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Summary

The evolution of the measured transverse mode spectra as a function of the e^+ beam intensity at 500 MeV for different chromaticities is described. Mode crossing is seen but does not result in beam loss. An explanation for this is advanced. A comparison with mode spectra computed from a Q = 1 resonator model of the ring impedance and taking into account the bunch lengthening is presented. Not only the transverse low-frequency impedance $|Z| = 2.4$ MΩ/m can be derived but also the incoherent synchrotron frequency and the longitudinal impedance can be estimated. Bunch lengthening up to a factor 2.5 at a bunch intensity of 1.5×10^{11} was measured at 500 MeV for e^+ and e^-. The data are compatible with a Q = 1 resonator model with the low-frequency impedance $|Z/r| = 21$ Ω. A rough measurement of the energy spread provides evidence for a blow-up. The increase of impedance compared to earlier measurements is entirely explained by the addition of kickers.

Introduction

The LEP pre-injector [1], composed of two linacs of 200 and 600 MeV (LIL) and an Electron Positron Accumulator (EPA), has been commissioned in 1986 with electrons [2] and in 1987 with positrons [3].

The first measurements with electrons [4] revealed a substantial transverse blow-up generated by ions trapped in the beam potential and a strong bunch lengthening due to the longitudinal impedance mainly contributed by the kickers. The predicted vertical mode-coupling instability has not been observed though the single bunch tune was found to be shifted by several synchrotron tunes at the highest intensity.

Beam studies on both electron and positron beams were performed last year at an energy of 500 MeV in order to:

- compare beam parameters and performance obtained with both kinds of particles,
- measure the effect on the electron beam of the increased impedance due to additional kickers required for positron operation and due to the modified ion clearing system [5],
- analyse with positrons the transverse higher order modes and their variation with the beam intensity.

Comparison of electron and positron equilibrium beam parameters

Transverse beam profiles for both kinds of particles have been recorded using a diode array camera to observe the synchrotron light [6] emitted in a bending magnet where the dispersion is negligible ($D_x = 0$; $\beta_x = 7.6$ m, $\beta_y = 11.8$ m). The equilibrium emittances are deduced by fitting a Gaussian distribution to the data (Fig. 1). For vanishing currents, they are very similar for electrons and positrons but 25% larger than the theoretical figures. The emittance ratio is $\varepsilon_y/\varepsilon_x = 0.15$. In case of a positron beam, independently of the number of bunches, or with one single bunch of electrons, the vertical emittance is fairly constant as a function of the beam intensity, whereas the horizontal emittance is sligthly increasing. On the other hand, both transverse emittances of a multibunch electron beam are strongly blown-up. This effect has been attributed to the ions created in the residual gas and trapped in the beam potential [5]. Thanks to the improved clearing electrodes, the blow-up of a 4.10^{11} electron beam in 8 bunches is reduced to a factor 1.3 horizontally and 6.3 vertically; the figures of last year were 3 and 23 respectively [4].

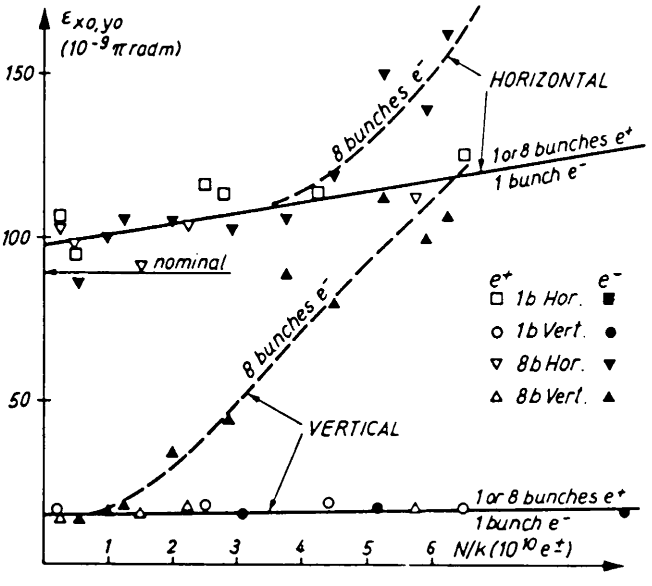

Fig. 1: Electron and Positron Transverse Equilibrium Emittances as a Function of the charge per bunch

