OVERVIEW OF THE LOW ENERGY COLLIDERS*

Q. Qin†, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, P.R. China

Abstract

The low energy colliders cover the beam energy from 500 MeV to 2.5 GeV or more, with relatively small sizes from several ten meters to several hundred meters in circumference. The physics requirements on phi particle, charm quark, tau lepton, Ds, XYZ particles, and R value measurement. Since the beam energies are close to the low energy synchrotron radiation light sources, these machines could be used as parasitic light sources. In this paper, we will investigate some selected beam dynamics issues of the low energy colliders like DAFNE [1], VEPP -2000 [2], BEPCII [3], and CESRc [4], the ways on how to enhance the luminosity at these colliders, the operation and some upgrades during operation, and the future possible super charm tau factory.

INTRODUCTION

Colliders for high energy physics study, have been developed from the pioneer AdA, built in Frascati in 1962, to the LHC, which started its operation at CERN from 2008, within the past five decades. During this half a century, General speaking, the higher beam energy, the larger collider size. Most of the low energy collider could be run at an energy range, and some could be used as a parasitic synchrotron facility. For example, BEPCII keeps running for 10 years as a parasitic light source with the E_b =2.5GeV and I=250mA, and can provide photons to users with 14 beam lines. Figure 1 gives the luminosity evolution of different lepton colliders during the past 40 years.

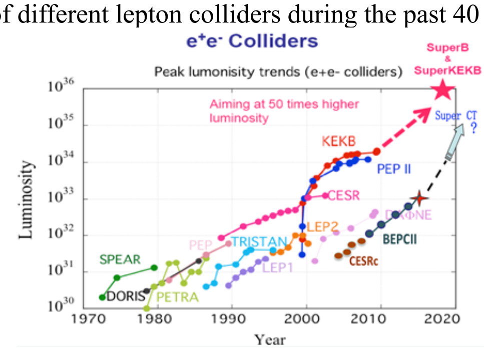

Figure 1: Lepton colliders' luminosity evolution within the past 40 years.

In this paper, low energy colliders, such as DAFNE, VEPP-2000, BEPCII and CESRc will be reviewed from their beam dynamics studies, luminosity tuning and enhancements, operation with some upgrades on the machines, to the future development to super charm-tau factory. Beam dynamics study covers such a large field that we cannot overview all of these machines and topics in this paper, so we just select several important issues. Since they are all operational machines, the topics like dynamic aperture, error effects, and interaction region design, which are all design topics, will not be included.

* Work supported by the Innovation Funding of IHEP 2015.
† qinq@ihep.ac.cn

DAFNE is a phi-factory collider with double-ring, running at the E_{cm} = 1 GeV for phi particle with the design luminosity of $5x10^{32}cm^{-2}s^{-1}$, locates at the LNF/INFN, Italy. The two rings of the collider are placed in parallel, with one collision point where the detector KLOE/ SINDDHARTA stays. Table 1 lists the main parameters of the DAFNE ring, and Fig. 2 shows the layout and a bird-view of the collider. From 2001 to 2009, the luminosity of DAFNE was enhanced gradually, and even doubled after the crab-waist scheme was applied to the machine with the modification of the IR in 2007 to 2008. The highest luminosity was reached as high as $4.5\times10^{32}cm^{-2}s^{-1}$.

Table 1: Main Parameters of the DAFNE Ring

Energy per beam	510 MeV
Machine length	97 m
Maximum beam current (KLOE run)	2.5(e-) /1.4(e+) A
No. of colliding bunches	100-111
RF frequency	368.67 MHz
RF voltage	100-250 kV
Harmonic number	120
Bunch spacing	2.7 ns
Max ach. Luminosity (SIDDHARTA run)	4.5×10^{32} cm^{-2} s^{-1}

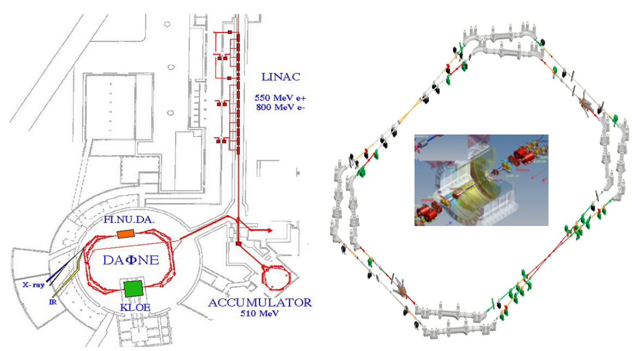

Figure 2: Schematic layout of the DAFNE machine (left) and rings with the detector (right).

The VEPP-2000 is the upgrade machine of the VEPP-2M in BINP, and started its operation from 2010, with the beam energy range from 200 MeV to 1 GeV. Figure 3 is the layout of the VEPP-2000, and its main parameters are given in the Table 2.

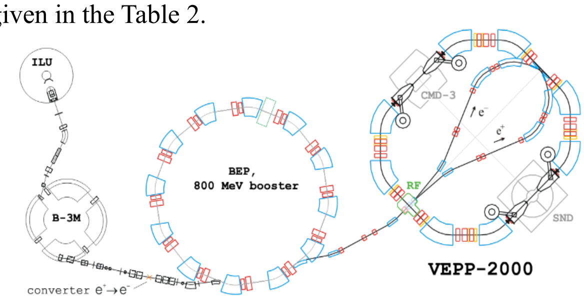

Figure 3: Layout of the VEPP-2000, and its boosters.

ISBN 978-3-95450-187-8

Table 2: Main Design Parameters of VEPP-2000@1GeV

Circumference (m)	24.388	Energy range (GeV)	0.2–1
Number of bunches	1	Number of particles	1×10^{11}
Betatron tunes	4.1/2.1	β-functions@IP (cm)	8.5
Beam-beam para.	0.1	Luminosity ($cm^{-2}s^{-1}$)	1×10^{32}

The VEPP-2000 ring has one bunch per beam to collide in the single ring. But with the round beam collision, the beam-beam parameter reached the highest value among the low energy colliders.

