The hot hELicon eXperiment (HELIX) and the large experiment on instabilities and anisotropy (LEIA)


1Department of Physics and Astronomy, West Virginia University, Morgantown, WV 26506, USA
2Department of Atmospheric and Space Sciences, University of Michigan, Ann Arbor, MI 48109, USA
3Los Alamos National Laboratory, Los Alamos, NM 87545, USA
4Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui 230026, China
5Wacker Polysilicon North America LLC, Charleston, TN 37310, USA
6US Army Research Laboratory, Adelphi, MD 20783, USA
7Department of Physics, Gonzaga University, Spokane, WA 99258, USA
8Center for Energy Research, University of California, San Diego, CA 92093, USA
9Department of Physics, Texas Lutheran University, Seguin, TX 78155, USA
10Department of Physics, University of Wisconsin, Madison, WI 53706, USA

(Received 4 March 2014; revised 14 May 2014; accepted 19 September 2014)

The West Virginia University Hot hELicon eXperiment (HELIX) provides variable density and ion temperature plasmas, with controllable levels of thermal anisotropy, for space relevant laboratory experiments in the Large Experiment on Instabilities and Anisotropy (LEIA) as well as fundamental studies of helicon source physics in HELIX. Through auxiliary ion heating, the ion temperature anisotropy \( T_{\perp}/T_{||} \) is variable from 1 to 20 for parallel plasma beta \( \beta = 8\pi nkT_{i}/B^{2} \) values that span the range of 0.0001 to 0.01 in LEIA. The ion velocity distribution function is measured throughout the discharge volume in steady-state and pulsed plasmas with laser induced fluorescence (LIF). The wavelengths of very short wavelength electrostatic fluctuations are measured with a coherent microwave scattering system. Operating at low neutral pressures triggers spontaneous formation of a current-free electric double layer. Ion acceleration through the double layer is detected through LIF. LIF-based velocity space tomography of the accelerated beam provides a two-dimensional mapping of the bulk and beam ion distribution functions. The driving frequency for the \( m = 1 \) helical antenna is continuously variable from 8.5 to 16 MHz and frequency dependent variations of the RF coupling to the plasma allow the spontaneously appearing double layers to be turned on and off without modifying the plasma collisionality or magnetic field geometry. Single and multi-species plasmas are created with argon, helium, nitrogen, krypton, and xenon. The noble gas plasmas have steep neutral density gradients, with ionization levels reaching 100% in the core of the plasma source. The large plasma density in the source enables the study of Alfvén waves in the HELIX device.

† Email address for correspondence: escime@wvu.edu
1. Introduction

The combined Hot hELIcon eXperiment (HELIX) and Large Experiment on Instabilities and Anisotropies (LEIA) facility was constructed in the mid-1990s to provide a plasma environment suitable for investigating phenomena of magnetospheric and heliospheric relevance. The primary scientific question of interest was whether theoretical models that predicted a beta dependent limit on the amount of thermal anisotropy in a collisionless plasma could be validated in laboratory experiments (Gary et al. 1997). The HELIX-LEIA experiments successfully demonstrated a threshold scaling for instability excitation and a limit on thermal anisotropy that were consistent with theoretical predictions (Keiter et al. 2000; Scime et al. 2000). The role of thermal anisotropy in setting instability thresholds is the subject of renewed interest in the past few years, especially in terms of anisotropy limits for mirror, firehose, and proton cyclotron instabilities in the solar wind (Bale et al. 2009).

In addition to being able to create space relevant plasmas, the HELIX plasma source was intentionally designed to have the capacity to test key predictions of helicon source theory. Early in the development of helicon sources, Boswell proposed that the density in a helicon source should obey a simple bounded whistler, i.e. helicon, wave dispersion relation (Boswell 1970).

\[
n \approx k_{||}^2 c B / 8 \pi^2 e f,
\]  

(1)

where \( n \) is the density, \( B \) is the magnetic field strength, \( e \) is the electron charge, \( c \) is the speed of light, \( k_{||} \) is the parallel wave number, and \( f \) is the antenna/wave frequency. Note that the density is predicted to scale inversely with wave frequency – at constant magnetic field. Therefore, HELIX was designed to operate over the continuous frequency range of 0.3 to 30 MHz. Typically, the source operates over the range of 8 to 16.5 MHz. Investigations of helicon source physics in HELIX have resulted in a deeper understanding of ion heating and ion anisotropy in helicon sources. Measurements of ion properties in helicon sources have also provided key details about the energy coupling process from the rf antenna to the plasma in helicon sources.

Observations of resonant ion heating, needed to enhance and control the natural thermal anisotropy in helicon sources for a series of magnetospheric physics studies, suggested that the neutral fraction in the core of helicon sources is much lower than would be naively calculated based on edge measurements of the neutral pressure. New diagnostic methods for the measurement of neutral densities within a plasma were then developed (Keesee and Scime 2006b; Keesee and Scime 2007). Subsequent radial profile measurements of the neutral density in argon, helium, and krypton helicon plasmas demonstrated that helicon sources are, in fact, much more ionized in the core of the plasma than edge measurements would imply (Keesee and Scime 2007; Magee et al. 2012a). The combination of low ion-neutral and electron-neutral collisionality and large plasma densities (>10\(^{13}\) cm\(^{-3}\)) permits the propagation of magnetohydrodynamic waves, Alfvén waves. From studies of magnetospherically relevant instabilities driven by thermal anisotropy to Alfvén wave propagation studies, the HELIX-LEIA facility has proven to be a versatile platform for space-relevant plasma physics in the laboratory, applied plasma physics experiments, and for the development of novel diagnostic methods.

