DAΦNE TECHNICAL NOTE
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DAΦNE DESIGN CRITERIA

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INTRODUCTION

The DAΦNE luminosity target, at the Φ energy (γ_{CM} = 1000), is

$$\mathbf{L} \sim 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$$

A value of $2 \div 3\ 10^{32}$ $\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$ should be obtained after one year of operation, while the upper limit will be gradually approached once the machine behaviour has been fully understood.

The general philosophy described in the initial proposal[1] is still valid, even if the design has evolved[2,3] in order to meet the higher luminosity requirement and to accommodate simultaneously two experimental apparatus.

The design will be based, as much as possible, on <u>conventional technology</u>, and will have enough <u>flexibility</u> built-in to allow the key machine parameters to be easily changed to fine tune the luminosity.

The main features are :

- electrons and positrons circulate in two horizontally separated storage rings and collide at a horizontal half-angle θ_x=10 mrad in one or two interaction points;
- the ring magnetic lattice is a 4 period modified Chasman-Green type with a 1.9 Tesla conventional wiggler magnet inside the achromat. This solution allows emittance tunability and at the same time gives strong radiation damping;
- a crab crossing option is contemplated.

At this point two questions are mandatory :

How do we get there ? Is this luminosity goal realistic ?

These are non trivial questions. We will try to answer by discussing, in this note, the choice of the parameters more relevant to the luminosity and to main machine components.

DAΦNE DESIGN PARAMETERS

Let us recall (see Appendix) the luminosity formula at the space charge limit

$$\mathbf{L} \propto \mathbf{f} \; \frac{\xi^2 \varepsilon \left(1+\kappa_\beta\right)}{\beta_y} \sqrt{\frac{\kappa_\beta}{\kappa}}$$

together with the values (upper limits) of the parameters appearing in it and the most important machine related quantities :

DAΦNE DESIGN PARAMETERS

ξ	.04	$\mathbf{f}^{max}$ (MHz)	~ 350
ε^{max} (m-rad)	10^{-6}	$\mathbf{N}^{max}$	$9 \; 10^{10}$
κ_β	.01	N^{er} of bunches	1÷120
β_y (m)	.045	$I_2 (m^{-1})$	~ 14
σ_z (m)	.03	$I_3 (m^{-2})$	~ 14
θ_x (mrad)	10	$\mathbf{U_o}$(KeV)	~ 14

Let us point out that the highest luminosity reached up to now in existing machine, at the Φ energy, is $4.3\,10^{30} cm^{-2} sec^{-1}$ at VEPP-2M (4) and there is an on-going effort to push up by a factor 2 this limit due to the available RF power.

Our design parameters are very similar to the VEPP-2M ones, with the exception of **f** (350 MHz against 16.8 MHz) and ε (10^{-6}m-rad instead of $4.6\,10^{-7}$m-rad). By just scaling the luminosity with the ratios of collision frequency and emittance and taking in account the improvement factor 2, we get:

$$\mathbf{L}^{\mathrm{DA\Phi NE}} = 2\ \mathbf{L}^{\mathrm{VEPP\text{-}2M}}\ \frac{350}{16.8}\ \frac{10^{-6}}{4.6\,10^{-7}} = 3.9\ \ 10^{32} cm^{-2} sec^{-1}$$

Moreover, if we consider that in VEPP-2M there are 2 interactions/turn ($\mathbf{n}_i$ =2) one could have an additional factor $\sqrt{2}$ on the luminosity for $\mathbf{n}_i$ = 1. This would bring the luminosity to a value

$$\mathbf{L} = 5.5\,10^{32} cm^{-2} sec^{-1}$$

that is not so far from our target luminosity.

VERTICAL β-FUNCTION

The luminosity increases linearly with the inverse of β_y at the IP. In order to take full advantage of this dependence, one has to be ready to pay a price in terms of RF system voltage, ring impedance and, since the r.m.s longitudinal bunch length must be small (=> high peak current), of single bunch instabilities. In fact, an empirical rule states that

$$\sigma_z \leq \sim \frac{\beta_y}{1.5}$$

in order to avoid geometrical luminosity reductions.

Moreover, due to the relatively low energy, the Touschek effect, limiting the useful lifetime ($\tau_T \propto \sigma_z$), becomes of paramount importance. Beside instability considerations, the minimum σ_z, and, consequently β_y, is limited by the lifetime acceptable by the experiments that, in our opinion, has to be $\geq 2 \div 3$ hrs.

