EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

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CM-P00059371

CERN PS/AR/90-06

B FACTORY WITH A FINITE CROSSING ANGLE

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Abstract

The R&D working group for the design of a B factory in the ISR tunnel has defined the characteristics of a very high luminosity machine based on a geometric separation of the beams at the interaction point (IP). Such a machine has the ISR configuration, namely two rings crossing horizontally. Each beam is made of many bunches with a relatively small number of particles per bunch and is flat at the IP. The orbits being straight in the interaction region, the synchrotron light background is maintained at a low level. In order to avoid synchro-betatron excitation through the beam-beam interaction and to preserve the luminosity, the bunches are rotated horizontally upstream to the IP and re-aligned after the crossing using two deflecting rf cavities per ring (*crab crossing* scheme); this way, the bunches fully overlap when they collide. The commissioning of the machine would begin with symmetric energies where the beam-beam effect is known and be progressively extended to asymmetric energies, a regime for which no experience exists yet.

Geneva, Switzerland

26 February 1990

■ Introduction

Given all the constraints imposed by the beam-beam interaction, the synchrotron radiation and the problems associated with short dense bunches, the only parameter which is, to some extent, free to reach extreme luminosities is the number of bunches. These bunches must collide at the interaction point only and be quickly separated to avoid extra interactions. Magnetic separation assumes a large asymmetry in beam energies and creates synchrotron radiation in the collision area. Geometric separation with a finite crossing angle is free of these limitations. One may thus contemplate a scenario of machine commissioning where the high luminosity regime would first be tested for beams of equal energies, then progressively extended to beams of unequal energies for which there is presently no experience.

■ Problems associated with finite crossing angle

The concept of crossing lepton beams at a finite angle has been tested on DORIS and turned out to be unsuccessful but for reasons which have been understood [1]. In the DORIS configuration, flat beams collide in the vertical plane and are thus submitted to strong transverse fields which vary along the bunch length and drive exceedingly large synchro-betatron resonances. Furthermore, if the crossing angle is calculated to make the optics independent for the two beams, its value is such that the luminosity is severely affected by a lack of overlapping of the incoming bunches.

■ Crab crossing

The solution to these problems lies in a method nicknamed *crab crossing* [2,3]. The bunches are rotated in the real space so that they fully overlap and, within some tolerances, synchro-betatron resonances are no longer excited [4,5].

The bunch rotation is produced by radio frequency transverse fields in a special cavity located at an odd multiple of quarter betatron wavelengths from the interaction point. A second identical cavity is located downstream to the interaction point to realign the bunch along the closed orbit. The spatial dependence of the transverse field is

$$E = E_0 \sin \left(2\pi \frac{z}{\lambda} \right)$$

where $2\sigma_z$ is the bunch length and λ the rf wavelength; the peak field necessary to achieve the bunch rotation is thus

$$E_0 = \frac{E}{\sin \left(2\pi \frac{\sigma_z}{\lambda} \right)}$$

The bunch rotation angle θ at the interaction point is achieved with an integrated field

$$E_0 l = \frac{p c}{e} \frac{\sigma_z \tan \theta}{\sin \left(\frac{2\pi \sigma_z}{\lambda} \right) \sqrt{\beta \beta^*}}$$

or, in the approximation of a large rf wavelength

$$E_0 l = \frac{p c}{e} \frac{\lambda \tan \theta}{2\pi \sqrt{\beta \beta^*}}$$

β and β^* are the values of the β -function at the cavity and at the interaction point. For a given rotation θ , the peak field is roughly proportional to λ ; there is however a tendency to choose a rather low frequency to reduce, as we shall see, the higher mode losses.

Principle of crab crossing. In an rf cavity where the transverse modes are excited, the particles at the head and at the tail of the bunch are deflected in opposite directions so that they oscillate in the magnetic field of the insertion quadrupoles and reach their peak amplitude at an odd multiple of quarter betatron wavelengths corresponding to the distance from the cavity to the interaction point (IP).

The β values at the cavity and at the interaction point have to be as large as possible to keep the rf deflection within reasonable limits. For this single reason, crossing must take place in the horizontal plane and the beams have to be flat. Any increase of luminosity related to round beams is thus discarded but, anyhow, it seems that round beams create too much complication for the reward that can be expected [6].

Super-conducting cavities are chosen because they can withstand a transverse field of 5 MV/m against .25 MV/m for normal cavities [7]. As for the accelerating cavities, a major concern is the evacuation of the higher order modes power. The loss factor k is estimated to be .15 V/pC/m at 350 MHz and varies like the square of the frequency. The rf power generated by the higher order modes is given by

$$P_{\text{hom}} = k f_b q^2$$

where f_b is the bunch frequency and q the bunch charge. Provisional estimates of the cavity impedance [8] cope with the tolerances imposed for bunch stability.

