CRAB CAVITY IN CERN SPS

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Abstract

Beam collisions with a crossing angle at the interaction point have been applied in high intensity colliders to reduce the effects of parasitic collisions which induce emittance growth and beam lifetime deterioration. The crossing angle causes the geometrical reduction of the luminosity. Crab cavity can be one of the most promising ways to compensate the crossing angle and to realize effective head-on collisions. Moreover, the crab crossing mitigates the synchro-betatron resonances due to the crossing angle. Crab cavity experiment in SPS is proposed for deciding on a full crab-cavity implementation in LHC. In this paper, we investigate the effects of crab crossing on beam dynamics and its life time with the global scheme.

INTRODUCTION

In order to achieve a high luminosity in high-field colliders with standard collision schemes, one can consider small bunch spacings inside the beam or a beam current increase. However, the increase of beam intensity may result in beam instability and high beam power loss. A number of bunches inside the beam bring into parasitic encounters at the interaction region which cause emittance growth and beam loss. Increasing the crossing angle to reduce the effects of parasitic collisions causes luminosity reduction by exciting the synchro-betatron resonance.

A crab crossing scheme has been proposed to allow a large crossing angle for both linear colliders and circular colliders without a loss of luminosity [1]. When a particle is passing through a crab cavity structure, it not only increases the longitudinal energy, but also changes its transverse momentum. The crab cavity can compensate the horizontal or vertical crossing angle at the interaction point. The two counter-moving beams, therefore, experience an effective head-on collision. For the LHC upgrade phase II, both local and global crab crossing schemes are under consideration. At present a possible configuration is to install only one global crab cavity in the IR4 section because a minimum separation of beam lines is required by the RF structure [2]. In addition, a compact cavity suitable for the two beam separation is under development.

We consider the experiment in the CERN SPS with KEK-B crab cavity, which has several advantages. Since the beam parameter of SPS is close to that of the LHC, the SPS is the best test bed for the LHC crab crossing. The KEK-B crab cavity could be available after KEK-B physics run, and installed in the SPS Coldex location. In this paper, we investigate the effects of crab crossing on beam dynamics and its life time with the global scheme.

Table 1: SPS optics parameters at two locations of crab cavity and cavity parameters.

| Quantity         | Coldex | Zero   |
|------------------|--------|--------|
| location         | 4010 m | 4094 m |
| length           | 10.272 m | (94.0, 23.5) |
| $(\beta_x, \beta_y)$ | (30.3, 76.8) | (15.477, 15.497) |
| $(\mu_x, \mu_y)$  | (15.173, 15.176) | (0.0, 0.0) |
| $(D_x, D_y)$      | (-0.476, 0.0) | 1.5 MV |
| voltage          | 509 MHz |
| frequency        | 509 MHz |

Figure 1: Twiss function in crab cavity location.

MODEL

In case of a horizontal crossing, the kicks from the crab cavity are given by [4]

$$
\Delta \phi' = -\frac{qV}{E_0} \sin \left( \phi_s + \frac{\omega z}{c} \right),
$$

$$
\Delta \delta = -\frac{qV}{E_0} \cos \left( \phi_s + \frac{\omega z}{c} \right) \cdot \frac{\omega}{c} x,
$$

where $q$ denotes the particle charge, $V$ the voltage of crab cavity, $E_0$ the particle energy, $\phi_s$ the synchronous phase of the crab-cavity rf wave, $\omega$ the angular rf frequency of the crab cavity, $c$ the speed of light, $z$ the longitudinal coordinate of the particle with respect to the bunch center, and $x$ the horizontal coordinate. The global crab cavity causes a closed orbit distortion dependent on the longitudinal po-
sition of particles, and has the equilibrium beam envelope tiled all around the ring. For a small bunch less than the rf wavelength of the crab cavity deflecting mode, the tilt angle of the beam envelope is given by

$$\tan \theta_{crab} = \frac{qV \omega \sqrt{\beta_{crab}}}{c^2 p_0} \left| \frac{\cos(\Delta \varphi - \pi Q)}{2 \sin \pi Q} \right|,$$

(2)

where $\beta$ is the beta function at the BPM position, $\beta_{crab}$ the beta function at the crab cavity, $\Delta \varphi$ the phase advance between the crab cavity location and the BPM, and $Q$ the betatron tune. The angle $\theta_{crab}$ is proportional to the crab cavity voltage and frequency, and the beta functions. Figure 2 shows the closed orbit at the beginning of the SPS optics which is a sinusoidal function versus the full wave length of crab cavity. The slope at $z = 0$ is related to the tilt angle of the beam envelope.

