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EXPLORING ACCELERATORS FOR INTENSE BEAMS WITH THE IBEX PAUL TRAP

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Abstract

Accelerators built from linear components will exhibit bounded and stable particle motion in the ideal case. However, any imperfections in field strength or misalignment of components can introduce chaotic and unstable particle motion. All accelerators are prone to such non-linearities but the effects are even more significant in high intensity particle beams with the presence of space charge effects. This work aims to explore the non-linearities which arise in high intensity particle beams using the scaled experiment, IBEX. The IBEX experiment is a linear Paul trap that allows the transverse dynamics of a collection of trapped particles to be studied by mimicking the propagation through multiple quadrupole lattice periods whilst remaining stationary in the laboratory frame. IBEX is currently undergoing a non-linear upgrade with the goal of investigating Non-linear Integrable Optics (NIO) in order to improve our understanding and utilisation of high intensity particle beams.

INTRODUCTION

When designing new particle accelerators, constructing test accelerators can be costly not only in terms of financial expense, but also in energy use. Once an accelerator is built, it is often difficult to change the lattice structure and thus is not practical to investigate large parameter spaces. This leaves accelerator physicists with simulations as their primary tool throughout the design process, however, theoretical simulations cannot truly replace experimental verification. With the push to higher intensity hadron machines, simulations struggle to reproduce the intricate physics of the many-body Coulomb interactions (space charge forces) over long timescales (tens of thousands of lattice periods).

These challenges led to the design and construction of linear Paul traps to investigate beam dynamics at Hiroshima University, Japan [1], Princeton University, US [2] and IBEX, at the Rutherford Appleton Laboratory (RAL), UK [3]. IBEX is a table-top sized experiment that can replicate the transverse betatron motion in alternating gradient accelerators in a dispersion- and chromaticity-free environment. This paper outlines a proposed experiment to test Non-linear Integrable Optics (NIO) in a future non-linear upgrade to IBEX.

THE IBEX PAUL TRAP

The IBEX Paul trap consists of four stainless steel, cylindrical rods and two sets of end caps, each made from four shorter cylinders as seen in Fig. 1. Argon gas is introduced into the trap and is ionised with an electron gun. Typically, a sinusoidal RF voltage is applied to the central rods with a maximum peak-to-peak of 300 V and frequency of 1 MHz. Voltages of the same form but opposite polarity are applied to the blue and red outlined rods in Fig. 1, providing the transverse confinement of ions. A DC offset is applied to the end caps to provide longitudinal trapping of ions. A sinusoidal voltage replicates a simple FODO lattice although it is possible to create more complex lattices in IBEX.

Adjusting the peak voltage applied to the rods is analogous to changing the quadrupole strength in an accelerator, which in turn changes the betatron tune in both the horizontal and vertical planes. This allows a wide range of tunes to be scanned in a short period of time, a feat which is challenging for simulations or conventional accelerators. Ions can be stored for around 1 s, corresponding to 10^6 RF periods, before the DC voltage on the end cap is dropped and the ions are directed onto either a Micro-Channel Plate (MCP) or a Faraday Cup (FC). The number of trapped ions can be varied by adjusting the amount of time that the electron gun is on which allows a wide range of intensities to be studied within the trap. Due to the low energy of the ions (< 1 eV), high intensity beam loss studies can be carried out in the trap without damaging or activating components. IBEX has already been used to study coherent and incoherent resonances at high intensities [4].

An upgrade to the IBEX trap is currently underway which will duplicate the linear trap but with the addition of four plate electrodes positioned between the rods (shown in Fig. 1 side view, shaded blue). This design is adapted from the non-linear trap designed by the Hiroshima group [5]. Grounding the rods whilst applying an equal voltage to all four plate electrodes will allow for octupole fields to be created in the trap. Argon gas will be ionised and trapped in the linear section before being transported to the non-linear trap. With this upgrade we aim to test proposed non-linear, integrable lattices [6, 7].

