BEAM INSTRUMENTATION FOR HIGH POWER HADRON BEAMS

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Abstract

This presentation will describe developments in the beam diagnostics which support the understanding and operation of high power hadron accelerators. These include the measurement of large dynamic range transverse and longitudinal beam profiles, beam loss detection, and non-interceptive diagnostics.

INTRODUCTION

Beam instrumentation is an important part of any accelerator. Modern machines are equipped with large numbers of diagnostics for measuring various beam parameters as illustrated by the Spallation Neutron Source diagnostics map in Fig. 1. Many of the diagnostics systems are common for different types of accelerators and accelerated particles but some can work in specific conditions only. In this paper we will discuss beam instrumentation systems used for megawatt-class hadron machines with relatively low energy of no more than a few GeV (essentially non-relativistic beams). There is a significant number of operating and emerging accelerators in this class, such as SNS, PSI, J-PARC, ESS, FRIB, Project-X and others. The major factors specific for these machines are related to their high average beam power:

- Small fraction of lost beam is of importance. Large dynamic range diagnostics are required to follow the dynamics of these small fractions.
- The damage threshold is reached quickly with high average beam power. Diagnostics systems for machine protection must have a fast response.
- The power density in the beam core can be very large. This can prevent the use of interceptive diagnostics.
- The average peak beam current is large. The space-charge effects can be significant and affect operation of some types of diagnostics.

Another important factor is the use of a superconducting RF linac for all or part of the acceleration. Although this is not a necessary requirement and some high power accelerators, like the PSI cyclotron, do not use it, the majority of new projects include high power superconducting linac in the design. This adds two more important factors:

- New damage mechanisms related to the superconducting cavities. Additional diagnostics may be required to protect the SRF linac [1].
- The SRF technology requires maintaining a very clean environment for the cavities and the surrounding vacuum chambers. This can impose severe restrictions on the design of the diagnostics in these areas up to complete a ban on using interceptive diagnostics, like in the case of the SNS SRF linac.

In the following sections we will discuss how the above factors affect the diagnostics requirements and the design choices.

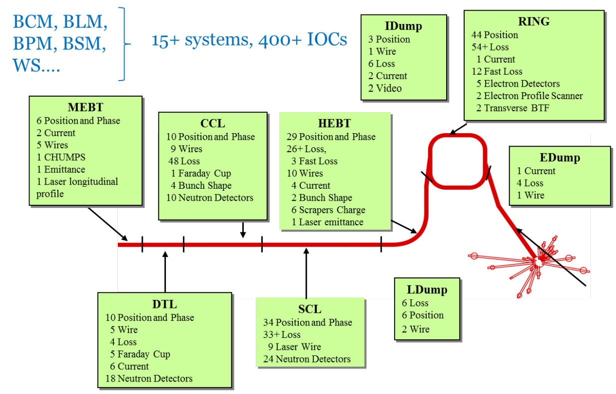

Figure 1: The Spallation Neutron Source diagnostics map.

MACHINE PROTECTION FROM LOST BEAM

Protecting the machine from damage by the lost beam is the most important application of the beam instrumentation. The main damaging factors are:

- Mechanical damage (melting, cracking, erosion). This mechanism is most important at lower energies (<10 MeV), where penetration depth for beam particles is relatively small. The damage threshold depends on many factors but typically it is of the order of magnitude of few hundred watts per meter, which represent a fraction of lost beam of few persent or higher. This level of fractional beam loss can be detected by a Differential Beam Current Monitor (DBCM) measuring beam current difference at two locations along the accelerator.
- Activation of the accelerator equipment. This mechanism is more important at higher energies and the commonly accepted threshold of 1 W/m is used for protons above 100 MeV, which corresponds to a very small fractional loss of $10^{-5} \div 10^{-7}$. As this threshold is significantly lower than the mechanical damage threshold, protection from the activation will automatically provide protection from the mechanical damage. Radiation Monitors (RM) are typically used for protection from small fractional beam loss at high energy [2].

