DIAGNOSTIC DEVELOPMENT OF GAS DELIVERY AND VIEWING SYSTEM FOR ANALYSING THE ELECTRIC FIELD STARK EFFECT ON H-ALPHA LIGHT EMISSIONS CLOSE TO A PLASMA EXCITATION ANTENNA

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Abstract

Fusion—the process that powers the sun—offers the possibility of a clean and abundant source of energy in a world where alternatives rely on dwindling resources or struggle to generate reliable base load power. On earth, attaining fusion requires magnetic confinement of hydrogen plasma (the fourth state of matter) heated to many millions of degrees. Advanced diagnostic tools are used by scientists to probe and understand the physics of such magnetically confined high temperature plasmas.

This project describes the development of a gas injection and associated optical spectroscopic imaging system for study of radio frequency electric fields in the sheath of an unshielded fast wave heating antenna on the H-INF (H-1) plasma confinement facility at the Australian National University. It is proposed that measurements of the Stark splitting and polarisation of Balmer-alpha light emissions emanating from a supersonic hydrogen gas beam injected into the plasma volume directly under the antenna system could be used to give information about the sheath field and a better understanding of near field ion heating effects. The primary work of this thesis concerns the development and testing of the gas delivery system and the positioning and validation of the related viewing apparatus.

The gas injection system was designed for high speed, short gas bursts with limited fluences in order minimise the perturbation on the plasma. It was also developed with a view to reducing the spread of the injected beam, as much as possible, by tailoring the geometric characteristic of the nozzle. To test theoretical expectations related to nozzle design, a method for characterising the gas beam was developed, that involved a sweeping orientation-tracked anemometer system installed in a vacuum test tank. The nozzle characterisation results showed that the delivered flow rates were consistent with theory and that the directionality and localisation of the beam was an improvement upon previous nozzles implemented on H-1.

The plenum/nozzle system was installed at a location above the heating antenna and plumbed out to a gas hub, allowing access to a variety of different gases. A control system for administering, managing, and acquiring data for the injector was also developed and was interfaced with the H-1 control and timing system.
The beam imaging requirements were ascertained and optimised using CAD models of H-1. Experimental images captured by the camera conformed well to modelling expectations; a clear view of the plasma volume of interest under and around the antenna was obtained. Images were obtained for a number of gases injected into various plasma configurations. The illumination of an electron beam, produced by an electron gun inserted in the closed magnetic volume, could be used to confirm the viewing geometry. The scope of this thesis work did not include spectroscopic or polarisation-based imaging. For appropriate injection conditions, it should be noted that the puffer could also be used as a gas fuelling device.
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<table>
<thead>
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<th>Description</th>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>ADC</td>
<td>Analogue to Digital Converter</td>
</tr>
<tr>
<td>ANU</td>
<td>Australian National University (ANU)</td>
</tr>
<tr>
<td>APERF</td>
<td>Australian Plasma Fusion Research Facility (APFRF)</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Drawing</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge Coupled Device</td>
</tr>
<tr>
<td>CF (flange)</td>
<td>ConFlat (flange)</td>
</tr>
<tr>
<td>DAQ</td>
<td>Data Acquisition</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>D-T reaction</td>
<td>Deuterium – Tritium reaction</td>
</tr>
<tr>
<td>EDM</td>
<td>Electric Discharge Machining</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width Half Maximum</td>
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<tr>
<td>H-1NF or H-1</td>
<td>Heliac (H-1 Stellarator) – National Facility</td>
</tr>
<tr>
<td>H-alpha</td>
<td>Hydrogen alpha (n=3 to n=2 emission photon)</td>
</tr>
<tr>
<td>HMI</td>
<td>Human Machine Interface</td>
</tr>
<tr>
<td>HW</td>
<td>Helical Winding</td>
</tr>
<tr>
<td>HWHM</td>
<td>Half Width Half Maximum</td>
</tr>
<tr>
<td>ICCD</td>
<td>Intensified Charged Coupled Device</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IVC</td>
<td>Inner Vertical Coil</td>
</tr>
<tr>
<td>LCFS</td>
<td>Last Closed Flux Surface</td>
</tr>
<tr>
<td>MHD</td>
<td>Magnetohydrodynamics</td>
</tr>
<tr>
<td>NTSX</td>
<td>National Spherical Torus Experiment</td>
</tr>
<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
</tr>
<tr>
<td>OVC</td>
<td>Outer Vertical Coil</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PFC</td>
<td>Poloidal Field Coil</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional, Integral, Derivative (control loop)</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse Width Modulated</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>SS314</td>
<td>Stainless Steel type 314</td>
</tr>
<tr>
<td>TFC</td>
<td>Toroidal Field Coils</td>
</tr>
<tr>
<td>TTL</td>
<td>Transistor – Transistor Logic</td>
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Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signature: ______________________

Date: 9 June 2020
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Chapter 1: Introduction

Fusion technology offers an amazing opportunity to generate clean base load energy. Reaching this goal is reliant on understanding the physics underpinning this technology, with one of the most important aspects being how plasma behaves while attempts are made to contain it. To start with: a brief overview of the energy landscape.

1.1 OUR CURRENT ENERGY MIX

Energy plays a vital role in society. Its importance is evident in the acute difficulties its continued generation and accessibility creates for many of our most advanced societies. Examining the advantages and shortcomings of the energy systems we rely on today shows that research into new forms of energy production is an important step towards generating clean base load power. A fusion reactor represents one of these possibilities.

The 2010 global energy make-up, as seen in Figure 1-1, consisted of fossil fuels, including oil, gas and coal, at 81.1%; biofuels and waste at 10%; hydroelectricity at 2.3%; nuclear (fission) at 5.7%; and all others, including renewables such as solar, wind and geothermal, at 0.9% (IEA Key World Energy Statistics 2012).

Figure 1-1: World energy usage (IEA Key World Energy Statistics 2012).
The largest component in our energy mix, the burning of fossil fuels, produces energy on demand but relies on non-renewable resources. Estimations of when these will run out vary, but it is clear that eventually they will exist in too small a quantity to be a viable option for our energy future. The process also produces by-product pollutants that are released into the atmosphere with strong evidence they contribute to global climate change.

Hydroelectricity is relatively easy to produce, the main requirement being a dam that releases water to drive large generators (Chen 2011). The power is on-demand, but drawbacks include displacement of wildlife and landscape inundation and, importantly, the number of acceptable sites around the world is limited.

Geothermal energy has been affected by a high capital expense and is by no means clean in itself with a variety of emission's that, dependant on the location, can be comparable to fossil fuel plants (Chen 2011).

Tidal/wave energy produces renewable energy predictably, but its drawbacks include damage to environment and limited locations. (energyinformative.org)

Other renewables, such as wind and solar, are valuable sources of clean energy, but their variable nature cannot produce on demand power. ‘The problems of energy storage, transmission and load levelling are overwhelming’ (Chen 2011, p. 94). Great advances are occurring in these fields, and they will continue to contribute to our energy needs, but there remains an unmet requirement for clean base load power.

Nuclear Energy is produced commercially through fission reactors, making up 5.7% of usage from the IEA statistics. This nuclear technology can produce large amounts of on demand power from an abundant fuel source. Pollutant by-products, such as carbon emissions, are extremely low, but other waste products have very long radioactive half-lives and require long term storage solutions. Due to some well publicised accidents a strong public perception of danger is attached to the running of these facilities, although new generation technology does promise improved safety in this area.
1.2 NUCLEAR ENERGY THROUGH FISSION

Nuclear energy, as it is produced today, is the product of nuclear fission. This process involves the splitting of an excited uranium nucleus into two approximately equal massed fragments and two or three neutrons. The binding energy per nucleon vs. mass-number curve seen in Figure 1-2 shows how the reaction produces energy.

Uranium has a mass number of 238 and a binding energy per nucleon of 7.6 MeV. At the point where the atomic mass number is about half the mass number of uranium ($A \approx 120$), the binding energy per nucleon is close to 8.5 MeV. When a high energy particle collides with and splits a uranium atom, the excess binding energy is released as radiation and the kinetic energy of the new particles (Enge 1966). Kinetically energised neutrons released from one split can collide with other uranium atoms inducing further splits and creating a chain reaction. The radiation energy can be used to heat water, driving steam turbines to produce electricity.

Figure 1-2: Binding energy per nucleon vs. mass number ($A$) in beta-stable nuclei. (Enge, 1966)
1.3 FISSION TO FUSION

The binding energy curve in Figure 1-2 shows that an increase in energy per nucleon is also achieved when moving from a low mass number (<56) to a higher one, that is, fusing two lighter nuclei into a heavier one (Krane 1987). To do this the two lighter particles need to have enough energy when they interact to overcome the Coulomb force. This energy is large and equates to temperatures in the order of 100 million Kelvin.

A variety of fusion reactions are possible, but the most easily accessible in terms of fusion cross-section is the deuterium-tritium (D-T) reaction (Chen 2011).

\[
\frac{2}{4}D + \frac{3}{1}T = \frac{2}{4}He + \frac{1}{0}n \quad (Q = 17.6MeV) \quad (1.1)
\]

The resultant kinetic energy of this reaction is split between the helium nucleus and the neutron. The helium particle’s energy can be used to keep the reaction going while the neutron can be captured, and its energy converted to heat (Chen 2011). There is some radioactivity induced as a result of the neutron present in this reaction, however, it is in the order of 1000 times less than an equivalent fission reaction, and some of the other fusion reactions promise even less.

For the fuel sources, deuterium can be readily extracted from sea water. Tritium is less abundant and requires additional complexity added to the reactor in the form of a lithium component that breeds tritium when bombarded with neutrons. The reaction has some challenges, but its successful implementation would be an important step towards harnessing other more difficult fusion reactions such as deuterium-deuterium (D-D).

\[
\frac{2}{1}D + \frac{2}{1}D = \frac{3}{1}T + \frac{1}{0}H \quad (Q = 4.03MeV) \quad (1.2)
\]

\[
\frac{2}{1}D + \frac{2}{1}D = \frac{2}{4}He + \frac{1}{0}n \quad (Q = 3.27MeV)
\]
1.4 PLASMA AND MAGNETIC CONFINEMENT

Something that all fusion reactions share is the energy required to overcome the Coulomb force and, therefore, the extreme temperatures required for the reactions to take place. At a temperature of 100 million Kelvin (required for D-T) the reactants exist in a state called “plasma”, sometimes referred to as the fourth state of matter. Plasma is an ionised gas and occurs when the thermal energy of a sample is large enough to dissociate ions and electrons, leaving a quasi-neutral fluid with a tendency to maintain electrical neutrality, characterised by the charge balance condition:

\[ n_i \cong n_e \]  

Where the density of free positively charged ions \( n_i \) are balanced by that of free negatively charged electrons \( n_e \).

“We shall use the name 'plasma' to describe this region containing balanced charges of ions and electrons” (Langmuir 1928, p. 628).

The nature of Plasma makes it very difficult to contain. High energy plasma colliding with the container wall would create deterioration and damage to the container material and possibly destroy the plasma itself.

A solution to this confinement problem comes from the fact that magnetic field lines apply force to moving charged particles. Appropriate manipulation of magnetic field lines can form a "magnetic bottle”, from which it is difficult for charged particles to escape. However, difficulties still exist as magnetic field inhomogeneity and self-consistent internal electric fields can transport the particles across field lines and out of the confining volume.

Many magnetic bottles have been investigated over the years including open ended systems, such as a dual mirror. The dual mirror design can be most simply imagined as a cylinder of length-wise oriented field lines pinched at the two ends of the magnetic tube. Pinched field lines create a region of high field intensity that acts to reflect the particles back toward the centre of the bottle.
Chapter 1: Introduction

Figure 1-3: A magnetic bottle showing trapped charged particles. In the dual mirror design they will move helically along the field lines between the two pinched ends (Fitzpatrick, 1998)

Closed toroidal system magnetic bottles include stellarators and tokomaks. (Miyamoto 2005). Toroidal systems retain charged particles by moving them along helical field lines that cycle around a torus, as seen in Figure 1-4. These helical pathways are a combination of toroidal and poloidal field lines. The toroidal field is generated by a set of electromagnetic coils. The way the poloidal field is generated defines the difference between a stellarator and a tokomak. A tokamak achieves a poloidal field by induction of a toroidal plasma current (Figure 1-4b), whereas in the stellarator it is achieved by additional helical windings. (Miyamoto 2005)

Figure 1-4: Magnetic field components as part of a closed toroidal bottle a) shows the toroidal field component of a toroidal Confinement System b) shows the poloidal component c) shows an example of a resultant field line which a charged particle might travel along. (The National Academies 2004)
1.5 PLASMA HEATING

There are a variety of ways to heat plasma to fusion relevant temperatures.

- Magnetic compression can be used in much the same way as a gas is heated when compressed. An increase in the magnetic field confining the plasma will force the particles closer together and consequently heat them.

- Ohmic heating results from inducing a current in the plasma with an electric field. Electrons accelerated by this field collide with and pass energy on to ions. As a plasma heats, the resistance of the plasma reduces making this method less effective (Eliezer 2001)

- High energy neutral beams can be injected into the plasma where they are ionised and pass on energy to the rest of the plasma body through Coulomb collisions (Miyamoto 2005).

- Electromagnetic wave heating can be applied through use of an external antenna system that couples high frequency electromagnetic waves to the plasma. (Miyamoto 2005). Ions and electrons in the plasma have different cyclotron resonance frequencies (related to their Larmor orbits).
  - Ion cyclotron antenna systems are located close to the plasma surface and are subjected to significant ion collisions during their working life.
  - Electron cyclotron heating is obtained using gyrotron generators at much higher frequencies (many GHz) with the radiation coupled via waveguides or launch horns located outside the plasma.
  - Additionally, lower-hybrid-heating involves radiation between the ion and electron resonances that generate current drive heating via ohmic mechanisms. (Chen 2011)

1.5.1 Shielding effects

Because plasma consists of free charged particles, electric fields are not generally supported within the plasma body. When an electric field is applied, the charged particles (predominantly the lighter electrons) respond to shield the E-field, in a process known as Debye shielding. The response time is in the order of the inverse of the electron plasma frequency:
\[
\omega_{pe} = \sqrt{\frac{n_e q_e^2}{m_e \varepsilon_0}} \tag{1.4}
\]

where \(\omega_{pe}\) is the electron plasma frequency, \(n_e\) is the number density of electrons \((m^{-3})\), \(q_e\) is the elementary charge \((C)\), \(m_e\) is the electron mass \((kg)\), and \(\varepsilon_0\) is the electric constant permittivity of free space.

If a biased probe is inserted into a plasma, a screening region is set up around that probe called a sheath (Bellan 2008). The electric potential change across this region ensures a close to zero E-field in the plasma body. The extent of the sheath is of the order of the Debye length, which is dependent on the thermal speed according to:

\[
\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{n_e q_e^2}} \tag{1.5}
\]

Where \(\lambda_D\) is the Debye length \((m)\), \(k_B\) is Boltzmann constant, and \(T_e\) is the electron temperature.

At typical fusion plasma temperatures of \(10^8 K\), and densities of \(10^{20} m^{-3}\), the Debye length will be in the order \(10^{-4} m\) or 0.1 mm.

