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Summary of Working Group I—Beam-Beam Instability with Crossing Angle

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INTRODUCTION

The luminosity of circular colliders is given by

$$L = \xi \frac{I_T}{e} \frac{\gamma}{r_e \beta_y^*},$$

where e=1.6×10^{-19}C and r_e=2.82×10^{-15}m are constants. The parameter ξ is the beam-beam tune shift parameter. It is limited by the beam-beam dynamics to ~0.05. The parameter γ is the beam energy, which is determined by the physics to be studied by the collider. The parameter β_y* is the vertical β-function at the interaction point (IP). It has to be comparable to the bunch length in order to avoid losing luminosity due to a geometrical factor increasing the overlap area. Therefore, the only possible parameter left for increasing luminosity is the total current I_T. We can write I_T=$N_b I_b$, where I_b is the current per bunch. It is limited by the single bunch instabilities. To increase I_T., the best one can do is to increase the number of bunches in the ring N_b.

In order to meet the high luminosity requirement of heavy quark factories, modern high-luminosity circular colliders take the approach of

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multibunch operation. The electrons and positrons are stored in two separate rings and brought together at a single interaction point. The key to achieving high luminosity in these machines is reducing the space between bunches. This makes the crossing angle collision scheme very favorable.

However, a crossing angle introduces synchro-betatron coupling. In a head-on collision, particles receive a transverse kick, $F(x)$, from the counter beam. This kick depends on the transverse coordinates. When a crossing angle, $\pm\Phi$, in x plane is introduced, the transverse kick becomes $F(x + \tan\Phi \cdot s)\cos^2\Phi$, where s is the longitudinal position, and a longitudinal kick is associated. Obviously, the crossing relates transverse motion with the longitudinal motion.

To compare machines with different parameters, the crossing angle should be scaled as

$$\phi = \frac{\sigma_s}{\sigma_x}\tan\Phi \approx \frac{\sigma_s}{\sigma_x}\Phi.$$

ϕ is called the normalized crossing angle. In most analysis and simulations, crossing angles appear in this form.

By now, two electron-positron colliders have operated with a crossing angle: DORIS I and CESR. Their experience is the most useful information on this issue.

HORIZONTAL CROSSING ANGLE VERSUS VERTICAL CROSSING ANGLE

A conclusion that was well agreed to is that a crossing angle in the horizontal plane is better than the one in vertical plane. The major reason leading to this conclusion, I believe, is the fact that DORIS I, which used a vertical crossing angle of ±12 mrad, had bad performance and eventually gave up, while CESR, which adopted a horizontal crossing angle ±2 mrad, has been performing very well. However, this is not completely convincing because CESR has a much smaller crossing angle than DORIS I.

To look into this problem, one can compare the normalized crossing angles in horizontal and vertical planes. The denominator in the normalized crossing angle definition is the transverse beam size corresponding to the crossing direction. Assuming the physical crossing angle and the bunch length are the same, the smaller the transverse beam size, the larger the normalized crossing angle is, and hence the stronger synchrobetatron coupling. In the newly designed high luminosity colliders, most of them have a flat beam at the collision point. Therefore, the normalized vertical crossing angle would be considerably larger than a horizontal one. This should be the primary reason for choosing a horizontal crossing angle.

Another view on this problem is the orders of emittances. Due to radiation noise, the longitudinal emittance is usually two magnitudes larger than horizontal emittance, and the horizontal emittance is about two orders of magnitudes larger than vertical emittance. So, the effect of coupling between longitudinal and vertical will be much more sensitive than the effect of longitudinal-horizontal coupling.

LIFETIME PROBLEM DUE TO CROSSING ANGLE

The best known consequence of a crossing angle is that it leads to a bad lifetime. Early experience of DORIS I was that the lifetime went bad even with a small beam-beam tune shift parameter, even before it saturated. Both simulation and observation show that the bad lifetime is correlated with longitudinal-vertical resonances induced by the vertical crossing angle[1].

The same problem happened in crossing angle operation at CESR. Simulations and analysis predicted that certain groups of synchrobetatron resonances are to be excited because of the crossing angle, causing a lifetime problem. This was confirm by experiment[2].

It is worth mentioning that the resonance family excited by the crossing angle depends on the normalized crossing angle ϕ. With larger ϕ, higher order sidebands tend to be excited. Simple simulations and analysis can provide reasonably good qualitative prediction of this. More sophisticated simulations can calculate the lifetime due to the crossing angle, but quantitative agreement is poor[3].

More analysis shows that a horizontal crossing angle may help in suppressing vertical synchrobetatron resonances excited by the bunch length effect[4]. Whether this will help the machine performance depends on the aperture that limits the lifetime.

PEAK LUMINOSITY PERFORMANCE WITH CROSSING ANGLE

The question here is: what is the maximum beam-beam tune shift parameter that can be achieved with a crossing angle?

DORIS I's experience is discouraging. The beam-beam tune shift achieved was between 0.005~0.01, far below what can be reached with head-on collisions. CESR made a change on this issue. CESR runs constantly with a beam-beam tune shift of more than 0.04[5,6].

Again, it is hard to draw conclusion from these experiences. DORIS I had a normalized crossing angle of 0.5, while CESR has 0.09. In addition, CESR is equipped with feedback system, etc., that DORIS I did not have.

From the underlying physics point of view, the small amplitude particles, or the beam core, should suffer from synchrobetatron coupling due to the crossing angle too. Because different amplitude particles experience quite different nonlinear forces, the sensitivities to various resonances are very different. As the result, there could be another family of resonances, different from the ones that limit the lifetime, that makes the luminosity performance bad.

Simulations have been carried out to study the luminosity performance of KEKB[7]. Tune scan shows reasonably large "workable" area.

EXPERIMENTAL INVESTIGATION

Since the beam-beam simulations have not been able to provide quantitative agreement with observation and adequate prediction of performance, an experimental investigation is well justified. There are two goals in doing experiments: checking the credibility and predictability of simulations and testing the machine performance under certain conditions.

Before a large crossing angle collider is built, a way to perform tests on a existing machine is proposed. A finite dispersion η^* at the IP functions essentially as a crossing angle. The beam-beam kick with η^* can be written as $F(x+\eta^*\delta)$. Compared with crossing angle kick $F(x + \tan\Phi \cdot s)$, one can see the major difference is in the longitudinal phase (s replaced by δ). This will only make a difference at resonances $Q_X \pm Q_S$. Therefore, a crossing angle can be emulated by a η^* which is chosen to have the equivalent normalized crossing angle: $\frac{\sigma_\delta}{\sigma_x}\eta^*=\frac{\sigma_s}{\sigma_x}\Phi$.

In principle, it is not difficult to generate a η^* in many existing e^+e^- colliders, such as VEPP-2M, CESR, BEPC, *etc.* The working group would like to call for an experimental study of a collider with dispersion at the collision point. It will be extremely helpful in new machine design, learning operating collider under new conditions which may speed up commissioning process, and understanding beam-beam physics.

REMARKS

Based on the discussion, the working group concluded that the crossing angle collision introduces new resonances that limited the choice of working points. Therefore, to live with a crossing angle, the most critical issue is finding a good working point in the tune space that provides the required performance. Experience has proved that a good working point can be found with a normalized crossing angle up to 0.09.

The underlying physics behind crossing angle collision is the introduction of synchrobetatron coupling. As the results, two families of resonances are introduced to the tune plane. One family of resonances causes bad lifetime, which has been studied and observed. The other family may limit peak luminosity performance. The composition of the families and the strength of the resonances vary with the normalized crossing angle. Experimental investigation is strongly recommended for larger normalized crossing angle.

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