

Experiments on LHC Long-Range Beam-Beam Compensation in the SPS

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Abstract

Long-range beam-beam collisions may limit the dynamic aperture and the beam lifetime in storage-ring colliders. Their effect can be compensated by a current-carrying wire mounted parallel to the beam. A compensation scheme based on this principle has been proposed for the Large Hadron Collider (LHC). To demonstrate its viability, a prototype wire was installed at the CERN SPS in 2002. First successful machine experiments explored the dependence of beam loss, beam size, and beam lifetime on the beam-wire distance and on the wire excitation. They appear to confirm the predicted effect of the long-range collisions on the beam dynamics. In 2004, two further wires will become available, by which we can explicitly demonstrate the compensation, study pertinent tolerances, and also compare the respective merits of different beam-beam crossing schemes for several interaction points.

INTRODUCTION

In the LHC, the two counterpropagating proton beams will suffer up to 30 long-range collisions around each of the four primary interaction points (IPs). In two IPs the beams are crossed with a horizontal crossing angle while at the other they are collided with a vertical angle (“alternating crossing”), which leads to a cancellation of the linear components of the long-range beam-beam force and, thereby, reduces the tune spread due to bunch-by-bunch tune variation [1], though it increases the number of excited resonances. Numerous simulations suggest that the dynamic aperture of the LHC will be limited, to about $6-8\sigma$, by the residual effect of the long-range collisions, both at top every and at injection [2].

The field of the opposing beam at the long-range collision points is well approximated by that of a current-carrying wire running parallel to the beam. As the rms variation of betatron phase advance over all 15 long-range collision points on one side of the IP is only about 2° , a single wire can provide a nearly perfect compensation [3]. The wire should be placed at a normalized beam distance equal to the average separation of the long-range beam-beam collisions. Such wire can be mounted where the beams are already separated. The average difference in betatron phase between the proposed compensator location, 112 m from the IP, and the associated long-range collisions is 2.6° [3]. According to simulations, this is sufficient [4].

The integrated strength $I_w l_w$ of the wire is related to the equivalent bunch population N_b and to the number of parasitic collision on one side of the IP, n_b , via $I_w l_w = N_b n_b e c$. The excited wire yields a deflection $\Delta y' = 2r_p l_w I_w / (\gamma e c (y - d))$, where r_p denotes the classical proton radius, l_w the length of the wire, I_w the wire excitation

current, γ the Lorentz factor, y the particle amplitude with respect to the (perturbed) closed orbit, d the separation between the beam center and the wire center when the wire is excited, the prime the derivative with respect to longitudinal position, e the proton charge, c the speed of light, and we have assumed a purely vertical separation. An analogous expression applies to the beam-beam long-range collision, in which case the parameter d denotes the distance between the two beam centers. For constant beam-wire (or beam-beam) distance in units of rms beam size and constant normalized emittance, the ‘diffusive aperture’ in units of σ is independent of the beam energy and independent of the beta function at the wire. This allows a scaling from the LHC to lower beam energies.

EXPERIMENTAL SET UP

In 2002 a prototype compensator, consisting of two adjacent 60-cm long copper wires, was installed in the CERN SPS. The two wires can be fed with a current of 300 A, which is adequate to model the accumulated effect of 60 long-range collisions in the LHC. An inductance of 25 mH was added to the electrical circuit in order to suppress current ripple. The nominal distance between the outer edge of a wire and the centre of the vacuum chamber is 19 mm; the wire stays about 1.5 mm inside the shadow of the arc-chamber aperture. Each wire has an outer diameter of 2.54 mm and contains a cooling-water channel of 1.54 inner diameter. With a water flow of about 0.36 l/min and an Ohmic heat of 300 W for 300-A operation, the temperature rise is a few tens of K.

