SECOND-GENERATION B-FACTORY PROPOSALS AND LESSONS LEARNED FROM B-FACTORY OPERATION

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Abstract

There are two proposed second-generation B-Factory designs: one from the INFN-Frascati laboratory in Italy and the other from the KEK laboratory in Japan. These proposed accelerators build on the recent successes of the PEP-II B-Factory at SLAC and the KEKB B-Factory at KEK and three other former colliders (DORIS-II at DESY, VEPP-4M at BINP, and CESR at Cornell) all operating at least part time at the Upsilon 4S resonance [1-18]. This paper discusses the technological advances of various aspects of these colliders covering the beam parameters with high currents, interaction region design, the beam-beam interaction, tune shifts, injection, and luminosity.

BEAM ENERGIES AND RING CIRCUMFERENCE

There have been 5 colliders that have operated on the Upsilon 4S resonance as shown in Table 1. DORIS-II at DESY produced B physics from 1978 to about 1984. VEPP-4M at BINP ran for B physics from 1983-1985. CESR at Cornell operated for B physics from 1979 through 2001. The PEP-II B-Factory at SLAC operated from 1999 through 2008. Finally, the KEKB B-Factory continues to operate for B physics from 2000 into 2010. There are two proposed second generation B-Factories under study: Super-B and Super-KEKB. Both of these colliders aim for a luminosity from 5 x 10^{35}/cm^2/s to 10^{36}/cm^2/s.

The early B colliders ran with symmetrical energies but the recent high luminosity colliders operate with asymmetrical energies to allow a boosted center-of-mass in the lab to allow separation of the generated B mesons. The future accelerators will also have separated energies.

The circumference of a collider is getting larger with each generation due to the need to have lower emittances which become smaller with reduced momentum compaction naturally with a longer circumference and also to allow a larger number of bunches.

BUNCH NUMBERS AND CURRENTS

The number of bunches and the beam currents used in previous colliders and the proposed new colliders are shown in Table 2. Early machines used single bunches. The CESR used pretzel orbits in the arcs to have bunch trains with 45 bunches total. Both PEP-II and KEKB had two rings each allowing over a thousand bunches. The future machines will likely put a bunch in each RF bucket, except for a small gap for ions in the e- beam. The total currents are increased to maximize the beam-beam parameter and the luminosity. These increased currents require reduced machine impedances, higher power RF systems, stronger bunch-by-bunch feedback systems and kickers, improved beam collimation, and background suppression systems. The increased current indicates a short Touschek lifetime and with the short "luminosity" lifetime leads to a reduced beam lifetime of about 10 to 20 minutes in the proposed new colliders. This leads to the requirement of continuous injection and low emittance injectors. Injection losses will need to be controlled.

Table 1: Colliders Operating at the Upsilon 4S Resonance

Collider	e+ energy	e- energy	Circumference
	(GeV)	(GeV)	(m)
DORIS-II	5.28	5.28	288
VEPP-4M	5.28	5.28	366
CESR	5.28	5.28	768
PEP-II	3.1	9.0	2200
KEKB	3.5	8.0	3016
Super-KEKB (future)	3.5	8.0	3016
Super-B (future)	4	7.0	1800

Table 2: Bunches and Currents of B Factory Colliders

Collider	Bunches	e+ current	e- current
		(mA)	(mA)
DORIS-II	1	42	42
VEPP-4M	1	12	12
CESR	5x9=45	375	375
PEP-II	1722	3210	2070
KEKB	1585	1662	1340
Super-KEKB (future)	5018	9400	4100
Super-B (future)	2500	2800	2800

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LUMINOSITY AND BEAM-BEAM PARAMETER

The luminosity in a collider and the vertical beam-beam parameter which limits the peak currents are given by:

$$L = 2.17x10^{34} \frac{n\xi_y E I_b}{\beta_y^*}$$

$$\xi_{y,+} = \frac{r_o N_- \beta_{y,+}^*}{2\pi\gamma_+ \sigma_{y,-}^* (\sigma_{x,-}^* + \sigma_{y,-}^*)}$$

where L is the luminosity, ξy the beam-beam parameter, I_b the bunch current, n the number of bunches, β_y* the IP lattice optics function (vertical beta), N the bunch charge, σ the beam size in x and y, and E (and normalized as γ) the beam energy (fixed for a given ring).

