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THE LATTICE DESIGN OF THE LEP ELECTRON POSITRON ACCUMULATOR (EPA)

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Summary

In large accelerators, the lattice cell is generally made as simple as possible. Special requirements are then fulfilled by appropriate insertions (dispersion suppressors, low β schemes, wigglers, etc.). In small machines, where space is limited, the lattice cell itself has to deal with all the machine constraints and requirements. The lattice design method developed consists of splitting the superperiod into specialized sections. Each section is built up to fulfil some of the basic requirements, then matched to the neighbouring sections. The best parameter values are deduced from systematic variation in the analytical expression of the corresponding beam transfer matrix. Applied to the LEP Electron Positron Accumulator (EPA), this method was very efficient in optimizing a large number of constraints.

Introduction: Operation Mode of EPA

An integral part of the LEP Injector Chain (1), the 600 MeV Electron Positron Accumulator EPA acts as a buffer between the fast cycling (100 Hz) but low intensity (6.10^8 e^+ per pulse) e± linacs and the slow cycling (0.8 Hz), high intensity (10^{11} e± in 4 or 8 bunches) PS and SPS synchrotron accelerators.

The basic operating scheme of EPA for LEP injection takes advantage of the long dead time (∿ 11s) necessary for SPS fixed target physics in order to build up eight bunches of 2.5 x 10^{10} positrons each. As the resulting charge per bunch would exceed the PS and SPS stability limits the positron bunches are cut into two batches of 8 bunches. Each batch is then consecutively transferred in one turn to the PS, accelerated via the SPS and finally stored in LEP after a double turn injection. The injector linacs then switch to the electron mode for two PS cycles. An accumulation time of 1.25 s is now sufficient to form 8 bunches of $1.3.10^{10}$ electrons each, which are then transferred to LEP. An equal and simultaneous LEP filling rate of 0.25 mA/min is thus obtained for both kinds of particle and with little disturbance for other PS and SPS users.

Basic Parameters

The main EPA parameters (Table 1) have been chosen in order to favour an efficient and stable accumulation up to at least the nominal intensity as well as to adapt the equilibrium beam properties to the particularities of the existing PS and SPS accelerator chain.

The circumference of 125.67m equals 1/5 that of the PS. It gives optimum cog-wheeling between EPA and PS, leaving just sufficient time separation between each of the eight bunches for the injection and ejection kicker rise and fall time. Restricted space near the PS favoured a race track accumulator shape (fig. 1) with symmetrical e± injections from inside the ring and a common e± ejection point to the PS.

The injection is obviously the basic process of this accumulator and particular care has been taken to assure effective betatron stacking in the horizontal plane.

A strong horizontal damping is foreseen in order to keep betatron oscillation amplitudes and vacuum chamber dimensions small.

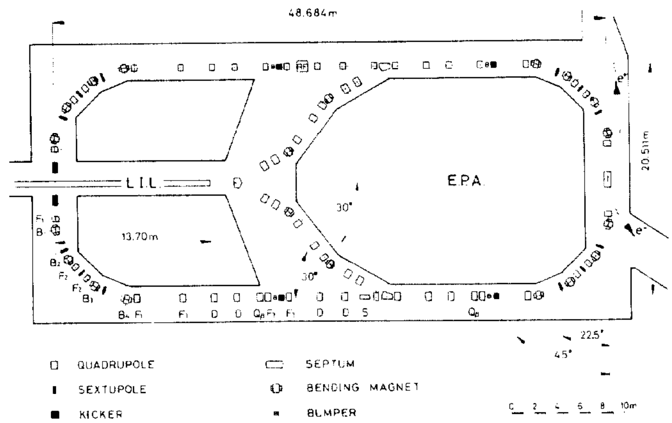

Fig.1: General EPA Layout

In fact, the emittance ε_T just after injection can be written:

$$\varepsilon_T = (r + s + 2a)^2/\beta_s \qquad \text{with } a = \sqrt{\beta_s}\cdot\varepsilon_L^{2/3}\cdot\varepsilon_T^{-1/6}$$

and

$$r = (\sqrt{\beta_s\varepsilon_T} - a)\,e^{-T/\tau_x} + \left[a^2 e^{-2T/\tau_x} + 4\beta_s\varepsilon_o\left(1 - e^{-2T/\tau_x}\right)\right]^{1/2}$$

where
- a — half beam width of the just injected bunch matched for smallest ε_T
- r — half beam width of the previously injected bunch having experienced damping and quantum excitation (2)
- ε_o — equilibrium beam emittance (1 σ) depending on the horizontal damping partition number Jx
- s — apparent injection septum width
- τ_x — horizontal damping time constant
- β_s — horizontal beta function at the injection point
- T — elapsed time between two successive injections into the same bunch
- ε_L — linac beam emittance

A small emittance ε_T is thus obtained by adopting a high magnetic field in the bending magnets (1,4 T) as well as a high horizontal damping partition number (J_x = 2), as shown in fig. 2, solving the above transcendental equation.