**RESULTS**

The SPS optics parameters are listed in Table 1. The Coldex Cryogenic Experiment location is proposed for an installation of KEK-B crab cavity of which maximum voltage and frequency is 1.5 MV and 509 MHz respectively. The full wave length of crab cavity is $\lambda_{cc} = 58.9$ cm.

$$\Delta \delta = -(qV \omega/E_{0c}) x.$$ After a first turn, one can get

$$\begin{pmatrix} x \\ x' \end{pmatrix} = (M + D) \begin{pmatrix} x \\ x' \end{pmatrix},$$

(3)

where $M$ is the transfer matrix for a full revolution. The periodic dispersion $\vec{\eta} = (\eta_x, \eta_y')$ at the cavity and the cavity kick determine $D = \left( - (qV \omega/E_{0c}) (I - M) \vec{\eta} \right)$. The stability boundary can be obtained from the determinant of $M + D$,

$$\eta_x (1 - \cos \mu + \alpha_x \sin \mu) + \eta_y' \beta_x \sin \mu = 0.$$ 

(4)

It is interesting to note that the condition depends on the twiss functions of lattice, the crab cavity parameters, and the dispersion functions at the cavity. Provided that the dispersion function in the cavity is zero, there is no stop
bend of the beam instability. In order to see the effects of the dispersion, the new cavity location where $\eta_x$ is zero is chosen. As shown in Figure 3, the horizontal emittance for a cavity at Zero location, i.e., $\eta_x = 0$, is much less than that for Coldex cavity. However, a finite increase of horizontal emittance is observed because $\eta'_x$ is finite. Figure 4 shows the horizontal emittance for different beam energy and bunch length. The emittance increase is large for small beam energy, which is related to a finite dispersion. For a fixed bunch length $\sigma_z = 7.5$ cm, the energy spreads are $\Delta E = 37.2$ MeV and $\Delta E = 51.6$ MeV for 120 GeV and 26 GeV respectively. The coefficient of momentum change due to the crab cavity becomes large when the beam energy is small. Furthermore, if we look at the effects of bunch length on the horizontal emittance, it is surprisingly found that the beam with small bunch length is less stable. The transverse kick $\Delta x'$ is approximately linear only over a small portion of the wave length of crab cavity, for example, $|z| < \lambda_{cc}/6$. The crab cavity distorts the beam envelope for a large longitudinal bunch. The average change of longitudinal momentum due to crab cavity becomes large for a short bunch because $\Delta \delta$ is proportional to $\cos \frac{\pi z}{\lambda_{cc}}$. The finite dispersion effect, therefore, seems stronger than that of nonlinearity due to the beam distortion. In addition, it is a reasonable motivation to check how the vertical crab cavity at the Coldex location gives effects on the vertical emittance because the vertical dispersion function is zero for both $\eta_y$ and $\eta'_y$ all over the ring at least in the lattice optics. Obviously, we do not see any emittance growth in both horizontal and vertical planes, as shown in Figure 5.

**SUMMARY**

In this paper, we investigate the effects of the global crab cavity on the dynamic aperture and the transverse emittance growth. The results show that the dispersion function at the crab cavity location matters. Even a finite dispersion can induce the emittance growth. Dispersion matching (both $\eta_x$ and $\eta'_x$) at the location where the crab cavity is installed is required to minimize the beam life time reduction. Vertical crab crossing scheme may be need to be considered due to its small vertical dispersion.

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