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THE CLOSED ORBIT OBSERVATION SYSTEM OF THE CERN ANTIPROTON ACCUMULATOR

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Summary

The Antiproton Accumulator (AA) works at 3.5 GeV/c central orbit momentum, has 50π m circumference, Q-values around 2 $^{1}/_{4}$ and a large dispersion, up to 10 m, over most of its circumference (see ref. 1 for description). Closed orbits have to be measured over the whole range of the very large momentum acceptance (6.5%) and at beam intensities as low as 5×10^9 particles (1.5 mA). Furthermore, the pick-up electrodes have to serve as clearing field electrodes and no straight section space was available for them. They have to be compatible with an UHV of 10^{-11} Torr and bakeable to 300°C.

The AA closed orbit observation system therefore has several unusual features: a wide range of dimensions of the pick-up electrodes, adapted to beam size, up to 70 cm horizontal width; location inside the main magnets and quadrupoles; high input impedance head amplifiers, mounted directly on the vacuum chamber feedthroughs; electronic normalizers to provide the ratio of difference/sum signals; high precision for measuring orbits far from centre.

Acquisition, calibration, data treatment and display are performed with the single, stand-alone, controls computer.

Systems Description

With Q-values around 2 $^{1}/_{4}$ and the need for at least 4 points of measurement per betatron wavelength as an adequate basis for closed orbit corrections, a pick-up station was placed in every other one of the 24 AA sectors. Of the 12 stations, 8 are located in the "wide" focussing quadrupoles and 4 in the bending magnets at either end of the long straight sections. The distribution in betatron phase is reasonably uniform.

In order to obtain useful signals with as few as $5 * 10^9$ particles in a single (h = 1) circulating bunch, a combination of electrostatic pick-up electrodes and high input impedance head amplifiers, mounted directly on the vacuum feedthroughs, was chosen. With a beam on central orbit of $5 * 10^9$ particles in a 50 ns long bunch, about 50 mV appear at the inputs of the head amplifiers connected to the electrodes with the largest plate capacitance of some 200 pF.

There is a head-amplifier for each horizontal or vertical plate pair (Fig. 1), i.e. 24 in total. Each head amplifier produces 2 signals: one proportional to the voltage difference between the two plates (V_Δ) and the other proportional to the sum of the plate voltages (V_Σ). Each of these signals is transmitted differentially to the local control room, where a reception amplifier rejects common-mode interference and provides 2 outputs of V_Δ and 2 outputs of V_Σ. One pair is used for analogue observation with a bandwidth from 2 kHz to 50 MHz, while the other is connected to a normalizer which produces an output signal proportional to V_Δ divided by V_Σ, i.e. proportional to the position of the beam with respect to the electrode centre.

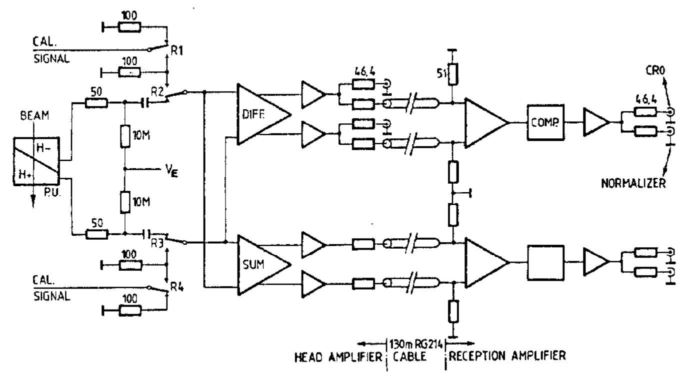

Fig. 1 – One of the 24 measurement channels (12 horizontal and 12 vertical)

The availability of an analogue signal indicating the beam position has proven very convenient, e.g. in the measurement of dispersion, α_p, by connecting this signal as well as the output of an rf-frequency-to-voltage converter to an x-y recorder.

The outputs from the normalizers are scanned by a multiplexer ADC and acquired by the controls computer.

Test signals can be applied to the inputs of the head amplifiers to calibrate the gain. This can be done under manual or computer control and allows the high precision to be maintained despite gain variations due to age, temperature and exchange of modules.

As mentioned in the summary, the pick-up electrodes are also used to provide an electrostatic field to clear the chamber volume of positive ions against the attraction by the antiproton beam. They are biased at -24 V via 10 MΩ resistors at the head amplifier inputs.

