VACUUM SYSTEM FOR HIGH POWER LEPTON RINGS

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Abstract

The vacuum system for a future high luminosity lepton rings are discussed citing the upgrade plans of KEKB and PEP-II as examples. The high luminosity means firstly the large beam currents as well as the short bunch length. The vacuum system has to cope with the resultant intense synchrotron radiation power and the high photon flux. Deliberate care should be paid for the beam impedance issues. The design will proceed based on the various experiences at present rings introducing novel ideas.

INTRODUCTION

The next generation of B-factories (Super B-factory, SBF) will have a luminosity of 10^{35} – 10^{36} cm^{-2} sec^{-1} to quest a new physics, SUSY related B-physics, for an example. Table 1 presents parameters of three high luminosity rings planed in KEK and SLAC [1,2]. Super KEKB is an upgrade plan of the present KEKB and Super PEP-II is that of PEP-II. The high luminosity firstly means the large beam currents, ten amperes typically, in addition to the small beam sizes at collision points. The vacuum system for such a high luminosity lepton collider has to cope with the resultant intense synchrotron radiation power and the high photon flux [2-4]. The material and the structure of beam chamber should be examined carefully to deal with the high power density. Photoelectron emission has to be cared for the positron ring to suppress the electron cloud instability [5]. Furthermore, since the bunch length should be short to relieve the hourglass effect at the collision point, the beam impedance issues will become much more important. A cautious attention should be paid for the smoothness of the beam chambers and the reduction of impedance. Here described is a strategy of vacuum system design for future high-luminosity rings, together with some conceptual designs of main vacuum components and their R&D status of Super KEKB and Super PEP-II.

ISSUES COMMING FROM HIGH CURRENTS

First of all, several basic issues are reviewed.

Heat and Gas Load by Synchrotron Radiation

As is well known, the total power, P, and the total photon number, N, of the synchrotron radiation (SR) are given by

$$P\,[\mathrm{W}] = 88.4\times10^{3}\,E\,[\mathrm{GeV}]^{4}\,I\,[\mathrm{A}]/\rho\,[\mathrm{m}],$$

$$N\,[\mathrm{photons\ s^{-1}}] = 8.08\times10^{20}\,E\,[\mathrm{GeV}]\,I\,[\mathrm{A}],$$

where E [GeV], I [A] and ρ [m] are the energy, the beam current and the bending radius of normal bending, respectively. The values are also summarized in Table 1. For the LER of Super KEKB, for an example, if the present single beam chamber (ϕ 94 mm, copper) is used, the maximum linear power density just downstream of a bending is 53.5 kW m^{-1} and the estimated temperature reaches up to 293 °C. The thermal stress is so high that the present beam chamber cannot be used as it is.

The average linear photon density along the ring is about 10^{19} photons s^{-1} m^{-1}. The gas load is, therefore, on the order of 10^{-8} Pa m^{3} m^{-1} s^{-1} even for the photon stimulated gas desorption rate, η, of 1×10^{-6} molecules photon^{-1}. If the goal pressure is on the order of 10^{-7} Pa, the linear pumping speed of about 0.1 m^{3} s^{-1} m^{-1} is necessary.

Tables 1: Vacuum related parameters of three future Super B-factories [1,2].

	Super KEKB (Phase I) LER (e^-)	Super KEKB (Phase I) HER (e^+)	Super KEKB (Phase II) LER (e^-)	Super KEKB (Phase II) HER (e^+)	Super PEP-II LER (e^-)	Super PEP-II HER (e^+)
Goal Luminosity [cm^{-2}s^{-1}]	1×10^{35}		4-10×10^{35}		1×10^{36}	
Energy [GeV]	3.5	8.0	3.5	8.0	3.5	8
Circumference [m]	3016 (arc 2200)		3016 (arc 2200)		2200	
Beam current [A]	9.4	4.1	17.2	7.8	15.5	6.8
Bunch number	5018		5018		6900	
Bunch current [mA]	1.87	0.82	3.43	1.55	2.25	0.99
Bunch Length [mm]	3		3.5		1.75	
Beam Life Time [min]	~150					
Bending Radius (ρ) [m]	16.31	104.46	16.31	104.46	13.75	165
Critical Energy of SR [keV]	5.84	10.88	5.84	10.88	6.92	6.89
Total SR Power [MW]	7.64*	14.21	13.99*	27.03	14.95	14.92
Total Photons [photons s^{-1}]	2.66×10^{22}	2.65×10^{22}	4.86×10^{22}	5.04×10^{22}	4.38×10^{22}	4.40×10^{22}

