COHERENT BEAM-BEAM RESONANCES IN SUPERB WITH ASYMMETRIC RINGS

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Abstract

One of the latest options of SuperB foresees exploiting rings with unequal circumferences. In such a configuration additional coherent beam-beam resonances can arise. In this paper we discuss the possible impact of the resonances on beam dynamics in SuperB, maximum achievable tune shifts and working point choice.

INTRODUCTION

The SuperB project [1, 2] aimed at construction of a very high luminosity asymmetric electron-positron flavour factory has been recently approved by the Italian government. The new collider will be located at the campus of the “Tor Vergata” University in Rome.

In order to reach the luminosity of 10^{36} cm^{-2}s^{-1} at the Y(4S) energy, i.e. by about two orders of magnitude higher than the luminosity achieved at the B-factories PEPII in USA and KEKB in Japan, the project relies on the novel crab waist collision scheme [3], that has been proposed and successfully tested at the Φ-factory DAΦNE at Frascati [4].

One possible option of the SuperB project is the asymmetric ring design with the high energy ring (HER) twice longer than the lower energy one (LER) (see Fig. 1). In this configuration it may be easier to optimize each ring separately [5].

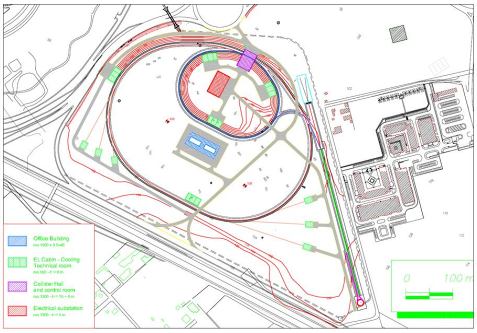


Figure 1: Schematic layout of SuperB with asymmetric rings.

However, as it was studied theoretically already more than 20 years ago [6-9], in asymmetric rings colliders new coherent beam-beam resonances are a potential danger for their performance. These low order linear resonances can drive very fast beam instabilities such that even modern feedback systems are not able to cope with them.

In this paper we study the coherent resonances for the asymmetric rings SuperB design option applying both the linear analysis and full scale 3D strong-strong beam-beam simulations (using DAΦNE examples). The simplified 1D linear analysis, described in the first part of the paper, is always useful to estimate the resonance bandwidth, the instability rise time and to find suitable working point areas. In turn, 3D simulations (the second part of the paper) are helpful to study effects of nonlinearities on beam dynamics, as, for example, possible Landau damping of the instabilities, instability saturation, impact of incoherent resonances on the coherent motion, crosstalk between different degrees of freedom. The latter is particularly important for colliders exploiting the crab waist collision concept.

In conclusion we discuss possible design solutions that can eliminate the negative impact of the resonances on the collider performance.

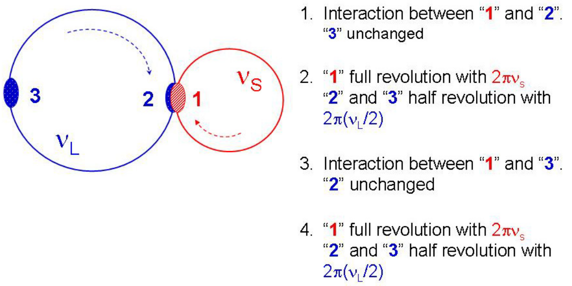
LINEAR ANALYSIS

The theory says that for a collider made of two asymmetric rings with a circumference ratio $C_+/C_- = K_+/K_-$, equal RF frequencies and all buckets filled, the following coherent beam-beam resonances can be driven:

$$K_+\nu_- = m/2; \quad K_-\nu_+ = l/2; \quad K_+\nu_- + K_-\nu_+ = n$$

Here $\nu_\pm$ are the betatron tunes for the long and short rings respectively, and m, n and l are integers. The most dangerous resonances are those coupling the tunes of the two rings. The physics mechanism is that in the asymmetric rings K_+ bunches of the long ring interact with K_- bunches of the short one and any initial perturbation in one of the interacting bunches can be transferred to the other beam and eventually amplified through the beam-beam interaction.

The SuperB case with ring circumference ratio 2:1 is the simplest one with two bunches of the long ring interacting with one bunch of the short ring, see Fig. 2.



1. Interaction between “**1**” and “**2**”.
   “**3**” unchanged
2. “**1**” full revolution with $2\pi\nu_s$
   “**2**” and “**3**” half revolution with $2\pi(\nu_L/2)$
3. Interaction between “**1**” and “**3**”.
   “**2**” unchanged
4. “**1**” full revolution with $2\pi\nu_s$
   “**2**” and “**3**” half revolution with $2\pi(\nu_L/2)$

Figure 2: Full superperiod of bunch interaction.

In order to study the center of mass motion of the interacting bunches we follow the approach of [7] writing the matrix M of the full turn or the “superperiod” shown in Fig. 2, $M = M_4.M_3.M_2.M_1$. The instability takes place if the absolute value of any eigenvalue of the matrix M is higher than 1. Note that here we will consider only the vertical instability since for SuperB the vertical tune shift ξ_y is much larger than the horizontal one ξ_x.

