COMMON PROBLEMS AND IDEAS OF MODERN PHYSICS (pp. 277–288)
edited by T. Bressani, B. Minetti & A. Zenoni

THE FRASCATI Φ-FACTORY PROJECT

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ABSTRACT

DAΦNE, the Frascati Φ-factory project, consists in the realization of a high luminosity electron-positron collider at the center of mass energy of the Φ resonance (≈1 Gev). The buildings of the existing accelerator complex (Adone+Linac) will accommodate a 270 MeV high current electron Linac section, a 540 MeV electron-positron Linac section, a small damping storage ring to be used as an accumulator for injection and two main rings where electrons and positrons circulate separately and collide at a small angle of 20 mrad in two low-β interaction regions. The main characteristics of the new accelerators are described together with the guidelines of the project.

1. Introduction

1.1. Beam-beam interaction and luminosity

The aim of DAΦNE, the Frascati Φ-factory project, is the realization of a high luminosity collider, running at the energy of the Φ resonance, and capable of a maximum energy of ≈ 0.75 GeV per beam. The luminosity goal after one year of commissioning is

$$L = 10^{32}\ \mathrm{cm^{-2}\ s^{-1}} \qquad (1)$$

while the target luminosity, after further improvements allowed by the experience gained with the operating machine, should reach [1]

$$L \approx 10^{33}\ \mathrm{cm^{-2}\ s^{-1}} \qquad (2)$$

The physical limitation on the luminosity obtainable from an electron-positron collider is given by the beam-beam interaction, which sets a limit to the stability of the stored beam. This limit depends on the number of particles, the size of the beams at the crossing points and the magnetic structure of the ring. More precisely, the luminosity is given by

$$L = f \frac{N^+N^-}{4 \pi \sigma_x \sigma_y} = f L_0 \tag{3}$$

where f is the frequency of the crossings, N^+ and N^- the number of positrons and electrons in each bunch stored in the ring, σ_x and σ_y the horizontal and vertical r.m.s. beam sizes. L_0 is therefore the luminosity per crossing. Each particle of a stored beam is confined in the storage ring by the focusing forces of the magnetic lattice, and "sees" the other beam as a perturbation, whose intensity depends on the particle energy, the number of particles in the other beam, its cross section and the betatron functions $\beta_{x,y}$ of the ring at the crossing point. The betatron functions vary with the position along the ring ideal orbit and are proportional to the square of the beam size: the effects of any perturbation to the particle motion, such as position or field errors, non-linearities and so on, increase with the value of the betatron functions. The beam-beam interaction is a strong non-linear perturbation to the beam stability, and this is the reason why all high luminosity storage rings have their crossing points with at least one of the betatron functions very small, of the order of few centimeters. A convenient description of the beam-beam interaction is given by the linear model, where the perturbation is schematized as the effect of a thin lens whose intensities in the horizontal and vertical planes are described by two adimensional numers $\xi_{x,y}$, called the linear tune shifts, given by

$$\xi_{x,y} = \frac{r_e \; N \, \beta_{x,y}}{2 \pi \gamma \sigma_{x,y} (\sigma_x + \sigma_y)} \tag{4}$$

where γ is the relativistic factor for the particles in each beam and r_e the classical electron radius. From the experience gained with the operation of many storage rings in the world, it is now clear that a limit exists on the maximum obtainable tune shifts. This limit, taking an average over the measurements performed on existing machines is

$$\xi_{max} = 0.038 \pm 0.013 \tag{5}$$

The maximum tune shift can be achieved at the same time for both beams in both planes, if the number of electrons and positrons in a bunch is the same, and if the horizontal (ε_x) and vertical (ε_y) emittances are in the same proportion as the horizontal and vertical β functions. This proportion is called the "coupling factor" and is usually indicated with the letter k, and this optimum situation can be summarized as

$$\xi_x = \xi_y = \xi_{max} \qquad N^+ = N^- = N \qquad \varepsilon_y/\varepsilon_x = \beta_y/\beta_x = \sigma_y/\sigma_x = k \tag{6}$$

where the last relation comes from the expression of the r.m.s. beam sizes at the crossing point as a function of the β's and the emittances

$$\sigma_x = \sqrt{\varepsilon_x \beta_x} \qquad \sigma_y = \sqrt{\varepsilon_y \beta_y} \tag{7}$$