*without wigglers

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Heating by Excited HOM

Since the bunch length is short and, furthermore, the bunch current is large, the power of excited higher order modes (HOM) should be intense. The HOM power generated by an impedance source can be written by

$$W = k(\sigma)[\mathrm{VC}^{-1}]I[\mathrm{A}]^2\tau_b[\mathrm{s}],$$

where k is the loss factor of the impedance source and a function of the bunch length, σ. In most case, the k is almost in proportion to σ^{-1}. The τ_b is the bunch interval. The total loss increases in proportion to the square of beam current for the same τ_b, i.e. the same bunch numbers. For an example, even the impedance source with a loss factor of 0.01 V pC^{-1}, it induces the HOM of about 2 kW (I = 10 A and τ_b = 2 ns). The excited HOM results in the heating of vacuum components around the source. The trapped modes are likely to induce the beam instability. The impedance sources should be removed as much as possible to suppress the unnecessary HOM excitation.

Heating and Discharge by Wall Current

For a Gaussian bunch, the wall current, $I_w(t)$, and the mean square of that, $\langle I_w(t)^2\rangle$, can be expressed by

$$I_w(t) = \frac{I\tau_b c}{\sqrt{2\pi}\sigma}e^{-\frac{c^2t^2}{2\sigma^2}},\ \left\langle I_w(t)^2\right\rangle \approx \frac{I^2\tau_b c}{2\sqrt{\pi}\sigma},$$

where c is the velocity of light. For a bunch with σ = 3 mm, the peak wall current is about 800 A (I = 10 A and τ_b = 2 ns). The high impulse wall current could cause a discharge at a gap of beam chamber. The high mean square of current leads to the joule loss, which will be a problem for the coating in the ceramics chambers and for the surface with low electric conductivity.

Direct Damage by Beam

The circulating high current beam has a huge energy in itself. When the beam is steered accidentally or the beam has to be aborted, the beam hit the chamber material and the energy is dissipated there. When all of circulating particle hit a material, the total dissipated energy is about 350 kJ For 10 A beam for LER of Super KEKB. The energy concentrates to the transverse beam size on the material within a time of revolution time (~10 μs). The relativistic beam, of course, interacts with material through various processes and all of the energy does not always dissipated in the small volume [6]. The energy, however, will be enough to melt the metal when the beam injected to that with a thickness of several radiation length (see Fig.6).

DESIGN STRATEGY

The designs of the vacuum system for SBF in KEK (Super KEKB) and PEP-II (Super PEP-II) are undergoing taking account above issues. Followings are the design strategy and conceptual designs of several main vacuum components. Some R&Ds performed or undergoing are also touched briefly.

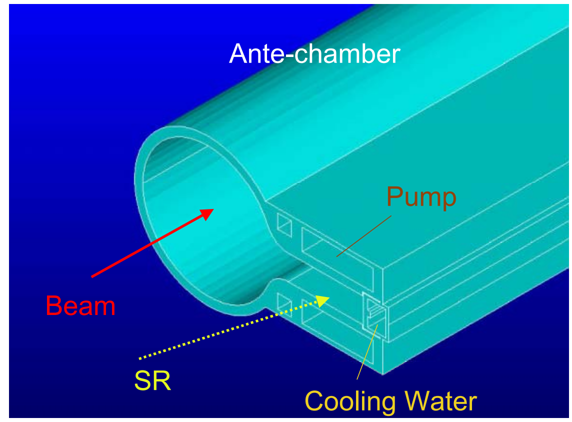

Figure 1: Typical structure of ante-chamber for the LER of Super-KEKB.