Importantly for heating, if the frequency of the applied field is greater than the plasma frequency, the electrons cannot effectively follow and undertake cancellation allowing the applied electromagnetic waves to propagate through the plasma to the resonance region, where their energy can be absorbed.

1.6 PLASMA INSTABILITIES

It is well known that ubiquitous plasma instabilities compromise efficient plasma confinement in closed magnetic field systems. The problem is exacerbated at high temperatures because of the steep pressure gradients in the system delivered by the high energy particle beams and electromagnetic waves used for plasma heating. (Horton 2012)

The charged particles of a plasma can act in collective ways to escape their confinement. An example of this phenomenon in fluids is the Rayleigh-Taylor
instability that allows a liquid to overcome atmospheric force and escape a container when turned upside down (Chen 2011). Small perturbations in the liquid surface create uneven force distribution. The growth of those perturbations allows the liquid to quickly find an escape path.

Similarly, any initial disturbance or perturbation in a plasma domain will result in propagation to the surrounding elements. The collective motion related to a particular displacement can be stable or unstable: stable if the motion is quickly corrected by the system (damped), or unstable if the disturbance produces positive feedback that amplifies the initial perturbation. (Elizer 2001).

There are several different plasma instability types, and they all act to increase the diffusion of particles from the plasma, lowering its confinement time. They can be broadly split into two categories: macroscopic and microscopic.
• Macroscopic instabilities can be studied and understood through magneto-hydrodynamic (MHD) equations. They have relatively fast growth rates and so pose a greater risk to the continued confinement of a system (Fitzpatrick 1998). Diffusion in these cases is generally based on classical effects, such as kink instabilities that were understood early in plasma confinement studies. Those based on neoclassical effects, such as banana instabilities, were not initially foreseen but eventually understood enough to apply rules in relation to torus geometry, such as quality factor or aspect ratio that could minimise their effects (Chen 2011).

  o Quality factor: A function of the number of times field lines traverse toroidally vs poloidally.
  o Aspect ratio: A function of a torus's large radius vs small radius.

• Microscopic instabilities are slow growing and are responsible for things like turbulent transport. They cannot be treated by MHD, are generally less well understood, and are responsible for many of the setbacks to fusion power as scientists and engineers have endeavoured to understand and control how they affect diffusion rates and confinement time.

1.7 THE H-1NF (H-1) FACILITY

The H-1NF (H-1) is a confinement facility located at the Australian Plasma Fusion Research Facility (APFRF) at the Australian National University (ANU). It is a general research facility for the study of plasma confinement and fusion research with a toroidal helical-axis stellarator at its core. The unit is designed with coils fully enclosed in a large vacuum chamber with a volume of approximately 33m$^3$ and has been termed a “coil in tank” design (Hamberger 1989). The chamber design allows for easy diagnostic access to the plasma via ports in the wall of the vessel, although the small plasma volume of about 1m$^3$ by comparison to the overall vessel volume can lead to some difficulties with density and impurity control. (Collis 2007)

The plasma confinement volume has a major radius of 1m and a minor radius of 0.15-0.2m. The magnets consist of a central conductor poloidal field coil (PFC) (central conductor) as well as 36 toroidal field coils (TFC) arranged in a toroidal helix that loops around the central conductor three times (Hamberger 1989). There is an
additional helical winding (HW) that wraps around the PFC in phase with the TFC’s. The HW provides additional control of the rotational transform and magnetic shear. Vertical field coils, both inner (IVC) and outer (OVC), are used to control the vertical magnetic field with major radius (Shats, 1994).

The field coils are capable of generating a steady state magnetic field strength of up to 0.25 Tesla through use of a 250kW motor generator to supply 2500A at 100V, or up to 1T by using a 1.4MW dual pulsed power supply with a flat top time of up to 0.5s. (S. Kumar 2007). Precise control of the primary (TFC) and secondary (PFC) currents, combined with various taps and shunts, allows access to a wide range of magnetic configurations. H-1 is therefore ideal for fundamental research of plasma confinement in stellarator fields, allowing exploration of both favourable and unfavourable magnetic features.

![Figure 1-7: Breakout view of the H-1 heliac stellarator facility in Canberra Australia](image-url)
1.7.1 Magnetic configurations

The two main configuration control parameters on H-1 are achieved through variation in HW or OVC current in relation to PFC current (Kumar 2009). The horizontal ratio, given by $\kappa_h = \frac{I_{HW}}{I_{PF}}$, affects the flux surfaces rotational transform $\tau$ (number of poloidal transits per toroidal transit by a field line) and shear (measure of the twisting of the magnetic field lines) (Shats 1994). The vertical ratio is given by $\kappa_v = \frac{I_{OVC}}{I_{PF}}$. The effective current in the OVC can be adjusted by varying the number of connected turns.

Configurations on H-1 include ‘standard’ ($\kappa_h = 0.0, \kappa_v = 1.0$), ‘full helical’ ($\kappa_h = 1.0, \kappa_v = 1.0$), and ‘half vertical’ ($\kappa_h = 0.0, \kappa_v = 0.5$). Figure 1-8 highlights how adjustments to the horizontal ratio on H-1 affects the poloidal cross section of magnetic flux surfaces and the rotational transform (Blackwell 2006).

Figure 1-8: Configurations on H-1 and the changing shape of the poloidal flux surfaces (Blackwell 2006)
1.7.2 Heating

The primary heating on H-1 is achieved through the application of electromagnetic waves at or above the ion cyclotron frequency. A 100kW tuneable 4-26 MHz transmitter, linked to a pair of saddle loop antennas shaped to match the last closed flux surface of the plasma, produces helicon wave heating at lower magnetic fields (<0.2 Tesla) and minority ion cyclotron heating (H/D, 0.5Tesla, 7MHz).

A gyrotron capable of 200kW pulsed power at 28GHz has also been used for second harmonic electron cyclotron heating at 0.5Tesla but is not used in this work. Using electron cyclotron heating, H-1 has produced plasmas with electron temperatures in excess of 100eV or around 1 million degrees Celsius. (Powell 2008)

Newly installed at the time of writing is a new cooled saddle-loop-type helicon antenna attached to a Thomson broadcasting system with available power of 200kW per saddle loop and capable of operating between 2-20MHz (see Figure 1-9). This new system is the focus of this development project: the gas injection system and viewing apparatus are targeted to probe and image the plasma volume directly under the antenna.

Figure 1-9: The new heating antenna on H-1

Anomalously high ion temperatures have been observed in the edge of helicon-heated argon plasmas in H-1, suggesting an unexpected ion heating mechanism (Miljak 1999) that could be attributed to stochastic ion heating in the bare RF antenna sheath (Michael 2003). Analysing the local electric fields (using RF Stark Effect) in this area could provide valuable information about possible heating mechanisms and explain the hollow ion temperature profiles.
1.8 PLASMA DIAGNOSTICS

High resolution plasma measurement systems (diagnostics) are becoming increasingly important for unravelling the complex physics of magnetically confined plasma and its various waves and instabilities. It is a broad area, and, in this thesis we concentrate on diagnostic issues most directly relevant to the gas injection diagnostic system developed, such as the spectroscopic analysis of line broadening and splitting effects.

Plasma diagnostics are tools used to measure the characteristics of plasma, such as the temperature, density, pressure, and related factors like magnetic field conditions and particle flow. These characteristics are important in understanding a plasma’s transport, energy, and momentum balance; why instabilities are created; and how they might be controlled.

Plasma diagnostics can be categorised into three categories: passive, active non-perturbative and active-perturbative. (Glass 2004)

- Passive techniques are those where radiation or particles emitted from the plasma are analysed and involve no interference with the plasma itself. Examples include spectroscopy on bound and free electrons and analysis of outward energy and particle fluxes.

- Active non-perturbative methods consist of the application of an external factor (e.g. a laser beam) that is altered by its interaction with the plasma. Interferometry and reflectometry can be used to measure electron density and its fluctuations, while electron temperature profiles can be ascertained using Thomson scattering.

- Active-perturbative methods involve the application of external tools that potentially have an effect on the plasma itself. Langmuir probes are the most common example of this type. Another 'diagnostic neutral beam injection' is the study of beam-plasma interactions through spectrographic techniques. It is the method being used in this project.

For our diagnostic system, the gas puff (made up of non-ionised gas molecules) is injected into the plasma volume under the excitation antenna. The gas molecules interact with the plasma through collisional processes causing transitions in the bound
electron energy levels that result in electromagnetic emissions. The intensity of light emitted relates to the density and energy characteristics of the populations interacting, and spectral examination can provide information on the thermal energy of plasma particles and the local electric and magnetic field.

1.9 PLASMA SPECTROSCOPY

"Spectroscopy is the study of the wavelength distribution of radiation from a sample that can be used to identify the characteristics of atoms or molecules in the sample" (Serway 1999). All atoms or molecules when excited or energised by interaction with external electromagnetic radiation will emit or absorb radiation at specific wavelengths dependent on the energy levels that electrons move between, through those interactive processes. Absorption occurring as part of a move from a lower to higher level and emission from a higher to lower.

The frequency of photons released when an electron decays from one energy state to another is given by:

\[ \nu = \frac{\left(\chi_f - \chi_i\right)}{h} = \frac{c}{\lambda} \]  

(1.6)

where \( \nu \) is the frequency of radiation emitted, \( \lambda \) is the wavelength, \( \chi_i \) and \( \chi_f \) are the energies of the two electron states, \( h \) is the plank constant and \( c \) the speed of light.

Spectral signatures can be very complicated due to the number of possible transitions that can occur from any given excited species. In laboratory plasmas, measured line intensity ratios can be used to determine the temperature of an emission source since this is linked to the populations of atomic species states. (Hutchinson 2002). The distribution of those populations can be estimated using radiative-distribution models, such as the Saha-Boltzmann equation. This equation relates the temperature and pressure of an element to its ionisation state.

\[ \frac{n_{i+1}n_e}{n_i} = \frac{2}{A^3} \frac{g_{i+1}}{g_i} \exp \left[ -\frac{(E_{i+1} - E_0)}{k_BT} \right] \]  

(1.7)
Where \( n_i \) is the number density of atoms in state \( i \), \( n_e \) is the electron density, \( \Lambda \) is the de Broglie wavelength, \( g_i \) is the degeneracy of energy level \( i \), \( \varepsilon_i \) the energy of states (energy required to remove the ‘i’ electron from the neutral atom), \( k_B \) is the Boltzmann constant, and \( T \) is Temperature.

The relationship between H-alpha photon emission and gas jet characteristics is examined by McNeill (1989), and he discusses aspects of this phenomenon and provides some estimation techniques. The Saha-Boltzmann equation in the case of H-alpha gives the photon emission coefficient:

\[
n_{32} = 1.3 \times 10^{-13} n_e^2 T_e^{-3/2} \exp\left(\frac{1.51}{T_e}\right) \text{photons/cm}^2\text{s} \tag{1.8}
\]

with \( T_e \) in eV and \( n_e \) in \( \text{cm}^{-3} \). This equation could be used to determine how different parts of a hydrogen gas jet density function relate to expected photon emission.

### 1.9.1 Line broadening mechanisms

The fact that the atom or ion energy levels are sensitive to the plasma environment implies that analysis of the spectral line shape can be a powerful tool for diagnosing the plasma. There are a number of line splitting and broadening mechanisms, including Doppler, Zeeman, and Stark effects, where the spectral emission lines broaden or split based on the atomic or local conditions experienced by the emitting atoms.

- **Doppler Broadening** is the effect seen on spectral lines due to the frequency shift affected on emitted radiation by the speed of the emitting atoms relative to the observer. It is commonly termed red and blue shifting when in the context of a bulk light emitter, such as relative galactic motion in astrophysics. The broadening effect in the case of plasma is created by the statistical spread of velocities present in a volume of light emitting atoms and can therefore be linked quite directly to the temperature of that volume or its kinetic energy distribution (Maxwellian). (Hutchinson 2002)

- **The Zeeman Effect** is due to the effect of a magnetic field on the electron energy levels in an atom or ion. The emission lines can be seen to split into three groups of components with spectral separation increasing with
magnetic field. Analysis of the line polarisations can be useful in determining magnetic field direction. Injected beams can be used to localise the emission. (Hutchinson 2002) Zeeman splitting is seen to be dominant in lower temperature, higher magnetic field situations (Michael 2003).

- Stark splitting is the electric field equivalent of the Zeeman Effect. "The atomic energy levels of an atom in an electric field are perturbed by the alteration of the form of the potential energy. States nearer the continuum are more strongly perturbed. The shift in a spectral line due to electric fields is called the Stark shift." (Hutchinson 2002). Stark broadening can also be used in lower temperature, higher density plasmas to determine electron density (Glass 2004).

In relation to this project, when hydrogen is puffed into the area of interest containing a fixed or oscillating electric field, such as in the sheath attached to an RF heating antenna, the atoms will be excited and emit photons. H-alpha emission from electron state n=3 to n=2 will be included in approximately half the cascades to ground state, and thus produce good light intensity. Due to the electric field, the atoms will be polarised, and the electronic states split resulting in a polarised multi-component H-alpha spectrum. The amount of splitting is proportional to the strength of the field, and the polarisation of the components can be used to determine the direction of the field (Fulcher 1915).

![Figure 1-10: Example of Stark effect splitting for hydrogen (starkeffects.com 2006)]
1.10 GAS INJECTORS AND MOLECULAR BEAMS

Gas injectors can be used as devices for fuelling of plasma discharges and also as part of diagnostic systems where the excited injected species is used as a spectroscopic light source.

Figure 1-11: A supersonic gas injector for the NSTX facility showing the nozzle and valve assembled and cut-out of nozzle design (Soukhanovskii 2004).

An operational example of gas injectors on a plasma facility is the 'Supersonic gas injector' on the National Spherical Torus Experiment (NSTX). It can be used for both fuelling and diagnostic applications, including localised impurity gas injections for transport and turbulence determinations as well as edge helium spectroscopy. (Soukhanovskii 2004). The Soukhanovskii nozzle shown in figure 2-10 was made using a technique of moulded graphite and is Laval-shaped in design so as to minimise gas dispersion and to produce a directional beam. The valving system is based on piezo technology for fast opening times and high frequency use.

1.10.1 Injector development for H-1

A previously developed injector implemented on H-1 was a helium gas molecular-beam system (Andruczyk 2005) that produced a highly collimated pencil-like free jet by inserting a gas skimmer downstream of the nozzle opening. The skimmer passed only the central core of the gas puff thereby creating a highly collimated beam of particles. Before installation on H-1, this injector was characterised.
in a test tank using a movable, fast ion gauge. The system was used to measure the plasma density and temperature using the atomic helium line-ratio technique (Collis 2009).

A non-skimmer gas injection system was also designed, characterised, and installed on the H-1 (Collis 2007) and additional upgrades undertaken to it in a subsequent project (Powell 2008). The Collis injector was a double conical nozzle piezo valve design that injected a supersonic gas stream at flow rates in the order of $10^{20}$ particles/s. The characterisation of the beam was undertaken in a test tank with use of a multi-wire hot wire anemometer setup. The rate of particle injection in Collis's injector was found to be too high for the purposes of diagnostics due to perturbations induced in the plasma (Powell 2008). Powell undertook a redesign of the nozzle dimensions to reduce the gas flux and developed additional methods for characterising the resultant beam. He also explored the effects of gas puff modulation on the plasma light emitted from the target region.