Combining Eqs. 3,4,6,7, the luminosity can be expressed as

$$L = \pi f \gamma^2 \xi^2 \varepsilon (1+k) / (r_e^2 \beta_y) \tag{8}$$

and the beam-beam parameter ξ as

$$\xi = r_e N / (2 \pi \gamma \varepsilon) \tag{9}$$

1.2. The choice of the magnetic lattice

From Eqs. 8 and 9 one can see that, given a maximum value for the linear tune shift (as suggested by Eq.5) and the center-of-mass energy for the experiments to be performed with the collider, one can increase the luminosity by reducing β_y, by increasing the emittance, or by increasing f, the frequency of the collisions at the interaction point.

Practical limits exist for any of these methods. The vertical betatron function cannot be smaller than the bunch length, which depends on the cavity voltage and frequency, on the stored bunch current via the the vacuum chamber impedance and on the magnetic structure of the ring, and for a Φ-factory is typically in the range of a few centimeters. Moreover, reducing the value of β_y at the crossing point requires strong focussing in the vertical plane at the interaction point, and this means introducing chromatic distorsions in the particle motion, which may be corrected only with non-linear elements in the lattice. Eq. 8 suggests also to gain a factor ≈2 by bringing the coupling near to its maximum value of 1, but this asks for a small β also in the horizontal plane, as shown by Eq. 6, so that the above mentioned difficulties are doubled. For this reason, the storage ring will work with k=1%, with the small β in the vertical plane. Increasing the emittance requires more particles to be stored in a bunch to keep the linear tune shift constant, thus imposing stronger requirements on instability control, and requires also a larger physical and dynamic aperture to accommodate the beam.

DAΦNE, the Frascati Φ-factory project, is based mainly on a large collision frequency. Two possible ways can be followed to achieve this goal. The first is to build a very short single ring where one electron bunch collides with one positron bunch in one or two crossing points, with very small beam size at the interaction point; proposals in this direction have been presented in USA and USSR. The second is to build two separate rings, crossing at one or two interaction regions, where a large number of bunches are stored at a small distance from each other, so that each bunch "sees" the other beam only at one or two positions at each turn.

The major drawback of the first solution is the difficulty of concentrating all the necessary items of a storage ring, such as available space for the experiment, low-β focusing, dispersion matching, injection equipment, RF cavity etc., in a small space. For a Φ-factory, practical limits constrain f below 10±20 MHz. In the second case, one can reach ≈0.5 GHz, at the expense of a very large total stored current and the necessity of carefully controlling longitudinal instabilities. This is the choice made for DAΦNE.

Another important advantage of the second approach is related to the contribution to beam lifetime coming from the high rate of particle loss due single beam-beam bremsstrahlung. The relative current loss is proportional to the ratio of luminosity to total stored current, and, as mentioned before, the second solution realizes the desired luminosity by storing a large total current in many bunches, each giving a small contribution to the total luminosity. The gain in lifetime scales roughly with the ratio of the crossing frequencies.

The maximum luminosity at the Φ energy has been reached until now at VEPP-2M at Novosibirsk (URSS), and its value is

$$L_{VEPP\text{-}2M} = 4.3\times10^{30}\ cm^{-2}\ s^{-1} \qquad (10)$$

with a single bunch of positrons colliding in two interaction regions with a single bunch of electrons. If one scales this luminosity with the emittance (10^{-6} m) and the crossing frequency of DAΦNE a luminosity of $4\times10^{32}\ cm^{-2}s^{-1}$ can be foreseen for the new project. Moreover, from experience with operating storage rings, it seems that the maximum beam-beam tune shift is a decreasing function of the number of crossings per turn, so that one can reasonably foreseee that DAΦNE with a single interaction region could reach a luminosity near $5\times10^{32}\ cm^{-2}\ s^{-1}$.