The two above mechanisms are common for all types of the accelerators and a well-established protection strategy typically includes DBCMs at energy below 10 MeV, RMs

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at energy above 100 MeV and a combination of both in the transitional region. As was mentioned in the introduction, the use of SRF technology adds additional damage factors:

- Thermal load on the cryogenic system from the lost beam. The threshold is typically about 1W/m and it does not depend on the beam energy.
- Degradation of SRF cavity electrical strength due to repetitive instantaneous loss with the total energy deposition of about few hundreds of Joules.

At the beam energy above 100 MeV, the protection from the first factor is provided by the RMs as the threshold is the same as for protection from the activation. The situation becomes difficult in the region between 10 MeV and 100 Mev, where the 1 W/m thresholds is too low for detection by both DBCM and RM. As there is no high power SRF linac in operation at that low beam energy there is no established strategy for cryo-system protection.

The second factor was discovered during the SNS SRF linac operation. The baseline SNS Machine Protection System (MPS) did not provide protection from a sporadic loss of 100% of beam current within a 30-50 μs period of time because such events were considered to be safe if they happen so infrequently that the average lost power does not exceed 1 W/m. As the lost fraction is significant the RMs respond within a few microseconds but the signal propagation time within the MPS from the detector to the beam shut-off mechanism is typically of 15-30 μs so that overall response time is of 20-35 μs. A fast DBCM with a dedicated line to the beam shut off-device, as illustrated in Fig. 2, is being implemented for SRF linac protection at SNS [3]. The expected response time of 5-6 μs is mostly limited by the propagation time in the cables.

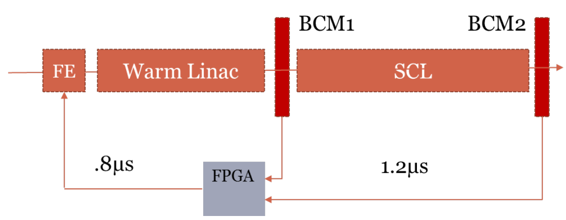

Figure 2: Diagram of the Fast DBCM protection system for the SNS Super Conducting Linac.

BEAM CURRENT AND POSITION MEASUREMENTS

Diagnostics for measuring the beam current and center of mass position are required for tuning of any accelerator independent of power. Typically, non-interceptive types of detectors are used: current transformers and electromagnetic pickups. With higher average beam power one can expect stronger signals from the detectors. An important caveat is that accelerator tuning is usually done at significantly lower beam power than in operation therefore the diagnostics should have a sufficient dynamic range or an adjustable gain to cover the required range of the signal strength. Also, depending on how the beam power reduction is implemented, an increased time response range maybe required. For example, the operational SNS beam parameters are 26 mA peak current, 1ms pulse width at 60 Hz repetition rate; the linac tuning is done with beam current reduced to 5 mA, pulse width shortened to 1 μs at 1 Hz. The reduced parameters are on the edge of the minimum design parameters for the beam position and phase monitors and do not provide the best signal-to-noise conditions but they had to be adopted to ensure the SRF linac safety.

TRANSVERSE BEAM CHARGE DISTRIBUTION MEASUREMENTS

Beam charge distribution measurements, usually in form of profiles or emittance, are the most challenging for high power beams. The biggest problem is that one has to have a "probe" inside the beam to sample the charge at different locations and the probe should be able to survive under a high beam power density. For high power beams specifically, as mentioned before, the dynamics of small fractions of the bunch are of interest, which requires measurement with large dynamic range. Typically, a dynamic range of 10^6 is desirable for understanding beam loss mechanism at the level of 1 W/m for 1 MW average beam power. In addition, if pulsed or chopped beam is accelerated, the diagnostics should have time resolution sufficient to resolve detail of the beam time structure. As we will show below, it is very difficult to combine all three requirements: non-intercepting, large dynamic range and good time resolution, in one diagnostic system.

