ANALYSIS OF THE VERTICAL BEAM INSTABILITY IN CTF3 COMBINER RING AND NEW RF DEFLECTOR DESIGN

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Abstract

In the last CTF3 run (November 2007) a vertical beam instability has been found in the Combiner Ring during operation. Possible sources of the instability are the vertical deflecting modes excited by the beam in the RF deflectors. In the first part of the paper we illustrate the results of the beam dynamics analysis obtained by a dedicated tracking code that allows including the induced transverse wake field and the multi-bunch multi-passage effects. To reduce the effects of such vertical trapped modes, two new deflectors have been designed. In the new devices special antennas absorb the power released by the beam to the modes. The structures will be made in aluminium to reduce the costs and delivery time.

INTRODUCTION

The second stage of the bunch train compression in CTF3 [1] is realized in the 84 m circumference Combiner Ring (CR). This is achieved by means of two travelling wave (TW) RF deflectors (RFDs) working at f_{RF}=2.99855 GHz already built [2] and successfully tested in the CTF3 Preliminary Phase [3]. In the last run a vertical beam instability has been observed during operation [4]. The phenomenology of such instability (described in detail in [4]) can be summarized as follows:

a) the profile of the vertical oscillation as a function of the bunch positions was the same shot by shot;
b) the measured Δ-frequency of the oscillation with respect to f_{RF} was ~48 MHz;
c) the instability is stronger if we increase the train length or the bunch charges;
d) changing the temperature of the deflectors by $8\,°C$ did not change the scenario;
e) the instability occurred both in the case of a single train and of recombined trains;
f) probably a better steering inside the deflectors yielded a weaker instability (no systematic study done).

A possible source of this instability has been identified in the vertical deflecting modes (VDMs) trapped in the RFDs and excited by the beam. A detailed study of the wakefields induced by these modes and their effect on beam dynamics is presented in the second and third paragraph. In the last paragraph we illustrate the design of the new RFDs with damped vertical modes.

VERTICAL MODES IN THE RFDS AND WAKEFIELD ANALYSIS

The RFDs intalled in the CR are TW devices that deflect the beam in the horizontal plane (Fig. 1a). The main parameters of the structures are reported in Table 1. Two metallic rods have been inserted into each cell to separate in frequency the deflecting mode with vertical polarity. The dimensions and position of the rods have been chosen to fix the polarity of the horizontal mode, avoiding tilt of the working polarity through the deflector and avoiding the excitation of the vertical mode by the beam power spectrum line at 2.99855 GHz. These vertical modes are not coupled to the input and output couplers, as shown in Fig. 1b where their typical H field lines are plotted.

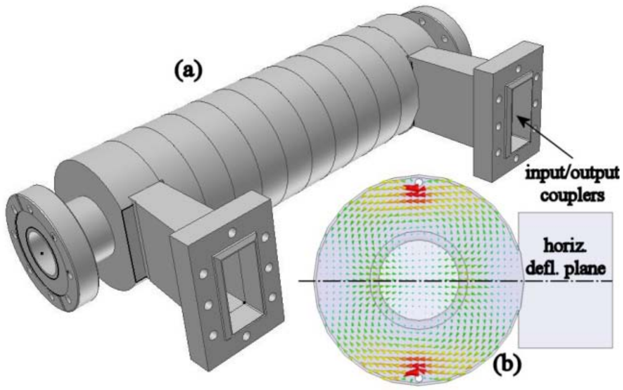

Figure 1: (a) RFD of the CR; (b) typical H field of the vertical modes.

Table 1: Main RFD Parameters

RFD frequency	2.99855 GHz
TW mode of operation	$2\pi/3$
Number of cells	12
Deflector length	~40 [cm]
Filling time	~47 [ns]
Deflection angle	5 [mrad]
Max input power	2 MW

To evaluate the effect on beam dynamics due to the transverse wakefields induced by VDMs, the resonant frequencies (f_{res}), quality factors (Q) and transverse shunt impedances (R_T)(*) of each VDM have been calculated by HFSS [5]. The results are plotted in Fig. 2. It is easy to note that there is a "dominant" mode (in term of R_T) corresponding to the mode with a ~2π/3 phase advance per cell. In the following calculations we have considered the contribution of this dominant mode only (whose parameters are reported in Table 2). It is straightforward to extend all the obtained results to the more general case of multi-modes.

