BEAM LOSS AND TRANSMISSION CONTROL AT FAIR

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Abstract

FAIR, the Facility for Antiproton and Ion Research is presently entering the final layout phase at GSI. The injector chain consists of the existing linear accelerator UNILAC and synchrotron SIS18, plus a new dedicated 70 MeV high-intensity proton Linac. Along the injector chain to the main synchrotron SIS100 as well as in the beam transport lines, which connect synchrotrons, storage rings and experimental areas, beam transmission and beam loss have to be controlled very precisely. To supply a maximum intensity of 5×10^{11} U^{28+}/spill to experiments and to prevent machine damages by intense beams, an integrated system for transmission and loss control is mandatory. While various kinds of beam current transformers control transmission online, intercepting Particle Detector Combinations (scintillators, ionization chambers, secondary electron monitors) are foreseen for optimization runs. External Beam Loss Monitors (BLM) indirectly detect loss positions by measuring secondary particles. This contribution summarizes the related detector systems and presents basic considerations for beam loss and transmission control at FAIR.

FAIR ACCELERATOR COMPLEX

At GSI the layout of the Facility for Antiproton and Ion Research FAIR is now being finalized. Figure 1 displays the modularized start version of FAIR. The future facility consists of the p-Linac for production of high-intensity proton beams, the main synchrotron SIS100 for acceleration of protons and heavy ions, the super fragment separator for production of rare-isotope beams (RIB), the pBar production target, the collector ring CR for accumulation of RIB and pBar, as well as the High-Energy Storage Ring HESR for pBar experiments. Details about the FAIR project are found in [1].

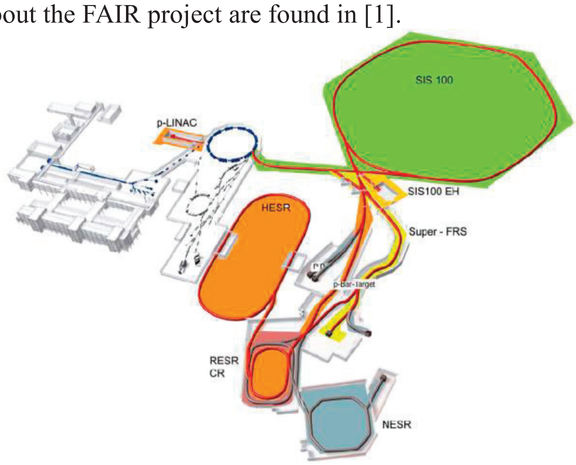

Figure 1: Existing GSI (left) and future FAIR accelerator complex (NESR, RESR not part of the start version).

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The discussion of beam diagnostic devices used for transmission control and beam loss is focussed on SIS100 as the main machine of FAIR and the beam lines of the High Energy Beam Transport (HEBT) section interconnecting the synchrotrons, storage rings and experimental areas. The task of SIS100 is to deliver high intensity, high-energy proton and heavy ion beams for the various experimental programs of FAIR. The radioactive ion beam program requires acceleration of up to 4×10^{11} U^{28+} ions/s to energies of 400-2700 MeV/u, either in single bunches of 30-90 ns, or as slowly extracted beam with extraction times of several seconds. Additionally, for pBar production 2.5×10^{13} protons per pulse will be accelerated to 29 GeV with a repetition rate of 0.2 Hz and an output bunch length of 50 ns. The different operational modes of SIS100 ask for a high dynamic range of the intensity measurements in the HEBT beam lines, as well as dedicated instruments for slow and fast extraction.

HIGH INTENSITY BEAM OPERATION

This contribution focuses on high-intensity beams extracted from SIS100 and transported by the HEBT section of FAIR, whereas the special challenges of the proton Linac are not discussed. Concerning the damage potential, the operation with the maximum beam intensity of 5×10^{11} U^{28+} ions/spill represents the worst case with a specific energy deposition of e.g. ~2 kJ/g for perpendicular impact on a Copper target [2]. In this operational mode no insertions will be allowed to be positioned inside the beam pipe, i.e. all pneumatic drives have to be in 'out' position, and any beam loss has to be absolutely minimized to prevent damage of the transport system. For high-intensity beams the 'pilot beam' concept is foreseen, which means that correct functionality of all systems will be certified by applying a beam of intermediate intensity (below damage threshold) and with otherwise equal beam parameters prior to high-intensity operation. On the other hand it is required to detect even smaller losses during a 'pilot beam' run, which again increases the required sensitivity of the diagnostic instruments for intensity measurement and/or beam loss. The requirements for the detectors of the transmission control system are very different from the beam loss detectors. Whereas the main goal of the intensity detectors during high-intensity operation is to detect tiny intensity deviations on a strong mean signal, the task of the BLMs will be to immediately react on small signals/count rates. In the latter case the detector signals might additionally be deteriorated by strong radiation background in the accelerator tunnel. In combination with the different loss spectra of various ion species at the different beam energies, the beam-loss system would

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require intricate settings for alarm thresholds as e.g. implemented at LHC [3].