■ Determination of the crossing angle

The crossing angle is determined by the separation of the two adjacent quadrupoles belonging to each beam next to the interaction point. This way, there are no quadrupoles common to the two beams, the optics design is simplified [9] and the synchrotron radiation is reduced to its lowest level.

The pole tip radius a of the quadrupole is equal to $10 \text{ Max}[\sigma_x, \sigma_y]$ augmented of 5 mm for the vacuum chamber. The beam sizes are calculated at the quadrupole location assuming the quadrupole infinitely thin. The distance between the quadrupole axes is $4a$. In this configuration, the final focussing is achieved with permanent magnets [10].

■ Parameter list

The parameter list has been established for symmetric energies. The bunch population n is determined from the luminosity expression

$$L = \frac{\gamma \Delta Q}{2 r_e} \frac{n f_b}{\beta_y}$$

for given high bunch frequency, low vertical β -value and moderate beam-beam tune shift ΔQ . r_e is the classical electron radius and γ the ratio of the total particle energy to its rest energy. The horizontal beam emittance ϵ_x is then inferred from the expression of the beam-beam tune shift

$$\Delta Q_y = \frac{r_e}{2 \pi \gamma} \frac{n}{\epsilon_x}$$

The vertical emittance corresponds to 2% coupling between the horizontal and vertical betatron oscillations. The horizontal β -value is such that the horizontal and vertical beam-beam tune shifts are the same

$$\frac{\beta_x}{\beta_y} = \frac{\epsilon_x}{\epsilon_y}$$

For both the higher order modes power and the synchrotron power density

$$P_{sy} = \frac{2 r_e E_0 I \gamma^4}{3 e \rho^2}$$

the beam current I has to be as low as possible. This is the reason why the vertical β -value at the crossing point is only 1cm at the cost of an accordingly small bunch length. Furthermore, as the geometry of the interaction region imposes two rings with a common horizontal median plane of symmetry, the ISR configuration becomes attractive and ρ has been deliberately increased with respect to the basic design in order to stimulate the study of a combined function lattice reminding that the ISR bending radius was 79 m.

.....General characteristics.....

Energy [GeV]	5.3
Revolution frequency [Hz]	318310.
Number of bunches	800
Bunch spacing [m]	1.18
Bunch population	7.11 10 ¹⁰
Beam current [A]	2.9
Half standard bunch length [m]	0.005
Bending radius [m]	75
Synchrotron power density [kW/m]	5.72
Horizontal emittance [mm.mrad]	0.102527
Vertical emittance [mm.mrad]	0.00205055

.....Interaction Region.....

Luminosity [cm ⁻² s ⁻¹]	1. 10 ³⁴
Half crossing angle [mrad]	20.13
Beam-beam tune shift	0.03
Beam disruption	0.188
Horizontal β at IP [m]	0.5
Vertical β at IP [m]	0.01
Distance from IP to first quadrupole [m]	1
Detector half integrated field [T m]	1

(over)

.....Crab crossing.....

Number of cavities per crossing	2
Horizontal β at the cavity [m]	30
Integrated electric field in a cavity [V]	$2.58 \cdot 10^6$
Deflecting rf frequency [GHz]	0.509296
Number of super-conducting cells	2
Length of a cavity [m]	0.707
Radius of a cavity [m]	0.373
Loss factor at 350 Mhz [$V \cdot pC^{-1} \cdot m^{-1}$]	0.15
Higher order mode power per cell [kW]	3.085

.....Beam separation.....

Vertical deflection at detector exit [mrad]	1.139
First quadrupole half aperture [cm]	1.006
Beam separation at first quadrupole [cm]	4.025

Parameter list for equal energies

■ Final remarks

A B-factory with a finite crossing angle has very promising features related to the high bunch frequency which paves the way towards ultimate luminosities and independent focussing for the two rings which almost eliminates the synchrotron light background in the interaction region. These advantages are at the cost of an extra system: the *crab-crossing* scheme. The preliminary studies do not reveal special difficulties when the needed deflecting cavities are compared with the accelerating cavities. More work has clearly to be done in the domain of the choice of parameters, cavity design, special magnets, coupled bunch instabilities, etc. but it is likely that the machine can be evaluated in detail by the end of 1990. Last, let us note that the interaction areas of a B-factory based on a crab-crossing scheme and of high energy linear colliders are quite similar. More generally, any high luminosity lepton colliders would benefit from the experience developed in bunch rotation schemes. It is therefore our recommendation that the present study be pursued beyond the present mandate of the working group.

■ Working group

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