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COMPUTER CONTROL OF RF-MANIPULATIONS

IN THE

CERN ANTIPROTON ACCUMULATOR

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Introduction

The Antiproton Accumulator uses a conventional RF system for bunched beam manipulations within the ring. These require precise control of the bucket size, the synchronous phase angle, and the radial position across the width of the vacuum chamber, over which the magnetic properties of the ring vary significantly. Several different manipulations are required, often in close succession, so a fast, reliable, and accurate method of switching between them is required.

This has led to an unconventional, computerised, beam control system. For a desired set of beam manipulations, the computer calculates the needed voltage and frequency as functions of time, using a mathematical model of the beam and lattice. These are then loaded into function generators which subsequently operate independently of the computer.

Uses of the RF System

Three main uses can be discerned: the normal stacking process to accumulate the antiprotons; unstacking the accumulated antiprotons for extraction; and then a variety of test and measurement purposes.

The normal stacking function is the most frequently used. Every few seconds a burst of antiprotons is collected on the injection orbit and pre-cooled. The RF system is then used to trap these particles, move them past the shutters which are opened when the pre-cooling is switched off, then deposit them at the stack tail. This function should be fast so as to allow as much time as possible for the pre-cooling, and efficient so as not to waste antiprotons.

The unstacking function is primarily used to extract dense bunches of antiprotons for use in SPS experiments. It is also used to extract pilot pulses for setting up the SPS, and to supply the low energy antiproton ring LEAR. Particles are first trapped at a suitable point in the stack. They are then moved clear of the stack. During this movement, once clear of the stack, a high pass phase lock is switched on to avoid particle loss due to noise and the digital nature of the frequency control. After a move at a faster rate to the extraction orbit, the bucket size is increased to shorten the bunch for extraction to the PS. Another paper[1] describes how this function is set up automatically by the computer, from the requirements and a Schottky scan of the stack.

Many of the test and measurement functions use a dense proton beam. This is injected as a bunch directly into the RF bucket, the high frequency phase lock being used to centre the bunch in the bucket. The protons can then be stacked, a few pulses giving a stack equivalent to a day's-worth of antiprotons for test purposes, or they can be moved to specific radii of the machine for measurements such as the betatron tune. Another test use is phase displacement acceleration of the injected antiprotons onto a target at the perimeter of the machine for intensity measurement. Three passes of a full voltage bucket through the beam achieve this result.

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The RF System

A dual gap, ferrite loaded cavity, see Fig. 1, is driven by a 4CX25000 power tetrode, which forms part of a feedback amplifier similar to the one used in the ISR[2]. The feedback lowers the effective impedance of the cavity at its fundamental resonance, which is necessary to avoid instabilities during the unstacking process.
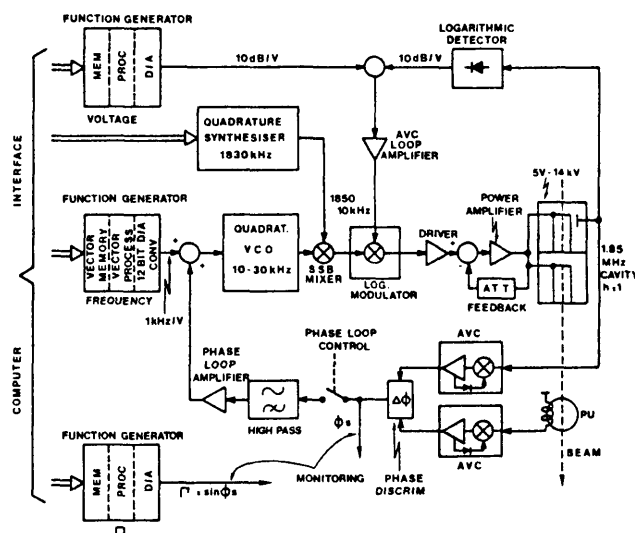

Fig. 1. Antiproton Accumulator RF System, simplified.

