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Status and perspectives of high luminosity Flavor Factories

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The quest for high precision measurements in rare flavor decays requires dedicated colliders with very high peak luminosity and high operation reliability, in order to collect the huge amount of data needed. In the past such Factories were in operation at SLAC (USA) and KEK (Japan) for the study of the B mesons decays, and are still collecting data at IHEP (China) at the Tau/charm energy and at LNF (Italy) and BINP (Russia) at the Φ resonance.
Future projects, such as SuperKEKB in Japan, already in the assembly phase, and Tau/charm colliders proposals at BINP and LNF, will deal with a different frontier of experimental subnuclear physics, with a research program complementary to CERN's LHC, by increasing the rate of particle beam collisions at a level that has never been reached before, producing extremely rare physical events which are influenced by the potential existence of new massive particles and thus provide unique information on them. A status of the present facilities and future projects in the "low energy, high luminosity" region will be presented.

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1. Introduction

Flavor Factories are e+e- ring colliders designed to produce a huge number of collisions to collect large samples of data to study charmed and strange mesons resonances, such as Y(4S), Ψ(3100), Φ(1020) and τ leptons. The energy of such machines can range from low to medium energy (1 GeV of the Φ resonance to 10 GeV of the B meson). The need for a large number of collected data raised in the '90 when CP violation related measurements were proposed.

Lepton colliders started operation since the 1960-1970 decade. To summarize their performances in Figure 1 is a plot of the achieved peak luminosity as a function of the center of mass energy for lepton colliders in the world, together with the proposed project at medium-low and high energy, like the Super B-Factory, the "extreme" circular colliders as TLEP and LEP3, and the linear ones like ILC and CLIC. The B-Factories PEP-II at SLAC (USA) and KEKB at KEK (Japan) reached the highest luminosity. New designs such as the SuperKEKB collider at KEK are based, to get higher luminosity, on a new collision scheme, which has been developed in the last years at LNF-Frascati [1,2] and tested at the DAΦNE Φ-Factory. On the same concept are based other proposals such as the Italian and Russian t/charm factories.

In the following a brief summary of achievements in past and present colliders and characteristics of future projects is presented.

2. Past colliders: B-Factories PEP-II, KEKB

In the '90 two asimmetric colliders, PEP-II at SLAC (USA) and KEKB at KEK (Japan) were designed and built to study the CP violation in the B mesons decay. PEP-II [3], running from mid-1999 to April 2008, has reached 4 times the design peak luminosity, delivering to the BaBar experiment an integrated luminosity larger than 557 fb^{-1}. It had two rings vertically superimposed, the High Energy Ring (HER), where electrons at 8.9 GeV were stored, was the old PEP collider, the Low Energy Ring (LER), with positrons at 3.1 GeV, was brand new. The two rings were one on top of the other, and a very long and complicated Interaction Region was built to bring the beams in head-on collision. Asymmetric beam energies were needed to have a boost in the centre of mass and have the B mesons to fly before decay. The design peak luminosity was $3x10^{33}$ cm^{-2} s^{-1}, a large number if compared to the values achieved at the time of its proposal, with a rather conservative approach with respect to KEKB, due to the HER lattice being not optimised for the B run. PEP-II ran from 1999 (first run without the BABAR detector) to the April 2008. table 1 shows a comparison of the design and achieved beam parameters. The gain factors are impressive, in particular the positron beam current is the higher ever achieved in a collider. Even more impressive is the factor of 7 in integrated luminosity/day with respect to the design. Pioneering work on the cure of electron cloud instability was also done. The large beam currents induced many problems of High Order Modes in the beam pipe, with consequent substitution of many BPMs, Feedback feed-through, etc.

