BEAM HALO CHARACTERIZATION AND MITIGATION

A. Aleksandrov
Oak Ridge National Laboratory, Oak Ridge, TN 37830, USA

Abstract

Beam halo is a serious issue in many machines, such as high intensity linacs and synchrotrons. This presentation reviews recent advances in halo characterization techniques, as well as methods to mitigate beam halo, such as collimation with associated handling of created secondary particles.

INTRODUCTION

Beam halo is a loosely defined low-density distribution of particles with large oscillation amplitudes, which can reach the aperture of the beam line enclosure thus creating uncontrolled beam loss. Because of this association with uncontrolled beam loss, halo, typically, is viewed as an unwanted phenomenon requiring mitigation. All aspects of halo beam dynamics, measurement and mitigation techniques have been receiving an increased attention since the emergence of new high beam intensity projects, e.g. APT, ESNS, SNS in the late 90s, early 2000s. Over the last 10-15 year many different methods of halo measurement have been successfully demonstrated and several halo characterization methods proposed; megawatt class accelerating facilities commissioned and reached the design parameters. However, beam halo and the associated beam loss mitigation still largely rely on an empirical machine tuning without use of halo measurements.

In this presentation we will consider a practical aspect of high intensity accelerators operation: how halo measurements can be used to facilitate halo mitigation. First, we will discuss what we call "halo" in the context of this paper. In the second section we will present several examples of large dynamic range transverse profile measurement techniques. That section is not intended to give a comprehensive review of all available methods and achievements; good reviews are available elsewhere [1]. Our purpose there is to demonstrate that halo measurements have been available for quite long time. In the third Section we will explore why ordinary low dynamic range beam profile measurements are so useful for accelerator tuning and operation and why halo measurements have not achieved the same level of usefulness. Our proposition is that RMS envelope formalism provides practical algorithm for beam core characterization, which can use profile measurement. We show that the same approach cannot be used to characterize the beam halo. Next we argue that using PIC beam simulation codes instead of RMS envelope codes allows including the halo in simulations. This requires new approaches to halo characterization and measurement beyond the RMS Twiss parameters. The most straightforward approach is to generate a particle distribution as input to a PIC code using a measured phase space distribution. This will require large dynamic range measurement of beam phase space distribution. We will review the existing and emerging measurement techniques in the fourth section. In the last section we will explore how this new approach can be used in practice for halo mitigation.

HALO DEFINITION

There have been many attempts to formulate a universal definition of beam 'halo', usable for experts in different fields of accelerator science: beam dynamics, beam instrumentation, beam simulations and accelerator operations. So far even a dedicated joint meeting of all interested parties over several days failed to produce one [2]. Recently, a narrower group of Beam Instrumentation experts was able to come to an agreement on what to call "halo" in beam measurements [3]. In short, the beam charge distribution inside the vacuum chamber can be separated to three parts: the beam core, the beam halo and the transition (the transition is often called "shoulders", "tails" etc.). The parts are characterized by the charge density relative to the peak density. The boundaries are not defined exactly but for the majority of the cases the beam core boundary is at about 10^{-2} level, the beam halo is at 10^{-4} -10^{-6} level and below. The low boundary of the halo region is decreasing with higher intensity beams, obviously, but the 10^{-4} -10^{-6} range represents a good reference number for a large range of today's accelerators and is the current state-of-the art in beam measurements. In the context of this paper we add to the halo definition a notion that the halo extends far from the beam core, it has a negative effect on an accelerator operation, and its effects has to be mitigated. Despite being seemingly vague this definition helps to clarify many practical issues in measuring and characterizing the halo. We will provide a more convincing argument for selection of the particular charge density ranges defining the halo vs. the core and the transition below in the section on the RMS beam size formalism.

From machine operation point of view the beam core density is important because it usually represents the figure of merit for performance e.g. luminosity; the halo density is important because it is directly related to beam loss; the particles in the transition zone have interesting dynamics but typically do not directly affect operations.

We should note that all practical examples below are given for the case of transverse beam motion. The same arguments are valid for the longitudinal degree of freedom but are not included because of the limited presentation time and space.

