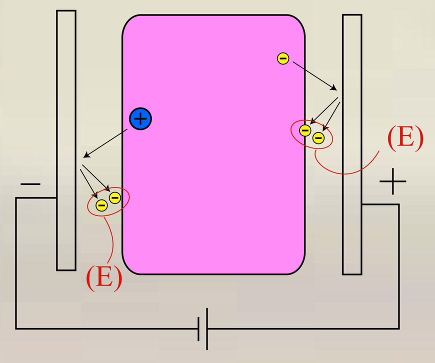
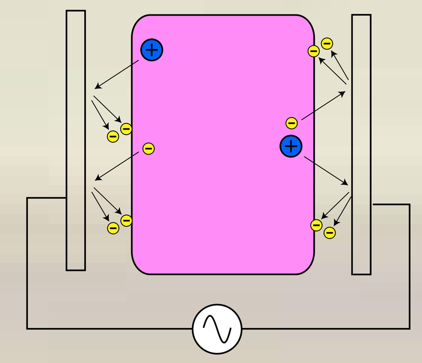
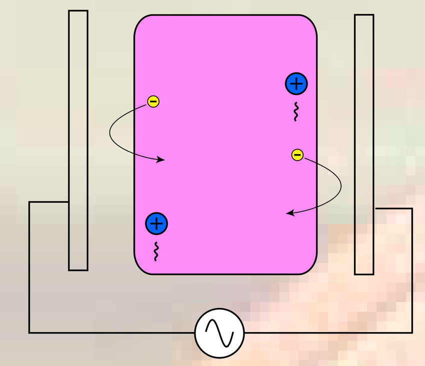


DC



40 kHz



> 10 MHz

Positively charged plasma ions are strongly attracted to the cathode. As the ion collides with the cathode, it may knock electrons free from the surface (on average, of them). These secondary electrons accelerate away from the cathode, becoming 'hot electrons'. These are much less abundant than the majority of plasma electrons, but they gain a much higher energy.

40 kHz plasmas have properties that are useful in industrial techniques, but they are not as well understood as DC and high frequency plasmas. They are still maintained by secondary electrons, which must be taken into consideration. But the secondary electron contribution is likely to be time varying.

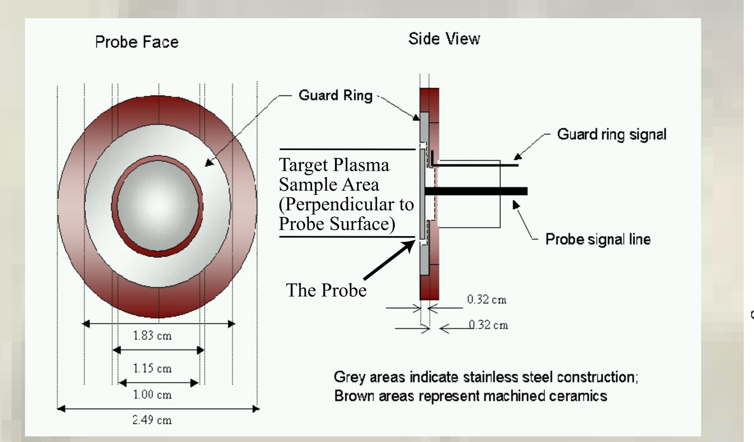
At high frequencies (more than ~ 10 MHz) secondary electrons are not important. In this case, electrons that in lower frequency plasmas would have interacted with the electrodes instead interact with the oscillating plasma sheath. The plasma is maintained by stochastic heating of the electrons by the sheath.

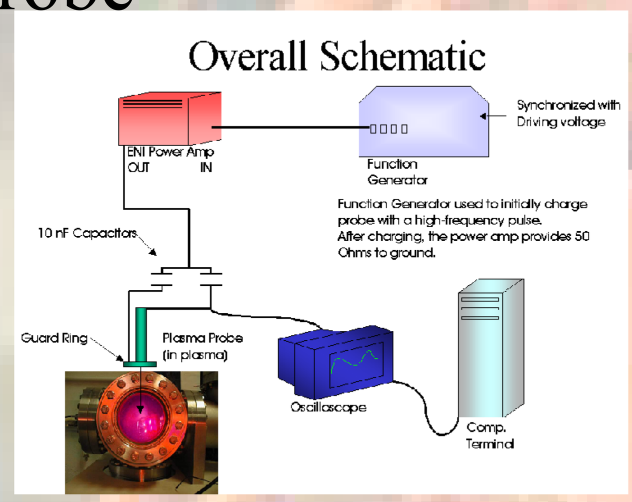
Stephen J. Ball*, Colin G. Palmer*, Jeremy Grace**, James G. McLean*
*Department of Physics, SUNY Geneseo, Geneseo, NY
**Kodak Research Labs, Rochester, NY

