Details on an AFRL Field Reversed Configuration Plasma Device

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A field reversed configuration (FRC) plasma device is being developed at AFRL Edwards. This geometry concept is based off of the coaxial slow source FRC fusion reactor concept developed at the University of Washington by Vlases, et al. A scaling energy model, COTS FEA, and a proof-of-concept experiment have been completed. In addition a complete suite of magnetic diagnostics as well as photometric/optical and internal plasma measurements have been constructed. This study details the initial testing, calibration, and operation of an FRC-based concept.

Nomenclature

β	=	The ratio of magnetic to particle pressures
e	=	Electron charge
k	=	Boltzmann's constant, $1.38\text{x}10^{-23}$ J/K
λ_D	=	Debye length, cm or mm
I	=	Probe collected current, mA
$I_{e,\,sat}$	=	Electron saturation current, A
$I_{ion,\,sat}$	=	Ion saturation current, A
m_e	=	Electron mass, $9.1094\text{x}10^{-31}$ kg
n_e	=	Plasma electron density, m^{-3}
δ	=	Sheath thickness, cm
r	=	Probe electrode radius, m
τ	=	Characteristic plasma resonance time, μs
Te	=	Maxwellian plasma electron temperature, eV

I. Introduction

Field Reversed Configuration (a compact toroid) plasma devices have an interesting development history. These plasma devices create a relatively high density, high β, high efficiency inductively coupled plasma that has many potential applications. FRCs in equilibrium have been studied extensively for fusion energy generation, while FRCs in translation have potential for devices ranging from space propulsion to tokomak refueling. In particular the Air Force Research Laboratory is interested in utilizing an FRC plasma as a propulsion concept. Currently, there is a basic scientific research program underway to examine FRC plasmas and their use as a space propulsion concept.

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 2005		-

4. TITLE AND SUBTITLE	
Details on an AFRL Field Reversed Configuration Plasma Device	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **David Kirtley; Daniel Brown; Alec Gallimore; James Haas**	5d. PROJECT NUMBER **1011**
	5e. TASK NUMBER **0009**
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Force Research Laboratory (AFMC),AFRL/PRSS,1 Ara Road,Edwards AFB,CA,93524-7013**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

II. FRC Technology Physics

A. FRC Physics Overview

In terms of modern FRC physics there are several subjects of interest. First, some general scaling laws of modern (1980+) FRC experiments and a general operational timeline are as follows:

- Diameters 15-90 cm
- B 1-13 kGauss
- β 0.5-1
- n (cm^{-3}) 10^{14} - 10^{17}
- τ 50-500 μs

Translating FRC Formation
1. Fill coil with gas
2. Fill coil with low level flux
3. Pre-Ionize to trap and freeze plasma to field lines
4. Force field reversal to tear and internally reconnect field lines
5. Fully formed self-consistent FRC at this point
6. Continue pulse to radially compress

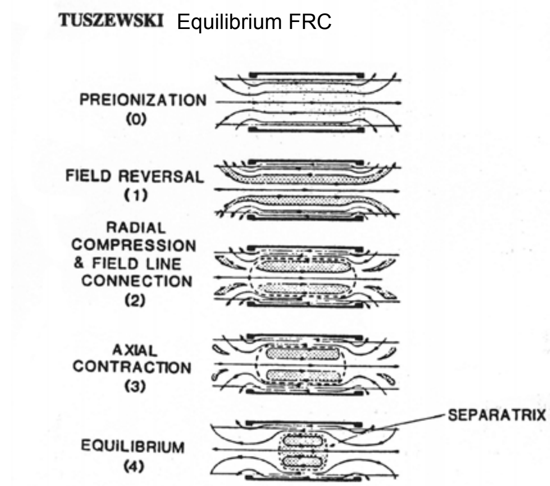

Fig 1. Formation Sequence and Geometry

At the exit of the FRC reactor is a compressed, relatively non-diffuse neutral toroidal plasma with a self-consistent magnetic field and large poloidal currents. It has been noted that forming efficient FRCs is a very empirical process of electrical circuit characteristic development; however, once a valid discharge scheme (and pre-ionization method) has been developed these reactors are very robust and repeatable[i,ii].

