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THE SUPER-ADONE ELECTRON-POSITRON STORAGE RING DESIGN

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Abstract.

The results of a design study[1] for a high energy electron-positron storage ring to be built at the Frascati National Laboratories are summarized.

1. - Introduction.

Super-Adone (SA) is a 10 GeV single-ring machine. Luminosity per crossing is $5 \times 10^{31} \div 10^{32}$ in the energy range from 5 to 10 GeV with one bunch per beam; multi-bunch operation is envisaged, to increase luminosity at energies lower than 5 GeV.

The design aim is to achieve good performances at relatively low cost; the following assumptions have been made: maximum RF power transferred to the beam 1.4 MW; maximum current per beam 200 mA; approximate linear tune shift per crossing 0.08; two interaction regions; maximum number of bunches per beam eight.

The limit on the current per beam is imposed by filling time since it is assumed to use ADONE as a booster with relatively minor changes to its injector.

The experimental regions are only two. The addition of two more experimental regions would increase costs (two more experimental halls, two more special "low-β" insertions) while four experimental apparatus would anyway not be able to run at the same time in the single bunch mode. At present it is considered more convenient to design the experimental halls in such a way as to guarantee a fast turn-over time for the experiments installed on the machine, rather than to have more straight sections.

As far as beam behaviour in a storage ring is concerned, the operation of existing storage rings allows to draw the following conclusions:

1) operation with charges per bunch of a few 10^{11} $e^{\pm}$ per bunch and peak currents of about 30 A has been achieved;
2) coherent single beam instabilities have been interpreted and cured;
3) the transverse incoherent beam-beam limit[2] is reasonably well explained by current models and numerical computations: the maximum linear tune shift per crossing obtained is about 0.08 (ADONE and SPEAR); a possible explanation for the γ^7 luminosity dependence observed at ADONE at energies lower than 1 GeV, could be a diffusion process in competition with radiation damping; the interpretation is not inconsistent with existing data, and would give, for Super-ADONE, the γ^{74} law for luminosity at energies below 2 GeV;
4) anomalous bunch lengthening has not been, so far, clearly interpreted, and although some light has come from the recent SPEAR results[3], extrapolation to new machines and higher peak currents is still difficult;
5) low-β operation has been proved possible and in agreement with expectation[5, 10];
6) experimental information on the longitudinal beam-beam limit is not complete[2]; data obtained with ADONE will be used in the following (although the actual limit might be somewhat higher).

The most relevant difference between the new generation of storage rings and the present one, is the required charge per bunch which is typically one order of magnitude higher; this represents the major unknown of these projects and requires careful studies to determine possible coherent losses in RF structures and bunch lengthening effects. The operation of DORIS and SPEAR II will cast some light on these phenomena and will allow to bridge at least part of the gap in terms of charge per bunch and peak current.

Another problem of the new generation of storage rings is the accumulation of intense positron beams in a single bunch; it turns out that an injection system consisting of a linear injector and a booster is the most convenient solution to keep filling times within tolerable limits and to avoid saturation in the stored current.

2. - Design criteria.

The very strong dependence of radiation loss on energy ($\propto E^4$), at fixed bending radius makes the optimum radius a sharply peaked function of energy. The solution described here has not been carefully optimized and corresponds to an energy somewhat higher than the optimum value for the bending radius chosen.

Assuming that the maximum value of the approximate linear tune shift due to beam-beam interaction, ξ_m, is a constant, the specific luminosity (for $\beta_z \leq \leq \beta_x$) at the beam-beam limit, is given by

$$L/I = 2.17 \times 10^{32}\, \xi_m E_{GeV} \frac{k}{\beta_z} \quad (cm^{-2} s^{-1} A^{-1}) \quad (1)$$

with β_z in m; k, in the present design, ranges from 1.07 to 1.2 (in general: $k_{max} = 2$ for $\beta_x = \beta_z$ at crossing).

