

COLLECTIVE EFFECTS IN THE LEP ELECTRON POSITRON ACCUMULATOR (EPA)

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ABSTRACT

As a part of the LEP injector chain, the main function of EPA consists in fast accumulation and damping in order to build up eight high intensity bunches ( $8 \times 2.5 \cdot 10^{10}$ ) of electrons or positrons at 600 MeV with a high injection efficiency and stability.

During design and construction, great care was taken to minimize the impedance of the ring as well as the effects of the residual gas on the beam. The longitudinal impedance of every element was measured and reduced when possible. Based on these measurements a model of the overall longitudinal and transverse impedances was conceived and the beam behaviour simulated. A stainless steel vacuum chamber was chosen to minimize the gas desorption by synchrotron radiation. Low impedance electrodes clear ions trapped in the beam potential well. Thanks to these design features and sufficient acceptance, high intensity bunches well above nominal current could rapidly be obtained. Measurements of current dependent beam effects are presented and compared with the prediction by the models.

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1. Summary

As a part of the LEP injector chain, the main function of EPA consists in fast accumulation and damping in order to build up eight high intensity bunches ( $8 \times 2.5 \cdot 10^{10}$ ) of electrons or positrons at 600 MeV with a high injection efficiency and stability.

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2. Introduction

The main design parameters of EPA [1,2] have been chosen in order to favour an efficient and stable accumulation up to, at least, the nominal intensity. At injection, low intensity pulses from the fast cycling LEP Injection Linac LIL [3], at 100 Hz, successively fill the eight EPA RF buckets. Accumulation in betatron phase space is based on a strong horizontal damping ( $J_x = 2$ ) provided by combined function magnets with small bending radius [4]. The moderate longitudinal damping ( $J_z = 1$ ) leads to relatively large momentum spread ( $\sigma_E/E = 6 \cdot 10^{-4}$ ) at equilibrium which contributes to beam stability. The threshold of the various instabilities is raised by the long equilibrium bunch length ( $\sigma_s = 21\text{cm}$ ) resulting from the low frequency of the RF cavity (19.1 MHz).

The main performance limitation was anticipated to come from a vertical mode-coupling instability excited by the transverse impedance of the kickers with a threshold of  $5 \cdot 10^{10}$  particles per bunch.

The accumulator has been commissioned with electrons during the last six months of 1986 at an energy of 500 MeV [5]. A charge of  $2.1 \cdot 10^{11}$  electrons in a single bunch and  $6 \cdot 10^{11}$  in eight bunches could be accumulated with an injection efficiency of 80%.

3. Model of the Beam Coupling Impedance

The longitudinal impedance of all elements implemented in EPA have been systematically measured with an improved coaxial line transmission method [6]. Great care was devoted to damp the high Q resonators detected in the different vacuum tanks as well as the higher order modes of the RF cavity [7]. The broad-band impedance was systematically minimized by tapering the vacuum chamber and by a careful design of the numerous elements like bellows or beam position monitors [8]. The overall impedance budget pointed out that high Q resonators driving multi-bunch instabilities are concentrated in the rf cavity with the more dangerous mode around 100 MHz and a quality factor of 150. Broad-band impedances are dominated by the

injection and extraction travelling wave kickers installed inside the vacuum tank for fast rise and fall times.

Thus, as far as single bunch effects are concerned, the impedance of the four installed kickers for electron-operation served as a basis for constructing a model of the ring impedance. The real and imaginary part of the measured longitudinal impedance could be well approximated by two broad band resonators with resonant frequency  $F_r$ , quality factor Q and shunt impedance  $R_{s\Omega}$ . Similar models were adopted in the transverse planes by scaling the shunt impedances  $R_{st}$  with the simple relation valid for circular cross sections,  $R_{st}/R_{s\Omega} = c/(\pi b^2 F_r)$  where b is the kicker half aperture ( $50 \times 17.5 \text{ mm}^2$ ). The parameters of the two resonators representing the impedance model are summarized in the following table.

Resonator	F <sub>r</sub> (MHz)	Q	R <sub>sΩ</sub> (kΩ)	R <sub>sh</sub> (kΩ/m)	R <sub>sv</sub> (MΩ/m)
1	17	1.14	0.24	540	4.40
2	635	1.02	4.0	240	1.96

In fact, the low frequency resonator can usually be neglected.

