SUPERCOOLING OF BUNCHED BEAMS BY COHERENT SYNCHROTRON RADIATION

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ABSTRACT

Longitudinal and transverse dimensions of bunched beams may be cooled by coherent synchrotron radiation in storage rings. The cooling starts if the bunches are short enough. Coherent synchrotron radiation with wavelengths of the order of the length of the bunch will propagate in the vacuum chamber of the bending magnet. Achievement of such condition, linked to the bunch dimensions, is generally not possible if only the main RF system is used. Therefore it is necessary to add a tunable idle or powered extra RF cavity, whose frequency depends on the transverse dimensions of the vacuum chamber of the bending magnet and on the radius of the orbit curvature. By this mean, a self-consistent effect can be achieved. The energy transfer among particles of the same bunch leads to a dynamic reduction of all bunch dimensions. For these reasons the whole radiated spectrum becomes coherent. This should be true for all storage rings with particles which emit synchrotron radiation. Our experimental results observed on a e^+/e^- storage ring are described.

MICRO-BUNCHING

Coherent synchrotron radiation can propagate when the particle bunch length is smaller or equal to the cutoff wavelength of the vacuum chamber of the bending magnet. This cutoff wavelength depends on the transverse size of the vacuum chamber and the curvature of the bending magnet [1], according to the formula:

$$\lambda_c \approx 2\,h\,(h / R)^{1/2} \qquad (1)$$

where h is the vertical dimension of the vacuum chamber, and R the radius of curvature. In order to attain the desired bunch length by using only a single RF system, one needs to increase the RF potential. If g represents the length gain (shortening), and σ_0 and σ_d the initial and desired bunch length respectively, $g = \sigma_0 / \sigma_d$, then the increase in RF potential is related to g^2 and the RF power to g^4, which rapidly becomes limiting.

One can overcome this problem by using a second RF system with a cavity tuned to a higher harmonic. The bunch length gain is then characterized by the formula:

$$g = [(n_1 V_1 \cos\phi_1 + n_2 V_2 \cos\phi_2) / n_1 V_0 \cos\phi_0]^{1/2} \qquad (2)$$

where V and ϕ are the potential and phase of the RF systems, and the indexes 0, 1 and 2 refers to the initial, first and second cavity respectively, and n is the number of the harmonic. In the special case when the characteristics of the main RF are maintained, in order to permit the acceptance energy at injection, and to compensate the losses at each turn, one has $V_1 \cos\phi_1 = V_0 \cos\phi_0$. In addition if the second cavity does not procure energy to the beam (at $\phi_2 \approx \pi$) equation (2) becomes:

$$g = [1 - (n_2 V_2 / n_1 V_0 \cos\phi_0)]^{1/2} \qquad (3)$$

and each bunch will be replaced by a group of micro-bunches (MB). The length of the MB will depend on the gain (g) defined above, and the number of MB will depend on the length of the bunch provided by the main RF system.

The energy acceptance (ε) of the two RF systems must be higher than the dispersion energy of the particles after dumping $\varepsilon = r\,(\sigma E / E)$. This determines the minimum level for V_2 described by:

$$V_2 = [\,2\pi r V_0 n_1 (g^2 - 1)\,\alpha E\,(\sigma E / E)^2\,]^{1/2} \qquad (4)$$

where α is the momentum compression, and E the energy. The potential on the second cavity must increase with the dumping of the particles, which implies that the second cavity must be passive. If the shunt resistance is sufficient to procure the needed potential, then the idle cavity can be excited directly by the beam, otherwise it has to be via a pick-up followed by an amplifier.

It should be mentioned that with a double RF system with different harmonics, the MB are not equally separated and therefore the slope at the loss potential seen by each MB is different. In case of phase oscillations, this gives a synchrotron spectrum with groups of closely spaced lines around the synchrotron main frequency side band and it's "harmonics", the later depending only on the main cavity. This was already seen on several rings, ACO, LEP [2,3], SuperACO (see below), which means that there is an inherent resonant element in these rings that induces MB.

SUPERCOOLING

When the MB becomes sufficiently short, coherent synchrotron radiation can also propagate in the vacuum chamber of the bending magnet. Because of the different path in the bending magnet for the particles (along the arc of circle) and for the coherent synchrotron radiation that they emit (along the cord), the particles at the rear of the bunch will interact with the particles in front of them by stimulated absorption. The former will transfer energy to the later and therefore they will accelerate them. The phenomenon will propagate gradually, from the tail to the front of the MB.

