Summary of Sessions A and D: Lattices, Beam Loss Handling and Collimation & Diagnostics and Instrumentation

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INTRODUCTION

Although beam loss handling is not a new discipline, the main challenges have evolved substantially with the increasing energy and intensity of accelerators. Initially, decreasing electronic noise and signal background for collider experiments was the main reason to collimate the circulating beam. The recent use of superconducting technologies demands the removal of halo particles that could be potentially lost and trigger a quench in the structure. In high brightness accelerators, the high power contained in the beam could damage hardware components and hinder operation. In parallel, the development of high power machines with high duty factors makes residual radioactivity a key limitation for maintenance and ultimate performance. Sources of beam losses and the different systems used to remove them before they become harmful were the subject of the first session summarized here.

Diagnostics and beam losses are intimately related when dealing with a high intensity accelerator. On one hand, operation is often limited by beam losses, so fast, reliable loss detection and protection systems become mandatory. On the other hand, the measurement of relatively low intensity halos and the detection of the minimum level of losses translate into very demanding specifications for instrumentation. The requirements imposed on the instrumentation of high intensity beams and some of the applied solutions were presented in the session on diagnostics and instrumentation. The joint working group of these sessions was mostly dedicated to the prevention of accidental beam losses. The participants showed examples of beam accidents and their identified causes. A list of hardware faults was drawn from participants' experience.

LATTICES, BEAM LOSS HANDLING AND COLLIMATION

The best moment to start thinking about avoiding losses is at the design stage of the accelerator. The final design should maximize acceptance, minimize space-charge and halo growth and avoid instabilities. Precise injection, stable ramping and clean extraction are also necessary. The low loss required will generally be achieved through precise beam control and practical experience during commissioning [1].

Even when all possible sources of beam loss are minimized, dedicated collimation systems are still necessary restrict remaining loss to specified regions of the machine. Several kinds of collimation systems are usually found:

- *Beam choppers:* generally used to clean the beam gap at low energy. In these systems, the beam orbit is periodically deflected into an absorber that cleans the gap between nominal bunches.

- *Transfer line collimators:* used to define the beam before injection into a ring. The beam shape is defined by one or more blocks of material that cut in the

transverse or longitudinal phase space by means of the phase advance and dispersion. In the special case of H^{-} injection, the removal of halo is made via electron stripping which allows much higher efficiencies.

- *Two-stage betatron collimation:* usually a multi-turn system in a circular accelerator designed to clean the transverse beam halo. Primary collimators intercept the beam and a secondary halo is formed that is, in turn, intercepted by secondary collimators at a larger aperture. The phase advance between primary and secondary collimators determines the efficiency of the system together with the relative acceptance and the material choice [2]. When beam power levels are very high (e.g. LHC [5]), the survival of the collimator systems depends on controlled distribution of the losses among the jaws.

- *Longitudinal collimation:* untrapped particles need to be removed before they hit the vacuum pipe either during ramping or at extraction. For ramping losses, placing a two-stage transverse cleaning system in a dispersion area will simultaneously clean the transverse and longitudinal halo. Programmable dipolar kickers can be also excited resonantly with the betatron tune to remove longitudinal halo particles. These are generally useful in the absence of acceleration

- *Passive protection:* in critical locations such as injection and extraction areas, passive absorbers need to be located to capture beam losses that will otherwise not reach or escape from the cleaning system.

There are some important differences when collimating ions. Firstly, continuous ionization of the partially stripped ions by the residual gas leads to nonlocalized loss which is impossible to remove in one location. Secondly, even for bare nuclei, the fragmentation of the ions inside the collimator material makes optimization of the secondary collimators difficult [3]. Out-scattering from the primary collimator has to be reduced and secondary locations depend strongly on the ion species and energy.

For many purposes, it is important to differentiate between the detailed instantaneous time structure of lost beam power, and the averaged values. In superconducting magnets, the temperature increase and likely hood of a quench depends on the rate of energy deposition and removal, as determined by loss, conductivity values and the heat removal capacity of the cryogenic system.

Hardware damage is similarly highly dependant on the time structure of loss. For higher repetition rate, medium energy machines it is often possible to design the hardware to withstand the stored power of the beam For the lower rep rate, higher energy case this may not be possible.

Residual activation, however, depends on average lost beam power. Hands on maintenance criteria (<100mrem/h) require very low levels of continuous losses in the order of 1W/m [4]. The final residual radiation will still depend on the exact geometry of the loss area, the materials surrounding the beam pipe, etc. The uncontrolled loss limits need to be estimated for each particular case.

