CRAB CAVITY IN CERN SPS

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Abstract

Beam collisions with a crossing angle at the interaction point are often necessary in colliders to reduce the effects of parasitic collisions which induce emittance growth and decrease beam lifetime. The crossing angle reduces the geometrical overlap of the beams and hence the luminosity. Crab cavity offer a promising way 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. A crab cavity experiment in SPS is proposed as a proof of principle before deciding on a full crab-cavity implementation in the LHC. In this paper, we investigate the effects of a single crab cavity on beam dynamics in the SPS and life time.

INTRODUCTION

In order to increase the luminosity in a collider one can increase the number of bunches or increase beam current. However, higher beam intensity may result in beam instability and high beam loss. More bunches can increase the parasitic encounters in the interaction regions which may cause emittance growth and beam loss. Increasing the crossing angle to reduce the effects of parasitic collisions also reduces luminosity both because of a smaller geometrical overlap and the excitation of 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 passes through a crab cavity structure, it experiences a transverse deflection and a small change in its longitudinal energy. Crab cavities can compensate for the horizontal or vertical crossing angle at the interaction point (IP) by allowing the two counter-moving beams to experience an effective head-on collision. For the LHC upgrade phase II, both local (crab cavities around each IP) and global crab (single crab cavity in the ring) crossing schemes are under consideration. At present a possible configuration is to install only one global crab cavity in the IR4 section where a single cavity can be installed in the common beam-pipe. [2]. In addition, a compact cavity which meets the aperture restrictions from the separation between beam pipes and can be installed around IP1 and IP5 (local scheme) is under development.

We consider a proposed experiment in the CERN SPS which plans to use a KEK-B crab cavity after some retuning. SPS injects beam into the LHC and could provide a good test of crab cavity operation in a proton machine. The KEK-B crab cavity may be available after the KEK-B physics run is over and installed in the SPS at the location of the COLDEX experiment. In this paper, we investigate the effects of crab crossing on beam dynamics and its life time with the global scheme in the SPS using a six dimensional weak-strong tracking code BBSIMC [3].

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

Quantity	COLDEX	Zero dispersion
location	4010 m	4094 m
length	10.272 m	
(β_x, β_y)	(30.3, 76.8)	(94.0, 23.5)
(μ_x, μ_y)	(15.173, 15.176)	(15.477, 15.497)
(D_x, D_y)	(-0.476, 0.0)	(0.0, 0.0)
voltage	1.5 MV	
frequency	509 MHz	

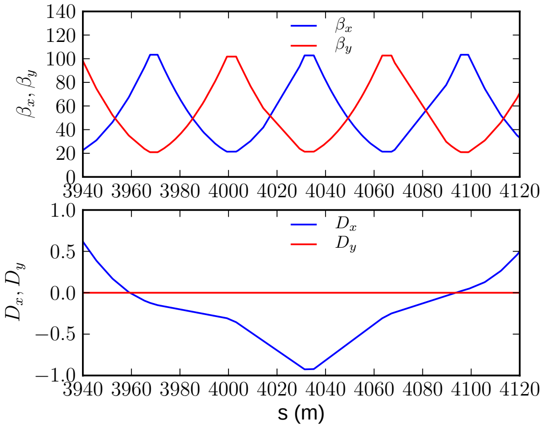

Figure 1: Twiss function in crab cavity location.

MODEL

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

$$\Delta x' = -\frac{qV}{E_0} \sin\left(\phi_s + \frac{\omega z}{c}\right), \tag{1a}$$

$$\Delta \delta = -\frac{qV}{E_0} \cos\left(\phi_s + \frac{\omega z}{c}\right) \cdot \frac{\omega}{c} x, \tag{1b}$$

where q denotes the particle charge, V the voltage of crab cavity, E_0 the particle energy, ϕ_s the synchronous phase of the crab-cavity rf wave, ω 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. In general this is a nonlinear map which introduces synchro-betatron coupling but

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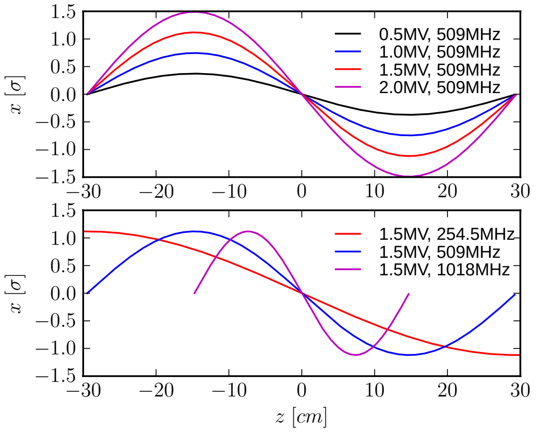

Figure 2: Closed orbit at the beginning of the SPS lattice due to a crab-cavity kick: (top) dependence on crab cavity voltage, and (bottom) dependence on crab cavity frequency. The closed orbit is a function of longitudinal position inside a bunch. The wave length of crab cavity is λ_{cc} = 58.9 cm.

for small z, this reduces to a linear map in the horizontal-longitudinal plane.

