PRELIMINARY STUDY OF A BEAUTY FACTORY IN THE ISR TUNNEL

B. Autin, Y. Baconnier, P. Bossard, M. Bouthéon, J.C. Brunet, P. Bryant, R. Cappi, J.P. Delahaye, R. Giannini, O. Gröbner, A. Hofmann, K. Hübner, J. Jowett, P. Lefèvre, D. Möhl, H. Moshammer, T. Pettersson, F. Pedersen, W. Pirkl, S. Pichler, J.P. Potier, B. de Raad, T. Risselada, J.P. Riunaud, R. Schmidt, T. Taylor, R. Valbuena, T. Wikberg, B. Zotter
CERN, CH-1211 Geneva 23, Switzerland
R. Abela, S. Adam, B. Berkes, H. Braun, J.F. Crawford, W. Joho, P. Marchand, S. Milton, L. Rivkin, U. Schryber,
PSI, Paul Scherrer Institute , CH-5232 Villigen, Switzerland
R. Eichler, Institut für Mittelenergiephysik der ETH Zürich, CH-3232 Villigen PSI

Abstract

A feasibility study of a beauty factory installed in the tunnel of the decommissioned Intersecting Storage Ring (ISR) of CERN is presented. Derived from the previous PSI proposal, it investigates the possibility of reaching a luminosity of 10^{33} cm^{-2}s^{-1}in a first stage and an ultimate luminosity of 10^{34} cm^{-2}s^{-1} after R & D has been made possible using the first stage machine. The basic scheme consists of an asymmetric collider (3.5 GeV against 8 GeV). The main components are chosen such that a conversion to a collider with equal energies is possible.

1) Introduction

This report summarizes the results of a feasibility study [1] carried out at the joint initiative of CERN and the Paul Scherrer Institute (PSI) [2] to explore the possibility of building a B-meson factory in the ISR tunnel at CERN. There is a wide consensus that an asymmetric energy collider with two rings working at about 8 GeV $\times$ 3.5 GeV offers the best chance for observing CP violation in the B-system.

The approach has been to study a machine which can start with a luminosity of 10^{33} cm^{-2}s^{-1}, but choosing major components such that they have the potential to work at 10^{34} cm^{-2}s^{-1}. The procedure has been as follows: 1) A tentative parameter list for a collider providing a luminosity of 10^{34} cm^{-2}s^{-1} is worked out. It is called "The stage II Machine". 2) The possibility of conversion to a symmetric scheme is introduced in the design because of the lack of experience with the beam-beam interaction in asymmetric colliders. 3) A parameter list for a 10^{33} cm^{-2}s^{-1} asymmetric collider is produced, based on technology which exists or can easily be developed. The essential features allowing an evolution towards the high luminosity asymmetric machine or conversion to the symmetric machine are introduced in the design. This is the "The stage I Machine"

The list of parameters of these 3 machines is given in Table 2. Thanks to the flexibility of the CERN injector complex, it looks possible to use the LEP injector with practically no interference to the other CERN programs.

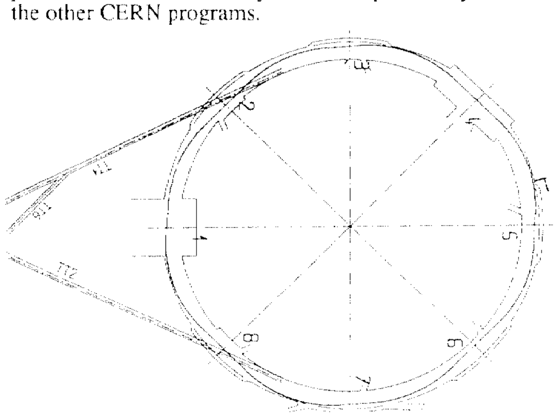

Fig. 1: The Beauty Factory Lattice installed in the ISR Tunnel

General Layout

The ISR was installed in a circular tunnel of 15 m width and 300 m diameter fig 1. Two transfer tunnels TT1 and TT2 provided the link to the PS as proton injector. The tunnel TT6 was added later to inject antiprotons from the PS into the ISR. It is proposed that the tunnel TT2 be used to inject into the B-factory 3.5 GeV positrons accelerated in the PS. The injection of 8 GeV electrons will require successive acceleration to 3.5 GeV in the PS and 8 GeV in the SPS. The injection of electrons will then be done from the SPS using the PS ring as a transfer line, then TT6 and TT1.

