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Accelerator Experiment: Observation of a Longitudinal Microwave Coasting Beam Instability in a Simulation of the CERN SPS Injection Conditions.

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1. Motivation

Unfortunately it was impractical to use the frequency 9.5 MHz of the CPS rf system for the SPS. At some time, either in the CPS or SPS, the beam must be debunched by switching off the 9.5 MHz until it forms a continuous ribbon and then adiabatically trapped in rf buckets. Attempts to do this in the CPS revealed an alarming microwave instability during debunching and coasting which diluted the bunch area far beyond the acceptance of the SPS.[1]

As far as theory could make predictions concerning this unexpected phenomenon the frequency switch would result in less blow up if performed in the SPS. Rather than wait with trepidation the running-in of the SPS to see if this was indeed the case, it was arranged to simulate SPS injection conditions at Fermilab.

A collaboration was arranged and the CERN author would like to warmly thank the Fermilab Accelerator Division for their enthusiastic help in this venture in providing machine time and diagnostics.

Together we were able to allay one of the major fears of the SPS team concerning its running-in.

2. Equipment

A coaxial directional coupler was used as a detector. The wall of the main ring vacuum pipe serves as the outer cylinder of this device. Figure 1(a) shows the raw signal transmitted through 20 m of 1-7/8" heliax cable to the RF Building.

This signal was fed into a Tektronix spectrum analyser. Figure 1(b) shows the response of the detector displayed on the full range, 1 to 1.8 GHz, of the analyser. The beam in the main ring was bunched at 52 MHz in normal operating injection conditions when this measurement was made. Detector response is assumed to continue above the range of the analyser in the same pattern of bumps.

During the experiment on microwave blowup the spectrum analyser was set to a narrow bandwidth to display two of the higher harmonics of the proton revolution frequency at 1710 MHz, close to a peak of the detector response. Nominal settings were:

Central Frequency	:	1710 MHz (f_o)
Range of Scan	:	10 kHz/division
Resolution	:	3 kHz
Reference Level	:	8 div ≡ -30dB
Vertical Scale	:	10dB per division
Scan Speed	:	5msec per division

Debunching takes only 2msec and we therefore assume the spectra can be analysed as normal Schottky scans[2] using the formula:

$$\frac{\Delta p}{P} = \pm \frac{1}{2\eta} \frac{\Delta f}{f_o}$$

where: $$\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_{tr}^2} = 0.0081 \text{ at } 8 \text{ GeV}$$

Δf is the full width of the spectral peak measured at 2 divisions (20 dB) below the peak of the distribution. This should include 98% of the protons within the momentum spread.

The uncertainty in measuring pictures, magnet ripple and the resolution of the analyser combine to produce a systematic and random error of 1 to 2 x 10^{-4} in the measurement of $\frac{\Delta p}{P}$. Later we shall see this is consistent with the scatter in the data.

3. Experimental Conditions

To reduce confusion with other possible bunch inflating effects, the main ring rf was off and shorted out by conducting pistons which ground the accelerating electrodes.

Because the microwave instability is believed, and was later shown to be, a local effect depending on the instantaneous current within a bunch rather than the total charge in the ring, we injected a single booster batch of 84 bunches, filling 1/13 of the main ring circumference.

The main ring field was set to continuous 8 GeV conditions and the intensity injected and accepted was 8 x 10^{11} protons per booster batch corresponding to over 10^{13} for a full ring.

4. Data and Results

Figure 2 shows the Schottky scans, triggered at various times during the first 200 msec following injection of the batch.

Figure 3 shows this data plotted after correction for the scan speed of the analyser. Because of this scan speed measurements in the first 10 milliseconds are impossible.

Crosses show data taken during the first run in which the trigger was made later. Circles show repeat measurements as a cross check that there was no drift during data taking.

To confirm that the effect was local rather than depending upon total main ring charge, further data was taken during loading 12 booster batches. Loading the main ring without rf tends to knock out some of the charge which has been already injected and which has spread around the ring, but final $\Delta p/p$ values after 12 batches had been thus loaded to give 5×10^{12} circulating protons were no higher than the single bunch data.

After this data had been plotted the $\Delta p/p$ derived from Booster experiments was supplied by Ruggiero. This point, also shown, agrees well with this experiment.

As a cross check of the Schottky scan technique bunch length measurements and Schottky scans were made with rf on under normal operation. Their ratio agrees with that expected from the 1.2 MeV/turn prevailing at the time. Debunching times measured added further to this confirmation.

5. Comparison with Theory and CPS Data

Microwave instabilities which blow up the $\Delta p/p$ of a coasting beam by as much as a factor 10 have been observed and analysed by Boussard.[1] Their source is thought to be inductive impedance presented by sharp transistions in vacuum chamber cross section. This leads to propagation of waves in the vacuum chamber, which resistively load local perturbations in the bunch current during and after the debunching process and decelerate parts of the bunch.[3]

In a later experiment report[4] we shall show that the growth of a factor 2 in $\Delta p/p$ is indeed accompanied by a microwave spectrum in the 1 to 3 GHz range similar to that seen at CERN in both CPS and ISR.

For the moment we are content to put the Fermilab parameters into a formula[1] which fits PS data provided $Z/n = 180\Omega$.

$$A_f = 6.6\pi^2 \frac{e}{E_0} \cdot \frac{|Z|}{n} \cdot \frac{\gamma}{|\eta|} \cdot \frac{I}{A}$$

where $A = \pi\Delta\beta\gamma\Delta\phi$ is the injected bunch

$A_f = 4\Delta\beta\gamma \times \pi$ is the growth in the debunched continum due to this effect

I = injected charge per bunch x f_{rf}

E_o/e = proton rest mass

γ and η have their usual meaning.