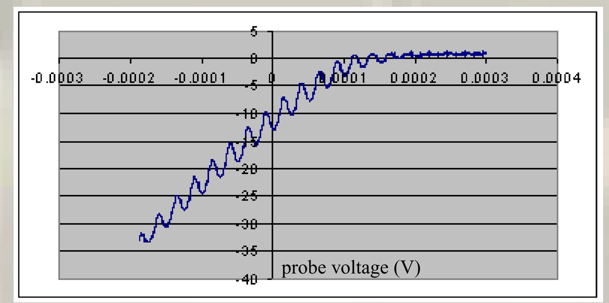
Abstract

Plasmas at radio frequencies ~40 kHz have been shown to produce chemical modification of polymer surfaces useful in industrial applications. These plasmas are sustained by secondary electron emission from electrode surfaces. Time-averaged electrical probe data can be fit by a model with electrons of lower density and much higher energy than the majority of electrons in the plasma. Model simulations suggest that the plasma is significantly modulated by these electron emissions. Our ultimate purpose is to design a plasma probe to better understand the magnitude of this modulation. The voltage of the probe is observed as it charges a capacitor from a negative bias to the floating potential of the plasma. The derivative of the probe voltage gives the current through the probe. This is similar to a probe design that has been successfully used by Braithwaite, Booth et al. to study 13.56 MHz inductively coupled plasmas. This presentation focuses on the methods by which the time-resolved data are taken and analyzed. Our analysis method requires taking a numerical derivative, sorting the data by phase relative to driving voltage, and multiple pass smoothing techniques. The current versus voltage behavior observed for 40 kHz plasmas are on the whole consistent with expectations, even with different data sampling rates and with various plasma powers. While the results seem to suggest a strong influence of the secondary electrons, further work is required to improve the probe design.

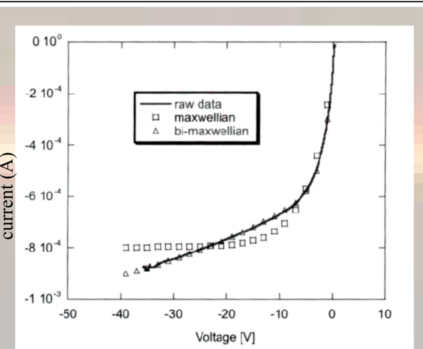
The Probe







This probe is based closely on the design found in N.St.J. Braithwaite, J.P. Booth, and G. Cunge, *Plasma Sources Sci. Technol.* **5** (1996), p. 677. How fast the probe charges depends on the density of ions and electrons. In an RF Plasma, this will vary with time.