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* We defin the transverse shunt impedance by the formula:

$$R_T = \frac{\left|\int_{cavity} \left(cB_x + E_y\right) e^{j\omega_{RF} z/c} dz\right|^2}{2P_{diss}}$$

where Bx and Ey are the magnetic and electric transverse field components, z is the beam traveling direction, , P_{diss} is the total dissipated power in the cavity.

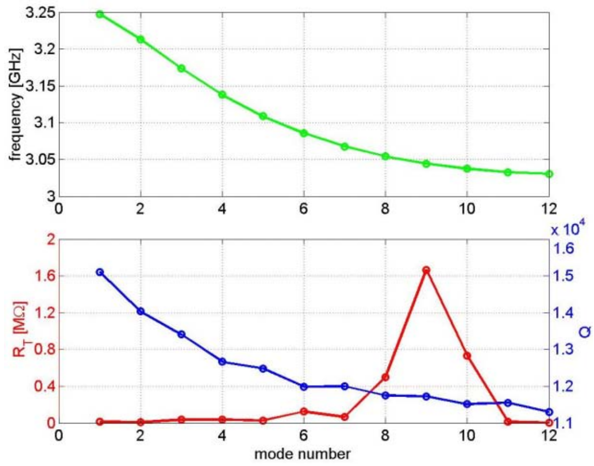

Fig. 2: Vertical trapped modes parameters.

The general expression of the transverse voltage (as a function of time) induced by a point-like charge (q) passing into the deflector with a vertical offset (y) with respect to the deflector axis is given by [6]:

$$V_T(\tau) \cong q\frac{\omega_{res}^2}{c}\frac{R_T}{Q}\, y e^{-\frac{\omega_{RF}}{2Q}\tau}\sin(\omega_{res}\tau)$$

The induced wakefield has a sine-dependence (it is so-called 90 deg. out of phase wake). It is straightforward to note than, since the separation between bunches is an integer multiple of f_{RF} this mode is not excited perfectly on resonance by the beam train. This may results in a net deflecting kick on the bunches of the same train. Moreover, for the same reason, the filling time can become much shorter than the nominal resonant mode filling time ($2Q/\omega_{res}$). Both aspects are important to intuitively understand the mechanism of such strong and fast instability.

Table 2: Parameters of the Dominant Vertical Mode

Q	11500
f_{res}	3.0443 GHz
R_T	1.6 MΩ

TRACKING CODE RESULTS

A dedicated tracking code has been written to study the multi-bunch multi-passage effects. In the code each bunch, represented as a macro-particle, enters the 1st deflector with a given vertical orbit (Y_{in1}), interacts with the wake left by the bunches ahead, contributes to the wake and exits from the deflector. The bunch is then transported to the other deflector by the CR transport matrix, enters the 2nd RFD with a given vertical orbit (Y_{in2}) plus the perturbation given by the residual oscillation induced by the wakes in the 1st RFD, interacts with the RF field and wakes of this second device and so on. At the end of the merging process each macroparticle ends up with vertical Δ-positions with respect to the original orbit (y_{out}, y'_{out}) given by the corresponding values of the Courant-Snyder invariant (I_{out}). The tracking allows studying the distribution of I_{out} for all bunches and its dependence on the resonant mode properties and ring optical functions. Since all the results scale with the charge per bunch (q) and beam energy (E_0) we fixed q=2.33 nC (nominal CTF3 charge) and E_0=100 MeV (beam energy during the last run). As an example the output vertical positions, angles and I_{out} normalized to the nominal CR emittance (ε=0.4 mm mrad) of one train of bunches after 4 turns are reported in Fig. 3 assuming the parameters shown in the same figure (β, α and ϕ are the usual optical functions at the RFDs). The FFT of the vertical oscillations have frequency components centered around 45-50 MHz (†) very similar to the measured ones.
The maximum I_{out}/ε as a function of the CR vertical phase advance (ϕ_{12}) and vertical β-function at the RFDs are given in Fig. 4 for different vertical phase advances between the two RFDs (ϕ_{21}).