Here we describe the essential features of the HELIX-LEIA facility as well as the key diagnostics and ancillary systems that make the experimental facility unique.
The hot hELicon eXperiment (HELIX)

Figure 1. (Colour online) The 61 cm long, 10 cm diameter glass source tube mated coaxially to the 91 cm long, 15 cm diameter stainless steel tube that constitutes the current HELIX vacuum chamber.

Figure 2. The balanced $\pi$ matching network for the rf antenna. Note that neither side of the antenna is held at ground potential. The (CL) is tunable from 20–2000 pF, two of the tuning capacitors are tunable from 4–250 pF and the third tuning capacitor is tunable over the range 5–500 pF.

2. HELIX-LEIA

The vacuum chamber of the original HELIX experiment, built in 1995, was constructed from a 150 cm long, 15 cm diameter, straight Pyrex™ cylinder (Keiter et al. 1997). In 1996 the vacuum chamber was upgraded to a Pyrex™ tube 15 cm in diameter and 157 cm long with two pairs of opposing 2.5 cm ports in a cross formation located 52 cm from one end (Balkey et al. 2001). The ports provided direct radial access to the core plasma in the source for probes and spectroscopy. In 2001, the vacuum chamber was again upgraded to provide access to multiple axial locations for probe measurements, to enable fluorescence measurements across the entire plasma column, and to reduce replacement costs for new glass chambers. HELIX operates in both steady-state and pulsed modes and twenty-four to forty-eight hour continuous experiments are not uncommon. For comparison, the total plasma creation energy in a single twenty-four hour period in HELIX is equivalent to fifty, 2 s long, 1 MW pulses. Thus, it is not surprising that the erosion of the glass chamber from ion bombardment necessitates complete chamber replacement every few years. The current HELIX source chamber consists of a 61 cm long, 10 cm diameter Pyrex tube mated coaxially to a 91 cm long, 15 cm diameter stainless steel tube (see Fig. 1).

The rf power for plasma generation in HELIX is supplied by a 30 dB rf amplifier (ENI 1000) in conjunction with a 50 MHz function generator (Wavetek model-80). Rf power of up to 2 kW is transmitted from the amplifier to the matching network through a high power, high frequency, type N, coaxial cable. The matching network (see Fig. 2) is a balanced $\pi$ network, i.e. neither side of the rf antenna is grounded. The load capacitor (CL) is a Jennings CVCD 2000 capacitor tunable from 20–2000 pF. There are three tuning capacitors (CT) wired in parallel. Two of the tuning capacitors are Jennings UCSL 250 capacitors tunable from 4–250 pF.
and the third tuning capacitor is a Jennings UCSL 500 capacitor tunable over the range of 5–500 pF. The (CL) is rated for a recirculating current of 40 Amps. The balanced matching configuration allows all four capacitors to be mounted on a single 0.6 cm thick, electrically isolated, copper plate. The copper plate provides robust mechanical support and also serves as a radiator for heat from the capacitors. Rf power from the matching circuit is coupled to the rf antenna through a transmission line consisting of a pair of 0.62 cm thick, silver-plated, copper bars, 2.54 cm wide and approximately 50 cm long. The bars are spaced 2.54 cm apart and surrounded by a grounded copper cylinder separated from the bars with a 1 cm thick teflon insulator. The entire matching network is contained in a shielded, grounded enclosure that is actively cooled with a high throughput fan. The fan is shielded from the internal rf voltages with a copper screen. The antenna is a 19 cm long, half wave, \( m = +1 \), helical antenna that is tightly wrapped around the Pyrex tube 37 cm from the end of HELIX (see Fig. 1). The antenna is cut from a single piece of 2 mm thick copper plate that is bent around the glass tube and the ends joined together with screws. Tabs on the antenna are mated to the transmission line with screws. The antenna is actively cooled by a series of fans placed above the chamber, directly over the antenna. The entire amplifier to antenna system has an operating frequency range of 8.5 MHz to 16 MHz; limited by the capacitance range of the matching network. The forward and reflected rf powers are measured with independent rf power meters. When well matched, typical reflected powers are 10–50 W for forward powers up to 1.5 kW. At very low fill pressures, the reflected power increases and the forward power has to be kept below 750 W to avoid damaging the rf amplifier. The matching network and antenna cooling are sufficient to permit continuous operation at 750 W. Experimental campaigns often last for more than 24 h. The rf network also operates in a pulsed mode. Typical pulse rates are 10 Hz at a 50% duty cycle, but lower pulse frequencies with smaller duty cycles are sometimes used to prevent damage to particularly sensitive internal probes. Because the rf source is based on a very wide range amplifier, the rf amplitude has successfully been modulated at much higher frequencies, e.g. 35 kHz, to drive ion cyclotron or Alfvén waves in the discharge.

Neutral gas is fed into the system at two locations, upstream of the antenna at the end of the glass tube and through a fitting mounted on one of the four ports on the stainless steel chamber closest to the glass chamber, i.e. halfway along the axis of the source. The gas (or gas mixture) is injected through two calibrated mass flow valves (MKS 1179) using a mass flow controller (MKS PR-4000). One mass flow valve has an operating range of 1–200 sccm with an accuracy of 1%. The other mass flow valve has a range of 0.1–20 sccm with an accuracy of 0.1%. The HELIX chamber is attached coaxially to the Large Experiment on Instabilities and Anisotropies (LEIA) chamber. LEIA is a 4 m long, 2 m diameter aluminum expansion chamber. Aluminum was selected over stainless steel because its lower outgassing rate requires less pumping to maintain the target base pressure of \( 1 \times 10^{-7} \) Torr. Although copper gaskets are used in the source region since they can survive the elevated wall temperatures in the source, Viton™ gaskets are used throughout the rest of the vacuum system. Vacuum pumping is accomplished with a total of three turbomolecular drag pumps backed with oil-free diaphragm pumps. Two 1600 l/s pumps are stationed at one end of the LEIA chamber and a 550 l/s pump is attached to the end of the HELIX chamber opposite LEIA. Rough pumping from atmospheric pressure is performed with an oil-free roots pump. Thus, the entire HELIX-LEIA chamber is an oil free system suitable for the testing of space plasma instruments containing microchannel plates.
The hot hELicon eXperiment (HELIX)

