Design Study of a Test Vessel to Investigate the ISIS H⁻ Penning Ion Source Plasma

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Abstract. A vacuum-vessel for extraction and source plasma analyses (VESPA) has been constructed with the aim of understanding the dominant plasma processes of negative hydrogen (H^-) ion formation in the ISIS Penning ion source. The VESPA has been designed to be simple and inexpensive, with all features of the ISIS ion source not directly responsible for plasma formation removed such that there is ample space for diagnostics close to the plasma. Diagnostics will include but are not limited to a beam current density monitor, a high resolution visible-light monochromator, a cesium mass deposition monitor, an electrostatic energy analyser, a magnetic mass spectrometer and an emittance scanner. Several existing parts and ancillary equipment are re-used to reduce costs and to speed up installation. The ultimate aim of the VESPA is to perform detailed analyses of the H^- production, cesium usage and beam formation such that an upgrade to the ion source is both well informed and possible using this setup. This report details the design philosophy, results of initial testing and future plans.

Keywords: Negative hydrogen, ion source, plasma, vacuum vessel, test stand, monochromator.
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INTRODUCTION

The ISIS Penning ion source [1] is one of the world's leading operational accelerator-based H^- ion sources for several reasons. Its high output beam current of 50-55 mA is routinely achieved with little to no tuning at start up. A discharge pulse length of 800 μs at 50 Hz repetition rate makes it one of the highest operational duty cycle (4%) ion sources. Its lifetime of three to four weeks, with a beam-off to beam-on replacement time of three hours, is highly advantageous in a user facility. There are many adjustable parameters available to ensure stable long term discharge operation and H^- beam production. Finally, 30 years' operational experience with the ion source on the ISIS accelerator has led to reliable usage and maintenance procedures.

Nevertheless, the ISIS ion source has much scope for improvement, as has already been demonstrated on the Front End Test Stand (FETS) [2]. FETS is a generic front end design for future high power proton accelerators such as an ISIS upgrade [3], a new spallation neutron source or a neutrino/muon facility [4]. FETS will demonstrate the production of a high power, high duty cycle, low emittance, perfectly chopped H^- ion beam. A comprehensive R&D program has been undertaken on the ISIS ion source for a number of years to meet the FETS requirements. As such, the FETS ion source can now produce 80 mA of H^- current, a transverse emittance of 0.3 π mm mrad, and 50 Hz, 2 ms pulse lengths (10% duty factor); albeit not quite simultaneously. This impressive improvement in performance is largely due to sequential overhaul of the beam transport components such as the post-extraction acceleration electrodes [5] and the analyzing sector dipole magnet [6], as well as the construction of high duty factor discharge and extraction power supplies. Further information on the overall upgrade strategy is given in [7].

To proceed further in the upgrade scheme, a detailed measurement of fundamental plasma parameters such as electron density and ion temperature are needed for accurate beam extraction simulations. However, plasma studies have never been undertaken on the ISIS ion source due to its compact form and the proximity to bulky beam transport systems such as the analyzing magnet. Available space and the choice of diagnostics are extremely limited. Therefore a plasma test vessel is being constructed such that the plasma is more freely accessible for study, and that room is available for new extraction and transport optics. The first version of this vacuum vessel for extraction and source plasma analyses (VESPA) has recently been commissioned and is outlined herein.

VESPA DESIGN CONCEPT

The ISIS ion source is mounted such that the beam is extracted vertically downward and then deflected 90° by an analysing dipole (AD). The AD removes electrons and also has a quadrupole field component to weakly focus the ribbon-beam into round profile for injection into the next section of beam-line. The AD is housed in a refrigerated 'cold box' which condenses cesium vapour escaping the source outlet aperture to prevent it contaminating downstream high voltage components. In order to perform plasma and extraction studies of the ISIS ion source, the AD and cold box must be removed, and ideally the ion source should be mounted for horizontal extraction. This allows diagnostics to look easily into the plasma and beam, rather than being mounted awkwardly from below or after beam loss in the AD. Once plasma studies have been completed, a new, more compact extraction system with minimal beam loss will be designed using real plasma parameters. A schematic diagram of the transition from the existing setup to the final proposed layout is shown in Fig. 1.