The Pick-up Electrodes

The need to match closely the beam size led to the otherwise uneconomic situation of 5 different electrode cross sections. Figure 2 shows one of the 2 types used in the wide quadrupoles.

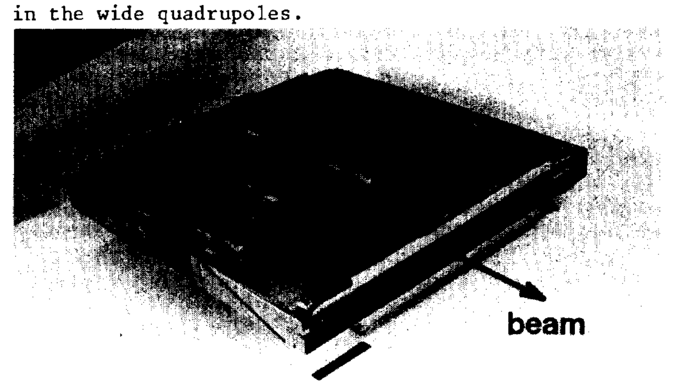

Fig. 2 – Pick-up electrode for mounting in wide quadrupole

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A classical diagonal-cut design was chosen, with a horizontal and a vertical plate pair at each location. For mechanical reasons, the cut is not perfectly diagonal, so that every single-plate signal contains a small contribution of a sum signal. This is allowed for in the data treatment.

The limited aperture in the quadrupoles and bending magnets and the need to minimize capacitance did not permit the customary ground electrode surrounding the pick-up plates. They had to be inserted directly into the vacuum chamber. Capacitive balance, for coincidence of electrical and geometric centre, is obtained by trim capacitors on the outside of the feedthroughs.

The supports function as grounded guard electrodes on either side of a plate pair, thus improving linearity. Flexible contacts provide continuity to adjacent liners in the interest of low wall impedance seen by the beam.

As for all other components of the AA exposed to the ultra-high vacuum, the stainless steel parts were pre-heated before assembly to 900°C. The gap spacers are of alumina. The design had to be made to withstand in situ baking to 300°C.

The feedthroughs are located within the coil overhangs, so that no extra space had to be used for the pick-up system.

Three prototype pick-up stations, mounted in prototype chambers, were measured. This was particularly important for the wide pick-ups in the quadrupoles, where beam position has to be measured far from centre and because of the fairly large inter-electrode capacitance which amounts to about 30% of the electrode-to-ground capacitance. The measured results enabled the calibration of the other types to be determined by calculation.

Head Amplifiers

Each amplifier box contains both the differential and sum amplifier and provides the clearing field voltage and the test signal switching (see Table below).

The differential amplifier was designed for input signals up to ± 6 V, a bandwidth from 2 kHz to 60 MHz and a common-mode rejection of > 60 dB up to 25 MHz. The high CMR has been achieved by using 3 successive FET differential stages, each of unit gain. High current and voltage biasing on the FETs was required to obtain the necessary slew rate and large dynamic range.

The sum signal is formed by adding currents, proportional to the potentials on the electrodes, at the virtual earth of a single stage amplifier. This stage is responsible for the slightly inferior noise figure and bandwidth of the sum amplifier.

Relays permit observation of single-plate signals as well as their substitution by remotely generated test signals. Thermally controlled relays had to be used as the amplifiers are located in magnet fields of several kG. As shown in Fig. 1, a calibration signal is applied to the inverting and then the non-inverting input, to compare the gains of the sum and difference channels. The same signal is applied also to both inputs, giving a difference output of zero and a sum of twice the original amplitude.

To summarize the characteristics:

	sum	difference
gain (50 Ω termination)	-6dB	-6dB
bandwidth	1 kHz to 57 MHz	10 Hz to 60 MHz
CMR	0	60 dB
max. input voltage	± 6 V	± 6 V
equivalent noise input	44 $nV.Hz^{-\frac{1}{2}}$	35 $nV.Hz^{-\frac{1}{2}}$
input impedance	900 kΩ	900 kΩ
output impedance	50 Ω	50 Ω

The outputs of all head amplifiers are transmitted differentially to the local control room over equal lengths of cable (130 m of RG214). On one station, an additional pair of difference signals is provided for the transverse feedback system.