INTENSITY AND TRANSMISSION MEASUREMENTS

The HEBT section of FAIR will be equipped with both, intercepting and non-intercepting diagnostic instruments. Dedicated detectors have to be foreseen for slow extraction (SE) and fast extraction (FE) schemes. For the SE-case pneumatic driven Particle Detector Combinations (PDC), an assembly consisting of scintillating counter, ionization chamber and secondary electron monitor, are used for the detection of low intensities up to 10^{10} particles/s [4]. During commissioning and machine trims, or for optimizations using the ‘pilot beam’ mode, the PDCs will serve as the endpoint of the transmission control line under study. In contrast, transformer-type detectors will be used as main input signals for the overall online transmission control.

As a non-intercepting device for precise detection of slowly extracted beams a specially developed Cryogenic Current Comparator (CCC) will be installed in the HEBT beam lines [4]. The CCC has been developed at GSI and is the only known device that reaches a detection threshold of ~1 nA. Its measurement principle is based on the precise detection of the beam’s azimuthal magnetic field using a low-temperature dc SQUID system. Since the current resolution of the CCC is limited by the magnetic noise, a superconducting magnetic shielding is presently investigated using FEM simulations [5].

Two transformer-types, Resonant Transformer (RT) and Fast Current Transformer (FCT), are foreseen for the measurement of fast extracted ion beams. The RT has been developed at GSI for precise bunch charge measurements. In the present setup the particle bunch excites a damped oscillation in the RT circuit and a peak detector measures the amplitude of the first maximum, which is proportional to the total bunch charge), for more details on the RT setup see [6]. Up to now the RT is the most sensitive device for fast extracted beams but still the resolution is limited to ~10 pC_{RMS} (i.e. 6×10^{7} protons/s). This sensitivity holds for the most sensitive RT range, which is not applicable for the high beam intensity case, where the resolution will drop to 100 nC or 6×10^{11} protons/s and the RT would become inoperative for transmission control. Thus the resolution needs to be improved by at least one order of magnitude and different options for enhanced post analysis of RT data were investigated. The basic idea is to omit the peak detector, record the complete oscillation with a high-resolution ADC and to derive the charge value by averaging over several maxima. Thus the number of relevant data points is increased significantly and measurement errors are minimized. Figure 2 (top) shows the RT signal (black) and a fit curve (blue), following the formulae given in [7] to calculate the damping constant which is a fixed device parameter of the RT. For fast calculations the chi-square minimisation is avoided, and the maximum values are derived from the coefficients of a 2^{nd} order polynomial which are calculated analytically. As depicted in Fig. 2 (bottom) the data points significantly scatter by 1.5% around the fit curve (blue) which in the present setup translates into erroneous peak detection and linearly affects the measured beam charge. After further evaluation of experiment data, the relatively simple algorithm may be implemented in a FPGA, thus allowing calculating the bunch charge with improved resolution.

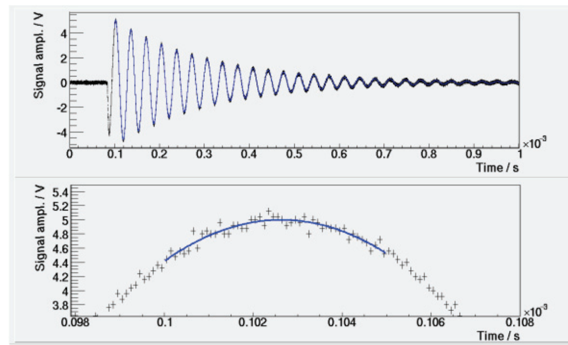

Figure 2: Top: raw RT signal (black) and fit curve (blue); Bottom: first maximum (black) and 2^{nd} order polynomial fit (blue).

In the FAIR HEBT section FCTs will be used on the one hand for observation of the bunch shape, but may also be calibrated for intensity measurements. The GSI-built FCT is a passive device with a switchable gain amplifier and a current resolution of 5 μA_{rms} (~1 MHz bandwidth). Up to now the FCTs are not used for charge measurements at GSI, but in preparation for transmission control at FAIR the resolution of the FCT is studied in comparison to the RT performance. A technical challenge of the FCT is the signal transmission of the bunch signals from the tunnel to equipment rooms because of the high-frequency attenuation of the long cables. Fig. 3 shows the raw FCT signal (blue) and values corrected for the cable response (green) of the RG213 (65 m) as detected with an 8-bit DSO (500 MHz bandwidth). The plot shows four bunches of a 400 MeV/u Uranium beam extracted from SIS18 (nominal particle number 4.8×10^{8} particles/spill), separated by the 253 ns gaps of the synchrotron.

