FIRST-PRINCIPLES SIMULATION AND COMPARISON WITH BEAM TESTS FOR TRANSVERSE INSTABILITIES AND DAMPER PERFORMANCE IN THE FERMILAB MAIN INJECTOR*

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Abstract

An end-to-end performance calculation and comparison with beam tests was performed for the bunch-by-bunch digital transverse damper in the Fermilab Main Injector. Time dependent magnetic wakefields responsible for "Resistive Wall" transverse instabilities in the Main Injector were calculated with OPERA-2D using the actual beam pipe and dipole magnet lamination geometry. The leading order dipole component was parameterized and used as input to a bunch-by-bunch simulation which included the filling pattern and injection errors experienced in high-intensity operation of the Main Injector. The instability growth times, and the spreading of the disturbance due to newly mis-injected batches was compared between simulations and beam data collected by the damper system. Further simulation models the effects of the damper system on the beam.

INTRODUCTION

The interaction between a charged particle beam and beam pipe is the *resistive wall* effect, so called because the beam pipe walls have a non-zero electrical resistivity. We studied transverse instabilities which arise from the "resistive wall" effects in the Fermilab Main Injector with a software simulation of the system.

The Fermilab Main Injector is a synchrotron approximately 3319 meters in circumference, accelerating protons or anti-protons from 8 GeV/c to 150 GeV/c. A *synchrotron* is a circular particle accelerator where the magnetic field of the steering magnets is increased synchronously with the increase in particle energy as the particles are accelerated, in order to keep the particles orbiting the accelerator ring. The Main Injector serves as an intermediate accelerator for Fermilab's Tevatron and also is used in anti-proton production and fixed target experiments.

The Main Injector circulates a bunched 53 MHz beam. Thus, the time between bunches is about 18.8ns and there are 588 buckets (bunch slots) available. The Main Injector is typically filled with six separate 84-bunch batches from the Fermilab Booster accelerator. There are two empty buckets between each batch of 84, with a longer empty space after the final batch.

The Main Injector's transverse bunch position is detected with a stripline pickup. A hybrid transformer's difference output produces the position signal, which is a bipolar signal with amplitude proportional to the bunch position. It is digitized at 212 MHz, four times the bunch frequency, which allows the system to find the bunch phase and amplitude[1].

The transverse signals are one set of inputs to a single board digital damping system developed for the Fermilab Main Injector[1]. This damper board performs all the calculations for bunch-by-bunch transverse and longitudinal beam damping. At its heart is field-programmable gate array (FPGA) logic, outputting a digitally synthesized damping kick to power amplifiers. The term "bunch-by-bunch" means that the damping kick is calculated separately for each bunch.

SIMULATION IMPLEMENTATION

The simulation was implemented in Matlab, a mathematical programming language and environment. The simulation models one transverse dimension. Matlab vectors were constructed containing the charge, position (x), and position derivative with respect to longitudinal position ($x' = \frac{dx}{ds}$) for each of 588 bunches. As the simulation runs, x and x' propagate from each station to the next.

The accelerator circumference was similarly divided into 588 equidistant locations, or stations. The strength of the magnetic wakefield is tracked at each of those stations. The simulation runs by taking discrete time steps, the time it takes for each bunch to advance from one station to the next. This is simply the circumference divided by the number of stations (588) divided by βc, the speed of the beam, or approximately 18.8ns (which is, of course, the same as the bunch spacing).

In each time step, the simulation performs the following calculations:

1. The position of the bunch at the damper readout location is recorded.
2. The kick for the bunch at the damper kick location is calculated.
3. If damping is active, the bunch at the damper kick location receives the calculated kick in x'.
4. Each bunch gets kick in x' from its current station's magnetic wakefield
5. The magnetic field at each station decays
6. Each bunch deposits wake field at each station proportional to the bunch's charge and position
7. x and x' of each bunch propagate to the next station

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8. The bunches (with their charge, x and x') advance in Z to the next stations

9. Time elapses

After each full turn (588 steps), the end-of-turn bunch positions are recorded in a vector for a time history of the beam evolution, and various maxima can be computed to show evolution of the beam as a whole.

BEAM PIPE DIAMETER

The Main Injector beam pipe width only produces noticeable wakefield effects in the dipole magnets. In other parts of the circumference, the aperture is wide enough that any wakefield effects are negligible. Approximately 75% of the circumference has of the narrower diameter pipe. To simulate this, I use a "mask" vector with each element corresponding to one station, and for stations where that mask is 0, no wakefield deposition or kick occurs. 25% of the diameter of the Main Injector is thus masked off so that there are no wakefield effects.

The magnetic wake field is divided into two parts because the computed model indicates that the field is the sum of two separate exponential decays. Thus, the decays are computed separately, and the field which kicks the beam is the sum of the two parts.

INSTABILITY GROWTH

To study the progression of the growth of a resistive wall instability, relatively simple input parameters were used for illustration purposes. Six batches of 84 bunches each are set into the simulation. The first five batches all have ideal $x = 0$ positions. To simulate an injection error, the sixth batch is assigned an x offset of 1mm. The bunch charge is identical for all bunches, corresponding to 5×10^{10} protons per bunch. After 100 turns, the effects of the injection error have begun to spread, and the betatron motion has begun to become apparent. The instability continues to grow and by 700 turns it blows up the whole beam.

