TRANSVERSE BEAM PROFILING FOR FAIR

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Abstract

The FAIR facility will provide intense primary beams of protons and heavy ions, or secondary beams of antiprotons and rare isotopes. The operation includes fixed-target experiments or subsequent facilities of independent storage rings and experiment beam lines. The particle beams greatly differ in ion species, energy, intensity, time structure, spot size and stopping power. Therefore, transverse beam profile measurements require a careful choice of detector type for each location in order to cope with the large dynamic range and operational demands. This contribution presents the actual status of FAIR detector developments for intercepting devices (SEM-grids, multi-wire proportional chambers, scintillating screens) as well as non-intercepting beam induced fluorescence monitors and ionization profile monitors. Recently, promising results were obtained with an 11.4 MeV/u Uranium beam in measurements of optical transmission radiation emitted from thin metal foils. The boundaries for the application area are described and basic detector parameters are summarized.

FAIR BEAM PARAMETERS

The main objectives of the upcoming FAIR (Facility for Antiproton and Ion Research) accelerator complex are to provide high-intensity ion beams, to generate beams of rare isotopes, as well as the production and storage of anti-protons [1]. Because the existing GSI accelerators Unilac and SIS18 will serve as injectors for FAIR a long-term upgrade program had been initiated including an extensive upgrade of beam diagnostic devices for the requirements of high-intensity operation. The foreseen FAIR standard operation modes require e.g. that Unilac routinely injects 5×10^{11} U^{28+} in a 150 µs macropulse into SIS18 as a booster synchrotron. From SIS18 the beam will be injected into the fast ramped superconducting heavy-ion synchrotron SIS100, the main accelerator of the future FAIR complex. SIS100 will deliver high-energy high-intensity proton- and heavy ion beams near the space charge limit. The requirements for the experiments with radioactive ion beams include acceleration of up to 4×10^{11} U^{28+} ions/s to end 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. For the production of anti-protons 2.5×10^{13} protons per pulse will be accelerated to 29 GeV with a repetition rate of 0.1 Hz and an output bunch length of 50 ns. It is clear that the large variety of beam parameters along the FAIR accelerator chain requests for well-matched diagnostic devices. Moreover, the high-energy beam transport lines (HEBT) have to be designed for the transport of ion beams with a large range of parameters. Because of the multiplexed experiment operation, the beams principally might differ on a pulse-by-pulse manner in ion species, energy, intensity, time structure and transverse beam width.

The interconnection of the existing SIS18 to SIS100 has a magnetic rigidity of 18 Tm and will transport slowly and fast extracted beams in the intensity range 1×10^4-3×10^{11} particles per pulse. Beams to and from the storage rings will be transported by 13 Tm and 100 Tm beam lines, but also here a large range of beam intensities of 10^3-10^{10} particles per pulse is planned. Additionally, the aperture has a range of 100-150 mm, which sets up additional requirements with regard to the mechanical layout of beam profile monitors.

INSTRUMENTATION FOR BEAM PROFILING

For the broad range of parameters adequate instruments for beam profile detection have been developed at GSI in the past years. Devices are divided into intercepting instruments, like SEM-grid, multi-wire proportional chamber (MWPC) or scintillating screens (SCR), that are specifically used for beam optimization procedures and non-intercepting devices, like beam induced fluorescence monitors (BIF) or ionization profile monitors (IPM) that allow for online profile measurements.

Table 1: Typical Parameters during Test Measurements for Development of FAIR Instrumentation

Device	Ion	Energy [MeV/u]	Detection Threshold [Part./Pulse]	Spatial Resol. [mm]
SEM-Grid	U^{39+}	11.4	5×10^6	<1
MWPC	Ar^{18+}	300	10^3	<1
SCR	U^{28+}	300	10^4	0.4
BIF	Ar^{11+}	11.4	10^{11}	0.25
IPM	C^{3+}	120	$\sim10^8$	0.16

Some typical areas of operation are listed in Table 1 for individual instruments. The measurement parameters reflect the usage for standard accelerator operation. In addition, most of the devices do feature expert modes or even dedicated hardware, e.g. for increased sensitivity. As an example the present IPM design includes a fast readout

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(single turn) option, which will allow for measurements on a µs time scale at the cost of position sensitivity. Nevertheless, the focus of this contribution is to present beam diagnostic devices for routine measurements in the various sections of the FAIR complex.

SEM-grids are foreseen for beam profile measurement at the p-Linac, a dedicated machine for the production of high-intensity (35 mA) 70 MeV proton beams. Also first turn diagnostics inside the SIS100 synchrotron and inside the collector ring CR will be monitored using SEM-grids. Additionally, for fast extracted beams inside the HEBT section again SEM-grids are planned, whereas the detection of slowly extracted beams requires installing also MWPCs in the HEBT section.