B. Coaxial FRC Physics

Traditional FRCs have demonstrated high-velocity translation and high-efficiency compression. However, they also have some inherent disadvantages, namely high voltages (20^+ kV) and fast discharge times leading to complicated propellant feed and switching. A possible solution to these issues is the Coaxial Slow Source FRC concept (CSS) developed at the University of Washington by Vlases, Brooks, and Pierce for deuterium fusion [iii,iv]. The CSS concept has demonstrated FRC formation and translation (in excess of 10^4 sec Isp with deuterium) at coil voltages of less than 100 volts and discharge times longer than 250 µs. The CSS is approximately 40cm in diameter, with 100-2000V discharge voltages, 20-60 mtorr propellant, and 100-250 µs discharge times. They successfully demonstrated results similar to traditional FRC concepts (LSX[v] etc.), however the temperatures were insufficient for fusion, and there was some evidence of the rotational n=2 instabilities that do not appear to be present in traditional FRCs. There was also evidence of excessive radiation losses due to the long discharge time and oxygen impurities. However, as our primary interest is FRC formation and immediate translation, these instabilities are of substantially less importance.

C. AFRL XOCOT Concept

The AFRL XOCOT concept geometry is based upon the CSS device, scaled to incorporate lower discharge voltages. Initial testing parameters are planned for 10-30 kA coil currents, 0.1-1 ms discharge times, over-all diameter of 40 cm, and 30cm length. In addition, with argon propellant and a theta-ringing RF pre-ionization discharge the XOCOT is projected to have less than 1 kV discharge voltage.

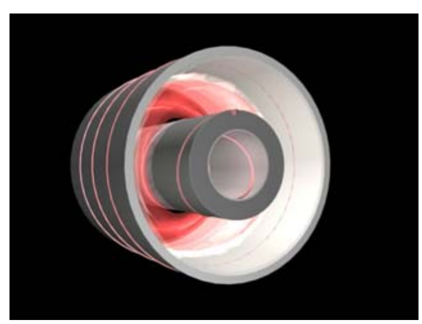
Figure 2. *3D rendition of XOCOT*

III. AFRL FRC Technology Status

A Hardware Status

After two summers of extensive hardware development the AFRL XOCOT FRC facility and experimental hardware have been completed. Figures 3-5 detail facility components which consist of the following:

- Two 1.5 m concentric quartz tubes form the ionization region as well as the annular vacuum chamber
- 8" diffusion pump and associated vacuum hardware
- Two in-house manufactured aluminum coils (4 cm thick) are external to the chamber and form the theta coil assembly
- 18kJ (max) reused and reconfigured MPD (magneto-plasma dynamic thruster) capacitor bank
- Two 30kA+ ignitrons form the switching/transfer network
- Extensive physical, EMI, and UV shielding
- Associated high-energy safety mechanisms

Currently installed, calibrated, and tested diagnostics include a single-pixel high speed photometer, high speed Mega Pixel (MP) single frame camera, excluded flux array (36+ B-dot probes and several flux loops), a rogowski coil, internal single and triple-langmuir probes, and current and voltage monitors. Future hardware development will be targeted towards diagnostics including high speed photography, interferometry, spectroscopy, and bolometry planned for the current testing geometry (external to the vacuum chamber).

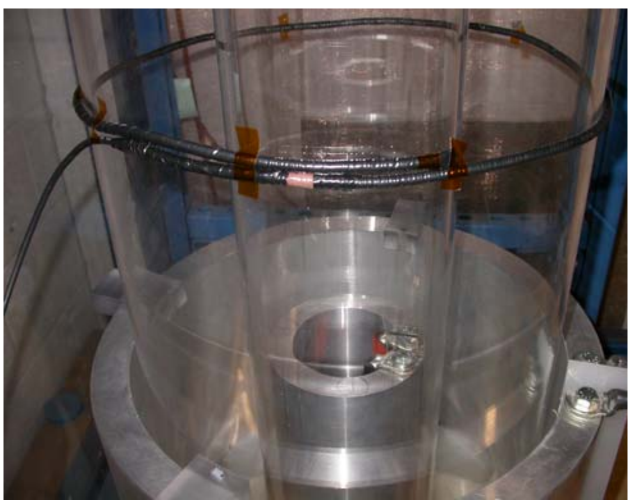

Figure 3. *Photo of the inner and outer discharge coils mounted with the annular quartz vacuum chamber. Also shown is a 40cm rogowski-coil and high-frequency electro-magnetic shielding*

Figure 4. *Photograph of the coils mounted in the E/M shielding cage, power supplies, and general facility setup. Important note is the vertical configuration of the coil/chamber assembly.*