The resulting energy change can be calculated from the Lorentz force:

$$\delta \gamma m c^2 = - e \int\int v E \; dt \, d\lambda \qquad (5)$$

where e is the electronic charge, v is the speed of electrons, E is the transverse electric field of the plane light wave, t is the time of interaction, and λ are the coherent wavelengths. The absorption will occur if this energy change is positive. From the energetic point of view, this phenomenon leads to a decrease in energy dispersion in the MB as a whole, which brings to a proportional reduction of the length of the MB, and to a dumping of the transverse horizontal and vertical movements, because of coupling. The shortening of the MB starts very slowly and accelerate with the increase in number of coherent wavelengths which are participating and which becomes shorter and shorter. The transferred energy increased faster than the sum of wavelengths, because the shorter ones transfer more energy. Concomitantly, the yield of the transfer increases with the increase in MB density. The phenomenon is cumulated in all bending magnets, and during a great number of turns in the ring. The overall synchrotron spectrum emitted in the magnets becomes totally coherent and is seen as a line spectrum with the separation among the lines corresponding to the higher harmonic of the idle cavity frequency. The beam becomes "single-energetic" with very shortened transverse and longitudinal dimensions.

As opposed to what happens in free electron lasers, here the MB are cooled down. Only the particles at the front, which have the lowest energy, gain energy by stimulated absorption of different wavelengths, higher or equal to the length of the MB. In free electron lasers stimulated emission and absorption occur at the wavelength of the laser, which is very short compared to that of the bunch, leading to heating.

RESULTS OBTAINED ON e^+/ e^- STORAGE RINGS

Measurements performed on the SuperACO storage ring, related to synchrotron oscillations, showed that the movement of particles is only dipolar, whatever the frequency of oscillation (figure 1). This result is in contradiction to current concepts. It confirms the presence of a passive cavity, which could be either a higher-order mode of the main cavity, or could be at any other position of the vacuum chamber. This idle cavity is close to a much higher harmonic than the main RF of the ring. If it is exactly tuned to a harmonic of rotation, the RF level permits to obtain very short and stable MB, leading to the presence of first wavelengths of coherent synchrotron radiation.

These exceptional conditions which were met on the old ACO ring, allowed us to see the self-consistent phenomenon of supercooling of MB. The synchrotron spectrum became totally coherent. The light leaving the magnet windows consisted of a succession of stable longitudinal slices of light, that were thin, vertical and perpendicular to the output axis. These slices of light were equally spaced without any light between them. Although partially unexplained, this phenomenon is a representation of the total coherence of the spectrum. The measurements of the emitted light, using a streak camera [4,5], reveled the presence of a discrete structure of the bunch of particles that had a period corresponding to the distance between two slices of light.

Two other features, which we think are related to total coherence, were also recorded under the mentioned conditions. The lifetime of the beam was independent of the current stored in the ring, and corresponded to the one usually seen at small currents. The beam-beam limit was one order of magnitude higher than the usual limit.

In order to confirm the results obtained on the ACO ring, test should be performed on rings that have similar characteristics, similar or smaller energy and curvature radius. Our results indicate that coherent radiation and supercooling of the beam could be implemented to all existing storage rings producing synchrotron radiation, which would extend noticeably their usage.