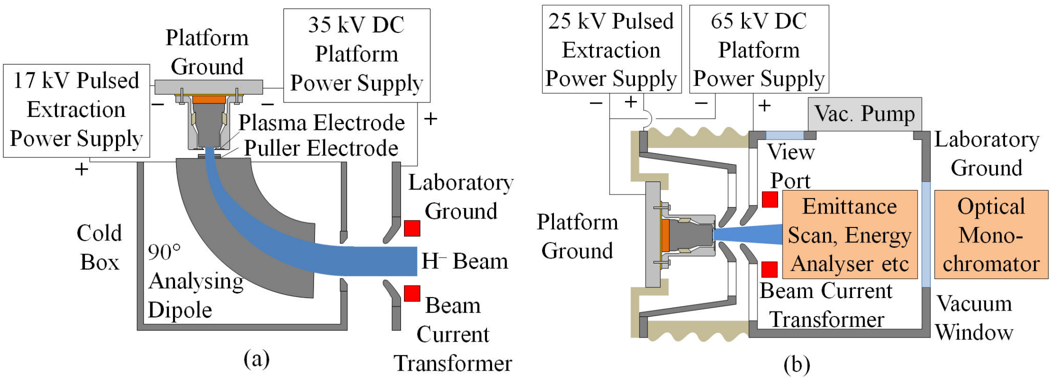


FIGURE 1. (Color online) Schematic diagrams of the existing ISIS setup (a) and the proposed VESPA Mk. 2 concept (b). Exact arrangement and voltages of VESPA extraction system yet to be finalized.

Staged Upgrade Plan

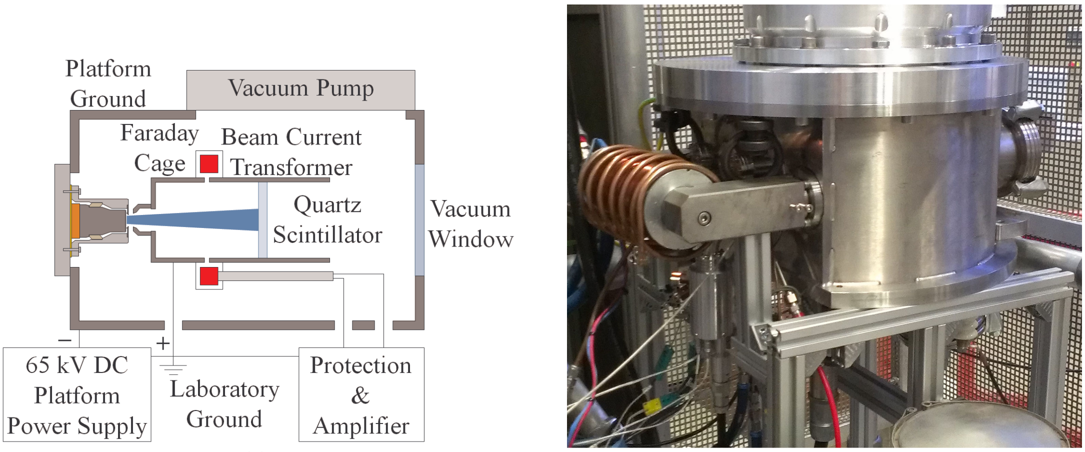
Because of the radical redesign envisioned for the ISIS ion source, it is prudent to proceed in stages. A new vacuum vessel with a horizontal mounting system will be rather expensive. In the ISIS ion source mounted vertically, molybdenum sputtered from the electrodes tends to form flakes which sometimes fall on the outlet aperture, partially blocking it and reducing beam output. If the source were mounted horizontally, the flakes may instead fall between the cathode and anode, causing an electrical short and requiring a premature source removal. Therefore, it may be found that long-term running of the ion source mounted horizontally adversely affects its lifetime. Additionally, the removal of the cold box to trap cesium may have drastic consequences in the design of the pumping and high voltage extraction systems. Cesium contamination on electrode surfaces enhances secondary emission and thus increases the likelihood of high voltage breakdown. It is already seen that significant cesium flux escapes the ion source, as evidenced by discolouration of the cold box after several months' use. Therefore it is wise to investigate whether the concept will work long-term before investing in a new vacuum vessel.