Table 1 – PEP-II achievements over 10 years of operation

Parameter	Units	Design	April 2008 best	Gain factor over design
I^+	mA	2140	3213	x 1.5
I^-	mA	750	2069	x 2.76
N. bunches		1658	1732	x 1.04
β_y*	mm	15-25	9-10	x 2
Bunch length	mm	15	10-12	x 1.4
ξ_y		0.03	0.05 → 0.065	x 2
Luminosity (x10^{34})	cm^{-2} s^{-1}	0.3	1.2	x 4
Integrated L/day	pb^{-1}	130	911	x 7

The KEB collider was a big competitor for PEP-II, with a smaller energy asymmetry. KEKB [4] operated from 1999 to June 2010, reached a peak luminosity more than double with respect to the design value, delivering >1040 fb^{-1} to Belle. The two rings, crossing with a small horizontal crossing angle of 22 mrad, were completely new, and the design beam parameters were pushed in order to achieve an unprecedented luminosity of 10^{34} cm^{-2} s^{-1}. Table 2 summarized the luminosity relevant parameters before the installation of the crab cavity and after.

Table 2 – KEKB parameters before and after the crab cavities

		Design		**November 2006 no crab cavities**		**June 2009 with crab cavities**	
Parameter	**Units**	**LER**	**HER**	**LER**	**HER**	**LER**	**HER**
Current	A	2.6	1.1	1.65	1.33	1.64	1.19
N. bunches		5000		1389		1584	
Bunch current	mA	0.52	0.22	1.19	0.96	1.03	0.75
Crossing angle	mrad	22		22		0	
Hor. emittance ε_x	nm	18	18	18	24	18	24
β_x*	cm	33	33	59	56	120	120
β_y*	mm	1	1	6.5	5.9	5.9	5.9
σ_x @IP	μm	77	77	103	107	147	170
σ_y @IP	μm	1.9	1.9	1.8	1.8	0.94	0.94
bb ξ_x		0.039	0.039	0.117	0.07	0.127	0.102
bb ξ_y		0.052	0.052	0.108	0.058	0.129	0.09
Luminosity x 10^{33}	cm^{-2} s^{-1}	10		17.6		21.08	

Both accelerators demonstrated that the transparency condition (i.e. having beam currents inversely proportional to the beam energy so to have equal beam-beam tune shifts for the two beams) is non strictly necessary, indeed the positron current exceeded 3 times the design value in PEP-II while is was 60% lower for KEB. The trickle charge (continuous) injection was the key to the average luminosity stability and integrated luminosity; this required a massive campaign for the reduction of the injection backgrounds. In KEKB an increment in luminosity, even if not the expected one, was given by the installation of one crab cavity per ring (theoretically 2 per ring were needed). Another improvement was coming from the use of skew sextupoles. KEKB achieved the largest beam-beam tune shift for lepton colliders.

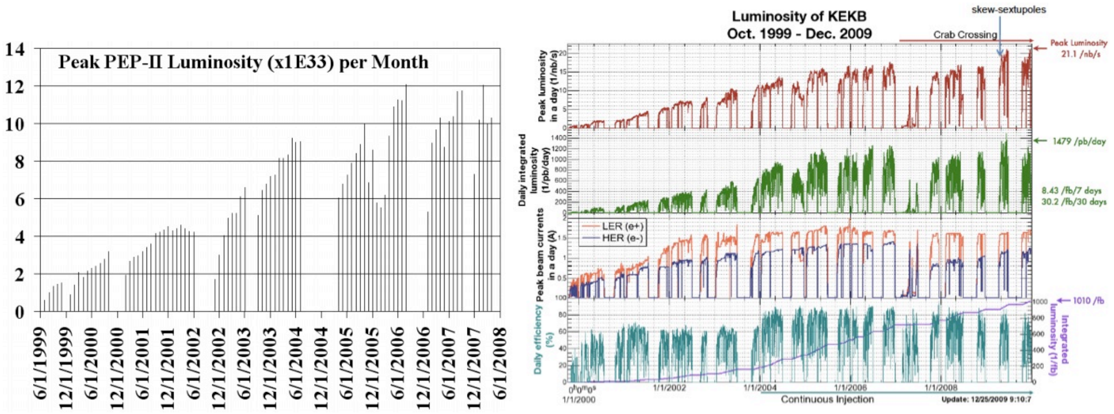


Figure 1: Peak luminosity vs. operation period for PEP-II (9 yrs.) and KEKB (10 yrs.).