This project undertook a similar conical nozzle design as the Collis/Powell version but with further adjustments to minimise flowrate and beam spread. The characterisation methodology was altered as per Powell’s design with the implementation of a single filament hot wire anemometer setup that could be tracked as it moved through the gas stream. Control system development for both the testing and H-1 experiments as well as successful development and implementation of a paired imaging system was also undertaken. Images of the resulting gas puff’s interactions on various H-1 states can be seen in Section 3.2 and show the successful positioning and control of the resultant nozzle and imaging apparatus.
Chapter 2: Injector Design

The design of the gas injector can be neatly broken into three main parts. The nozzle and its requirements for flow and directionality, the valve and its speed and repeatability, and the plenum component for holding the required gas volume and allowing feedthrough of control wiring.

A variety of theoretical and modelling techniques were used to direct design decisions and to compare against results from characterisation work. Topics in gas dynamics, aspects of piezo technology, fast speed valve design, and anemometry techniques were all used to support the final outcome.

Characterising the gas injector required setup and development of a vacuum test tank, including a variety of diagnostic data collection items to measure aspects of flow and beam dispersion.

2.1 NOZZLE DESIGN

A variety of nozzle shapes were examined, including free jet, conical, Laval, and aero-spike (see Figure 2-1).

![Figure 2-1: Examples of nozzle types and their gas divergence (a) free-jet (b) Laval (c) conical or convergent-divergent (d) aero-spike (Soukhanovskii 2004)](image)
Free jets are simple to manufacture but provide little directional control, unless used in conjunction with a collimation skimmer. The aero-spike is a more complicated design to model and manufacture, especially if considering small flow rate targets. Laval and convergent-divergent were considered more feasible options. A smoothly curving Laval-style nozzle shape offers good directionality and can be designed to give a good degree of flow uniformity across any particular cross section point along the nozzle but presents some manufacturing challenges. A convergent-divergent design compromises between gas beam concentration and manufacturing difficulty. Available manufacturing techniques and time frame considerations made the convergent-divergent option preferable.

A gas injector previously designed and tested on H1 for the purpose of fuelling (Collis 2007) incorporated convergent-divergent nozzle inserts. These nozzles were seen to inject too much gas at too wide an angle for the diagnostic purposes of this project. It was considered advantageous to maintain the mechanical form of the insert in designing a new a nozzle of smaller throat dimensions and tighter divergence angle. This arrangement would allow the previous nozzle to be inserted for any possible future work involving fuelling.

2.1.1 Modelling flow

Designing a plasma gas injection system relies on an understanding of the desired interaction outcomes and then how an estimated puff will fulfil those outcomes. The desired puff character can then be targeted through modelling various nozzle dimensions.

Restricting gas dispersion to below a full width spread of 20 degrees was postulated, maximising the proportion of beam directed toward the last closed flux surface (LCFS) from the puffers likely positioning above the H-1 antenna and at least 10cm from the average plasma boundary to avoid impinging on any plasma volume configurations (Collis 2006).

H-1 produces a \(1m^3\) plasma with densities around \(2.3 \times 10^{18} m^{-3}\) and a particle confinement time of 2-3ms. This means a loss rate of \(\approx 10^{21} s^{-1}\).

Additionally, the rate of particles crossing the LCFS due to static fill is evaluated by applying the impingement rate over the surface area of an H-1 plasma; \(f = \Gamma A\).
where the surface area of an H-1 plasma, defined by its large and small radius, is $A = 2\pi r.2\pi R$, and the impingement rate is given by $\Gamma = \frac{n.v_p}{4}$. For evaluating this, the most probable velocity $v_p = \sqrt{\frac{2kT}{m}}$ and particle density $n = \frac{P}{kT}$ are used, where $m$ is the mass of a particle of the static fill gas, $P$ its pressure, $T$ its temperature, and $k$ its Boltzmann constant. In this way, an Argon static fill at $5 \times 10^{-6}$Torr and 300K results in a flux across the LCFS of $\approx 6 \times 10^{19}$ s$^{-1}$ using $(r=0.1\text{m}, R=1\text{m})$.

Collis (2007) investigated the perturbative effects of a gas injection on the plasma and concludes that flowrates in excess of $1 \times 10^{20}$ s$^{-1}$ can cause a drop on electron temperature at higher electron temperatures (>40eV) much of the neutral beam is ionised. His work also indicates that at lower electron temperatures (5-10eV) the mean free path of neutral particles increases beyond the plasma diameter making the plasma more transparent to the beam and lessening the perturbative effect.

From these evaluations of loss rate and flux it can be seen that a gas injector particle flow rate spanning into the order of $\sim 10^{20}$ particles/s, although not insignificant, would be capable of ensuring a small perturbing effect on the plasma being studied.

For this design’s modelling it is considered reasonable, in way of simplification, to assume the flow to be isentropic; whereby entropy is maintained. It is also reasonable to consider that the flow will approximate an even radial expansion along a centreline direction of flow and so can be modelled as quasi-one dimensional,
whereby the variables vary primarily over a single direction. The flow’s centre line Mach number (along the nozzle) can thus be described by the following equation (Anderson 1982).

\[
\left( \frac{A^#}{A^i} \right)^2 = \frac{1}{M^2} \left[ \frac{2}{(\gamma+1)} \left( 1 + \frac{(\gamma-1)}{2} M^2 \right) \right]^{(\gamma+1)/(\gamma-1)} \tag{2.1}
\]

\(A^#\) is the cross-sectional area at the throat of the nozzle, \(A^i\) is the cross-sectional area at the nozzle location being examined, \(M\) is the centreline Mach number, and \(\gamma\) is the heat capacity ratio of the gas.

Equation 2.1 can be solved for \(M\) through numerical inversion and has two solutions for all areas before and after the throat area \((A^#)\), a subsonic and a supersonic solution. In this case, we are most interested in the divergent supersonic character of the nozzle, i.e. the expanding component of the nozzle flow, and the Mach solutions greater than one can be taken as the solution. With knowledge of the throat area and the cross-sectional area at points along the divergent section, the Mach number at those points can be determined.

An equation modelling flow rate through a nozzle can be derived based the isentropic flow relations taken at the throat of the nozzle with an assumption of choked flow. Choking occurs when the ratio of the nozzle exit pressure \(P_e\) and the source (plenum) gas pressure \(P_o\) is less than 0.528 \(\left( \frac{P_e}{P_o} \right) < 0.528 \) (Anderson 1982). This condition will invariably hold when injecting into a high vacuum environment from anything above even a few Torr, which is the case for plenum pressures within the scope of this project. The equation for flow rate assuming choked flow (derivation available in Appendix A) is given by:

\[
\dot{N} = \frac{p_0 A^# N_A \left( \frac{2}{\gamma+1} \right)^{\frac{1}{\gamma-1}} \sqrt{-\frac{2\gamma R T_0}{M_{gas}(\gamma+1)}}}{R T_0} (Particles/s) \tag{2.2}
\]

\(N_A\) being Avogadro’s constant, \(M_{gas}\) is the molar mass of a gas, \(p_0\) the pressure in the plenum, \(R\) the ideal gas constant, \(T_0\)is the temperature in the plenum (use room
temp at 298K), and $A#$ is the area of the throat. The heat capacity ratio $\gamma$ for the various gases can be well described using $5/3$ for a monoatomic gas and $7/5$ for a diatomic gas.

The significant design parameters that determine the flow rate are the throat diameter and the source/plenum pressure. By applying equation 2.2 for a number of gases, it was possible to investigate design decisions for the target throat diameter. Figure 2-3 presents the results of some of these examinations, showing that for hydrogen at pressures of around 700Torr a target throat diameter of below 0.1mm would be required to maintain a flow rate around $1 \times 10^{20}$ n/s. Lowering the plenum pressure to 100Torr allows this to approach closer to 0.2mm. Figure 2-4 shows the results for various different gas species at 750Torr for a variety of throat diameters. The larger gas molecules have reduced flow rates at the same pressure throat diameter settings as would be expected, and the results for argon, neon and nitrogen show that close to a $1 \times 10^{20}$ n/s flow rate can be maintained with a throat diameter approaching 0.2mm.

![Flowrate vs Throat Diameter (Hydrogen)](image)

Figure 2-3: Theoretical flow rate vs the throat diameter graphed comparing multiple plenum pressures for hydrogen gas.
The gas dynamics equations highlighted in appendix A can be further used to understand various flow characteristics along the length of the nozzle’s divergent exit section, including temperature, pressure, density, and flow velocity. Characteristics of the spread after the end of the divergent section is not defined by these equations, and the dynamics at this point would be reliant on interactions with the external environment. The pressure environment of H1-NF being much lower than plenum and nozzle pressures would likely result in additional expansion at and after the nozzle exit (Anderson 1982). To more fully model this scenario a CFD analysis could be undertaken, however, this was not done for the purposes of this project, which required instead, characterisation through test tank experimentation.

Figure 2-4: The theoretical flow rate vs throat diameter compared for various gas types at a 750Torr plenum pressure.
2.1.2 Nozzle manufacture

A few manufacturing techniques were examined, including moulded graphite and both wire and sinker varieties of electric discharge machining (EDM). Moulded graphite proved to be prohibitively expensive and wire EDM limited the possible throat size of the nozzle due to workshop restrictions of available machinery and wire size. Sinker EDM was evaluated as the most likely to achieve a throat diameter in the region of 0.1mm. This technique involved a copper cone, matching the required nozzles convergent/divergent geometry, being repeatedly lowered toward the work piece (nozzle blank). A high voltage difference between the two items meant a current discharge would jump the shortest air gap distance on each approach and result each time in a small removal of material from the working piece, thereby slowly carving out a negative of the copper cone into the nozzle blank. This process was undertaken with significant precision from both sides of the blank to ensure an accurate alignment along the centre line of the divergent-convergent sections, and to prevent over-extension of depth, from either side over-expanding the throat diameter.

A target of 0.1mm was a best outcome, and anything below 0.2mm was considered an acceptable outcome, based on the modelled flow results and previous gas puffing characterisation work (Collis 2007). A divergent open angle of 12 degrees was used to target a minimised gas divergence of less than 20 degrees. The resultant nozzle is shown in Figure 2-5.

![Figure 2-5: Photos of manufactured nozzle (with o-ring) from different angles](image)

Validation of the general geometry was undertaken with Vernier callipers while the throat diameter was measured with a backlit magnification system and determined a throat diameter of 0.18+/-0.01mm. This can be seen in Figure 2-6.
Figure 2-6: Picture of the nozzle on a backlit magnifying measurement system. The nozzle is placed on the unit and the backlight shielded, except through the nozzle throat opening. The small circle light in the centre is the light shining through the nozzle throat opening being magnified by an adjustable viewing system. Using dials on the unit, the magnified image can be moved in relation to a central crosshair on the viewing screen. When positioned at one side of the nozzle opening, a measurement can be read from an onscreen graduated rule.

Dimensional drawings in Figure 2-7 detail the resultant nozzle dimensions, including verified throat diameter.

Figure 2-7: CAD drawing for nozzle design showing finalised as-built dimensioning and surface finishes required for appropriate sealing in a high vacuum environment.
Updating the flow rate modelling work using the now known throat diameter (0.18mm), the theoretical plenum-pressure vs particle-flow-rate for a number of different gases can be seen in Figure 2-8, for use in comparisons against characterisation results.

![Nozzle Flowrate vs Plenum Pressure (Dth=0.18mm)](image)

Figure 2-8: Nozzle flow rate vs plenum pressure graph showing the theoretical flows determined using the gas dynamics equations. The throat diameter is set to 0.18mm to match the measured value of the manufactured nozzle piece. This shows the expectations for nozzle performance for a variety of gas types.

### 2.2 VALVE DESIGN

The purpose of the valve design was to produce a fast and responsive gas injector. Previous gas puffer assemblies on H-1, such as the one implemented by Scott Collis (Collis 2007), integrated a now discontinued piezo type valve assembly. The assembly included a Viton seal attached to a piezo bi-morph, such that the seal was pressed hard up against the nozzle entrance. A voltage applied to the bi-morph would actuate the seal away from the nozzle, opening the valve. Piezo-based valve designs are fast, low power, and considered an ideal methodology in developing valve system for the high performance and accuracy required by this project. To help select a piezo model, a paper discussing performance results on a variety of setups was examined;
the fastest, at 1 kHz repetition rates, being a slightly modified Physik-Instruments piezo element. (Flettner 2001). The P-286 piezo device chosen for this project includes the same piezo element described in Flettner’s work but comes fully assembled with a factory supplied mounting housing and centrally threaded insert, allowing for fast integration into the design.

The integration involved positioning the piezo and nozzle to create a movable seal against the nozzle entrance while also accommodating the gas containment and electrical connection requirements. The piezo and nozzle were mounted on a baseplate, making up the lower part of the plenum as illustrated in Figure 2-9.

![Figure 2-9: Piezo valve assembly shows how the bolt with attached Viton seal, locked in place in the piezo bender, is held against the nozzle entrance to seal when not actuated. The sprung copper maintains a separating force between the piezo and the plenum base so that height adjustment screws can be used to set the sealed position. When actuated the bender deforms and pulls the bolt away from the nozzle allowing flow.](image)

Through the centrally threaded insert, a stainless steel (SS314) flathead bolt was inserted, with the bolt head located on the nozzle side of the piezo unit. The bolt was positioned to stand proud of the piezo housing and held in place with a locking nut. To the bolt head, a small piece of vacuum prepared Viton was attached, using low vapour glue (Loctite 403) and a Viton primer (Loctite 770).

The nozzle was then inserted into the outward-facing side of the base plate, sealing on a Viton o-ring, and the valve assembly attached to the internal side, aligning the nozzle entrance with the Viton seal on the bolt. The valve assembly was connected to the base plate via four screws, and a piece of sprung copper located between, to force the valve assembly away from the nozzle. The screws could then be used to position the valve in relation to the nozzle, allowing adjustment to the hardness of seal.
pressure applied to the nozzle entrance. Figure 2-10 shows photographs of the components and assembled lower unit.

![Figure 2-10: The valve assembly components, including the piezo, plenum base, and copper spring, shown separated and assembled.](image)

2.3 PLENUM DESIGN

The plenum container holds the gas ready for use by the injection system. In this project the design consisted of upper and lower sections with the lower section, as already discussed, being the base plate used to integrate the nozzle and valve componentry. The upper section attached to the lower creating an enclosed volume around the valve assembly; and when removed, provided access to the valve components for setup purposes. The upper plenum included the gas line inlet and the electrical feed-throughs required to energise the piezo device. A Viton o-ring, inserted into a circular channel in the lower plenum component, sealed the unit when assembled.