Equ. (1) shows that specific luminosity depends only on the operating energy and the minimum β, ξ_m being constant. The β value cannot be made much smaller than the bunch length for the assumed value of ξ_m; very small β's at the crossing entail very large values of the same quantity in the quadrupoles adjacent to the straight section, with the consequent complications of large aperture and very high sensitivity to errors in the focusing field.

We assume $\beta_z = 0.2$ m; from ADONE and SPEAR results we take $\xi_m = 0.08$ and obtain, with k=1.1:

$$L/I = 0.95\times 10^{32}\, E_{GeV} \quad (cm^{-2}s^{-1}A^{-1}) \qquad (2)$$

In the choice of the total current per beam three variables have to be taken into account:
a) maximum RF power to the beams;
b) maximum current that can be stored in a reasonable time;
c) limit set by the transverse and longitudinal beam-beam effects on the beam transverse density.

Point b) sets an absolute limit on the maximum luminosity that can be achieved with a given injection system; a) influences the luminosity at the maximum energy and c) luminosity at low energies, both through economical factors (cost of the RF power and cost of the ring aperture). For a luminosity of 5×10^{31} cm^{-2} s^{-1} at 10 GeV, 50 mA per beam are required, and the RF power transferred to the two beams is 1.4 MW; at constant RF power to the beams and at a total current per beam smaller than 200 mA the allowed beam current is :

$$I = 50\times(10/E_{GeV})^4 \text{ mA} \qquad \text{for } E \geq 7 \text{ GeV},$$

$$I \leq 200 \text{ mA} \qquad \text{for } E < 7 \text{ GeV}.$$

Transverse and longitudinal beam-beam effects limit the current per beam to :

$$I = 48.7 \cdot h \cdot \xi_m \frac{E^3_{GeV}}{R} H^*_m \qquad (3)$$

where h is the number of bunches per beam and H^* is a quantity depending on the ring magnetic structure and related to the r.m.s. beam radial dimension σ_x at the interaction point; in the optimum condition of $\xi_x = \xi_z = \xi_m$, and for negligible coupling:

$$\sigma_x = \sigma_p \sqrt{2\,\beta_x H^*} \propto E\sqrt{\beta_x H^*}\;.$$

Eqs. (1) and (3) show that for a given magnetic structure (i.e. given H^*) and number of bunches, the luminosity L is proportional to E^4; if one wants to keep I constant, and therefore obtain $L \propto E$, the product hH^* has to vary like E^{-3}. A possible choice is that of varying the number of bunches; in a double ring the method is easy and the most convenient; in a single ring multiple bunch operation is conceivable, with an upper limit for the number of bunches per beam of 4 to 8.

Many different ways have been devised to increase H^*:
a) use of high dispersion function ψ at the crossing, within the longitudinal beam-beam limit[6];
b) variation of the betatron wavenumber Q_x with energy[7, 8];
c) use of special magnetic lattices that allow a continuous variation of H^*[9].

The present design is based on method a) and multibunch operation, with vertically separated beams (except in the interaction regions) and $h \leq 8$. Method b) makes injection somewhat more complicated, while method c) may turn out to be the most flexible and convenient; a more systematic analysis is needed to make the final choice.

A plot of the expected luminosity versus energy is shown in Fig. 1.

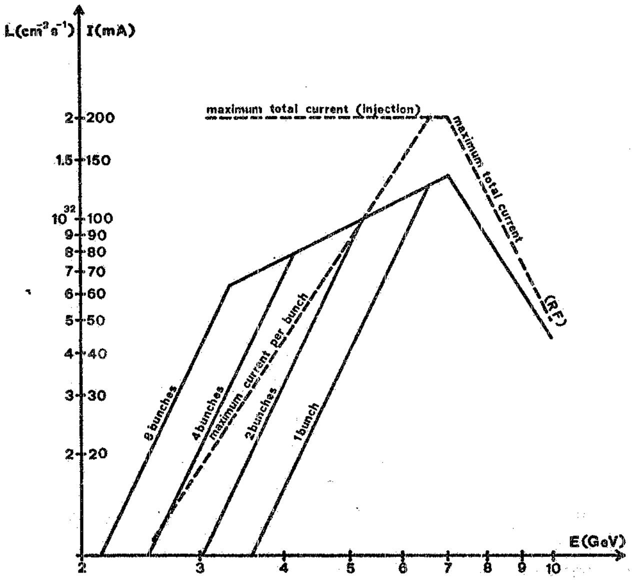

Fig. 1 - Luminosity and current dependence on energy.

