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Rapid closed orbit correction at interaction points in the LHC

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Introduction

As bunches approach and leave an interaction point (IP), they pass bunches in the opposing beam and experience the electromagnetic forces created by the other bunch. These long-range beam-beam interactions result in bunches receiving a deflecting kick. The pacman effect, which results from bunches near the ends of a train experiencing substantially fewer parasitic collisions than the majority of bunches within a train, causes the deflecting kick to vary on a bunch-by-bunch basis along the front and back of the bunch trains. This results in different closed orbits for the pacman bunches. Since the kicks from long-range interactions are almost symmetric about a given interaction point, the closed orbit offset is small at that interaction point. The effects elsewhere in the lattice, however, are dependent on machine parameters, and these orbit deviations may result in pacman bunch separations as high as one sigma at other IP's in the case of high-luminosity operations with several IP's [1]. Although pacman orbit effects can be large [1], it is hoped to reduce them by proper phasing of the IP's [2]. A detailed, self-consistent orbit calculation is under way at CERN [Ruggiero et. al.] and the final recommendation concerning a bunch-by-bunch orbit control system will depend on it's results, taking into account also the transient phase when beams are brought into collision. The maximum orbit effect of about one sigma, estimated by Herr, was for a crossing angle of 200 μrad. It will be decreased by a larger crossing angle (the machine will allow up to 300 μrad).

Here, a closed-orbit correction scheme that responds within a bunch train is outlined, which would correct for these bunch-by-bunch orbit offsets, and avoid the luminosity reduction that would result.

The bunch train pattern in the LHC is determined by the rise times of various kickers in the machine and the injection complex. Figure 1 shows the fill pattern. Herr [1] has computed the kick for each bunch resulting from long-range collisions in the lattice version 4.1, figure 2 shows the kick distribution along the most common bunch trains labeled A, B,

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and C. It is the difference in bunch-by-bunch orbit arising from these kicks, at each interaction point, that must be compensated to achieve highest luminosities.

