BEAM DIAGNOSTICS FOR THE DETECTION AND UNDERSTANDING OF BEAM HALO

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Abstract

A general view that has been recently reached by different methods of halo diagnostics of high brightness hadron beams will be given. The performance (dynamic range, accuracy …) of various monitor types will be combined with the demands from beam dynamics of different machines to discuss which methods can be envisaged for the future. The discussion will include low and high energy machines and their related halo detection schemes

INTRODUCTION

Especially in the high power proton accelerator already a very small number of lost protons may cause serious radiation dose. In particle accelerator beam experiments, background due to beam halo can mask the rare physics processes in the experiment detectors. Both are unwanted effects of beam halo and therefore the high intensity beam quality is strongly connected to the existence of (transverse) beam halo. However, the definition of halo is still open:

In the summary of the HALO'03 workshop [1] is written: "…it became clear that even at this workshop (HALO'03) a general definition of "Beam Halo" could not be given, because of the very different requirements in different machines, and because of the differing perspectives of instrumentation specialists and accelerator physicists… ". At IPAC2014 [2] wrote: "It is very difficult to give a simple definition of the "halo". It could be a sole beam characteristic or a beam accelerator system characteristic linked to the potential losses it can produced. It could be defined by a number of particles (in the halo) or a size (of the halo). It could be described in the geometric space or in the phase-spaces… ".

This report has a look to "Halo" from the beam instrumentation point of view, that is focused more on the number of particles (in the halo) or on the size (of the halo); and on the dynamic range for halo measurements that should be of the order of 10^5 or better (e.g. > 12 bit).

There are numerous sources of halo formation, in linear and circular accelerators, which are not discussed here. A good summary for that topic can be found in [3].

WHAT IS BEAM HALO

It should be stressed that there is an important difference between beam tails and beam halo: Tails are deviants from the expected beam profile in the order of percent or per mille while halo goes much beyond. As a consequence one should note that the topic "emittance" is related to the beam tails only. The emittance of the beam is defined by the core of the beam while including more or less of the tails. The emittance can be measured with special emittance measurement devices (e.g. pepperpot) and/or by profile monitors by knowing the β-function, momentum spread and dispersion at the location of the measurement (see e.g. [4]). A good profile monitor can reach a dynamic range of $\approx 10^3$ (e.g. > 8 bit), and a resolution of < 1% which is often sufficient for the emittance determination of the beam.

Unfortunately quite often the terms "tails" and "halo" are used in an undefined way. See Fig. 1 as an example of reported "halo" generation due to mismatch, while almost all effects happened in the tail regime. The reason of this uncertainty of definition might lie in the beam dynamics simulation tools which are very useful to understand the core beam behavior while computing with a limited number of particles. Therefore results in the real halo-regime have larger uncertainties or can't even be reached by these tools.

From the instrumentation point of view it is very useful to have a definition of halo in 1D spatial projection for which experimental measurements are easier to obtain by a beam profile/halo monitor. But note that the phase-space rotations of the beam might result in oscillations of the 1D projection along the accelerator. For example, at some locations the halo may project strongly along the spatial coordinate and only weakly along the momentum coordinate, while at other positions the reverse is true; with the consequence that the halo can be hidden from the 1D spatial projection [see e.g. 6]. For a complete understanding it is necessary to extend the 1D work to the whole phase space, in the measurement (resulting in many monitors at different location) as well as in the theoretical work and in the simulations [7, 8].

High power accelerators need very low losses during the beam transport to avoid serious activation and damage of components. Beam halo far beyond the beam core is one of the major reasons for these losses and therefore for activation of components. This can be illustrated by the following: Beam losses should be limited at least to a level which ensures hands-on-maintenance of accelerator components during shutdown. The hands-on limit has been found approximately between 0.1 W/m ≤ $H_L \leq 1$ W/m [9, 10]. Without any major beam disturbance losses are typically distributed along ½ of a β-period L_β (typical near the focusing quadrupole). The fraction of losses which will generate the hands on limit activation is than:

