LONGITUDINAL STABILIZATION OF BUNCHED BEAMS IN THE ISR BY A HIGHER HARMONIC CAVITY

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(presented by E.Keil)

1. Introduction

In the ISR bunched beams are longitudinally unstable and a coupled bunch mode instability occurs which has a growth rate of $1/\tau \sim 2\ s^{-1}$ at 100 mA beam current/1/. The beam is usually only bunched for a short time after injection (during the stacking process in longitudinal phase space/2/) and this instability is not harmful as long as the injected current does not exceed ~100 mA. However, a microwave instability inside the bunches occurs and leads to a longitudinal blow-up/3/. This instability can be reduced by increasing the injected bunch area and current at the same time. With this larger bunched current the coupled bunch mode instability has to be stabilized. This is done with a cavity operating at a harmonic n of the RF frequency, called a "Landau cavity", which increases the spread of the phase oscillation frequencies. Some studies were carried out earlier with an experimental cavity which was first used as a passive cavity driven by the beam/1/ and was later driven by an amplifier/3/. Both methods worked well to stabilize bunched beams. However this experimental cavity has a relatively large impedance which caused instabilities during debunching and made it unsuitable for stacking. One of the normal RF cavities was then converted into a Landau cavity operating at the 3rd or 4th harmonic of the RF frequency. It has an impedance which is small enough for it to be used for stacking large injected currents. It is also used to keep beams bunched for longer for special purposes.

2. Frequency spread provided by the higher harmonic cavity

A cavity oscillating at a harmonic n of the RF frequency can increase the phase oscillation frequency spread and provide Landau damping/4/,/5/,/6/. If we consider stationary buckets with $\sin \Phi_s = 0$ only, we obtain, for the total voltage seen by the beam,

$$V = V_o \sin(\omega_{RF} t) + V_n \sin(n\omega_{RF} t) = V_o(\sin\Phi + k\sin(n\Phi)) \quad .$$

The ratio $k = V_n/V_o$ between the amplitudes of the two voltages is either positive (increasing the phase oscillation frequency Ω_s) or negative (decreasing Ω_s); we do not consider other phase relations. From the equation of motion we obtain by integration

$$\dot{\Phi} = \sqrt{2}\,\Omega_o \left[\cos\Phi - \cos\Phi_o + \frac{k}{n}\left(\cos(n\Phi) - \cos(n\Phi_o)\right)\right]^{\frac{1}{2}}$$

with Φ_o being the amplitude of the phase oscillation and Ω_o its frequency for small amplitudes in the absence of the higher harmonic cavity:

$$\Omega_o = \left(\frac{\omega_o^2 h|\eta| e V_o}{2\pi\beta^2 m_o c\gamma}\right)^{\frac{1}{2}}$$

with ω_o = rev. freq., h = harmonic number (30 for the ISR), $|\eta| = |1/\gamma_T^2 - 1/\gamma^2|$.

The phase oscillation frequency $\Omega_s(\Phi_o)$ with the cavity and for finite amplitudes Φ_o and the phase space area $A(\Phi_o)$ (in Φ, $\dot{\Phi}$ - coordinates) covered by the oscillation can be obtained from

$$\Omega_s(\Phi_o) = \frac{\pi}{2}\left[\int_o^{\Phi_o} \frac{d\Phi}{\dot{\Phi}}\right]^{-1} \quad , \quad A(\Phi_o) = 4\int_o^{\Phi_o} \dot{\Phi}\, d\Phi \quad .$$

In Fig. 1 the relative phase oscillation frequency Ω_s/Ω_o is shown as a function of A/Ω_o for n = 3 and 4 and for different voltage ratios k. The case where 1 + kn = 0 gives a very strong dependence of Ω_s on A and hence a large frequency spread. It is evident from Fig. 1 that the spread does not increase much more if the bunch area becomes larger than $A/\Omega_o \approx \frac{\pi^3}{n^2}$ or $\Phi_o \approx \frac{\pi}{n}$.

