PROGRESS WITH LONG-RANGE BEAM-BEAM COMPENSATION STUDIES FOR HIGH LUMINOSITY LHC*

A. Rossi, O. Aberle, J. Albertone, A. Barnyakov†, A. Bertarelli, C. Boccard, F. Carra, G. Cattenoz, Y. Delaup, S. Fartoukh, M. Fitterer††, G. Gobbi, J. Lendaro, A. Levichev†, D. Nikiforov†, Y. Papaphilippou, A. Patapenka††, D. Perini, S. Redaelli, H. Schmickler, G. Stancari††, A. Valishev††, C. Zanoni, CERN, Geneva, Switzerland

† Budker Institute of Nuclear Physics, Novosibirsk, Russia

†† Fermi National Accelerator Laboratory, Batavia IL, USA

Abstract

Long-range beam-beam (LRBB) interactions can be a source of emittance growth and beam losses in the LHC during physics and will become even more relevant with the smaller β* and higher bunch intensities foreseen for the High Luminosity LHC upgrade (HL-LHC), in particular if operated without crab cavities. Both beam losses and emittance growth could be mitigated by compensating the non-linear LRBB kick with a correctly placed current carrying wire. Such a compensation scheme is currently being studied in the LHC through a demonstration test using current-bearing wires embedded into collimator jaws, installed either side of the high luminosity interaction regions. For HL-LHC two options are considered, a current-bearing wire as for the demonstrator, or electron lenses, as the ideal distance between the particle beam and compensating current may be too small to allow the use of solid materials. This paper reports on the ongoing activities for both options, covering the progress of the wire-in-jaw collimators, the foreseen LRBB experiments at the LHC, and first considerations for the design of the electron lenses to ultimately replace material wires for HL-LHC.

INTRODUCTION

Parasitic beam-beam encounters in the interaction regions, called Long-Range Beam-Beam interactions, have been recognised to have significant adverse effects on the beam in high intensity accelerators like the CERN LHC and HL-LHC [1]. Alternating the crossing plane in the two low-beta collision points only compensates for the linear part of these interactions. At LHC and HL-LHC, the remaining non-linear long-range kick still leads to a decrease of dynamic aperture down to ~ 6σ [1], [2], [3], [4], entailing a degradation of the beam lifetime and ultimately machine performance. A simple method to correct both linear and non-linear perturbations was proposed in [5], using the electro-magnetic field of a current carrying wire placed at a specific distance from the beam. A first demonstration of the concept was performed in the CERN SPS from 2002 to 2012 [6] using two 'wire' compensators, one to perturb and the other to correct. Although this did not directly demonstrate LRBB compensation, the results obtained confirmed simulations, suggesting that wire compensators could significantly increase the operational flexibility and performance of the LHC. As the BBLR compensation is an integral part of an HL-LHC alternative scenario with flat optics [7], [8] it was essential to pursue the study in the LHC itself with wire-in-jaw collimators, installed around the CMS (2017) and ATLAS (2018) experiments, to directly demonstrate compensation [5], [9], [10]. This paper presents the progress with the LHC demonstrator tests to be performed in 2017 and gives an outlook for possible further installations in 2018. It also shows some preliminary results of investigations for HL-LHC, where electron beams are being studied as a replacement for current carrying wires.

WIRE COMPENSATION IN THE LHC

It has been shown in numerical simulations that LRBB effects can be mitigated using wires [5], [10]. In order to correct all driving terms, the compensation has to be performed locally and symmetrically left and right of the collision points, in the plane of crossing. The current should correspond to the average current of all bunches undergoing long-range interactions, equivalent to 100A for LHC, and 200A for HL-LHC [10]. Inherent to the optics, the best location to place the wires are where the beam β-function has an aspect ratio $\beta_{x(y)}/\beta_{y(x)}$=1.8 for LHC, and 2 for HL-LHC. The left and right wires should be at a normalized distance 15-20% larger (or smaller) than the crossing angle for the wire on the side of the smallest (or largest) beta [11]. For the LHC demonstrator tests the wire is embedded in a collimator jaw (see Figure 2), the only object able to approach close to the intense LHC bunches. Suitable locations could be found in IR5 (CMS) by replacing existing tertiary (TCT) and physics debris (TCL4) collimators, where β_x/β_y=1.41 and 0.7 respectively for the optics foreseen for 2017 run [7].