As can be seen from Table 1, the intensity ranges of MWPCs and SCRs overlap, such that in some cases SCRs are a cost effective alternative to SEM-grids. Moreover, recent studies have shown the applicability of SCRs also for fast extracted beams [2], making SCRs an even more versatile tool.

During high-intensity operation of Unilac as injector SEM-grids may not be inserted, because in the given energy range the transferred beam energy will immediately destroy any intercepting device. Thus, BIF monitors are installed for online profile measurement along the Unilac. In addition, BIF monitors are foreseen in front of the target stations of the FAIR experiments.

It is planned to equip all synchrotrons (SIS18, SIS100) and storage rings (ESR, CR, HESR) with IPMs. Experiences are obtained since many years with the SIS18-IPM and, more recently, a novel IPM has been installed in the existing Experimental Storage Ring ESR. At present different IPM designs are worked out to fulfil the special requirements of each installation location. The following sections summarize the present status of the device developments for FAIR.

SEM-Grid & Multi-Wire Proportional Chamber

As standard devices for beam profile determination Secondary Electron Emission (SEM-) grids and multi-wire proportional chambers (MWPC) are commonly used in almost every accelerator facility. In the simplest form a SEM-grid consists of a set of horizontal and vertical wires mounted on a pneumatic drive. For beam energies above 10 MeV/u, the impinging ion beam penetrates the grids and deliberates secondary electrons. The charge of each wire (diameter e.g. 0.1 mm) is amplified and detected separately. Many well-elaborated technical solutions for analog signal treatment and data acquisition of SEM-grids exist worldwide. For the requirements of FAIR a dedicated readout electronics POLAND (PrOfiLe Acquisition Network Digitizer) based on an ASIC for charge to frequency conversion has been developed at GSI [3]. A POLAND unit contains 32 input channels. Four units will be combined for the readout of 64 wires each, in horizontal and vertical plane. Via a fibre optical link POLAND units can be daisy-chained. A central PCIe PC card concentrates the data and builds the interface to the control system. In order to detect profiles at low beam intensities, e.g. during slow extraction, MWPCs are required, that make use of gas amplification by an electron avalanche [4]. The POLAND electronics can, without change, be applied also for the read-out of MWPCs. An example for a time resolved MWPC measurement is shown in Fig. 1.

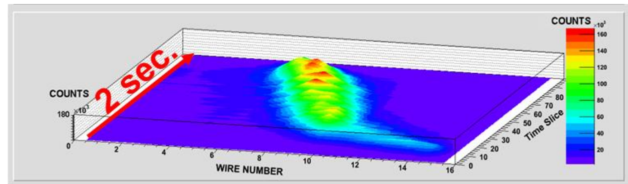

Figure 1: Time resolved profile (20 ms/slice) of slow extracted of Ar^{18+}-beam (1.8 s spill) at 300 MeV/u.

Scintillating Screens & Optical Transition Radiation

Scintillating screens (SCR) serve as simple, cost-effective standard instruments for beam profile detection. For the application at FAIR a large variety of scintillating materials has been studied with regard to light output, radiation defects and material degradation due to beam heating for both, low beam energies (11.4 MeV/u) [5] and high beam energies (300 MeV/u) [6]. As a result of these studies the scintillating material P43 seems the best choice for usage in the HEBT beam lines of FAIR, due to its relatively high light output, good linearity and robustness against radiation damage. The SCR setup for FAIR consists of a scintillator (active area up to 120×85 mm^2) mounted on a pneumatic drive with optical viewport. The scintillation light is observed in 45° with respect to the beam using a commercial monochrome GigE-CMOS camera with remote-controlled iris and target LED illumination for position calibration. The 8 bit VGA camera is externally triggered and features 10 µs – 2 s integration time. With the prototype SCR setup useful beam profiles were obtained at beam intensities as low as 10^4 U^{28+} ions at 300 MeV/u [6].

A different approach to measure beam profiles makes use of Optical Transition Radiation (OTR). OTR is produced when charged particles penetrate the borderline between two materials with different dielectric constants. For OTR the number of emitted photons depends on the square of the ion charge state. The produced light yield is linear to the number of incident particles. Whereas the basic measurement parameters, like spatial resolution, are similar to scintillating screens OTR measurements are inherently much more reliable. This linearity is advantageous if the goal is to measure high intensity beams and to prevent radiation defects or material aging, e.g. as observed for scintillating screens. For Unilac energies, i.e. 11.4 MeV/u, the proof-of-principle had been shown in a test setup with removable stripper foil upstream of the OTR screen, see Fig. 2. In accordance with theory the experimentally observed OTR light yield increases linear with the number of incident particles [7].