Two plenum designs where undertaken as part of this project. The initial design, with a larger volume, was used for the test tank and puffer characterisation work but proved too large for install at the required location in H-1. The two designs additionally differed slightly in method of assembly between the upper and lower parts and the positioning of the gas inlet, but all dimensioning essential to the valve and nozzle interaction were identical. The plenum designs used for operation within a test tank system can be seen in Figure 2-11 and the H-1 version in Figure 2-12. The H-1 plenum
version seen in Figure 2-12 was designed with the help of H-1 technical lead, John Wach.

Figure 2-11: Test tank gas puffer plenum assembly. The CAD image on the left shows the internal structure of the plenum design and how the valve and nozzle assembly is fitted to the lower plenum, allowing easy access when disassembled. Electrical feedthroughs and a gas inlet are included in the upper plenum assembly. An o-ring between the upper and lower parts seals the unit. The photo on the right shows the unit assembled and ready for install in the test tank. Four of the six bolts used to assemble the unit are visible in the photo using threaded holes machined into the upper plenum.

Figure 2-12: H-1 gas puffer plenum assembly. The CAD design for this plenum is courtesy of John Wach. The volume is reduced by comparison to the test tank version, mostly due to the reduction in height seen above the valve assembly. The flange-based bolt connection design of the original is changed to one with threaded holes included directly onto the wall of upper plenum. This in turn reduces the width of the unit significantly, which was a primary issue with the test tank version.
2.4 CHARACTERISATION EQUIPMENT

To characterise the gas injector’s flow properties, a vacuum test tank incorporating a variety of instruments, including a gas anemometer system, was constructed. The test tank setup is discussed in the following section.

2.4.1 Test tank overview

The test tank used for the characterisation of the gas injector was a cylindrical stainless-steel container, approximately 1.2m long. The tank included, at one end, a pumping assembly with a manual gate valve for isolating the tank from the pump and a pair of viewing windows. On the other end, was an opening to suit an ISO250-K flange. Figure 2-13 a) shows the tank with the flange opening covered by aluminium foil to prevent contamination of the internal tank surfaces. Figure 2-13 b) shows the flange setup with all experimental data collection tools installed.

Figure 2-13: The characterisation test tank. a) Shows the tank with pumping and experimental end marked. The experiment end's CF flange is detached and covered with foil in this picture. b) Shows the experimental end with CF flange attached.

The flange plate, attached with 16 double claw clamps, itself had three of its own 2.75 CF flange assemblies onto which all supply and data collection elements could be fitted, including:

- an ion and Convectron gauge for measuring tank pressure;
- a manometer for measuring plenum pressure;
- a movable anemometer assembly for characterisation measurements;
• electrical feedthroughs to supply:
  o actuation power to the valve
  o power to the anemometer filament; and
• a gas feedthrough to supply gas to the injector.

The gas injector assembly was installed on the internal side of the large flange so that it puffed down the length of the test tank along the centre line of the cylinder toward the pumping end.

2.4.2 Anemometer design

Anemometers use the cooling effect on a heated wire, placed in the flow, to determine characteristics of the flow. The smaller the dimensions of the wire the more sensitive it is to small flowrates, and the shorter the wire the more spatially refined the measurements can be. This project tested various techniques when looking for the best anemometer fit for characterising the low flow regimes being considered. The following section highlights considerations leading to the final setup.

Filament and Assembly

An assembly is required to allow an electrically heated wire to be held in the flow regime with minimal disturbance to the flow. This was achieved for this project by locating a single coiled wire (filament) between two copper probes, extending from a housing into the flow regime, as shown in Figure 2-14.

![Figure 2-14: The anemometer setup considered for this project. Its design allows electrical heating to the filament and minimises flow interference at filament location.](image-url)
In determining a suitable filament, various test units where tried using different diameter wires, however, it proved difficult to make use of short sections of single wire, less than 5mm in length. Attempts to make anemometers with 2-3mm long $25\mu m$ diameter tungsten wire crimped between the ends of hypodermic needles (size 25) as the probes, produced approximately 3 Ohm filaments that resulted in excessively small power changes in the monitoring electronics when trying measure flow. Changing to 10 $\mu m$ diameter tungsten wire produced higher but highly variable resistances, likely due to damage and deformation of the wires during the difficult crimping process. The fragility of these thin wires came with an excessively high failure rate that could not be overcome.

Filaments from 240V light bulbs proved more successful. Bulbs with approximately 10mm long helically coiled tungsten filaments were selected. The bulbs used copper pins, crimped to either ends of the filaments, to hold them in place. By scoring and breaking the bulb glass to gain access, the filament/pin assembly could be removed as one by snipping from the base of each copper pin. The assembly could then be re-attached to the ends of a pair of longer copper probes by soldering the copper base pins to them. This process minimised any handling of fragile filament parts. A rod-shaped ceramic cylinder($\varnothing 10mm$), with two pipe-like holes running its length, was used as a housing; the probes were inserted into each of the housing holes, to hold them parallel, and extended out of the back so that Teflon-coated electrical cables with push-on connectors could be attached. The ceramic rod was then inserted and grub-screw secured into a Teflon arm, connected to an extension rod (1/2” 314 stainless steel), making up the rest of the positioning assembly, as can be seen in Figure 2-15.
Figure 2-15: Anemometer probe and arm setup. The stainless steel extension rod seen at the top right is rotated around its long axis to move the arm cylinder and probe assembly through a flow regime in an arc. The geometry is such that the arc travels through the centreline of a puff, allowing capture of anemometer results over a range of radial positions through the flow.

**Position in the tank**

The anemometer setup was installed in the test tank by inserting the extension rod through an o-ring seal on one of the test tank’s smaller CF flanges. The offset afforded by the extension rod (90mm) allowed the filament to be rotated directly through the centreline of the gas injection regime, as seen in Figure 2-16.
Figure 2-16: The experimental setup of the anemometer in the test tank. The orientation of components shows how the anemometer is able to be rotated in an arc through a flow regime that passes through the centreline of the gas puff. The location of the accelerometer for measuring the anemometers angle of rotation away from the flow centreline ($\theta_{an}$) and the ruler for measuring the anemometers length of insertion into the tank ($X_{an}$) are shown external to the tank.

To ascertain the position of the anemometer’s wire/filament within the flow regime, measurement of its rotational position and extension into the tank were required. This was achieved with:

- a ruler with mm graduations installed alongside the extension rod, used to determine the position of the anemometer along the length of the test tank; and
• a 3-axis accelerometer located on the external end of the anemometer rod, which measured the rotational angle of the setup, feeding three analogue x, y, and z variables back to the control system for calculation.

The positioning of these two items on the test tank setup can be seen in Figure 2-16, while Figure 2-17 shows an additional end view with the in-depth the rotational geometry of the setup.

![Diagram](image)

Figure 2-17: A front-on view of the anemometer and puffer setup shows the geometry of the system: the radius of the arc taken by the anemometer ($r_{an}$), the angle of the anemometer away from the puff centreline ($\theta_{an}$), and the linear distance from the centreline ($d_{an}$).

The radial distance from the centreline of the puffer’s flow, as depicted in Figure 2-17, is calculated using:

$$d_{an} = 2r_{an} \sin \left(\frac{\theta_{an}}{2}\right)$$

(2.3)

where $\theta_{an}$ is the rotational angle of the anemometer arm away from its position when directly aligned with the centreline, determined using the 3-axis accelerometer; $r_{an}$ is the radius of the arc taken by the anemometers probe given by the length of the Teflon arm (90mm), and $d_{an}$ is the straight line distance from the puffer centreline to the anemometer filament.
The distance $d_{an}$, in conjunction with the ruler measured $X_{an}$, can be used to determine any other desired geometric factors, such as the divergent puff angle from the nozzle to the filament $\phi_{noz}$:

$$\phi_{noz} = \tan^{-1}\left(\frac{d_{an}}{X_{an}}\right)$$

(2.4)

Figure 2-18: A side view of the anemometer and puffer setup shows the geometry of the system highlighting variables for eq 2.4.

The accelerometer device used is pictured in Figure 2-19. The mathematics related to extracting the angle from its three feedbacks is presented in Appendix B but essentially requires the dot product evaluation of two vectors: one from the real time feedback of the accelerometers current and desired position; and the other, a carefully collected home or zero position evaluated with the anemometer aligned to the puffer centreline. For this project, the zero/home vector was achieved by positioning the anemometer filament 1mm directly in front of the nozzle exit.
Figure 2-19: The accelerometer set-up used to determine anemometer angle. Positioned on the end of the rotational shaft with the y-axis pointing approximately down the steel rod used to rotate the anemometer.

Inaccuracy in the homing setup could be removed post-collection by assuming a peak flux along the central axis of the gas injection regime and appropriately shifting collected flux/density data to place peak flux reading at the zero-angle centreline. Although in the case of FWHM evaluations, not even this would be a requirement, and the more important factor is the relative accuracy of the accelerometer’s orientation.

OEM data sheets for the accelerometer claimed an accuracy of 0.1 degrees. To check this, a large radius physical protractor was setup in conjunction with the accelerometer and multiple rotational positions measured and compared. This examination verified the claimed relative accuracy and, in fact, showed better.

*Heating the filament*

To heat the filament an anemometer control unit (J849), built for previous characterisation work (Powell 2008), was requisitioned for this project. A requirement of its integration was the replacement of the balancing resistors to match the new wire filament. The bridge circuit is shown in Figure 2-20.
The adjustable resistor in the circuit shown in Figure 2-20 was set to maximise the probe temperature and the circuit would be enforcing a constant resistance on the probe, according to equation 2.5.

\[ R_{\text{probe}} = R_2 \frac{R_3}{R_4} \]  

(2.5)

The current through the probe \( I_{\text{probe}} \) is the same as that running through \( R_2 \) and so determined from the voltage at monitoring point 1 \( (V_{\text{MON1}}) \) across \( R_2 \). The difference in power is calculated from the measurements of voltage both with and without the puff being applied according to the following.

\[ P_{\text{probe}} = I_{\text{probe}}^2 R_{\text{probe}} = \left( \frac{V_{\text{MON1}}}{R_2} \right)^2 R_{\text{probe}} \]  

(2.6)

\[ \Delta P_{\text{probe}} = P_{\text{probe(flow)}} - P_{\text{probe(background)}} \]  

(2.7)

The change in power corresponds to the mass flow moving past the anemometer by the following equation.

\[ \Delta P_{\text{probe}} = C \cdot \Phi_m^n \]  

(2.8)
where $\Phi_m$ is the mass flow, $n$ is a dimensionless factor dependant on the Reynolds number (generally taken as 0.25), and $C$ is a proportional constant taking account of the probe’s dimensions and the gas properties (Löters 1999).

The goal for this work was evaluating the divergent spread of the puff’s mass flow, using a Gaussian full width half maximum (FWHM) fitted to mass-flow data, determined from anemometer power measurements collected at radial increments across the puff.

A Gaussian distribution is given by the following.

$$f(x) = ae^{\frac{-(x-b)^2}{2c^2}}$$

where $a$ determines the maximum height of the curve, $b$ the maximum’s position on the x axis, and $c$ the width of the curve:

$$FWHM = (2\sqrt{2ln2})c$$

In equation 2.7, $C$ is linearly related to the mass flow and so has no effect on the FWHM value of a data set being converted from power change to mass flux. The determination of calibrated mass flow measurements using $C$ is therefore not required for mass flow FWHM calculations. It is useful to understand the relationship between the FWHM determined from the Gaussian fit applied to a delta power dataset ($\Delta P_{probe}$) to that of mass flow ($\Phi_m$) based on (2.7) and (2.8):

$$FWHM_{\Phi_m} = FWHM_{\Delta P} * \sqrt{n}$$

where $n$ is the dimensionless factor from equation 2.7.

### 2.4.3 Test tank control

The control system for the characterisation work undertaken on the gas injector consisted of a PC, Texas Instruments I/O card (including ADC and DAC), and a purpose-built software application for control developed in LabVIEW. Using the main application window (shown in Figure 2-21), the operator could view diagnostic information from the test tank setup, including plenum and tank pressures, anemometer variables, and valve voltage.

The control software was a state-machine design, including time critical modules for the gas puffing and anemometer data collection. Adjustable variables included the
system’s data acquisition rate and a square wave valve signal with variable length and amplitude (also selectable as a single or multiple pulse event). The operator would manually enter a centre line distance from the anemometer to the nozzle, taken from the graduated rule installed next to the anemometer’s extension arm. This value, along with the rotational angle returned from the accelerometer, was used to calculate the angle from the nozzle centreline to the anemometer.

![Image](image.png)

**Figure 2-21:** Main screen for the test tank control and acquisition system. This main screen allows monitoring of all experimental feedbacks. Setting experimental variables are available here or in additional settings windows reachable from here.

The control system also allowed the user to choose a target plenum pressure and drive the plenum to that value using an adjustable PID (Proportional, Integral, Derivative) control loop (opening the piezo to reduce pressure and opening a pneumatic valve, inline on the plenum supply gas, to increase it).

This automated plenum pressure adjustment proved troublesome when working in low plenum pressure regions due to electrical breakdown problems across the piezo, and so software limits were set for the available target pressures and voltage levels to restrict the probability of damage to the piezo during operation.

The operator was able to save all diagnostic data from an injection event to an output file.
2.5 **INJECTOR-SETUP**

Initial puffer characterisation work involved benchtop setup and calibration of the gas injector’s valve system out of the test tank, including an investigation of its opening voltage characteristics. Test tank installation and experiments to collect flow rate and gas divergence data were then undertaken. Discoveries of valve restrictions and operating limits were made along the way.

Early on, it became clear that the non-actuated pressure of the Viton seal on the nozzle entrance was an important factor in a successfully operating valve. Over-compression resulted in the valve restricting flow when fully open, as it was not able to move away from the Viton enough. Too little compression resulted in an unacceptable leak. Electrical breakdowns (further discussed in section 2.6.2) across unknown parts of the piezo at lower pressures and higher voltages, made it important to keep voltages as low as possible and so getting the seal just to the point of removing the leak.

### 2.5.1 Leak tests

A helium leak test was used to ensure no leaks were present around the assembled plenum parts and that a good seal was maintained by the valve when not actuated. Based on a technique developed during the Manhattan Project, the test used a vacuum pump arrangement that feeds a helium calibrated mass spectrometer. The vacuum was applied to one side of the item being tested, in this case the exit side of the valve assembly. A small amount of helium was wafted over the areas where leaks could be possible, in this case the entrance side of the valve around the nozzle/valve o-ring. A leak would allow helium to get drawn through where it would be registered by the mass spectrometer. The setup is seen in Figure 2-22 and very small leaks could be monitored with this method.

To isolate the o-ring seal during this process, hard-pressure was applied to a small piece of Viton placed over the nozzle entrance. Leaks detected were dealt with by disassembling, examining, and then cleaning or replacing any parts seen as the possible culprits before reassembling and repeating the testing. When no more leaks could be found, the setup was deemed acceptable for valve assembly.
Figure 2-22: Helium leak test setup (using test tank plenum) to confirm acceptable seal for H-1 installation. The letters on the image indicate the following: A) the lower plenum setup on the detectors input; B) the piezo voltage wiring including monitoring voltmeter; C) roughing pump; D) unit for measuring helium with sensitivity settings; E) the helium tank/dispenser; and F) the turbo and controller unit.