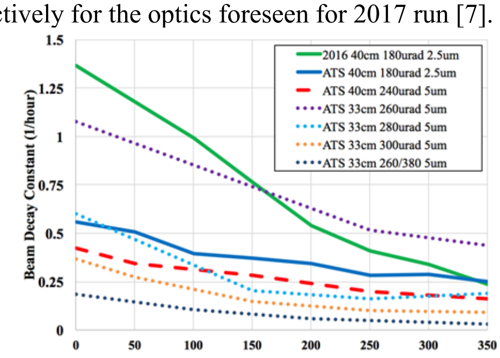

Figure 1: Impact of 2 wires on lifetime with left collimator jaw at 6 collimation σ (ε = 3.5µm.rad), as a function of optics, crossing angle and emittance [12].

* Research supported by the HL-LHC project.

ISBN 978-3-95450-182-3

The wires can thereby approach the beam in the crossing plane and bear a high current (design value of 350A). Nevertheless, due to mechanical constraints, the distance of the center of the wire to the surface of the jaw is 3 mm (see Figure 3), i.e. 5 to 8 beam σ depending on the collimator, limiting the minimum wire-beam separation. In this configuration, using a large emittance bunch (ε = 5μm.rad) to probe the long-range beam-beam interactions from a train of nominal bunches, simulations show that wire compensation of the octupolar driving term can be clearly demonstrated by measuring the beam lifetime at various crossing angles [12] (Figure 1).

In IR1 (ATLAS) the crossing is vertical, while the TCL collimators are horizontal. Since the closest available slot for a vertical wire, behind Q4, would have a defavourable β-function aspect ratio, it was decided [13] to postpone the installation in IR1.

WIRE-IN-JAW COLLIMATORS

Wire-in-jaw collimators have a tungsten jaw into which a copper wire with a thin silicon dioxide insulator is embedded [13], [14]. These wires can be placed parallel to the beam at variable distances (accuracy ~ 20 μm), and can carry high current (up to 350 A).

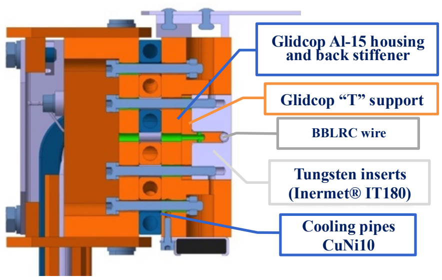

Figure 2: Section view of a TCTW collimator.

Thermo-Mechanical Analysis

The design main challenge was to embed an electrical wire in a jaw while maintaining the complete machine protection and beam cleaning functionality of the tertiary collimator. When the wire is powered at 378 A (slightly higher than the specified maximum of 350 A), the thermal load generated by the Joule effect and absorbed by the jaw is ~ 1 kW. For comparison, the thermal losses on a jaw induced by the beam shower intercepted are estimated to be < 0.4 kW. In order to evacuate the 1 kW load, the wire is brazed to a Glidcop "T" shaped support (see Figure 2), minimizing the thermal resistance between the wire and the cooling pipes. The tungsten block is in turn pressed against the Glidcop support by means of screws. A small gap (0.1 mm) between the wire and the tungsten insert avoids the generation of stresses by Hertz contact on the insert (Figure 3). Outside the collimator jaw, the wire diameter is increased from 2.48 to 3.45 mm to decrease the Joule losses. To assess the behaviour of the collimator in operation, temperatures, stresses and deformations reached in the jaw with a 350 A wire current were estimated, and a beam impact scenario (asynchronous beam dump) was analysed. At 350 A, with nominal water cooling in the jaw, a maximum wire temperature of 260°C is reached (Fig. 4) leading to a predicted thermally-induced deflection of 150 μm. The rest of the jaw remains at the cooling water temperature of ~27°C. In the case of direct beam impact, the threshold of plastic deformation for the jaw occurs for a proton bunch intensity of 5.10^9. This is the same as for a standard tertiary collimator, showing that robustness is not compromised.