As far as injection is concerned, an injection system consisting of a linac and an intermediate energy booster has many advantages : the number of pulses injected on the same stored beam is small (order of $10^2 \div 10^3$); the number of pulses to be transferred from the booster to the main ring is quite low (order of 10^2) so that the booster energy need not to be very high; the linac energy can be in the 500-1000 MeV range.

In the present design it is foreseen to use ADONE as a booster, operating with six bunches that can be individually extracted; to keep the total filling time within one hour, or one tenth of the lifetime in the main ring at 1.5 GeV, the linac energy has to be increased to 500 MeV with the addition of 4 accelerating sections (two klystrons).

The overall positron filling time is about 45 minutes for 200 mA of positrons and the electron filling time is about 10 minutes. The damping time for betatron oscillations in the main ring is 1.3 sec at 1.5 GeV which allows a maximum repetition rate for successive injection pulses on the same RF bucket of 1 pulse per second.

3. - Lattice description.

The lattice consists of 24 normal cells and 2 low-β insertions each containing 8 magnets: the magnetic elements of a half-insertion are shown in Fig. 2. The experimental straight section is 7 m long, and the distance between its center and the first magnet is 18.1 m. Each half-insertion has 10 independent quadrupoles and 4 magnets.

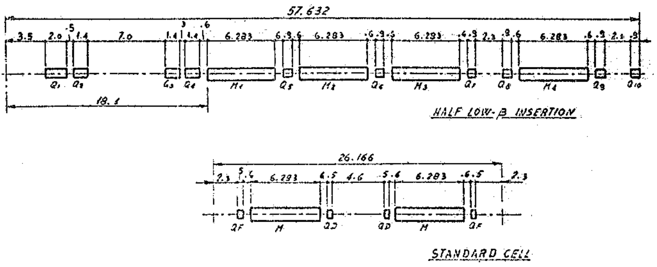

Fig. 2 - Magnetic structure.

The standard cell structure

$$\frac{0}{2}\,;\,QF\,;\,M\,;\,QD\,;\,0\,;\,QD\,;\,M\,;\,QF\,;\,\frac{0}{2}$$

is symmetric with respect to the center of the 4.6 m straight section; most of the straight sections are occupied by RF cavities, and all of them contain a sextupole for the correction of chromaticity. Optimization of luminosity as a function of energy requires ψ^2/β_x at the crossing point $(\psi^2/\beta_x)_I$), the number of bunches per beam (h), and the coupling between radial and vertical betatron oscillations (ε) to be adjustable.

Four values of $(\psi^2/\beta_x)_I$ have been chosen, which define four configurations S_A, S_B, S_C, S_D, the number of bunches can be 1, 2, 4, 8 and ε is varied continuously within a given configuration ($\varepsilon_{min} \cong 0.2$). The optical parameters of the standard cell and of the low-β insertion for the 4 configurations S_A, S_B, S_C, S_D are given in Table I.

TABLE I

E_m = 10 Gev　τ^o_x = 4.3 msec　$\tau_x = \tau^o_x(E_m/E)^3$　$\sigma_x = \sigma^o_x(E/E_m)$　$\nu_x = 9.2$

$A = A^o(E/E_m)^2$　τ^o_z = 4.1 msec　$\tau_z = \tau^o_z(E_m/E)^3$　$\sigma_z = \sigma^o_z(E/E_m)$　$\nu_z = 9.2$

$\sigma^o_p = 1.1 \times 10^{-3}$　τ^o_y = 2.0 msec　$\tau_y = \tau^o_y(E_m/E)^3$　$\sigma_p = \sigma^o_p(E/E_m)$

