EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN - AB Department

CERN-AB-2008-028
CLIC-Note -763

FAST VERTICAL BEAM INSTABILITY IN THE CTF3 COMBINER RING

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Presented at
EPAC'08, 11th European Particle Accelerator Conference, Genoa, Italy - June 23-27, 2008

Geneva, Switzerland
August 2008

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The CLIC Test Facility CTF3 is being built at CERN by an international collaboration, in order to demonstrate the main feasibility issues of the CLIC two-beam technology by 2010. The facility includes an 84 m combiner ring, which was installed and put into operation in 2007. High-current operation has shown a vertical beam break-up instability, leading to high beam losses over the four turns required for nominal operation of the CTF3 ring. Such instability is most likely due to the vertically polarized transverse mode in the RF deflectors used for beam injection and combination. In this paper we report the experimental data and compare them with simulations. Possible methods to eliminate the instability are also outlined.

INTRODUCTION

The experimental program of the present CLIC Test Facility, CTF3 [1], addresses most of the main issues of the CLIC study in order to get an answer on the feasibility of the scheme before 2010. In particular, one of the critical issues is the validation of the drive beam generation scheme with a fully-loaded linac and bunch train combination by transverse RF deflectors [2].

CTF3 is being built and commissioned by an international collaboration formed at present by 24 institutes from 14 countries [3]. The facility, located at CERN in the area of the former LEP Pre-Injector (LPI), includes a 70 m long linac followed by two rings, where the bunch train combination is obtained: a 42 m delay loop and an 84 m combiner ring. The drive beam thus produced can then be used for RF power production, deceleration and two-beam operation tests in a close-by experimental area (CLEX).

The 4 A, 1.2 µs long beam-pulse from the electron gun is bunched by the three sub-harmonic buncher (SHB) cavities such that only every second 3 GHz RF bucket is populated. The SHB is a wide-band system and allows a very fast (5-6 ns) switch of the RF phase by 180°. The drive beam can thus be easily "phase coded" into eight 140 ns long sub-pulses, in which the main bunches occupy either even or odd buckets. The bunched beam is then accelerated to about 120 MeV/c in the linac, operated in full beam-loading mode [4].

The role of the delay loop that follows the linac is to rearrange the 1.2 µs beam-pulse from the drive-beam linac into four 140 ns pulses, separated by 140 ns gaps, increasing at the same time by a factor 2 both the current and the bunch repetition frequency. A transverse RF deflector working at 1.5 GHz sends the first phase-coded sub-pulse into the delay loop. The loop length of 42 m corresponds to the sub-pulse length of 140 ns, thus the first sub-pulse is back at the deflector at the same time as the next sub-pulse from the linac. The delay loop length is precisely tuned to an integer number of RF wavelength, therefore phase-coded bunches from different sub-pulses are interleaved. They then receive opposite kicks and are thus combined into the same orbit. The bunch spacing is halved to 10 cm and the beam current is doubled. The process also naturally produces the 140 ns gap needed for clean extraction from the combiner ring.

The combiner ring (see Fig. 1) has four achromatic and isochronous arcs, with three dipoles each. Injection and extraction regions are located in the long straight sections. For injection, two 3 GHz RF deflectors separated by a π betatron phase advance and located at each side of the injection septa are used. On the opposite side, a fast kicker is used for extraction. The ring has also a path-length tuning wiggler in one of the two short straights.

The four 140 ns pulses from the delay loop are combined in the ring using a principle similar to the one described above. The ring length is equal to the distance between pulses and it is precisely tuned to $(n + ¼)\ \lambda$, where n is a (large) integer. The RF deflector after the injection septa kicks each incoming pulse into the closed orbit. The deflector located before the septa is synchronized with the first one to generate a closed bump, such that the injected pulses are kept on the closed orbit when they come round and are interleaved with the incoming ones. After four turns, before the circulating beam can hit the septum, the combined pulses are extracted by the kicker on the other side of the ring to be sent to the CLEX area. The final beam current is eight times the initial one and the bunch distance is 2.5 cm.