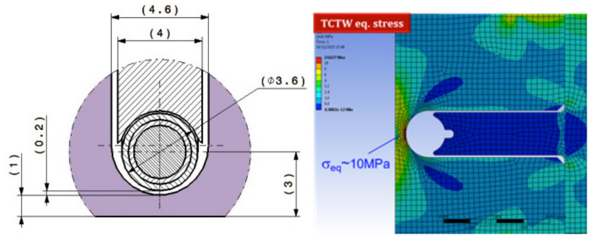

Figure 3: Mechanical analysis of the assembly of the tungsten block and Glidcop support.

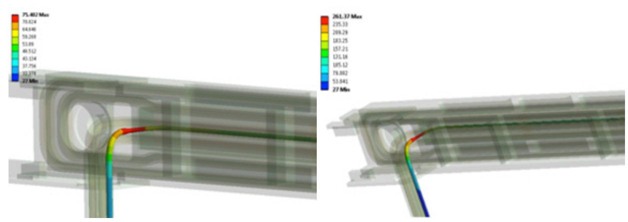

Figure 4: Wire temperature profile at 200 A (right hand side, with maximum ~75°C) and 350 A (left hand side, with maximum ~260°C) estimated with active cooling.

Tests on a Wire-in-Jaw Prototype

A full jaw prototype has been tested under high vacuum (1×10^{-9} mbar), with current up to 350 A to bechmark the thermo-mechanical analysis. Additional temperature sensors were added to the standard jaw sensors to measure portions of the wire exiting the jaw and not actively cooled. When the jaw and wire are cooled (Figure 5), the hottest point of the wire is measured close to the elbow where the wire exits the collimator block, as was also found in simulations. It should be noted that the cooling circuit used during the tests was under-dimensioned, with the water outlet ~ 20°C warmer than the inlet. Up to 200 A the measurements compare very

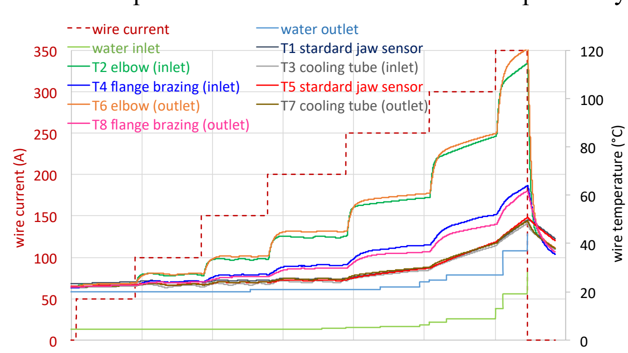

Figure 5: Temperature evolution along the wire with current ramped up to 350 A.

ISBN 978-3-95450-182-3

well to values found in the simulations, while for higher currents, due to the limited cooling power, the temperature does not reach steady state.

FIRST INVESTIGATIONS OF ELECTRON BEAMS FOR LRBB COMPENSATION IN HL-LHC

The feasibility of replacing the solid wires with electron beams [15] for LRBB compensation in the HL-LHC is currently under study. So-called "electron-lenses" are magnetically confined, low-energy electron beams, with electromagnetic fields that can affect the circulating proton (or ion) beam. Such an 'electron wire' would provide a non-material wire that could approach the circulating proton beam without the possibility of damage or excessive beam loss. Space for such structures has been reserved in the HL-LHC layout at locations where the β-function aspect ratios are close to 2 and 0.5, between the Q4 and Q5 matching quadrupoles (at ~190 m from the interaction points). Here the proton beam β-function is ≈ 500 m, corresponding to a σ of 0.4 mm (at nominal emittance ε = 2.5 μm.rad). This translates in a required transverse distance of the wire with respect to the circulating beam (~10 σ [10]) of the order of 4 mm. To avoid overlapping with the circulating proton beam, the electron beam must therefore be confined to a transverse size of 1 to 2 mm. For a bunch intensity of $N_p = 2.2\times10^{11}$ protons [16] each LRBB interaction corresponds to an equivalent current of 10.56 Am [10]. This would lead to an integrated current of ~ 200 Am for each of the two wires, assuming 19 LRBB interactions. Co-propagating electrons (as needed for compensation) travelling at a velocity $\beta_e = v_e/c$ produce a kick which is amplified by the factor $(1+\beta_p\beta_e)/\beta_p\beta_e$, where the proton velocity $\beta_p \approx 1$ and electron velocity β_e is 0.28 to 0.31 for reasonable accelerating potentials (20 to 25 kV).

