Summer Internship Report

Jonathan Sapan, Department of Electrical Engineering
Professor Sam Cohen, Advisor
15 September 2001

Abstract

I worked on the antenna system for the RMF/FRC apparatus. My tasks included simulation of the tuning circuit and antenna system as a whole, the characterization of various equipment to be used (RF amplifiers, phase shifters, etc.), design and construction of current probes, as well as experimenting with coupling RF power to relatively steady-state plasmas. The effect of various environmental variables upon circuit characteristics was noted, as was successful coupling of RF power to plasmas in a florescent bulb and the effect of plasmas on circuit characteristics.

Introduction

My first week at PPPL was spent attending lectures on plasma and experimenting with the apparatus in the "grad lab." While the interferometry experiment was not completed due to problems with the equipment and time constraints, I did experiment with various microwave components (phase shifters, attenuators, and polarizers), gaining a feel for the behavior of microwave and RF power transmission, noticing some unexpected phenomena. I then moved on to characterizing a variable phase-shifter from Sage, a quadrature hybrid from Werlatone, and two RF amplifiers from Amplifier Research. During the course of these characterizations, the effects of standing waves, power reflections, and other wave phenomena on RF power transmission were observed, serving to underscore the importance of impedance matching and choosing lengths of cable carefully. Towards the middle of the summer, I began working, along with a graduate student, on constructing current probes to measure current flowing through the individual antenna arms. After several attempts, coils with suitable gain were constructed, but difficulties arose with their sensitivity to orientation and placement. Later, a florescent bulb was placed inside the RMF/FRC apparatus cylinder and plasmas generated and sustained by a DC voltage (~300V). The antenna system was driven with RF power and the effects upon plasma luminance and current were monitored. The effects of the plasma on reflected power measurements and circuit characteristics were also observed.

Observations

The time spent in the "grad lab," while quite instructive, was not particularly remarkable, though some interesting phenomena were noticed. Coupling of microwave power between two dangling (i.e., left with free space at one end of the cavity) waveguides was observed, which, initially, was not entirely surprising as the dangling ends were facing each other at a distance of 5 cm or so. These observations occurred with the microwave source and waveguides configured for an interferometry experiment. Attenuating the reference signal (which was left dangling to observe only the signal passing through the plasma vessel) with an inline attenuator caused the signal to drop by approximately 1% (phase adjustments had similar effects), while blanking the beam with foil or attenuating foam produced up to a 3% change. Similar effects of lesser magnitude were observed with the reference beam at a distance of 10 cm and oriented at 90^{o} to the waveguide attached to the detector. In addition, in experimenting with inline phase-shifters, it was noticed that the effect of a phase-shifter depended upon its position along the waveguide and, furthermore, that two phase shifters coupled directly together in series, do not behave linearly at all, suggesting complicated standing wave effects. Though these observations were interesting, they were not pursued further, as they did not constitute the main thrust of my activities (namely to gain broad intuition about RF and microwave power and begin work on the RMF/FRC apparatus).

Phenomena suggesting the presence of standing waves were also noticed in the characterization of the splitter, quadrature hybrid, and amplifiers for use with the RMF/FRC experiment. These effects (see packets labeled “Sage Variable Phase Shifter Performance” and “AR 10-L Amplifier Performance”), were generally eliminated by ensuring proper impedance matching through the use of 50Ω terminators where necessary and by attempting to ensure unidirectional coupling when transmitting RF power (the quadrature hybrid and attenuators were used under different circumstances).

After numerous attempts, 2 current probes were constructed by wrapping formvar wire around small cylindrical metal slugs with diameters of roughly 5 mm. Difficulty constructing conventional Rogowski coils arose due to small clearances between the antenna arms and the glass vessel and due to the difficulty of making coils with adequate uniformity in turn density. The former approach was used because suitable gain was achieved and due to the ability to fasten the coils closely to the antenna in the hopes of being able to obtain consistent flux through the coils by carefully controlling their positions relative to the antenna arms. While the coils did initially provide consistent results, unexplained changes in coil gain occurred, possibly due to a greater sensitivity to position than expected or proximity to fields other than the radial fields of the antenna posts. Surprisingly, RF pickup from the MNX apparatus (approx. 10-15 feet away from the probes) was observed, and the waveforms appeared to be dependent upon plasma conditions in the MNX vessel, though no clear systematic phenomena were noticed. The interference was almost completely eliminated by carefully shielding the coil leads, which consisted of roughly 6 inches of twisted pair formvar wire.