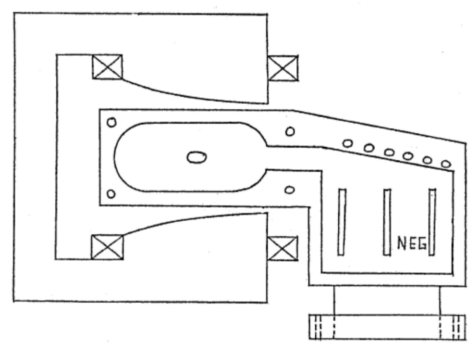

Figure 2: Cross section of beam chamber for Super PEP-II [2].

Beam Chamber

An ante-chamber scheme as adopted in the LER of PEP-II [7], where the SR goes through an adjacent channel, is a promising structure for a beam chamber in high current machine. A typical structure of the ante-chamber is shown in Fig.1 [3]. The ante-chamber consists of two channels, one is for the beam and another is for the SR. A narrow long slot connects those channels each other. The SR hit the sidewall at far side of the ante chamber, not the photon stop. The photon stop scheme cannot be realized due to the high concentrated power. Since the irradiated point of SR at the chamber wall goes far from the emitting point, the input SR power is diluted. For the LER of Super KEKB, the maximum power density at the sidewall of the ante-chamber will be about 40 W mm^{-2}, which is about 30 % of that for the single beam chamber and almost same as that of the present one. The maximum temperature and the thermal stress expected are about 150 °C and 260 MPa, respectively. The stress is well below the yield strength of a drawn copper (~350 MPa).

For the Super KEKB (Phase II) or Super PEP-II, however, the simple ante chamber as Fig.1 is not enough. A cross section of the beam chamber for the Super PEP-II is shown in Fig.2 [4]. The side wall of the antechamber is tilted to dilute further the power density. In this case, the bore of the beam chamber is also enlarged to reduce the resistive wall effect.

The ante-chamber scheme will be especially preferable for positron ring from the point of photoelectron emission since the irradiation of SR is at the side wall far from beam channel. The beam field is also small and, therefore, the multipactoring will be hard to occur in the SR channel. In 2002, a test model of ante-chamber was installed in the LER of KEKB. The measured electron number in the beam channel reduced to about 1/7 of that for the usual single beam chamber [3]. The effectiveness reducing electrons in the beam channel by adopting ante-chamber scheme was demonstrated.

Pumping Scheme

The ultra-high vacuum in the high luminosity rings is necessary to reduce the background noise in the particle detector and to avoid ion-related instability rather than ensure the long lifetime (see Table 1). The linear pumping speed of about 0.1 m^3 s^{-1} m^{-1} is required as estimated above to get the average pressure on the order of 10^{-7} Pa during the operation. The pumping scheme is the distributed one to get high linear pumping speed. The pump will be a combination of the strip type NEG pumps and the ion pumps as the present KEKB [8,9]. The pump ports are equipped at SR channel to remove the impedance of pumping ports in the beam channel and to evacuate effectively the desorbed gas as shown in Fig.1 and 2.

Material of Chamber

At present, copper is the most suitable material for the beam chamber for its high thermal strength, the high electrical conductivity, the low thermal gas desorption (after proper chemical cleaning) and the relatively low photoelectron yield [7-9]. The copper beam chambers have been used in DESY (HERA), SLAC and KEK and their manufacturing technique, such as the welding (brazing) method and the cleaning procedure, has been well established.

Aluminium is another candidate of material [4]. The manufacturing and welding is actually easier than copper. Extrusion with a complex cross section is also possible. But the thermal strength and the melting point are inferior to copper. The application of aluminium may be limited.

Surface Treatment

Whether it is copper or aluminium, the recent technique to clean the surface and the η of less than 1×10^{-6} molecules $photon^{-1}$ will be achieved within the integrated linear photon density of about 10^{25} photons m^{-1} [8].

More important issue for the positron ring is to form a surface with low electron emission rate to suppress the electron cloud instability (ECI) [5]. The electron cloud consists of photoelectrons and secondary electrons. The secondary electrons are emitted from the surface by bombardment of high energy electrons accelerated by the beam induced field. Solenoid field seems successful in the present KEKB and PEP-II [10,11] and the ante-chamber structure described above will release the problem. To form a surface with a low photoelectron and secondary emission rate, however, will be a fundamental measure.

