Electron-Proton Instability in the CERN ISR

Workshop on Two-Stream Instabilities
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The CERN ISR

The CERN ISR - or “Intersecting Storage Rings” - consisted of two roughly circular rings of about 1 km circumference which crossed each other in 8 places at an angle of about 15 degrees. Protons were injected from the synchrotron CPS at energies from 12 to 26 GeV in opposite directions. The bunches were moved with RF to the stacked beam location and debunched. Currents of several tens of Amperes were thus routinely accumulated - I believe the record was 56 A.

The stacked beams were colliding in 8 intersection regions during operation. However, only 4 of them were equipped with detectors. The vacuum was so good that the beams could circulate in the machine for tens of hours and even several days.

Current Limitations in the ISR

Beam current in ISR was originally limited by several effects - e.g. the “brickwall effect” led to partial beam loss every time a certain current level was reached. This transverse instability found to be caused by deformation of the working line during beam stacking. Cured by correcting working line with magnetic multipole fields every time a few amperes were added - using existing pole-face windings.

Another limitation were “pressure bumps” due to gas released by ions impinging on the SS vacuum chamber wall. Out-gassing at higher temperatures was not sufficient, supplemented by glow discharge cleaning. Electron multipactor was found only for bunched beams, in particular when an Aluminium section was installed for testing, will be discussed by O. Groebner.

The vacuum chamber had oval cross section (160x52 mm) in dipole magnets, but widened to circular (160 mm diameter) in between. The large number of cross-section variations thus formed (about 300) caused high impedances, could have led to instabilities at low current levels. Therefore all widened chambers were retro-fitted with damping resistors.

Observations during Operation

An “experimental cavity” with variable impedance and quality factor had been installed to measure the current limits. In spite of variable damping and detuning loops it was found to constitute a rather large impedance itself and had to be short-circuited by movable “jaws” which were closed during operation. Remaining collective instabilities were counteracted by various feedback systems.

Beam signals were observed on oscilloscopes and spectrum analyzers. Thus the “Schottky lines” were discovered which led to construction and test of first “stochastic cooling system”. Such a system had been proposed several years earlier by Simon VanderMeer on a simple sheet of paper, its author did not have much hope of its possible realization because of the extremely large bandwidth required to cool large beam currents. He wrote an internal report only when the system was already being tested - the lack of a proper early publication almost cost him the Nobel prize!

e-p Oscillations

Another observation made at that time on the spectrum analyzer was a group of spectral lines, in the region of about 40-60 GHz, which all moved slowly down in frequency with time. I think it was Pierre Lapostolle who first proposed that they might be caused by oscillations of electrons in the potential well of the proton beam. Electrons were generated e.g. by rest gas ionization or multipactor. A similar effect had also been seen in the Bevatron and described by Grunder and Lambertson (report UCRL 20691, 1971).

An analysis of “two-species oscillations” was known from Plasma physics and had been applied to particle accelerators in a paper by Koshkarev and Zenkevich, published originally in Russian in 1970 (ITEP report 841). It was translated into English 1971, just when first observations of electron oscillations were made in the ISR. A refined theory, taking into account the finite life time of electrons in a proton beam, was subsequently developed by Hugh Hereward.

Background Spikes

In addition to the observation of spectral lines, large background spikes where seen in the detectors about every second, which brought some experimenters screaming with rage to the control room. These spikes were suspected to be caused by the e-p oscillations, when the oscillation amplitude had increased until electrons reached the vacuum chamber wall and were lost there. Then the build-up of electrons started again and the effect repeated itself over and over. The heavier protons oscillated at much smaller amplitudes and would experience a small emittance blow-up.

In spite of the excellent vacuum - with an average pressure of 10^{-10} torr it was ten times better than originally specified in the design report - enough electrons were generated inside the vacuum chamber to drive the e-p instability.

Cures

To avoid emittance blow-up and to offer a lower background to the experimenters, it was judged necessary to eliminate the e-p oscillations by reducing the number of electrons in the beam. A number of clearing electrodes had originally been installed in the ISR straight sections to avoid excessive tune shifts due to neutralization. Inside the dipole magnets, crossed-field and gradient drifts would eliminate the electrons. However, pockets could form between two of these rather long magnets.

In a double-headed crash program, clearing electrodes were added in all locations where pockets could form, and also more and better vacuum pumps were installed. This brought the average pressure to below 10^{-11} torr, the e-p oscillation signals disappeared, and the undesirable background spikes did not occur any longer.

Koshkarev-Zenkevich Model (1)

Based on earlier work by Budker and Chirikov, the authors made a model of transverse multipole oscillations of two beams. For simplicity they assumed either uniform cross section or a ribbon beam, and considered only forces due to external focusing and the charged particles of the other beam.

For simple dipole oscillations, in which we were mainly interested, they wrote a system of 2 coupled differential equations for the transverse particle displacements of electrons and protons $Z_{e,p}$. They were then averaged over all particles to describe the beam motion:

$$\begin{aligned} \frac{d^2\bar{Z}_e}{dt^2} &= -Q_e^2\Omega^2(\bar{Z}_e - \bar{Z}_p) \\ \frac{d^2\bar{Z}_p}{dt^2} + Q^2\Omega^2\bar{Z}_p &= -Q_p^2\Omega^2(\bar{Z}_p - \bar{Z}_e)\ , \end{aligned} \qquad (1)$$

where Ω is the revolution frequency and Q the (vertical) betatron tune due to external focusing. The tunes $Q_{e,p}$ describe the “bounce frequencies” $\omega_{e,p} = \Omega Q_{e,p}$ with which electrons and protons oscillate in the potential well of the other beam.