In Table 3 are listed the bunch lengths and IP beta functions of the colliders. The design of the PEP-II IR and Super-B IR are shown in Figs. 1 and 2. The trend is to reduce the vertical IP beta with the newer machines to increase the luminosity and, of course, the bunch length has to follow to reduce the hour glass effect. KEKB collides with a crossing angle and uses crab cavities to successfully realign the beams at the IR (Fig. 3). Super-B also has a crossing angle and will use a crab waist scheme of Raimondi (Figs. 4 and 5) to recover the luminosity and beam-beam parameter by focusing differently (longitudinally) the left and right sides of the beam at the IP. This scheme allows vertical betas much smaller than the bunch length. It is planned for Super-B to provide longitudinally polarized electrons at the IP for particle physics. The e- spin in the arcs is vertical and is rotated into the longitudinal with spin rotators near the IP and is then returned to the vertical. The IR lattice design that does this spin rotation, chromatic corrections, and crab waist sextupoles is shown in Fig. 6.

L*, CROSSING ANGLES, EMITTANCES

The distance from the IP to the face of the first quadrupole, the IP crossing angle, and the horizontal emittances for all the colliders are shown in Table 4. The new colliders have several magnets inside the detectors being either permanent magnets or super-conducting. The later colliders have a crossing angle which can be compensated by crab cavities, travelling focus, or crab waist schemes. The horizontal emittances are smaller with the newer colliders to reduce the currents in the beams to minimize high synchrotron radiation power costs, HOM losses, and beam instability issues. The low horizontal emittance of 2 to 3 nm has been achieved by recent ring light sources. The vertical emittances of order 5 to 10 pm have also been achieved in these light sources.

The interaction region with very low betas must be added. The new arc lattice with 2-3 nm emittance is in Fig. 7.

Table 3: Bunch Length and IP Betas of B Colliders

Collider	Bunch length	βy*	βx*
	(mm)	(mm)	(mm)
DORIS-II	36	40	630
VEPP-4M	50	50	700
CESR	18	18	1000
PEP-II	11	9	26-50
KEKB	7	6	900
Super-KEKB (future)	3/5	3/5	200
Super-B (future)	6	0.25/0.35	20/35

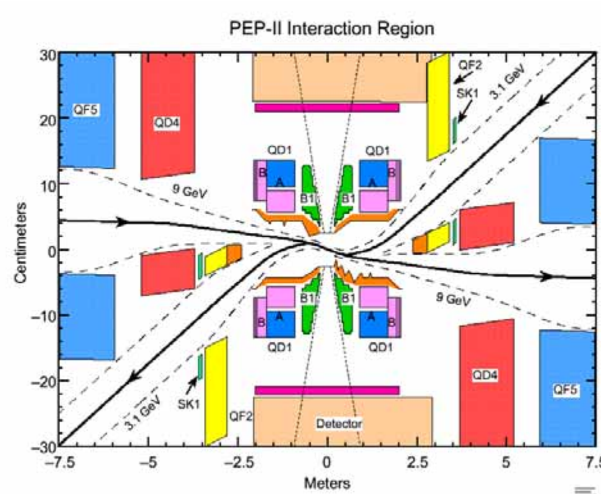

Figure 1: PEP-II interaction region.