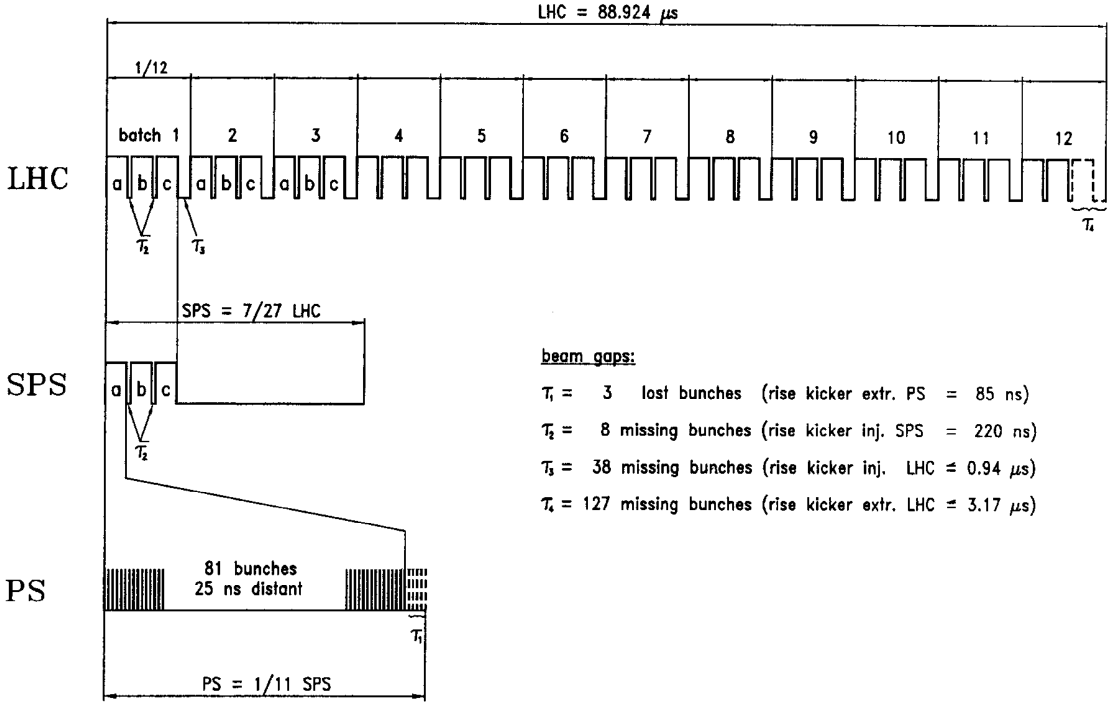


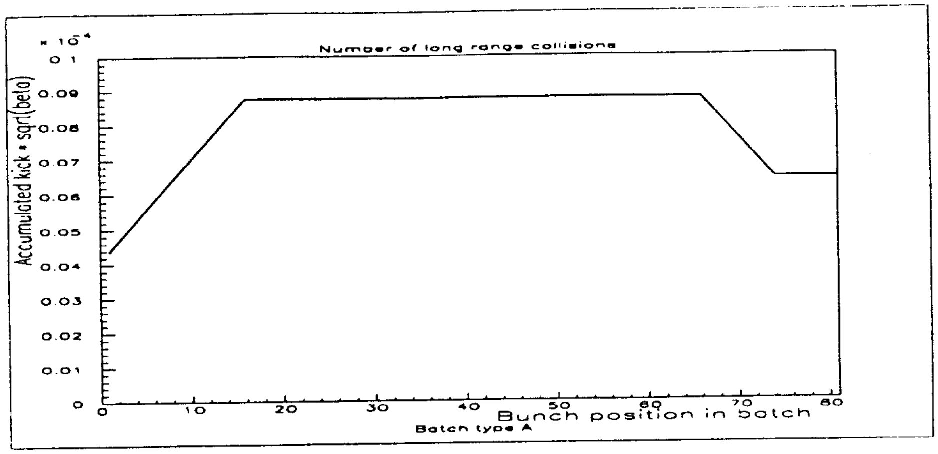
Figure 1: LHC bunch pattern [3]

Control of the pacman bunches

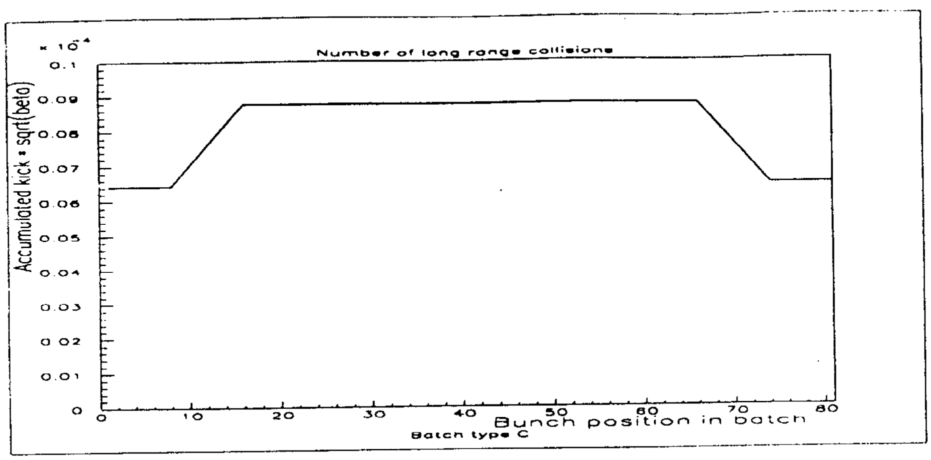
The proposed correction scheme involves measuring bunch-by-bunch closed orbit deviation in the neighborhood of an interaction point and applying a corrective deflection to compensate for the different positions of bunches along bunch trains. This assumes that the pacman effect is the only cause of bunch-by-bunch orbit displacements. A pair of kicker structures, located one on each side of an IP produce a time-varying closed orbit bump, but quasi-static on a turn-by-turn basis. The bump amplitude varies along a bunch train, and reduces the orbit deviations of the bunches to an acceptable level. A static steering bump may then be used to bring the beams into collision. Pickups and kickers must be outside the dipoles D2, where the beams are separated, since each beam requires independent correction.

Figures 3 and 4 show the layout and lattice functions in these regions. Our present calculations are made for pickups and kickers located between D2 and the arc quadrupoles. Figure 5 shows a sketch of the orbit of the pacman bunches with and without correction.