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$$M_1 = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ -4\pi\Xi & 1 & 4\pi\Xi & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 4\pi\Xi & 0 & -4\pi\Xi & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \quad \Xi = \begin{cases} \xi_y/2, & Gaussian \\ \xi_y, & Uniform \end{cases}$$

$$M_2 = \begin{pmatrix} \cos(\mu_s) & \sin(\mu_s) & 0 & 0 & 0 & 0 \\ -\sin(\mu_s) & \cos(\mu_s) & 0 & 0 & 0 & 0 \\ 0 & 0 & \cos\left(\frac{\mu_L}{2}\right) & \sin\left(\frac{\mu_L}{2}\right) & 0 & 0 \\ 0 & 0 & -\sin\left(\frac{\mu_L}{2}\right) & \cos\left(\frac{\mu_L}{2}\right) & 0 & 0 \\ 0 & 0 & 0 & 0 & \cos\left(\frac{\mu_L}{2}\right) & \sin\left(\frac{\mu_L}{2}\right) \\ 0 & 0 & 0 & 0 & -\sin\left(\frac{\mu_L}{2}\right) & \cos\left(\frac{\mu_L}{2}\right) \end{pmatrix}$$

$$M_3 = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ -4\pi\Xi & 1 & 0 & 0 & 4\pi\Xi & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 4\pi\Xi & 0 & 0 & 0 & -4\pi\Xi & 1 \end{pmatrix}, \quad M_4 = M_2$$

The direct negative impact of the beam-beam instability on the asymmetric ring SuperB design is that the good working point area above the half-integer tunes, used by many other electron-positron colliders (PEPII, KEKB, CESR, VEPP4M etc.), is now affected by the coherent beam-beam resonance $2\nu_y^{short} + \nu_y^{long} = 2$, seen in Fig. 3.

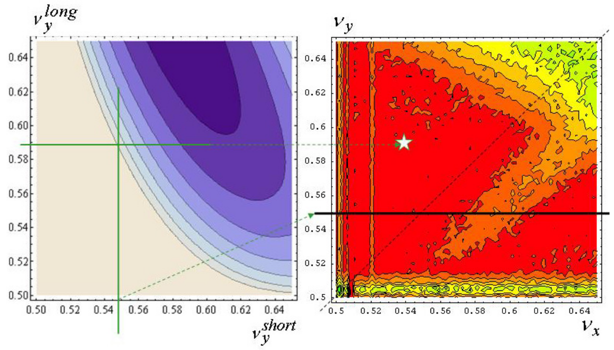

Figure 3: Instability growth rate scan (left plot) and luminosity tune scan (right plot, courtesy D. Shatilov).

The left plot in Fig. 3 shows the instability growth rate as a function of the vertical tunes of the short and the long rings calculated using the above matrix analysis. In our calculations we assume interaction point parameters reported in [2] with ξ_y = 0.097. Both beams become unstable for the working points falling inside the violet tune area. The more intense violet colors correspond to the faster instability. The typical growth rate inside the area is a few revolution turns. So the instability can be hardly damped even by modern feedback systems.

The coherent instability affects seriously the collider working point choice and can limit the maximum achievable bunch current, i.e. the luminosity. This can be understood looking at the luminosity tune scan plot in Fig. 3. The red color on the plot corresponds to the design luminosity of 10^{36} cm^{-2}s^{-1} while the white star indicates the desired working point where both the design luminosity and a good dynamic aperture can be achieved, $(\nu_x, \nu_y) = (0.54, 0.59)$. Since the tune shifts for both the short and the long rings are the same, the luminosity scan is similar for the both rings.

Now assume the vertical tune of the long ring is 0.59, i.e. nominal. Then, according to the left plot, in order to avoid the coherent beam-beam instability the vertical tune of the short ring must be below 0.55. This means that the available tune space for the short ring shrinks to the small area below the thick line on the luminosity scan plot where it is much more difficult to provide a decent dynamic aperture. Clearly, the situation becomes much worse for higher bunch currents (and the tunes shifts, respectively).

3D SIMULATIONS

In order to check the validity of the linear model and to study instability features more deeply we have performed a series of 3D strong-strong beam-beam simulations. For this purpose we have used the numerical code SBBE [10] that has been successfully benchmarked against the results of dedicated crab waist experiments at DAΦNE [11] and is in a routine use for beam-beam interaction studies for the Beijing Tau-Charm factory BEPCII.

As the first step, we have used the DAΦNE example to study the coherent resonance $\nu_y^+ + \nu_y^- = 1$, where $\nu_y^\pm$ are the positron and electron ring vertical tunes, respectively. This resonance can be met in symmetric ring colliders with the tune of one ring above the integer and that of the other ring above the half-integer (see Fig. 4).

