Preliminary Study of a Beauty Factory in the ISR Tunnel


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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.

PRELIMINARY STUDY OF A BEAUTY FACTORY IN THE ISR TUNNEL

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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 I 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 $10^{34}$ 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 II 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](image)

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 11 to 18. It is proposed that two interaction areas for the B-factory are installed in 14 and 18. The rf straight sections are placed in 12 and 16. Four short straight sections in 13, 17 and 11, 15 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 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>
<thead>
<tr>
<th>Parameter</th>
<th>CERN/PSI</th>
<th>Novosibirsk</th>
<th>KEK/SLAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energies (GeV)</td>
<td>3 x 8.5</td>
<td>3 x 8.5</td>
<td>3 x 9</td>
</tr>
<tr>
<td>Vertical beta (cm)</td>
<td>5.3 x 8.5</td>
<td>3 x 8.5</td>
<td>3 x 9</td>
</tr>
<tr>
<td>low energy ring</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>high energy ring</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Horizontal beta (cm)</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>low energy ring</td>
<td>100</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>high energy ring</td>
<td>100</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>Tune-shift</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Bunch distance (m)</td>
<td>12</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>80</td>
<td>48</td>
<td>150</td>
</tr>
</tbody>
</table>

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 cm 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, p = 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:

$$D = 4 \pi I_c / B \leq 0.25$$ to 0.3

(1)

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

$$eU \approx 2 \pi e (\sigma_E \epsilon_0 / \epsilon_0) (R^2 / \epsilon_0^2) \alpha / h$$

(2)

This equation shows the interest to have a small momentum compaction factor $\alpha$ 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 $k(\sigma_E)$. Assuming that induced signals decay from one bunch to the next, one has:

$$k(\sigma_E) = \frac{e^2}{\epsilon_0}$$

(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 ($\alpha_y \leq 50$ m; $\alpha_x \leq 30$ m) equals $\pm 10$ rms beam sizes plus a closed orbit distortion of $\pm 6$ mm. The beam size in the horizontal plane is obtained by quadratic addition of the uncoupled horizontal 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](image_url)

### Table 2: Parameter List of the three Machines

<table>
<thead>
<tr>
<th>Type</th>
<th>Luminosity</th>
<th>$\text{cm}^{-2} \text{s}^{-1}$</th>
<th>Stage I 10^{23}</th>
<th>Symmetric 6-10^{23}</th>
<th>Stage II 10^{24}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>[GeV]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circumference</td>
<td>[m]</td>
<td>993.43</td>
<td>993.43</td>
<td>993.43</td>
<td>993.43</td>
</tr>
<tr>
<td>Bending radius</td>
<td>[m]</td>
<td>55</td>
<td>65</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>$n_b$</td>
<td>80</td>
<td>80</td>
<td>48</td>
<td>320</td>
</tr>
<tr>
<td>RF frequency</td>
<td>[MHz]</td>
<td>497.9</td>
<td>497.9</td>
<td>497.9</td>
<td>497.9</td>
</tr>
<tr>
<td>Momentum compaction factor $\alpha$</td>
<td></td>
<td>0.0086</td>
<td>0.0086</td>
<td>0.017</td>
<td>0.0086</td>
</tr>
<tr>
<td>Horizontal tune $Q_H$</td>
<td></td>
<td>14.3</td>
<td>12.3</td>
<td>8.3</td>
<td>14.3</td>
</tr>
<tr>
<td>Vertical tune $Q_V$</td>
<td></td>
<td>18.4</td>
<td>13.4</td>
<td>14.3</td>
<td>16.4</td>
</tr>
<tr>
<td>Aspect ratio $\epsilon / \epsilon_0$</td>
<td></td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Vertical tune shift $\epsilon_0$</td>
<td></td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Horizontal tune shift $\epsilon_H$</td>
<td></td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Vertical beta at interaction point $\beta_y$</td>
<td></td>
<td>1</td>
<td>1.0</td>
<td>0.33</td>
<td>0.33</td>
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<tr>
<td>Horizontal beta at interaction point $\beta_y$</td>
<td></td>
<td>0.009</td>
<td>0.009</td>
<td>0.011</td>
<td>0.003</td>
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<td>Horizontal emittance $\epsilon_H \sigma$</td>
<td>[10^{-4} m]</td>
<td>0.39</td>
<td>0.39</td>
<td>0.36</td>
<td>0.09</td>
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<tr>
<td>Horizontal emittance $\epsilon_H \sigma$</td>
<td>[10^{-4} m]</td>
<td>0.32</td>
<td>0.32</td>
<td>0.30</td>
<td>0.30</td>
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<tr>
<td>Bunch length $\sigma_t$</td>
<td>[mm]</td>
<td>0.02</td>
<td>0.02</td>
<td>0.0048</td>
<td>0.0048</td>
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<tr>
<td>Energy spread $\sigma_E / E$</td>
<td>[10^{-4}]</td>
<td>0.52</td>
<td>0.52</td>
<td>0.56</td>
<td>0.41</td>
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<tr>
<td>Longitudinal damping time</td>
<td>[ms]</td>
<td>37</td>
<td>4.6</td>
<td>16</td>
<td>50</td>
</tr>
</tbody>
</table>

**Additional Details**
- The table lists parameters for the three stages of the machine, including energy, luminosity, horizontal and vertical tunes, aspect ratios, beta functions, emittances, and energy spreads.
- The table also includes details on the vacuum chamber and magnet designs, highlighting the importance of considering the power deposited by HOM losses.

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Note: The image_url placeholder should be replaced with the actual image URL for the cross section figure.
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 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 3 horizontal 0 at 3 m from the main crossing point which corresponds to 150 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.

References