$$H_W = H_L * ½*L_\beta/P_B$$

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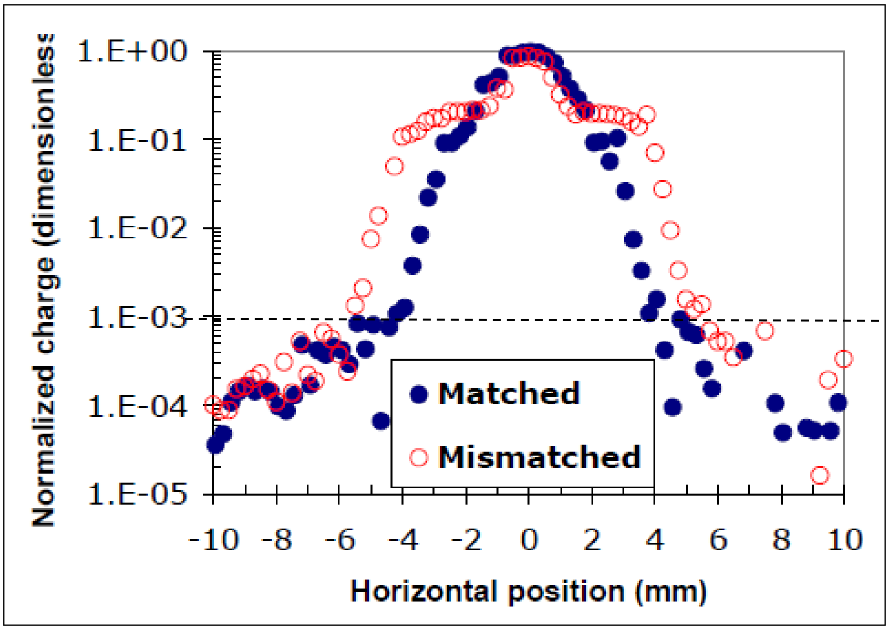

Figure 1: From [5]. Reported "Halo" generation due to mismatch. But note that almost no effect is observed below 10^{-3} (halo) while a large beam tail > 10^{-3} is generated.

while P_B is the total beam Power. Assuming a total beam power of $P_B = 1$ MW, $H_L = 1$ W/m and $L_\beta = 20$ m, it results in

$$H_W = 10^{-5}$$

BEAM HALO QUANTIFICATION

A measurement of the halo should result in a quantification of the halo; at least in 1D spatial projection. Four different methods will be discussed shortly in the following which are used to characterize beam halo:

1) Kurtosis
2) Ratio of beam core to offset
3) Ratio of halo to core
4) Gaussian area ratio

An important feature of such quantifiers is that they are model independent and rely only on the characteristics of the beam distribution itself.

1) Kurtosis

This method is based on analyzing the fourth moment of the beam profile. The kurtosis k is a measure of whether a data set is peaked or flat relative to a normal (Gaussian) distribution:

$$k \equiv \frac{\left\langle (x - x_0)^4 \right\rangle}{\left\langle (x - x_0)^2 \right\rangle^2} - 2,$$

where x_0 is the beam center coordinate and x is the measured value of the profile distribution. The denominator is the standard deviation of the distribution and the numerator is the 4th order moment. The sample kurtosis of n values with mean x_0 is defined by:

Therefore a constant loss of 10ppm of the beam is enough to reach the activation limit under these assumptions. These small losses can easily be generated by beam halo and halo monitoring might become useful to quantify the halo and finally to find measures to its generation.

$$k \equiv \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - x_0)^4}{\left(\frac{1}{n}\sum_{i=1}^{n}(x_i - x_0)^2\right)^2} - 2$$

Distributions with high kurtosis have sharp peaks near the mean that come down rapidly to heavy tails. For more details see [7,11,12]. It is obvious, that this more theoretical method is much more sensitive to tails and almost not sensitive to halo.

2) Ratio of Halo to Core

[13] proposed recently a new method for determining the core-halo limit applicable to any particle distribution type: The core-halo limit is defined as the location where there is the largest slope variation in the density profile, i.e. where the density second derivative is maximum. A pure Gaussian profile with σ RMS has with such a definition already a halo starting from $\sqrt{3}*\sigma$, containing thus 8.3% particles of the beam while a triangular or K-V distribution does not have a halo. Since the largest slope variation is mainly created by the beam core, this method is quite sensitive to tails, too.