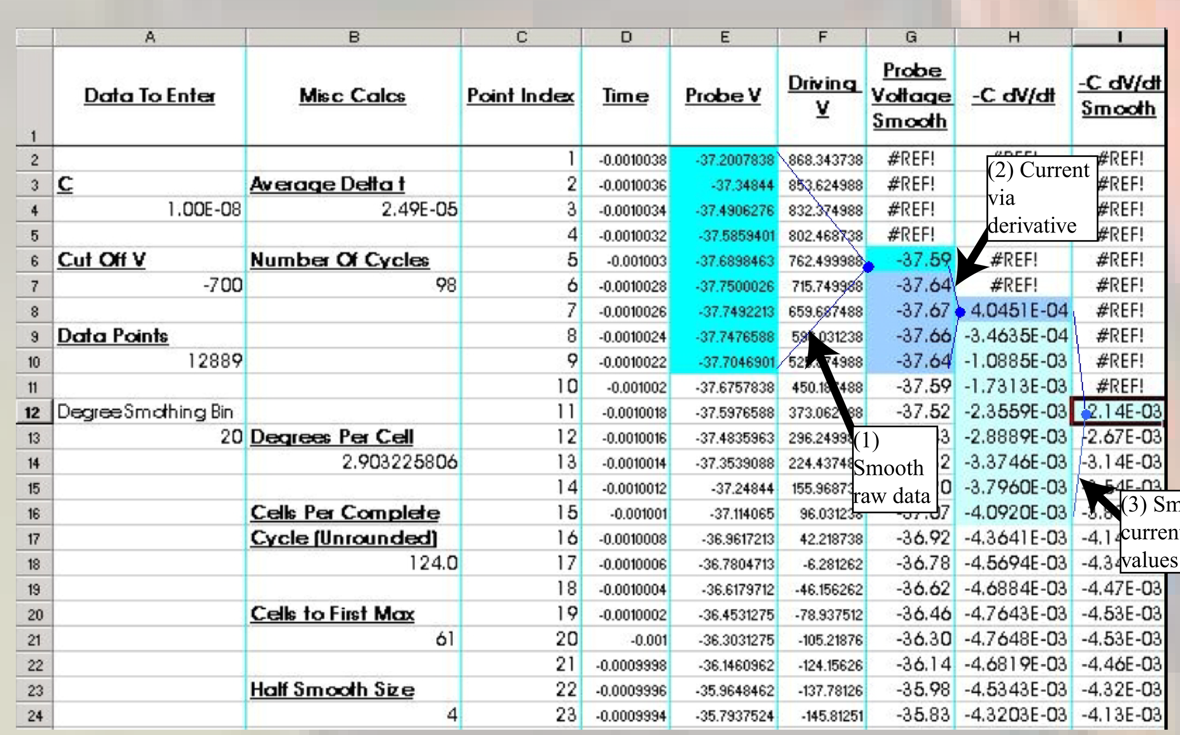


To the left is an example of a time-averaged I-V curve. The probe is inserted into the plasma, and charged negatively. As time progresses, the probe collects ions and eventually charges up to the plasma's floating potential. When the probe is at a very negative potential only hot elections (very high energy electrons) and ions are able to reach the probe.

Time-averaged data shows a change in the current even at large bias. This is consistent with a Maxwellian distribution of hot electrons. However, we believe that the hot electrons are time-modulated, not a thermal distribution [S. Conti, P.I. Porshnev, A. Fridman, L.A. Kennedy, J.M. Grace, K.D.Sieber, D.R. Freeman, K.S. Robinson, *Exp. Thermal Fluid Sci.* **24** (2001), p.79].

The Analysis

Synchronizing data acquisition with the driving voltage allows us to obtain clean data by averaging many runs without loosing time-resolved information.



	A	B	C	D	E	F	G	H	I
1	Data To Enter	Misc Calcs	Point Index	Time	Probe V	Driving V	Probe Voltage Smooth	-C dV/dt	-C dV/dt Smooth
2			1	-0.0010038	-37.2007838	868.343738	#REF!	[illegible]	#REF!
3	C	Average Delta t	2	-0.0010036	-37.34844	853.624988	#REF!		#REF!
4	1.00E-08	2.49E-05	3	-0.0010034	-37.4906276	832.374988	#REF!		#REF!
5			4	-0.0010032	-37.5859401	802.468738	#REF!		#REF!
6	Cut Off V	Number Of Cycles	5	-0.001003	-37.6898463	762.499988	-37.59	#REF!	#REF!
7	-700	98	6	-0.0010028	-37.7500026	715.749988	-37.64	#REF!	#REF!
8			7	-0.0010026	-37.7492213	659.687488	-37.67	4.0451E-04	#REF!
9	Data Points		8	-0.0010024	-37.7476588	[illegible]	-37.66	-3.4635E-04	#REF!
10	12889		9	-0.0010022	-37.7046901	[illegible]	-37.64	-1.0885E-03	#REF!
11			10	-0.001002	-37.6757838	[illegible]	-37.59	-1.7313E-03	#REF!
12	DegreeSmothing Bin		11	-0.0010018	-37.5976588	[illegible]	-37.52	-2.3559E-03	2.14E-03
13	20	Degrees Per Cell	12	-0.0010016	-37.4835963	[illegible]	[illegible]	-2.8889E-03	-2.67E-03
14		2.903225806	13	-0.0010014	-37.3539088	[illegible]	[illegible]	-3.3746E-03	-3.14E-03
15			14	-0.0010012	-37.24844	[illegible]	[illegible]	-3.7960E-03	[illegible]
16		Cells Per Complete	15	-0.001001	-37.114065	[illegible]	[illegible]	-4.0920E-03	[illegible]
17		Cycle (Unrounded)	16	-0.0010008	-36.9617213	42.218738	-36.92	-4.3641E-03	[illegible]
18		124.0	17	-0.0010006	-36.7804713	-6.281262	-36.78	-4.5694E-03	[illegible]
19			18	-0.0010004	-36.6179712	-46.156262	-36.62	-4.6884E-03	-4.47E-03
20		Cells to First Max	19	-0.0010002	-36.4531275	-78.937512	-36.46	-4.7643E-03	-4.53E-03
21		61	20	-0.001	-36.3031275	-105.21876	-36.30	-4.7648E-03	-4.53E-03
22			21	-0.0009998	-36.1460962	-124.15626	-36.14	-4.6819E-03	-4.46E-03
23		Half Smooth Size	22	-0.0009996	-35.9648462	-137.78126	-35.98	-4.5343E-03	-4.32E-03
24		4	23	-0.0009994	-35.7937524	-145.81251	-35.83	-4.3203E-03	-4.13E-03

