NC State University

Recent Progress on the RF-Breakdown Test Stand

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OUTLINE – PART 1

RF Breakdown

- *Motivation and Focus*
- *Experimental Apparatus*
- *Previous Results*
- *Experimental Method*
- *Recent Results*
- *Conclusions and Future Work*

Motivation Behind RF Breakdown Research

• One of the main power-limiting factors in antenna systems is the maximum voltage that the antenna can sustain before breaking down.

- Antennas can often withstand 50 kV in vacuum conditions
- Reductions of 30 to 50 per cent are common when exposed to plasma and magnetic field during machine operations

• Breakdown detection is important for protection of the RF system.

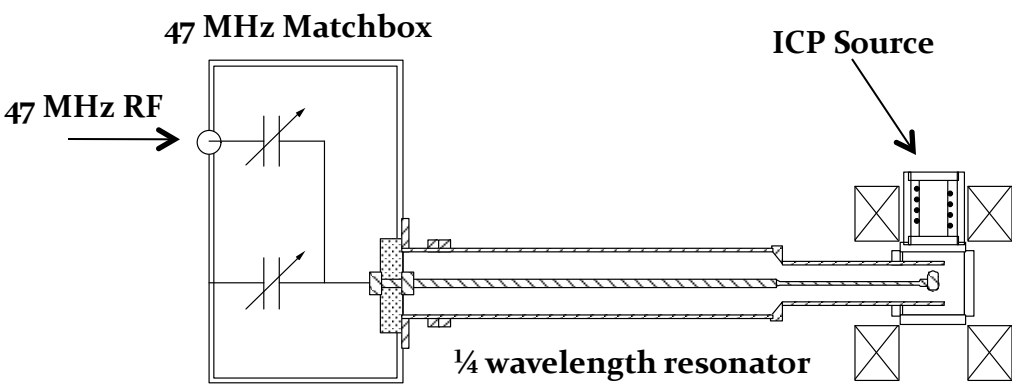
Focus for this Study

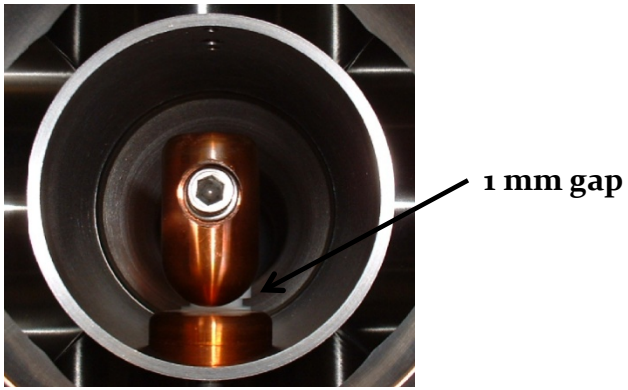
• To quantify the relationship between the magnitude of the stand-off RF electric field and plasma density for similar pressures seen by ICRF antenna.

- Low magnetic field strength – 50 Gauss
- High magnetic field strength – 1 kGauss

Experimental Apparatus – RF High Voltage Breakdown Tester

- The RF High Voltage Breakdown Tester (HVBT) is a ¼ wavelength resonator consisting of a vacuum transmission line terminated on an open circuit electrode structure.
  - Transmission line impedance of 134 ohms, this impedance maximizes voltage for a given input power
- Power is delivered to the ¼ wavelength resonator by a 20 kW variable frequency Continental 816R RF generator.
  - Modeling indicates that the electrode voltage is approximately 30 kV for an input power of 10 kW.
  - Directional couplers monitor forward and reflected power.
  - Capacitive probe monitors voltage at electrode.

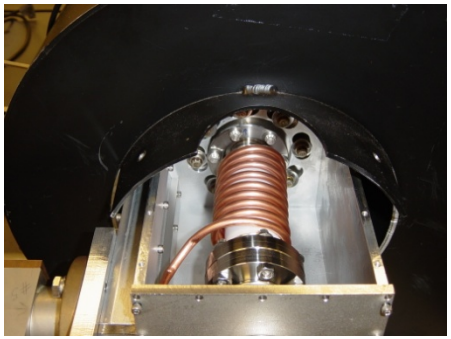


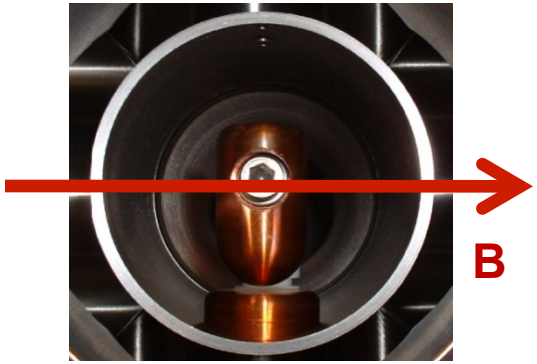


resonance frequency ~ 47.2 MHz
circuit Q ~ 800

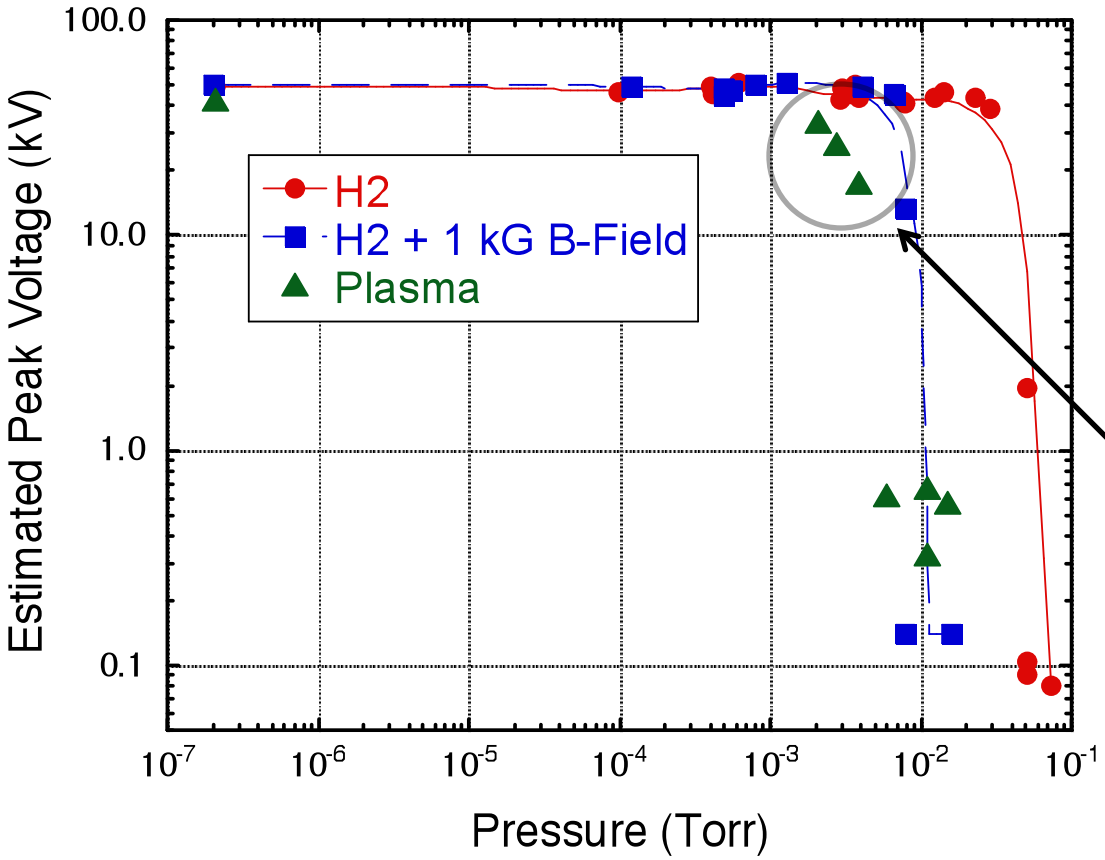
Experimental Apparatus – ICP Source

- A beam of plasma is extracted from an inductively coupled plasma (ICP) source
  - 13.56 MHz drive frequency
  - 500 watt maximum input power
  - Directional couplers monitor forward and reflected power
- An aperture of variable size is located between the ICP source and the vacuum chamber housing the ¼ wavelength resonator.
  - Allows ICP source to operate at higher pressure while maintaining a lower pressure in the chamber.
  - Limits plasma density at electrode structure
- Solenoid coils are capable of up to 1 kGauss field on axis.





Previous Results



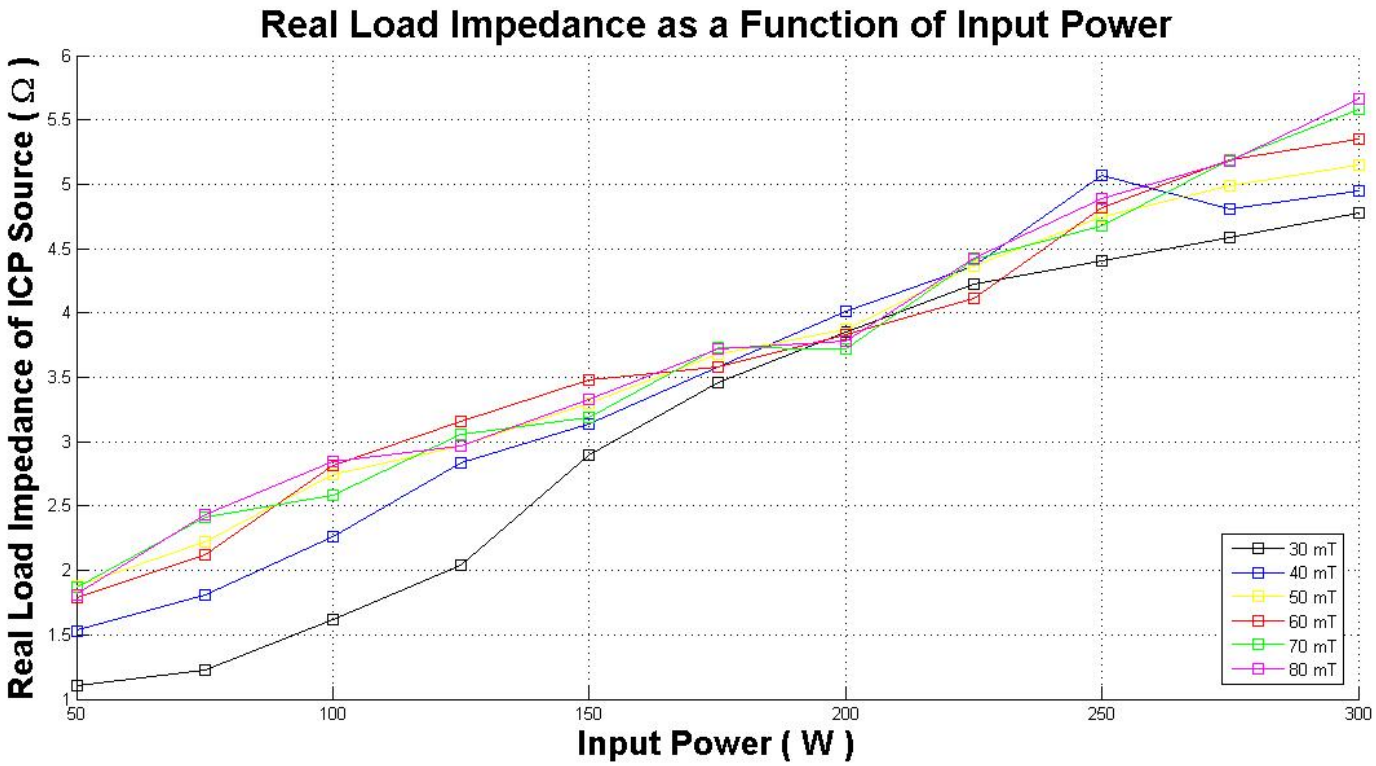
- Previous results show that plasma can severely decrease the magnitude of the stand-off electric field.
- Need to quantify the effect of plasma density on the magnitude of the stand-off electric field.

What is the plasma density at which this occurs?