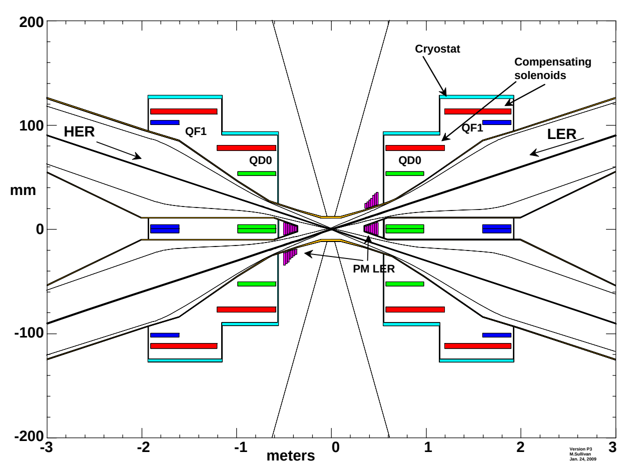

Figure 2: IR design for Super-B.

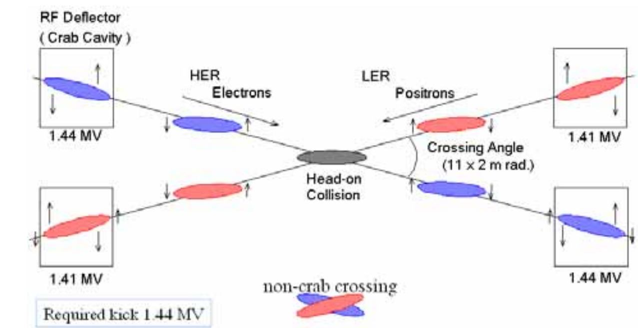

Figure 3: Crab cavity correction for Super-KEKB.

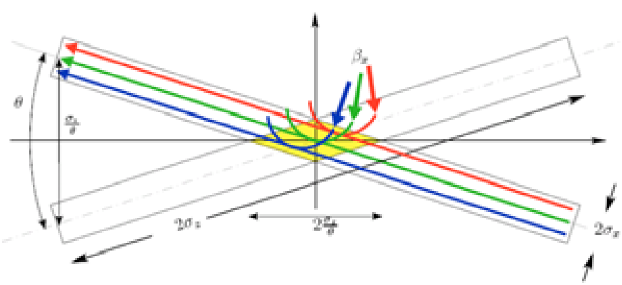

Figure 4: Crab Waist scheme for Super-B.

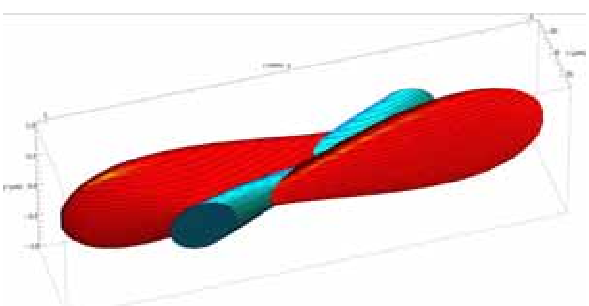

Figure 5: IP beam sizes with Crab Waist correction.

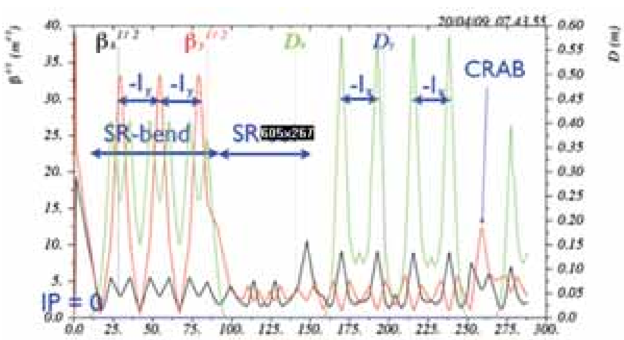

Figure 6: Super-B IR lattice design.