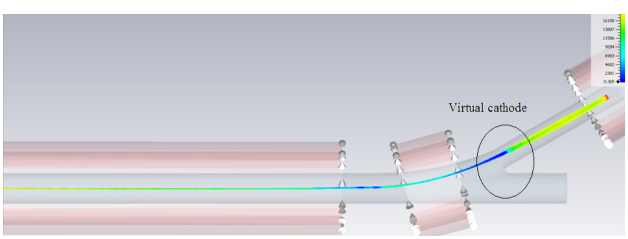

Figure 5: Potential of 20 A electron beam initially accelerated to 25 kV. A virtual cathode is formed as the electron beam is compressed

To obtain the equivalent of 200Am therefore implies an electron current of 15 - 20 A over a length of 3 - 5 m per lens. This corresponds to a very high-density beam, largely dominated by space charge effects, which needs to be confined by high solenoid fields. The ultimate value of the magnetic field of the main solenoid will depend on how small a beam can be produced at the cathode, which will then be magnetically compressed by a factor $f = \sqrt{B_{main}/B_{cathode}}$ to the required size (where B_{main} and $B_{cathode}$ are the magnetic field in the main and cathode solenoids respectively). At present the largest current density achieved at a cathode surface is ~15 A/cm^2 [17], [18], [19].

First feasibility studies on such systems were performed using a geometry designed for a hollow electron lens, foreseen for collimation [20]. A cathode size of 1 cm^2 was assumed, with B_{main} = 5 T and $B_{cathode}$ = 0.2 T (f = 5). With compression, the electron beam potential decreases, and if the initial potential is not large enough, a 'virtual cathode' (= 0 V in Figure 5) can be generated, causing the electrons to be reflected backwards. The minimum initial potential (U_{anode}) depends on the electron current and the beam perveance. For an infinitely long tube and a ratio between the vacuum chamber radius and the electron beam radius R_t/R_b, the perveance can be expressed as [20], [21], [22]: $P_t = \frac{\sqrt{2e/m}}{3\sqrt{3}}\frac{4\pi\varepsilon_0}{\ln R_t/R_b}$. From simulations it was found that for a 80 mm diameter vacuum chamber, $U_{anode} \geq 35$ kV is required. At U_{anode} = 35 kV, the average energy at the main solenoid is estimated to be ~20 keV (Figure 6). The actual size of the electron beam is found to be 2.5 × 3 mm with a distortion observed due to effect of the large opening at the intersection between the electron injection line and proton beam line. One solution (shown in Figure 6) is to add a longer taper to the electron injection line.

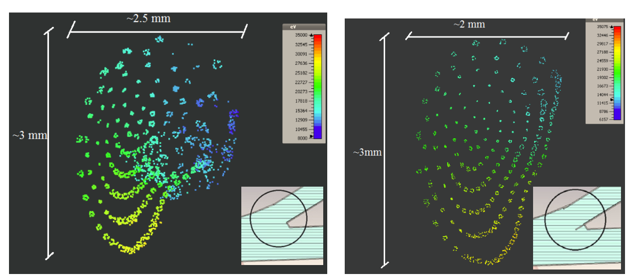

Figure 6: Transverse electron profile for a 20A - 35 kV source. The radial energy distribution and transverse dimensions are shown for 2 different pipe geometries.

CONCLUSIONS

Long Range Beam-Beam interactions can be mitigated by compensating with a correctly positioned and dimensioned current carrying wire or an electron beam. Wire-in-jaw collimators with this purpose in mind have been designed, tested and installed in the LHC left and right of IR5. Simulations show that improvements in beam lifetime should be observed during machine tests foreseen for 2017, hopefully confirming for the first time the ability of such schemes to enhance machine performance by allowing a reduction in the crossing angle for long-range beam-beam limited machines.

Investigations are also underway to replace current carrying wires with electron beams for HL-LHC. Further studies are required to find the optimal configuration, minimise the required electron current, and check the effect of electron beam size, asymmetries and imperfections on the proton beam.

