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MEASURING AND MANIPULATING AN ACCUMULATED STACK OF ANTIPROTONS IN THE CERN ANTIPROTON ACCUMULATOR

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Summary

The antiproton stack is observed through Schottky scans, both longitudinal and transverse. A particular feature is the wide dynamic range needed for observing both the dense core and the freshly-deposited tail. Separating batches of antiprotons from the stack (unstacking) is a highly automated process including the measurement of the momentum distribution and the generation of a suitable RF function to remove a slice of the desired density. Multiple slices may be removed successively and a process for locally flattening the distribution to obtain equal batch intensities is used. When successive batches are unstacked and ejected, the process may have to be aborted if the particles do not arrive correctly at the user. A "restack" facility is provided to return any antiprotons to the stack that have been unstacked but not ejected. A missing-bucket scheme for unstacking low-intensity batches for LEAR is also described.

Stack Observation by Schottky Scans

The stack in the 3.5 GeV/c accumulator is fed by low-density $\bar{p}$ batches deposited at its high-momentum edge every 2.4 s. From there, the particles are continuously pushed towards the stack centre (into a region with 10^5 times higher density) by stochastic momentum cooling, while at the same time transverse cooling reduces the horizontal and vertical emittances by 2 orders of magnitude. To check on this process, longitudinal and transverse Schottky scans are used. The required sensitivity at the low-density end is realized by resonating the pick-ups with $\lambda/4$ stubs around the 40th revolution harmonic ($\sim$70 MHz). It is fortunate that the large dynamic range (>60 dB over $\Delta f/f = 2 \times 10^{-3}$) can be covered with only a little care to keep the amplifier chain between pick-ups and spectrum analyser far from saturation. Fig. 1 shows the longitudinal scan as an example.

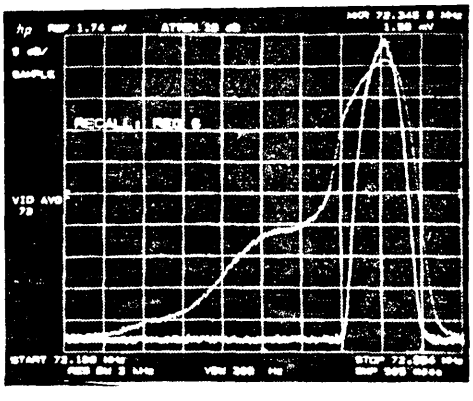

Figure 1 - Longitudinal Schottky scan of the AA stack. Note the logarithmic density scale (5dB/div). Particles are added to the stack at the left. The narrow trace shows the stack 60 min after stacking has stopped; the low frequency tail has been pushed inward by cooling.

The transverse stack emittance is measured by taking the total power in a betatron sideband, divided by the total power in a longitudinal band. This figure (which is proportional to the r.m.s. emittance) is obtained by computer acquisition and suitable numerical treatment of the analyzer display. For the normally occurring transverse distributions, the value so obtained is found to be proportional within 10% to the more usual "95% emittance" obtained from scraper measurements; it is therefore calibrated and displayed as such. This method has allowed us to study the evolution of the emittances after stacking is stopped (Fig. 2). The effects that keep the emittances large during stacking are discussed elsewhere[1].

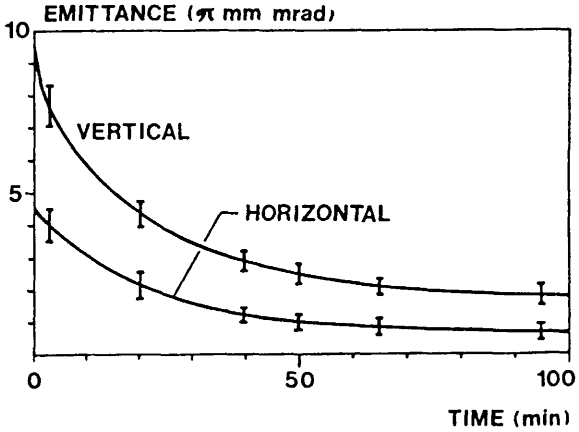

Figure 2 - Evolution of emittances after stacking is stopped.

Unstacking for SPS Collider Operation

When the stack has reached a sufficient intensity (at present 1 or 2 × 10^{11} $\bar{p}$) the particles must be transferred to the PS machine to be accelerated to 26 GeV, and from there to the SPS where they are further accelerated, together with protons, to 270 GeV and stored. Because of bucket area restrictions in the PS and SPS, this transfer is done in batches (usually 3). The entire process is first checked by transferring some low-intensity batches, called pilot pulses.

To transfer a batch, a small first harmonic RF bucket is adiabatically turned on at a frequency where the local stack density is suitable for capturing the required number of particles (i.e. anywhere between the low-frequency stack edge and the density peak). This bucket is then removed from the stack towards a much lower frequency corresponding with the ejection orbit; the voltage is then increased before ejection so that the bunch is matched to the RF system of the PS ring. This unstacking sequence takes less than 2 seconds.

In the process, the low-frequency stack tail is phase-displaced towards the peak so that the hole in the frequency distribution that would otherwise have appeared after unstacking is filled up.

The process is entirely computer-controlled. The bucket area and the required number of $\bar{p}$'s per batch are

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specified, as well as the number of batches. At the push of a "prepare" button, a longitudinal Schottky scan is acquired and normalized by measuring the circulating beam current. The required capture frequency is calculated and a suitable RF function generated automatically, using the algorithms described elsewhere[2]. This includes the phase-loop timing; as soon as the batch has been displaced to a frequency where the surrounding stack density is sufficiently low, the phase loop must be switched on to prevent blow-up of the bunch area by RF or magnet noise.