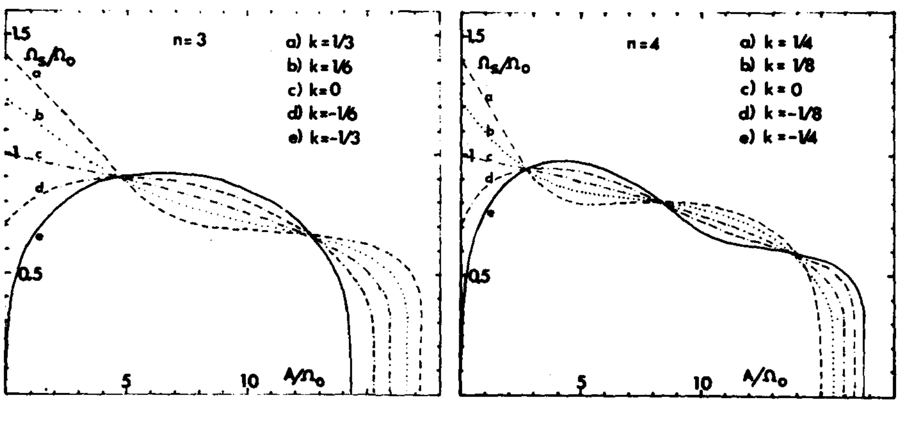

Fig. 1. Synchrotron frequency vs. area covered by the oscillation (Φ, $\dot{\Phi}$ coordinates).

For small oscillation amplitudes $\left(\Phi_o < \frac{3}{4}\frac{\pi}{n}\right)$ we can derive approximate formulas for $\Omega_s(\Phi_o)$ and $A(\Phi_o)$ /3/. We give them here only for the interesting case where 1 + kn = 0:

$$\Omega_s = \frac{\pi\Omega_o}{2K(1/\sqrt{2})}\sqrt{\frac{n^2-1}{6}}\,\Phi_o \quad , \quad A = \frac{4}{3}\Omega_o\sqrt{\frac{n^2-1}{6}}\,K(1/\sqrt{2})\,\Phi_o^3$$

with K being the complete elliptic integral ($K(1/\sqrt{2})$ = 1.8541). The frequency increases in this case approximately linearly with amplitude.

3. Landau cavity

The principle of acceleration and stacking in the ISR is described in ref. /2/. The accelerating cavities and the beam load compensation systems are described in refs. /7/ and /8/. Each ring is equipped with seven RF cavities, capable of producing a total of 21 kV peak RF voltage per turn (3 kV per cavity). The standard operating voltage is 16 kV per turn, which can be produced by six cavities. This allows one cavity to be disconnected as a normal accelerating cavity and to be modified to a higher harmonic one.

The ISR cavities are of the re-entrant type, tuned to 9.5 MHz (30th harmonic of the revolution frequency) by loading the accelerating gap with about 1000 pF of capacity. By removing these capacitors, it is possible to tune the cavity to the 3rd harmonic of the RF frequency and, by shortening the electrical length by a displacement body, the cavity can be tuned to the 4th RF harmonic.

The modified cavity has the normal 10 kW amplifier disconnected and is driven by the 25 kW beam load compensation amplifier, as shown in Fig. 2. This amplifier can produce 4 kV peak RF voltage of the 3rd and the 4th RF harmonic. The normalized shunt impedance Z/n' seen by the beam is about 27 Ω at the 3rd and 15 Ω at the 4th harmonic.

Fig. 2 gives a simplified block diagram of the interconnection between the normal RF system and the higher harmonic cavity. During normal acceleration and stacking in the ISR, the RF voltage is reduced at the end of the acceleration cycle in order to produce tightly-fitting buckets before approaching the stack. An amplitude modulator keeps the ratio between the accelerating voltage and the Landau cavity voltage constant. The correct frequency is obtained by multiplying the 9.5 MHz accelerating frequency by either 3 or 4. Correct phase relations are obtained by adjustable delays. After initial adjustments, the Landau cavity is completely locked on the normal RF system.

