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Simulations Of Long-range Beam-beam Interaction And Wire Compensation With Bbtrack

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We present weak-strong simulation results for the effect of long-range beam-beam (LR-BB) interaction in LHC as well as for proposed wire compensation schemes or wire experiments, respectively. In particular, we discuss details of the simulation model, instability indicators, the effectiveness of compensation, the difference between nominal and PACMAN bunches for the LHC, beam experiments, and wire tolerances. The simulations are performed with the new code BBTrack [1].

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We present weak-strong simulation results for the effect of long-range beam-beam (LR-BB) interaction in LHC as well as for proposed wire compensation schemes or wire experiments, respectively. In particular, we discuss details of the simulation model, instability indicators, the effectiveness of compensation, the difference between nominal and PACMAN bunches for the LHC, beam experiments, and wire tolerances. The simulations are performed with the new code BBTrack [1].

MOTIVATION AND PRINCIPLE

The nonlinear forces caused by LR-BB interaction (average beam-beam separation $d = 9.5\sigma$) in the nominal LHC scheme (crossing angle $\alpha \approx 300\ \mu rad$) result in an emittance growth or particle losses, which limits the ultimate luminosity. Attempting to reduce the strength of the long-range interaction by increasing the crossing angle is not recommendable as this would result in unacceptable geometrical luminosity losses. One of the possible LHC-upgrade scenarios contains the installation of wires parallel to the beam inside the beam pipes next to the two high luminosity interaction points (IPs) (CMS & Atlas; Fig 1). The deflecting electromagnetic field of the opposite beam (e.g: round Gaussian beam shape $\Delta x' \propto 1/r(1-e^{\frac{-r^2}{2\sigma^2}})$,where r is the particle's distance to the center of the opponing beam) is - within limits - similar to the magnetic field of a current-carrying wire ($\Delta x' \propto 1/r$). A current of 81A for a 1m long wire at a distance of 9.5σ from the beam-center would be ideal. In addition to a small discrepancy due to the different field shapes the following issues decrease the compensation effectiveness: a phase advance between the LR-IPs and the wire (in average $2.6\ ^\circ$), a variation of the beam-beam spacing between the different long range beam beam encounters (LR-IPs, min: 7σ, max: 13σ), the actual beam's deviation from a perfect Gaussian shape, an offset from the optimal wire position (the wire must be positioned in the shade of the collimators instead of at the optimal distance (9.5σ)).

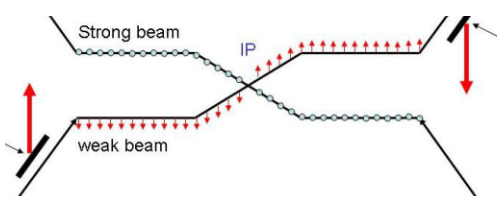


Figure 1: The position of the LR-BB IPs and of a potential wire-compensator. The arrows indicate the direction and strength of the caused kick to the beam.

SIMULATION MODEL

In the BBTrack simulation a weak-strong tracking code, similar to the one described in [2], was used to track test-particles (initial momentum deviation: $\delta p = 2.7 * 10^{-4}$) for 300.000 turns (which corresponds to approximately 30s in LHC) and to decide about their stability by examining the particles emittance-growth and the Liaponov-exponent. Apart from the LR-BB-interactions a set of typical triplet errors were included. In order to allow a fair comparison between the results the additional linear tune shift due to the wire is corrected for.

NOMINAL BUNCHES

The effectiveness of the compensation is manifested in the reduction of the footprint from the uncompensated (left) case to the compensated (right) case in Figure 2. The tune spread due to the LR-BB is almost completely canceled and only the tune footprint of the Head-on collision remains.

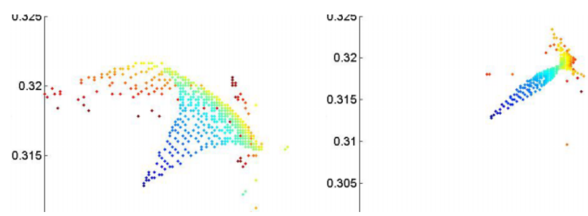


Figure 2: Tune footprint in the uncompensated (left) and compensated (right) case ($0 - 10\sigma$). The color indicates the particles' initial amplitude (blue=low, red=high).

As mentioned above the wire cannot be positioned at the ideal beam-wire distance but must stay behind the collimators. As expected the simulation (Fig 3) shows the best efficiency at 9.5σ, which corresponds to the average beam-beam separation, but the wire still improves the stability even for slightly higher distances. Some unstable islands within the stable region are found.

For the optimal position the sensitivity to the applied current was examined and the result is shown in Figure 4. Due to the structue of the stable region the distinction is not that clear but an optimum can be seen at 65A, which is below the theoretically expected value of 81A.