Phase Loop Instabilities

Under certain circumstances, the phase loop[2] has caused instabilities in the stack with resulting blow-up and loss.

When a bunched beam is circulating simultaneously with an unbunched stack, a density modulation in the stack is seen by the phase loop as a phase modulation, which is fed into the VCO as a frequency modulation, which creates phase modulation sidebands in the cavity signal. One of these sidebands falls on the same frequency as the stack density modulation causing it. For low modulation indices, the induced voltage is proportional to the current producing it, and can be described by the equivalent coupling impedance:

$$Z_c(j\omega) \cong \frac{V_{RF}}{4I_b} * \frac{G_p(j(\omega - \omega_{RF}))}{j(\omega - \omega_{RF})} , \qquad (1)$$

where V_{RF} is the RF voltage, I_b the bunched beam current, $G_p(j\omega)$ the gain of the phase loop (in (rad/s)/rad), and ω_{RF} the frequency of the bunched beam. The approximation is valid when the frequency difference $(\omega - \omega_{RF})$ is well outside the closed loop bandwidth of the phase loop.

It is seen that the impedance is most harmful when the RF voltage V_{RF} is high, the bunched current I_b is small (pilot pulses), and the RF frequency is close to the stack.

The problem has been solved or avoided by the following measures:

1. using a sufficiently low voltage when close to the stack,
2. reducing the phase loop gain to the lowest possible value while still providing enough RF noise reduction.
3. adding a 800 Hz low-pass filter in the phase loop filter $G_p(j\omega)$ which makes it possible to use the full voltage (14 kV, required for ejection matching) when the beam is on ejection orbit and thus furthest away from the stack.

Flattening of the Distribution

If more than one consecutive batch must be unstacked, the batch intensities may be made equal by first pushing an "equalize" button; this will cause a flattening out of the stack distribution over the frequency interval from where the batches will be unstacked This is done by applying for a few seconds a frequency-modulated carrier to the kickers that are normally used for longitudinal cooling of the stack tail. The carrier frequency is the 156th harmonic of the revolution frequency in the centre of the region to be flattened; the modulation frequency is 15 Hz and the modulation width is 156 times the range of revolution frequencies over which the flattening is required. The flattening signal is produced by a computer-controlled signal generator and the selection of frequency and width is automatic. Fig. 3 illustrates the process.

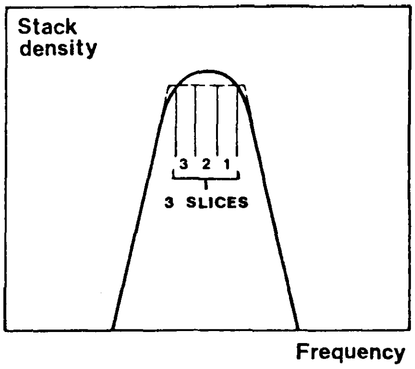

Figure 3 - Unstacking of 3 equal batches. First, the distribution is flattened locally (dotted line). Then, each batch is captured and unstacked successively. After unstacking each batch, the remaining slices are phase-displaced to the right, so that all batches can be captured at the frequency corresponding to slice no. 1.

After this has been done, an "unstack and reject" button may be pushed when the PS and SPS are ready for the transfer. This will start the unstacking and ejection process in a synchronized way.

Restacking

Occasionally a batch is unstacked, but for some reason (e.g. a last-minute failure somewhere along the chain AA-PS-SPS) ejection does not take place. The antiprotons are so valuable that a special "restack" button has been provided that will cause the unstacked batch to be put back into the stack at the frequency it came from. To do this, a RF function is generated that inverts in every way (including phase-lock timing) the unstacking function. In fact, the stack distributions before unstacking and after restacking turn out to be nearly the same.

Unstacking for LEAR

The low-energy antiproton ring LEAR will work most of the time as a beam stretcher. For this purpose, every 10 or 15 minutes a small batch of antiprotons (e.g. 10^9 or less) will be transferred to LEAR, from where they will be distributed to several experiments through an ultra-slow extraction process.

Stacking will continue for most of the time between transfers. It is expected that the effects that keep the emittances large during stacking will be cured in the near future[1]. Nevertheless, the emittances of newly injected particles will only be cooled to the desired values after they have migrated for some time towards the stack core. This means that for obtaining sufficiently low transverse emittances we must unstack the LEAR batches from the core. Unfortunately, because of the low batch intensity and the high core density we would need a very small bucket area; with the normal first-harmonic RF system this would result in a RF voltage of a few mV and such buckets would be very susceptible to RF and magnet noise, and result in prohibitively long unstacking time.

An unstacking system working on the 128th harmonic and using the stack tail cooling kickers as "RF cavity" is therefore under development. Because these kickers cover a wide band (250-500 MHz), it will be possible to gate out all buckets except a few. The voltage will be a few kV, i.e. much higher than at the 1st harmonic, so that the noise will become unimportant. With 10 adjoining buckets (out of 128) the total duration and momentum spread would be similar to the normal values at the first harmonic. The control of the RF function will also use the same function generators and software.

References

1. G. Carron, R. Johnson, S. van der Meer, C. Taylor, L. Thorndahl, Recent with Antiproton Cooling (Proceedings of this Conference).

2. R. Johnson, S. van der Meer, F. Pedersen, G. Shering, Computer Control of RF-Manipulations in the CERN Antiproton Accelerator (Proceedings of this Conference).