The ISR beams collided in 8 interaction areas numbered I1 to I8. It is proposed that two interaction areas for the B-factory are installed in I4 and I8. The rf straight sections are placed in I2 and I6. Four short straight sections in I3, I7 and I1, I5 are used for injection and for the installation of wigglers. The new ring installed in the ISR tunnel is shown in fig 1.

2) Choice of parameters

Assumptions

Different studies of high-luminosity B-factories [1,3,4,5], have all adopted the following set of simplifying rules: a) equal beam size at the interaction point: b) equal bunch frequency c) equal tune shifts d) zero effective crossing angle (i.e. head-on or crab crossing).

Choices

The beam-beam effect and the low-beta optics for unequal energy colliders are the subject of ongoing studies in many laboratories. The lack of experimental data on this subject has stimulated intense simulation and theoretical studies, as well as proposals for experiments to be done on existing single-ring colliders. Different choices concerning beam aspect ratio and beta functions have been made by different groups (Table 1), LBL/SLAC have chosen round beams and equal currents whereas Novosibirsk and KEK have selected flat beams and equal betas in the low and high energy ring. Awaiting further studies we have followed the latter convention and based our feasibility exploration on values of betas and tune-shifts as indicated in table 1.

Table 1

Beam-beam tune-shift parameters and beta-functions in the interaction region as assumed in different studies

Study	CERN/PSI			Novosibirsk	LBL/SLAC
Parameter	Stage I	Sym.	Stage II		
Beam energies (GeV)	3 x 8.5	5.3	3 x 8.5	4 x 7	3 x 9
Vertical beta (cm)					
low energy ring	3	1	1	1	2
high energy ring	3	1	1	1	6
Horizontal beta (cm)					
low energy ring	100	100	33	50	2
high energy ring	100	100	33	40	6
Tune-shift	0.03	0.05	0.05	0.05	0.05
Bunch distance (m)	12	20	3	4	2.5
Number of bunches	80	48	320	150	880

Beam currents and emittances are then determined by the luminosity and tune-shift equations. Wigglers have been included in the low energy ring to adjust the emittance.

Bunch separation

The bunch frequency is constrained by the requirement that the two beams be sufficiently separated at the first parasitic crossing. A distance between the beam centers at the parasitic crossing of 5 σ_h was imposed for vertical separation schemes. In the first stage asymmetric machine a bunch spacing of 12 m has conservatively been taken, to simplify the multibunch feedback system. In contrast to asymmetric operation, beam separation in the symmetric mode cannot be done with magnetic separation, and must rely upon either rf dipoles or electrostatic deflectors. This results in much smaller number of bunches, requires higher emittance values and causes higher HOM losses. In asymmetric machines a large bunch frequency f_b permits small emittances and lower intensity per bunch.

Lattice and bending radius

The synchrotron radiation power, which enters into the design of the rf and vacuum systems, depends critically on the bending radius. For the ISR tunnel, ρ = 65 m turned out to be a reasonable upper limit achievable with a densely packed FODO type lattice. Special dispersion suppressors, which use quadrupoles instead of missing magnets save space for bending and allow tuning of the lattice properties. The straight section space is distributed over 8 straight sections 4 x 50 m plus 4 x 25 m.

