Summary of the LARP Mini-Workshop on Beam-Beam Compensation 2007

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1.1.1 Introduction

The LARP Mini-Workshop on Beam-Beam Compensation 2007 was held at SLAC, 2-4 July 2007. It was attended by 33 participants from 10 institutions in Asia, Europe, and America. 26 presentations were given, while more than one third of the time was allocated to discussions. The workshop web site is Ref. [1]. The workshop's main focus was on long-range and head-on beam-beam compensation, with a view towards application in the LHC. Other topics included the beam-beam performance of previous, existing and future circular colliders; beam-beam simulations; new operating modes, theory, and unexplained phenomena.

1.1.2 Performance of circular colliders, simulations, theory

The expected LHC beam-beam performance was presented by F. Zimmermann, CERN. In the nominal LHC there will be 4 experiments. In 3 of them the beams collide head-on, at the fourth they are separated by 5 σ. In each of the four interaction regions the bunches also experience 30 long-range interactions. Half of these are at an average separation of 9.5 σ, and are expected to have a significant impact on the beam dynamics. The other half is expected to have little impact. To alleviate the impact of long-range interactions, the LHC beams collide under a crossing angle of approximately 300 µrad. This puts the LHC in a new operating regime for hadron colliders, where the long-range interactions lead to the emergence of a "diffusive aperture", namely a threshold in the betatron amplitude at which the transverse diffusion rate increases by orders of magnitude. The total beam-beam induced tune spread is expected to be 0.010-0.012 for the nominal beam paramters (25% of this is contributed from long-range interactions), and up to 0.015-0.017 for the ultimate beam parameters. In light of the new challenges, the operating experience of other colliders was reviewed.

The B-factories KEKB and PEP-II were presented by K. Ohmi, KEK. These machines have delivered record luminosities above 10^{34}cm^{-2}s^{-1}, and in both machines beam-beam effects are a dominant luminosity limit, typically leading to beam size blow-up. Beam-beam parameters of up to 0.132 have been reached in PEP-II, and up to 0.175 in KEKB. With such strong beam-beam interactions, the interplay with a number of other machine properties is important, such as working point (both machines operate near the half integer resonance), global linear optics errors, local optics errors at the IP, chromatic

optics errors, sources of noise, static and dynamic offsets at the IP, feedback noise, and electron clouds.

A. Valishev, FNAL, summarized the Tevatron beam-beam performance. In this machine long-range beam-beam effects at injection cause 5-10% proton beam loss. At store, long-range interactions had caused beam lifetime deterioration and emittance increases. These effects could be reduced in 2006 through the implementation of a new separation scheme ("helix"), leading to a 16% increase in luminosity lifetime. Currently the dominant beam-beam effects in stores are proton beam losses due to head-on interactions. The antiproton losses are almost entirely due to burn-off. The total beam-beam induced tune shift reached 0.026 for the antiprotons, and 0.016 for the protons. To increase the luminosity further, a working point near the half integer is considered, which does require a correction of the momentum dependency of the β-functions. Such a correction is also expected to be beneficial at the current working point.

In RHIC proton operation the total beam-beam induced tune spread reached 0.012, with 2 head-on collisions and no long-range interactions. (For heavy ions the beam-beam parameter is 2.5 times smaller.) With this about 10% of the luminosity decays exponentially with a lifetime of 0.3 h, the remainder has a lifetime of 12 h. A number of effects reduce the luminosity lifetime in conjunction with beam-beam effects. Nonlinear chromaticity induces a tune spread of approximately 0.003. A correction was implemented in 2007, but not yet tested with protons. 10 Hz triplet vibrations lead to offset modulations at the IP, for which an orbit feedback became operational in 2007. A modification of the triplet assemblies is under study to eliminate the 10 Hz vibrations at the source. A new 9 MHz rf system will become operational in 2008, allowing to match the proton bunches longitudinally at injection, leading to a smaller hour-glass effect (currently 23% at the beginning of stores). A new working point near the integer resonance will be tested in 2008, as presented by C. Montag, BNL. Simulations show a better dynamic aperture and a larger tolerance against tune errors. The implementation requires an improved orbit and beta-beat correction.

Simulations for hadron colliders are still challenging, since time scales of interest (hours) can still not easily be reached with large numbers of particles (tens of thousands) using a detailed model (like element-by-element with magnetic errors). A. Kabel, SLAC, pursued the question of what we can learn from beam-beam simulations in proton machines, with examples from his code PLIBB. The code had been developed to calculate beam lifetimes for the Tevatron. He concluded that the calculation of observable quantities may now be within reach. A. Valishev, FNAL, showed simulations that explain and predict beam-beam effects in the Tevatron, using the code LIFETRACK [2]. Problems investigated were the bunch-by-bunch variations (due to the PACMAN effect) in orbit, tune, emittance growth, and chromaticity, as well as the effect of different helix settings. For time scales up to 5 min, the code has been shown to have predictive power, for longer time scales less so. J. Qiang, LBNL, showed strong-strong simulations for RHIC and the LHC obtained with his code BeamBeam3D, including emittance growth rates for different beam separations, and tunes in RHIC, and emittance growth rates for mismatched and offset beams in the LHC.