The BEPCII, upgrade project of the Beijing Electron Positron Collider, finished its construction by the end of 2006, and later, commissioned beams and luminosity until the national test and check in July 2009. As a double-ring collider, the BEPCII can run at the beam energy range of 1–2.1 GeV. It can be run as a factory-like machine in the energy region of tau-charm, and a synchrotron radiation (SR) light source with a bit large ring as well, which is combined by each of the outer half-ring of the two collision rings. It's a kind of machine with 3-ring configuration, shown as Fig. 4. The main parameters for both collider and SR facility are listed in the Table 3.

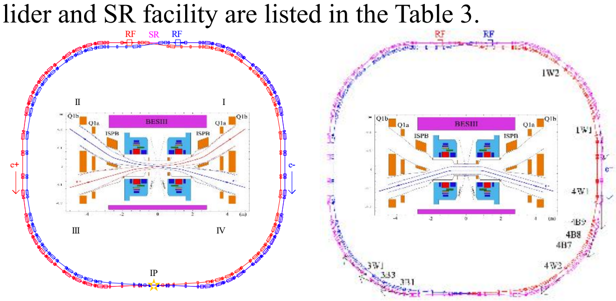

Figure 4: BEPCII collision rings (left) with the IR, and SR ring (right) with different beam trajectories at the IR.

The detector of BEPCII, BESIII, took data at different beam energy after 2009, with only running at the design energy of 1.89 GeV for one year (2010–11). During that time, the luminosity of BEPCII reached $6.5\times10^{32}cm^{-2}s^{-1}$. In the following years, the luminosity is enhanced gradually during machine study time, and reached the design value of $1\times10^{33}cm^{-2}s^{-1}$ in the April of 2016 [5].

Table 3: Main Design Parameters of the BEPCII

Parameters	Collision	SR
Beam energy (GeV)	1.89	2.5
Circumference (m)	237.53	241.13
Beam current (A)	0.91	0.25
Bunch current (mA) / No.	9.8 / 93	~1/160-300
Natural bunch length (mm)	13.6	12.0
RF frequency (MHz)	499.8	499.8
Harmonic number	396	402
Emittance (x/y)(nm·rad)	144/2.2	140
β function at IP (x/y) (m)	1.0/0.015	10.0/10.0
Luminosity ($cm^{-2}s^{-1}$)	1×10^{33}	—

With the budget of CAS, the energy of BEPCII collision mode was upgraded to 2.3 GeV as the request from high energy physics several years ago. As a result, the possible 4-quark state particle Z_c(3900) was found, which was thought as the most important physics result of the BEPCII in recent years.

The rival of the BEPCII, CESR at the Wilson lab in Cornell University, which lowered its energy from B quark region to compete with the BEPCII around 2000 as called CESRc, has an advantage of large circumference compared to the BEPCII. But after it ran at the tau energy, the peak luminosity reached only about 1/3 of its design value, as shown in the Table 4. The schematic layout of CESR/CESRc is shown in Fig. 5. It can provide synchrotron light to users as a platform of light source too. The CESRc stopped its physics running after the BEPCII started its operation for users in mid-2009.

Table 4: Design and Achieved Parameters of CESR and CESRc

Parameter	Achieved	Design	Achieved	Achieved
Circumference (m)	768	768	768	768
Beam Energy (GeV)	5.3	1.88	1.88	2.09
Luminosity ($10^{30}cm^{-2}s^{-1}$)	1250	300	65	73
I_b (mA/bunch)	8.0×45	4.0×45	1.9×40	2.6×24
I_{beam} (mA)	370	180	75	65
ξ_y	0.06	0.04	0.023	0.03
ξ_x	0.03	0.036	0.028	0.035
σ_E/E_0 (10^{-3})	0.64	0.84	0.86	0.86
$\tau_{x,y}$ (ms)	22	55	50	50
B_w (T)	-	2.1	2.1	1.9
β_y^* (cm)	1.8	1.0	1.15	1.3
ε_x (nm·rad)	220	220	140	125

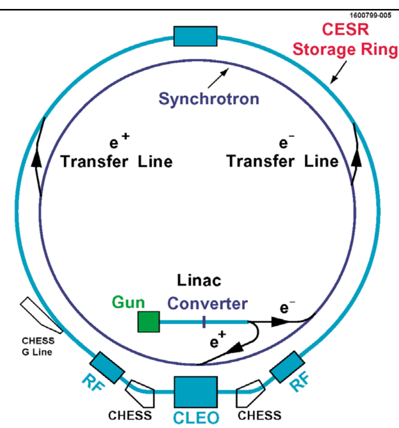

Figure 5: Schematic layout of CESR/CESRc collider.

BEAM DYNAMIC STUDY

In this section, we mainly review the studies on single beam, beam-beam and luminosity tuning, which are selected as main topics of affecting luminosity performance in the colliders, mostly the four machine mentioned in this paper, at their operation stages. Linear and non-linear lattice influence the luminosity indirectly, but by means of the working point, chromaticity tuning, optics realization, coupling control, etc.

ISBN 978-3-95450-187-8

Single Beam Dynamics

Single bunch and multi-bunch dynamics, especially the impedance caused instabilities, are the main study issues in low energy colliders. Bunch lengthening due to low frequency broadband impedance plays more important rule than other single bunch effects, since the maximized luminosity appears when the bunch length equals to the vertical beta function at IP. Multi-bunch instability is always caused by narrow band impedance in storage rings and results bunch oscillations, limiting the luminosity.