Disruption and RF

Results from existing machines [6] led us to adopt a limit on the disruption parameter:

$$D = 4\pi\, \xi_v\, \sigma_s / \beta_v \;\leq 0.25 \text{ to } 0.3 \qquad (1)$$

This indicates that the high luminosity colliders working with a low value of β at the crossing point must also have short bunches. The rf voltage to produce very short bunches is

$$eU \cong 2\pi E\, (\sigma_{E/E})^2\, (R^2/\sigma_s^2)\, \alpha/h \qquad (2)$$

This equation shows the interest to have a small momentum compaction factor α especially in the high energy ring. The energy loss due to incoherent and possibly coherent [1] radiation in the case of very short bunches as well as "higher order mode" losses also contribute to the rf voltage requirement.. The losses are described by a loss factor $k(\sigma_s)$. Assuming that induced signals decay from one bunch to the next, one has:

$$P_{HOM} = k(\sigma_s)\, I^2/f_b \qquad (3)$$

The HOM losses estimated for the proposed 500 MHz cavities are given in Table 2 together with values for the rest of the ring obtained by extrapolating measured data [5].

3) Hardware

A detailed study of the hardware required for the stage I machine has been conducted in order to make a cost evaluation.

General services

No new building or tunnel is needed. The civil engineering work required to install the B-factory in the ISR tunnel is mainly concerned with the installation of klystron galleries on top of the two long straight sections reserved for the rf. The existing water cooling capacity is sufficient for the requirements of the B factory but needs some overhaul. The air conditioning is operational.

Magnets and vacuum chamber

Magnets and vacuum chambers are designed to be compatible with the 3 machines: stage I, stage II and symmetric conversion (Table 2). The machine aperture in both planes ($a_h = \pm 50$ mm; $a_v = \pm 30$ mm) equals ± 10 rms beam sizes plus a closed orbit distortion of ± 6 mm. The beam size in the horizontal plane is obtained by quadratic addition of the uncoupled betatron rms beam size and the contribution of the rms energy spread; in the vertical plane, full coupling is assumed. The vacuum chamber is made of copper. This is imposed by the large power (15 kW/m) deposited by synchrotron radiation along the outer wall in the 8 GeV ring of the stage II machine. At high luminosity the power deposited by HOM losses is close to 1 MW, a special effort is required to design low impedance equipment (bellows, flanges etc.) A schematic cross section of the vacuum system and magnet is shown in fig. 2. The magnet is a classical C-shaped design with a gap of 84 mm. The two rings will be installed on top of each other.