3) Ratio of Core to Offset

An experimentally robust technique to quantify the halo was used at Fermilab [14]. The raw data of the detector (profile monitor) are fitted to the function:

$$f(x) = g(x) \cdot l(x),$$

where g(x) is a Gaussian core

$$A \cdot e^{\frac{-(x-x_0)^2}{2\sigma^2}}$$

and l(x) is the non-Gaussian halo of the beam:

$$l(x) = c_0 + c_1 x.$$

Defining a region of interest (ROI) which includes the tails/halo of the interesting beam profile, one can define the properties L and G as

$$L = \int_{ROI} l(x)dx$$

and

$$G = \int_{ROI} g(x)dx.$$

The beam halo can be calculated by the ratio L/G. A perfectly Gaussian beam will have L/G = 0, whereas a beam with tails/halo will have L/G > 0. It is very important for this procedure to eliminate noisy and dead channels for the fit as well as knowing the pedestal for each channel. Each pedestal has to be subtracted from the data set. The standard deviation of many pedestal measurements can help to find noisy (σ_{ped} is large) and dead channels (σ_{ped}=0). Studies have shown that the L/G method is a good indicator for beam tails by using a profile monitor. However, this method can easily extend into the halo regime e.g. by adding a second baseline below the beam tail and by using a halo monitor.

4) Gaussian Area Ratio

The method quantifies the “non-Gaussian” component of the beam profile by comparing a Gaussian fit of the core with the complete data set. Typically the Gaussian fit is applied to the top (90 percent) of the profile to represent the core (most beam core distributions can be represented by a Gaussian). The next step is to find the integral or area of the measured distribution (e.g. by summation of the midpoint [15]) and to normalize it to (divide it by) the area under the Gaussian fit. Since the core (±some σ) is the same in both cases one can use the area outside some σ only. The result (>1) gives a quantitative value of the halo content while a result =1 represents a beam without halo. If the measured distribution has also tails, one might use 2 gaussians to represent the core plus tails and compare it with the measured distribution.

Comments

The methods 1) and 2) are quite sensitive to beam tails and not to beam halo but these are robust methods in simulations (with low numbers of particles) where the behavior of the beam in the tail region is studied. The methods 3) and 4) are more useful for beam halo measurements and large number of particles. With their help one can derive two halo parameters [13] which can be used to compare and optimize the accelerator settings:

PHS = 100 * Halo size/Total beam size
= Percentage of halo size
PHP = 100*Nb of particles in halo/total Nb of particles
= Percentage of halo particles

Note that a measurement always contains instrumental effects. To define the halo contents in such a theoretical way one has to exclude these effects in advance. Therefore a useful halo instrument and measurement should reach a resolution of (much) better than 10^{-2} of the beam size and a noise level << 10^{-5} of the beam peak. When comparing halo measurements with simulations it is obvious that even powerful simulations are useless if significant physical mechanisms are missing or if the beam input distribution is unrealistic.

TRANSVERSAL HALO MEASUREMENTS

One can find two types of halo monitors; the first type measures the whole beam with very high dynamic range and very good resolution (e.g. wire scanner), the second type is a sensitive monitor at a more or less fixed transversal position which measures the rate of particles hitting this monitor (see e.g. [16, 17]).

Halo calibration of the second type is done by normalizing the measurement to the whole beam current resulting in PHP. Moveable scrapers equipped with beam loss monitors fall into this type although the distribution of the halo can be measured by moving the jaws and recording the loss rate [18]. Since a cross calibration with a beam current monitor is required, the resulting resolution in terms of an absolute number of halo particles might be limited but a relative observation of changes in the halo can be done with very high resolution.

A detailed discussion of the first halo monitor type can be found in [19] and references herein (some additional references are listed below). One of the most used halo monitors are wire scanners which are able to measure the profile of the whole beam (PHS) with very high dynamic ranges and very good resolution (< 10 microns). Various techniques are used to archive dynamic ranges up to 10^8, including counting techniques at high and at low energies [20] and vibrating wire techniques [21]. Since scanning techniques are often very time consuming (up to minutes), optical methods can be much faster: [22] reported recently results of using different types of screens with higher sensitivity in the tails and halo regime. For a high dynamic readout of screens CID cameras with a dynamic range of ≈ 10^6 are commercial available. Scintillation screens might be limited in their linearity but OTR screens did not show any saturation effects even at these high dynamic ranges. Adaptive masking techniques with micro mirror arrays [23] and by coronagraph [24] show reliable beam halos of smaller than 10^{-6}.

CONCLUSION

Some definitions of halo have discussed in this report showing the requirement to distinguish clearly between the halo and tail of the beam. Different methods of quantization of halo were discussed in view of their sensitivity to tails and to their utility to halo

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measurements. The “state of the art” instrument for a full horizontal halo measurements is still the wire scanner; a dynamic range of better than 10^8 has been achieved. Optical methods using readout by a CID camera or a coronagraph have the potential to reach even higher dynamic range.

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