(1) Smooth raw data

(2) Current via derivative

(3) Smooth current values

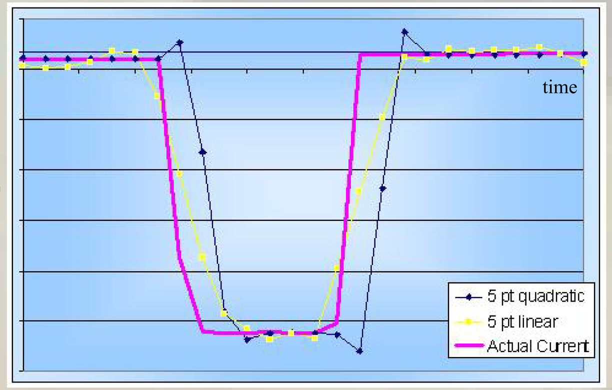
To find the current:

(1) A moving window average was used to smooth the raw data. The window size is adjusted relative to the sampling rate of the data set. Without this feature, data sets with different sampling rates cannot be meaningfully compared.

(2) A five point linear fit was then used to find the slope at the middle point. This value was then multiplied by the capacitance value to determine the current at that point.

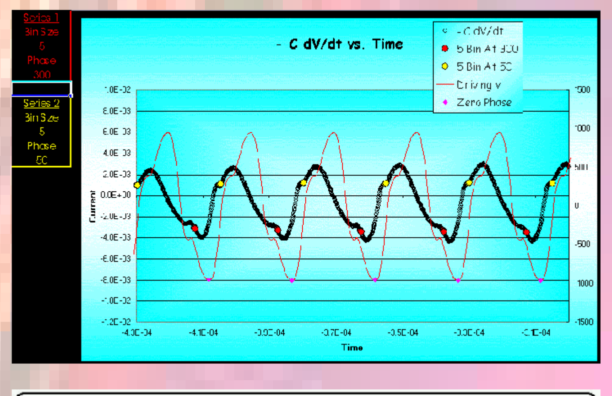
(3) Second iteration of data smoothing. Once again, the windows size varied depending on the sampling rate.

This smoothing/differentiating sequence was chosen because of its superior performance when compared to other methods (see below).

