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New Outlooks on Bunched Beam Instabilities in Particle Accelerators. A Proposal for a Simple Method to Release a Potential Self-Consistent High Quality Beam

M. Bergher

LURE, Bat. 209 D, Centre Universitaire Paris-Sud, 91405 ORSAY CEDEX FRANCE,

Abstract

Several hypotheses have been proposed to explain bunched beam instabilities under increasing intensity. In fact, the cause of these instabilities can be used to generate a very high quality beam. Total coherent synchrotron radiation brings the bunches to plasma density by self-consistent supercooling in the three bunch dimensions i.e. by reduction of energy dispersion. Maximal density and minimal residual instabilities can be controled by feedback loops. Thus, more efficient machines can be made available, opening new possibilities in many fields.

I. INTRODUCTION

In bunched beam instabilities, if "practice" agrees with "theory" within some limits, there is divergence outside. The cause of these instabilities can be used to transform this "natural" disavantage into a mean to generate a very high quality beam [1].

A specific example for a lepton ring is given below.

II. BUNCH "LENGHTENING"

First, let us assume that there is an unique bunch in the ring vacuum chamber. This bunch is not pertubed by any other accelerating voltage than the monopole generated by the main RF cavity without higher multipole modes. Below the beam current threshold, where instabilities appear, classical beam dynamic studies give gaussian shape for the three dimensions and for particle energy which depends only on ring characteristics. No other instability than synchrotron radiation noise can be given if Robinson criterion is satisfied. Let us now place an other ideal cavity in the ring. The choice of the frequency of the accelerating monopole is close to the cutoff of the vacuum chamber and the harmonic number of the rotation frequency corresponds to the inverse of the bunch-length before the effect of the new cavity. The field produced by the circulating beam excites this cavity and then, if Q and the shunt impedance are sufficient, at the new turn, the composit accelerating voltage seen by particles leads to a different longitudinal shape of the bunch. In other words, the second cavity is a passive or idle cavity. By self-consistent effect, the bunch can split up into microbunches (MB) partially or totally. This effect depends on the bunch intensity and becomes stronger at low energy of the ring. It is boosted by the other effects described in the following section. All MB do not have the same density. The bunch length average density appears identical after and before the installation of the new accelerating cavity.

If we inject into the ring more particles, two opposit forces act in concert: on one hand, the main RF voltage brings the new particles to the same place, and on the other hand, for each injected particle, preexistent MB contained in the micro-buckets becomes like a macroparticle whose Coulomb force prevents new particles to go into these buckets. They go preferentialy into the nearest empty buckets. This is sufficient to explain the observed "lengthening" of the bunch, espacially if we do not have an apparatus of sufficient bandwidth to observe the micro-temporal structure.

Usually, for one accelerating voltage, the synchrotron oscillating coupled mode number is equal to the number of bunches, but for only one frequency of synchrotron oscillation. With two accelerating cavities, the synchrotron oscillation frequencies are not identical for the different MB [2]. Another reason jumbles up explanation of the phenomenon: groups of MB have one more mode of synchrotron oscillation which depends on the main RF voltage and is near the frequency oscillation given by the main RF voltage alone. If the second high frequency cavity is tuned to the first, in order to fulfil Robinson's criterion for two cavities [3], the MB are stable. If not, MB are unstable and can strongly be subjected to multi-mode synchrotron oscillations. As shown in Figure 1, this depends on the second RF voltage and therefore on the beam current. This explains the discrete and multiple longitudinal oscillations mesured in two rings of very different sizes [4,5]. When the beam current increases, the synchrotron oscillation frequency of a few MB goes to the same value. Thus, these MB can have strongly coupled oscillations and therefore they disappear above a new current threshold. When the MB oscillate with strong amplitude at the synchrotron oscillation frequency, giving a broad FM swing modulation, their fields can excite the nearest transverse modes and then produce transverse instabilities, the later leading to total loss of the concerned MB. When multimode synchrotron oscillations are present without beam lost, at the same current threshold, the beam shows bunch "lengthening" and apparent widening of energy dispersion [6]. In summary, the preceeding explanations are sufficient to account for the bunched beam "lengthening" and the instabilities which come with it. But in reality, this leads to a self consistent shortening!

Among the superior accelerating modes of the main cavity or open accelerating structure like multiflanges or winding corrugations between two pipes [7], one single mode can emerge owing to a self-consistent effect if its frequency is at the rotation frequency harmonic or is near to it, and has the highest Q and the highest shunt impedance. Then, the other modes can no more be excited because the spectral field changes and many harmonics disappear. If we can adjust the frequency, amplitude and phase in accordance with the main RF cavity, MB become stable. The later has important concequences, as seen below.

III. COHERENT BEAMS

The harmonic oscillating fields produced by the MB are coherent below a borderline frequency corresponding to the inverse of the temporal MB length. The oscillating fields propagate into the beam-pipe beyond its cutoff frequency. As a concequence, the self micro-bunching can be very strong and the micro-bunching length very short.

Four phenomena act together on the beam.

In the bending magnet, since the orbit is curved, two new favorable consequences arise :

An enhancement of coherent synchrotron radiations takes place at all harmonics of the rotation frequency until the inverse of the MB length is reached. The radiation intensities have a quadratic dependence on the number of particles in the MB [8].

1) For a beam above the ring transition energy, the trailing particles are those with the highest energy. They emit more energy, and this energy is provided to the leading particles in the same MB. The particles are moving on the arc of circle and the emitted energy following the cord path. In other words, a stimulated absorption for the leading particles is present. A new gradual and strong shortening appears for every MB.

