PRELIMINARY STUDY OF A CRAB CROSSING SYSTEM FOR DAΦNE

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Abstract

The implementation of a crab crossing scheme at the Frascati Φ-factory DAΦNE is under consideration, together with several other ideas and upgrades to increase the collider luminosity. The crab crossing is beneficial to the luminosity because it is expected to optimize the geometrical superposition of the colliding bunches and to weaken the synchro-betatron beam-beam resonances. The basic specifications of such a system, the expected luminosity increase, a preliminary design of the crab cavities and the architecture of the dedicated RF system are presented.

INTRODUCTION

The double-ring Frascati Φ-factory DAΦNE is in operation since spring 1999 and will continue delivering luminosity to the experiments until year 2009. The time remaining before the end of the machine operation will be used also to improve the machine performances and to test different ideas to increase the luminosity, as described in [1]. This accelerator physics experimental activity is considered of primary importance by the DAΦNE team since the results may contribute to confirm or re-address the design criteria of the next generation lepton factories.

The DAΦNE layout includes two Interaction Regions (IRs) where the two rings merge to accommodate the experiments, and in both of them the beam trajectories cross with an horizontal angle ϑ_{cross} ranging from ± 11 to ± 17 mrad. One of the most promising ways to increase the luminosity is to implement the “crab-crossing” system [2,3] to compensate the horizontal crossing angle and colliding the bunches in a head-on like configuration. The luminosity is expected to increase because of a better superposition of the two beams at the Interaction Point (IP). The geometrical reduction of the luminosity caused by a ± 16.5 mrad horizontal crossing angle has been analytically calculated for DAΦNE with the collider parameter set of the KLOE run [4]. For an average bunch length of ≈ 2.5 cm, the estimated geometrical reduction of the luminosity has been ≈ 8 % in the KLOE run.

However, the major mechanism of luminosity reduction caused by the crossing angle is the excitation of beam-beam synchro-betatron resonances that produce beam blow-up. Crab crossing weakens the resonances, leading to smaller bunch sizes of the colliding beams. Estimates of the luminosity increase expected from crossing angle compensation can be drawn from beam-beam simulation codes. The case of DAΦNE at the KLOE run working point has been studied with the LIFETRAC code and simulation results are summarized in Table 1. The perfect compensation of the crossing angle can provide up to %70 of luminosity increase for bunch currents of 10 mA.

Table 1: DAΦNE luminosity vs. crossing angle

	I [mA]	**L/L_0**
$\vartheta_{cross} = 0\ mrad$	6	0.88
$\vartheta_{cross} = 15\ mrad$	6	0.69
$\vartheta_{cross} = 0\ mrad$	10	0.75
$\vartheta_{cross} = 15\ mrad$	10	0.43

CRAB CROSSING SYSTEM DESIGN

There are different ways to implement a crab crossing system in a circular collider. The most straightforward one consists in placing 2 crab cavities per ring in symmetrical positions around the IP at a betatron phase advance of $\pi/2$ with respect to the IP. In this case the first cavity provides a horizontal tilt in order to eliminate the crossing angle at IP, while the second one removes completely the tilt. Thus the bunch equilibrium envelope is horizontally tilted only in the region between the cavities around the IP.

If only one crab cavity per ring is used, the equilibrium envelope is tilted all around the ring. The crabbing voltage produces a single particle closed orbit distortion dependent on the longitudinal position of the particle itself. For usually small values of the synchrotron tune the bunch envelope is horizontally tilted at the IP by an angle θ_{crab} given by [5]:

$$\theta_{crab} = \frac{\pi\sqrt{\beta_{IP}\,\beta_{cav}}}{\lambda_{RF}\sin\left(\pi Q_x\right)}\frac{eV_\perp}{E}\cos\left(\left|\phi_{IP}-\phi_{cav}\right|-\pi Q_x\right) \qquad (1)$$

where $V_\perp = p_\perp c/e$ is the peak horizontal kick voltage, Q_x is the horizontal tune, β and ϕ are local values of the horizontal betatron function and phase advance, and λ_{RF} is the RF wavelength of the crab cavity deflecting mode.

We propose to implement the single cavity crabbing scheme in DAΦNE since there is very limited space available on the machine. Moreover, this scheme is very efficient at low horizontal tunes, and it requires half of the hardware (cavities and RF power sources) with respect to the two-cavities, insertion-like scheme.

The crab crossing compensation is optimal when the crabbing angle θ_{crab} at the IP is equal to the crossing angle. The required transverse voltage to fulfil this condition is given by eq. (1). The optimal betatron phase advance between crab cavity and IP is given by:

$$\left|\phi_{IP}-\phi_{cav}\right| = (n+Q_x)\pi \qquad (2)$$

Large values of the horizontal β function and small values of λ_{RF} are preferable to increase the system efficiency. However, the transverse kick is reasonably linear only over a portion of the wavelength ($\pm\lambda_{RF}/6$) and this put a limit on the choice of λ_{RF} to tilt the beam envelope without distortion over the full bunch length ($\pm 3\sigma_z$). The trade-off between linearity on one side and efficiency and compactness on the other side leads to the choice of designing the crab crossing system for DAΦNE at 736 MHz, i.e. the 2nd harmonic of the main RF systems. The design parameters of the DAΦNE crab crossing system are summarized in Table 2.