Two digital function generators control voltage and frequency of the cavity. The voltage function is logarithmic, and is fed into an AVC loop, which contains a logarithmic detector and modulator. This makes it possible to control the gap voltage continuously over a 69 dB range, 5 V to 14 kV with a .05 dB resolution. High voltage is needed for stacking and matching for transfer, while low voltage is needed for unstacking.

The frequency function controls a 10 to 30 kHz quadrature VCO, which is mixed with the outputs of a quadrature synthesiser producing an 1840 to 1860 kHz frequency range, sufficient to cover the AA momentum aperture, with a 5 Hz resolution.

RF phase noise (~ 95 dB/Hz) and magnet noise turned out to be harmful while manipulating low emittance proton and antiproton bunches. A high-pass phase loop acquires beam cavity phase, and by adding AC corrections to the frequency program this problem was eliminated. Additionally, the acquired value of ϕ_s can be compared to the output of a third function generator, which is loaded with the calculated $\Gamma = \sin \phi_s$ program, so as to check the Γ, V, η, df/dt relationship.

The cavity tune is maintained by a tuning loop (not shown) acting on the DC ferrite bias so as to correct for variations of tune caused by variations of frequency, temperature, or RF level.

The Computer Control System

The overall system has been described in

a previous paper[3] so only the main elements involved in the RF control need be mentioned. Most visible is the "Touch Terminal" whose touch panel and monochrome graphics screen are used interactively to set up the functions required for the various manipulations, and to display the calculated results. The programs are written in NODAL running on a NORD 10 computer, one of the PS controls network. To speed up and simplify the program, the main calculations were moved into compiled NODAL. The program communicates the values to the function generators mentioned in the previous section via standard low level software and the serial CAMAC interface.

The Model

Each complete RF function is broken up into several simpler sequences. Each sequence performs an identifiable part of the RF function, and is much easier to describe and calculate than would be the function as a whole. The sequences are of two main types: those which manipulate the beam at constant bucket area; and those which vary the bucket in an adiabatic manner.

Using standard notation[4], the bucket area per bunch expressed in units of electron voltseconds is

$$A\left[eVs\right] = \alpha(\Gamma)\ \frac{16\beta}{2\pi f}\ \sqrt{\frac{eVE}{2\pi\ h^3|\eta|}} \tag{1}$$

E, f, and η are related by the machine lattice. This is too complicated for on-line calculation so polynomial approximations are used[5]. These give (E in MeV, f in kHz).

$$E = 3631.355 - 17.369(f-1850) - .288(f-1850)^2 \tag{2}$$

$$|\eta| = .10732 - .0023668(f-1850) - .00043535(f-1850)^2 \tag{3}$$

$$f = 1850 - (17.369 - \sqrt{4485.003 - 1.152E})/.576 \tag{4}$$

β is of course related to the total energy E as

$$\beta = 1 - (938.2796/E)^2 \tag{5}$$

If Γ and V are non-zero then the beam is being accelerated or decelerated. Thus f and V are functions of time, determined by the energy gain per turn, so that

$$dE/dt = \Gamma\ eVf \tag{6}$$

Adiabatic changes in bucket area are defined by the iso-adiabatic law

$$dA/A = \alpha_c\ dt/T_s \tag{7}$$

where T_s is the synchrotron oscillation period $1/f_s$. The adiabaticity coefficient α_c should be $\ll 1$ for good adiabaticity, typically in the range 0.25 to 0.5. The synchrotron frequency can be expressed in terms of the bucket area given by equation (1) as

$$f_s = \frac{\pi}{8}\ \frac{(1-\Gamma^2)^{1/4}}{\alpha(\Gamma)}\ \frac{f^2}{\beta^2}\ \frac{|\eta|h^2}{E}\ A \tag{8}$$

This can reasonably be approximated, as discussed further later, by

$$f_s = kA \tag{9}$$

where k is a constant. Substituting in (7) gives

$$dA/dt = \alpha_c\ k\ A^2 \tag{10}$$

which when integrated between the initial area A_1 at time t_1 and the final area A_2 at time t_2 gives the adiabatic law

$$A(t) = \frac{A_1}{1 - \dfrac{t - t_1}{t_2 - t_1}\left[\dfrac{A_2 - A_1}{A_2}\right]} \tag{11}$$

The value of $\alpha(\Gamma)$ is not calculated on-line, but is obtained by interpolation of reference tables[3].

