DESIGN OF THE VACUUM SYSTEM FOR THE HIGH ENERGY RING OF AN ASYMMETRIC B-FACTORY BASED ON PEP

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ABSTRACT

The multi-ampere currents required for high luminosity operation of an asymmetric B factory leads to extremely stressing requirements on a vacuum system suitable for maintaining long beam-gas lifetimes and acceptable background levels in the detector. We present the design for a Cu alloy vacuum chamber and its associated pumping system for the 9 Gev electron storage ring of the proposed B factory based on PEP. The excellent thermal and photo-desorption properties of Cu allows handling the high photon flux in a conventional, single chamber design with distributed ion pumps. The x-ray opacity of the Cu is sufficiently high that no additional lead shielding is necessary to protect the dipoles from the intense synchrotron radiation generated by the beam. The design allows chamber commissioning in <500 hr of operation.

I. INTRODUCTION

The vacuum system of the asymmetric B-factory based on PEP [1] (APIARY) presents a technical challenge beyond that of any existing electron storage ring. Each technical sub-system must meet demanding design criteria to meet the overall system requirements. The sub-systems for the high energy (electron) ring (HER) are the beam chamber, the pumping sub-system, the cooling sub-system, and the special components.

The 9 GeV HER will have a circulating beam current of ≈1.5 A for a design luminosity of 3×10^{33} $cm^{-2}s^{-1}$. To allow for possible upgrades and to provide for luminosity "breathing room", we specify a maximum limiting current of 3 A. This value is an order of magnitude beyond that which typifies present colliders. As such it presents an appreciable challenge to the system designer. The system requirements specifying pressures during collider operation at a maximum limiting current of 3 A are as follows:

- ≤ 10 nTorr in the dipole arcs,
- ≈3 nTorr in the straight sections,
- ≈1 nTorr in the straight upstream of the detector,
- ≈ 0.1 nTorr base pressure with no beam.

The circulating electron beam subjects the walls of the vacuum chamber to copious synchrotron radiation. As the angular distribution of the radiation fan is narrow, the associated thermal flux is high enough to require considerable cooling of the chamber wall. The cooling sub-system is designed to remove the waste heat safely under the conditions of high radiation flux regardless of machine tune. As is common, cooling is accomplished by water flowing in channels exterior to the chamber. In addition to assuring the mechanical stability of the chamber under thermal loads as high as 10 MW in the HER maintaining the chamber wall at a relatively low temperature minimizes the gas load due to thermal desorption.

II. CHAMBER SIZE

The HER lattice outside the interaction region is composed of 48 standard straight cells, 72 standard arc cells and 24 dispersion suppressor cells. The chamber size in the arcs is determined by the beam's emittance, its energy spread, and the lattice functions. For adequate quantum lifetime regardless of tune, we designed the chamber to accommodate the uncoupled horizontal emittance and the fully coupled vertical emittance. The chamber cross section is kept constant throughout the bends to minimize the constribution to the impedance budget from the chamber. Hence, we use the maximum values of the optical functions to size the chamber. In the absence of extensive wigglers, the beam's energy spread should be close to its natural value, 6.1×10^{-4}. For conservatism, we assume a value of 10^{-3}. As the optics are similar to PEP, the closed orbit allowances should also be similar. The emittance and optical specifications for the HER are given in Table 1.

Table 1. Optical parameters for the HER

Max uncoupled ε_{xo}	100 nm
Fully coupled ε_{yo}	50 nm
Max. horiz. β in arcs, β_{xmax}	25.6 m
Max. vert. β in arcs, β_{ymax}	32.9 m
Max. dispersion, η_{max}	1.86 m
Horiz. closed orbit, CO_x	± 10 mm
Vert. closed orbit, CO_y	± 5 mm

The minimum horizontal and vertical sizes are given by

$$\sigma_{xtot} = 10\left\{\varepsilon_{xo}\,\beta_{xmax} + \eta^2_{max}\left(\frac{\sigma_E}{E}\right)^2\right\}^{1/2} + CO_x \qquad (1)$$

and

$$\sigma_{ytot} = 10\left\{\varepsilon_{yo}\,\beta_{ymax}\right\}^{1/2} + CO_y \qquad (2)$$

respectively. To include allowances for fabrication and mechanical positioning, we adopted the following chamber (inner) dimensions for the HER: $BCS_x \times BCS_y$ = ±45 mm × ± 25 mm. The corresponding conductance of a 1 m section of beam pipe is 35 l/s.