Configuration	$\alpha = \frac{\Delta l}{l}/\frac{\Delta E}{E} \times 10^2$	β^I_x (m)	β^I_z (m)	ψ^I (m)	H (m)	H* (m)	$A^o \times 10^6$ (m)	σ^o_x out of coupling		σ^o_x on coupling		σ^o_z on coupling		$C_x = \frac{\Delta\nu_x}{\nu_x}/\frac{\Delta E}{E}$	$C_z = \frac{\Delta\nu_z}{\nu_z}/\frac{\Delta E}{E}$
								crossing point (mm)	max (mm)	crossing point (mm)	max (mm)	crossing point (mm)	max (mm)		
S_A	1.5	1.00	.20	0	.31	.31	.72	.8	9.7	.6	6.9	.26	6.4	- 2.1	- 2.4
S_B	1.3	1.00	.20	.98	.26	.74	.60	1.3	9.3	1.2	6.8	.24	6.3	- 2.1	- 2.4
S_C	1.3	2.16	.20	2.33	.26	1.52	.62	2.7	10.8	2.6	8.6	.24	4.8	- 2.3	- 3.5
S_D	1.2	1.25	.20	2.90	.54	3.91	1.28	8.3	15.0	3.2	11.9	.35	6.9	- 2.9	- 3.6

Figs. 3 and 4 shows the optical functions β_x, β_z and ψ for configurations S_A and S_D respectively.

While it is not possible to pass continuously from S_A and S_B to S_C and S_D, it is possible to pass from S_A to S_B and from S_C to S_D: only two injection configurations are therefore needed. The two injection structures have β^I_z = 1 m and $\psi^I = 0$.

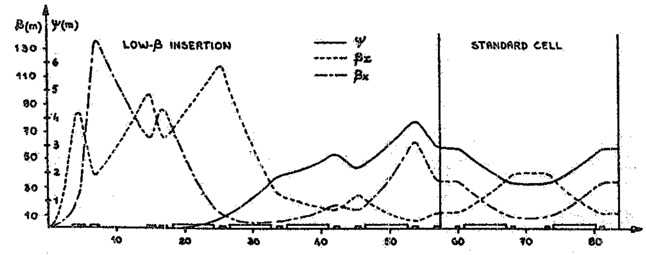

Fig. 3 - Optical functions for configuration S_A.

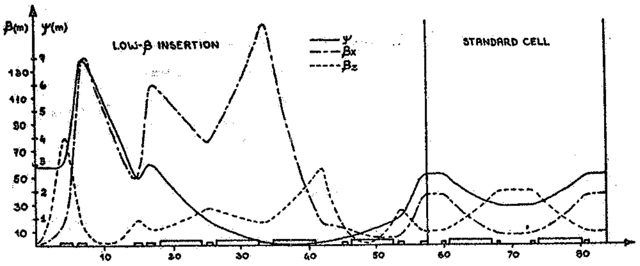

Fig. 4 - Optical functions for configuration S_D.

Operation with more than one bunch per beam can be obtained by separating the beams at all crossing points in the vertical plane (except for the experimental straight sections) using three independent pairs of electrostatic plates in each quarter of the machine.

There will be three kinds of quadrupoles having the following half-apertures (A): A = 105 mm (Q_2, Q_6); A = 90 mm (Q_3, Q_4, Q_5, Q_9); A = 75 mm (Q_1, Q_7, Q_8, Q_{10} and periodic cell) and two different kinds of magnets (the 16 low-β insertion magnets$^{(b)}$, and the 48 magnets of the periodic cells$^{(a)}$), having the following characteristics:

	Gap height	Useful field region	total gap width
(a)	110	120	285
(b)	150	170	425

All magnets and quadrupoles will have laminated structures, assembled from precision-punched steel laminations. Magnets will be of the "C" type for ease of access and to make vacuum chamber assembly easier. With laminated cores "C"-type magnets are cheaper than "H"-type ones.

4. - Injection system.

For injection it is proposed to use ADONE as a booster. Injection in ADONE will be at 0.5 GeV over six equally spaced (58 ns) bunches which can be individually extracted after acceleration to 1.5 GeV.