In the standard ISIS configuration, the Penning magnetic field used to drive the plasma is generated parasitically from the AD. A 'top-loading' ion source vessel was developed a number of years ago to allow for the separation of the Penning and AD fields [8]. This vessel has been recycled for use in the first stage of the VESPA project (VESPA Mk. 1). With the AD removed and the top-loading vessel tilted 90°, the ion source is now mounted for horizontal extraction, with a residual 7° beam deflection from the Penning field. Although not designed for plasma experiments and beam extraction in this manner, the Mk. 1 is capable of supporting initial investigations and yields vital information of features beneficial to design into a future Mk. 2 vessel.

VESPA MK. 1

In normal operation, the ion source mounting flange is held on a high voltage insulating column; in turn cantilevered off a vacuum pumping vessel. The 'top-loading' mounting flange is larger and forms its own small vessel, but is nevertheless still pumped downstream of the column. For use in the VESPA Mk. 1, the top-loading vessel is modified such that it can be separately pumped. To maintain a good vacuum in operation, approximately 10 ml min^{-1} of hydrogen gas must be removed from the vessel. Therefore a large 2200 l min^{-1} turbomolecular pump is mounted on the Mk. 1. When fully assembled with the vacuum pump, iron yoke and coil for the Penning magnet, the Mk. 1 weighs approximately 300 kg. A suitably robust frame is used to support the VESPA with enough space underneath for the various high voltage connections. Fig. 2 shows a diagram and a photograph of the complete Mk. 1 system.

For beam extraction, the ion source is traditionally mounted on an insulator and floated at high voltage, with the rest of the vessel at laboratory ground. This will be the scheme used on the VESPA Mk. 2. The Mk. 1, however, has no insulator as the ion source and vessel are electrically connected. Therefore, a small shielded region inside the vessel is held at laboratory ground, whilst the rest of the vessel is floated to



(a) (b)

FIGURE 2. (Color online) VESPA Mk. 1 schematic diagram (a) and hardware installed on the FETS high voltage platform (b).

high voltage. A photograph of the internal electrical layout is shown in Fig. 3. With the ion source and vessel at volts, beam is extracted from the ion source using the standard ISIS puller electrode held on insulating posts. The puller is electrically connected to a cylindrical Faraday cage, isolated from the vessel walls with more insulating posts. Within the cage, the beam drifts through a Bergoz AC current transformer (ACCT) toroid to measure the extracted current, before being intercepted by a quartz scintillator to measure its profile for comparison with simulations [9]. The Faraday cage is perforated with 2 mm holes for vacuum pumping. The differential ACCT signal is sent to an amplifier through two high voltage feed-throughs. To prevent damage to the amplifier from high voltage breakdowns, a protection box comprised of spark gaps and back-to-back zener diodes ensures all signal voltages above 15 V are safely shorted to ground. The ACCT is calibrated with a test turn to ensure the amplifier signal is not affected by stray capacitance in the protection circuit.