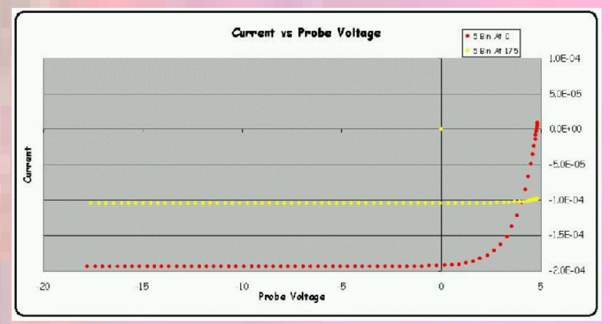


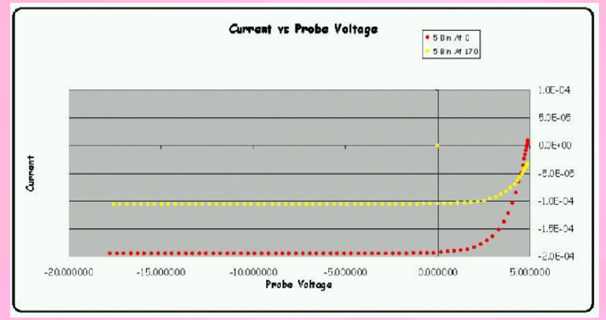
To determine the best method for taking a derivative, a simulated data set was created based on a known values of current. The derivative -C dV/dt was taken by fitting a window of points with a polynomial. One might expect that a higher order polynomial fit would be best. However, this is not so with data sets that contain sharp corners. In this case, a quadratic fit has a tendency to overshoot the correct value of the derivative, as illustrated in the adjacent graph. As a result of this discovery, we modified our spreadsheet to use the linear fit as opposed to the higher order fit.

Sorting by Phase



After the data from the probe is converted into current, it is sorted with respect to the phase of the driving voltage. We arbitrarily define the lowest value of the driving voltage as zero phase. The user then enters the phase they wish to look at, and the spread sheet extracts the appropriate data from the entire set. At the same driving voltage phase, the plasma should be in the same state. Thus, each phase can be thought of, and analyzed as, a DC plasma. The RF plasma is an amalgamation of an infinite number of DC plasmas, and this method parses the RF plasma into its DC parts.





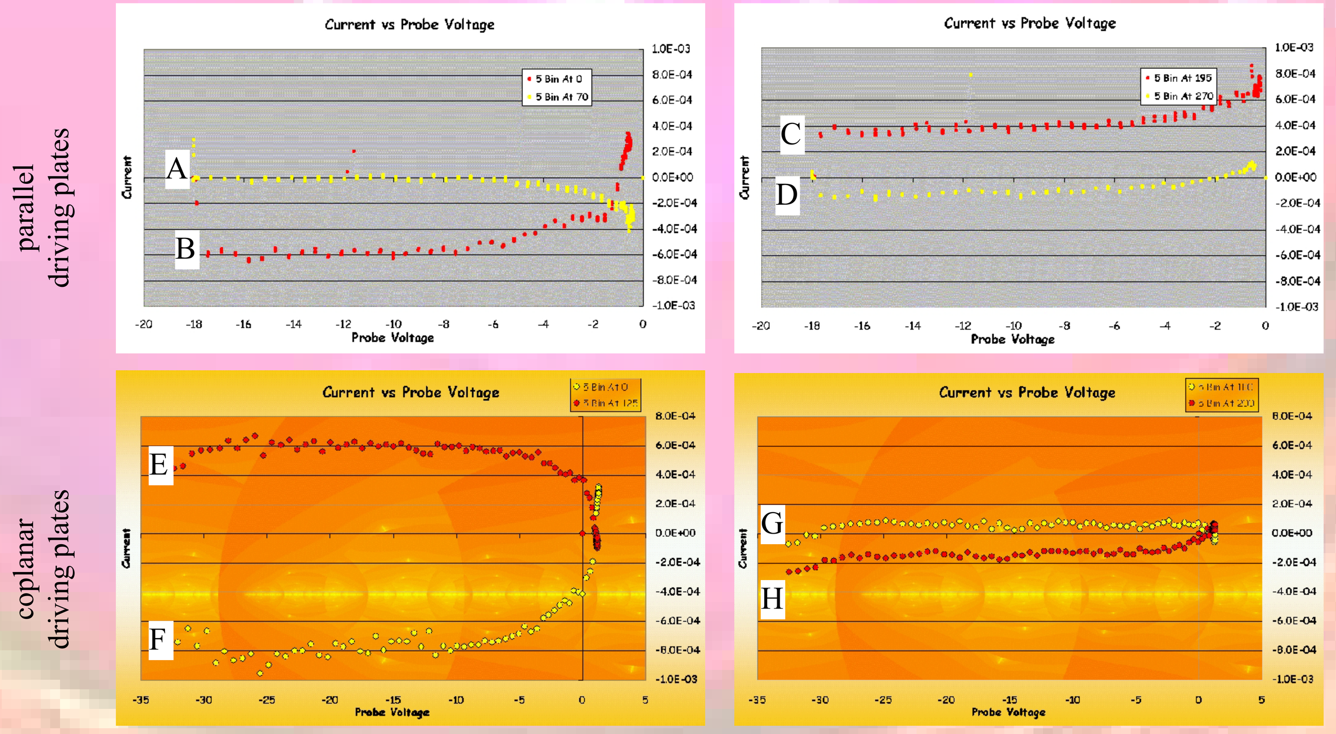
These are examples of simulated data. For most of the probe voltage, the current is fairly constant. The probe voltage is high enough to repel most thermally distributed electrons. As the probe reaches the plasma floating potential, more electrons are able to surmount the potential barrier and reach the probe.