A schematic diagram of the injection equipment connecting SA to the Linac/Adone facility is shown in Fig. 5.

Extraction from ADONE requires a slow "bumper", a fast kicker magnet and two septum magnets. The kicker magnet will occupy one of the interaction straight sections. The beam transport system both matches the ADONE emittance to the acceptance of SA and allows for a compensated deflection in the vertical plane. The overall system is achromatic to first order.

For injection into SA a perturbed closed orbit is excited by means of a bumper coil (EB) located in the high β_x section preceding the (I) sections, and switched off with two similar coils (SB) in the following high β_x sections. To achieve a complete compensation, in position and angle, of the perturbed closed orbit, two correcting bumps (CB) will be put in sections (I) near the deflectors D_1, D_2.

The same bump excites the perturbations for both injected beams making the overall number of oc-

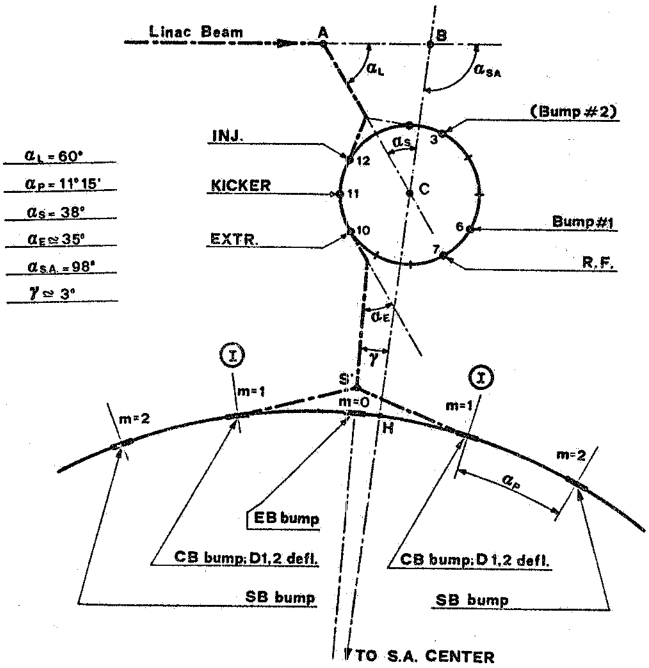

Fig. 5 - Injection system.

cupied high-β_x sections equal to 5.

The final deflection onto the right injection orbit is accomplished by means of two pairs of septum deflectors D_1, D_2 placed in sections (I).

5. - Radiofrequency system.

A reasonable choice for the RF frequency is 102.8 MHz, twice the frequency of the new ADONE RF system. At 102.8 MHz, 20 MV per turn are needed to ensure the required beam lifetime. We assume the shunt impedance per cavity to be 3 MΩ and the maximum voltage per cavity to be 0.36 MV. There are therefore 56 cavities (two per straight section). The power lost in the cavities is 1.2 MW at 20 MV, and power to the beam is 1.4 MW at 10 GeV, totalling 2.6 MW.

The cavities are normal reentrant resonators, under vacuum. Cavities only will be placed in the tunnel, while power amplifiers (one per cavity) will be located in nearby buildings and connected to the cavities through power coaxial cables.

6. - Vacuum system.

The system is designed for an average pressure of 10^{-9} Torr, with two 200 mA beams at 10 GeV. Pressure in the experimental sections will be 10^{-10} Torr.

The vacuum chamber material is S.S. AISI 304 L; its surface area is : chamber 13.4×10^6 cm^2, cavities 5×10^6 cm^2; the volume is: chamber 16×10^3 liters, cavities 90×10^3 liters.

Details on the required vacuum equipment, which includes distributed pumping in all magnets, can be found in the following 'parameter summary'.

Parameter summary.