(which are extremely sensitive to oil contamination). Since the gas inlet ports are on the HELIX chamber and the bulk of the pumping occurs at the far end of the LEIA chamber, there is a pressure gradient along the source axis. In the expansion chamber, the neutral pressure is one order of magnitude smaller than the pressure in HELIX. Typical gas species are argon and helium, although xenon, krypton, hydrogen, and nitrogen have been employed. Nitrogen is particularly damaging to the glass chamber and extreme care must be employed when creating nitrogen plasmas. A unique mode of operation demonstrated in HELIX is the ‘static’ mode. In a static mode plasma, all active pumping is discontinued by closing the gate valves between each pump and the vacuum chamber. The chamber is brought up to a target neutral pressure and the discharge initiated. Static, steady-state, helium plasmas have significantly reduced core neutral densities and higher electron densities compared to their actively pumped analogs (Houshmandyar and Scime 2012). Static discharges are particularly attractive when using expensive neutral species such as xenon.

Ten, water-cooled, copper solenoids with a 40 cm bore create the steady-state axial magnetic field in HELIX. Two Xantrex XFR dc power supplies in parallel provide up to 375 A current for the electromagnets. The maximum attainable magnetic field is 1225 G. The electromagnet spacing is designed for optimal field uniformity in HELIX. By reversing the current in the electromagnets, cusp fields may be created at either end of the source. Seven, 2.75 m diameter, water-cooled, aluminum solenoids confine the plasma in the LEIA chamber. See Fig. 3 for a typical magnetic field profile in HELIX. Square cross-section (1.27 cm × 1.27 cm) extruded aluminum wire with a circular cooling channel and insulated with a paper wrapping was selected for construction of the solenoids to reduce the weight and cost of the LEIA electromagnet system. Since there is no constraint on the physical thickness of the solenoid conductor, the better conductivity of copper is compensated by using aluminum conductors with a larger cross section. The ratio of densities divided by the ratio of conductivities for copper and aluminum results in a weight reduction of a factor of 1.84 when using aluminum instead of copper. Given that raw copper is also more than an order of magnitude more expensive than aluminum, aluminum provides the same overall magnet resistance at half the weight and a tenth of the cost of copper. Water connections are created by tapping the ends of the aluminum extrusion for 1/8” NPT fittings. Each aluminum solenoid contains 10 distinct pancake coils, each with four layers, i.e. a total of 40 turns per 12.7 cm wide solenoid.

Current of up to 200 Amps is provided by an EMI dc power supply and the maximum achievable axial magnetic field in LEIA is 140 G. Figure 3(b) shows the on-axis magnetic field strength and its gradient in the HELIX-LEIA combined system. Figures 3(a) and (b) were created with a two-dimensional numerical model that was validated with measurements along the system axis and at multiple radial locations. The evolution of contour lines of constant magnetic flux (flux tubes) are shown in Fig. 3(c) for the magnetic field strength profile shown in Fig. 3(b). Under typical operating conditions, in the boundary region between the helicon source and the expansion chamber there is an axial magnetic field gradient of nearly 30 G/cm that extends for tens of centimeters.

A rendering of the combined HELIX-LEIA facility including the electromagnets is shown in Fig. 4. Typical temperatures and densities in steady state argon plasma for a magnetic field of 800 G and 750 W of rf power are \( T_e \approx 4 \) eV, \( T_i \approx 0.4 \) eV and \( n = 1 \times 10^{13} \text{ cm}^{-3} \) as measured with an rf compensated Langmuir probe and (LIF). Perpendicular ion temperatures of up to 2.5 eV have been achieved with a 200 W auxiliary ion cyclotron resonant heating system in low pressure, 2 mTorr, plasma.
With the auxiliary ion heating system, the ion thermal anisotropy is variable from unity to more than a factor a five (Kline et al. 1999).

3. Diagnostics

The diagnostic complement of the HELIX-LEIA facility includes conventional rf compensated Langmuir probes (Keiter et al. 1997), swept frequency microwave interferometry (Scime et al. 2001), internal and external magnetic sense coil arrays (Balkey et al. 2001), coherent microwave scattering for the detection and analysis (space and time) of very short wavelength electrostatic waves (Hardin and Scime 2008; Scime et al. 2013), multi-tip probes for electrostatic wave detection and analysis (Chakraborty Thakur et al. 2009), retarding field energy analyzers for ion energy distribution function measurements (Harvey et al. 2008), emission spectroscopy for electron temperature measurements in argon and helium (Boivin et al. 2001), and rotational and vibrational temperature measurements in nitrogen (Biloiu et al. 2006, 2007a, 2007b), and a broad spectrum of temporally and spatially resolved LIF systems.
for the measurement of ion and neutral velocity distribution function measurements, from which plasma ion temperature, flow, density, and internal magnetic field values are determined (Scime et al. 2007). One scanning probe system is simultaneously able to acquire Langmuir probe current versus voltage measurements, measure magnetic field fluctuations along 3 orthogonal axes, and perform LIF-based velocity space tomography at any location in a horizontal plane that covers most of the LEIA vacuum chamber (Biloiu et al. 2004). All diagnostics that require direct plasma access are inserted through KF-40 mini gate valves on which are mounted an evacuated double o-ring seal. The double o-ring seals are fabricated from modified Ultra-Torr™ fittings welded to KF-40 flanges and are typically designed for 0.5″ and 1.0″ shafts. Because the double o-ring seals are created from commercially available fittings, manufacturing requirements and costs are minimal. The two most unique diagnostics are LIF and coherent microwave scattering.