A standard florescent bulb (with half its length uncoated for better viewing) was placed inside the apparatus and typical DC voltages of ~250V were applied across the bulb. Plasmas were sparked by discharges from a Tesla coil. The vertically oriented antenna (the top-bottom pair) of the FRC/RMF apparatus was driven by the output from an SRS function generator routed through a 50dB ENI RF amplifier (see Fig. 1 for a schematic of the equipment configuration). RF power (as much as 50W peak) was pulsed on and off at various modulation rates. While no quantitative measurement was made, the length of the cathode dark space of the discharge was observed to decrease in phase with the RF pulse, accompanied by a noticeable increase in the brightness of the discharge as a whole. A photodiode was placed a few cm from the bulb, its output routed to a lock-in amplifier, and measurements of output vs. input signal were taken with a series of flux conservers spanning the entire length of the apparatus vessel between the antennae and 50% of the length of the antenna region with similar behavior observed, aside from an approximately constant difference in the two amplifier signals (see Fig. 2). Later, a Pearson Rogowski coil was used to measure modulated current passing through the bulb as a function of input voltage. The output was again routed to a lock-in amplifier using the RF modulation as the reference and what appeared to be a power relationship was observed (see Fig. 3). The vertical antenna was also connected to a network analyzer and the ratio of reflected to transmitted power observed as a function of frequency in the absence and presence of plasmas. While details of the traces varied from run to run (possibly due to delamination of transmission lines and heating of circuit components; for instance, coupling was seen to improve when the transmission lines were warm, having just been disconnected from the pulsed RF output at higher powers, and seen to slowly degrade as the lines cooled), changes in circuit parameters – decreased reflected power ratios, impedance changes, and a narrowing of the peaks of the reflected power curves – were clearly visible upon the ignition of glow discharges. Calculations (assuming a 50Ω source impedance) for one run showed a series impedance without plasma of 48Ω and an impedance of 48.33Ω in the presence of a glow discharge at an input frequency of 13.0 MHz, calculated in the following manner, using the depth of the reflected power peak at the point in question (see Fig. 4; note that Q in the figure refers not to the circuit Q, but rather to the simple ratio of the frequency of the reflected power curve's peak to its bandwidth).

$$\frac{P_{reflected}}{P_{transmitted}} = \frac{Z_{load} - 50\Omega}{Z_{laod} + 50\Omega}$$

Additionally, on two occasions, particularly bright and/or unstable plasmas were seen in the bulb, producing reflected power curves of the same general form as the others, but with broader, lower peaks occurring at higher frequencies, and sawtooth patterns along their contours (as opposed to relatively fluid lines). These observations were not reproducible, particularly since the incidents coincided with burnt fuses in the DC power supply due to excessive currents.

Conclusions

The results above clearly indicate that RF power is being successfully to target plasmas and provides the beginning of a qualitative picture of the performance of the RMF/FRC apparatus antenna system. However, more careful measurements need to be made to make any precise quantitative conclusions from being drawn. The variability of observations, in many cases, points not only to issues with the measurements made, but also to physical variables that should not be neglected.

Over the summer, obtaining accurate current measurements proved an extremely difficult task. True Rogowski coils are clearly desirable due to their relative insensitivity to position around the current to be measured, but space constraints within the apparatus make the construction of a hand-made Rogowski coil with adequate uniformity problematic at best. Manufactured solutions may be available at reasonable cost.

Another problem area over the summer was transmission lines. Two different hand-made sets of transmission lines were constructed and appeared to behave adequately. Circuit simulations revealed low impedance, low delay lines ($Z_O \leq 1\Omega$) to be desirable in order to make tuning to lower frequencies (~2-4 MHz) more feasible. The impedance and delay of the lines constructed were calculated to be suitable; however, the hand-made lines tended to delaminate and fray. A manufactured solution capable of handling the currents expected through the circuit in the near future was ordered, but performance at higher currents (>10A) is unknown. Additionally, the effects of temperature upon the transmission lines is not well-known, aside from the observations mentioned above, nor is it known whether the temperature dependence in performance was due to transmission line heating, heating of other circuit components (capacitors), or both. The Faraday cage enclosing the apparatus was also observed to cause significant changes in circuit characteristics (e.g., changing the resonance) and finding a set of conditions for which the circuit characteristics are constant would obviously be desirable.

