OVERVIEW OF THE DESIGN OF THE IBEX LINEAR PAUL TRAP

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Abstract

We report on the status and design of the Intense Beam Experiment (IBEX) at RAL. This small experiment consists of a linear Paul trap apparatus similar to the S-POD system at Hiroshima University, confining non-neutral Argon plasma in an rf quadrupole field. The physical equivalence between this device and a beam in a linear focusing channel makes it suitable for accelerator physics studies including resonances and high intensity effects. We give an overview of the design and construction of IBEX and outline plans for commissioning and the future experimental programme.

INTRODUCTION

The design of the IBEX Paul Trap has been developed in collaboration with Hiroshima University, based on their successful S-POD Paul Trap system [1–3]. The machined and constructed Paul trap can be seen in Fig. 1.

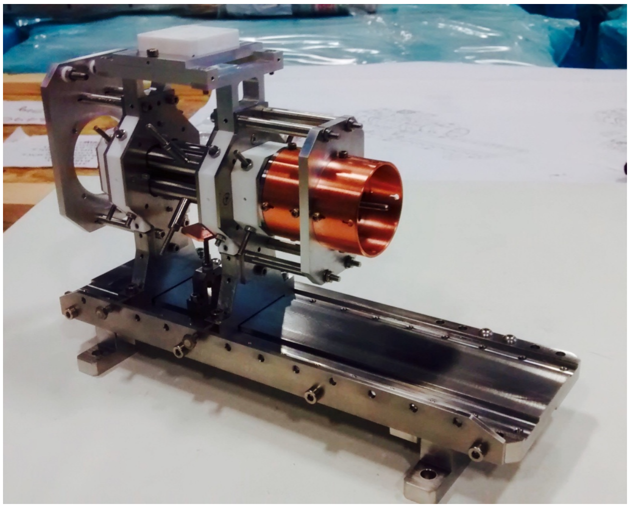

Figure 1: The constructed IBEX Paul trap. The constructed trap including the base plate is 280 mm long, 120 mm wide and 187 mm high.

The heart of the system is a set of four cylindrical rods in a quadrupole formation, mounted inside a vacuum vessel. Argon gas is leaked into the vessel and ionised to form a non-neutral plasma using a small electron gun. A 1 MHz low power sinusoidal rf waveform is applied to the four rods, setting up a time-varying electric quadrupole which confines the ions.

DESIGN OVERVIEW

Components

Vacuum The vacuum vessel has a base pressure of 10^{-8} Pa (i.e. 10^{-10} mbar) and has been designed with ample space and many ports to allow future upgrades to the experiment. Gas flow into the vessel will be controlled using a VAT variable leak valve. This allows precise control over the vessel pressure, in combination with a regulated air-conditioned room temperature to remove major temperature fluctuations.

Detectors There are two Faraday cups mounted on the device. One is beneath the electron gun for calibration purposes, the other is the main Faraday cup for ion counting. At the opposing end is an MCP detector and phosphor screen setup for imaging the ions directly.

Timing and control Each experimental run in IBEX will take of the order of one second. The process is automated via LabView. The operational sequence begins with the electron gun ionising Argon gas inside the trap region for around 200 ms to 1 sec. The duration and beam parameters will be optimised to produce the required number of ions. During ionisation the main confinement rf wave is switched on. After confinement, a waiting period gives time for the plasma to stabilise, taking roughly 50 ms.

Depending on the exact experiment to be performed, the rf waveform voltage may be swept in time, a dipole perturbation or some other bias may be applied to perturb the plasma. Measurement of the resulting ion distribution occurs by extracting the ions from the trap. The longitudinal confining ‘gate’ voltage is dropped and the ions are extracted either to a Faraday Cup or an MCP and phosphor screen for imaging. More detail for the similar S-POD system can be found in Ref. [4]. The interaction between various system components is shown in Fig. 2.

Paul Trap Alignment

In the ideal case, the Paul trap rods should be a perfect cylinder, of equal diameter along their length and aligned perfectly straight with respect to one another. They should also meet exact specifications for rod diameter and distance from the Paul trap centre to the rod centre. Due to the stringent requirements for mechanical alignment, some changes were made in the mechanical design stage. To help alignment, the trap has been mounted on a single machined piece and a 2-point system of contact was implemented where the rods meet the supporting structure, shown in Fig. 3.

If the Paul trap is aligned or machined imperfectly, non-linear components of the field will exist which may then affect the experiment and drive non-linear resonances which