The 300 GHz coherent microwave scattering system (Hardin and Scime 2008) (see Fig. 5) is a homodyne quasi-optical interferometer consisting of three beam paths: an ‘interaction’ beam path, a ‘scattered’ beam path, and a ‘reference’ beam path. All optical component dimensions were designed so that their radii are at least a factor of two larger than the beam waist. The lenses are fabricated from high density polyethylene (HDPE). Hyperbolic and ellipsoidal lens surfaces are used to produce and maintain a planar phase front and correct any phase lag. HDPE windows are also used as vacuum interfaces for the interaction and scattered beams since standard viewports heavily attenuate the 300 GHz signal. The windows have a 2.5° wedge cut into each face, relative to the surface normal, to minimize direct reflections. The microwave source is a frequency tripled Gunn oscillator with a tunable frequency range of \( \pm 1 \text{ GHz} \) and an output power of \( \sim 3.3 \text{ mW} \) at 300 GHz. The source uses a ‘potter horn’ antenna to produce a linearly polarized cylindrically symmetric Gaussian beam. The 300 GHz beam is directed into the plasma with the polarization direction parallel to the magnetic field of HELIX. The detector is a Schottky diode detector-mixer, centered at 300 GHz, with a sensitivity of 600 mV/mW, and an output intermediate frequency (IF) bandwidth of approximately 500 MHz. Data acquisition of the IF signal is performed using either a spectrum analyzer or a 100 MHz Digitizer. The spectrum analyzer has a noise floor voltage of approximately 450 nV. Given the detector sensitivity, the scattered power detection threshold is approximately 750 pW. Beam splitting is accomplished with stretched Mylar sheets. In Fig. 5, BS1 is a 76.2 \( \mu \text{m} \)
Figure 5. Schematic of the mm-wave system and the optical path through a cross section of the helicon source (at \( z = 85 \) cm): (S) is the mm-wave source, (D) is the detector, (M) are mirrors, (VM) is the adjustable vacuum mirror, (BS1) and (BS2) are the beam splitters. The cross sectional view includes the source chamber and additional structures that house that injection lens and collection mirror assembly.

A thick Mylar sheet that yields a 90–10 (Transmission-Reflection) ratio. The 10% reflection creates the local oscillator (LO) reference beam while the remaining power is directed into the plasma as the interaction beam. The scattered and reference beams are recombined at BS2, a 127 \( \mu \)m thick Mylar sheet. The two mirrors in the reference path are mounted on a single linear stage for correction of the reference leg path length relative to the combined interaction and scattered path lengths. The translating mirror system maintains the overall optical path length difference between the reference and scattered paths to within a single wavelength (1 mm).

For coherent fluctuations, the scattered power is proportional to the square of the incident wavelength, \( P_s = \frac{1}{4} P_0 r_e^2 \bar{n}^2 L_v \lambda_0^2 \), where \( P_s \) is the scattered power, \( P_0 \) is the incident power, \( r_e \) is the classical electron radius, \( \bar{n} \) is the density fluctuation amplitude, \( L_v \) is the scattering volume length, and \( \lambda_0 \) is the incident wavelength (Sheffield 1975). Thus, for the same incident power, fluctuation levels, and scattering volume, a 1 mm wavelength (300 GHz) beam will produce a scattered signal nearly 10,000 times larger than a 10.6 \( \mu \)m CO\textsubscript{2} laser. In the vacuum chamber, a flat mirror (VM) directs the scattered radiation from the vacuum chamber to the optical table. The mirror is oval in shape, to allow linear translation and rotation in the 4 in. diameter vacuum tube while maximizing the reflective surface area. The translation, via two shafts mounted on a linear stage, allows for scanning the collection volume across the plasma column. The mirror pivots by sliding along a fitting attached to the end of one shaft while the relative position of other shaft controls the angle of the vacuum mirror through a micrometer and an inline ball joint. Rotating the mirror changes the angle of collection and thereby selects the wave number to be observed. The measurable scattered angles in HELIX range from 60° to 90°; corresponding to fluctuation wave numbers of 63–89 rad/cm via the Bragg condition, \( k = 2k_0 \sin(\theta_s/2) \), where \( k_0 \) is the incident wave number, \( k \) is the fluctuation wave number, and \( \theta_s \) is the scattering angle. The radial location of the collection volume depends on the angle and location of the collection mirror. Observable radii for 60° scattering are from \( r = -5 \) cm to \(-1.5 \) cm, while for 90° scattering the observable radii range from
The hot hELicon eXperiment (HELIX)

−1.5 cm to 5 cm. Given our scattered power detection threshold of 750 pW, a density fluctuation amplitude of $5.5 \times 10^{11}$ cm$^{-3}$ is required for observation of an electrostatic wave; a 5% density fluctuation for a peak density of $10^{13}$ cm$^{-3}$.