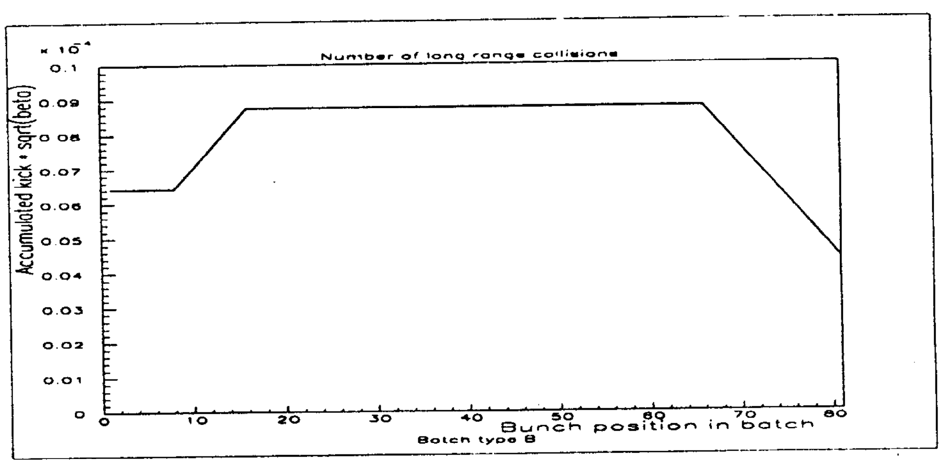
Figure 6 shows a schematic of the proposed system. The product of bunch current and transverse position of each bunch is measured and digitized at the full bunch rate of 40 MHz, using pickups located outside the interaction region. The current per bunch is also measured (perhaps as the sum output from the pickups) and is used to normalize the position signal and obtain a true position measurement of each bunch. This processing is performed in the digital-signal-processing section, which may occur at a slow rate, certainly less than the bunch rate, and would be determined by the rate of change in beam-beam kicks which will presumably have a time constant of minutes. Averaging over many



Accumulated kick, bunch train A



Accumulated kick, bunch train B



Accumulated kick, bunch train C

Figure 2: Accumulated kick from long-range beam-beam interaction; distribution along bunch trains [1]

turns helps to reduce effects of coherent bunch oscillations. With the position of each bunch stored in memory, a corrective deflection is calculated independently for each bunch, and this kick signal sent to the kickers around an IP, with appropriate phase and amplitude for each kicker. The applied bump acts to cancel the closed orbit deviations (c.o.d.) of the bunches that are *outside* the IP, and thus reduces the c.o.d. of bunches at other IP's.

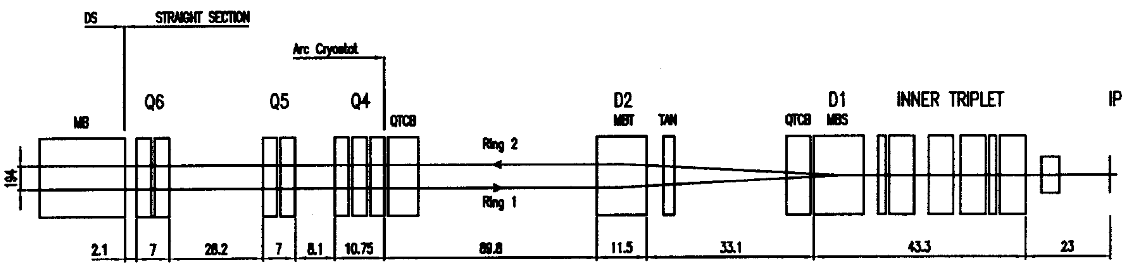


Figure 3: Schematic layout showing locations of components around IP1 [3]