The Program

The program maintains a suite of ten functions, any one of which can be loaded at will. Figure 2 shows one of these functions, the standard stacking function. Each function is made up of several sequences, the sequence number being shown in the left hand column of Fig. 2. In turn each sequence is made up of several vectors. The calculation of these vectors for each sequence, according to the model in the previous section, is the main work of the program. Finally the hardware is loaded with the vectors to control f and log V as required.
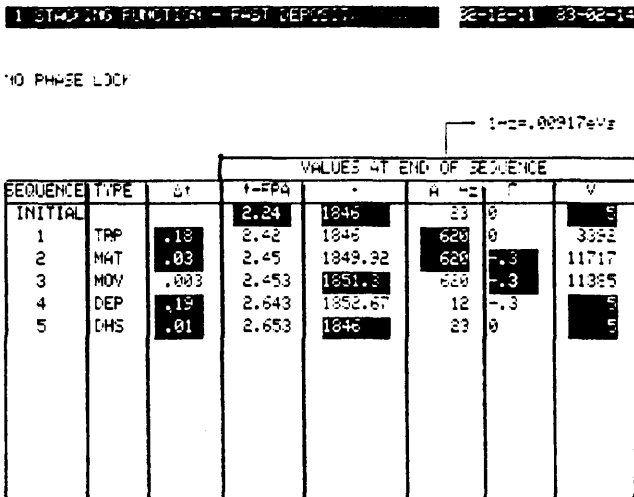

Fig. 2 Computer display of sequences in the stacking function.

Five different types of sequence have proved sufficient, in combination, to make up all the required functions. The normal stacking function shown in Fig. 2 uses five sequences, one of each type, so is a useful example. The mnemonics for the sequence type are shown in the second column of Fig. 2. Other functions can have more sequences, for example the standard unstacking function has nine sequences, with two DHS sequences, followed by a TRP sequence, then three pairs of MAT followed by MOV sequences.

The remaining columns show the duration Δt of the sequence, the time from the function generator start pulse, the frequency in kHz, the bucket area A, Γ, and V in volts. The bucket area is expressed in terms of a frequency bite in Hz. This is much more meaningful in the AA as most stack measurements are taken by spectrum analysers calibrated in frequency, so that even position in the vacuum chamber is expressed in terms of frequency. For an unbunched beam the frequency bite Δf is

$$\Delta f = \frac{f \, \eta}{\beta^2 E} \Delta E = \frac{f^2 \eta}{\beta^2 E} A \text{(eVs)} \qquad (12)$$

This varies across the aperture, so to be rigorous we specify the longitudinal phase space area in terms of Hz at the injection orbit, where 1 Hz = .00917 eVs.

The values shown are the end of sequence values. The beginning of sequence values are the initial conditions for sequence 1, then the final values of the previous sequence for the others. Thus the curves continue smoothly from sequence to sequence. Facilities are available to delete, insert or modify a sequence, including selecting its type.

The values of a sequence which can be chosen or modified are shown inverted. The column can be selected using the touch panel, then the touch panel used like a calculator keyboard to select the new values. Once all the required parameters are chosen, the computer can calculate the remaining final conditions using the model. More significant, it will also calculate a sequence (hence the name) of values of V and f versus t so that the required bucket and beam relationship are smoothly varied between the initial and final conditions of the sequence.

The TRP or trapping sequence is an adiabatic sequence where only the new bucket area A and the Δt are specified, Γ assumed zero. The change in A is divided into ten logarithmically equal increments. The adiabatic law of equation (11) is applied to get the times, and the model used to get the associated voltage values. Note that since $\Gamma = 0$, hence f, E, η, β constant, then relation (9) is exact so the adiabatic law is exact. The time Δt is specified, implying a value of the adiabaticity coefficient, rather than the inverse. This is because the timing is more critical in terms of exact value. Once the function is calculated the computer can give a display of the adiabaticity to check or optimise the function.