III. SYNCHROTRON RADIATION LOAD

Each cell of the HER arcs has a length of 15.2 m and is divided into two two halves, each containing a PEP dipole (0.182 T), a quadrupole and a bellows. Our estimate of the

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thermal load from the synchrotron radiation generated in the dipole follows from the analysis of [2]. The relative power profile is displayed in Fig. 1. At the design current of 1.5 A maximum power deposited is 51 W/cm.

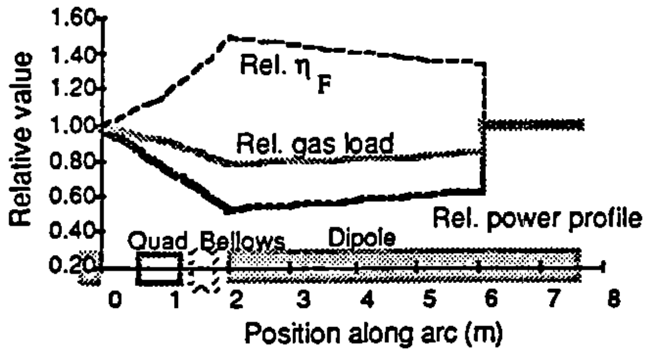

Fig. 1. Relative distribution of synchrotron radiation, η_F, and gas load in arcs of 9 GeV APIARY ring.

In the arcs the bending radius is 165 m, and the a maximum angle of incidence of the radiation is 23 mrad. For conservativism in estimating the power density, we ignore the contribution to the height of the synchrotron fan due to the finite emittance. Thus, the minimum height of the illuminated strip is ≈0.5 mm. The corresponding maximum thermal flux at 1.5 A is P_A, 1.14 kW/cm^2, two-thirds of the design value for the present PEP chamber. The corresponding photon flux, which has a typical synchrotron radiation spectrum with a critical energy of 9.8 keV, is 4×10^{19} s^{-1}cm^{-2}. This value provides the basis for the EGS4 calculations of radiation absorption in the chamber.

IV. ABSORPTION OF SYNCHROTRON RADIATION

Depending upon material and thickness of the beam pipe, synchrotron radiation may escape and deposit energy in the surroundings. This radiation can damage magnet insulation, wire insulation and cooling water hoses. The damage threshold for the magnets is a function of the potting compound. The expoxy insulating the PEP magnets is expected to tolerate ≈10^{10} rad. We have adopted 3×10^9 Rads as a conservative criterion, which sets a limit of 10^8 Rads/yr for a magnet lifetime of 30 years. For 6000 hr of operation at the 1.5 A current, the allowed yearly dose translates to 4.9×10^{-19} Rads/e$^-$. This criterion is used to compare with EGS4, which calculates dose *per incident electron*, either in terms of fluences, energy deposited, or Rads (using appropriate conversion factors).

For most calculations the cutoffs for tracking the electromagnetic cascade set at 10 keV (photons) and 1 MeV (electrons). Upper energies for both electrons and photons were 10 MeV. The photon spectrum was sampled uniformly within an energy range from 0.1 ε_{crit} to 10 ε_{crit}. A weight was carried along with each photon (and progeny) for scoring purposes. The final results were later normalized per incident beam electron.

