Impedance and Beam Dynamics in DAΦNE

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Abstract

In DAΦNE single bunches of $9*10^{10}$ electrons or positrons are stored in an accumulator where they reach the suitable intensity necessary for a smooth injection into the multibunch e^+e^- rings. DAΦNE is envisaged to operate with 30 bunches, with about 1.3 Amps, in order to achieve the goal luminosity of a few 10^{32} (cm^{-2} s^{-1}). Then operation with a higher number of bunches, up to 120, might be necessary to explore the limits of the machine.

Single bunch and multibunch instabilities are among the main concerns for this high current machine. In this paper we report the main results of the analysis of dynamics for the e+ e- beams in the accumulator and in the main rings of DAΦNE machine. The impedances of both machines have been estimated by fitting the loss factor calculated by the TBCI and MAFIA codes [1] for all the ring components. Some results of the loss factor bench measurements performed on the accumulator kicker are shown as comparison with the computer estimates.

The single bunch longitudinal and transverse microwave thresholds appear to be safely far from the nominal current. An investigation of the multibunch instabilities excited by the RF cavity HOMs is presented. Absorption of e.m. energy stored in the parasitic modes is necessary in order to keep the instability rise time long enough to be acted upon by a feedback system.

1. ACCUMULATOR RING

1.1. Impedance estimate

Bunches with $9*10^{10}$ electrons and positrons are stored and ejected from the accumulator with a repetition frequency of 1 Hz. The single bunch instabilities can limit the performance of the accumulator ring. The instabilities are driven by the short term wake-fields resulting from the bunch interaction with the vacuum chamber broad-band impedance.

We estimate the longitudinal Z_l and transverse Z_T broad-band impedances using numerical calculation of the longitudinal k_l and transverse k_T loss factors by 2D TBCI and 3D MAFIA codes [1] for different bunch lengths σ. To obtain Z_l and Z_T from the above numerical results for k_l and k_T, we use the relation between the loss parameters of a Gaussian bunch with rms length σ and the broad-band model impedance:

$$k_l(\sigma) = \frac{1}{\pi}\int_0^{+\infty} d\omega \, \mathrm{Re}\{ Z_l(\omega) \} \exp\{ -(\omega\sigma/c)^2 \}$$

$$Z_l(\omega) = R_l / \{ 1 - jQ_l(\frac{\omega_l}{\omega} - \frac{\omega}{\omega_l})\}$$

$$k_T(\sigma) = \frac{1}{\pi}\int_0^{+\infty} d\omega \, \mathrm{Im}\{ Z_T(\omega) \} \exp\{ -(\omega\sigma/c)^2 \}$$

$$Z_T(\omega) = R_T \, \omega_T/\omega \; \{ 1 - jQ_T(\frac{\omega_T}{\omega} - \frac{\omega}{\omega_T}) \}$$

and find the shunt impedances R_l, R_T, the angular resonant frequencies ω_l, ω_T and the quality factors Q_l, Q_T of the model broad-band resonator by fitting the numerical results to the analytical dependences $k_l(\sigma)$ and $k_T(\sigma)$. The analytical dependences $k_l(\sigma)$ with R_l = 1.527 kOhm, $\omega_l/2\pi$ = 4.14 GHz, Q_l = 0.82, and $k_T(\sigma)$, with R_T = 69 kOhm/m, $\omega_T/2\pi$ = 4.3 GHz, Q_T = 1, fit well the numerical estimates.

1.2 Kicker loss parameter measurements

As the numerical simulation shows, the main contribution to the loss factor (and impedances) in the accumulator comes from the injection-extraction kickers (almost 90%). So it is very important to measure the RF energy loss and compare it with numerical results. The longitudinal loss factor has been measured for an accumulator kicker prototype by an indirect method [2]. The experimental and numerical results are shown in Fig.1. The agreement between the two is satisfactory, showing the goodness of both approaches (simulation and measurement method).

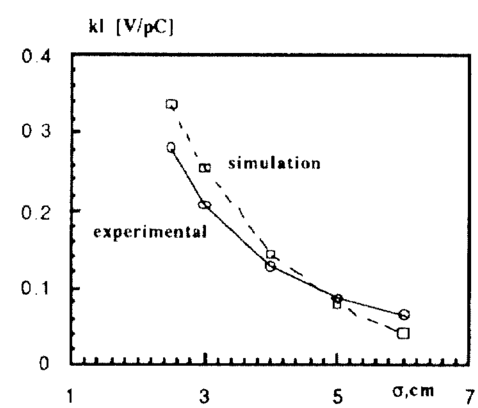

Figure 1. Loss factor k_l as function of bunch length σ: experimental (solid line) and simulation (dashed line) data.