We find from the data

$A = 0.005$ radians

$I = 75$mA

$\eta = 0.0081$

$\gamma = 9.5261$

$I\gamma/\eta = 88$

$\Delta\beta\gamma_f = \frac{\Delta p}{P} \times \beta\gamma = 4.7 \times 10^{-3}$

$A_f = 60$ milliradian.

Giving $Z/n = 50\Omega \pm 25\Omega$

This is below the CPS figure but confirms that the microwave coasting instability affects large rings, as it does small ones.

6. Conclusions

(a) For Fermilab: The instability is of no consequence since the capture process does not involve debunching and adiabatic recapture with an intermediate coasting beam situation.

(b) For the SPS: The injection conditions in this experiment closely resemble those to be expected when raw 9.5 MHz bunches are injected into the SPS main ring. As expected, but with some uncertainty since it involves extrapolation of an as yet uncrystallized theory to a much larger ring, the blow up in this situation will be smaller in the SPS than in the CPS and within the acceptance of the rf system. Betatron acceptance of the momentum spread, provided there is no further large blowup during adiabatic trapping, should not prove intractable in the SPS.

But perhaps the most significant observation is that in contrast to the CPS the growth takes some tens of milliseconds and can be avoided altogether if trapping promptly follows injection into the SPS.

This allows one to contemplate SPS development to 10^{13} with some serenity.

Looking much further to the future when multibatch injection from the CPS might imply debunching and capture in the CPS leads us to conclude that CPS studies should be continued but in the content of a long-term development such as 200 MHz acceleration from 800 MeV throughout the CPS cycle. Decisions on this can wait until the running in to 10^{13} reaches its conclusion.

(c) For Future Machines: Should present theories of the phenomenon prove correct, future synchrotrons should be constructed with as few discontinuities in the vacuum chamber as possible.

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References

1. D. Boussard - Observation of Microwave Longitudinal Instabilities in the CPS - CERN/LAB II/RF/Int./75-2.
2. J. Borer, P. Bramham, H. G. Hereward, K. Hubner, W. Schnell, L. Thorndahl - Non-Destructive Diagnostics of Coasting Beams with Schottky Noise - Proc. IXth International Conference on H. E. Accelerators (1974).
3. H. G. Hereward - Private Communication
4. D. Boussard, et al. - Main Ring Experiment (to be published)

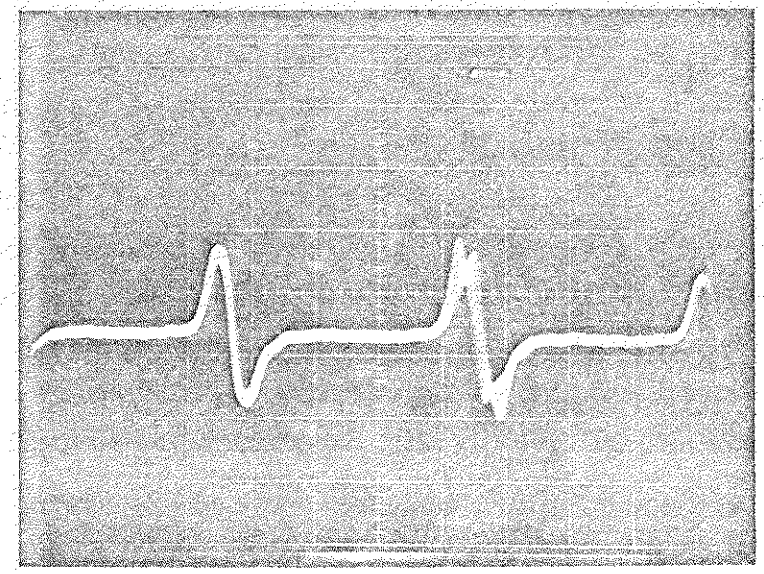

Fig. 1(a) - Raw Signal from Coaxial Directional Coupler (5ns/div).

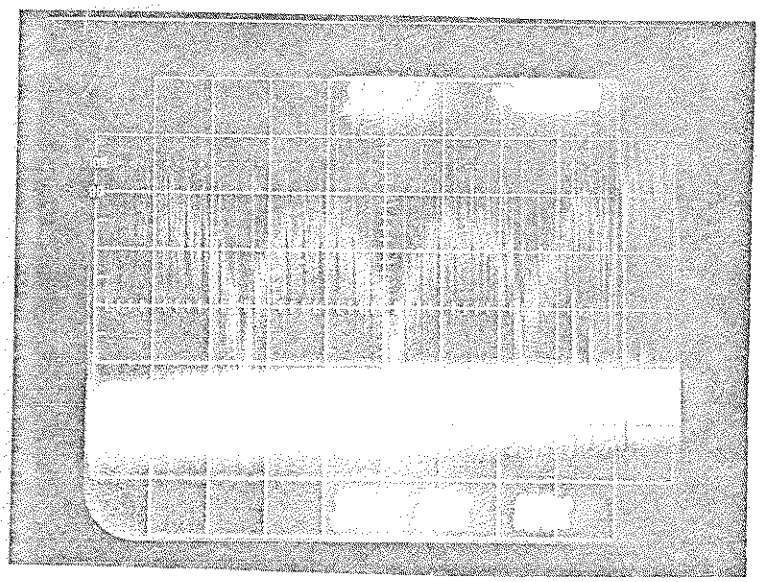

Fig. 1(b) - 0 - 1.8 GHz Spectrum Showing Detector Response (200 MHz/div).