Experimental Method – 13.56 MHz Match Characterization

• The matchbox associated with the 13.56 MHz RF generator driving the ICP source was characterized to determine:

- Real load impedance of 13.56 MHz matchbox and its efficiency
- Load impedance of ICP source



Note: pressure values shown above 1 mTorr in this presentation were measured with a convectron gauge and have not been corrected to give the actually H2 pressure – it is a linear relationship.

Experimental Method – Langmuir Probe Measurements

- A cylindrical Langmuir probe compensated at the drive frequency and its fist harmonic was constructed to measure electron density and temperature at the throat of the ICP source.
  - tip length – 5 mm
  - tip radius – 0.125 mm

- The numerical results of Laframboise give the relationship between ion collection current and probe voltage.

$r_p/\lambda_D < 2.5$

$$i_+ = \left[\frac{2Z_i e^3 n_e^2 A_p^2}{\pi^2 M_i}\left(\phi_p - V\right)\right]^{1/2}$$

$r_p/\lambda_D > 3.5$

$$i_+ = e n_e A_p \left[\frac{Z_i k T_e}{2\pi M_i}\right]^{1/2} C\left[\frac{e\left(\phi_p - V\right)}{k T_e}\right]^n$$

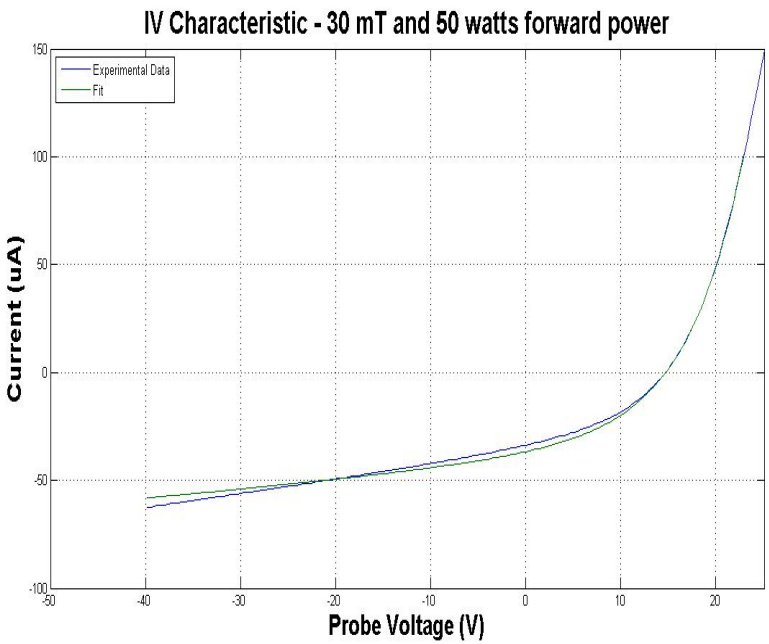
$$C = C\left(\frac{r_p}{\lambda_D}\right) \qquad n = n\left(\frac{r_p}{\lambda_D}\right)$$

- For all process conditions investigated the condition $r_p/\lambda_D < 2.5$ was satisfied.

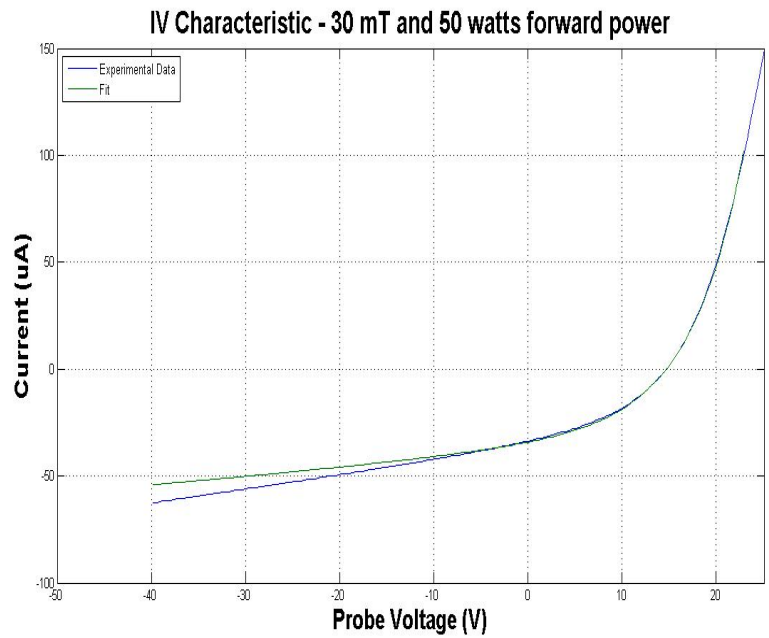
Experimental Method – Fitting of the IV Characteristic

• The IV characteristics were fit over the voltage range: -40 to ϕ_p and -10 to ϕ_p to estimate the error in the fit due to finite cylindrical probe effects.

-40 to ϕ_p

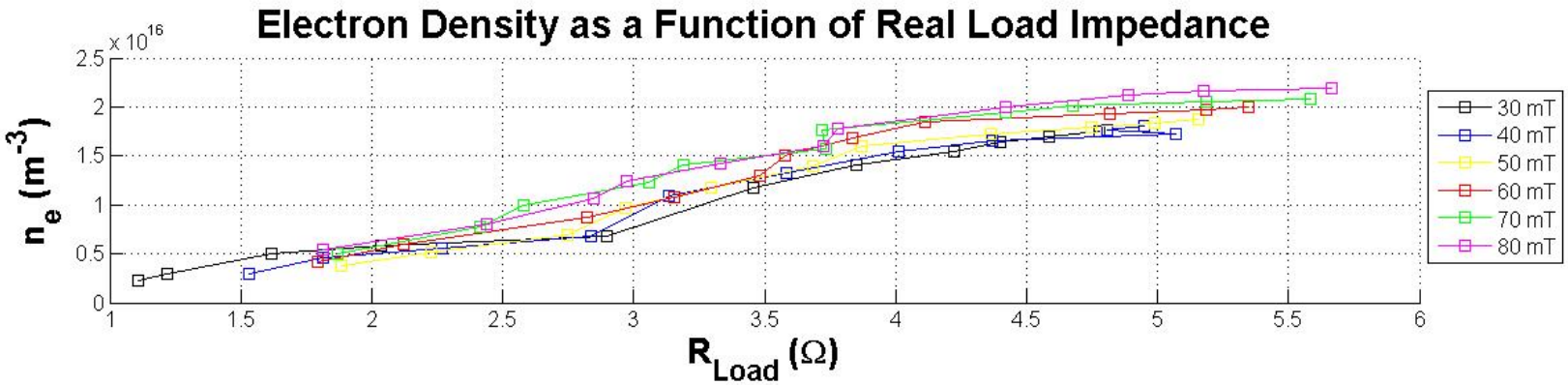


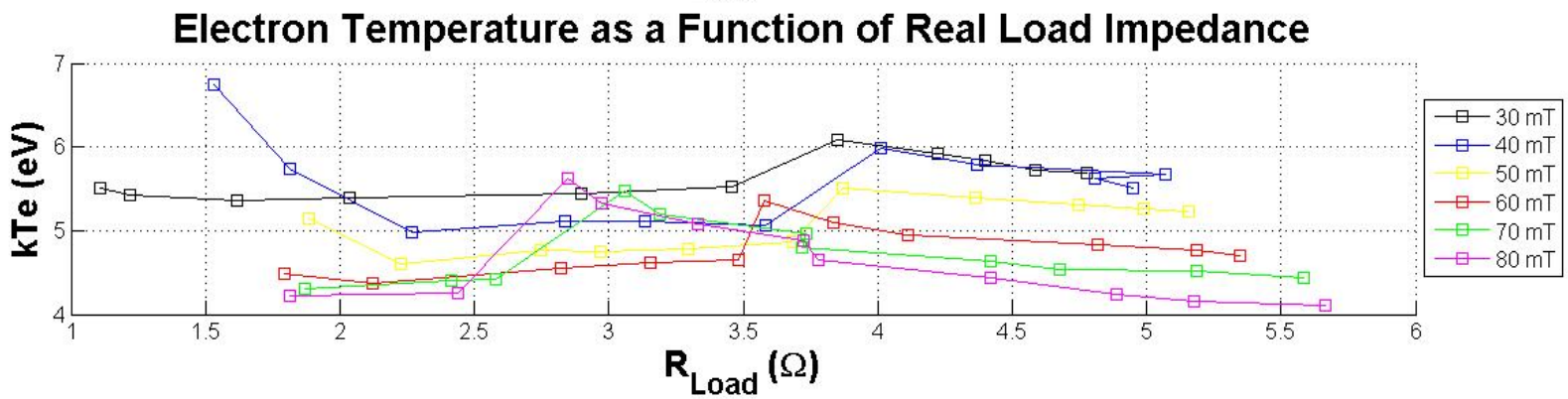
-10 to ϕ_p



Experimental Method – ICP Source Plasma Parameters

• The electron density and temperature was averaged over the two values found from the fits to the IV characteristic.



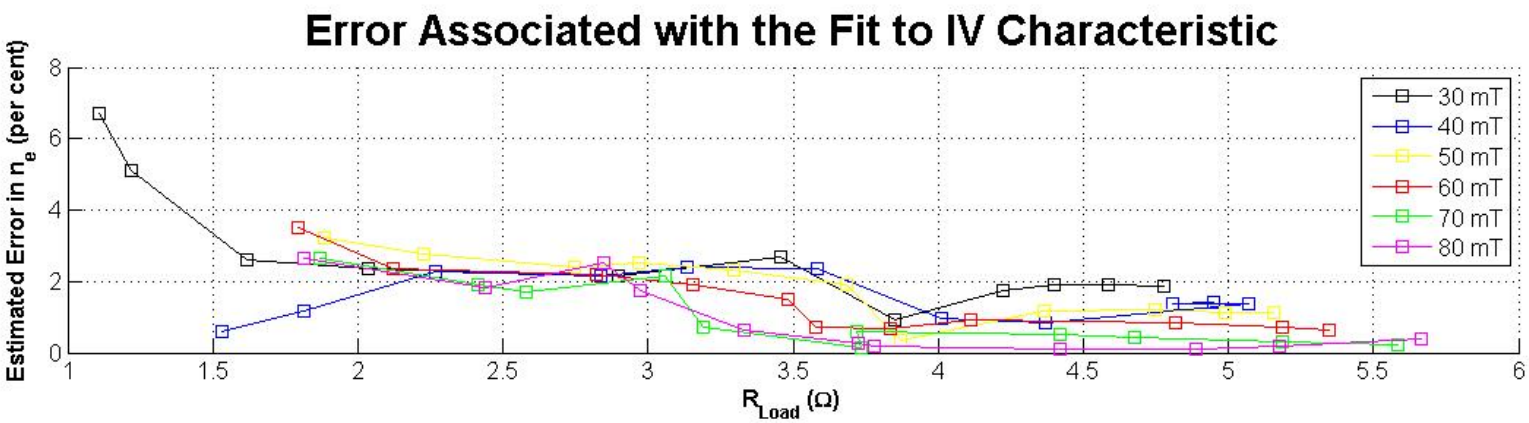


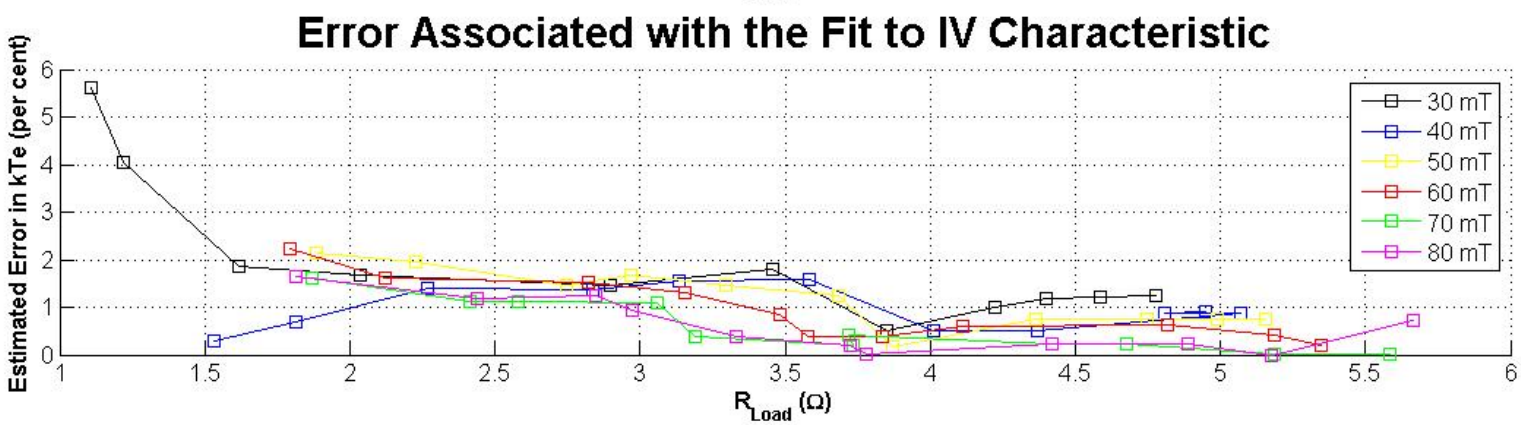
• The plasma parameters are plotted as a function of real load impedance of the ICP source because the real load impedance will be used to estimate the ICP plasma parameters with the aperture in place.