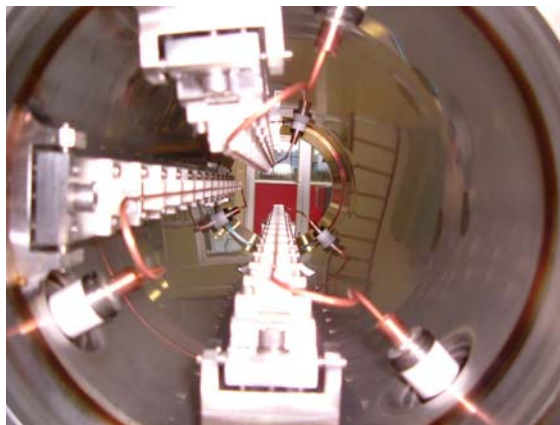


Figure 1: Photo of a new 3-wire device during assembly.

Presently, two novel devices are being installed, whose purpose is to demonstrate the effectiveness of the compensation and to explore the associated tolerances. The new devices are equipped with two times three wires each, positioned in the two transverse planes and at 45° ; see Fig. 1. One of these devices has been mounted adjacent to the ex-

isting one, at a betatron phase distance of 2° . Its vertical position can be remotely controlled over 5 mm. The second new device, to be installed on the opposite side of the SPS, will explore long-distance compensation. It will also allow an experimental comparison between alternating x-y crossings at two IPs (LHC baseline), a two times stronger collision at 45° (inclined hybrid crossing), and purely vertical or horizontal crossings.

Simulations confirm that the SPS wire and the long-range collisions in the LHC should cause similar fast losses at large amplitudes. The growth in particle amplitude over 1 second, due to the simulated diffusion, is shown as a function of the starting amplitude in Fig. 2, for the LHC and for the SPS experiment, respectively. Both pictures reveal a ‘diffusive aperture’, above which the amplitude growth rate steeply increases, and outside which the growth rates exceed several mm per second.

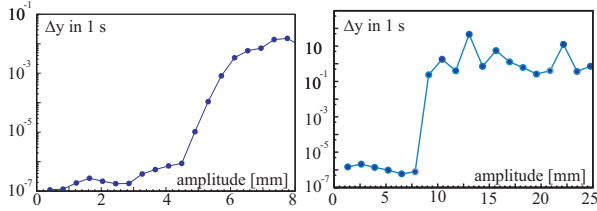


Figure 2: Simulated amplitude growth in mm over 1 second due to long-range beam-beam collisions in the LHC at injection (left) and due to the wire at 267-A excitation in the SPS at 55 GeV/c (right) as a function of starting amplitude, for $\beta=80$ m (LHC) or 50 m (SPS).

MEASUREMENTS

The effects of the wire that can be detected most easily are changes in the linear beam optics, i.e., closed-orbit distortion and betatron-tune change. The shifts in the beam-wire distance d and in the tune $Q_{x,y}$ are given by

$$\Delta d = \frac{\beta_{x,y} I_w l_w r_p}{\gamma e c (d_0 + \Delta d) \tan(\pi(Q_{x,y} + \Delta Q_{x,y}))}$$

$$\Delta Q_{x,y} = \pm \frac{r_p I_w l_w}{2\pi \gamma e c} \frac{1}{(d_0 + \Delta d)^2}$$

where d_0 denotes the initial beam-wire distance (prior to wire excitation). The measured changes in the closed-orbit distortion and in the tunes as a function of the beam-wire separation are in excellent agreement with MAD calculations, as is illustrated in Fig. 3. Therefore, the beam-wire distance can be inferred from either the tune shift or the orbit change with a few percent precision.

The beam position was measured turn-by-turn after applying kicks of various amplitudes. A reduction in decoherence time could be seen, when the wire was excited, in particular for larger kick amplitudes (6 mm or 8 mm) [5]. Changes in the tune shift with vertical kick amplitude \hat{y} were also observed [5], roughly consistent with

$$\Delta Q_x \approx + \frac{3}{4} \frac{I_w l_w r_p}{\gamma e c} \frac{\beta_x}{d^4} \hat{y}^2, \quad \Delta Q_y \approx - \frac{3}{8} \frac{I_w l_w r_p}{\gamma e c} \frac{\beta_y}{d^4} \hat{y}^2.$$