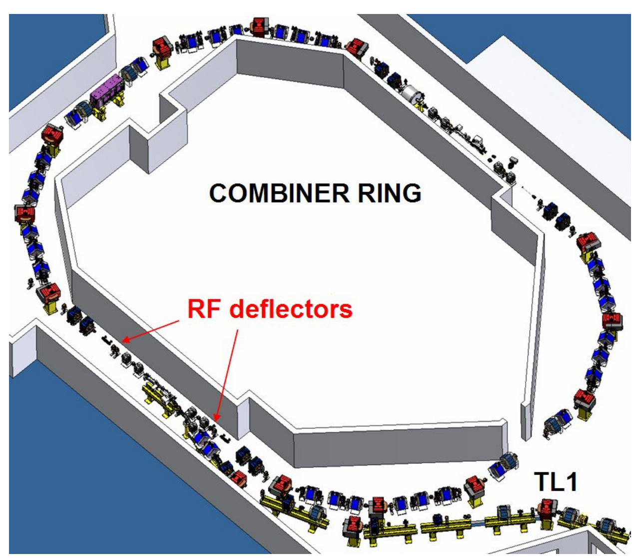

Figure 1: Combiner ring layout. On the bottom the transfer line from the delay loop to the ring (TL1). The position of the RF deflectors is also indicated.

OBSERVATION OF THE INSTABILITY

Beam commissioning of the transfer line TL1 and of the combiner ring to the nominal beam performance took place in 2007. The setting-up procedure requires to establish injection using the RF deflector located after the septa, timing the RF pulse such that both travelling-wave deflectors would be empty of RF power during the second turn. Such a procedure (RF injection) permits to store the beam pulse for a large number of turns, making it possible to perform a number of beam studies, such as tune measurement and precise determination and correction of the closed orbit. The number of circulating turns is in principle limited only by synchrotron radiation losses (no accelerating cavity is installed in the combiner ring).

After having solved several hardware and modeling problems [5] it was possible to get a beam circulating for many turns with the nominal isochronous optics. However, only a small fraction of the beam current survived to up to 180 μs, corresponding to more than 600 turns, while most of it was lost in the first few turns.

Further observations showed how the beam loss was much faster for longer pulses (see Fig. 3) and for higher beam current, a clear indication of a collective effect taking place. A closer look at the analog BPM signals with a fast scope revealed a strong vertical oscillation along the pulse, barely visible in the bandwidth-limited digitized signals. The oscillation started from the 2^{nd} or 3^{rd} turn for the nominal beam parameters, and caused rapidly heavy losses (see Fig. 4). It should be noted that the amplitude and phase of the oscillations were remarkably stable, every pulse showing almost exactly the same trace on the scope.

The oscillation frequency was determined by an FFT of the vertical signal, and was find to be equal to 48 MHz. This was the first strong hint that the instability was due to the vertically polarized mode of the RF deflectors used for injection.

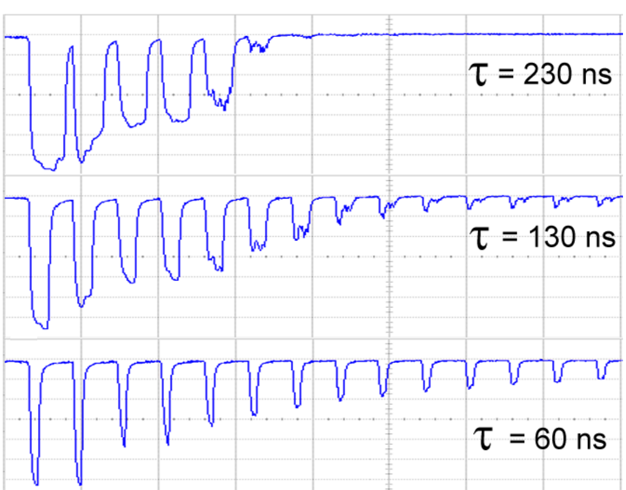

Figure 2: Scope traces showing the beam current at a ring BPM as a function of time, for different injected pulse lengths. Shorter pulses, with less charge, survive for longer times, indicating a collective instability.

