THE SUPER-ADONE ELECTRON-POSITRON STORAGE RING DESIGN

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Abstract.

The results of a design study1 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 $5 \times 10^{31}$ 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-$\beta$" 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 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 $\gamma^3$ 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 $\gamma^4$ 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, extrapolation to new machines and higher peak currents is still difficult;
5) low-$\beta$ operation has been proved possible and in agreement with expectation;
6) experimental information on the longitudinal beam-beam limit is not complete; 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 the 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, $\xi_\text{m}$, is a constant, the specific luminosity (for $\beta_x \leq \beta_z$) at the beam-beam limit, is given by

$$\frac{L}{I} = 2 \times 10^{32} \frac{E_\text{GeV}}{E_\text{GeV}} \frac{k}{\beta_z} \frac{1}{\text{cm}^{-2} \text{s}^{-1} \text{A}^{-1}}$$

(1)

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

Equation (1) shows that specific luminosity depends only on the operating energy and the minimum $\beta_z$, $\xi_\text{m}$ being constant. The $\beta$ value cannot be made much smaller than the bunch length for the assumed value of $\xi_\text{m}$; very small $\beta$'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 $\beta_0 = 0.3 \text{ m}$; from ADONE and SPEAR results we take $\xi_m = 0.08$ and obtain, with $k^21,1$:\[ L/I = 0.95 \times 10^{32} E_{\text{GeV}} \left( \text{cm}^{-2} \text{s}^{-1} \text{A}^{-1} \right) \quad (2) \]

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 RF power and cost of the ring aperture). For a luminosity of $5 \times 10^{31} \text{ cm}^{-2} \text{s}^{-1}$ 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:

- $I = 50 \times (10/E_{\text{GeV}})^{3/4} \text{ mA}$ for $E \geq 7 \text{ GeV}$,
- $I \leq 200 \text{ mA}$ for $E < 7 \text{ GeV}$.

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

\[ I = 48.7 \times h \times \frac{E_{\text{GeV}}^{3/4}}{R} \text{mA} \quad (3) \]

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

\[ \sigma_x = \sigma_p \sqrt{2 \beta_x H^*_{\xi}} \propto E \sqrt{\beta_x H^*_{\xi}}. \]

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 the beam constant, and therefore obtain $L \sim E^4$, the product $h H^*_{\xi}$ has to vary like $E^{-3}$. A possible choice is that of varying the number of bunches; in a single 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 $\psi$ at the crossing, within the longitudinal beam-beam limit;  
b) variation of the betatron wavenumber $Q_x$ with energy;  
c) use of special magnetic lattices that allow a continuous variation of $H^*$.

The present design is based on method a) and a 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.

\[ \text{Fig. 1 - Luminosity and current dependence on energy.} \]

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 $10^2$ to $10^3$); 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-$\beta$ 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.
The standard cell structure

\[ \frac{0}{2}; Q_7; M; Q_D; 0; Q_D; M; Q_7; \frac{0}{2} \]

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 \( \psi^2/\beta_x \) at the crossing point (\( \psi^2/\beta_x \)), the number of bunches per beam (h), and the coupling between radial and vertical betatron oscillations (ε) to be adjustable.

Four values of \( \psi^2/\beta_x \) 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 (\( \varepsilon_{\text{min}} \approx 0.2 \)). 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>
<thead>
<tr>
<th>Configuration</th>
<th>( \psi^2/\beta_x )</th>
<th>( \psi^2/\beta_x )</th>
<th>( \psi^2/\beta_x )</th>
<th>( \psi^2/\beta_x )</th>
<th>( \psi^2/\beta_x )</th>
<th>( \psi^2/\beta_x )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_A )</td>
<td>1.2</td>
<td>1.0</td>
<td>0.8</td>
<td>0.6</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>( S_B )</td>
<td>1.2</td>
<td>1.0</td>
<td>0.8</td>
<td>0.6</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>( S_C )</td>
<td>1.2</td>
<td>1.0</td>
<td>0.8</td>
<td>0.6</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>( S_D )</td>
<td>1.2</td>
<td>1.0</td>
<td>0.8</td>
<td>0.6</td>
<td>0.4</td>
<td>0.2</td>
</tr>
</tbody>
</table>

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 0.1 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 \( \beta_x \) section preceding the (I) sections, and switched off with two similar coils (SB) in the following high \( \beta_x \) 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-
cuped high-\( \beta_x \) 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 \( \text{M\Omega} \) 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 \( \times \) \( 10^6 \) cm\(^2\); cavities 5 \( \times \) \( 10^6 \) cm\(^2\); the chamber is 16 \( \times \) \( 10^5 \) liters, cavities 90 \( \times \) \( 10^3 \) liters.