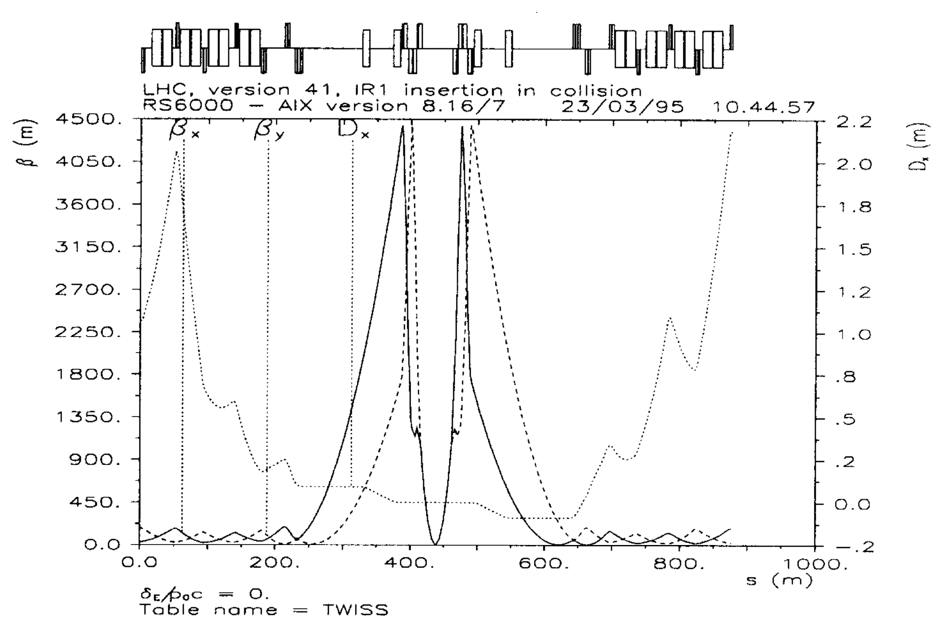


Figure 4: Collision optics lattice functions around IP1 [3]

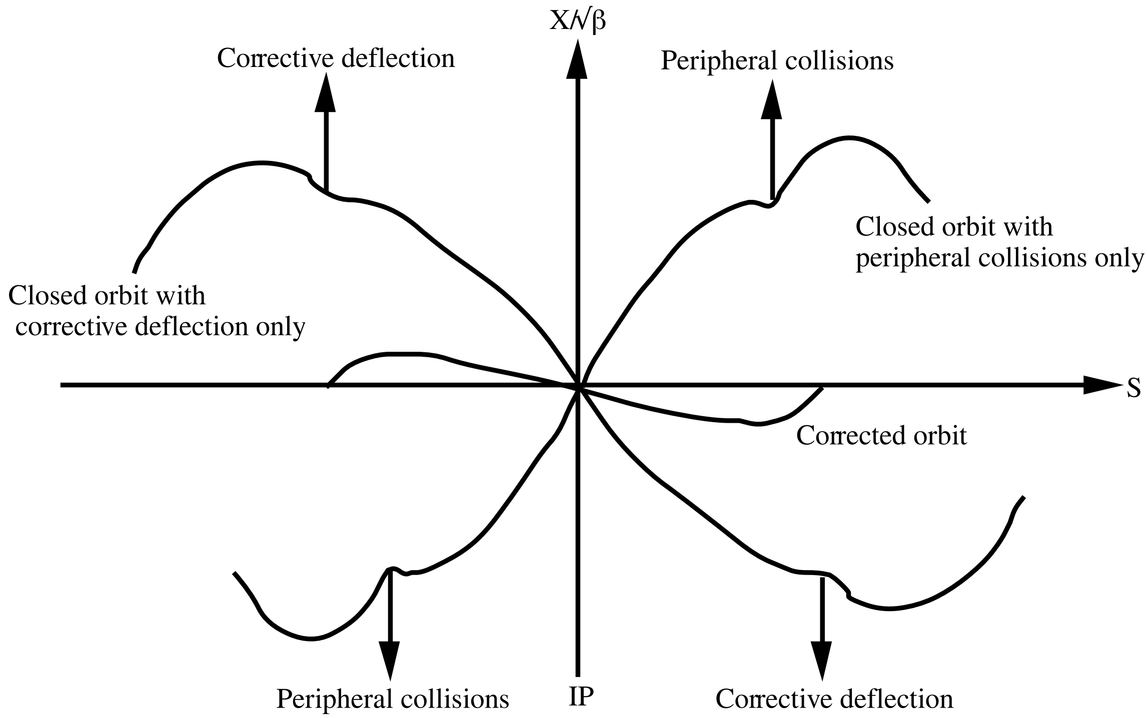


Figure 5: Schematic of pacman bunch orbit with and without correction

By designing the system to hold it's output signal level until the next populated bucket arrives, we a/c. couple the output and the kick signal is then a modulation about the average beam offset. This has significant advantages in power requirements, since we do not try to correct the full transverse displacement of each bunch, but rather correct for deviations about the average offset. The average offset may be corrected by beam steering through the IP.

