COMMISSIONING AND FIRST RESULTS OF THE INTENSE BEAM EXPERIMENT (IBEX) LINEAR PAUL TRAP

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Abstract

The Intense Beam Experiment (IBEX) is a linear Paul trap designed to replicate the dynamics of intense particle beams in accelerators. Similar to the S-POD apparatus at Hiroshima University, IBEX is a small scale experiment which has been constructed and recently commissioned at the STFC Rutherford Appleton Laboratory in the UK. The aim of the experiment is to support theoretical studies of next-generation high intensity proton and ion accelerators, complementing existing computer simulation approaches. Here we report on the status of commissioning and first results obtained.

INTRODUCTION

The Intense Beam Experiment is a linear Paul trap similar to the Simulator of Particle Orbit Dynamics (S-POD) system at Hiroshima University. Using an electric rf quadrupole which focuses and defocuses a bunch of ions in time, the transverse dynamics of this system are equivalent to the strong focusing systems in quadrupole focusing channels of accelerators. The equivalence between this system and that of a linear focusing channel has previously been well established [1–4]. This method of rf electric focusing produces equations of motion which take the form of Matthieu equations, analogous to those in a strong focusing accelerator channel.

Previous studies with linear Paul traps have addressed topics in high intensity beam dynamics such as halo formation and long term stability [6], parametric resonances [5] and resonance crossing [7, 8]. IBEX will address questions pertinent to next generation high intensity hadron accelerators, particularly those of fundamental interest in accelerator physics that are challenging to study in existing facilities due to the requirement for a wide parameter range or the combination of high intensity with intentional losses. For example, studies of integer and half integer resonance mechanisms at low and high intensity, lattice stability and collective effects and in the future implementations, tests of novel accelerator concepts such as non-linear integrable optics (NIO).

Experiment Overview

Ions are created *in situ* inside the vessel by means of electron ionisation of low pressure Argon gas.

Ion Number The total number of ions N_i created from the electron gun per unit time is a function of the effective interaction length L, the electron current i.e. electron number per unit time dN_e/dt and the number density of the Argon gas. Assuming a pressure of 2.7×10^{-7} mbar, so $n_a = 6.678 \times 10^{15}\mathrm{m}^{-3}$, an electron current of $100\,\mu$A, an effective interaction length of 5 mm which is the inscribed radius between the four rods and a cross section of $\sigma = 2.33 \times 10^{-16}\mathrm{cm}^2$, Eqn. 1 gives 4.86×10^8 ions created per second.

$$\frac{dN_i}{dt} = \frac{dN_e}{dt} n_a L \sigma \tag{1}$$

Not all of the ions produced will be trapped, but this is more than sufficient given an expected ion number range of $10^5 - 10^7$ required to cover the range from low to high intensity for accelerator physics studies.

Ion Trapping The produced Ar^+ ions are confined longitudinally along the trap length with a DC potential applied to two sets of shorter rods, referred to as the end caps. Ions are confined transversely using a 1 MHz sinusoidal focusing waveform. This is supplied using two synchronised channels from a LeCroy WS2052 arbitrary waveform generator, 180 degrees out of phase. The waveforms are amplified using Falco WMA300 amplifiers and applied to the two pairs of rods in the central region in quadrupole formation. In full operation mode, this waveform will also be applied to the end cap rods.

Ion Distribution After trapping, the ions are left for a period of up to 50 ms to stabilise to an equilibrium distribution. It is useful to estimate the measurable signal expected on extraction from the trap. We estimate the current expected at the Faraday cup by considering the case where 10^6 ions leave the trap at the thermal velocity. From the experience of S-POD, a temperature of roughly 0.5 eV can be expected giving a thermal velocity v_{th} in the longitudinal direction of 1095 m s^{-1}. The time taken to extract is then $2L_{\mathrm{trap}}/v_{\mathrm{th}}$ where L_{trap} is the length of the Paul trap, since ions with initial velocity away from the Faraday cup will need to make a round trip before they escape the central region. The extraction time is then 136 μs. The total charge divided by this time results in a current of 1.2 nA. This is a very low current to measure using the Faraday cup, so to improve the signal quality of the nA level ion signal, a transimpedance amplifier was implemented with a factor of 1×10^6 to allow conversion the small current to a reasonable voltage that can be observed by an oscilloscope.