Note: The cylindrical Langmuir probe measurements were taken at the throat of the ICP source.

Experimental Method – ICP Source Plasma Parameter Error

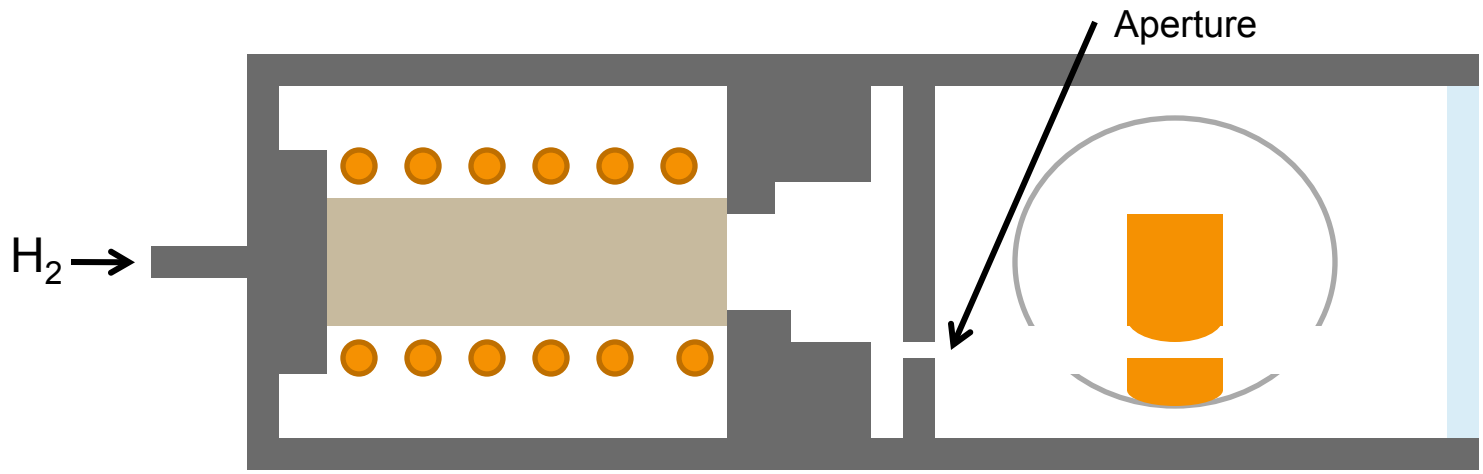
- The error associated with the electron density and temperature was taken as the difference in the values obtained from the fit divided by the average.

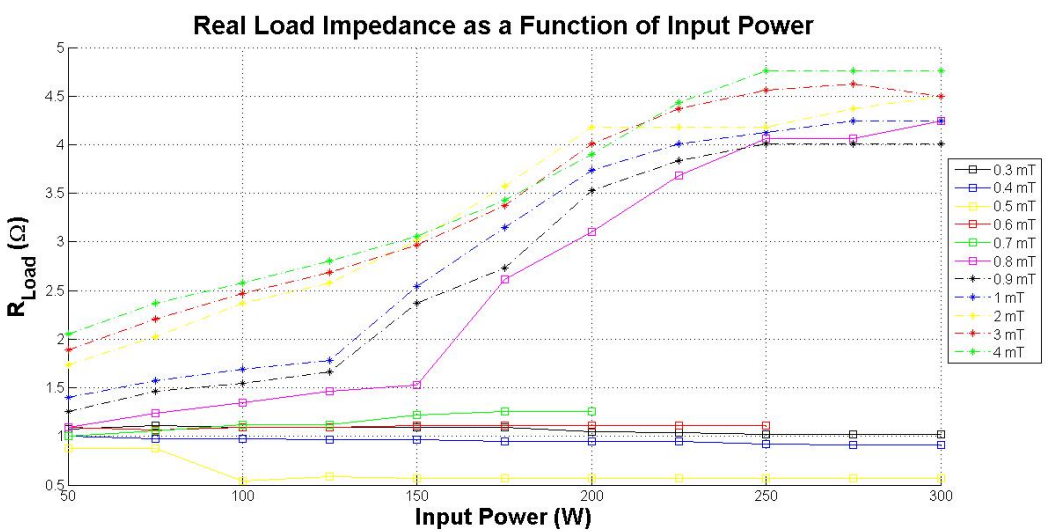




Experimental Method – ICP Source with Aperture

- A 5/32" diameter aperture was placed at the throat of the ICP

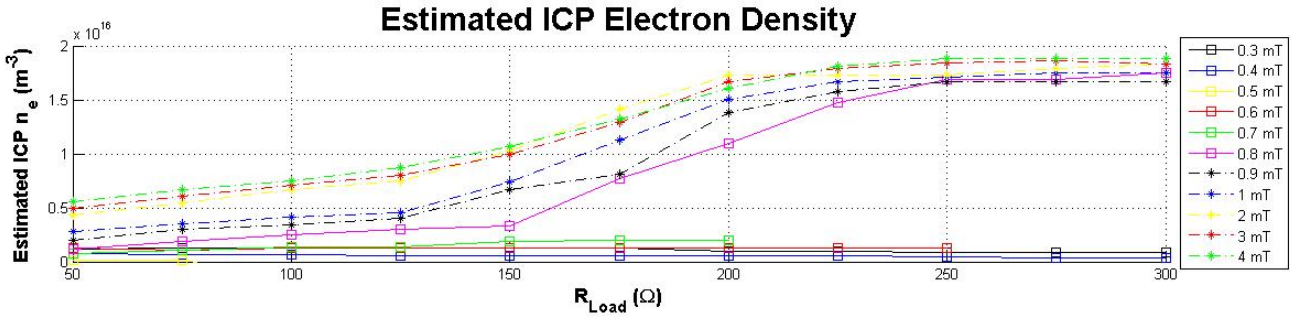


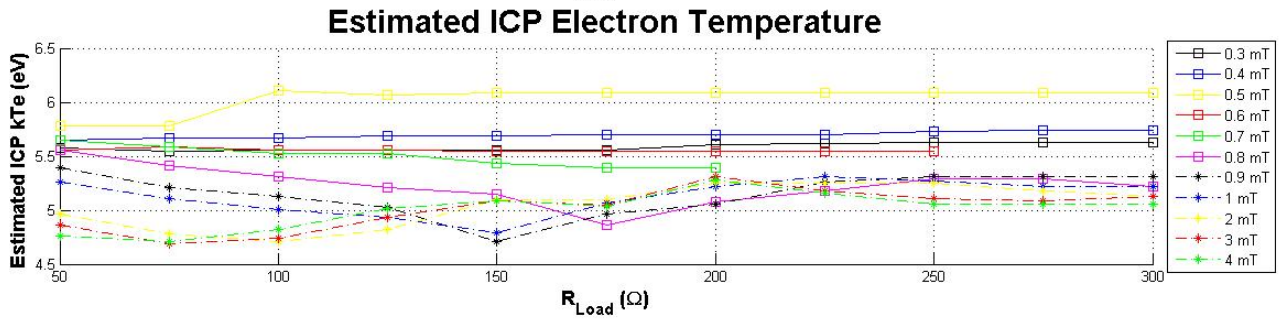


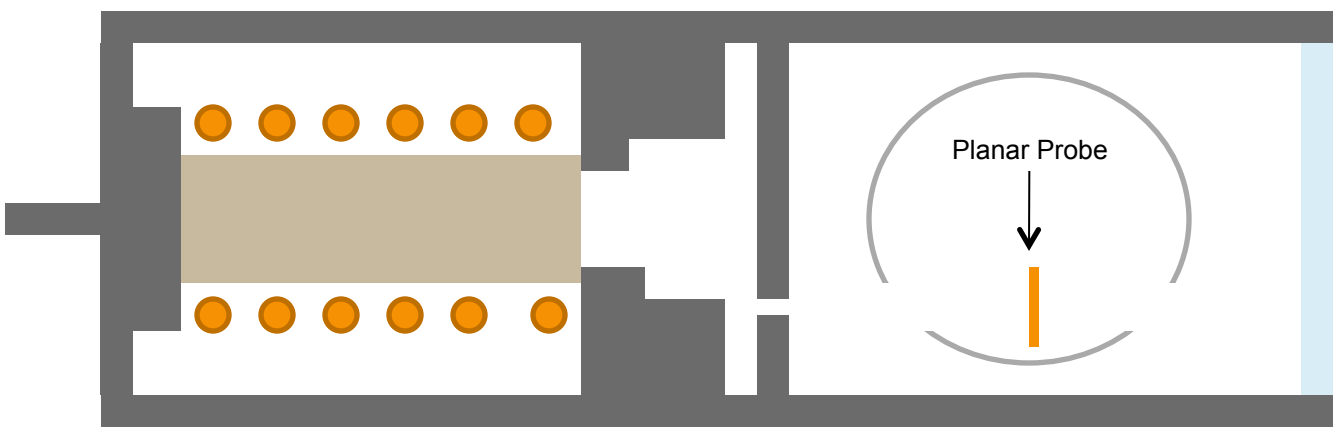
- The ICP source was characterized with the aperture in place.
- The pressure measurements are made in the chamber housing the ¼ wavelength resonator.
- ICP pressure is not know but given loading an estimate of n_e and kT_e can be found.

Note: The magnetic field strength for this characterization and what follows is 50 Gauss on axis.

Experimental Method – ICP Source with Aperture Plasma Parameters







- Correlating the ICP source loading with the aperture to the ICP source loading without the aperture an estimate of the plasma parameters can be found.

- A RF compensated planar probe was constructed to measure electron density and temperature of the plasma extracted from the ICP source.
  - 14.3 mm x 14.3 mm
  - copper

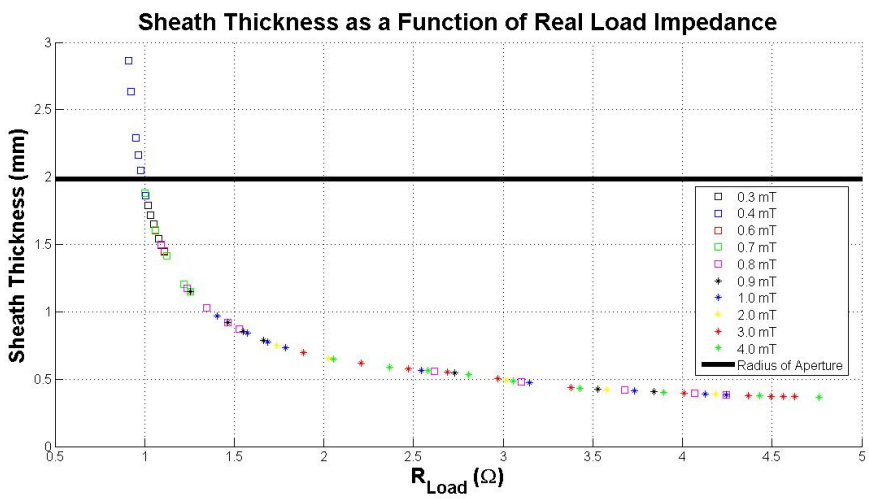
- The electrode structure was removed and the planar probe was positioned such that the probe was centered about the aperture.