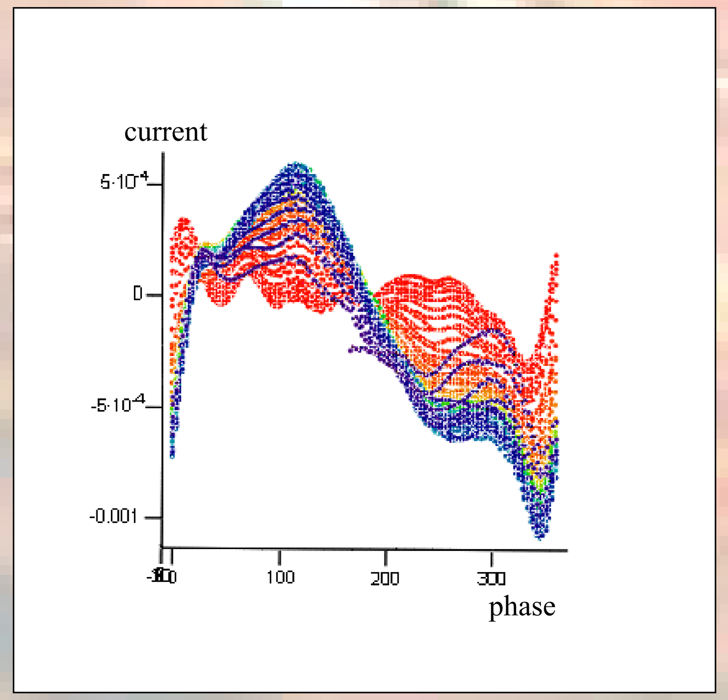
This model used a sinusoidally varying plasma density, which raises the IV curve because of the lower ion density. High energy electrons would have a similar effect.

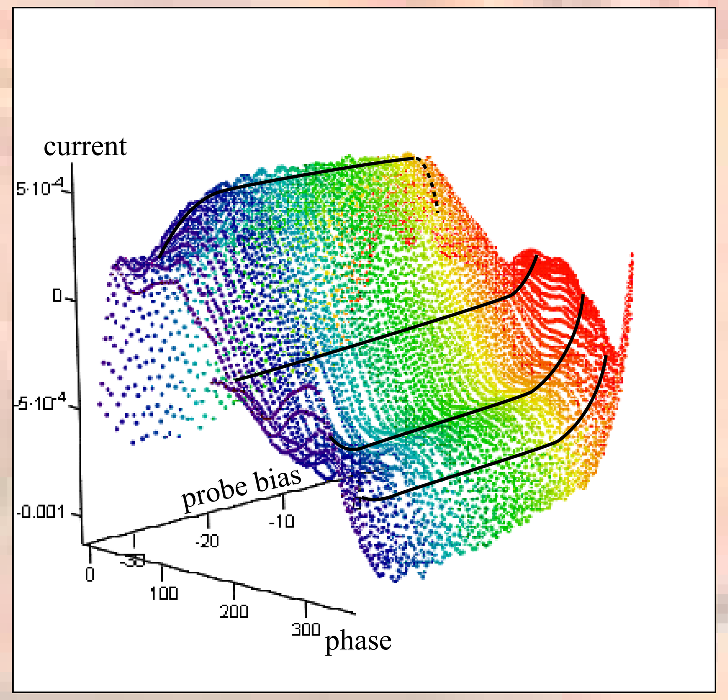
Real Data

These I versus V graphs have been taken from real data sets. Depending on the phase, there can be good agreement with expectations (classic ion charging, e.g. B or F) or inexplicable behavior. Currently it is not known whether these behaviors are properties of the probe, of the plasma, or some of each.

For instance, D and H could indicate low plasma densities. C is similar, however the positive currents could only be explained by hot electrons. A and E cannot currently be explained.







A good way to view an entire data set (rather than picking phases) is a 3D surface. However, these are difficult to use without the ability to rotate then on the computer screen.

