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MULTIBUNCH INSTABILITIES AND CURES

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Abstract

The common approach to achieve the high luminosity needed for high precision measurements adopted by the particle factories now under construction consists in storing high current e^+e^- beams distributed in many bunches in separate rings. The beams are brought together to collide at one interaction point. An inconvenience of this strategy is that the performances can be seriously limited by unstable coupled-bunch oscillations excited by transients or noise and sustained by long-lasting parasitic resonating modes (high order modes-HOM) in the vacuum chamber, mainly in the RF cavities. Minimization of the HOM content and broad-band feedback systems together with the reduction of the driving transients are the complementary cures to this kind of disease. This paper introduces the subject with some examples and special emphasis on bunch-by-bunch feedback systems.

1 INTRODUCTION

All the e^+e^- particle *factories* aimed at high precision measurements now approved and under construction [1-3] have adopted a similar luminosity strategy that consists in resorting to "comfortable" single bunch beam-beam parameters and increasing as much as possible the number of colliding bunches.

The high current, multi-bunch approach moves the technical challenges elsewhere to the vacuum, RF and multibunch feedback systems. In fact, the operation is very critical with respect to longitudinal and transverse coupled bunch (CB) instabilities, caused by parasitic higher order modes in the ring, mainly in the RF cavities, and resistive wall impedance. These instabilities have been identified as a potentially severe limit on the ultimate achievable luminosity. The reduction of the beam-cavity interaction is of utmost importance and particularly demanding. The RF cavity designs have been aimed at reducing significantly the impedance of the high order cavity modes (HOM) by various means [4]. On the other hand, additional damping must be provided by a broad band feedback system capable of damping all coupled modes on a bunch by bunch basis. In this paper, after an introduction to the coupled modes terminology, we review the cures against multibunch instabilities with accent on time-domain digital feedback systems and we describe the first implementation at ALS.

2 MULTIBUNCH MODES

An ultra-relativistic beam in a storage ring of length $2\pi R$, with revolution time $T_0 = 2\pi R/c$ (c: speed of light) and revolution frequency $f_o = \omega_0/2\pi$, consisting of M equally-spaced bunches, can oscillate coherently in M different modes, depending on the phase relationship between the individual oscillations [5].

In order to look for suitable phase shifts between synchrotron oscillations (frequency = $\Omega_s/2\pi$) of adjacent bunches we consider the idealized situation of point-like bunches consisting of N particles of charge e on the same phase-plane orbit of radius τ_s . In the case of rigid bunch motion, the linear charge density is the sum of M periodic contributions :

$$\lambda(t) = \frac{Ne}{c} \sum_{b=1}^{M} \sum_{k=-\infty}^{\infty} \delta\left[t - \left(\frac{b}{M} + k \right) T_0 - \tau_b \right] \qquad (1)$$

where

$$\tau_b = \tau_s \cos(\Omega_s t + \psi_b) \qquad (2)$$

By expressing (1) as a Fourier series, we find non-zero terms at angular frequencies

$$\omega_{p,n} = (pM + n + mQ_s)\omega_0 \qquad (3)$$

with Q_s the synchrotron tune, p running from $-\infty$ to $+\infty$, n = 0, 1, 2, .., M-1, defining the n-th mode of coherent CB motion and m = 1, 2, 3, ... , defining the phase-plane periodicity, provided the phase shifts between the perturbations of two adjacent bunches satisfy

$$(\psi_{b+1} - \psi_b) = \frac{2n\pi}{M}\text{, modulo } 2\pi \qquad (4)$$

With M equal bunches, M distinct longitudinal coherent CB modes can be excited. In Fig. 1 we show as an example a coherent synchrotron oscillation of six bunches, each oscillating with a phase advance of $2\pi/6$ with respect to the adjacent (mode number n = 1).

We see that the overall pattern of detected amplitudes can be fitted by two classes of sinusoidal signals, at positive and negative frequencies, equally spaced at M times the revolution frequency. Going to a representation with positive frequencies only, each coupled mode shows up as a pair of lines in the span Mf_0, i.e.: all modes appear once in any frequency span between pMf_0 and $(p+1/2)Mf_0$.

