 kW/mm^3 in unfavourable cases) a modular beam loss monitoring and control system has been developed for the cyclotron and high energy beam lines. The architecture of the system is described and the considerations for the major design choices discussed. The system uses the CAN-bus for communication and verification of system integrity. The injected beam is chopped at 1 kHz with a variable duty factor between 5 and 90 %. The beam intensity at injection and a number of locations in the high energy beam line is measured by inductive pick-ups. Furthermore, localized beam losses on slits and diaphragms are directly measured. When beam loss in any section exceeds the predefined maximum value, the duty factor of the beam is automatically reduced.

INTRODUCTION

The AGOR-facility delivers heavy ions beams up to Pb for experiments in the framework of the TRIμP programme on fundamental symmetries. Experiments on violation of time reversal symmetry in β-decay are performed with beams up to ^{40}Ar at energies between 20 and 30 MeV. The beam intensity in these experiments is currently limited by constraints in the experimental setup to 4×10^{12} pps (300 W). The cyclotron has demonstrated its ability to deliver the 1 kW beam aimed at by the experiment. For experiments on permanent electric dipole moments and atomic parity violation in Ra-atoms and ions beams of various Pb-isotopes with an energy in the range 7 – 10 MeV per nucleon and an intensity up to 3×10^{11} pps (100 W) are used. A further intensity increase by at least a factor 3 is requested, requiring improvement of both the experimental setup and the cyclotron output

The power density in materials hit by in particular the Pb-beams is up to 1 kW/mm^3, leading to damage at the ms time scale. Therefore a monitoring and control system for the beam losses, both in the cyclotron and in the high energy beam lines, is essential for safe operation of the AGOR-facility for this type of experiments.

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SYSTEM SPECIFICATIONS

The beam loss monitoring and control system (BLMCS) has to ensure that the unavoidable beam losses in the cyclotron and high energy beam lines remain within preset limits by controlling the beam intensity injected into the accelerator. The system operates in a uni-directional way: deterioration of the transmission leads to automatic reduction of the beam intensity, but intensity increase made possible by improved transmission requires operator intervention. In case of more or less complete loss of the beam, as occurs due to equipment failure, the system suppresses the beam at injection within 10 ms.

The semi-interceptive beam profile monitors in the cyclotron and high energy beam lines can not withstand the full beam intensity. Therefore the system also supervises the status of all beam diagnostics equipment in the cyclotron and high energy beam lines. Under normal operating conditions insertion of a beam diagnostics device leads to immediate interruption of the beam by the BLMCS. After reducing the primary beam intensity to a safe level by inserting a pepperpot in the injection line and switching the BLMCS to tuning mode, beam can be injected into the cyclotron again. Removing the pepperpot while in tuning mode results in suppression of the beam in the injection line.

Lay-out

The path of the beam from the injection beam line below the cyclotron up to the experimental setup at the end of the high energy beam transport system has been divided in seven sections for which the transmission is measured individually. The experiments with high intensity beams are performed at one of the four experimental setups only, so there was no need to implement beam line selector logic. For each section of the high energy beam line and the cyclotron a Beam Loss Control Module (BLCM) has been installed that assesses the beam losses, verifies the status of the beam diagnostic devices and triggers actions if necessary. This modular structure is easily adapted to the operational experience.

The BLCM has six analog inputs for current measurements. Two of these are used for non-destructive pick-ups measuring the beam current at the entrance and exit of the section, the others are used to measure the current on diaphragms and/or slit jaws in the section that intercept part of the beam. The non-destructive pick-ups are shared between sections: the BLCM of section N receives its entrance current signal from the BLCM of section N-1 and sends its exit current signal to the BLCM of section N+1, where it serves as the entrance current signal. The BLCM integrates the currents over each chopper cycle to determine the losses.