In a typical LIF measurement, the frequency of a very narrow bandwidth laser is swept across a collection of ions or atoms that have a thermally broadened velocity distribution. An atom or ion absorbs a photon when the photon is at the appropriate frequency in the particle's rest frame. After a short time, depending on the lifetime of the excited state, the atom or ion emits a photon, either at the same or another frequency. Measuring the intensity of the emitted photons as a function of laser frequency constitutes a LIF measurement. Originally employing an argon-ion laser to pump a coherent 899–21 ring dye laser (Scime et al. 1998), the current LIF laser system consists of a 10 W Spectra-Physics Millennium Pro diode laser that pumps a Sirah Matisse-DR tunable ring dye laser running rhodamine-6G dye. The dye laser is tuned to 611.6616 nm (vacuum wavelength) to pump the Ar-II $3d_{2}G_{9/2}$ metastable state to the $4p_{2}F_{7/2}$ state, which then decays to the $4s_{2}D_{5/2}$ state by emitting 461.086 nm (vacuum wavelength) photons. Approximately 5% of the output of the Matisse-DR is picked off via a beamsplitter for diagnostic purposes. The diagnostic beam is passed through an iodine cell for a consistent zero-velocity reference measurement. Fluorescent emission from the iodine cell is detected with a photodiode for each scan of the dye laser wavelength. The wavelength is also measured via a Bristol Instruments 621- VIS wavelength meter. The remainder of the output is coupled into a single mode, non-polarization preserving optical fiber to transport laser light to the injection optics. The parallel injection optics consist of a 2.54 cm diameter collimating lens, followed by an Oriel polarizer plus 1/4-wave plate to circularly polarize the light exiting the fiber. With laser light of a single circular polarization injected along the source axis, only one of the two $\pi$ transitions, specifically the $\Delta m = +1$ transition, is pumped. For absolute flow measurements, it is necessary to account for Zeeman splitting during analysis of the parallel injection data. The perpendicular injection optics consist of another 2.54 cm collimating lens and a linear polarizer, which is aligned with the magnetic field. The polarizer limits pumping to the $\pi$ transitions ($\Delta m = 0$); the much larger Zeeman splitting of the $\sigma$ transition $\Delta m = \pm 1$ lines is avoided, and the ion velocity distribution function (ivdf) is fit with a single thermally broadened Gaussian function. The internal Zeeman splitting of the $\pi$ lines, Stark broadening, the natural line width of the absorption line, and the laser line width are ignorable in comparison. The collection optics consists of a multimode fiber cable coupled to a 2.54 cm collimating lens with a matching numerical aperture (NA = 0.22) to maximize light collection. The collection line of sight is perpendicular to the injection paths. The output of the fiber is filtered via a narrowband filter (~1 nm bandwidth around 461 nm) and coupled into a high-gain Hamamatsu photomultiplier tube (PMT). The PMT signal is composed of fluorescence radiation as well as background contributions from electron-impact-induced radiation and electronic noise. To eliminate the background contributions the modulated LIF emission is filtered with a SR830 lock-in amplifier referenced to the mechanical chopper in the path of laser beam.

For LIF measurements in steady-state plasmas, the lock-in amplifier is simply recorded as a function of laser frequency. For pulsed plasmas the high speed output of the lock-in is recorded with a digitizer and the PMT waveform is averaged over multiple plasma pulses. A typical ivdf measurement, acquired over 60 s, is shown in Fig. 6(a) and a time resolved ivdf measurement, acquired over approximately 600 s, is shown in Fig. 6(b) for a pulsed plasma. The time-resolved ion temperature and bulk ion flow is obtained from fits to the measured ivdf at each time step. In
Figure 6. (Colour online) (a) Typical LIF measurement of the ion velocity distribution function (ivdf) in argon plasma. (b) Time-resolved measurement of the ivdf in a repetitively pulsed argon plasma. Two cycles of the modulated rf pulse are shown. Note the appearance of an energetic ion beam approximately 20 ms into the plasma pulse.

In the case shown, the time resolution is only limited by the 1 ms integration time of the lock-in amplifier. The laser output can also be split into two beams, which are then independently modulated and injected into the plasma in the perpendicular and parallel directions simultaneously. A single emission measurement performed at the point of overlap then yields simultaneous measurements of the parallel and perpendicular ivdfs at a single location in space (Hansen et al. 2010). The full
two-dimensional ivdf at a single point in space is measureable through LIF tomography (Koslover and McWilliams 1986; Zintl and McWilliams 1994). Using a custom probe that brings the laser light and the collection optics into the chamber, a collection of one-dimensional LIF scans at different injection angles relative to the external magnetic field is acquired and then processed by a filtered back projection method to give a complete 2D reconstruction of the velocity distribution (Biloiu et al. 2009). Since a complete set of scans spans only π radians (scans in opposite direction give same information) the probe is rotated in the quadrants where it does not block the plasma flow. In the example tomographic measurement shown in Fig. 7, both the bulk ion population and a distinct, accelerated ion beam population are well resolved.

4. Experimental regimes and key findings

A wide range of experiments have been accomplished in the HELIX-LEIA facility. Here we highlight a select group of those experiments; those that were only possible because of the unique capabilities of the facility or its diagnostic complement.

As noted previously, one of the original design goals of the HELIX plasma source was to be able to access a variety of plasma densities without changing the magnetic field strength or the fill gas pressure. To achieve this goal, the antenna frequency is
Figure 8. (Colour online) (a) Electron density versus driving frequency for a magnetic field strength of 600 G. The transition from the inductive to the helicon mode is seen at about 11 MHz. (b) Electron density versus driving frequency for 800 G (circles) and 1000 G (squares). The rf power was 1.0 kW in all cases. Reprinted with permission from Keiter et al., Phys. Plasmas 4, 2741. Copyright 1997. American Institute of Physics.

continuously variable from 8.5–16 MHz. To the best of our knowledge, HELIX is the only helicon source in the world with this capability. Figure 8 summarizes the antenna frequency dependence of the measured electron density for plasmas in the helicon mode for three different magnetic field strengths. In the low-field case of 600 G (Fig. 8(a)), below $1/f = 0.952 \times 10^{-6}$ s ($f = 10.5$ MHz) the rf power is insufficient to maintain the helicon mode and the density decreases dramatically. In Fig. 8(a), the data corresponding to the helicon mode (filled circles) is consistent with the simple helicon dispersion relation of (1). At higher magnetic fields, the electron density is still inversely dependent on driving frequency, but with different slopes (Fig. 8(b)). The different slopes suggest that the helicon wavelength in (1) depends on the magnetic field strength for a fixed driving frequency and fixed antenna length. Although the HELIX LIF system is not absolutely calibrated, we have determined that for argon helicon plasmas, the total LIF signal is roughly proportional to the square of the plasma density times the square root of the electron temperature and can be used as a non-invasive measure of qualitative changes in the plasma density (Hardin et al. 2004; Sun et al. 2004). See Ref (Sun et al. 2004) for an explanation of the atomic physics responsible for this approximate relationship. Shown in Fig. 9 is the measured LIF intensity and the square of the Langmuir probe measured plasma density times the square root of the electron temperature as a function of antenna frequency. The LIF measurements provide independent confirmation that the helicon source plasma density is controllable by adjusting the antenna frequency.