Instability Growth vs. Measurements

The simulation data was analyzed to measure the growth times of the instability. These measurements are compared with analysis of real Main Injector beam measurements which were also unstable. Data to measure the instability growth time was acquired with the Main Injector digital damper system with the dampers off. All measurements are taken at a fixed, non-accelerating, beam energy.

Figure 1 shows one set of results comparing the simulation with the measured beam data across 33 bunches from the same batch. For analysis the maximum transverse position envelope across these 33 bunches is used to show the rise time of the instability. The Y axis shows logarithmic scaling Figure 1. The curve which is broader near Turn 0 is the simulated data. The "simulation" curve is created by taking the maximum transverse position across all 84 bunches in batch 1. Both curves are then plotted as a function of turn number.

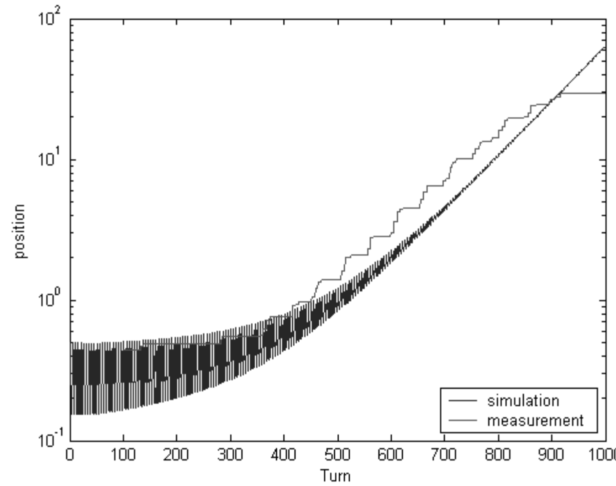

Figure 1: Transverse Displacement Maximum Across Bunches Evolving Through Time (Turns) — Simulated and Measured. The Y axis is in millimeters, but arbitary data acquisition units from the beam data were scaled to match the other curve.

The maximum of the beam positions also shows the point at which the beam starts scraping against the beam pipe, after about 900 turns.

The two curves of Figure 1 are quite similar, neglecting the part of the measured curve after the beam starts physically scraping against its beam pipe around turn 900.

Each curve from Figure 1 was fit to an exponential function. Only the data between turns 300 and 800 was used, in order to avoid the beam scraping in the later turns and the earlier turns where the instability was still developing.

The results of the fit confirm the similarity in slope seen in Figure 1. The simulated data was proportional to $e^{0.0071t}$ and the measured data rose proportional to $e^{0.0073t}$.

DAMPING

The Matlab simulation includes simulation of a damping kick which can produce a 0.1mm transverse displacement after a quarter of a betatron oscillation. The position for the kick is sensed at one position and the kick is applied at one position. For the purposes of these simulations, the readout and kick position are the same, although in practice, they are not at the exact same location. The same algorithm that is used in the FPGA for calculating the damping kick is used in the simulation. This includes a calculation of the bunch motion phase.

For the simulation shown in Figure 2, starting conditions were: 5×10^{10} protons per bunch, $\nu = 24.4$, five batches of 84 bunches with no initial position offset, and the sixth batch of 84 with an initial position offset error of 1mm.

Figure 2 shows the maximum bunch position across the 84 bunches of batch #1 measured for 200 turns. The damp-

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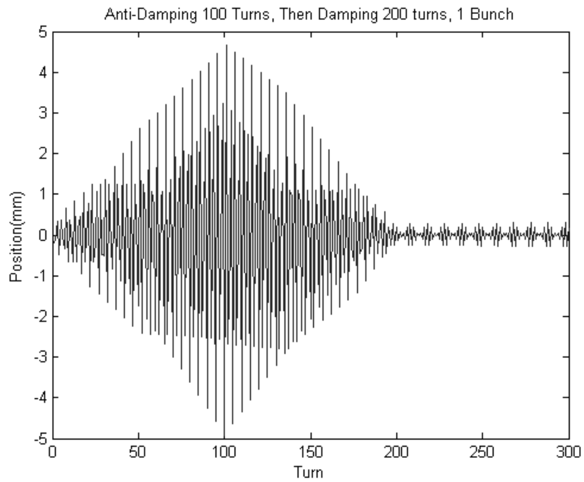

Figure 2: Maximum Bunch Position, Anti-Damping for 100 turns, then Damping

ing kick was turned on for the entire simulation, but for the first 100 turns, the phase of the dampers was adjusted to provide anti-damping — encouraging the beam position oscillations to grow faster than normal. For the second 100 turns, the phase was changed to the optimal phase to provide damping. Figure 2 clearly shows the beneficial effects of damping to control the beam oscillations.

Both the simulation and the Main Injector digital damper card provide the ability to provide a different kick to each bunch of the beam. For ordinary damping, this allows each bunch to be damped according to its individual betatron amplitude and phase. However, this also allows us to select certain bunches for anti-damping by changing the phase of the damper kick for those bunches. This allows a more exotic bunch structure to be created.

CONCLUSIONS

This rigid bunch simulation has proven to be a useful tool for understanding the behavior of the beam in the Fermilab Main Injector. The simulation also is a useful aid to understanding the Main Injector digital bunch-by-bunch damper card, the need for such damping, its performance, and its capabilities.

REFERENCES

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