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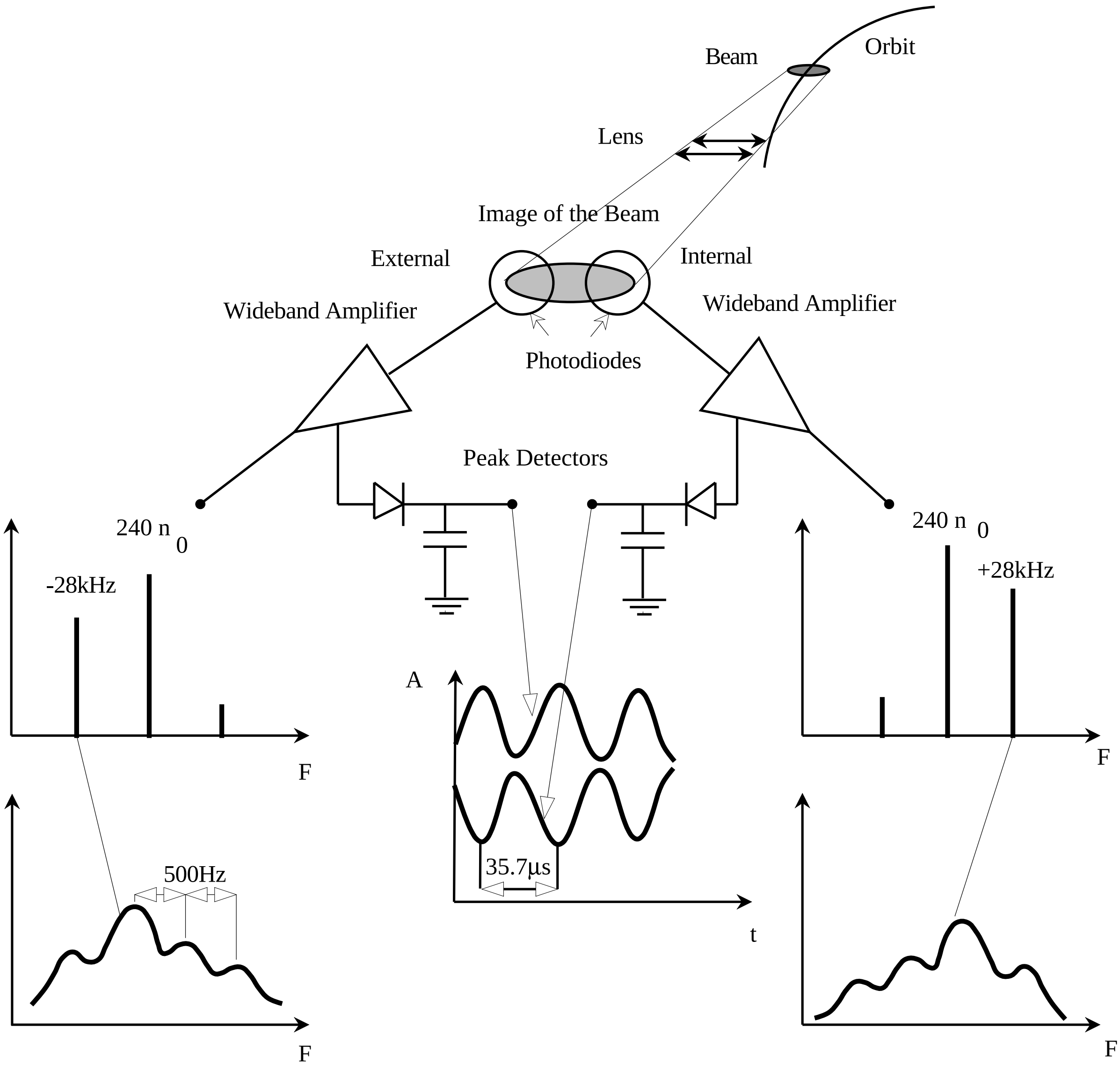

Figure 1. Spectral analysis of the synchrotron oscillations and the demonstration that the movement of the beam is only dipolar.

Measures were performed on the SuperACO storage ring, using two ultra fast PIN photodiodes (35 ps rise time, PD15, Opto-Electronics, Oakville, Canada). The photodiodes were positioned to see the internal and external part of the image of the horizontal synchrotron beam behind the optics at the exit of a magnet. Each circuit consisted of one photodiode followed by a wideband amplifier with two outputs, one for measurements with a spectrum analyzer, the other for peak detection. This second output permitted to detect and extract the amplitude modulation of the pulses which represent the bunches. This modulation is the consequence of oscillations in energy of the particles of the beam. The modulations detected were of opposite phase, as expected for dipolar movements of the particles. This was true for different frequencies of synchrotron oscillations. The recorded spectrum shows that the dipolar movement consists of a series of closely spaced frequencies, which indicates the presence of micro-bunches. For a theoretical and measured synchrotron oscillation frequency of 14.6 kHz, two dipolar frequency oscillations were detected: one at 28 kHz for a current between 72 mA and ≈ 100 mA, and an other one at 39 kHz for a current above 100 mA to the limit of 200 mA. The limit is determined by the high temperature tolerance of the sapphire window. All measurements were performed with two equal "bunches" of particles at the opposite sides of the storage ring.