4. Equilibrium Beam Parameters

The main beam parameters at equilibrium like bunch length and transverse emittances as well as their variation with the circulating beam intensity, have been recorded under various conditions.

The bunch length was measured by means of the wide-band pick-up monitor [9]. For vanishing current, it is found to be 10% higher than expected. With higher charge per bunch, potential well and turbulence [10] induce bunch lengthening. The absolute value of the impedance of an equivalent broad-band resonator in the limit of zero frequency,  $|Z/r|_0 = 13.6\Omega$ , can be extracted [11] from the bunch lengthening above the turbulence threshold (Fig.1). The corresponding shunt impedance,  $R_{s\Omega} = 3.6 \text{ k}\Omega$  for  $F_r = 635 \text{ MHz}$  is close to the above impedance model.

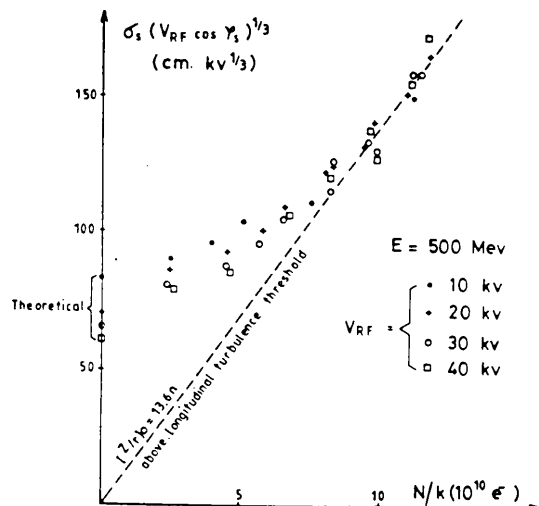


Fig. 1: Variation of the bunch length,  $\sigma_s$ , with the charge per bunch,  $N/k$ , for different rf cavity voltages,  $V_{RF}$ .

Transverse beam profiles in horizontal and vertical planes have been recorded from observation by a diode array camera of the synchrotron light [12] emitted in a bending magnet where the dispersion is negligible. The corresponding equilibrium emittances are deduced after fitting a gaussian distribution (Fig. 2). For vanishing currents, they are close to the theoretical figures with a 11% coupling between transverse planes. With one circulating bunch only, both emittances are independent of the charge per bunch. However, a high-intensity multi-bunch beam suffers a strong blow-up by a factor 3 in horizontal and 23 in vertical ending up with equal emittances and a full transverse coupling. This effect has been clearly attributed to a beam perturbation by positive ions created in the residual gas and trapped in the beam potential as simulations had shown. In fact, if the clearing electrodes are switched off, the transverse blow-up is enormously increased with profiles which are not gaussian anymore.

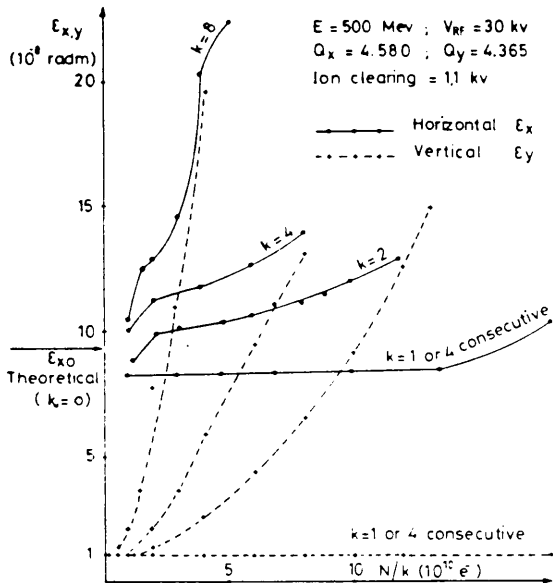


Fig. 2: Variation of the transverse equilibrium emittances  $\epsilon_x$ ,  $\epsilon_y$ , with the charge per bunch,  $N/k$ , for different numbers of bunches,  $k$ .

### 5. Transverse Modes

The effect of the ions is even more obvious from the variation of the vertical tune (betatron mode zero) with the charge per bunch (Fig. 3).