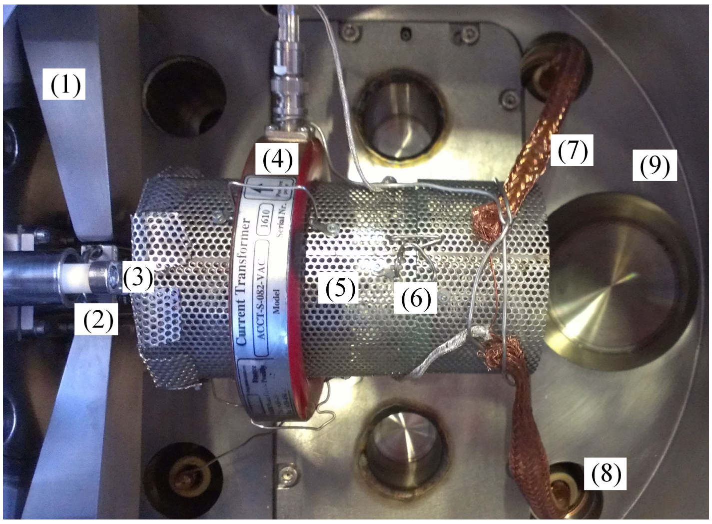


FIGURE 3. (Color online) Internal layout of the VESPA Mk. 1. Components include: Penning magnet (1); ion source (2); puller electrode (3); ACCT (4); Faraday cage (5) with internal quartz scintillator (6); screened signal cables (7); high voltage feed-through (8), and vacuum vessel at high voltage (9).

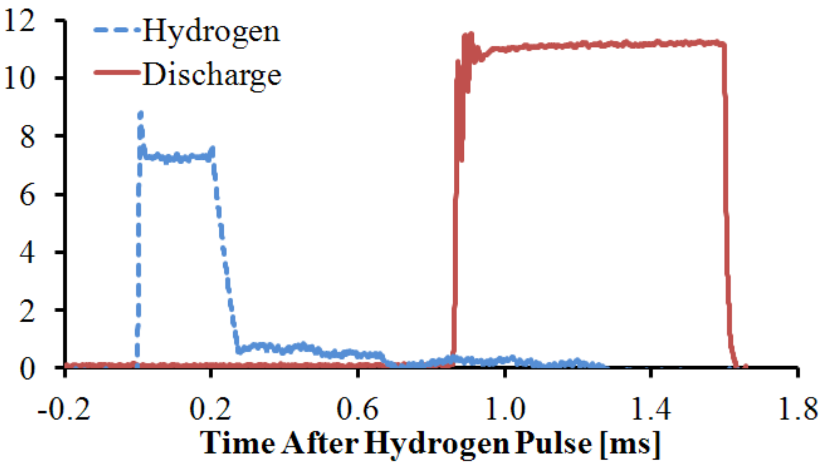


FIGURE 4. Stable pulsed discharge operating on the VESPA Mk. 1. Discharge (solid line) is struck 600 μs after the hydrogen (dashed line) is injected to allow time for the gas to travel from the valve to the plasma. Vertical scale gives discharge current in amps and voltage applied to piezoelectric valve.

Operational Discharge Plasma

Stable running of a high current pulsed discharge on the VESPA Mk. 1 has been achieved, as shown in Fig. 4. Operating the source in the horizontal position with a large turbo pump in close proximity, and without the available magnetic flux afforded by the analysing dipole, makes initial start-up of the discharge more difficult. The operating speed of the turbo pump must be reduced by 40% to prevent the hydrogen being removed too quickly. However, once in pulsed mode, a stable discharge is possible under a wide range of conditions. Unfortunately, as sometimes happens with ISIS operational ion sources, the source tested in the VESPA cannot operate stably in pulsed mode without a small ‘keep alive’ DC voltage. This means that a large DC electron current is extracted which acts as a drain in the charging circuit of the 65 kV power supply, limiting the available voltage to 3 kV. Therefore at the time of writing, the voltage is too low for accurate measurement of the pulsed H^- beam current.

Emission Spectroscopy

To further some vacuum ultraviolet spectroscopy measurements made in collaboration with the University of Jyväskylä, an Horiba Jobin Yvon FHR1000 monochromator has been purchased with a wavelength resolution of 0.01 nm over a range from 200-900 nm. Two exit ports allow either a photomultiplier tube to study emission variation in time during a plasma pulse, or a CCD camera to study emission variation in position across the plasma. When fully calibrated, the system will be used to measure fundamental plasma parameters [10, 11]. Emission line width variation caused by Doppler and Stark broadening will be used to measure atom temperature and ion density, respectively. Good signal to noise will allow accurate intensity ratio measurements of hydrogen Balmer lines, cesium, molybdenum, molecules and impurities to determine the electron temperature. Fig. 5 shows the improvement in quality of data to be expected with the new monochromator, compared with the Stellarnet CCD spectrometer used in an initial plasma spectroscopy study [12].