INJECTION AND TOP-OFF MODES

The injectors for these colliders are shown in Table 5. The early machines used small linacs with a synchrotron. The later accelerators used full energy linacs and in some cases damping rings. PEP-II was the first accelerator to use top-off injection with the detector taking data and KEKB followed very shortly after. The future B-factories will need full energy injectors with damping rings as the beam lifetimes are short requiring top-off and the injected emittances need to be very small to fit into the dynamic aperture. Integrated luminosity with top-off injection is increased by about 40 to 50% as seen in Figs. 8 and 9.

VERTICAL BEAM-BEAM PARAMETERS AND LUMINOSITY

The vertical beam-beam parameters and the peak luminosity of these colliders are shown in Table 6. The beam-beam parameters have grown from 0.03 in early machines to 0.09 in KEKB. These values come from specific luminosity plots as shown in Figs. 10 and 11. The new proposed colliders use beam-beam parameters in the range of 0.07-0.09. Over 30 years the luminosity will increase about x 30,000 if a new machine is successful.

Table 4: Collider Crossing Angle, Horizontal Emittances and Distance from IP to the First Quadrupole

Collider	L* to 1st IR Quadrupole	Crossing Angle	ε_x
	(m)	(mrad)	(nm)
DORIS-II	~2	0	571
VEPP-4M	2	0	1333
CESR	0.6	~2	211
PEP-II	0.9	0	23-48
KEKB	1.35/1.68	22	20-23
Super-KEKB (future)	~1	30	18-24
Super-B (future)	0.36/0.58	60	2-3

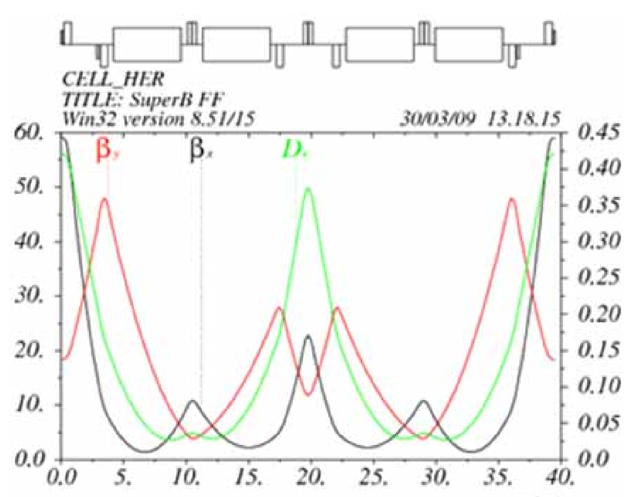

Figure 7: Super-B arc lattice design.

Table 5: Collider Injector and Top-Off Modes

Collider	Injector	Top-off (continuous)
		Detector on
DORIS-II	Linac/Synch	No
VEPP-4M	Synch/Ramp	No
CESR	Linac/Synch	Possible
PEP-II	Linac/DR	Yes
KEKB	Linac	Yes
Super-KEKB (future)	Linac/DR	Planned
Super-B (future)	Linac/DR	Planned

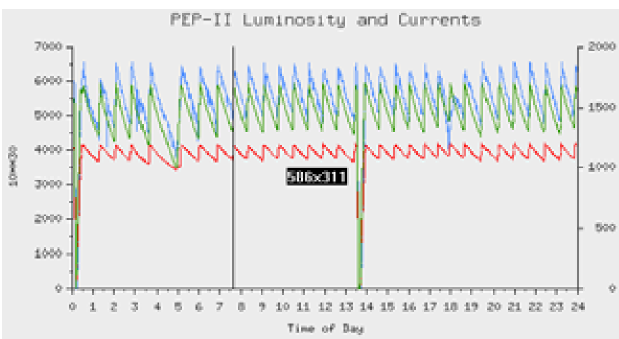

Figure 8: PEP-II luminosity and currents versus time with fill and coast injection.