Reception Amplifier

Each reception module has 2 identical amplifiers, one for the sum and one for the difference signal. DC-coupled differential input stages provide CMR of interferences. They are followed by passive filter networks to compensate the high frequency cable losses. With a dc attenuation of 6 dB it was possible to obtain a flat response up to 55 MHz. The uncompensated bandwidth is 78 MHz. Each amplifier has 2 outputs, one for analogue observation, the other for the normalizer. To summarize:

gain (50 Ω termination)	- 12 dB
bandwidth	200 Hz to 78 MHz
CMR	48 dB at 1 MHz 20 dB at 25 MHz
max. input voltage	6 Volts differential
max. output voltage into 50 Ω	1.5 V pp
equivalent noise input	43 nV . $Hz^{-\frac{1}{2}}$
input/output impedance	50 Ω

Normalizer

This module produces a dc signal proportional to the ratio V_Δ/V_Σ. The design is derived from the one used in the CERN 800 MeV Booster radial control system (ref. 2). The main modification is the inclusion of an input filter (1.85 ± 0.4 MHz) enabling a wide range of bunching factors to be handled and eliminating the need for inverting polarity when changing from protons to antiprotons. Maximum input is ± 1.5 V, which corresponds to the limit given by the preceding amplifiers.

$V_\Sigma + V_\Delta$ and $V_\Sigma - V_\Delta$ signals are formed and alternately amplified by the same variable-gain amplifier and the average values of these two signals are memorized in separate elements. The sum and difference of the two signals are proportional to V_Σ and V_Δ , resp. The variable-gain amplifier is controlled to produce a constant sum amplitude and consequently the difference output is proportional to the beam position in the pick-up.

Computer Acquisition and Data Treatment

The outputs from the normalizers are scanned, on demand, by a multiplexer and an ADC and the digital data for all horizontal and vertical measurements loaded into a local memory in about 160 µs. This set of data is then used by the computer to calculate and display the closed orbit distortions. For this, the program reads also the data files containing the effective widths of the electrodes and geometric offsets of electrode centres from central orbit and calculates the nominal positions from the measured revolution frequency. It also uses the latest calibration table, which is obtained on request, about once a day, by the same process as the position measurements and stored on a disk file.

Performance

Several factors determine the overall accuracy of the system.

The mechanical tolerances of pick-up fabrication and alignment in the vacuum chamber are around ± 0.5 mm. An error of about the same amount can be assigned to the alignment of the vacuum chamber within the quadrupoles and bending magnets.

The electrical centre of a pick-up depends on the equality of the plate capacitances to ground, which can be obtained to within ± 0.05%, corresponding to ± 0.3 mm for the largest pick-up. A ± 0.05% error is contained in the determination of the effective width, based on capacity measurement, i.e. ± 0.2 mm for a beam at the limit of aperture.

The 60 dB CMR of the head amplifier guarantees the error to be less than 0.1% of the reading. Any changes in gain are taken care of by frequent calibration.

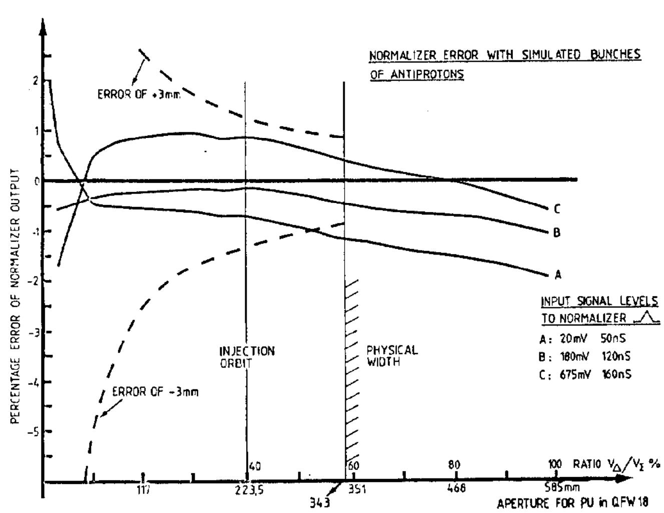

Fig. 3 - Performance of normalizer for various signal levels and bunch lengths

Most important is the performance of the normalizer (Fig. 3). Within a range of 10^{10} to $5 * 10^{11}$ particles circulating, its accuracy is ± 0.5% of the measured value ± 0.1% of the effective half-width.

Overall, the absolute accuracy is about ± 1 mm on central orbit, with a reproducibility of about ± 0.2 mm. On injection/ejection orbit, which is at approximately 2/3 of the physical half-aperture in the quadrupoles, the absolute accuracy is about ± 1.5 mm and the reproducibility from day to day around ± 0.5 mm.

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