Many different types of probes have been tried for high power beams. The results are summarized in Table 1 showing the best parameters demonstrated at high power hadron machines. The two numbers in parentheses show the expected parameters the existing systems are believed to be able to achieve with well understood modifications. We will discuss these options in more details in the next sections.

Table 1: Typical Parameters for Transverse Beam Charge Distribution Diagnostics

	Dynamic range	Time resolution	Non-intercepting
Solid material (wires, screens)	10^5 (10^6)	10 ps	No
Photons (laser beam)	10^2 (10^4)	10 ns	Yes
Charged particles (electrons, ions)	10	10 ns	Yes
Gas (residual, jet)	10^2	1 μs	Yes

Intercepting Diagnostics with Large Dynamic Range

The wire scanner is a typical example of a profile measuring system using solid material as a probe. As shown in Table 1, wire scanners can provide a very large

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dynamic range and a good time resolution. The simplest way of measuring the result of the beam interaction with the wire is to measure the charge collected on the wire. Figure 3 shows a typical transverse beam profile measured using the charge collection method at SNS. The system has a dynamic range of 10^5, which is currently limited by the digitizer resolution. It is believed the dynamic range can be improved further by upgrading the digital electronics. The advantage of the charge collection method is its simplicity and low cost. The disadvantage is the slow time response. It is not practical to achieve a good time resolution simultaneously with a large dynamic range for the charge collection method because the system bandwidth has to be limited in order to separate the DC coupled charge on the wire from the AC coupled signal induced by the electrostatic field of the beam.

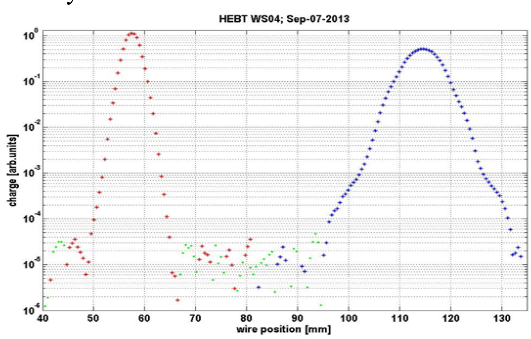

Figure 3: Typical transverse profiles measured with a wire scanner at SNS (red is vertical; blue is horizontal).

Measuring the number of beam particles scattered by the wire is another popular method of obtaining a signal from wire scanner. An example of an advanced wire scanner system of this type is described in [4] and a typical measured profile is shown in Fig. 4. The system allows profile measurements with very high temporal resolution of about 10 ps by detecting the arrival time of each scattered particle. The reported dynamic range is 10^5.

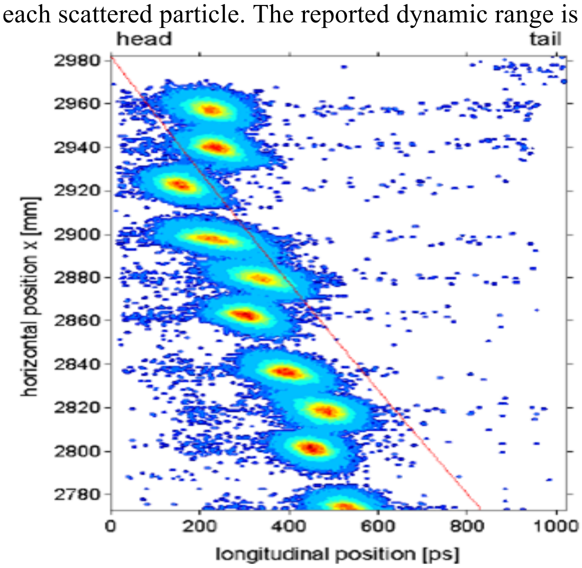

Figure 4: Typical transverse profiles with high temporal resolution measured at PSI (from [4]).