2. The storage ring lattice

2.1. The choice of the crossing plane

A very important decision to be taken for the lattice of a separate rings collider is the plane of the crossing. As explained before, the machine will work with a small coupling factor and this means that the vertical r.m.s. beam size will be much smaller than the horizontal one. There is a minimum distance at which the interaction between two beams is no more harmful to particle dynamics, and this distance depends on the transverese beam sizes and the geometry of the interaction region. Being the vertical beam size much smaller than the horizontal one, it seems that separation in the vertical plane could allow (at a given crossing angle) a smaller longitudinal distance between the bunches stored in the ring, and therefore a higher interaction frequency and luminosity. However, another consideration must be made, concerning the maximum allowed tune shift as a function of the crossing angle. Introducing the adimensional parameter

$$A = \theta\, \sigma_z/\sigma_{x,y} \tag{11}$$

where θ is the crossing angle, $\sigma_{x,y}$ the horizontal or vertical r.m.s. beam size at the interaction point and σ_z the r.m.s. bunch length, one can observe from experimental results on existing machines and from beam-beam computer simulations that the maximum ξ drops down when A increases and that a reasonable assumption is that

$$\xi_{max} \approx 0.005/A \tag{12}$$

where the constant can be estimated from the experience gained in DORIS, where the maximum tune shift was 0.01 with A=0.50 with the crossing in the vertical plane. In the case of DAΦNE, with 20 mrad separation between the trajectories of the two beams, we reach A=0.13, so that the maximum tune shift should be near 0.04. In the case of vertical crossing, due to the very small vertical beam size ($\approx$20 μ), the maximum tune shift would drop by two orders of magnitude (at constant separation), and the luminosity would be too low. In principle, in the case of vertical crossing, one could decrease the crossing angle, but then the space necessary to physically separate the two rings would increase too much with respect to the available space in the Adone hall. Moreover, separation in the vertical plane requires careful correction of the vertical dispersion created by the vertical bendings, and this is an additional complication to the lattice design.

2.2. The magnetic layout

Fig.1 shows a schematic view from above of the two rings. Positrons will be injected in the long straight section indicated with LS^+ at the bottom of the drawing, will be deflected by the bending magnet and forced to pass through the wiggler W. After the following bending magnet the positrons reach the separator MS, which is a magnetic septum with opposite fields with respect to the central axis, so as to bend particles of opposite charge in opposite directions. After the separators both electrons and positrons travel in the same vacuum chamber, passing into the quadrupole triplet FF which focuses the vertical beam size to its very small value at the interaction point IP. After passing through the following FF, positrons will go through the short straight section SS^+, where an RF accelerating cavity (not shown in the drawing) will provide to the beam the energy lost by synchrotron radiation. After SS^+ the particles will pass through the second IP, where they will interact with the other beam, if two experiments run at the same time; if not they will be magnetically separated in order to gain in luminosity, as explained before. The electrons will obviously follow the opposite path.

Particular attention should be deserved to the structure of the low-β triplets surrounding the interaction regions. In order to obtain the very strong focusing required to squeeze the vertical beam size to $\approx 20\mu$, the gradients in these quadrupoles are rather high. The two beams cross at an angle of 20 mrad, so that the paths of the two beams are not on the central axis of the quads, but symmetrically displaced with respect to it, thus requiring large free aperture. On the other hand, the external size of the quads should be small, so that angular acceptance of the experimental setup can be near 4π. For all these reasons, the low-β triplet will be realized with permanent magnets instead of the classical electromagnetic solution. An additional complication to the design of the interaction region comes from the necessity of a longitudinal solenoid field for the experiment, which gives a small, but not negligible contribution to the coupling factor k, so that a skew quadrupole compensation scheme will be required. With this arrangement of crossing angle and quadrupole fields, the minimum distance between the bunches, satisfying the above mentioned condition of minimum separation is approximately 80 cm, corresponding to a crossing frequency of 380 MHz.