The measurements above were somewhat problematic due to the fact that fluctuations caused by the RF power were relatively small compared to baseline signals, necessitating the use of a lock-in amplifier whose calibration was unknown. Additionally, when using the photodiode, readings were observed to drift upward over time, perhaps due to the heating effects mentioned earlier, but possibly due to other, unknown, phenomena, making it impossible to compare readings at different positions along the bulb. Also, luminosity and current readings varied widely between plasmas.

In summary, this summer provided important confirmation that RF power can be coupled to plasmas in the RMF/FRC apparatus, but also illustrated the potential usefulness to conduct more rigorous measurements and characterizations of the apparatus, in order to fully understand future results.

FIGURE 1 GOES HERE

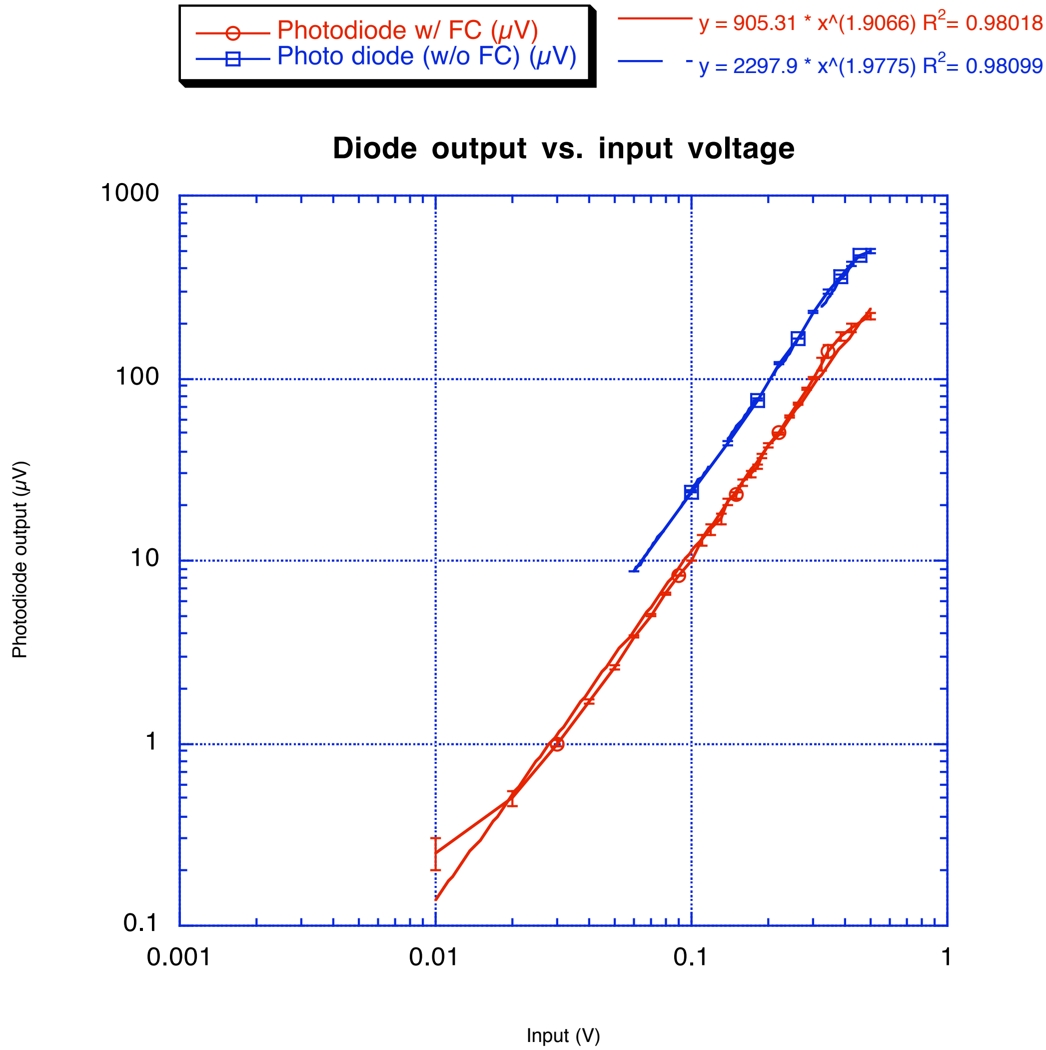

Figure 2. Diode output (fed through a lock-in amplifier) is shown as a function of input voltage. The upper curve represents data taken with the flux-conservers removed from 50% of the antenna region, while the lower curve shows the results with flux-conservers completely in place. A 10.35 MHz input signal was used, pulsed at 100 Hz.