Important conditions for achieving large dynamic range in wire scanner measurements are good vacuum and small beam loss in the vicinity of the device. These conditions are difficult to satisfy at the low energy end of a linac or in the injector. A simple solution is to use a slit instead of the wire and measure charge collected in a Faraday Cup behind the slit. An example of slit system with large dynamic range and good temporal resolution is given in [5].

Non-Intercepting Diagnostics

The intercepting diagnostics discussed above are well developed, can provide large dynamic range and good temporal resolution, but they cannot be used if the beam power density is too high or clean environment requirements forbid any intercepting devices. Non-intercepting diagnostics are highly desirable in these situations. A very good general review of non-intercepting beam instrumentation is given in [6]. In this section we will give more focus to the techniques tested with high power hadron beams.

Laser Wire: A laser beam can provide an excellent probe for beam profile measurements if the interaction of the beam particles with the photons has a significant cross-section. In the case of H^- beam the cross-section for electron photo-detachment is large and peaks at the wavelengths of readily available commercial lasers as shown in Fig. 5. By crossing the beam with a narrow laser “wire” and detecting the products of the photo-detachment reaction (H^0 or electrons) the beam profile can be measured. An example of a large scale laser wire system with multiple measurement locations is described in [7]. It is possible to measure not just the profile but also the beam emittance using the laser wire as a slit as described in [8]. An example of an emittance measurement for a 1 GeV H^- beam at SNS is shown in Fig. 6. The profiles and emittance can be measured with high temporary resolution if a pulsed laser is used (about 10 ns for a typical Q-switched Nd-YAG laser). The dynamic range of about 10^2 of the SNS laser wire is limited by spurious reflections of the laser beam.

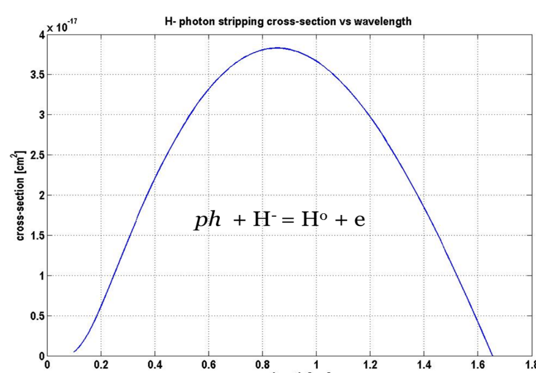

Figure 5: Electron photo-detachment cross-section vs. photon wavelength for H^-.

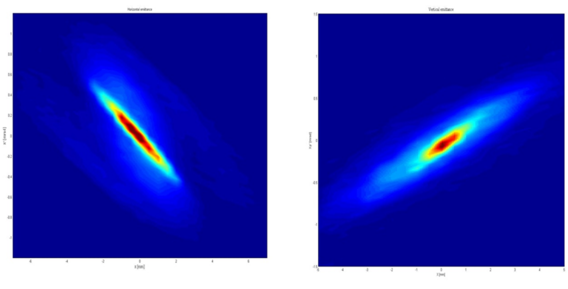

Figure 6: A typical emittance measurement using the SNS laser emittance monitor.

It is believed, based on the signal-to-noise measurements, that with proper engineering improvements the dynamic range could reach 10^4 or higher. In this case, the laser wire would be a rare case of the perfect diagnostic: non-intercepting, large dynamic range and with good temporal resolution. The biggest limitation of this diagnostic is its applicability for H^- beams only.

Ionization Profile Monitor (IPM): The Ionization Profile Monitor (IPM) is a popular non-intercepting diagnostic for beam profile measurement, widely used in proton and ion accelerators, especially in synchrotrons [6]. Its principle of operation is based on imaging of the ionization trace left by the beam in the residual gas by transferring the products of the ionization (ions or electrons) to a position sensitive charge collector. The dynamic range of an IPM is limited by the residual pressure gas and the ionization cross-section and typically does not exceed ~100. The time response can be of the order of few nanoseconds if electrons are collected. In order to mitigate distortion of the image by the space charge force of the beam a guiding electrical and/or magnetic field is used. In the case of high intensity beams the required field strength becomes the major factor determining the size, complexity and cost of the device. An example of an IPM designed for the SNS accumulator ring is shown in Fig. 7.