DIAGNOSTICS AND INSTRUMENTATION

As was illustrated during the workshop, spacecharge painting, e-cooling, acceleration and accurate halo measurements require very large dynamic ranges. Access to instrumentation for servicing is often limited, for example due to high radiation, its location inside cryostats or e-cooling systems. Robustness is therefore mandatory.

Another important concern when considering the instrumentation for high intensity, high brightness beams is the survival of the detector itself. Non destructive methods are necessary. Two profile measurement devices were presented during the workshop.

- *Beam induced fluorescence monitors*: The beam traverses a gas target and the excitation of the gas molecules produces visible light. A combined optical and light detection system provides the required beam information. In general, the solid angle seen by the detector is limited. The signal is generally small and the injected gas degrades the vacuum. These monitors are suitable in accelerators where a high pressure bump is not critical.

- *Ionization profile monitors:* The beam ionizes the residual gas producing a cloud of charged ions and electrons, which are swept across the vacuum vessel by appropriate electric fields, to a detector. Signals are usually large. In the high intensity limit, the space-charge between ions will distort the signal and correction via magnetic devices is needed. These monitors are more suitable for synchrotrons.

- *Laser wire scanners:* are used for H⁻ beam profiling mostly in transfer lines.

The final requirement comes from the fact that the instrumentation is linked to the protection systems of the accelerator. This imposes additional requirements in reliability. Quantified risk analysis is a valuable tool in improving system reliability.

ACCIDENTAL LOSS SCENARIOS

In terms of machine protection it is important to predict failure scenarios leading to accidental beam loss. These accidents may harm hardware components and cause costly and lengthy repairs or they may simply produce quenches in superconductor magnets preventing accelerator operation.

As mentioned above, the effect of beam losses depends on its characteristic time. At the same time, the ability to intercept or dilute these losses also depends on it. We classify losses in three main regimes [5]:

- *Ultra fast losses:* Losses over time scales of a few turns or less. Passive protection is needed as no collimation is possible.

- Very Fast losses (few turns< t < 5 ms): Losses happen in a time interval smaller than the diagnostic response time. Collimation systems are designed to intercept these losses.

- *Fast losses* (t > 5 ms): The beam loss monitors and other diagnostics can detect the losses and apply a correction or even trigger a beam dump before any damage occurs.

The scenarios leading to accidental losses and quenches in existing accelerators have been explored during the workshop [6]. A non-exhaustive list of the recurring hardware faults found is given below:

- *Kicker failures*: The asynchronous firing of a kicker may produce ultra fast losses lasting less than a turn.

- *Magnet power supplies failures*: The characteristic time of the loss is fast for most magnets but can be very fast for special magnets as at interaction regions.

- *Instabilities:* For example, those due to electron or ion clouds are usually in the fast regime and thus detectable by the instrumentation.

- *Radio Frequency System failures*: Losses driven by RF failures can be very fast or fast depending on the magnetic field ramping rate. RF faults may also drive very fast instabilities.

- *Faulty Diagnostics*: combined with automatic correction systems or feedback may lead to losses in the fast regime.

- *Collimators:* can be the cause of quenches because they localize the losses in a limited part of the accelerator. Wrong settings and electronic or mechanical failures have been the main causes. For this category of very fast loss, it is not expected that the collimators themselves will provide any protection.

- *Human errors:* are the cause of a significant fraction of recorded accidents. They are not generally predictable and can have any time range.

Accidents are often a consequence of several faults in the accelerator hardware and protection systems. Interlock system failure, faulty diagnostics or inadequate thresholds are not a direct source of loss but can lead to accidental loss in the presence of otherwise controlled losses.

Dividing critical systems into smaller independent units, with built-in redundancy, was a useful approach, as used on the SNS kickers. Hardware alarms are also valuable, for example to notify a magnet power supply failure. The identification and continuous monitoring of a limited number of critical elements inside the interlock system has also proven to be very valuable.

Self testing instrumentation was viewed as essential. Monitoring of additional diagnostics that could indicate a drift from normal conditions, provides another layer of protection.

Experience presented at the workshop clearly demonstrated that post mortem logging of diagnostic systems and hardware status is a valuable tool. It allowed identification of the causes of accidents, and therefore helped improve safety systems, and reduce facility downtime.

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