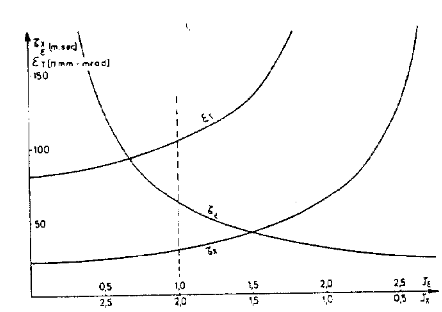

Fig.2: Damping constants $\tau_{x,\varepsilon}$ and horizontal beam Emittance ε_T after Injection in four bunch mode.

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<u>Single bunch instability</u>, known as turbulence, is completely avoided in spite of the high charge per bunch foreseen. In a ring of mean radius R at an energy E the respective thresholds per bunch $(N/K)_S$ can be written as follows:

a) in the longitudinal plane by correcting the classical "Keil-Schnell" coasting beam criterion by the bunching factor and the potential well bunch lengthening(3)

$$\left(\frac{N}{K}\right)_{S\parallel} = \frac{8\cdot 10^{-12}\cdot R\cdot B^{3/2}\cdot E^{5/2}}{h_{RF}\cdot (Z/n)_{\parallel}\cdot \gamma_{tr}^{2}\cdot J_{\varepsilon}^{3/2}\cdot(\Delta E/E)}$$

b) in the transverse plane by relating the frequency shift of the lowest head tail mode to the synchrotron frequency corrected by a bunch length dependant factor $G(\sigma_s)$(4)

$$\left(\frac{N}{K}\right)_{S\perp} = 1.5\cdot 10^{4}\,\frac{G(\sigma_s)\cdot Q_{\perp}\cdot B^{1/2}\cdot E^{3/2}}{\gamma_{tr}^{2}\cdot Z_{\perp}\cdot J_{\varepsilon}^{3/2}}$$

Moreover, the longitudinal turbulence thresholds at EPA equilibrium and PS injection are linked by the relation(5)

$$\left[\left(\frac{N}{K}\right)_{S\parallel}\right]_{PS} = 0.7\cdot\left[\frac{(\gamma_{tr})_{EPA}}{(\gamma_{tr})_{PS}}\right]^{2}\cdot\frac{(Z/n)_{EPA}}{(Z/n)_{PS}}\cdot\left[\left(\frac{N}{K}\right)_{S\parallel}\right]_{EPA}$$

It is thus possible to raise the beam stability in EPA and at PS injection to twice the nominal charge per bunch (table 1) by an appropriate choice of machine parameters:

- $B = 1.4T$ — the highest magnetic field in the bending magnets still avoiding saturation effects
- $h_{RF} = 8$ — the minimum RF harmonic number compatible with an 8 bunch operation
- $\Delta E/E = 1.2\%$ — the smallest RF bucket height to accept the e^+ linac beam momentum dispersion
- $\gamma_{tr} = 5.5$ — a rather low transition energy still providing the bucket height with a reasonable V_{RF} voltage (50 KV)
- $J_\varepsilon = 1$ — a low longitudinal damping partition number, limited by the corresponding acceptable damping time (fig. 2)

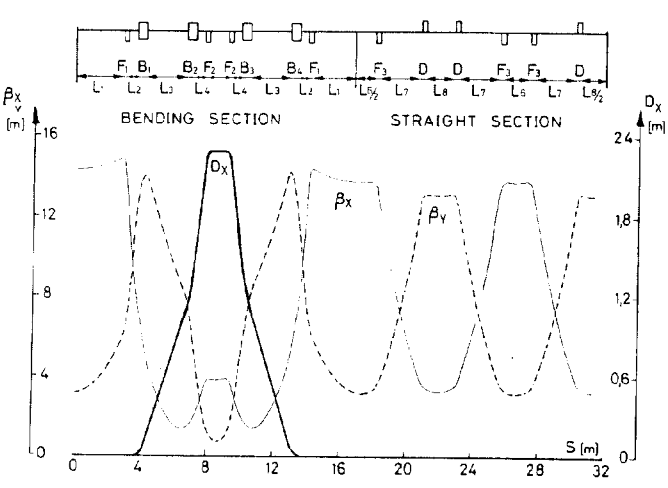

Fig.3: Twiss Parameters in EPA Half Superperiod

Lattice design

The symmetrical layout for the two kinds of particle together with a race track ring shape suggest quite naturally a lattice superperiod of two. In order to satisfy the various requirements and constraints of the accumulator, the superperiod has been divided into specialized sections each composed of quadruplet cells, namely two bending sections and a matching section to link them, which leads to the desired race-track shape of the ring (fig.1).