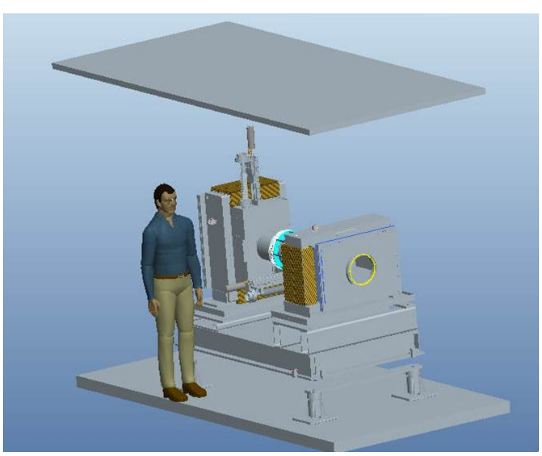

Figure 7: A model of an IPM design for the SNS accumulator ring.

Electron Beam Probe: The beam space charge force, detrimental for the IPM operation, can be used to an advantage in another type of transverse profile monitor: the electron beam probe [9]. The principle of operation is based on measuring the deflection of low energy electrons (or ions), typically in the 10 – 100 keV range, moving across the measured high intensity ion beam. The ion beam profile can be derived from the electrons deflection pattern under certain conditions. The dynamic ran is fundamentally limited by the principle of operation to a relatively low number of 10-15. The temporal resolution of few nanoseconds can be achieved with pulsed electron probe beam. An example of time resolved single turn profile measurement in the SNS accumulator ring is shown in Fig. 8.

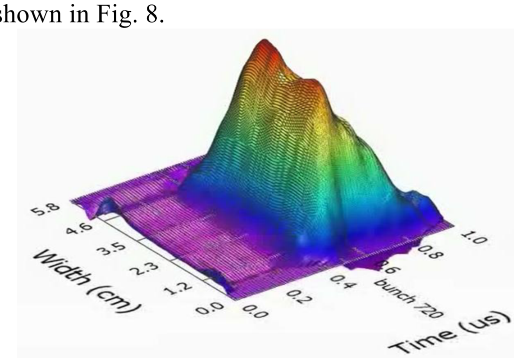

Figure 8: A typical result of a one turn transverse profile measurement with the electron beam probe monitor in the SNS accumulator ring.

Residual Gas Luminescence Monitor: Another type of a device not sensitive to the space charge forces of the high intensity beam is the residual gas luminescence monitor [6]. Its principle of operation is based on optical imaging of the residual gas luminescence induced by the measured beam. A relatively weak signal due to low cross section of the process, especially at high energy, requires long integration times and limits the dynamic range to no more than ~100.

LONGITUDINAL PROFILE MEASUREMENTS

Measuring the longitudinal bunch profile in high power non-relativistic beams is challenging for the same reason as transverse measurements discussed above: the necessity to put some kind of a probe inside the bunch. Naturally, the same types of probes used for the transverse measurements have been tried for the longitudinal diagnostics. The results are summarized in Table 2.

Table 2: Typical Parameters for Longitudinal Bunch Profile Diagnostics

	Dynamic range	Time resolution	Non-intercepting
Solid material (wires, screens)	10^4	1 ps	No
Photons (laser beam)	10^2	10 ps	Yes
Charged particles (electrons, ions)	?	?	Yes
Gas (residual, jet)	?	?	Yes

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Beam Shape Monitor (BSM)

Similar to the transverse measurements, the best results in terms of dynamic range and temporal resolution are achieved with an intercepting diagnostics using a metal wire as a probe. The BSM (aka Feschenko device) is a widely used device of this type [10]. Its principle of operation is based on measuring the profile of a low energy electron bunch created by the secondary emission from a wire positioned inside the measured ion beam. The electron bunch profile is measured using the RF deflection technique. A dynamic range of 10^4 with temporal resolution of a few picoseconds can be achieved as illustrated by Fig. 9. Further reduction of the temporal resolution is limited by space charge distortion of the low energy electron bunch. The dynamic range is limited by the ion beam scattering in the wire.