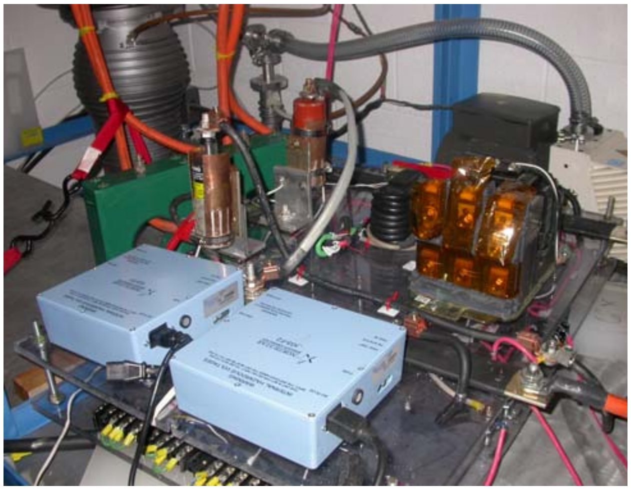

Figure 5. *Ignitron Switching Network. This photo details the constructed type-A ignitron switch, diffusion pump, and low/high voltage switching networks. Also of note is the optical ignitron controllers from Richardson Electronics.*

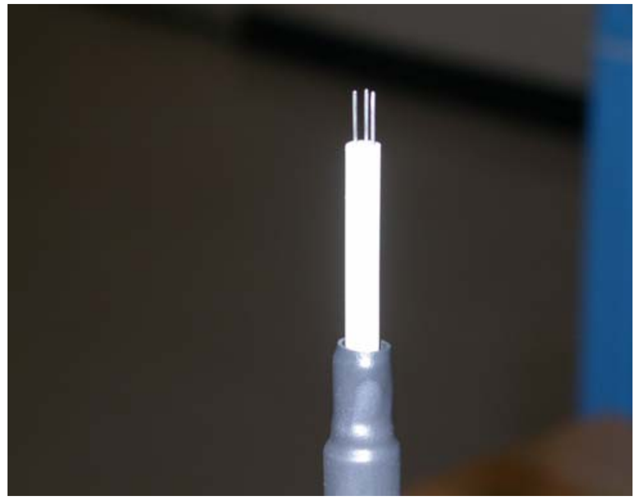

Figure 6. *Close-up photograph of the triple probe used internally with the XOCOT coils. Probe leads are 7mm x 0.25 mm dia, clad in a boron-nitride ceramic sheath and sealed with a generic vacuum-rated epoxy.*

The main capacitor bank has been fully configured/constructed and tested with electrical, safety, and discharge cleanliness verified; in addition, the three main safety mechanisms, large bleed and balancing resistors, small resistance dump resistors, and capacitor grounding circuits, have been fully tested and are operational.

The primary switching, power transfer network consists of two ignitrons (mercury spark gap switches) with high speed, high accuracy triggering circuits. They are fully operational with timing accuracy and turn on times within 1 μs and shot-to-shot repeatability demonstrated ~10% (ESR, inductance).

B. Construction Timetable

June 2004 to September 2004 comprised the main construction period. As of October 2004 the XOCOT, facility, and most of the diagnostics were completely constructed. This construction period built upon a previous summer of the basic construction of the facilities, structural, and vacuum components.

The ignitron switching network was constructed using two 30kA type A ignitrons and fiber-optic switches. This network can trigger the two coils or more interestingly, the two coils and a secondary capacitor bank for pre-ionization. The capacitor bank upgrades, safety, and electronics systems were constructed.

The primary hardware development during this construction period was geared towards diagnostics. A DICAM 2 single color mega-pixel, 10 ns resolution, single frame camera and a single pixel MHz visible light photodetector were installed in several locations to optically characterize the plasma formation and heating.

Several triple probes (also used as a single Langmuir probe) were constructed from tungsten wire and alumina tubing and installed 1” inside of the coils, centered between the two (2” from each).

Figure 7. *Photograph of the 16kJ G capacitor bank. Not included in this photograph is the later-added RF shielding, and full kinetic shielding infrastructure.*

Concomitant to hardware/facility, an extensive program of magnetic field probe (also called b-dot probes) development was underway. Several arrays of high speed (1/8'') 3-axis probes were completed for the installed configuration between the quartz tube and discharge coil as well as between the two coils in order to fully map the transient magnetic field profiles of the XOCOT coils. In addition a steady state oscillating Helmholtz coil setup was constructed and used to calibrate the b-dot probes at similar operating frequencies as the main discharge bank.