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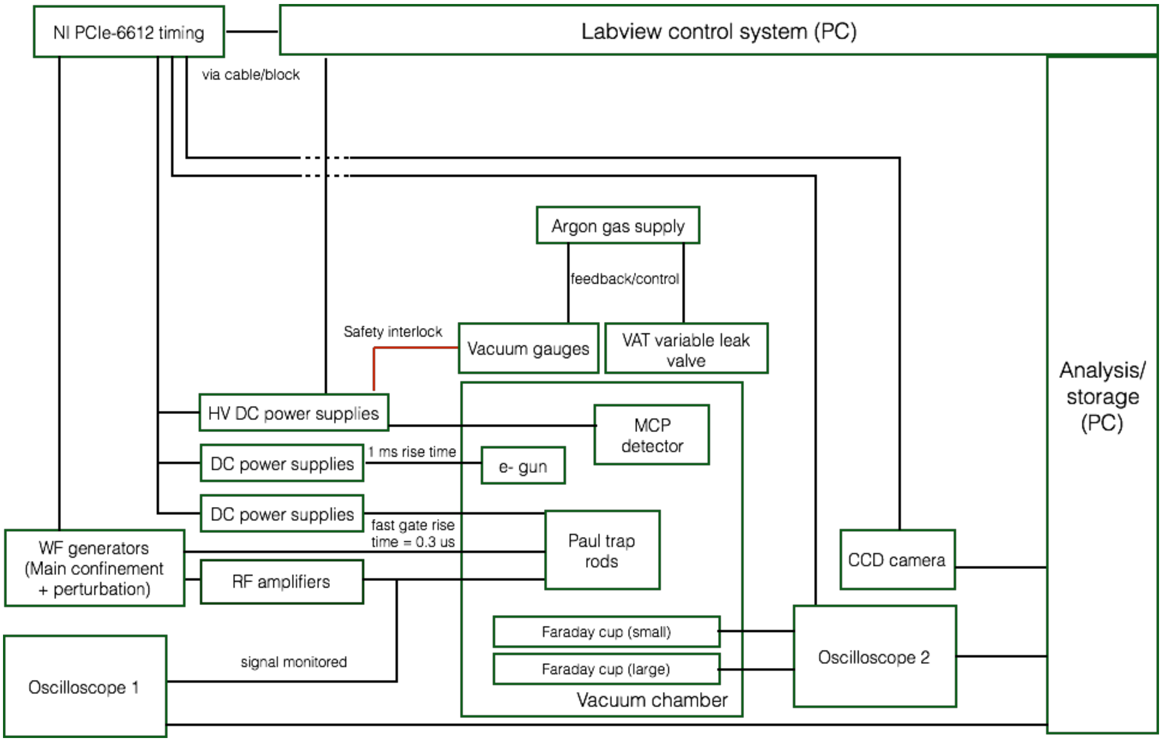

Figure 2: Block diagram of the IBEX experimental system.

will lead to ion losses during operation. In reality, there will always be some imperfections and non-linear field components present in such a device. To ensure the IBEX Paul trap meets the mechanical specifications and to create an accurate model for simulations, it is important to have some knowledge of the real level of misalignments and imperfections in the device. Detailed alignment measurements were made of the constructed Paul trap using a CMM (co-ordinate measuring machine) at STFC Rutherford Appleton Laboratory. The key findings are twofold: all four rods were found to have the nominal diameter or larger, within roughly 50 μm (Fig. 4) and the gap distance between the rods was found to be always the nominal value or smaller. In particular, we can tell from the alignment measurements in Fig. 5 that the rods are aligned straight with respect to one another to less than 10 μm.

With this detailed knowledge of machining deviations and misalignments present in the trap, we can estimate the level of multipole fields present and predict how it may affect the performance of the experiment, as shown in Fig. 6. An estimate of the multipole components was found by simulation, solving the Laplacian in 2D using Mathematica. In the worst case, the relative multipole components at a radius of 3 mm from the trap centre were found to be $c_3/c_2 = 0.0008$ for sextupole (c_3) with respect to quadrupole (c_2) and $c_4/c_2 = 0.0004$ for the relative octupole. This is the same order of magnitude as the typical multipole errors found in accelerator magnets (typically 10^{-4}). The effects of multipole errors in experiments have previously been studied in detail in the S-POD system [5].

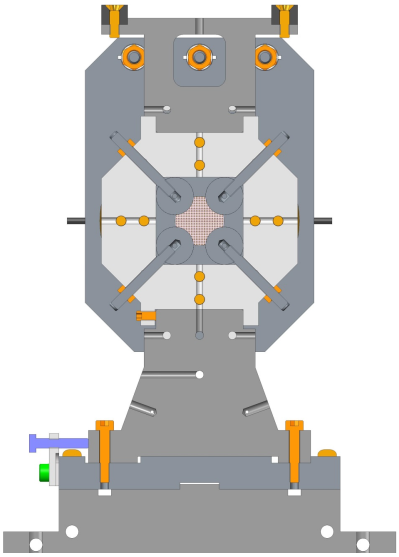

Figure 3: Cross-sectional view of the mechanical design of the Paul trap showing alignment system, including 2 point contact for the rods, a common alignment reference feature and a base alignment feature. Overall dimensions are 120 mm wide by 187 mm high. Image courtesy of STFC Daresbury Laboratory Technology Division.