Beam

Energy (GeV)	5	7	10
Luminosity $\times 10^{-32}$ (cm^{-2}s^{-1})	0.96	1.3	0.43
Current (mA)	200	200	50
Number of bunches per beam	4	1	1
Radiation loss per turn (MeV)	0.86	3.3	13.8
R.m.s. dimensions at interaction point (mm)			
radial uncoupled	1.6	0.9	0.8
radial coupled	1.6	0.85	0.6
vertical coupled	0.17	0.16	0.3
azimuthal (radiation)	50	70	75
Lifetime (hours)	~21	~14	~9

Magnetic structure

Central orbit length (m)	857	
Average radius (m)	136.51	
Experimental straight section total length (m)	2 x 7	
Number of periodic cells	24	
Periodic structure	0/2-F-B-D-0-D-B-F-0/2	
Period length (m)	26.166	
Bending magnet radius (m)	64	
Bending magnet length (m)	64 x 6.283	
Maximum field (Tesla)	0.52	
Periodic cell quad length (m)	96 x 0.5	
Maximum gradient (Tesla/m)	5	
Weight (Tons) magnets	Fe 900	Cu 120
quadrupoles	Fe 185	Cu 40
Magnet gap aperture (cm^2)		
periodic cell	28.5 x 11	
insertion	42.5 x 15	
Quadrupole maximum inner radius (cm)		
periodic cell	7.5	
insertion	10.5	

Focusing characteristics

Periodic cell	$\beta_{x,z}$ (m)	max	35÷37; 39÷41
		min	8÷9 ; 10÷12
	ψ (m)	max	2.90÷3.10
		min	1.60÷1.80
	α R (m)		1.61÷2.08
Insertion	$\beta_{x,z}$ (m)	max	140÷170; 80÷140
	ψ (m)	max	3.5÷7
Interaction point	$\beta_{x,z}$ (m)		1.0÷2.2; 0.2
	ψ (m)		0÷2.9
Natural chromaticity :	radial		-2.1÷ -2.9
	vertical		-2.4÷ -3.6
Betatron frequency :	radial		9.2
	vertical		9.2
Revolution frequency (MHz)			0.35

Radiofrequency system

Frequency (MHz)	103
Harmonic number	294
Number of cavities	56
Number of amplifiers	56 (2 x 28)
Maximum power to the beam (MW)	2 x 0.7
Total R.F. power (MW)	2.6
Peak voltage (MV)	20

Vacuum system

Number of 200 l/s Ti-pumps	120
Number of 270 l/s turbomolecular pumps	32

Distributed pumps:	
pumping speed (l/s.cm)	10
length (m)	400
Pressure with beam in the experimental straight section (Torr)	10^{-10}

Injection

Extracted beam emittance (mm x mrad):	
horizontal	~5
vertical	3
Average injection rate (A/hour)	e^+ 0.2; e^- 1÷2
Injection energy in SA (GeV)	1.5
Injection energy in Adone (GeV)	0.5
Injection rate in Adone (p.p.s.)	5

7. - Buildings and utilities.

The tunnel will be built under ground between section 1 and section 5; the remaining part will be built at surface level. Two experimental halls ($20 \times 40\ m^2 \times 16$ m height) will cover the experimental sections.

The maximum required electric power is 25 MVA including spare power, and is no problem.

The required cooling water flow is about 12.5 l/sec and could also be easily available.

A simple building, serving the machine and plants, will collect the electric, water, cooling, heating and conditioning stations tohether with the machine services; control and data rooms will be put in a connected building.

The RF final stages will be accomodated in a different building.

8. - Higher energy ring.

A very preliminary study of the maximum dimension ring that can be built in the Frascati National Laboratories area shows that a circular ring with mean radius of 340 m (or a race-track with a total length of about 2.500 m) is feasible.

The storage ring energy could be 15-16 GeV, and the corresponding energy loss per turn would be (25-33) MeV/turn; the RF power transferred to the beams, required to obtain a luminosity of $5 \times 10^{31}\ cm^{-2}s^{-1}$ at the maximum energy would be (1.75÷2.3) MW. The injection system discussed above could be adequate, if a slight reduction in luminosity (8×10^{31} max, at 10÷11 GeV) is accepted.

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