TESLA LINAC-IP SIMULATIONS

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Abstract

In order to asses the luminosity performance of the TESLA linear collider, an integrated simulation environment has been set up to perform multi-bunch tracking through the linac and Beam Delivery System (BDS) and including the beam-beam interaction at the IP. Ground motion is combated through IP position and angle fast feedback systems. The importance of a luminosity tuning system based on the optimisation of the angle and IP feedback parameters using a fast signal from the beamstraahlung monitor is shown. The simulation environment consists of: PLACET for the linac, MatMerlin for the BDS and GUINEA-PIG for the beam-beam interaction all run in Matlab with a Simulink model for the fast feedback systems. Due to the amount of CPU time required, the simulation is deployed on the Queen Mary High Throughput computer cluster where up to 100 seeds can be run simultaneously.

INTRODUCTION

Luminosity loss at Tesla [1] occurs through natural and man-made sources of ground motion through the relative motion of magnetic elements. This occurs through the emittance growth of the beams and through the resulting misalignment of the colliding beams at the Interaction Point (IP). Due to the strongly non-linear behaviour of the interacting beams, the luminosity loss calculation is not straightforward and requires the use of tracking models to simulate the passage of the beam through the accelerator and to simulate the beam-beam interaction itself. This allows for effects such as systematic bunch-shape distortions ('banana bunches') caused by short-range wakefield effects in the accelerating structures to be taken into account. This effect only causes emittance growths at the 1-2 percent level, but due to the complexity of the beam interaction, has been shown [2] to lead to up to a third loss in luminosity if not specifically taken into account. The banana-bunch beam leads to a change in the optimal set-up of any intra-train feedback system, so there is a strong link between the modelling of how these bunches form and the ultimate luminosity performance of the collider.

The aim of this research then is to set up a simulation environment which models in detail the multi-bunch transport of the beam from the start of the linac through to the IP. This should include wakefield effects, so that the operation of the feedback systems that null the effects of ground motions can be studied in detail and an accurate assessment of the luminosity performance of the Linear Collider (LC) can be made. The simulation detailed in this report is of the Tesla LC as detailed in the Tesla TDR[1].

TESLA FAST-FEEDBACK AND LUMINOSITY OPTIMISATION SYSTEMS

Luminosity rapidly drops off at Tesla as the beams become misaligned through the relative motion of magnets as a result of ground motion. The most sensitive magnetic elements in the machine to this effect are the final focussing quadrupoles where a 1-1 correspondence exists between their vertical position and the vertical position of the beam due to the parallel-to-point focussing. This implies an extremely tight nm-scale tolerance on these elements. The slower classical feedback systems in use to control the beam orbit cannot address ground motion above approximately the 1 Hz level. To combat the effects of ground motion at smaller timescales, fast-feedback systems are to be employed that operate within the timescale of a single bunch train. In the interaction region to null the vertical beam offsets, an IP fast-feedback is envisioned that comprises of a stripline beam position monitor (BPM) and a stripline kicker. At Tesla it is possible to read out the BPM, digitally process this signal and calculate a feedback response and to kick the next bunch that comes along (337 ns later). The beam size near the IP is far too small for a BPM to directly measure the incoming offset to a useful level. Fortunately, due to the huge fields at the IP where the beams collide, very small offsets of the order of 0.1nm or more lead to substantial angular kicks of 10s-100s of μrads. This enables the feedback algorithm to calculate the beam offset and formulate a correction signal based on a signal produced from the outgoing beam in a BPM a few metres downstream of the IP.

In addition to the effects of a vertical position offset at the IP, problems arise if a vertical angular offset (significant compared to the IP angular divergence (12.5μrad)) exists. This leads to a drop in luminosity although not as pronounced as the position offset effect. It also leads to an additional component of the beam-beam kick that confuses the position feedback leading to an incorrect correction being applied. For the angle feedback, a BPM-kicker system is used upstream where the beta functions are larger. The BPM is placed at a point 400m upstream from the IP, and three 1m stripline kickers a further 450m upstream from that (90 degrees apart in phase). Here, a 2μm resolution BPM is required to correct the angle at the IP to the 0.1 $\sigma_{y'}$ level and the system has a 10-bunch latency. The maximum kick that can be applied corresponds to a 10 $\sigma_{y'}$ correction at the IP. Simulations of the worst expected ground motion case indicate the maximum correction required will be approximately 3 $\sigma_{y'}$ at the IP.