Without ions, the effect of the vertical impedance reduces the tune as observed with a single bunch. The measured tune shift is in agreement with the calculation [13] based on the impedance model. Taking into account bunch lengthening the modes 0 and -1 were predicted to couple for a charge per bunch of  $5 \cdot 10^{10}$  particles. However, a charge four times higher has been accumulated with a vertical tune shift of three times the synchrotron tune. The mode -1 could not yet be observed.

The vertical tune of a multi-bunch beam is increased by up to  $3 \cdot 10^{-2}$  due to an additional focusing by the ions. They induce also a large tune spread up to  $\pm 1 \cdot 10^{-1}$  as shown on Fig. 4a in the particular case of 4 equidistant bunches. As a consequence, the particles cross betatron resonances which results in blow-up, coupling and intensity limitations. If the four bunches occupy consecutive buckets leaving half of the ring empty, the ions escape to the vacuum chamber and the transverse frequency spectrum shows narrow and well separated modes

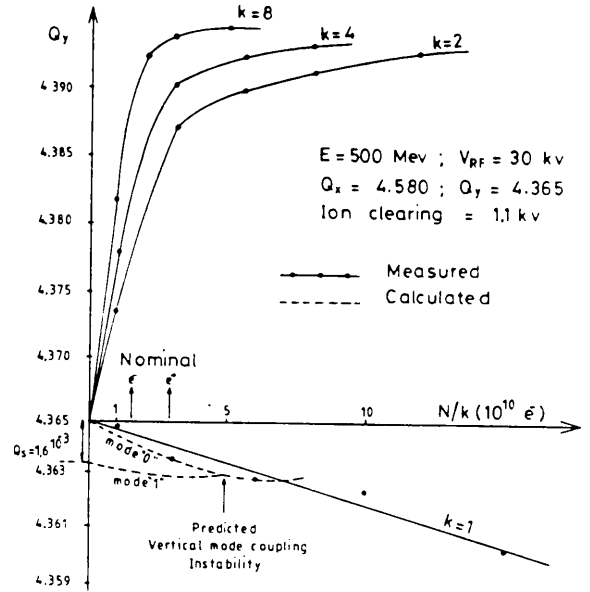


Fig. 3 Shift of the vertical tune,  $Q_y$ , versus the charge per bunch,  $N/k$ , for different number of bunches,  $k$ .

(Fig. 4b) as in the case of a single bunch. As a consequence, the charge per bunch, limited only by the rf cavity beam loading, can be doubled without any transverse blow-up (Fig. 2).

### 6. Beam Stability

A single bunch beam does not show any coherent instability neither in the transverse nor in the longitudinal plane even at the maximum charge of  $2 \cdot 10^{11}$  particles.

A multi-bunch beam is also very stable up to nominal intensity. With higher currents, intermittent transverse coherent instabilities have been observed in both planes with growth and repetition rates depending on the voltage applied to the clearing electrodes. The detected frequencies around 900 kHz are compatible with beam modes excited by  $H_2^+$  ions oscillating in the beam potential well.

Although the foreseen longitudinal damping of the higher order modes of the cavity [7] preserves the beam stability up to nominal current, coupled-bunch dipole oscillations ( $m = 1$ ) start above a threshold of  $2.2 \cdot 10^{11}$  particles in eight bunches without any beam losses. The driving source of this instability has been attributed to higher order modes in the rf cavity, as the mode number  $n$ , of the beam oscillation, deduced from the phase shift between following bunches, can be modified from 1 to 5 by slight changes of the cavity tuning. The thresholds of the instability,

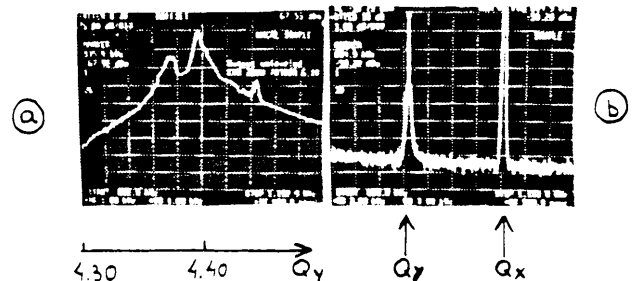


Fig. 4: Shift and spread of the transverse tunes,  $Q_x$  and  $Q_y$  with four bunches ( $3 \cdot 10^{11} e^-$ ) equidistant (case a) or consecutive (case b).

just above the design intensity should be increased by a factor three, when operating at the nominal energy of 600 MeV. For higher intensities, a longitudinal feedback will be developed.