The capability to operate over a range of antenna frequencies also enables exploration of other interesting regimes. For example, the typical 13.56 MHz operating
The hot hELicon eXperiment (HELIX)

Figure 9. For an rf power of 750 W, neutral pressure of 1.2 mTorr, $B_{\text{HELIX}} = 730$ G, and $B_{\text{LEIA}} = 34$ G the LIF intensity (solid circles) and the square of the plasma density times the square root of the electron temperature (open squares) versus antenna frequency.

Figure 10. (Colour online) (a) Electron temperature (b) plasma density and (c) ion temperature versus antenna frequency and magnetic field strength. The white line indicates where the antenna frequency equals the on-axis lower hybrid frequency. Reprinted with permission from Kline et al., Phys. Rev. Lett. 88, 1950. Copyright 2002. American Physical Society.

The frequency of helicon sources is close to the argon lower hybrid frequency. By varying both the antenna frequency and the magnetic field strength, the HELIX facility can operate above and below the argon lower hybrid frequency and explore resonant behavior when the antenna frequency matches the lower hybrid frequency in the plasma core and at the plasma edge (Kline et al. 1999, 2002). The electron temperature, electron density, and perpendicular ion temperature in the middle of the helicon source as a function of antenna frequency and magnetic field strength are shown in Fig. 10. Also shown in Fig. 10 are curves indicating where the antenna frequency equals the on-axis lower hybrid frequency, $1/\omega_{LH}^2 \cong 1/(\omega_{pi}^2 + \omega_{ci}^2) + 1/(\omega_{ce}\omega_{ci})$. 
\[ \omega_{ce} = eB/m_e \text{ and } \omega_{ci} = eB/m_i \] are the electron and ion cyclotron frequencies respectively and \[ \omega_{pi} = \sqrt{ne^2/m_i e_i} \] is the ion plasma frequency. For typical plasma densities at the center of the discharge, the ion plasma frequency term is ignorable and \[ \omega_{LH}(0) \approx \sqrt{\omega_{ce} \omega_{ci}}. \]

Looking from left to right in Fig. 10(a), there is a clear increase in electron temperature as the antenna frequency nears the lower hybrid frequency. For antenna frequencies from 8–12.5 MHz, the largest plasma densities occur for \[ \omega \approx \omega_{LH}. \]

As shown in Fig. 10(c), the perpendicular ion temperature peaks for \[ \omega < \omega_{LH}(0). \] Because of the low plasma densities near the plasma edge, the local lower hybrid frequency drops below 10 MHz even though the lower hybrid frequency on axis is 12 MHz. Radial profiles of the perpendicular and parallel ion temperature indicate that the perpendicular ion temperature is constant across the inner portion of the discharge and increases at the edge (Kline et al. 2002b, 2003). To create a perpendicular ion temperature profile that is flat or increases at the edge, the ions must be heated anisotropically at the edge of the plasma or the heat conductivity along the axis must be extremely large. The most likely explanation for the profile measurements is strong perpendicular ion heating at the edge. In the low-density edge plasma, the ‘fast’ or helicon wave cannot propagate. However, the slow wave branch of the cold plasma dispersion relationship can propagate and has a resonance at the lower hybrid frequency (Kline et al. 2002a). When the antenna frequency equals the local lower hybrid frequency, the slow wave becomes predominately electrostatic and the perpendicular wavenumber of the wave goes to infinity in a collisionless plasma (Kline et al. 2002a). At large perpendicular wavenumbers, \[ k_\perp \sim 600 \text{ cm}^{-1}, \] the wave phase velocity is low enough that ion Landau damping can occur. Our modelling of the wave propagation, including modest levels of collisionality, predicts a peak in the perpendicular wavenumber of the electrostatic mode for exactly the range of antenna frequencies and magnetic field strengths for which the peak in ion temperature is observed (Kline et al. 2003). Other experiments in HELIX confirmed the excitation of short perpendicular, electrostatic waves for the same experimental conditions (Scime et al. 2013). Therefore, the capability to operate over a wide range of antenna frequencies has enabled the HELIX experiment to address fundamental questions about the coupling of rf power into the helicon source.

Expansion into the LEIA chamber allows the ratio of the plasma pressure to the magnetic field pressure, \[ \beta_{t\parallel} = 8\pi nkT_{t\parallel}/B_o^2, \] to increase rapidly and approach values relevant to the study of space plasma phenomena. In the collisionless plasmas of certain regions of space, it appears that the isotropization of ions can be described by a simple expression of the form (Anderson and Fuselier 1993; Anderson et al. 1994; Phan et al. 1994; Tan et al. 1998):

\[ \frac{T_{t\perp}}{T_{t\parallel}} - 1 = \frac{S_p}{\beta_{t\parallel}^{\alpha_p}}. \]

