EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

SVDM/afm

CERN PS/89-30 (AR)

ACCEPTANCE MEASUREMENTS IN THE AA AND AC RINGS

S. van der Meer

Summary

The method used for routine transverse acceptance measurement in the AA and AC machines is explained. It uses an aperture-limited beam obtained by blow-up with random noise, and localisation of the beam edges with scrapers.The problem of finding the faint beam edges and its solution are described.

Geneva, Switzerland
March 1989

1. INTRODUCTION

Most accelerators and storage rings are designed with sufficient acceptance margins to ensure correct operation. The precise acceptance values are then not of great interest. In antiproton accumulator rings, on the other hand, the entire aperture is filled and the accumulation rate depends strongly on acceptance. Experimental optimisation of transverse acceptance by closed orbit adjustment is of great importance, the more so because in practice the physical aperture is often displaced with respect to the theoretical orbit. For this optimisation, numerous acceptance measurements are needed. Their reproducibility must be good (say 1%), since an increase of acceptance can only be obtained by many successive small adjustments.

The method used is to inject particles into the ring and then blow up the beam by noise excitation with a transverse kicker until a certain fraction (e.g. 20%) of the beam is lost. The beam envelope then touches the aperture somewhere. The excitation is stopped and a scraper is moved inwards until it starts touching the beam edge and removing some particles. From the scraper position at that moment, the acceptance may be found if the lattice parameter β at the scraper is known.

The measurement must be repeated with a second scraper on the other side of the beam since the exact closed orbit position at the scraper is not known with sufficient precision. (In fact, orbit optimisation may imply changes in this position). The acceptance is then found from the difference between the opposite scraper positions. Of course, before doing the measurement with the second scraper, the first one must be removed and the beam must be blown up again.

2. FINDING THE EDGE - THE PROBLEM

It turns out to be surprisingly difficult to find the exact point where the scraper touches the beam. To begin with, the resolution of the scraper movement must be good (e.g. in the AA, the smallest steps are 0.1 mm, corresponding to 1.5% in acceptance). What is much worse is that a beam whose emittance is blown up by random noise will not present sharply defined edges where it touches the aperture limit.

Sharper edges may be obtained by giving a single large kick to the beam so that part of it is lost, e.g. using an injection kicker. The problem here is that such kickers are expensive and therefore in practice only available in one plane. Moreover, such sharp-edged beams have a short lifetime when touching the wall, which makes it difficult to find the first point of intersection by the scraper.

Amplitude distributions of aperture-limited beams blown up by random noise are discussed in Appendix A. It is shown that the edge of such distributions may be described by a function

$$L \approx 2.2(1 - A)^2 \tag{1}$$

where L is the fraction lost after all particles with amplitude larger than A have been scraped off, A being normalised with respect to the aperture limit. This parabolic approximation is valid for $0.9 < A < 1$, for beams that have started out as a pencil beam and lost 20% by blow-up.

As a consequence, for $A = 0.995$ (where the acceptance is reduced by 1%), only a fraction of 5.5×10^{-5} is lost. Even for $A = 0.975$ (5% acceptance reduction), only 0.16% is lost. This makes it so difficult to measure acceptance to within 1% with this method. In fact, early measurements yielded wildly varying results.

3. *FINDING THE EDGE - THE SOLUTION*

The method that is used in the AA and AC rings is to continue the stepwise scraper movement until a fraction of about 10% is lost, meanwhile measuring the remaining beam intensity at every step. The points so obtained (vs scraper position) are then fitted with a straight line (for the region of movement where the scraper was still outside the beam) and a parabola, according to Eq. (1) but with a free coefficient, for the region where the scraper cuts into the beam. The straight line may have any slope, because the lifetime of an aperture-limited beam is not infinite, and the parabola is required to be tangential to this line. The point where the straight line merges into the parabola (and which is used for calculating the acceptance) is adjusted until the best least-squares fit is obtained. The fitting procedure is described in more detail in Appendix B.