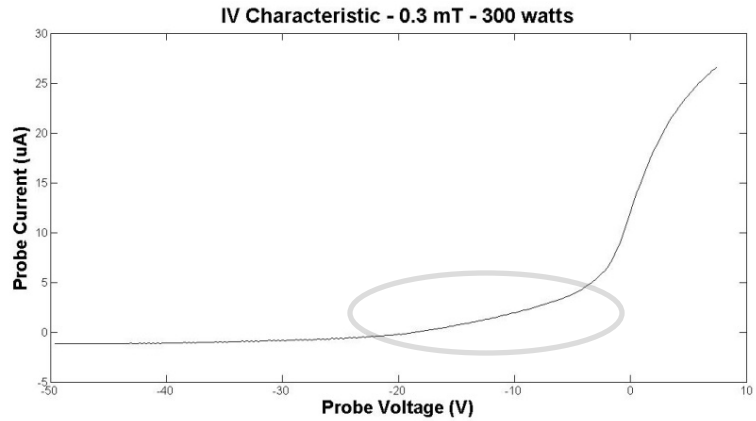
Experimental Method – Planar Probe Measurments

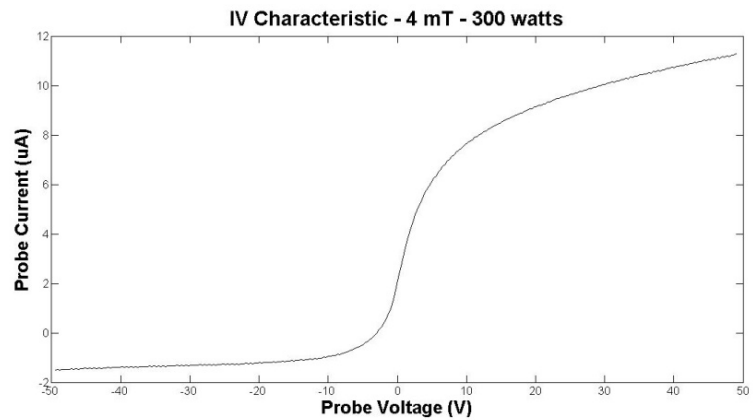
- For pressures less than 2.0 mT the IV characteristic was found to be non-ideal in the sense that there was a presence of hot non-thermal electrons.

- Above 2.0 mT the IV characteristic approximately behaved ideal.

- The sheath thickness was compared to the aperture diameter to give insight to the mechanism by which plasma is extracted.





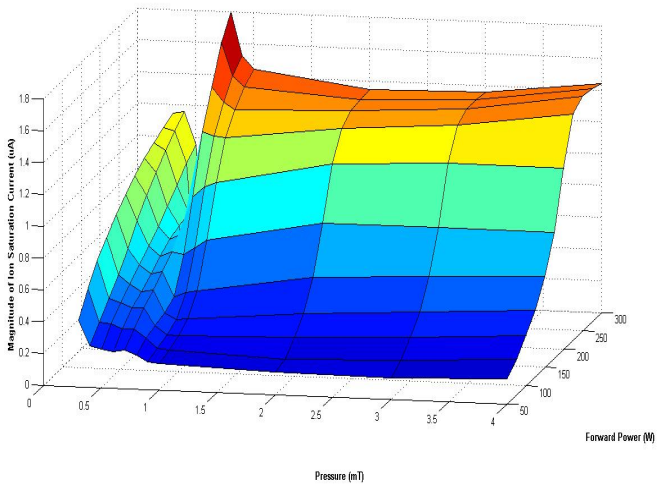


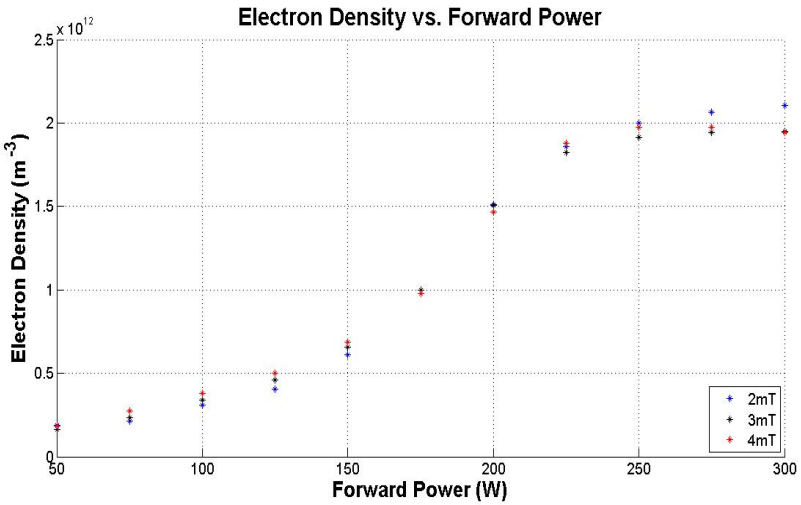
Experimental Method – Plasma Parameters of Extracted Beam

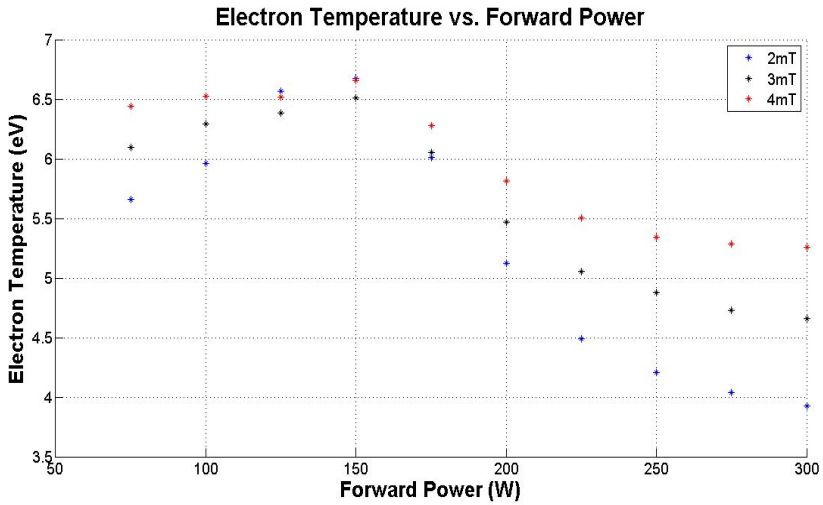
- Due to the non-ideal nature of the planar probe IV characteristic for chamber pressures less than 2 mTorr plasma density cannot be reliably extracted from the IV characteristic.

- Above 2.0 mT the plasma parameters can be reliably extracted from the IV characteristic

  - Will show that for chamber pressures below 2mTorr the RF breakdown is not significantly affected by the extracted beam of plasma – need higher density.



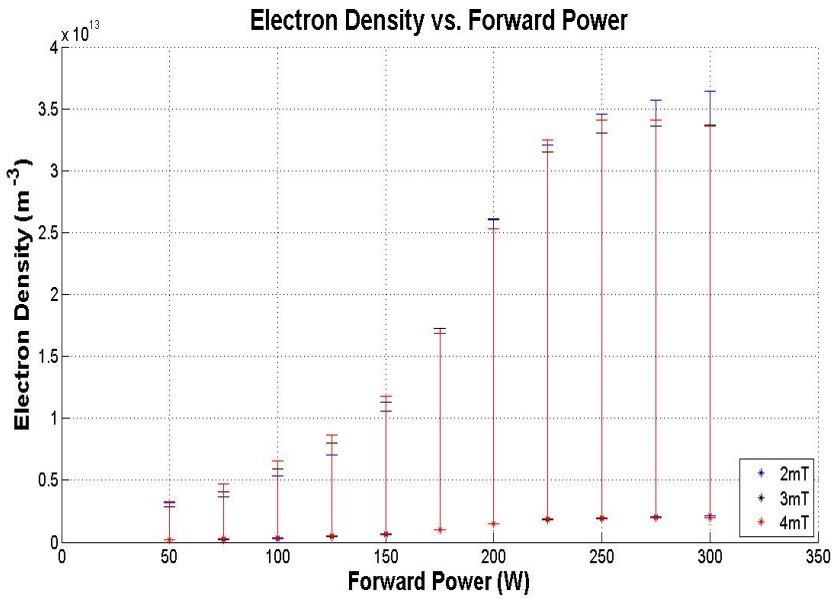




Note: The collection area was considered the surface area of the planar probe for these calculations.

Experimental Method – Error Estimate on electron density

• The highest level of uncertainty in the calculation of electron density from the planar probe IV characteristic is the area over which the current is collected.



• Bounds on the collection area can be set by:

- ➢ Lower bound – area of planar probe
- ➢ Upper bound – area of aperture

• The upper bound on the collection area was chosen as the area of the aperture due to the fact the plasma could be confined to a flux tube.

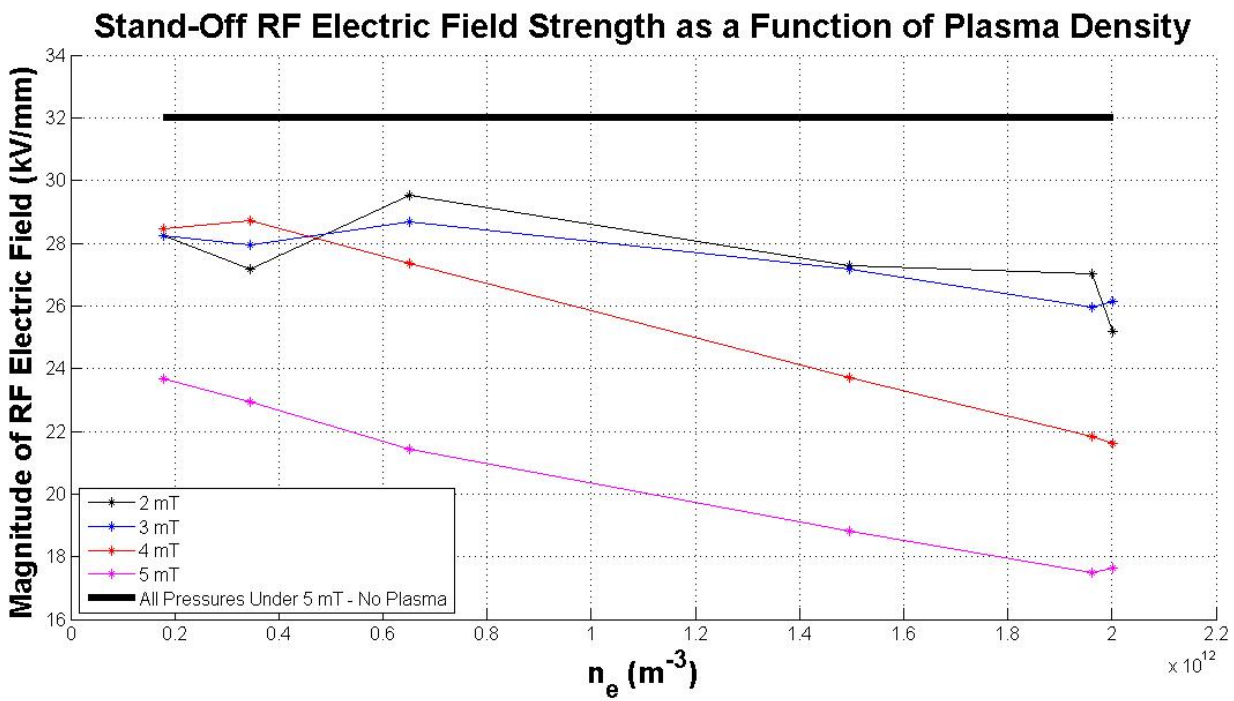
• The profile of the extracted plasma beam was measured with the planar probe.

- ➢ Suggests that the beam is localized to the area of the aperture.

• Need to construct new probe for a more conclusive profile measurement.