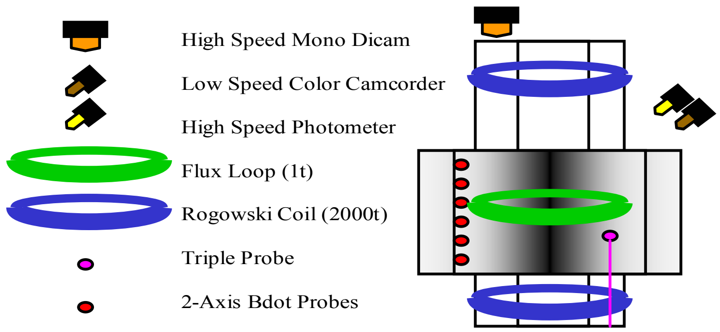

Figure 8. *Detailed probe diagram showing the locations and configuration of probes used for the initial XOCOT Testing.*

C. Analytical/Computer Models

Currently two rudimentary computer models have been developed. The first model, developed in order to facilitate the development of the initial concept, is a zero-dimensional energy balance assuming a compressed, equilibrium state (empirically based) which showed the temperature/density/energy deposition scaling as a function of size. It also takes into account the energy loss mechanisms (non-formation losses) and variations in circuit parameters. This model shows quite clearly that at the energy levels considered, ohmic losses are a main driver and that radiation losses would not become a major loss contributor for several orders of magnitude of discharge energy. It also predicted (as discussed in CSS literature[iv]) that small increases in coil size would lead to <100V discharges. Secondly, by modeling the XOCOT with the COTS finite element (FEA) Magnet 3D Transient solver, the B-fields in the coils were quantified in order to validate the excluded flux array and the actual transient current density profiles for a given connection scheme. These models have clearly demonstrated that fast, large current pulses (of this type) in a large cross-sectional area are distinctly non-uniform. Future Magneto-hydrodynamic (MHD) models will enable detailed study of the internal, real-time processes occurring in the XOCOT Concept.

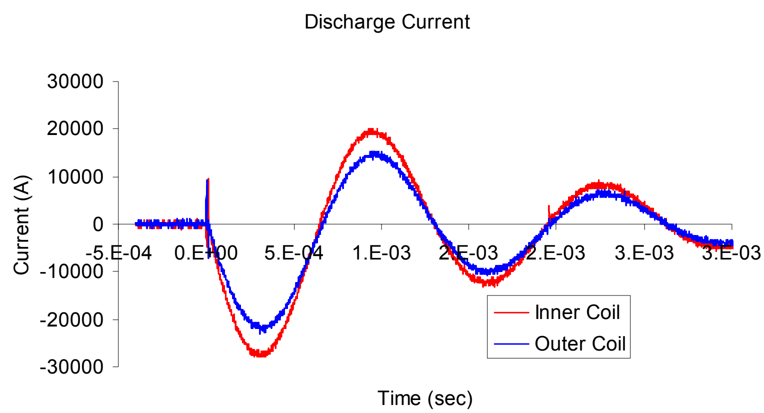

Figure 9. *A typical coaxial discharge, showing the clear oscillatory and mis-matched current profiles.*

IV. XOCOT Initial Tests

All data presented for the AIAA Joint Propulsion conference were collected prior to December 2004 with more advanced data to be presented at a later date. The XOCOT has been firing repeatably and reliably. Figures 9-11 detail typical operating characteristics and discharge current profiles. This section provides a summary and preliminary data from an XOCOT discharge.

A. XOCOT Initial Discharges

Extensive work has gone into an actual discharge, however, this phase of the FRC formation appears to be the most complicated of the required stages. Literature searches, as well as personal correspondences confirm the position that for such a large, low speed, low voltage FRCs, the pre-ionization discharge is the most critical phase of the discharge. As such three discharge methods have been investigated.

B. Pre-ionization discharge

The traditional theta-ringing technique of pre-ionization entails discharging a high speed (the XOCOT current design is 2MHz) ringing discharge at a higher voltage than the main bank (4-10kV) but with significantly less energy than the main discharge (10's of Joules). Extensive work was done with actually getting a plasma and the ignitrons to discharge fast enough with full current reversal. With only a pulsed pre-ionized discharge there was some evidence of ionization, but it was not efficient, hot, or dense enough for a proper FRC discharge. In addition, with this pre-ionization technique plasma data is lost in discharge electromagnetic noise which sponsored an extensive grounding study, isolation, E/M noise, and investigation into pulsed discharge diagnostics. In addition, noise cancellation and post processing methods were designed (filtering and reference vacuum discharge comparison).