NON-LINEAR INTEGRABLE OPTICS

Accelerators mainly consist of linear elements such as dipole and quadrupole magnets. Assuming there is no coupling between the horizontal and vertical directions, an ideal linear lattice is fully integrable. In other words, the Hamiltonian associated with a single particle is time-independent and can be separated into two invariants of motion. However, in reality these linear lattices are susceptible to perturbations, and so non-linear components such as sextupoles and octupoles are often used to apply higher order corrections. The addition of these nonlinear components results in a non-

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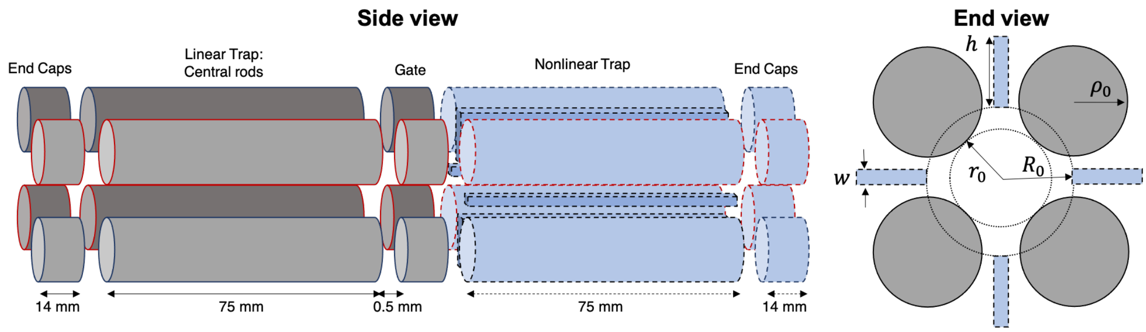

Figure 1: Diagram of the IBEX trap (grey, solid outline) and non-linear upgrade (light blue, dashed). Opposing RF voltages are applied to the red and blue outlined rods for transverse confinement of ions. A DC voltage is applied to the end caps to provide longitudinal trapping. The longitudinal dimensions are displayed on the left and the transverse dimensions are: $r_0 = 5$ mm and $\rho = 5.75$ mm. Four additional plates will be added between the rods in the nonlinear trap at an inscribed radius of R_0 to enable the creation of octupole fields.

integrable system, which limits the available phase-space area where the particle motion is non-chaotic.

The theory of NIO was laid out in 2010 by Danilov and Nagaitsev [6] in which they proposed an integrable, non-linear lattice consisting of a linear T-insert and non-linear drift region. In an accelerator, a T-insert is comprised of a quadrupole lattice and a nonlinear drift region. In IBEX the T-insert is produced by applying a piecewise constant waveform of the same pattern to the central rods. The beta functions are plotted for a T-insert lattice designed for IBEX in Fig. 2. The three conditions of the T-insert lattice are: 1 - $n\pi$ (where n is an integer) phase advance over the linear section to provide quasi-periodic motion through the non-linear region. 2 - Equal beta functions in the non-linear drift region ($\beta_x = \beta_y$). 3 - The non-linear element strength should scale with $1/\beta^3(s)$.

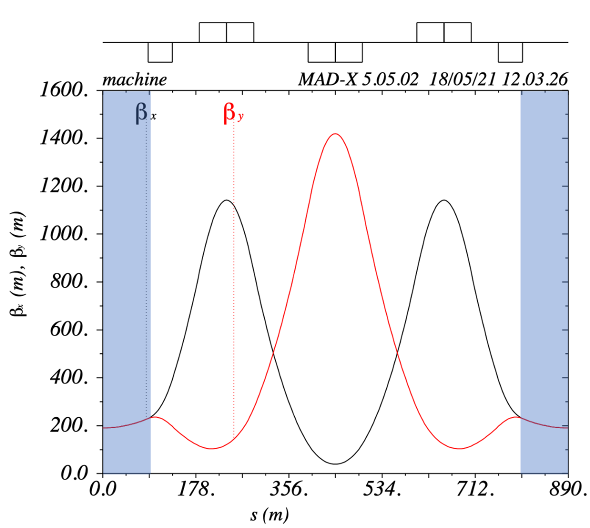

Figure 2: Beta functions of T-insert lattice designed for the IBEX trap. Blue shaded region is the drift region for the nonlinear insert.