The 8 wigglers shown in Fig.1 are inserted in the lattice for two very important reasons. The first is that it is clear from machine theory and experience that radiation emitted by the particles in strong magnetic fields helps a lot in damping instabilities and is beneficial to the maximum beam-beam tune shift and luminosity obtainable in electron/positron colliders. The second is that wigglers inserted in a straight section where the horizontal dispersion is high can increase and possibly tune the emittance of the beam. They will have a maximum field of ≈ 2 T and the emittance variation will be obtained by changing the gradients in the nearby quadrupoles to change the value of the dispersion and horizontal β in the wigglers, which determine the emittance of the beam.

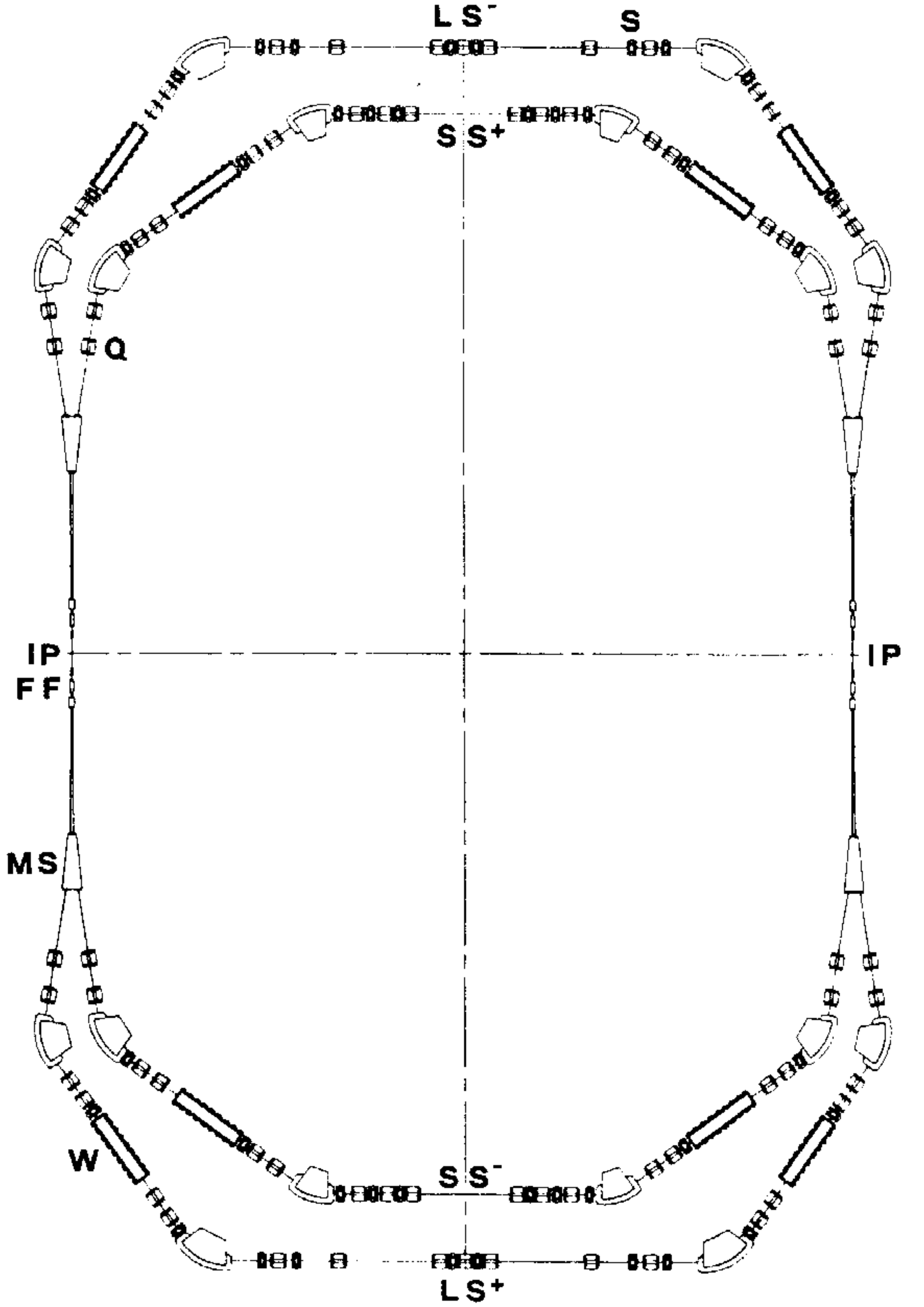

Fig.1 - Schematic layout of the DAΦNE main rings

Magnetic elements indicated with Q in Fig.1 are the quadrupoles which mantain the stability of betatron oscillations. The smaller elements indicated with S are sextupoles, and they are used to correct the chromatic aberrations of the focusing fields, mainly those created in the low-β triplets. The arrangement of the chromatic correction fields is one of the crucial subjects of the lattice design, since it limits the available space for stable oscillations of the particles, and therefore the lifetime of the beam.

The beam parameters most relevant to the luminosity [2] are summarized in Table 1.

Table 1. DAΦNE beam parameters

Energy (GeV)	0.51
Luminosity ($cm^{-2}s^{-1}$)	$5.5x10^{32}$
Circumference (m)	94.56
Emittance (m)	$0.95x10^{-6}$
Horizontal β at IP (m)	4.5
Vertical β at IP (m)	0.045
Coupling factor	0.01
Horizontal r.m.s. beam size at IP (mm)	2.11
Vertical r.m.s. beam size at IP (mm)	0.021
Bunch length (mm)	30.0
Crossing angle (mrad, horizontal)	20.0
Crossing frequency (MHz)	380.44
Number of bunches per ring	120
Max. number of particles per bunch	$9.0x10^{10}$
Max. total average current (A)	5.5

3. The injection system

3.1. Design criteria