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COMMISSIONING

Vacuum and Gas Pressure

The vacuum vessel (Fig. 1) routinely achieves a UHV base pressure lower than 2.0×10^{-10} mbar after a bakeout period of 24 to 36 hours at 150°C. The vessel has ample space and many ports to allow future upgrades to the experiment. Gas flow into the vessel is achieved using a remote controlled VAT Series 59 variable leak valve. This works in combination with a regulated air-conditioned room temperature to ±2°C to control temperature and pressure fluctuations in the system which would otherwise affect ion number.

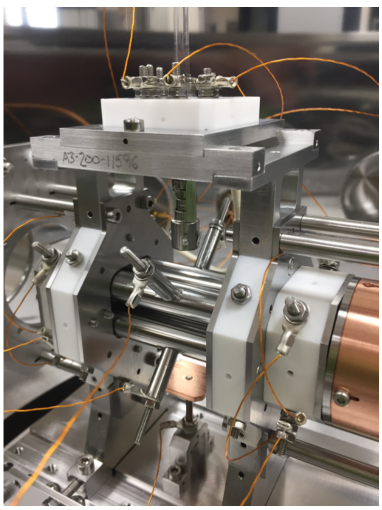

Figure 1: Close up view of the IBEX Paul trap inside vacuum vessel. The electron gun points downward between the main quadrupole rods (75 mm in length, 11.5 mm diameter), beneath which sits the electron faraday cup. To the RHS is the faraday cup and the MCP detector will be mounted on the LHS.

Electron Gun and Ionisation

The electron gun is a low cost thermionic gun from Tuoma (Japan). It is expected to produce a current of around 10 to 100 μA depending on the filament current and grid voltages. It was modelled in CST studio, as shown in Fig. 2, to ascertain appropriate grid voltage settings and then tested experimentally in a separate vacuum vessel with a phosphor screen to determine the output beam size. This established experimental control over the beam diameter from around 3 − 5 mm.

Once mounted in the IBEX vacuum vessel, the electron beam current can be measured by a small Faraday cup located beneath the rods. Note that even when the rods are unpowered, only a fraction of the beam current hits the Faraday cup, so the resulting measurement is lower than the full output current of the electron gun. Some electrons also hit the rods, so these can also be used like a Faraday cup to read electron current to provide additional insight. The electron gun faraday cup provides a relative measurement of

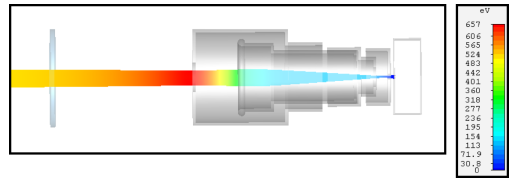

Figure 2: CST model of the IBEX electron gun in operating mode.

the current for different grid voltage settings and is used to ensure the electron gun is operating consistently for each experimental run. Experimentally, it was found that the electron gun output parameters are dependent on the argon gas pressure in the vessel. An example measurement to optimise the gun output current as a function of filament current, for varying gas pressures, is shown in Fig. 3. Note that the output current is reliably reproduced as long as consistent operating conditions are employed. In the operating region where the electron beam current changes rapidly with filament current, some systematic time-based drift in current can occur otherwise.

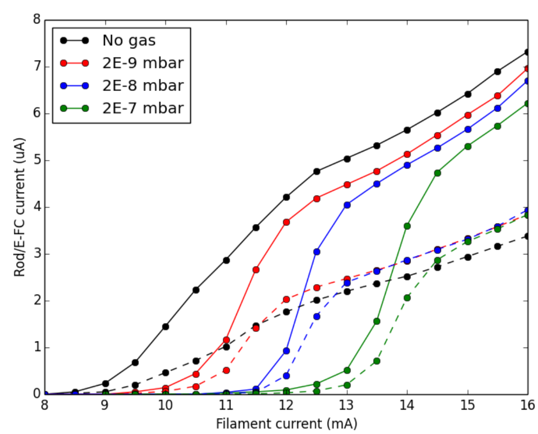

Figure 3: Variation of electron gun current as a function of filament current, measured on the electron faraday cup (dashed) and from the main rods (solid line). The output current varies with argon gas pressure.

Confinement Waveforms and DC Potentials

The main 1 MHz confinement waveform is provided by a LeCroy Wavestation 2052. After confinement, a fast switching circuit drops the DC potential on one end cap to zero to extract ions. A base level DC voltage on the main rods provides an additional push longitudinally toward the faraday cup.