In the accumulator ring of DAFNE, the bunch lengthening was observed and measured as functions of bunch current and RF voltage, together with the corresponding analyses of wake potential and broad band impedance, as shown in Figs. 6 and 7 [6]. In the measurement at the DAFNE accumulator ring, bunch lengths were in very good agreement with the simulation results obtained at different RF voltages, confirming the validity of the calculated wake field for the bunch lengthening calculations. The low frequency broad band impedance $|Z/n|_0$ was got as 3.55 Ω from the bunch lengthening measurement.

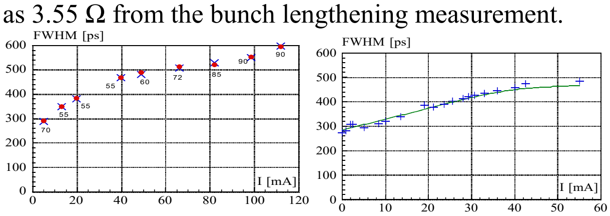

Figure 6: Bunch lengthening as functions of RF voltage (left) and bunch current (right).

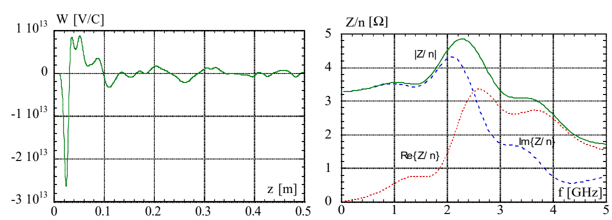

Figure 7: Analytical calculations on wake potential and impedance of the DAFNE ring.

Bunch lengthening with different momentum compaction factors in the electron ring DAFNE was also compared and fit well with the simulation from wake fields, as shown in Fig. 8. It is easy to see that the bunch lengthening is reduced due to a negative momentum compaction.

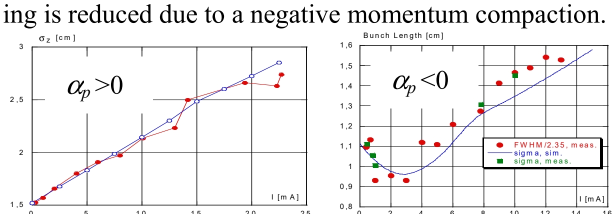

Figure 8: Bunch lengthening at different momentum compaction factors.

The vertical bunch size blow-up was observed at the DAFNE rings, shown as Fig. 9, together with the bunch lengthening. This is correlated with the longitudinal microwave instability. The measurement results show that the threshold of microwave instability is higher for higher momentum compaction, and it is more pronounced for e- ring, which has a higher coupling impedance than e+ ring.

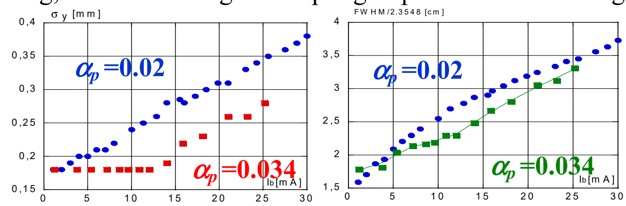

Figure 9: Vertical bunch size blow-up at different α_p (left), with bunch lengthening at same conditions (right).

The bunch lengthening was observed clearly in the two rings of BEPCII, which was considered more than 10% at the designed bunch current I_b =9.8mA [3]. The low frequency longitudinal broad band impedance got from the bunch lengthening is about 3 times larger than expected by numerical analyses. Figure 10 shows the bunch lengthening measurement in two rings of BEPCII.

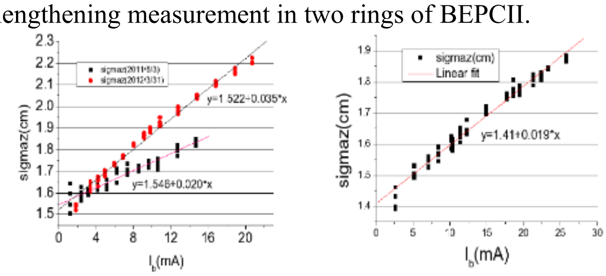

Figure 10: Bunch lengthening at two rings of BEPCII (Left: e+ ring, Right: e- ring).

In the VEPP-2000, the bunch length caused by potential well distortion and microwave instability, was measured with phi-dissector, as a function of single bunch current at different RF voltage and at the beam energy of 478 MeV. The energy spread was also measured together with the bunch lengthening, as shown in Fig. 11.

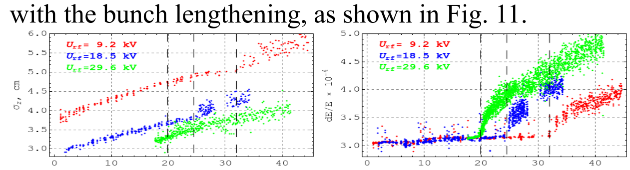

Figure 11: Bunch length measurement at VEPP-2000.

It is very clear that bunch lengthening happens due to potential well distortion at very low bunch current, and is enhanced at the threshold of microwave instability. The higher the RF voltage, the less bunch lengthening, but the lower the threshold current of microwave instability.

As an effective way, longitudinal feedback systems are adopted in DAFNE and BEPCII when longitudinal dipolar oscillation happened in the rings. This helps luminosity to be increased ~20%. In CESRc, a multi-bunch instability due to electron cloud was observed clearly in the positron beam when 4ns bunch spacing was adopted [4].

Beam Parameters Optimization

In normal operation, the beam optics is usually not the exactly same as that of design. Deviations come from multipolar errors of magnets, ripple of power supplies,

ISBN 978-3-95450-187-8

and alignments as well. In small-size rings, magnet model is quite different from the real one, which also contributes the deviations of beam optics parameters. All these deviations widen the transverse stop-bands in tune diagram and make the horizontal tune difficult to move to half integer and thus result a luminosity reduction. Ways to compensate or correct the optics functions were developed and adopted in the re-modelling the lattice of rings.