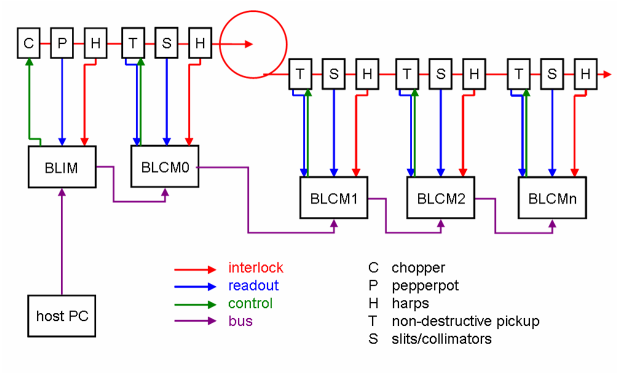

Figure 1: Layout of the Beam Loss Monitoring and Control System (BLMCS). The BLIM and BLCM0 modules are located in the injection beam line, the other modules in the high energy beam line. The bus contains the CAN-bus connection, the synchronization of the measurements with the chopper cycle and the transfer of the beam intensity measured by the non-destructive pick-up of a given BLCM to the next.

The BLCM compares both the localized losses on the diaphragms and slits and the non-localized loss, evaluated as the difference of the total loss determined with the non-intercepting probes and the localized losses, with individual preset high, low and alarm levels. Any loss exceeding the high level results in requests to the Beam Loss Interrupt Module (BLIM) that controls the chopper to reduce the duty cycle until the beam loss is lower than the low level. Beam loss exceeding the alarm level causes a request to the BLIM to completely suppress the beam.

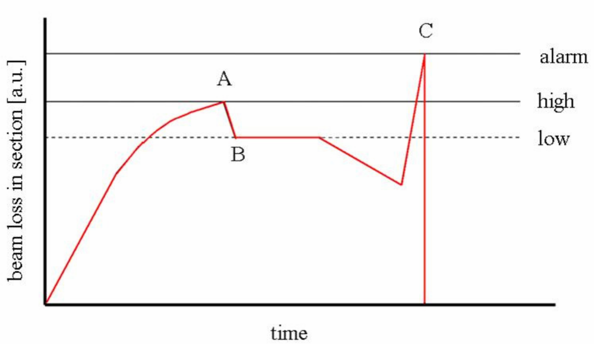

Figure 2: Principle of operation of the BLMCS. At time A the beam loss exceeds the "high" level and the system starts to reduce the duty cycle of the chopper until the loss is below the "low" level (time B). Decreasing losses do not result in a increase of the duty cycle. Losses exceeding the alarm level at time C result in complete suppression of the beam.

The BLCM also has eight digital inputs for the status of the (semi-)destructive beam diagnostics in the section of the beam line it supervises. Currently all beam profilers and beam stops in the high energy beam line have been connected to the system: thermal calculations indicate the aluminium core of the beam stop will be damaged by the 1 kW anticipated beam power.

System Architecture

Both the BCLMs that supervise the different sections of the beam lines and the BLIM that controls the chopper and the pepperpot are based on ARM7-processors. For the communication in-between the modules and with the PC supervising the system the CAN-bus has been adopted because of its robustness and real-time properties. The CAN-bus is used to load the limit values into the BLCMs and to transfer the request for reduction of the chopper duty cycle or suppression of the beam from the BLCMs to the BLIM. The software is loaded into the modules via a separate RS232-port.

A watchdog mechanism is used to verify the proper operation of the individual modules and the system as whole. Failures detected by the watchdog result in suppression of the beam via the "red line" of the radiation protection system.

The proper synchronization of the integration of the beam intensity over each chopper pulse is ensured by a separate PulseBus that distributes the trigger signal of the chopper. The synchronization pulse to the BLCMs in the high energy beam line has a variable delay to compensate for the propagation delay of the beam through the cyclotron, which varies between 50µs for a beam energy of 5.5 MeV per nucleon and 15 µs for 190 MeV protons.