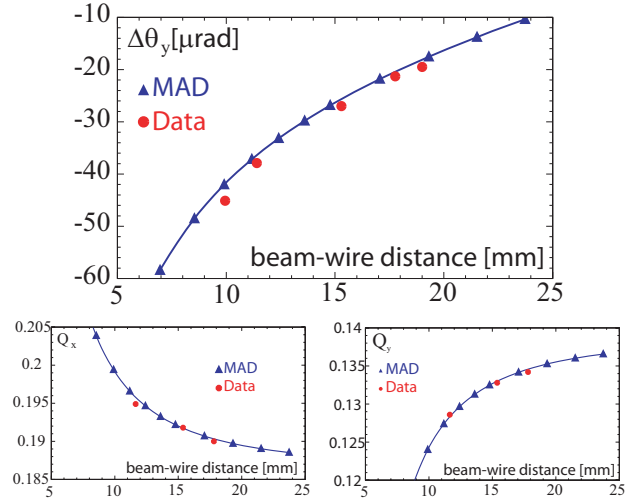


Figure 3: Closed-orbit deflection angle at the wire fitted from the nearby BPM readings (top) and the measured horizontal (bottom left) or vertical betatron tune (bottom right) as a function of the beam-wire distance compared with MAD predictions; for a wire current of 267 A at 55 GeV/c.

Three types of signals were used to quantify the ‘diffusive’ or ‘dynamic’ aperture as function of beam-wire separation and wire current: (1) lifetime and background, (2) final emittance, and (3) scraper-retraction experiments.

Figure 4 displays the beam lifetime and background detected by a photo-multiplier (PMT) as a function of the beam-wire separation. A drop in the beam lifetime and an increase in the beam losses are visible for separations smaller than about 9σ . At $7-8\sigma$ separation, the beam lifetime decreases to 1–5 h when the wire is excited.

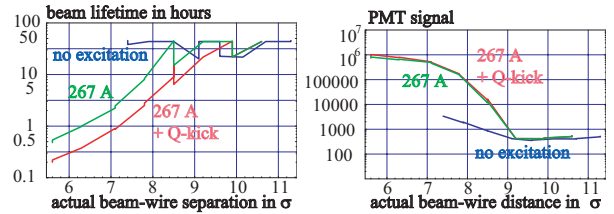


Figure 4: Beam lifetime (left) and beam-loss signal (right) as a function of beam-wire separation at 55 GeV/c. The three curves refer to cases without (blue) and with wire excitation (green), and with tune kicker also active (red).

In the second type of nonlinear studies, the beam emittance was blown up by creating a mismatch in the injection line. The beam size was measured before bumping the orbit locally and exciting the wire, and 1.7 s after the start of the wire excitation, respectively, during the same SPS cycle. Wire scans before and during excitation at 267 A are illustrated in the left picture of Fig. 5. In this example, the initial and final emittances were $3.40 \mu\text{m}$ and $1.15 \mu\text{m}$. The wire-scan profiles can be converted into amplitude distributions by an Abel transformation [6], as in the right picture, which assumes the model beta function. The difference distribution represents the ‘scraped’ part. Figure 6 shows the final normalized emittance after wire excitation as a

function of beam-wire separation, for three different wire currents. Multiple values reflect a variation due to small tune changes. For the left points without wire excitation, the reduction in emittance is consistent with mechanical scraping at the edge of the wire. We also scraped the beam mechanically at various known amplitudes, which permits converting the measured emittances into an effective aperture. Figure 7 displays the diffusive aperture, deduced via the scraper calibration, as a function of the square root of the wire current. The observed linear variation is consistent with a scaling law derived by Irwin [7]. The measured aperture is smaller than the simulated.

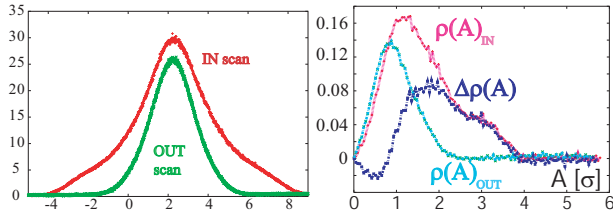


Figure 5: Left: IN and OUT wire scans for a bump amplitude of -9.4 mm and a wire current of 267 A; right: the corresponding amplitude distributions and their difference vs. the normalized amplitude in units of σ for $\epsilon_N=3.75 \mu\text{m}$.