Short-range wakefield effects of bunches passing through accelerating cavities offset from the centre causes systematic distortions in the y-z bunch shape (so called 'banana' bunches). Such effects change the behaviour of the beam-beam interaction. Figure 1 shows luminosity as a function of y and y' offset for an example 'banana' bunch. For a perfect Gaussian shape, the maximum luminosity curve would be a straight line through the origin. With banana bunches, the luminosity is maximised at a non-zero position and/or angle offset. The beam-beam kick behaviour is also changed- a zero beam-beam kick no longer corresponds to a zero offset. The coloured ellipse in figure 2 shows the approximate region where the IP and angle feedback systems naturally settle- i.e. with a zero angle, but a finite position offset which the zero beam-beam kick corresponds to (fortunately always slightly in the direction of maximum luminosity). To get the maximum possible luminosity, a luminosity feedback is used to scan in position and angle around this point. The Tesla fast beam calorimeter provides bunch-by-bunch signals of the integrated energy from electron-positron pairs produced in the beam interaction, which is approximately proportional to luminosity.

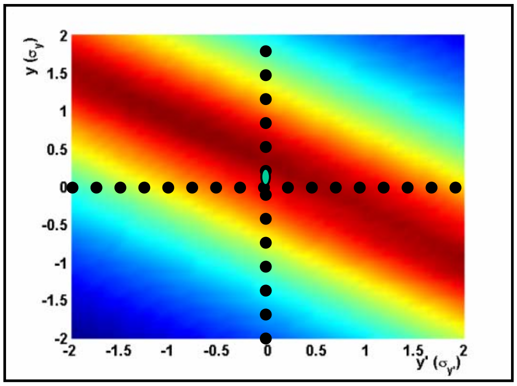

Figure 1: Luminosity as a function of vertical angle and position offset. The ellipse shows the position found by the fast feedback systems.

SIMULATION ENVIRONMENT

The Tesla bunch train consists of 2820 bunches, in this simulation the first 500 only are modelled. This is enough to investigate the full kinematics of the intra-bunch feedback systems and to use the tail end of the simulated part of the train to be representative of the other 2320 bunches. This bunch train is tracked through the 14.4 km Tesla Linac with PLACET [3] including short and long range wakefield effects in the 10,292 9-cell accelerating cavities. Two different seed sets are used to simulate the electron and positron linacs. Each bunch in PLACET is represented as 31 longitudinal slices; each slice is represented as 11 different energies to model the energy spread of the bunch. A 'typical' bunch train is produced by misaligning the linac structures and BPMs relative to the quadrupole magnets to that expected after beam-based alignment has been performed. RMS errors for the structures are 500 μm in y and 300 μrad in y'. The BPMs are given a 25 μm RMS offset in y. Only the y axis is perturbed in this simulation as this axis is the most sensitive to ground motion effects due to the 100-1 aspect ratio of the beam at the IP. A 1-1 steering algorithm is then applied to the lattice where each quadrupole is moved to centre the beam in each accelerating structure BPM. 100 different seeds of (single) bunches tracked through the generated lattices are generated. Seeds that correspond to approximately 50% emittance growths through the linac are chosen for the full simulation which correspond to the nominal Tesla luminosity with a perfectly aligned BDS. RMS vertical jitter is then added to the quadrupole magnets to simulate fast (inter-train) ground motion.

Each bunch is then binned into 80,000 macro-particles for input into MatMerlin [4], which treats the BDS by ray-tracing the macro-particles through this section of the LC. Within the BDS simulation, 1.4ppm energy spread is added to the electron beam to simulate passage through the undulator used for positron production. RMS vertical jitter is also added to the BDS quadrupole magnets to simulate fast ground motion.

Finally, the bunches are passed to GUINEA-PIG [5], which simulates the beam-beam interaction and provides luminosity information in addition to the beam-beam kick and various background products including electron-positron pairs.

The full simulation is run in Matlab, which handles the calls to PLACET and MatMerlin and contains all the simulation parameters. The fast feedback systems are implemented using a Simulink model which includes both IP and angle fast feedbacks. The feedback algorithm is implemented as a PI controller, programmed to give a fast response with good noise rejection to maintain position and angle collisions to within 0.1σ of the desired value. Errors in the feedback systems enter through the resolution limits of the BPMs used and the field stability of the stripline kicker(s). BPM resolutions of 5,2 μm for the IP, angle BPMs were assumed and a 0.1% field stability for the kicker was used. It models the luminosity optimisation system using e^+e^- pairs generated with the GUINEA-PIG simulation. It tracks the pairs produced through the magnetic field of the detector solenoid, and counts the number of hits passing an area where the beamcal is. This forms the signal to be used for the luminosity optimisation.

To investigate the effects of ground motion and different machine configurations etc. the Queen Mary High Throughput Cluster [6] is used. This allows up to 100 simultaneous seeds to be run on the cluster of P4 2.8 GHz Xeon processors running linux.

PRELIMINARY RESULTS

Figure 2 shows the response of the IP fast feedback system to the incoming beam for 1 modelled seed. It can be seen how the feedback quickly brings the beams into alignment within the first ~10 bunch crossings. It then keeps the beams at the offset corresponding to a zero beam-beam kick. The inset plot shows how, after 150 bunches the luminosity feedback system ramps one beam past the other and looks for a peak in the e^+e^- production rate; the offset corresponding to this peak is then fed as a set-point into the feedback control algorithm.