LARGE DYNACMIC RANGE BEAM PROFILE MEASUREMENTS

The halo, as defined above, has a relatively low charge density. However, the actual number of particles in the halo is typically quite large for high intensity beams. The halo would not present a problem otherwise. Therefore, in many situations it is not difficult to detect the halo or quantify its density in "more" or "less" terms. The loss monitors of various kind do this quite reliably in all high intensity accelerators. What is difficult is measuring quantitatively the distribution of a small charge density in the halo simultaneously with a large charge density in the core, present at the same time almost at the same location. Such a measurement requires large dynamic range or, in other words, ability to resolve small details on top of a large signal. Typically, the dynamic range is expressed as a ratio of the highest signal to the lowest measurable one in linear or logarithmic scale. To measure the halo, as we defined it above, a system with a dynamic range of 10^4–10^6 (or 80–120 dB in logarithmic scale; or 20 bits in binary representation) is required. Below we will review several examples of diagnostics that have demonstrated the required dynamic range.

Imaging Beam Synchrotron Radiation

The most straightforward way of measuring a 1D or 2D profile of a beam is to image the synchrotron light in cases when there is emitted light, e.g. in an electron storage ring. The dynamic range of a typical digital camera (of the order of 10^4 for a good quality consumer grade sensors) is the main limiting factor of the overall dynamic range of such systems. A concept of chronograph, developed for solar corona observation in astronomy, has been successfully used to extend the dynamic range of the camera [4]. The general idea is to block the bright beam core image with a mask when imaging the dim halo. The core image is obtained separately using a light attenuator and then combined with the halo image. Lately, digital light processor micro-mirror array chips were used in place of the solid mask in the coronagraph to better conform the mask to the shape of the core image [5]. A dynamic range of 10^5 - 10^6 was successfully demonstrated in both cases. There have been new types of imaging sensors developed (so-called HDR sensors) [6], which should allow direct beam profile imaging with a dynamic range of 10^6 or more. A great care has to be taken to avoid spurious light reflections and scattering in the optical system, which ultimately limit the maximum achievable dynamic range. An example of beam profile measurement using direct imaging with a high dynamic range camera is shown in [7].

Using View Screens

In the cases when beam does not emit sufficient amount of light, e.g. in linacs and hadron rings, light-emitting screens can be used. Luminescent screens typically have a dynamic range of about 10^3, limited by the allowed beam power density at the brightest spot. A combined system of two screens with different light emitting efficiency (high efficiency luminescent screen for the halo and low efficiency optical transition radiation screen for the core) was proposed and successfully realized in [8].

By introducing the screen we break away from the important non-interceptive nature of synchrotron light imaging diagnostics. This puts significant limitations for the power density on the beam probe but, on other hand, allows using non-optical signal read out methods.

Wire Scanners

Wire scanners are the most common devices for measuring beam profile in the situations when solid wire can be inserted in the beam without destroying the beam or the wire. The most common methods to obtain signal proportional to the beam density are to measure secondary particles scattered by the wire or to measure charge induced by the beam. Both methods have demonstrated large dynamic range of 10^6 or larger [9, 10]. The main factors limiting the maximum achievable dynamic range of a wire scanner are poor vacuum and significant beam losses in the vicinity of the wire. In case of charge collection mode of operation the AC coupling of the wire to the beam core has to be suppressed, which typically limits the measuring bandwidth to few kilohertz or lower.

HALO CHARACTERIZATION

As the examples above show, large dynamic range profile measurements are possible and have been achieved by different methods. However, not many practical uses of this kind of measurements for halo mitigation have been reported. In order to understand why, it is instructive to review how the beam core profile measurements are typically used for accelerator set up and operation. A typical result of beam size measurement is shown in Fig.1. In this example from SNS linac the beam size is measured at five points only but the beam envelope is extrapolated to a much large portion of the beam line spanning tens of meters with tens of focusing elements. Obtaining such a continuous beam envelope plot using beam profile measurements alone would require a very large number of measuring devices – one device per each focusing element, which is obviously impractical. Alternatively, one can use an algorithm to reliably extrapolate the beam size beyond few measured points. The existence of such mathematical formalism described below is what makes the beam core profile measurements useful. We need something similar for the halo measurements to make them useful for accelerator tuning and operations.

