Issues Confronting Vacuum System Design for e^+e^- Storage Rings[1]

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Abstract

The next generation of electron/positron storage rings will pose an intense challenge to designers of the vacuum systems. For colliders such as B-factories, tau-charm factories and ϕ-factories, beam currents in the ampere range will produce very high power densities of synchrotron radiation (SR). The enormous gas-load due to SR-induced desorption requires particular ingenuity in providing sufficient pumping speed and capacity to achieve the required average pressure. Constraints on beam-gas induced detector backgrounds produced in the interaction region (IR) influence not just the vacuum system but the optics as well as the geometry of the IR. Experience gained by several groups in solving these problems for B-factory storage ring designs is discussed and some of the solutions used in new Synchrotron Light Sources are presented.

I. INTRODUCTION

The design of vacuum systems for storage rings has become a full-fledged science requiring broad application of many different diverse fields. It is no longer possible to be an artist and put together a system of pipes and pumps on the spot and launch it on a ten-year career without much further attention! The design of an ultra high vacuum (UHV) system for an electron/positron storage ring requires a knowledge of surface science; materials science; thermal and mechanical stress analysis; beam induced RF fields; X-ray absorption, reflection and fluorescence; scattering of beam particles and production of secondaries; and above all, a flair for the art of magic to put all this together and make a UHV system out of narrow beam pipes with very low conductance, no space for pumps and permission denied to make large holes for pumping ports!

These considerations arise in the design of UHV systems for e^+e^- colliders and for high energy Synchrotron Light Sources (SLS) with large circulating beam currents in the ampere range containing hundreds of short intense bunches. Colliders have high energy physics (HEP) detectors at the interaction point which are extremely sensitive to backgrounds from synchrotron radiation (SR) and beam particle losses. SLS have large numbers of X-ray ports and beam lines that must be capable of handling intense light beams of tens of kW. Dynamic pressures are required to be in the low 10^{-9} Torr range or even lower, to allow beam storage times from a few hours to as much as 24 hours.

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Some of the problems presented for UHV design are very similar in the two applications while others are peculiar to each:

- Very high intensity of SR incident on chamber walls, absorbers, beam stops and X-ray windows.
- Large rates of gas desorption induced by the SR.
- Short intense beam bunches give rise to beam induced RF fields and power losses that can cause damage to sensitive vacuum components such as bellows, ceramic windows, ceramic chambers, etc.
- Severe problems arise in collider interaction regions (IR) due to synchrotron radiation and particle loss backgrounds which interfere with the HEP detectors.
- Positive ion trapping in the potential well of the electron beam exacerbates all the problems of residual gas density in the beam path. Positron beams are happily immune to this, so that light sources can avoid this problem altogether by using only positron beams.
- In light sources, severe constraints are introduced by small, variable aperture insertion devices and by the requirement for many X-ray beam lines with crotches, beam-stops, windows, etc.

We will briefly describe the solutions to some of these problems adopted for new light sources currently under construction and for collider rings proposed as "B Factories".

II. TYPICAL PARAMETERS

We show below some parameters relevant to vacuum system design. Table 1 lists parameters for B-Factory proposals at Cornell[2]and CERN[3] and SLAC[4]. Table 2 lists typical parameters of a light source (the European Synchrotron Radiation Facility, ESRF)[1].

The intense power of SR striking chamber walls and absorbers is illustrated by the examples below. In the SLS, due to the short length of the magnets, discrete absorbers and localised massive pumping is particularly suited to the geometry. In the B Factories, solutions include both continuous and specially designed discrete absorber concepts in various parts of the rings to accomodate a range of linear SR power densities. For example in CESR-B, the B Factory proposed at Cornell, the SR power density ranges from about 0.3 kW/m in a soft-bend magnet

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Table 1: Typical parameters for B Factories

