Excitation of Large Transverse Beam Oscillations Without Emittance Blow-up Using the AC-Dipole Principle

O. Berrig, W. Hofle, R. Jones, J. Koopman, J.P. Koutchouk, H. Schmickler, F. Schmidt,
CERN, Geneva, Switzerland

Abstract

The so-called "AC-Dipole" principle allows the excitation of transverse oscillations to large (several σ) excursions without emittance blow-up. The idea was originally proposed and tested at BNL for resonance crossing with polarized beams, using an orbit corrector dipole with an excitation frequency close to the betatron tune, hence "AC-Dipole". This method of beam excitation has several potential applications in the LHC, such as phase advance and β-measurements, dynamic aperture studies and the investigation of resonance strengths. The technique was recently tested in the CERN SPS using the transverse damper as an "AC-Dipole" providing the fixed frequency excitation. results from this experiment are presented, along with an explanation of the underlying principle.

1 INTRODUCTION

The measurement of transverse beam parameters requires either kicking the beam or exciting a coherent oscillation. In both cases the emittance of hadron beams increases in the absence of a significant radiation damping. Furthermore the decoherence due to the incoherent betatron tune spread and head-tail damping perturbs the measurement in a complicated way in the presence of non-linearities.

In LHC, the latter are expected to be significant, requiring corrections of the geometric and chromatic sextupole, octupole, decapole and dodecapole field perturbations. The emittance budget for nominal performance is only 7%. The blow-up due to beam measurements integrated over a machine cycle should therefore be limited to $\approx 1\%$.

Another requirement is the understanding of the non-linearity. If it is significant, the transverse signal due to a kick decoheres very rapidly. The number of possible sources is too large for an empirical optimization. The emittance blow-up can be tolerated at injection energy as the machine can be refilled rapidly. At collision energy, however, the measurement of the non-linearity by kicking the beam would become very costly in time, on top of being very delicate if quenching the machine is to be avoided.

There is therefore a strong motivation to explore other means of transverse beam measurements for small and large transverse amplitudes.

2 PRINCIPLE OF THE AC DIPOLE EXCITATION

The emittance-conserving beam excitation was studied at BNL for adiabatic resonance crossing with polarized hadron beams [1]. It was realized that the same principle can be used to diagnose the linear and non-linear transverse beam dynamics [2] [4] [3]. The principle is as follows: the beam is excited coherently at a frequency close but outside its eigenfrequencies by an oscillating dipolar field. Hence the name of AC dipole given to the excitor. In the simplified model of a linear oscillator, the beam is expected to oscillate at the excitor frequency with a phase shift of $\pi/2$. The energy of the coherent oscillation does not couple with the incoherent oscillations of the individual beam particles. There is therefore no change of the beam emittance. The amplitude of the forced oscillation is given by, e.g. [2]:

$$ z(s) \approx \frac{1}{4\pi|Q_z - Q_e|} \frac{B_e l}{B\rho} \sqrt{\beta(s)\beta_e} \qquad (1) $$

where z stands for x or y, Q_z the eigentune of the z-mode, Q_e the tune of the excitor (frequency divided by the revolution frequency), $B_e l/B\rho$ the kick angle and β the usual focusing function.

There is no constraint which would prevent selecting a rational excitor frequency of the form $Q_e = n/p$. The beam can then be seen to circulate on a dc closed orbit which closes after p turns.

3 ADIABATICITY CONDITION

The field of the AC dipole must be turned on and off in such a way that no beam blow-up occurs during these phases. The adiabaticity condition can be calculated by integrating the equation of the motion for a simple linear ramp. The results (Figure 1) show that a ramp duration in the few ms range is enough to guarantee a blow-up less than 1% up to amplitudes of the order of 100σ. This adiabaticity condition may be understood qualitatively in two ways:

- Considering that the beam circulates on a p-turn closed orbit, the usual criterion of bumping the beam closed orbit can be used. The orbit increment on each turn shall be small compared to the beam size, giving a blow-up of the order of this increment. This criterion explains why the ramp rate must be reduced when the tune difference $|Q_z - Q_e|$ decreases. The orbit increment per turn indeed increases like $1/|Q_z - Q_e|$.
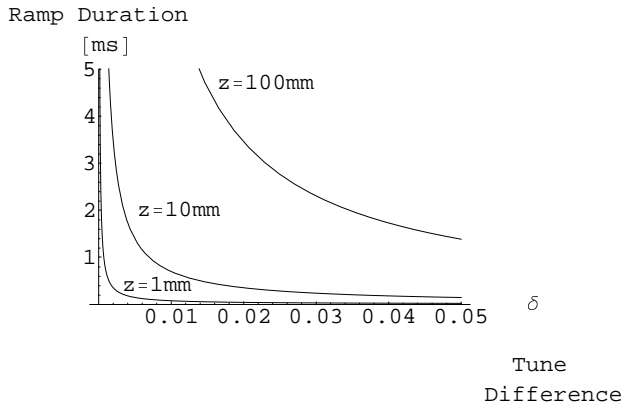
Figure 1: Minimum rise time of the field versus tune split

- The spectrum of the ramping excitor is the convolution of the excitor pure frequency with the Fourier transform of the ramp envelope. The convolution simply shifts the ramp envelope spectrum towards the beam eigenfrequencies. A proper shaping of the ramp envelope and the choice of its duration minimizes the overlap between the excitor and beam spectra.

4 EXPERIMENT AT THE SPS
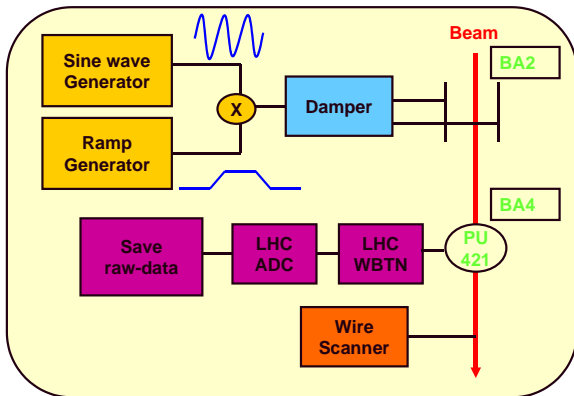
4.1 Experimental Set-up

Figure 2: Experimental set-up in the SPS

The feasibility of emittance-free excitation has already been verified at the AGS [2]. It was noted that a careful tuning of the chromaticity is important. We therefore checked this feasibility on the SPS under conditions closer to that of LHC. The experimental set-up is shown on figure 2. The machine was operated at 26 GeV with the LHC bunch pattern, 72 bunches spaced by 25 ns, with a bunch intensity of $1.5 \ 10^{10}$ protons. The transverse damper was used as an AC-dipole. Two signal generators were used to produce the excitation, one for the 15-20 kHz sine excitation and another to generate a $\cos^2$ ramp up and down. The durations

were set to 25ms for the ramp up or down and 50ms for the flat top (5000 turns) scalable by a factor of 2 or 4. The maximum deflection $B_e l / B\rho$ was 4.2μrad. The prototype LHC orbit system was used to record the transverse beam oscillation (figure 3). It is capable of recording up to 30000 turns. The beam size was measured before and after excitation with a wire scanner but had to be performed on consecutive cycles. The error bars (figure 4) arise mostly from the beam reproducibility over several injections and much less from the instrumentation. The chromaticity was corrected to a value close to zero. The tune spread (FWHM) was measured to be 0.009, mostly due to the space charge. A single kick was applied to the beam after the AC-dipole excitation to measure the tunes. It appears on the right of figure 3.
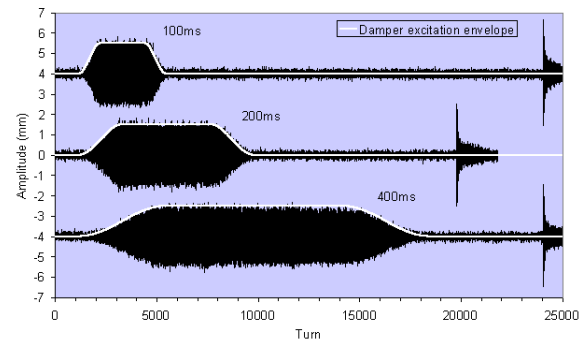
4.2 Results