With this method, the steps may be relatively large (e.g. 0.5 mm, corresponding to 8% of the AA acceptance). Large steps help to keep the measurement time short. All the same, a reproducibility of 1%, far less than the step size, is easily obtained.

4. *AUTOMATISATION*

Although seemingly only a small practical detail, automatisation of the measurement reduces the time required by at least an order of magnitude and is therefore essential. For a measurement the following steps are needed:

- specification of plane (H or V),
- specification of revolution frequency at which the measurement is to be made,
- various checks:
  - correct operating mode set,
  - cooling off,
  - shutters open (for AA),
  - rf on, remote-controlled.
- move all scrapers outside beam aperture,
- move ejection kicker in (for AA, in "loop" mode where protons are injected by this kicker),
- kill any remaining beam by moving a stopper in and out,
- set up rf for capturing injected beam,
- ask for beam from PS and wait for injection,
- check intensity; if insufficient, back to preceding step,
- move ejection kicker out (AA),
- move beam (by means of a suitable rf function) to the required revolution frequency,
- debunch the beam,

- blow-up until 20% is lost,
- measure intensity vs time and wait until beam decay is below a given limit; this is sometimes needed if microwave instability of a small beam fraction has occurred,
- move scraper in by 0.5 mm steps until at least 5 steps have shown a loss of more than 0.5%,
- move out scraper,
- calculate beam edge,
- blow up beam until 20% is lost,
- move in opposite scraper in the same way,
- move out scraper,
- calculate beam edge,
- calculate acceptance.

A measurement takes about 3 minutes. Most of this time is needed at present for the blow-up process. This could be speeded up by using a stronger excitation.

REFERENCES

1. H. Bruck, Accélérateurs circulaires de particules, Presses Universitaires de France, Paris 1966, ch. XIV-II.
2. H.S. Carslaw, J.C. Jaeger, Conduction of Heat in Solids, Clarendon Press, Oxford 1959, ch VII-7.4.

APPENDIX A

AMPLITUDE DISTRIBUTION OF AN APERTURE-LIMITED BEAM BLOWN UP BY RANDOM NOISE

The betatron amplitude distribution of an aperture-limited beam blown up by small random kicks has been described by Bruck[1]. According to this analysis (which concerns beams blown up by multiple scattering, but is equally valid for beams blown up by a kicker excited with noise) we may describe the evolution by a diffusion equation. With some small changes in notation we have:

$$\frac{\partial(p/A)}{\partial t} = \frac{D}{A}\frac{\partial}{\partial A}\left[A\,\frac{\partial(p/A)}{\partial A}\right] \tag{2}$$

where p is the normalised distribution ($p = (1/N)(dN/dA)$), A is the amplitude normalised with respect to the aperture limit and $D = \frac{1}{2}\,d\overline{A^2}/dt$ depends on the excitation.

Equation (1) may be rewritten

$$\frac{\partial(p/A)}{\partial t} = D\left(\frac{\partial^2(p/A)}{\partial A^2} + \frac{1}{A}\,\frac{\partial(p/A)}{\partial A}\right). \tag{3}$$

This equation is the same one that describes 2-dimensional heat conduction in a cylindrical bar, for temperature distributions with circular symmetry[2]. The quantity p/A, which is proportional to phase space density, is analogous with the temperature, and A with the radius. If the temperature for A = 1 is zero (which corresponds to the aperture limit in our case), we have the solution

$$p(A,t) = A\sum_{n=1}^{\infty} a_n \exp(-j_n^2 Dt)J_0(j_n A) \tag{4}$$

where j_n is the n^{th} zero of the Bessel function J_0.

The coefficients a_n depend on the initial distribution:

$$a_n = \frac{2}{J_1^2(j_n)} \int_0^1 P(A,0) J_0(j_n A) dA \ . \tag{5}$$

The higher-order terms will die out rapidly because of the increasing j_n^2 in the exponential factor. The influence of the initial distribution then decreases with time. However, to save time, we blow up the beam until only 20% is lost; this results in a final distribution that still depends significantly on the initial one.