RESULTS – RF BREAKDOWN

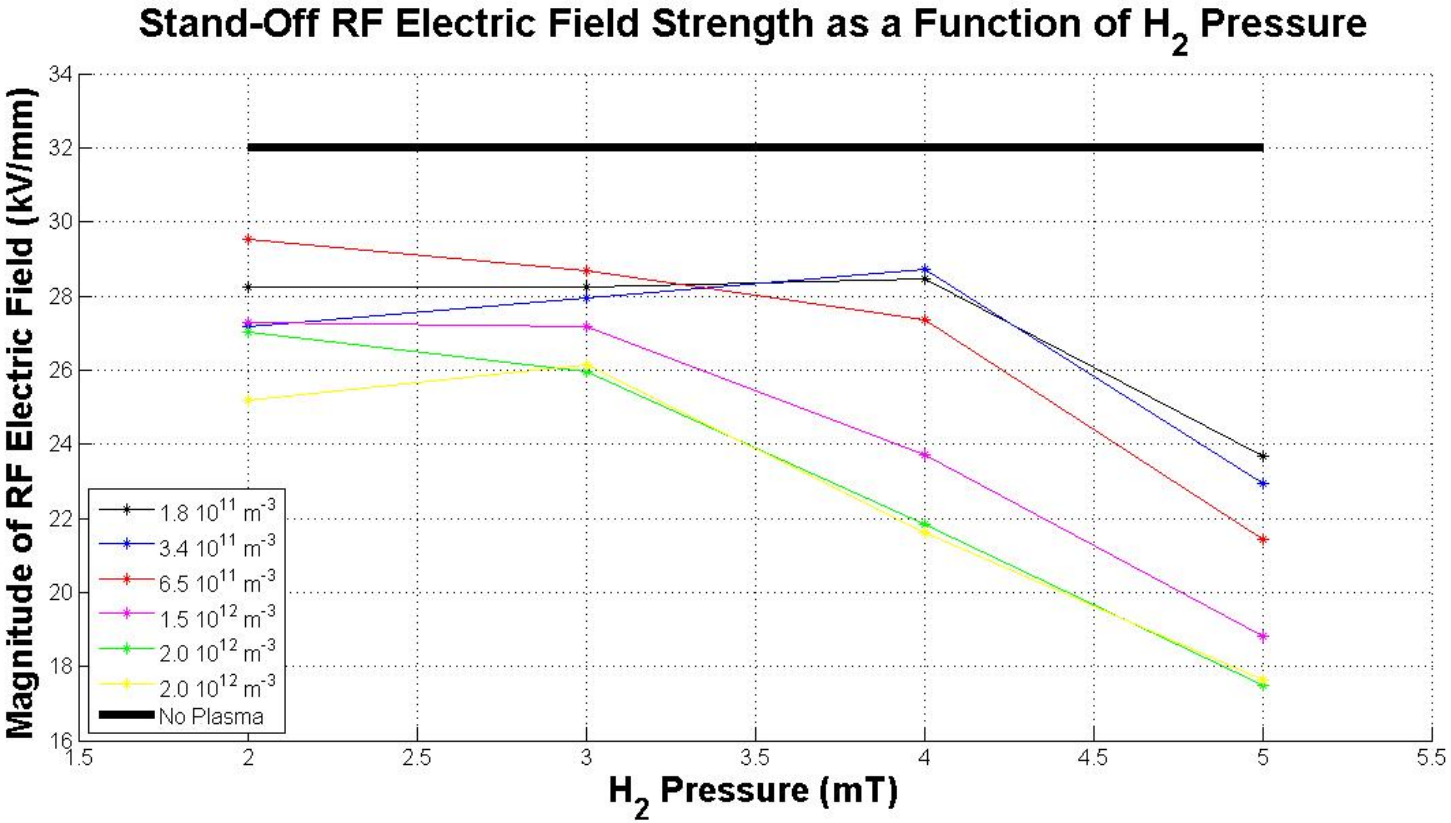
• The magnitude of the stand-off RF electric field was measured as a function of plasma density for H_2 pressures of 2, 3, 4, and 5 mTorr.



• For H_2 pressures of 1 and 0.9 mTorr the magnitude of the stand-off RF electric field was decreased from its no plasma value of ~32 kV/mm to ~30 kV/mm with maximum achievable density in the extracted beam of plasma from the ICP source.

• For H_2 pressures below 0.9 mTorr the magnitude of the stand-off RF electric field was not affected by the extracted beam of plasma from the ICP source.

Results – RF Breakdown



• The RF breakdown data suggests that for the plasma densities investigated the stand-off electric field strength is decreased by up to a factor of 2.

• Very low plasma densities can have a big effect of the stand-off electric field strength.

Note: On NSTX, antenna pressures have been measured up to ~1 mTorr.

Conclusions

- The magnitude of the RF stand-off electric field was significantly decreased in the presence of a beam of plasma having a density ranging from approximately 2 10^{11} to 2 10^{12} m^{-3} for chamber pressures of 2 - 5 mTorr.

- The magnitude of the RF stand-off electric field was slightly decreased for chamber pressures of 1.0 and 0.9 mTorr in the presence of a beam of plasma but due to the nature of the plasma extraction mechanism a reliable density cannot be determined.

- The magnitude of the RF stand-off electric field was not effected for chamber pressures lower than 0.9 mTorr in the presence the extracted beam of plasma.

Future Work

- Currently the aperture is off center from the ICP source, thus the plasma density is very low in the region of the ICP source linked by flux tubes to the electrode structure.

  - Redesign ICP source such that the bulk plasma is linked by flux tubes to the electrode structure.

- A beam of plasma could not be extracted in the presence of a 1 kGauss magnetic field, thus investigation of RF breakdown was not possible.

  - Due to the aperture being off center from the ICP source.
  - The redesigned ICP source should allow for plasma extraction in the presence of a 1 kGauss field.

- Construct new planar probe (tantalum/tungsten) for density measurements and to measure the profile of the extracted beam.

OUTLINE – PART 2

Optical Diagnostic for Near Field Measurements of ICRF Antenna

- *Motivation*
- *Line Splitting of the Balmer Series of Hydrogen*
  - *Dynamic Stark Effect*
  - *Dynamic-Static Stark Effect*
- *Recent Results*
- *Future Work and Conclusions*

Motivation Behind Experimental ICRF Near Field Measurements

- To efficiently launch the required megawatts of ICRF power across the scrape off layer control of the RF sheath and the nonlinear interaction associated with antenna near-field must be achieved.
  - Requires an understanding of the underlying physics
- A simulation of the RF sheaths for a realistic geometry of the ITER ICRF antenna indicates that the DC potential in front of the antenna can approach 5.2 kV for the maximum input power of 20 MW[1].
  - DC potentials of this order can lead to enhanced erosion of PFC material and unipolar arcing.
  - The resulting parallel heat flux from this simulation approached 16 MW/m^2.
- To gain insight on ICRF near field analytical models have been derived capable of predicting the RF fields and sheath potentials near an ICRF antenna in a simple geometry[2].
- To validate existing models and aid the development of the theory an experimental investigation is needed.
- We propose to utilize the line splitting of the Balmer series of hydrogen, a dynamic-static Stark effect, to measure the near fields of ICRF antenna and possibly the harmonic content of the RF sheath produced by near-field interactions with the edge plasma.

[1] L. Colas et al., J. Nuc. Mat. 390-391 (2009) 959
[2] D. A. D'Ippolito and J. R. Myra, Phys. Plasma 16 (2009) 022506

Line Splitting of H I Balmer Series – Dynamic Stark Effect

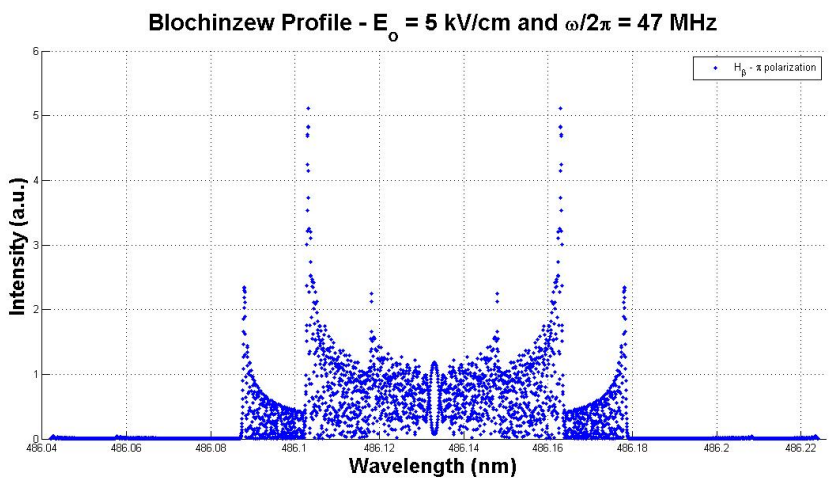
- The line splitting of a stark component in the presence of a monochromatic electric field was first calculated by Blochinzew and published in 1933[3].

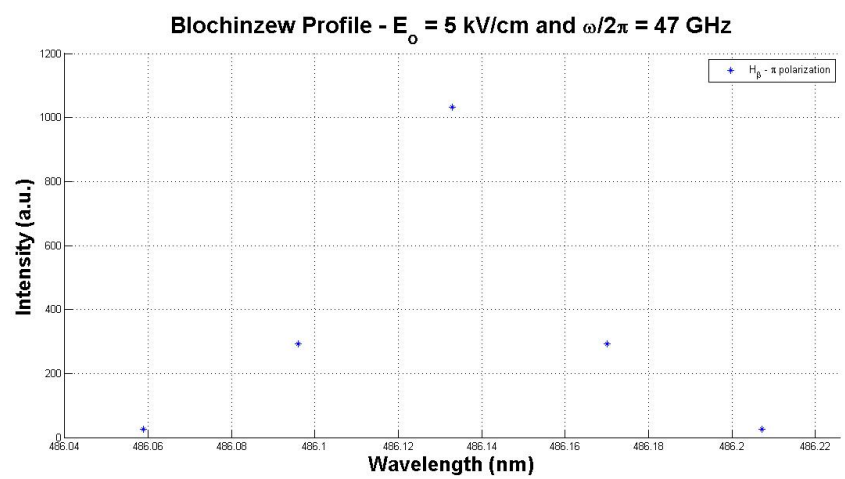
- It was found that the line splits into an infinite number of satellites separated from the line center by an integer value of the frequency at which the monochromatic electric field is oscillating.

$$I(\Delta\omega) = \sum_{p=-\infty}^{\infty} \sum_{k=1}^{k_m} f_k J_p^2(X_k \varepsilon)\delta(\Delta\omega - p\omega)$$

$$X_k = \left[n(n_1 - n_2) - n'(n_1' - n_2')\right] \qquad \varepsilon = \frac{3\hbar E_o}{2m_e e\omega}$$

ω - angular frequency of the monochromatic electric field
f_k - intensity of the kth Stark component
J_p - Bessel function of the first kind of order p
n and n' - principal quantum numbers of the initial and final states respectively
n_x and n'_x - parabolic quantum numbers of the initial and final states respectively
E_o - magnitude of the oscillating electric

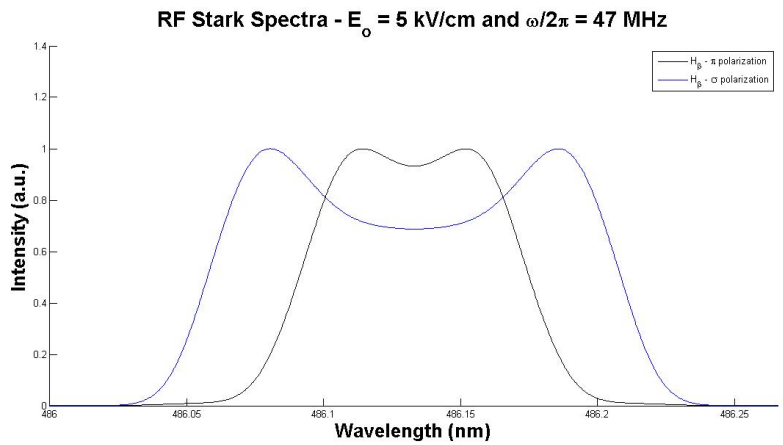


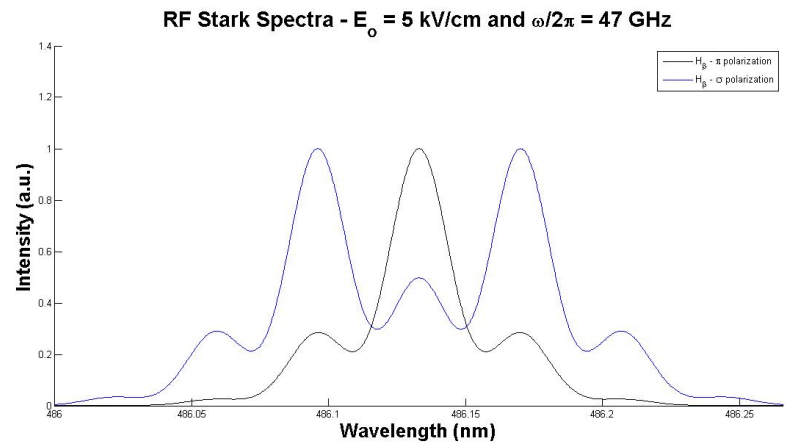


[3] D. I. Blochinzew, Phys. Z. Sov. Union 4, (1933) 501

Line Splitting of H I Balmer Series – Dynamic Stark Effect

• The observed line profile is given by the convolution of the Blochinzew profile with the instrument function of the spectroscopic system.