The response of the angle fast feedback is shown in figure 3. It is noted that the beam is very noisy for the first ~150 bunches which corresponds to the HOM damping time in the accelerating cavities. This is the reason for performing the position scan at the 150-bunch point. The angle feedback behaves in a similar fashion to the IP feedback, with the luminosity scan performed at the 290-bunch point after the position scan is complete.

Figure 4 shows the luminosity for this seed as a function of bunch number in the train. The luminosity estimate for this seed would be calculated as a sum of these 500 bunches with the last 50 bunches being weighted to account for the rest of the 2320 bunches in the Tesla train.

As a test of the multiple-seed production system, figure 5 shows a luminosity histogram of 50 seeds for 3 different machine configurations. For the purpose of speed for this report, the HOMs in the linac were switched off for this run. Switching off this effect allows steering to be done in single bunch mode and provides a good estimate of the luminosity performance. In future, the full and proper treatment of multi-bunch steering with HOMs on will be applied. The 3 cases shown in figure 7 show the luminosity performance with no ground motion, an expected level of fast ground motion and that with an additional injection error into the linac from the damping ring. The system recovers luminosity well, with a mean loss of 8% luminosity in the worst of the simulated cases.

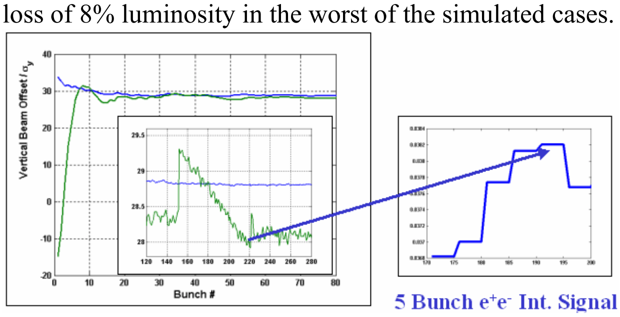

Figure 2: Vertical beam position at the IP in units of the vertical beam spot size (blue electron, green positron). Integrated electron-positron pair signal shown for corresponding beam scan by luminosity feedback system.

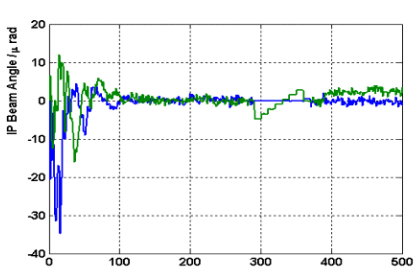

Figure 3: Vertical angle of beams at IP (blue electron, green positron).

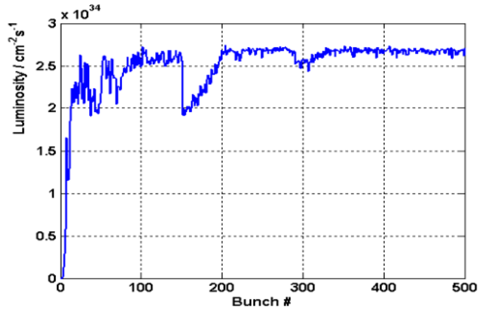

Figure 4: Luminosity as a function of bunch number in train.

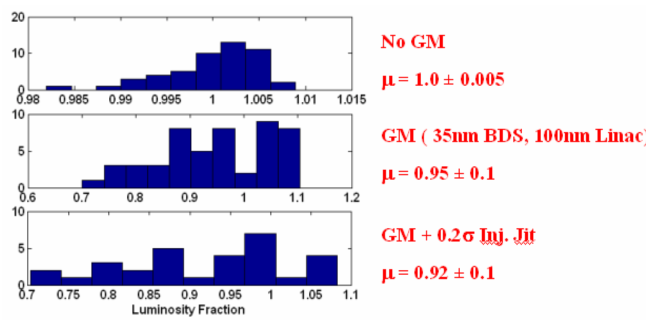

Figure 5: Luminosity histograms for different cases of ground motion and linac injection errors.

SUMMARY

An integrated simulation environment has now been set-up to examine the performance of the Tesla collider in the presence of fast ground motion. An example of the simulation environment examining the luminosity performance of the fast feedback systems has been shown. Work is now ongoing to improve the way in which these systems are implemented as well as to develop the simulation environment to better represent reality. Future development work planned includes the implementation of collimator wakes; the use of crab cavities to perform the angle feedback; the incorporation of lower frequency feedbacks and the use of newer BDS schemes.

As much data as possible acquired during the running of these simulations is kept on a public web site: http://hepwww.ph.qmul.ac.uk/lcdata.

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