In addition, the Liouville theorem prescribes that, to a very small β_y at the IP, there must correspond a large beam divergence; the latter has to be corrected locally, as close as possible to the IP, or the necessary machine acceptance will become too large.

In practice, one is forced to put a very strong quadrupole close to the interaction point that will necessarily limit the solid angle available for the experiment.

This kind of limitation, common to all the low-β schemes, is particularly severe in the case of a Φ-factory; it imposes a coordinated design of the low-β insertion and the experimental apparatus.

The beam divergence correcting quadrupole also has the effect of raising the machine chromaticity, which has to be corrected by the addition of strong sextupoles; the dynamic aperture is consequently reduced.
In conclusion, the value of β_y can not be arbitrarily small; a reasonable choice for the design value turns out to be :

$$\boxed{\beta_y = 4.5 \text{ cm} \quad ==> \quad \sigma_z = 3.0 \text{ cm}}$$

Lower values of β_y, such as those claimed by other designs, could therefore be attempted once the machine behaviour has been fully understood, providing an upgrade potential for luminosity.

FLAT BEAM, β-FUNCTION RATIO, COUPLING COEFFICIENT

The β-function ratio @ IP is :

$$\boxed{\kappa_\beta = .01}$$

this choice, apparently in contrast with the main goal of maximizing the luminosity, is justified by our <u>preference for flat beam</u>, also if round beam gives, on paper, an attractive factor 2 on the luminosity.

The main reasons for this choice are the following :

- at the moment there are only computer simulations[5] that seem to indicate the possibility to achieve ξ values larger than in the case of flat beam (other computer simulations[6] indicate the contrary), but no experimental experience with round beam;

- to take full advantage of the round beam configuration it is necessary to have small β in both planes; this implies further chromaticity increase and dynamic aperture and lifetime decrease;
- for flat beam the long-range beam-beam effect is less, so one can adopt a scheme with horizontal crossing and push-up the collision frequency;
- for flat beam it is much easier to design a crab crossing scheme[2], if necessary;
- for flat beam it is much easier to satisfy the Bassetti's criterion (see Appendix) while keeping the required I_3 value manageable.

Finally, to gain in luminosity, it is also necessary to work with a low value of the coupling coefficient

$$\boxed{\kappa \leq .01}$$

Theoretically, how much down one can go, with the κ's value, will depend on the achievable ξ_y value.

Practically, to achieve such very low value of the coupling coefficient is not easy; the experimental solenoidal field has to be exactly compensated, the orbit has to be measured and corrected very precisely, and the vertical dispersion function has to be carefully minimized.

The problems are nevertheless solvable; many storage rings in operation have obtained κ values less than 1%. In particular, the Brookhaven 750 MeV VUV ring has reached $\kappa = 0.0017$, after careful machine alignment and residual closed orbit correction to the desired precision.

A potential advantage of the low coupling is the reduction of ion trapping at least when a design dynamic vacuum of ~ 10^{-9} torr is assumed.

A larger value of κ_β, let us say .02÷.03, gives for the same coupling better luminosity, but is more demanding for the crab-crossing cavities and for the Bassetti's criterion. Larger values of κ_β should however be attempted during the commissioning period.

EMITTANCE

The emittance ε affects the luminosity linearly but it cannot be made arbitrarily large; the limit is given by the machine physical and dynamic apertures necessary for a reasonable beam lifetime. Very large emittance also implies that the number of particles, **N**, necessary to achieve a large ξ, is very large.

All considered, a reasonable choice for the max design emittance is :

$$\boxed{\varepsilon^{max} = 10^{-6}\ \mathrm{m\cdot rad}}$$

but the storage ring lattice is designed to allow a wide range of tunability, while keeping constant the radiation damping times.

COLLISION FREQUENCY AND HORIZONTAL (CRAB) CROSSING

The luminosity increases linearly with the collision frequency, therefore it is convenient to have a large $\mathbf{f}$. The maximization of $\mathbf{f}$ basically implies the choice between two different strategies

- small ring footprint and single bunch (max value ~30 MHz)
- larger footprint and multibunch (max value 100÷500 MHz)

The second solution, which we adopt, allows to gain one order of magnitude in the collision frequency and consequently on the luminosity.