2.5.2 Valve height

To set the valve height correctly, the lower valve components were assembled onto the lower plenum but with a small visual gap left between the Viton and the nozzle. The unit was setup on the test tank such that vacuum could be applied to the exit side of the nozzle as shown in Figure 2-23. The tank’s diagnostic pressure sensors were then able to monitor the leak rate.

Figure 2-23: The plenum/valve height setup on test tank. By monitoring tank pressure, height adjustments on the valve can be applied so that the non-actuated leak rate is removed, and the opening characteristics of the valve are set at as low a voltage range as possible.
With the test tank actively pumped, the height adjustment screws were adjusted incrementally to lower the valve towards the nozzle entrance. Vernier calliper measurements between the piezo housing and the base plate at the radial screw locations ensured even height adjustment and a parallel relationship between the Viton sealing face and the nozzle were maintained. The valve sealing point was initially estimated by monitoring the tank pressure, as a distinct pressure drop was experienced when contact was made between the Viton and the nozzle. Once this seal was detected, the tank was isolated from the pump and the pressure monitored for an increase to indicate any significant leak rate past the valve seal, with further height adjustments made to minimise or remove it.

2.5.3 Opening characteristics

Once an approximately satisfactory seal was in place, the effect on opening characteristics in terms voltage and flow rate were examined by driving the piezo with square wave voltage pulses and monitoring the change in test tank pressure. The flow rate was calculated using the ideal gas law and the known tank volume.

From the ideal gas law, we have:

\[ \Delta N = \frac{\Delta PV}{k_B T} \]  

(2.12)

and to evaluate average flow rate from a change in pressure over time:

\[ \dot{N} = \frac{\Delta N}{\Delta t} = \frac{\Delta PV}{k_B T \Delta t} \]  

(2.13)

where \( \dot{N} \) is the average flow rate in particles per second, \( \Delta N \) the change in number of particles, \( \Delta t \) the time period over which the change occurs, \( \Delta P \) the change in pressure, \( T \) the absolute temperature, and \( k_B \) Boltzmann constant.

Experiments were then undertaken to examine the effect of different levels of seal pressure on the flow-rate/voltage relationship. This involved making small ¼ turn adjustments to each of the piezo height bolts and collecting the opening characteristics
for each setup. A single quarter turn on each height adjustment screw shifted the opening characteristic curve by between 50V and 100V. Examples of the data taken can be seen in Figure 2-24, and the voltage range for the piezo valve to move from closed (no flow) to fully open (maximum flow), was approximately 300V. This voltage range corresponded to an approximate distance attenuation, by the centre point of the piezo, of 30um in relation to the nozzle entrance (piezo datasheet).

![Valve Voltage vs Flow Rate (Plenum at atm AIR)](image)

Figure 2-24: Valve opening characteristic change resulting from a ¼ turn tightening of piezo height - note the larger voltage required to start flow, and similar maximum flow when fully open. Also plotted is a theoretically calculated flow rate for a 0.18mm throat diameter.

At lower plenum pressures (<350Torr) and higher voltages (>700V) electrical breakdown (shorting) across the piezo was a known issue (discussed in upcoming section), and so it was desirable that the valve be usable in as low a voltage range as possible, while still maintaining a good seal for purposes of H-1 installation. This would allow maximum versatility for future use, especially considering cases where lower plenum pressures might be required to achieve a minimised flow into the plasma.

From the valve-height setup work it was found that if the height was set such that the opening started at close to 100V (as shown in the blue line in Figure 2-24) it did not provide adequate sealing when not actuated, evidenced by a noticeable increase in tank pressure while the valve sat undisturbed. Lowering the height and hardening the seal such that the opening started at 200V (green line) removed this leak. Further
hardening from here only served to push up the operating range of the valve with no perceivable effect on the leak rate, thus subjecting the valve to more potential for electrical breakdown under any possible low plenum pressure situations.

The set-up deemed acceptable (due to a negligible leak rate when closed and a minimised voltage opening point) was one with an opening starting at 200V as per the green line in Figure 2-24. The red line indicates the theoretical flowrate calculated using equation 2.2 using variables for air at room temperature and atmospheric pressure as the back pressure of the nozzle and a 0.18mm nozzle diameter.

### 2.6 TEST TANK CHARACTERISATION

This section presents the results of the test tank characterisation experiments following the installation of the test tank plenum arrangement into the test tank as per Section 2.4. It presents results from a variety of experiments looking at the dynamic behaviour of the piezo valve, some additional flow rate experiments, and beam divergence characteristics for various configurations; divergence being defined as full-width-half-maximum (FWHM) values extracted from Gaussian fit analysis of the anemometer data with respect to its radial distance from the gas puff centreline.

#### 2.6.1 Piezo drive character

The manufacturer of the P-286 piezo device integrated into this project’s valve presents equations describing their dynamic behaviour (PI 2012), including an equation for constant charging:

\[
t_o \approx C \left( \frac{U}{i} \right)
\]  

(2.14)

where \( t_o \) is the opening time (s), \( C \) is piezo capacitance (F), \( U \) is voltage supplied (V), and \( i \) is current available (A).

Equation 2.3 can be used in evaluating capacitive charge time i.e. the time for the piezo to move to its commanded position given the maximum current available from the power supply system. Manufacturer's data for the P-286 piezo specifies a
65nF ±20% operating capacitance and a maximum drive signal of 1000V for its full contraction.

**NB:** Actually -1000V if referencing the housing-connected terminal of the piezo as ground as is done in this work.

The high-speed, high-voltage amplifier (Trek 10/10B) available to this project was rated to supply 10mA to a capacitive load and up to 1000V. With an input gain of 1000x it required a 0-1V input signal to trigger an output voltage between 0-1000V. The input was supplied by a low voltage DAQ unit under LabVIEW control. The control system also used ADC inputs on the same DAQ to monitor amplifier feedback signals of its voltage and current status. To check the dynamic behaviour of the piezo, drive-time data was collected from the feedback signals of square wave piezo actuations. Figure 2-26 and Figure 2-27 both show the piezo taking approximately 4ms to move to a -693V drive position with a peak absolute current drawn during the dynamic actuation period of 10.65mA both as it turns on and off.

**Piezo Electrical Drive Characteristics (DA=10)**

![Piezo Electrical Drive Characteristics](image)

Figure 2-25: Piezo drive characteristics showing the rise time for the piezo voltage and its relationship to the maximum available current of 10mA.

Applying the drive variables, used to collect the Figure 5-5 data, to the piezo equation for constant charging gives:
\[ t_o \approx C \left( \frac{V}{I} \right) \approx 65 \times 10^{-9} \left( \frac{693}{10.75 \times 10^{-3}} \right) \approx 0.0042 \text{s} \pm 20\% \quad (2.15) \]

This shows the equation accurately aligning with piezo behaviour and indicates it can be used with reasonable confidence to determine the required current for improved valve speed in any future versions of the piezo drive system. For example, choosing a high voltage amplifier system that can provide 40mA instead of 10mA could be reasonably assumed to increase the opening speed by a factor of 4 and thus reduce the opening time for a 700V move from approximately 4ms to 1ms.

An additional note on opening dynamics when using the TREX amplifier, is a ‘dynamic adjustment’ setting affecting the transient response of the unit’s output. When set at its maximum value (10), significantly less voltage-ringing was observed at the end of the valves transient stage, seen in Figure 2-26. This could be a consideration for higher frequency modulated puffer signals (>500Hz) where a fast move into steady state operation may be required.

Amplifiers Dynamic Adjustment Comparison

![Graph showing Amplifiers Dynamic Adjustment Comparison](image)

Figure 2-26: Effect of the Trek amplifiers 'Dynamic Adjustment' variable on the transient response of the system to an approx. -700V amplitude square wave signal. With DA of 0, the system has a large transient response. At DA of 10, this is almost eliminated.
2.6.2 Piezo breakdown

While testing the electrical characteristics of the valve, it was discovered that, under certain conditions, the piezo suffered electrical breakdowns (or short circuiting). The effect was seen when the piezo was operating in lower pressure environments (internal plenum pressure) and being driven at higher voltages. An understanding of the breakdown relationship to voltage and pressure was attempted, as it was believed to be related to the Paschen curve phenomenon.

This relationship proved difficult to define due to a level of randomness in the results. The behaviour of the piezo device, both to the effects of breakdown and application of vacuum, remained largely unpredictable. Avoiding breakdown all together is the recommendation of this paper.

Figure 2-27 shows an example of breakdown data. The voltage can be seen to intermittently spike towards zero, in this case recovering quickly each time and attempting to return to its set point before reaching zero volts. Each recovery is accompanied by a -10amp current draw as the piezo recharges at a rate defined by the previous sections constant current charging equation (2.11). The current associated with each drop or discharge is not seen by the amplifier. This is expected if breakdown is causing a temporary, and unknown, pathway to earth. The final discharge shown in the graph, as the puffer’s piezo voltage being purposefully removed, and shows the expected 10mA flow associated with the capacitive discharge running back through the amplifier.
Chapter 2: Injector Design

Figure 2-27: An example of a piezo breakdown shown in the amplifier’s voltage and current data. The transient part of each voltage drop sees the current drop to 0 due to a shorting event across the piezo circuit, while the recovery is accompanied by a -10mA current draw. This behaviour was observed when the piezo was approaching an undesirable voltage/pressure setting combination (generally voltage too high/pressure too low). If the situation is maintained or made worse through further negative adjustment to the operating settings, the piezo will further degrade in performance and breakdowns can begin shorting for the entirety of the applied voltage period. Damage to the piezo from excessive breakdown occurrence is a strong possibility.

Other breakdowns were observed where a small number of spikes were seen at the beginning of the voltage application followed by a flat line zero voltage for the rest of the time. These sustained breakdowns generally aligned with higher voltage applications.

In further examination of the possible Paschen curve relationship, the breakdown voltages at different pressures were collected. Figure 2-28 shows some of this data for air and argon. It was noted that as more breakdowns were allowed to occur on a device, the more easily subsequent breakdowns would occur (i.e. breaking down at lower voltages given the same pressure). This degradation in piezo performance was likely occurring during collection of the data shown in Figure 2-28, but catastrophic damage to the piezo being tested prevented confirmation of this and further experimentation of this fashion was not pursued to prevent damage to the replacement unit. Paschen curves derived from experimentally backed theory are overlaid for comparison,
showing, at least, that the piezo data meets theoretical expectations of how breakdown voltage is affected by gas type. It should be noted that the width and geometry of the breakdown gap on the piezo is not known and the degrading nature of the breakdown on the piezo indicate it is likely changing as a result of each breakdown occurrence (perhaps through process of carbon build-up). Various gap distances were modelled, and those ranging from 0.1mm to 2mm provided similar comparative value to the graph. The equations and variables used for the theoretical Paschen curves for Figure 2-27 are presented below and in Table 1.

**Breakdown Curves for Peizo Device**

![Graph of breakdown voltages vs pressure collected from a piezo valve device compared to theoretical Paschen curves.](image)

The Paschen curve equation is:

\[
V_B = \frac{Bpd}{\ln(Apd/\ln(1+\gamma))}
\]  

(2.16)

where \( V_B \) is the breakdown voltage, \( A \) and \( B \) are experimentally determined fit parameters, \( p \) is the pressure, and \( d \) is the gap distance across which the breakdown occurs. The secondary-electron-emission coefficient \( \gamma \) is poorly understood and often combined with the parameter \( A \) into \( A' \) (Massarczyk et al 2017). The theoretical Paschen curves in Figure 2-27 are derived using the following:
\[ V_B = \frac{Bpd}{\ln(A'dd)} \]  

(2.17)

<table>
<thead>
<tr>
<th></th>
<th>(A') (cm Torr)</th>
<th>(B)</th>
<th>(d) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>3.8</td>
<td>649</td>
<td>0.01</td>
</tr>
<tr>
<td>Argon</td>
<td>3.1</td>
<td>320</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 1: Constants selected for the Paschen breakdown comparison curves shown in Figure 2-28 (Massarczyk et al 2017)

Recommendations from the piezo manufacturer 'Physik Instrumente' for managing this problem are given in relation to air. The manufacturer's data states that care should be taken when operating between approx. 0.75Torr – 375Torr and that it should be either not operated or operated at a reduced voltage.

This paper recommends maintaining a plenum pressure above 375Torr, and if it is to be operated at lower pressures, a limit of 400V should be applied.

2.6.3 Flow rate results

Initial examinations of the puffer were aimed at determining how closely the measured flow rate corresponded to values estimated by the theoretical examination. By measuring the change in pressure of both the test tank and the plenum for drive signals of various amplitudes and duration, it is possible to calculate flow rate as per Equation 2.13.

The volume of the plenum was determined using the CAD assembly-project used in its design and manufacture (order of magnitude checked with geometry) and to this was added the volume of the gas line from the plenum to the gas input valve (located outside the test tank), calculated using the line’s inner diameter and measured length. The test tank calculation used the previous measured volume from the valve setup experiments but subtracted the plenum volume as it was now located within the tank.

First studies monitored plenum pressure change, as its smaller size resulted in larger changes than any effect on the tank volume. In this case, the test tank’s vacuum pump was applied continuously to the chamber to retain as low a vacuum as possible on the exit side of the nozzle.
The results in Figure 2-29 show that as the voltage is increased the flow rate rises approximately linearly at first before tapering off at higher voltages as the valve approaches a fully open state.

Figure 2-29: Graph of the nozzle flow rate vs piezo voltage for various selected plenum pressures. The selected gas is air, and the graph shows that as the voltage (valve opening position) increases, the flow rates approach a maximum or fully open state over an approximate 300V range, approximately linearly for the first 100V to 150V. An increase of plenum pressure increases the flow rate experienced for the same voltage application (valve opening) but maintains the same characteristic opening shape along the voltage axis.

An additional data set, similarly collected, examines how the results of the experiments on the valve compare to the theoretical calculations for flow rate. The comparison is shown in Figure 2-30. As the voltage is increased towards a fully open state (towards 700V), the flow rate can be seen to approach the theoretical value for the nozzle. This shows good agreement between the experimental results and theory.
Figure 2-30: Graph of nozzle flow rate vs plenum pressure for various selected piezo drive voltages. The data approaches a theoretical determined rate as the valve approaches its fully open state.

To further compare the measured flow rate of the nozzle against theory, an additional experiment with longer opening time at 700V was undertaken (considered to be close to fully open). The voltage was applied for 10 seconds and the plenum pressure tracked as it dropped, at 1k samples/s. Figure 2-31 shows the results. The slope of the pressure drop is shown in the upper graph and converted into its derivative flow rate in the lower. On both graphs, the theoretical values of expected flow rate and pressure drop over time, calculated using the gas dynamics equation, are plotted for comparison. There is excellent agreement between measurement and theory, mainly indicating that the pressure monitor and the plenum volume estimate can be considered accurate.
Figure 2-31: Flow rate of the nozzle compared with gas dynamics theory. Plenum pressure drop test was run over 10 seconds with nozzle fully open (700V). The upper graph displays the pressure drop in the plenum over that time with an overlaid theoretical estimate from the gas dynamics equations. The lower graph compares the flow rate in particles/s calculated from the plenum pressure drop data compared with the theoretical expectation from gas dynamics equations.

