ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAF068

SUPPRESSION OF INSTABILITIES GENERATED BY AN ANTI-DAMPER WITH A NONLINEAR MAGNETIC ELEMENT IN IOTA[*]

E. Stern[†], J.F. Amundson, A. Macridin, Fermilab, Batavia, IL 60510, USA

Abstract

The Integrable Optics Test Accelerator (IOTA) storage ring is being constructed at Fermilab as a testbed for new accelerator concepts. One important series of experiments tests the use of a novel nonlinear magnetic insert to damp coherent instabilities. To test the damping power of the element, an instability of desired strength may be intentionally excited with an anti-damper. We report on simulations of beam stabilization using the Synergia modeling framework over ranges of driving and damping strengths.

INTRODUCTION

Fermilab is constructing the IOTA [1] storage ring as a machine to experimentally new concepts in high space charge accelerators. Progress in building future high intensity accelerators is hindered by fundamental beam physics phenomena. Attempts to increase beam current are foiled by instabilities and particle losses. The IOTA experimental program will provide a test-bed for studying and evaluating and strategies and techniques for measuring and ameliorating deleterious effects. There will also be a robust simulation effort along with the experimental program to guide the experiments and assist with interpretation of results.

An integrable nonlinear magnetic element [2] will be tested for its ability to suppress coherent instability growth. Impedance drives instability growth in current running accelerators and thus it would be useful to be able to test the suppression ability of the nonlinear element. However, impedance effects are small [3] at the low energies of the IOTA ring. An anti-damper has been suggested [4] as an alternative mechanism to intentionally excite instabilities of the sort that will need to be suppressed. To that end, we have numerically simulated a model of the IOTA ring with an anti-damper and integrable nonlinear element with the Synergia accelerator simulation framework.

Table 1: Parameters of the Simulated IOTA Ring

Parameter	**Value**	**unit**
particle	proton	
length	40	m
beam kinetic energy	2.5	MeV
x, y emittance (no lens)	4.1	m rad
x, y emittance (lens)	4.1, 8.6	
RMS bunch length	0.69	m
RMS bunch $\Delta p/p$ spread	0.0	

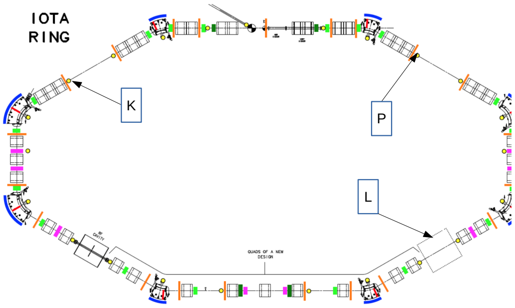

Figure 1: Schematic of the IOTA ring. The nonlinear lens is at position L, the pickup for the damper is at position P, and the kicker is at position K.

IOTA RING

The IOTA ring has a 40 m circumference with four straight sections into which experimental devices may be placed. The main parameters are listed in Table 1 and a schematic view is shown in Fig. 1. At location P, a special element marked the location of a damper pickup for measuring the mean bunch position. A simulated damper kicker was placed at location K. The phase advance between P and K is 2.5 π. Given this phase advance, applying a momentum kick at K

$$\frac{\Delta p}{p} = g \left\langle x \right\rangle$$

where g is the damper gain, results in damping motion for $g > 0$ or anti-damping for $g < 0$. The simulations used lattice description files containing one insertion region from the Iota6-6 series of lattices from the `ioptics` module [6] distributed by RadiaSoft. The lattice `lattice_1IO_center.madx` does not contain the nonlinear element, while `lattice_1IO_nll_center.madx` does contain the nonlinear element.

SYNERGIA

Synergia is a particle-in-cell (PIC) based framework for self-consistent, high fidelity modeling of charged particle beam transport in accelerators or storage rings in the presence of collective effects such as space charge and wake fields. Synergia tracks macro-particles contained within one or more beam bunches through same set of common magnetic elements and RF cavities including the special elliptical nonlinear element as are supported by the MAD-X [5].

Synergia simulations can use the `Python` programming language to dynamically control the simulation during execution. We used a feature that allows an arbitrary script to run at the end of every step of the simulation. When the beam bunch reached the pickup element at location P, the

---

[*] FERMILAB-CONF-18-132-APC-CD

[†] egstern@fnal.gov

script calculated and saved the mean bunch position $\langle x \rangle$. When the beam bunch reached the kick element at location K, the script applied a momentum kick equal to $g\langle x \rangle$. Initial bunch distributions were stable Gaussian distributions without the nonlinear insert and KV distributions with the nonlinear insert.