Our choice is

$$\boxed{\mathbf{f}^{max} = \mathbf{f}_{RF} \approx 350\ \mathrm{MHz}}$$

In order to achieve these large values of the collision frequency and to avoid parasitic collisions we adopt a design in which electrons and positrons circulate in two horizontally separated storage rings and collide horizontally with an half-angle θ_x = 10 mrad in one or two IP.

Such a solution should not excite synchrobetatron resonances(2), but, if this should occur, it is more favourable for a correcting crab-crossing scheme.

An important advantage of the multibunch solution is the possibility to keep at acceptable levels the beam-beam lifetime. Let us point out that this solution, by requiring a large number of particles, will be very demanding from the INJECTOR system point of view, but, in our opinion, this is the price that one has to pay in order to make real experiments.

On the 'minus' side it should also be mentioned that multibunch operation is prone to multibunch instabilities, that have to be carefully suppressed, and is at risk of ion trapping unless proper countermeasures are taken.

LINEAR TUNE SHIFT PARAMETER

The linear tune shift ξ , appearing squared in the luminosity formula, plays the most important role.

Our design value is

$$\boxed{\xi = .04}$$

and it is based on the following considerations.

The maximum attainable ξ value cannot be computed from theory. Experimentally, however, the maximum value for ξ (<u>in the case of two interactions per turn</u>), averaged over most of the existing electron colliders, is remarkably constant at :

$$< \xi^{max} > = .038 \pm .013$$

ξ is generally assumed to depend quadratically on the number of crossings per turn $\mathbf{n}_i$ (for equal β-phase advance between crossings). Namely :

$$\xi \propto \frac{1}{\sqrt{\mathbf{n}_i}}$$

Our design value is rather conservative, at least with $\mathbf{n}_i = 1$, so we should have a potential gain factor on ξ and, consequently 2 on $\mathbf{L}$.
Let us point out that with the design value I_2= 14 m^{-1} we satisfy the Seeman's criterion(see Appendix) up to $\xi \approx .053$.

SYNCHROTRON INTEGRALS

The values for $\mathbf{U}_0$, I_2 and I_3 have been dictated by a compromise between the tentative to satisfy Seeman's and Bassetti's criteria , to increase the radiation damping times and, at the same time, to keep at a reasonable levels the requirements on RF and VACUUM systems.

Our choice is $\mathbf{U}_0$= 14 KeV and in case more damping should prove to be necessary, it can be produced by inserting additional wiggler magnets.

The synchrotron radiation power is 14 KW/Amp and one has to add the parasitic losses ($\approx$4KW/Amp for σ_z = 3.0 cm and Z/n = 1 Ω).

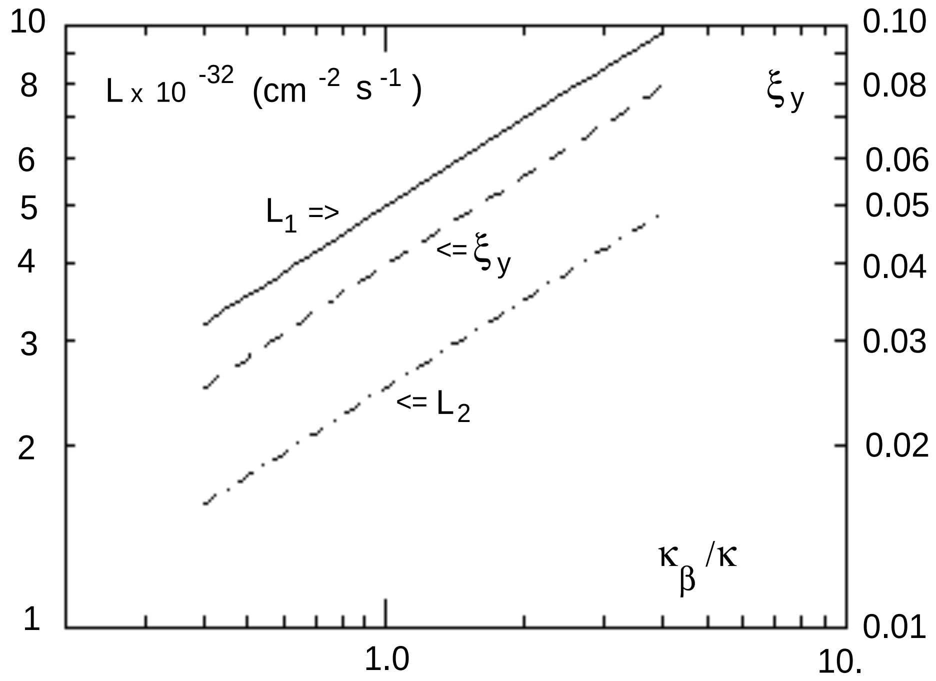
LUMINOSITY SCENARIO

Let us make a simple exercise by evaluating the luminosity for some possible set of the design parameters and keeping constant **f**,ξ and β_y at the design values:

f = 350 MHz ξ = .04 β_y = 4.5 cm

ε (mm·mrad)	**N** /10^{10}	<i> (Amp)	κ	κ_β	ξ_y	**L**/10^{32} ($cm^{-2}sec^{-1}$)
1.0	8.90	5.0	.025	.010	.025	3.2
1.0	8.90	5.0	.010	.010	.040	5.0
1.0	8.90	5.0	.005	.010	.056	7.0
1.0	8.90	5.0	.025	.020	.036	4.5
1.0	8.90	5.0	.010	.020	.056	7.0
1.0	8.90	5.0	.005	.020	.079	9.8
0.5	4.45	2.5	.025	.010	.025	1.6
0.5	4.45	2.5	.010	.010	.040	2.5
0.5	4.45	2.5	.05	.010	.056	3.5
0.5	4.45	2.5	.025	.020	.036	2.25
0.5	4.45	2.5	.010	.020	.056	3.5
0.5	4.45	2.5	.005	.020	.079	4.9

The previous table is also summarized in the following graphic



L_1 => N = 8.9 10^{10} ; $\varepsilon = 10^{-6}$ m rad ; ξ ~.04

L_2 => N = 4.5 10^{10} ; $\varepsilon = .5\ 10^{-6}$ m rad ; ξ ~.04

By inspecting the above results we observe that:

- No matter how, to bring the luminosity in the range $10^{32} \div 10^{33}$ <u>high current</u> is necessary, as well as <u>flexibility to change the bunch pattern configuration</u>. For example if we fix the max av. current to be 2.5 Amp we see that the same luminosity can be obtained with ($\varepsilon=10^{-6}$- **f** =175 MHz) as well as with ($\varepsilon=5.10^{-7}$- **f** =350 MHz). We set the maximum current to

$$\boxed{\langle i^{max} \rangle \approx 5 \text{ Amp}}$$

  in order to have enough safety margin, also if, in our opinion, 2÷3 Amp should be enough. Let us point out that high current values have been reached at storage rings now in operation (a current in excess of 1.3 Amp has been accumulated in the BNL-VUV ring that runs routinely with stored currents of .8÷.9 Amp and has the same $\mathbf{U_0}$ value);

- a κ_β value >.01 is better from the luminosity point of view, but it can be more critical from the synchrobetatron resonances point of view(2);

- due to the high number of bunches a powerful feedback system for multi-bunch instabilities is necessary.

COMMISSIONING AND OPERATING SCENARIO

The commissioning period will be devoted to change all the machine parameters (Q_x, Q_y, β_x, β_y, κ_β, ε, etc.) to understand single, multibunch and beam-beam limits and find the optimum for the luminosity.

During operation the standard procedure will be to inject the maximum single bunch current with high value of κ and then shrink the beam size by reducing κ up to the ξ_y limit value, i.e the maximum luminosity.

MAIN RING SYSTEM DIMENSIONING

A first dimensioning of the main ring system, at this point, has to be given and it is prudent to dimension the performance on the maximum values that one can reasonably assume :

MAIN RF SYSTEM (1 ring)

FREQUENCY	$\approx$ 350 MHz
PEAK VOLTAGE	$\approx$ 500 KV
TOTAL POWER TO THE BEAM	$\approx$ 100 KW

A higher harmonic RF system to control the bunch length and a 500 MHz alternative solution must be investigated.

VACUUM SYSTEM (1 ring)

No matter what, 10^{-9} torr with $\approx$100 KW of synchrotron radiation power must be obtained.

INJECTOR

The design depends critically on the very high number of positron that is necessary to accumulate in a reasonable time :

MAX N^{er} of POSITRONS	$\approx 10^{13}$
MAX N^{er} of POSITRONS /bunch	$\approx 9\ 10^{10}$
POSITRON ACC. TIME	$\approx$ 2÷5 min
N^{er} OF BUNCHES	1÷120

With the above numbers, a solution LINAC+DAMPING-RING seems the only pursuable.