In the BEPCII rings, all the dipoles and quadrupoles were re-modelled from the hard edge model to a soft edge model with nonlinear fringe field set at both ends of magnets. Then the linear part of the magnet model was modified with the code LOCO for on-line optics correction. The simulation shows a 10% increase of luminosity with the new magnet model, which is believed to help to enhance the luminosity at the design energy in April 2016. A typical beta function measurement result at the BEPCII is shown in Fig. 12 [5], which is a routine correction (every two weeks) during operation.

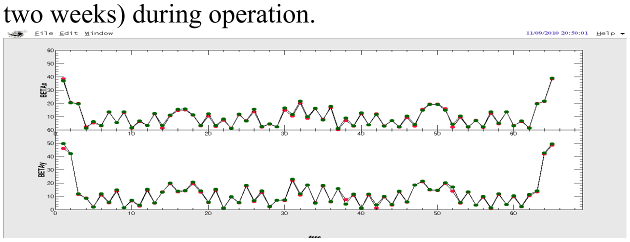

Figure 12: Difference of β functions between measured and setup along the ring of BEPCII (w/o IR).

The transverse beam coupling was diagnosed and tuned during luminosity commissioning. In CESRc, Local coupling in the interaction region was measured with beam shaker and corrected with analytical way, shown as Fig. 13 [4], while in the arc, the local coupling could be tuned with skew sextupoles.

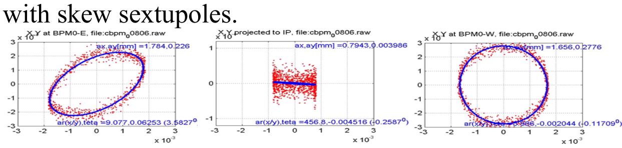

Figure 13: x-y coupling measured with two BPMs aside the IP of CESRc (hori. scale 1 mm/div, vert. 0.1mm/div).

In BEPCII, local coupling of two rings was measured and corrected via the closed orbit response and coupling coefficient tuning. Smaller coupling shows a higher luminosity in most of these small-size colliders.

Beam-beam Interaction

Interactions between two beams, which collide at IP, is the most important issue in a collider. The off-line beam-beam simulation will help us to understand the influence of beam-beam interaction, and on the other hand, results of beam-beam simulation will show the working point region of high luminosity. On-line beam-beam study for luminosity enhancement focuses on the real tunes scan and the non-linearity terms during the luminosity tuning.

Figure 14 shows the strong-strong beam-beam simulation results of single bunch collision for different horizontal tunes. The results are very much consistent to the real operation of BEPCII, in which the luminosity increased ~20% when the horizontal working point was moved close to half integer. From 2010, the storage rings of BEPCII keeps running at the half-integer region for the horizontal working point during the routine operation. The horizontal tunes could be as close to the half integer as 0.503, which requests high stability to the hardware.

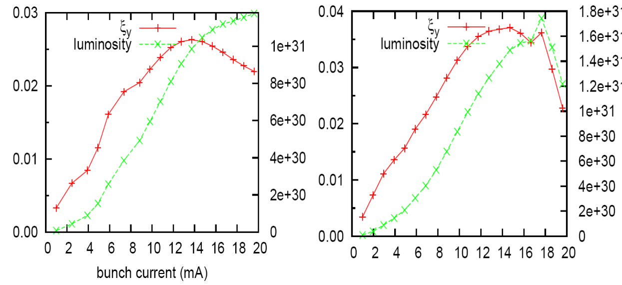

Figure 14: Beam-beam simulation with strong-strong model for single bunch collision in the BEPCII (left: ν_x~0.53, right: ν_x~0.51)

In the DAFNE rings, the peak luminosity was increased too when the horizontal working point approached to the half integer. But the lifetime of beams were increased in DAFNE, in contrast to the beam lifetime in the BEPCII. This was possible with the wigglers since dynamic aperture was satisfactory at low tunes. Figure 15 shows the luminosity of single bunch collision for different working points at the DAFNE[7].

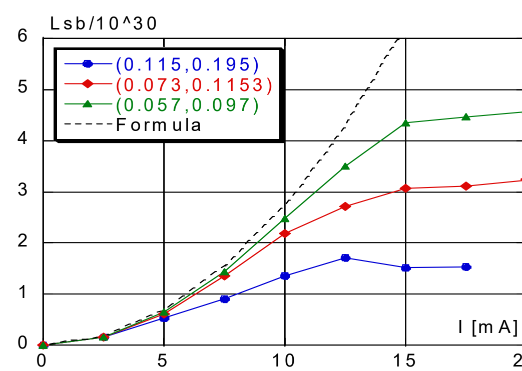

Figure 15: Luminosity of single bunch collision of DAFNE with different working point regions.

In CESRc, the horizontal tune was also chosen to be close to half integer, say ~0.526, for high luminosity. In this region, less beam-beam driving resonances were found than the high tune region, which mainly located near 0.6. Figure 16 shows clear beam-beam driving resonances but less machine resonances at different single bunch head-on collision.

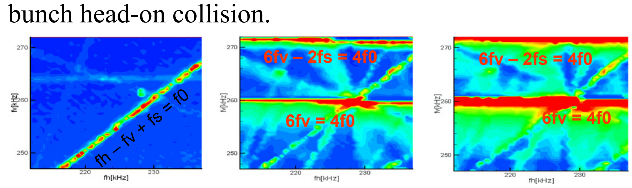

Figure 16: Tune plane exploration at high tune region of CESRc (right: single beam, middle: 0.5mA 1×1 collision, right: 1.0mA 1×1 collision).

In VEPP-2000, both "weak-strong" and "strong-strong" beam-beam simulations were done to compare with the operation data, shown in Fig. 17. It was found that the beam-beam threshold was improved with bunch lengthening, as shown in right one of Fig. 17. A "flip-flop" effect was observed in the VEPP-2000 ring, which was supposed to be the coherent beam-beam pi-mode interacted with the machine nonlinear resonances.