The present beam chamber of LER of PEP-II has TiN coating inside [7]. Recently it was reported that the NEG (Non-Evaporable Getter) coated surface has a low photoelectron and secondary electron yield [12,13]. The coated chamber was used in ESRF [14] and will be applied for LHC [15]. The NEG coated surface seems promising but the further R&Ds for the surface with low electron emission rate should be continued.

Connection of Chambers

Usually the number of connections sums up to about one thousands to construct a ring. Connection of chambers will raise a serious impedance problem in high luminosity machine. The present KEKB used a helico-flex seal between flanges, which matches the cross section of beam chamber [9]. The helicon-flex gasket has also a role of tight RF-shield and has been working successfully. However, even for the helico-flex seal, the loss factor of a flange connection goes up to about 1 V nC^{-1} for the short bunch length (σ_z = 3 mm). In the design of Super-PEP-II or Super-KEKB, the flange less connection is considered, where the adjacent ducts are connected by welding in situ [3,4].

The bellows chamber, which is usually inserted between adjacent beam chambers, raises another impedance problem and heating problem. In the Super-PEP II and Super-KEKB, the bellows less design was proposed [3,4]. The adjacent chambers will be connected directory by welding in situ. If the temperature of beam chambers during the beam operation is well controlled (less than 10 °C, for an example), the deformation of beam chamber may be tolerable. Remaining crucial problems are how to absorb the manufacture and alignment errors, and how to fit the welding surface. The further practical considerations should be necessary.

In the Super-KEKB, the connection using a bellows

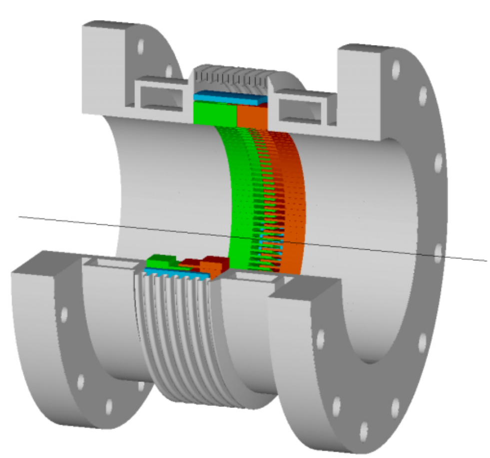

Figure 3: Conceptual drawing of bellows chamber with a new RF-shield structure.

chamber is also considered using a new RF-shield structure as described below [16].

RF-Shield in Bellows and Gate Valves

Usual RF-shield in bellows or gate valves are lots of thin fingers aligned azimuthally around the inner surface of beam chambers [17,18]. However, for the high current ring, the heating of those due to the HOM, especially the TE modes, will become a serious problem. The troubles have been reported at KEKB and PEP-II near the movable masks or the interaction region [8]. The impedance of a step (~1 mm) at RF shield structure (k ~ 10 V nC^{-1} at σ = 3 mm) will be also a problem for the beam stability due to the large amount of it. The discharge at the sliding point will be another source of trouble due to a high wall current as described above.

Recently a new structure of RF-shield is proposed [19]. The shield is no more than fingers but nested comb teeth, aligned azimuthally with a pitch of 3 mm typically [16]. Since each tooth (copper) has a width and a radial thickness of 1 mm and 10 mm, respectively, the thermal strength is much better than a usual finger. The calculated loss factor is smaller than that of usual one by a factor of 3 ~ 4. The R&D to apply the RF shield to the bellows or gate valves has just started. A conceptual drawing of the new RF-shield bellows chamber is shown in Fig.3 A trial model of bellows chamber with the new RF-shield will be installed in this summer in the KEKB and studied.

HOM Absorber

In the high current machine, the intense HOM can be generated at various kinds of vacuum components. The interaction region is also a big source of HOM where the cross section changes drastically and the beam passes at the off-centre of beam pipe. The intense HOM leads to the extra heating of vacuum components or the discharges inside those. The HOM absorbers will be indispensable to avoid these troubles caused by the HOM.