Here \( S_p \) and \( \alpha_p \) are dimensionless fitting parameters and \( T_{t\parallel} \) and \( T_{t\perp} \) are the ion temperatures measured parallel and perpendicular to the local magnetic field, \( B_o \). Theoretical investigations of the stability of collisionless anisotropic plasmas indicate that two instabilities are likely to grow in the high beta, \( \beta \sim 1 \), anisotropic, \( T_{t\perp} > T_{t\parallel} \), conditions of the magnetosheath: the mirror mode, and the Alfvén Ion Cyclotron Instability (also known as the anisotropic ion cyclotron instability). To relate the ion temperature anisotropy to the plasma beta requires the additional assumption that a plasma instability threshold introduces a bound on the anisotropy driving the unstable
Figure 11. (a) Ion temperature anisotropy, $A = T_i/|T_i|$, versus $\beta_i$ (open circles). These data were obtained over a wide range of operating magnetic fields but at fixed rf power and neutral pressure. Also shown are averaged values of anisotropy and $\beta_i$ for similar operating conditions (solid circles) investigated on different days with standard deviation error bars. (b) A subset selected so that the ion-ion and ion-neutral collisional relaxation rates vary by less than 10%. Also shown are fits to (2) for the laboratory measurements (heavy solid line), the magnetospheric observations of Phan et al. (short dashes) (Phan et al. 1994), the magnetospheric observations of Anderson et al. (long dashes) (Anderson et al. 1994), and a linear Vlasov theory prediction (thin solid line) (Gary et al. 1997).

mode, thereby creating a negative feedback cycle. A series of experiments in LEIA provided the first laboratory demonstration of the existence of an upper bound on the ion temperature anisotropy that scales inversely with the ion beta in low collisionality plasmas (Keiter et al. 2000; Scime et al. 2000). Shown in Fig. 11 are measurements of the ion thermal anisotropy versus parallel ion beta in the LEIA facility. Consistent with measurements in space (Fig. 11(a)), there is a clear inverse scaling of anisotropy with plasma beta. When the data are restricted to those with nearly identical collision rates (Fig. 11(b)), the measured scaling is consistent with the theoretical predictions and demonstrates that, independent of plasma collisionality, there is in fact a limit to the level of ion thermal anisotropy. Additional measurements provided direct evidence of enhanced electromagnetic fluctuations for the same plasma conditions (Keiter et al. 2000; Scime et al. 2000).

Perhaps one of the most unique experimental campaigns completed in the LEIA facility was the detailed measurement of the ivdf along the axis of the current-free double layer (DL) that spontaneously forms in the expansion region of a low pressure helicon source (Cohen et al. 2003; Keesee et al. 2005; Sun et al. 2005a, 2005b; Cohen et al. 2006). At a neutral pressure of 1.3 mTorr, we obtained the plasma potential and LIF measurements of the parallel ivdf shown in Figs 12(a) and (b), respectively. The end of the HELIX source is located at $z = 150$ cm, at nearly the same spot as the DL evident in the plasma potential and LIF data. The ions accelerate through the pre-sheath upstream of the DL and reach a peak energy of approximately 18 eV. Each ivdf measurement used to create Fig. 12(b) has been corrected for the changing Zeeman shift as the ions move along the weakening axial
magnetic field. The ivdf is well fit by a single Maxwellian distribution. Since the plasma electron temperature is 5.0 eV, the ion beam is supersonic with a Mach number of roughly 2.0. The LIF measurements indicate that the total ion acceleration occurs over approximately 20 cm (with strong ion acceleration occurring over a much narrower region, \(\sim 5\) cm, located at the maximum of the magnetic field strength gradient). Consistent with the LIF-determined peak ion beam energy, the measured jump in the plasma potential across the DL in the plasma potential was 18 V (Fig. 12(b)). Also shown in Fig. 12(b) as solid triangles are the predicted potential difference (plasma potential minus 9.8 V) upstream of the DL based on the measured gain in ion beam kinetic energy. The solid line in Fig. 12(b) is the magnitude of the axial magnetic field strength. It is notable that the relative changes in the plasma potential, and therefore the ion beam energy, clearly track the axial magnetic field strength, i.e. the ion beam energy and magnetic field strength axial gradients are nearly identical. These LIF measurements confirmed hybrid model predictions of the location and general features (ion beam energy and trapped ion population distribution) of a magnetic field strength gradient induced DL in a current free plasma (Sun et al. 2005a; Biloiu et al. 2008; Biloiu and Scime 2009; Scime et al. 2010).

Deeper understanding of the physics of spontaneous DL formation was obtained by again turning to the antenna frequency dependent features of the HELIX-LEIA facility. Whereas other groups had explored the threshold for DL formation as a function of gross changes in the magnetic field geometry or neutral pressure, it is possible to turn the DL on and off in HELIX-LEIA through small changes in the antenna frequency while keeping the magnetic field strength, magnetic field profile, and the neutral fill pressure fixed (Chakraborty Thakur et al. 2010). Variations in the antenna frequency alter the coupling of rf power into the plasma and thereby change the plasma density. As shown in Fig. 13, the effect is to turn the DL on and off,
thereby enabling detailed study of physics of spontaneous, current-free, DL formation under very controlled conditions (Kline et al. 1999). The ability to precisely control the threshold for DL formation and the repeatability of HELIX-LEIA plasmas was recently used to confirm a phenomenon we had long suspected occurs in these expanding helicon plasmas – the formation of multiple accelerating structures, i.e. multiple DLs. Through very long duration measurements of the ivdf, which requires continuous and stable operation of the plasma source over many hours, we have been able to obtain ivdf measurements which unequivocally demonstrate the formation of multiple accelerating structures. Shown in Fig. 14 is the ivdf measured downstream of the expansion region of the HELIX-LEIA system at very low neutral pressure. Three different ion populations are evident, a bulk ion population at rest and two accelerated ion beams. The two beam populations have identical widths. These novel measurements suggest that complex ivdfs, such as the one shown in Fig. 14, can arise spontaneously from nothing more than a simple magnetic field gradient. Since similar looking ivdfs are often used to infer the existence of complex and impulsive plasma phenomena, these measurements provide a note of caution for such conclusions from space-based measurements (Carr et al. 2013a, 2013b).

