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BEAMSCOPE - A NOVEL DEVICE FOR MEASURING EMITTANCES AND BETATRON AMPLITUDE DISTRIBUTIONS

H. Schönauer*

Summary

BEAMSCOPE (BEtatron AMplitude Scraping by Closed Orbit PErturbation) is a device developed at the CERN Proton Synchrotron Booster (PSB) for fast emittance measurements as well as the display of betatron amplitude distributions at any moment in the acceleration cycle.

A local closed-orbit bump, produced by three synchronously pulsed dipoles, deflects the circulating beam in a controlled way into a fixed precision aperture restriction, where it is gradually lost within about 1 ms. During the whole loss period, five ADCs simultaneously track the three dipole shunt voltages, and the beam current as provided by a beam current transformer and its derivative. In the NORD-10 Beam Measurement Computer the bump amplitude at the position of the precision scraper is synthesized from the dipole shunt signals after correction for non-linearities due to saturation in the dipole yokes and to eddy currents. The beam diameter and emittance can then be derived from this synthesized orbit bump amplitude and from the properly normalized beam current signal, and likewise the betatron amplitude distribution is computed from the derivative of the beam current and displayed. The computer also controls, via Serial CAMAC, both the multiplexing (4 rings, 2 planes) of power supplies and acquisition electronics, and the setting of process timing and sensitivities of the acquisition channels appropriate for the particular case out of the wide spectrum of beam properties encountered in the PSB. The accuracy of emittance measurements is comparable to that with the present mechanical targets. Comparison of BEAMSCOPE with target measurements over widely varying beam dimensions allows one to draw conclusions about systematic errors of both BEAMSCOPE and the targets. The fact that BEAMSCOPE provides directly the amplitude distribution greatly facilitates the interpretation and preserves fine structure and accuracy of the amplitude distribution. This is a clear advantage over instruments based on the detection of the projected density from which the amplitude distribution can only be obtained via an integral transform. The price to be paid is the complete destruction of the beam. If, however, the 95% emittance is wanted only partial scraping of about 10% of the beam particles is sufficient and an emittance measurement by BEAMSCOPE then causes less total beam loss than a (lengthy) target measurement.

Principle of operation

Machine hardware layout

Three stacks of eight dipoles (out of the 16 stacks dedicated to closed-orbit correction) located at identical positions in three consecutive machine cells, can be connected to three pulsed power supplies. When triggered, the latter (tuned to equal half sine period) excite the three dipoles of one ring synchronously with a half sine wave current of 20 ms half period. Powered with the correct ratio of central dipole to the outside ones they create a well localized closed-orbit (C.O.) bump, increasing with time in a sine-like way and reaching the maximum after 10 ms. Near the spatial maximum of the C.O. bump there is a fixed, accurately machined aperture restriction (70 × 80 mm diameter). During the rise of the C.O. bump, the beam is driven into this aperture restriction and gradually lost, the largest betatron amplitudes first.

Data acquisition

During the whole beam loss interval five fast ADCs record the shunt voltage of the three bumper supplies, and the circulating beam current I (from a beam current transformer) and its derivative dI/dt (obtained by electronic differentiation).

The digitized signals are immediately transferred via Serial CAMAC to the computer. There I and dI/dt are normalized, whereas the three shunt signals are processed into one synthetic signal, the computed bump amplitude (see Fig. 1). If the C.O. bump would rise linearly with time, the derivative of the beam current signal would be proportional to the amplitude distribution (large amplitudes to the left). Here the bump rise is not strictly linear but even the slightly distorted "raw profile", which can be very quickly displayed, contains much qualitative information frequently sufficient to understand machine phenomena. With the help of the computed bump amplitude, it is easy to produce any kind of calibrated amplitudes profiles, series of normalized profiles to track the evolution of a beam, etc. Examples of this application are shown in Fig. 2.