3.Towards better performances

Very good performances and high operation reliability represent a big success for these Factories. For an upgrade of an order of magnitude or more in luminosity, desirable for investigation on particle physics beyond the Standard Model to two other projects were studied, the so called "Super" B-Factories: SuperKEKB (presently in construction at KEK) and SuperB (a collider to be built in Italy near Frascati, which has been cancelled for lack of funding). The construction and operation of multi-bunch $e^+ e^-$ colliders have brought about many advances in accelerator physics in the area of high currents, complex interaction regions, high beam-beam tune shifts, high power RF systems, controlled beam instabilities, rapid injection rates, and reliable uptimes (about 95%). The past B-Factories have proven that their design concepts are valid, since asymmetric energies work well, the beam-beam energy transparency conditions are weak, high currents can be stored and the electron cloud instability (ECI) can be managed. On the detector-machine side the Interaction Regions (IR) backgrounds can be handled successfully and IR with two energies can work. Moreover unprecedented values of beam-beam parameters have been reached (0.06 up to 0.09), and continuous injection in production has helped increasing the integrated luminosity. However a step forward is needed in order to increase luminosity by one or even two order of magnitude.

Luminosity depends on the beam parameters (beam sizes, β-functions at the Interaction Point) and on the beam current. Pushing the beam current higher at constant beam parameters has been done for several years, but this "brute force" approach has shown many issues, like for example beam-beam tune shift limit, instabilities due to the high current, High Order Modes heating the beam pipe, cost of the facility in terms of electrical bill. In 2006 P. Raimondi [1,2], while LNF-Frascati and SLAC had joined forces in a study group for a Super B-Factory project with 10^{36} cm^{-2} s^{-1} luminosity, invented a new collision scheme, with a large collision angle and super squeezed beams at the IP, so to reduce the beam overlap area and maximize the number of collisions/area. To avoid the rise of synchro-betatron resonances due to the large collision angle, a couple of sextupoles (called “crab waist”) at a proper betatron phase from the IP could be used in each ring: this allowed the two beams to collide always at the waist of the vertical betatron function, in spite of the particle x-position in the bunch, and to decouple the x-z motion, lowering the effect of the dangerous synchro-betatron resonances. The scheme, called Large Piwinski Angle and Crab Waist (LPA+CW), was first applied to the DAΦNE Φ-Factory at LNF giving an increase in luminosity of a factor of three. The same scheme, without the CW sextupoles, is now the basis of the SuperKEKB collider project.

4.Present colliders: Φ-Factories (DAΦNE, VEPP2000), τ/charm Factory (BEPCII)

The LPA+CW scheme applied to the DAΦNE Φ-Factory in Frascati [5] was adapted to a previous IR design. The implementation on an existing collider with a very short circumference (97 m) was not obvious and a lot of modifications to the IR have to be made. The test was performed in 2008-2009, with a non-magnetic detector, SIDDHARTA, installed at the IP. The results were extremely good, the peak luminosity reaching the predicted value, a factor of 3 with respect to the previous one. This result proved the effectiveness of the CW sextupoles approach, with a very good agreement with numerical predictions and simulations (see Fig. 2). The installation in 2011 of the KLOE magnetic detector did not obtain the same good performances, however the same peak luminosity was reached with less bunches and less current. Beam current was limited by a damaged bellow in the IR, which was discovered and substituted this year, together with many other hardware upgrades aimed at improving the performances. One of the most successful upgrade was the installation of electron-cloud clearing electrodes in the positron ring, which increased the current threshold of the e-cloud instability.