A typical data set. (These are the same set from different angles.)
The axis parallel to the color is the phase.
Colors range over different voltages
The black lines are to guide the eye along different IV curves that can also be seen in 2D graphs.

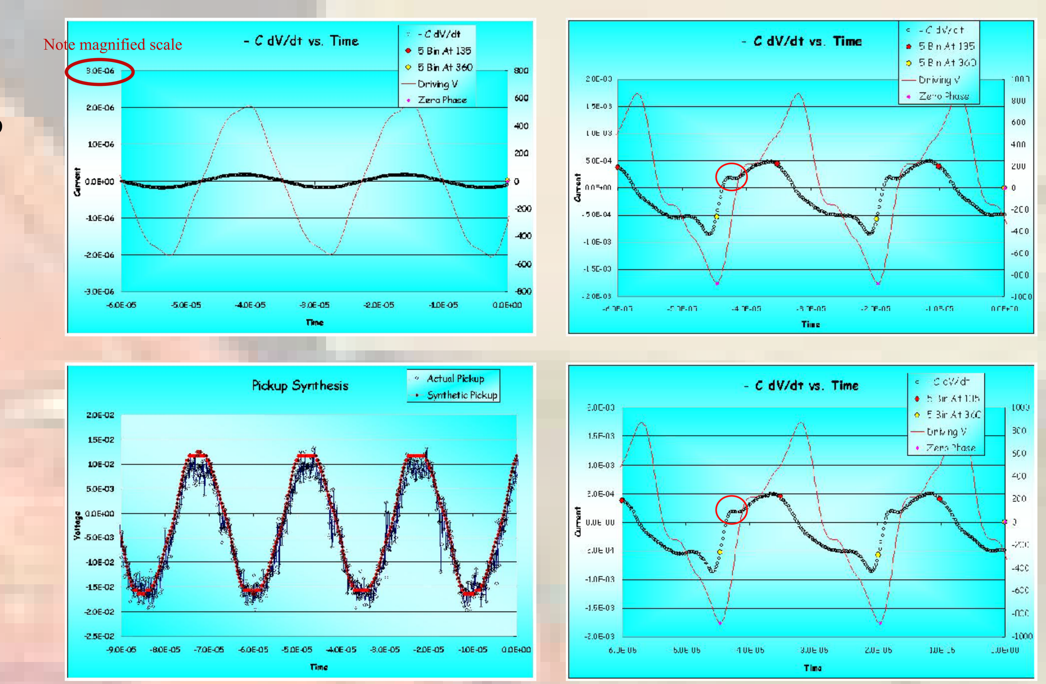
Evaluation of Probe Behavior

Rough Attempt at Removing Capacitive Pickup

Top: The system running without any plasma present results in some capacitive pickup from the driving voltage.

Bottom: To recreate this pickup in the real data sets, an FFT was taken of the driving voltage, and components were shifted by 90 degrees, scaled, and recombined. The blue data is the actual pickup, and the red is our recreation.

By following this procedure, pickup can be calculated even when the driving voltage is perturbed by the plasma.



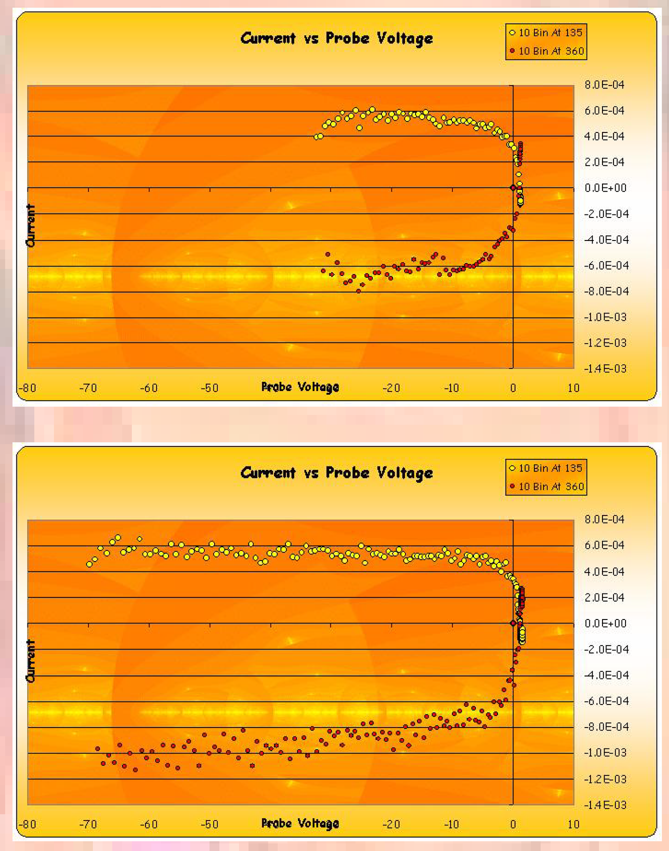
When applied to our data sets, the pickup was less than 5 percent of the total signal.