Table 2: Parameters of the DAΦNE crab crossing system

Crossing Angle	ϑ_{cross}	17 mrad
RF freq. /wavelength	f_{RF}/λ_{RF}	736.5 MHz / 0.41 m
β_x-function @ IP / Cav	β_{IP}/β_{Cav}	1.5 / 9 m
Horizontal betatron tune	Q_x	< 0.15
Peak transverse voltage	$V_\perp$	< 120 kV
Crab cavity shunt imp.	$R_\perp$	1 MΩ
RF power	P_{RF}	< 10 kW

In analogy with the accelerating modes, the transverse mode shunt impedance is defined as $R_\perp = V_\perp^2/2P$.

CRAB CAVITY DESIGN

The crab cavity design for DAΦNE is based on a single-cell bell-shaped resonator working on the TM110-like horizontal mode at room temperature. Since a peak transverse voltage of 120 kV is a relatively modest value, the cavity design is mainly addressed to optimize the cavity compactness, the efficiency and simplicity of the HOM damping, and to reduce the costs.

The basic 2D profile of the cavity is shown in Fig. 1. The cell diameter essentially defines the resonant frequency of the operation mode, while the cavity efficiency (i.e. the transverse impedance) has been optimized by tuning the length of the cell.

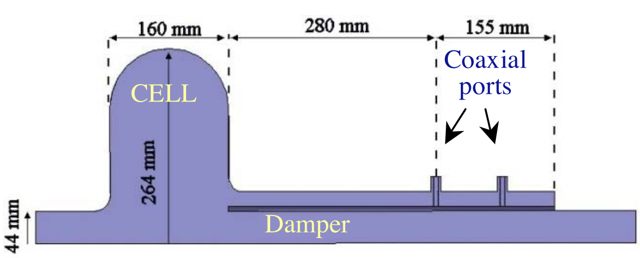

Figure 1: Basic profile of the DAΦNE crab cavity.

The HOM damping is obtained by an integrated coaxial coupler whose inner conductor is the prolongation of the beam tube. The whole coaxial coupler acts like a huge antenna loading the cavity HOM, and the HOM power travelling in the damper is extracted through 8 smaller coaxial transducers connected to matched loads through vacuum feedthroughs. The transverse shape of the outer conductor and the penetration of the inner conductor into the cell are both crucial to obtain a satisfactory HOM damping without affecting the operation mode.

The transverse cut-view of the coaxial damper is shown in Fig. 2. The coaxial TEM mode, which couples with the cell longitudinal (monopole) modes has no cut-off. This allows coupling the cavity lowest mode (TM010-like, 470 MHz) provided the damper inner conductor protrudes sufficiently into the cell.

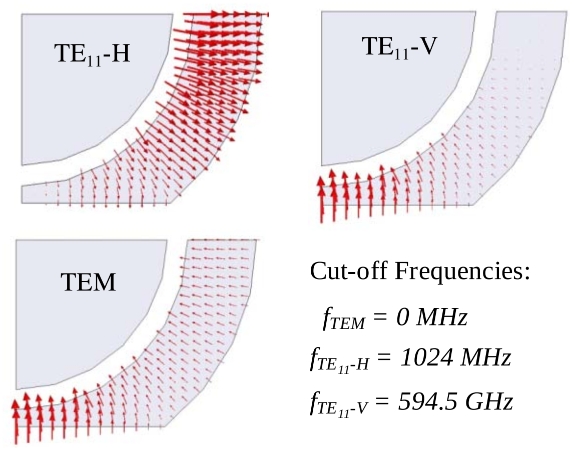

Figure 2: Damper propagation modes - Field distribution.

The transverse (dipole) modes of the cell couple to the coaxial damper TE11 modes. The shape of the outer conductor, as shown in Fig. 2, has two flat cuts parallel to the horizontal plane to decrease the vertical separation of the 2 conductors. With this shape the cut-off frequencies of the TE11 polarities are widely split so that the vertical polarity of the cell TM110 dipole mode can propagate in the damper, while the horizontal polarity (i.e. the operation mode) is under cut-off and remains undamped.

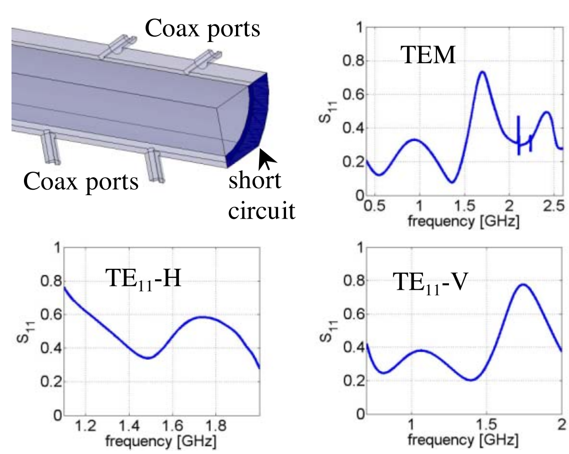

Figure 3: Matching of the damper with coax transducers.