<u>The bending section structure</u> (fig. 3) is composed of four combined-function horizontally defocusing bending magnets and four focusing quadrupoles. This arrangement provides:

- an alternating transverse FDDF focusing structure
- fairly high horizontal βx values to ease injection/ejection hardware design
- an easy way to adjust the damping partition numbers and the normalized transition energy
- a localized dispersion function with optimum space for chromaticity correction between dispersion free sections.

The dispersion function Dx is created and cancelled by the bending magnets B_1 and B_4 through their bending angle Φ. Its value in the central bending magnets B_2 and B_3 is adjusted by the choice of the drift length L_3 separating B_1 and B_2 (respectively B_3 and B_4). It is linked to the normalized transition energy γ_{tr} by the relation

$$\gamma_{tr}^{-2} = \frac{1}{2\pi R}\oint \frac{Dx}{\rho}\,ds \sim \frac{L_3\cdot\Phi}{2R}$$

The longitudinal damping partition number J_ε is then determined by the choice of the normalized field gradient K in the bending magnets. For parallel end faces

$$J_\varepsilon = 2 - \frac{1}{\pi B}\oint Dx\,K\,B\,ds = 2\left(1 - R\,K\rho\,\gamma_{tr}^{-2}\right)$$

<u>The long dispersion free straight part</u> (fig. 1) has been divided into three symmetrical quadruplet cells to provide optimum conditions for the injection ejection processes and to match the bending sections.

In fact, a quadruplet cell provides four free parameters necessary to match the Twiss parameters βx, βy ($\alpha x = \alpha y = 0$) of the bending section and to obtain a certain cell horizontal and vertical phase advance. Transverse phase advances of $\mu x = \mu y = \pi/2$ have been chosen firstly to the advantage of an efficient injection bump scheme and secondly to allow a simple design of a high beta insertion (fig. 4).

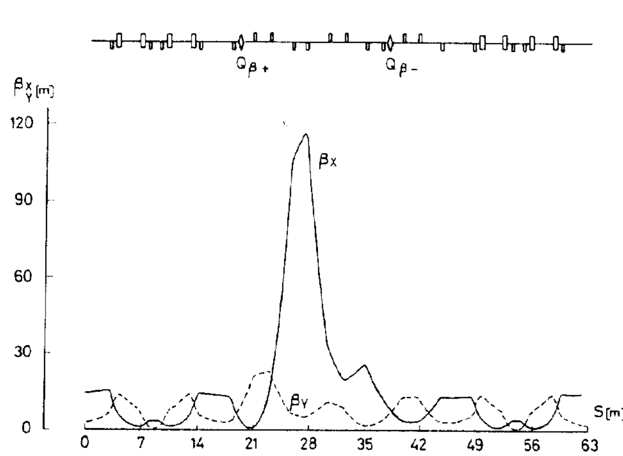

Fig.4: Example of horizontal High Beta Insertion

It is based on equal and opposite excitation of a pair of quadrupoles $Q_{\beta\pm}$ at π phase advance in both transverse planes, which localizes the perturbation of the β-function without affecting the transverse working point (fig.4). This scheme is essential for the beam slicing process and helps to reduce systematic beam losses on the slicer septum.

Lattice synthesis and refinement

The phase advance in the bending section is chosen to be near $3\pi/2$ in both planes such that the EPA working point keeps clear of betatron resonances up to the 4th order : $Qx = 4.45$; $Qy = 4.38$.

The range of possible Twiss parameters at the ends of each structure is then derived from an analytical expression of the corresponding transfer matrix in thin lens approximation by systematic variation of all free parameters (fig.5).