A Q_x-tune scan of the dynamical aperture (DA) defined by the Liaponov exponent (Fig 5) confirms the improvement over a wide tune-range. The improvement proves to

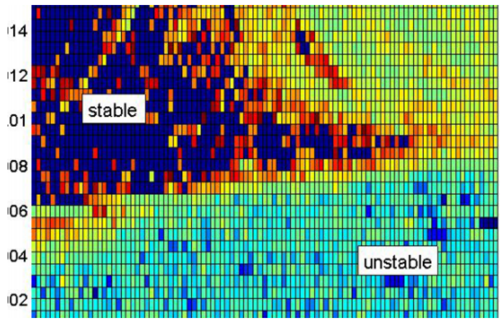


Figure 3: Beam-stability as a function of the beam-wire separation at a current of 81A. X-axis: particle's initial offset, Y-axis: beam-wire distance, Color: indication when the particle becomes unstable (dark blue: stable, green/red: onset of chaos detected at low/high turn number.

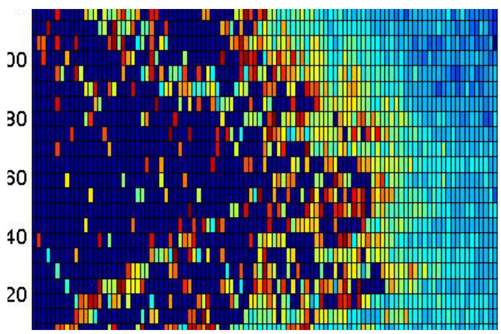


Figure 4: Beam-stability as a function of the wire-current at a distance of 8mm. X-axis: beam-wire separation, Y-axis: beam-wire distance, Color: indication when the particle becomes unstable (dark blue: stable, green/red: onset of chaos detected at low/high turn number

be most effective if the onset of chaos is around 6 σ. It is seen that - choosing a favorable tune - an improvement by more than 1 σ in the DA is feasible.

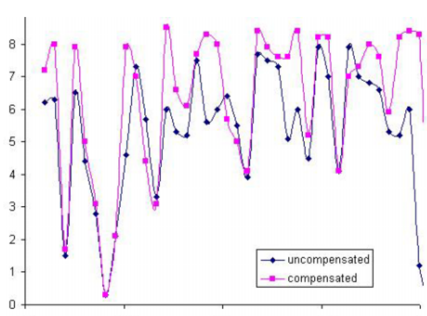
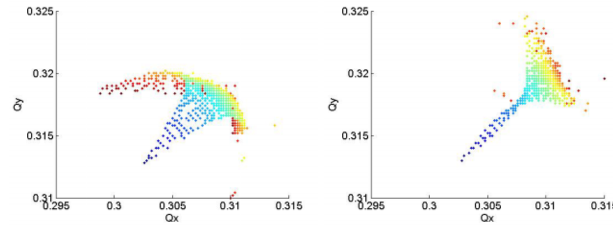
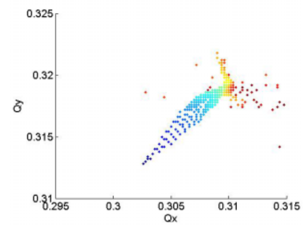


Figure 5: A Q_x-tune scan showing the compensation effectiveness for a beam-wire distance of 9.5σ.

COMPENSATION OF PACMAN BUNCHES

Pacman bunches, located at the end of a bunch train, encounter less LR-BB than the nominal ones. A DC-current in the wire would overcompensate such bunches, as it is seen in figure 6 for the extreme case (no LR-BB at all on one side of each IP). A pulsed wire could be adjusted to the needed corrector strength for optimal compensation.





Border of chaos [σ]	
nominal bunch	6.2
nominal compesated	7.2
Pacman only	6.5
nominal compensation	5.8
adjusted compensation	7.8

Figure 6: The compensation effecting the extreme Pacman bunch; top, left: Pacman only; top, right: Pacman with full compensation; bottom left: Pacman with adjusted compensation.

REQUIREMENTS FOR A PULSED CURRENT SUPPLY

In the given frequency range a pulsed wire can be modeled as an inductivity of 800nH. The current pattern is given by the LHC-bunch pattern which results in a ramp time (0-81A) of 374.25 ns. It seems to be best to archive this slope by applying an appropriate voltage to the inductivity. Having reached the desired current the voltage will be switched to a lower level to match the ohmic resistivity. Due to radiation issues the current supply cannot be positioned close to the device and therefore transmission line effects need to be accounted for. As we want to keep the power consumption as low as possible, a low impedance cabling ($Z_0 \approx 2\Omega$) with matching on the generator side only seems currently to be the best approach and will be studied further in the future. In addition an extremely high turn-to-turn stability is required. Figure 7 shows the emittance growth due to a turn-by-turn jitter. The simulated curve matches the theoretically expected quadratic behavior quite well. Allowing a 10 % emittance growth within 20 hours, the relative turn-to-turn stability needs to be better than $0.5 * 10^{-4}$ or 4mA, which is equivalent to an introduced position jitter of 0.1 nm at the IP. With a linear slope this amplitude requirement corresponds to a timing precision of less than 20ps for Pacman bunches.