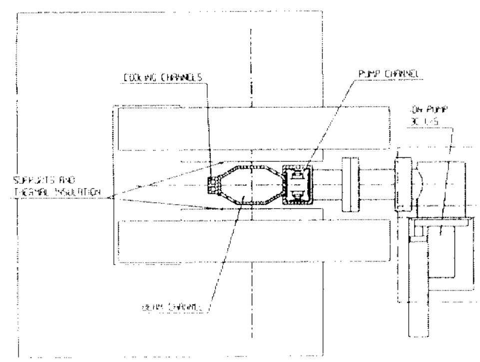

Fig. 2: Schematic Cross Section of Magnet and Vacuum Chamber

Table 2: Parameter Lists of the three Machines

Type		Stage I 10^{33}		Symmetric $6\cdot10^{33}$	Stage II 10^{34}	
Luminosity	[$cm^{-2}s^{-1}$]					
Particles		e^+	e^-		e^+	e^-
Energy	[GeV]	3.5	8	5.3	3.5	8
Circumference L	[m]	963.43	963.43	963.43	963.43	963.43
Bending radius ρ	[m]	65	65	65	65	65
Number of bunches n_b		80	80	48	320	320
Harmonic number		1600	1600	1600	1600	1600
RF frecuency	[MHz]	497.9	497.9	497.9	497.9	497.9
Momentum compaction factor α		0.0086	0.0086	0.017	0.0086	0.005
Horizontal tune Q_H		14.3	12.3	8.3	14.3	18.3
Vertical tune Q_V		16.4	13.4	14.3	16.4	16.4
Aspect ratio σ_V/σ_H		0.03	0.03	0.03	0.03	0.03
Vertical tune shift ξ_V		0.03	0.03	0.05	0.05	0.05
Horizontal tune shift ξ_H		0.03	0.03	0.05	0.05	0.05
Vertical beta at interaction point β_V^*	[m]	0.03	0.03	0.01	0.01	0.01
Horizontal beta at interaction point β_H^*	[m]	1.0	1.0	0.33	0.33	0.33
Vertical emittance $\varepsilon_V=\sigma_V^2/\beta_V^*$	[10^{-6} m]	0.009	0.009	0.011	0.003	0.003
Horizontal emittance $\varepsilon_H=\sigma_H^2/\beta_H^*$	[10^{-6} m]	0.30	0.30	0.36	0.09	0.09
Disruption parameter $\mathcal{D}$		0.25	0.25	0.30	0.30	0.30
Bunch length σ_s	[m]	0.02	0.02	0.0048	0.0048	0.0048
Energy spread σ_ϵ/E	[10^{-3}]	0.52	0.84	0.56	0.41	0.85
Longitudinal damping time	[ms]	37	4.6	16	50	4.6
Total current	[A]	1.28	0.56	1.0	2.56	1.12
Current per bunch I_b	[mA]	16	7	21	8	3.5
Particles per bunch	[10^{11}]	3.21	1.4	4.2	1.6	0.70
Radiation loss per turn	[MeV]	0.3	5.6	1.1	0.22	5.6
Synchrotron radiation power	[MW]	0.39	3.1	1.1	0.56	6.24
Radiation loss per meter in bending magnets	[kW/m]	0.64	7.6	2.7	1.28	15.3
Peak RF voltage V_{RF}	[MV]	2.0	13	115	20.5	120
Total RF power P_{RF}	[MW]	0.70	4.4	3.4	1.4	6.8
Number of 1 MWatt klystrons		1	5	5	2	8
Number of cavities		4	20	40	8	64
Beam power loss P_{beam}	[MW]	0.6	3.2	3.4	1.4	6.8
Dissipated power per cavity P_{diss}	[kW]	34	60	s.c.	s.c	s.c.
Higher order mode losses per cavity P_{HOM}	[kW]	8.2	1.6	36	34	6.5
HOM power in vacuum chamber P_{VAC}	[kW]	140	27	850	590	110
Total input power per cavity	[kW]	175	220	85	180	110
Accelerating field	[MV/m]	1.6	2.2	9.5	8.5	6.3

RF system

The stage I machine uses normal-conducting monocell rf cavities working at 500 MHz. The parameters can be found in table 2. The cavities must be optimized for minimum impedances and optimum accelerating field. A model cavity is being tested in PSI. For the stage II machine superconducting cavities are proposed in order to obtain the high voltage per turn required mainly to achieve a σ_s of 5 mm. Continued R&D effort on these superconducting cavities is required for reaching accelerating fields of 10 MV/m, input power of 200 kW and extracted HOM power of 40 kW.

Instabilities, damper

Single bunch instability thresholds have been estimated including the correction factor for short bunches. Threshold impedances were compared to expected values estimated from calculated cavity impedances, from experimental values of loss factors and from measured impedances in existing machines. The results indicate that with careful impedance control single bunch longitudinal instabilities can be avoided in all 3 machines. The potential well bunch lengthening is small. Threshold impedances to avoid transverse mode-coupling instabilities are less critical.

Multibunch instabilities mostly driven by parasitic resonances in rf cavities have growth rates well above the natural damping rate. Active dampers are therefore required. Power requirements have been estimated for an initial perturbation of 1σ of the beam sizes and energy spread. In the stage I machine the longitudinal damping uses two 800 MHz cavities with overlapping bandwidth of 8 MHz. The peak power of 50 kW is available from commercial klystrons. The transverse damper will require about 1 kW applied to a pair of kicker plates of 1 m with an impedance of 50 Ω.