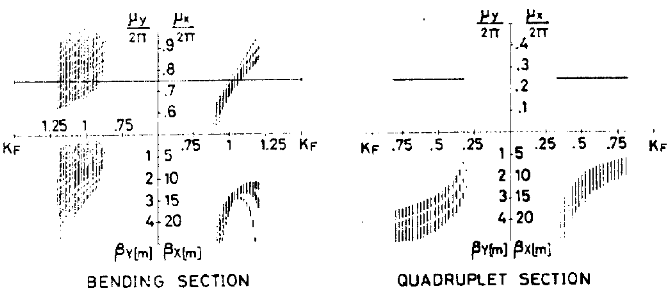

Fig.5: Range of possible Twiss parameters

A superposition of both diagrams reveals in the overlapping areas a small subset of Twiss parameters which are identical for both the bending and quadruplet sections, which is the necessary condition for betatron matching.

The approximate solution thus obtained undergoes then a final optimization with the MINUIT routine of the synchrotron design program AGS[6] where the required accuracy is achieved, also taking into account the fringe field of the bending magnets.

Due to the small bending radius ρ of EPA this effect is very important as it results in the vertical plane in a drastic modification ψ of the angle δ between the magnet pole faces and the central trajectory [7]:

$$\psi = \frac{1}{\rho}\left(\frac{1+\sin^2\delta}{\cos\delta}\right)\cdot\int\frac{B(s)\cdot[B_0 - B(s)]\,ds}{B_0^2}$$

where B(s) is the magnetic field in the fringe field extension and Bo its value in the magnet centre.

Brief description of the ring

The 20.56 x 48.66 m^2 race track shaped ring contains 16 identical combined-function straight bending magnets, 40 quadrupoles distributed in 4 families and 12 sextupoles in two families for chromaticity correction.

The main parameters are listed in table I

The injection systems from the inside of the ring are identical for e^+ and e^-. Two fast kickers at $\pm\ \pi/2$ phase advance from the injection septum form a local fast bump for any individual stored bunch and are assisted by closed orbit deformation dipoles. The kicker systems work at the linac repetition rate of 100Hz and their strength is fairly weak ($\sim$ 46 Gm).

Ejection to the PS is handled by a common septum magnet and fast kicker system (tr $\sim$ 50ns) for both e^+ and e^- particles thanks to the choice of the working point near a half integer. The constant and high $\beta x \simeq 14$m over a few meters limits the kicker strength requirement to some 36 Gm, low enough to envisage an "Eight Shot Kicker" able to transfer the eight EPA bunches within one PS turn (2.1 µs).

The arrangement of the kicker system opposite to the ejection septum magnet allows also the easy addition of a beam slicing facility. The kicker shifts the beam, first blown-up by the high beta insertion, halfway over a thin septum deflector. Whereas one half is ejected with a modest slicing septum deflection (<1mrad), with support of the high beta insertion, the oscillation of the remaining part of the bunch is cancelled by the same kicker system delivering a second pulse after one revolution time delay.

CONCLUSION

A lattice built with two different, matched structures effectively satisfies the numerous requirements of the LEP Electron-Positron Accumulator:

- high beam stability thresholds and damping
- optimized machine functions for the numerous injection/ejection processes for e^+ and e^- particles
- simple transfers of e± particles between injector Linacs and PS
- race track shape to solve space constraints on the PS site

Table I

Machine Parameters

Circumference	$C = 125.67$ m
Working energy	$E = 600$ MeV
Number of bunches	$K = 8$ or 4
Nominal charge/bunch	$N/K = 2.5 \cdot 10^{10}$ e±
Betatron wave numbers	$Qx = 4.45$; $Qy = 4.38$
Synchrotron frequency	$Fs = 5.062$ KHz
Transition energy	$\gamma tr = 5.5$
Natural chromaticities	$\xi_x = -1.1$; $\xi_y = -2.6$
Energy loss/turn	$U = 8.04$ KeV
Damping partition numbers	$Jx = 2$; $J_\varepsilon = 1$
Damping time constants(ms)	$\tau x = 31.8$; $\tau_\varepsilon = 60.5$
Acceptances (hor/vert.)	$A = 100/10$ πmm.mrad
Momentum acceptance	$\Delta p/p = 1.2\%$

Equilibrium Beam characteristics (± 1 σ)

Horizontal emittance	εx	$= 0.144\ \pi$ mm.mrad
Energy dispersion	σ_ε/E	$= \pm\ 6.07 \cdot 10^{-4}$
Bunch length	σ_s	$= 25.9$ cm

Turbulence thresholds

EPA longitudinal	$N/K = 6.8 \cdot 10^{10}$ e±/bunch
EPA transversal	$N/K = 2.8 \cdot 10^{11}$ e±/bunch
PS at injection	$N/K = 2.8 \cdot 10^{10}$ e±/bunch

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