INFLUENCE OF DISTANCE SPREAD

In [3] it is shown that the stability is better in case of a modified LHC-optics (DO-option), which entails a single

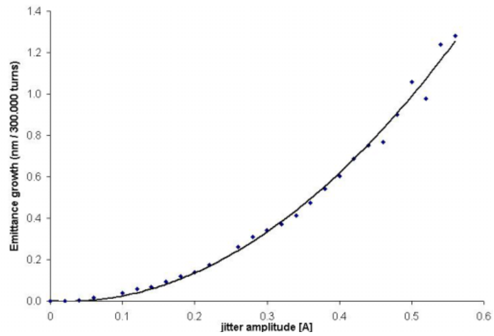


Figure 7: The simulated emittance growth due to a turn-to-turn current-amplitude jitter for a wire length of 1m and a quadratic fit $(4 * 10^{-9} I^2)$.

LR-encounter at low distance but the other ones at higher, varying separation (compared to the nominal LHC). This motivated the examination of the influence of distance-spread on the DA. First the separation of (15-n) LR-BB-IPs was set to 9.5σ while (n) were set to 5σ and the resulting DA plotted (Fig 8, blue dotted line) as a function of n. Of course the DA is reduced with increasing n, but the observed linear dependence shows that the close LR-BB encounter still do not dominate the behavior completely. One can therefore think of an optics with few close encounter but with the other one further separated (like it is demonstrated in [3]). In Figure 8 this result is compared to the case where all 15 LR-BB collisions are at the same separation D (green-line, x-axis: beam separation D). One can see that having all LR-BB at 7 sigma is equivalent (concerning beam-beam induced instability) to having 7 encounters at low (5σ) separation and the other 8 at 9.5 σ.

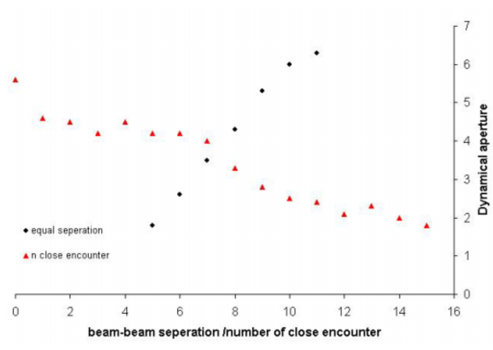


Figure 8: The DA as a function of the number of close LR-BB encounters (with others at 9.5σ) and with all LR-BB equal as a function of beam-beam seperation.

RHIC

RHIC performed dedicated LR-BB experiments [5] where the beam-beam seperation of a single interaction was scanned. Our simulations found no chaotic behaviour and even in the worst encountered case of 3.5 σ beam-beam separation only a linear detuning with amplitude. The magnitude of the Liaponov exponent after 300.000 turns is indicated in Figure 9 by different colors for particles initially launched betwenn 0 and 7 σ.

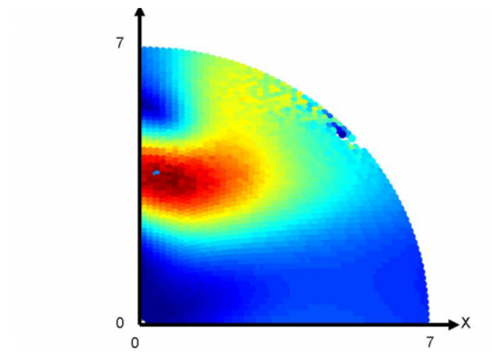


Figure 9: The Liaponov-exponent after 300.000 turns for a single LR-BB interaction at 3.5 σ in RHIC (blue: low, red: high).

OUTLOOK

Experiments in the SPS performed in 2004 showed promising results [4] for the wire compensation but raised several questions which need to be addressed in future experiments and in simulation. More detailed studies for RHIC including triplet-errors will be performed.

ACKNOWLEDGMENTS

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REFERENCES

[1] U. Dorda , "BBTrack, manual for the weak-strong tracking-code", http://ab-abp-bbtrack.web.cern.ch.

[2] Y. Papaphilippou and F. Zimmermann,"Weak-strong beam-beam simulations for the Large Hadron Collider", Physical review special topics (1999).

[3] J.-P. Koutchouk, G. Sterbini,"An early beam separation scheme for the LHC luminosity upgrade", EPAC 06.

[4] J.-P. Koutchouk, J. Wenninger, F. Zimmermann, "Experiments on LHC Long-Range Beam-Beam Compensation in the SPS"

[5] W. Fischer (BNL), U. Dorda, J.-P. Koutchouk, F. Zimmermann (CERN), J. Qiang (LBNL), T. Sen (Fermilab), J. Shi (KU), "Observation of the Long-range Beam-beam Effect in RHIC and Plans for Compensation", EPAC 06