• The instrument function of our spectroscopic system was found to be a Gaussian profile with a FWHM of 0.25 angstrom for maximum resolution conditions.

• For equivalent RF electric field strength the line profile is highly dependent on the frequency of the oscillating electric field.

• As the frequency of the oscillating electric field is decreases the intensity of the satellites is increase along with the number of satellites associated with each Stark component.

• The RF electric field has a big effect on the line profile.

Dynamic Stark Effect Validation for the Balmer Series of Hydrogen

- The satellite structure of Balmer lines of deuterium arising from the dynamic stark effect was successfully measured by Kamp and Himmel[4].

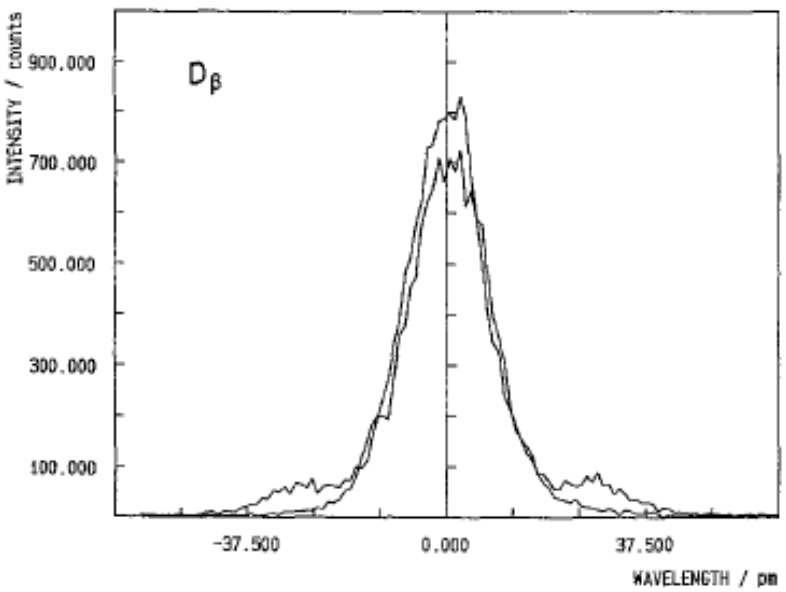


Fig. 14. Line profile of D_β with and without rf electric field

- Showed that for an electric field oscillating at 34.8 GHz the Blochinzew profile accurately represents the line profile.
- The RF electric field strength resulting from this profile was found to be 2 kV/cm.
- Verification of the Blochinzew profile in the MHz range is still needed.
  - ➢ The fine structure of hydrogen may alter the Blochinzew profile.

[4] A. Kamp and G. Himmel, Appl. Phys. B 47 (1988) 177

Dynamic-Static Stark Effect – RF and DC Electric Field

• When both an RF and DC field are present two cases need to be considered:

DC electric field parallel to the RF electric field

• The resulting line profile is a convolution of the two line profiles found by treating the DC Stark effect separately from the dynamic Stark effect.

• Thus the Stark components are further separated in the line profile.

DC electric field perpendicular to the RF electric field

• The line profile can only be calculated numerical by conducting a perturbation analysis of the Schrodinger equation.

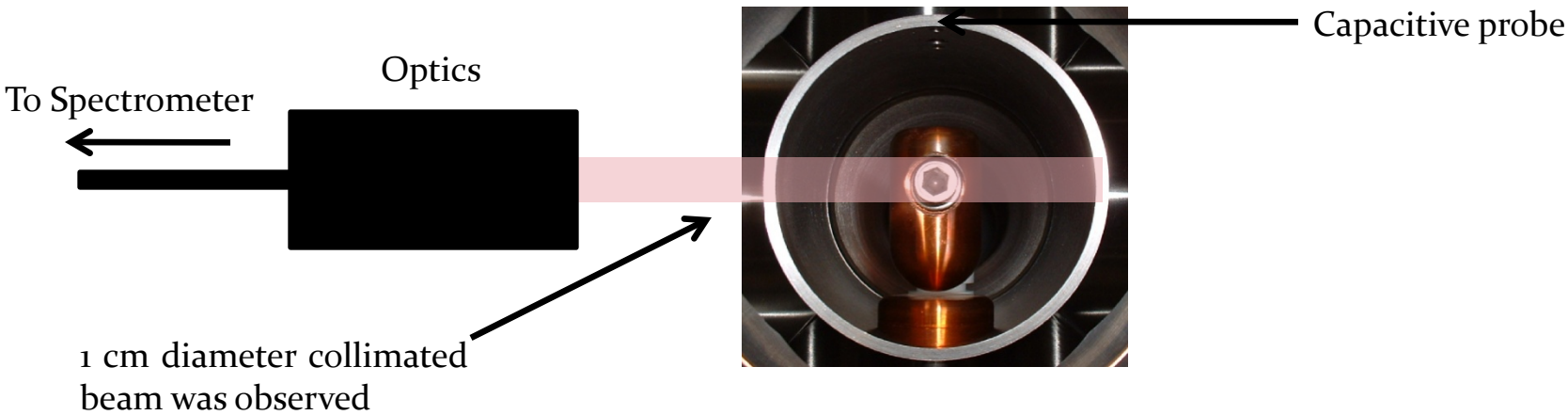
• Resonance effects can be important which distort the line profile significantly from that predicted by Blochinzew.

Recent Results

- A series of experiments was conducted on the RF High Voltage Breakdown Tester, a condition was found that allowed for plasma formation throughout the chamber while a high RF voltage was maintained on the electrode.

  - The electrode was rotated 180 degrees, such that the electrode gap was approximately 1.5 cm .

  - Electrode RF voltage was measured by a capacitive probe.

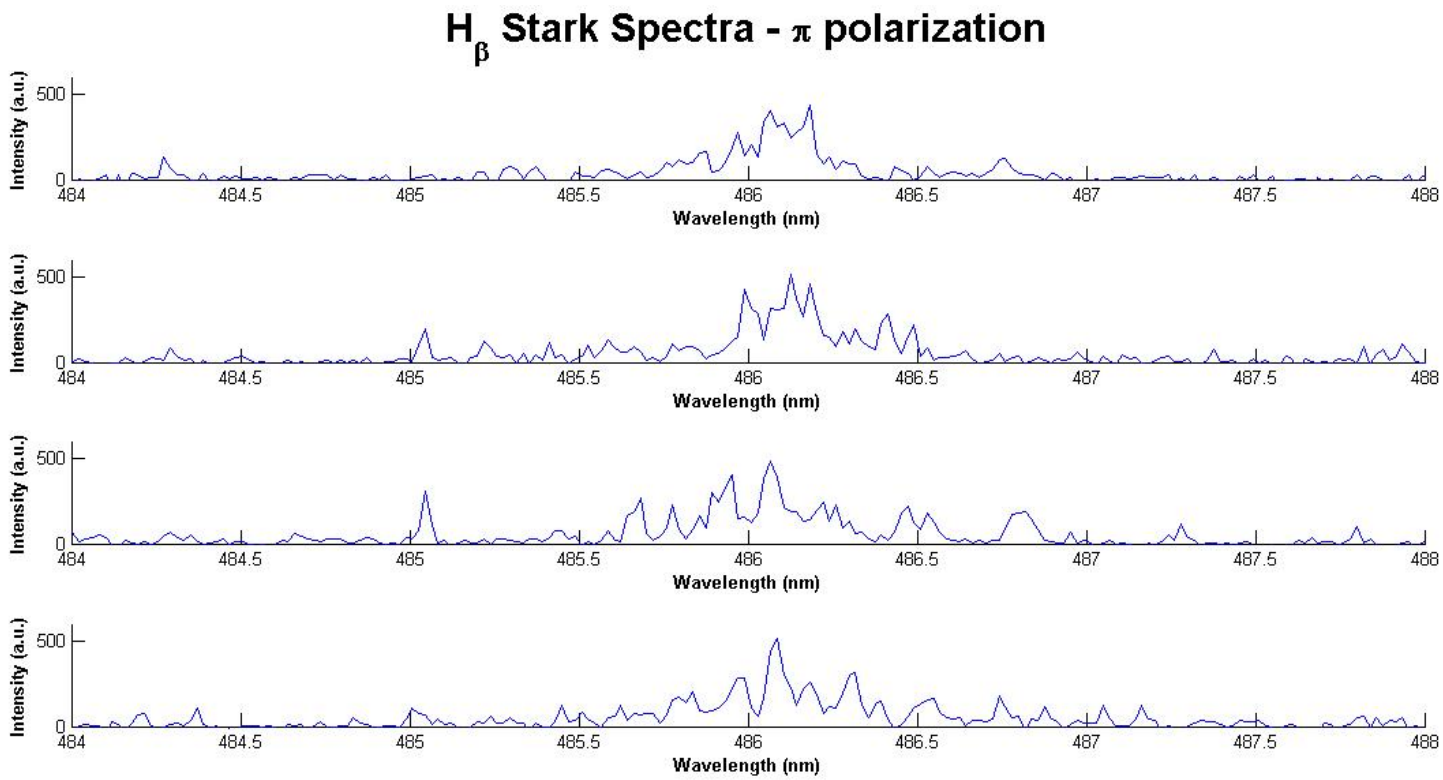


- The plasma density is assumed to be very low due to the fact the reflected power did not change significantly when compared to a match in vacuum. This indicates low loading and thus low plasma density.