K. Ohmi, KEK, discussed the recent experience with crab crossing in KEKB, the first time such a scheme has been used in a collider. The KEKB beams meet under an angle of 22 mrad, and strong-strong simulations suggest that the beam-beam parameter can be increased by a factor 2 with crab crossing. So far the crab cavities were shown to actually tilt the beams in the expected manner, and they were operated at beam currents up to 1.3 A for the positrons, and 0.7 A for the electrons, although no absolue luminosity increase has been obtained yet (the specific luminosity did increase by about 15%). An rf phase fluctuation of 20 s period was observed in high current operation, and only with colliding beam.

Y. Alexahin, FNAL, reviewed coherent effects in hadron colliders. These are well established in e^+e^--colliders but were not important in the SPS collider or the Tevatron in the past (the ISR had seen some coherent effects but with their continuous beams of very high current and small beam-beam parameter the ISR situation was quite different from today's hadron colliders in a number of ways). About a decade ago, Alexahin and Gareyte had raised the possibility of an instability arising because the coherent π-mode tune created through the strong-strong beam coupling lies outside the incoherent beam-beam spectrum. π-mode tunes were observed later in RHIC, although only with an external excitation. Coherent beam-beam coupling lowered the TMCI threshold in LEP, and it leads to instability at low chromaticities in the Tevatron and RHIC. A number of suppression mechanisms were proposed including a break in the symmetry, and active damping.

Y.Cai, SLAC, presented unexplained phenomena in lepton machines. For example, currently it is not understood why the beam-beam parameter can be increased near the half integer working point to the values that have been observed. Some bunches, typically at the beginning of a PEP-II train "flipped" and were found to have very short lifetimes. The achieved vertical beam-beam parameter follows approximately a $\lambda^{-0.4}$ scaling, where λ is the damping decrements. While single bunch effects are generally well understood with simulations, this is less so with multiple bunches and in the presence of one or several other strong effects (such as ions, electron clouds, or other nonlinearities).

T. Pieloni, CERN and EPFL Lausanne, showed tune spectra calculated for the LHC, using COMBI. These are computed to predict bunch-by-bunch differences, and investigate beam-beam effects for different operational scenarios. In RHIC tune spectra were measured with colliding proton bunches, and compared to the calculated spectra. Taking into account that the RHIC BTFs are currently measuring predominantly the most intense bunches (i.e. bunches with only 1 head-on collision instead of 2 for most of the bunches), a good agreement for both the total tune spread, and the number of peaks in the spectrum was found.

1.1.3   Long-range beam-beam compensation

Long-range beam-beam interactions are important in the Tevatron (70 per turn, distributed), and the LHC (30 per IR, localized). In RHIC there are nominally no long-range beam-beam interactions at store, but up to 12 can be generated for machine

experiments. Long-range interactions, in conjunction with other effects, have also limited the performance of e$^+$e$^-$ colliders such as DAΦNE (24 in main IR), KEKB (4 in IR), and PEP II (2 in IR). General strategies to mitigate the effect of long-range beam-beam interactions are a reduction of their number, or and increase in the beam separation. This can be done with early separation schemes using dipoles (as in RHIC, or an LHC upgrade scheme proposed by J.-P. Koutchouk and G. Sterbini, CERN), or via larger crossing angles. Another way to reduce long-range beam-beam effects is to compensate the field of the opposite beam by a magnetic field of opposite sign, that can be generated with either an electron beam (proposed for the Tevatron by V. Shiltsev) or a wire (proposed for the LHC by J.-P. Koutchouk). Such a compensation scheme appears to be practical only if the long-range interactions are localized around an IR, and a location for a compensator can be found with a phase advance only a few degrees away from the average betatron phase of the nearby long-range interactions. Space for long-range wire compensators is reserved in the LHC, and the compensation was shown to increase the dynamic aperture by about 2 σ both for the nominal LHC and for a possible upgrade, as shown by U. Dorda, CERN. A number of other important tests have been made so far.

Two wires were installed next to each other in the SPS in 2002 for beam test. Three types of signal were used in previous experiments: beam lifetime and background, final emittance, and scraper retraction. The beam lifetime scales with the 5th power of the distance between beam and wire. In 2004 two new movable units with three wires each were installed, only 2.6° away in betatron phase from the single-wire units, which is the same phase advance as between long-range collisions and wire in the LHC, to test the efficiency of the compensation, and different crossing schemes by means of two wires. Open questions from these tests were shown by F. Zimmermann, CERN. These include the scaling from the SPS to the LHC, discrepancies between measured and simulated dynamic aperture and beam lifetime, the breakdown of the 2-wire compensation at certain tunes, and the lifetime scaling with the wire distance to the beam (this is found to be different for the SPS, Tevatron and RHIC). Some of the SPS measurements were affected by the relatively short beam lifetime, which is only 5-10 min at 26 GeV/c.