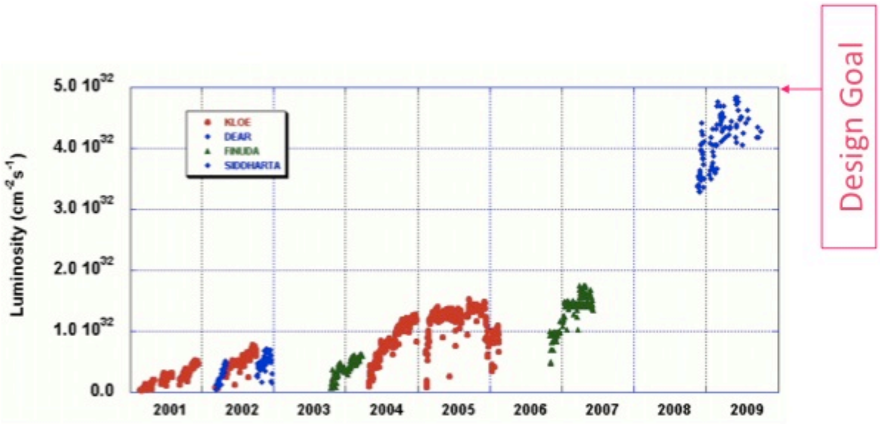


Figure 2: DAΦNE peak luminosity vs. year. LPA+CW scheme was implemented end of 2008.

As a demonstration of the effect of the CW sextupoles in Fig. 3 are the beam profiles (from the Synchrotron Light Monitor) without (left) and with (right) the CW sextupoles. The effect of beam squeezing and of beam distribution tails becoming more Gaussian is evident.

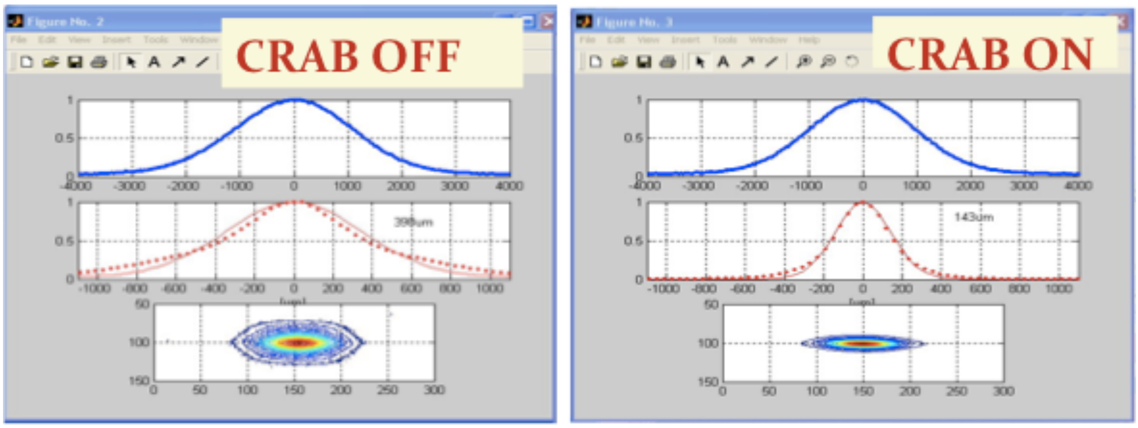
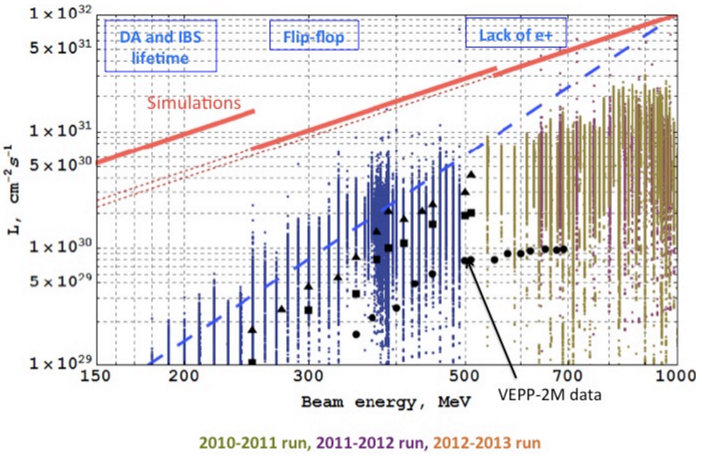


Figure 3: Beam profiles (elaborated from the Synchrotron Light Monitor) without (left) and with (right) the crab waist sextupoles.