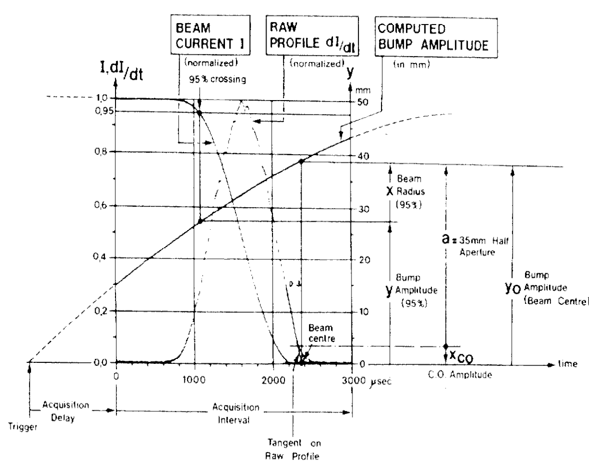

Fig. 1 The three basic BEAMSCOPE signals and their interpretation.

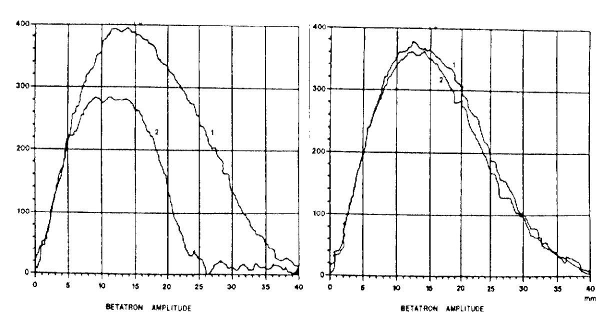

Fig. 2 Effective compensation of a systematic 3rd order resonance[6] seen with BEAMSCOPE: Profiles prior to (1) and after resonance crossing (2) without (left) and with compensation (right).

*PS Division, CERN, Switzerland.

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Measurement procedures and data reduction

In the CERN Proton Synchrotron complex, the definition of emittance commonly used is that of the area in phase space containing 95% of all particles. If just this emittance is to be measured two methods can be used, differing essentially in the way the amplitude of the unperturbed C.O. is found:

i) Single pulse method. As can be seen from Fig. 1, the "raw profile" ends at its zero amplitude side with a small tail, rendering the determination of the beam centre ambiguous. This tail comes from momentum dispersion and, in the horizontal plane, from synchrotron motion. In addition, the beam control system ceases to operate below a threshold intensity and may interfere in the last phase of the beam loss. Assuming constant phase-space density in the neighbourhood of the zero amplitude, the amplitude distribution should be decreasing linearly towards small amplitudes. According to this assumption the software fits a tangent on the r.h.s. slope of the raw profile and interprets the intersection of the tangent with the abscissa as the beam centre. Taking the difference between the computed bump amplitudes $y_0(i)$ at this "moment" and $y(i)$, the one corresponding to the 95% crossing of the beam current, the beam radius x is obtained by $x = y_0(i) - y(i)$, where $i = 1, 2$ is one of the two possible polarities of the bump (in/out or up/down, for horizontal or vertical measurement, respectively). The amplitude of the unperturbed closed orbit is then, (referring to the quantities defined in Fig. 1) $x_{co} = (-1)^i \left[a - y_0(i)\right]$, $i = 1, 2$. Taking the results obtained when pulsing with different polarities $y_0(1) + y_0(2) = 2a$ obviously should hold. This provides a simple check of the validity of the computed bump amplitude.

ii) Double pulse method. The simple relations given immediately suggest the possible elimination of $y_0(i)$ and x_{co} from the results of two measurements with changed polarity: $2x = 2a - \left[y(1) + y(2)\right]$. The beam diameter measured this way is the mean of two consecutive machine pulses, but in general one performs a series of measurements anyway. As an advantage, there is no need to continue to lose the beam once the 95% level is crossed and the corresponding bump amplitude is recorded. In fact, when this mode of operation is selected, an additional analogue comparator sends a stop pulse to the bumper supplies after crossing of that level. This pulse triggers the dumping of the remaining stored energy of the capacitor bank into a crowbar. The dipole currents stop rising further, but the beam continues to be lost until the eddy currents in the vacuum chamber have decayed. Although this causes the total loss to be 10 to 15% instead of the unavoidable 5%, it remains a tolerable value and makes this method ideal for frequent monitoring of emittances.

Detailed hardware configuration

The hardware may be divided into ring elements (dipoles and precision scrapers), excitation system (power supplies and multiplexers) and acquisition and data transmission (CAMAC). The NORD-10 Beam Measurement Computer (temporary until passage to the new control system) and its organization is described elsewhere[1]. All the electronics exists only once and is multiplexed to the ring and the plane to be measured. The three stacks (of eight dipoles each) and the four precision scrapers are the only non-multiplexed elements. The dipoles[2] designed for closed orbit correction, and d.c. operation up to 20 A are excited up to 100 A (beginning of saturation).