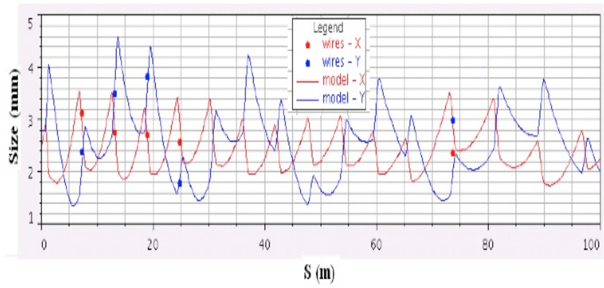

Figure 1: An example of beam size vs. distance along the SNS linac. Measured data are shown by dots.

RMS Beam Size and Twiss Parameters

The RMS envelope equation is the main tool for describing the beam size evolution along an accelerator [11]. Only the three parameters that describe the beam distribution, the so called RMS Twiss parameters, are required to find the RMS beam size anywhere in a beam line with known focusing properties. These parameters can be calculated using a set of three or more beam profile measurements in one or several locations by various techniques, e.g. the so-called quad scan technique [12]. Therefore the beam core profile measurements are an integral part of practical use of the RMS envelope formalism in accelerator set up and operation.

It is natural to try expanding the same approach to the beam halo characterization. Unfortunately, the RMS beam size is not sensitive enough to the halo density. This can be illustrated using a simple 1D distribution, shown in Fig. 2, consisting of a Gaussian core and a uniform halo inside a reasonably sized aperture.

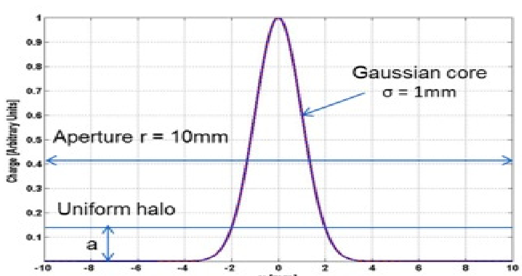

Figure 2: A test beam profile consisting of a Gaussian core and a uniform halo.

This distribution makes a very good example because it does not contain any particles in the transition zone, which can mask the effect of the halo proper. The dependence of the RMS size on the halo amplitude for this distribution is shown in Fig. 3 by blue line plot.

As one can see, the RMS size is almost insensitive to the halo amplitude until the amplitude is significantly above approximately 10^{-4} level, where it is not a halo anymore according to our definition.

Other statistical quantities based on higher order moments of the distribution were proposed to use in order to increase the sensitivity to the outlying particles. A well-known example is the kurtosis [13]. The dependence of the kurtosis on the halo amplitude is shown in Fig. 3 by the green line plot. Indeed, the kurtosis is more sensitive to the halo amplitude. Unfortunately, statistical quantities using high order moments, including kurtosis, are very sensitive to small variations of the beam density in the transition zone, which makes them impractical to use for real life measurements. And, more important, there is not an equation, similar to the RMS envelope equation, to calculate the kurtosis everywhere in the beam line using a limited number of profile measurements.

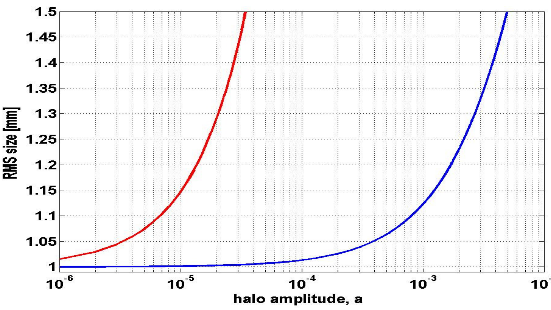

Figure 3: Dependence of the RMS size (blue line) and of the kurtosis (red line) on the halo amplitude for the profile of Fig. 2.