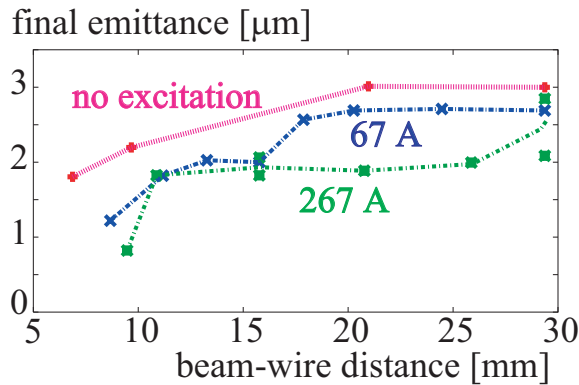


Figure 6: Final normalized emittance versus the distance between wire-centre and beam at 26 GeV/c. The three curves correspond to wire currents of 0 , 67 and 267 A.

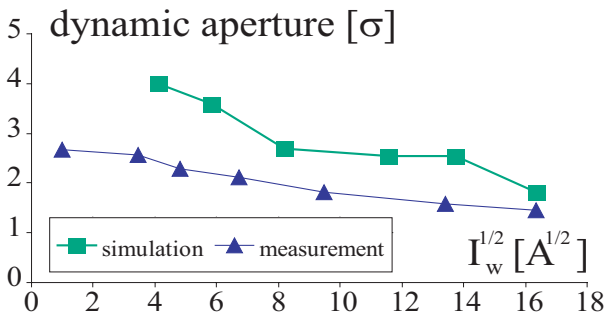


Figure 7: Diffusive aperture inferred from emittance measurements at 26 GeV/c as a function of wire current compared with simulation.

Figure 8 presents typical PMT beam-loss signals during the SPS cycle when the wire is excited without (left) and with mechanical scraping (right picture). From the signal drop after scraping and the subsequent slow increase one

can extract a diffusion coefficient [8]. At larger amplitudes the diffusion is faster than the speed of the scraper. In the right picture a nonzero beam-loss signal is visible prior to wire excitation, since the scraper moving to its target position already intercepts beam halo.

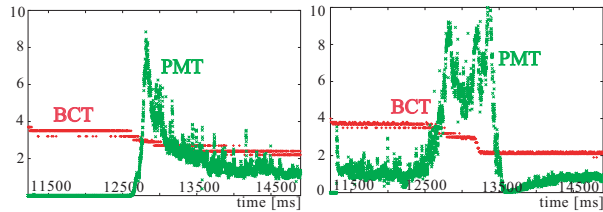


Figure 8: Beam current (BCT) and beam-loss signal (PMT) versus time in ms, for a wire excitation of 267 A starting at 12725 ms, without (left) and with (right) mechanical scraping at an amplitude of 1σ around 13325 ms.

SUMMARY AND THANKS

A long-range beam-beam compensator prototype in the SPS models the effect of long-range collisions in the LHC. Six machine experiments were performed in the years 2002 and 2003. The measured linear and nonlinear optics perturbations induced by the wire appear consistent with analytical estimates and simulations. Our measurements indicate that, if the LHC crossing angle would be reduced by 10%, the beam lifetime might drop to 4 h. We observed a distinct shrinkage of the beam emittance due to particle loss at large amplitudes, and we used this effect to infer the diffusive aperture. The latter tends to be smaller than predicted, requiring further checks. It is found to vary linearly with the square root of the excitation current, and to depend nonlinearly on the beam-wire distance. Attempts to directly measure amplitude-dependent diffusion rates by fast scraper retraction have so far proven difficult. In 2004, two novel devices will demonstrate the compensation proposed for the LHC and study its sensitivity to errors. They will also allow for a comparison of various crossing schemes.

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