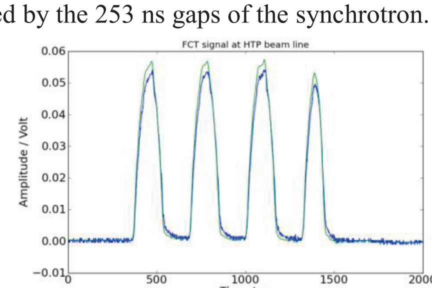

Figure 3: Raw FCT signal (blue) and values corrected for cable response (green).

For this preliminary test the minimum FCT charge quantum is estimated as 0.3 pC, corresponding to 5% of the total measured charge (~6 pC). For the FAIR HEBT installations 8-bit analogue-to-optical converters are

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foreseen for the signal transmission. As a result of the on-going tests a higher resolution of the optical transmission line should be foreseen and care has to be taken to prevent thermal instabilities, in order to reach a maximum precision of the transmission control system. Moreover, the bunch shape as measured with the FCT is intrinsically deteriorated, e.g. by eddy currents of the vacuum pipe, which decreases the achievable resolution.

A first comparison of the RT bunch charge with the one calculated from the FCT signal shows a discrepancy of 7%, which has to be investigated in more detail.

BEAM LOSS DETECTION

As the counterpart of transmission control the precise detection of instantaneous beam losses is mandatory for high-intensity beam operations. At present the LASSIE system (Large Analogue Signal and Scaling Information Environment) is in operation at GSI for the distributed readout of analogue signals in general and especially for beam loss detectors (ionization chambers, scintillators). As its predecessor ABLASS, the LASSIE system is mainly based on the idea of converting analogue signals into frequencies and use 32 channel VME scaler modules as a common acquisition platform also for particle detectors. LASSIE is designed to handle 200 (or more) scaler channels, to store data of the full accelerator cycle with varying duration (at present up to 15 s) at selectable sampling frequencies. For dedicated high-resolution measurements a subset of channels can be switched to 1 MHz sampling frequency, for more details see [8].

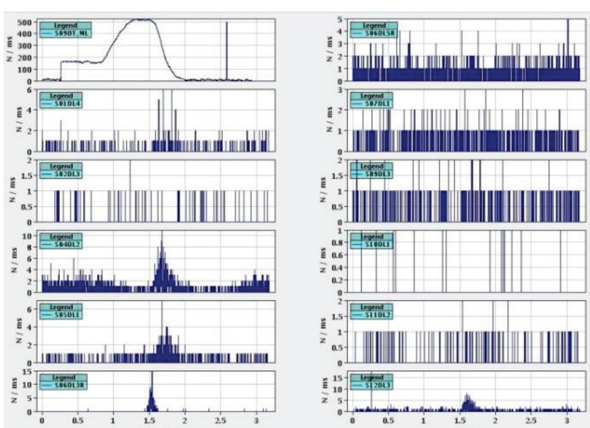

Figure 4: Screenshot of the LASSIE system at GSI SIS18. Top left: signal of dc current transformer; 11 beam loss monitors around the synchrotron.

Figure 4 presents beam loss data acquired with the LASSIE system, for 11 beam loss monitors (scintillators) around the SIS18 synchrotron. Additionally, the top left plot shows the analogue signal of a dc current transformer, which is used for time correlation of the loss data. The three plots on the bottom left show relatively low beam losses during slow extraction starting at 1.5 s. LASSIE is designed and used only for relative loss detection for machine tuning and does e.g. not include any alarms or monitoring of tolerance bands. For routine operation at GSI, or in the future at FAIR, the setting of detector thresholds would become very intricate, because of the wide variation of ion species, beam energies and intensities which may change in each machine cycle. Thus, an upgrade to a CERN-style machine protection system [3] would require a long-term study of the operational scenarios and expected loss spectra of FAIR. On the other hand the damage potential of FAIR accelerators is significantly lower than for LHC [2]. Therefore consequent beam loss monitoring to optimize the beam alignment, to prevent excessive activation of machine parts and to keep the radiation level for tunnel equipment reasonably low become the main tasks.

With regard to the beam loss monitors beam tests were carried out using plastic scintillators (BC400) and CERN-type ionization chambers BLMI [9]. The first goal of the experiment was to define the sensitivity for typical use cases. A 300 MeV/u Uranium beam was focused on a 1 cm thick Copper target and detected with 3 ionization chambers placed around the target in forward direction. Particle showers produced by 2×10^{7} Uranium ions were clearly detected with the BLMI connected to the LASSIE system. Therefore, beam loss monitoring during operation at much higher nominal particle intensities, like e.g. 4×10^{11} U^{28+} ions/s as planned for SIS100, should be feasible with the BLMI.

SUMMARY AND OUTLOOK

The transmission control system relies on the precision of FCT and RT data. On-going studies show possible ways to improve the sensitivity of the detectors. First beam tests with BLMI ionization chambers have shown their principal usability for beam loss monitoring at FAIR and will be compared with detailed FLUKA simulations in the near future.

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