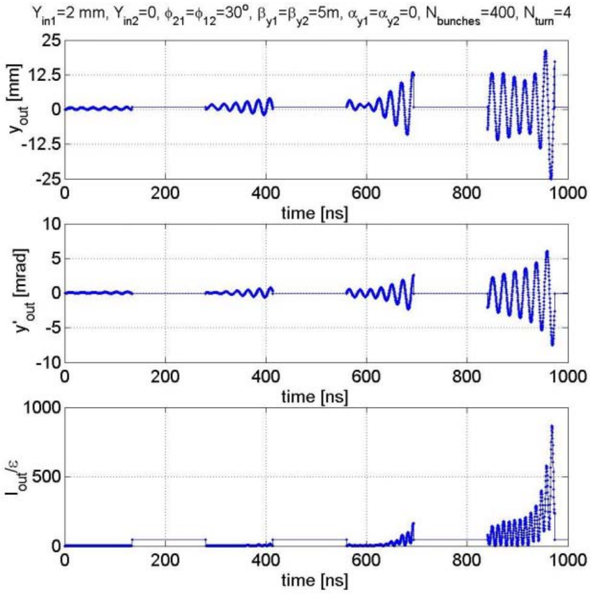

Figure 3: Output vertical positions, angles and I_{out}/ε of a circulating train after 4 turns.

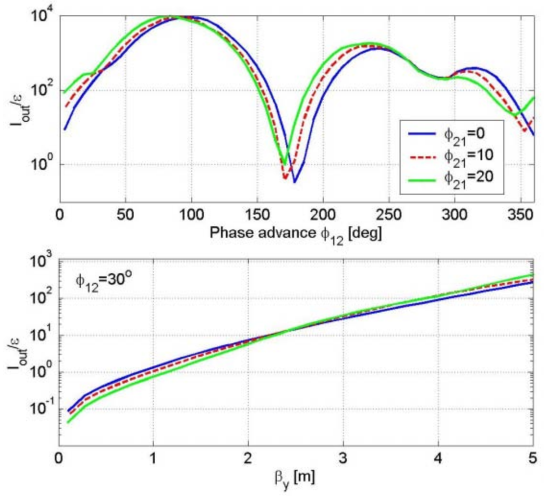

Figure 4: Maximum I_{out}/ε as a function of the CR vertical phase advance (ϕ_{12}) and vertical β-function at the RFDs.

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† Equal to the difference between f_{RF} and f_{res}.

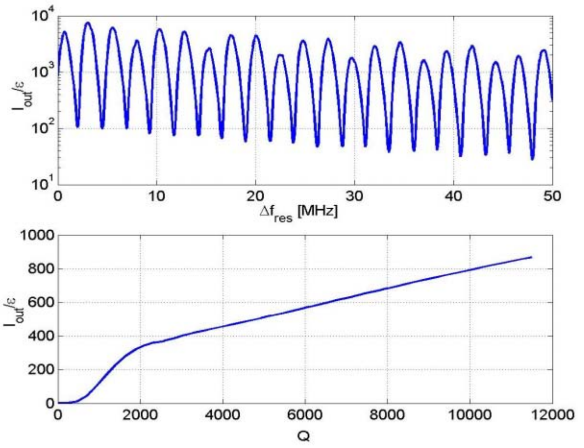

Figure 5: Maximum I_{out}/ε as a function of the mode resonant frequency and quality factor.

Fig. 5 shows the maximum I_{out}/ε as a function of the mode resonant frequency and quality factor (‡). In the first case the maximum I_{out}/ε has a periodic behaviour due to the interaction between the finite bandwidth resonance and the periodic spectrum of the circulating beam. Similar results can be obtained considering different train lengths or recombination.