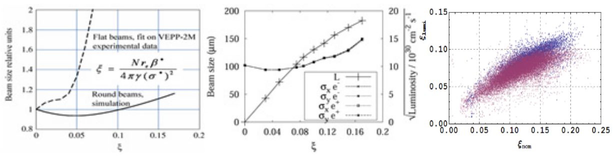

Figure 17: Vertical size dependence on beam-beam parameter with weak-strong (left), strong-strong (middle) simulations, and the bunch lengthening under different RF voltages (right, blue: V_{rf}=17kV; purple: V_{rf}=35kV).

In both long and short bunch cases, flip-flop developed for beams intensity higher than 15 mA, which meant the maximum beam-beam parameter was about 0.1 with the round beams. But the long bunch tended to mitigate the troublesome due to specific luminosity degradation for higher bunch current [2].

WAYS ON LUMINOSITY ENHANCEMENT

Higher luminosity is always the goal of colliders no matter what kind of stage they are, design or in operation. But for different machine, the way on increasing luminosity is somehow different.

Luminosity Upgrade in DAFNE

Crab-waist (CW) [8] scheme was first developed and applied in the DAFNE rings after several years' normal commissioning on luminosity. A large Piwinski angle and a pair of crab waist sextupoles are used to make the vertical β at IP comparable with the overlap area, say $\beta_y \approx \sigma_x/\theta$. Figure 18 shows the difference of β_y at the collision area with and without crab waist scheme.

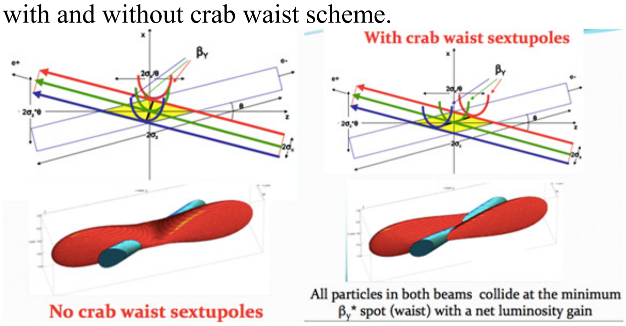

Figure 18: Collisions with/without crab-waist sextupoles.

In the CW scheme, the Piwinski angle is increased by reducing the horizontal beam size and increase the crossing angle to enhance the luminosity and decrease the horizontal tune shift. In addition, parasitic collisions become negligible due to the larger crossing angle and the smaller horizontal beam size. The luminosity gain mainly comes from the lower vertical β at IP, which can be much smaller than the bunch length. The other benefits from CW are suppression of vertical synchrotron resonances, and the reduction of the vertical tune shift with synchrotron oscillation amplitude. Moreover, there's no need to decrease the bunch length, which helps to solve the problems of electromagnetic high order mode heating, coherent synchrotron radiation of short bunches, and excessive power consumption. But the new beam-beam resonances are introduced by the large Piwinski angle, limiting the maximum obtainable tune shifts. A pair of sextupoles, with one placed at each side of the IP in counterphase with the IP in the horizontal plane and at π/2 in the vertical plane, provides the CW vertical β rotation. The strength of crab sextuple should satisfy the so called crab-condition as following:

$$K = \frac{1}{\theta}\frac{1}{\beta_y^*\beta_y}\sqrt{\frac{\beta_x^*}{\beta_x}}\ , \qquad (1)$$

where is the crossing angle, and $\beta^*_{x,y}$ and $\beta_{x,y}$ the β's at the IP and the location of sextupoles. Thus the crab-waist transformation helps the luminosity enhancement. More details about the crab-waist scheme itself will be given by Riamondi [9] at this workshop.

The luminosity of DAFNE was increased dramatically after adopting the CW scheme in 2007. The new collision scheme based on large Piwinski angle and the CW transformation, together with an experimental detector SIDDHARTA, was commissioned. Table 5 lists the different parameters using for normal and CW optics and the corresponding luminosities and detectors [8].

Table 5: Parameters of Different Schemes at DAFNE

Parameter	Unit	KLOE	FINUDA	SIDDHARTA
I_{e-}	A	1.38	1.50	1.52
I_{e+}	A	1.18	1.10	1.00
Bunch No.		111	106	105
ε_x	nm·rad	340	340	250
β_x	m	1.5,	2.0	0.25
β_y	cm	1.8	1.9	0.93
Bunch length	cm	1.5-2.0	1.5-2.0	1.5-2.0
Crossing angle	mrad	2×12.5	2×12.5	2×25
ξ_y		0.025	0.029	0.044
Luminosity (10^{32})	cm^{-2}s^{-1}	1.53	1.60	4.53

The peak luminosity of SIDDHARTA was got in June 2009, after two years' upgrade and the installation of new IR and detector. Figure 19 shows the luminosity evolution of DAFNE from the very beginning of commissioning. At last, the luminosity reached 90% of the design value with the CW scheme in early 2009.

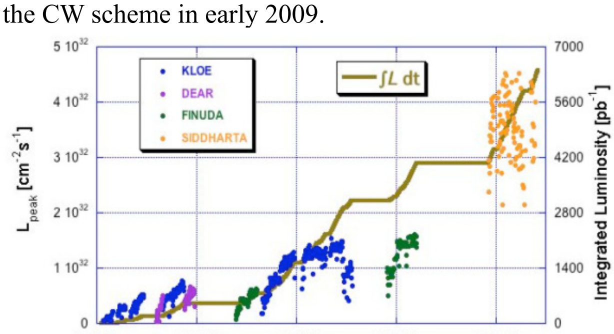

Figure 19: Luminosity evolution at DAFNE.