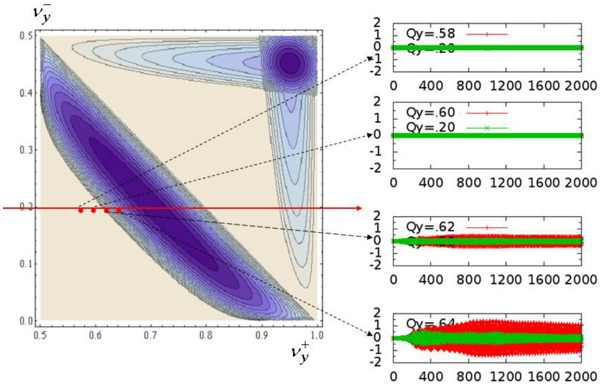

Figure 4: Instability growth rate scan (left) and barycenter motion of the positron (red) and electron (green) beams.

The simulations for DAΦNE are much faster (about 2 orders of magnitude) with respect to the SuperB case since the required number of longitudinal slices is by a factor of 10 lower. Besides, no numerical code modifications are necessary to simulate the beam-beam interaction in the symmetric rings. On the other hand, both DAΦNE and SuperB use the crab waist collision scheme and the instability behavior is expected to be similar for both colliders. Besides, there is a possibility to test experimentally this kind of instability at DAΦNE.

In our simulations, as shown in Fig. 4, we choose four different working points: two of them remain outside the resonance bandwidth predicted by the linear model; one stays just at the resonance boundary; and the last one is placed deeper inside the unstable area. The left column in Fig. 4 shows the centers of mass motion (normalized by the nominal vertical beam size) as a function of revolution turns.

As we can see, the agreement is very satisfactory. There is no barycenter motion for the first two working points. The instability starts for the working point at the resonance border and it becomes stronger for the last working point. As predicted by the linear model, the instability is very fast. The Landau damping does not help in damping it, but the instability saturates at some level due to nonlinear filamentation.

Two important observations have been done during the simulation studies. First, to obtain the good agreement between the linear model and the 3D simulations we have to use the Uniform distribution approximation instead of Gaussian one, despite the colliding beams are Gaussian. In our opinion, this is due to the fact that in crab waist collisions the beam interaction area is much smaller than the bunch length so that the charge distribution over the area is almost unchanged. Second, we have also observed that switching on the crab sextupoles helps greatly in reducing the amplitude of the barycenter oscillations. Nevertheless, this does not eliminate the instability completely.

At the next step, the numerical code has been modified in order to permit simulations of collisions of a single bunch circulating in one ring with two different bunches of the other ring. As it is seen in Fig. 5, no surprises with respect to the 1D model predictions have been found also in the asymmetric ring case.

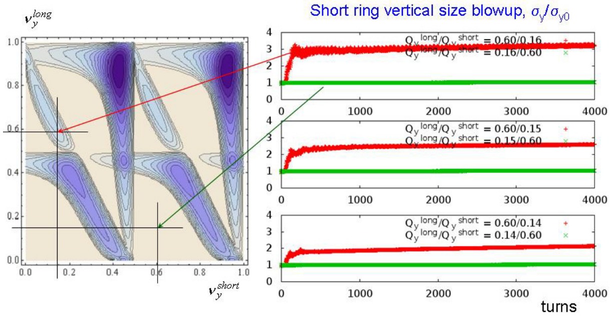

Figure 5: Instability growth rate tune scan (left) and the short ring bunch vertical blow up (right).

When we choose the vertical tunes of the rings in such a way to drive the instability (see the left tune scan plot in Fig. 5) the barycenters of both beams start oscillating and the vertical beam sizes blow up. The right column in Fig. 5 shows the normalized vertical size blow up of the short ring bunch (red trace) for that case for three different tunes inside the unstable region. If we exchange tunes of the short and the long rings there is no longer instability and the vertical blow up disappears (green traces). Note that there is no such a striking difference with respect to the tune exchange in weak-strong beam-beam simulations that do not take into account the coherent beam-beam resonances.

DISCUSSION

Both the 1D linear model and the 3D strong-strong simulations indicate that the coherent beam-beam resonances can have a serious negative impact on beam dynamics in SuperB with asymmetric rings. In particular, if working in the typical tune range above the half-integers only a small good tune area will be available for achieving the design luminosity. However, this "safe" area stays very close to the half-integer tunes and is situated between the horizontal synchro-betatron resonance and the main coupling resonance (see the luminosity scan in Fig. 3). So, obtaining a decent dynamic aperture and small coupling becomes questionable there. Moreover, there are almost no margins left to store higher bunch currents, i.e. to achieve the higher luminosity.

The coherent beam-beam resonance problem can be eliminated by reducing the number of bunches in the long ring by filling only every other bucket. Clearly, that for the design bunch current the luminosity will be by a factor of 2 smaller in that case and storing significantly higher bunch currents (and, respectively higher tune shifts) will be mandatory to recover the luminosity loss.

In our opinion, the best solution to solve the problem is to shift the vertical tune of the long ring (or both rings) closer to the integer value. As it is seen in Fig. 5 (tune scan) the working point areas $\left(\nu_y^{short} > 0.0,\ \ \nu_y^{long} > 0.0\right)$ and $\left(\nu_y^{short} > 0.5,\ \ \nu_y^{long} > 0.0\right)$ are far from the coherent resonances. Preliminary estimates have shown that both good beam-beam performance and a reasonable dynamic aperture [12] can be achieved there.

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