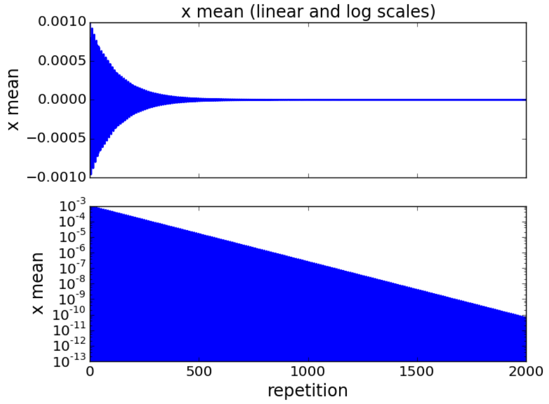

Figure 2: Linear and log plots of the centroid position of a bunch started at an initial offset of 0.001 running with the damper gain set to 0.01.

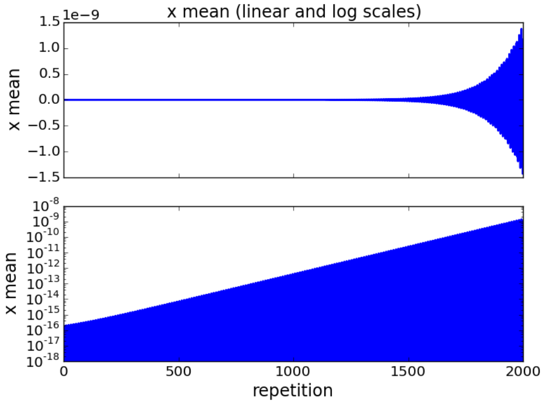

Figure 3: Linear and log plots of the centroid position of a bunch operating in anti-damper with the gain set to −0.01.

SIMULATION RESULTS

We first verified the correct operation of the damper. The propagation in the ring was linearized to eliminate all other sources of instability growth. We begin without using the nonlinear element. Figure 2 shows a log and linear plot of the bunch centroid position over a 2000 turn run for a bunch initially at a 0.001 offset. The damper gain was set to 0.01. The bunch centroid is clearly damped exponentially. Figure 3 shows the log and linear plot of bunch centroid position for the damper gain is −0.01. The bunch position begins at the numerically smallest value of 10^{-16} and grows exponentially over the course of 2000 turns.

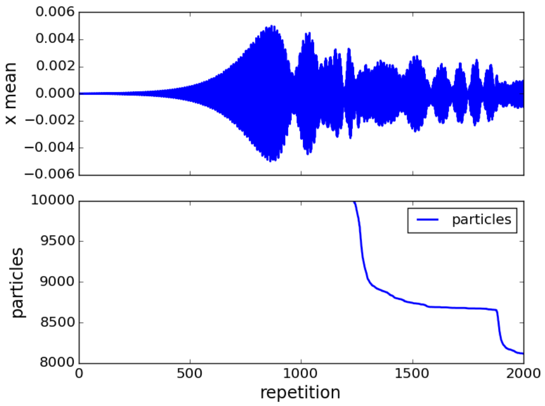

Figure 4: The centroid position of a bunch operating in anti-damper with the gain set to −0.01 and the number of macro-particles using the full nonlinear propagation of drifts.

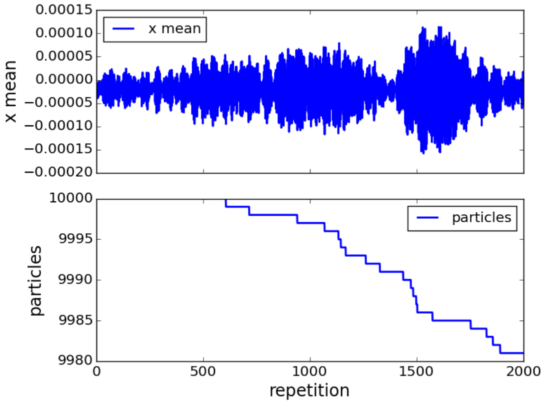

Figure 5: The centroid position of a bunch and the number of macro-particles operating in anti-damper mode with the gain set to −0.01 using the full nonlinear propagation of drifts with an integrable nonlinear element.