The global crab cavity causes a closed orbit distortion dependent on the longitudinal position of particles, and the beam envelope is tilted all around the ring. For a bunch shorter than the rf wavelength of the crab cavity deflecting mode, the tilt angle of the beam envelope is given by

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

where β is the beta function at the BPM position, β_{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. Figure 2 shows the closed orbit at one location in the SPS; it has a sinusoidal form with the wave length of the crab cavity deflecting mode. The slope at $z = 0$ is related to the tilt angle of the beam envelope.

RESULTS

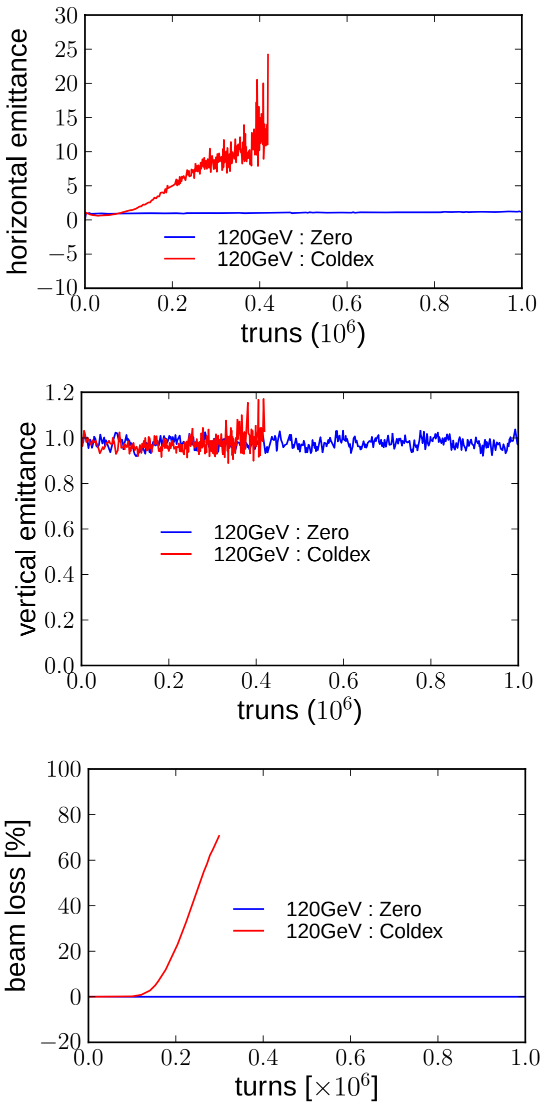

Figure 3: Transverse emittance and beam loss for 120GeV SPS beam when a crab cavity is installed at two different locations.

The SPS optics parameters are listed in Table 1. The COLDEX Cryogenic Experiment location is proposed for an installation of the KEK-B crab cavity which has maximum voltage 1.5 MV and frequency 509 MHz. The wave length of the crab cavity is λ_{cc} = 58.9 cm. Figure 3 shows the transverse emittance and beam loss for 120 GeV SPS beam when a crab cavity is installed at the COLDEX location. It is observed from the simulation results that the crab cavity leads to blow-up of the horizontal beam emittance and significant particle losses while the vertical emittance stays constant. In order to see the effects of crab cavity on beam dynamics, consider a synchronous particle, i.e., $z = \delta = 0$. The horizontal and longitudinal momentum due to the crab cavity is $\Delta x' = 0$, and $\Delta\delta = -\left(qV\omega/E_0 c\right)x$. After a first turn, one can get

$$\begin{pmatrix} x \\ x' \end{pmatrix}_1 = \left(\mathbf{M}+\mathbf{D}\right)\begin{pmatrix} x \\ x' \end{pmatrix}_0, \qquad (3)$$

where $\mathbf{M}$ is the transfer matrix for a full revolution. The periodic dispersion $\vec{\eta} = (\eta_x, \eta_x')$ at the cavity and the cavity kick determine $\mathbf{D} = \begin{pmatrix} -\left(qV\omega/E_0 c\right)\left(\mathbf{I}-\mathbf{M}\right)\vec{\eta} & \vec{0} \end{pmatrix}$. The determinant of $\mathbf{M}+\mathbf{D}$ is given by

$$1 - \left(qV\omega/E_0 c\right)\left(\eta_x(1 - \cos\mu + \alpha_x \sin\mu) + \eta_x'\beta_x \sin\mu\right). \qquad (4)$$