2.6.4 Gas jet divergence

To determine the divergence of the gas jet, the anemometer setup, as described in Section 2.4.2, was used to collect anemometer power data before, during, and after a variety of puff strengths (flow rates) at different longitudinal and radial distances from the nozzle. The user input the anemometers distance from the nozzle before the shot, and the control system collected and captured all other relevant data. A python script was used to extract the data, graph the results, and evaluate the anemometer’s power change and the gas flow rate for each shot. A typical example of a gas pulse output can be seen in Figure 2-32, with relevant variables shown in the shot info box.
Figure 2-32: Example of typical anemometer data-set collected with the anemometer positioned in the flow regime. An initial jump in anemometer voltage can be seen at the start of the puff and the effect of background build up in the tank is shown by the positive slope throughout the puff’s application.

As the piezo was actuated and the gas puff initiated, as seen in the top graph of Figure 2-32, the bottom graph shows a fast increase in the anemometer voltage (and thus power draw) due to the cooling effect on the wire of the puff’s mass flux (as described in section 2.4.2). Over the length of the puff, there was a slow increase in the voltage due to a build-up of background pressure in the tank and its additional contribution to the cooling of the probe. By measuring the flux in this manner from a location well outside of the puff, the lower graph would be seen to simply rise gradually due to the background increase without the puffer related step.

Anemometer power change can be measured between both points 1 and 2 as well as points 3 and 4 and an average taken (although this was not seen to improve the eventual divergence analysis in any noticeable way). The middle graph shows the plenum pressure decrease over the length of the puff from which the flow rate was calculated.
The puff’s divergence for a particular gas-type, flow rate, and nozzle distance was determined by collecting power change for a number of shots, incrementally rotated across the front/face of the nozzle with those variables held the same. An example of the power change ($\Delta P$) vs distance from the puff’s centreline ($d_{an}$) is shown Figure 2-33.

![Gaussian Fit for Swept Anemometer Data](image)

Figure 2-33: Gaussian fit for swept anemometer data (varying anemometer angle across the face of the nozzle).

The data in Figure 2-33 takes on a distinct bell curve shape and a Gaussian fit can be seen overlaid. The full width half maximum (FWHM) of this curve is represented in the sweep info box along with other relevant shot data. It shows the FWHM in terms of power change without the application of mass flow adjustments described in Section 2.4.2. The flow rate $\dot{N}_{Average}$ is the average taken across all measurements making up the bell curve.

The process was repeated at varying distances from the nozzle exit and then additionally for different flow rates. Data for a variety of nitrogen measurements is
shown in Figure 2-34. In this case the power change data has been converted to mass flow as described in Section 2.4.2. The divergence is also represented in half width half maximum (HWHM) rather than FWHM so that the graphical representation gives an indication of the linearity of spread from nozzle.

The slope of linear regression lines seen in Figure 2-34 is representative of the mass flow divergence in degrees as shown in Table 2.

<table>
<thead>
<tr>
<th>Gas (Nitrogen)</th>
<th>Graph Properties (Figure 2-34)</th>
<th>Divergence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flowrate (N/sec)</td>
<td>slope (mm/mm)</td>
<td>x crossing (mm)</td>
</tr>
<tr>
<td>5.60E+19</td>
<td>0.16</td>
<td>-4.14</td>
</tr>
<tr>
<td>7.60E+19</td>
<td>0.14</td>
<td>-3.32</td>
</tr>
<tr>
<td>9.80E+19</td>
<td>0.11</td>
<td>-5.13</td>
</tr>
<tr>
<td>1.50E+20</td>
<td>0.09</td>
<td>-5.39</td>
</tr>
</tbody>
</table>

Table 2: Divergence values converted to degrees for nitrogen gas at different flowrates using regression line-fits on mass flow divergence (mm) vs distance from the nozzle (mm) data shown in Figure 2-34.
The regression lines in Figure 2-34 show that for the evaluation of angled divergence to be accurate, account should be taken of the zero-point selected for the measurement of the anemometer’s distance from the nozzle ($x_{an}$) and its effect on the anemometer’s calculated angular position. The zero-point for this data was the face of the nozzle, at which point the nozzle exit opening of $\varnothing0.8\text{mm}$ means the puff should already have a width of this value. The y axis (HWHM-mm) crossing for the graphs of Figure 2-34 should be close to 0.4mm. The average of 0.54mm seen by the data is high, but the dataset is limited and complicated gas dynamics at the nozzles exit, such as overexpansion into low vacuum, are possible factors in this discrepancy. The x axis crossing’s average of -4.5mm could also be used as an offset for the anemometers angular position to the nozzle but does not line up with any nozzle geometry (the nozzle throat is located -2.5mm behind the face of the nozzle exit).

For a larger set of data at various flow rates, it was not possible to undertake the linear regression due to the lack of subsets of equal flow rate, but by applying a y-offset factor of 0.54mm in the conversion to angular FWHM, the nitrogen divergence in degrees as a function of flow rate is presented in Figure 2-35.
Figure 2-35: The mass flow divergence for nitrogen as a FWHM measure of radial spread measured in degrees from the nozzle (with nozzle exit diameter offset applied) graphed against the nozzle flowrate.

Figure 2-35 indicates the relationship of decreasing divergence as the flow rate was increased, highlighted by the fitted power curve. The data also highlights the increased inaccuracy in determining divergence as the flow rate was reduced. This is related to the anemometer approaching its limits, where the power change due to the puff was challenged by increasing dominance from power change due to background build-up. This caused the Gaussian fit to be less reliable.

The same evaluation of divergence undertaken for nitrogen was done for hydrogen and the results presented similarly in Figure 2-36, Table 3 and Figure 2-37. The more limited dataset, in terms of flow rate spread, means the relationship between divergence and flow rate is limited to a linear zone of operation, if broader set of flow rate data was collected a relationship more like to the fitted power curve of the nitrogen data would likely be seen.
Figure 2-36: Mass flow divergence for hydrogen, as a HWHM measure of radial spread in mm from the puff centreline, is graphed against the distance from nozzle $x_{an}$ with various flow rate datasets for comparison.

<table>
<thead>
<tr>
<th>Gas (Hydrogen)</th>
<th>Graph Properties (Figure 2-36)</th>
<th>Divergence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate (N/sec)</td>
<td>Slope (mm/mm)</td>
<td>x crossing (mm)</td>
</tr>
<tr>
<td>2.35E+20</td>
<td>0.19</td>
<td>-5.34</td>
</tr>
<tr>
<td>3.18E+20</td>
<td>0.18</td>
<td>-6.16</td>
</tr>
<tr>
<td>4.36E+20</td>
<td>0.11</td>
<td>-9.93</td>
</tr>
</tbody>
</table>

Table 3: Divergence values converted to degrees for hydrogen gas at different flow rates using regression line-fits on mass flow divergence (mm) vs distance from the nozzle (mm) data shown in Figure 2-36.
Figure 2-37: The mass flow divergence for hydrogen, as a FWHM measure of radial spread measured in degrees from the nozzle (with nozzle exit diameter offset applied), graphed against the nozzle flow rate.
Chapter 3: Installation and Testing on H-1

The final diagnostic system on H-1 incorporated the characterised puffer, with its H-1 plenum, into a position above the H-1 heating antenna along with all the viewing elements required to collect and analyse the plasma/gas-jet interactions. The viewing system was made up of a re-entrant port with lensing, angled mirror, and a fibre optics bundle. A plasma model incorporated into the H-1 CAD model was used to support the positioning and design considerations. This chapter describes the outcomes of design and installation work on H-1 and presents view confirmation and imaging results from the system in operation, with analysis of some basic physical phenomena, such as the dynamic behaviour of the gas puff, $H\alpha$ line ratios, and observations from use with varied plasma parameters.

3.1 SYSTEM SETUP

The following section describes the design and installation considerations for the diagnostic subsystems including the puffer, its new H-1 specific control system, and the viewing apparatus.

3.1.1 Gas puffer

The H-1 version of the gas plenum was assembled and the valve setup to an appropriate height using helium leak tests. The final opening characteristics of this setup are shown in Figure 3-1. Setup aimed at minimizing the voltages required in operation resulted in a valve opening starting at about 200V and by 500V a close to maximum flowrate. This setup allowed use of the valves full opening range at voltages that minimized the possibility of breakdown. Desired flowrate ranges are achievable through plenum pressure selection. For example, to restrict the flowrate for hydrogen at close to $1 \times 10^{20} \text{s}^{-1}$ with a plenum pressure of 375Torr an upper voltage limit of approximately 350V could be used as shown in Figure 3-1.
Figure 3-1: The final voltage opening characteristics of the valve setup for installation on H-1. The flowrate data was physically collected using air puffed from atm (virtual plenum) and the curves for helium and hydrogen extrapolated by gas law conversion. The setup provided an acceptable removal of leak rate when in an un-actuated state, verified with helium leak tests. It also maintained a relatively low opening voltage range (200-600V) allowing good flow control with voltages that avoid areas of possible Paschen breakdown (particularly if driving at lower plenum pressures i.e. <300Torr).

The 375Torr extrapolated hydrogen plot shows that a $1*10^{20}$ n/s flowrate can be achieved by restricting the voltage to 350V (as is also recommended for a low-pressure plenum environment).

Figure 3-2 shows how the puffer assembly was fitted at the end of the antenna re-entrant tube using of a curved positioning arm, placing it directly over the upper antenna section and oriented to inject through the antenna loop into the plasma below. Figure 3-3 shows a photograph of the installed gas puffer, taken from above, where it can be seen located between two TFC coils with related electrical and gas plumbing.
Figure 3-2: The puffer positioning above the antenna on H-1 used a curved positioning arm to orient the puff through the antenna and toward the plasma’s LCFS. The dimensional drawing presents its orientation design, and CAD view shows the setup at installation position with a modelled gas puff.

Figure 3-3: Image of gas puffer installed within H-1. This image, taken from directly above, shows gas puffer installed between TFC coils with antenna just seen below it. The electrical and gas feedthroughs can be seen on the top of the puffer unit.

3.1.1 Puffer control on H-1

The gas puffer control system for H-1 was based on the test tank software but with repurposing of its valve control modules, and related hardware and removing all anemometer and characterisation elements. Major adjustments included the integration of H-1 timing trigger, and functionality to support changing gas type. This section describes the software and control system elements. Figure 3-4 shows the architecture of the new system.
Figure 3-4: The experimental gas puffing setup on H-1 included an integrated H-1 timing trigger through to the main LabVIEW control centre via the data acquisition card (DAQ). The system allowed full puffer parameter setting, status monitoring, acquisition functionality, and the ability to flush and change between three selectable gas types.

As with the test tank system the core control component was a purpose-built LabVIEW state machine program, running on a PC, with time critical modules for controlling and acquiring data from the gas puff events. To interface the software with the physical instrumentation, a Texas Instruments data acquisition card (DAQ) was utilised. An analogue output from the DAQ (0-1V) was supplied to a high voltage amplifier (Trek 10/10B), where it was boosted by 1000x to produce the actuation signal for the piezo valve with a 10mA current limit. The software allowed the operator to define various gas puff variables related to the period and amplitude of the puff and its data acquisition settings. A trigger signal from the H-1 control system was integrated into the puffer control via the DAQ card and delay settings for the puffer allowed variable timing alignment between the puffer and H-1 shots.

During operational testing on H-1 it was discovered that the valve would begin leaking after some use, becoming apparent between gas puffs, as a gradient on the plenum pressure graph. This was possibly due to piezo hysteresis or material relaxation of the valve’s Viton sealing component. The leak could be removed by applying a
reverse voltage bias to the valve when not in operation. The voltage made the piezo apply more pressure to the valve opening improving the seal on the nozzle flange. The magnitude of the required voltage bias seemed to depend on the gas species (e.g. higher for hydrogen) and perhaps the hysteresis state of the valve but was generally in the range of 0-200V. A controllable bias voltage variable was added to the control system, such that a user was able to adjust the bias voltage until the leak was visibly removed from the plenum pressure graph.

To control plenum pressure the control system provided a plenum gas fill signal (5V TTL) to a solenoid valve that allowed regulated compressed air to be applied to a pneumatic valve on the gas line input to the plenum. The fill rates could be varied by pulse width modulating the TTL signal: a higher duty cycle resulting in an increased flow rate. From the software interface a user could set a desired plenum pressure and then either intermittently request the system drive the plenum to that set point or, set the action to automatic, such that the pressure was checked after each gas puff and driven to the set point if required. This ‘plenum pressure control loop’ used the plenum pressure feedback for proportional and integral control to dictate the duty cycle; that is the gas flow was reduced as the plenum pressure approached the set-point and increased as a function of time taken to get to that set point. Stability was achieved through careful selection of the control-loop gain settings so that the set point was reached in a reasonable time (generally seconds) without set point overshoot.

A manually operated ‘gas hub’, located upstream from the pneumatic valve, allowed the choice of one of three regulated gas sources. To change the gas in the puffer, the user would first flush the plenum of its existing gas using a rotary ‘flush’ pump (roughing pump). Ensuring all gas selection valves were closed and the gas fill valve open, the flush pump could be run-up and then applied to the plenum using the manual ‘flush’ valve. Once flushed, the pump could be isolated from the plenum using the same valve, the plenum fill valve closed, and the new gas type manually selected via the hub. The plenum could then be re-filled to a desired pressure under software control.
3.1.2 Viewing re-entrant port

To observe Stark effect or other light emissions from the injected gas puff required that the plasma illuminated by the gas puffer be viewed from an angle that was as perpendicular as possible to the poloidal cross section under the antenna, and that took in as much of the plasma cross section as possible. Locations no more than a few toroidal field coils away from the antenna and looking toroidally towards the injector were investigated.

Previous H-1 viewing systems deployed toroidally angled viewing mirrors close to the plasma, relaying light to a camera located outside a viewing port and adjacent to the H1 tank (Collis 2007). For the current project, images from the tank were transferred to an external camera via an angled mirror and an optic fibre bundle, housed in a specially designed re-entrant port, which was installed through Port 113 of the H1 tank.

Centred at 255.2°, Port 113 was a short distance clockwise from the antenna’s location at 275°, and aligned with a gap between two TFC coils. This allowed a straight re-entrant port to be inserted into the available space between the inner TFC wall and the plasma to obtain a wide-angle view of the antenna. Figure 3-5 shows a CAD model of the system together with a synthetic representation of the plasma view.

![Figure 3-5: Viewing location analysed with CAD and approximated camera view](image)

The picture on the left shows a generous space between a representative model of the re-entrant and the plasma model. The picture on the right shows the estimated view from the end of the modelled re-entrant.
The final re-entrant port was designed by Mark Gwyneth, a member of the H-1 technical team; Figure 3-6 shows mechanical drawings of the final product. It consisted of a hollow tube with a CF flange plate at one end for attaching the unit to the selected H-1 port. An optic fibre imaging bundle was inserted approximately 660mm down the centre of the tube, which bent at the light collection end at a 40° angle. A protective shutter rotated via a linkage assembly, was used to cover the end window to reduce possible damage when not in use. The re-entrant port was installed on H-1 with a 22.5° roll to point to the area of interest under the antenna. Figure 3-6 shows the unit located between the coils to obtain a clear line of sight to the antenna and puffer assembly.