The beam pipe is an octagonal chamber with a copper cooling bar as shown in Fig 2. Our calculations show that only 2.5 mm of Cu is needed to meet the radiation leakage criterion at the point of maximum dose (top and bottom of the beam pipe) for 9-GeV beams. In contrast an octagonal aluminum pipe that is 5 mm thick requires a lead liner. We have adopted 5 mm of Cu as the wall thickness to allow for sufficient shielding at energies as high as 12 GeV.

Using the details of radiation absorption from EGS4, we calculate the temperature distribution in the walls using the thermal analysis program, TOPAZ. For 25° C water flowing at 3 m/s through stainless steel cooling tubes the maximum temperature in the beam tube is 160° C. A 2-D stress analysis with NIKE2D indicates a maximum vertical deflection of 0.021 mm of the flat horizontal faces of the beam tube (an acceptable value). This analysis also shows maximum stresses of 90 MPa, exceeding the yield stress of the 98%Cu-2% Sn alloy in the region where the radiation fan strikes the chamber. This calculation is overly conservative since it does not account for stress relief that would be obtained through bending out of plane axis. We therefore believe that the alloy will actually have sufficient yield strength to withstand the thermal load. We are making a 3-D analysis to evaluate the effects of bending. If the 3-D calculations also indicate that the material yields, we will make a cyclic fatigue analysis to determine if there is a structural problem.

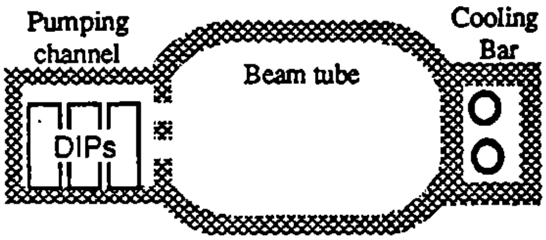

Figure 2. Cross section of the HER arc vacuum chamber.

V. GAS LOAD AND PUMPING

During collider operation photo-desorption from the chamber walls dominates the gas load. Following ref. [2] we can translate the thermal load into a dynamic gas load including the leveling effects due to a non-uniform photo-desorption efficiency, η_F (Fig. 1). Measurements of η_F [3, 4, 5] for well exposed samples of Al, stainless steel and high conductivity, oxygen free Cu indicate minimum values ranging from $<2\times10^{-6}$ for Cu and stainless steel to 2×10^{-5} for Al. Although the beam-gas lifetimes in storage rings with lower ε_{crit} than APIARY suggest that Al may eventually develop an effective $\eta_F \approx 10^{-6}$, we believe a more reliable approach is to adopt Cu or stainless steel as the chamber material despite their higher bulk cost. As the data [5] indicate that pure Cu can attain $\eta_F \le 2\times10^{-6}$, we selected this value as the design basis. Such a low desorp-ion coefficient allows the vacuum chamber to have a conventional shape instead of an ante-chamber configuration that is more difficult and expensive to fabricate. The apparent cost disadvantage of Cu or stainless vis á vis Al is more than offset by the relative simplicity of the chamber shape, by the reduction of the required pumping and by the reduced commissioning time.

With a minimum η_F of 2×10^{-6}, the maximum gas load at 3 A is 1.2×10^{-6} Torr-l/s/m with the profile of Fig. 1.

Such low values of η_F have been measured in pure Cu. Confirming the practicality of our design choice for η_F is a key part of an experimental validation program.

To pump this gas load, we have selected an all sputter ion pump design. We show the inventory of pumping capacities for each pumping element in a typical cell in Table 2. At 1.5 A the desired average pressure (5 nTorr) is maintained with distributed pumping of 125 l/s/m. To achieve these speeds the distributed ion pumping in the dipoles of PEP has been redesigned to operate in a 0.18 T field. The anode was increased to 1.8 cm diameter, and one more row was added, increasing the number of anodes by 33% with a packing factor of about 90%. Distributed ion pumping (DIPs) has been added at the quadrupoles in stainless steel housings to one side of the beam tube and below but none on the top to preclude particles dropping into the beam chamber. As the available space is restrictive, the anodes have been reduced in size. The calculated pumping speed in the beam tube will be about 75 l/s/m from each of the steel housings. However, the total pumping speed for the defocusing and focussing quadrupoles are different owing to their different lengths. To augment the DIPs we have added 60 l/s lumped ion pumps in each of the quadrupole spaces of the cells. Given the low conductance of the beam pipe, larger pumps would not improve system performance. Moreover, the ports are designed to accommodate additional pumps if needed.