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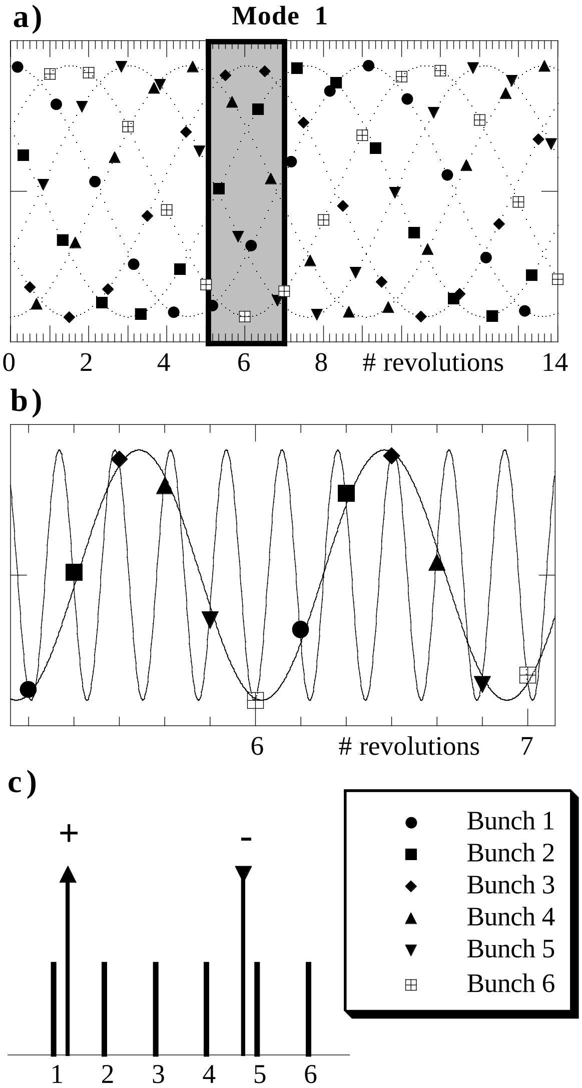

Figure 1: Example of a detected oscillation of $M = 6$ bunches executing coherent oscillations with $2\pi/6$ (n = 1) phase advance. **a)** Individual amplitude of oscillations for each bunch. **b)** Enlarged view of the shaded portion of a), with superimposed two high frequency modes at $(1 + Q_s)\omega_0$ and $(-6 + 1 + Q_s)\omega_0$. **c)** Spectrum analyzer representation (positive frequencies only) of modes b). The pattern repeats indefinitely every M-th revolution harmonics.

It is worth pointing out that among the sinusoids fitting the detected oscillation, those with ($p \geq 0$) present the same slope of the actual oscillation, while those with ($p < 0$) have an opposing slope.

We can now understand that if the real part of the impedance of a narrow band resonator crosses with a substantial value a CB mode frequency line, the bunch motion can be excited or damped, according to the relative slope of the motion and of the induced voltage in the resonator. In Fig. 1-c, we have labeled the stable line with "-" and the unstable one with "+". The situation is similar for all the other modes.

In the case of short (compared to the beam pipe radius) bunches, which is appropriate for high luminosity colliders, the growth rate of instability for each mode n can be computed approximately as [6]

$$\alpha_n = \frac{I_0\, \alpha_c}{4\pi Q_s E} \sum_p \omega_{p,n}\, e^{-(\omega_{p,n}\sigma_t)^2}\, \Re\left\{Z_l\left(\omega_{p,n}\right)\right\} \quad (5)$$

with I_0 the total current, α_c the momentum compaction factor, E the beam energy (eV), $\Re\left\{Z_l\left(\omega_{p,n}\right)\right\}$ the real part of the impedance and σ_t the rms bunch duration.

Since all coupled modes appear in a frequency interval $(M/2) f_0$, the growth rates α_n and the sum of offending impedances in (6) can be represented in an *aliased* way in the interval $0 \div (M/2) f_0$ [7]. Moreover, the minimum bandwidth required for an active feedback system to damp all the coupled modes must be half the bunch frequency.

In the high luminosity factories under construction it is very likely that undamped high order modes (HOM) in the storage ring, mainly in the RF cavities, give rise to growth rates much larger than the natural (radiation, Landau) damping rate because of the large total current and of the large number of possible CB modes, which are spaced at ~ the revolution frequency. In DAΦNE the line spacing is around 3 MHz, giving in principle some latitude to HOM displacement, but in larger rings (PEP-II, KEKB) the spacing of ~ 100 KHz is such that harmful interaction of some HOM impedance with CB modes is almost unavoidable: it is crucial to reduce the HOMs impedance as much as possible.

In addition, in large rings, the fundamental mode of the RF cavity itself can drive several CB modes and a feedback system around the cavity is needed.