Figure 3-6: Re-entrant port design drawings showing its dimensions and install angles on H-1 (courtesy Mark Gwyneth).
3.1.3 Imaging elements

Imaging elements incorporated into the re-entrant tube were carefully selected to transfer the view to an imaging camera located externally. This is shown in Figure 3-7; the following section describes the specifics of each.

![Diagram of H-1 imaging setup showing imaging elements that transition the desired plasma view to an external camera.](image)

Figure 3-7: H-1 imaging setup showing imaging elements that transition the desired plasma view to an external camera.

The light from the plasma/gas interaction passed through the window at the end of the re-entrant port and a negative lens (-60mm) allowed a wide field of view of the plasma volume to be directed onto an angled dielectric mirror, optimised to preserve the polarisation of light on reflection at 660nm (H-alpha). The light was then collimated by a 150mm lens and focused into the imaging bundle by a 35mm lens. Directly prior to the 35mm lens there was space to mount a polarimeter for linear polarisation measurements. The 1.8m long coherent imaging bundle (Schott IG-163) had an 8 mm x 10 mm rectangular image format consisting of 800 x 1000 lead silicate cores at 10μm core spacing. It was supplied with borosilicate cladding and C-mount connectors at both ends. The attenuation at 650nm was reported at 1.3dB/m as shown in Figure 3-8 alongside a photograph of the bundle.
Figure 3-8: The fibre bundle used for the system’s image capture and some attenuation graphs from the manufacturer.

After the bundle a 50mm and then 85mm (F-mount) lens relay formed the image onto a Princeton Instruments PI-MAX3 intensified CCD camera. An optical filter could be placed between the two lenses as required. A desktop PC running the camera-control software package 'Lightfield' recorded the images and allowed manipulation of the camera settings. An external trigger from H-1 was integrated into the camera’s control to allow synchronisation with H-1 shots. Figure 3-9 shows the external physical componentry.

Figure 3-9: An external snapshot of the viewing apparatus on H-1. The fibre imaging bundle can be seen snaking out of H-1’s port 113. A dark cloth covers the external lens and filter arrangement to prevent ingress of external light sources.
3.2 IMAGING ON H-1

The following section presents a variety of image sets captured using the installed system which highlighted its functionality. The aim here is not to undertake a systematic study into the physics of H-1, though aspects of the system’s use in certain areas of interest are explored as part of its function.

3.2.1 System validation

Images collected clearly showed the antenna and other H-1 features as expected from the design work. To properly analyse the images collected, a registered view that allowed a precise localisation of the collected light was needed. To assist this, an existing registration undertaken on the re-entrant port (Thorman 2018) was reviewed, revealing that an orientation adjustment had occurred between the time of this work and that registration. This could have happened when the fibre bundle was removed and during optical system adjustment or re-alignment. The antenna was also modified between the two works to address issues of interference with TFC coils.

A python script was developed to map known H-1 features (extracted from CAD) onto acquired images. By using the Thorman registration as the starting point adjustment to the roll, zoom, and centre variables to match known features with their position in the image provided an updated view registration. The results are presented in Figure 3-10 and Table 4.
Figure 3-10: A view registration taken after adjustments to the viewing system is remapped using known H-1 features for alignment. The yellow lines are of TFC items, green lines are the PFC and the three red lines on the left image are sketched on the surface of the helical coil. Additional roll and decentre applied to the existing registered view were required to fit to the images taken in this project, and the new registration is presented in Table 4. The result of the adjusted registration allows mapping of field lines and puncture points as shown on the right with a BLINE generated Poincare plot at 275° mapped onto a standard H-1 hydrogen plasma image.

<table>
<thead>
<tr>
<th>View Parameter</th>
<th>Adjusted Port 113 Re-entrant Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>r</td>
<td>1.287m</td>
</tr>
<tr>
<td>$\phi$</td>
<td>255.5°</td>
</tr>
<tr>
<td>z</td>
<td>0.373m</td>
</tr>
<tr>
<td>Yaw</td>
<td>$-43.7^\circ$</td>
</tr>
<tr>
<td>Pitch</td>
<td>19.1°</td>
</tr>
<tr>
<td>Roll</td>
<td>$-49^\circ$</td>
</tr>
<tr>
<td>Effective Focal Length</td>
<td>18.12mm</td>
</tr>
<tr>
<td>Decentre</td>
<td>(0.5,0.128)</td>
</tr>
</tbody>
</table>

Table 4: Updated view registration values for this project’s port 113 images. The new roll, pitch, and yaw definitions are changed (Thorman 2018), with the view defined along the x axis at $(r,\phi,z)$ and starting orientation with x directed at the H-1 z-axis $(0,0,z)$.

As a further crosscheck, the registered view was then used to map BLINE modelled field-line data onto electron beam images captured by the system. A thermionic filament inserted into H-1 launched an electron beam into the magnetic confinement region (Thorman 2018). Adjustments in the filament’s initial position determined the magnetic surface traversed by the electrons. The beam emitted light through collision with background gas, tracing visible lines around the system. The lines and the modelled overlays can be seen in Figure 3-11 with an indication of the magnetic surfaces (at the puffer toroidal location) being traversed by the different electron beam setups. The alignment is considered satisfactory for the purpose of
confirming diagnostic functionality and supporting the re-registered view as acceptable for further image analysis work.

Figure 3-11: Images of BLINE line overlays in dark blue on electron beam images. The electron beams in each have been fired into H-1 at different radii and, therefore, are captured by different magnetic layers, as indicated by the Poincare plots overlayed in lighter blue. The H-1 magnetic model used was the h1model15c using 1912 Biot-Savart filament elements per period and 151 circular filaments. This was the most accurate model available and a slight improvement on the one used in previous work by Kumar (2014).

3.2.2 Images of the injected puff

A number of image collection experiments were undertaken with the aim of highlighting the system’s capabilities as a diagnostic or fuelling tool. Examinations included measuring the effects of puffer flow rate on light intensity, manipulating images to visualize the temporal evolution of the puff into the area under the antenna, combining helium line image data into line ratio maps to examine radial electron temperature and density profiles, analysing and comparing different plasma configurations and shapes.

Varying the puffer flow rate

Helium puffs of increasing flow rate were applied to a ‘standard configuration’ hydrogen plasma (0.56Tesla). A 707nm He atom light filter was used to isolate the plasma/puff interactions. The plenum pressure was maintained at approximately 700Torr while varying voltage to affect flow rate. Image analysis reveals the change in light intensity as the puffer’s flow rate was increased. The flow rates and non-
calibrated 707nm light intensity are shown in Figure 3-12 where an approximate linear increase in light intensity in response to the flow rate increase is shown, within the range analysed: a doubling in flow rate results in a doubling of 707nm light intensity.

![Graph of non-calibrated 707nm light emissions vs helium puffer flow rate on hydrogen plasma (0.56Tesla ‘standard’ configuration).](image)

Figure 3-12: Graph of non-calibrated 707nm light emissions vs helium puffer flow rate on hydrogen plasma (0.56Tesla ‘standard’ configuration). The image to the left shows an example of the images collected and an approximated example of the area of maximum intensity from which the values would have been taken (in the vicinity of the LCS closest to the antenna).

**Temporal Evolution of a Puff**

The study of the gas puff evolution is useful for confirming the results obtained in the test tank. Images were taken throughout a 10ms helium puff of approximately $3 \times 10^{20}$ particles/s (400V, 700Torr valve parameters) into a ‘standard configuration’ 0.56Tesla hydrogen plasma with a 707nm (helium) filter. The light for each image was collected for 0.1ms and non-puff background images subtracted. The graph shown in Figure 3-13 presents the evolution in light intensity at selected times during the 10ms puff. A fast increase occurred in the first 2.5ms as the valve opened. This aligns well with the characterised puffers’s valve response time of 2.6ms for a 400V valve application (eq 2.13). The intensity was then relatively stable for the rest of the puff period to 10ms (although with a slight positive slope). On removal of the puff the light intensity dropped as the helium gas dissipated from the plasma body.
Normalised radial line profiles are shown in Figure 3-14. The profile shape can be seen to move closer to the antenna only in the initial stages (<0.4ms). As the puff progresses, the emission shifts towards the centre of the radial profile, visible graphically by the increase in relative intensity between 0 and 40mm compared with the peaks at approximately 65mm.
Figure 3-14: Normalised intensity line profiles throughout and after a 10ms puff. The profiles are taken along the orange line shown in the inlayed image, starting from the centre of the Poincare plot and progressing toward the antenna.

To further examine the dynamic behaviours of the puff in its early stages, the exclusive light for each 1ms timeframe was isolated by subtraction of the previous timeframe.

The sequence of images shown in Figure 3-15 highlight the dynamic behaviour of the gas puff in its earliest stages of expansion into the plasma. The exclusive light for each 1ms timeframe is isolated by subtraction of the previous timeframe. In these images the puff can be seen lighting up the plasma region closest to the gas puffer and antenna system, before emissions increase and spread into the plasma in the direction of the puff.
Figure 3-15: Images taken at progressively incremented start times into a puff. Each has had its proceeding image subtracted and the intensity normalised to isolate and highlight only light new to the timeframe. The images have had a standard Poincare plot overlaid to provide a reference for the puff’s evolution into the plasma (standard hydrogen 0.56Tesla).

**Helium line ratios from puffer/plasma interactions**

Electron temperature and density distributions using helium line ratio techniques (based on collisional radiative model) have been evaluated on H-1 (Ma et al 2012) and have produced results in good agreement with other diagnostic techniques. This section presents images captured on a standard 0.56Tesla hydrogen plasma with helium puffed at an approximate flow rate of 3.3e20 particles/s (600V, 700Torr valve settings). The images are integrated over 8ms (central to the 10ms puff) with background removed. Separate filters for 668nm, 707nm and 728nm helium emission lines where successively placed in front of the camera. Figure 3-16 presents the three emission line images, each normalised to place the intensity range of the light collected between 0 and 1. Figure 3-17 compares their intensities along a radial profile line from the centre of a Poincare plot toward the antenna.
Figure 3-16: Images are of three separate emission line wavelengths from puffed helium (3e20part/s) into standard hydrogen plasma (0.56Tesla). The images are integrated over 8ms (central to a 10ms pulse) with background removed and normalised to highlight shape rather than intensity. The Poincare overlay (red points) for a $\kappa_B = 1$ provides reference for changes in intensity shape along with isolines of the light emissions ranged every 20%. The coloured lines (orange, green, purple) show where non-normalised intensity profiles have been extracted for the graph in Figure 3-17.

![Helium Lines vs Radial Distance from Plasma Centre](image)

Figure 3-17: 668nm, 707nm and 728nm helium line profiles from figure 3-17 images compared. Note that the relative intensities of these lines are not calibrated.

Specific ratios of these lines have been shown to be strongly linked to electron temperature $T_e$ and density $n_e$ (Ma et al 2012). Specifically, the two singlet lines of 668nm and 728nm to the $n_e$ and the triplet singlet pairing of 707nm and 728nm to $T_e$. Images mapping these ratios are shown in Figure 3-18 and the related profile line intensity graph in Figure 3-19.
Figure 3-18: Comparison of light emission intensity at 668nm, 707nm and 728nm from puffed helium (approx. $3\times10^{20}$ particles/s) on standard hydrogen plasma (0.56 Tesla).

Figure 3-19: Helium line ratio profiles extracted from the images in Figure 3-17 as indicated by the coloured line overlays. The radial distance is measured from the starting point at the centre of the Poincare plot (red) toward the antenna.

The helium line ratio data indicates an expected drop in the electron-density linked ratio ($668/725$nm) from a high point in the centre of the plasma towards the last closed flux surface (LCFS) closest the antenna where the value flat lines outside the LCFS. It also shows an increase in the electron-temperature linked ratio ($728/707$nm) along the same line with the higher temperature experienced closest to the antenna. This behaviour has been observed in other work on H-1 (Ma et al 2012)
**Puffer Emissions on Varied Plasma Configurations**

The shape of the magnetic flux surfaces can be adjusted by altering the helical and vertical current ratios, as described in Section 1.7.1. To examine the effect of this flux surface shape change, images were collected in 707nm light on hydrogen plasmas puffed with helium for a variety of helical current ratios $\kappa_h$, while maintaining a vertical current ratio $\kappa_v$ of 1. The 707nm light is loosely tied to the electron temperature, which should highlight changes in the temperature profile for the various configurations.

The $\kappa_h$ values for a hydrogen plasma (0.56 Tesla) were adjusted from 0 to 1.1, and helium was puffed at approximately $3e20$ particles/s (400V, 700Torr valve settings), used to generate and capture 707nm light. The images are integrated over the last 8ms of a 10ms puff and background removed. A comparison of the images is presented in Figure 3-20; normalised intensity line profiles from the Poincare centre of a $\kappa_h = 0$ field line plot across the peak light intensity area of the LCFS closest the antenna are shown in Figure 3-21. They show that as the configuration of H-1 is adjusted with $\kappa_h$ values there is a movement of the LCFS, evident as the peak of the profiles and the slope leading to the antenna shifts in relation to the centre of the $\kappa_h = 0$ field line plot or antenna.
Figure 3-20: Normalised 707nm intensity images for helium puffed into a hydrogen plasma (0.56 Tesla) at different helical current ratio ($\kappa_h$) settings. The images are integrated over the last 8ms of a 10ms puff and background removed.

Figure 3-21: 707nm intensity line-profiles (normalised to all range 0-1) for helium puffed into hydrogen plasma (0.56 Tesla) at different helical current ratios ($\kappa_h$). The lines over which the profiles are taken are shown on the images of Figure 3-19. All profiles are over the same line running from the centre of the $\kappa_h = 0$ Poincare toward the antenna.
**Island Investigation**

While analysing the images from the hydrogen plasma over varied helical current ratios ($\kappa_h$) an anomaly was noted at $\kappa_h = 0.4$. A portion of the plasma edge appeared to separate from the main body in terms of the light emissions being collected. To further analyse this feature due to effects of a possible island, additional data was collected from either side; every $0.2\Delta\kappa_h$ from $\kappa_h = 0.3$ to $0.5$. The results of this are shown in Figure 3-22, where the most prominent location of the separation ($\kappa_h = 0.38$) is shown as well as the values of $\kappa_h$ to either side where the feature disappears.

![Images Investigating Possible Island Feature](image)

Figure 3-22: images of a possible anomaly in a hydrogen plasma seen while adjusting helical current ratios ($\kappa_h$). The anomaly is most prominent at $\kappa_h = 0.38$ and either side of this value by $\kappa_h = 0.34$ $\kappa_h = 0.46$ the feature is no longer visible. The isolines added highlight the visual separation when present.