Bandwidth requirements are determined by the necessity of the system to respond within the time period of the pacman bunches, about 400 ns, and the settling time thereafter. 2.5 MHz bandwidth will probably be sufficient, but actual bandwidth may be determined by the availability of power amplifiers, and acceptable deviation along a bunch train, and requires further consideration.

The kick amplitude has been calculated by Herr and is shown in figure 2 for the most common bunch trains [1]. Power requirements for the closed orbit control have been estimated from these calculations. The variation from minimum to maximum accumulated kick for the bunch trains A and C is 4.4×10^{-6} $m^{1/2}$ (normalized to local β-function). Here, we assume that we will need to provide an equivalent accumulated deflection with our system (half on each side of the IP). If the kickers could be optimally placed at a quarter betatron wavelength from the orbit deviation produced by the parasitic beam-beam collisions, only half of this value would be needed. Here, we are assuming that the kickers must be placed somewhere with a betatron phase advance of 45° from the location of the long-range beam-beam interaction.

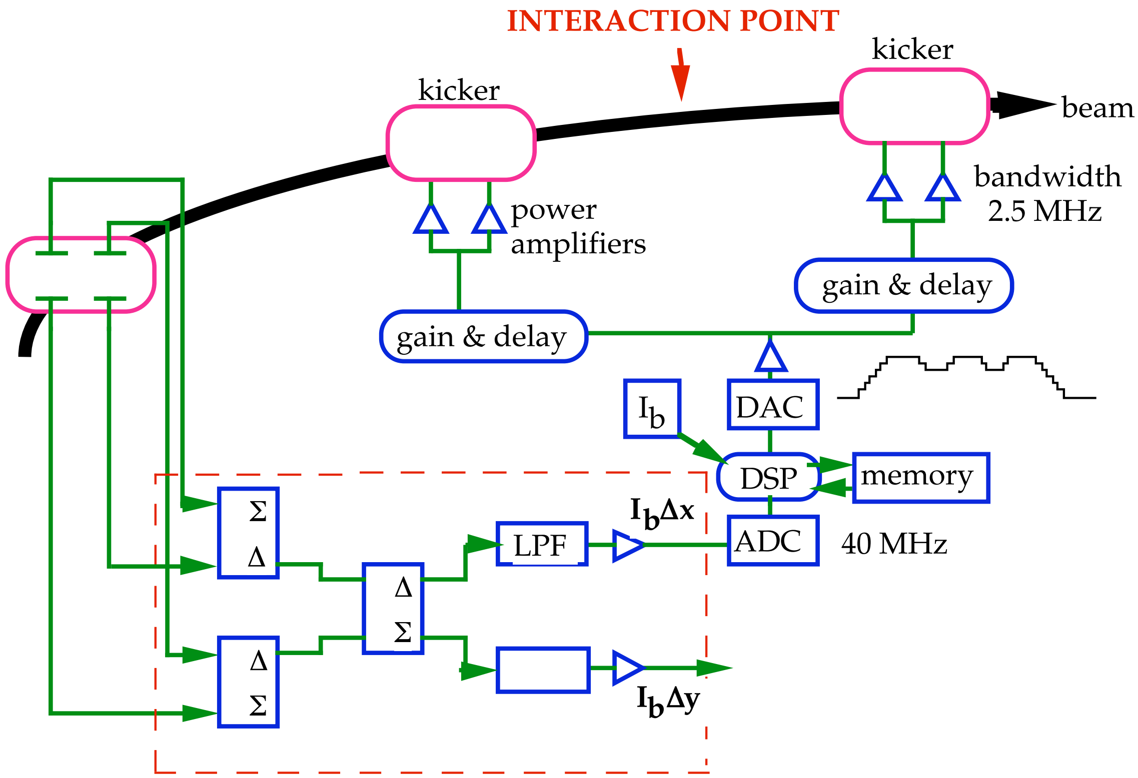


Figure 6: Schematic of fast closed-orbit correction scheme

From figure 4 we see that the β-functions between D2 and the arc quadrupoles vary from approximately 200 m to 1800 m. Taking β-functions ˜ 200 m, we find the maximum kick angle per kicker