Top: the signal before subtracting the pickup

Bottom: the slightly changed signal after pickup subtraction

Note: This procedure does NOT take into account the fact that the plasma will change the coupling. However, the coupling is expected to be reduced by the plasma.

Transient Initial Behavior

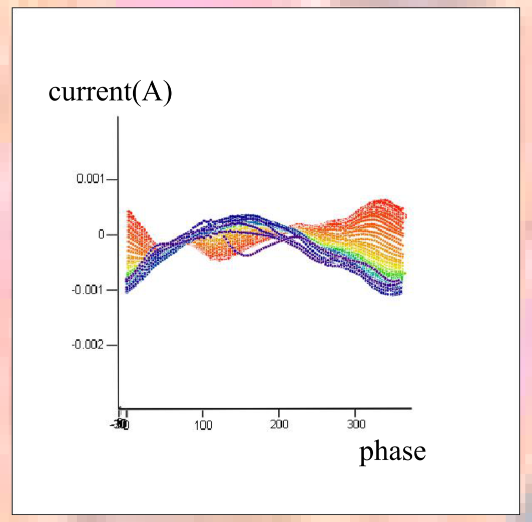


Top: Most data sets from the coplanar plasma showed some sort of initial increase in the amplitude of the oscillating current. These graphs show the I vs. V contour along the maximum and minimum. (Compare to the 3D images.)

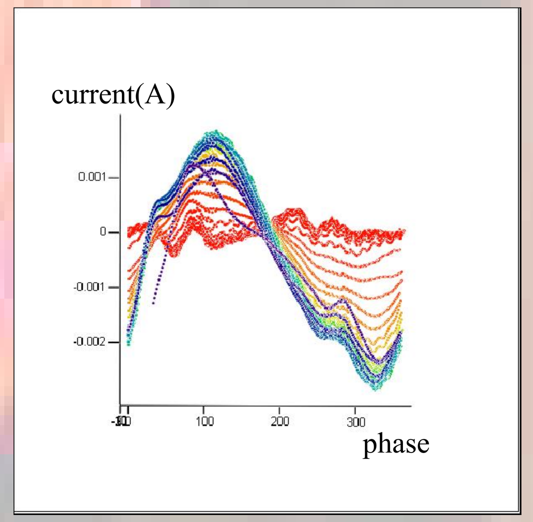
Below: The probe was charged to a larger negative bias. The lack of the same shape around -30V proves that this initial effect is caused by the probe and is not an actual property of the plasma.

The guard ring may be the cause of this effect if it is not tracking the potential of the probe properly. If there is a lag or tracking delay where the probe surface and guard ring are not at the same potential, then the area of the plasma that the probe effectively samples will vary with time. The capacitance between probe and guard ring may also become a factor.

(In)Sensitivity to Probe Contamination



Probe coated with a few nm of CF_x



After 30 minutes of exposure to a nitrogen plasma, probe response returns to uncoated shape. This is presumably an aluminum nitride surface.

Because of the capacitive design, this probe is electrically insensitive to buildup of non-conductive surface layers. However, it is sensitive to chemical changes on the surface.

For instance, even with the same actual ion current, changes in the (E) parameter change the apparent ion current ion the probe.

Conclusion

We have developed data analysis techniques that allow us to effectively analyze data from RF plasmas with our time-resolved ion flux probe. Data taken from real plasmas shows some indication that the hot electron density is time-modulated, rather than being a thermal distribution. However, the data cannot be completely explained by current theories.

Some of the analysis indicates a need for more study of this probe design. Although there is some capacitive pickup from the driving plates, it is negligible and can possibly be removed in future analysis. The transient behavior may indicate that the guard ring needs to be kept more closely at the same potential as the probe. The probe's response to contamination suggests that detailed information about the surface chemistry is required to interpret the data completely.