Particles distribution in phase space

Particle-In-Cell (PIC) simulation codes can provide an alternative to the RMS envelope equation. However, the RMS Twiss parameters are not sufficient to initialize PIC simulation. The detailed particle distribution in 6D phase space is required. We can assume no coupling between the horizontal, vertical and longitudinal planes as a first step. Then 2D phase space measurements in combination with a PIC code can provide a replacement for profile measurements and RMS envelope equations.

A convenient way of visualizing general properties of the 2D phase space distribution is plotting the phase space density vs. the normalized radius according to the following procedure:

- generate N particles using measured 2D phase space distribution as a probability function
- transform the particles coordinates x, x' to new coordinates: $x_n = {}^{x}\!/\!\sqrt{\beta_{RMS}}$;
- $x_n' = {}^{\alpha_{RMS} \cdot x}\!/\!\sqrt{\beta_{RMS}} + x'\beta\gamma\sqrt{\beta_{RMS}}$, where $\alpha_{RMS}, \beta_{RMS}$ are the RMS Twiss parameters, $\beta = {}^{v}\!/_{c}$, and γ is the relativistic factor
- $r = \sqrt{x_n^2 + x_n'^2}$
- count number of particles N_r within $r \cdot dr$ intervals
- plot $n(r) = {}^{N_r}\!/_{2\pi r dr}$ vs. r using in semi log scale

The plot of n vs. r is independent of the beam energy or location along the beam line. It can be used for comparing general distribution properties for different accelerators or even different particles species. An example of phase space density plots measured at SNS linac at 2.5 MeV and 1 GeV is shown in Fig. 4. The beam core dilution and tails growth are clearly seen on the plots.

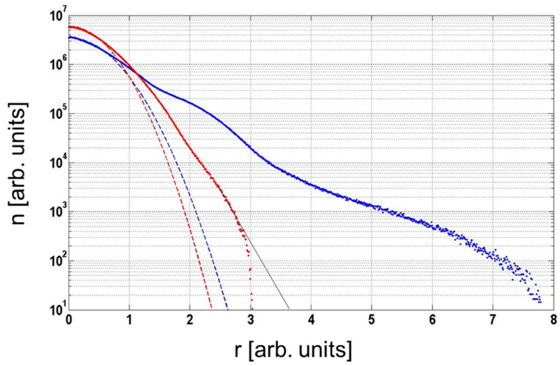

Figure 4: A phase space density plot for beam distributions measured in SNS 2.5MeV MEBT (red line) and 1GeV HEBT (red line).

LARGE DYNAMIC RANGE 2D PHASE SPACE MEASUREMENTS

There are a number of techniques for measuring the 2D phase space distribution (often called simply 'emittance') in transverse and longitudinal planes. They have to provide a large dynamic range of the order of 10^4 -10^6 to be useful for the halo characterization.

Direct Phase Space Measurement at Low Energy

The 2D phase space can be measured relatively easily at low energy (particles have to have sub-millimeter range in a solid material) using the slit-slit scan technique. A general measurement set up is shown in Fig. 5. A similar slit-grid arrangement is often used but the slit-slit arrangement allows achieving the required dynamic range much easier [14] because of the possibility of using a single high quality detector.

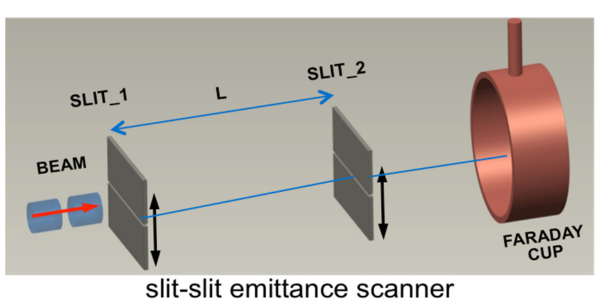

Figure 5: A schematic view of a slit-slit emittance scanner.

Direct Phase Space Measurement at High Energy

The only method for direct emittance measurement at high energy successfully demonstrated to date is the laser wire emittance scanner [15]. This method is suitable for H- beams only. The currently achieved dynamic range of 10^3 can be possibly improved by an order of magnitude but further extension to the halo region is limited by the laser beam quality.