It can be shown that for the transverse motion of M equally spaced bunches only every M-th line occurs for every n-th coupled mode:

$$\omega_{p,n} = \left(pM + n + Q_\beta + mQ_s\right)\omega_0 \quad (6)$$

where Q_β is the betatron tune and, again, $-\infty \leq p \leq +\infty$, n = 0, 1, .., M-1 and m = 0, ± 1, ±2, ..., defining the m-th head-tail mode number. Note that a coherent transverse mode m = 0 exists, corresponding to a dipolar transverse oscillation of the center of mass of a bunch with a stationary distribution in the longitudinal phase space; on the other hand, there are no longitudinal coherent modes at m = 0.

In the transverse case, multibunch motion can be driven by transverse HOMs in the cavities, but, in addition, modes at low frequency can be excited by the resistive wall impedance, which is large at low frequency. The bigger the size of the storage ring, the faster is the growth rate.

If the bunches carry unequal charges or they are not equally spaced we have a more complicated line pattern, but any motion can still be decomposed in terms of the orthogonal modes (3), (6).

3 HOM DAMPING

In synchrotron light facilities operating in the multi bunch mode, such as, for example, ALS (revolution frequency ~ 1.5 MHz) and Elettra (rev. freq. ~ 1.16 MHz) it has been possible to *park* the HOMs in *quiet* positions, by acting on the RF cavity temperature set point. In ALS it is possible to store 400 mA in 328 bunches without beam loss, but with self-limiting longitudinal multibunch instabilities. In Elettra, almost all longitudinal modes amplitudes can be reduced below 1° at 250 mA , with no sign of transverse effects [8].

The HOM shift approach above implies too many risks with respect to a predictable and consistent operation of a factory; therefore, extensive R&D work has been devoted to the development of HOM-free cavities. PEP-II and DAΦNE [4] adopt a similar design which consists of a room temperature resonator loaded with waveguides (WG) , whose cutoff frequency is higher than that of the accelerating mode. The WGs are connected to the cavity body to let the parasitic modes propagate out, with an effective reduction of their impedances by order of magnitudes.

In the PEP-II cavity the damping WGs are loaded with lossy ceramic tapers brazed inside [9]. In the DAΦNE cavity the WGs are terminated onto 50 Ω in air by means of broadband (0.5÷3 GHz) waveguide to coaxial transitions under vacuum, which have been developed at LNF to this purpose. This solution avoids the risks related to the heating of RF lossy materials brazed within the waveguides, in the ultra high vacuum environment of the accelerator.

The first DAΦNE cavity has been delivered and successfully tested at full power [10]. We have checked with a simulation program that the measured HOM Q are well within the capability of our bunch-by-bunch feedback system. In Fig.2 we show the measured spectrum of longitudinal impedance with and without the waveguide loads.

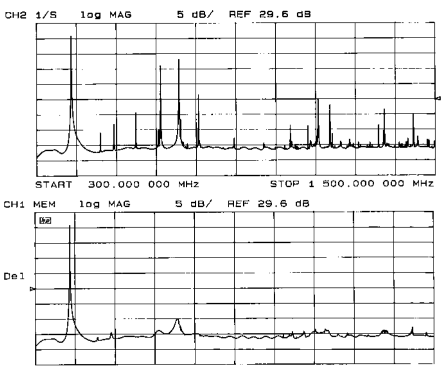

Figure 2: Spectrum of longitudinal HOM impedance of the DAΦNE RF cavity [10] with (lower) and without (upper) 50 Ω loads on the waveguides.

KEK has developed two designs for the B-Factory [3]. One, at room temperature (ARES), is based on a "choked" accelerating cavity coupled with an energy storage cell, and the other, superconducting, is a high gradient single cell with large aperture beam pipes to allow the propagation of HOMs outside the cell, where they are absorbed by ferrite loads.

4 FEEDBACK

In the presence of heavily damped HOMs in the accelerating cavity, the chance for a HOM to interact with a CB mode frequency becomes large and, because of the large total current, the growth rate of unstable modes can still be stronger than the natural damping rate. The complementary cure is an active feedback system capable to damp all the CB modes.

In principle the system can be equivalently realized in the frequency domain (mode feedback), or in the time domain (bunch by bunch). Regardless of the type of realization, as we have seen in section 3, the minimum bandwidth requirement is half the bunch frequency.

The mode feedback has been used successfully with few bunches [11] or in cases where a few dangerous cavity modes have been identified.

4.1 Bunch by bunch feedback

The bunch by bunch approach is more attractive since an *a-priori* knowledge of the endangered CB modes is not required. However, because of the HOM damping, they are likely to be evenly distributed over the spectrum.