The fully integrable solution requires a complex elliptical potential in the non-linear drift region which will be tested at the Integrable Optics Test Accelerator (IOTA), Fermilab. However, the elliptical potential is a challenge to create experimentally. Therefore, IBEX will first test the quasi-integrable case, which uses an octupole potential of the form

$$V(x, y, s) = \frac{k_4}{\beta^3(s)} \left(\frac{x^4}{4} + \frac{y^4}{4} - \frac{3x^2y^2}{2} \right), \quad (1)$$

where k_4 is the strength of the octupole field.

SIMULATION RESULTS

In order to test the T-insert lattice, a quadrupole perturbation of 0.2 V (≈ 0.35 % of the average quadrupole strength) will be applied to the rods at a frequency of twice the lattice tune. This will replicate a half-integer resonance and kick particles to higher amplitudes twice per 2π phase advance. Particle loss will then be measured for a T-insert lattice with a quadrupole perturbation applied but no octupole applied in the non-linear drift region (Octupole OFF). This particle loss will then be compared to the loss for the same perturbed T-insert but with a correctly scaled octupole field applied in the nonlinear region (Octupole ON).

A 2D model of the non-linear IBEX trap has been created in the Particle-in-Cell software VSim and builds upon previous simulations that used Warp to investigate NIO in IBEX [8, 9]. Four plate electrodes ($w = 1$ mm, $h = 6$ mm) are added between the rods at an inscribed radius of 8.5 mm to allow for the creation of octupole fields (see Fig. 1 end view). The dimensions of the plates were chosen to minimise unwanted non-linearities in the quadrupole field (specifically the dodecapole, c_6, component) [5]. The lattice was first tested in the absence of space charge. Around 26,000 particles were created in a matched Gaussian distribution inside the trap, with an emittance of 2.16×10^{-9} mrad. The particles were tracked for 200 lattice periods with the quadrupole perturbation of 0.2 V applied for the Octupole OFF lattice.

Figure 3 shows the y, y' phase space for the Octupole OFF lattice after 0, 50, 100 and 200 lattice periods, along with the number of particles left in the simulation. The loss of particles implies the perturbation is having a strong effect

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by kicking particles out to higher amplitudes where they are lost to scraping on the rods. The arms of the distribution are believed to be from non-linearities (c_6 and c_{10} multipole components) in the quadrupole field causing a tune shift at higher amplitudes. After 200 lattice periods with the perturbation applied, 91.6 % of particles from the initial distribution were lost.

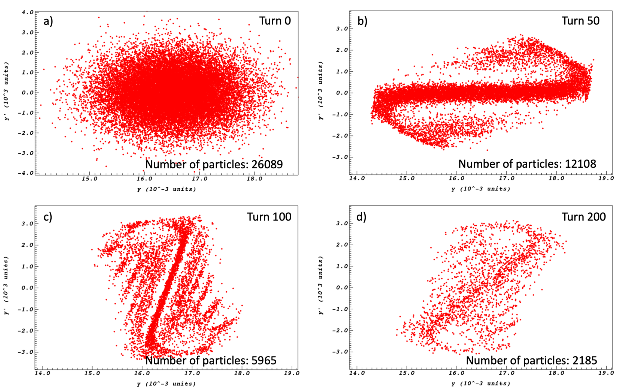

Figure 3: Phase space when a quadrupole perturbation is applied to the T-insert lattice, at a frequency of $2 \cdot 2\pi Q$, with the octupole potential switched off.

An octupole field which scales as $1/\beta^3(s)$ was then applied in the nonlinear region by supplying a voltage pulse to the plates, while grounding the rods. At a plate inscribed radius of 8.5 mm and peak octupole voltage of 500 V, a maximum tune shift of around 3.7 % can be created in the trap.