The fraction of particles remaining at time t is found by integrating Eq. (4) over all amplitudes

$$\begin{aligned} F(t) &= \int_0^1 p(A,t) dA \\ &= \sum_{n=1}^{\infty} a_n \exp(-j_n^2 Dt) J_1(j_n)/j_n \end{aligned} \tag{6}$$

We shall now consider two extreme initial distributions:

a) all particles have zero amplitude:

$$a_n = 2/J_1^2(j_n) \tag{7}$$

b) constant phase-space density ($P(a,0) = 2A$):

$$a_n = 4/j_n J_1(j_n) \tag{8}$$

We apply blow-up until 80% of the particles remain. We may find Dt at that point from (6) and then find the distribution from (4). After stopping the blow-up and subsequently scraping the beam down to A_0, the remaining fraction is again found by integrating (4):

$$F(A_0) = A_0 \sum_{n=1}^{\infty} a_n \exp(-j_n^2 Dt) J_1(j_n A_0)/j_n \ . \tag{9}$$

This fraction, divided by the fraction before scraping, is shown in Table 1 vs A_0 for both sets of initial conditions a) and b) above. A parabolic fit is also given for the first 10% scraped off; this is evidently a good approximation. It turns out that the fraction lost is

$$L(A_0) = 1 - F(A_0) \approx 2.2(1 - A_0)^2 \quad \text{for a)}$$
$$\approx 6.4(1 - A_0)^2 \quad \text{for b)} \tag{10}$$

For all realistic initial conditions, the result will be in between. For the measurements considered here, the initial beam size is quite small so that case a) is a reasonable approximation.

Table 1

Remaining beam fraction vs aperture fraction after blow-up until 20% is lost

A_0	Case a)		Case b)	
	$F(A_0)$	Parabola	$F(A_0)$	Parabola
0.05	0.007		0.003	
0.10	0.027		0.012	
0.15	0.061		0.028	
0.20	0.106		0.050	
0.25	0.161		0.078	
0.30	0.225		0.112	
0.35	0.296		0.153	
0.40	0.371		0.200	
0.45	0.449		0.253	
0.50	0.527		0.312	
0.55	0.604		0.378	
0.60	0.678		0.450	
0.65	0.747		0.528	
0.70	0.809		0.611	
0.75	0.865		0.697	
0.80	0.912	0.911	0.784	
0.85	0.949	0.950	0.867	
0.90	0.977	0.978	0.936	0.936
0.95	0.994	0.994	0.983	0.984
1.00	1.000	1.000	1.000	1.000

APPENDIX B

Suppose that we have measured n points with beam intensity y_1, y_2, ..., y_n at scraper position x_1, x_2, ..., x_n. We shall first assume that the edge is at x_0, with $x_k < x_0 < x_{k+1}$. We fit a straight line to points 1, 2, ..., k and a parabola to points k+1, k+2, ..., n, and determine the sum S of the squares of the deviations between these curves and the measured points y. Then, we vary x_0 (note that k may or may not change) and repeat the process until we have found the minimum value of S. This adjustment of x_0 is done by a simple step-halving routine.

The fit is made as follows:

Straight line : $y_1 = a + bx$
Parabola : $y_2 = c + dx + ex^2$

We require $y_1 = y_2$ and $dy_1/dx = dy_2/dx$ at $x = x_0$. This allows us to eliminate a and b, with the result

$$y_1 = (c - ex_0^2) + (d + 2ex_0)x.$$

We may now express S in terms of c, d and e (for the linear and the parabolic region combined). Minimising this means that the three partial derivatives with respect to c, d and e must be zero. This yields three linear equations from which c, d and e may be found. The resulting S is finally minimised by adjusting x_0.