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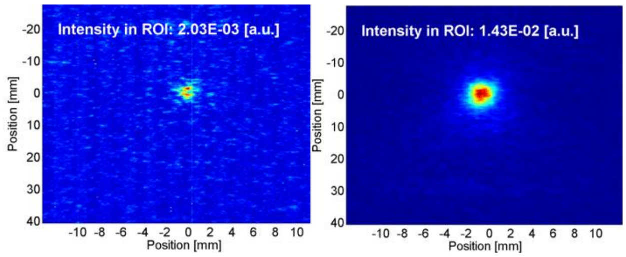

Figure 2: False colour OTR images of 7×10^8 Uranium ions, without stripping foil (left, U^{28+}) and with stripping foil (right, $U^{\sim73+}$) at 11.4 MeV/u (pulse length 300 µs), from [7].

Beam Induced Fluorescence Monitor

For non-intercepting online detection of transverse beam profiles of high-intensity ion beams Beam Induced Fluorescence (BIF) monitors [8] were developed at GSI. The detection principle relies on the excitation of a specifically introduced working gas, e.g. Nitrogen, by the passing ion beam. By observation of the interaction region with two image-intensified CCD cameras mounted in horizontal and vertical direction a two-dimensional image of the beam profile is obtained. In the past years BIF monitors have been installed at four locations at GSI Unilac and evolved to a standard tool for beam optimization [9].

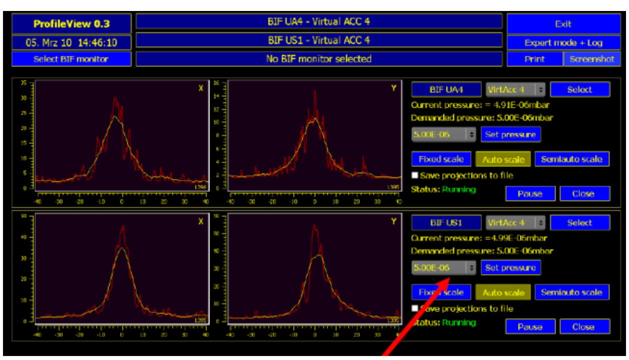

Figure 3: ProfileView software showing online data of two successive BIF monitors. The red arrow indicates the remote adjustment of working gas pressure for ‘gain control’, for details see [9].

The BIF setup includes a Proxitronic camera system (BV 2582 BX-V 100N) with a two-stage multi-channel plate, which is optimized for detection of photons in the range of 390-470 nm [9]. The yield of the fluorescence photons increases proportionally to the pressure of the working gas, to the beam current and to the square of the charge state of beam particles. Since the pressure of the inserted working gas has of course to stay reasonably low to prevent beam distortions or spoiling of the vacuum system, signal amplification by increased pressure is limited. A typical value for the local nitrogen gas pressure is 5×10^{-6} mbar. With the present optical setup a resolution of ~4.5 pixel/mm is reached at a field of view of 100×80 mm^2. With the BIF monitors at GSI Unilac beam profiles of an Ar^{11+} beam at 11.4 MeV/u with 3×10^{11} particles per pulse were achieved at signal-to-noise ratio >5.

Ionization Profile Monitor

For locations where introduction of working gases is prohibited, e.g. in the UHV of a synchrotron or storage ring, ionization profile monitors (IPM) allow for online detection of beam profiles. An IPM measures the spatial distribution, either of residual gas atoms ionized by the ion beam, or of the electrons generated in the ionization process. The setup consists of an electrical field box to apply a homogeneous electric field transverse to the beam path which extracts and accelerates the ionized particles towards a position sensitive detector. In the existing IPM prototype inside ESR and for the IPM setups foreseen for the future heavy ion synchrotron SIS100 and the storage ring CR, a combination of multi-channel plate and phosphor screen (P47) is used [10]. The beam profile as imaged by the phosphor screen is recorded using a CCD camera, presently at a fixed rate of 100 profiles/s. The active area of the FAIR IPM is 44×94 mm^2. The CCD images are corrected with MCP calibration and noise is reduced by the dedicated IPM software.

OUTLOOK

Many of the instruments described above are mature, fulfil the FAIR requirements, and are partly already tested with beam during routine operation. The next development steps are: further standardization of the devices and their infrastructure, optimization of reliability and system integration in the overall data acquisition concept. In addition, novel detector types may be introduced to allow for simplification or extension of measurement ranges.

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