The only existing “round beams” collider is the compact (24 m circumference) VEPP2000 Φ-Factory at BINP, Russia [6]. The revolutionary design aimed at increasing the luminosity by colliding two beams with equal horizontal and vertical emittances that theoretically give a gain of a factor of two, due to the geometrical gain factor and to the larger beam-beam limit expected. The round beams are produced by means of 2 pairs of 13 T superconducting solenoids, one in each IR, which can be powered with a combination of different polarities to have different beams conditions (round, Mobius, double Mobius, flat). The design peak luminosity at 1 GeV in the c. of m. was 10^{32} cm^{-2} s^{-2}, the maximum achieved was 10^{31} cm^{-2} s^{-2}. Fig. 4 shows a luminosity scan performed in three runs between 2010 and 2013 and compared with the results achieved by the VEPP-2M collider (black dots, squares and triangles). For different energies the luminosity is limited by different reasons: at energies > 500 MeV mostly because of insufficient positron production rate, while over 800 MeV is the necessity of energy ramping in the collider. For lower energies beam-beam effects, especially the flip-flop, limit the luminosity, and at the lowest energies the main limiting factors are the small dynamic aperture, the emittance growth due to the Intra Beam Scattering process, and the low beam lifetime due to the Touschek scattering. However the beam-beam limit is indeed increased, reaching a limit value of 0.08, beyond that a flip-flop phenomenon arises, probably caused by the interaction of beam-beam effects with nonlinear lattice resonances.



2010-2011 run, 2011-2012 run, 2012-2013 run

Figure 4: Luminosity vs. energy in 3 different runs. Red lines are simulation predictions.

BEPCII at IHEP, Beijing, is the only τ/charm factory presently running [7]. The rings have a bypass at the IR, which allows for shared operation as a synchrotron light source. Operation started in 2008 and continuous luminosity optimization has been carried out since. For example, Fig. 5 shows how in 2011 the change in tune working point, closer to the integer, has produced a rise of a factor 30% in the peak luminosity. The design peak luminosity at 1 GeV in the center of mass was 10^{33} cm^{-2} s^{-2}, the maximum achieved is $8x10^{32}$ cm^{-2} s^{-2}. Continuous tuning of the machine parameters, new optics studies such as a low momentum compaction, different bunch patterns, improvement of the Dynamic Aperture, together with work on the detector BESII for backgrounds reduction will allow in the next year to reach the design luminosity.

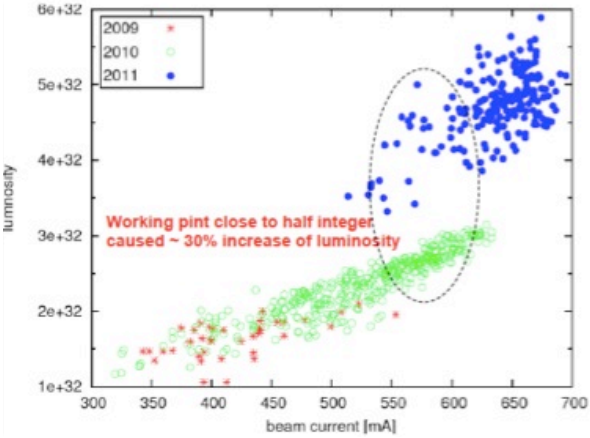


Figure 5: Luminosity vs. beam current, showing the increase due to the change in tune working point.

5. Future colliders: SuperKEKB, Super τ/charm Factories

The only collider that will continue to collect data at the B meson will be the SuperKEKB B-Factory at KEKB, at present in the assembling phase. The accelerator still uses the KEKB tunnel and part of the rings and injections system, however massive improvements have been done to all systems, such as: a new Damping Ring for positrons, a Linac upgrade (positron capture section and new low emittance RF gun), improved monitors and control system, reinforced RF system to cope with the higher beam currents, new TiN-coated beam pipes with antechambers, new LER lattice to squeeze the emittance (replacing short dipoles with longer ones, increasing wiggler cycles), new superconducting final focusing magnets near the IP. In Table 3 is a comparison of the KEKB and SuperKEKB parameters [8]. The main issues, to cite only the ones related to the rings, are: design of the complicated, packed Interaction Region (8 quadrupoles, 48 correcting coils, detector solenoid, 4 antisolenoids), control of the IP orbit and position of the quadrupoles (vibrations, tunnel deformation), dynamic aperture (no solutions have been found up to now for the configuration with crab waist sextupoles), beam-beam (degradation of luminosity due to space charge and lattice non linearities), tuning of the very low emittance. The upgrade of the injection system and of the rings is in progress, and commissioning is foreseen for 2015, with the first luminosity with the detector and IR quadrupoles in Autumn 2016.