ISBN 978-3-95450-187-8

Luminosity Commissioning at BEPCII

The BEPCII storage rings have been running for HEP from 2009. Most of its HEP experiments are not at the design energy, 1.89 GeV/beam, but higher or less than it. This makes the luminosity enhancement during normal operation become difficult. Each year, dedicated luminosity commissioning or machine study (~3 weeks) was done during the routine operation for HEP experiments. The luminosity commissioning means the optimization of all the parameters related to ring optics, feedback systems, RF system, injection, and the stability of all the hardware systems, which was the requirement from the horizontal working point near half integer. After several years' commissioning, the main parameters are optimized from the original design values to the ones list in Table 6.

Table 6: Main Parameters of the BEPCII Rings @1.89GeV

Parameter	Original design	New design (after 2014)
Beam current	910 mA	910 mA
Bunch current	9.8 mA	7.0 mA
Bunch number	93	130
β at IP (x/y)	1/0.015 m	1/0.0135 m
Horizontal emittance	144 nm.rad	100 nm.rad
Transverse coupling	0.01	0.001-0.005
Working point (x/y)	6.53/5.58	7.505/5.58
Harmonic number	396	396
Bunch spacing	2.4 m	1.8 m
Mom. compaction	0.0235	0.0170
RF voltage	1.5 MV	1.5 MV
Natural bunch length	1.35 cm	1.15 cm
Beam-beam parameter	0.04	0.04
Luminosity ($\times10^{33}$)	1.0 $cm^{-2}s^{-1}$	1.0 $cm^{-2}s^{-1}$

With the new lattice model, in which the magnets were considered as an ideal one plus two fringe field lenses, the optics parameters were optimized to the "New design" as listed in the above table. In the machine study dedicated to the luminosity commissioning, single bunch luminosity was tuned first, aiming at the maximum beam-beam parameter. With the help of feedback systems, multi-bunch luminosity increased linearly as the number of bunches. Smaller transverse coupling compensated the lower bunch current and also helped to increase the beam-beam parameter. Finally, the design luminosity of $1.0\times10^{33}cm^{-2}s^{-1}$ at 1.89 GeV was achieved in April 5, 2016, with the single beam current of ~850 mA and the bunch number of 119. Figure 20 shows the BEPCII luminosity evolution.

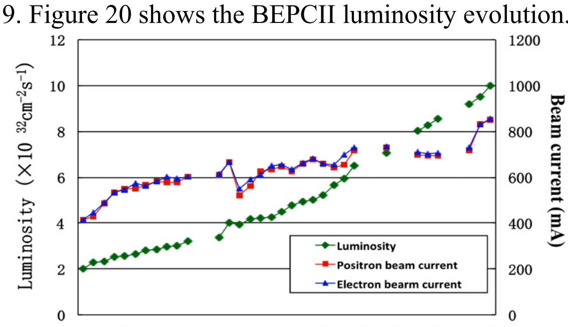

Figure 20: Luminosity evolution of the BEPCII.

Round Beam Collision at VEPP-2000 [2]

The round beam concept (RBC) [10] was studied and adopted in the VEPP-2000, to increase the beam-beam limit and then the luminosity. The longitudinal component of angular momentum as an additional integral of motion was provided by the X-Y symmetry of the transfer matrix between the two IPs and by the axial symmetry of the counter-beam force. Requirements to the ring lattice include head-on collision, low and equal β functions at IP, equal beam emittances and same fractional part of transverse tune. Two pairs of superconducting final focusing solenoid with a magnetic strength of 13 T were placed at the two IR symmetrically wrt the collision points. A "flat" combinations of solenoid polarities (+− +− or +− −+) was found to have enough dynamic aperture. The optics, which satisfies the RBC scheme, should have the betatron tunes lie on the difference resonance $\nu_1-\nu_2=2$ to provide equal emittances by eigenmodes coupling. With these setup, both lattice optics and hardware installation, VEPP-2000 started data taking from the lowest energy of collider, 160 MeV, to high energy range. Figure 21 depicts the luminosity achieved during HEP experiments at different beam energy. At the energy above 500 MeV, luminosity was limited by positron beam production rate. For the energy from 300 to 500 MeV, beam-beam effect limited the luminosity. At the lowest beam energy, the main limit factors were the small DA, IBS, and low beam lifetime.

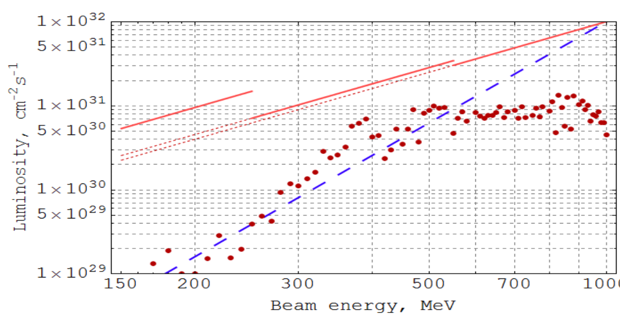

Figure 21: VEPP-2000 luminosity. (red line: peak luminosity overestimated, $L\propto\gamma^2$; blue line: fixed lattice energy scaling low, $L\propto\gamma^4$)

The achieved beam-beam parameter could be written as

$$\xi=\frac{Nr_e\beta^*_{nom}}{4\pi\gamma\sigma^{*2}_{lumi}}, \quad (2)$$

where the β function is nominal while the beam size is got from the measured luminosity. A maximum $\xi\sim0.09$ was achieved during the regular operation. As depicted above, the beam-beam parameter could be enhanced to 0.12-0.15 with higher RF voltage. The luminosity of VEPP-2000 is about 2 to 5 times higher than that achieved by the VEPP-2M at the whole energy range of 0.16-1 GeV.