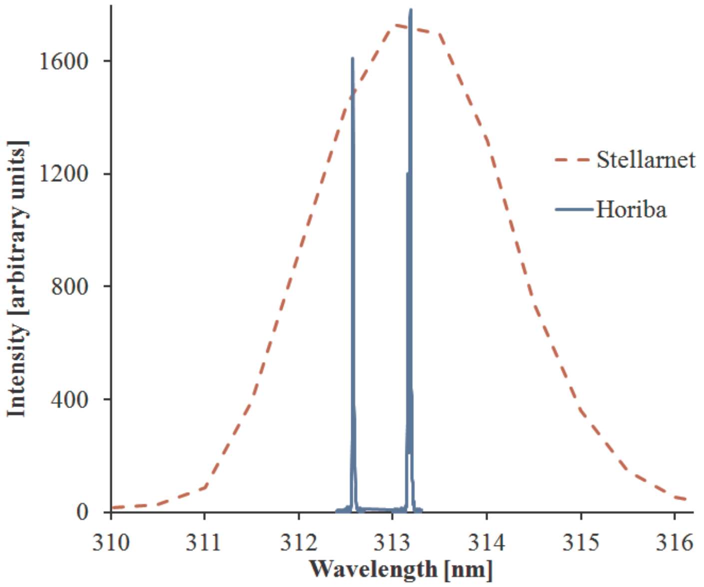


FIGURE 5. Measurement of the atomic emission lines near 313 nm in a mercury test lamp. Dashed line indicates measurement using the CCD-based spectrometer used in [12]. Solid line indicates measurement with new monochromator. The monochromator has 50 times greater resolution and easily resolves the doublet at 313.156 nm and 313.184 nm, just visible at the given scale of the plot.

Lessons Learnt to be Implemented in the VESPA Mk. 2 Design

The removal of the analysing dipole magnet and ‘cold box’ means that no cooling of the extraction optics is in place on the Mk. 1. A large extracted electron current heats the extraction system. Either a dedicated electron dump or cooling channels are required. The ion beam extraction simulation code IBSimu [13] is used to design an electron dump, shown in Fig. 6. In the standard ISIS extraction system, electrons deflected by the 0.2 T Penning magnetic field do not terminate on a specific dump. They travel far from the extraction region, causing noise, drain currents, secondary emission, breakdown and heating elsewhere. Using ferromagnetic material in the puller electrode shapes the magnetic field lines such that all electrons are guided onto the puller, which would then have dedicated cooling in the VESPA Mk. 2.

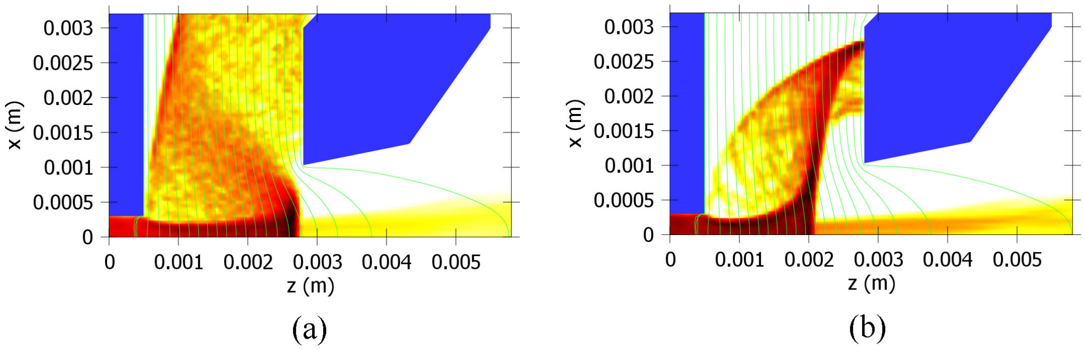


FIGURE 6. (Color online) Simulation of extracted H⁻ ions (pale) and electrons (dark). Standard ISIS extraction (a) and modified ferromagnetic puller onto which the electrons are dumped (b).