Reconstruction of 2D Phase Space Distribution from a Set of 1D Projections

The so-called phase space tomography allows finding the 2D emittance using several 1D projections (profiles) measured at different angles in phase space. The method has been demonstrated for transverse and longitudinal phase space. The dynamic range of the reconstructed 2D emittance depends on the dynamic range of the profiles and the method of reconstruction. An example of a reconstruction with ~10^3 dynamic range using four wire scanner profiles with 10^4 dynamic range and several iterations of the MENT algorithm is shown in Fig. 6. The measured profiles are plotted in red color; the profiles obtained by integrating the reconstructed 2D emittance are plotted in blue color. A reasonably good agreement is observed down to the 10^{-4} level. Further development of the method is required to extend the dynamic range to the halo region. The SNS HEBT beam line having a straight section containing several individually settable quadrupole magnets, five large dynamic range wire scanners and a laser wire emittance scanner is an ideal test bench for large dynamic range tomographic reconstruction methods development. Even if the laser emittance scanner dynamic range is limited to 10^4, the possibility of a direct verification of the reconstruction quality to this level is indispensible.

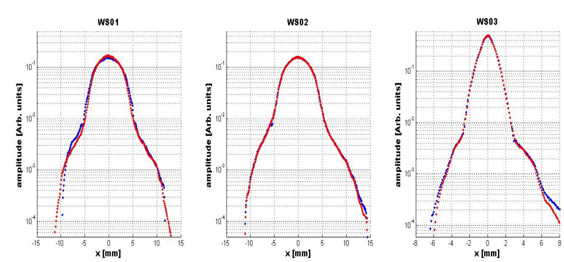

Figure 6: Comparison of measured (red) and obtained from results of 2D emittance reconstruction with large dynamic range (blue).

HALO MITIGATION

Operation of high intensity accelerators with low beam loss provides existence proof of successful practical halo mitigation methods. However, typically these methods do not involve the halo measurements and characterization but rely on empirical loss reduction using beam loss detectors and/or on the use of collimation systems to localize the beam losses at radiation shielded areas thus reducing beam spill elsewhere. Availability of the halo measurement and characterization in 2D phase space should facilitate the knowledge based halo mitigation techniques.

Understanding Halo Formation

Understanding the mechanisms of the halo formation could help in developing methods of its prevention. The first dedicated halo formation study experiment was conducted at the LEDA facility in Los Alamos [16]. The experimental beam line consisting of 52 quadrupole magnets in FODO arrangement, as shown in Fig 7, was equipped with seven wire scanners capable of measuring the beam profiles with dynamic range of about 10^5. The two main

ISBN 978-3-95450-147-2

goals of the experiment were: 1) to confirm the halo formation in mismatched beam transported through a periodic focusing system with significant space charge; 2) to validate the beam dynamics simulation codes. The experiment demonstrated formation of strong shoulders in the transition zone, which were not predicted by the state-of-the-art simulation codes of that time. The halo formation was neither confirmed nor disproved.

Recently, a similar experiment but with a shorter FODO beam line of 28 quadrupole magnets was conducted with similar results [17].

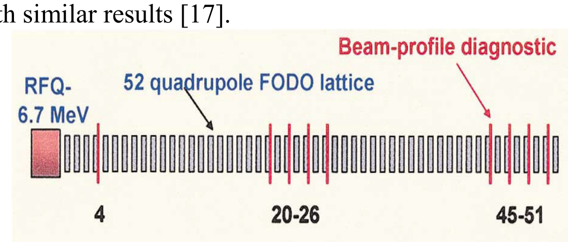

Figure 7: A schematic view of the LEDA halo formation experiment. From Ref. 16.

A similar experiment but with significantly improved diagnostics capability is being built at SNS [18]. The experimental set up will have equipment for measuring the beam distribution in 6D phase space at the entrance to the FODO line and 4D distribution with large dynamic range at the exit.