The analysis of the same kind of profiles in the horizontal plane generated in another bending magnet where the dispersion function is large and the betatron contribution small ($D_x = 1.8$ m, $\beta_x = 1.95$ m) allows to extract the relative energy spread of the equilibrium beam. Preliminary measurements with positrons yielded a momentum spread compatible with the theoretical figure ($\sigma_E/E = 5.1\ 10^{-4}$) but the increase with current above the longitudinal turbulence threshold seems to be smaller than predicted.

The equilibrium bunch length has been deduced from beam observation with a wide band pick-up monitor [6], and recorded for both kinds of particles as a function of the charge per bunch for various r.f. cavity voltages (Fig. 2). As in previous measurements with electrons [4], the bunch lengths for vanishing currents are found to be 15% larger than expected. Using normalized coordinates, all data above the longitudinal turbulence threshold, independently of r.f. voltage, are well fitted for both kinds of particles by a straight line which

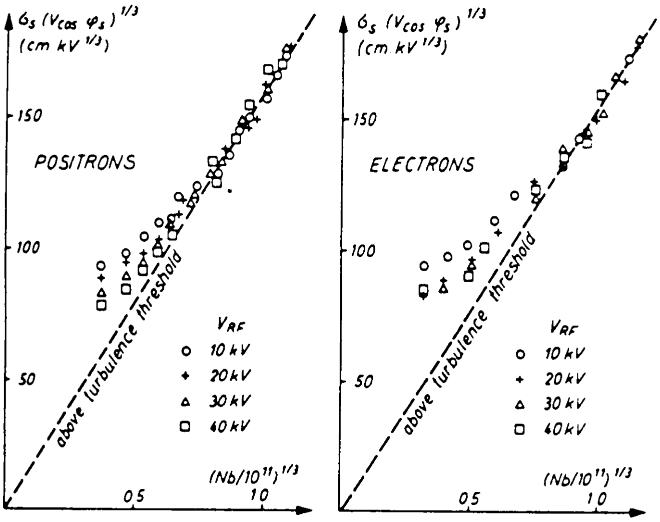

Fig. 2: Electron and Positron Bunch Lengthening as a Function of the Charge per Bunch

has a slope related to the longitudinal beam coupling impedance [7]. Taking the mean value between electron and positron measurements the absolute value $|Z/r|_0 = 21\Omega$ of the impedance of an equivalent broad-band resonator in the limit of zero frequency is deduced. This is 1.5 times larger than the corresponding impedance found last year with the same method, confirming the dominant impedance contribution of the injection and extraction kickers which have been increased in number in the meantime by the same ratio.

Transverse Mode Behaviour

Fig. 3 shows typical spectra of a single positron bunch at different bunch intensities. The bunch is excited vertically by a swept frequency. Observation [8] at 1 MHz of higher order transverse modes at low intensity (Fig. 3a) has been made possible by working with a positive chromaticity. The frequency shift of the modes with intensity is clearly visible especially the shift of mode m = 0 towards the mode m = -1 (Fig. 3b) which then merge into a single one (Fig. 3c). At a very high intensity, the higher order modes m = - 2 and - 3 become coupled (Fig. 3d). The mode signals are magnified when the frequency difference between modes has sufficiently decreased to enable an energy transfer from one mode to the other.

The measured shift of the modes +1 to -4 is summarised in Fig. 4 as a function of the charge per bunch and compared with the real shift calculated by the computer program MOSES [9]. The ring impedance is approximated by a Q = 1 resonator with a transverse shunt impedance of R_s = 2.5 MΩ/m; the latter is obtained by fitting the calculated to the measured shift of mode m = 0. The modes m = 0, -1, -2 and -3 show a fair agreement between measurements and simulation over the whole intensity range, but the measured shift of the mode m=+1 is significantly different from the simulation, which remains unexplained.