A winged HOM damper as shown in Fig.4 was newly designed base on that for KEKB ARES cavity system [20,21] and the trial model was installed near the movable masks of the KEKB in 2002, where the heating of bellows chambers has been observed [22]. The long narrow slots in the beam direction connect the beam chamber and two SiC HOM absorbers, and the damper can absorb effectively the TE mode. The loss factor is less than 10 V nC^{-1} at the bunch length of 10 mm. The capacity of a SiC rod is about 10 kW.

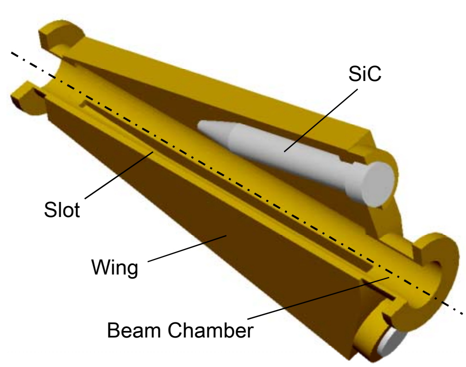

Figure 4: Structure of winged HOM damper developed in KEK.

Movable Mask (Collimator)

To protect the particle detector from damages by spent particles, the movable mask (collimator) system will be equipped. The trapped HOM free masks have been installed in the PEP-II and KEKB [23,24]. Even if the masks do not trap the HOM, however, they excite the HOM in any way. The HOM propagates along the beam chamber and heats up the components nearby [8]. Future masks should be combined with HOM absorbers. The reduced HOM design will be adopted at the same time [25].

Another problem expected is the damage of mask head, which have been already experienced in the KEKB [24]. The damages at the mask head resulted from the attack of beam steered abnormally. The same problem will arise at the beam abort window. An effective way to avoid the damage is to use the light material with a minimal length as a mask head. The temperatures along the beam path in copper, titanium, carbon and beryllium calculated by EGS4 as a function of the radiation length are shown in Fig.5 [26]. New ideas are to use spoiler scheme (Fig.6) and to use a rotating or a liquid metal as a spoiler [27,28].

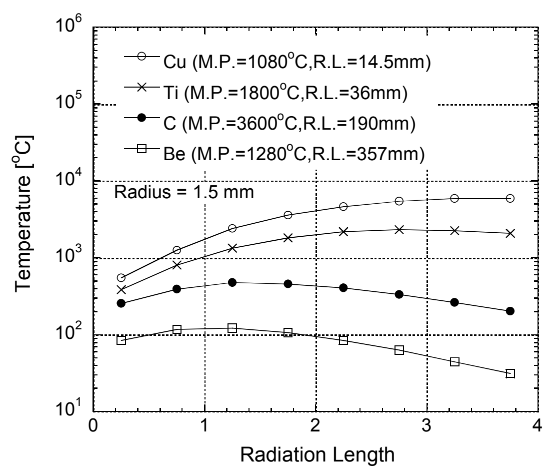

Figure 5: Estimated temperatures along the beam path when an 8 GeV electron beam with a radius of 1.5 mm is incident on copper, titanium, carbon and beryllium.

Figure 6: Spoiler type collimator [27].

The safe and rapid beam abort system using the beam orbit or the beam loss monitor will also help the damage of mask head.

OTHER ISSUES

The following are other key issues to be carefully considered.

(1) Design of the beam chambers at the interaction region. The design should take into account the aperture (the beta function should be large near the collision point), the impedance, the SR mask and the effective pumping scheme.

(2) Radiation shielding. Lead shielding around the beam chamber may be necessary.

(3) Alignment. An accurate alignment of the beam chamber will be a great importance for the accelerator dealing with an intense beam.

(4) Abort system. Once an accident occurs, such as a malfunction of machine components or a wrong operation, the steered beam easily damages the vacuum chamber or the movable masks as described above. A rapid and safe beam abort system is required.