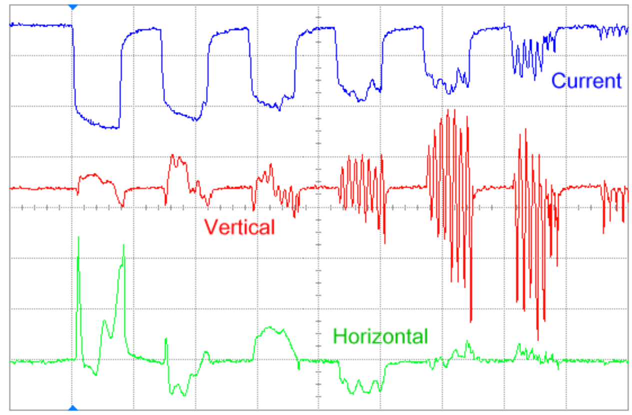

Figure 3: Scope traces from a ring BPM showing, from top to bottom, the circulating beam current and the vertical and horizontal signal. The fast growing oscillation in the vertical plane is obvious and well correlated with beam losses. No such behaviour is visible in the horizontal plane.

Such mode had been in fact decoupled in frequency from the main horizontal mode by inserting metallic rods in the deflector cells, in order to avoid mode conversion of the injected power. The resulting frequency for the vertical mode is 3.0443 GHz, while the main mode has the same frequency of the bunch train, 2.9985 GHz. The frequency difference is therefore equal to the measured beam oscillation frequency, within the experimental uncertainties. In order to exclude the possibility of a fast beam ion instability, which could cover a similar frequency range, the vertical oscillation frequency was measured for different beam currents. Contrary to the predictions of the theory of fast beam ion instability [6], the oscillation frequency remained stable. We also tried to change the operating temperature of the deflectors. A temperature variation of 8°C essentially did not change the scenario. Changing the orbit in the vertical plane seemed to have some effect. However, no systematic study was done and the instability was always present, constituting a limiting factor in the recombination test [7].

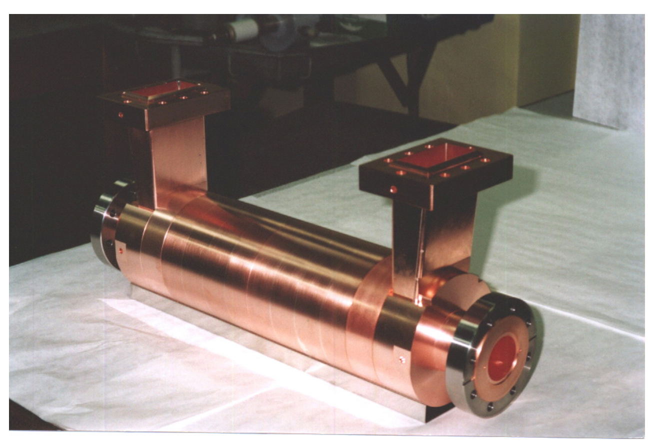

Figure 4: CTF3 Travelling wave RF deflector. The horizontally polarized mode is coupled in and out through the waveguide couplers. The vertically polarized mode, excited by the beam, is trapped in the cavity.

SIMULATIONS AND OUTLOOK

The possibility of an instability arising from the deflector had been indeed considered in the design phase of CTF3. But while a thorough analysis [8] had been made for the effect of the horizontal polarization (resonant with the bunch frequency) the vertical mode had been considered less relevant, since the bunch train spectrum have a very small component at its excitation frequency. However, while the horizontally polarized mode is rapidly extracted by the output coupler the vertical mode can be trapped over subsequent turns. In order to confirm the suspicion and to determine the possible remedies, a dedicated tracking code has been written to study the multi-bunch multi-turn effects [9].