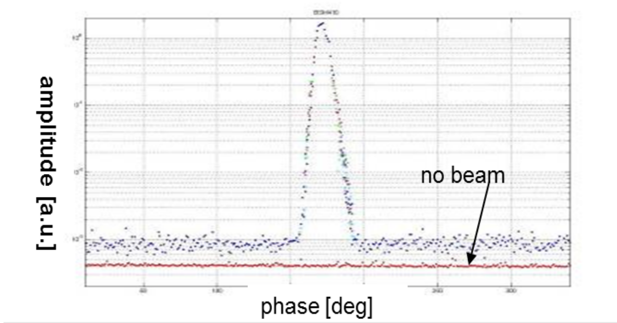

Figure 9: A typical measurement of the longitudinal bunch profile in SNS linac using BSM.

Laser Wire

The only operationally demonstrated non-intercepting type of longitudinal profile diagnostic with a good temporal resolution of few tens of picosecond and dynamic range of ~100 is based on the electron photo-detachment form H^-, similar to the laser wire described above [11]. A typical measurement of the longitudinal bunch profile in the SNS injector is shown in Fig. 10.

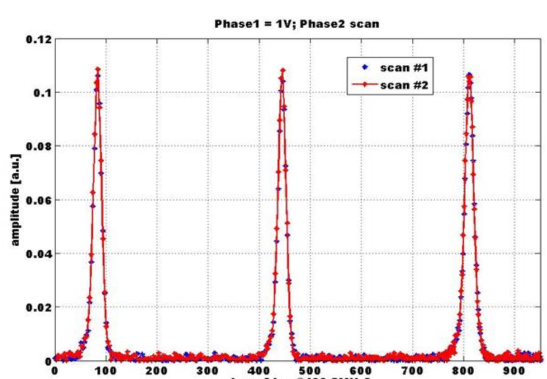

Figure 10: A typical measurement of the longitudinal bunch profile in the SNS injector using the laser wire

The dynamic range in this case is limited by a relatively poor vacuum at the device location. The temporal resolution is limited by the transverse ion beam size. The method is applicable for H^- beams only and this is its major limitation.

Non-intercepting BSM

There is an ongoing effort to develop a longitudinal diagnostic based on the IPM principle [12]. There are significant obstacles to overcome: complex electro-optical transport line, low signal and distortion from the ion beam space charge. A typical measurement with a low intensity heavy ion beam is shown in Fig. 11.

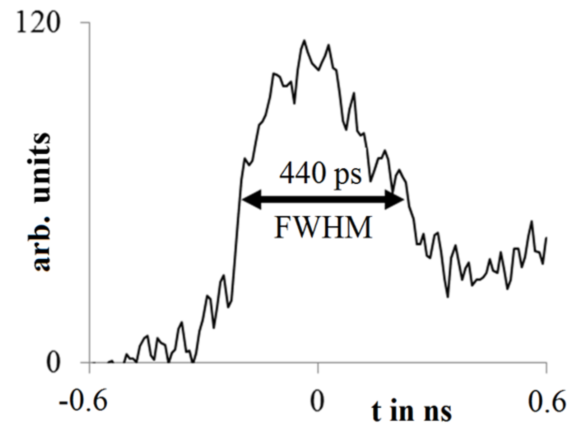

Figure 11: A typical measurement of the longitudinal bunch profile at GSI using the non-intercepting BSM (from [12]).

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