Access into the VESPA Mk. 1 is accomplished by removing the vacuum pump. In its current location this is acceptable as a crane is readily available and the pump can simply be lifted vertically. However in the Mk. 2, it would be wise to implement access hatches that do not require the use of a crane.

The VESPA Mk. 1 has shown that the vacuum configuration is important to source operation. Adequate pumping speed must be made available, with the ability to reduce the pumping speed if necessary.

For the short timescale and small budget VESPA Mk. 1 test, the extraction voltage is generated with the external FETS 65 kV DC power supply (DCPS). In normal FETS operation, a dedicated pulsed power supply is used to extract beam at lower energy before the DCPS post-accelerates up to full beam energy. The pulsed extraction power supply is based around a 25 kV tetrode valve which is able to withstand high electron current loading on the puller electrode as it only operates for relatively short periods (~1 ms) of the 50 Hz cycle. On the other hand, the DCPS only needs a capacitor large enough to prevent voltage droop during the beam pulse, so ordinarily operates with a DC current drain below about 4 mA. Using the DCPS for extraction puts a much larger demand on the power supply. Learning from this, the VESPA Mk. 2 will again use a multi-stage extraction system. A pulsed, medium voltage power supply able to tolerate high currents will initially extract beam; a higher voltage DC power supply will accelerate the beam to full RFQ input energy.

CONCLUSIONS AND TIMESCALE FOR VESPA MK. 2

The first version of the vessel for extraction and source plasma analyses (VESPA Mk. 1) has been successfully used to support a pulsed discharge in an ISIS ion source. Initial extraction tests show a large co-extracted electron current which prevents measurement of produced H^- beam; plans are in place to address this. However, this experiment is the first to run the ISIS ion source with horizontal extraction and insight has been gained about stable running of the plasma in this configuration. The plasma discharge ignites immediately but takes a little longer to warm up into high current pulsed mode than normal. Although the unusual high voltage arrangement of the Mk. 1 is not suitable for complete extraction and beam studies, its compact footprint and the transferral of existing ancillary equipment has expedited commissioning.

New laboratory space will become available by the end of 2012, allowing commencement of plasma spectroscopy studies with the high resolution monochromator. This laboratory will become a dedicated accelerator ion source plasma test facility at ISIS and the monochromator will be the workhorse diagnostic tool. Design of the VESPA Mk. 2 will begin in the Winter of 2012 after the measurement campaign is complete on the Mk. 1. The complete timeline for mechanical design, physics approval and manufacturing is expected to be complete for installation in the new laboratory by the Autumn of 2013. As well as the new vacuum vessel and support stand, a compact suite of beam diagnostics is required. Diagnostics on the Mk. 2 will include transverse emittance scanning, profile measurement and a magnetic particle mass analyser. To measure the emittance of the small extracted beam may require the design of emittance scanners with higher resolution than the existing slit-slit scanners used at ISIS. A method to measure cesium deposition rates and usage will also be required if the ‘cold box’ is to be permanently removed from the extraction system, as enhanced lifetime is a key factor in ion source operations at ISIS. Equally, the Mk. 2 will be required to mount on existing flanges in the ISIS linac, which will influence the design and placement of diagnostics.

Although still in its infancy, the VESPA program has already shown that the ISIS ion source can operate in a different orientation and with a different vacuum pumping regime. Items that collimate the beam after extraction are removed. Therefore, once a pulsed discharge operates stably with no additional DC component, a significantly higher H^- beam current than usually measured is expected. The successful operation of a pulsed discharge on the VESPA Mk. 1 gives confidence that the principle is sound, meaning the design of a Mk. 2 can commence. This being the case, many more interesting findings are anticipated using the VESPA in the future.

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