Koshkarev-Zenkevich Model (2)

The bounce frequencies are given by

$$\begin{aligned} \omega_e^2 &= \frac{2N_p r_e c^2}{\pi b(a+b)R} \, , \\ \omega_p^2 &= \frac{2N_e r_p c^2}{\pi b(a+b)\gamma R} \, . \end{aligned} \qquad (2)$$

Assuming exponential solutions $Z_p = \xi_p \exp[i(n\theta - \omega t)]$ and $Z_e = \xi_e \exp[i - \omega t]$, one obtains a dispersion relation for the oscillation frequency ω as function of mode number $n = kR = 2\pi R/\lambda$:

$$(n\Omega - \omega)^2 = Q^2\Omega^2 + Q_p^2\Omega^2 \frac{\omega^2}{\omega^2 - Q_e^2\Omega^2} \, . \qquad (3)$$

This is a quartic for the oscillation frequency ω.

Koshkarev-Zenkevich Model (3)

Approximate solutions of the dispersion relation can be obtained by assuming that ω is close to ω_e. The solutions become complex - and hence unstable - when Q_p is larger than a threshold value

$$Q_p^{thresh} = \frac{(n - Q_e)^2 - Q^2}{2\sqrt{Q_e(n - Q_e)}} \ , \tag{4}$$

with a growth rate given by

$$\frac{1}{\tau} = \frac{Q_p \Omega}{2} \sqrt{\frac{Q_e}{n - Q_e}} \ . \tag{5}$$

For larger values of Q_p - corresponding to a large number of electrons N_e - several modes with mode numbers n around Q_e could become unstable with rapid growth rates of the order of a revolution frequency. These frequencies decrease with Q_e as the number of protons N_p goes down or the beam blows up, increasing a and b.

Hereward’s Model

Hereward included the finite lifetime of the electrons in the beam by taking a production rate μ electrons per proton and a decay rate $1/\tau$ of the electrons due to clearing, corresponding to a fractional neutralization $\mu\tau$. He obtained the dispersion relation

$$(n\Omega - \omega)^2 = Q^2\Omega^2 + Q_p^2\Omega^2 \frac{\omega^2}{\omega^2 - Q_e^2\Omega^2 + 2i\omega/\tau} \ . \qquad (6)$$

It can be seen that it agrees with that of KZ when $\tau \to \infty$. Including the finite lifetime yields somewhat larger imaginary parts of the oscillation frequency and hence a stronger instability. He also estimated the effect of Landau damping by taking a tune shift limit, but to obtain the thresholds correctly the actual frequency spread had to be included in the analysis.

Landau Damping (1)

The unavoidable spread due to the dependence of oscillation frequencies on energy and/or amplitude usually leads to damping and should thus be included in the analysis. Putting $x = \omega/\Omega$, the dispersion relation (for infinite lifetime) can be written

$$(Q_{e0}^2 - x^2)[Q_0^2 - Q_{p0}^2 - (n-x)^2] = Q_{e0}^2 Q_{p0}^2 F_e(x) G_p(n-x) \; , \tag{7}$$

where Q_0 and $Q_{e,p0}$ refer to the centers of the betatron and bounce frequency distributions $f(Q)$ and $f_{e,p}(Q_{e,p})$, and where

$$F_e(x) = \left(1 - \frac{x^2}{Q_{e0}^2}\right) \int dQ_e \, \frac{Q_e^2 f_e(Q_e)}{Q_e^2 - x^2} \; ,$$

$$G_p(x) = \left(1 - \frac{x^2 - Q_0^2}{Q_{p0}^2}\right) \int dQ \int dQ_p \, \frac{Q_p^2 f_p(Q_e) f(Q)}{Q^2 + Q_p^2 - x^2} \; . \tag{8}$$

Landau Damping (2)

The integrals over the tunes can be evaluated assuming e.g. parabolic distributions. The astonishing result of this analysis was the appearance of an initial reduction of the threshold with increasing spread - which we christened “Anti Landau-damping”. A similar effect was found later in the theory of transverse mode coupling, where it is easier to see that a widening of approaching tune lines leads to an earlier overlap.

However, for larger spreads, one gets again an increase of the threshold and finally suppression of the instability. For ISR parameters, the threshold neutralization was reduced from 0.02 in the simple theory to a few times 10^{-4}, hence clearing and/or pumping had to be improved considerably to reach these low values.

Conclusions

In the early days of the ISR operation, the occurrence of repeated background spikes accompanied by the appearance of spectral lines in the 40-60 MHz region led to the supposition that they were due to electrons oscillating in the proton beam with increasing amplitude until they reached th wall. Since electrons were created by the protons due to rest gas ionization, and accumulated in pockets where clearing was not effective, both vacuum pressure and clearing electrodes were added in a crash program and suppressed the effect.

An unfortunate side effect of successful cures is the immediate loss of interest in the phenomenon by the management, and hence no development of further analysis and verification by experiment. Nevertheless, it was the theoretical understanding of the effect which led to the right choice of steps to be taken.