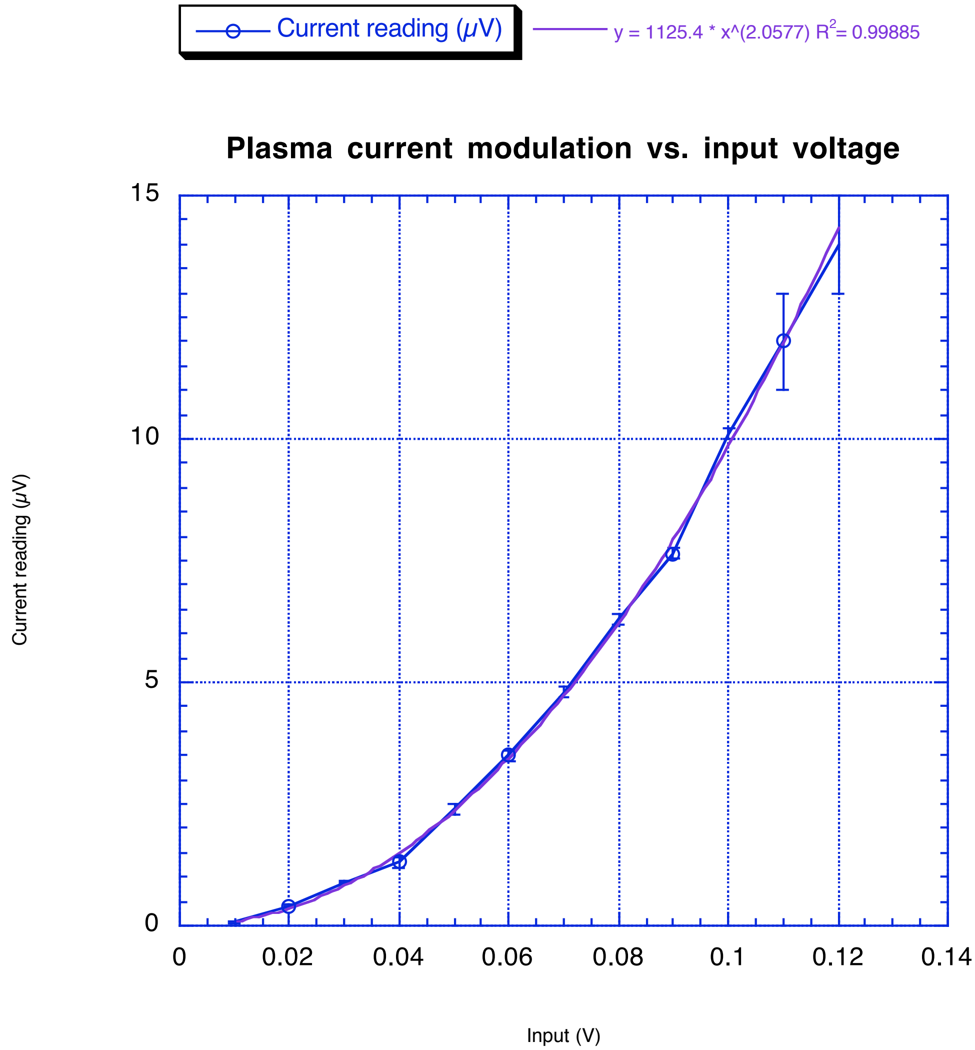

Figure 3. Signal from Rogowski coil (1 V/A) fed through lock-in amplifier vs. input voltage. A 10.33 MHz input signal was used, pulsed at 100 Hz.

FIGURE 4 GOES HERE

Summer Internship Report

Jonathan Sapan, Department of Electrical Engineering
Professor Sam Cohen, Advisor
15 September 2001