In this system each bunch is treated as an individual oscillator. The basic components are: a time gated phase detector capable of continuous single bunch measurement; a bank of M parallel filters producing the correction kick signals, phase shifted by $\pi/2$ [12]; a broad-band power amplifier and a broad band kicker. See for example PEP [13] and UVSOR [14] with three and four bunches.

With a number of bunches of the order of thousand, as in the case of the B Factories, the parallel filter approach is of difficult realization. Fortunately, the electronic technology now available allows the realization of a mixed microwave-analog-digital system employing fast (≥ 500 Msamples/sec) analog to digital and digital to analog converters (ADC - DAC) and fast Digital Signal Processors (DSP) as filters. In Fig. 3 we illustrate the architecture of the DSP system adopted for PEP-II, ALS and DAΦNE, based on the results of considerable R&D work on feedback systems for the next generation of electron-positron colliders, carried out at SLAC.

The filter response is realized with an FIR (finite impulse response) band-pass filter, with peak gain at the base-band synchrotron frequency. It has to be software tunable in order to maintain the right phase shift over the range of the allowable synchrotron tunes.

The design specifications are such to meet the ultimate performance specifications of ALS, PEP-II and DAΦNE. Several components are the state of art of microwave and digital electronics, but all of them are commercially available.

A detailed description can be found in [15] and references therein. The first complete system is now running at ALS [16], where stable operation with 400 mA in 324 bunches has been routinely obtained. The capabilities of this system to collect and record data while operating can be exploited to carry on interesting machine studies, which are presented in [17].

The main advantage of such a system is that the same DSP can process several bunches, thus reducing the hardware complexity. Moreover, it is possible to take advantage of the relatively low synchrotron frequency and reduce substantially the sampling rate at which the synchrotron phase is detected. This results in less complex filters and reduces the overall data rate and computational load in the DSP section [18].

Table I below shows the relevant parameters for feedback systems at various machines. We remark the similarity of synchrotron damping times, bunch frequencies and data rate requirements. The approach taken by KEKB results in a similar architecture, with the important exception that it does not make use of down-sampling. The digital filter is implemented as a two-taps FIR with taps of value ±1 at 90° and 270° of the synchrotron oscillation [3,19]. This type of filter requires only a signed addition, but no multiplications, thus it is very fast. The DSPs are realized with CMOS memories and programmable logic. Each one is capable of dealing with 320 bunches. The fast data stream at the front-end is demultiplexed onto a parallel bank of 16 such DSPs by means of two custom GaAs fast demultiplexer chips. The processed data are multiplexed into the back end with a similar pair of fast GaAs multiplexers specially developed by OKI for KEK.

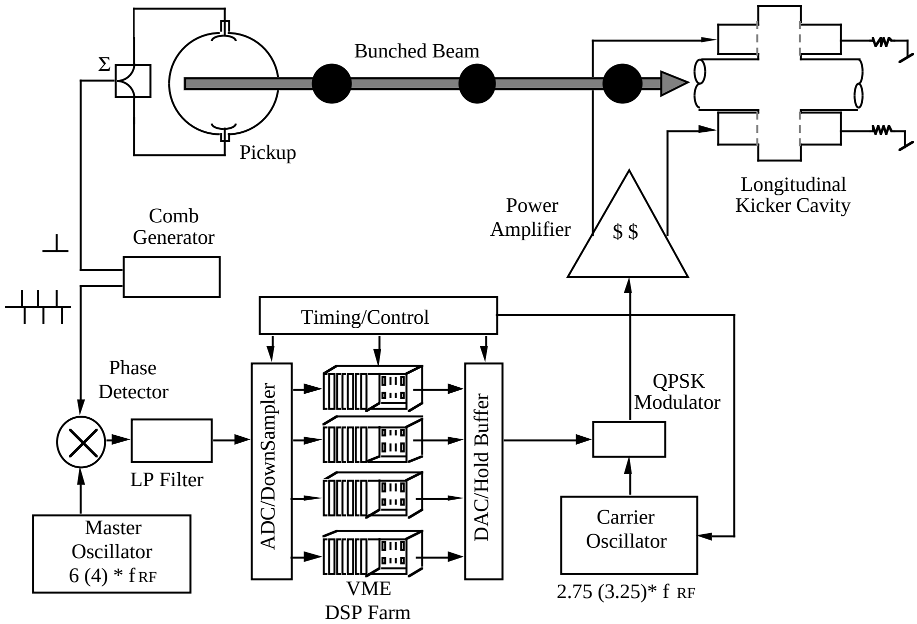

Figure 3 : Block diagram of the DSP based feedback system.