C. Steady state RF discharge

As the previous ionization methods failed to produce efficient FRC currents in the plasma a new pre-ionization scheme was devised. Using a steady state 13.56MHz RF supply, an efficient, stable plasma could be formed.

After a steady state RF plasma is formed, the main bank discharges the coils into it. This method should provide poorer flux trapping, however, because of the geometry of the coils (and simply using two coils) there will still be field line tearing and FRC formation. As an early ionization technique steady state RF has demonstrated easy, low voltage FRC formation, compression, and heating.

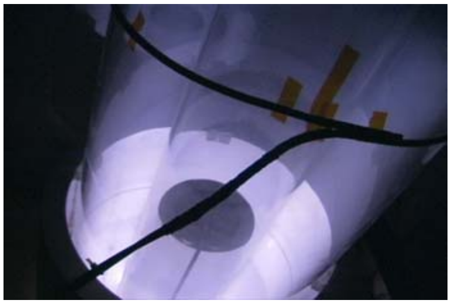

Figure 10. *Long exposure discharge photograph*

Using this method steady RF pre-ionization was created, enabling the deposition of hundreds of watts into the main coils. However, this method still has <1% ionization, while a traditional goal for the pre-ionization stage is 50%. When the main bank is discharged into this RF plasma, the applied diagnostic yields interesting results. Below in figures 11-13 is a summary of the preliminary findings, most of which data were collected in mid-December.