During initial commissioning, it was observed that an electrical connection exists between two of the end-cap rods and the vacuum vessel, which should be electrically isolated from ground. While not preventing operation, this is expected to introduce some unwanted effects into the dynamics which reduces ion trapping efficiency and will be rectified in the near future.

Measurement of Ions on Faraday Cup

The two main diagnostics in the present system include the main Faraday cup for ion counting and at the opposing end an MCP detector and phosphor screen setup for imaging the ions directly. During the current commissioning phase only the Faraday cup was installed. First ions were trapped, extracted and observed in January 2017. Due to fast switching gate noise, the signal is determined from a difference between FC signals with and without argon gas. An example trace of the ion signal is shown in Fig. 4.

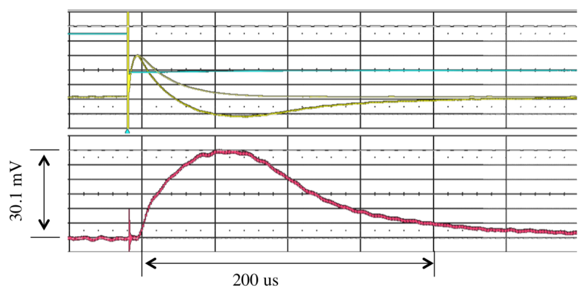

Figure 4: Oscilloscope trace of ion signal on the Faraday cup after extraction from the IBEX Paul trap. The upper trace shows timing signal (blue) and signals in yellow without (upper) and with argon gas (lower), the difference between these gives the ion signal (pink) shown on the lower trace. The noise arising from the fast gate switch can also be observed. Note that 1 mV corresponds to 0.2 nA on the vertical axis.

The ion signal will vary depending on the operating point at which trapping occurs. The operating tune can be controlled using either the waveform amplitude (voltage) V_0 or frequency f, according to Eqn. 2.

$$\nu_0 = \frac{\sqrt{2}eV_0 g}{\pi^3 m}\left(\frac{1}{f r_0}\right)^2 \tag{2}$$

where $r_0 = 5$ mm is the inscribed radius of the trapping region and g is a geometrical factor roughly equal to unity [9]. At each operating point a different number of ions will be confined stably, as shown in Fig 5. At some values one expects almost no ions (i.e. tune of 0.25) as the value is near to a resonance driven by any trap imperfections.

DISCUSSION

The experimental commissioning has proceeded well. However, a few adjustments will be made to improve operation going forward. At present, there is noise detected on the FC from the fast switching of the end caps. In addition to the signal amplifier, adjustment of the position of the faraday cup, additional shielding of cables and adjusting the switching speed should all improve this scenario to improve signal to noise ratio.

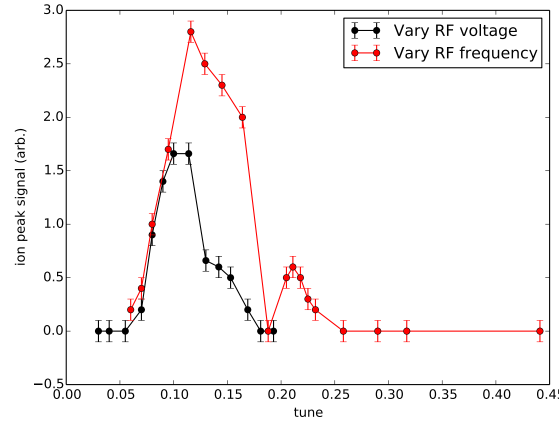

Figure 5: Variation of ion number with varying tune using either voltage or frequency to shift the operating point. The tune is the number of betatron oscillations per rf period (at 1MHz). Note that for the frequency (red) data, an additional DC bias was applied to all four rods, which increases the proportion of ions that reach the Faraday cup by providing a longitudinal velocity. Uncertainty is an estimate of oscilloscope measurement error.

To provide an additional diagnostic and information of the transverse ion distribution, an MCP detector with phosphor screen is being installed. As the MCP gain is known to saturate for high ion number, an analysis method for correcting this and extracting ion number from the resulting images has been developed [10]. The MCP will be calibrated against ion signal from the faraday cup to determine ion number.

To stabilise the number of ions trapped during the ionisation period, the usual operating scenario will include trapping at one tune value, before shifting the experiment to a chosen working point for an experimental period prior to extraction. In this way the starting ion number can be made predictable between each run of an automated set of experiments, allowing a true comparison of ion number data. This scenario will be implemented in the near future. The LabView controls will be further developed to ensure the experiment is automated, such that large parameter variations can be reached without intervention from the experimentalist.

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