Table 3 – Comparison of KEKB and SuperKEKB parameters.

		KEKB		**SuperKEKB**	
Parameter	**Units**	**LER**	**HER**	**LER**	**HER**
Beam energy	GeV	3.5	8	4	7.007
Crossing angle (full)	mrad	22		83	
Max beam currents	A	2	1.4	3.6	2.6
N. bunches		1584		2500	
Bunch length	mm	6	6	6	5
Hor. emittance ε_x	nm	18	24	3.2	4.6
Emittance ratio κ		0.88	0.66	0.27	0.28
β_x*	mm	1200	1200	32	25
β_y*	mm	5.9	5.9	0.27	0.3
σ_x @IP	µm	150	150	10	11
σ_y @IP	µm	0.94	0.94	0.048	0.062
bb ξ_y		0.129	0.09	0.0881	0.0807
Luminosity	10^{33} cm^{-2} s^{-1}	**21**		**80**	

Several proposals for a high luminosity τ/charm collider are also in progress. Detailed designs of the INFN-LNF (Frascati, under the coordination of the Nicola Cabibbo Laboratory) and BINP (Russia) projects can be found in [9,10], while a preliminary study for the Chinese and Turkish projects (latest an ERL plus positron ring) are in [11,12]. The aim is to extend the energy range of the collider from very low to medium (from Φ to τ/charm) so to assure many years of good physics in this field. All designs, except for the Turkish one, are based on the crab waist collision scheme. Table 4 shows a comparison of the main beam parameters.

Table 4 – Comparison of τ/charm Factory proposals

	Units	**LNF**	**BINP**	**IHEP**	**Turkish**
		2 rings	2 rings	2 rings	ERL+Ring
Luminosity	cm^{-2}s^{-1}	1 x 10^{35}	1 x 10^{35}	1 x 10^{35}	1.4 x 10^{35}
Circumference	m	340	360/800	990	250
Beam energy	GeV	1 →2.3	0.5 →2	3	1 + 3.56
Emittance H	nm	5	3/10	10	16
Coupling	%	0.25	0.5	0.5	0.3
IP β (x/y)	mm	70/0.6	200/0.6→20/0.76	1000/1	80/5
bb V tune shift		0.64 → 0.08	0.095→0.17	0.06	0.12
Crab waist		YES	YES	YES	NO
Beam current (A)		1 → 1.7	1.8 → 1.7	2.7	0.48+4.8
N. of bunches		530	418	540	125

The Italian project aims to a target luminosity is 10^{35} cm^{-2} sec^{-1} at 4.6 GeV in the c. of m. This design is a natural evolution of the SuperB B-Factory to be built in the Rome Tor Vergata University campus as an Italian Flagship Project. The design keeps all the features that made SuperB a state-of-the art accelerator, such as the LPA+CW collision scheme, the super squeezed beams, and the polarized electron beam. As a plus, it would be possible to collect data at high luminosity in a large energy range (2 to 4.6 GeV c. of m.), with a peak luminosity target of 10^{34} cm^{-2} sec^{-1} at 2 GeV. The possibility to extend the Linac for a SASE-FEL facility is also taken into account. A Conceptual Design Report [9] was published in September 2013.

6. Conclusions

Flavor Factories played an important role in the particle physics field, with outstanding performances and applications of new ideas and R&D technology. Their future is strictly linked to the interest in middle and low energy particle physics discoveries, and to the availability of funding and international cooperation. At least one new, large infrastructure will anyhow be running as a B-factory at KEKB and will provide good opportunities for the accelerator community to test new concepts.

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