4. Experiments

4.1 Stable bunches

Most of the experiments were carried out with the cavity voltage being of opposite phase relative to the RF and $1 + kn \approx 0$. This gives a large frequency spread and allows the stabilization of high-intensity bunches. The maximum stable current achieved (in 20 bunches) was ∿300 mA for $n = 3$ and ∿200 mA for $n = 4$. The smaller stability limit in the second case can be explained

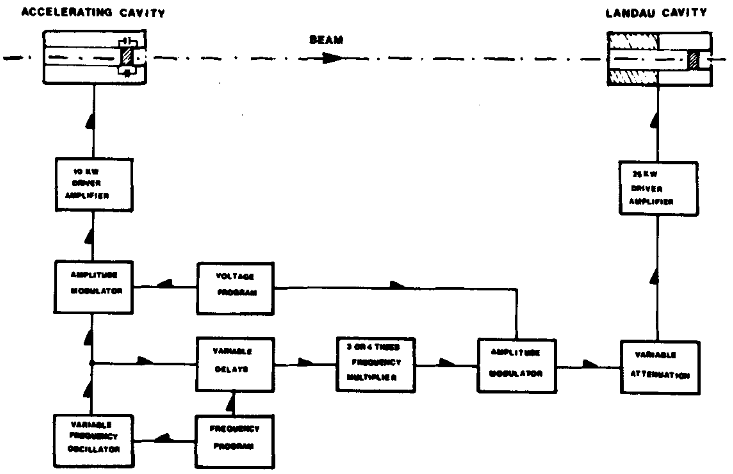

Fig. 2. Block diagram of the Landau cavity set-up.

qualitatively by the shorter bunch. The relatively large inductive impedance of the ISR vacuum chamber leads to self fields which are large for short bunches and which reduce the longitudinal stability[9]. Stable bunches for these cases are shown in Fig. 3, together with the wave form of the total voltage seen by the beam. The bunch form is flat on the top because the phase focusing vanishes in

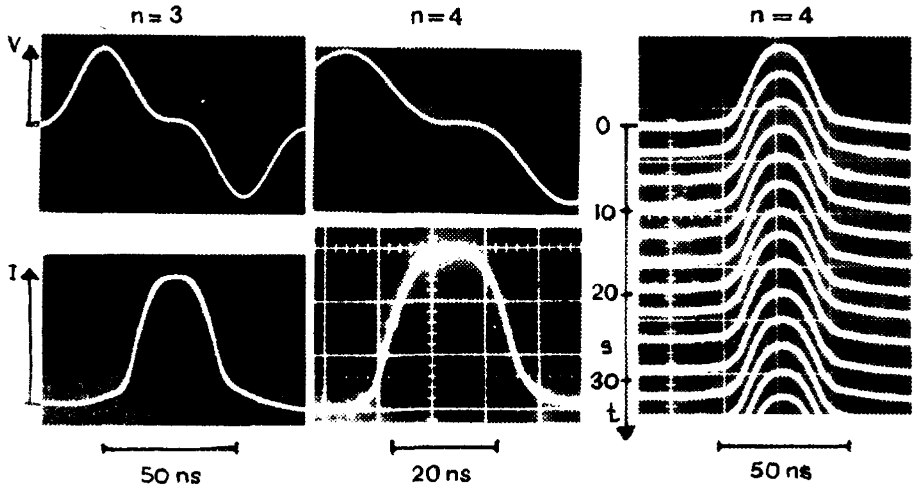

Fig. 3. Stable bunches and voltage wave form for the Landau cavity operating with $1 + kn = 0$.

the bunch centre; for this case $1 + kn = 0$. The last part of Fig. 3 shows a mountain-range display which demonstrates the long-term stability of the bunches.