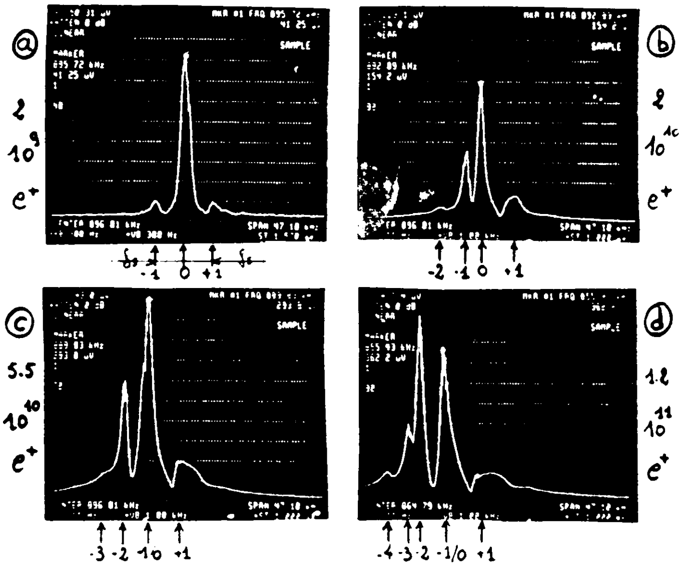

Fig. 3: Spectrum Analysis of Higher Order Transverse Modes for Various Beam Intensities and a Vertical Chromaticity Q'_y = + 2

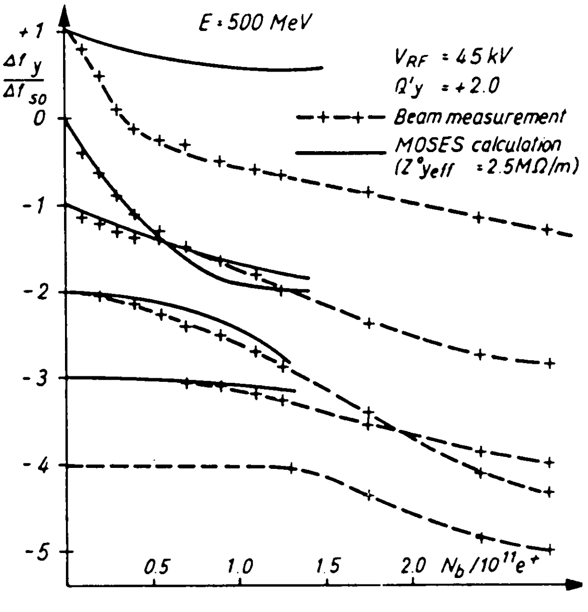

Fig. 4: Shift with the intensity of the Theoretical Modes of a Positron Single Bunch Beam

The coupling of the modes m = 0 and m = -1 is observed without any sign of instability above a threshold of 6.10^{10} particles as expected from simulation. The absence of instability is also in agreement with the simulation which shows that the growth rate of the instability deduced from the imaginary part of the mode frequency shift is always smaller than the damping rate by the synchrotron radiation. This has been observed in all machines with long bunches because in this case the real part of the effective impedance driving the instability is small in the low frequency range where the spectra of modes 0 and -1 lie.

At higher currents, the modes m = 0 and m = -1 remain coupled and undistinguishable up to the highest bunch intensity observed (2.8×10^{11}) which is 4.5 times the mode coupling threshold.

Transverse and Longitudinal Beam Coupling Impedance

Not only the transverse beam coupling impedance $Z^m_{T\,eff}$, but also the longitudinal one, Z_L/r can be deduced from the shift of the transverse modes $\Delta f\,(m)$.