The data acquisition system is located in one dedicated Serial CAMAC crate. Its organization is depicted in Fig. 3. The only commercial modules are the five 10 bit SA/D1001 High Speed Digitizers with 1K word Memory and 1 MHz maximum sampling frequency, and the service module; preset counters and multiplexer are PS standard. Level adapters allows choice to be made

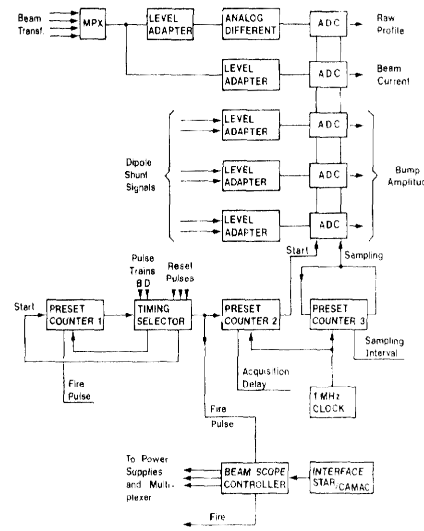

Fig. 3 Organization of BEAMSCOPE CAMAC crate.

amongst four different attenuation factors between 0 and -20dB. The timing selector contains all the logic to select the type of machine cycle (the PSB operates with pulse-to-pulse intensity modulation within a supercycle), the type of pulse train, and the reset pulse used to define the measurement timing. It enables the power supplies only when the computer is ready for acquisition and data input.

Preset counter 1 outputs the "FIRE" pulse triggering the bumper supplies. Preset Counters 2 and 3 control the "Acquisition Delay" (see Fig. 1) and the sampling interval of the ADCs.

Software

In spite of the simplicity of the method and the rather limited amount of mathematics involved, the BEAMSCOPE software is the largest and most complex program used at present in the Beam Measurement Computer. This is a consequence of the widely varying beam properties the system has to cope with. As an experimenter watching a signal on a scope has to adjust sensitivity, sweep and delay of the scope, the BEAMSCOPE operator has to choose timing, acquisition delay and interval, and the sensitivities of the five level adapters. An interactive program is catering for the task. The setting found in general varies from ring to ring, with machine cycle (there are 8 intensity programmes), between horizontal and vertical plane and sometimes even with the polarity of the bump. In order to reduce this set-up work all these parameters of the measurement process for all combinations of operational conditions are systematically stored on disk, together with all relevant software parameters, calibration factors, etc. In fact there are two files, a "read-only" one for operational measurements and another where the experimenter can store the process parameters for "his" operating conditions. Also stored are the coefficients of the polynomial approximations of relevant lattice functions dependent on Q_H, Q_V and of magnetization curves of the 24 individual dipoles involved. The latter have been measured[3] at their correct position within the spare quadrupole triplet, with and without vacuum chamber to find the delay due to eddy currents.

The whole program package comprises more than 30 individual programmes, one third of them doing measurements, the others being test, backup, calibration, and postprocessing programs to facilitate error analysis. The program is written in NORD-10 FORTRAN.

Resolution limits, error sources and Preliminary Results

Purely geometrical considerations show that there is a limit to the resolution related to the scraping speed. Resolution may become poor for those particles whose fractional Q-value $q \simeq M/N$, where $M < N$ are small integers of the order < 10. This is because the scraper intercepts essentially the same phase space slice it had intercepted N turns before. Here we give just a table of the width Δr of the theoretical resolution function for Q-values not too close to these special values. More details can be found elsewhere[4]. For $|q - M/N| < \delta$, Δr increases and reaches the value $\Delta r = r[1 - \cos(\pi/N)]$ for particles sitting right on the resonance M/N. In practice, synchrotron motion together with chromaticity and the Q-spread always present completely swamp extreme values of Δr.