BEAM INTENSITY MEASUREMENT

The extraction of heavy ion beams from the AGOR-cyclotron has an efficiency of ≥ 85 % up to the maximum intensities delivered so far. The beam loss during extraction mainly occurs in the electrostatic deflector, with minor losses in the subsequent electromagnetic channels.

The use of DCCTs or fast inductive or capacitive probes operating at the RF-frequency (24 – 62 MHz), which would have avoided continuous thermal cycling of the septum, was unfortunately not feasible. The inductive probes available had too low S/N-ratio at our intensities, whereas the capacitive probes required a rather complex signal treatment to ensure a sufficiently accurate relative calibration. Also for the DDCT to be installed in the injection line as a reference the S/N-ratio was marginal at our intensities. We therefore adopted the chopping scheme as used at e.g. GANIL [1] and GSI [2]. The 1 kHz chopper frequency and 90 % nominal duty cycle are the result of a compromise between the following aspects:

- fast response time of the system.
- minimal thermal cycling of the septum.
- up to 10 µs variation in cyclotron transit time.
- time needed for signal handling per chopper period.

Full 3D-simulations of the thermal transients of the septum including radiation show temperature variations of the septum below 10 K for a beam loss on the septum of 100 W, which was considered acceptable. During the first year of operation with beam losses on the septum up to 25 W no deterioration of deflector operation has been observed.

Inductive Pick-up

The inductive pick-up and associated front-end electronics is based on that used at the UNILAC at GSI [3]. The reference pick-up in the injection line is integrated in a flange that also includes the required diversion of the wall current. The pick-ups in the high energy beam line are mounted in an electrically insulated magnetic shielding and slid over the aluminium beam tube. The diversion of the wall current is in this case realized by interrupting the electrical continuity of the beam tube at the nearest coupling point between sections of beam tube. As a result these pick-ups have a signal-to-background-ratio that is significantly lower than that of the reference pick-up, but this is not compromising the performance of the system.

The pick-ups consist of a Vitrovac 6025F core with four winding sets. The two winding sets for the measurement of the beam current are wound such that signals induced by currents not enclosed by the core are cancelled. The beam current signal is obtained by integrating the signal of the pickup. The integrator is reset after each chopper cycle to take into account drifts and low frequency background. Droop of the output signal is negligible thanks to the short integration period. The other two winding sets serve for calibration and offset compensation. The calibration windings of all cores are connected in series to so that the calibration current of all cores is identical.

OPERATIONAL EXPERIENCE

From operation of the system in test experiments we conclude that the measurement of the cyclotron transmission merits further consideration and can be improved. In the current layout the overall transmission between the non-destructive pick-ups in the injection beam line below the cyclotron and in the high energy beam line at the exit of the cyclotron and the losses on the collimators in front of the four extraction channels are measured and compared with the preset limits to control the beam intensity.

The transmission through the cyclotron is dominated by the injection efficiency of 25 % (mainly determined by the buncher) and for certain beams the losses due to charge exchange during acceleration, which strongly depend on the energy ion species, energy and intensity. Consequently the sensitivity of the overall transmission to changes in the extraction efficiency is rather limited. Furthermore the losses in the extraction channels, which are from the point of view of damage risks more important than those on the collimators, can not be assessed. Consequently rather tight limits on the losses have to be imposed to warrant safe operation.

We are investigating whether we can improve the assessment of the transmission through the cyclotron by using the innermost and outermost phase probes. By comparing the pick-up in the injection line and the innermost phase probe the injection efficiency can be determined, while the comparison of the two phase probes yields a measure of the internal beam losses. By combining the intensities measured with the outermost phase probe, the pick-up at the cyclotron exit and the losses on the collimator the losses in the extraction channels can be assessed.

The measurement of the beam intensity from the phase probes requires the development of a new multiplexer system to allow the dual use of the phase probes and a super heterodyne detector combined with a lock-in amplifier locked to the chopper drive signal.

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