(5) Alarm system. Many components, such as the photon stops, the bellows chambers, gate valves and so on, can be easily heated up by the intense synchrotron radiation or HOM if the cooling system failed. The flow rate of cooling waters and the temperatures of these components should be kept watching any time. A highly reliable alarm and interlock system should be prepared.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. K.Oide, Dr. K.Kanazawa and many other staff of the Accelerator Laboratory in KEK for their continuous encouragement.

REFERENCES

[1] http://www-kekb.kek.jp/SuperKEKB/home.html; Y.Ohnishi, KEK Proceedings 2002-17 (2002) 1.
[2] http://www-user.slac.stanford.edu/seeman/index.html, “B- Factory Upgrade Scenarios”.
[3] Y.Suetsugu, KEK Proceedings 2002-17 (2002) 7.
[4] J.T.Seeman, “HIGHER LUMINOSITY B-FACTORIES”, PAC’01, Chicago, June 2001, p.305.
[5] For example, K.Ohmi and F.Zimmermann, P.R.L. 85 (2000) 3821.
[6] For example, “Review of Particle Physics”, The European Physical Journal 15 (2000) 163.
[7] J.Dorfan, “PEP-II STATUS REPORT”, EPAC’98, Stockholm, June 1998, p.33.
[8] K.Kanazawa et al., N.I.M. A 499 (2003) 66.
[9] K.Kanazawa et al., Appl. Surface Sci., 169-170 (2001) 715.
[10] K.Akai et al., N.I.M. A 499 (2003) 191.
[11] J.Seeman et al., “PEP-II STATUS AND FUTURE PLANS”, EPAC’00, Paris, June 2002, p.434.
[12] B.Henrist et al., Appl. Surface Sci. 172 (2001) 95.
[13] J.M.Jimenez et al., “ELECTRON CLOUDS – RESULTS FROM SPS AND EXPERIMENTS FOR 2003”, Proc. Chamonix XII (CERN-AB-2003-008 ADM), Chamonix, March 2003, p.327.
[14] R.Kersevan, “NEG-COATED VACUUM CHAMBERS AT THE ESRF: PRESENT STATUS AND FUTURE PLAN”, EPAC’02, Paris, June 2002, p.2565.
[15] I.Collins et al., “VACUUM CALCULATIONS FOR THE LHC EXPERIMENTAL BEAM CHAMBERS”, PAC’01, Chicago, June 2001, p.3153.
[16] Y.Suetsugu, et al., “CONCEPTUAL DESIGN OF VACUUM SYSTEM FOR SUPER KEKB”, in these proceedings.
[17] Y.Suetsugu et al., Rev. Sci. Instrum (1996) 2796.
[18] J.T.Seeman, “PEP II STATUS AND PLANS”, PAC’95, Dallas, May 1995, p.486.
[19] Y.Suetsugu, KEKB Machine Advisory Committee, March 2003.
[20] T.Kageyama et al., “THE ARES CAVITY FOR THE KEK B-FACTORY”, EPAC’96, Sitges, November 1996, p.2008.
[21] Y.Takeuchi et al., “THE SiC ABSORBER FOR THE KEKB ARES CAVITY”, EPAC’96, Sitges, November 1996, p.2020.
[22] Y.Suetsugu et al., “DEVELOPMENT OF WINGED HOM DAMPER FOR MOVABLE MASK IN KEKB”, in these proceedings.
[23] J.Seeman etal., “PEP-II HIGH POWER LOW IMPEDNCE MOVABLE COLLIMATOR”, EPAC’00, Vienna, June 2000, p.2298.
[24] Y.Suetsugu et al., “DEVELOPMENT OF THE MOVABLE MASK FREE FROM TRAPPED MODE FOR THE KEKB”, PAC’01, Chicago, June 2001, p2186.
[25] K.Shibata et al., “DEVELOPMENT OF MOVABLE MASK WITH REDUCED-HOM DESIGN FOR KEKB”, in theses proceedings.
[26] W.R.Nelson et al., KEK Proceedings 2000-20 (2000) 182.
[27] K.Bane et al., “Collimator Design and R&D”, Machine Advisory Committee, SLAC, May 2001.
[28] J.Frisch et al., “ADVANCED COLLIMATOR ENGINEERING FOR THE NLC”, PAC’01, Chicago, June 2001, p.1258.