Table: Theoretical resolution Δr in mm for $|q - M/N| > \delta$

d \ r	0.5	1	2	4	8	16	32	δ
0.005	0.05	0.06	0.08	0.1	0.13	0.17	0.21	
0.01	0.08	0.1	0.13	0.17	0.21	0.26	0.33	0.192
0.02	0.13	0.17	0.21	0.26	0.33	0.41	0.52	0.152
0.04	0.21	0.26	0.33	0.41	0.52	0.66	0.82	0.121
δ	0.024	0.03	0.038	0.048	0.06	0.076		0.096

r : betatron amplitude in mm
d : scraping speed in mm/revolution
δ : table values on a diagonal have the same limit of validity δ ; here δ is given for M/N = 1/3

Another rather insidious possible error is related to the choice of the aperture restriction: parasitic shaving on an aperture restriction other than the BEAMSCOPE aperture may occur if the latter is made too wide. Extensive computer studies had to be performed[5] to find a trade-off between emittance restriction at injection and correct operation of BEAMSCOPE.

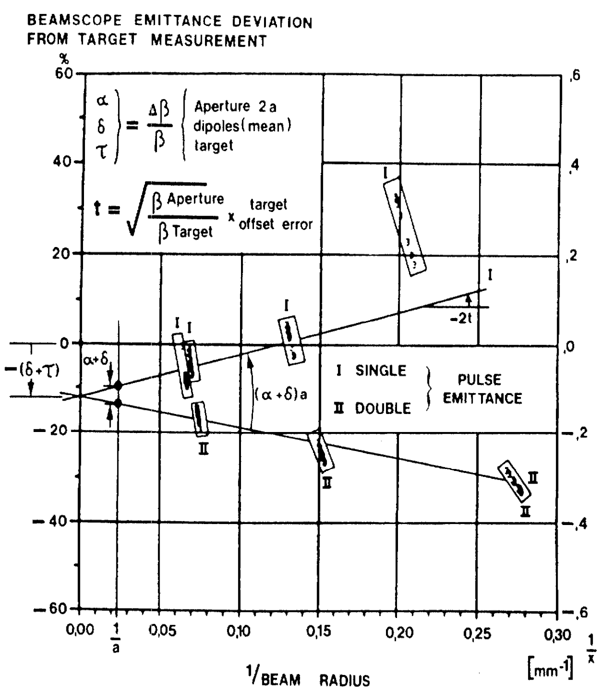

Fig. 4 Information about real lattice function values and systematic target errors can be obtained from straight line fitting through a scatter plot of many measurements in appropriate coordinate systems[4].

All individual errors such as calibration errors, dipole field inhomogeneity, digitizing errors, errors of polynomial approximations, etc., have been checked to be inferior to $\pm 5 \times 10^{-3}$. Yet the deviations of the lattice functions involved, from their theoretical values, are unknown. Analysis of data covering a wide range of beam diameters gives empirical information on how to correct for these errors in the course of data processing[4]. Figure 4 shows the scatter plot of a set of measurement results: yet uncorrected, they show systematic divergence between the emittance values obtained with the methods (i) and (ii) described above. After correction, the results from both methods should fall on the same straight line; a non-zero slope of this line would indicate a systematic offset of the comparison target and its distance from the abscissa indicates deviations from the ideal value of the Courant β function at the target and/or dipole locations.

From the data taken up to now (rings 3 and 4 only) one can infer a divergence of less than 10% between vertical emittances measured by BEAMSCOPE and by targets, respectively. Laboratory tests of the measurement targets only can indicate whether this is an error of BEAMSCOPE or targets. Horizontal BEAMSCOPE measurements systematically give emittances 5-20% smaller than the comparison target results. Further studies will help to find out whether there is a local irregularity of the lattice functions or another, as yet unknown, error source. In the meantime BEAMSCOPE renders already valuable services for accelerator studies[6].

Acknowledgements

BEAMSCOPE was first proposed for the PSB by P. Krempl[7], who demonstrated its feasibility. F. Sacherer started the implementation using a position monitor immediately upstream of the scraper to determine the amplitude of the orbit bump. This system, while attractive in its simplicity, failed to give interpretable results when compared with target measurements, probably due to intrinsic limits of the accuracy of the electrostatic pick-up electrode and its associated analogue electronics, particularly in the presence of beam loss. I would like to acknowledge the contribution of the persons already mentioned and of G. Baribaud[8], M. Bourgeois, C. Carter, J. Donnat, L. Magnani (hardware builders), of C. Metzger (computer organization) and of L. Mérard and W. Remmer (software). K.H. Reich continuously encouraged and supported the work.

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