From the previous plots it is possible to conclude that this strong instability is caused by a few mm off-axis beam passage into the deflectors (1-2 mm was the order of magnitude of the orbit inside this devices in the last run) and that a better orbit control inside these structures can reduce the instability. A vertical tune near half integer can reduce the instability effects also (§) as well as the reduction of the vertical β-functions at the RFDs. For this reason a new optics with half integer vertical tune has been implemented and is now under test in the new run [4]. Changing the mode resonant frequencies by few hundred kHz (for example, by changing the temperature of the RFD by few degree) does not help much because we need few MHz of detuning to measure some relevant effects. A strong reduction of the Q-factors of the modes can instead strongly reduce the instability.

NEW RF DEFLECTORS DESIGN

The new RFDs have been designed to increase the vertical modes frequency separation (by few hundred MHz) and to strongly reduce the quality factor of the vertical modes (**). The mechanical drawing is shown in Fig 6. In the new RFD the vertical mode in each cell is damped through an antenna/loop directly connected to the rods. Moreover the rods themselves have been moved towards the deflector axis in order to increase the vertical modes frequency separation of more than 300 MHz. The quality factors of the vertical modes in this new RFDs are so low that they cannot be well calculated. The power flowing through the antennas in the external loads is given by the power transferred from the main RF source at f_{RF} that is slightly coupled to the antennas because the structure is not perfectly symmetric and by the contribution of the power transferred from the beam to the accelerating mode which is coupled to the antennas themselves. The two contributions do not exceed few watts rms at least from HFSS simulations. To reduce the cost and the delivery time of the device we decided to built the new RFDs in aluminium. The cells will be clamped together and soldered. RF power tests before the installation in the CTF3 CR will be done to investigate if multi-pacting phenomena occur. If this is the case we intend to provide Ti-coating to reduce the secondary emission yield.

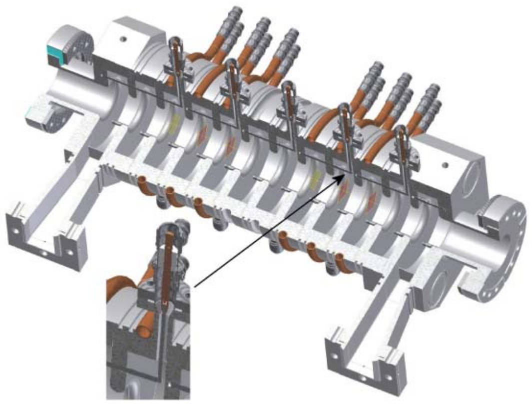

Figure 6: New RFDs mechanical drawing.

CONCLUSIONS

Vertical trapped modes in the RFDs of the CR are probably responsible for the vertical beam instability found in the last CTF3 run. To study the beam dynamics a dedicated tracking code has been implemented. The results show that the instability can be mitigated by a more accurate control of the orbit inside the RFDs, by adopting a half integer vertical tune or by reducing the vertical β-function at the RFDs. The instability can be completely cancelled with a strong reduction of the Q factors of the modes. For this reason new RFDs have been designed and are now under construction. In the new devices special antennas absorb the power released by the beam to the modes. The structures will be made in aluminum to reduce the cost and delivery time.

REFERENCES

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[2] D. Alesini, et al., EPAC 2002, p.2115.
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[4] R. Corsini, MOPP011, This conference.
[5] www.ansoft.com
[6] for example, D. Alesini, et al., EPAC04, p. 2077.

[‡] In both cases we suppose that the two VDMs of the two RFDs have exactly the same frequency and Q.

[§] This can be intuitively understood because, in the case of an half integer tune, the vertical kicks given by the wakefields do not change the vertical beam offset at the RFD after one turn. On the contrary the maximum instability occurs when the vertical kick is completely transformed into vertical displacements (tune near 0.25 or 0.75).

[**] The design has been done using HFSS.