Table 2. Pumping inventory of HER arc cell

2 Dipole DIPs	800 l/s
1 Quad DIP	110 l/s
1 Quad DIP	80 l/s
1 Lumped ion pumps	60 l/s
Total distributed pumping	125 l/s/m

VI. STRAIGHT SECTIONS & SPECIAL COMPONENTS

To keep the contribution of the ports to the machine impedance negligible the ports are shielded with perforated screens with longitudinal slots 10 cm long by about 0.2 cm wide. The pumping slots in the septum between the pump channel and beam tube have been calculated as rows of slots 9 cm long by about 0.2 cm wide at a pitch of 10 cm, similar to HERA, giving a conductance of about 500 l/s/m. These slots contribute a negligible amount to machine impedance.

Each bend cell contains a beam position monitor (BPM) located at and anchored to the defocusing quadrupole. The BPM for APIARY follows the HERA design with minor modifications. The housing will be accurately machined from a solid Cu block having recesses on its end faces to index the ends of the beam tube for alignment during brazing. Cooling on both sides will preclude a temperature asymmetry between lateral sides.

Changes in cross section between the arcs of octogonal cross section and the straight sections of circular cross section are made with tapered transition elements. To keep the total contribution to the chamber impedance within the impedance budget, the taper angle is <10°.

A typical cell in the straight sections is 15.125 m in length. The vacuum conduit is a 10 cm diameter, stainless steel tube of circular section sized to clear the 100 mm bore of the magnets. To produce an average pressure <3 nTorr in the straight sections we will install lumped sputter ion pumps rated at 230 l/s spaced by ≈8 m. We have calculated the pump size and spacing assuming a thermal outgassing rate of 10^{-11} torr-l/cm^2/s and a pressure differential in the beam tube of 0.5 nTorr. In situ baking compatibility to 150° C is provided to reduce the initial outgassing and to allow for pressures in the 0.1 nTorr range if such low pressures are required.

To aid in the assembly both bend and straight cells contain bellows designed to permit 130°C of thermal expansion. In their extended position at room temperature, the bellows are 22.9 cm long. They can compress ≈4 cm to 18.9 cm at the maximum temperature (150° C) to which the ring can be baked in situ without disassembly. The inner bellows which carry the surface currents is fabricated as one piece with formed convolutions in the plane of the beam tube flats and has narrow slits at the intersecting corners to permit axial movement. A narrow slit permits synchrotron radiation to shine through to thick-wall, water cooled, Cu absorbers cantilevered from the flanges to carry away the thermal load.

A calculation of a commissioning scenario [2] shows that the time needed to store the design current for >2 hours varies with the initial value of η_F as determined by fabrication procedures. For $\eta_F(0) = 10^{-3}$, commissioning the Cu chamber requires ≈500 hr. For an appropriately cleaned chamber we expect $\eta_F(0) = 10^{-4}$, in which case the full design current can be stored after 150 hours (Fig. 3).

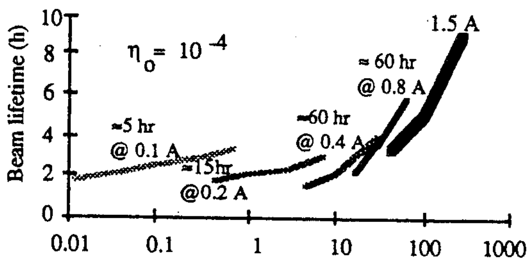

Figure 3. Commissioning scenario for an etched Cu chamber.

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