$$\Delta x' = \frac{4.4\text{x}10^{-6}}{2\sqrt{200}} = 0.16\ \mu\text{rad}$$

We suggest using stripline electromagnetic kickers of length 10 m. These kickers have a high shunt impedance, which increases with the length of the structure, and a 10 m device is used for illustrative purposes. The 10 m kicker has sufficient bandwidth to operate up to several MHz. The shunt impedance for a stripline kicker is given by

$$R_\perp T^2 = 2\, Z_L \left(g_\perp \frac{2}{kh}\right)^2 \sin^2\Theta$$

where Z_L is the stripline impedance, $g_\perp$ the coverage factor, k the wavenumber ω/c, h the aperture between electrodes, l the length of electrodes, and Θ = kl. The shunt impedance as a function of frequency for a kicker with aperture 5 cm is shown in figure 7. A 5 cm aperture allows for beam stay-clear during injection.

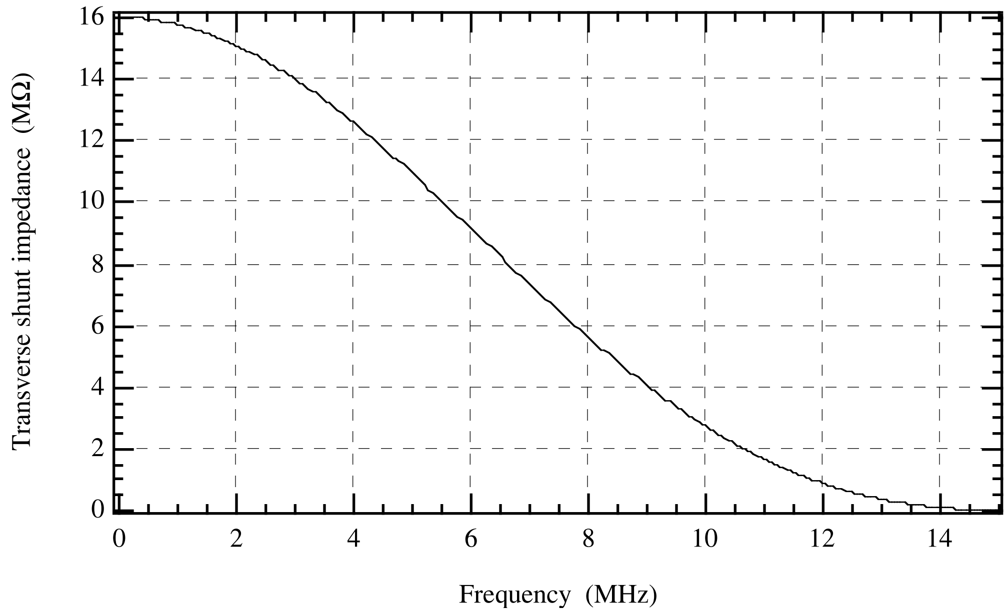


Figure 7: Stripline kicker shunt impedance; electrodes 10 m long, 5 cm aperture

The required voltage kick is a function of the β-function at the location of the kicker:

$$V_{kick} = \frac{E}{e} \Delta x' = 7e12 \, \frac{4.4x10^{-6}}{2\sqrt{\beta}}$$

The kicker shunt impedance is 15 M? at 2.5 MHz, and using this value we find the power requirement per kicker to be

$$P_{kick} = \frac{V_{kick}^2}{2\, R_{shunt}} = \frac{\left(1.1 \text{ x } 10^6\right)^2}{2 \text{ x } 15^6} = 40 \text{ kW}$$

resulting in a radiofrequency (RF) power requirement of 80 kW per plane per IP per beam. If we scale the kicker aperture with the square root of the β-function we find that the power requirement for the kicker is independent of β for a given angular deflection. We may, however, reduce the power requirement by using more kickers. Using two kickers on each side of an IP, the total RF power requirement for a given deflection angle is reduced by a factor of two. In this case we could achieve a 0.16 μrad deflection with 10 kW per kicker (making a total of 40 kW per plane per IP per beam).

References

[1] "Effects of pacman bunches in the LHC", W. Herr, LHC Project Report 39, August 1996.

[2] "Minimizing the Pacman Effect", D. Ritson & W. Chou, FERMILAB-TM-2029, October 1997.

[3] “LHC The Large Hadron Collider Conceptual Design”, The LHC Study Group, CERN/AC/95-05 (LHC), October 1995.