The condition depends on the the crab cavity parameters, and the dispersion and twiss functions at the crab cavity. Provided that the dispersion function and its slope in the cavity are zero, there is no stop band of the beam instability. In order to see the effects of the dispersion, a new

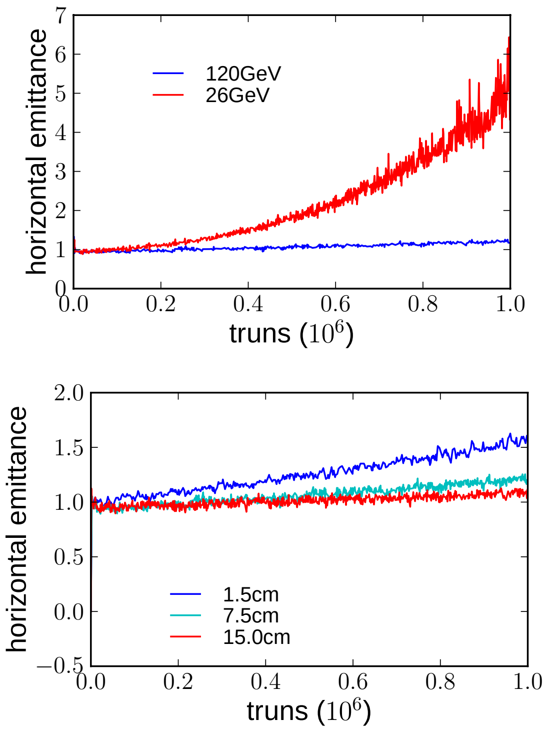

Figure 4: Transverse emittance variations for different energy (top) and different bunch length (bottom). Crab cavity is installed at a zero dispersion location.

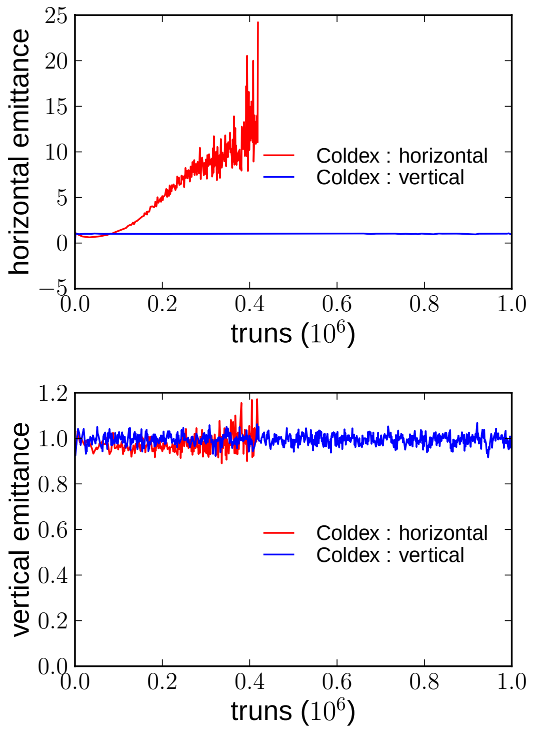

Figure 5: Transverse emittances of 120GeV SPS beam for horizontal and vertical crossings. Crab cavity is installed in COLDEX location.

cavity location where η_x is zero was chosen. As shown in Figure 3, the horizontal emittance for a cavity at a zero dispersion location, is much less than that for the cavity at the COLDEX location. However, a non-zero increase of horizontal emittance is still observed because η'_x is non-zero. Figure 4 shows the horizontal emittances for different beam energies and bunch lengths. The emittance increase is larger for lower beam energy, which is related to the larger energy spread. For a fixed bunch length $\sigma_z = 7.5$ cm, the energy spreads are ΔE = 37.2 MeV at 120 GeV and ΔE = 51.6 MeV at 26 GeV. The coefficient of momentum change due to the crab cavity becomes larger when the beam energy is small. Furthermore, if we look at the effects of bunch length on the horizontal emittance, it is found that the beam with smaller bunch length is less stable. The transverse kick $\Delta x'$ is approximately linear only over a small portion of the wave length of the 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 the crab cavity becomes larger for a short bunch because the average of $\Delta\delta \propto \cos\frac{\omega}{c}z$ is closer to zero for the longer bunch. The finite dispersion effect, therefore, seems stronger than that of nonlinearity due to the beam distortion. The effect due to the dispersion is a reasonable motivation to check how a vertical crab cavity at the COLDEX location impacts the beam because the vertical dispersion function and its slope are zero all over the ring, at least in the ideal lattice optics. 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 η'_x) at the location where the crab cavity is installed is required to minimize the beam life time reduction. A vertical crab crossing scheme would have much less impact due to the negligibly small vertical dispersion.

ACKNOWLEDGMENTS

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