The coaxial damper is terminated through 8 RF ports connected with match loads. The geometry of the transducers is optimized to reduce as much as possible the reflection of the various propagating modes in the damper. A view of the vertical and horizontal transducer together with their frequency response over the bandwidth required to damp the cell HOMs as computed by the 3D code HFSS are shown in Fig. 3.

CRAB CAVITY 3D SIMULATIONS

The cell equipped with the coaxial damper and the 8 small coaxial transducers has been modelled in the 3D electromagnetic code HFSS, as shown in Fig. 4. The complete scattering matrix referred to the various ports of the whole structure has been computed, and the parameters of the loaded modes has been worked out from the transmission frequency responses. The list of the modes together with their resonant frequencies, R/Q factors and external (damper loading) Q-factors are reported in Table 3.

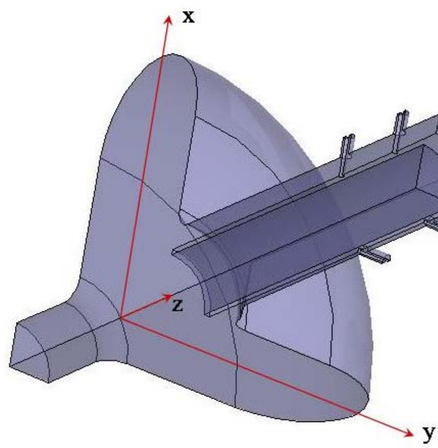

Figure 4: 3D HFSS model of cell and damper assembly.

It may be seen in Tab. 3 that the operation mode is very weakly loaded by the damper ($Q_{ext} > 3 \cdot 10^5$) while all the other modes couple to the damper, with Q_{ext} values ranging form few tens to few thousands. The least damped HOMs are transverse, with impedances up to $R_\perp \approx 20$ kΩ. Even in the pessimistic case of full coupling with beam betatron sidebands, the coupled bunch instability growth rate would be $\alpha \approx 10$ ms^{-1} for a stored current of $I_b = 2$ A. The DAΦNE transverse feedback system provides damping rates $\alpha_f > 100$ ms^{-1} [6] and it is expected to strongly damp residual instabilities coming from the cavity HOMs. It may be noticed that the list in Table 3 includes a dipole mode whose field distribution can not be described in terms of pill-box modes. For this mode the fields are localized in the region where the damper is connected to the cell, and the residual transverse impedance is a modest value ($R_\perp \approx 3.5$ kΩ).

THE CRAB CAVITY RF SYSTEM

The DAΦNE crab cavities will be powered through a coupling port consisting in a loop magnetically coupled to the cell in the equator region, very similar to the DAΦNE main cavity one. A tuning plunger will be locate opposite to the coupling port, to compensate temperature variations and to follow beam loading second order effects. In fact, bunches travelling along the symmetry axis in a pure dipole field do not interact with the mode, while a modest coupling is expected for off-axis trajectories, proportional to the orbit error.

Table 3: Parameters of the DAΦNE crab cavity modes.

	MODE	f [MHz]	R/Q [Ω]	Q_{ext}
Horizontal	**TM_{110}-like (H)**	**736**	**31.8**	**338000**
	Cell-damper trans.	924	2.05	1700
	TE_{111}-like (H)	1042	4.12	300
	TM_{111}-like (H)	1261	11.2	100
	TM_{120}-like (H)	1315	3.24	7300
	TE_{121}-like (H)	1365	0.51	400
	TE_{112}-like (H)	1702	5.93	480
	TM_{121}-like (H)	1749	3.72	2500
Vertical	TM_{110}-like (V)	736	31.8	90
	TE_{111}-like (V)	980	4.12	80
	TM_{111}-like (V)	1251	11.2	186
	TM_{120}-like (V)	1314	3.24	5306
	TE_{121}-like (V)	1360	0.51	198
	TE_{112}-like (V)	1705	5.93	707
	TM_{121}-like (V)	1749	3.72	3055
Mon.	TM_{010}-like	473	85	234
	TM_{020}-like	1073	---	<50
	TM_{011}-like	1118	---	<50

There is a wide variety of RF commercial sources covering the crab cavity frequency band, mainly for the broadcasting market. A commercial 10 kW solid state source seems a very suitable choice because of its simplicity and reliability.

CONCLUSIONS

The study of a crab crossing system to be installed in DAΦNE is well in progress. The proposed system is based on a single crab cavity per ring, with bunch equilibrium distribution tilted in the x-z plane all along the ring. According to beam-beam simulations, a collider luminosity increase up to a factor ≈ 2 is expected in case of perfect compensation of the crossing angle. The electromagnetic design of the cavity is almost complete. The proposed crab cavity is tuned on the 2nd harmonic of the main DAΦNE RF cavities, and is based on a single-cell working on the horizontal polarity of the TM110-like mode loaded by a special coaxial damper integrated on one of the cavity beam tubes. Modes different from the operation one are well damped. The cavity is also sufficiently compact and efficient, and can provide the required peak voltage being powered with a commercial, 10 kW RF power source.

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