The head-tail stability has been deduced from the damping and growth rates of the beam response to coherent transverse excitations (Fig. 5). Fitting the variation with chromaticity of the calculated growth rates [14] with the measured ones yields shunt impedances of the high-frequency resonator of  $R_{sh} = 300 \text{ k}\Omega/\text{m}$  close to the model in the horizontal plane, but a factor five below,  $R_{sh} = 400 \text{ k}\Omega/\text{m}$ , in the vertical plane. For vanishing chromaticities, the damping rates are found higher than expected from synchrotron radiation with a factor two in the horizontal plane and two orders of magnitude in the vertical one.

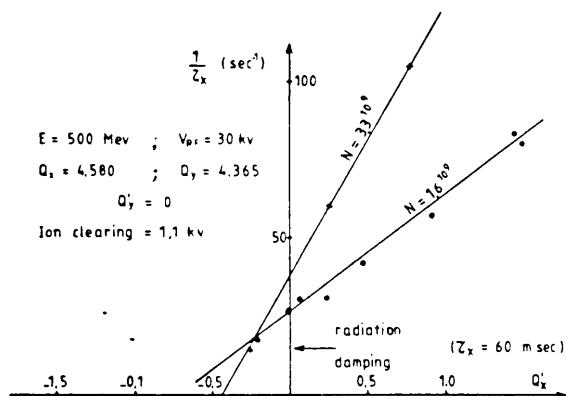


Fig. 5: Variation with the chromaticity,  $Q'_x$ , of the coherent horizontal damping rate  $\tau_x^{-1}$

### 7. Lifetime and Performance limitations

The lifetime of a stored single bunch varies from three hours at low intensity to one hour for the maximum charge recorded, which is compatible with beam particles scattering on the residual gas (Fig. 6). The observed minimum of lifetime for bunches of  $8 \cdot 10^{10}$  particles occurs at the expected onset of self-clearing of the  $\text{H}_2^+$  ions by the beam. The saturation of the accumulation around  $2 \cdot 10^{11}$  particles in a single bunch coincides with a strong lifetime reduction of the stack when kicked towards the septum for successive injections.

The large transverse blow-up generated by the ions trapped in an eight bunch beam decreases its lifetime to some minutes and limits the accumulation to about  $7.5 \cdot 10^{10}$  particles per bunch.

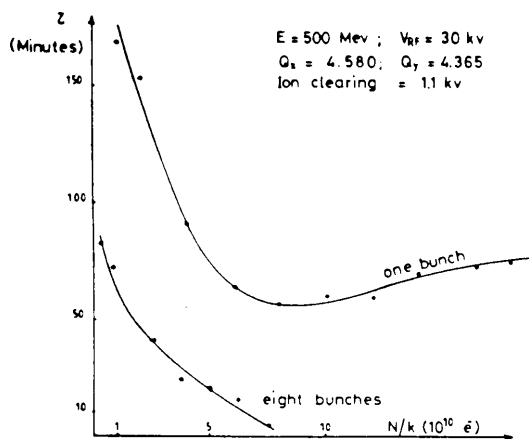


Fig. 6: Variation of the beam lifetime,  $\tau$ , with the charge per bunch,  $N/k$ .

### 8. Conclusions

All the design specifications with electrons have been fulfilled. The beam quality, at the maximum intensity, a factor six above the nominal current, suffers mainly from the transverse beam blow-up generated by the ions trapped in the beam potential. More powerful clearing electrodes closer to the beam have just been installed. Their beam coupling impedance could be reduced by two orders of magnitude with a new design using ceramics with a resistive coating.

The predicted vertical mode coupling instability has not been observed though the single bunch vertical tune was found to be shifted by several synchrotron tunes at the highest intensity. Operation with positrons, just starting, will demonstrate, if this instability has been suppressed for the electrons, possibly by Landau damping resulting from the spread in frequencies due to the trapped ions.

### 9. Acknowledgements

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