The resonant frequencies, quality factors and transverse shunt impedances of the vertical modes have been calculated by HFSS and used in the code.

The simulation results confirmed the presence of a strong instability, driven by a few mm off-axis beam, and showed a good agreement with the experimental observations. In particular:

1. The profile of the vertical oscillation as a function of the bunch positions is the same shot by shot.
2. The oscillation spectrum show side-bands at Δf = 40/50 MHz with respect to the fundamental.
3. The instability is stronger for an increased bunch charge.
4. The instability is stronger for longer bunch trains, at fixed bunch current.
5. Dependence on the temperature of the deflectors: no large effect for a frequency change of ~ 3 MHz, corresponding to 8°C.
6. The instability occurs both in the case of a single train doing different turns than in the case of recombination.
7. A better vertical steering inside the deflectors minimize the oscillations.

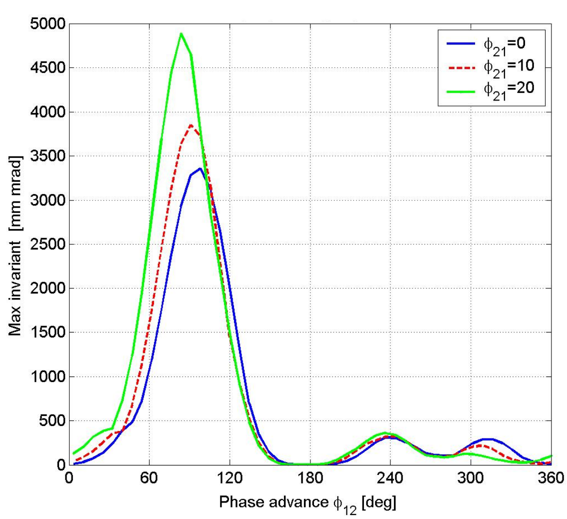

Figure 5: Emittance increase after four turns for 2 mm initial offset; ϕ_{21} is the vertical phase advance between the deflectors across the septa, ϕ_{12} the phase advance in the rest of the ring (the tune is the sum of both).

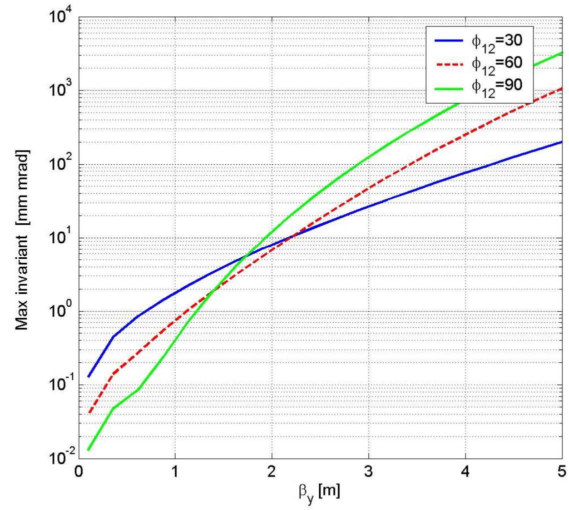

Figure 6: Emittance increase as a function of the local β-function, for different phase advances ϕ_{21}.

A study on the dependence on the ring tune show that a tune near the half integer can reduce the effect by a large factor (see Fig.5). The reduction of the vertical β-function at the deflector can also help in the control of the instability (Fig. 6). Similar conclusions were obtained in the past for the horizontal instability [8], and the combiner ring horizontal β-function and tune was indeed chosen following this requirement. A new working point for the ring had now been calculated, and beam tests are presently ongoing. However, the best method to avoid the instability is to damp the vertical deflector mode.

Several possibilities had been studied, and it has been decided to build new RF deflectors with polarising rods as well as loop antenna in each cell, to efficiently extract the vertical mode [9]. They should be installed in October 2008 and are expected to definitively solve the problem.

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