Beam Core and Halo matching

Matching the RMS Twiss parameters at transitions between sections of an accelerator minimizes the maximum size of the beam RMS envelope. It is also believed (though there has been no experimental prof) that the matching prevents the halo from growing in the case of strong space charge. It is possible though that the Twiss parameters for the halo (e.g. the parameters of an ellipse enclosing the halo) are different from the RMS Twiss parameters. In this case matching the RMS Twiss parameters leaves the halo unmatched. The net effect on the maximum beam extension and loss will depend on the interplay of two factors: the halo growth due to unmatched RMS Twiss parameters and maximum beam size increase due to unmatched halo Twiss parameters. Often, like in the case of the SNS linac, measurement based matching of the RMS Twiss parameters does not ensure the minimum beam loss, which probably is an indicator that matching the halo would give an advantage. Availability of 2D emittance measurements for the halo would allow efficient model based loss reduction in this case.

Collimation at Low Energy

The most efficient way to clean a beam from the halo formed in the injector is to collimate it at low energy where particles can be stopped by a relatively thin block of a material. The problem is typically to find free space available in the beam line because the strong space charge at low energy requires large density of focusing elements. Therefore the collimators are often placed where space is available and the beam line optics needs to be adjusted for effective collimation, i.e. the halo needs to have the correct orientation in phase space. This is much easier to achieve if 2D emittance measurements of the halo are available.

Collimation at High Energy

At high energy the collimator design is much more complicated because particles cannot be stopped within a reasonable thickness of a material. Two or more staged collimation systems are used in this case. Optimal design process of multistage collimation is well developed and described in literature [19]. In a single pass beam line e.g. linac or transfer line the beam only passes the collimator once therefore the halo orientation in phase space has to be just right for efficient collimation. Similar to the case of low energy collimation, availability of 2D halo emittance measurements allows model based tuning of the halo orientation.

ACKNOWLEDGEMENT

SNS is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy.

REFERENCES

[1] K. Wittenburg, in Proceedings of the CAS-CERN Accelerator School 2008, p.557.
[2] Proceedings of HALO'03.
[3] A.S. Fisher, "Summary of the 2014 Beam-Halo Monitoring Workshop", in *Proc. IBIC'15,* paper THBLA01, pp. 630-636.
[4] T. Mitsuhashi, "Beam Halo Observation by Coronagraph", in *Proc. DIPAC'05*, paper ITMM03, pp. 7-11.
[5] H.D. Zhang *et al.*, *PRST-AB* 15, 072803 (2012).
[6] www.embedded-vision.com/
[7] J. Egberts *et al.*, "Design of a Beam Halo Monitor with a High Dynamic Range", in *Proc LINAC'08*, paper TUP076, pp. 570-572.
[8] Y. Hashimoto *et al.*, "Two-Dimensional and Wide Dynamic Range Profile Monitor Using OTR / Fluorescence Screens for Diagnosing Beam Halo of Intense Proton Beams", in *Proc. HB'14,* paper TUO2AB04, pp.187-191.
[9] R. Dölling, "Variants of Grounding and Shielding in a Beam Diagnostics Measurement of Low Signal Currents", in *Proc. CYCLOTRONS'13,* paper TUPPT010, pp.174-176.
[10] A. Aleksandrov, Beam Instrumentation for High Power Hadron Beams, in *Proc NA-PAC'13,* paper TUYBA1, pp. 380-384.
[11] Handbook of Accelerator Physics and Engineering, 3rd Printing, World Scientific, 2006, p. 568.
[12] M. Minty, F. Zimmerman, 'Measurement and Control of Charged Particle Beams', Springer, 2003.
[13] C. Allen *et al.*, *PRST-AB* 5, 124202, 2002.
[14] A. Aleksandrov *et al.*, "Diagnostics Tools for Beam Halo Investigation in SNS Linac", *Proc. LINAC'12,* paper THPB013, pp. 873-875.
[15] Y. Liu *et al.*, *NIM* A 675(2012).
[16] C. Allen *et al.*, *Phys. Rev. Letters*, 89, 214802, 2002.
[17] Hongping Jiang, in *Proc. IBIC'15,* paper TUPB030, p.393-395.
[18] A. Aleksandrov *et al.*, "Status of New 2.5 MeV Test Facility at SNS", in *Proc. LINAC'14,* paper THPP108, pp.1105-1107.
[19] Handbook of Accelerator Physics and Engineering, 3rd Printing, World Scientific, 2006, pp. 270-274.