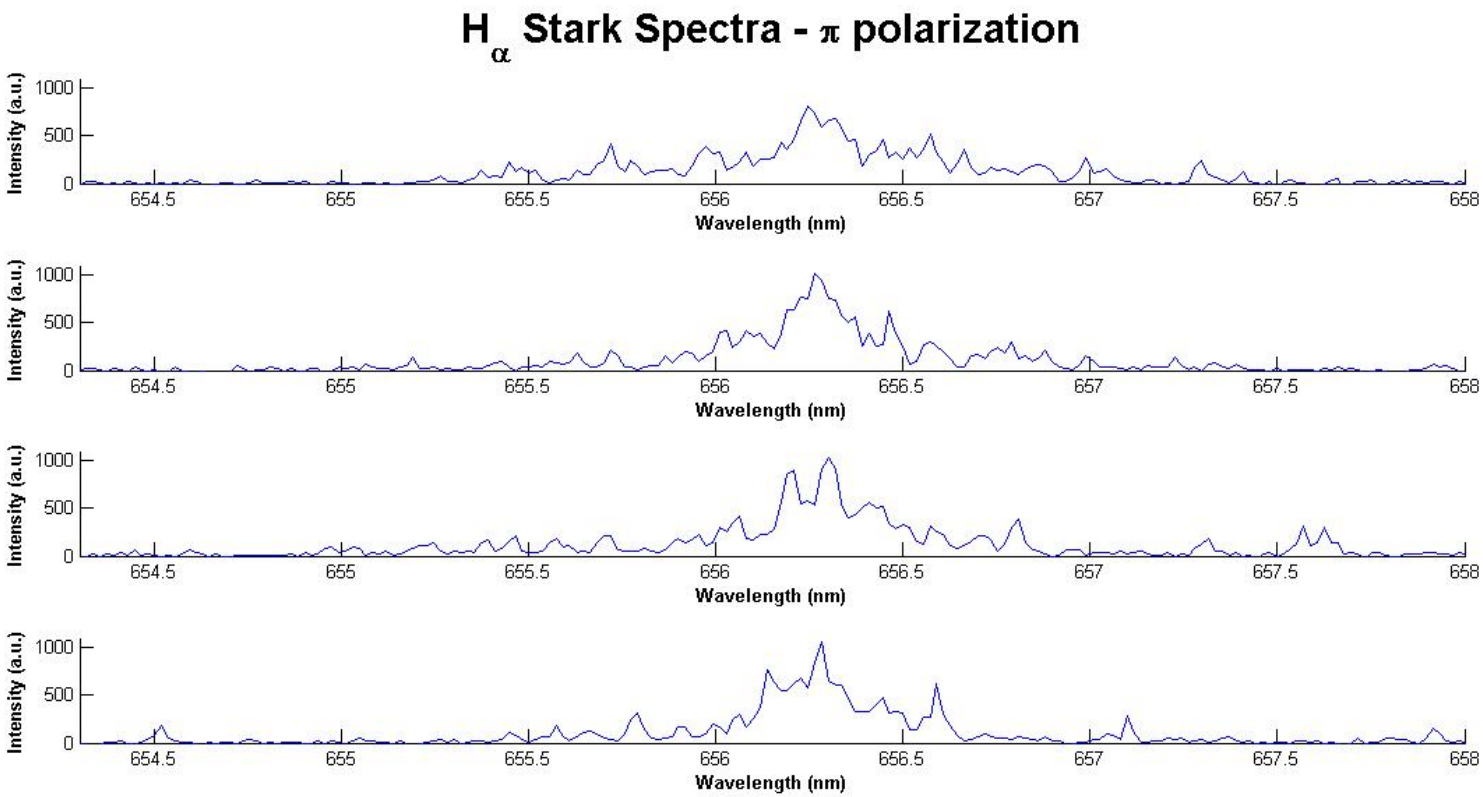
RECENT RESULTS - H_{BETA} STARK SPECTRA

• The RF high voltage was pulsed with a period of 5 seconds and a pulse length of 100 msec.

• Optical emission was observed for 70 msec with a 30 msec delay from the turn on of the RF high voltage. A spectra was taken for each RF high voltage pulse, approximately 30 spectra were obtained for each run



RECENT RESULTS - H_{ALPHA} STARK SPECTRA

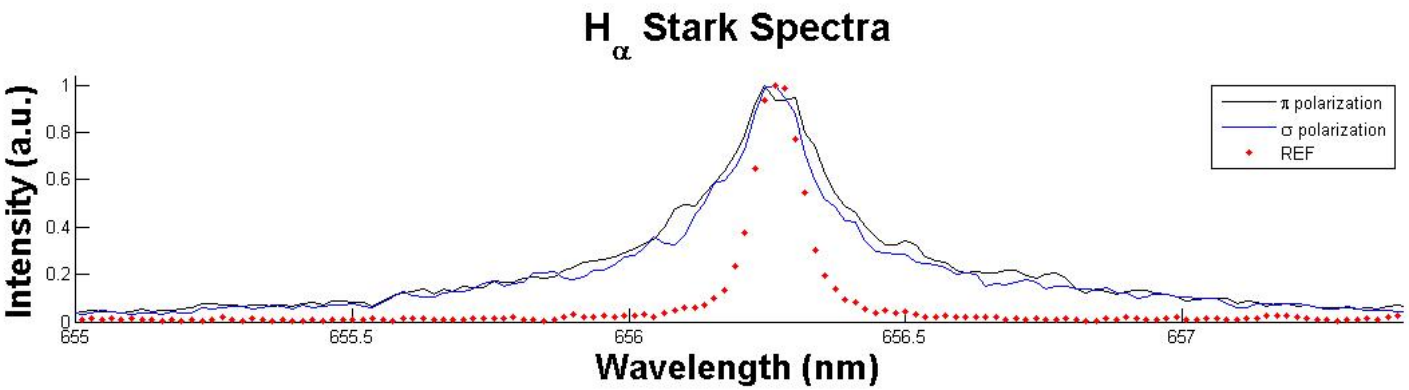


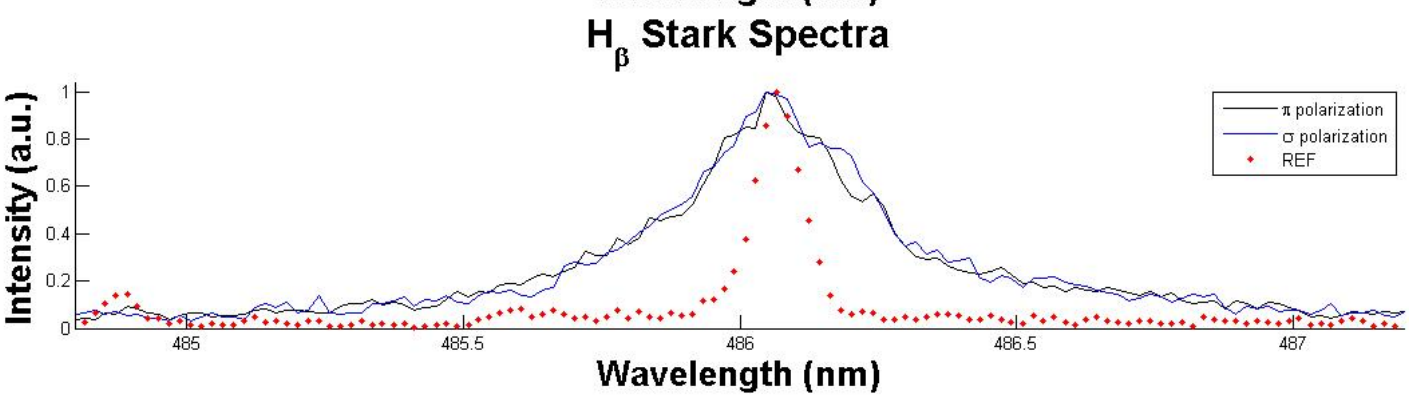
- The H_{beta} and H_{alpha} Stark spectra show that a series of peaks is present.
- The series of peaks seems to be relatively consistent for every two shots

Recent Results - Averaged Stark Spectra

• The Stark spectra were averaged over all shots in a run to determine if there were any dominate lines in the spectra. The Stark spectra are also compared to the spectra obtained in a region of low field.

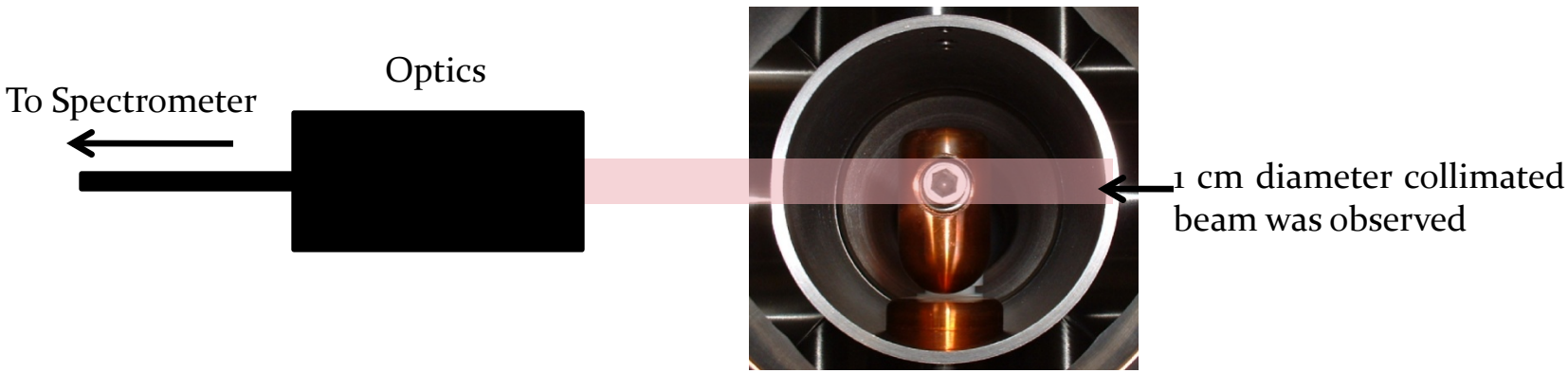
• A very broad peak with a semi-smooth profile is obtained. The pi and sigma profiles are approximately the same





Recent Results - Analysis

• To understand these results the location of the beam of observed emission is re-visited.



• It is believed that due to the complex field topology of the location at which the emission is observed the resulting Stark spectra is an average over a wide range of RF electric field magnitudes and both polarizations.

• The variation in the Stark spectra from shot to shot could be due to resonance effects arising from a DC electric field perpendicular to the RF electric field, where the DC electric field is due to rectification of the RF in the sheath.

• The broadening at the FWHM of the averaged line is consistent with an RF electric field strength of ~ 10-15 kV/cm

• A very large effect was successfully measured and is most likely due to the RF electric field, this warrants further investigation with RF field in a “good” geometry.

Future Work

- An experiment has been designed that would allow for the study of the Stark spectra of the Balmer series lines of hydrogen in a 47 MHz RF field with "good" field topology. This experiment was designed to take place on the RF High Voltage Breakdown Tester with very little modification to the existing setup.

  - High resolution spectroscopic system with phase lock capability supplied by NCSU

- A collaborative effort is currently being built between the theoretical and experimental work being conducted at ORNL and spectroscopic measurements of the near fields of Tore Supra ICRF antenna led by Chris Klepper.

  - It is proposed that theoretical development of line profile calculations would be developed at ORNL and verified with experiment, Chris Klepper would then apply these calculations to his measurements.

Conclusions

- Currently we are capable of modeling the line profile of the Balmer series of hydrogen for a DC electric field superimposed in parallel with an RF electric field.

- The addition of magnetic field requires a numerical solution to the Schrödinger equation and is currently being pursued.

- The addition of an RF electric field with harmonic content is also being pursued with the hypothesis that harmonic content of the RF electric field could be extracted from the spectrum.

- Initial experiments indicate that the RF electric field plays a major role in the line profile.

ACKNOLEDGEMENTS

I would like to thank all of the staff and scientist in the FED for there willingness to lend there assistance.

I would like to thank Chris Klepper for many useful discussions and suggestions.

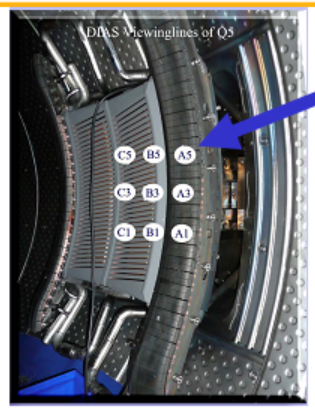
I would especially like to thank John Caughman and Steve Shannon for there mentorship throughout this research, it is greatly appreciated!

Association Euratom-CEA

DIAS: Dedicated ICRH Antenna Spectroscopy

irfm

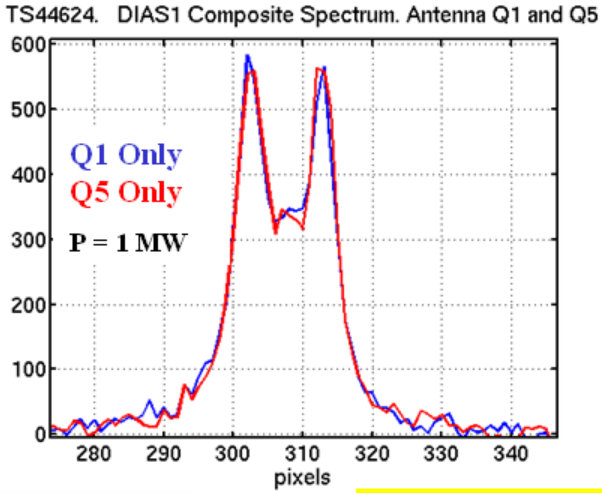
cadarache



- ❖Tangential views resolve bumper and Faraday Shield
- ❖Access via existing endoscope
- ❖Each view to 1m spectrometer with CCD detector.