The total number of positrons required to obtain the quoted luminosity of $5x10^{32}$ is $\approx 10^{13}$, ≈ 3 times larger than the charge stored in LEP. Reliable operation of a Φ-factory asks for a short injection time, typically less than 15 minutes, to store the full current of both beams. To keep the average luminosity very close to the maximum one, however, it is convenient to design an injection system operating at the same energy of the main ring, so that only a fraction of the total current can be injected when the luminosity drops below a given value, due to the decay of the stored current.

Positrons to be stored into the ring are created by inserting a target at the output of an electron Linac. Electrons emit high energy photons in the high-Z material of the target, and these photons convert into electron-positron pairs. The low-energy positrons coming out from the target have a large energy and angular spread, so that very powerful focusing lenses are necessary to focus the beam into the following accelerating sections. The number of positrons from the target is proportional to the total electron energy deposited on the target, namely to the product of the number of electrons times their energy. The cost and the length of electron Linacs are roughly proportional to the energy of the beam, so that practical limits are set to the conversion energy. In the case of DAΦNE, the complete Linac must be housed in the existing building (see Fig.2) and, as explained before, ≈0.54 GeV positrons are needed to inject with a reasonable safety margin into the main ring. Taken into account the available space, ≈0.4 GeV electrons could be used to produce positrons, but cost considerations drop this value to 0.27 GeV. At this energy the conversion and capture efficiency (the number of positrons accelerated in the Linac divided by the number of electrons striking the target) is ≈0.8%.

A very important constraint on the design of the injection system is the necessity of storing one bunch at a time into the main rings. This possibility allows to store into the ring any combination of bunches and helps a lot during machine commissioning and normal operation. The length of the pulse from the injector cannot therefore be larger than one period of the RF cavity (≈3 nsec), while the optimum length for a Linac pulse, when the pulse-compression scheme [3] is used to increase the energy gain, is of the order of 10 nsec.