Another key design goal of the HELIX-LEIA system was the ability to investigate magnetohydrodynamic waves in a compact experiment. Shown in Fig. 15 are
Figure 14. LIF measured ivdf (circles) as a function of velocity in the expansion chamber 38 cm downstream of the plasma source. A three Maxwellian component fit (solid line) yields identical ion temperatures of $\sim 0.16$ eV for all three components.

Figure 15. (Colour online) The measured dispersion relation (circles) and theoretical curves for a (red) kinetic shear Alfvén wave assuming a magnetic field of 560 G, plasma density of $6 \times 10^{12}$ cm$^{-3}$, neutral density of $5 \times 10^{12}$ cm$^{-3}$, electron temperature of 7 eV, ion temperature of 0.25 eV, ion-sound gyroradius of 0.8 cm/rad, and perpendicular wave vector of 0.85 rad/cm and for the same parameters (blue) but using a theoretical expression that includes additional kinetic effects (Vincena et al. 2001).

measurements of the wave number of driven, low-frequency, electromagnetic waves in helium HELIX plasmas versus normalized wave frequency. Also shown in Fig. 15 are two theoretical dispersion relations for kinetic Alfvén waves for the measured plasma conditions. The first expression (the red curve) is the dispersion relation for a
Boltzmann electron response, cold ions, and a diagonal dielectric tensor:

\[ k_{||} = \frac{\omega}{V_A} \left( 1 - \frac{\omega^2}{\omega_{ci}^2} + k^2 \rho_s^2 \right)^{-1/2}, \]  

where \( \omega \) is the wave frequency, \( k \) is the wave number, \( \omega_{ci} = qB/m \) is the ion cyclotron frequency for ions of mass \( m \) and charge \( q \) in a magnetic field of strength \( B \), and \( \rho_s = c_s/\omega_{ci} \) is the ion sound gyroradius for an ion sound speed of \( c_s \). The second theoretical expression (the blue curve) includes additional kinetic effects and off-diagonal dielectric tensor elements as described in Ref. (Vincena et al. 2001). The excellent agreement between the measurements and the more complete theoretical prediction provide strong evidence of the successful excitation of Alfvén waves in HELIX plasmas (Houshmandyar et al. 2011). A critically important aspect of the theoretical model is that it assumes that the perpendicular wave length of the Alfvén waves is constrained by the radial extent of the high plasma density, low neutral pressure, plasma ‘core.’ Helicon sources are well known for having a bright, high-density, core region (Houshmandyar et al. 2010). An example of such a plasma core is provided in Fig. 16 for an argon plasma. Plasma density measurements indicate that the high-density core is approximately 1 cm in diameter. Two-photon absorption measurements of the absolute neutral density in another helicon source in our laboratory demonstrated that the core region is nearly 100% ionized in krypton helicon plasmas (Magee et al. 2012a, 2012b, 2013; Galante et al. 2014). For the helium plasmas used in the Alfvén wave experiments, relative LIF measurements of

---

**Figure 16.** (Colour online) The HELIX-LEIA facility in argon plasma mode. The inset photo is of the bright ‘core’ plasma. The core is so bright that the camera is saturated over a much larger region than the approximately 2 cm wide, naked-eye visible, bright blue core.
the metastable neutral helium density also indicate a strong depletion of neutrals in the core. Therefore, the region of Alfvén wave propagation is restricted to the high plasma density, low neutral density, plasma core (Keesee and Scime 2006a, 2007). The radial localization of the wave propagation region introduces a boundary condition on the kinetic Alfvén wave perpendicular wavelength, as evidenced by the wave dispersion measurements and also measurements of the electric and magnetic fields associated with the Alfvén waves (see Figs 17 and 18). Without the imposed perpendicular wavelength arising from the strong density gradient, the parallel wavelength of Alfvén waves would be too long for the waves to fit into the HELIX portion of the facility. Therefore, it is the unique, high-density core structure and the overall high plasma densities of the HELIX-LEIA facility that enable kinetic Alfvén wave studies in such a compact experimental facility. The focus of the Alfvén wave experiments continues to be the interaction of the kinetic Alfvén waves with the strong density gradients of the helicon plasma, akin to the interactions of Alfvén waves in the solar corona with higher density coronal loops.

5. Summary
The HELIX-LEIA facility is capable of providing highly ionized, high density plasmas for a range of space physics relevant experiments. As a result of the unique capabilities of the experimental apparatus and the breadth of the diagnostic complement, novel studies of helicon source physics, spontaneous double layer formation, and Alfvén wave propagation have been accomplished. The facility operates in both continuous and pulsed modes with a high degree of reproducibility and reliability. Novel cost saving approaches in design, such as aluminum conductor electromagnets, were instrumental in achieving a versatile facility at a modest cost.
Figure 18. (Colour online) Synchronously averaged and digitally filtered azimuthal magnetic field fluctuation signal versus time and radius at $z = 85$ cm. Note the localization of the large amplitude fluctuations to the edge of the plasma. Additional measurements indicate that the wave group velocity changes sign at a radial location of 3.5 cm, i.e. the Alfvén wave is reflected at the boundary between the helicon plasma and the very low density plasma edge.

Acknowledgements

This work was supported by NSF award PHY-0611571. The authors thank one referee for suggesting the additional comparison with the theory of Reference 51 that is now shown in Fig. 15.

REFERENCES

Biloiu, I., Scime, E. and Biloiu, C. 2009 Plasma Sources Sci. Technol. 18, 025012.