The full calculation of propagation through of drift of length L is nonlinear:

$$x_{\text{final}} = x_{\text{initial}} + \frac{p_x}{\sqrt{p^2 - p_x^2 - p_y^2}}$$

Sector bends are also nonlinear. Particle trajectories in a uniform magnetic field are circles. The output position of a particle in a sector bend is the intersection of circular orbit and the straight line of the exit edge of the magnet. This is a quadratic equation, hence the magnet is nonlinear.

Introducing these nonlinearity in addition to the anti-damper drives significant instability as shown in Fig. 4 which is run with the same gain setting of −0.01. Almost 20% of the macro-particles are driven to infinite coordinates and are lost. Adding the nonlinear element to this simulation shows some stabilizing effect as shown in Fig. 5 with losses at the 0.2% level although there still appear to be bouts of unstable growth. It turns out that using the nonlinear element with full nonlinear propagation results in losses at the 0.2% level.

Reducing the driving gain to −0.005 results in motion that appears quite stable as shown in Fig. 6 although with the same 0.2% level of losses.

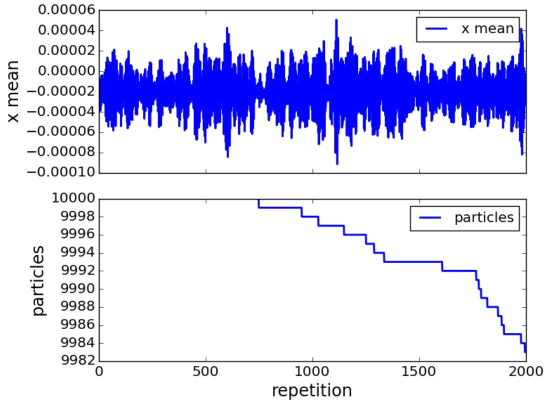

Figure 6: The centroid position of a bunch and the number of macro-particles operating in anti-damper mode with the gain set to −0.005 using the full nonlinear propagation of drifts with an integrable nonlinear element. The motion appears more stable than with the gain of −0.01, but the level of losses is about the same.

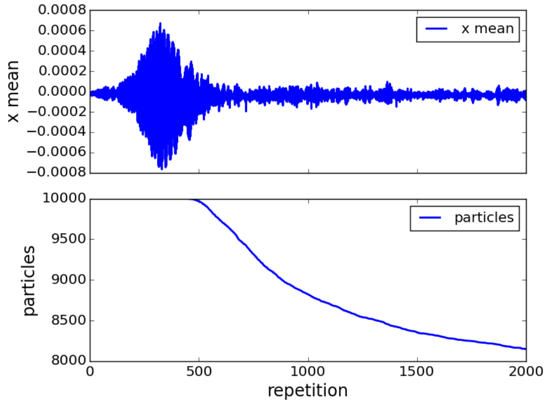

Figure 7: The centroid position of a bunch and the number of macro-particles operating in anti-damper mode with the gain set to −0.05 using the full nonlinear propagation of drifts with an integrable nonlinear element. The increased anti-damper strength drives the motion back into instability even with the nonlinear element, with 20% losses.

Increasing the anti-damper strength to −0.05 moves the simulation back into the unstable region as shown in Fig. 7 with losses of 20%.

CONCLUSION

We have simulated the actions of an anti-damper device in a model of the IOTA test ring with the Synergia accelerator modeling framework. Anti-damper driven instabilities can be suppressed by a nonlinear integrable element, but unstable behavior returns when the anti-damper strength is increased.

ACKNOWLEDGEMENTS

We thank A. Burov and A. Valishev of Fermilab and D. Bruhwiler, N. Cook and C. Hall of RadiaSoft LLC for helpful discussions. This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. Synergia development was partially supported by the Scientific Discovery through Advanced Computing (SciDAC) program through the office of High Energy Physics of the U.S. Department of Energy.

REFERENCES

[1] S. Antipov, *et al*. "IOTA (Integrable Optics Test Accelerator): facility and experimental beam physics program", 2017 JINST 12 T03002

[2] V. Danilov and S. Nagaitsev, "Nonlinear accelerator lattices with one and two analytic invariants", Phys. Rev. ST Accel. Beams 13 (2010) 084002.

[3] A. Burov, "Beam Stability Issues in IOTA", Fermilab technical memo FERMILAB-TM-2580-AD, `DOI:10.2172/1331790`

[4] A. Burov, private communication (2016).

[5] "The MAD-X Program", CERN, `http://madx.web.cern.ch/madx/`.

[6] `https://github.com/radiasoft/ioptics`