The most commonly used pre-injection system into the Linac, consisting in a high temperature cathode followed by a grid for pulse forming and by a high voltage anode for the first acceleration, are capable of currents around 10 A. Taking into account electron-positron conversion and transport efficiency through the linac, a good estimate for the number of accelerated positrons in each 3 nsec pulse is $5x10^8$, so that $\approx 2x10^4$ would be necessary to fill the positron ring. A limit to the pulse injection rate is given by the damping time of the ring (the time needed to decrease by 1/e the amplitude of synchrotron and betatron oscillations generated by the injection procedure), which for DAΦNE is near 20 msec. Injecting therefore at 50 Hz, ≈7 minutes will be necesary to fill the positron ring. However, the number of injected pulses is very large and, since injection rate comes from a balance between the number of particles accepted by the ring and the fraction of already stored particles lost on the septum at each injection pulse (the particle distribution is gaussian, so that in any case there are tails of the distribution which cannot be kept away from the injection septum), one has to keep the loss below $5x10^{-5}$ to avoid saturation.

For the above described reasons, the best solution for the injection system is a small intermediate storage ring [4], working at the same energy of the main ring, to be used as an accumulator for both electrons and positrons. The RF system of the ring can run at a lower frequency (76 MHz), so that 10 nsec pulses from the Linac can be efficiently accepted. The small size of the ring ensures the same damping time of the main ring even without the use of wigglers, and injection can therefore be performed at 50 Hz. Extraction of the beam, and injection into DAΦNE, can be performed at 1÷2 Hz, so that the saturation limit drops by two orders of magnitude. An additional advantage of using the accumulator is that the beam going into the main ring has small emittance and energy spread, much better than a beam coming from the Linac, so that the aperture of the DAΦNE vacuum chamber is not affected by injection requirements.

Fig.2 shows the layout of this small ring (≈ 10 m diameter): positrons from the Linac [5] are bent on the right by the switching magnet SM, they pass through M1 (which is not powered during positron injection) and enter the ring through septum magnets S1 and S2, with the four kicker magnets performing the closed orbit deformation required to inject the beam. 45 pulses are stored in the accumulator at 50 Hz, and then injection stops for 0.1 sec in order to completely damp the beam before extracting it with a magnetic field pulse in K2 and K3 through S3 and S4. The extracted beam is deflected by M2 and directed towards the injection line to the main ring. The electrons follow the opposite way and are injected when positron filling is completed. About three positron pulses from the accumulator are necessary to reach the desired charge in a single DAΦNE bucket, while for electrons, due to the larger available current from the Linac, a single shot will be sufficient. In order to ease synchronization between the two storage rings, the circumference of the accumulator is exactly one third of the main ring one, while the R.F. frequencies are in the proportion of 1 to 5.

With this injection system the total injection time (positrons + electrons) starting with no current in the main rings, will be ≈10 minutes. "Topping up" time, when the beam will be refilled at a given luminosity drop, will be obviously faster, and will depend on the amount of current to be injected.

Fig.3 shows the general layout of the Linac, the accumulator and the main rings assembled in the buildings now occupied by Adone, the existing Linac, and an experimental hall used previously for nuclear physics experiments.

4. References

1. S. Bartalucci, M. Bassetti, M.E. Biagini, C. Biscari, S. Guiducci, M.R. Masullo, L. Palumbo, B. Spataro, G. Vignola, *DAΦNE design criteria*, DAΦNE Technical Note G-2 (12/11/1990)
2. M. Bassetti, M.E. Biagini, C. Biscari, S. Guiducci, M.R. Masullo, G. Vignola, *High emittance lattice for DAΦNE*, DAΦNE Technical Note L-1 (30/10/1990)
3. B. Spataro, *Studio di un sistema per aumentare l'energia del Linac di Frascati*, LNF Internal Note LNF-14/12/R (13/3/1984)
4. M. Preger, *A positron and electron accumulator for DAΦNE*, DAΦNE Technical Note I-1 (8/11/1991)
5. S. Kulinski, R. Boni, B. Spataro, M.Vescovi, G. Vignola, *The linear accelerator for the DAΦNE injection system*, DAΦNE Technical Note LC-1 (11/2/1991)