Parameter	CESR-B @($\mathcal{L} = 3 \times 10^{33} cm^{-2}s^{-1}$)		CERN/PSI @($\mathcal{L} = 1 \times 10^{33} cm^{-2}s^{-1}$)		SLAC/LBL @($\mathcal{L} = 3 \times 10^{33} cm^{-2}s^{-1}$)	
E_o, beam energy (GeV)	3.5	8.0	3.5	8.0	3.1	9.0
I_{beam}, nominal current (A)	2.0	1.0	1.28	0.56	2.14	1.50
ρ, bend radius in arcs (m)	20	87	65	65	30.5	165
P_{SR}, radiated power (kW/m)	10.6	7.6	0.64	7.65	2.1	5.1
ϵ_c, critical energy (keV)	4.75	13.1	1.5	17.5	2.2	9.8
Absorber material	copper		copper		copper	
$\dot{q}$, dynamic gas load (torr-ℓ/s/m)	6.7×10^{-6}	1.8×10^{-6}	0.83×10^{-6}	0.5×10^{-6}	1.7×10^{-6}	0.63×10^{-6}
$\dot{q}_T$, thermal gas load (torr-ℓ/s/m)	0.2×10^{-6}	0.2×10^{-6}	-	-	0.2×10^{-6}	0.13×10^{-6}
P_o, ave. pressure in arcs (ntorr)	2.7	3.6	1.7	1.0	7.5	5
S, ave. pumping speed (ℓ/s/m)	2555	583	500	500	225	125

Table 2: Typical Light Source Parameters

E_o (positron beam)	:	6 GeV nominal
I (beam current)	:	0.2 A maximun
n_B	:	992 bunches maximum
Circumference	:	850 m
Total SR Power	:	0.900 MW
ϵ_c (critical SR energy)	:	19.2 KeV typical
SR power density on discrete absorbers	:	$\sim 400 W/mm^2$
Beam-induced gas load	:	$\sim 8 \times 10^{-5}$ torr-ℓ/s
Thermal gas load	:	$\sim 6 \times 10^{-5}$ torr-ℓ/s
Total gas load	:	$\sim 1.4 \times 10^{-4}$ torr-ℓ/s
Total Pumping Speed for 10^{-9} torr	:	1.4×10^5 ℓ/s

to about 25.2 kW/m in a hardbend magnet of the high energy ring (HER). Similarly, gas loads in the rings vary over a wide range of values in different sections. For example, in CESR-B the linear gas load evolved is about 3.3×10^{-7} Torr-ℓ/s/m in the soft-bends of the HER and about 6.8×10^{-6} Torr-ℓ/s/m in the hard-bend magnets of the low energy ring (LER). These parameters call for new and ingenious solutions tailored to each situation.

III. SR INDUCED GAS DESORPTION

The main gas load in the arcs is produced by desorption induced by the SR incident on the absorber walls and by scattered X-rays on the rest of the chamber. Thermal outgassing is a small fraction of the SR- induced gas load except in the long straight sections such as the interaction region and RF straights. Hydrogen, CO and CO_2 are the main components of the gas desorbed by SR from clean UHV chamber walls. Although H_2 usually makes up almost 50% of the residual gas, the effects on beam lifetime and detector background are both dominated by the N_2-equivalent gases CO and CO_2 because of the Z dependence of the scattering processes. For estimating the SR-induced gas load, the parameter of interest is the desorption coefficient η_{SR} expressed in molecules desorbed per incident photon. It is well known from CESR, PEP, PETRA and other existing electron rings that beam-scouring produces the most effective means of reducing the desorption coefficient. The desorption rates for aluminum alloy, stainless-steel and recently, for copper, have been carefully measured and compared,[5,6,7,8,9] and the art of predicting outgassing rates has been turned into a science[10,11]. Nevertheless, there is still a wide range of η_{SR} used by various groups to predict the gas load of their rings. All available data indicate that at very high doses (e.g., above 10^{24} photons per meter) the desorption coefficients for aluminum, stainless steel and copper are very close to each other, although initial desorption is considerably higher for cleaned aluminum than for copper or stainless steel. However, none of the experiments listed above have measured η_{SR} at doses large enough to be directly useable for predictions of "ultimate" desorption rates after many amp-hours of operation. Thus, the data obtained in experiments at Orsay and elsewhere must be extrapolated to different extents by the proponents of the various storage rings.

An additional factor to be taken into account is the effect of *scattered* photons which desorb gas from the regions of the chamber that have received only 10% of the primary dose that is incident on the narrow stripe of absorber hit *directly* by the SR beam. The desorption coefficient on a large part of the chamber can thus be more than an order of magnitude higher than that assumed for the primary stripe and the outgassing due to scattered photons may dominate the gas load!