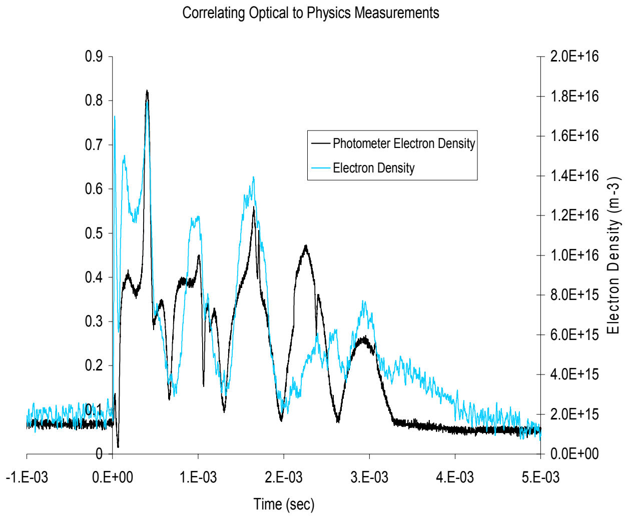

Figure 11. *Optical versus Internal probe Measurements*

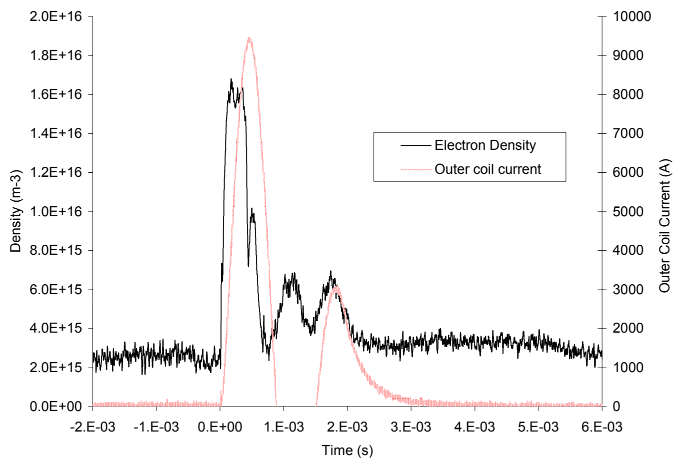

Figure 12. Secondary translation coil current density profile

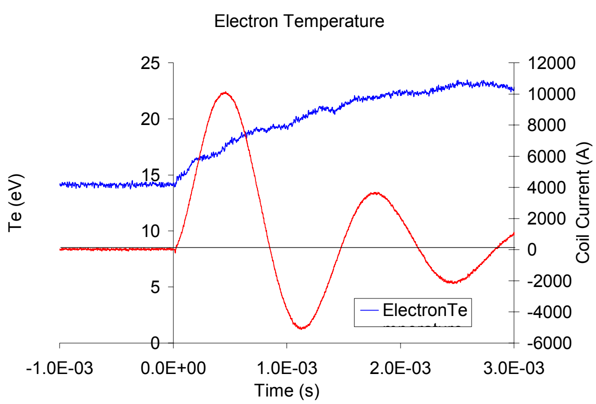

Figure 13. *Typical electron temperature profile*

The high speed photometer data shows several orders of magnitude increase in optical emission. The triple probe current, which corresponds linearly to electron density, follows the same general time scales and trends as the photometer data. Triple probe voltage corresponds with electron temperature and was consistently ~20eV, hot for a plasma device (see Figure 13). In addition, figure 10 shows the comparison of using optical measurements (through a simple Boltzmann energy relation) to the internal physical probe measurements of plasma density, showing remarkable similarities in terms of general structure, the formation and heating of the plasma during a typical discharge. These very preliminary data show defined plasma compression and heating during the main discharge, as well as over-all favorable local and general plasma structures. As a validation of the construction phase for this project they show that repeatable, EMI clean compact toroids can be produced.

In addition, preliminary data using a secondary 'kicker' or translation coil (altering the magnetic profile of the mirror such to drive a translation instability) shows marked change in operation suggesting a significant decrease in plasma contained within the mirror geometry. Further work must be done to analyze plasma toroid exit velocities and profiles.

See figures 14-15 for actual discharge photographs.

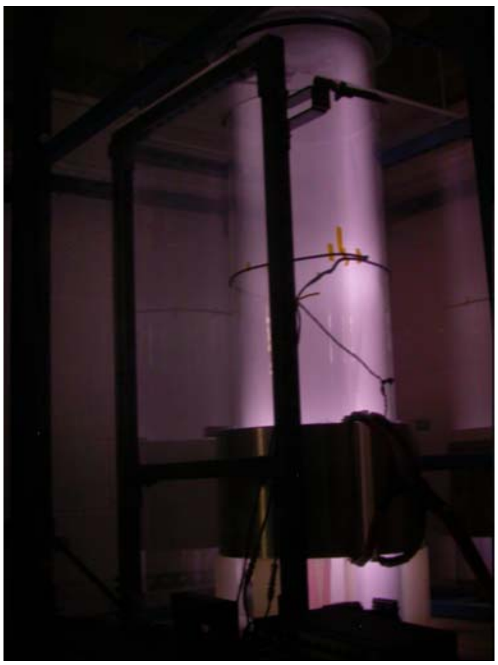

Figure14. *RF Breakdown XOCOT Coils Argon*

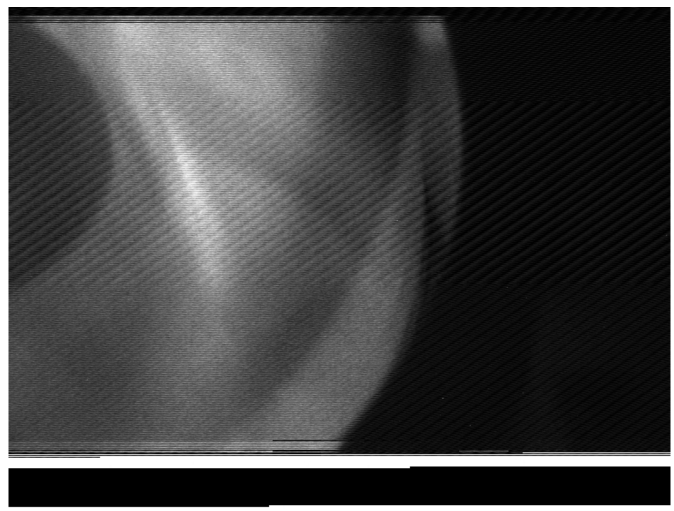

Figure 15. *Example of a high-speed (1μs) resolution photograph during a discharge*

V. Conclusion

As shown above great progress has been made in the construction and testing of a field reversed configuration plasma device at the Air Force Research Laboratory. The design and construction of a facility to house the studies has been completed and preliminary testing shows that an FRC plasma has been successfully initiated, heated, and as suggested by the data, translated. Current work into characterizing the performance and detailed operation/optimization of the XOCOT is underway, in addition to general facility upgrades, EMI reduction, and data acquisition improvements. These devices hold great promise in a variety of plasma applications and warrant further study. For more information, detailed practical application, and the motivation for the study of these devices, the authors invite readers to attend the Joint Army, Navy, NASA, Air-Force Conference in December 2005.

Acknowledgments

I would like thank the National Science Foundation and Air Force Research Laboratories spacecraft propulsion group, without who's funding this research would not be possible. Also, I would like to thank Daniel Brown, John Asher, and Robert Gregory for their diagnostic and technical construction support.

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