OPERATION, UPGRADE AND FUTURE

The new detector, KLOE-2 was installed at the DAFNE machine after the successful CW commissioning with SIDDHARTA. The data taking for HEP was then started with the new detector. At KLOE-2, a peak luminosity of

ISBN 978-3-95450-187-8

$2.13\times10^{32}cm^{-2}s^{-1}$ was obtained with the beam currents of 1.13A (e-) and 0.88A (e+), and the maximum integrated luminosity per day of 14.03 pb^{-1}[11]. Figure 22 shows the delivered, acquired and target integrated luminosities of KLOE-2 after its running. The comparison of old and new IR is also given in Fig. 22.

The BEPCII keeps running at different beam energy regions due to the physics requirements. Different optics parameters are adopted for different energy regions to maximization the beam-beam limit and peak luminosity. Table 7 lists the main parameters for such a kind of luminosity "levelling" at different beam energy regions.

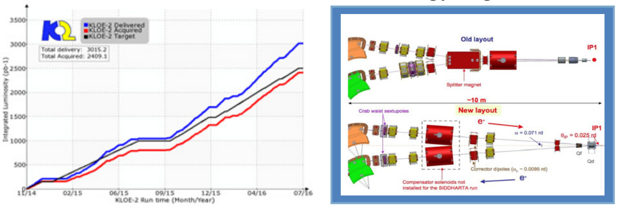

Figure 22: Integrated luminosity at KLOE-2 and the comparison of the IR before and after KLOE-2 installed.

The routine operation of BEPCII will focus on higher integrated luminosity at different beam energy. Beam energy higher than 2.4 GeV is also being considered for physics requirements. Top-up injection is the next step to increase integrated luminosity, which was already realized at the KEKB and PEP-II.

Table 7: Main Parameters of BEPCII Optics at Different Beam Energy Regions (Typical Values are Listed Here)

Beam energy (GeV)	1.0	1.89	2.3
β at IP (x/y, m)	1.0/0.012	1.0/0.0135	1.0/0.015
Hori. emittance (nm·rad)	54	122	144
Working point	6.505/5.58	7.505/5.58	7.505/5.58
Momentum compact.	0.0286	0.018	0.017
Nat. bunch length (cm)	0.6	1.15	1.5

The VEPP-2000 was run from 2010 to 2013 for HEP data taking, followed by an upgrade of its injection complex, booster, transfer channels and ring modifications from 2013 to 2016. The injection complex was improved for high intensity and higher beam energy, and thus for a high quality beam. The booster BEP was upgraded to 1 GeV and the transfer channels from BEP to VEPP should also be upgraded to 1 GeV. The modification of VEPP-2000 were new scraper, additional kicker electrodes in the ring, and new optics. The beam commissioning for K-500, BEP, and VEPP-2000 ring started in early 2016. The VEPP-2000 passed through beam scrabbing procedure and is ready to start data taking with both detectors at designed luminosity level.

Future Charm-τ Factory Design

At least 3 labs proposed to construct the super charm-τ factory at their campuses: Cabibbo lab in Italy, BINP in Russia, and USTC in China. The main requirements of the super charm-τ factory include the energy of center of mass of 1-5 GeV, with a peak luminosity of $10^{35}cm^{-2}s^{-1}$ at the charm/τ threshold. Electron beam should be polarized longitudinally at IP, and the energy calibration could be as small as $(5\text{-}10)\times10^{-5}$ by Compton backscattering. These demands cause the consideration of the accelerator design as the following detailed conditions:

- Two rings with CW collision and single IP with the β^*_y smaller than 1 mm.
- Preservation of emittance and damping time through the energy range to optimize luminosity with SC wigglers.
- Siberian snakes to obtain longitudinally polarized e-.
- Highly efficient positron source (high rate top-up injection).
- Full energy injection (linac) with polarized e- source.

The storage ring of such a super charm-τ factory could be used as a low emittance synchrotron radiation source, accommodating tens of beam lines. As an example, BINP developed a lattice design of the super charm-τ factory. Figure 23 gives the schematic layout of this machine.

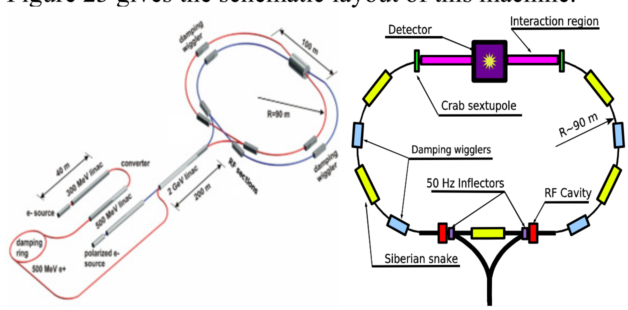

Figure 23: Schematic layout of super charm-τ factory designed in BINP (left: the whole machine; right: main accelerator parts in double-ring case with CW).

Table 8: Main Parameters of the Super Charm-τ Factory in BINP

Beam energy	1.0GeV	1.5GeV	2.0GeV	2.5GeV
Circumference	780m			
Emittance (x/y)	8nm/0.04nm @ 0.5% coupling			
Damping time (x/y/z)	30/30/15ms			
RF frequency	508MHz			
Harmonic number	1300			
Bunch current	4.4mA			
Beam current	1.7A			
Bunch length	16mm	11mm	10mm	10mm
Energy spread (10^{-4})	10.1	9.98	8.44	7.38
Momentum comp. (10^{-3})	1.0	1.06	1.06	1.06
Synchrotron tune	0.007	0.010	0.009	0.008
Beam-beam parameter	0.15	0.15	0.12	0.095
Luminosity (10^{35} $cm^{-2}s^{-1}$)	0.63	0.95	1.00	1.00

Table 8 compares main parameters at different beam energy from 1.0 to 2.5 GeV [12]. But due to the budget limit, the design was reduced to a circumference of 380m.

The main elements like the QD0 at IR, and the SC damping wiggler, were designed together with the lattice and IR, shown as Fig. 24. The injection facility kept the current machine at BINP, and the 2mA beam current at the damping ring was commissioned.