One way to obtain a realistic estimate for the overall outgassing due to the beam is to use an *effective* desorption coefficient derived from an operating storage ring. At CESR, where in the hard-bend regions the photon dose rate and energy spectrum are very similar to that expected in the proposed CESR-B normal arcs, we "observe" an effective η_{SR} of 5×10^{-6} molecules/photon, derived from the observed specific pressure rise of 3.2×10^{-11} Torr/mA of beam after several years of operation at 100 mA. This pressure rise is for an aluminum chamber and for the *total* gas load including about 50% H_2. By using this as the effective coefficient for CO and CO_2 we build in a conservative safety factor of about two. In addition, this desorption coefficient represents actual operating experience that includes a history of several ventings to pure N_2 of virtually every part of the ring for improvements and upgrades, an inevitable experience to be expected at all storage rings. Note that the low value of the specific pressure rise quoted above is now reached within a few days of venting the sector to pure N_2.

Further exploration of desorption coefficients from copper is necessary to determine whether the desorption coefficients continue to fall with exposure below the levels assumed in Tables 1. Another direction to pursue is the search for low photodesorption coatings for absorbers and chamber walls. Coatings of gold or hard carbon (i.e., diamond) may hold the promise of low desorption and good heat dissipation. Such experiments are in progress at the NSLS at Brookhaven National Laboratory[12]. Similar coatings may also be very useful in the design of SR masks used in the interaction region of colliders, where these SR masks have to absorb high power densities without scattering too much into the detector.

IV. CHAMBER GEOMETRY AND PUMPING

The actual configuration of the vacuum chamber is dictated by the two constraints of safe absorption of the intense synchrotron radiation power emitted in the bend regions and of sufficient pumping to meet the pressure requirements. A further constraint due to the short bunch length and high current is the need for a smooth profile in the beam chamber to minimize parasitic higher order mode (HOM) power losses and induced fields.

The conventional solution is to absorb the SR on a continuous water-cooled wall of the chamber and install distributed pumping in a parallel pump chamber on the opposite side of the beam. Pumping slots provide a fairly large conductance to the pump chamber. This solution has been used in SPEAR, CESR, PEP, PETRA and most recently in LEP.

New light sources have been designed with discrete SR absorbers placed between bend magnets, with massive discrete pumping to take the main gas load. The Argonne APS uses an "ante-chamber"[13] to allow the SR fan to pass through and incorporates distributed pumping in the ante-chamber. However, to make full use of the ante-chamber concept one has to incorporate distributed pumping on *both* sides of the beam channel to take advantage of the isolation provided by the slot to the ante-chamber where the SR is absorbed.

A unique chamber profile has been adopted for the hard-bend ($\rho = 45$ m) regions of the arcs flanking the IR in CESR-B, where the pressure must average 1×10^{-9} Torr due to experimental beam-gas background constraints. In these regions of intense SR and consequent high gas load per meter, it is necessary to allow the SR to pass through a continuous slot and impinge upon an absorber bar within a large pumping chamber. (See Figure 1.) This configuration provides the necessary high conductance for gas molecules between the absorber and the sublimated getter material on the walls of the pump chamber. Differential pumping is provided by NEG (non evaporable getter) modules on the opposite side of the beam chamber. A similar

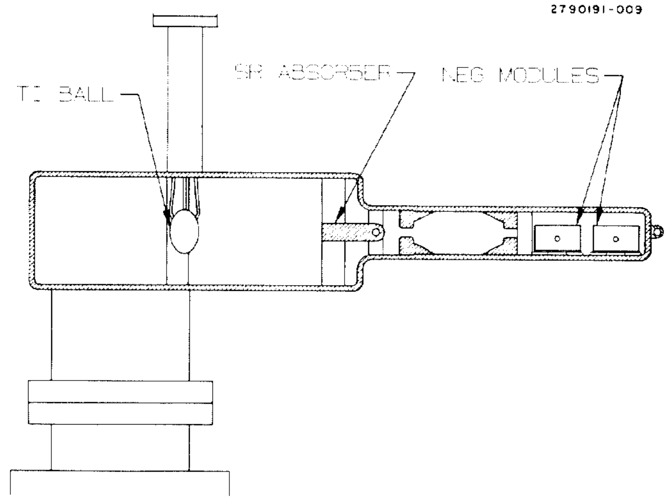

Figure 1: The copper vacuum chamber for the hard-bend region of CESR-B. The SR beam passes out from the beam chamber through a continuous slot and is absorbed on the water-cooled absorber bar in the pumping region (on the left).

solution is adopted for the LER, but the absorber bar and enlarged pump chamber lie in the drift space between arcs of a half-cell as shown in Figure 2. This configuration is intermediate between the continuous wall and discrete absorber concepts.