4) Interaction region

It is the advantage of the asymmetric machines that the separation can be made by magnetostatic fields. We propose to produce this transverse field by tilting the detector solenoid. A tilt of 5 degrees is sufficient to obtain a vertical separation of 5 horizontal σ at 3 m from the main crossing point which corresponds to 160 bunches. A larger tilt will allow the 320 bunches required for stage II. The complex geometry and optics of the interaction area has been analyzed. Satisfactory solutions were found for the stage I and preliminary ones for the stage II machines. The straight sections are long enough to accept the separators required in the case of the symmetric machine. The question of detector shielding from particles lost upstream has been addressed in detail, Fig 3 gives the layout of the detector vacuum chamber, masks, pumping ports and circulating beams in the vicinity of the interaction point. The background is acceptable in the stage I machine. The protection against background of the stage II machine with only twice the beam current does not seem out of reach.

5) Injectors

The LEP e+e- injector can be used in interleaved mode with the other duties of the CERN injector complex. In this way it is possible to feed the B-factory without interfering with the CERN programme (including LEP). In order to speed up the filling of the Beauty Factory the production rate of the positrons has to be improved by a factor 7. The stage I machine will be able to achieve an average to peak luminosity of 60% with physics runs of two hours. The Stage II machine consumes particles at a very high rate owing to its higher luminosity so that after 2 hours the luminosity has dropped to 10% . In that case the practical run time will be around one hour with an average to peak luminosity of 40% .

6) Further studies

This feasibility study, of necessity, left aside all problems which take more than a few months to treat. The theoretical studies to be pursued include: 1) interaction region optimization, vertical dispersion matching, compensation of coupling, 2) masking and background, 3) shielding of the superconducting rf cavities from the harsh environment. 4) experimental studies of beam-beam interaction issues relevant to the B-factory design.The "Crab crossing" variant should be studied in detail, experiments should be made at existing machines on crab crossing and short bunches. Prototype work must be done on copper vacuum chambers with extreme cooling requirements, low HOM rf cavities (including HOM dampers and couplers), low impedance bellows, kickers, septa and radiation masks, separators for the symmetric machines and crab crossing cavities.

7) Conclusion

The present feasibility study shows that a B-factory could be built on the CERN site. No civil engineering is required, a modest upgrade of the LEP injectors is sufficient. The machine can run without interfering with other CERN programmes. It is remarkable that a B-factory with a luminosity two orders of magnitude above presently achieved values seems accessible provided one plans the necessary intermediate stage.

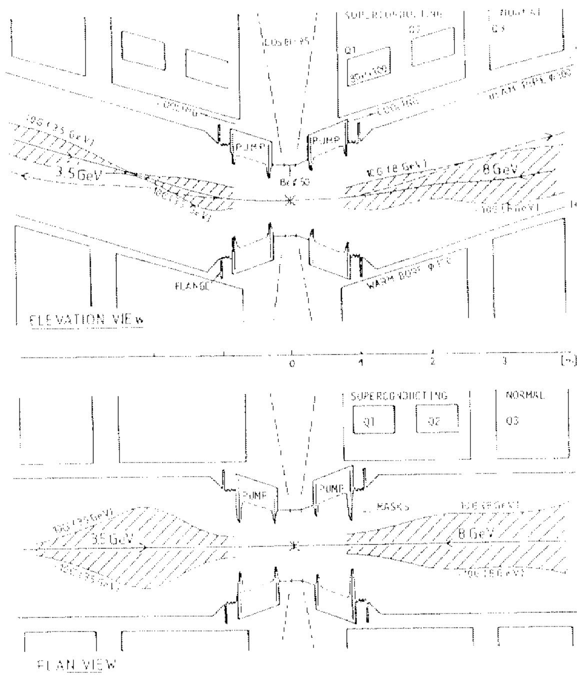

Fig. 3: Geometry of the Interaction Area.

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