STATUS AND EXPERIMENTAL PLANS

The Paul trap itself has now been manufactured and a detailed alignment measurement undertaken using CMM

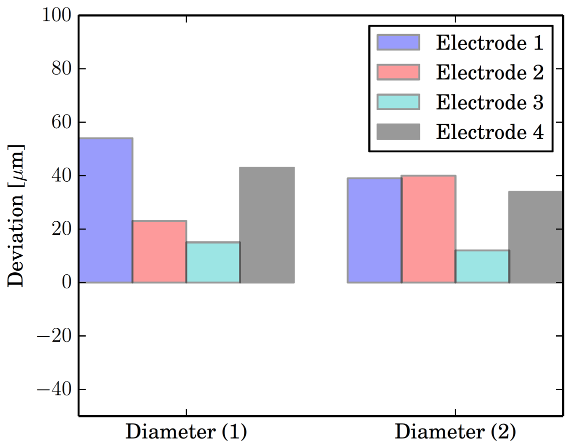

Figure 4: Precision measurement of the Paul trap rod diameter measured at two different longitudinal positions. The nominal diameter is 11.50 mm.

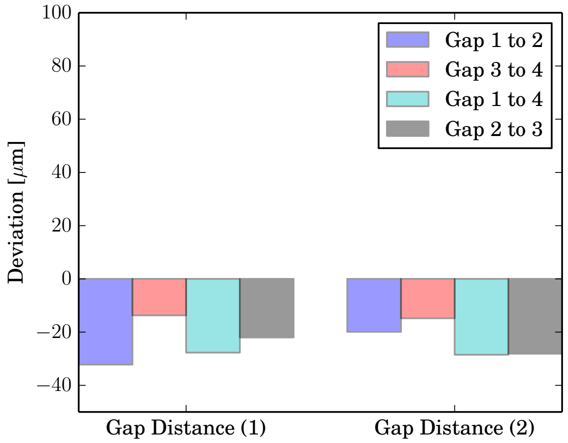

Figure 5: Precision measurement of the gap distance between each of the four Paul trap rods, measured at two different longitudinal positions. The nominal gap width is is 3.7 mm.

by the Metrology department in STFC RAL Technology Division. The vacuum vessel has now been manufactured and vacuum processing is underway at STFC Daresbury Laboratory. Commissioning of the apparatus will take place over summer 2016.

Previous collaborative work using the S-POD system has focused on integer resonance crossing [6, 7] and initial experimental work will be benchmarked against these results. Future experiments with IBEX will be focused on beam dynamics studies including:

- Half-integer studies of ISIS and other rings.
- Long-term stability studies at various intensities.
- Benchmarking codes to simulate high intensity rings.
- Halo production driven by space charge.
- Comparison of different lattice types.

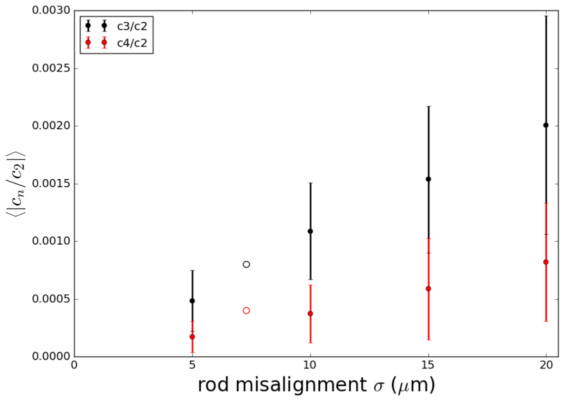

Figure 6: Mean normalised multipole coefficients c_3 (black) and c_4 (red) as a function of the magnitude of rod misalignment. A set of 50 rod misalignments with Gaussian distribution truncated at 3 standard deviations was applied. The error bars represent the standard deviation of the results. The open circles show the result for the magnitude of measured trap misalignment.

Looking further ahead, a non-linear version of the trap will allow studies of more complex phenomena and novel accelerator variants. Studies aim to include the Integrable Optics concept [8].

ACKNOWLEDGEMENTS

We would like to acknowledge the invaluable contribution of H. Okamoto and his group at Hiroshima University. We would also like to thank the STFC Daresbury Laboratory Technology Division, D. Wilsher from STFC Rutherford Appleton Laboratory Technology Division, R. Mathieson and others from ISIS Neutron and Muon Source and J. Fopma from Oxford Physics Central Electronics.

REFERENCES

[1] H.Okamoto, Nucl. Instr. Meth. A 485 (2002) 244-254.

[2] R.Takai et al., Nucl. Instr. Meth. A 532 (2004) 508-512.

[3] K. Fukushima, K. Ito, H. Okamoto et al., Nucl. Instr. Meth. A 733 (2014), 18-24.

[4] K. Ito, K. Nakayama, S. Ohtsubo, H. Higaki and H. Okamoto, Jpn. J. Appl. Phys., 47, (2008), 8017-8025.

[5] H. Takeuchi, K. Fukushima, K. Ito, K. Moriya, H. Okamoto, and H. Sugimoto, Phys. Rev. ST Accel. Beams, 15, no. 7, 074201 (2012).

[6] K. Moriya et al., Phys. Rev. ST Accel. Beams 18, 034001 (2015).

[7] D.J. Kelliher et al., in Proceedings of HB2014, East Lansing, MI, USA, 85 (2014).

[8] V. Danilov and S. Nagaitsev, Phys. Rev. ST Accel. Beams, 13, 084002 (2010), 1-10.