1.3 Single bunch instabilities

Above the threshold of longitudinal microwave instability a bunch lengthens turbulently. The threshold average current is given by [3]:

$$I_l^{th} = \sqrt{2\pi}\,\alpha_c (E/e)\,\sigma_{p0}^2 / (|Z_l/n|\,\nu_s)$$

where α_c is the momentum compaction, E is the total energy of a particle, ν_s is the synchrotron tune, σ_{p0} is the rms energy spread at zero current.

At low frequencies the normalized longitudinal impedance $Z_l/n = R_l\omega_0 Q_l/\omega_l$, where $n = \omega/\omega_0$ is the mode number and ω_0 is the angular revolution frequency. For the accumulator ring $\omega_0/2\pi = 0.0092$ GHz and hence $Z_l/n = 4.14$ Ohm. Taking into account the contributions of diagnostics, which is 0.16 Ohm for the accumulator, the total normalized longitudinal impedance is $Z_l/n = 4.3$ Ohm.

For $Z_l/n = 4.3$ Ohm a bunch is in the turbulent regime and its equilibrium length is equal to 5 cm and the rms energy spread $\sigma_p = 9.15*10^{-4}$ at the average current of 130 mA and RF voltage of 200 kV. The loss factor that corresponds to this bunch length is $k_l = 0.115$ V/pC. It means that the bunch loses 1.66 keV per turn because of RF radiation.

The transverse single bunch instabilities are destructive for a stored bunch. The most dangerous are the transverse fast blowup instability, transverse mode-coupling instability and resistive wall instability. For $\sigma > (4\sqrt{\pi}/3)b$, where b is the beam pipe radius, the transverse mode-coupling instability dominates over the transverse fast blow up. That is the case of the accumulator ring. The mode coupling instability is driven by the imaginary part of the transverse impedance and its threshold is given by [4]:

$$I_T^{th} = \frac{4\,(E/e)\,\nu_s}{[\mathrm{Im}(Z_T)]\,\langle\beta_T\rangle R}\,\frac{4\sqrt{\pi}}{3}\,\sigma$$

where $\langle\beta_T\rangle$ is ring-averaged transverse beta function and R is the ring average radius.

At low frequencies for long bunches $\mathrm{Im}(Z_T) = Z_T = R_T/Q_T$. This approximation is valid for the accumulator because the bunch in the turbulent regime is rather long (5 cm). Taking the numbers from the broad-band impedance model the threshold current is by a factor ~5 higher than the nominal current.

2. MAIN RING

2.1 Single bunch dynamics

For the main ring we also use the broad-band impedance fit of the numerical dependences $k_l(\sigma)$ and $k_T(\sigma)$. The same procedure as described in 1.1. is used for this purpose. The normalized longitudinal impedance Z_l/n comes out to be about 1.2 Ohm and the transverse one Z_T about 64 kOhm/m.

Table 1 shows the relative contributions of different vacuum chamber elements to the total loss factors at the nominal bunch length $\sigma = 3$ cm. The main contribution comes from the 2 injection kickers. Now other possible kicker designs are under consideration to reduce the impedance [5].

In our calculation we did not take into account the contributions of bellows and flanges. Since DAΦNE is a rather small machine, the number of bellows and flanges is not large and in any case they will be RF shielded. So the goal of $Z_l/n = 2$ Ohm is quite achievable for the main ring. To keep the bunch length $\sigma = 3$ cm we need to supply $V_{RF} = 270$ kV at full current.

The transverse current threshold with a transverse impedance of 64 kOhm/m is by a factor 1.5 higher than the nominal current I = 45 mA.

Table 1

	k_l [V/pC]	k_T [V/pCm]
RF cavity	0.129	4.71
Longitudinal feedback kicker	0.0485	2.37
Injection kicker	0.255	40.9
Slot in the vacuum chamber (100cm* 2cm)	$2*10^{-7}$	0.002
Taper in the interaction region.	0.0013	1.5
Transition between the beam chamber and the wiggler section	0.0004	20.1
Vacuum chamber in the split magnet (intersection of two rings)	$4*10^{-6}$	0.716

2.2. Multibunch Instabilities

Coupled-bunch instabilities, driven by the parasitic HOMs of the RF cavity, are one of the main concerns in the design of the machine. A longitudinal feedback system for DAΦNE may provide at best a damping time of about 100 μsec, much faster than the natural radiation damping, not sufficient, however, to damp those relative modes significantly coupled to strong resonances. The spectrum of the unperturbed motion of k_b bunches shows frequencies at

$$\omega_{p,s,a} = (p\,k_b + s + a\,\nu_s)\,\omega_0$$
$$p = 0, \pm 1, \pm 2, \ldots$$
$$a = 1, 2, 3, \ldots$$
$$s = 0, 1, \ldots 29.$$

where $\omega_0 = 19.295*10^6$ rad/sec is the revolution angular frequency, "a" describes the longitudinal motion in the phase space (dipole mode a=1, quadrupole mode a=2 etc), and "s" specifies the longitudinal mode number. When a relative mode of oscillation "s" is excited by the e.m. resonating fields, the motion is intrinsically stable or unstable depending on the sign of the rise time:

$$\tau_{s,1} = \frac{4\pi\,(E/e)\,\nu_s}{k_b I_b \omega_o \alpha_c}\,\frac{1}{(Z_{s,1})^{\mathrm{eff}}}$$

where the effective impedance $(Z_{s,l})^{eff}$ is computed for each relative mode s, interacting with N parasitic HOM of the RF cavity:

$$(Z_{s,l})^{eff} = \sum_{-\infty}^{\infty}{}_p \sum_{1}^{N}{}_n F(\omega_p) \frac{R_{s,n}}{1 + Q_r^2\left(\frac{\omega_p}{\omega_{r,n}} - \frac{\omega_{r,n}}{\omega_p}\right)^2}$$

R_s, ω_p and Q_r being the relevant parameters of the parasitic resonators. The form factor for a gaussian beam is:

$$F(\omega_p) = \pm \frac{\omega_o}{\omega_p} (k_b p + s)^2 e^{-\left(\frac{(k_b p+s)\,\sigma_l}{R}\right)^2}$$

We have analyzed for the dipole-mode (a=1) the instability rise time due to a sample HOM with a resonant frequency spanning the region where the maximum of the form factor occurs, i.e. at around 1.125 GHz. We assumed $k_b I_b$ = 1.3 A, R_s/Q_r = 20 Ω, and consirered four significative cases Q_r = 50000, 5000, 500 and 100. For Q_r = 50000 the rise time becomes dramatically low, of the order of fraction of microseconds, when the resonant frequency is fully coupled to a relative mode sideband. However, as soon as the resonant frequency shifts from the full coupling condition, the rise time goes to much higher values, increasing by a factor 10^4. These results are explained by the fact that for such a short machine two consecutive stable or unstable sidebands are spaced of about the revolution frequency, i.e. 3 MHz. A single high Q HOM may excite only one relative mode at time. The instability rise time is due to the resistive impedance of the parasitic resonator at the sideband frequency. Its effect is maximum when the resonant frequency overlaps an "unstable" relative mode sideband. For $Q_r \leq 500$, corresponding to a shunt impedance of 10 kΩ of the sample HOM, the rise time remains above 100 µs for all relative modes that, therefore, can be stabilized by a powerful feedback system. In this case the resonator bandwidth is large enough to cover two consecutive unstable sidebands, so that a frequency shift of the HOM is ineffective. A compensation effect, occurring around s = 0 (an identical compensation happens for s = 15) because of the Robinson damping, is also recognized.

In Fig. 2 we plot versus the frequency what is the shunt impedance exciting the instability with a rise time τ=100 µs, for a stored current of 0.1, 0.5, 1.0 and 1.5 Ampere. On the same plot are reported for comparison the parasitic shunt impedances of the "day one" cavity [6] proposed for the beginning of the machine operation.

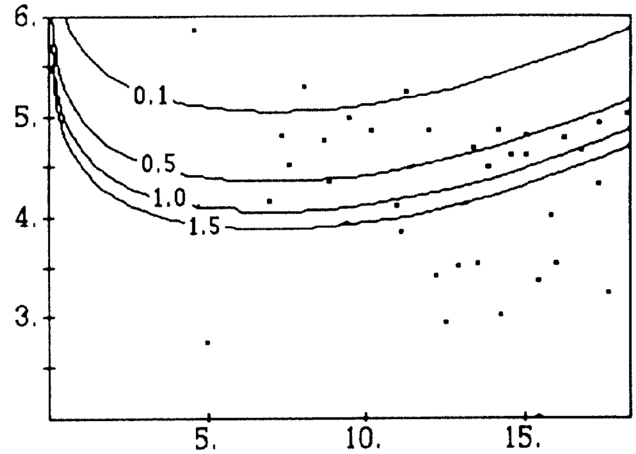

Figure 2. $\text{Log}_{10}\,[R_s(\Omega)]$ vs. ω_r (*10^9 rad/sec) for τ = 100 µs; I_o = 0.1, 0.5, 1.0 , 1.5 A.

The results show that, despite the small contribution of the cavity to the overall parasitic loss, many individual modes are characterized by a shunt impedance too high for storing 1.3 Amps. A recent further optimization of the cavity shape has improved the shunt impedance of the TM_{011} by a factor 6, and within the present constrains, we hardly expect that a further optimization of the cavity shape can reduce the HOM shunt impedances below the desired values. This goal can in principle be pursued by developing either the damping technique (by coupling the cavity to energy absorbers such as loops, loaded waveguides etc.), or the shifting technique, changing the resonant HOM frequency such that the resistive coupling impedance is strongly reduced. R&D activities on this field are reported in Ref.[6]. It seems hard today, however, to control the frequency of many potentially dangerous modes, whereas damping techniques based on the absorption of the e.m. energy stored in the HOMs, by means of antennas or waveguide couplers look more promising.

3. References

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