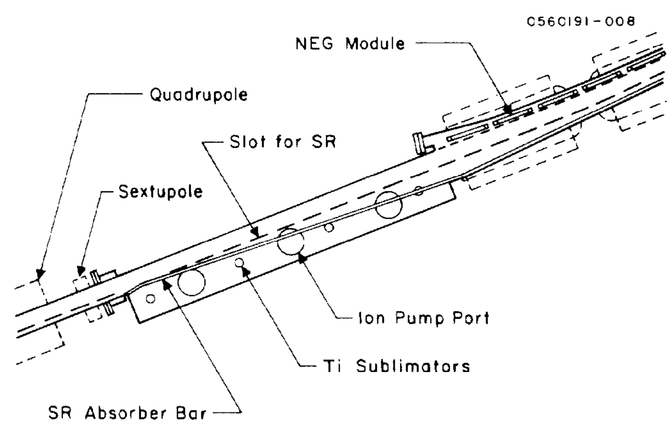

Figure 2: The copper vacuum chamber for the LER arcs of CESR-B. The SR beam is absorbed on the inclined water-cooled absorber bar in the enlarged pumping region between the bend magnets.

In the SLAC B Factory design, the conventional configuration is used for the HER. However, the LER uses a different approach, with straight pumping chambers of double-walled design as shown in Figure 3. The inner beam chamber is a copper water-cooled extrusion and the outer pumping manifold is a stainless-steel tube with lumped sputter-ion pumps. Most of the SR power is absorbed in these chambers which lie downstream of the shorter bend-magnet chambers.

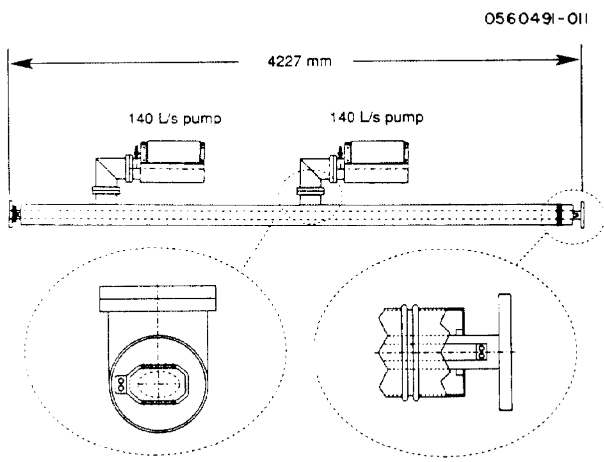

Figure 3: The pumping chamber which is downstream of the bend magnets in the LER arc cells of the SLAC B-Factory.

In LEP as also in the APS and ESRF light sources, and in the proposals for B Factories from KEK and CERN, the distributed pumping is provided by NEG strips. In CESR-B, distributed pumping will be provided by Ti-sublimation and NEG surfaces as described above. (Distributed sputter-ion pumps are limited to about 125 ℓ/s/m at these pressures and cannot provide enough pumping speed in these rings.) However, the getters pump only chemically active gases and thus lumped sputter-ion pumps must be installed throughout the rings to provide sufficient pumping speed for noble gases and for non-getterable gases such as methane. Indeed, one must be careful that sufficient conductance is provided to these pumps so that the average partial pressure of methane does not become the limiting factor in beam lifetimes! In the SLAC B Factory design, due to the large ring radius and consequent lower linear gas load, distributed sputter-ion pumps operating at 125 ℓ/s/m are sufficient to maintain the required pressure profile in the HER arcs.

As described above, the ultimate desorption coefficients for aluminum, stainless steel and copper appear to be very similar. This is reflected in the diverse choice of materials in various designs. The APS chamber is made of extruded aluminum, while the ESRF chamber is fabricated from stainless-steel. Most of the B Factory proposals favor copper which provides shielding to limit the radiation damage to magnet and tunnel components due to scattered X-rays.

V. INTERACTION REGION

In colliders, the residual gas pressure and composition in the IR immediately flanking the interaction point (IP) are of particular concern because this region is a prime source for lost particles which create spurious background in the detector[14]. The IR includes the straight sections of each ring around the crossing point and the "soft bend" magnets immediately adjacent. The pressure in this region should be no higher than 1×10^{-9} of N_2 equivalent molecules, e.g., CO and CO_2 combined. The end of the last soft bend magnet is a source of bremsstrahlung-induced background and could profitably be kept at an even lower pressure.