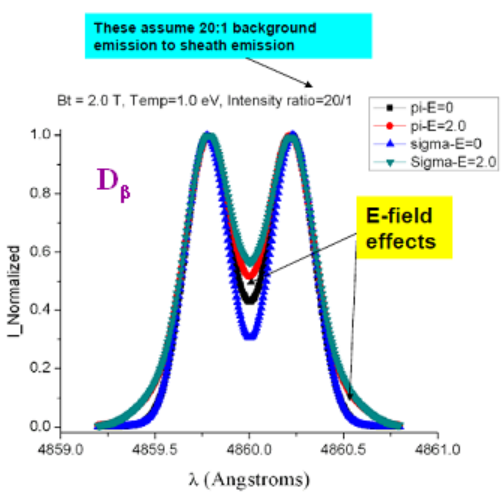
FIRST SPECTRA (Commissioning Stage)

- DIAS is viewing Antenna Q5
- Compare D_α spectra with only Q5 and only Q1 active
  - ✓Provides good "control case"
- E << 2 kV/cm for 1 MW case



SIMULATION (R.C. Isler codes)

- External E-field Stark Effect modifies Zeeman profile
- Unperturbed Dα emission can swamp effect for low E
  - ✓ Measurable effects for E >~ 2kV/cm



TORE SUPRA

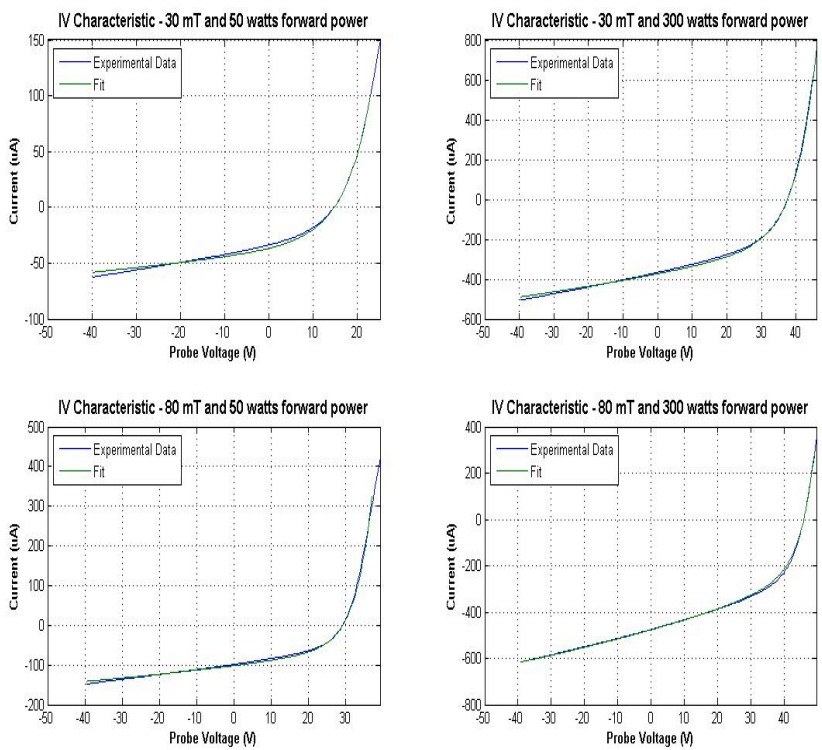
*Present optical view limits time resolution and signal-to-noise

OAK RIDGE National Laboratory

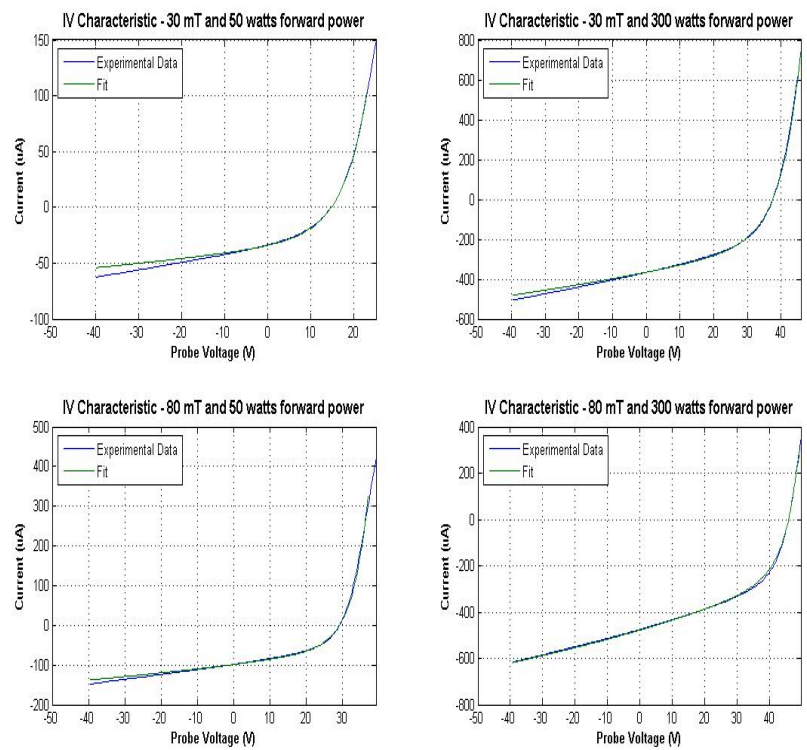
Experimental Method – Fitting of the IV Characteristic

- The IV characteristics were fit over the voltage range: -40 to ϕ_p and -10 to ϕ_p to estimate the error in the fit due to finite cylindrical probe effects.

-40 to ϕ_p



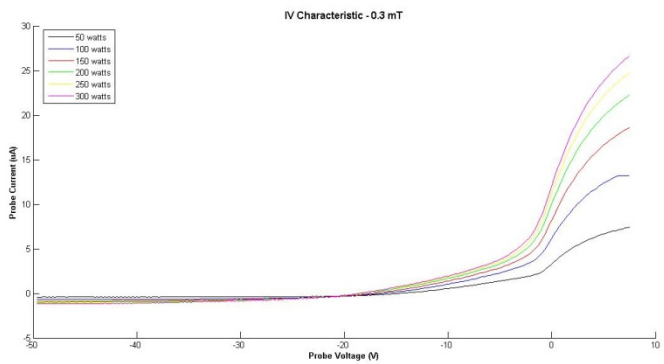
-10 to ϕ_p

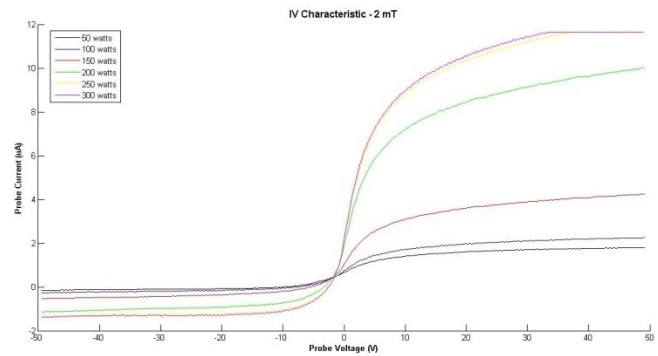


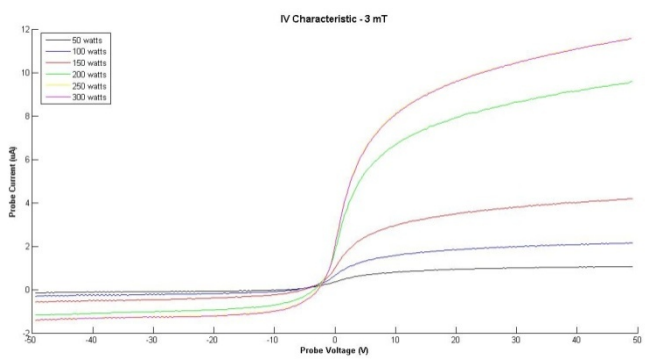
PLANAR PROBE IV CHARACTERISTICS

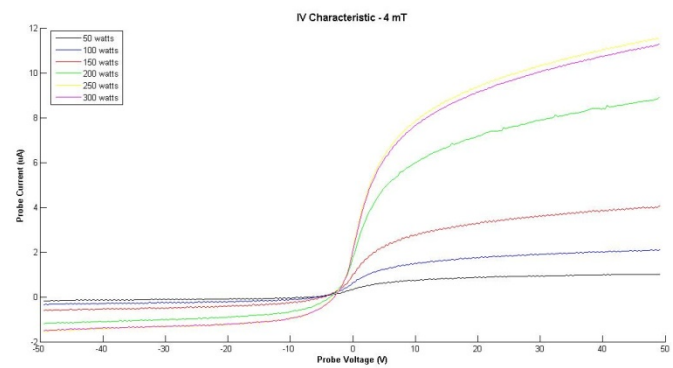
- The planar probe IV characteristics for chamber pressures of 2, 3, and 4 mTorr for all ICP source powers investigated do not show evidence of a non-thermal hot electron population.

- A non-thermal hot electron population is an indicator that the sheath thickness is on the same order as the size of the aperture the plasma is being extracted through.



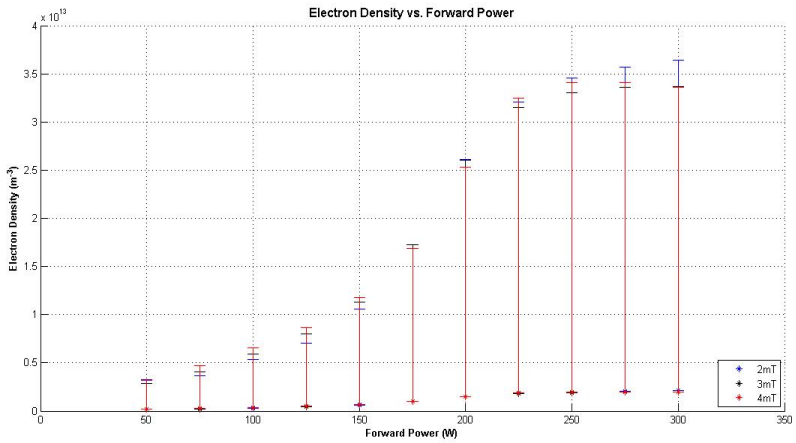


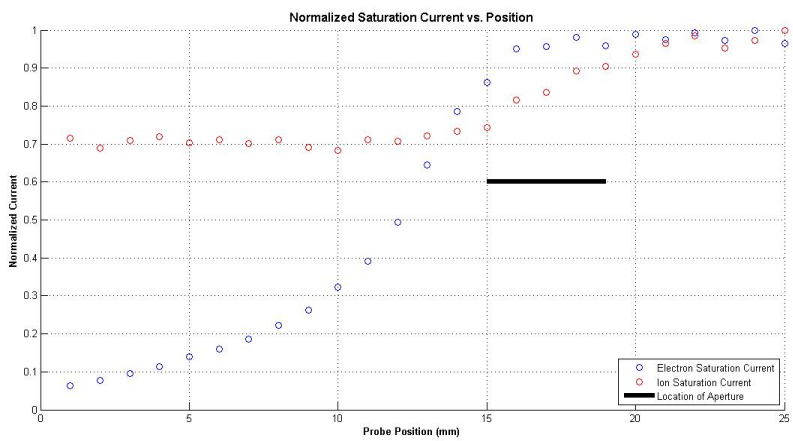




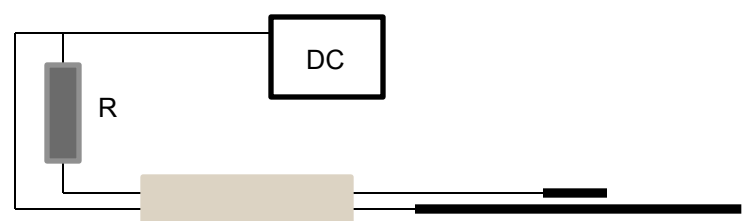
Experimental Method – Error Estimate on electron density

- The highest level of uncertainty in the calculation of electron density from the planar probe IV characteristic is the area over which the current is collected.





- Bounds on the collection area can be set:
  - Lower bound – area of planar probe
  - Upper bound – area of aperture

- The profile of the beam was measured with the planar probe.
  - Suggests that the beam is not localized to the area of the aperture.

Need to construct new probe for a more conclusive profile measurement.