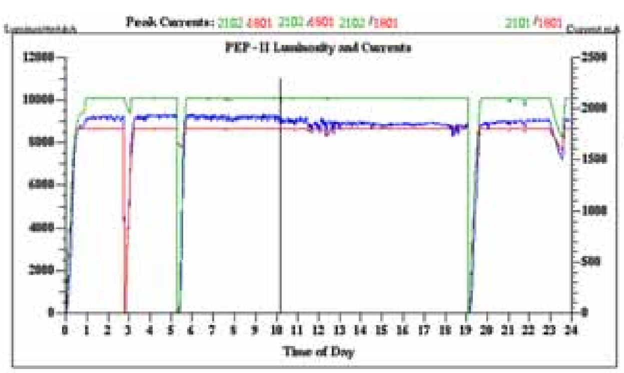

Figure 9: PEP-II continuous injection.

NEXT B-FACTORY DESIGN

The present design parameters for the proposed next generation B-Factories are shown in Table 7. Super-B has gone the route of very low emittances, very low IP betas, crab waist and modest beam currents. Super-KEKB has gone the route of high currents, high power, short bunches, and keeping the arc lattice layout unchanged.

The Super-KEKB design members are also considering an alternate set of parameters more similar to those of Super-B but without crab waist. For both design teams, the high cost of delivering RF power to the beam is a big factor in determining which direction to go as well as how hard it is to make and collide small emittance beams.

Table 6: Collider Beam-Beam Parameters and Luminosity

Collider	ξ_{y*}	Luminosity
		X 10^{32}/cm^2/s
DORIS-II	0.026	0.33
VEPP-4M	0.059	0.2
CESR	0.068	12.8
PEP-II	0.065	121.
KEKB	0.09	191.
Super-KEKB (future)	0.3 (design)	5300 (projected)
Super-B (future)	0.09 (design)	10000 (projected)

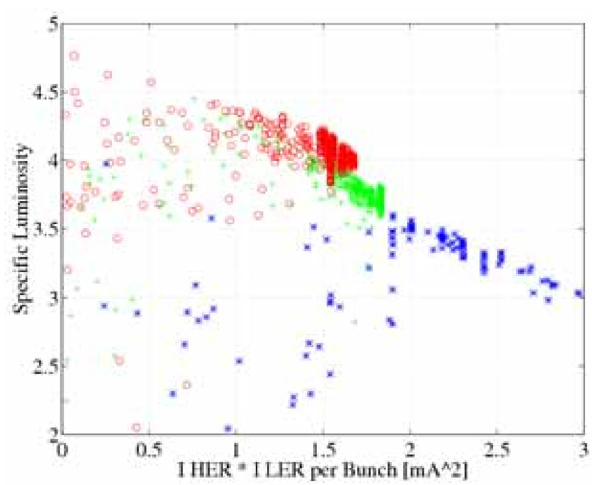

Figure 10: PEP-II specific luminosity with beam-beam parameter of about 0.07.

CONCLUSIONS

There has been a lot of progress in collider design since the first colliders at the Upsilon resonance 30 years ago with Fig. 12 showing the respective peak luminosities. The recent KEKB and PEP-II B-Factories have been very successful with Nobel prizes this year! Innovations are still being made to significantly enhance the luminosity of a future collider. The accelerator field is approaching the technical readiness to build the next very high luminosity collider (perhaps Super-B or Super-KEKB).

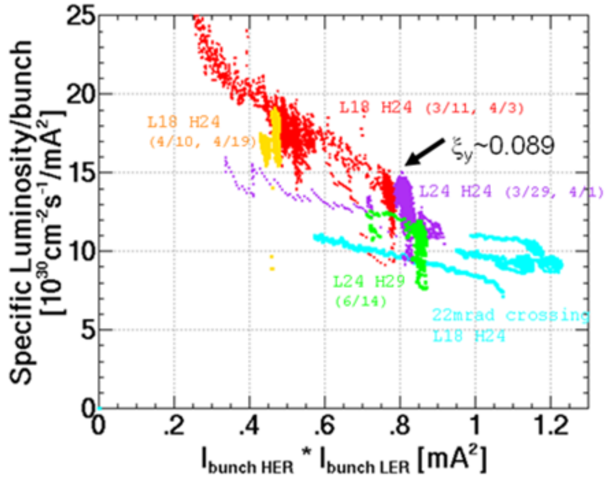

Figure 11: KEKB specific luminosity with beam-beam parameter of about 0.09. (Courtesy of KEKB staff).