4.2 Stacking

Since the luminosity available for physics in a colliding beam device is directly proportional to the product of the two beam intensities, any increase in the maximum stacked current increases the available maximum luminosity.

The maximum stacked current one can obtain in a storage ring such as the ISR depends on the final phase-space density of the stack, the available aperture and the average dispersion $\bar{\alpha}_p$ (∿1.9 in the ISR).

A convenient way of expressing the longitudinal density in a stack is the current per radial aperture ($I/\Delta R$). With no blow-up due to instabilities and 100% stacking efficiency this is related to the phase-space density in the bunch by

$$\frac{I}{\Delta R} = \frac{I_o h}{A_b' M} \frac{2\pi\beta\gamma}{\bar{\alpha}_p} \quad \text{(amperes/metre)}$$

Here the bunch area A_b' is given in the more practical units $(\Delta\beta\gamma, \Delta\Phi)$ instead of the units $(\Delta\dot{\Phi}, \Delta\Phi)$ used in chapter 2; M is the number of bunches and I_o is the average current.

The longitudinal density of a stack is measured from longitudinal Schottky scans/10/. For standard operation of the ISR without the Landau cavity the injected current is kept limited to ∿150 mA ($3 \cdot 10^{12}$ protons/pulse) giving a maximum stack density of ∿0.8 A/mm for a bunch area at injection of $A_b' \approx 10^{-2}$. This yields an overall efficiency of ∿40%. With an increase of the injected current to 300 mA and at the same time an increase of the injected bunch area by a factor of 2, a maximum density of 1.25 A/mm was obtained using the Landau cavity during the stacking process. This yields an overall efficiency of ∿60%, and a potential maximum current of 75 A in the 60 mm available aperture in the ISR. Figure 4 shows a Schottky scan of a 20 A stack with a peak density of 1.25 A/mm.

5. Conclusions

A Landau cavity oscillating with opposite phase with respect to the RF, in such a way that the phase oscillation frequency becomes zero for small amplitudes ($1 + kn = 0$), provides strong Landau damping, is easy to operate and not critical to adjust. Large currents in large bunch areas could be stabilized and stacked with the help of this cavity and the longitudinal density in the final stack could be improved.

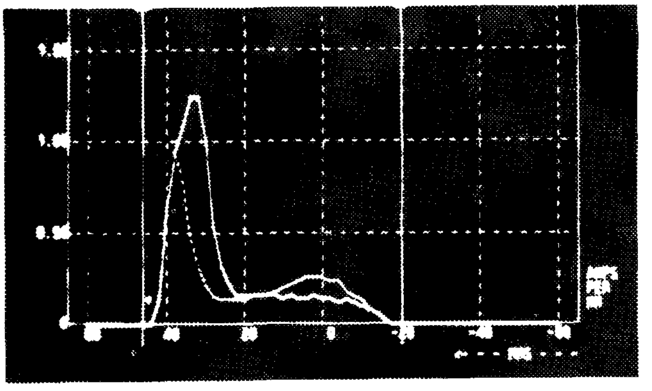

Fig. 4. Longitudinal Schottky scan of a 20 A stack, giving the longitudinal density vs. the radial position.

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ДИСКУССИЯ

Н.С.Диканский: Мы когда-то рассматривали аналогичный способ демпфирования когерентных дипольных колебаний. Однако такой способ может привести к усилению мощности когерентных мультипольных колебаний, которые сложнее подавить.

E.Keil: In our experiments no excitation of higher than dipole modes was observed.

Н.С.Диканский: Измерялось ли время жизни банчированного протонного пучка ?

E.Keil: The lifetime of bunched beams for long times was not measured in this experiment. The results of lifetime measurement were reported at the 1977 Particle Accelerator Conference, Chicago, USA.