By subtracting an averaged baseline image from either side of the 0.38 images the edge feature is highlighted further. This can be seen as the low (or dark) area between two highs in Figure 3-23. Overlaying a Poincare plot of the same helical current ratio generated in BLINE, shows an approximate spatial alignment between the modelled Poincare island and the low of the feature.
Figure 3-23: Image of the anomaly at $\kappa_h = 0.38$ with a subtracted baseline, created from the average of images to either side (with respect to $\kappa_h$). All images were normalized before subtraction. An overlaid BLINE Poincare for the same helical current ratio shows approximate alignment between modelled island and the extracted feature.
Chapter 4: Discussion

The aim of this research work is to highlight the functional capabilities of a successfully designed, characterised, and tested diagnostic tool, installed on the Australian National University’s H-1 fusion plasma confinement facility. The tool was designed to investigate electric field properties in the region of a plasma excitation antenna by examining Stark effect splitting on H-alpha photons emitted from excited hydrogen gas atoms injected into the area using a high velocity gas puffer.

The final integrated puffer and imaging system was successfully installed and tested, with results supporting its ability as a diagnostic tool, in particular, for measuring electron temperature ($T_e$) and electron density ($n_e$) using helium line ratios. The system has been used in other work, including a PhD by Alex Thorman (2018), which presents its use for synchronous imaging of RF heating wave propagation. The current project did not attempt any systematic study into the physics of H-1 including by Stark effect analysis. Thorman’s work also investigated polarisation imaging of the electric field via Stark effect but concluded that insufficient nett polarization was available most likely due to broadening of the $H\alpha$ multiplet.

This thesis describes the design and development of the diagnostic tool and can be divided into two main sections: the development and characterisation of the puffer system; and the installation/testing of the puffer and a newly designed viewing system on the H-1 facility. The main outcomes of these two main phases are reviewed in the following sections.

4.1 PUFFER DESIGN AND CHARACTERISATION

The puffer was designed to control the flow and limit the divergent spread of gas molecules into the plasma. Light emissions from the interactions were captured by a viewing apparatus incorporating a purpose-built re-entrant port, an imaging fibre-optics bundle, ICCD camera, and varied light collection optics and filter elements.

The diagnostic gas puffer design aimed to minimise the gas beam divergence and to deliver a controllable flow rate of less than $1.0e^{20}$ particles/s—lower than
previous puffer work (Collis 2007)—in order to allow for a minimised disturbance effect on the plasma. A fast valve response was also desirable to allow precise temporal control of the injection and maintain options for high frequency modulated flow control.

Nozzle design was guided by theoretical gas dynamics equations and available manufacturing techniques leading to a convergent/divergent design using a wire EDM manufacturing technique. Retention of the same nozzle form factor as previously designed Collis’ nozzles allowed for interchangeability of the puffer assemblies in case of future diagnostic or fuelling requirements. The new nozzle had a throat diameter of 0.18mm and 20° convergent/divergent sections.

At the core of the valve design, an OEM piezo bender provided the high speed and precision actuation. Installed into the plenum assembly, a Viton seal was held against the nozzle entrance. Manually setting the height of the piezo against a copper spring while monitoring the leak and opening characteristics set the very important opening voltage range for the valve.

Characterisation of the puffer was undertaken in a test tank with a purpose-built LabVIEW control system and instruments to measure valve voltage, tank/plenum pressure, and gas flow. A constant temperature anemometer (CTA) probe and positioning system was designed that allowed the collection of mass flow data from adjustable distances and angles from the nozzle entrance. Characterisation efforts highlighted various system behaviours including:

- fine dynamic behaviours of the valve, including its opening speed and the effects of the voltage-amplifier settings on piezo responsiveness;
- for reliability, important operational limits related to the drive signal and plenum pressure as a result of electrical breakdowns;
- flow rate measurements showed reasonable agreement to theoretical prediction models (Section 2.6.3) and confirmed the ability to limit output to $1.0 \times 10^{20}$ particles/s given appropriate plenum pressure and voltage application settings; and
- beam divergence measured using a movable anemometer varied between 10° and 35° depending on the selected gas and puffer settings (Section
2.6.3. Comparing results to previous work (Collis 2007) the hydrogen and nitrogen divergence values collected in this work were both lower than previous helium results when taken at the same flow rate.

One issue found during the characterisation work, and an area where future improvement may be found, was a limitation in the level of flux that could be measured by the anemometer. High density gas puffs (those generated from high plenum pressures and high opening voltages) produced centrally peaked expanding jets, whose angular distribution could be well fitted by a Gaussian. At lower flow rates, or at larger distances from the nozzle, a far smaller change in the anemometer value was experienced with unreliable Gaussian fit. This problem was caused by the sensitivity of the anemometer setup and could have likely been improved by driving the filament harder (at a higher constant temperature) but at the risk of increased fragility of the filament at higher temperatures.

4.2 H-1 INSTALLATION AND TESTING

Once characterisation work was concluded, installation and testing on H-1 was undertaken. The major developments during install included positioning the puffer above the heating antenna with a curved positioning arm to correctly orient the gas puff in the desired direction.

Secondly, an updated control system for the H-1 environment allowed status monitoring; adjustment of required puffer parameters; and setting alignment between puff, plasma and imaging timing using an H-1 trigger signal. It included automated plenum pressure regulation, gas type swap-out, and valve-closed voltage biasing for removal of any unexpected leak rates.

Finally, a re-entrant style viewing system successfully collected light from the desired location under the antenna, encompassing the majority of any plasma shapes on the antenna’s 275° plane. It included a re-entrant port extending between two TFC’s close to the antenna, a window facing the antenna, angled mirror, imaging fibre bundle, optics, filters, ICCD camera, and is also linked to the H-1 trigger.

As detailed in section 3.2.1, view registration (defined by the position and orientation of the effective lens and focal point) was investigated, based on images taken as part of Thorman’s (2018) work. Alterations to the camera and fibre bundle,
made between Thorman’s assessment and this work, meant some adjustment was required. By mapping known H-1 features onto acquired images it was necessary to adjust the centre and roll of the camera field of view (Section 3.2.1). The adjusted registration was checked by comparing modelled BLINE line traces onto electron beam images. These confirmed satisfactory alignment for the purpose of assessing the system functionality.

Plasma experiments to test the diagnostic capability produced the following outcomes.

- Measured light intensity against puffer flow rate provided basic confirmation of puffer control with expected light intensity increased in the plasma edge region under the antenna.
- Temporally incremented images through a puff’s evolution confirmed the system’s ability to successfully set timing between the puffer, camera, and H-1. The results aligned with piezo valve opening characteristics. The puff’s evolution showed an expected transition of light emission starting at the LCFS closest to the antenna and puffer.
- Helium line emission images for 668, 707 and 728nm light collected using optical filters and ratios (linked to electron temperature $T_e$ and density $n_e$) were mapped across the images and along the radial profile. The results for $T_e$ and $n_e$ profiles agree with previous work (Ma et al 2012) and the application of its collisional radiative model (or similar) to extract values presents a diagnostic method for the system that may be of further interest.
- Examinations of varied plasma configurations ($\kappa_h$) highlighted the ability to visualise configuration changes using isographic intensity plots and radial profiles. The images, collected in 707nm helium light, were tied to electron temperature and expanding this examination to helium ratios by including 628nm and 728nm poses an opportunity for future work directions.
- An anomaly in the ($\kappa_h$) adjusted image set for hydrogen plasma was further probed and a possible island, aligning approximately with Poincare field maps, was extracted. Further helium line ratio work to
more deeply probe these electron density and temperature features would provide an interesting study of magnetic confinement in the vicinity of magnetic islands.

The perturbative effect of the gas puffer on the plasma was not fully explored in this work although Thorman’s (2018) paper (discussed in section 4.3) indicates limited enough effect at least in the arrangement of that work. Further examination could be undertaken using helium line ratios (examined already in this work) and comparing electron temperature profiles at a variety of flowrate settings.

### 4.3 SUBSEQUENT USE AND RECOMMENDATIONS

A subsequent project by Alex Thorman attempted to use the system to measure the RF electric field near the antenna via Stark effect and polarisation imaging techniques but found insufficient nett polarisation due to a number of possible reasons, including Doppler broadening, line integration effects, and a possibly weaker electric field than expected. The project did, however, successfully use the puffer system for synchronous imaging of RF heating waves and revealed a 7MHz oscillation in the light intensity linked (through density perturbations) to a probable ion cyclotron wave launched from the antenna (Thorman 2018). The discovery shed light on some previously unexplained features such as edge peaked electron temperatures and was the first time this type of imaging had been used to measure RF heating waves.

It is clear that the further use of helium line ratios is a potentially powerful diagnostic direction for this tool, and one recommended by this author. Similarly, further application of a collisional radiation model to the ratio results (with proper relative density calibration) may lead to the ability to study density and temperature aspects of the plasma under the antenna to investigate islands/anomalies and instabilities related to heating mechanisms. The success of Thorman’s (2018) work on imaging waves additionally highlights the possibility of using a modulated puffer flow to observe density perturbations using the helium 668/728nm ratio and could be a useful technique for studying plasma transport properties in the future.
4.4 FINAL THOUGHTS

This project has been a fascinating and eye-opening experience into the fascinating topic of fusion science and plasma confinement. The hope of a clean and abundant source of energy is elusive but greatly needed and the chance to contribute to that endeavour has been a great and exciting challenge. That this work can be a small piece in the decades-long endeavour of so many great people would be a great privilege indeed.
Bibliography


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Appendices

Appendix A

Derivation of Particle Flowrate Equation

If the throat area and the cross-sectional areas along the divergent section of a nozzle are known (through knowledge of the geometry), the Mach number at points along the divergent section can be determined. Using the Mach number, flow components of pressure, density, temperature and velocity can be calculated (Anderson, 1990).

\[
\frac{T}{T_0} = \left(1 + \frac{y-1}{2} M^2\right)^{-1} \quad (A.1)
\]

\[
\frac{P}{P_0} = \left(1 + \frac{y-1}{2} M^2\right)^{\frac{y}{y-1}} \quad (A.2)
\]

\[
\frac{\rho}{\rho_0} = \left(1 + \frac{y-1}{2} M^2\right)^{-\frac{1}{y-1}} \quad (A.3)
\]

\[
\nu = M\sqrt{\gamma R_{\text{gas}} T_0} \left(1 + \frac{y-1}{2} M^2\right)^{-\frac{1}{2}} \quad (A.4)
\]

\( R_{\text{gas}} \) is the specific gas constant and items with subscript 0 are values in plenum and the equivalent items without the subscript are the values at the nozzle centreline location with a Mach number \( M \) (as defined by equation 2.2 in section 2.1.1). The heat capacity ratio \( \gamma \) can be well described using 5/3 for a monoatomic gas and 7/5 for a diatomic gas.

When the pressure ratio between the nozzle exit and the gas pressure source (plenum) \( \left(\frac{P_e}{P_p}\right) \), is smaller than 0.528 flow is choked (Anderson, 1990), the flow rate becomes dependant on the area of the throat alone. The Mach number at this point becomes \( M=1 \) and the following equations apply:
The flow density at the nozzle throat with $M=1$:

$$\frac{\rho^#}{\rho_o} = \left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}} \implies \rho^# = \rho_o \left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}} \tag{A.5}$$

The temperature at the Throat

$$\frac{T^#}{T_o} = \frac{2}{\gamma+1} \implies T^# = T_o \frac{2}{\gamma+1} \tag{A.6}$$

Speed of sound at the Throat:

$$a^# = \sqrt{\gamma R_{gas} T^#} \tag{A.7}$$

The gas density in the plenum can be calculated using a derivation of the ideal gas law:

$$\rho_0 = \frac{P_o}{R_{gas} T_o} \tag{A.8}$$

The flow through the nozzle in kg/s can then be converted to particles/second by dividing by the molecular mass:

$$\dot{m} = \rho^# A^# a^# \text{ Kg/s} \tag{A.9}$$

$$\dot{N} = \frac{\dot{m}}{m_{gas}} \text{ Particles/s} \tag{A.10}$$

Where the specific gas constant is the ideal gas constant divided by the Molar mass:

$$R_{gas} = \frac{R}{M_{gas}} \text{ and the molecular mass is the molar mass divided by Avogadro’s constant}$$

$$m_{gas} = \frac{M_{gas}}{N_A}.$$ 

By combining A.5 through A.9 into A.10 the equation for flow through a choked nozzle is thus:

$$\dot{N} = \frac{p_o A^# N_A \left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}} \sqrt{\frac{2^\gamma T_o}{M_{gas} \gamma + 1}}}{R T_o} \text{ (Particles/s)} \tag{A.11}$$

$N_A$ being Avogadro’s constant, $M_{gas}$ is the molar mass of a gas, $p_0$ the pressure in the plenum, $R$ the ideal gas constant, $T_o$ is the temperature in the plenum (use room temp at 298K) and $A^#$ is the area of the throat.
Appendix B

Accelerometer Equations

An accelerometer is a device that is sensitive to linear acceleration in a particular direction as well as any local gravitational field. When using three devices in a set-up that is sensitive in x y z direction they are termed three axis accelerometers. In this form they are useful tools for measuring orientation and can be used to feedback the change in motion of any device they are attached to.

Accelerometers come in a variety of sensitivities which are usually specified in a 'g' rating. A 1g rating would mean that the accelerometer will sense up to a single Earth g field, approximately 9.8m/s^2.

A 3-axis accelerometer will have three outputs, one for each axis. The outputs can take several forms depending on the make of the device. Analogue outputs that span voltages such as 0-5V or currents like 4-20mA. This can be converted to units of g as follows:

\[
G = g_L + \left[ \frac{(S-s_L)}{(s_H-s_L)} (g_H - g_L) \right]
\]  \hspace{1cm} (B.1)

Where S is the signal from the accelerometer axis, \(s_L\) is the low signal point, \(s_H\) is the high signal point with \(g_L\) and \(g_H\) being the respective low and high g ratings those signals represent. In many cases the low points of both signal and g-rating will be zero and in these cases equation 3-23 simplifies to:

\[
G = \frac{S}{s_H} g_H
\]  \hspace{1cm} (B.2)

Any particular orientation of the accelerometer can be shown in its vector matrix form and the length of any vector defined by the three accelerometer-axis for an at-rest device in a gravitational field should be 1 and in practice very close to 1.
The vector of the 3-axis accelerometer will end anywhere on a sphere with a radius of 1 centred on the point around which the accelerometer rotates.

Roll and pitch angles can be calculated from the following formulas assuming rotation about x axis to be roll and about y axis to be pitch

Roll: \( \tan \phi_{xyz} = \frac{G_{py}}{G_{pz}} \) \hspace{1cm} (B.4)

Pitch: \( \tan \theta_{xyz} = \frac{-G_{px}}{G_{py} \sin \phi + G_{pz} \cos \phi} \) \hspace{1cm} (B.5)

For calculating the absolute angle between any two vectors generated by the accelerometers the following can be used:

\[
\begin{align*}
  a \cdot b &= \begin{pmatrix} a_x \\ a_y \\ a_z \end{pmatrix} \cdot \begin{pmatrix} b_x \\ b_y \\ b_z \end{pmatrix} = a_x b_x + a_y b_y + a_z b_z = ab \cos(\alpha) \\
\cos(\alpha) &= \frac{a_x b_x + a_y b_y + a_z b_z}{\sqrt{a_x^2 + a_y^2 + a_z^2} \sqrt{b_x^2 + b_y^2 + b_z^2}} 
\end{align*}
\] \hspace{1cm} (B.6)