The frequencies of the possible transverse modes m are given by:

$$f(m) = f_{pmn} = (n + pk + Q_T)\, f_0 + m\, f_s$$

where k is the number of bunches and f_0 the revolution frequency. Introducing the variation of the transverse tune Q_T and of the synchrotron frequency f_s with the charge per bunch $\Delta\,(N/k)$ yields two terms (8):

$$\Delta f\,(m) = \Delta f^m_T + \Delta f^m_L$$

$$\Delta f^m_T = f_0 \Delta Q_T\,(m) = \frac{-\,3.82\;10^{-12}}{\sqrt{|m|+1}}\, j f_0\, \beta_T\, \frac{Z_{t\,eff}}{\tau_L} \frac{e}{E}\, \Delta\left[\frac{N}{k}\right]$$

$$\Delta f^m_L = m\, \Delta f_s = -5.48\;10^{-3}\; mj\left(\frac{\alpha_p e}{E}\right)^{1/2} \frac{R}{\tau^3_L\,(hV|\cos\varphi|)^{1/2}} \left|\frac{Z_L}{r}\right| \Delta\left[\frac{N}{k}\right]$$

where τ_L is the total bunch length. Transverse and longitudinal effective impedances pertaining to a mode m are related to the sum and the difference of the frequency shift of the modes ± m.

$$Z^m_{T\,eff} = \frac{\sqrt{(|m| + 1)}\;\tau_L}{7.64\;10^{12}\; f_0\; \beta_T}\left(\frac{E}{e}\right)\left[\frac{\Delta f(+m) + \Delta f(-m)}{\Delta\,(N/k)}\right]$$

$$\left|\frac{Z_L}{r}\right| = \frac{\tau^3_L\,(hV|\cos\varphi|)^{1/2}}{1.1\;\;10^{-2}\;R}\left[\frac{E}{e\alpha_p}\right]^{1/2}\left[\frac{\Delta f(m= +1) - \Delta f(m=-1)}{\Delta\,(N/k)}\right]$$

which shows a strong dependence on the bunch length. The beta function β_T has to be taken at the location of the impedance.

Taking into account $\tau_L = 3.5\,\sigma_s$, valid for a Gaussian distribution (10), the impedances deduced from the measured mode frequency shifts become

$$Z^0_{T\,eff} = 2.4\ \mathrm{M\Omega/m} \qquad Z_L/r = 21\ \Omega$$

being not far from the impedance model derived from longitudinal impedance measurements of the kickers (4)

$$Z^0_{T\,eff} = 2.9\ \mathrm{M\Omega/m} \qquad Z_L/\,r = 21\ \Omega$$

and very consistent with the transverse impedance derived from MOSES simulations ($Z^0_{T\,eff} = 2.5$ MΩ/m) and with the longitudinal impedance derived from bunch length measurements (Z_L/r) = 21 Ω.

Incoherent Synchrotron Frequency

The variation of the incoherent frequency Δf^{inc}_s with current can also be directly deduced from the variation of the longitudinal contribution to the transverse mode shift, namely:

$$\Delta f^{inc}_s/\Delta\;\;(N/k) = \frac{1}{2}\;\Delta f\left[(m=+1) - \Delta f\;(m = -1)\right]$$

This variation compared with the variation of the frequency of the second synchrotron side band Δf_{s2} around the 20th harmonic of the r.f. frequency yields the relation

$$\Delta f_{s2}\;/2 = 0.29\;\;\Delta f^{inc}_s.$$

Conclusion

Analysis of the transverse modes is a very powerful tool to deduce not only transverse but also longitudinal parameters such as impedances and incoherent synchrotron frequencies. The impedances are consistent both with the impedance model based on kickers measurements and with values derived from bunch length measurements if the ratio of total bunch length to the standard deviation is 3.5 and not 4 as usually assumed.

Electron and positron beam parameters and performances are very similar except for a transverse blow-up with electrons which is induced by the ions trapped in the beam potential. This blow-up has been strongly reduced by putting clearing electrodes closer to the beam and by increasing the voltage. The electrodes are made from ceramic with metallic coating making a negligible contribution to the ring impedance.

Acknowledgements

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