The same distribution of particles was tracked for 200 lattice periods with the octupole field turned on. The y, y' phase space is plotted in Fig. 4. The tune spread created by the octupole field within the non-linear region of the T-insert restores the phase space to something that more closely resembles the initial distribution. The particle loss after 200 lattice periods was 36.1 %. This is a significant improvement compared to the 91.6 % loss in the lattice with the octupole off.

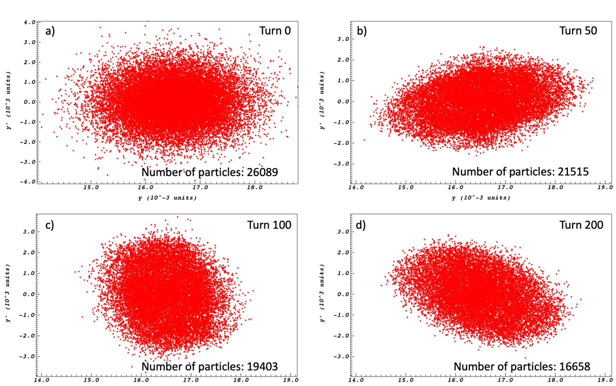

Figure 4: Phase space when a quadrupole perturbation is applied to the T-insert lattice, at a frequency of $2 \cdot 2\pi Q$, with the octupole potential switched on.

To recreate this experiment on IBEX, once the non-linear upgrade has been completed, a voltage pulse with a peak voltage of 500 V and pulse width of < 600 ns will need to be applied to the plates. This is a demanding slew rate for the current voltage amplifiers and so the plate inscribed radius was varied in subsequent simulations to test the possibility of reducing the voltage requirement. Inserting the plates closer to the center of the trap increases the octupole strength and thus reduces the voltage requirement. This comes at the cost of raising unwanted nonlinearities in the quadrupole field. Table 1. summarises the effect on particle loss when inserting the plates further toward the center of the trap for the case of Octupole OFF (no perturbation applied to the T-insert), Octupole OFF with perturbation and Octupole ON with perturbation. The simulations for inscribed radii of 7.1 mm and 7.4 mm had a peak plate voltage of 200 V, which is the current limit of our existing voltage amplifiers.

The results show that there is a significant difference in particle loss between the Octupole OFF and Octupole ON when the plates are inserted to 7.4 mm and 7.1 mm, with a peak voltage of 200 V applied to the plates. This is promising as it means that substantial tune spreads can be achieved in the non-linear trap with the existing amplifier specifications.

Table 1: Particle Loss for Octupole OFF (No Perturbation), Octupole OFF with Perturbation and Octupole ON with Perturbation for Inscribed Plate Radii of 8.5 mm, 7.4 mm and 7.1 mm

Inscribed Plate Radius	**Plate Voltage**	**Particle Loss**		
		Oct OFF	Oct OFF with pert.	Oct ON with pert.
8.5 mm	500 V	3.75 %	91.6 %	36.1 %
7.4 mm	220 V	3.78 %	81.6 %	35.6 %
7.1 mm	200 V	4.03 %	71.8 %	27.5 %

CONCLUSION

The IBEX experiment is currently undergoing an upgrade to allow for the creation of octupole fields within the trap in order to test non-linear accelerator lattices. One application of this upgrade is to investigate the T-insert needed for NIO. Simulations show that there is a significant difference in particle loss when comparing Octupole ON to Octupole OFF in a perturbed T-insert lattice. After the commissioning of the non-linear trap, the simulations presented here will be replicated experimentally, and a scan away from the integrability conditions (i.e. $n\pi$ phase advance and $\beta_x = \beta_y$ requirements) of the T-insert will be performed to test the robustness of NIO.

We intend to then extend these studies of NIO to higher intensity particle beams to investigate whether space charge instabilities can be damped by these non-linear lattices. In this way, we hope IBEX will continue to be a powerful tool for exploring new developments in accelerator physics.

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