Another concern is the masking of SR X-rays arising from the IR quads and the nearest bend magnets. These X-rays can easily pass through the thin beryllium beampipe in the detector and can be a serious source of spurious hits and current in a vertex detector. The design must also incorporate the shadowing of upstream chamber wall surfaces that can "shine" with reflected (Rayleigh scattered) high-energy synchrotron X-rays into the thin beryllium beam pipe at the IP. For this reason, the SR-absorbing surfaces of the last few magnets leading into the IR straight must be angled inward so that they are not visible from the thin beryllium pipe or from the tips of the SR masks within the detector region.

The masks in the IR must be smoothly tapered to avoid inducing large HOM fields and the central beryllium pipe must be adequately cooled to withstand the power losses arising from both HOM and image currents. A double walled beryllium tube appears to be a satisfactory solution. The SLAC design uses gaseous helium as the coolant, while at CESR-B the pipe is cooled by water. The inner and outer walls are tied together by beryllium ribs for strength and the inner wall is coated with 25 μm of copper and 100 μm of aluminum to absorb scattered X-rays.

The vacuum chamber in the IR region of CESR-B is shown schematically in Figure 4. The average pressure is maintained at or below 1×10^{-9} Torr by sputter-ion and Ti-sublimation (TSP) pumps as shown.

VI. SR ABSORBERS, BEAM STOPS, etc.

The high intensity of the SR fans around the rings calls for special designs for the safe absorption of unwanted radiation on the walls, at crotches and at beam-stops and windows in X-ray lines. For the new light sources, special discrete absorbers and crotches have been designed, e.g., an inclined vee-shaped crotch used in the APS[13]. The total power intercepted by the crotch is about 13 kW. Materials such as dispersion-strengthened copper are proposed for the absorbers, as the thermal stresses may exceed the yield strength of copper.

Beam-stops for undulator and wiggler lines may have to intercept power densities of about one kW/mm^2. This is twice the power density absorbed on a wedge-shaped beryllium/copper beam-stop[15] at the CHESS facility at CESR, which is designed to stop radiation from a 25-pole

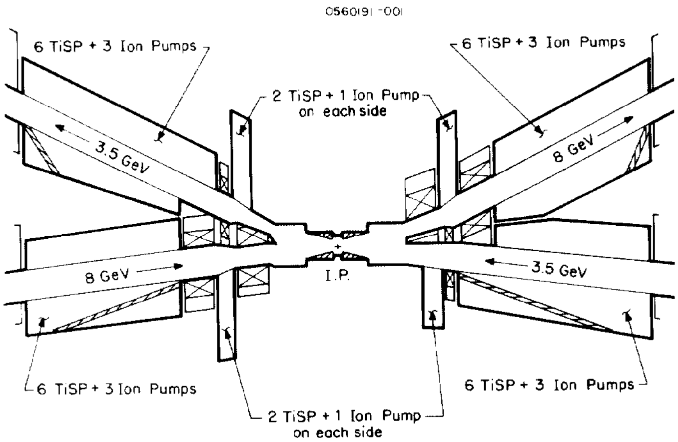

Figure 4: Schematic view of the CESR-B IR vacuum system. The horizontal scale is highly foreshortened.

wiggler delivering 17 kW of total power at a power density of 500 W/mm^2. The beryllium serves to diffuse the intense stripe of SR and to scatter an appreciable fraction (about 25%) of the power out of the beam-stop into the surrounding water-cooled walls.

Beryllium exit windows in X-ray beam lines have to withstand very severe thermally induced stress without failure. Windows in use at CHESS[16] have been designed for the wiggler beam described above where a linear power density of 3.8 kW/cm may be expected at 6 GeV, 200 mA operation. A 250μm thick vacuum tight brazed Be window is preceded by a 500μm thick Be prefilter which is clamped by friction but not brazed rigidly. This prefilter absorbs the bulk of the low-energy photons in the beam without failure and the stress on the brazed window remains within acceptable limits. A similar design has been used earlier at the Photon Factory[17] in Japan. To absorb higher power levels, it may be necessary to cool the Be windows to 77 K, to take advantage of higher thermal conductivity, lower thermal expansion coefficient and higher mechanical strength at low temperatures. An alternative is to use a thin diamond window or diamond-coated beryllium windows.

VII. SUMMARY

We have explored some of the challenges that face vacuum system design for high intensity synchrotron light sources and for high luminosity e^+e^- colliders. Many of these challenges are common to the two types of storage rings. The new light sources have been designed to solve some of the problems and the proposed B Factory colliders will have to use new and ingenious methods to achieve the required performance.

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