ISBN 978-3-95450-187-8

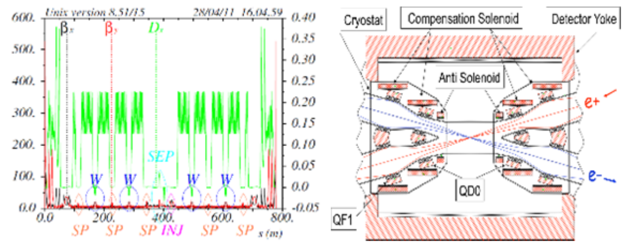

Figure 24: Optics functions along the main ring (left) and the IR design (right) for super charm-τ factory in BINP.

The design of super charm-τ factory in Cabibbo/INFN, also experienced from the relatively bigger ring to a small ring with a circumference of 330m [13]. Figure 25 shows the layout of the ring. Multi-bend achromat was adopted in the ring design to get a quite small emittance. Table 9 lists the main parameters for different beam energies.

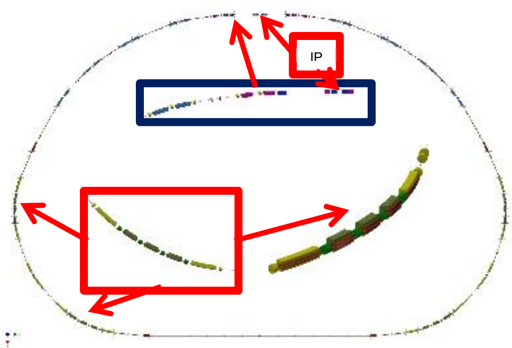

Figure 25: Layout of the super charm-τ factory designed in Cabibbo/INFN.

The design provided an option of FEL with its long linac. A lot of hardware, such as main ring dipole and gradient dipole, were designed, together with the linac and the damping ring.

Table 9: Main Parameters of the Ring for Cabibbo Super Charm-τ Factory.

Beam energy (GeV)	2.0	2.0
Circumference (m)	330.16	330.16
Crossing angle (mrad, full)	60	60
Beam-beam parameter	0.088	0.119
β_x/β_y at the IP (cm)	6/0.06	6/0.06
Emittance (nm, x/y)	5.14/0.0128	5.61/0.0140
Bunch length (mm)	6.9	7.2
Beam current (A)	1.735	2.565
Bunch current (mA)	3.38	5.00
Bunch number	513	513
RF frequency (MHz)	476	476
Harmonic number	524	524
Energy loss/turn (MeV)	0.09	0.09
Luminosity (10^{35} $cm^{-2}s^{-1}$)	1.0	2.0

In the University of Science and Technology China, a conceptual design of super charm-τ factory was proposed in 2013, with the beam energy of 1-3.5 GeV. The luminosity aims at $5\times10^{34}cm^{-2}s^{-1}$ in phase 1 and $10\times10^{34}cm^{-2}s^{-1}$ in phase 2 [14]. The detailed design is still under way.

CONCLUSION

During the past decades, very fruitful beam dynamics studies were carried on at low energy colliders. Among these studies, the impedance induced instabilities are more serious than the high energy colliders. The relatively small size of rings limits the performance of low energy collider, but the parasitic synchrotron light source make it easy to be a platform for multi-disciplinary sciences.

Different ways to increase luminosity were realized in all these low energy machines as the pioneers for the family of collider. The super charm-τ factory, as the future direction for low energy collider, is very much promising to be the luminosity of ~10^{35} $cm^{-2}s^{-1}$ by adopting the crab-waist scheme and could be run as a 3rd generation synchrotron light source.

ACKNOWLEDGEMENT

The author is grateful to the help of Dr. C. Malardi, M. Biagini, and M. Zobov from LNF/INFN, Dr. D. Shwartz, and E. Levichev from BINP, Dr. Y. Zhang and C.H. Yu from IHEP. Without the communication and fruitful discussion, it is difficult to get all materials well understood.

REFERENCES

[1] C. Milardi *et al.,* "Present status of the DAΦNE and perspectives", Int. J. Mod. Phys. A 24, pp. 360-368 (2009).

[2] D. Shwartz *et al.,* "Recent Beam-beam Effects and Luminosity at VEPP-2000", in Proceedings of IPAC'14, Dresden, Germany, June 2014, pp. 924-927.

[3] Q. Qin, "Performance and Prospects of BEPCII", in Proceedings of IPAC'12, New Orleans, USA, May 2012, pp. 1030-1034.

[4] A. Temnykh, "Overview of the Beam Dynamics Study in CESR", in Proceedings of the 40th ICFA Workshop on Beam Dynamics in e^+e^- Factories, Novosibirsk, April 2008.

[5] C.H. Yu *et al.,* "BEPCII Performance and Beam Dynamics Studies on Luminosity", in Proceedings of IPAC'16, Busan, Korea, May 2016, pp. 1014-1018.

[6] R. Boni *et al.,* "DAFNE Accumulator Ring Coupling Impedance Measurements", NIM A 418 (1998) 241-248.

[7] B. Spataro and M. Zobov, DAFNE Technical Note G-64, 2005.

[8] M. Zobov *et al.,* "Test of 'crab-waist' collisions at DAΦNE Φ-Factory", Phys. Rev. Lett. 104, 174801 (2010).

[9] P. Riamondi, presented at eeFACT2016.

[10] V.V. Danilov *et al.,* "The Concept of Round Colliding Beams," in *Proc. EPAC'96*, Sitges, p. 1149 (1996).

[11] C. Milardi *et al.,* private communication, 2016.

[12] E. Levichev, Baseline of Super-c-tau in Novosibirsk, Proc. Workshop on Tau-charm at high luminosity, 2013.

[13] M. Biagini, tau/charm accelerator overview, in Proc. Workshop on Tau-charm at high luminosity, 2013.

[14] J. Luo, private communication, 2016.

ISBN 978-3-95450-187-8