2) Because of the coherent synchrotron radiations, the beam quickly reaches the point of zero energy dispersion. The noise due to incoherent synchrotron radiations disappears.

On straight line , two other phenomena are present:

3) When each MB shortens, it follows the propagating azimutal electric fields and it lags behind the crest of the electric field. A particle in front of the MB acquires more energy than the one at the back. This is valid for particles above the ring transition energy [9,10] and the complex electric field is equivalent to the accelerating voltage given by multiple cavities at every harmonic frequency.

4) Particles with higher energy go faster than those with less energy; this phenomenon has the same effect than that given by optical klystron in a FEL and acts in agreement with the above effect. This is valid only if the MB becomes very short.

Additional effects :

- The dynamic reduction of energy dispersion and of particle momentum lead to cumulative effects at each turn, and turn after turn.
- By synchrotron-betatron effect, the transverse dimensions reach zero.
- The beam quality limit depends on the perfect agreement of the couples of relative voltages and phases of one accelerating cavity to the next one, i.e. correct tune of both cavities.
- A very fast self-consistent supercooling in the three bunch dimensions is obtained and may thus conduct to plasma density. Raman radiations replace Compton radiations. Strong superradiant effect can arise [11].
- We observed once coherent synchrotron radiations in visible light in the ACO ring, under particularly favorable circumstances. Meanwhile, Touchek and beam-beam effects were also strongly modified. The large aperture of the vacuum chamber (15 cm by 6.5 cm) and the low radius of the curvature in the bending magnet (1.1 m) of this small ring give a wavelength cutoff of 3.2 cm, according to the rate formula, Eq. 1 in [12]. This can explain, when the micro strutures [13] become stable, all the beneficient effects observed in ACO.

Consequences :

The particles have the same energy; the beam has very low longitudinal and transversal dimensions; the emittance is also very low; the Touchek effect disappears; beam-beam effect also disappears, and as a result, luminosity becomes very high; the multiple waves of synchrotron radiation light are coherent harmonics of the rotation frequency; the synchrotron beam light is enhanced by the number of particles in MB and totally polarized.

IV. CONCLUSION

All current particle accelerators coud be transformed into far more efficient machines with only moderate investments.

The very high beam quality generated by these improvements would lead to new outcomes in many fields.

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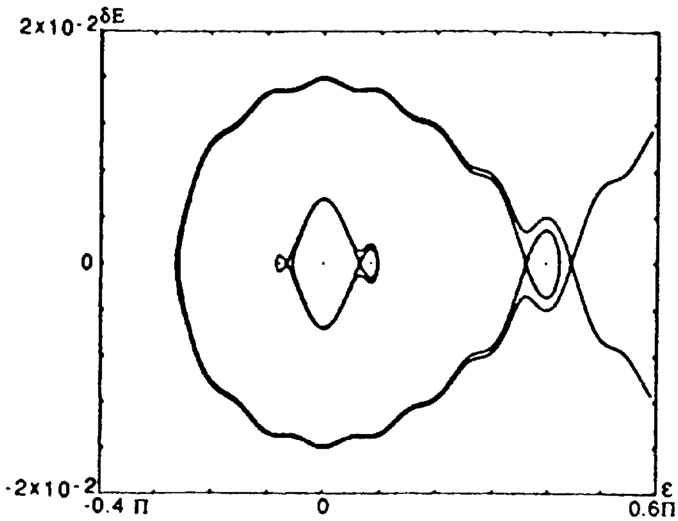

Fig.1a

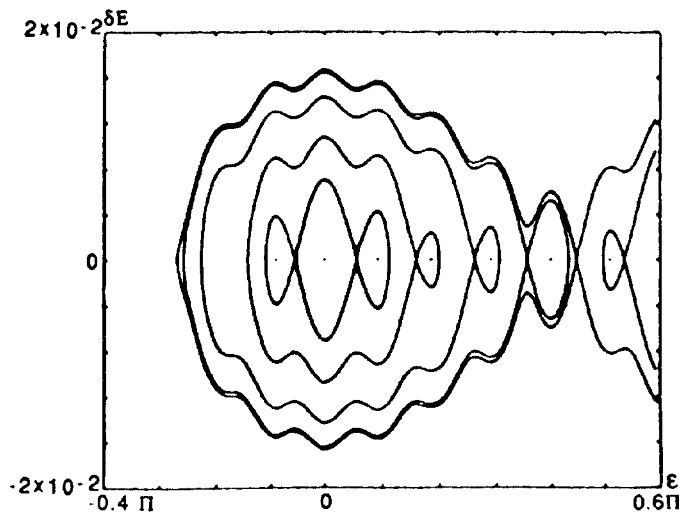

Fig.1b

Evolution of the complex separatrix for two significant values of the second RF voltage .

Both in Fig.1a, where α=0.5 and Fig.1b, where α=1, we have $V_2 = \alpha V_1$, $h_2=10\ h_1$, $h_1=2$, $\phi_1=\phi_0$, $\phi_2=\pi$, h, corresponding to the harmonic of the rotation frequency and ϕ_0 to the energy loss for one cavity with $eV \sin \phi_0 = \Delta E\gamma$. Separation between the two cavity frequencies has been limited for a clear view. According to these curves, it is evident that the different possible synchrotron oscillations would be more and more complicated if the harmonic of the second cavity is very high. They are often interpreted as bunch multipole turbulences by many machine specialists.