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Table 7: Parameters of Super-B and Super-KEKB

	Super-B	Super-KEKB
I (Amp)	2.8/2.8	9.4/4.1
$N_{bunches}$	2400	5018
β_x* (mm)	35/20	200
β_y* (mm)	0.21/0.37	3
ε_x* (nm)	2.8/1.6	12
ε_y* (pm)	7/4	60
σ_x* (µm)	9.9/5.7	49
σ_y* (nm)	38/38	424
ξ_x	0.004/0.001	~0.1
ξ_y	0.09/0.09	0.3/0.5
Circumference (km)	1.8	3.0
Luminosity	10^{36}	$5.5x10^{35}$

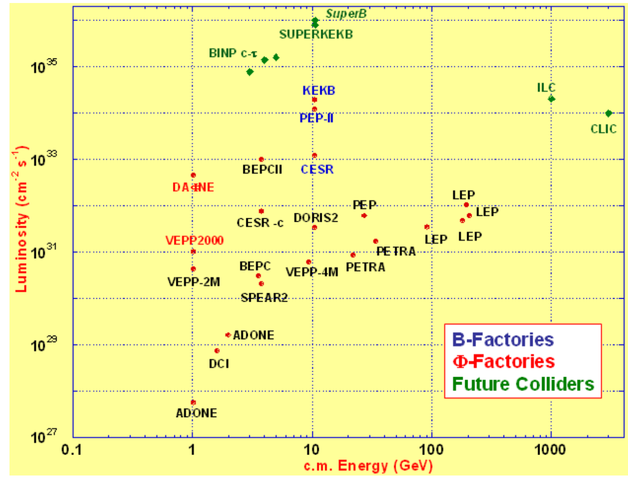

Figure 12: Peak luminosity of various colliders showing the proposed Super-KEKB and Super-B approaching 10^{36}. (Courtesy of M. Biagini.) acknowledgments.

REFERENCES

[1] P. Raimondi et al, “Super-B Design”, PAC 2007, Albuquerque, US.
[2] C. Milardi et al, “DAFNE Results”, PAC 2009.
[3] Super-B Conceptual Design Report, arXiv:0709.0451
[4] M. Biagini et al, “Overview Super-B Design”, PAC 2009.
[5] D. Shatilov, Part. Accel.52:65-93, 1996.
[6] K. Ohmi, “Beam-Beam Calculations’ PAC 2009.
[7] E. Levichev et al, “Super-B Beam-Beam Effects”, PAC 2009.
[8] M. Boscolo et al, “Super-B Toushek Effects”, PAC 2009.
[9] M. Sullivan et al, “Super-B IR Design”, PAC 2009.
[10] E. Paoloni et al, “Super-B IR Quadrupoles, PAC 2009.
[11] W. Wittmer et al, “Super-B IR Lattice”, PAC 2009.
[12] S. Tomassini et al , “Super-B site issues”, PAC 2009.
[13] D. Rubin et al, “CESR Status”, PAC 2001 p. 3520.
[14] P. Gurtler, H. Nesemann, “DORIS-II”, Catalogue of HEP Accelerators, XVth Int. Conf. on High Energy, p. 62, 1992.
[15] K. Oide, “KEKB & Super-KEKB status”, PAC 2009.
[16] P. Raimondi, “Super-B Lattice Design Update”, Super-B Mini-MAC Review, April 23, 2009.
[17] V. Pindyurin, “VEPP-4M”, Catalogue of HEP Accelerators, XVth Int. Conf. on High Energy Accelerators, p.103, 1992.
[18] V. Smaluk et al, “Status of VEPP-4M”, RuPAC 2008, p. 79.