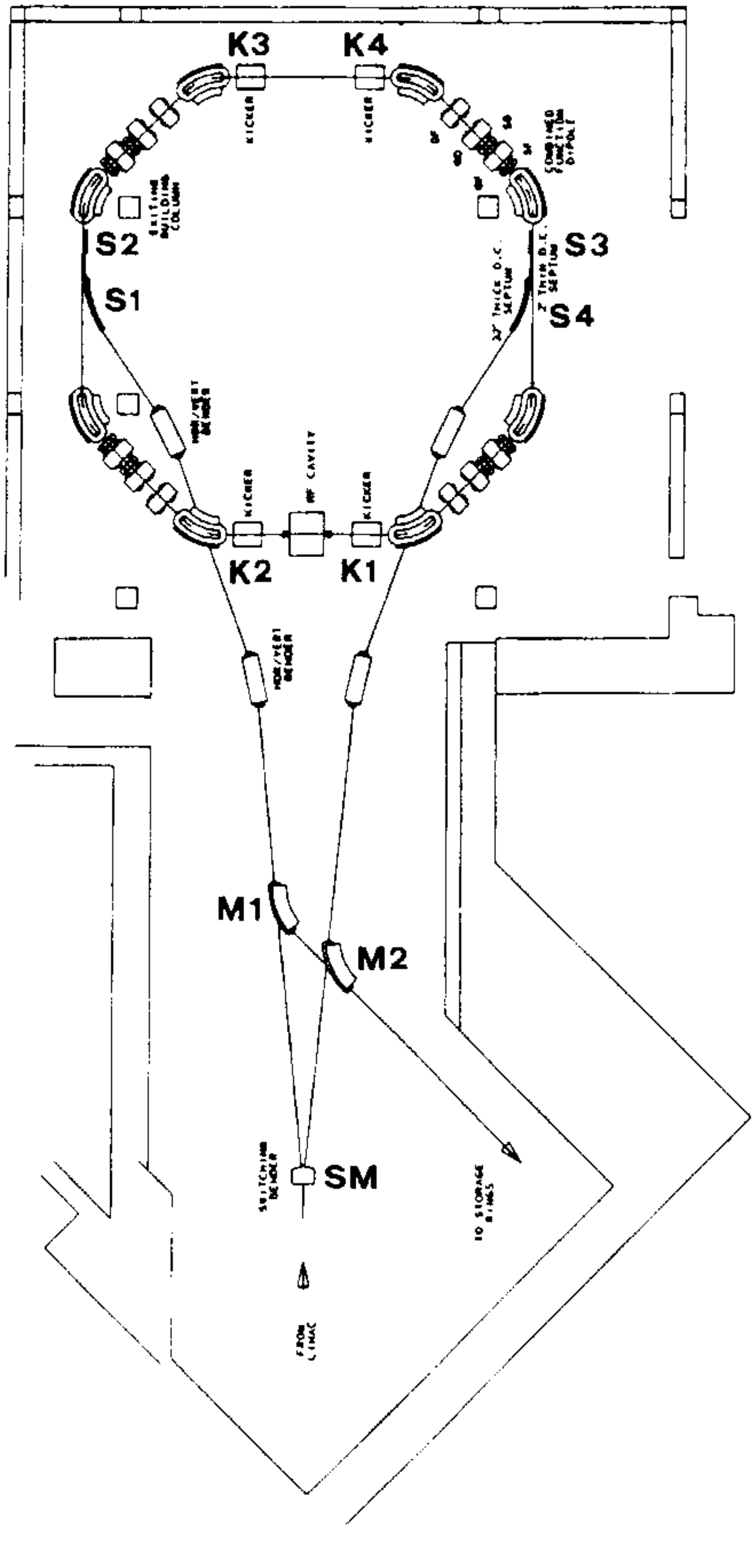

Fig.2 - Magnetic structure of the electron-positron accumulator