REFERENCES

1) Proposal for a Φ-FACTORY - LNF-90/031(R) - April 1990.

2) S. Bartalucci et al : The horizontal vs vertical crossing angle and the crab crossing scheme - DAΦNE Tech. Note G-1 - October 1990.

3) S. Bassetti et al : High emittance lattice for DAΦNE - DAΦNE Tech. Note L-1 - October 1990.

4) P.M. Ivanov et al : Luminosity and beam-beam effects on the electron positron storage ring VEPP-2M - Proc. 3rd advanced ICFA beam dynamics workshop Novosibirsk 1989 - Ed. I. Koop and G. Tumaikin.

5) R. H. Siemann : Simulation of Electron-Positron Storage Rings - Proc. 3rd advanced ICFA beam dynamics workshop Novosibirsk 1989 - Ed. I. Koop and G. Tumaikin.

6) Y.C. Chin - Talk presented in the workshop on Beam Dynamics Issues of High Luminosity Asymmetric Collider Rings LBL, February 1989.

APPENDIX

BASIC FORMULAE :

Luminosity per interaction point **(IP)** :

$$\mathbf{L} = \frac{\mathbf{f}\ \mathbf{N}^2}{4\pi\sigma_x\sigma_y}$$

Tune shift parameter per **IP** :

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

Equal tune shift in both planes ($\xi = \xi_x = \xi_y$) is obtained for

$$\kappa = \kappa_\beta = \frac{\beta_y}{\beta_x}$$

For flat beam luminosity **L** and tune shift parameter ξ can be rewritten as :

$$\mathbf{L} \sim \pi\left(\frac{\gamma}{r_e}\right)^2 \mathbf{f}\ \frac{\xi^2\varepsilon\,(1+\kappa\beta)}{\beta_y}\ \beta_y)\ \sqrt{\frac{\kappa_\beta}{\kappa}}$$

$$\xi \sim \frac{r_e}{2\mu\gamma}\frac{\mathbf{N}}{\varepsilon} \qquad \xi_x \sim \xi \qquad \xi_y \sim \xi\sqrt{\frac{\kappa_\beta}{\kappa}}$$

Crab cavities :

$$V_{RF} \sim \frac{E}{2\pi e}\frac{\theta\lambda_{RF}}{\sqrt{\beta_{x,y}\beta_c}} \qquad \Delta\phi << \frac{2\pi\sigma_{x,y}}{\theta\lambda_{RF}} \qquad \frac{\Delta V}{V} << \frac{1}{\sqrt{N_{x,y}}}\ \frac{\sigma_{x,y}}{\sigma_z}$$

Seeman's criterion :

$$I_2^{min}\ (m^{-1})\ \sim\ 5.1\ 10^9\ \mathbf{n}_i \left(\frac{\xi}{\gamma}\right)^2$$

Bassetti's criterion :

$$I_3^{min}\ (m^{-2})\ \sim\ 4.5\ 10^{30} \left(\frac{r_e}{\gamma^{3.5}}\right)^2 \mathbf{n}_i\ \kappa\ \kappa_\beta \left(\frac{\mathbf{N}}{\beta_y}\right)^2$$

Symbols definition :

$\mathbf{f}$	collision frequency per **IP**
$\mathbf{N}$	number of electrons and positrons per bunch
$\sigma_{x,y}$	horizontal(vertical) r.m.s. beam size @ **IP**
σ_z	longitudinal r.m.s. beam size
$\beta_{x,y}$	horizontal (vertical) β-function @ **IP**
ε	natural emittance
κ	coupling coefficient
κ_β	β-function ratio @ **IP**
$\mathbf{n}_i$	number of crossing per turn
E	electron energy
γ	electron energy in units of its rest mass
r_e	classical electron radius
e	electron charge
θ	crossing half-angle @ **IP**
λ_{RF}	RF crab-cavity wavelength
β_c	β-function in the crab plane @ RF cavity position
$N_{x,y}$	number of damping turns in the crab plane
$\mathbf{U}_o$	energy loss per turn

$$I_2 = \int_{Dip} \frac{ds}{\rho^2}$$

$$I_3 = \int_{Dip} \frac{ds}{|\rho^3|}$$