In the e$^+$e$^-$-collider DAΦNE the beam and luminosity lifetime could be improved with a combination of octupoles and long-range wire compensator, as shown by C. Milardi, LNF-INFN. This is the first time that long-range beam-beam compensation was demonstrated in an operating collider. In DAΦNE there are 24 long-range beam-beam interactions in the main IR. The compensating wires, built and installed in 2005, are outside the vacuum chamber, in-between the two beams, 4.9 m from the IP, and allow for a partial compensation of the long-range interactions. The observed beam lifetime improvements could be reproduced with the code LIFETRACK [2]. In the future a new vacuum chamber will be installed in the interaction region, by which all but two long-range interactions will be eliminated.

In RHIC there are nominally no long-range interactions in store, but up to 12 per turn can be generated for accelerator experiments. In the last two years the effect of a single long-range interaction was tested at injection and at store, where it was found that distances as small as 4 σ at store are needed to create visible beam losses under normal operating conditions. Last year, a vertically movable wire with an integrated strength of

up to 125 A·m was installed in each of the RHIC rings. The experiments this year, presented by N. Abreu, BNL, measured loss rates of Au beams at 100 GeV/nucleon as a function of wire current and distance to the beam. The RHIC measurements complement the earlier SPS measurements, with the beam conditions of an actual collider ring and a good base beam lifetime. Simulations of the RHIC were done by U. Dorda, CERN, H.J. Kim and T. Sen, FNAL, and A. Kabel, SLAC. These aim to reproduce general features of the measured data, such as the onset of increased beam losses at certain wire distances and strengths. In some cases, a remarkably good agreement has been found but the simulation work is still ongoing. For next year, it is planned to test the compensation of a single long-range beam-beam interaction in RHIC with proton beams. In the LHC different bunches have different long-range interactions, and an optimum compensation requires that the wire current changes from bunch-to-bunch. This is technically challenging, and was discussed by U. Dorda, CERN.

1.1.4   Head-on beam-beam compensation

The compensation of the head-on beam-beam effect can only be done with an electron beam that creates the same amplitude dependent force like the opposite beam, which typically has an approximately Gaussian profile.

A head-on compensation scheme was tested in DCI [3] with four beams (two e^+ and two e^- beams). However, due to coherent beam-beam effects, the space-charge compensation of the beam-beam effect did not work as expected. In hadron colliders, with much smaller beam-beam parameters, such strong coherent effects are not expected to be a problem. Head-on beam-beam compensation had been proposed for the SSC by E. Tsyganov, now at UT Southwestern, and his co-workers. E. Tsyganov reviewed this work at the workshop.

W. Scandale and F. Zimmermann, CERN, presented the possible LHC luminosity gain from an electron lens. Together with an injector upgrade an electron lens may be able to double the beam brightness under collision conditions. For the LHC ultimate beam parameters, and assuming no increase in the total beam intensity, this would result in 20% more average luminosity since the initial luminosity lifetime with head-on compensation would be only 7 h, half of the lifetime without the compensation. Head-on compensation would yield larger gains if the ultimate beam parameters had not yet been reached.

Much progress has been made with operating electron lenses in the Tevatron, presented by V. Kamerdzhiev, FNAL. The 2 Tevatron electron lenses were used for the compensation of beam-beam effects of colliding antiproton and, recently, in proton beams with energies of 980 GeV. They have been shown to improve the proton beam lifetime by us much as a factor of 2.3 under operating conditions. The compensation effect was most prominent in a few bunches (3-6 out of 36 total) having the largest tune shifts due to the PACMAN effect. Although this compensation is mostly due a fast tune shift, not a reduction in the tune spread needed for head-on compensation, it shows that electron lenses can improve the performance of an actual collider without creating emittance growth or other harmful effects for the beam.

At RHIC an effort has started, presented by Y. Luo, BNL, to investigate the benefits of an electron lens in simulations, and to define the hardware parameters of an electron lens, taking advantage of the EBIS [4] technology. The simulations aim to show by how much the beam-beam parameter can be increased with an electron lens. It is planned to conclude the simulation effort in about a year. With a positive outcome, a decision could be made for the construction of an electron lens at RHIC, which would then also become a test bed for such a device in the LHC.

The possible uses of electron lenses in the LHC were explored in more detail by V. Shiltsev, FNAL. Not only could these lenses be used as a head-on beam-beam compensator, potentially doubling the luminosity, they could also be used to create a stabilizing tune spread if needed, as a soft hollow collimator, and as a soft beam conditioner eliminating satellite bunches. By now a task has been created within LARP to investigate the configuration details of electron lenses, and to define the main parameters for possible electron lenses in the LHC.

1.1.5   References

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