The MAT or matching sequence is also an adiabatic sequence where both A and Γ can be changed in a given time Δt. Again ten vectors are used, here equal in time. Equation (11) gives the associated values of A, whilst Γ is made to vary linearly. The values of V and f as functions of time can thus be calculated from the model, being effectively a stepwise integration of equation (6). In this sequence relation (9) is far from exact, k changing by up to a factor of 2 mainly due to changes in $\alpha(\Gamma)$. This shows up as a variation of the adiabaticity through the sequence. This is not important as all that is required is that it be $\ll 1$. More difficult is the use shown in Fig. 2, to change Γ at constant A. Here equation (7) gives no guidance so human judgement must be used to ensure that the bucket shape is not changed too fast.

The MOV or move sequence is designed to move the beam at constant bucket area. Γ can also be modified during the sequence if required. The sequence is broken up into equal increments of f, and the model used to calculate the times and corresponding voltages. If Γ is to be changed, this is done linearly over the sequence. The number of vectors is fixed at 10 if there is a significant change in Γ. For the most common case where Γ is constant the voltage varies little and the number of vectors is determined mainly to ensure that the vector times remain below the maximum of 160 ms. Since the acceleration rate is proportional to ΓV, the approximation

$$EN = \left| \frac{80 \, \Delta f_{\text{(kHz)}}}{\Gamma V} \right| + 1 \qquad (13)$$

gives, as integer part, the number of vectors EN up to a maximum of 40.

The DEP or deposit sequence is used to deposit the particles at the stack tail. This is done by shrinking the bucket as it moves at constant Γ towards the stack core. Thus the denser beam core and smallest buckets penetrate furthest into the stack. This best matches the stack tail distribution and minimizes the effect of phase displacement acceleration in the wrong direction. The limiting case is when the reduction in the total bucket area equals the phase space area traversed, i.e.

$$dA/dt \text{ (eVs/bucket)} = \Gamma \text{ eV/h} \qquad (14)$$

From equation (1) since Γ is constant and the other parameters change little over the deposit sequence we have eV proportional to A^2, which when substituted in equation (14) again gives the iso-adiabatic law similar to equation (10) with the same solution of equation (11). Solving and integrating from the initial voltage V_1 to the final voltage V_2 gives the sequence time

$$\Delta t = \frac{4 \, \alpha(\Gamma)}{\pi^2 \Gamma} \frac{\beta h}{f} \sqrt{\frac{2\pi E}{|\eta| h^3 \, eV_1}} \left(1 - \sqrt{\frac{V_1}{V_2}} \right) \qquad (15)$$

This is the minimum time so that particles from the centre of the bunch are always closer to the stack core than outer particles. If a Δt shorter than this is requested, e.g. .001, the computer supplies this minimum, e.g. .081 in Figure 1. A larger value of Δt can be requested, however, to push the bunch centre nearer the stack core.

The DHS or direct hardware set sequence allows direct control of the voltage and frequency functions. A common use of this sequence is to move the frequency fast enough to ensure no bucket ($\Gamma > 1$), as in figure 2 where it changes the frequency from the stack tail back to the injection orbit. The model is only used to calculate Γ for reference purposes.

Once all the sequences have been entered or modified, a graph of the resulting function can be obtained. This can be a plot of V, f and Γ against time, or any up to three of V, f, Γ, the synchrotron frequency f_s, α_c, and A. A further option is to select if phase lock is required for the function, and if so the required on and off times. Alternatively the choice of times can be left to the computer. This is always done for the delicate unstacking process[1]. Finally, or firstly in logical sequence, the harmonic number can be changed from its usual values of 1 to the special value of 128 for LEAR unstacking[1], and the model used unchanged.

References

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5) H. Koziol, private communication.