Table I - Summary of feedback related parameters of multi-bunch machines [1-3]

	PEP-II		KEKB		ALS	DAΦNE
	HER	LER	HER	LER		
Energy (GeV)	9	3.1	8	3.5	1.5	0.511
Revolution frequency (KHz)	136.3		99.39		1523.3	3068.8
Average current/bunch (mA)	0.59	1.29	0.22	0.51	1.22	43.7
Total beam current (A)	0.99	2.14	1.1	2.6	0.4	5.24
RF Voltage	14	5.5	10-20	5-10	1.5	.25
Number of cavities	20	6	36	10-20	2	1
Synchrotron damping time (ms)	19.8	26.4	23		10.7	17.8
Harmonic number	3492		5120		328	120
RF frequency (MHz)	476		508.9		499.6	368.3
Number of bunches	1658		5000		328	120
Bunch spacing (ns)	4.2		1.97		2.0	2.7
# revolutions per synchrotron period	22	28	50-100		138	56
Down-sampling factor	4	5	1		21	12
Next kick computation time (μs)	1.5		0.031		1.5	1.5
Data rate (MBytes/s)	56	45	500		24	31
# DSPs	80	64	16	16	40	60
Modular VXI/VMEArchitecture	√	√	"Single Board"		√	√

4.2 Longitudinal Kicker

The maximum power at the kicker is determined by the energy gain needed to achieve the required damping rate and the maximum synchrotron phase error allowed. The design of the kicker structure must be optimized in terms of shunt impedance and bandwidth in order to reduce the power requirement on the final stage, because broadband power is very expensive.

PEP-II and ALS [20] use two full coverage 25 Ω striplines connected in series by $\lambda/2$ lines to increase the shunt impedance (nominal value 400 Ω). In principle, this device is a matched load for the power amplifier and, being directional, no power from the beam is directed to power amp. On the other hand, proper tuning of this device is not easy. According to simulations and laboratory measurements, the stripline kicker is rich in HOM content and requires additional damping loops.

In order to increase the kicker shunt impedance and decrease the HOMs, a longitudinal kicker based on a WG loaded pill-box cavity has been designed for the DAΦNE feedback system [21]. A sketch is shown in Fig. 4.

The large bandwidth required to fill the cavity to any kick value in a time interval corresponding to the bunch time spacing is obtained by loading the accelerating mode with three single-ridged waveguides placed 120^{o} apart on each pill-box side. Broadband waveguide-to-coaxial transitions similar to those in the RF cavity allow external connections to the power amp and loads.

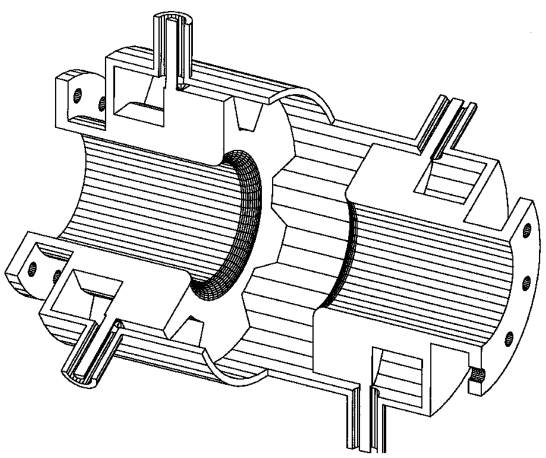

Figure 4: CAD view of the DAΦNE kicker cavity.

The measured shunt impedance is 620 Ω, with a half power bandwidth of 250 MHz, centered at ~ 1200 MHz, i.e. (3+1/4) times the RF frequency. According to simulations with the values of the RF HOM impedances, a large bandwidth power amplifier of ~ 200 Watt is enough to damp an initial offset of 100 ps with operation at 30 bunches. Two kicker cavities per ring will eventually be installed for operation at the full nominal current with 3x200 Watt power amplifiers per cavity, each feeding separately a waveguide coupler.

Being broadband, the kicker cavity does not need to be tuned in operation, nor cooled, since almost all the power is dissipated in the external loads. Moreover, the damping waveguides couple out the HOMs as well. However, the overloaded cavity is not a directional device like the stripline kicker: it extracts power from the beam. Ferrite circulators are then necessary to isolate the output section of the power amplifier.

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