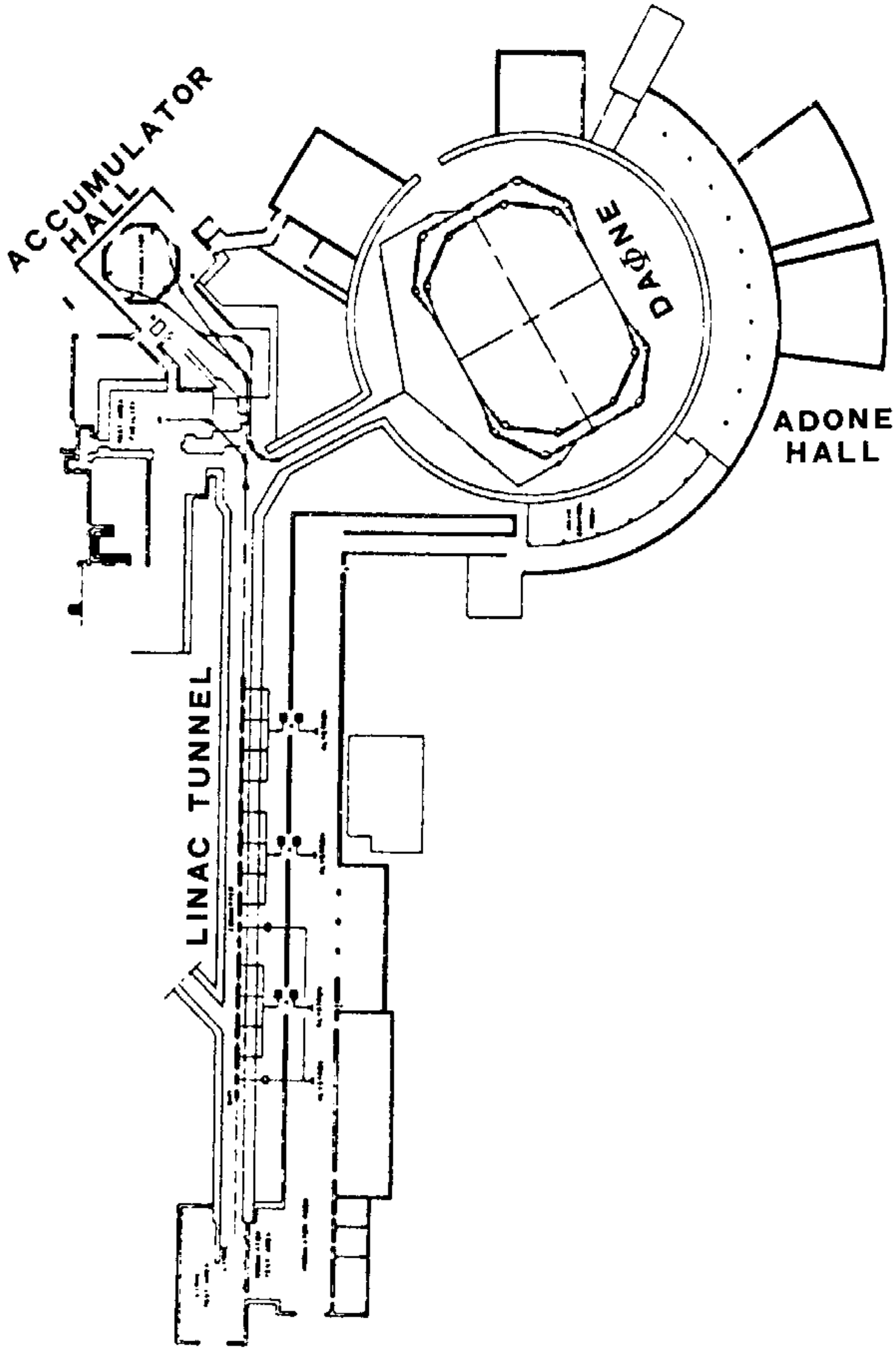

Fig.3 - General layout of the DAΦNE accelerator complex