REFERENCES

[1] D. Neuffer, S. Peggs, SSC-63 (1986); W. Herr, CERN/SL/90-06 (AP) (1990).

[2] *Proceedings of the Workshop on Beam-Beam Effects in Large Hadron Colliders—LHC99*, Geneva, Switzerland 1999, edited by J. Poole and F. Zimmermann (CERN Report No. CERN-SL-99-039-AP 1999).

[3] Y. Papaphilippou and F. Zimmermann, "Weak-strong beam-beam simulations for the Large Hadron Collider", in *Phys. Rev. ST Accel. Beams 2, 104001 (1999).*

[4] Y. Papaphilippou and F. Zimmermann, "Estimates of diffusion due to long-range beam-beam collisions", in *Phys. Rev. ST Accel. Beams 5, 074001 (2002).*

[5] J.-P. Koutchouk, CERN-LHC-Project-Note 223 (2000); Proc. PAC2001, Chicago, p. 1681 (2001).

[6] F. Zimmermann, "10 years of wire excitation experiments in the CERN SPS", in *Contribution to the ICFA Mini-Workshop on Beam-Beam Effects in Hadron Colliders*, CERN, Geneva, Switzerland, 18-22 Mar 2013, CERN Yellow Report CERN-2014-004, pp.153-166.

[7] S. Fartoukh, "An Achromatic Telescope Squeezing (ATS) scheme for LHC upgrade", *Proceedings of the 2nd International Particle Accelerator Conference, San Sebastiáán, Spain* (EPS-AG, Spain, 2011), p. 2088.

[8] S. Fartoukh et al, "An alternative High Luminosity LHC with Flat Optics and Long-Range Beam-Beam Compensation", *Proceedings of the International Particle Accelerator Conference* (Richmond, VA, USA, 2015), p. 2199.

[9] F. Zimmermann, "Weak-Strong Simulation Studies for the LHC Long-Range Beam-Beam Compensation", CERN-LHC-project-report-502 (2004).

[10] S. Fartoukh et al, "Compensation of the long-range beam-beam interactions as a path towards new configurations for the high luminosity LHC" in *Phys. Rev. ST Accel. Beams 18, 121001 (2015).*

[11] S. Fartoukh, "Potential of wire compensation for (HL-)LHC & Optimal optics and hardware conditions" presented at the *2nd Workshop on Wire LRBB, Divonne, France,* 20 Mar 2017.

[12] A. Valishev et al, "Simulation of LRBB Impact on Lifetime" presented at the *2nd Workshop on Wire LRBB*, Divonne, France, 20 Mar 2017 and *LARP CM28/HiLumi meeting, Napa, CA*, 23-26 Apr 2017.

[13] *2nd Workshop on Wire LRBB, Divonne, France,* 20 Mar 2017, `https://indico.cern.ch/event/615088/`.

[14] A. Dallocchio et al., "Collimators with embedded beam position monitors: A new advanced mechanical design", in *Proceedings to IPAC2011.*

[15] V.D. Shiltsev, "Electron Lenses for Super-Colliders", Springer ed. 2016, ISNB 978-1-4939-3317-4, DOI 10.1007/978-1-4939-3317-4.

[16] L. Rossi, in *Proceedings of the 2nd International Particle Accelerator Conference, San Sebastiáán, Spain* (EPS-AG, Spain, 2011), p. 908.

[17] G.I. Kuznetsov, "High temperature cathodes for high current density", Nuclear Instruments and Methods in Physics Research A340 (1994) 204-208.

[18] G.I. Kuznetsov, "IrCe Cathodes For EBIS", Journal of Physics: Conference Series 2 (2004) 35–41.

[19] Y. Wang et al., "Development of High Current-Density Cathodes With Scandia-Doped Tungsten Powders", IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 54, NO. 5, MAY 2007.

[20] C. Zanoni and D. Perini, "Preliminary Design Study of the Hollow Electron Lens for LHC" CERN-ACC-NOTE-2017-0004.

[21] A. Haeff, "Instability of beams of charged particles in a Plasma", PIRE 27, 586 (1939).

[22] M. V. Nezlin. 1971, Sov. Phys. Usp. 13, 608.

ISBN 978-3-95450-182-3