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

**Parameter summary.**

<table>
<thead>
<tr>
<th>Beam</th>
<th>5</th>
<th>7</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV)</td>
<td>5</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>Luminosity ( \times 10^{-32} ) (cm(^{-2})s(^{-1}))</td>
<td>0.96</td>
<td>1.3</td>
<td>0.43</td>
</tr>
<tr>
<td>Current (mA)</td>
<td>200</td>
<td>200</td>
<td>50</td>
</tr>
<tr>
<td>Number of bunches per beam</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Radiation loss per turn (MeV)</td>
<td>0.86</td>
<td>3.3</td>
<td>13.8</td>
</tr>
<tr>
<td>( R, m, s ), dimensions at interaction point (mm)</td>
<td>radial uncoupled</td>
<td>1.6</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>radial coupled</td>
<td>1.6</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>vertical coupled</td>
<td>0.17</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>azimuthal (radiation)</td>
<td>50</td>
<td>70</td>
</tr>
<tr>
<td>Lifetime (hours)</td>
<td>21</td>
<td>14</td>
<td>9</td>
</tr>
</tbody>
</table>

**Magnetic structure**

- Central orbit length (m) | 357  
- Average radius (m)      | 136.51 |
- Experimental straight section total length (m) | 2 \( \times \) 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) | 84   
- Bending magnet length (m) | 64 \( \times \) 6.238 |
- Maximum field (Tesla)    | 0.52  
- Periodic cell quad length (m) | 96 \( \times \) 0.5 |
- Maximum gradient (Tesla/m) | 5   |
- Weight (Tons) magnets Fe 900 Cu 120 |
- quadrupoles Fe 185  Cu 40 |
- Magnet gap aperture (cm\(^2\)) per periodic cell  | 28.5 \( \times \) 11 |
- insertion 42.5 \( \times \) 15 |
- Quadrupole maximum inner radius (cm) per periodic cell  | 7.5 |
- insertion 10.5 |

**Focusing characteristics**

| Periodic cell \( \beta_x, z \) (m) | max | 10^{-37}; | 39 \( \times \) 41 |
|\( \psi \) (m) | max | 2 \( \times \) 9,4 \( \times \) 10 |
| \( a \) (m) | max | 1,6 \( \times \) 1,8 |
| Insertion \( \beta_x, z \) (m) | max | 140 \( \times \) 170; | 80 \( \times \) 140 |
| \( \psi \) (m) | max | 3,5 \( \times \) 7 |
| Interaction point \( \beta_x, z \) (m) | max | 1,9 \( \times \) 2,0; | 0,2 |
| \( \psi \) (m) | max | 9,2 |
| Natural chromaticity : radial | -2,4 \( \times \) 3,9 |
| vertical | -2,4 \( \times \) 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 | 2\( \times \) 28 |
| Maximum power to the beam (MW) | 2 \( \times \) 0 |
| Total R, F, power (MW) | 2,6 |
| Peak voltage (MV) | 20 |

**Vacuum system**

| Number of 200 l/s Ti-pumps | 10 |
| Number of 270 l/s turbomolecular pumps | 20 |
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^- 142
- 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 underground between section 1 and section 5; the remaining part will be built at surface level. Two experimental halls (20 x 40 m^2 x 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 12,51/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 together with the machine services; control and data rooms will be put in a connected building.

The RF final stages will be accommodated 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 x 10^{31} cm^{-2}s^{-1} at the maximum energy would be (1,75 x 2,3) MW. The injection system discussed above could be adequate, if a slight reduction in luminosity (8 x 10^{31} max, at 10^11 GeV) is accepted.

**References**
9. M. Bassetti, Resonant methods for beam size control in storage rings, This Conference.