Figure 3: Transverse amplitude versus time

Outside of the beam eigenfrequencies, the beam response is indeed well modelled by that of a linear oscillator (figure 4) and reaches an amplitude of about 1mm, i.e. 1σ. The beam blow-up remains insignificant in this domain. Figure 5 shows that a response at the beam eigenfrequencies is observed under conditions causing a blow-up. The small left-right asymmetry of the blow-up curve on figure 4 is not understood, but is at the limit of significance. The frequency analysis (figure 5) shows indeed no activity within the beam eigen-frequencies for $Q_z - Q_e = \pm.014$. A variation in emittance of the injected beam seems the most plausible explanation. The duration of the large coherent oscillations was about 100 times longer than after a kick (figure 3), allowing potentially a significantly improved accuracy of beam measurements.

5 CONCLUSIONS

The SPS beam could indeed sustain a coherent oscillation of about 1σ amplitude for a large number of turns without measurable beam blow-up. The limit on the duration of the excitation was not explored, but the gain is already at least an order of magnitude larger than a kick excitation. As expected, the shortest ramp time of 25 ms did not violate the adiabaticity criterion. These results appear sufficient
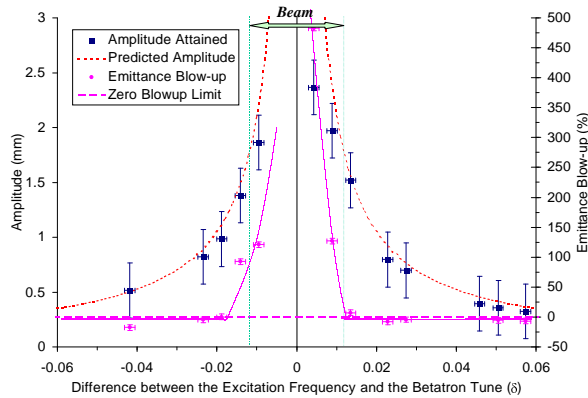
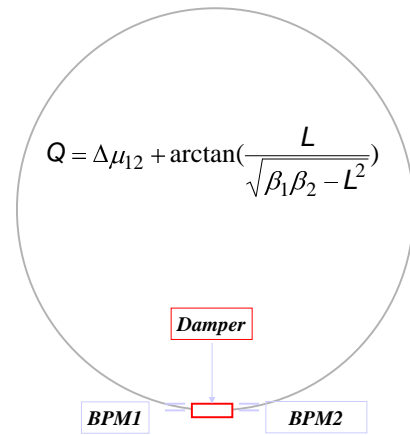Figure 4: Amplitude response and emittance blow-up versus tune split

Figure 6: LHC set-up for the tune measurement

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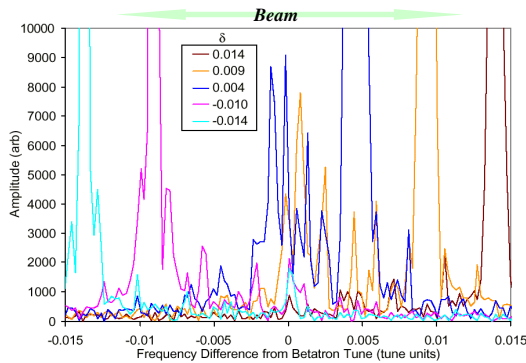

Figure 5: Frequency response versus tune split

to establish the interest of this excitation method for the LHC. The experiment will be repeated in view of exploring the parameter space more precisely (adiabaticity condition, length of the excitation plateau) and the capability in measuring linear and non-linear optics parameters (linear optics functions, chromatic and amplitude detunings, resonance strengths,...). In spite of the forced oscillation outside the beam eigenfrequencies, a measurement of the betatron tunes seems at hand with a set-up as indicated on figure 6. This opens the possibility of harmless continuous tune/chromaticity measurements. The additional BPM's required for this measurement have been added to the LHC layout.

6 REFERENCES

[1] M. Bai *et al.*, 'Overcoming intrinsic spin resonances with an RF dipole', BNL-65149.

[2] M. Bai *et al.*, Experimental test of Coherent Resonance Ex-